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Canyon de Chelly National Monument

Geologic Resources Inventory Report



Photograph of the De Chelly Sandstone. Referred to as “massive,” “grandiose,” and “swooping,” the cross-beds in the sandstone are a conspicuous feature. The horizontal bedding planes (between cross-bed “packages”) are also conspicuous. The cross-beds formed about 275 million years ago as prevailing northeasterly winds blew across the supercontinent Pangea. Today, prevailing winds are from the southwest.
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Canyon de Chelly National Monument: Geologic resources inventory report

Science Report NPS/SR—2024/159

Katie KellerLynn

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

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Abstract

Geologic Resources Inventory reports provide information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in GRI reports may also be useful for interpretation. This report synthesizes discussions from a scoping meeting held in 2007 and a follow-up conference call in 2022. Chapters of this report discuss the geologic heritage, geologic history, geologic features and processes, and geologic resource management issues of Canyon de Chelly National Monument. Guidance for resource management and information about the previously completed GRI GIS data and poster (separate products) is also provided.

Acknowledgements

The GRI recognizes the long history of this land (more than 300 million years) and the connections that Indigenous Peoples have to it. Called Tséyi' by Navajo speakers, this place is referred to as the "monument" throughout this report. The monument is located entirely within the Navajo Nation. In addition to the Navajo Nation of Arizona, New Mexico, and Utah, traditionally associated Tribes and Pueblos include the Hopi Tribe of Arizona; Ohkay Owingeh of New Mexico; the Pueblos of Acoma, Cochiti, Isleta, Jemez, Kewa, Laguna, Nambe, Picuris, Pojoaque, San Felipe, San Ildefonso, Sandia, Santa Ana, Santa Clara, Taos, Tesuque, Zia, and Zuni of New Mexico; and the Ysleta del Sur Pueblo of Texas (National Park Service 2016).

The GRI team thanks the participants at the 2007 scoping and the 2022 follow-up meetings for their assistance in this inventory.

Because the GRI team does not conduct original geologic mapping, we are particularly thankful to the USGS for its maps of the area. This report and accompanying GIS data could not have been completed without them. Also, thanks very much to William G. "Bill" Parker (Petrified Forest National Park) for clarifying and updating (since geologic mapping shown in the GRI GIS data) the nomenclature of the Chinle Formation and its correlation to the monument's geology.

Thanks very much to all those who reviewed this report. Special thanks to Steven Semken (Arizona State University) for his thoroughness and insights into the current geologic interpretations of this part of Arizona. Also, thanks very much to Hal Pranger (NPS Geologic Resources Division) for his geomorphic insights on the "Watershed Restoration" section. Moreover, thanks very much to Keith Lyons (Canyon de Chelly National Monument/Hubbell Trading Post National Historic Site/Navajo National Monument) and Josh Ramsey (Canyon de Chelly National Monument) for taking the time to discuss reviewers' comments and answer questions as part of the final review process of this report.

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The following lists of people reflect the names and affiliations of participants at the time of those meetings. The lists are organized either alphabetically by last name or with respect to relative contribution to a project.

2007 Scoping Participants

Ailema Benally (NPS Canyon de Chelly National Monument)

Arthur Benally (NPS Canyon de Chelly National Monument)

Pamela Benjamen (NPS Intermountain Region)

Ron Blakey (Northern Arizona University)

Tim Connors (NPS Geologic Resources Division)

Hank Hayou (NPS Canyon de Chelly National Monument)

Margaret Hiza Redsteer (US Geological Survey)

Deanna Greco (NPS Geologic Resources Division)

Katie KellerLynn (Colorado State University)

Elaine Leslie (NPS Canyon de Chelly National Monument)

Keith Lyons (NPS Canyon de Chelly National Monument)

Lisa Norby (NPS Geologic Resources Division)

Steven Semken (Arizona State University)

Lisa Skinner (Northern Arizona University)

Phil Stoffer (US Geological Survey)

Scott Travis (NPS Canyon de Chelly National Monument)

Paul Umhoefer (Northern Arizona University)

2022 Follow-Up Meeting Participants

Lyn Carranza (NPS Canyon de Chelly National Monument, Navajo National Monument, and Hubbell Trading Post National Historic Site)

Tim Connors (NPS Geologic Resources Division)

Thom Curdts (Colorado State University)

Tim Henderson (NPS Geologic Resources Division, associate)

Katie KellerLynn (Colorado State University)

Keith Lyons (NPS Canyon de Chelly National Monument)

Heather Morrison (NPS Canyon de Chelly National Monument and Hubbell Trading Post National

Historic Site)

Maryann Neubert (NPS Hubbell Trading Post National Historic Site)

Rebecca Port (NPS Geologic Resources Division)

Hal Pranger (NPS Geologic Resources Division)

Cassandra Reed (NPS Hubbell Trading Post National Historic Site)

Steven Semken (Arizona State University)

Justin Tweet (NPS Geologic Resources Division, associate)

Darren Wagner (NPS Canyon de Chelly National Monument)

Don Weeks (NPS Department of the Interior Regions 6–8)

John R. "Jack" Wood (NPS Geologic Resources Division)

JoAnne Young (NPS Navajo National Monument)

Ryan Young (NPS Canyon de Chelly National Monument)

Report Author

Katie KellerLynn (Colorado State University)

Report Review

Michael J. Evans (NPS Interior Regions 3, 4, 5 [Midwest])

Heather Morrison (Canyon de Chelly National Monument)

Hal Pranger (NPS Geologic Resources Division)

Rebecca Port (NPS Geologic Resources Division)

Pat Seiser (NPS Geologic Resources Division and National Cave & Karst Research Institute)

Steven Semken (Arizona State University)

Justin Tweet (NPS Geologic Resources Division, associate)

John R. "Jack" Wood (NPS Geologic Resources Division)

Report Editing

Suzanne McKetta (Colorado State University)

Report Formatting and Distribution

Rebecca Port (NPS Geologic Resources Division)

Cullen Scheland (NPS Geologic Resources Division)

Source Map Authors

H. M. Beikman (US Geological Survey)

V. P. Byers (US Geological Survey)

R. J. Hackman (US Geological Survey)

A. B. Olson (US Geological Survey)

R. B. O'Sullivan (US Geological Survey)

R. E. Thaden (US Geological Survey)

GRI GIS Data Production

Jim Chappell (Colorado State University)

Kajsa Holland-Goon (Colorado State University)

Lucas Chappell (Colorado State University)

Stephanie O'Meara (Colorado State University)

James Winter (Colorado State University)

GRI Poster Design

Thom Curdts (Colorado State University)

Shea Slonkosky (Colorado State University)

Executive Summary

Comprehensive park management to fulfill the National Park Service (NPS) mission requires an accurate inventory of the geologic features of a park unit, but park managers may not have the needed information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.

Canyon de Chelly National Monument (referred to as the "monument" throughout this report) is near the town of Chinle in Apache County, Arizona. The monument includes three major canyons—(1) Canyon de Chelly, about 43 km (27 mi) long; (2) Canyon del Muerto, about 29 km (18 mi) long; and (3) Monument Canyon, about 16 km (10 mi) long—as well as tributary canyons to these three major canyons and the land within 0.8 km (0.5 mi) of the rims of these canyons. The monument encompasses approximately 34,000 ha (84,000 ac).

The monument was authorized and proclaimed in 1931 as part of the National Park System and is administered by the NPS, but it is not composed of federal land. Rather, the monument is located entirely within the Navajo Nation.

The monument was established to maintain and preserve an outstanding concentration of archeological resources, representing thousands of years of occupation and agriculture, as well as other features of scientific, historical, and educational interest. The monument also contains stunning geologic resources, for example, iconic Spider Rock and the cross-bedded De Chelly Sandstone. The monument provides opportunities to appreciate the interplay between geology, history, and contemporary experiences through its intimate scale and sheer cliffs, geologic shapes, patterns, and vibrant hues, and the contrasts of light and shadow cast by canyon walls.

While the human story represented here covers about 5,000 years, the geologic story records 60,000 times more, that is, 300 million years of Earth's history. Significant events include the development of the Ancestral Rocky Mountains and the accumulation of sediments that would become the monument's bedrock. Also, entrenchment (downward incision by a river through surficial deposits and into bedrock) by the Colorado River system is significant as is the eruption of the Navajo volcanic field. Views from the monument are enhanced by nearby volcanic landforms.

This GRI report is based on the most accurate, up-to-date geologic mapping known at the time of writing and compiles and summarizes park-specific geologic information and research. It was written with park management in mind and incorporates the monument's significance as expressed in its foundation document.

This report—which is the culmination of the GRI process—contains the following chapters:

Introduction to the Geologic Resources Inventory—This chapter provides background information about the GRI and highlights the GRI process and products. A geologic map in GIS format (referred

to as “GRI GIS data” throughout this report) is the principal deliverable of the GRI. US Geological Survey (USGS) source maps were used by the GRI team in compiling these GRI GIS data for the monument. The chapter provides specific information about the use of these GRI GIS data and calls attention to the poster that illustrates these data. GRI GIS data were originally delivered to monument managers in 2008, but an unfixable spatial shift was discovered in those data during the writing of the GRI report, so different source data were selected and compiled in 2022.

Park Background and Establishment—This chapter orients readers to the geologic setting of the monument, provides a historical context, and highlights the monument’s establishment and operation. A timeline applicable to the monument’s history is provided.

Geologic Heritage—This chapter introduces the concept of geologic heritage, which exists at the overlap of geology and human experiences and values. The chapter draws connections between geologic resources and other park resources and stories. The concept of geologic heritage evokes the idea that geologic landscapes are an integral part of the history and cultural identity of the United States. In the case of the monument, geologic heritage encompasses iconic rock features such as Spider Rock, Face Rock, and Navajo Fortress. Other features of geologic heritage value include ancient sand dunes (preserved in the De Chelly Sandstone), fossils, lithics (discussed in the archeological sense of “stone tools”), plaster, volcanic landforms, sources of water, rock shelters (considered a type of cave by the GRI; commonly referred to as “rock alcoves” by monument staff), desert varnish, and rock art (petroglyphs and pictographs).

Geologic History—This chapter describes five significant geologic events that led to the monument’s present-day landscape: (1) development of the Ancestral Rocky Mountains, (2) accumulation of sediments in marine and terrestrial settings, (3) the Laramide Orogeny (mountain-building event), (4) volcanism (in the Navajo volcanic field), and (5) entrenchment of the Colorado River system. The chapter includes a table that serves as a geologic time scale, putting the monument’s bedrock and other map units in a context of geologic time. The chapter also includes four paleogeographic maps that show what Earth looked like when the monument’s bedrock was being deposited.

Geologic Features and Processes—This chapter describes the geologic features and processes of significance to the monument. The monument’s bedrock is made up of the Supai Formation, the De Chelly Sandstone, and the Chinle Formation. Other features include unconformities (breaks in the rock record); folds (bends in rock strata), faults (breaks in rock strata along which movement has taken place), and related landforms; the Navajo volcanic field; pediments (erosion surfaces); river and stream features and processes; the genesis (timing and process of formation) of rock shelters; and sand dunes.

Geologic Resource Management Issues—This chapter discusses management issues related to the monument’s geologic resources (features and processes). The issues were identified by participants during the scoping meeting in 2007 and the follow-up meeting in 2022. Issues are listed alphabetically, not in the order of management priority. Inventory, monitoring, and protection of the monument’s caves (referred to as “rock shelters” throughout this report) is an important issue.

Although climate change planning is beyond the scope of the GRI, climate change is discussed because of the potential disruption it may cause to park resources, including geologic resources. Geologic hazards are a management issue, and a checklist (table) identifies known and potential hazards. Known hazards include dust/sandstorms, flash floods, quicksand and dry sand, riverine ("regional") floods, rockfall, and shrink/swell soils. Potential hazards include contamination of rock shelters, earthquakes, radon, slope movements (other than rockfall), and volcanic eruptions. Other issues include a legacy of uranium exploration; paleontological resource inventory, monitoring, and protection; and rock art documentation. Finally, the long-standing and ongoing issue of watershed restoration is discussed, and a geomorphic perspective is applied.

Guidance for Resource Management—This chapter provides resource managers with a variety of ways to find and receive management assistance for the issues discussed in the "Geologic Resource Management Issues" chapter or other geologic issues. The chapter includes a section citing laws, regulations, and policies relevant to managing NPS geologic resources.

In addition to these chapters, "Additional References, Resources, and Websites" lists online and other publications that may be useful for geologic resource management at the monument. "Literature Cited" provides a bibliography of all the references cited in this GRI report. It serves as a source of park-specific geologic information applicable to the protection, management, and interpretation of the monument's geologic resources.

Introduction to the Geologic Resources Inventory

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the National Park Service (NPS) Natural Resource Stewardship and Science Directorate (NRSS), provides geologic map data and pertinent geologic information to support resource management and science-informed decision making throughout the National Park System. The GRI is funded by the NPS Inventory and Monitoring Division.

GRI Products

The GRI team—which is primarily a collaboration between the NPS and the Department of Geosciences at Colorado State University—completed the following tasks as part of the GRI process for Canyon de Chelly National Monument (referred to as the "monument" throughout this report): (1) conduct a scoping meeting and provide a scoping summary, (2) provide geologic map data in a geographic information system (GIS) format, (3) create a poster to display the GRI GIS data, and (4) provide a GRI report.

GRI products are available on the "Geologic Resources Inventory—Products" website and through the NPS Integrated Resource Management Applications (IRMA) DataStore (see "Access to GRI Products"). Ground-disturbing activities should neither be permitted nor denied based on the information provided in GRI products. The graphic and written information provided in this report is not a substitute for site-specific investigations.

Scoping Meeting

On 15–16 February 2007, the NPS held a scoping meeting at the monument. At that time, the GRI was called the Geologic Resource Evaluation (GRE) program but has since changed names. The scoping meeting brought together monument staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (KellerLynn 2007) summarizes the findings of that meeting.

GRI GIS Data

In 2008, the GRI team used *Geologic Map of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah* (scale 1:24,000), which is plate 1 of *Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, with a Section on Vegetation* (Cooley et al. 1969), to compile the GRI GIS data for the monument. Although the geologic interpretation provided on that map and in the accompanying report by Cooley et al. (1969) are accurate, during the initial research and writing stage of the GRI report in 2022, the GRI team discovered a spatial "shift" (i.e., geology and topography did not line up) on the map. The so-called shift was deemed "unfixable," so the GRI team selected two different source maps, which were then compiled into the GRI GIS data in 2022. Portions of the following two USGS maps now comprise the GRI GIS data for the monument (Figure 1):

- O'Sullivan, R. B., and H. M. Beikman. 1963. Geology, structure, and uranium deposits of the Shiprock quadrangle, New Mexico and Arizona (scale 1:250,000), sheet 1 of 2. Miscellaneous Geologic Investigations Map I-345. US Geological Survey, Washington, DC.
- Hackman, R. J., and A. B. Olson. 1977. Geology, structure, and uranium deposits of the Gallup 1° × 2° quadrangle, New Mexico and Arizona (scale 1:250,000), sheet 1 of 2. Miscellaneous Investigations Series Map I-981. US Geological Survey, Washington, DC.

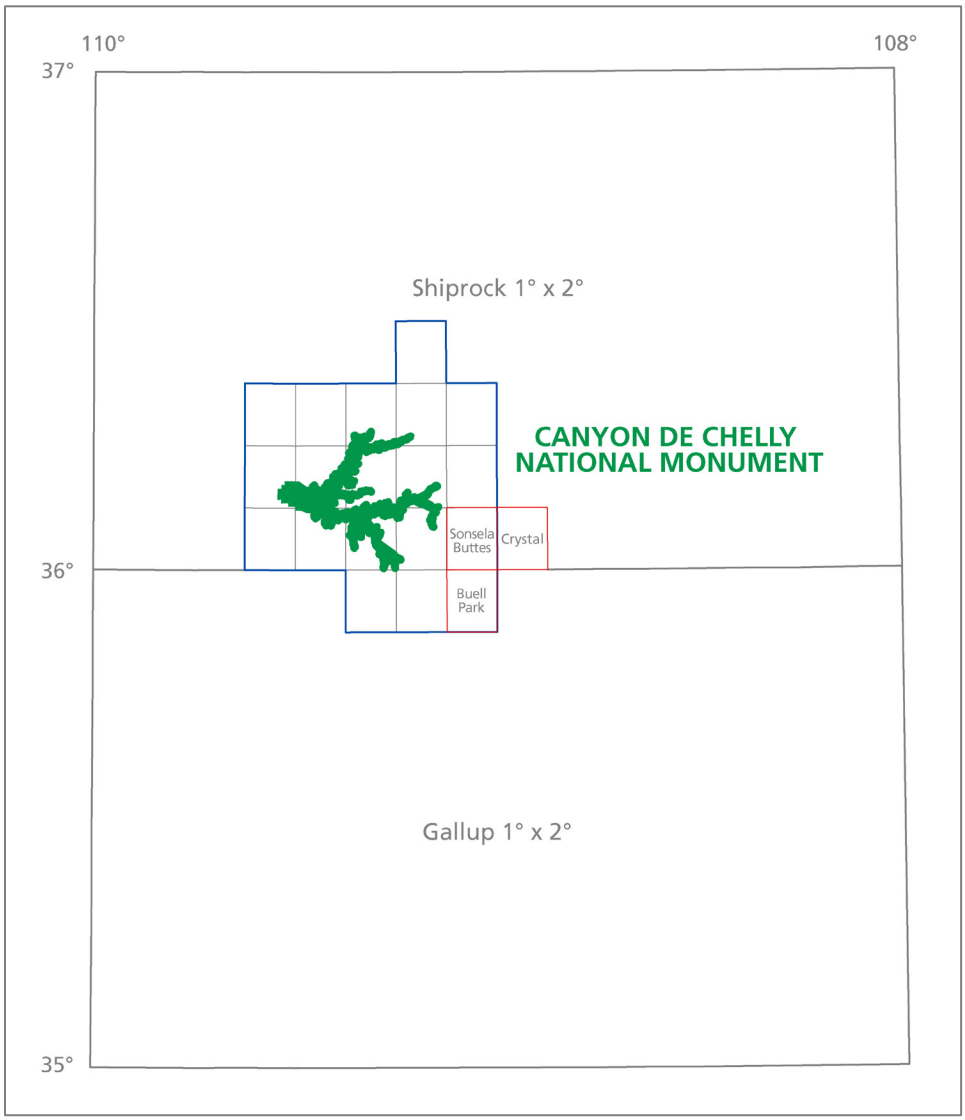


Figure 1. Index map of the GRI GIS data. The index map displays the extents of the GRI GIS data produced for the monument. These data compile five total source maps. The two principal source maps are O'Sullivan and Beikman (1963) and Hackman and Olson (1977) for the Shiprock 1° × 2° and Gallup 1° × 2° quadrangles, respectively (blue outline). Those two source maps and the corresponding GIS data were the principal maps used in the preparation of this report and were also used to prepare the poster. Three other maps—Buell Park, Sonsela Buttes, and Crystal 7.5-minute quadrangles (red outline)—also have corresponding GRI GIS data, but those maps are not included on the poster. The monument is shown with green fill. Graphic by Kajsa Holland-Goon (Colorado State University).

Based on the scale of these source maps (1:250,000) and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are expected to be horizontally within 127 m (417 ft) of their true locations.

In addition, the GRI team compiled geologic GIS data for the Crystal, Sonsela Buttes, and Buell Park 7.5-minute quadrangles (Figure 1) from source maps by Byers (1979), Byers (1980), and Thaden (1990), respectively. During scoping, monument managers expressed interest in these maps because they cover areas at the head of the monument's watershed. Based on the scale of these source maps (1:24,000) and US National Map Accuracy Standards, geologic features represented in those data are expected to be horizontally within 12 m (40 ft) of their true locations. At a scale of 1:24,000, these data provide more detail than the data based on the 1:250,000-scale source maps.

Significantly, starting in the 1990s, that is, since the timing of mapping of the source maps, the stratigraphic nomenclature of the Chinle Formation—one of three bedrock units in the monument—has undergone revisions. The Monitor Butte Member and the red member (map unit symbol **TRcmb**; see the "Geologic History" chapter for an explanation and further discussion of map unit symbols) are now correlated with the Bluewater Creek Member of the Chinle Formation. In addition, the Sonsela Sandstone Bed of the Petrified Forest Member (**TRcps**) is now recognized as the Sonsela Member of the Chinle Formation (see "Three Formations: Chinle Formation"). The GRI GIS data do not show these revisions, but the changes are noted on the geologic map poster (see "GRI Poster").

GRI GIS data are the principal deliverable of the GRI. The GRI team did not conduct original geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data. The GRI team standardizes map deliverables using a data model that dictates GIS data structure, including layer architecture, feature attribution, and relationships within Esri ArcGIS software (see "Access to GRI Products"). The GRI GIS data may be updated again if new, more accurate geologic maps become available or if software advances require an update to the digital format.

More information about the GRI GIS data can be found in the files accompanying the data on IRMA. The GIS readme document explains the available file formats for the GRI GIS data, how to use the different file formats, and where to find more information about the GIS data model. The ancillary map information document includes essential elements of the source maps such as a map unit list; map unit descriptions from all source maps; map legends, references, and cross sections from each source map; correlation charts and/or schematic diagrams showing correlations of rock units; and an index map of the GRI GIS data (Figure 1).

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the monument and surrounding area is the primary figure referenced throughout this GRI report. The poster is not a substitute for the GIS data but is supplied as a helpful tool for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the poster. Geographic information and selected

park features have been added. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources.

The GRI GIS data displayed on the poster are from the source maps by O'Sullivan and Beikman (1963; Shiprock 1° × 2° quadrangle) and Hackman and Olsen (1977; Gallup 1° × 2° quadrangle). Posters of the Crystal, Sonsela Buttes, and Buell Park quadrangles were not produced.

GRI Report

This report is a culmination of the GRI process. It is based on the GRI GIS data and follows interpretations used by the source map authors, primarily O'Sullivan and Beikman (1963) and Hackman and Olsen (1977), as well as the previous source map by Cooley et al. (1969). The report synthesizes discussions from the 2007 and 2022 meetings and incorporates reviewers' comments, additional discussions with monument staff, additional input from subject matter experts, and more up-to-date geologic findings.

The primary audience of the GRI report is the monument's resource managers, but the GRI team hopes that the report will also be appealing and useful to other audiences, such as park interpreters, canyon residents, and visitors. To that end, the report attempts to avoid technical terms and be accessible to readers without a background in geology. Nevertheless, like other sciences, geology is based on complex concepts and is full of jargon related to these concepts. Thus, this GRI report uses geologic terminology, but the terms are defined at their first instance, usually in parentheses following the term. Commonly, graphics are provided to illustrate unfamiliar concepts.

Geologic and geographic names used in this report reflect the formal nomenclature found in the US Geologic Names Lexicon ("Geolex") and the spellings recorded in the Geographic Names Information System (GNIS), respectively. Geolex is a national compilation of names and descriptions of geologic units maintained by the USGS (see "Additional References, Resources, and Websites"). The GNIS contains geographic terms that the US Board on Geographic Names has formally accepted. In 1947, the Secretary of the Interior was given joint authority with the US Board on Geographic Names and has final approval of the board's actions. The online GNIS database is maintained by the USGS (see "Additional References, Resources, and Websites").

In some cases, park maps and other publications use names that are not recorded in the GNIS but are used by park staff and others living in the area. In these cases, exceptions are pointed out, and variant names and spellings are noted in the report.

Navajo words for place names, people, and historic events are included in this report. In general, Navajo words are provided at first instance, with an English translation following in parentheses. Typically, the English word is then used throughout the remainder of the report.

Park Background and Establishment

This chapter provides a general geographic and geologic orientation to the monument. It also provides a historic timeline, including establishment of the national monument.

Physiographic and Geologic Setting

The monument is part of the Colorado Plateau physiographic province, which is roughly centered on four states: Arizona, Utah, Colorado, and New Mexico. As such, the aptly named "Four Corners Area" and the Colorado Plateau are commonly associated (Figure 2). The monument lies near the center of the Colorado Plateau.

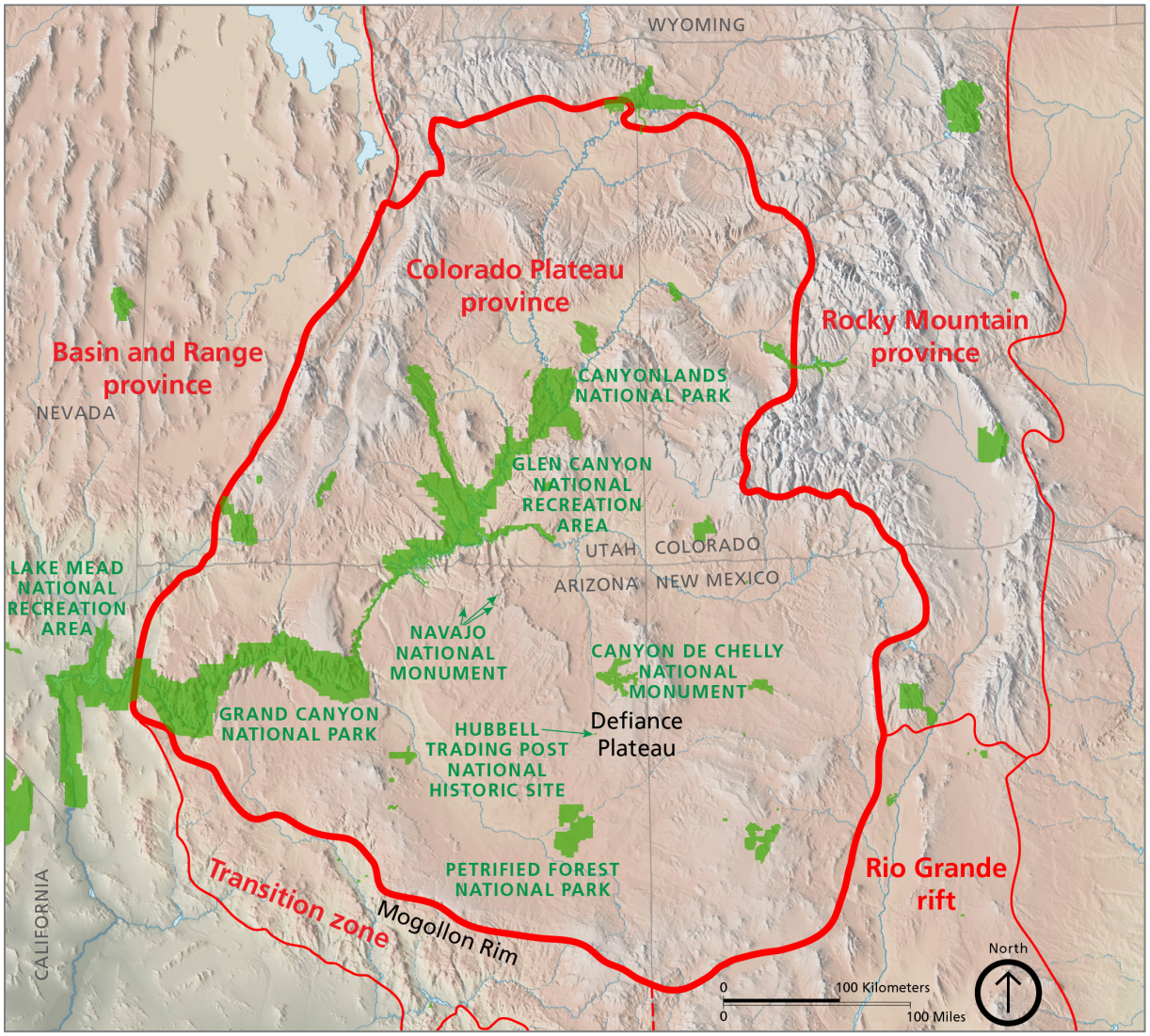


Figure 2. Map of the Colorado Plateau physiographic province. Located in the Four Corners Area of Arizona, Utah, Colorado, and New Mexico, the monument is one of many NPS areas in the region. The figure shows these areas in green; labels identify a selection of them. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University). Base map by Tom Patterson (National Park Service).

The Colorado Plateau displays flat-lying to mildly deformed, multihued, sedimentary rocks in cliffs, broad mesas, steep-sided canyons, and badlands topography (Baars 1983). In geologic terms, "deformed" means having folds (bends in originally flat layers of rock) or faults (fractures in a body of rock along which movement has occurred). The spectacular scenery in the Colorado Plateau region is mostly due to differential erosion (caused by differences in the resistances of adjacent rock layers), which has created the colorful, stair-stepped appearance that is so typical of the region (Reynolds 1998). Tectonic processes have also played a role in creating the types, shapes, and geographic positions of many large landforms (see "Folds, Faults, and Related Landforms").

At least two key features define the Colorado Plateau. First, Earth's crust that underlies the plateau is thick, much thicker than the crust in the adjacent Basin and Range physiographic province (Figure 2). Geologic interpretations concerning the thickness of the plateau's crust vary; work by Parsons et al. (1996) provides a range between about 30 and 48 km (19 and 30 mi) thick, with the thickest area being the Kaibab Plateau on the north rim of the Grand Canyon. Second, the Colorado Plateau stands high above sea level. Elevations range from 3,700 m (12,000 ft) above sea level in the high plateaus of Utah to 610 m (2,000 ft) above sea level in the western Grand Canyon; the average elevation is 1,900 m (6,200 ft) above sea level (Price 2010). For context, Chinle, Arizona (west of the monument), is 1,683 m (5,522 ft) above sea level (Figure 3).

Bedrock in the monument rises to the east in an uplifted area known as the Defiance uplift (geologic term) or Defiance Plateau (geographic term). The uplift/plateau is structurally high and separates the basin of the Black Mesa (named for the coal mined there) from the San Juan Basin, west and east of the monument, respectively. Notably, the term "San Juan Basin" is capitalized throughout this report because it is a formally recognized feature in the GNIS (see "Additional References, Resources, and Websites"). Although "Black Mesa" is a formally recognized geographic feature, the "Black Mesa basin" is not; thereby, that term is not capitalized.

The Defiance Plateau is about 160 km (100 mi) long and has an average width of about 60 km (40 mi), except along the Puerco River, where the average width is 100 km (60 mi) (De Harport 1959). The Chuska Mountains (see poster), which mark the eastern part of the Defiance Plateau, rise to elevations of about 2,900 m (9,500 ft) above sea level. By comparison, the elevation of the western rim of the Defiance Plateau is about 1,800 m (6,000 ft) above sea level (De Harport 1959).

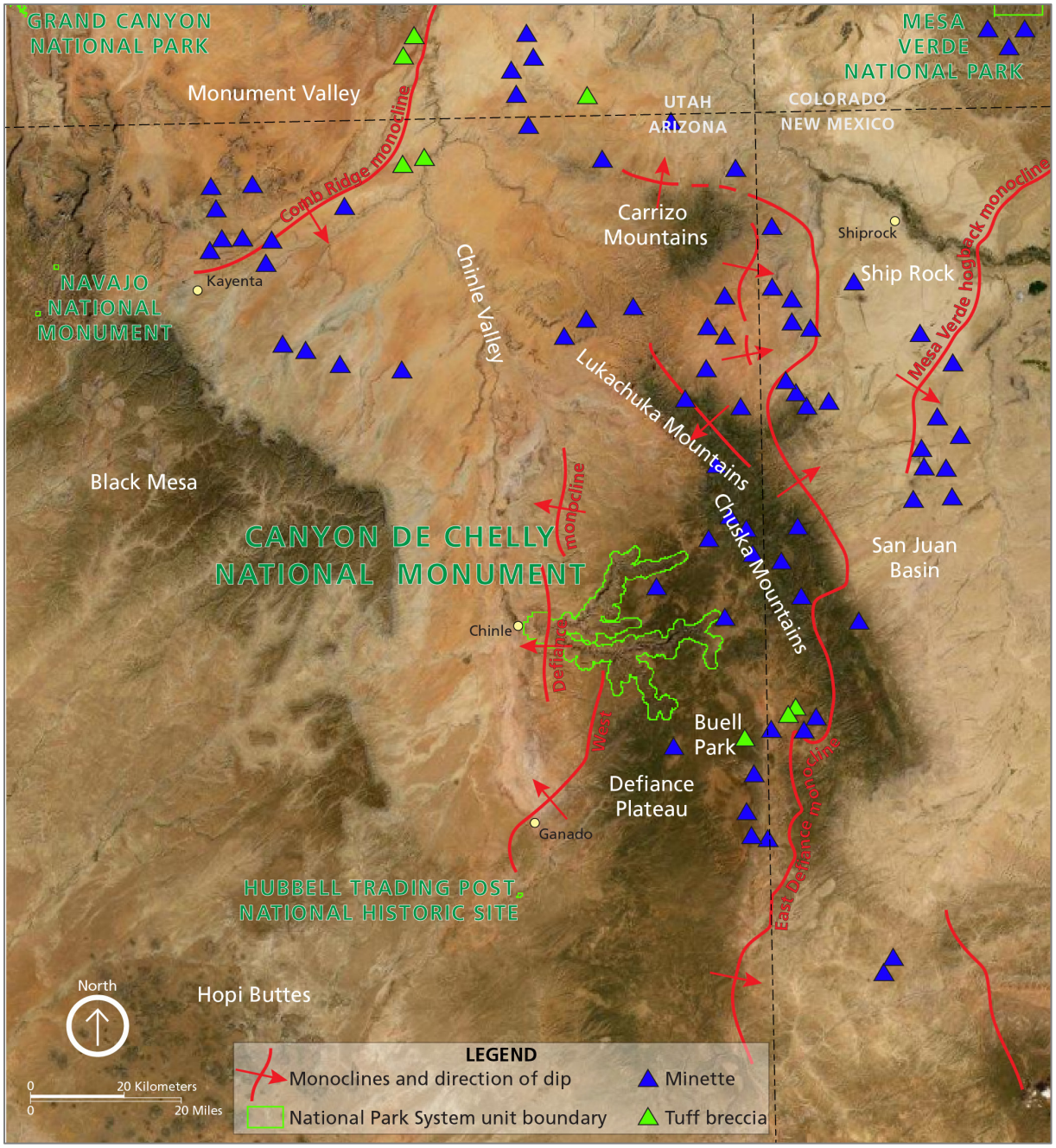


Figure 3. Map of regional geologic features. The monument (outlined in green) is on the Defiance Plateau. Major monoclines (single bend in otherwise uniformly dipping or horizontal strata) transect the area. Informally named monoclines include Mesa Verde hogback, East Defiance, West Defiance, and Comb Ridge. The Navajo volcanic field, which covers about 20,000 km^2 (7,700 mi^2), is characterized by the remains of about 80 maar-diatreme volcanoes, including Ship Rock and Buell Park. These volcanic landforms are composed primarily of two types of rock—minette (blue triangles) and tuff breccia (green triangles). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Roden and Smith (1979, figure 1) and a graphic by Maximilian Dörrbecker (Chumwa), used under the Creative Commons Attribution-ShareAlike 2.5 Generic license, https://creativecommons.org/licenses/by-sa/2.5/deed.en (accessed 27 February 2024). Base imagery by Esri World Aerial Imagery, taken February 2022.

The Defiance Plateau is essentially an elongated dome (uplifted area, circular or elliptical in outline) that is cut by faults. These faults bring ancient rocks to the surface, including Proterozoic rocks that are more than 1 billion years old. Near the monument, however, the oldest exposed strata are the Pennsylvanian and early Permian "red beds" of the Supai Formation (**PPNs**; see "Three Formations: Supai Formation"), which is 310 million to 280 million years old (Figure 4; Richard et al. 2000). Red beds are sedimentary strata (layers of rock) composed primarily of sandstone, siltstone, and shale that are largely red due to the presence of ferric oxide (hematite) coating sand-size and smaller grains. Permian and Triassic red beds also drape across either side of the plateau. From the crest of the Defiance uplift, red, white, and tawny gray Pennsylvanian, Permian, and Triassic strata dip (angle between a bed or other geologic surface and the horizontal plane) to the west and east (Figure 4). The uplift itself trends (the way the strata are oriented across the landscape) from northwest to north.

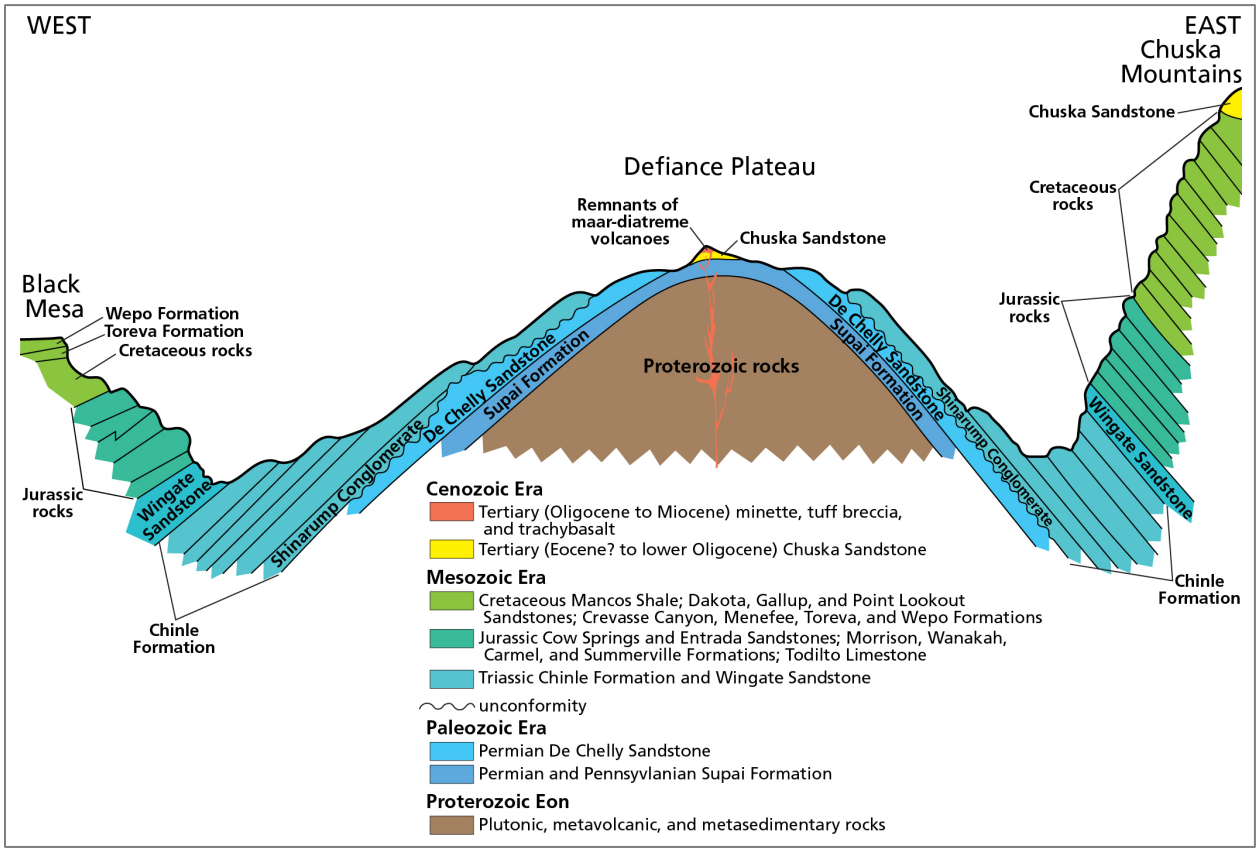


Figure 4. Generalized cross section of the Defiance Plateau. The Defiance Plateau is the modern topographic expression of the Defiance uplift, which was a highland in the Ancestral Rocky Mountains system. Strata, including the monument's bedrock—the Supai Formation, the De Chelly Sandstone, and the Chinle Formation—dip away from the uplift. In the monument area, the oldest rocks exposed in the uplift are the Permian and Pennsylvanian Supai Formation. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after cross section by Hackman and Olsen (1977) and information from Cooley et al. (1969).

In general, the Defiance Plateau lacks mesas and buttes that interrupt the skyline, so those that are present assume unusual prominence (De Harport 1959). These distinctive features, such as Black

Rock Butte (see poster), are the eroded remnants of past volcanoes (see "Navajo Volcanic Field"). Although these features are mostly outside the monument's boundaries, they are part of the monument's viewshed and compose "scenic views and vistas," which are a fundamental resource and value identified in the monument's foundation document (National Park Service 2016).

Historic Timeline

Cultural continuity is of primary significance (National Park Service 2016), and the monument preserves one of the longest continually inhabited locations in the United States. The monument sustains a human community connected to a landscape of great historical and spiritual significance—a landscape "composed of places infused with collective memory and defining moments" (National Park Service 2016, p. 8). Navajo hogans (traditional Navajo dwellings of logs and earth) and agricultural fields set among ancient cliff dwellings visually reinforce the long span of human use and the continuing importance of the canyons for the resident Navajo community (National Park Service 2016).

Approaches to human history at the monument vary. In many Indigenous traditions, for example, the passage of linear time is not important; the so-called past is part of the present, kept alive through traditional beliefs, stories, images, and activities. Interestingly, a connection may be drawn between Indigenous and geologic ways of thinking, in particular through the popular summary statement—"the present is the key to the past"—that encompasses the work of one of geology's famous founders, Charles Lyell (Lyell 1830). That statement refers to the rates of geologic activity as well as the record of life.

Another approach to human history is archeology, in which physical evidence—objects and written accounts—is used to place human events in a chronologic timeline. Organizing events chronologically is also a geologic convention, though on a much longer scale than archeology. Significantly, recent findings in the National Park System are fundamentally changing the timeline of North American human habitation, turning back the clock of human arrival in the Americas by many thousands of years (Pigati et al. 2022). The oldest human footprints in North America were recently discovered in what is now White Sands National Park in New Mexico (Bennett et al. 2021). These footprints were found alongside the tracks of Pleistocene (ice age) mammals. Fossilized prints were made between 23,000 and 21,000 years ago along the shores of an ice age lake—Lake Otero (see the GRI report about White Sands National Monument by KellerLynn 2012).

The following cultural chronology is an archeological account of human occupation of the monument. Where possible, connections are made to geologic resources. The chronology follows a basic outline provided by the monument's official map and guide (National Park Service 2013).

Archaic

From about 4,500 to 2,200 years ago, mobile groups of hunters and gatherers migrated within a territory familiar to them, including in what is now the monument; they seasonally occupied campsites in rock shelters. These mobile groups used extremely steep trails—marked by images

painted on canyon walls and boulders (see “Rock Art”)—which connected the canyon floor with the upland plateau.

Basketmaker

About 2,500 years ago, a fundamental change took place in how people occupied what is now the monument. The Basketmaker culture—a group of people named for their extraordinary weaving skills—farmed small fields on canyon floors and mesa tops. Basketmaker rock paintings have been interpreted as showing a society of extended families growing and storing food and engaging in religious and communal activities, all in a more sedentary and less nomadic lifestyle than during the Archaic cultural period. Relevant objects and features include evidence of dispersed households, large granaries, and basic public structures.

Ancestral Puebloan

About 1,250 years ago, human occupation of the region and monument grew even more settled, as evidenced by the development of villages with multistoried stone and adobe-walled structures in rock shelters. These people, known as Ancestral Puebloans, constructed the dwellings at White House, Antelope House, and Mummy Cave (National Park Service 2013). In addition, Ancestral Puebloans crafted beautiful pottery. They also grew cotton, which led to new weaving techniques. Puebloan habitation of the monument ended about 700 years ago, though regular use continued as part of a migratory cycle of seasonal farming, pilgrimages, and occasional stays until about 400 years ago (Houk 1995). Interaction with other cultural groups, drought, and disease led people elsewhere.

Hopi

The Hopi are among the descendants of the Ancestral Puebloans; their connection to the monument continues to the present day. The precious peach orchards at the monument were originally planted by the Hopi. Peaches, which are not native to the Southwest, were introduced to the Hopi by the Spanish, along with other fruits such as apricots, apples, pears, and plums (Houk 1995). Although the Hopi left the area to permanently settle on mesa tops—for example, Black Mesa, to the west of the monument, as well as mesas along the Little Colorado River—traditions, which developed in the canyons of the monument, are maintained, and pilgrimages back to the canyons are ongoing.

Navajo

The Navajo or Diné (the Navajo word for “the People”) are primarily the descendants of Athabaskan bands from northern Canada and Alaska, as well as from clans that originate among Pueblo groups in the American Southwest. The traditional Navajo homeland is called Diné bikéyah. Archeologists generally report that Navajo bands entered Canyon de Chelly about 400 years ago, but a Navajo presence likely extends back several hundred years earlier to the time of the Nihinasaazi (earlier inhabitants), as reflected in oral histories, ceremonies, and offerings. Although Navajo ancestry spread from the north and from throughout the Colorado Plateau, the present-day culture emerged from this place—called Tséyi’ (see “Geologic Heritage”)—which nourishes its people and is intrinsic to the activities of daily life (Benally 2013).

Spanish

About 250 years ago (1770s), Don Bernardo de Miera y Pacheco was the first to record Canyon de Chelly (using the form "Chegui") on a map. Don Bernardo was perhaps the most prolific and important cartographer of New Spain (parts of North and Central America). Whether Don Bernardo actually visited the monument is unknown, though errors on maps suggest that he did not (Brugge and Wilson 1976). He may have relied solely upon the reports of others who had penetrated the area, or he may have been a member of the poorly documented military operations during the war of 1774–1775 (Reeve 1960; Brugge 1968; Brugge and Wilson 1976).

Conflict and Survival

As Spanish and later colonists encroached on and sought to seize territory that was Indigenous land, warfare erupted. Rock shelters and other natural features, such as Navajo Fortress (see "Iconic Rock Features"), provided places of refuge during periods of conflict. These features figure prominently in Navajo stories. Remnants of fortified places and pictographs (rock paintings) provide evidence of conflict and illustrate a history of survival in the monument.

Mexican–American War

In 1846–1848, the US Army, under Brigadier General Stephen Watts Kearny, subdued Mexican forces during the Mexican–American War—also known in the United States as the "Mexican War" and in Mexico as the "Intervención Estadounidense en México" (meaning, US intervention in Mexico)—claiming present-day Arizona and New Mexico as US territory. Kearny proposed a peace agreement to end decades of mutual raiding among Tribes, but for the next 17 years, the conflict and military expeditions into "Navajo country" (northeastern Arizona and parts of New Mexico and Utah, that is, the central Colorado Plateau) continued.

"Navajo Wars"

As part of the so-called "Navajo Wars," New Mexico District Military Governor, General James Henry Carleton, told 18 Navajo chiefs that they must surrender by 20 July 1863 and move to Fort Sumner in New Mexico Territory. When this did not happen, Carleton ordered Colonel Christopher Houston "Kit" Carson to begin a simultaneous campaign against the Mescalero Apache and Navajo. Carson's mission was to destroy subsistence sources and force a final surrender (Thybony 1997).

"Battle of Canyon de Chelly"

In winter 1864, US Army troops led by Carson entered Canyon de Chelly and forcibly removed all those living there during the "Battle of Canyon de Chelly." US Army troops traversed the entire canyon, as well as Canyon del Muerto, engaging in skirmishes and employing a "scorched earth policy," destroying homes, food, and supplies, including thousands of peach trees. Facing starvation, thousands of Navajo surrendered by spring 1864, when they were then gathered and held at Fort Defiance in Arizona Territory (now part of the Navajo Nation).

The Long Walk

A bitter, humiliating trial awaited survivors of the Battle of Canyon de Chelly and other so-called battles of the Navajo Wars. Thousands were forced to march over 500 km (300 mi) to Bosque Redondo (an internment camp at Fort Sumner). Many people perished from thirst, hunger, and

fatigue during what became known as Hwéeldi, or the "Long Walk to Bosque Redondo," or simply "The Long Walk."

Fort Sumner

Internment at Fort Sumner was no kinder than The Long Walk. By March 1865, the US military had confined 9,000 Navajo on a desolate reservation and attempted to transform them into a settled, village-dwelling people (Thybony 1997). Four years of famine, disease, lack of fuel, and difficulties with Apache also confined at Fort Sumner brutalized the Navajo survivors (Houk 1995). In 1868, the US government saw Fort Sumner as a failed experiment, and government officials allowed the People to return home.

Trading Posts

Without crops, sheep, or housing, the People faced starvation and exposure upon returning home. Food distribution centers, like the one at Fort Defiance, helped. These centers and the associated business practices, which were patterned after Spanish and Mexican traders, provided a model for the trading posts that grew up in the region (e.g., see the GRI report about Hubbell Trading Post National Historic Site by KellerLynn, forthcoming). Trading posts—where people could exchange news, discuss problems, and trade jewelry, rugs, and crafts for staples—became focal points for Navajo communities.

The trading post near the mouth of Canyon de Chelly, which was established in 1902, was later adapted to accommodate canyon visitors. The trading post eventually became the Thunderbird Lodge, which remains today. The lodge is a concessions operation offering tours, lodging, and a restaurant.

Scientific Exploration

The first scientific expedition to enter the monument was the "Hayden Survey" in the 1870s (Brugge and Wilson 1976). The expedition was the congressionally supported US Geological and Geographical Survey of the Territories. The leader of the survey was geologist Ferdinand Vandeveer Hayden, who is best known for his exploration of the region that became Yellowstone National Park.

The first scientific investigation of the rock shelters and cliff dwellings in the monument took place in 1882 under the direction of James Stevenson from the Smithsonian Institution. A party of 19 investigators studied and photographed the large and well-preserved dwelling known as Mummy Cave. The party found a burial cist with two mummified bodies still wrapped in coarse yucca fiber. The burial cist was located below the main section of the cliff dwelling in a deposit of talus (rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have fallen). "Mummy Cave" received its name from this discovery. In addition, Stevenson named the gorge "Cañon de los Muertos," which today is referred to as "Canyon del Muerto" (Grant 1978; Houk 1995; Thybony 1997).

The basic geologic framework of the region was first outlined by Herbert Ernest Gregory. His work includes the first published geologic map of the region (Gregory 1916a). Gregory was a Yale University geologist well known for his explorations of the Colorado Plateau. *Colorado Plateau*

Region (Gregory 1933) is one of his most important works; it was published on the occasion of the 16th International Geological Congress, an event organized every four years, which took place in Washington, DC, that year (Nelson 2009). Many stratigraphic units originally described by Gregory became accepted as standard nomenclature (Cooley et al. 1969), including the Chinle Formation (Gregory 1915, 1916a, 1916b, 1917; see poster and "Three Formations: Chinle Formation").

Looting and Sightseeing

The earliest visit by a journalist to the monument was probably that of J. H. Beadle in 1871, who subsequently published a popular account in book form (Beadle 1873). In 1890, F. T. Bickford discussed the area in a magazine article (Bickford 1890). Visitation by sightseers soon followed, resulting in looting of both archeological and geological items; pilfered items were commonly sold to private collectors and museums.

Protection of Antiquities

The first recorded attempt by the US government to protect the antiquities of Canyon de Chelly and associated canyons was made in 1903. That same year, the first custodian of the so-called ruins was appointed. In 1906, the Antiquities Act was passed. In 1909, a permit system was put into place for examining the cliff dwellings and rock shelters and for sightseeing. In 1917, erosion as a threat to archeological resources was documented for the first time.

Establishment of the National Monument

Serious consideration toward establishing a national monument to protect the archeological resources in Canyon de Chelly and associated canyons first occurred in 1919. The initial response by the People was one of resistance because the canyons were sacred ground. Also, traders were fearful of losing their special or privileged position (Brugge and Wilson 1976).

In 1925, the Bureau of Indian Affairs formally proposed the establishment of a national monument at a meeting of the Navajo Tribal Council. After serious discussion, council members, who were "equally troubled by increasing numbers of visitors digging and removing fragile remnants of the past" (Travis 2005, p. 19), unanimously agreed to accept the proposal, provided that grazing and other Navajo rights were not interfered with. Moreover, the Tribal Council wanted local Navajo to continue to serve as canyon guides.

The lack of an accurate map and boundary descriptions delayed establishment, but ultimately, Canyon de Chelly National Monument was authorized on 1 April 1931 by President Herbert Hoover with the consent of the Navajo Tribal Council. Notably, Hoover is the only US president who was also a geologist (see the GRI report about Herbert Hoover National Historic Site by Graham 2017). The act authorizing the establishment of Canyon de Chelly National Monument included the preferential right to provide visitors with riding animals. This practice continues today, although motorized vehicles are more commonly used. The Canyon de Chelly Guides Association, which has a board of directors, formally organizes this service using certified guides (Travis 1994).

Approximately 80 extended families maintain rights to lands in Canyon de Chelly and Canyon del Muerto (Houk 1995; Thybony 1997). These families, the Navajo Nation, and the NPS work together

to manage monument resources and enable traditional and contemporary lifeways (National Park Service 2016). The Navajo Nation retains use of the land and minerals of the monument and is responsible for surface and subsurface uses, including residential development, agriculture, and grazing practices. No significant sand, gravel, or mineral extraction is known to have taken place within the monument (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023). The NPS is charged with the preservation of prehistoric structures and other features of scientific and historic interest, as well as the administration of the visitor service facilities.

Geologic Heritage

This chapter highlights the geologic heritage of the monument. Geologic heritage exists at the overlap of geology and human experiences and values. The topics are discussed more or less in order of geologic age, oldest to youngest.

In an attempt to document the monument's geologic heritage, this GRI report starts by unraveling the meaning of "Canyon de Chelly" because place names can reveal cultural insights into how human communities organize and interpret their physical surroundings, as well as what these communities value. Tséyi'—the Navajo name of the place referred to as the "monument" throughout this report—is essential to the cultural identity of many Indigenous Peoples (see "Acknowledgments"). Spanish military leaders and explorers of the early 19th century usually referred to the Canyon de Chelly drainage by a single word—Chegui, Chelli, or Chelle—which were all attempts to reproduce the sound of the name Tséyi'.

Spanish cartographer Don Bernardo de Miera y Pacheco (see "Historic Timeline") was the first to record Chelly—as "Chegui"—on a map. The most readily available copy of Don Bernardo's map is from 1778 (see Brandon 1961).

The GNIS lists eight variants for Canyon de Chelly: Canon Chenelle, Canon de Chille, Canon de el Challe, Canyon Chennele, Challe Canyon, Chelly Canyon, Chgelley Canyon, and De Chelly Canyon. These terms were used on topographic maps between 1976 and 2000.

Notably, tsé is the Navajo word for rock, which is used as a prefix or modifier in many words referring to geologic features (Table 1). As a general term, the word tséyi' means "canyon" (Blackhorse et al. 2003). Thus, an unfortunate but literal translation of the place name, Canyon de Chelly, is "Canyon Canyon." Navajo poet Laura Tohe translates Tséyi' as "the place deep in the rock" (Tohe and Strom 2005).

Table 1. Geologic terms with tsé. Sources: Blackhorse et al. (2003) and Semken (2012).

English	Navajo
agate	tsé bee nátseeł
boulder	tsétsoh
canyon	tséyi', tsékooh
cave	tsé'áán, tséyi'nií'
cliff	tséńt'i'í
concretion or fossil	tsé dínísé
crevice (in rock)	tsék'iz
crystal	tséghádi'nídínii
dike (mafic)	tsézhiin 'ii 'áhí
geologist	tsé ndeiłkaahígíí

Table 1 (continued). Geologic terms with tsé. Sources: Blackhorse et al. (2003) and Semken (2012).

English	Navajo
geology	tsé na'alkaah
gravel	tsézéí
lava	tsézhin
lava flow	tsézhin ndaneezhyęęzhí
lava plug, volcanic neck	tsézhin 'íí'áhí
monolith, rock spire	tsé 'íí'áhí
mudstone	tsé hashtl'ishníí
petrified wood	tsé nástáán
pinnacle	tsé' íí á
quarry	tsé haha'níɬɬídí
quartz	tsé'áwózí, tséghádi'ńdínii
rock depression or concavity on the surface	tsé'édzis
rock overhanging ledge	tséyaa hatsoh
rockslide	tsé náázhoozhí
sandstone	tsé dizéígíí

The following discussion describes some of the history around the named geologic and archeologic features at the monument and illustrates the connection that humans have with the monument's geology. Recognizably, in endeavors that attempt to highlight connections between people and the land, a common temptation is to suggest meaning—or romanticize or spiritualize—cultural features. Generally, however, things simply are what they are, that is, a landmark or "geographic locator." A notable exception to the pragmatism applied to place names at the monument is the meaning given to—what this report refers to as—"iconic rock features."

Iconic Rock Features

The names applied to smaller erosional forms on the Colorado Plateau are almost endless, and no general term like mesa or butte has come into widespread use (Stokes 1969). English terms applied to these forms include pillar, pinnacle, spire, monolith, castle, cathedral, and tower, to name a few. Navajo terms for such rock features are tsé 'íí'áhí and tsé' íí'á (Table 1).

In the classic work *Scenes of the Plateau Lands and How They Came to Be* (1969), the author William Lee Stokes settled upon the term "monument" for these erosional forms. Using "monument" in this GRI report would be appropriate because of the many "monuments" that have separated from the cliff walls in Monument Canyon. However, to avoid confusion, the word "monument" is not used for these rock features because this same word refers to the monument (i.e., Canyon de Chelly National Monument). Instead, "rock feature" or "iconic rock feature" are used.

Three well-known rock features—Spider Rock, Face Rock, and Navajo Fortress, which are marked on the official map and guide (National Park Service 2013)—are discussed in this section. Other iconic rock features, such as Standing Rock, Blade Rock, Bat Rock, Dog Rock, and Sleeping Duck, are not discussed in this report but are deserving of further interpretation. In addition, the hoodoo-like spires in upper Canyon de Chelly and Monument Canyon are both geologically and culturally significant, warranting further study.

A study of the geologic heritage values of the monument's rock features could be conducted by a Scientists in Parks (SIP) participant; a Navajo student studying geology would be an ideal candidate for such a project (see "Guidance for Resource Management"). No known project has been completed to date (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023).

The genesis of rock features on the Colorado Plateau is commonly attributed to differential erosion. As described in Stokes (1969, p. 5):

> *Nature quickly and unerringly distinguishes between hard and soft rock by the processes of weathering and erosion. By noting the effects of erosion, we can tell which rocks are hard and which are soft even from a distance. The secret is simple: hard rocks withstand erosion better than soft ones and will be more prominent in any scene where hard and soft occur together. This means that hard rocks will eventually stand higher or protrude farther while soft rocks will stand lower or recede. This is the Principle of Differential Erosion.*

Differential erosion explains the development of some areas of the monument, but many of the iconic rock features are composed of a single, resistant member of the De Chelly Sandstone—the White House Member (see "Three Formations: De Chelly Sandstone"). As such, differential erosion between layers of hard and soft rock does not clearly explain the genesis of many iconic rock features in the monument. Another process—progressive erosion—may play a role (Figure 5), though further study is needed. Nevertheless, once the canyon formed (see "Significant Geologic Events: Entrenchment of the Colorado River System"), ribs or fins of the De Chelly Sandstone apparently separated from the canyon walls. As erosion progressed, the resistant sandstone fins retained a relatively uniform height but became narrower, eventually breaking into the distinctive pillars farther out on the canyon floor (Figure 5).

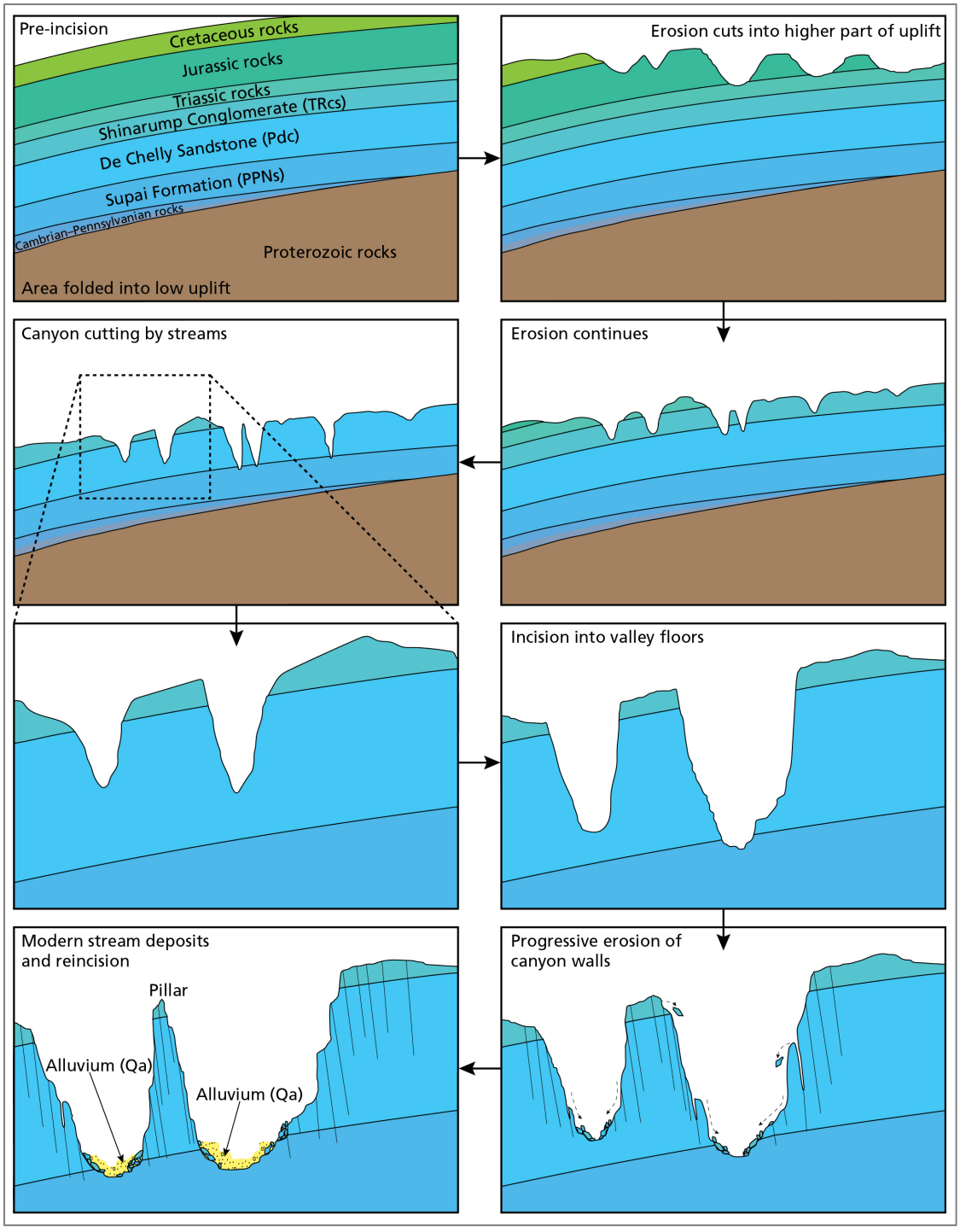


Figure 5. Schematic diagram of landscape development. Today's landscape formed through stages of deposition, uplift, incision, and erosion. With respect to progressive erosion (starting lower right), canyon walls initially appear flat and unbroken, but from this seemingly unbroken rim, many "fins" or "ribs" of rock extend into the canyon, not yet separated from the main mass of rock. Eventually, the eye-catching rock features (labeled as "pillar" on the figure) form farther out in the canyon, cut off and separated from the canyon walls. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using information in Stokes (1969) and a PowerPoint presentation by Ron Blakey (Northern Arizona University, GRE scoping meeting, 16 February 2007).

Spider Rock

Spider Rock marks the mouth of Monument Canyon (see poster), which is a major tributary entering Canyon de Chelly from the southwest. Jutting upward from the canyon floor for 251 m (825 ft; Baars 1998), Spider Rock is arguably the most dramatic rock feature in the monument. The bifurcated stone column resembles two gigantic fingers thrusting out of the earth, pointed toward the sky (Figure 6).



Figure 6. Photograph of the view from Spider Rock Overlook. Without some recognizable object such as a truck or horse for scale, the size of Spider Rock is difficult to appreciate. The spire rises 251 m (825 ft) from the floor of Canyon de Chelly. It is a geologic keystone because it displays the monument's three rock formations. The Supai Formation (PPNs) and Chinle Formation (i.e., Shinarump Member, TRcs) underlie and overlie the De Chelly Sandstone (Pdc), respectively. Across the valley to the north, Face Rock juts toward Spider Rock. In the photograph, Face Rock casts a human head–like shadow across the canyon wall. Note Black Rock Butte on the horizon. Photograph by Ron Karpilo (Colorado State University), taken 2005. Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Because Spider Rock has appeared in "big screen" movies, it is probably the most recognizable of the monument's rock features. Scenes in *Mackenna's Gold* (1969), *The Trial of Billy Jack* (1974), *Contact* (1997), *Poltergeist II* (1986), *Wild Wild West* (1999), *Black Cloud* (2004), and *The Lone Ranger* (2013) were all filmed in the monument with Spider Rock playing a starring landscape role (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023).

Three variant names—Monument Rock, The Captain (or The Captains, when associated with Face Rock), and The Monument (or The Monuments, when associated with Face Rock)—have appeared on maps. In 1959, however, the US Board on Geographic Names recorded "Spider Rock" as the formal name of this feature (US Board on Geographic Names 1959).

The Navajo name for Spider Rock is Tsé Na'ashjé'ii or Na'ashjéé'tsé (note the inclusion of the word "tsé" in these names; see Table 1), meaning the home of Spider Woman. Spider Woman has two important roles in Navajo tradition: one as the teacher of weaving and the other as the enforcer of moral behavior, especially in children.

The monument's three bedrock units—each referred to as a "formation" (a significant term in geology, meaning a fundamental rock-stratigraphic unit; see "Three Formations")—are found in Spider Rock. Furthermore, Spider Rock is the only place in the monument where the De Chelly Sandstone (**Pdc**) is fully exposed, bottom to top, marked by lower and upper contacts (the surface between two types or ages of rocks). Underlying the De Chelly Sandstone and composing the base of Spider Rock is the Supai Formation (**PPNs**), which represents the oldest rocks in the monument. Overlying the De Chelly Sandstone, and forming the top of Spider Rock, is the Shinarump Member of the Chinle Formation (**TRcs**), or more simply, the Shinarump Conglomerate (see "Three Formations").

No explanation is known to have been published for the genesis of Spider Rock, but the existence of faults in proximity to the rock feature is intriguing (see poster). These faults run across Canyon de Chelly and on either side of Tsaile graben (down-dropped basin [see poster], bounded by normal faults [Figure 7]). A possible explanation is that fluids traveling along these faults more durably cemented the De Chelly Sandstone (Steven Semken, Arizona State University, professor of geology, written communication, 17 May 2023). Given that both the unusual Spider Rock pinnacle and the cross-canyon faults occur together and that no similar relationship occurs anywhere else in the canyons, the explanation seems plausible (Steven Semken, Arizona State University, professor of geology, email communication, 18 December 2023).

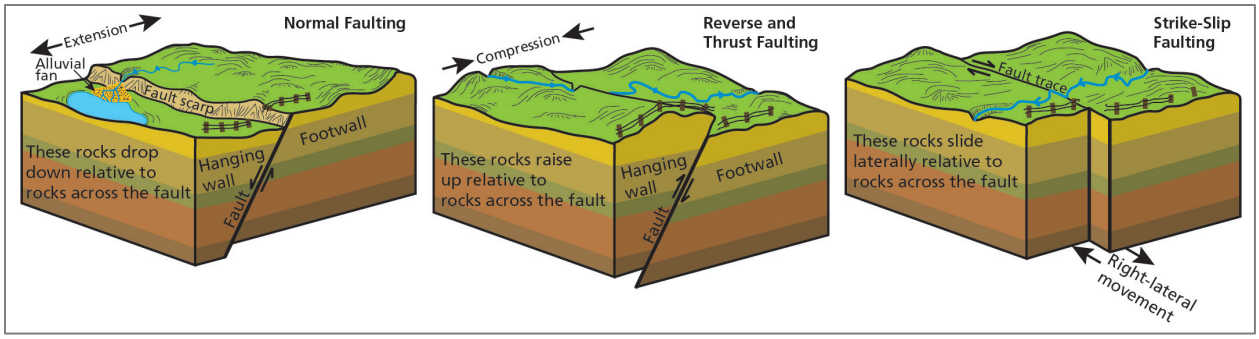


Figure 7. Illustration of fault types. The three primary types of faults are normal, reverse or thrust, and strike-slip. Movement occurs along a fault plane. Footwalls are below the fault plane; hanging walls are above it. The faults that transect the monument are normal faults. Reverse and strike-slip are the other two main types of faults. In a reverse fault, crustal compression (squeezing together) moves the hanging wall up relative to the footwall. A reverse fault with a dip angle of less than 45° is a thrust fault. In a strike-slip fault, movement is horizontal. When movement across a strike-slip fault is to the right, it is a right-lateral strike-slip fault (as illustrated in the figure). When movement is to the left, it is a left-lateral strike-slip fault. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Face Rock

Across the valley from Spider Rock is Tsé Binii'í, meaning rock and face, respectively. In profile, the upper portion of Face Rock resembles a human face looking toward Spider Rock (see Figure 6). Face Rock is also known as Talking Rock, Speaking Rock, or Whispering Rock (Jett 2001).

Face Rock as a "talking rock" has a dual meaning. First, Tsé Binii'í (Face Rock) talks to Tsé Na'ashjé'ii or Na'ashjéé'tsé (Spider Woman), reporting on human behavior, especially that of children. Second, talking rocks are places of inspiration for people such as Navajo medicine men (Jett 2001). Some (e.g., Semken 2005, p. 149) would argue that Face Rock and similar talking rocks also inspire geologists:

> *Field geoscientists develop rich senses of the places where they do their research; Rossbacher (2002) evocatively described this phenomenon as a definitive and appealing attribute of a geological career. Other geoscientists have argued that the intimate, intuitive, or spiritual knowledge of places acknowledged by many in the profession appeals to a fundamental human need for direct contact with the Earth, and should be brought to bear on current problems of scientific illiteracy and anthropogenic environmental degradation (Leveson 1971; Savoy 1992; Moores 1997).*

Like Spider Rock, most of Face Rock is composed of the De Chelly Sandstone (**Pdc**) and its top consists of the Shinarump Conglomerate (**TRcs**). The Supai Formation, however, is not exposed as the base of Face Rock.

At 1,828 m (5,998 ft) above sea level, Face Rock stands 41 m (135 ft) higher than Spider Rock, which rises to 1,787 m (5,863ft) above sea level. Nevertheless, Face Rock appears less impressive than Spider Rock because it is not wholly separated by progressive erosion from the canyon wall (see

Figure 6). Face Rock consists of a fin of De Chelly Sandstone (Pdc) still connected to the north wall of Canyon de Chelly.

Navajo Fortress

The tip of the promontory where Canyon del Muerto and Black Rock Canyon meet is Navajo Fortress (see poster). It is a large, semi-detached, sheer-sided rock monolith composed of the De Chelly Sandstone (**Pdc**) and the Shinarump Conglomerate (**TRcs**).

The official geographic name listed in the GNIS is "Navajo Fortress," though scoping participants referred to it as "Fortress Rock" (KellerLynn 2007). It has also been called "Black Rock Navajo Fortress" (Jett 2001). The Navajo name—Tséláá—is descriptive, literally meaning "rock tip"; -nteel (meaning wide), as in, Tséláánteel, is sometimes added to the name to distinguish it from Little Navajo Fortress (Jett 2001), which is to the west. Little Navajo Fortress, or Refuge Rock (Tséláá Ndzits' o'[í]), is a rock feature separated from the north-rim plateau by an uncrossable gap (Jett 2001).

In the 19th century, rumors of a fort or castle with thick stone walls lured US military surveyors to the monument area. In 1849, an expedition led by Lieutenant Colonel John MacRae Washington—who became the military governor of New Mexico shortly after the end of the Mexican–American War (see "Historic Timeline")—entered what is now the monument. Lieutenant James Hervey Simpson, a member of the expedition, took three assistants and 60 troops into Canyon de Chelly in search of a Navajo fortress reputed to be located on a high, isolated plateau near the mouth of the canyon. Simpson's journal suggests that he was looking for a large masonry or earthwork structure, which he did not find (McNitt 1964).

The rumored "fort" or "castle," which was never located, was ultimately considered a myth (McDonald 1976). Nevertheless, Navajo Fortress—a place of refuge—does indeed exist. Its rock ledges and top are accessed by a trail that could be defended from invaders. From the Black Rock Canyon side (see poster), the main trail to the top of Navajo Fortress ascended to the saddle, crossed a parallel log bridge, and then continued to the top. Eleven pole ladders and cut steps had to be climbed. Twenty-two arcuate stone walls provided protection for defenders of the approach; piles of stones were assembled for throwing onto would-be intruders (Kipp 1983).

Ancient Sand Dunes

Today, large deserts—including the Mojave, Sonoran (see the GRI report about Organ Pipe Cactus National Monument by KellerLynn 2022), Chihuahua, and Great Basin in North America; the Sahara in Africa; the Negev in the Middle East; the Gobi in Asia; and the dry interior of Australia—lie between 15° and 35° latitude, north and south of the equator. At these latitudes, easterly trade winds of the tropics brush against westerly trade winds of the temperate belts. The trade winds blow away cloud cover, causing the land to heat up and drying conditions to prevail.

The situation was much the same during the early Permian Period (298.9 million–273.0 million years ago). At that time, immense sand seas existed at these latitudes. The monument's namesake rock—

the De Chelly Sandstone—formed in such a setting about 275 million years ago (Blakey and Knepp 1989; Blakey 1990).

Sources of sand for the Permian dunes that comprise the De Chelly Sandstone were floodplains emanating from the Appalachian Mountains (Blakey 1996) and lowlands developed on exposed Pennsylvanian eolian sandstones, northwest of the monument, in Montana and Wyoming (Blakey et al. 1988). Prevailing winds blew predominantly from the northeast, sweeping across these source areas and depositing thick accumulations of sand. This contrasts present-day conditions where prevailing winds are southwesterly.

Evidence of the eolian nature of the De Chelly Sandstone includes the rounded, pitted, or frosted sand grains that make up the rock. Also, the steep laminae of the cross-beds are indicative of its origin; these sedimentary structures formed as sand grains were blown in an erratic fashion up the shallow windward slope of a dune, to eventually be deposited on the steeper leeward side (Figure 8).

Another criterion for recognizing eolian deposits is the presence of trace fossils (evidence of an organism's activity; in contrast to a body fossil, which is evidence of an organism itself). In the De Chelly Sandstone, the trace fossils are trackways or trails made by animals and insects moving across the dunes. Outside the monument, the De Chelly Sandstone has yielded tracks from both vertebrates (tetrapods [four-limbed animals]) and invertebrates (spiders and scorpions), which were first documented by McKee (1934) and Sadler (1993), respectively. A survey by Lockley et al. (1995), which summarizes vertebrate and invertebrate tracks in the De Chelly Sandstone in Mystery Valley (northwest of the monument), concludes that vertebrate tracks are much more common than invertebrate tracks. This finding is likely due to the preferential preservation of larger trackways.

The monument has a single known trackway in the De Chelly Sandstone (Tweet et al. 2009, p. 41). The trackway is composed of tetrapod tracks (Justin Tweet, NPS Geologic Resources Division, associate, informal report, 16 January 2022).

Because most dune fields leave no stratigraphic record (Kocurek and Day 2018), let alone a complete record of dune-field construction (e.g., Ewing and Kocurek 2010; Kocurek et al. 2010; Gao et al. 2015), the Permian and Jurassic eolian strata that spread across the Colorado Plateau are exceptional (see, e.g., Walker and Harms 1972; Chan and Parry 2002; Kocurek and Day 2018). These cross-bedded sandstones provide textbook-quality examples of geomorphic processes and stratigraphic features (e.g., Summerfield 1994; Boggs 1995).

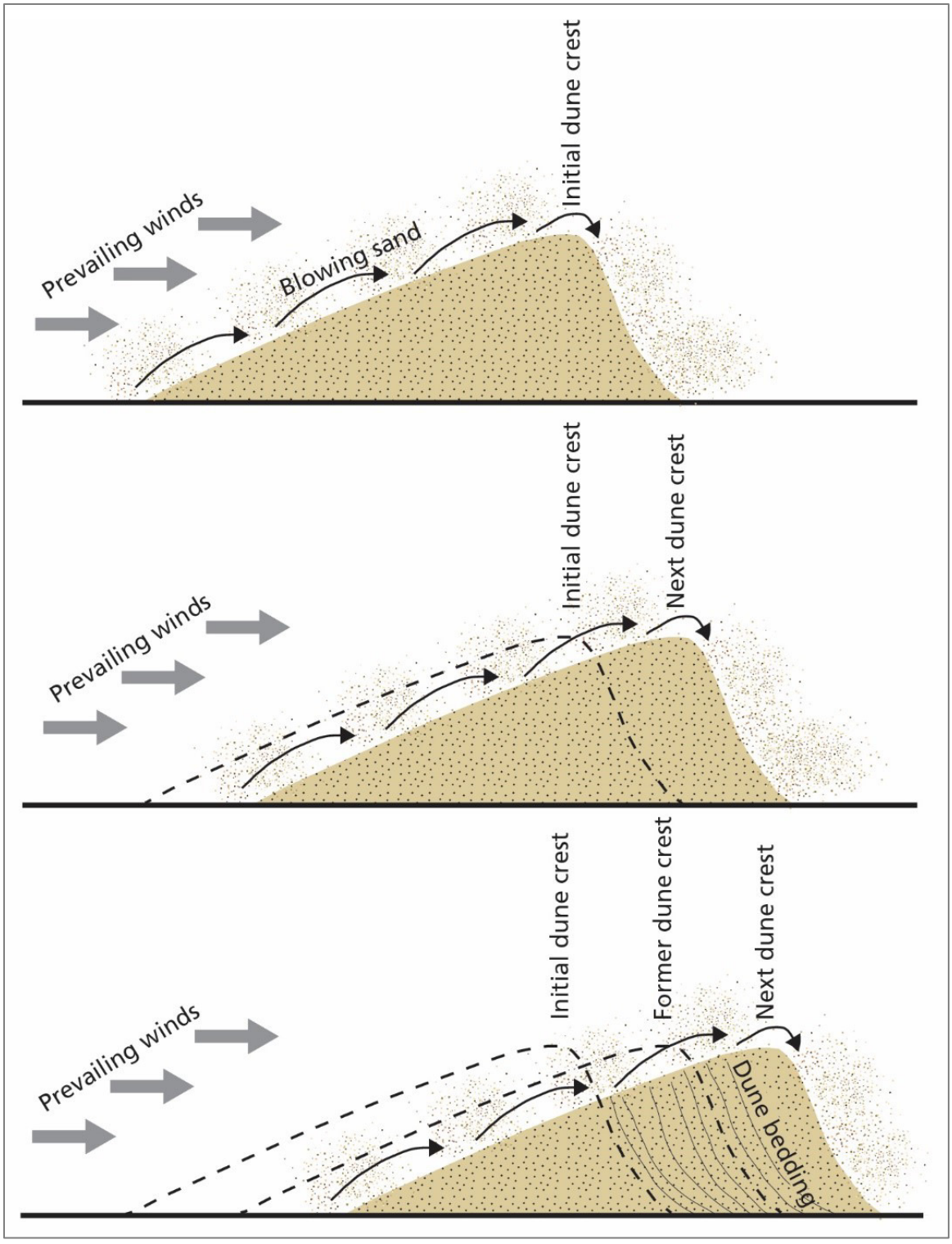


Figure 8. Model of the development of eolian cross-beds. Cross-beds in windblown sand deposits, such as the De Chelly Sandstone, form as sand is deposited on the sheltered, lee side of a dune. Oversteepened deposits at the crest of the leeward side slump to form steep bedding surfaces that may be preserved in the rock record. The windward slopes are rarely preserved in nature. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Of all the remarkable sedimentary structures preserved in the eolian sandstones of the Colorado Plateau, the most conspicuous are cross-beds (Figure 9), which in the De Chelly Sandstone have been called “massive,” “grandiose,” “swooping” (Chronic 1983, p. 271), and “very obvious” (Baars 1998, p. 7). In the monument, sets of cross-beds vary in thickness between 3 and 15 m (10 and 50 ft). Thickness is an indication of the eolian nature of the sandstone because cross-stratification that is thicker than about 10 m (30 ft) is rare in subaqueous deposits (Summerfield 1994). Cross-bed thickness is an indication of the height of a dune, suggesting that the strata preserved in the monument represent a mature dune field (Baars 1998).



Figure 9. Photograph of the White House Trail. As hikers descend from the canyon rim, they pass through massive cross-beds in the De Chelly Sandstone. Northeasterly winds blowing across an ancient dune field formed these cross-beds about 275 million years ago. NPS photograph, taken 2009.

The horizontal bedding planes between cross-bed sets are another conspicuous feature of the De Chelly Sandstone. Significantly, these bedding planes may represent longer spans of time than the cross-beds themselves. Many dune-field events are likely collapsed into a single horizontal surface (Loope 1984; Talbot 1985; Kocurek 1988; Mountney 2006).

Stokes (1969, p. 510) provides the following explanation for the horizontal bedding planes: [Because wind has little effect upon water-saturated material, it is assumed that] "previously accumulated sand was removed down to the water table, thus creating the very smooth, horizontal surfaces that now separate intervals of cross-bedded sandstone." Although this explanation is still valid, a greater complexity is warranted (KellerLynn 2007) because in any given basin, the elevation of the water table may be a function of climate, tectonism (deformation of Earth's crust), and/or sea level (i.e., in coastal dune fields) (Kocurek et al. 2001).

Fossils in Bedrock

Fossils are part of the geologic heritage of the monument. Fossil specimens have been collected for scientific purposes as well as for use as projectile points and other tools (see "Lithics: Sources of Information"). The source of petrified wood at the monument is the Triassic Chinle Formation; both the Shinarump Member (**TRcs**) and the Monitor Butte Member (**TRcmb**) yield fossils. Notably, in northeastern Arizona and western New Mexico, the Monitor Butte Member (**TRcmb**) is now recognized as the Bluewater Creek Member (see "Three Formations: Chinle Formation").

In 1850, a piece of petrified wood from a tributary canyon of Canyon de Chelly was the first plant fossil collected for scientific purposes in the American Southwest. Lieutenant James Hervey Simpson found the specimen on 5 September 1849 during an expedition of the Corps of Topographical Engineers, which commissioned Simpson to undertake the first scientific survey of "Navajo Country" (McNitt 1964). Although the whereabouts of the specimen are now unknown (Ash 1972a), it was likely from the Shinarump Conglomerate (Ash 1969, 1972a, 1972c).

Petrified wood from the Monitor Butte Member (**TRcmb**) was used as construction material for dwellings at Petrified Forest National Park such as "Agate House" (Ash 1972c; Santucci et al. 2021) and as decorative elements in construction at Hubbell Trading Post National Historic Site (see GRI report by KellerLynn, forthcoming). The Monitor Butte Member is now recognized as the Blue Mesa Member at Petrified Forest National Park and as the Bluewater Creek Member at the monument. None of the cliff dwellings within the monument are known to have been constructed or decorated with petrified wood, but an inventory of paleontological resources has not been conducted to verify this use (see "Paleontological Resource Inventory, Monitoring, and Protection").

Paleontological studies at the monument led to the Monitor Butte Member (**TRcmb**)—now recognized as the Bluewater Creek Member—of the Chinle Formation becoming well known for its petrified flora. Work by Ash (1972a, 1972b, 1972c; 1980; 1996) provides the most detailed descriptions of plant fossils within and around the monument. Three taxa are based on holotypes (type specimens upon which the description and name of new species are based) that were found within the monument: (1) the lycopod *Selaginella anasazia* (known from leafy shoots and cones), (2) the conifer *Masculostrobus clathratus* (known from cones), and (3) a plant of uncertain classification *Dechellyia gormani* (known from leafy and fertile branches with winged seeds). The specimens are housed at the US National Museum of Natural History (USNM) in Washington, DC, and are specimens USNM 168905, USNM 168984, and USNM 168919, respectively (Justin Tweet, NPS Geologic Resources Division, associate, informal report, 26 January 2022).

In the Western Archeological and Conservation Center (WACC) collection, most (88/147 catalog numbers or 60%) of the fossils associated with the monument are petrified wood. However, during the preparation of *Paleontological Resource Inventory and Monitoring—Southern Colorado Plateau Network* (Tweet et al. 2009), four non-petrified wood fossils were also documented. Later, in 2015, Justin Tweet (NPS Geologic Resources Division, associate, informal report, 26 January 2022) identified the non-petrified wood specimens as (1) a tooth of a phytosaur (crocodile-like reptile from the Late Triassic Period; specimen number CACH 4501), likely from the Chinle Formation; (2) specimen CACH 34 was thought to be a proboscidean (elephants and their extinct relatives) but is now apparently lost; (3 and 4) two ammonite specimens—one from the subfamily Acanthoceratinae of the family Acanthoceratidae (CACH 11222), and the other possibly a member of the family Collignoniceratidae (CACH 859)—which lived during the Jurassic and Cretaceous Periods (201.3 million to 66.0 million years ago). Notably, ammonites do not occur in the rocks of the monument but are known from the rocks of Black Mesa to the west.

Lithics: Sources of Information

Archeological landscapes and associated museum collections are a fundamental resource and value of the monument (National Park Service 2016). Stone tools, referred to as "lithics" by archeologists, are among the varied archeological resources at the monument. Lithics include items commonly thought of as "arrowheads" and "spearheads," as well as "ground stones." Lithics were used in hunting, defense, foraging, harvesting, and food preparation (e.g., chopping, scraping, and grinding).

Because lithics are made of geologic resources (e.g., rocks, minerals, and fossils), they are part of the monument's geologic heritage and of interest to the GRI. In geology, however, the term "lithics" has a different meaning; lithics are rock fragments from previously formed rocks. For example, lithics in the rocks of the Navajo volcanic field are not newly formed like lava but were preexisting rock fragments ejected into the air, exploded across the landscape, or erupted onto the surface (see "Navajo Volcanic Field").

A comprehensive inventory of the monument's lithics (i.e., stone tools) has yet to be conducted; neither the types of raw materials nor the geologic provenance (e.g., source area or geologic formation) of these materials have been systematically documented. A geologic inventory of lithics would make an interesting project. A researcher with geologic expertise could identify the lithic material (rock, mineral, or fossil), determine the potential geologic formation of the material, and investigate potential quarry locations. Knowing this information would allow the researcher to make connections to regional, national, and global geologic stories as well as to other NPS areas. Receiving geologic expertise for a geologic inventory of lithics found at the monument may be possible through the SIP program (see "Guidance for Resource Management").

Although a thorough inventory of lithics is beyond the scope of the GRI, the following publications may serve as a starting point of such an inventory:

An Archeological Assessment of Canyon de Chelly National Monument (McDonald 1976) states that the Shinarump Conglomerate, which forms a resistant cap over the northern portion of the Defiance

Plateau (see "Geologic Setting"), contains cobbles of basaltic rock, quartzite, chert, and petrified wood, which "provided material for the manufacture of chipped stone tools by the prehistoric occupants of the monument. [The cobbles] are most commonly found eroded out on the plateau near the canyon rims and in stream gravels in the canyon bottoms" (McDonald 1976, p. 1).

A dissertation by Green (1982) identifies source locales for 95% of the flaked raw materials collected on Black Mesa (west of the monument). That dissertation provides descriptions of the raw materials and their source formations as well as maps on which the locations of specific sources are pinpointed. Except for a locale on the Red Lake 7.5-minute quadrangle (west of the Grand Canyon), all sites investigated by Green (1982) are on the western side of Black Mesa, spreading in a northeast–southwest direction from Tuba City to Kayenta. According to Green (1982), this source information should apply to much of northeastern Arizona and the Four Corners Area because the same rocks exist throughout. Notably, however, the rocks that compose Black Mesa are younger than those in the monument; they are from the Cretaceous Period (145 million to 66 million years ago) and include the Wepo and Toreva Formations (Cooley et al. 1969). Some of the sites investigated by Green (1982) also yielded material from Jurassic and Triassic rocks, including the Late Triassic Chinle Formation (Table 2).

Table 2. Geologic sources of lithics. Primary source: Green (1982).

Geologic Period/Epoch	Formation Name	Lithic Material
Unknown	Unknown	Ochre
Possibly Eocene to lower Oligocene	Possibly the Chuska Sandstone (**Tc**)	"Chuska chert" (Heather Morrison, Canyon de Chelly National Monument, archeologist, written communication, 19 April 2023)
Cretaceous	Wepo Formation (beyond the extent of the GRI GIS data/no map unit) *Note*: Coal on Black Mesa occurs in the Wepo Formation.	• Petrified wood • White baked siltstone ("clinker"; naturally altered by fires that spread along coal seams) • Siderite (iron carbonate [FeCO3])
Jurassic	Morrison Formation (**Jm**, **Jmw**, **Jmr**)	Creamy opaque silicified claystone
Jurassic	• Cow Springs Sandstone (**Jcs**) • Entrada Sandstone (**Je**) • Carmel Formation (beyond the extent of the GRI GIS data/no map unit)	• Chert (hard, dense rock composed for silica [SiO2]) • Quartzite (recrystallized sandstone [metamorphic rock] or silica-cemented quartz sandstone [sedimentary rock]) • Petrified wood • Jasper (silica gemstone, usually red) • Chalcedony (silica gemstone, usually blue) *Note*: These materials are in gravel deposits of rivers that flowed through the Cow Springs and Entrada Sandstones and the Carmel Formation.

Table 2 (continued). Geologic sources of lithics. Primary source: Green (1982).

Geologic Period/Epoch	Formation Name	Lithic Material
Jurassic and Triassic	Navajo Sandstone (beyond the extent of the GRI GIS data/no map unit)	Navajo chert
Triassic	Chinle Formation (**TRc**)	Chinle chert
Triassic	Chinle Formation, Owl Rock Member (**TRco**)	Owl Rock chert
Triassic	Chinle Formation, Petrified Forest Member (**TRcp**, **TRcpa**, **TRcps**, **TRcpb**)	Petrified wood
Triassic	Chinle Formation, Shinarump Member (**TRcs**)	Chert nodules (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023)

Paleontological Resource Inventory and Monitoring—Southern Colorado Plateau Network (Tweet et al. 2009) and follow-up work by Justin Tweet (NPS Geologic Resources Division, associate) document lithics collected from the monument that are composed or potentially composed of paleontological materials (e.g., petrified wood). The archeological collection, now housed at WACC, includes choppers, hammerstones, cores, debitage, flaked stone tools, projectile points, ringing stones, rubbing stones, and worked stones. The geologic provenance of these specimens is not known.

A geoarcheological investigation by Arakawa and Miskell-Gerhardt (2009) highlights rocks of the Navajo volcanic field (see "Navajo Volcanic Field") and their use as stone tools and in ceramics. The major rock type in the Navajo volcanic field is minette (an intrusive basaltic rock; Semken 2010). Aphanitic (fine-grained) minette is used for making flaked stone tools. Trachybasalt ("extrusive minette") is used to temper pottery. Tuff breccia (formed during a volcanic eruption from angular rock fragments) may contain xenoliths (inclusions in volcanic rocks that are conspicuous in size and differ distinctly from their host rocks); a small percentage of xenoliths contain flakable lithologies. The study by Arakawa and Miskell-Gerhardt (2009) focuses on the central Mesa Verde region of Colorado, but because that region and the monument are both part of the Navajo volcanic field, connections may be drawn between them.

In-house knowledge is an undocumented source of information about lithics at the monument. For example, during the 2022 follow-up meeting, a volcanic rock, referred to as "rhyolite," was identified as comprising lithics (Keith Lyons, Canyon de Chelly National Monument, integrated resource manager/archeologist, Teams meeting, 26 January 2022). Notably, rhyolite (the volcanic equivalent of granite) did not erupt as part of the Navajo volcanic field. However, clasts of rhyolitic lava or tuff as large as 8 cm (3 in) in diameter are part of the Shinarump Conglomerate, though such clasts are sparse, making up 5% or less of the total number of clasts (Riggs et al. 2016). In addition, Fluted

Rock (south of the monument) has been identified as a possible source area of lithics (Alton Joe, Hubbell Trading Post National Historic Site, Maintenance supervisor, personal communication with Maryann Neubert, Hubbell Trading Post National Historic Site, museum curator/cultural resources specialist, email communication, 25 October 2023). Fluted Rock is composed of minette (Hackman and Olson 1977). Also, the USGS topographic map labels a "quarry" on the small minette butte (**Tmn**) at the eastern boundary of the monument (west of Sonsela Buttes; see poster), which warrants investigation.

Plaster

Another geologic resource of cultural interest is plaster, for example, used in the construction of White House. Both the Navajo name, Kiníí Na'ígai, meaning "there is a white strip across the middle house" (Jett 2001, p. 75), and reference to "Casa Blanca" by Lieutenant James Hervey Simpson derive from White House.

White plaster covers a wall of the dwelling (Figure 10). The plaster is composed of gypsum (an evaporite mineral consisting of hydrous calcium sulfate [$CaSO_4 \bullet 2H_2O$]), which can form thick, extensive beds. A quarry for the gypsum used in White House has not been identified and may be difficult to pinpoint because small deposits of gypsum (beds, nodules, or plates) occur in much of the stratigraphic section in the area, most notably, in the Supai Formation (**PPNs**). However, a possible source of the plaster is an area east of the monument known as "White Clay," though the location has no known evidence of quarrying (Keith Lyons, Canyon de Chelly National Monument, integrated resource manager/archeologist, personal communication, 1 November 2023).

White House, which was occupied from 1060 CE until about 1260 CE by multiple generations of Ancestral Puebloan families (at any one time and over time), is one of the largest and best-preserved cliff dwellings in the monument (Bradley 1973). The location of the rock shelter that encompasses White House is below the canyon rim but above the canyon floor and, thereby, served as a natural defense against marauders from other tribes. To reach the dwelling, the residents used ladders, which could be pulled up during emergencies. Its elevation also provided protection during flash floods, which periodically roar down the canyon (Quinn 2023).

White House is the most accessible cliff dwelling in the monument, though as of 24 January 2024, the White House Overlook and Trail remained closed because of safety and law enforcement concerns. When open, visitors can access White House via the trail, which descends from the overlook on South Rim Drive. Historically, it is the only trail in the monument where visitors who are not accompanied by a guide can descend into the canyon (National Park Service 2016; see Figure 9).



Figure 10. Photograph of White House. At White House, the canyon walls are 160 m (525 ft) high (De Harport 1959). The coating and streaks of dark-colored patina on these walls are desert varnish, composed mostly of clay minerals, arriving as windblown dust. White House gets its name from the gypsum plaster used in construction. On the photograph, a white circle highlights the namesake wall. Photograph by Ron Karpilo (Colorado State University), taken 2005.

Sources of Water

Water is the central element woven throughout the landscape, history, and cultures associated with the monument. In this environment, Tó éí ííná át'é, or "water is life" (National Park Service 2016, p. 6). In the foundation planning effort, which resulted in the monument's foundation document (National Park Service 2016), both Navajo and Hopi contributors "emphasized the importance of water in this desert environment. Water is key to past, present, and future lifeways" (National Park Service 2016, p. 61).

Groundwater from the De Chelly Sandstone (**Pdc**), which is an aquifer (groundwater reservoir; Cooley et al. 1969), helped to create a scenario for human habitation (Keith Lyons, Canyon de Chelly National Monument, integrated resource manager/archeologist, follow-up meeting, 26 January 2022). Along with the underlying Supai Formation (**PPNs**), which confines the groundwater in the overlying De Chelly Sandstone, the sandstone aquifer has enabled generations of farmers to produce food in the canyons (Houk 1995).

Yielding a dependable water supply at wells and springs, the De Chelly Sandstone is the primary source of the monument's "life-giving" water. The underlying Supai Formation is largely impermeable to groundwater flow and assures a consistent water table, usually within 0.9 to 1.2 m (3 or 4 ft) of the surface (Cooley et al. 1969; McDonald 1976). Locally, the Shinarump Member of the Chinle Formation (**TRcs**), which is hydrologically connected to the De Chelly Sandstone in the Defiance Plateau area (Cooley et al. 1969), yields minor amounts of water to wells and springs.

According to the *Arizona Water Atlas, Volume 2* (Arizona Department of Water Resources 2009), the monument's groundwater comes from the "C-aquifer." Depending on location (and geology), the C-aquifer is primarily composed of the Coconino Sandstone, from which it received its name, but the water-bearing De Chelly Sandstone and Shinarump Conglomerate make up the aquifer on the Defiance Plateau.

With an areal extent of 56,086 km^2 (21,655 mi^2), the C-aquifer is the largest in the Eastern Plateau Planning Area (a classification used by the State of Arizona); it is also the most productive (Arizona Department of Water Resources 2009). The C-aquifer extends from the Mogollon Rim in the south (see Figure 2) to an area west of the Little Colorado River (see ("Fluvial Features and Processes") and northeast into New Mexico. Water in the aquifer generally flows in a west–northwest direction. Recharge to the aquifer is along the Mogollon Rim and on the Defiance Plateau (Hart et al. 2002).

Alluvium (**Qa**; see "Fluvial Features and Processes") is another source of groundwater in the monument. Canyon residents commonly dig shallow wells to reach this water source, both for watering crops and for personal use (Houk 1995). Alluvium consists mostly of sand, silt, and gravel in small stream valleys and on floodplains. Canyon bottoms in the monument contain moisture-retaining sandy alluvium, which receives considerable water as discharge from the sedimentary rocks (Cooley et al. 1969). As a result, canyon bottoms, which are underlain by alluvium, make the "best agricultural land in the monument" (McDonald 1976, p. 12).

Terrace deposits (sand, silt, and gravel; see "Fluvial Features and Processes") and dune deposits (mostly sand; see "Sand Dunes") also yield small amounts of water to springs (Cooley et al. 1969). A terrace is a long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) along a stream. Although both terraces and sand dunes occur within the monument, at a scale of 1:250,000, none appear on the geologic map; however, alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) are mapped south of the monument (see poster).

Volcanic Landforms

Scenic views and vistas are a fundamental resource and value at the monument (National Park Service 2016). Many of these vistas are enhanced by volcanic features of the Navajo volcanic field (Tsézhin 'íí' áhí, meaning "Black Rocks Protruding Up"). These features are scattered throughout the area, with significant clusters in Buell Park and the Chuska Mountains (southeast and east of the monument; see Figure 3).

The landforms of the Navajo volcanic field are composed of the following three rock types (see poster):

- Minette (**Tmn**) is the major rock type in the Navajo volcanic field. The name "minette" originated with miners who encountered the same type of rock in France (Semken 2010). Minette forms from melt (a liquid, fused rock) that originates at the crust-mantle boundary, approximately 150 to 200 km (90 to 120 mi) below Earth's surface. Most melts originate about 50 km (80 mi) below the surface and have a very different chemistry; thus, minette is distinctive. At the surface, minette is typically friable and crumbles into sand-sized particles as it weathers. In the field, it is identified by the presence of abundant reflective mica and small crystals of olive-green olivine and apple-green pyroxene. Aphanitic (fine-grained) minette has the same chemical composition as friable minette, but because the individual crystals are so small, they form a dense, hard, dark-colored rock, which is flakable (see "Lithics: Sources of Information").
- Trachybasalt (**Tt**) forms lava flows and shallow plugs (bodies of magma, such as a former vent or a lava-filled crater) in the Chuska Mountains (east of the monument) and Lukachukai Mountains (northeast of the monument). Trachybasalt is the extrusive equivalent of minette (Semken 2003), and the name "extrusive minette" is more accurate (Steven Semken, Arizona State University, professor, written communication, 17 May 2023). Trachybasalt, or extrusive minette, is sometimes referred to as "friable minette" (Arakawa and Miskell-Gerhardt 2009). In the archeological literature, these rocks are also called "sanidine basalt" or "trachyte."
- Tuff breccia (**Ttb**) consists of tuff (consolidated volcanic ash and other relatively fine-grained materials) that has been fragmented into breccia (consisting of angular rock fragments). Tuff breccia is generated during an eruption by the ascending minette as it encounters groundwater (e.g., in a regional aquifer such as the Chuska Sandstone [**Tc**]) and undergoes phreatic (steam-driven) explosions. During the explosion, magma is fragmented into tiny solid particles that are blown against the walls of the subterranean magma chamber and plastered into near-vertical beds that resemble upturned sedimentary rocks. Pieces of wall rock may also be ripped off and intermixed with sand-sized tuff particles. Xenoliths (conspicuous inclusions in volcanic rock) that ascended from a deep level as part of the volcanic melt may be incorporated into the tuff breccia. Some xenoliths, for example, in Ship Rock (northeast of the monument), may be as large as a house (Semken 2010).

The rocks of the Navajo volcanic field have been of considerable interest to researchers because of their unique chemistry and xenoliths. In the past 50 years, studies of the Navajo volcanic field have helped gain insight into the origin and evolution of magmas (Powell and Bell 1970; Ehrenberg 1979, 1982a, 1982b; Roden and Smith 1979; Roden 1981; Jones and Smith 1983; Rowell and Edgar 1983; Vaniman et al. 1985; Alibert et al. 1986; Laughlin et al. 1986, 1989; Roden et al. 1990; Beard and Johnson 1993; Nowell 1993; Carlson and Nowell 2001). Additionally, investigators have used the crust- and mantle-derived igneous rocks brought to the surface in the Navajo volcanic field to map the petrology (origin, occurrence, structure, and history of rocks) of the lithosphere (Earth's relatively rigid outer shell that consists of the entire crust plus the uppermost mantle) beneath the Colorado Plateau (Semken 2003).

Eruptions in the Navajo volcanic field produced both extrusive features (erupted onto the surface) and intrusive features (emplaced below the surface). Extrusive features include lava flows and tephra rings. “Tephra” is a collective term for all the fragmented materials erupted by a volcano, particularly the materials ejected into the air. Tephra rings surround the craters of maar (crater)-diatreme (vent structure) volcanoes, which are the type or volcano composing the Navajo volcanic field (see “Navajo Volcanic Field”). Intrusive features include volcanic necks, which are vertical, pipelike intrusions that represent the vent of a volcano; a vent is an opening at Earth’s surface through which magma erupts or volcanic gases are emitted. Another intrusive feature is dikes (sheet-like bodies of magma that ascend through fractures in preexisting rock; the term is usually applied to erosional remnants). Feeder dikes are of interest in the Navajo volcanic field. At Ship Rock (Tsé bit’a’í, meaning “Rock with Wings”), for example, six dikes radiate from a point just west of the central intrusion (Figure 11). Linear dikes of minette also are found east and west of Sonsela Buttes (see poster). According to the 2007 scoping participants, compared to other volcanic features, only a few feeder dikes have been discovered in the volcanic field. Possibly with more detailed mapping, additional feeder dikes will be discovered near the monument (KellerLynn 2007).

Volcanic landforms of significance for the monument include Black Rock Butte (see Figure 6) and Sonsela Buttes (east of the monument; see poster). Black Rock Butte is composed of minette that rose to the surface along the fault that marks the southeastern boundary of Tsaile graben (see poster; Steven Semken, Arizona State University, professor of geology, email communication, 18 December 2023). Sonsela Buttes are composed of trachybasalt, tuff breccia, and minette. They are eroded craters capped by lava flows (Semken 2003).

Volcanic landforms, including Black Rock Butte and Sonsela Buttes, appear as red “spheres” and orange or yellow “blobs” on the geologic map (see poster). The most conspicuous is the Buell Park diatreme, southeast of the monument. The Buell Park diatreme is a volcanic pipe filled with tuff breccia. It is the largest diatreme in the Navajo volcanic field (Roden et al. 1979).

The volcanic landforms of the Navajo volcanic field figure prominently in Navajo empirical knowledge and culture (Semken 2003). The People invoke a direct connection between their cultural identity and the physical attributes of Diné bikéyah, their homeland on the Colorado Plateau. Navajo empirical knowledge of nature has been accrued through millennia of living in direct contact with the environment. Knowledge pertaining directly to Earth is Diné ethnogeology (tsé na’alkaah, meaning “rock study”; see Table 1). An example is Ship Rock, which is considered sacred and, although viewing is allowed, is off limits to hikers and climbers (Crumpler, n.d.). The role of Ship Rock and other volcanic landforms of Navajo creation stories can be found in the compilations by Matthews (1897) and Zolbrod (1984) and the children’s book by Browne and Whitethorne (1993). It is important to note that such stories should be retold only with great respect. The place and time of storytelling are intertwined; the telling of creation stories occurs in the shelter of the hogan and only during the winter months (Semken 2003; Steven Semken, Arizona State University, professor, written communication, 17 May 2023).



Figure 11. Photograph of Ship Rock. Ship Rock in New Mexico is a classic feature of the Navajo volcanic field, or Tsézhiin ‘ii ‘áhí, meaning “Black Rocks Protruding Up.” Ship Rock itself is known as Tsé bit'a'í, that is, “Rock with Wings.” The three largest “wings,” or dikes, radiating out from Ship Rock, are 9, 4, and 3 km (6, 2, and less than 2 mi) long and trend S 12° E, N 80° W, and N 55°E, respectively. The other three dikes are approximately parallel to the northern dike and trend N 55° E and are less than 1 km (0.6 mi) long (Crumpler, n.d.). The extensive, 9-km- (6-mi-) long, south dike (extending towards the lower, lefthand corner of the photograph) is nearly 30 m (100 ft) tall in some places, yet it is only a meter (few feet) thick (Semken 2010). Photograph (2012_05_06_lax-bos_shiprock_10) by Doc Searls, used under license Creative Commons Attribution 2.0 Generic, https://creativecommons.org/licenses/by/2.0/ (accessed 27 February 2024).

Rock Shelters, Cliff Dwellings, and Middens

Cliff dwellings (concentrated village sites consisting of stone and adobe-walled structures, commonly multistoried) are significant for the monument’s geologic heritage and of interest to the GRI because they are built of geologic materials within a geologic feature—rock shelters. For the purpose of managing these resources, the GRI considers the monument’s rock shelters as a type of cave. According to NPS management policies (National Park Service 2006), the term “cave” includes karst, such as limestone and gypsum caves, and nonkarst caves, such as lava tube, littoral (located along a shoreline), and talus (unstable rock debris at the base of a cliff or on a steep slope) caves. The NPS manages caves in accordance with approved cave management plans (see “Cave Inventory, Monitoring, and Protection”) to perpetuate the natural systems associated with caves, such as karst and other drainage patterns, air flows, mineral deposition, and plant and animal communities. The

NPS also manages the use of caves, particularly when such actions are required for the protection of cave resources or for human safety (National Park Service 2006, section 4.8.2.2).

Notably, with respect to archeology, rock shelters and caves differ. Caves are subterranean systems containing areas that are, to some degree, permanently dark, whereas rock shelters are cavities that are always lit by direct or indirect sunlight (Pat Seiser, National Cave and Karst Research Institute, cave and karst management science director, written communication, 9 May 2023).

In Canyon de Chelly, rock shelters in the lower part of the canyon (between its mouth and the junction with Canyon del Muerto) are typically on the canyon floor, or within a few feet of it, and are easy to access. In the middle part of Canyon de Chelly (between the mouth of Canyon del Muerto and The Window; see poster), rock shelters are typically located between 15 and 60 m (50 and 200 ft) above the canyon floor. Most of these rock shelters can be entered by climbing the talus slopes below them. In the upper canyon (beyond The Window), the relatively few habitable rock shelters are usually located above the high talus slopes (De Harport 1959).

Most cliff dwellings in the monument were built in rock shelters that occur in the De Chelly Sandstone (**Pdc**). The Supai Formation (**PPNs**) hosts some rock shelters, but they are small, and the overhang is usually low, thereby providing less habitation and storage space than the rock shelters in the De Chelly Sandstone (McDonald 1976).

Cliff dwellings are characteristic of the Puebloan period (750–1300 CE) (National Park Service 2016). Prior to Navajo arrival in what is now the monument, Puebloans had constructed White House and other pueblos. For the past 700 years, no humans have permanently inhabited the cliff dwellings in the monument (McDonald 1976).

In addition to humans, packrats (*Neotoma* spp.) have inhabited the monument's rock shelters. Packrat middens (heaps or moundlike accumulations of refuse) are important tools for reconstructing the ecology and climate of the southwestern United States during the Late Pleistocene and Holocene Epochs (about the last 129,000 years; Strickland et al. 2001).

Based on two documented middens at the monument—found near the mouth of Canyon del Muerto (Betancourt and Davis 1984; Betancourt 1990)—the known paleoecologic and paleoclimatic record covers about 14,000 years. The older of the two middens is dated to 11,900 ± 300 radiocarbon years before present (Tweet et al. 2012) or 13,847 calendar years ago (mean probability, converted from radiocarbon years using CALIB REV8.2; Reimer et al. 2020). The younger midden is dated to 3,120 ± 110 radiocarbon years before present (Tweet et al. 2012) or 3,313 calendar years ago (mean probability, converted from radiocarbon years using CALIB REV8.2; Reimer et al. 2020). The two middens have quite different fossil assemblages. The older assemblage is dominated by Douglas fir (*Pseudotsuga menziesii*) needles whereas the younger assemblage is dominated by herbs and shrubs. The younger midden includes some evidence of humans.

In addition, a large, multi-level midden was recovered from a rock shelter at Wide Rock Butte in Canyon del Muerto. Levels 4 and 2 (of four total levels) were dated, yielding ages of 6,210 ± 90

radiocarbon years before present or 7,097 calendar years ago (mean probability, converted from radiocarbon years using CALIB REV8.2; Reimer et al. 2020) and 1,930 ± 80 radiocarbon years before present or 1,852 calendar years ago (mean probability, converted from radiocarbon years using CALIB REV8.2; Reimer et al. 2020; Schmutz et al. 1976; Mead et al. 1978; Tweet et al. 2012).

Desert Varnish

Also called "rock varnish," desert varnish is a natural veneer composed of clays, oxides of manganese and iron, and organic compounds that covers many rock surfaces in the monument. Generally, desert varnish develops best on rocks with moderately rough surfaces that are resistant to weathering. At the monument, sandstone is commonly well varnished, whereas siltstones and shales disintegrate too rapidly to retain such a coating. Elsewhere, basalt and many metamorphic rocks are well varnished (Bezy et al. 2000).

Despite the extensive literature related to rock varnish, many uncertainties regarding its composition and formation remain. However, about 70% of the total mass of a deposit of desert varnish is composed of clay minerals. Notably, the clay component comes from windblown dust and is not an alteration product of the underlying rock surface. Many researchers have proposed that microbial activity is significant for the formation of desert varnish, though others have invoked an inorganic origin, such as silica (SiO_2) coatings composed of opal (Dickerson 2011).

The oft-lustrous coating of rock varnish ranges in color from light brown to black, depending on how much has accumulated. Well-varnished surfaces have a luster that causes entire hillsides to glisten in the intense desert sunlight. This mineral coating adds warm tones of brown and ebony to the landscape, commonly masking brilliantly colored red bedrock underneath (Bezy et al. 2000).

Dark tendrils of rock varnish streak the De Chelly Sandstone cliff above White House, enhancing the setting and creating a classic tableau for photographers (see Figure 10). Indeed, the scene is instantly recognizable as one of the best known by Ansel Adams, arguably the most famous photographer of the 20th century (Quinn 2023). Upon first traveling to the monument in 1937, Adams thought it was the most beautiful place on Earth. Astonished by the "flowing patterns" of cross-bedded sandstone, he wrote to his wife, Virginia Best, "The Canyon de Chelly exceeds anything I have imagined at any time!" Inspired by the monument's geology to return again and again, Adams wrote in his autobiography: "Some of my best photographs have been made in and around the rim of the canyon" (Guerreiro 2020, online information).

Rock Art

Rock art is drawing, painting, carving, or similar work on stone that dates to prehistoric or historic periods, although some may be more recent. Rock art adds cultural significance to geologic features at the monument, including the sheer canyon walls and rock shelters. Restrictions on travel, not only for the safety of visitors but also to protect fragile archeological sites and the privacy of Navajo families living in the monument, permit access only to such prominent rock art sites as Antelope House (Figure 12), Standing Cow Ruin, Mummy Cave, and White House. These locations provide ample opportunities for an introduction to the monument's rock art, however.



Figure 12. Photographs of Antelope House and pictographs. Antelope House in Canyon del Muerto is named for the colorful antelope pictographs painted on a nearby rock face. These were painted by Navajo artist Little Lamb (Dibe Yazhi) in the 1830s. Other figures in white paint are probably the work of prehistoric inhabitants. Photographs by Ron Karpilo (Colorado State University), taken 2005.

Worldwide, rock art falls into two basic categories: (1) pictographs (images painted on rock) and (2) petroglyphs (images pecked or carved into rock). In both cases, a suitable rock surface is needed. At the monument, the primary canvas for rock art is the De Chelly Sandstone (**Pdc**).

Pictographs

The abundance of rock shelters at the monument probably led to painting as a favored technique (Grant 1978). With rare exceptions, pictographs were painted on light-colored rock surfaces in sheltered locations where the effects of wind and rain were minimal or nonexistent (Grant 1978).

The variety of colored clays in the region, which were used as pigment, gave the artists great diversity in painting pictographs. White, yellow, black, several shades of red, green, greenish white, brown, orange, gray, buff, and purple enliven rock walls at the monument. The most common colors are white, greenish white, and red whereas darker colors such as black are rare. Identification and/or a survey of source areas for pigment are not known to have taken place, but Grant (1978) concludes that most of the colors were of mineral origin; charcoal for black being a notable exception.

Other colors, which were likely chosen for their brilliance, were vegetable based. Those colors, however, have not stood up over the centuries. For example, many of the depictions of turkeys—a common design element of the Modified Basketmaker/Developmental Pueblo stage—painted on rock walls appear to be headless because the colors used have faded with time; occasionally, the missing head can be faintly seen. Similarly, bi-colored human figures, where the color division was longitudinal, sometimes appear as half figures.

The medium that ancient artists used for binder is speculative. Blood, urine, egg whites, and seed oil mixed with finely ground pigment have been suggested (Grant 1978). Animal fat is another possibility (Keith Lyons, Canyon de Chelly National Monument, integrated resource manager/archeologist, personal communication, 1 November 2023).

Petroglyphs

Petroglyphs were created by pecking, scratching, or abrading, commonly into the brown-black coating or patina of desert varnish on canyon walls (see "Desert Varnish"). In this way, the design stands out—light on dark—as a "negative image."

Most darkly patinated rock surfaces at the monument occur as streaks high on canyon walls, whereas accessible surfaces occur near the bottom of canyon walls. However, at these accessible locations (lower on canyon walls), patina formation is slight to nonexistent. As a result, petroglyphs were deeply carved so that they would be visible, especially in oblique light, despite minimal color contrast (Grant 1978).

Geologic History

This chapter describes five significant geologic events that led to the monument's present-day landscape. These events are discussed more or less in order of geologic age (oldest to youngest). Paleogeographic maps help illustrate these events. A geologic time scale shows the monument's rocks and unconsolidated deposits—which are representative of these significant geologic events—in a context of geologic time.

As a point of reference, the monument's bedrock was deposited when Earth's continental crust was configured into the supercontinent Pangea (Figure 13). Configuration of Pangea began about 335 million years ago (Middle Mississippian Period). Deposition of the monument's bedrock (Supai Formation, De Chelly Sandstone, and Chinle Formation) began about 310 million years ago (Middle Pennsylvanian Period) and ended about 210 million years ago (Late Jurassic Period). The supercontinent reached its greatest extent about 250 million years ago (Early Triassic Period). Breakup of the supercontinent began about 200 million years ago (Early Jurassic Period).

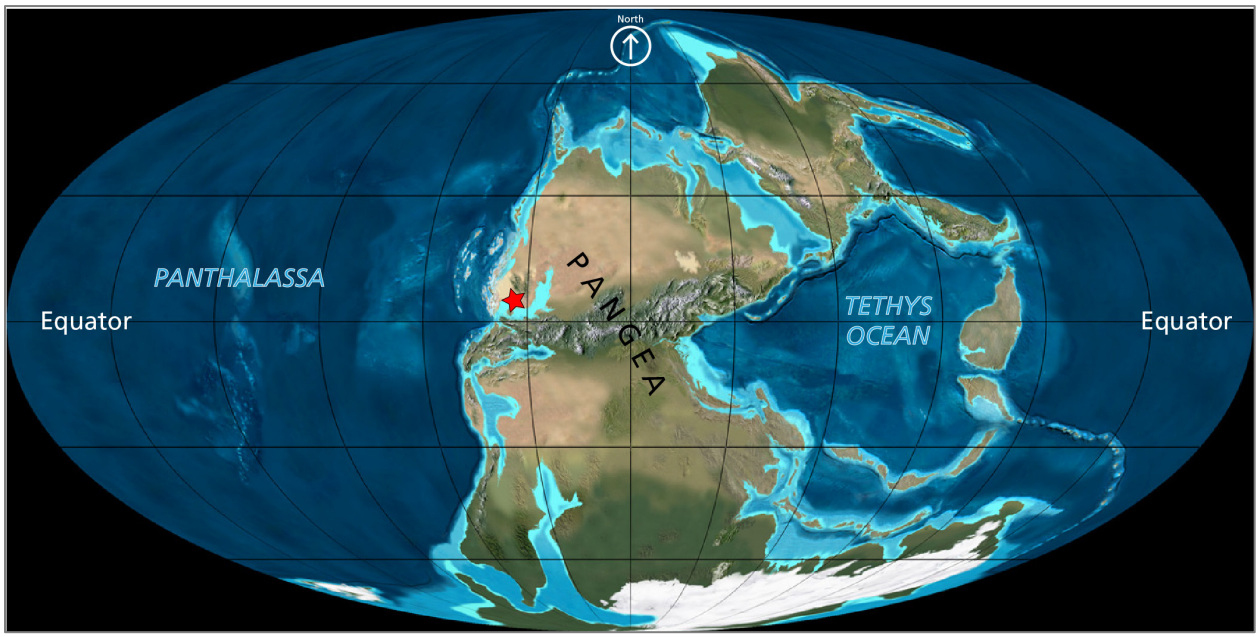


Figure 13. Paleogeographic map of Pangea. Spanning from pole to pole and shaped like a huge letter "C," the supercontinent Pangea cupped the Tethys Ocean. The "super-ocean" Panthalassa covered the remainder of Earth's surface. The monument (red star) was on the western edge of Pangea, near the equator. Note the uplifted swath of ancient mountains spanning the width of the continent. At the South Pole, the white area represents a continental ice sheet. Base paleogeographic map by Ron Blakey, "Paleogeography of Southwest North America," © 2012 Colorado Plateau Geosystems Inc., used under license; see https://deeptimemaps.com/ (accessed 27 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Pangea is commonly described as having two parts: Laurasia (representing northern Pangea and including continental crust that would compose North America [referred to as "Laurentia"], Europe,

and Asia) and Gondwana (representing southern Pangea and including continental crust that would compose South America, Africa, Antarctica, Australia, and India). A mountain belt bifurcated these two parts. Of significance for the monument, the Ancestral Rocky Mountains were at the western edge of this transcontinental mountain belt.

Significant Geologic Events

The following geologic events are significant for the monument:

Development of the Ancestral Rocky Mountains

During the Pennsylvanian and Permian Periods, the Defiance uplift (see "Geologic Setting") was part of the Ancestral Rocky Mountains system, which consisted of a group of highlands (above sea level) and adjacent basins (below sea level). Today, remnants (uplifts and basins) of the Ancestral Rocky Mountains are concentrated in a northwest–southeast-oriented swath across the Four Corners Area (see Figure 2), Oklahoma, and Texas (Figure 14).

The tectonic origin of the Ancestral Rocky Mountains system—with its rising uplifts and subsiding basins—began about 315 million years ago (Blakey and Ranney 2008). The origin is poorly understood, but various tectonic processes have been invoked to explain its genesis. A convincing hypothesis is that interactions between the Panthalassa oceanic plate (proto-Pacific Ocean) and the Laurentian continental plate (proto-North America) combined with stress from collision along the Ouachita-Marathon belt (part of the transcontinental mountains; see Figure 14) and possibly along the proto-Nevada margin produced an overall northeast–southwest-directed stress field that drove uplift and basin development (Leary et al. 2017). Tectonic processes/plate interactions included both subduction, which occurs when an oceanic plate slides deeply (for hundreds of kilometers/miles) beneath a continental plate into a subduction zone, and transpression, which involves the combination of compression and horizontal plate motion when two plates meet (see areas of subduction and transpression labeled on Figure 14). Interestingly, no evidence exists of magmatism or volcanism related to the development of the Ancestral Rocky Mountains system.

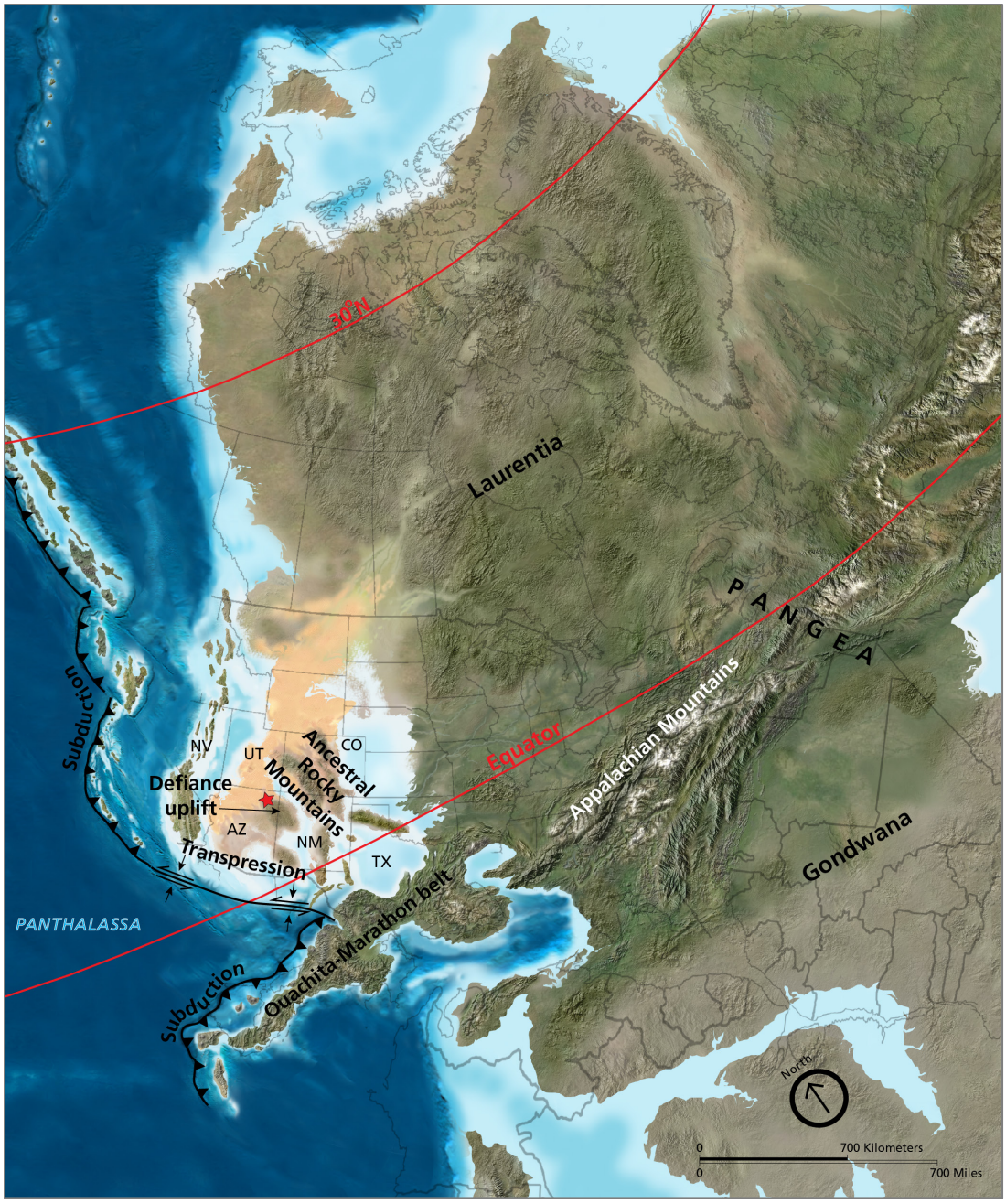


Figure 14. Paleogeographic map of the Late Pennsylvanian Period (about 300 million years ago). The Ancestral Rocky Mountains system dominated the western margin of Laurentia (proto-North America). Tectonic stresses including the convergence to the west–northwest in Nevada, transpression to the southwest in present-day Sonora, and the suturing between Laurasia (northern Pangea) and Gondwana (southern Pangea) in the Ouachita-Marathon belt to the south–southeast drove uplift and basin development. At that time, the Supai Formation was being deposited in a sabkha. A red star marks the location of the monument. Base paleogeographic map by Ron Blakey, "Paleogeography of Southwest North America," © 2012 Colorado Plateau Geosystems Inc., used under license; see https://deeptimemaps.com/ (accessed 27 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Accumulation of Sediments

Subsiding basins in the Ancestral Rocky Mountains system provided areas for sediments to accumulate. Sources of sediment included voluminous material shed from the Ancestral Rocky Mountains. These sediments are preserved as part of the brilliantly colored stack of sedimentary rocks on the Colorado Plateau (Blakey and Ranney 2008). Relatively speaking, the Defiance uplift provided few sediments to adjacent basins. However, the uplift acted as an effective deterrent to marine circulation between the San Juan Basin and the Black Mesa basin, to the east and west, respectively (Figure 15), which ultimately affected the types of sediments preserved in the basins.

The primary influx of sedimentary material that accumulated in the basins was probably delivered via eolian transport (Soreghan et al. 2018), in part owing to ephemeral wetting across a broad, continuously subsiding region consisting of settings such as sabkhas (flat-lying areas subject to periodic flooding and evaporation, typically located between a desert and ocean), mudflats (sections of shoreline covered by silt or clay and submerged at high tide), dune fields, and loess sheets (composed of windblown dust). Additionally, copious amounts of glacially scoured silt became available for windblown transport, particularly as the climate became increasingly arid throughout the Permian Period. At that time, a continental ice sheet covered the southern part of Pangea, where it extended over Earth's South Pole (see Figure 13). In addition, alpine glaciers formed in higher elevation areas of uplifts (Soreghan and Sweet 2013; Soreghan et al. 2018; Pfeifer et al. 2021).

The presence of mineral grains (i.e., highly durable zircons that can travel great distances in rivers) in the Chinle Formation demonstrates a shift in provenance from a significant Ancestral Rocky Mountains source in the Pennsylvanian–early Permian Periods to the Cordilleran arc during the Triassic Period (Riggs et al. 2016). Cordilleran arcs are belts of deformation, magmatism, and volcanism associated with subduction, in this case, of the Panthalassa oceanic plate and the overriding proto-North American continental plate (Figure 16). The Chinle Formation was deposited in an elongated basin that was formed by dynamic subsidence behind the nascent Cordilleran arc. The arc originated in a marine setting—offshore and separated from the continent. As the arc developed and magmatism became more widespread, eruptions probably breached the air-water interface. As development progressed, volcanic edifices in the arc became more common and had the effect of bringing the arc above water and establishing a land bridge between the arc and the continent about 230 million years ago (i.e., the start of deposition of the Chinle Formation). At that point, eroded material from the growing arc began to accumulate in the fluvial (river) strata of the Chinle Formation (Riggs et al. 2016). Other sources of Chinle sediment include the southern Appalachian Mountains (Blakey and Ranney 2008) and the Ouachita-Marathon belt (Oberling et al. 2010; Oberling 2015; Figure 16). Deposition of the Chinle Formation ushered in the continental sedimentation that has dominantly characterized the region ever since (Riggs et al. 2016).

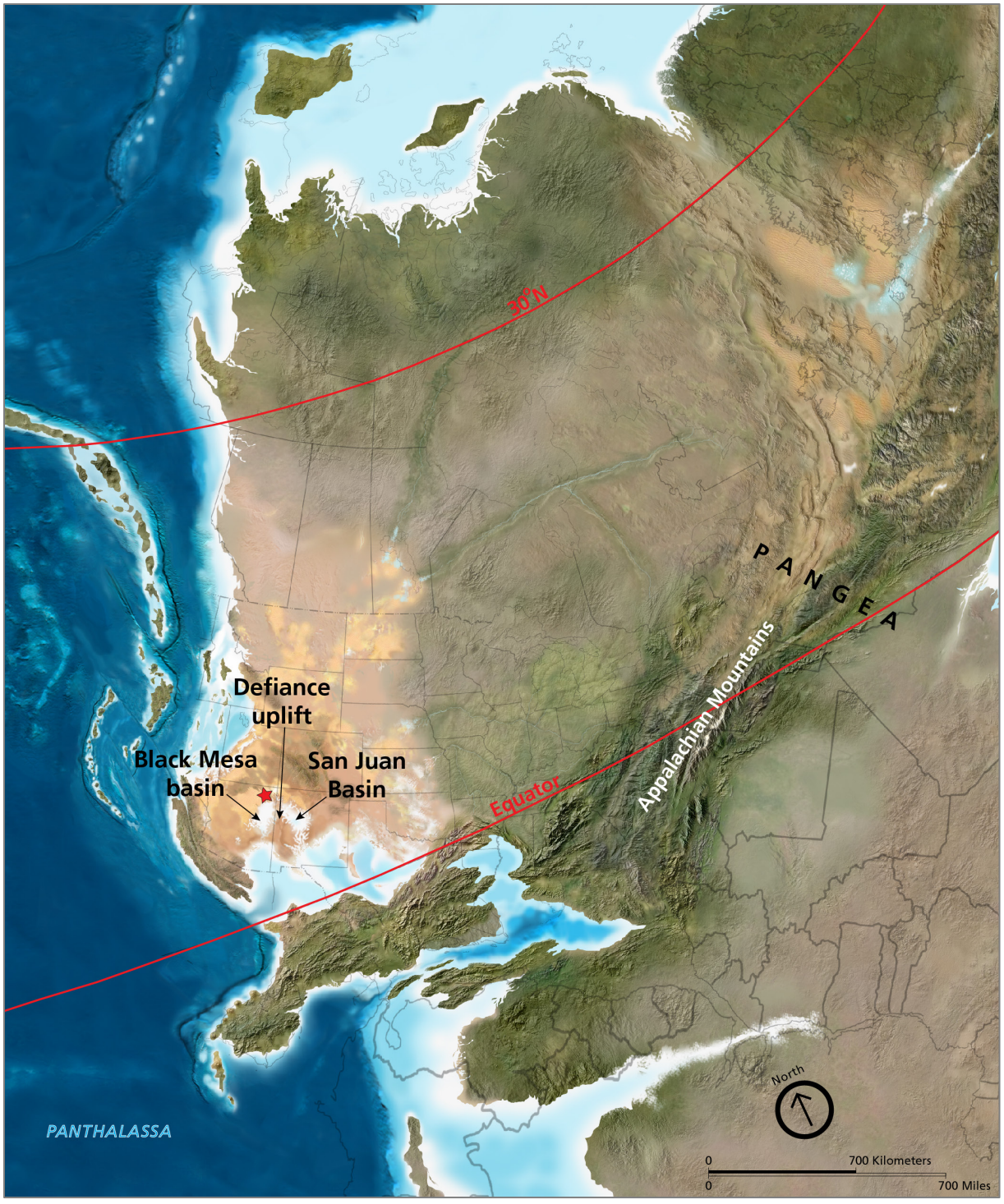


Figure 15. Paleogeographic map of the early Permian Period (about 280 million years ago). The Defiance uplift was still a highland. The De Chelly Sandstone was being deposited in a dune landscape. Prevailing winds blowing from the northeast across Pangea generated large, conspicuous cross-beds. A red star marks the location of the monument. Base paleogeographic map by Ron Blakey, "Paleogeography of Southwest North America," © 2012 Colorado Plateau Geosystems Inc., used under license; see https://deeptimemaps.com/ (accessed 27 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).



Figure 16. Paleogeographic map of the Late Triassic Period (about 220 million years ago). The Chinle Formation was being deposited by rivers flowing across Pangea toward the Panthalassa Ocean. The source of sediment was primarily the Cordilleran arc (on the western margin of the continent) but also the Ouachita-Marathon belt and the Appalachian Mountains. A red star marks the location of the monument. Base paleogeographic map by Ron Blakey, “Paleogeography of Southwest North America,” © 2012 Colorado Plateau Geosystems Inc., used under license; see https://deeptimemaps.com/ (accessed 27 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Laramide Orogeny

By the time the Laramide Orogeny (the most recent mountain-building event in North America) began about 80 million years ago (Late Cretaceous Period), the Ancestral Rocky Mountains were no longer a highland, having been beveled by erosion and buried in sediment. The rise of the modern Rocky Mountains followed that of the Ancestral Rocky Mountains by as much as 235 million years. The Laramide Orogeny ended about 50 million years ago (Paleogene Period; Coney 1978; Humphreys et al. 2003; Liu and Gurnis 2010).

The Laramide Orogeny was first recognized and named for sediments shed into the Laramie Basin in southern Wyoming (Dana 1895; Tweto 1975). Over the years, however, uplifted mountain ranges have come to characterize the orogeny (Blakey and Ranney 2018). Numerous national parks and monuments preserve the scenery created by the Laramide Orogeny, including alpine peaks in Rocky Mountain National Park (see GRI report by KellerLynn 2004), spectacular folds in Grand Canyon National Park (see GRI report by Graham 2020), and the Waterpocket Fold that runs the length of Capitol Reef National Park (see GRI report by Graham 2006).

The significance of the Laramide Orogeny for the monument is uplift. At the beginning of the Laramide Orogeny, the Colorado Plateau was near sea level. The high elevation of today's plateau was mostly the result of Laramide uplift. Moreover, compressive forces associated with the Laramide Orogeny reactivated the Defiance uplift, caused westward tilting, and created significant folds. Large folds appear to be associated with ancient, steeply dipping fault zones (Davis 1984). A commonly cited plate tectonics mechanism for the Laramide Orogeny is shallow-slab or flat-slab (low-angle) subduction (Saleeby 2003; Figure 17).

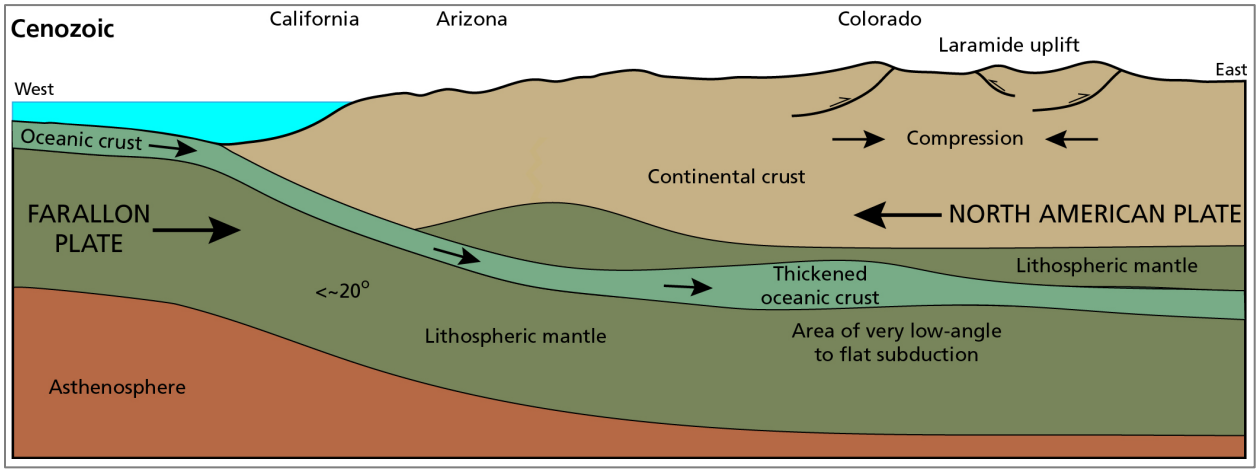


Figure 17. Cross section of flat-slab subduction. A commonly cited plate tectonics mechanism for the Laramide Orogeny is flat-slab subduction, which is also called "shallow-slab" or "low-angle" subduction. About 80 million years ago (Cretaceous Period) as the Farallon oceanic plate slid beneath the North American continental plate, a large oceanic plateau (thickened oceanic crust) that was riding on the Farallon plate subducted beneath the continent. The additional buoyancy provided to the Farallon plate caused the angle of the subducting plate to become less steep. Figure by Trista L. Thornberry-Ehrlich (Colorado State University) after Lillie (2005, figure 1.19b) and Blakey and Ranney (2018, figure 8.13).

Volcanism

From about 25.9 million to 24.5 million years ago (Nybo et al. 2011), the Navajo volcanic field developed during a short but widespread pulse of magmatism (intrusive activity) and volcanism (extrusive activity). Eruptions were phreatomagmatic (explosive volcanic eruptions caused by the interaction of magma and groundwater) and took place in maar-diatreme volcanoes (see "Navajo Volcanic Field").

In general, intrusive features in the Navajo volcanic field are associated with major regional structures (see Figure 3), such as monoclines (a type of fold; see "Folds, Faults, and Related Landforms"). Dike trends and fracture patterns in the region are consistent with north–northeast compression that developed during the Laramide Orogeny and are represented by monoclines. Compression was followed by the onset of regional crustal extension about 30 million years ago (during the Oligocene Epoch). Crustal extension, which is characterized by normal faulting (see Figure 7), provided avenues for the invasion of mantle magmas that gave rise to dikes in the Navajo volcanic field (Gonzales et al. 2010). Although the volcanoes are not situated along exposed faults, magma ascent was probably facilitated by fractures at depth (Delaney 1987).

The surface expressions of volcanoes in the Navajo volcanic field have long since eroded away. For example, the maar (crater) at Ship Rock volcano was an estimated 1,000 m (3,300 ft) above the present-day land surface prior to exhumation (Delaney and Pollard 1981). Contemporaneous post-eruptive uplift of the Colorado Plateau and regional incision of the landscape by the Colorado River system (discussed below) likely facilitated the exhumation of the maar-diatreme volcanoes in the Navajo volcanic field.

Entrenchment of the Colorado River System

Canyon de Chelly and associated canyons are deep clefts cut into the gently inclined plain of the Defiance Plateau (Figure 18). Intense stream erosion resulting in entrenchment (creation of a "trench" via downward incision by a river through surficial deposits and into bedrock) of the Colorado River system created Canyon de Chelly and the other canyons in the monument. The Colorado River system consists of the Colorado River and its four primary tributaries—the Green, Little Colorado, San Juan, and Virgin Rivers. The monument is in the San Juan River watershed (see "Fluvial Features and Processes").

In addition to Canyon de Chelly and associated canyons, other well-known features created by entrenchment of the Colorado River system are the spectacular goosenecks (entrenched meanders) of Goosenecks State Park in San Juan County, Utah, and Horseshoe Bend in Glen Canyon National Recreation Area, Utah (see GRI report by Graham 2016). Other "Colorado River parks" experiencing entrenchment include Grand Canyon National Park, Arizona (see GRI report by Graham 2020); Lake Mead National Recreation Area, Nevada (see scoping summary by Connors and Covington 2004); and Canyonlands National Park, Utah (see GRE report by KellerLynn 2005).

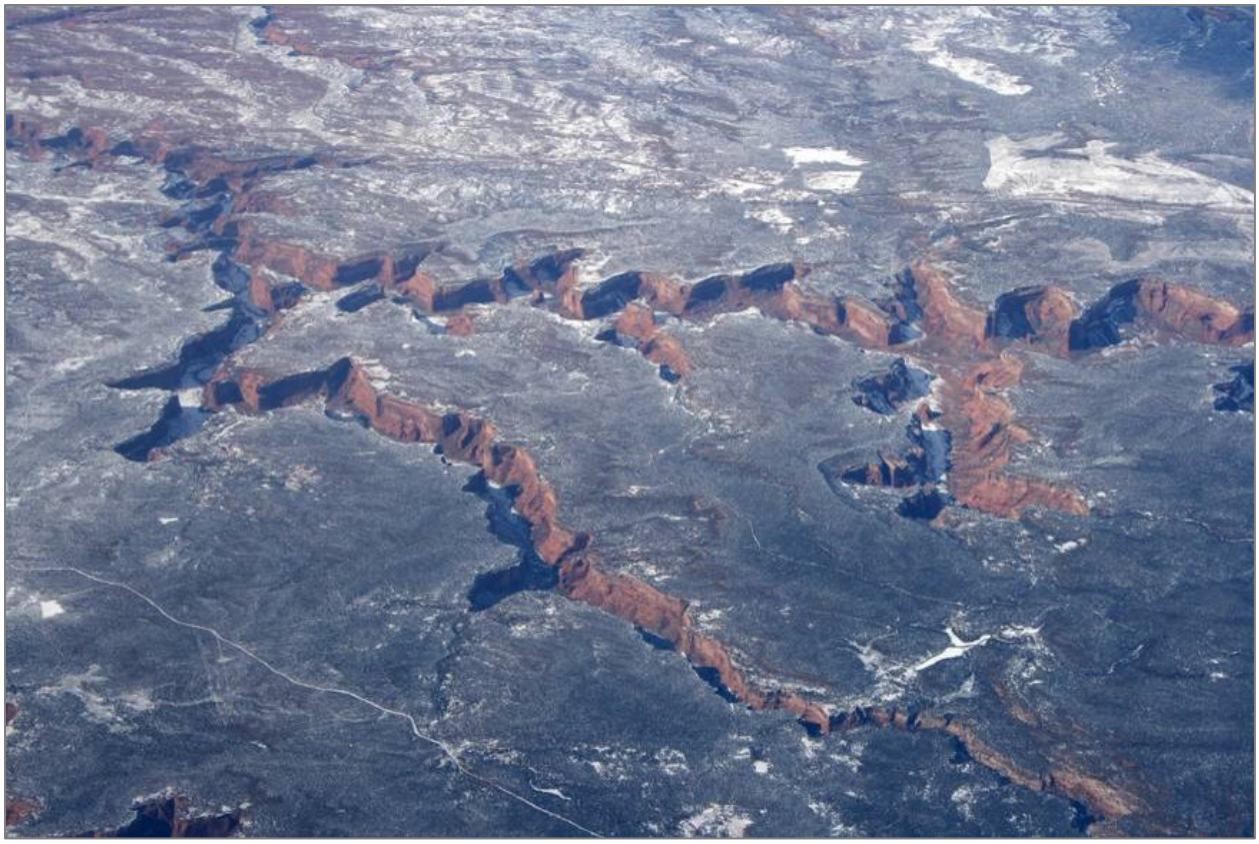


Figure 18. Photograph of entrenchment on the Defiance Plateau. The oblique aerial photography highlights entrenchment of the Colorado River system. The photograph shows the monument, including Canyon de Chelly and other canyons. Entrenchment took place during the Black Point cycle of the late Pliocene and early Pleistocene Epochs (3.6 million to 774,000 years ago). Photograph courtesy of Ron Blakey (Northern Arizona University, GRE scoping meeting, PowerPoint presentation, 16 February 2007).

The timing of initial downcutting by the Colorado River system is uncertain but is known to predate incision of the Grand Canyon, which is interpreted as having started about 6 million years ago (for a summary, see Karlstrom et al. 2014 and/or the GRI report about Grand Canyon National Park by Graham 2020). The lower Colorado River drainage became established when the San Andreas Fault ripped open the Gulf of California. That is an important event in understanding the origin of the Grand Canyon because the opening of the gulf provided an outlet to the sea for the previously disorganized system of rivers on the Colorado Plateau. Integration of these rivers and the lowering of base level (the lowest level to which a stream channel can erode, ultimately sea level) would have caused the Colorado River to deepen its track, which in turn would have caused it to lengthen its course in the upstream direction, facilitating the inception and capture of rivers that previously were not connected to it (Blakey and Ranney 2008).

Systemic development of drainages in the monument occurred during four erosional events that correspond to four widespread erosion surfaces. These surfaces were not mapped on the source maps for the GRI GIS data, so they do not appear in the data or on the poster. However, they appear on

"Physiographic Map of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah" (Cooley 1968, which is plate 3 of Cooley et al. 1969).

The following four erosional events/surfaces are significant for the monument's landscape development:

1. Valencia cycle (Cooley and Akers 1961) of probable Miocene age (23.0 million to 5.3 million years ago). The eroded surfaces of the Chuska Mountains (east of the monument) and Black Mesa (west of the monument) correspond to this surface. Streams that flowed on the Valencia surface began the Colorado River system (Cooley et al. 1969).
2. Hopi Buttes-Zuni cycle (Gregory 1917; McCann 1938), undifferentiated, of Pliocene age (5.3 million to 2.6 million years ago). The ancestral Colorado River system became entrenched during this cycle.
3. Black Point cycle (Gregory 1917) of late Pliocene and early Pleistocene age (3.6 million to 774,000 years ago). Streams that flowed on the Black Point surface cut Canyon de Chelly and other canyons in the monument. On mesa tops within and near the monument, remnants of the Black Point surface cut across the Shinarump Conglomerate (**TRcs**; see poster).
4. Wupatki cycle (Childs 1948) of middle to late Pleistocene age (774,000 to 11,700 years ago). Canyon cutting at the monument continued during this cycle.

Entrenchment of the Colorado River system was at its maximum during the late Pliocene and Pleistocene Epochs (Cooley et al. 1969), which suggests an estimate of about 3 million years ago. Maximum entrenchment took place in the Grand Canyon, where as much as 760 m (2,500 ft) of downcutting occurred. Upstream from the Grand Canyon, the depth of downcutting decreased progressively (Cooley et al. 1969). For example, entrenchment was generally less than 180 m (600 ft) in the upper reaches of Chinle Wash (see "Fluvial Features and Processes").

Regional downcutting continued intermittently throughout the Pleistocene Epoch and is recorded by several levels of preserved terraces along large streams, including the San Juan River (O'Sullivan and Beikman 1963; Cooley et al. 1969). Following the wetter (than today) conditions of the Pleistocene ice ages, deposition of sediments replaced canyon cutting as the primary geomorphic process. Deposition of alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) represents the end of downcutting (Hackman and Olson 1977); these deposits cover the Black Point surface. In historic times, modern stream deposits were incised locally (see Figure 5).

Geologic Time Scale

The geologic time scale puts the divisions of geologic time and associated rocks or unconsolidated deposits in stratigraphic order, with the oldest divisions and rock units at the bottom and the youngest at the top. As represented here, the geologic time scale (Table 3) is divided into the following columns:

Eon, Era, Period, and Epoch—The first four columns of Table 3 show the divisions of geologic time. On the global time scale (i.e., International Chronostratigraphic Chart), the Permian Period is divided into three epochs (Cisuralian, Guadalupian, and Lopingian), whereas regionally it has been divided into four epochs (Wolfcampian, Leonardian, Guadalupian, and Ochoan). Correlation between the global and regional scales is shown in Table 4. This correlation is included because the source maps use the regional scale.

Boundary Age—The various boundary ages, which separate segments of geologic time, are from the International Chronostratigraphic Chart (International Commission on Stratigraphy 2023). When a more specific age for a rock unit or geologic event is known, that age and a reference citation are included.

Geologic Map Unit—Geologic units mapped within the monument are included on the geologic time scale. In addition, rocks associated with the Navajo volcanic field—minette (**Tmn**), tuff breccia (**Ttb**), and trachybasalt (**Tt**, better referred to as "extrusive minette"), and the regional aquifer encountered during the eruption (Chuska Sandstone [**Tc**])—are included because they form distinctive features in the monument's viewshed. One small area of minette (**Tmn**) does occur in the monument—on the rim between Whiskey and Crystal Creeks—west of Sonsela Buttes (see poster).

Geologic Event—By reading the geologic events in Table 3 from bottom to top, a geologic history is provided. Detailed descriptions of geologic events and associated geologic features are given in the "Significant Geologic Events" section of this chapter as well as in the "Geologic Features and Processes" chapter. In general, the timing of geologic events follows interpretations from the source maps (O'Sullivan and Beikman 1963; Hackman and Olson 1977) as well as Cooley et al. (1969).

Location—This column lists examples of where a geologic event is represented in the rocks and deposits within or near the monument.

Table 3. Geologic time scale.

Eon	Era	Period	Epoch	Boundary Age	Geologic Map Unit	Geologic Event	Location
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	• Holocene (H)	Less than 11,700 years ago	• Alluvium (**Qa**)	Beginning as early as 1850, fluctuations in the stream regime cause arroyo (flat-floored channel of an ephemeral stream) cutting, changes in the length of perennial reaches of streams, and the general decline of streamflow (Cooley et al. 1969). Fluctuations in the stream regimen create terraces in some places.	• Chinle Wash • Along Tsaile, Weatherfields, and Whiskey Creeks; at the heads of Canyons del Muerto and de Chelly (outside the monument)
	Cenozoic (CZ)	Quaternary (Q)	• Holocene (H)	Less than 11,700 years ago	• Colluvial deposits, undifferentiated (**Qc**)	Talus slopes form below cliffs of broken or fractured bedrock or where steep bedrock ledges are undercut by natural or anthropogenic processes.	• At 1:250,000 scale, none are mapped in the monument. • On the flank of Zilditloi Mountain (south of the monument)
	Cenozoic (CZ)	Quaternary (Q)	• Holocene (H) • Pleistocene (PE)	Less than 2.6 million years ago	• Landslide debris (**Ql**)	Triggers such as intense rainfall, rapid snowmelt, earthquake, volcanic eruption, and stream erosion induce slope movements.	• At 1:250,000 scale, none are mapped in the monument. • Chuska Mountains (east of the monument)
	Cenozoic (CZ)	Quaternary (Q)	• Holocene (H) • Pleistocene (PE)	Less than 2.6 million years ago	• Alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) *Note*: Mapped by Hackman and Olson (1977) on the Gallup sheet only.	The deposition of sediments replaces canyon cutting as the primary geomorphic process.	• Deposited atop dissected surfaces of the Shinarump Member (**TRcs**) on mesa tops
	Cenozoic (CZ)	Quaternary (Q)	• Early Pleistocene (PE) • Pliocene (PL) • Early Miocene (MI)	Approximately 11 million–774,000 years ago	• Erosional surfaces (no map unit)	The canyons of the monument cut into the Defiance Plateau. Erosional cycles began as early as the late Miocene Epoch. The Black Point cycle (during which the monument's canyons form) took place in the late Pliocene and early Pleistocene Epochs.	• Represented by dissected surfaces of the Shinarump Member (**TRcs**) on mesa tops
	Cenozoic (CZ)	Tertiary (T) or Neogene (N)	• Miocene (MI) • Oligocene (OL)	33.9 million–5.3 million years ago *Note*: The Navajo volcanic field is active from 25.9 million to 24.5 million years ago (Nybo et al. 2011).	• Minette (**Tmn**) • Tuff breccia (**Ttb**) • Trachybasalt (**Tt**), better referred to as "extrusive minette"	The Navajo volcanic field is briefly but explosively active. Magma penetrates the regional aquifer (composed of **Tc**), causing phreatomagmatic eruptions of maar-diatreme volcanoes in the Navajo volcanic field.	• Only **Tmn** occurs in the monument. • Black Rock Butte (**Tmn**) • Sonsela Buttes (**Tmn**, **Ttb**, **Tt**) • Buell Park diatreme (**Ttb**, **Tt**, **Tmn**)
	Cenozoic (CZ)	Tertiary (T) or Paleogene (PG)	• Oligocene (OL) • possibly Eocene (E)	56.0 million–33.9 million years ago	• Chuska Sandstone (**Tc**)	Sediments shed from uplifted areas accumulate as **Tc**.	• None in the monument • Chuska Mountains (east of the monument)
	Cenozoic (CZ), and Mesozoic (MZ)	Tertiary (T) or Paleogene (PG), and Cretaceous (K)	• Eocene (E) • Paleocene (EP) • Late/Upper • Early/Lower	~145.0 million–33.9 million years ago *Note*: The Laramide Orogeny occurs 80 million–50 million years ago (Coney 1978; Humphreys et al. 2003; Liu and Gurnis 2010).	• Folds and faults • Dakota Sandstone (**Kd**)	Compressive forces associated with the Laramide Orogeny create an assortment of folds; faulting occurs locally. Reactivation of the Defiance uplift takes place. Initial uplift of the Colorado Plateau occurs.	• Chinle monocline • De Chelly upwarp • Tsaile graben

Table 3 (continued). Geologic time scale.

Eon	Era	Period	Epoch	Boundary Age	Geologic Map Unit	Geologic Event	Location
Phanerozoic	Mesozoic (MZ)	Jurassic (J)	• Late/Upper • Middle • Early/Lower	201.3 million–~145.0 million years ago	• Morrison Formation (**Jm**, **Jmr**, and **Jmw**) • Summerville Formation (**Js**) • Cow Springs Formation (**Jcs**) • Todilto Limestone (**Jt**) • Entrada Sandstone (**Je**) • Wingate Sandstone (**TRw** and **TRwr**)	Deposition of the fluvial Morrison Formation closes out the Jurassic Period. A vast desert covers the continent, particularly during the Early Jurassic Period. During the Middle Jurassic Period, the desert is not as regionally extensive. Floodplains of the formerly extensive river system of the Appalachian Mountains are the source of sand. Pangea begins splitting apart about 200 million years ago.	• None in the monument • East and west of the Defiance Plateau
	Mesozoic (MZ)	Triassic (TR)	• Late/Upper	~237 million–201.3 million years ago *Note*: The Chinle Formation is about 230 million–210 million years old (Richard et al. 2000).	• Chinle Formation (**TRc**): • Petrified Forest Member (**TRcp**) • Petrified Forest Member, upper part (**TRcpa**) • Petrified Forest Member, Sonsela Sandstone Bed (**TRcps**); now recognized as the Sonsela Member • Petrified Forest Member, lower part (**TRcpb**) • Monitor Butte Member (**TRcmb**), now recognized as the Bluewater Creek Member • Shinarump Member (**TRcs**)	The Colorado Plateau is near sea level. A widespread river system spreads sediments across the continent.	• Canyon rims (**TRcs**) and mesa tops (**TRcmb**) • South sides of Canyon de Chelly and Monument Canyon (**TRcp**) • Top of Spider Rock (**TRcs**) • Most roads and overlooks in the monument are on **TRcs**.
	Mesozoic (MZ), and Paleozoic (PZ)	Triassic (TR), and Permian (P)	• Middle • Early/Lower • Lopingian • Guadalupian (Table 4)	273.0 million–~237 million years ago	• Unconformity—a gap of about 50 million years in the rock record of the Colorado Plateau	Erosion removes most sediments from the Defiance uplift.	• Unconformity nicely displayed along White House Trail
	Paleozoic (PZ)	Permian (P)	• Cisuralian (Table 4)	298.9 million–273.0 million years ago *Note*: The De Chelly Sandstone is about 275 million years old (Blakey and Knepp 1989).	• De Chelly Sandstone (**Pdc**)	Sediments accumulate in a landscape of sand dunes; prevailing winds blowing from the northeast across Pangea generate large, conspicuous cross-beds.	• Exposed in canyon walls, iconic rock features, and on valley floors
	Paleozoic (PZ)	Permian (P), and Pennsylvanian (PN)	• Cisuralian (Table 4) • Late/Upper • Middle • Early/Lower	323.2 million–251.9 million years ago *Note*: The Supai Formation is 310 million–280 million years old (Richard et al. 2000).	• Supai Formation, main body (**PPNs**) *Note*: **PPNs** is the oldest unit in the GRI GIS data.	Pangea reaches its greatest extent about 250 million years ago. Newly uplifted mountains (i.e., the Ancestral Rocky Mountains) supply abundant gravel, sand, and mud to depositional environments, including a sabkha in which **PPNs** is deposited.	• Parts of the valley floors of Canyon del Muerto and Canyon de Chelly • Base of Spider Rock
	Paleozoic (PZ)	Mississippian (M), Devonian (D), Silurian (S), Ordovician (O), and Cambrian (C)	• All C, O, S, D, and M epochs	538.8 million–323.2 million years ago	• n/a	Starting about 335 million years ago, the supercontinent Pangea starts assembling from existing continental crust.	• None in the monument area

Table 3 (continued). Geologic time scale.

Eon	Era	Period	Epoch	Boundary Age	Geologic Map Unit	Geologic Event	Location
Proterozoic–Phanerozoic	Paleoproterozoic Era to Cambrian Period	Paleoproterozoic Era to Cambrian Period	• n/a	2.5 billion–538.8 million years ago	• Unconformity—a gap of 1.25 billion years in the rock record of Arizona	A long period of erosion takes place.	• The “Great Unconformity” (e.g., at the bottom of the Grand Canyon)
Proterozoic	Neoproterozoic (Z), Mesoproterozoic (Y), and Paleoproterozoic (X)	n/a	• n/a	2.5 billion–538.8 million years ago	• n/a	Earth’s nascent crust assembles, and an early system of faults forms. Arizona’s oldest rocks form about 1.75 billion years ago.	• Proterozoic rocks are exposed in three small areas on the Defiance Plateau: two small canyons near Hunters Point (southeast of the monument) and in Bonito Canyon (south of the monument).
Archean	n/a	n/a	• n/a	4.0 billion–2.5 billion years ago	• n/a	Earth’s basement (foundation) forms.	• Earth’s oldest rocks (4.4 billion years old) occur in the Hudson Bay area, northern Quebec, Canada. No representative rocks occur in Arizona.
Hadean	n/a	n/a	• n/a	~4.6 billion–4.0 billion years ago	• n/a	Planet Earth forms.	• No representative Earth rocks

Table 4. Correlation of the global and regional time scales for the monument's bedrock. Sources: US Geological Survey (1988); International Commission of Stratigraphy (2023); Geolex (accessed 31 January 2024).

Period and Years Ago	Global Epoch[A]	Regional Epoch[A]	Regional Age	Associated Formation in the Monument
Triassic (TR) 251.9 million–201.3 million	Upper or Late	Upper or Late	n/a	Chinle Formation
	Middle	Middle	n/a	none
	Lower or Early	Lower or Early	n/a	none
Permian (P) 298.9 million–251.9 million	Lopingian	Upper or Late	Ochoan	none
	Guadalupian	Upper or Late	Guadalupian	none
	Cisuralian	Lower or Early	Leonardian	De Chelly Sandstone
	Cisuralian	Lower or Early	Wolfcampian	Supai Formation
Pennsylvanian (PN) 23.2 million–298.9 million	Upper or Late	Upper or Late	Virgilian	Supai Formation
	Upper or Late	Upper or Late	Missourian	Supai Formation
	Middle	Middle	Desmoinesian	Supai Formation
	Middle	Middle	Atokan	Supai Formation
	Lower or Early	Lower or Early	Morrowan	Supai Formation

[A] By geologic convention, the terms "Lower," "Middle," and "Upper" are used when describing rocks; when describing time, the terms "Early," "Middle," and "Late" are used.

Items in parentheses in the geologic time scale include GRI map abbreviations for geologic time units such as era, period, and epoch. For example, "**PN**" in a map unit symbol indicates that the rocks were deposited during the Pennsylvanian Period (323.2 million to 298.9 million years ago). "**T**" in a map unit symbol—for example, the rocks (**Tmn**, **Ttb**, and **Tt**) in the Navajo volcanic field—stands for "Tertiary," which is no longer a formally accepted unit of geologic time by the International Commission on Stratigraphy. However, the term is commonly used in geologic mapping projects in the United States—such as the source maps (O'Sullivan and Beikman 1963; Hackman and Olson 1977) and Cooley et al. (1969)—so the GRI GIS data and this GRI report use the term. Two periods—the Paleogene (66.0 million to 23.0 million years ago) and the Neogene (23.0 million to 2.6 million years ago)—have formally replaced the Tertiary. These two periods are further divided into five epochs, from oldest to youngest: Paleocene, Eocene, Oligocene, Miocene, and Pliocene.

In a map unit symbol, the lowercase letters that accompany the time-period symbol represent the name of a map unit. For example, "**dc**" stands for the De Chelly Sandstone (**Pdc**). "**P**" represents the Permian Period (298.9 million to 251.9 million years ago).

Geologic Features and Processes

This chapter highlights the geologic features and processes significant to the monument's geologic heritage and history. Selection of these features and processes was based on input from meeting participants and reviewers, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. These features and processes are discussed more or less in order of geologic age (oldest to youngest).

Three Formations

The monument's bedrock consists of three formations: (1) the Pennsylvanian–Permian Supai Formation (**PPNs**), (2) the Permian De Chelly Sandstone (**Pdc**), and (3) the Triassic Chinle Formation (**TRc**, **TRcs**, **TRcmb**, **TRcpb**, **TRcps**, **TRcpa**, **TRco**). In geologic terminology, a formation is the fundamental rock-stratigraphic unit, meaning it is mappable (at a particular scale), lithologically distinct (with respect to rock type and other characteristics such as color, mineral composition, and grain size) from adjoining strata, and has a definable upper and lower contact. A formation can be divided into "members" or combined into a "group."

Supai Formation

Map unit: **PPNs**

As recorded by the oldest rocks in the monument (Supai Formation, **PPNs**), the monument's geologic story began during the Pennsylvanian to early Permian (Morrowan to Wolfcampian; see Table 4) Periods, or about 310 million to 280 million years ago (Richard et al. 2000). At that time, most of Earth's continental crust was joined into the supercontinent Pangea (see Figure 13).

The Supai Formation was named for the conspicuous exposures at Supai (a "village" or populated place) on Cataract Creek, Coconino County, northern Arizona (Darton 1910). The type section (place where the formation is most clearly revealed and from which it was originally described) is within Grand Canyon National Park (McKee 1975). There, the formation is more than 430 m (1,400 ft) thick (Darton 1910).

Within the monument, the Supai Formation is visible at the base of Spider Rock (see "Iconic Rock Features"). Additionally, the formation underlies spurs and benches in the canyon bottom to the east of Spider Rock. These spurs are commonly terminated by escarpments (steep cliffs or topographic steps), which vary in height between 45 m and 60 m (150 ft and 200 ft) above the valley floor. In the subsurface, the Supai Formation may be as much as 580 m (1,900 ft) thick (Hackman and Olson 1977). The base of the formation is not exposed in the monument.

The Supai Formation mostly consists of alternating reddish-brown and reddish-orange, fine-grained, thin- to thick-bedded sandstone and siltstone. The main body of the formation also contains subordinate beds of impure limestone, mudstone-pebble conglomerate, gypsum, and basal conglomerate (Hackman and Olson 1977), which are indicative of its depositional setting in a sabkha. "Sabkha" is an Arabic word referring to places in arid regions that have high water tables. In

that setting, water is brought to the surface through a reflux pumping action. As the water evaporates, it pulls more groundwater upward. This reflux process leaves crusty minerals such as calcite, dolomite, gypsum, and salt in the soil just below the surface. These salts push away existing sediments as they grow, distorting the original bedding into a crinkly and contorted mass. This bedding pattern is a good indicator of past sabkha conditions and is common in Permian rocks across the southern Colorado Plateau region (Blakey and Ranney 2008).

De Chelly Sandstone

Map unit: **Pdc**

The De Chelly Sandstone is beautifully displayed in the canyon walls and iconic rock features of the monument. Canyon de Chelly was selected as the type locality (an important geologic designation) not only because it is where these rocks were first geologically recognized and described (Gregory 1915, 1916a, 1916b, 1917) but also because Canyon de Chelly is the place where the formation is most clearly revealed.

The age of the De Chelly Sandstone is early Permian (Cisuralian [on the global time scale] or Leonardian [on the regional time scale]; see Table 4). The source maps (Hackman and Olson 1977 and O'Sullivan and Beikman 1963) show the De Chelly Sandstone as "lower Permian" and "Permian," respectively. Work by Blakey and Knepp (1989) suggests that deposition of the formation took place about 275 million years ago.

A plethora of geologists—including Gregory (1915, 1916a, 1916b, 1917), Baker et al. (1929), McKee (1934), Momper (1957), Stewart (1959), Read and Wanek (1961), Baars (1962), Peirce (1962, 1964), and Blakey (1990)—mapped the De Chelly Sandstone and made efforts to correlate it with other rocks in four widely separated regions across the Colorado Plateau: the Grand Canyon, Mogollon Rim, Monument Valley, and the Defiance Plateau (see Figure 2). Peirce (1964) focused on the Defiance Plateau (including the monument area) and divided the sandstone into five members (Table 5). All five members do not occur at any single locality, and only three of these members are found within the monument. Notably, these members are not exposed everywhere together. For example, along the White House Trail, the White House Member, which was named for the trail and the cliff dwelling, is the only member exposed in that area. By contrast, all three members are exposed near the mouth of Monument Canyon (Figure 19).

Geolex recognizes the five members of the De Chelly Sandstone subdivided by Peirce (1964). Significantly, none of the source maps separate the De Chelly Sandstone into these members.

Depending on location, the De Chelly Sandstone is recognized as a member of the Cutler Formation or a formation in the Cutler Group (Geolex, accessed 26 February 2024). Regarding significant citations for this GRI report, O'Sullivan and Beikman (1963), Cooley et al. (1969), and Byers (1980) recognize the De Chelly Sandstone as a member of the Cutler Formation.

Table 5. De Chelly Sandstone stratigraphy.

Formation	Member	General Characteristics
Chinle	Shinarump	The base of the Chinle Formation marks the top of the De Chelly Sandstone. Yellowish-orange to yellowish-gray rocks form a hard caprock, protecting the underlying De Chelly Sandstone. Forms horizontal ledges.
De Chelly Sandstone[A]	Fort Defiance	Not exposed in the monument.
	Black Creek	Not exposed in the monument.
	White House	Forms the widely photographed, sheer canyon walls in the monument. As much as 174 m (570 ft) thick. Red-orange and pale orange. Commonly covered by black desert varnish. Contains large-scale cross-beds; the direction of dip in the sloping beds is remarkably constant. Truncation surfaces between cross-bed sets give the member a layered appearance. Corresponds to the “upper member” of McKee (1934).
	Oak Springs Cliffs	Deep red, particularly when compared to underlying Hunters Point Member (Peirce 1964). As much as 14 m (45 ft) thick. No cross-beds. Forms slopes. Corresponds to the “middle member” of McKee (1934).
	Hunters Point	Red-brown; lighter colored than the overlying Oak Springs Cliffs Member. Contains cross-beds that dip in many directions, thereby contrasting the cross-beds in the White House Member, which are remarkably constant. Typically, weathers into rounded surfaces, but in places, it forms sheer cliffs and, with the White House Member, makes one continuous perpendicular wall from bottom to top of the canyon. As much as 62 m (202 ft) thick. Grades southward as a tongue into the red strata of the Supai Formation. Corresponds to the “lower member” of McKee (1934).
Supai	main body	The top of the Supai Formation marks the base of the De Chelly Sandstone.

[A] The five members of the De Chelly Sandstone were mapped by Peirce (1964); only three are found in the monument and not always everywhere. The source map (O’Sullivan and Beikman 1963) does not separate the De Chelly Sandstone into members.



Figure 19. Photograph of the De Chelly Sandstone from Face Rock Overlook. Although the source maps and GRI GIS data do not subdivide the De Chelly Sandstone (Pdc), Peirce (1964) divides the formation into five members. Three of these members—Hunters Point, Oak Springs Cliffs, and White House—are found within the monument, as seen here at Face Rock Overlook. Not all members are exposed everywhere in the monument. NPS photograph, n.d., available at https://home.nps.gov/cach/learn/photosmultimedia/index.htm (accessed 27 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Chinle Formation

Map units: **TRc**, **TRcs**, **TRcmb**, **TRcpb**, **TRcps**, **TRcpa**, **TRco**

The Chinle Formation—which is characterized by badlands topography including colorful hills, flat-topped mesas, and sculpted buttes—was named for the beautiful exposures in the Chinle Valley west of the monument (Gregory 1916a, 1917). Moreover, the floor of the Chinle Valley is underlain by easily eroded sediments of the Chinle Formation (Cooley et al. 1969). Within the monument, the Chinle Formation tops Spider Rock (**TRcs**); underlies most of the roads and overlooks on the rims (**TRcs**); occurs on mesa tops (**TRcmb**); and was mapped on the south walls of Canyon de Chelly and Monument Canyon (**TRcp**) (see poster).

The age of the Chinle Formation is Late Triassic (Geolex, accessed 26 February 2024), that is, approximately 237 million to 201.4 million years old (International Commission on Stratigraphy 2023). The Chinle Formation itself was deposited over a period of about 20 million years, between

about 230 million and 210 million years ago. With respect to the global chronology, the Chinle Formation was deposited entirely within the Norian Stage (Rassmussen et al. 2020). At the time of deposition, the monument was located 5–15° N (paleo-latitude) of the equator (see Figure 16 and "Significant Geologic Events: Accumulation of Sediments").

The Chinle Formation is entirely terrestrial and predominantly fluvial in origin. The formation was deposited in a broad complex of floodplains and tributary streams, draining into larger rivers that flowed across western equatorial Pangea toward the eastern margin of Panthalassa (Stewart et al. 1972a, 1972b; Blakey and Gubitosa 1983; Dubiel 1994; Riggs et al. 1996; Dickinson and Gehrels 2008a, 2008b; see Figure 16). The overall flow direction of this widespread river system was to the northwest; variation in paleo-flow directions in the rock record likely represents radial drainage off a large fluvial fan or flow within meander bends (Trendell et al. 2013). The depositional style of the fluvial system varied considerably over the life of the Chinle Formation, with large meandering streams and poorly drained floodplains in the lower part of the formation transitioning into flashier, more seasonal flow with well-drained floodplains in the upper part of the formation (Blakey and Gubitosa 1983; Dubiel et al. 1991; Dubiel 1994; Dubiel and Hasiotis 2011; Trendell et al. 2012, 2013; Atchley et al. 2013; Howell and Blakey 2013).

Representative of its widespread depositional setting, the Chinle Formation now crosses many state lines. In Arizona, Colorado, New Mexico, Nevada, Texas, and Utah, it is recognized primarily as a formation. In parts of New Mexico and Texas, however, the formal status of these rocks has been elevated, and they are known as the Chinle Group (Geolex, accessed 26 February 2024). The formation is commonly divided into members (Table 6). Table 6 shows the current "working" stratigraphy at Petrified Forest National Park with correlation to northeastern Arizona and western New Mexico as well as to the monument.

Table 6. Geologic correlation of the Chinle Formation. Information presented in this table was guided by geologic mapping at Petrified Forest National Park (e.g., Martz et al. 2012) and input from William G. Parker (Petrified Forest National Park, program manager, email communications, November 2023 and January 2024).

Petrified Forest National Park (PEFO)	Northeastern Arizona and Western New Mexico	Canyon de Chelly National Monument
Rock Point Member	Rock Point Member	Rock Point Member
Owl Rock Member	Owl Rock Member	Owl Rock Member
Petrified Forest Member	Petrified Forest Member	Petrified Forest Member[A]
Sonsela Member	Sonsela Member	Sonsela Member[A] Following Martz et al. (2012), the Sonsela Member replaces the Sonsela Sandstone Bed of the Petrified Forest Member (as mapped by Hackman and Olson 1977, Byers 1980, and Thaden 1990).

[A] Member is exposed in the monument. More information is available from the Colorado Plateau Coring Project at https://www.nps.gov/pefo/learn/nature/coring.htm (accessed 27 February 2024).

Table 6 (continued). Geologic correlation of the Chinle Formation. Information presented in this table was guided by geologic mapping at Petrified Forest National Park (e.g., Martz et al. 2012) and input from William G. Parker (Petrified Forest National Park, program manager, email communications, November 2023 and January 2024).

Petrified Forest National Park (PEFO)	Northeastern Arizona and Western New Mexico	Canyon de Chelly National Monument
Blue Mesa Member (upper)	Blue Mesa Member (upper)	Blue Mesa Member (upper)
Blue Mesa Member (lower)	Bluewater Creek Member (Lucas and Hayden 1989) The lower part of the Blue Mesa Member in the PEFO area is a stratigraphic equivalent to the Bluewater Creek Member, but mappers do not advocate using "Blue Mesa Member" outside of the PEFO area (William G. Parker, email communication, 7 November 2023).	Bluewater Creek Member[A] (Lucas and Hayden 1989) The Bluewater Creek Member replaces the red member (as mapped by O'Sullivan and Beikman 1969) and the Monitor Butte Member (as mapped by Hackman and Olson 1977, Byers 1980, and Thaden 1990). The red member was grouped with the Monitor Butte Member in the GRI GIS data.
Mesa Redondo Member	Does not occur in the area	Does not occur in the area
Shinarump Member	Shinarump Member As mapped by Hackman and Olson (1977) in the southern part of the Defiance Plateau, the Shinarump Member includes a northward-thinning wedge of the overlying Mesa Redondo Member, which is the muddy facies of the depositional system and interfingers with the Sonsela Member (William G. Parker, email communication, 8 November 2023).	Shinarump Member[A]

[A] Member is exposed in the monument. More information is available from the Colorado Plateau Coring Project at https://www.nps.gov/pefo/learn/nature/coring.htm (accessed 27 February 2024).

Since mapping by O'Sullivan and Beikman (1969) and Hackman and Olson (1977), that is, the source maps for the GRI GIS data, the stratigraphic nomenclature of the Chinle Formation has undergone revisions. Geologic correlation and reinterpretation of the Chinle Formation at Petrified Forest National Park (south of the historic site; Raucci et al. 2006; Martz and Parker 2010; Martz et al. 2012) have received widespread recognition, and this interpretation is now being applied to rocks beyond that national park.

The Shinarump, Monitor Butte, Petrified Forest, and Owl Rock Members occur on the source maps by O'Sullivan and Beikman (1969) and Hackman and Olson (1977). The following descriptions describe these members, incorporating updated geologic correlations as applicable:

Shinarump Member

The Shinarump Member of the Chinle Formation (**TRcs**) was named for the Shinarump Cliffs in the southern part of Kane County, Utah. The member is also formally known as the Shinarump Conglomerate in Arizona and Nevada (Gilbert 1875; Howell 1875; Powell 1876; Geolex, accessed 26 February 2024). The member is the basal (bottom) unit of the Chinle Formation and rests unconformably (see "Unconformities") atop the De Chelly Sandstone throughout the Defiance uplift (Baars 1998).

Clasts (individual grains of a sedimentary rock) in the conglomerate range from 1 to 2 cm (0.4 to 0.8 in) to a maximum 6–8 cm (2.4–3.1 in) in diameter and are dominantly chert, quartzite, and limestone. Volcanic clasts—including latitic, dacitic, and rhyolitic lava and tuff (see "Lithics: Sources of Information")—are sparse and make up a maximum of 5% of the total number of clasts (Riggs et al. 2016). In the monument, the dark-brown rocks of the Shinarump Member form a hard caprock that protects the underlying, less resistant De Chelly Sandstone from erosion.

Bluewater Creek Member (Formerly the Monitor Butte Member)

The Monitor Butte Member (**TRcmb**) was named for Monitor Butte, which is about 23 km (14 mi) northwest of Oljato, San Juan County, Utah (Witkind et al. 1963). In the monument and vicinity, rocks mapped as the Monitor Butte Member (**TRcmb**) by Hackman and Olson (1977) or as "the red member" by O'Sullivan and Beikman (1969) are now correlated with the Bluewater Creek Member following work by Lucas and Hayden (1989) (William G. Parker, Petrified Forest National Park, program manager, email communication, 7 November 2023). Work by Lucas and Hayden (1989) proposes that "Monitor Butte" should be restricted to the dominantly green-gray bentonitic claystone and clayey fine-grained sandstone of San Juan County, Utah, where the unit's type section is at the north end of Monitor Butte (Witkind et al. 1963). The type section of the Bluewater Creek Member is in the San Juan Basin of Cibola County, New Mexico, where it consists of dominantly gray-red and red-brown sandstone, silty mudstone, and sandy siltstone (Lucas and Hayden 1989).

Petrified Forest Member

The Petrified Forest Member (**TRcp**, **TRcps**, **TRcpb**) was named for the Petrified Forest in Navajo and Apache Counties, northeastern Arizona, though interestingly, the member was first described in Zion National Park, Utah (Gregory 1950). The Petrified Forest Member is present across northern Arizona and southern Utah and extends into southeastern Nevada and west-central New Mexico. In most of these areas, it forms the thickest and most characteristic part of the Chinle Formation. The varicolored badlands of the Beautiful Valley (west of the monument) are composed of the Petrified Forest Member (**TRcp**). Regarding stratigraphic nomenclature, rocks now recognized as the Bluewater Creek, Blue Mesa, and lower part of the Sonsela Members (see Table 6) were previously mapped as the lower Petrified Forest Member (William G. Parker, Petrified Forest National Park, program manager, email communication, 9 January 2024).

Sonsela Member (Formerly the Sonsela Sandstone Bed of the Petrified Forest Member)

The source map by Hackman and Olson (1977) identifies a distinctive layer—the Sonsela Sandstone Bed (**TRcps**)—in the Petrified Forest Member. Following geologic mapping in Petrified Forest

National Park (Martz et al. 2012) and guidance from William G. Parker (Petrified Forest National Park; program manager; email communications; 2, 7, and 8 November 2023), this GRI report recognizes the rocks mapped as the Sonsela Sandstone Bed in the monument and vicinity as the Sonsela Member of the Chinle Formation. Work by Heckert and Lucas (2002), Woody (2006), Martz and Parker (2010), and Parker and Martz (2011) informed geologic mapping at Petrified Forest National Park (Martz et al. 2012). Notably, Geolex (accessed 26 February 2024) has yet to recognize the Sonsela Member and still lists these rocks as the "Sonsela Sandstone Bed" of the Petrified Forest Member (Akers 1958; Stewart et al. 1972b).

The type section of these rocks is a few kilometers east of the monument at Sonsela Buttes (see poster). At its type section, the "Sonsela Sandstone Bed" of the Petrified Forest Member comprises two conglomeratic sandstone units separated by a siltstone unit (Akers et al. 1958). Notably, the upper part of the buttes themselves is composed of volcanic rocks (see "Volcanic Landforms" and "Navajo Volcanic Field"). Because mapping by O'Sullivan and Beikman (1969) does not subdivide the Petrified Forest Member, the GRI GIS data and, therefore, the geologic map poster, do not display the Sonsela Sandstone Bed at its type section. South of the monument, however, the map by Hackman and Olson (1977) shows the layer (**TRcps**).

The difference in mapping by the source map authors results in a so-called "boundary fault" (Figure 20) at the intersection of the Shiprock 1° × 2° quadrangle (mapped by O'Sullivan and Beikman 1969) and the Gallup 1° × 2° quadrangle (mapped by Hackman and Olson 1977). "Boundary faults" represent differences in interpretation, not actual geologic conditions in the field. Indeed, the rocks that comprise the Sonsela Member are present at the type section.

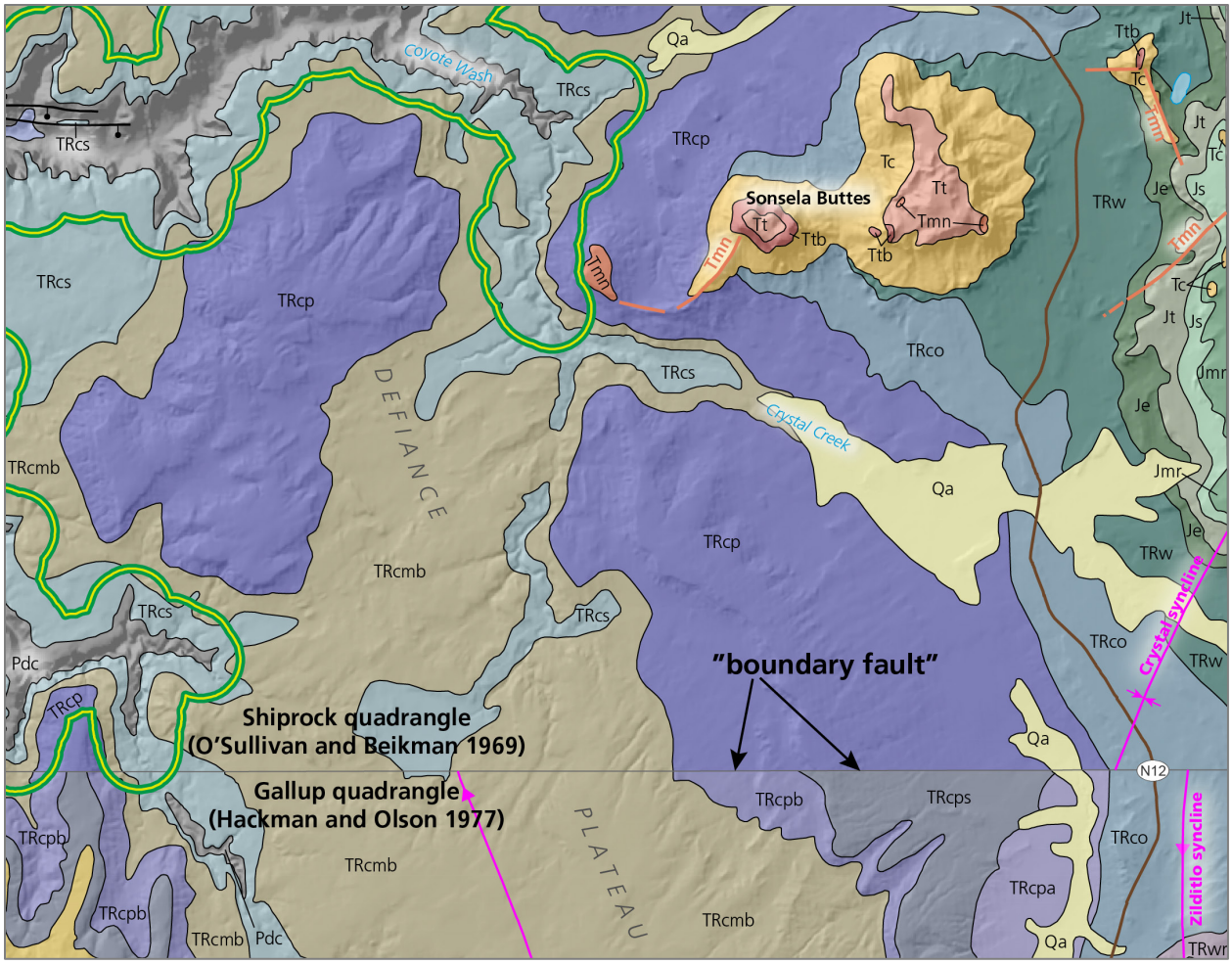


Figure 20. Illustration of a "boundary fault." Geologic units and features that end abruptly (such as at a quadrangle boundary) reflect differences in mapping by source map authors rather than actual geologic conditions. Geologists commonly refer to the apparent change as a "boundary fault." On the Shiprock quadrangle (north of the "boundary fault"), O'Sullivan and Beikman did not map the "Sonsela Sandstone Bed" at its type section at Sonsela Buttes because they did not subdivide the Petrified Forest Member of the Chinle Formation (TRcp). On the Gallup quadrangle (south of the "boundary fault"), Hackman and Olson subdivide the Petrified Forest Member (TRcp), so the "Sonsela Sandstone Bed" (TRcps) is displayed. The green line indicates the park boundary. Map poster by Thom Curdts and Shea Slonkosky (Colorado State University). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Unconformities

Layers of rock are referred to as "conformable" where they are found to have been deposited essentially without interruption. Although particular sites may exhibit conformable beds representing significant spans of geologic time, no place on Earth contains a full set of conformable strata. Breaks in conformable strata are called "unconformities."

Each unconformity represents a period when deposition ceased or where erosion removed previously formed rocks. Simultaneous uplift and erosion may cause an unconformity. Upheaval of the land

surface by faulting or folding then tilting and eroding may result in an unconformity. A drop in sea level followed by exposure to weathering is another possible cause.

Because unconformities may be widespread across a region, they can be useful for correlating rock units and tectonic histories over long distances. Also, unconformities may provide opportunities for geologists to "fill in the gaps" of geologic stories; that is, while one area may lose its geologic record through erosion, another will gain its geologic record through sedimentation (Timmons 2017).

Within and near the monument, as many as seven unconformities occur in the rocks (Hackman and Olson 1977). The most notable one is between the De Chelly Sandstone (deposited about 275 million years ago) and the Shinarump Conglomerate (deposition starting about 230 million years ago). This unconformity is clearly visible along the White House Trail where a slot canyon incised into the De Chelly Sandstone and became filled with the coarse river deposits of the Shinarump Conglomerate. Based on its genesis, the unconformity is sometimes called the "slot canyon unconformity" (KellerLynn 2007). A sharp contact—representing about 45 million years—occurs between the coarse-grained, dark red conglomerate and the fine-grained, light-red sandstone (Figure 21). The "slot canyon" (eroded portion) of the De Chelly sandstone is an estimated 23–30 m (75–100 ft) deep (Josh Ramsey, Canyon de Chelly National Monument, archeologist, email communication, 21 November 2023).



Figure 21. Photograph of the slot canyon unconformity. The sharp-edged contact between the coarse-grained, dark red Shinarump Conglomerate (on the left) and the fine-grained, pale orange De Chelly Sandstone (on the right) is clearly visible along the White House Trail. The conglomerate was deposited about 275 million years ago, while the sandstone was deposited about 230 million years ago; thus, the unconformity represents about 45 million years. The unconformity is about 0.6 km (0.4 mi) from the trailhead. NPS photograph by Josh Ramsey (Canyon de Chelly National Monument), taken 2023.

Folds, Faults, and Related Landforms

Map units (i.e., line features): **plunging anticlines**, **plunging synclines**

"Folds are visually the most spectacular of Earth's structures" (Davis 1984, p. 354). They are extraordinary displays of strain and conspicuous natural images of how the original shapes of rock bodies can be changed during deformation.

Large-scale folds—termed "uplifts," "basins," and "upwarps" (Eardley 1951; Cooley et al. 1969)—produce the broader features of continents and oceans (Gilbert 1890). In the context of the monument, the largest fold is the Defiance uplift, which formed as part of the Ancestral Rocky Mountains system (see "Significant Geologic Events"). At successive viewpoints along the rim drives, the presence of the Defiance uplift is revealed to geologically aware visitors: the rock walls become higher eastward as the once flat-lying strata rise onto the uplift (see Figure 4). Although the Defiance uplift appears to be a simple, geologic structure consisting of a broad fold, it is composed of many smaller folds. These individual structures become apparent in aerial photographs (Figure 22).

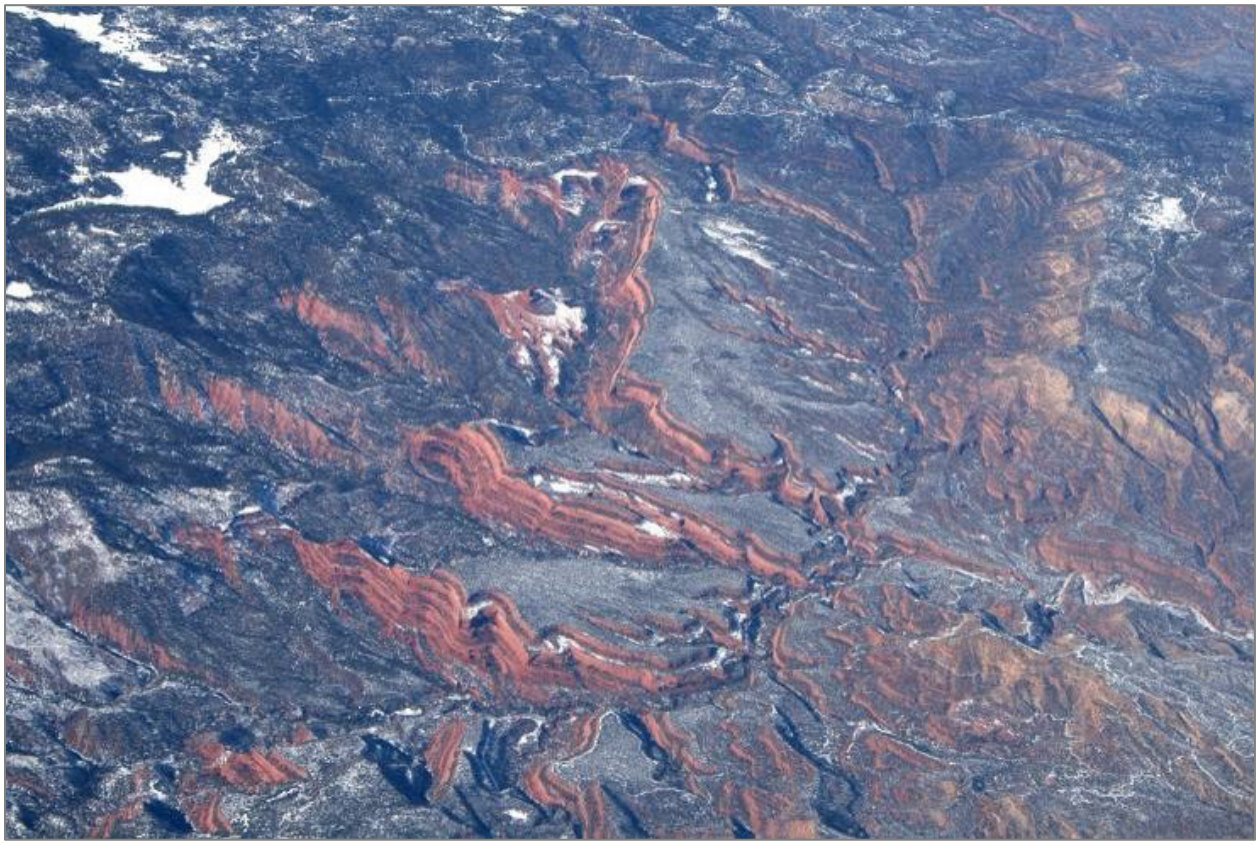


Figure 22. Photograph of folded landforms on the Defiance Plateau. Many individual folds—anticlines, synclines, and monoclines—compose the Defiance uplift. Photograph courtesy of Ron Blakey (Northern Arizona University, GRE scoping meeting, PowerPoint presentation, 16 February 2007).

Smaller folds are termed "anticlines," "synclines," and "monoclines" (Figure 23). The GRI GIS data display a variety of informally named and unnamed smaller folds: Chinle monocline, five synclines

(Zilditloi, Chuska, Nazlini, Crystal, and Fuzzy Mountain), and two anticlines (Rock Mesa and unnamed) (see poster).

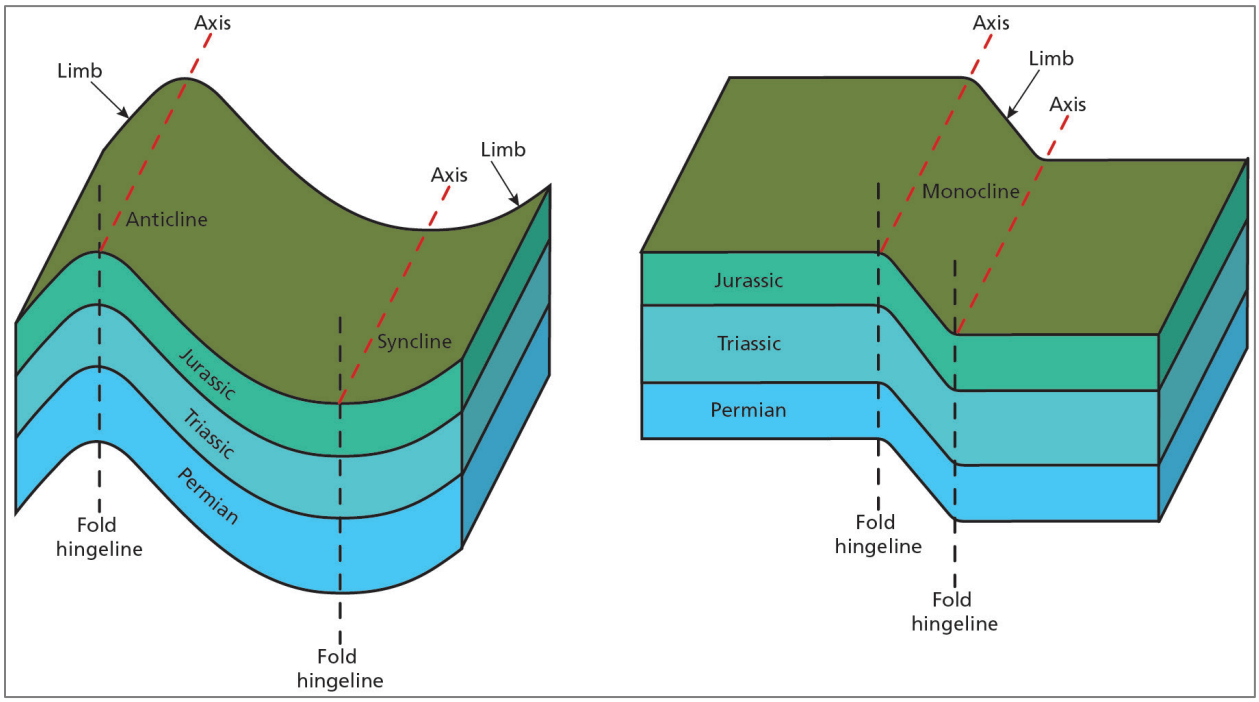


Figure 23. Illustration of fold types. An anticline is an arch-like fold in which strata dip in opposite directions from a common ridge or axis; the core of an anticline contains the oldest strata. A syncline is a fold that is generally concave upward; the core of a syncline contains the stratigraphically younger rocks. A monocline is a single bend in otherwise uniformly dipping or horizontal strata. Monoclines commonly form the boundaries of larger folds (i.e., uplifts). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Monoclines are the most conspicuous of the smaller fold type on the Colorado Plateau (Cooley et al. 1969). Dips along monoclines are usually less than 15°, but locally they are more, and in a few places the beds are overturned slightly, making for stunning displays.

Four informally named monoclines flank the Defiance uplift: The East Defiance monocline extends along the east side of the Chuska Mountains (east of the monument). The West Defiance monocline marks the western edge of the uplift; a segment of the monocline runs between Chinle, Arizona, and the mouth of the monument. The Mesa Verde hogback monocline bounds the San Juan Basin to the northeast of the monument. The Comb Ridge monocline is northwest of the monument (see Figure 3).

The smallest tectonic structures in the monument are faults, which caused local deformation in "Tertiary and Quaternary time" (Cooley et al. 1969, p. A1); the specific timing of movement is not known. Five faults transect the monument (see poster). Although the offset/displacement on these faults is unknown (O'Sullivan and Beikman 1963; Hackman and Olson 1977), typical displacement is between 15 and 45 m (50 and 150 ft) on faults in the area (Cooley et al. 1969). No fault in the

monument is known to be active (US Geological Survey, n.d.). An interesting fault-related structure is Tsaile graben, which cuts through the monument (see poster).

Navajo Volcanic Field

Map units: **Tmn**, **Ttb**, **Tt**

The Navajo volcanic field is an array of more than 80 individual volcanic and magmatic landforms (see Figure 3). The volcanic field extends across the Colorado Plateau for about 430 km (270 mi), covering about 30,000 km^2 (11,600 mi^2) of the Four Corners Area. Recognition of the Navajo volcanic field in the scientific literature has been around for more than 100 years, since Gregory (1917), but early investigators (e.g., Williams 1936; Akers et al. 1971) tended to emphasize the field's parts rather than the whole, dividing it into smaller centers such as Tuba, Monument Valley, Red Rock Valley, Chuska Valley, Chuska Mountains, Wheatfields, Zilditloi, and Twin Cones. Early investigators distinguished individual centers by rock type. In that vein, the source map authors classified minette (**Tm**), tuff breccia (**Ttb**), and trachybasalt (**Tt**) as "Rocks of Zilditloi and Twin Cones Volcanic Fields—Minette Province" (Hackman and Olson 1977). The source map (Hackman and Olson 1977) does not mention the "Navajo volcanic field" in and of itself.

Work by Roden and Smith (1979) was probably the first to focus on the Navajo volcanic field as the sum of its parts and to use the term "Navajo volcanic field" [singular]. Before that, "Navajo volcanic fields" [plural] was used. Semken (2003) was probably the first to document the overall significance and breadth of the volcanic field.

The Navajo volcanic field is composed of maar-diatreme volcanoes (Figure 24). In this type of volcano, "maar" is the crater, and "diatreme" is the vent structure through which magma ascends. A third major feature of a maar-diatreme volcano is the tephra ring that surrounds the crater.

Ultimately, the diatreme of the volcano becomes filled with juvenile (derived from magma) and lithic (derived from previously formed rock) fragments. The terms "lithic" and "lithics" in this context should not be confused with the use of "lithics" in archeological studies, meaning stone tools (see "Lithics: Sources of Information").

Unlike cinder cones (e.g., Capulin Volcano; see the GRI report about Capulin Volcano National Monument by KellerLynn 2015b), shield volcanoes (e.g., Mauna Loa; see the GRI report about Hawai'i Volcanoes National Park by Thornberry-Ehrlich 2009), and composite volcanoes (e.g., Mount Rainer; see the GRE report about Mount Rainer National Park by Graham 2005), maar-diatreme volcanoes are thought to form when magma interacts with groundwater at depth and causes subsurface explosions, which in turn fracture the surrounding host rock and shatter the way for magma, juvenile products, and liberated lithics to be propelled upward and out of the newly formed subterranean volcanic structure (White 1989, 1991; White and Ross 2011; Valentine et al. 2017). These phreatomagmatic eruptions are mostly sourced by explosions in the uppermost 200 m (650 ft) of the volcanic system (Figure 24). Shallower-seated explosions are expected to dominate the emplacement of material onto tephra rings, whereas deeper explosions cause mixing within the diatreme fill (Valentine et al. 2014). In the Navajo volcanic field, phreatomagmatic eruptions

occurred when minette magma interacted with groundwater within the permeable and friable Chuska Sandstone (**Tc**), which is between 85 m (280 ft) and 365 m (1,200 ft) thick in the area (Byers 1979; Brand et al. 2009).

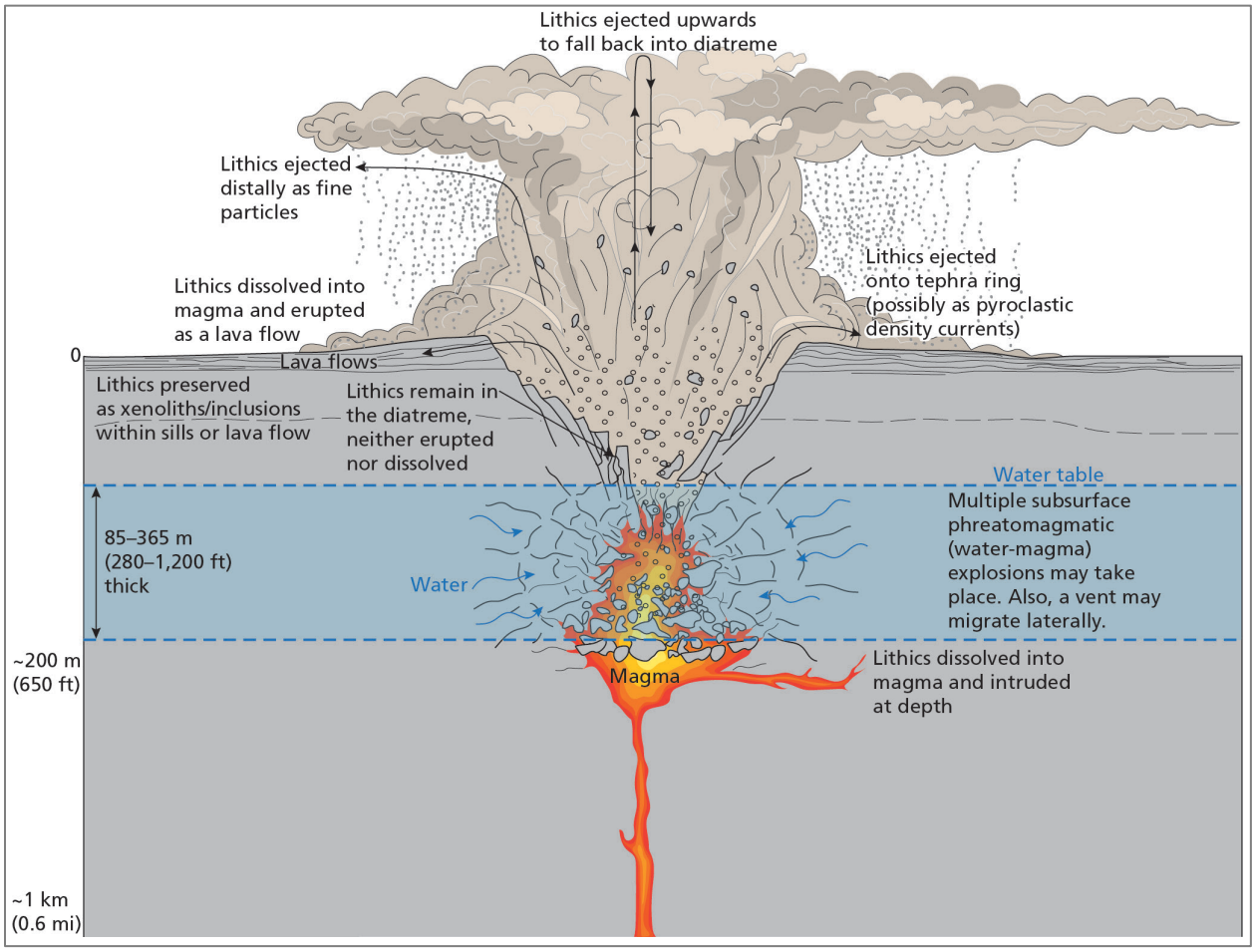


Figure 24. Illustration of a maar-diatreme volcano. Explosive eruptions caused by magma-groundwater interactions formed the maar-diatreme deposits of the Navajo volcanic field. The illustration shows possible trajectories of lithics. The blue area on the figure represents a regional aquifer composed of the Chuska Sandstone. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Wohletz and McQueen (1984, figure 12.1), Heiken et al. (1996, figure W11), and Fitzgerald and White (2021, figure 1).

Pediments

Map unit: **Qao**

Pediments are broad, gently sloping erosion surfaces of low relief. Pediments are significant for the monument's geologic story because they mark the initiation of canyon cutting/entrenchment (see "Significant Geologic Events: Entrenchment of the Colorado River System") and they provide a "starting date" for the development of the rock shelter (see "Genesis of Rock Shelters").

Pediments are underlain by bedrock or, occasionally, by older alluvial deposits. Commonly, the surface is partly mantled with a thin, discontinuous veneer of alluvium, though they may be bare. Within the monument, alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) cover the Black Point surface, identified by Gregory (1917), which formed during the late Pliocene to early Pleistocene Epochs (Cooley et al. 1969). Streams that would eventually incise Canyon de Chelly and the other canyons in the monument flowed across this surface (see "Significant Geologic Events: Entrenchment of the Colorado River System").

Fluvial Features and Processes

Map units: **Qao**, **Qa**

The canyons of the monument are part of the Colorado River system (Figure 25). From larger to smaller, the monument is part of the Upper Colorado River region (USGS hydrologic unit codes [HUC] 14), San Juan River subregion (HUC 1408), Lower San Juan River basin (HUC 140802), and Chinle subbasin (HUC 14080204). The monument contains two watersheds: Canyon del Muerto (HUC 1408020404) and Canyon de Chelly (HUC 1408020405).

The San Juan River is a tributary to the Colorado River. It joins the Colorado Plateau's principal river (i.e., the Colorado River) at Lake Powell in Glen Canyon National Recreation Area (see GRI report by Graham 2016). All runoff and streamflow from the monument drain to the Colorado River (Cooley et al. 1969), funneling first through Chinle Wash. Derived from the Navajo word ch'inili, meaning "where the waters came out," Chinle Wash is aptly named for its location at the mouths of Canyon de Chelly and Canyon del Muerto. Variant names of "Chinle" found on maps include Chinle Wash, Chin-lee Wash, Chinlee Wash, Chnle River, Nazlini Wash, and Rio de Chelly (US Board on Geographic Names 1981). De Harport (1959) uses "Rio de Chelly" for the stream channel in Canyon de Chelly itself. Near the Utah border, where the drainage is perennial for approximately 10 km (6 mi), the wash is referred to as "Chinle Creek" (Arizona Department of Water Resources 1994, 2009).

Neither Canyon del Muerto nor Canyon de Chelly carry water year-round, though water flows more regularly during the spring runoff and summer monsoon periods (National Park Service 2016). Portions of Tsaile Creek, Wheatfields Creek, Whiskey Creek, and Coyote Creek are perennial (Cooley et al. 1969, figure 16). Tsaile Creek, which flows into Canyon del Muerto, is perennial from the western escarpment of the Chuska Mountains nearly to the confluence of Canyon del Muerto and Canyon de Chelly. The perennial portion of the stream occurs where the canyon floor is on the relatively impermeable Supai Formation (**PPNs**). Flows are maintained in part from discharge from the De Chelly Sandstone (**Pdc**) aquifer (see "Sources of Water"). Downstream from these outcrops of the Supai Formation, the flow percolates into sandy alluvium (Cooley et al. 1969), where the stream is referred to as "Tsaile Wash." In Canyon de Chelly, the so-called Rio de Chelly is usually perennial as far as Spider Rock. During the summer thunderstorm season, streamflow often reaches the junction of Canyon del Muerto and Canyon de Chelly for weeks at a time. For brief periods, water may run past the town of Chinle, blocking the entrance to the canyon (Grant 1978). Flows in the

other monument drainages dissipate before entering the main drainage by seepage into channel floors, evapotranspiration, or diversion for irrigation.

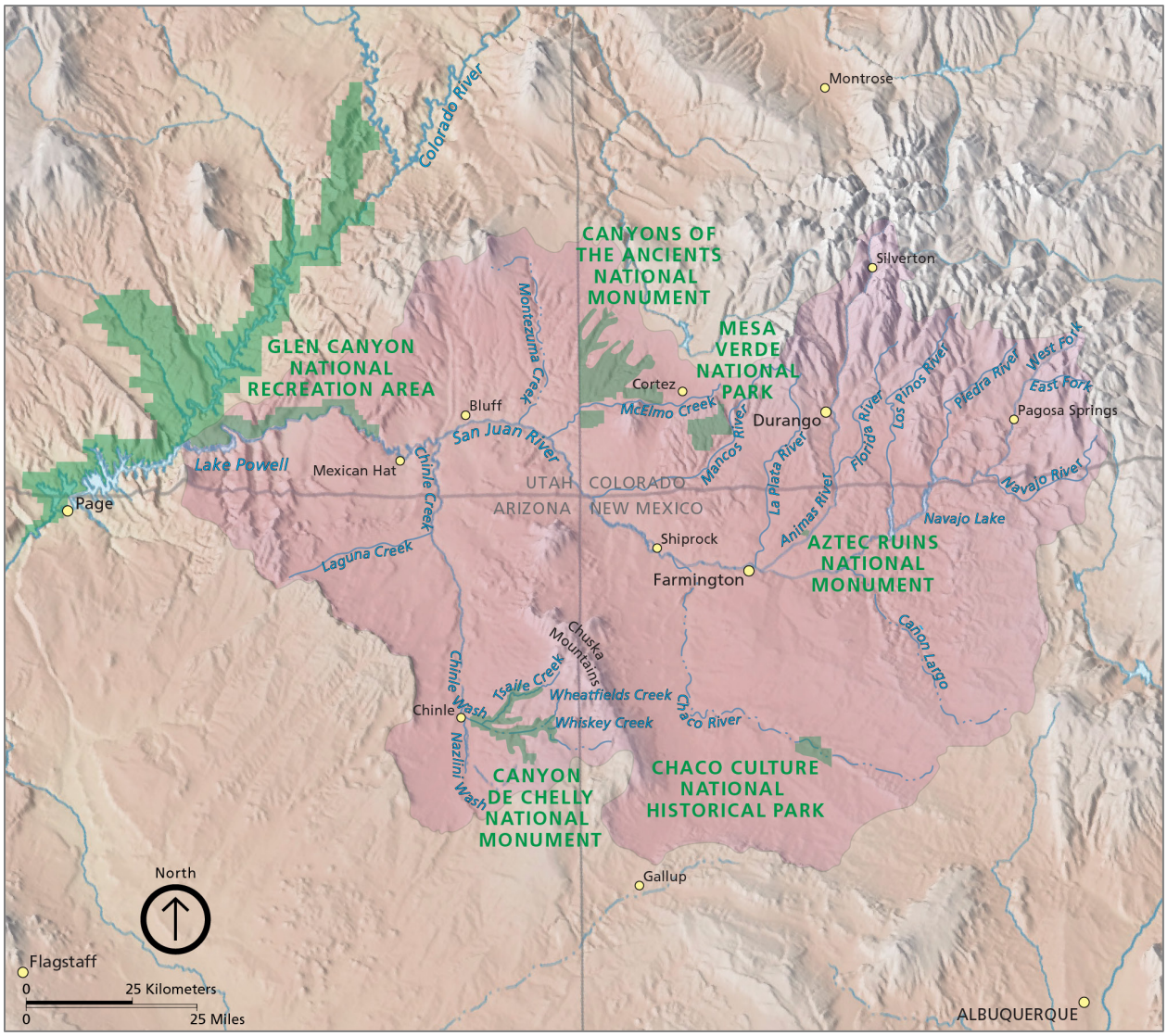


Figure 25. Map of the San Juan River watershed. Drainage through Chinle Wash begins in the Chuska Mountains (east of the monument). Tsaile, Wheatfields, and Whiskey Creeks drain much of the western escarpment of the Chuska Mountains. Tsaile Creek flows intermittently through Canyon del Muerto. Wheatfields and Whiskey Creeks flow intermittently through Canyon de Chelly. Portions of these creeks are perennial. All discharge funnels into Chinle Wash, which is joined by Nazlini Wash (south of the monument) to flow north. Closer to the Arizona-Utah border, flow from Laguna Creek joins the stream system, which becomes Chinle Creek, a tributary of the San Juan River. The San Juan River joins the Colorado River at Lake Powell in Glen Canyon National Recreation Area in Utah. Green shading and labels mark NPS areas. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University). Base map by Tom Patterson (National Park Service).

Terraces

As a river system becomes established on a landscape, it leaves a distinctive record of landforms, in particular, alluvial terraces. Various terrace levels show where a river pauses in its downcutting (Elston et al. 1965), and multiple terraces indicate that incision was not steady (Connell et al. 2005). The lowest terrace level in a vertical sequence, stepping up from the active channel, will be the youngest; the highest terrace will be the oldest.

The source map authors did not map terraces in the monument because the scale (1:250,000) is too coarse (see poster). However, alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) mark the presence of either terraces or pediments (Hackman and Olson 1977). Also, O'Sullivan and Beikman (1963) noted the presence of low-level terraces as containing some alluvium (**Qa**). Cooley et al. (1969, figure 15) identifies terraces in Canyon de Chelly and Canyon del Muerto. Detailed mapping of terraces and other geomorphic features on canyon floors would have multiple applications, including geoarcheological studies, a clearer understanding of geomorphic processes and conditions, and informing a conceptual model for use in watershed planning, restoration, and management (see "Watershed Restoration").

The foundation document (National Park Service 2016) includes alluvial terraces as part of a fundamental resource and value—cultural landscapes. As significant locations for farming in the canyons, terraces record human occupation (McDonald 1976). De Harport (1959) defines three river terraces in the monument and concludes that the most likely time represented by the oldest terrace was the late 13th century. No eroded archeological sites have been found on the two more recent terraces, suggesting that the middle terrace was formed during one of the periods of drought that occurred in the 15th, 16th, and 17th centuries, and that the youngest terrace had been formed no more than 70 years prior (ca. 1889).

Alluvium

The primary map unit representing fluvial activity at the monument is alluvium (**Qa**), which delineates active, intermittent, and abandoned stream channels that flowed with water during the past 11,700 years (Holocene Epoch). Alluvium consists of silt, sand, and gravel in small stream valleys and on floodplains. Mappers have included some eolian deposits (windblown sand and silt) and colluvial material (loose, incoherent deposits, transported by gravity) as part of alluvium. The thickness of alluvium may be as much as 64 m (210 ft) (Cooley et al. 1969; Hackman and Olson 1977), making it a local aquifer and source of groundwater (see "Sources of Water").

Genesis of Rock Shelters

Map units: **PPNs**, **Pdc**

Work by Ratté (2000, 2001) in Gila Cliff Dwellings National Monument in New Mexico (see GRI report by KellerLynn 2014) provides a model for the formation of the rock shelters at the monument. As the informally named "Cliff Dweller creek" at Gila Cliff Dwellings National Monument incised into bedrock (Gila Conglomerate) and created Cliff Dweller Canyon, the creek likely encountered a relatively soft layer of rock and cut laterally into it, initiating formation of the rock shelters. Thus,

rock shelters at Gila Cliff Dwellings National Monument were probably at stream level at the bottom of a former valley at the time of their genesis, though they would have been high above the valley floor when humans inhabited them.

The applicability of that model to the monument has been suggested in archeological reports by De Harport (1959), McDonald (1976), and Grant (1978). De Harport (1959, p. 94) states that rock shelters "were formed by the meandering streams undercutting the cliffs before the canyon reached its present depth." Moreover, scoping participants noted that rock shelters typically occur at meanders (bends) of the stream (see KellerLynn 2007, p. 9), so the Ratté (2000, 2001) model has veracity.

Based on the stream-incision model, rock shelters in what is now the monument would have coincided with erosional development of the monument's drainage system, that is, between 3.6 million and 11,700 years ago. That time frame is estimated based on the timing of entrenchment of the Colorado River system (see "Significant Geologic Events: Entrenchment of the Colorado River System"). Canyon cutting in the monument was initiated during the Black Point cycle, which Cooley et al. (1969) proposes to have taken place during the late Pliocene and early Pleistocene Epochs (i.e., 3.6 million and 774,700 years ago). Cooley et al. (1969) does not provide a numerical age, so corresponding ages from the International Chronostratigraphic Chart (International Commission on Stratigraphy 2023) are applied here. Canyon cutting ended with the Wupatki cycle, that is, by the end of the Pleistocene Epoch (Cooley et al. 1969), or about 11,700 years ago.

Sapping is another factor in cave formation. Sapping is an erosional process that occurs along the base of a cliff where softer layers are worn away, thereby removing the support for an upper mass of rock which breaks off into large blocks, falling from the cliff face. The process often involves weakening by groundwater along the contact between rock strata (Neuendorf et al. 2005). Under favorable (i.e., "wet") conditions, sapping is enlarging present-day caves. Sapping results in grain-by-grain erosion, spalling away of thin surface layers of rock, and increased susceptibility to wind erosion. If rock shelters are along fractures or other structural features that channel groundwater, or at the bottom of valleys, general seepage results in sapping. In addition, scoping participants noted that the intersections of cross-beds are avenues for groundwater seepage, which dissolves the calcium-carbonate cement that holds sand grains together, thus enlarging rock shelters grain-by-grain (see KellerLynn 2007, p. 2).

A 1937 geologic report for the monument shows an advocacy for sapping and provides the following explanation:

> *The tangential cross-bedding permits ready access of the surface waters along the angular bedding planes in the porous sandstone. Such waters percolate into the face of the cliff and thus at first small units are weakened as the loose cement is dissolved and the shell-like forms are carried down by gravity. These processes are repeated over long periods of time, the curved laminae being removed on an increasing larger scale, until the shells have cut back into the cliff to form alcoves [rock shelters] large enough to house whole settlements of*

> *Pueblo people. The jointing [fractures in rock] is generally of lesser importance than the tangential cross-bedding in this process although in some instances it is a major factor. For many of the larger alcoves [rock shelters] especially in Navajo Canyon, at Mesa Verde, and at Zion [National] Park it is a common occurrence to observe a concentration of surface water at the top of a cliff directly over the alcove [rock shelter], giving a funnel effect, with the result that there is a concentration of water above the cave [rock shelter] site. Alcoves [rock shelters] and recesses may be observed in all stages of formation. In some cases the shells are so loose that they might seemingly be expected to crash to the floor at any minute, as in the alcoves [rock shelters] in Navajo Canyon (Vandiver 1937, p. 62–63).*

Grant (1978, p. 20) considers freezing water as another factor in rock-shelter formation: "water percolating into the bedding planes can freeze, and, through expansion, exfoliate or peel off masses of rock like layers of an onion." Although no studies are known to have been conducted on the rocks at the monument, Riggins et al. (2009) conducted weathering experiments on samples of the Tshirege Member of the Bandelier Tuff from Bandelier National Monument in New Mexico (see the GRI report by KellerLynn 2015a). Rock samples were immersed in water before being frozen, and a significant loss of cohesion resulted in the disintegration of all samples after just six freeze-thaw cycles. Tuff and sandstone are different types of rocks, of course, but those findings are suggestive. A similar experiment on the De Chelly Sandstone may be appropriate for determining whether freeze-thaw is a factor in rock-shelter formation, as well as the cause of rockfall hazards in rock shelters at the monument (see "Geologic Hazards").

Sand Dunes

Sand dunes are the most distinctive eolian feature at the monument. Eolian (also spelled "aeolian" from Aeolus, Greek goddess of the wind) refers to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Although winds may be modified by local topography, the prevailing winds at the monument are southwesterly. The pattern of prevailing winds has changed throughout geologic history (see "Ancient Sand Dunes").

During scoping in 2007, monument staff commented, "We love dunes" (KellerLynn 2007, p. 10). Presumably, this comment stemmed from the enjoyment of interpreting these features—which come in a variety of sizes, forms, and colors—for visitors. Furthermore, "dunes as habitat" for native grasses and other endemic species may be compelling for visitors (KellerLynn 2007). Moreover, cultural aspects of the dunes may delight visitors; for example, *Queen of the Nile* (1961) was filmed on the dunes at the mouth of Canyon de Chelly. Popular legend suggests that the film set is still there, being buried by the sand (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023).

A large dune near the southwestern edge of the monument is commonly interpreted for visitors. This dune is active. Monument staff refer to it as "The Sand Dune" (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023). Previously, this dune was displayed on

the monument's official map and guide (National Park Service 2013) as a stippled map symbol (south of the visitor center). Unfortunately, the currently available online map of the monument (created in 2016) does not show this feature.

Dunes at the monument include barchan (crescent-shaped dunes in which the arms of the crescent point downwind) and longitudinal (long, narrow dunes, usually symmetrical in cross profile, oriented parallel with the direction of the prevailing wind). Barchan dunes occur at the mouth of Canyon de Chelly. Longitudinal dunes are found in Chinle Wash, Chinle Valley, and Beautiful Valley (Cooley et al. 1969, figure 14). In addition, blowouts (small, saucer-, cup-, or trough-shaped hollows or depressions on a preexisting dune or other sand deposit) occur on the dune in Tunnel Canyon (KellerLynn 2007). Areas of red dunes occur on the south side of Canyon de Chelly, within about 4.0 km (2.5 mi) of its mouth (De Harport 1959). Because of the color, sand or dust storms associated with these dunes are referred to as "pink outs" (KellerLynn 2007; see "Climate Change Planning" and "Geologic Hazards").

The source maps (O'Sullivan and Beikman 1963 and Hackman and Olson 1977) and poster show no eolian deposits mapped in the monument, but this lack is a consequence of map scale (1:250,000), not the existence of dunes. Maps of greater detail show the dunes. For instance, a map by De Harport (1959) shows three notable localities: (1) high on the south side of Canyon de Chelly, opposite the junction with Canyon del Muerto; (2) on the floor of Cottonwood Canyon; and (3) near the mouth of Canyon de Chelly. Moreover, dune deposits (**Qd**) appear in two of the GRI GIS data sets that were mapped at a scale of 1:24,000—Sonsela Butte 4 SE (Byers 1980) and Buell Park (Thaden 1990) quadrangles (see Figure 1). Dunes in those quadrangles consist of pale yellowish–brown, fine-grained, well-sorted sand, which may be very slightly silty. The sand grains are subrounded and rounded quartz. In the Buell Park quadrangle, the sand forms fields of low dunes along the margin of Black Creek. The source of that sand is sediment removed principally from alluvium by persistent and strong seasonal winds. Those dunes are mostly migratory but are partially stabilized by salt cedar (aka tamarisk [*Tamarix* sp.]), shad scale (*Atriplex*), and other shrubs locally. The maximum dune height is about 2 m (7 ft) (Thaden 1990).

Geologic Resource Management Issues

This chapter highlights issues (geologic features, geologic processes, and human activities affecting or affected by geology) that may require management for human safety, protection of infrastructure, or preservation of natural and cultural resources. The NPS Geologic Resources Division (GRD) provides technical and policy assistance for these issues (see "Guidance for Resource Management").

During the 2007 scoping meeting (see scoping summary by KellerLynn 2007) and 2022 follow-up meeting, participants (see "Acknowledgments") identified the following geologic resource management issues. They are listed alphabetically, not by management priority.

- Cave Inventory, Monitoring, and Protection
- Climate Change Planning
- Geologic Hazards
- Legacy of Uranium Exploration
- Paleontological Resource Inventory, Monitoring, and Protection
- Rock Art Documentation
- Watershed Restoration

Cave Inventory, Monitoring, and Protection

The Federal Cave Resources Protection Act of 1988 requires the identification of significant caves on federal lands; the regulations stipulate that all caves on NPS properties are significant. In addition, the act requires that caves be considered in any land management planning and their use be regulated or restricted as needed to protect cave resources. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act (FOIA) request. Other laws, such as the Archeological Resources Protection Act (ARPA), also provide managers with tools to protect specific resources found within caves (and on the surface above them) by exempting their nature and location from FOIA requests.

Three caves are labeled on the monument's official map and guide (National Park Service 2013): (1) Yucca Cave, (2) Mummy Cave, and (3) Massacre Cave. All three are in Canyon del Muerto (see poster).

A thorough inventory of the monument's caves—referred to as "rock shelters" throughout this report and called "rock alcoves" by monument staff—is not known to have taken place. A PhD dissertation and archeological survey by De Harport (1959), however, provides a general—albeit brief—discussion of the rock shelters in Canyon de Chelly. No other scientific inquiries about the rock shelters in the monument are known to have taken place.

Based on descriptions in the monument's foundation document (National Park Service 2016), the monument's rock shelters are considered archeological and/or cultural resources and have been managed as such. A cave management plan that would address all aspects of the resource—including natural and geologic—is not known to have been conducted. Monument managers are encouraged to contact the GRD and/or the National Cave and Karst Research Institute (NCKRI) for assistance in developing a cave management plan (see "Additional References, Resources, and Websites").

Threats to cave resources include the following:

- Significant precipitation events can result in groundwater entering the rock shelters through bedrock fractures. This water has the potential to damage cliff dwellings and rock art.
- Vandalism, including unintentional damage by visitors, and some animal activities can cause degradation of archeological resources in rock shelters.

Climate Change Planning

The monument's foundation document (National Park Service 2016) listed climate change scenario planning as a planning need with respect to the following fundamental resources and values: archeological landscapes and associated museum collections, cultural landscapes, and continuing cultural connections. In addition, a climate change vulnerability assessment was listed as a data and/or GIS need for continuing cultural connections (National Park Service 2016).

Although climate change planning is beyond the scope of the GRI, a discussion of climate change is included in this report because of the potential disruption it may cause to park resources, including geologic resources. Monument managers are directed to the NPS Climate Change Response Program (see "Additional References, Resources, and Websites") to address climate change planning.

Climate change has the potential to exacerbate issues associated with the following geologic features and processes at the monument:

- Eolian features and processes. A drier landscape due to climate change may result in increased soil desiccation and desertification, leading to increased transport of windblown sediment (sand and silt), causing "sand blasting" of cultural and natural resources such as signs and wayside exhibits, building facades, pictographs and petroglyphs, tree bark, and new plant growth. Increased eolian transport of silt could result in greater dust accumulation within and surrounding buildings, such as in doorways and windowsills, as well as within rock shelters and cliff dwellings. Also, prolonged drought may increase the number and magnitude of dust storms, which decrease visibility and increase safety hazards for drivers.
- Erosion. An increase in storm frequency/intensity (e.g., Wuebbles et al. 2017) could accelerate current erosion rates. Increases in mean annual temperature, storm frequency/intensity, and extreme temperature events projected for the region due to climate change could impact fundamental resources and values (i.e., the archeological landscape, and scenic views and vistas) through erosion (National Park Service 2016).

- Flooding. More frequent or intense floods could increase the vulnerability of park infrastructure, resources, archeological sites (e.g., on terraces), and the cultural landscapes along stream channels and washes.
- Groundwater and surface water. The Sonoran Desert Network monitors several vital signs that will likely show the effects of climate change (Sonoran Desert Network 2010); some of these vital signs are also geologic indicators of change, such as seeps, springs, and tinajas; streams; washes; and groundwater. Future climate scenarios predict declines in recharge of varying magnitudes in the southwestern United States (Meixner et al. 2016), potentially impacting regional and local aquifers.
- Landforms. Understanding landscape history and learning from past changes recorded in landforms will help to indicate how geomorphologic systems will adapt to the speed and scale of projected climate change. Direct impacts from climate change will principally arise through changes in geomorphologic processes and in vegetation cover. Features may be lost to greater erosion or become obscured by sediment deposition or increased vegetation cover. Geologic processes may become either more or less dynamic, change entirely, or cease to operate. Some geologic features may shift location, including migrating outside NPS boundaries. Because many changes in geomorphologic processes will also impact biodiversity, climate change action plans for nature conservation require an integrated approach (Gordon et al. 2022).
- Slope movements. Fire frequency is predicted to increase by as much as 25% globally by 2100 (Moritz et al. 2012). Changes in the pattern of wildland fire may cause a greater frequency of slope movements (see GRI reports about Bandelier National Monument and Redwood National and State Parks by KellerLynn 2015a and 2021, respectively).

Geologic Hazards

The dynamic landscapes preserved at many National Park System units present a variety of natural hazards that threaten facilities, staff, and visitors. Many of these natural hazards are geologic (e.g., earthquakes, landslides, and volcanic eruptions). NPS Policy Memorandum 15-01 (Jarvis 2015) directs NPS managers and their teams to proactively identify and document facilities vulnerable to climate change and other natural hazards. *Geological Monitoring* (Young and Norby 2009) provides guidance for monitoring many of these geologic hazards.

Table 7 summarizes the geologic hazards at the monument. The table is appropriate for use in park-scale discussions and assessments. It is not a substitute for site-specific investigations or National Environmental Policy Act (NEPA) analysis and compliance. Ground-disturbing activities should neither be approved nor denied based on the information in Table 7.

Table 7. Geologic hazards checklist.

Potential Hazard	Best Professional Judgment	Risk or Secondary Hazard	Sources of Information
Cave/karst[A]	Known Hazard for rockfall Potential Hazard for contamination	• Rockfall potential, especially at entrances	• Land et al. (2013) • Scoping summary (KellerLynn 2007) • Wachter (1978)
Coastal storm surge/ sea or lake level change/ shoreline erosion	Not applicable	• Not applicable	• Not applicable
Dust/sandstorms	Known Hazard	• Blowing sand may cause pitting on cultural features. • Active dune migration may negatively affect farming. • Sandstorms stop traffic on Interstate 40 (south of the monument). • Sandstorms are frequent in all areas that do not have forest cover. • Called “chindi” in Navajo, dust devils or whirlwinds are commonly seen on Chinle Wash, even on summer days when the wind velocity is low. On days of generally high winds, the air is full of dust and sand. Frequently, gusts of wind carry silt and sand from the floodplain over the walls of Canyon de Chelly, 150 to 210 m (500 to 700 ft) above (De Harport 1959).	• Cooley et al. (1969) • De Harport (1959) • GRI GIS data: alluvial and/or eolian deposits (**Qes**; Byers 1979); alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**); dune deposits (**Qd**; Byers 1980, Thaden 1990) • GRI scoping summary (KellerLynn 2007) • Lancaster (2009) • McDonald and Sweeney (2017) • Sweeney et al. (2011) • Sweeney and McDonald (2017)

[A] The monument’s caves are referred to as “rock shelters” in this report.

[B] Referred to as “regional floods” by the Arizona Geological Survey.

[C] Not including rockfall.

Table 7 (continued). Geologic hazards checklist.

Potential Hazard	Best Professional Judgment	Risk or Secondary Hazard	Sources of Information
Earthquakes	Potential Hazard	• Earthquake probability is low. • No active faults occur within or in the vicinity of the monument. • The Arizona hazards map shows three earthquakes that have occurred in the vicinity of the monument: two had Modified Mercalli Intensities (MMI) I (generally not felt) and one had MMI II (felt only by a few persons at rest, especially on upper floors of buildings).	• Natural Hazards in Arizona, interactive map (Arizona Geological Survey 2022b) • US Geological Survey (n.d.) • USGS seismic hazard map (Figure 26)
Flash floods	Known Hazard—Flash floods rarely cause major economic impact, but they can be deadly.	• Flash floods occur as a result of sudden, heavy rains. Little of this precipitation goes into the ground, and the runoff is great. During flash flood events, small gullies discharging water at the edge of the canyons form many waterfalls. Within minutes, the broad floodplain becomes covered with water. In less than an hour, the floodplain may be visible again, and the channel may carry a small stream. • The most dangerous factor for travel in the monument is the possibility of a flash flood, which, without warning, can turn dry washes into boiling torrents of muddy water. • Flash floods from “cloud bursts” can originate many miles to the east, while threatened canyon areas are still enjoying clear skies and sunshine.	• Arizona Geological Survey (2022a) • De Harport (1959) • Federal Emergency Management Agency (FEMA) flood maps • Grant (1978) • GRI GIS data: alluvium (**Qa**); fan deposits and slope wash (**Qf**; Byers 1979, 1980); slopewash (**Qs**; Byers 1980, Thaden 1990)
Hydrothermal activity	Not applicable	• Not applicable	• Not applicable
Permafrost	Not applicable	• Not applicable	• Not applicable

[A] The monument’s caves are referred to as “rock shelters” in this report.

[B] Referred to as “regional floods” by the Arizona Geological Survey.

[C] Not including rockfall.

Table 7 (continued). Geologic hazards checklist.

Potential Hazard	Best Professional Judgment	Risk or Secondary Hazard	Sources of Information
Quicksand and dry sand	Known Hazard	• After a heavy summer rainfall, saturated sand can become quicksand, as many unwary drivers have discovered. The weight and/or vibration of a vehicle in saturated sands can induce a "quick" condition and seize a vehicle firmly in place. • Prolonged dry conditions can make the lower canyons a sea of loose sand, and even a four-wheel-drive vehicle can bog down.	• Grant (1978) • Pranger (2005)
Radon	Potential Hazard—Radon levels in Arizona are generally low, but several hot spots occur throughout the state, including Tucson (the area around Cardinal Avenue), the Cave Creek area, parts of the Verde Valley, and the Granite Dells near Prescott.	• Health hazard • Elevated levels of radon are found in both new and old buildings. • Radon can be found in buildings constructed on all types of foundations, including crawlspaces and slab-on-grade basements. • Sub-floor ductwork for forced air furnaces and air conditioners can draw radon-laden gas into a building. • Radon levels in Arizona can often be higher during summer/air-conditioning months than during months with milder temperatures.	• Arizona Geological Survey (2022c) • EPA Map of Radon Zones (Environmental Protection Agency 1993)
Riverine floods[B]	Known Hazard—1% annual chance of flood hazard	• Destruction of infrastructure • Stream channel migration • Stream bank erosion	• GRI GIS data: alluvium (**Qa**) • Federal Emergency Management Agency (FEMA) Map Service Center • Natural Hazards in Arizona, interactive map (Arizona Geological Survey 2022b) • Rosenlieb and Smillie (1990)

[A] The monument's caves are referred to as "rock shelters" in this report.

[B] Referred to as "regional floods" by the Arizona Geological Survey.

[C] Not including rockfall.

Table 7 (continued). Geologic hazards checklist.

Potential Hazard	Best Professional Judgment	Risk or Secondary Hazard	Sources of Information
Rockfall	Known Hazard—Depending on the location, rockfall could be a safety hazard for canyon residents, hikers, and campers. For instance, people often congregate in the shade of the cliffs, and some residents use rock shelters for livestock penning. Also, in Canyon del Muerto, segments of the road follow the contours of overhangs. In these situations, rockfall can be considered a threat to visitors, residents, and staff.	• Rockfall hazards have been identified at Sliding Rock Ruin, White House Ruin, and Antelope House (Wachter 1978). • A hazard associated with rock shelters is spalling of rock debris as a result of wind and water erosion. • The primary concern is the loss of cultural information such as pictographs (e.g., "Doe Panel" in the Spider Rock area). • Large pillars have fallen at Big Cave in Canyon del Muerto, Junction Ruin, and Massacre Cave. • Rockfall is evident near Spider Rock and Standing Rock. • Big Cave was the site of a major rockfall event in 2002; minor rockfalls regularly occur throughout the canyon system.	• GRI GIS data: colluvial deposits, undifferentiated (**Qc**); talus (**Qt**; Thaden 1990) • Scoping summary (KellerLynn 2007) • Wachter (1978) • Written communication (Keith Lyons, Canyon de Chelly National Monument, integrated resource manager/archeologist, 8 May 2007)
Shrink/swell soils	Known Hazard	• Commonly associated with the Triassic Chinle Formation clays (e.g., montmorillonite and bentonite). • Hazards include cracking of foundations, walls, driveways, swimming pools, and roads; and slippery trail conditions. • Shrink/swell soils are widespread on the Colorado Plateau in northern Arizona and are notable for their popcorn textures.	• Arizona Geological Survey publications (e.g., Murphy 1975; Harris and Pearthree 2002) • GRI GIS data: Chinle Formation (**TRc**, **TRcs**, **TRcmb**, **TRcpb**, **TRcps**, **TRcpa**, **TRco**) • Natural Resources Conservation Service (NRCS) Web Soil Survey (WSS)

[A] The monument's caves are referred to as "rock shelters" in this report.

[B] Referred to as "regional floods" by the Arizona Geological Survey.

[C] Not including rockfall.

Table 7 (continued). Geologic hazards checklist.

Potential Hazard	Best Professional Judgment	Risk or Secondary Hazard	Sources of Information
Slope movements[C]	Potential Hazard	• No known active landsliding is occurring within the monument, but the lack of identification/mapping of these deposits may be an outcome of the scale of the GRI GIS data (1:250,000). The closest mapped deposits are in the Chuska Mountains, east of the Chuska syncline (see poster). In addition, the interactive map (Arizona Geological Survey 2022b) shows landslides at Sonsela Buttes.	• GRI GIS data: landslide debris (**Ql**), landslide deposits (**Tls**; Byers 1980); and Toreva block (rotational slump block) (**Qtb**; Byers 1979) • Natural Hazards in Arizona, interactive map (Arizona Geological Survey 2022b)
Tsunami	Not applicable	• Not applicable	• Not applicable
Volcanic eruptions	Potential Hazard	• The San Francisco, Uinkaret, and Pinacate volcanic fields have hosted multiple eruption events in the past 10,000 years, and all have a high likelihood of future eruptions. These volcanic fields largely erupt basaltic lavas and tephra, so hazards include lava flows and ash.	• Arizona Geological Survey (2022d) • Natural Hazards in Arizona, interactive map (Arizona Geological Survey 2022b)

[A] The monument's caves are referred to as "rock shelters" in this report.

[B] Referred to as "regional floods" by the Arizona Geological Survey.

[C] Not including rockfall.

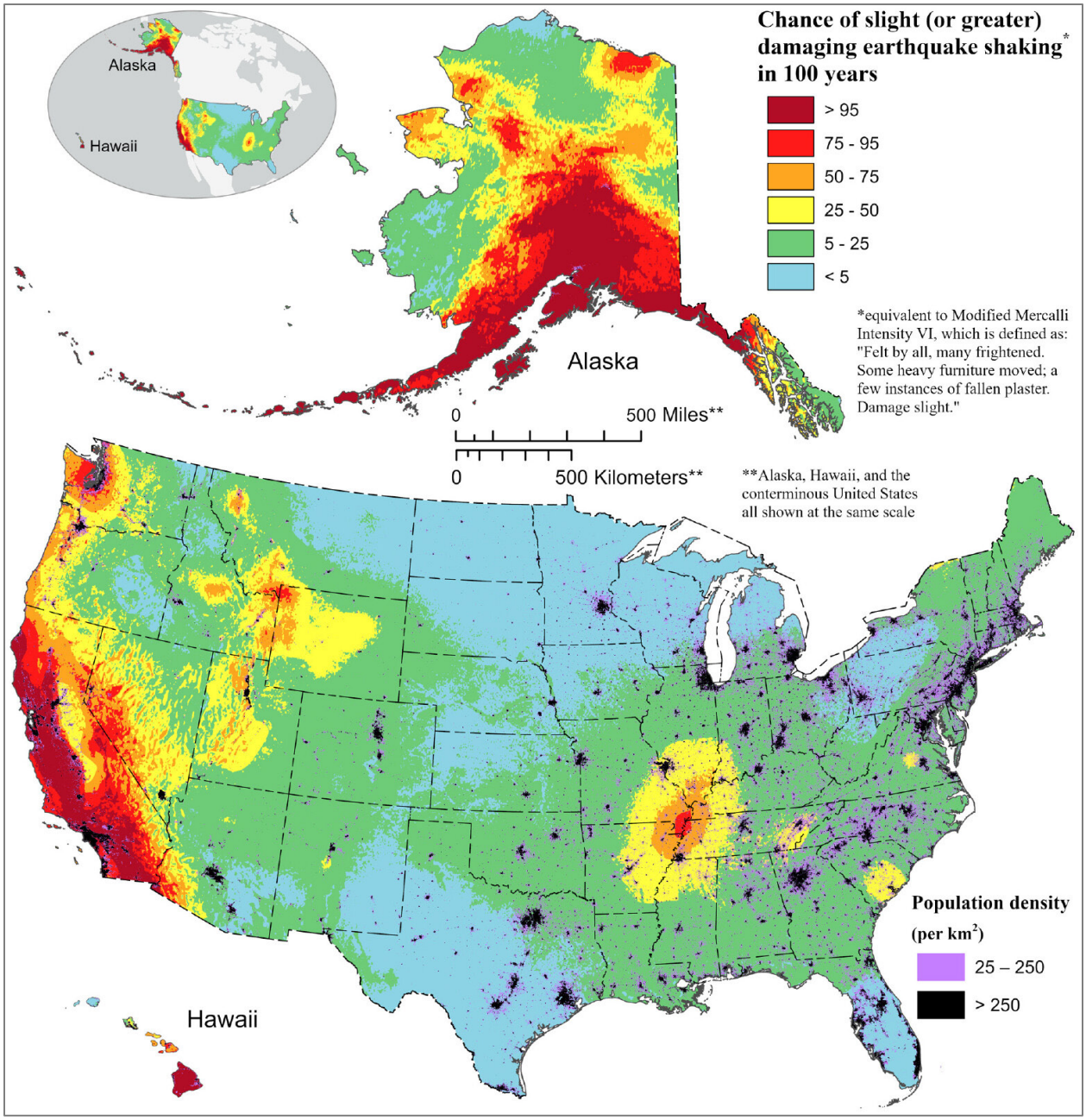


Figure 26. National seismic hazard map. The map shows the chance of any level of damaging earthquake shaking in 100 years from the 2023 50-State National Seismic Hazard Model. The shaking is equivalent to Modified Mercalli Intensity VI and higher and is based on the average peak ground acceleration and 1-s horizontal spectral response acceleration (using Worden et al. 2012 model without uncertainty). Ground motions are amplified using hybrid VS30 estimates (Heath et al. 2020). Population density (LandScan, Dobson et al. 2000 with 1 km×1 km resolution from Oak Ridge National Laboratory) is superimposed on the map. Map by Peterson et al. (2024, figure 3), available at https://doi.org/10.1177/87552930231215428 (accessed 27 February 2024).

The table is modeled after the Natural Hazard Checklist (see National Park Service 2015 and Jarvis 2015). It is meant to provide general information to identify the full range of natural hazard risks at

the monument. The table is a synthesis of existing GRI-compiled data and information and includes published USGS and state geologic survey information. The "sources of information" in the table were the primary resources used to make the "best professional judgment" determination. "Sources of information" include the GRI GIS data and ancillary map information document.

Explanation of hazard ratings (i.e., Best Professional Judgment in Table 7):

- Known hazard: Conditions that cause the hazard are well documented at the monument. If applicable to a project site, these hazards should always be addressed in a project plan.
- Potential hazard: Conditions that cause or underlie the hazard are known to occur nearby or are likely to occur based on studies with conditions similar to the monument. If applicable to a project site, these hazards should be considered for inclusion in a project plan.
- Not applicable: No evidence was identified showing that this hazard is relevant to the monument. Note this is a coarse filter evaluation; local knowledge of a hazard should be used when available.

Legacy of Uranium Exploration

Uranium occurs in Earth's crust and is naturally present in low concentrations in rock, soil, and water. Observations recorded during the 2007 scoping meeting (i.e., the high-uranium content of water in pothole wells dug for livestock and the [possible] existence of a uranium mine in upper Canyon del Muerto) highlight the presence of uranium in the Chinle Formation (see KellerLynn 2007). Notably, correspondence with Perry Charley (Diné College–Shiprock, Uranium Education Program) did not corroborate the presence of a uranium mine in upper Canyon del Muerto. Charley worked on reclamation of abandoned uranium mines under the Navajo Nation for many years prior to his tenure at Diné College and knows of no mines within the immediate monument area or more specifically within Canyon del Muerto (Perry Charley, Diné College, Uranium Education Program, senior scientist/director, email communication, 26 March 2007). Charley surmised that participants must be referring to several, possibly three, small mine plots where the US Atomic Energy Commission conducted exploratory drilling for uranium and vanadium at the northwestern edge of the monument in the early 1950s. These sites are located near the Canyon del Muerto area. Due to the low grade of the deposits, however, no active mining resulted from any of these drilling operations. Charley suggested two reports—US Atomic Energy Commission (1953) and Scarborough (1981)—for further information. The administrative history of the monument (Brugge and Wilson 1976) makes no mention of uranium.

The nearest uranium mines to the monument are located at Black Mesa, approximately 50 km (30 mi) west of Canyon de Chelly; 13 properties were mined in this area (Perry Charley, Diné College, Uranium Education Program, senior scientist/director, email communication, 26 March 2007). The most significant uranium mine in the region was the Monument No. 2 Mine in Monument Valley (north of the monument, close to the Arizona-Utah state border). Uranium was first noted in the Monument Valley region by Gregory (1917). The area would later become Arizona's largest mined uranium deposit (Scarborough 1981). The Monument No. 2 Mine was active from 1942 to 1967 (Peterson 1983).

Monument Valley uranium ores are found predominantly in paleochannels of the Shinarump Member of the Chinle Formation and, to a much lesser extent, in the underlying Moenkopi Formation. The best ores from the Monument No. 2 Mine were found as "cigars" or "rods" as much as 2 m (8 ft) in diameter and 30 m (100 ft) long. Ores filled in sandstone voids and replaced quartz grains, clay particles, and abundant fossil plant debris. They also filled vertical fractures that extend beneath the scour base and into the Moenkopi Formation or De Chelly Sandstone below. This latter observation led Finnell (1957) to suggest a hydrothermal source for the ores that rose from depths along en echelon (approximately parallel) fractures produced during the Laramide Orogeny (see "Significant Geologic Events: Laramide Orogeny"). Most other workers, however, subscribe to the groundwater-style ore emplacement hypothesis that envisions the movement of ore solutions along Shinarump channelways during the Mesozoic Era, prior to erosional removal of much of the Shinarump Conglomerate (Scarborough 1981).

Paleontological Resource Inventory, Monitoring, and Protection

Rocks and unconsolidated deposits within the monument have yielded in situ paleontological resources (Table 8), which are any evidence of life preserved in a geologic context (Santucci et al. 2009). In situ paleontological resources may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism's activity such as tracks, nests, burrows, or coprolites [fossil feces]). The monument has both body and trace fossils (Table 8).

Table 8. Paleontological resources at Canyon de Chelly National Monument. Sources: Tweet et al. (2009) and Justin Tweet (NPS Geologic Resources Division, associate, informal report, 26 January 2022, and written communication, 12 April 2023).

Rock or Unconsolidated Deposits with Fossils	Age	Fossils Found within the Monument
Quaternary sediments in rock shelters (unmapped, therefore no map unit symbol)	Pleistocene–Holocene	• Ground sloth (Pleistocene) • Human coprolites with pollen (Holocene) • Packrat middens (late Pleistocene–Holocene)
Chinle Formation, Owl Rock Member (**TRco**)	Late Triassic	• None known to date, but the potential for discovery is great.
Chinle Formation, Petrified Forest Member, upper part (**TRcpa**)	Late Triassic	• None known to date, but the potential for discovery is great.
Chinle Formation, Petrified Forest Member, Sonsela Sandstone Bed (**TRcps**)[A]	Late Triassic	• None known to date, but the potential for discovery is great.
Chinle Formation, Petrified Forest Member, lower part (**TRcpb**)	Late Triassic	• None known to date, but the potential for discovery is great.

[A] Now recognized as the Sonsela Member (see "Three Formations: Chinle Formation").

[B] Now recognized as the Bluewater Creek Member (see "Three Formations: Chinle Formation").

Table 8 (continued). Paleontological resources at Canyon de Chelly National Monument. Sources: Tweet et al. (2009) and Justin Tweet (NPS Geologic Resources Division, associate, informal report, 26 January 2022, and written communication, 12 April 2023).

Rock or Unconsolidated Deposits with Fossils	Age	Fossils Found within the Monument
Chinle Formation, Monitor Butte Member (**TRcmb**)[B]	Late Triassic	• Lycopods • Bennettitales (some with insect traces) • Conifers • *Dechellyia* (unclassified plant) • Arthropod traces on plants • Possibly reptile remains
Chinle Formation, Shinarump Member (**TRcs**)	Late Triassic	• Petrified wood • Unidentified leaves
De Chelly Sandstone (**Pdc**)	Early Permian (Cisuralian [on the global time scale] or Leonardian [on the regional time scale]; see Table 4)	• Tetrapod tracks and trackway
Supai Formation (**PPNs**)	Pennsylvanian and early Permian	• None known to date, but the potential for discovery is great.

[A] Now recognized as the Sonsela Member (see “Three Formations: Chinle Formation”).

[B] Now recognized as the Bluewater Creek Member (see “Three Formations: Chinle Formation”).

Additionally, museum collections and other cultural contexts may contain fossils. Work by Kenworthy and Santucci (2006) presents an overview and cites selected examples of NPS fossils found in cultural resource contexts. The monument is not cited, but other parks in the Southern Colorado Plateau Network (SCPN) are.

The following publications document specific information about fossils found within the monument:

- Ash (1972a, 1972b, 1972c; 1980; 1996) provides the most detailed descriptions of plant fossils found in and around the monument. The focus of these studies is the Chinle Formation, which contains petrified wood ranging in size from twigs to trunks, as well as leaves.
- Tweet et al. (2009) provides a baseline paleontological resource inventory for the SCPN, including the monument. In addition, Justin Tweet (NPS Geologic Resources Division, associate) visited the WACC in 2015, documenting paleontological materials that had been collected in the monument. Because of the great number of petrified wood specimens (88 of 147 catalog numbers), Tweet focused on other fossil materials stored in both the natural history and cultural history collections.

- Tweet et al. (2012) provides a baseline inventory of packrat middens at the monument (see "Rock Shelters, Cliff Dwellings, and Middens").

A monument-specific, field-based, paleontological survey has not been conducted. Such an inventory would more fully document in situ paleontological resources and potentially find yet-to-be discovered fossils. For example, the potential is great for finding more tracks or trails in the Permian De Chelly Sandstone and potentially in the Triassic Shinarump Conglomerate (Tweet et al. 2009). A field-based inventory could potentially be conducted by a SIP participant (see "Guidance for Resource Management"). Traditional knowledge about fossils would be a significant addition to a field-based inventory.

A condition assessment and formal site documentation for known fossil localities, for example, the trackway in the De Chelly Sandstone and localities documented in work by Ash (1972a, 1972b, 1972c; 1980; 1996), may be warranted. Depending on the outcome, annual monitoring of significant sites may be needed. A chapter (Santucci et al. 2009) in *Geological Monitoring* (Young and Norby 2009) provides guidance for monitoring in situ paleontological resources.

One notable threat to in situ paleontological resources is the theft of petrified wood. Much of the fossil wood in the Chinle Valley has disappeared through time, taken by collectors (Baars 1998). The GRI report about Petrified Forest National Park (KellerLynn 2010) thoroughly discusses resource theft and other types of paleontological resource damage that may be applicable to the monument.

The baseline paleontological resource inventory by Tweet et al. (2009) provides recommendations for monument managers. These recommendations highlight the significance of coordination between paleontological and archeological studies because fossils can be both cultural and geologic resources. Fossils found in a cultural context should be documented as a paleontological resource but will also require the input of an archeologist. Moreover, any fossil found in a cultural context may be culturally sensitive (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. WACC and GRD can coordinate additional documentation/research of such material. Likewise, archeological excavations, infrastructure developments, or a cave inventory may yield paleontological material from the Quaternary Period and should, thereby, consider scheduling site monitoring by a trained paleontologist in order to document and protect fossil resources.

Among other recommendations, Tweet et al. (2009) suggests a multi-park, cooperative research effort to study the ancient fluvial ecosystems preserved in the Chinle Formation. The Chinle Formation is exposed in the following five parks: (1) Canyon de Chelly National Monument, (2) Glen Canyon National Recreation Area, (3) Grand Canyon National Park, (4) Hubbell Trading Post National Historic Site, and (5) Petrified Forest National Park. A previous multi-agency project (Turner et al. 1998; Turner and Peterson 2004), which studied the ancient ecosystems of the Jurassic Morrison Formation, could serve as a model. The "Morrison Formation Extinct Ecosystems Project" involved 11 parks in the NPS Intermountain Region. Principal investigators were from the USGS, NPS, University of Nebraska, and Exxon Production Research Company; other universities were also

involved. A similar project conducted for the Chinle Formation would identify ancient ecosystems, help refine the stratigraphic nomenclature of the formation, and make connections across parks.

In addition, because worked (human-modified) petrified wood from the Chinle Formation is found in cultural resource contexts in many SCPN parks (Tweet et al. 2009), a multi-park investigation into the provenance of the wood may yield information regarding source locations of lithics (stone tools) and subsequent trade routes.

Rock Art Documentation

The monument's foundation document states that the canyon system "contains one of the largest concentrations of pictographs and petroglyphs in North America" (National Park Service 2016, p. 6). No North American database of rock art is known to exist that could confirm this, but the NPS Cultural Resources Inventory System (CRIS), which contains site records that document petroglyphs/petrographs within the National Park System, sheds some light on this statement. Analysis of CRIS revealed 79 park units with either petroglyphs or pictographs. With 343 known sites listed with either petroglyphs or pictographs, the monument ranks #1 out of 79. However, this and other numbers in CRIS reflect the number of sites within a park unit, not the number of individual pictographs/petroglyphs. For instance, Petroglyph National Monument has more than 20,000 individual petroglyphs, but only 67 sites are recorded in CRIS (Michael J. Evans, NPS Interior Regions 3, 4, 5 [Midwest], regional cultural anthropologist, written communication, 11 April 2023, and email communication, 23 January 2024).

Notably, data in CRIS only reflect what has been entered, so the list for the monument is likely incomplete and will grow in the future with the collection of new information (Joshua M. Torres, National Park Service, acting bureau archeologist, email communication, 1 July 2022). At present, *Canyon de Chelly: Its People and Rock Art* (Grant 1978) is still the most comprehensive documentation of the monument's rock art (Keith Lyons and Josh Ramsey; Canyon de Chelly National Monument; integrated resource manager/archeologist and archeologist, respectively; personal communication; 1 November 2023). The author (Campbell Grant) and a small team of coworkers spent five weeks recording and photographing pictographs and petroglyphs at the monument between 1969 and 1975. The study investigated about 100 sites in Canyon de Chelly, Canyon del Muerto, and nine smaller side canyons.

In general, past rock art studies, including at the monument, have focused on the figures displayed in rock art. The actual rock surface, that is, the "canvas for the art," was ignored in favor of the imagery (Meijer and Dodd 2018). Not until the late 1980s did the focus change from "figure-based" to "surface-based." That change is of interest for the monument's geologic heritage because, in addition to realizing the significance of the rock canvas itself, a surface-based approach can determine whether an artist incorporated specific geologic features such as sedimentary structures (e.g., bedding, lamination, and ripple marks) or glacial striations (though not at the monument) into a work. Moreover, a surface-based approach allows for monitoring changes in the structure of the surface caused by weathering or other damage.

Although the monument's foundation document (National Park Service 2016) identified detailed documentation of pictographs and petroglyphs throughout the monument as a low-priority data need, the documentation of rock art is significant because degradation occurs over time. It may happen through natural processes (e.g., wind and water erosion or rockfall), climate change (i.e., possible accelerated weathering), anthropomorphic activities (e.g., impacts from unauthorized entry into sites and vandalism, including the removal and sale of pictographs and petroglyphs), or animal activities (e.g., impacts from grazing and burrowing animals). Documentation is vital to retain a record for future analysis, study, and interpretation.

Forms of documentation include photographs, negatives, measured drawings, field notes, written descriptions, written correspondence, and collection catalogs (e.g., Chaco Culture National Historical Park 2012). With more focus on the documentation of an entire surface and the need to reproduce as much of the information on the surface as possible before it is destroyed, researchers are constantly in search of improved methods. One such method is photogrammetry, such as Structure from Motion (SfM). SfM has many advantages, including the following (described in Bertilsson 2015; Meijer 2015; Meijer and Dodd 2018; John R. "Jack" Wood, NPS Geologic Resources Division, program support staff, written communication, 2 May 2023):

- Making it possible to analyze rock art at a micro level, unlocking the sequence of its creation in more detail, including initial pecking marks, updates, and later reworking by one, or possibly more, artists, as well as changes in tooling, which reveal significant clues about the creation of an image and the importance of a specific work.
- Creating a 3D model that can be rotated and illuminated from various positions.
- Creating a scaled reproduction that can be used for research, interpretation, and outreach purposes. Reproductions can be made of composite materials and enhanced to look like the original.
- Making it possible to document the surface at regular intervals, enabling resource managers to monitor the weathering of the surface in more detail.
- Enabling the creation of textured images and ortho-photographs that can be integrated into GIS, allowing visualization of the surface in the wider topographic and geologic context of the rock surface as well as its position within the landscape.

A rock art documentation project, namely compiling existing documentation, could be conducted by a SIP participant (see "Guidance for Resources Management"). In addition, a SIP participant may also be able to analyze the compiled information—with guidance from monument archeologists, curators at WACC, and the Navajo Nation Division of Natural Resources or Navajo Nation Archaeology Program—and propose interpretations of the data and future research. Such a project could also incorporate new sources of documentation, such as photogrammetry. The GRD has developed a photogrammetric data program to support parks and regions (see "Additional References, Resources, and Websites"); however, utilizing the NPS cultural resources network, including SfM practitioners, may make more sense for such a project. Research, published articles, and visitor information would likely result from systematic documentation. Park Science—an NPS

online magazine, covering research and stewardship related to national parks—is a potential venue for publication as well as a repository of information (see "Additional References, Resources, and Websites").

Many states have avocational interest groups that could assist with documentation. An example is the Colorado Rock Art Association (see "Additional References, Resources, and Websites"). If no interest group exists in Arizona, the Office of the State Archeologist may help develop one as well as provide training for documentation. This is known to have occurred for the Colorado Archeological Society, an avocational archeology interest group; other efforts to compile rock art information in other Four Corners Area states have not been investigated (Joshua M. Torres, National Park Service, acting bureau archeologist, email communication, 30 June 2022).

Documentation efforts will benefit from continuous innovation, the evolution of research methods, and greater cultural understanding. The process of documentation will require consultation with the Navajo Nation Tribal government and the 19 Pueblo Tribal governments culturally associated with the monument. Research for resource management purposes (i.e., Section 106 of the NHPA) requires Tribal consultation. Research done by an outside entity through a research permit would also require consultation.

In the future, documentation of the monument's rock art could be archived and possibly shared in a regional or national database, which would better assist with scientific research. At present, State Historic Preservation Officer (SHPO) databases are thought to compile rock art information most thoroughly. SHPO databases manage and track all archeological resource data within a given state, including those on federal lands within a state (Joshua M. Torres, National Park Service, acting bureau archeologist, email communication, 30 June 2022).

Site locations for sensitive sites and those eligible for inclusion in the National Register of Historic Places are not generally disclosed to the public; thus, a shared database would likely be for internal (NPS, Navajo Nation, SHPOs, and those granted access) use only. Moreover, the meaning and significance of the images are not usually shared publicly. For example, Petroglyph National Monument (see GRI report by KellerLynn 2017) has more than 20,000 documented petroglyphs (both Indigenous and Spanish), but the meaning and significance of those images remain only with the members of the associated Pueblos or the Navajo Nation. Any work done with rock art sites will most likely require a Tribal consultation component (Michael J. Evans, NPS Interior Regions 3, 4, 5 [Midwest], regional cultural anthropologist, email communication, 24 August 2022).

Watershed Restoration

The monument's foundation document (National Park Service 2016) identifies a watershed restoration plan as an immediate planning need. Additionally, comprehensive intergovernmental watershed restoration and revegetation projects are high priorities (National Park Service 2016).

The development of a watershed restoration plan is beyond the scope of the GRI, and monument managers are encouraged to consult experts in floodplain/riparian restoration of arid fluvial systems. Within the National Park Service, monument managers are encouraged to contact the following for

assistance in watershed restoration planning: GRD; Water Resources Division; Biological Resources Division, in particular, the Invasive Plant Management Team (IPMT); Climate Change Response Program; and Southern Colorado Plateau Network. Additionally, the Natural Resource Condition Assessment (NRCA) may be able to help monument managers understand stressors (i.e., activities and features that alter hydrology, alter sediment budget, or alter topography; see Lord et al. 2009). Other potential partners outside the bureau include the Navajo Nation Department of Water Resources; the Bureau of Indian Affairs, Navajo Regional Office, and Navajo Nation, Integrated Weed Management Plan (e.g., see Department of the Interior, Bureau of Indian Affairs 2021); US Army Corps of Engineers; US Geological Survey; and Arizona Geological Survey.

While the formulation of a watershed restoration strategy is outside the purview of the GRI, the following geomorphic considerations are included to aid such an endeavor:

"When evaluating rivers or streams, the tendency is to focus on a segment, or 'reach' of the channel. Typically, the segment size is determined by the needs and scope of the project. With respect to a national park, the segment might be dictated by the park boundaries. Whereas the reach-specific perspective may appear to be a logical approach, it will invariably prove to be insufficient for most purposes" (Lord et al. 2009, p. 70). That is, any segment of a river must be recognized as being a part of an integrated system, and the characteristics and dynamics of a segment of interest will be significantly affected by circumstances prevailing in the drainage basin upstream of the reach and may also be affected by processes and events occurring downstream (Schumm 1977). Therefore, any section of stream should be evaluated within the context of its position in a drainage basin or watershed, regardless of whether the upper basin is within or extends outside of park boundaries (Lord et al. 2009). In every case, it is important to view any segment of river within the framework of a fluvial system (Schumm 1977; Petts and Amoros 1996).

Watershed restoration planning at the monument may be able to take advantage of data already compiled by other organizations (see "Additional References, Resources, and Websites"). For example, the USGS organizes watersheds by hydrologic unit codes (HUC; see "Fluvial Features and Processes"). In a system used by the Arizona Department of Water Resources, the monument is part of the Eastern Plateau Planning Area, which occupies the northeastern quarter of Arizona and consists of one groundwater basin—the Little Colorado River Plateau Basin. As such, the "Eastern Plateau Planning Area" and the "Little Colorado River Plateau Basin" may be considered interchangeable for planning purposes. The majority (63.9%) of the Little Colorado River Plateau Basin is Tribal land; only 1.4% is under the stewardship of the National Park Service (Arizona Department of Water Resources 2009).

In the monument, the planting and subsequent spread of tamarisk (e.g., *Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) was—and remains—the primary cause of geomorphic change (Birken and Cooper 2006; Manners et al. 2014). These invasive species stabilized banks and induced floodplain aggradation (buildup of sediments). Stabilization and aggradation may sound like a "good thing" (and indeed this was the original intent of planting), but well-intended planting caused the stream channel to narrow and incise, in effect changing the fluvial system from wide, shallow, and

braided (with scattered cottonwoods and willows along the margins) to narrow, deep, and single threaded (with a dense gallery of tamarisk and Russian olive trees; see, e.g., Cadol et al. 2011 and Reynolds and Cooper 2017). Planted "floodplain forests" also blocked historically significant views, resulting in a loss of openness and seeing from canyon wall to canyon wall. They also changed the vegetation community from riparian to upland species (Reynolds and Cooper 2011, 2017). The outcome of well-intended plantings at the monument should serve as a cautionary tale for future restoration efforts that rely exclusively on revegetation efforts.

In addition to tamarisk and Russian olive, the watershed has a plethora of other anthropogenic impacts. For example, agricultural practices (floodplain farming and livestock grazing)—known to have occurred in the canyons 3,120 radiocarbon years before present (Betancourt and Davis 1984) or 3,313 calendar years ago (mean probability, converted from radiocarbon years using CALIB REV8.2; Reimer et al. 2020)—have undoubtedly altered the natural geomorphic system. Other impacts include so-called stabilization structures (i.e., hard [rock] structures built in channels and along banks), upstream dams (i.e., Tsaile Dam at the head of Canyon del Muerto and Wheatfields Dam on Wheatfields Creek, upstream from Canyon de Chelly), and in- and cross-channel roads.

Stream stabilization, especially in the arid southwestern United States, is largely a misnomer. Fluvial systems are not "stable" in the engineering sense but rather adjust and change in cross-section and profile shape due to meeting an intrinsic geomorphologic threshold or in response to changes in water or sediment inputs; that is, they are only somewhat stable because they are highly sensitive to natural erosion and sedimentation changes. "Stable" is neither "real" nor desirable if the goal is a naturally functioning stream channel network (Hal Pranger, GRD, manager, Geologic Features & Systems Branch, written communication, 29 January 2024).

The primary recommendation resulting from scoping in 2007 is for resource managers to consult experts to create a surficial geologic map, which would be useful for visualizing geomorphic change on the landscape. Investigators from Northern Arizona University discussed creating a surficial map of the bottom of the canyon area that would show significant recent geomorphic features. Mapping was proposed to take place at a scale of 1:12,000, which would provide significantly greater detail than the GRI GIS data (scale 1:250,000). At 1:12,000 scale, features as small as about 6 m (20 ft) across would be mapped. Scoping participants suggested the following map units: fluvial terraces, landslide deposits, talus cones, sand dunes, alluvial fans, and stream deposits. Participants discussed the possibility of convening a meeting of cooperators interested in creating a surficial map. Notably, as a cooperator of the GRI, the Arizona Geological Survey is a candidate for mapping. Its mapping efforts in the Verde Valley, for example, could serve as a model. As an added benefit, as well as for use in restoration planning, surficial maps by the Arizona Geological Survey—e.g., Cook et al. (2010b, "Verde River map") and Cook et al. (2010a, "tributaries map")—include a geoarcheological evaluation with information about archeological resources along the mapping project corridor.

Soils data could complement a surficial geologic map. A soils map would clearly delineate agricultural areas in the floodplains, and these areas may need to be accounted for—and potentially preserved as a geologic heritage value—when determining the goals of restoration (Hal Pranger,

GRD, manager, Geologic Features & Systems Branch, written communication, 14 April 2023). Soils data at a scale of 1:24,000 currently exist for the monument (see National Park Service and Natural Resources Conservation Service 2013; and National Park Service, Inventory and Monitoring Division 2021). However, obtaining a soils map at the same scale as the surficial geologic map would be prudent.

A second recommendation is for resource managers to consult experts to create a conceptual model for understanding geomorphic change on the canyon floor. In Dinosaur National Monument in Colorado, for example, Scott et al. (2018) presents a conceptual model showing how largely unvegetated active-channel features along a relatively unregulated river like the Yampa are converted to vegetated floodplain during channel narrowing. Having a model to assist in visualization of the monument's fluvial system would be useful not only for watershed restoration planning but for resource management, monitoring, interpretation, and outreach.

Notably, the model by Scott et al. (2018) is the basis of a monitoring design that involves intensive monitoring at sentinel sites and rapid monitoring assessments, or rapidos, across a broad spatial range of geomorphic features with known sensitivities to narrowing. A conceptual model and associated monitoring design are significant because, although removal of invasive vegetation in river restoration is now common practice, post-removal monitoring of channel change is lacking (Wieting et al. 2020). For example, only two years of monitoring took place at the monument (i.e., control of invasive species ended in 2006, and post-removal monitoring ended in 2008).

A study by GRD staff (Pranger 2005) provides additional recommendations for watershed restoration at the monument: (1) establish stream corridor zones, outside of the protected cultural features and landscapes, through which the monument's streams are allowed to flow in as undisturbed a geomorphologic and hydrologic condition as possible; (2) develop a plan to robustly stabilize the perimeters of protected cultural features and landscapes from the effects of erosion and sedimentation from the main channels in the monument; (3) incorporate a statement into the general management plan that prioritizes restoration of the monument's streams primarily by removing anthropogenic disturbances to the maximum extent possible; and (4) identify and remove, as much as possible, all human disturbances such as riprap (rocky material placed to protect from scour or erosion), gabions (metal cages filled with rocks), roads, dams, and nonnative woody species (i.e., tamarisk and Russian olive) to restore the physical processes and ecological characteristics of the monument's fluvial system.

Recent findings show the benefit of whole plant removal of tamarisk and Russian sage at the monument (i.e., statistically significant increases in channel width; Wieting et al. 2020) and experience suggests it (Hal Pranger, GRD, manager, Geologic Features & Systems Branch, written communication, 14 April 2023). However, the extent to which other stressors—such as agricultural practices, which began disrupting the fluvial system long before the planting of tamarisk and Russian olive—are present is not known and requires study. From a geomorphologic perspective, agricultural practices are a possible "competing interest" with respect to watershed restoration. Also, unregulated, in-channel heavy vehicle traffic from tours appears to be one of the causes of extensive localized

downcutting, especially in Canyon del Muerto (National Park Service 2004), though no study has confirmed this. A watershed restoration plan will need to have clear goals that consider the limitations imposed by the local situation.

Building on the study by Pranger (2005), GRD staff proposes that resource managers consider the following:

If fluvial and watershed restoration is a goal, the first task is to identify to what extent the system can be restored to a natural state. This task is difficult but can be simplified by thinking of restoration as involving the removal of as many impediments to natural processes as possible, then letting the river develop (meaning: pass water and sediment, and erode and deposit sediment within its bed, banks, and floodplain) as unimpeded as possible until it reaches a new dynamic equilibrium. Ideally, a restoration plan for the monument would remove all nonnative forests on the floodplain, both upstream dams, and all hardened in-channel structures (except where needed to protect cultural sites), then let the system freely develop and adjust to its "near natural" hydrologic and sediment inputs. Such a simple approach would likely accomplish more than a detailed restoration plan that a consultant, agency, or NGO could develop (Hal Pranger, GRD, manager, Geologic Features & Systems Branch, written communication, 14 April 2023).

Guidance for Resource Management

Information in this chapter will assist resource managers in addressing geologic resource management issues and applying NPS policy. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), Management Policies 2006, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Three Ways to Receive Geologic Resource Management Assistance

First, monument managers may contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm). GRD staff members provide coordination, support, and guidance for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; laws, regulations, and compliance; resource management planning; and data and information management.

Second, monument managers may formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (only available on the Department of the Interior [DOI] network). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance.

Third, monument managers may submit a proposal to receive geologic expertise through the SIP program: https://www.nps.gov/subjects/science/scientists-in-parks.htm. Formerly the Geoscientists-in-the-Parks program, the SIP program places scientists (typically undergraduate students) in parks to complete science-related projects that can address the geologic resource management issues discussed in this report as well as other resource management issues. Proposals may also be for assistance with research, interpretation, outreach, inventory, and monitoring. The GRD can provide guidance and assistance with submitting a proposal. The Geological Society of America and Environmental Stewards are partners of the SIP program. Visit the internal SIP website to submit a proposal at https://doimspp.sharepoint.com/sites/nps-scientistsinparks (only available on the DOI network).

Geological Monitoring

Monument managers may find *Geological Monitoring* (Young and Norby 2009) useful for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Access to GRI Products

- GRI reports, GRI GIS data, geologic map posters, and scoping summaries are publicly available at https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm. They are also available through the NPS Integrated Resource Management Applications (IRMA) DataStore at https://irma.nps.gov/DataStore/Search/Quick. Enter "GRI" as the search text and select a park from the unit list.
- The GRI GIS data model is available at https://www.nps.gov/articles/gri-geodatabase-model.htm.
- A GRI glossary of geologic terms is available at https://www.nps.gov/subjects/geology/gri-glossary-of-geologic-terms.htm.
- Many GRI graphics from GRI reports are available at https://www.nps.gov/media/multimedia-search.htm#sort=score+desc&q=%22geologic+resources+inventory%22&fq%5B%5D=Type%3A%22Gallery%22&.

NPS Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/subjects/policy/index.htm
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- NPS-75: Natural Resources Inventory and Monitoring Guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: https://doi.org/10.36967/nrr-2283597

Geologic Resource Laws, Regulations, and Policies

The following sections, which were developed by the GRD, summarizes laws, regulations, and policies that specifically apply to NPS geologic resources, processes, and energy and minerals. The first section summarizes law and policy for geoheritage resources, which includes caves, paleontological resources, and geothermal resources. The energy and minerals section, includes abandoned mineral lands, mining, rock and mineral collection, and oil and gas operations. Active processes include geologic hazards (e.g., landslides), coastal processes, soils, and upland and fluvial processes (e.g., erosion). Laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, NEPA, or the National Historic Preservation Act) are not included, but the NPS Organic Act is listed when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available.

Geoheritage Resource Laws, Regulations, and Policies

Caves and Karst Systems

Resource-specific laws:

- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about the specific location of a significant cave from a Freedom of Information Act (FOIA) requester.
- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources.
- **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.

Resource-specific regulations:

- **36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units.
- **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.

NPS Management Policies 2006:

- **Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts.
- **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
- **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact the cave environment, and to remove existing developments if they impair caves.
- **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Geothermal

Resource-specific laws:

- **Geothermal Steam Act of 1970, 30 USC. § 1001** et seq. as amended in 1988, states:
    - No geothermal leasing is allowed in parks.
    - "Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead).
    - NPS is required to monitor those features.

    - Based on scientific evidence, the Secretary of Interior must protect significant NPS thermal features from leasing effects.
- **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.

Resource-specific regulations:

- **43 CFR Part 3200** requires BLM to include stipulations when issuing, extending, renewing, or modifying leases or permits to protect significant thermal features in NPS-administered areas (see 43 CFR §3201.10), prohibit the bureau from issuing leases in areas where geothermal operations are reasonably likely to result in significant adverse effects on significant thermal features in NPS-administered areas (see 43 CFR §3201.11 and §3206.11), and prohibit BLM from issuing leases in park units.

NPS Management Policies 2006:

- **Section 4.8.2.3** requires NPS to:
    - Preserve/maintain integrity of all thermal resources in parks.
    - Work closely with outside agencies.
    - Monitor significant thermal features.

<u>Paleontological Resources</u>

Resource-specific laws:

- **Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1)** Archaeological Resource—nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law.
- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5)** Cave Resource—the term "cave resource" includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources.
- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects.
- **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa** et seq. provides for the management and protection of paleontological resources on federal lands.

Resource-specific regulations:

- **36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof.
- **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted.
- **43 CFR Part 49** contains the DOI regulations implementing the Paleontological Resources Preservation Act, which apply to the NPS.

NPS Management Policies 2006:

- **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
- **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Energy and Minerals Laws, Regulations, and Policies

Abandoned Mineral Lands and Orphaned Oil and Gas Wells

Resource-specific laws:

- **The Bipartisan Infrastructure Law**, **Inflation Reduction Act**, and **NPS Line Item Construction** program all provide funding for the reclamation of abandoned mineral lands and the plugging of orphaned oil and gas wells.

Resource-specific regulations:

- None applicable.

NPS Management Policies 2006:

- None applicable.

Coal

Resource-specific laws:

- **Surface Mining Control and Reclamation Act (SMCRA) of 1977, 30 USC § 1201** et. seq. prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.

Resource-specific regulations:

- **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.

NPS Management Policies 2006:

- None applicable.

Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)

Resource-specific laws:

- **Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.
- **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas.
- **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area for local use, as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.

Resource-specific regulations:

- None applicable.

NPS Management Policies 2006:

- **Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and:
    - Only for park administrative uses;
    - After compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment;
    - After finding the use is the park's most reasonable alternative based on environment and economics;
    - Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan;
    - Spoil areas must comply with Part 6 standards; and
    - NPS must evaluate use of external quarries.
- Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Federal Mineral Leasing (Oil, Gas, and Solid Minerals)

Resource-specific laws:

- **The Mineral Leasing Act, 30 USC § 181** et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq. do not authorize the BLM to lease federally owned minerals in NPS units.
- **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in Glen Canyon National Recreation Area, which is the only park unit that contains a STSA.
- **Exceptions:** Glen Canyon National Recreation Area (NRA) (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration.
- **American Indian Lands** Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108, all minerals on American Indian trust lands within NPS units are subject to leasing.
- **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.

Resource-specific regulations:

- **36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law.
- **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing.
- Regulations re: Native American Lands within NPS Units:
    - **25 CFR Part 211** governs leasing of tribal lands for mineral development.
    - **25 CFR Part 212** governs leasing of allotted lands for mineral development.
    - **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development.
    - **25 CFR Part 224** governs tribal energy resource agreements.
    - **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC §§ 2101-2108).
    - **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases.

- **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases.
- **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases.
- **30 CFR § 1206.450** governs the valuation of coal from Indian Tribal and Allotted leases.
- **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.

NPS Management Policies 2006:

- **Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Mining Claims (Locatable Minerals)

Resource-specific laws:

- **Mining in the Parks Act of 1976, 54 USC § 100731** et seq. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas.
- **General Mining Law of 1872, 30 USC § 21** et seq. allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA.
- **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.

Resource-specific regulations:

- **36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law.
- **36 CFR Part 6** regulates solid waste disposal sites in park units.
- **36 CFR Part 9**, Subpart A requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability.
- **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.

NPS Management Policies 2006:

- **Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A.
- **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.

Nonfederal Minerals other than Oil and Gas

Resource-specific laws:

- NPS Organic Act, 54 USC §§ 100101 and 100751

Resource-specific regulations:

- **NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a business operation (§ 5.3) or for construction of buildings or other facilities (§ 5.7), and to comply with the solid waste regulations at Part 6.

NPS Management Policies 2006:

- **Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.

Nonfederal Oil and Gas

Resource-specific laws:

- **NPS Organic Act, 54 USC § 100751** et seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).
- Individual Park Enabling Statutes:
    - 16 USC § 230a (Jean Lafitte NHP & Pres.)
    - 16 USC §450kk (Fort Union NM)
    - 16 USC § 459d-3 (Padre Island NS)
    - 16 USC § 459h-3 (Gulf Islands NS)
    - 16 USC § 460ee (Big South Fork NRRA)
    - 16 USC § 460cc-2(i) (Gateway NRA)
    - 16 USC § 460m (Ozark NSR)
    - 16 USC§698c (Big Thicket N Pres.)

- 16 USC §698f (Big Cypress N Pres.)

Resource-specific regulations:

- **36 CFR Part 6** regulates solid waste disposal sites in park units.
- **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights in parks outside of Alaska to:
  - Demonstrate valid right to develop mineral rights;
  - Submit an Operations Permit Application to NPS describing where, when, and how they intend to conduct operations;
  - Prepare/submit a reclamation plan; and
  - Submit financial assurance to cover reclamation and potential liability.
- **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.

NPS Management Policies 2006:

- **Section 8.7.3** requires operators to comply with 9B regulations.

<u>Recreational Collection of Rocks and Minerals</u>

Resource-specific laws:

- **NPS Organic Act, 54 USC. § 100101** et seq. directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law.
- **Exception: 16 USC. § 445c (c)** – Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).

Resource-specific regulations:

- **36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units.
- **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown National Recreation Area.
- **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.

NPS Management Policies 2006:

- **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Transpark Petroleum Product Pipelines

Resource-specific laws:

- The **Mineral Leasing Act, 30 USC § 181** et seq., and the **Mineral Leasing Act for Acquired Lands, 30 USC § 351** et seq. authorize new rights of way across some federal lands for pipelines, excluding NPS areas.
- The only parks with the legal authority to grant new rights of way for petroleum product pipelines are:
    - Natchez Trace Parkway (16 USC §460a)
    - Blue Ridge Parkway (16 USC §460a-8)
    - Great Smoky Mountains National Park (P.L. 107-223 – 16 U.S.C. §403 notes)
    - Klondike Gold Rush National Historical Park (16 USC §410bb(c) (limited authority for the White Pass Trail unit)
    - Gulf Islands National Seashore - enabling act authorizes rights-of-way for pipelines for oil and gas transported across the seashore from outside the unit (16 USC §459h-3)
    - Gateway National Recreation Area - enabling act authorizes rights-of-way for gas pipelines in connection with the development of methane gas owned by the City of New York within the unit (16 USC §460cc-2(i))
    - Denali National Park – 2013 legislation allows for issuance of right-of-way permits for a natural gas pipeline within, along, or near the approximately 7-mile segment of the George Parks Highway that runs through the park (Public Law 113–33)

Resource-specific regulations:

- NPS regulations at **36 CFR Part 14 Rights of Way**

NPS Management Policies 2006:

- **Section 8.6.4** states that new rights of way through, under, and across NPS units may be issued only if there is specific statutory authority and there is no practicable alternative.

Uranium

Resource-specific laws:

- **Atomic Energy Act of 1954** allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.

Resource-specific regulations:

- None applicable.

NPS Management Policies 2006:

- None applicable.

Active Processes and Geohazards Laws, Regulations, and Policies

Coastal Features and Processes

Resource-specific laws:

- **NPS Organic Act, 54 USC § 100751** et. seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).
- **Coastal Zone Management Act, 16 USC § 1451** et. seq. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone.
- **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** requires that dredge and fill actions comply with a Corps of Engineers Section 404 permit.
- **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs.
- **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.

Resource-specific regulations:

- **36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands.
- **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.

NPS Management Policies 2006:

- **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress.
- **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.
- **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/park facilities/historic properties.
- **Section 4.8.1.1** requires NPS to:

- Allow natural processes to continue without interference,
- Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions,
- Study impacts of cultural resource protection proposals on natural resources,
- Use the most effective and natural-looking erosion control methods available, and
- Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Geologic Hazards

Resource-specific laws:

- **National Landslide Preparedness Act, 43 USC §§ 3101–3104** strengthens the mandate to identify landslide hazards and reduce losses from landslides. Established the National Landslide Hazards Reduction Program. "…the United States Geological Survey and other Federal agencies, shall – identify, map, assess, and research landslide hazards;" Reduce landslide losses, respond to landslide events

Resource-specific regulations:

- None applicable.

NPS Management Policies 2006:

- **Section 4.8.1.3**, Geologic Hazards
- **Section 9.1.1.5**, Siting Facilities to Avoid Natural Hazards
- **Section 8.2.5.1**, Visitor Safety
- **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.

Soils

Resource-specific laws:

- **Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources.
- **Farmland Protection Policy Act, 7 USC § 4201** et. seq. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal

agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).

Resource-specific regulations:

- **7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.

NPS Management Policies 2006:

- **Section 4.8.2.4** requires NPS to (1) prevent unnatural erosion, removal, and contamination; (2) conduct soil surveys; (3) minimize unavoidable excavation; and (4) develop/follow written prescriptions (instructions).

Upland and Fluvial Processes

Resource-specific laws:

- **Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE.
- **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]).
- **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**).
- **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**).

Resource-specific regulations:

- None applicable.

NPS Management Policies 2006:

- **Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems.
- **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress.
- **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.

- **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding.
- **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams.
- **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes.
- **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Additional References, Resources, and Websites

The online and other publications listed in this chapter may be considered "further reading" but were selected because of their applicability to the geologic features, processes, and resource management issues discussed in this report.

Arizona Geology

- Arizona Geological Survey (AZGS): https://azgs.arizona.edu/
- Ask a Geologist (most commonly asked questions and online form for submitting questions to AZGS geologists): http://azgs.arizona.edu/ask-a-geologist
- AZGS Document Repository (more than 1,000 publications dating from 1915 to the present): https://repository.arizona.edu/handle/10150/628301
- AZGS Arizona Geology e-magazine: http://blog.azgs.arizona.edu/
- AZGS YouTube channel: https://www.youtube.com/user/azgsweb/playlists
- Colorado Plateau Coring Project: https://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page_general.html. Note: This project is significant for the changes in nomenclature of the Chinle Formation.
- *Highlights of Northern Arizona Geology* (Frisch-Gleason 1998): https://repository.arizona.edu/handle/10150/629405

Cave Management

- Many resources are available for cave management, including NPS policies and directives (see "Guidance for Resource Management"), inventory and monitoring reports, and the work at other parks to create cave management plans and management documents. The NPS Cave and Karst Program coordinator, who is located at the National Cave and Karst Research Institute (NCKRI) in Carlsbad, New Mexico, provides technical assistance.
- Karst Information Portal: https://digitalcommons.usf.edu/kip/
- NCKRI: http://www.nckri.org/
- NCKRI, Report of Investigation 4: *Evaluation of Cave and Karst Programs and Issues at US National Parks* (Land et al. 2013): https://www.nckri.org/publications/reports-of-investigation/
- NPS Caves and Karst: https://www.nps.gov/subjects/caves/index.htm
- NPS information about white-nose syndrome—a fatal disease caused by the fungus *Pseudogymnoascus destructans* that affects cave-dwelling bats: https://www.nps.gov/subjects/bats/white-nose-syndrome.htm

- *Geological Monitoring* (Young and Norby 2009) chapter about geological monitoring of caves and associated landscapes by Toomey (2009): https://www.nps.gov/subjects/geology/geological-monitoring.htm

Climate Change

- Four documents provide information about climate change at the monument: (1) weather and climate inventory (Davey et al. 2006), (2) climate change resource brief about climate change exposure (Monahan and Fisichelli 2014), (3) park-specific resource brief about how future warming might alter visitation (Fisichelli and Ziesler 2015), and (4) climate change summary (Gonzalez 2015).
- *A Record of Change: Science and Elder Observations on the Navajo Nation* (Redsteer and Wessells 2017): https://pubs.er.usgs.gov/publication/gip181
- Fourth National Climate Assessment (Reidmiller et al. 2018)—climate change impacts, risks, and adaptation information for the US Southwest: https://nca2018.globalchange.gov/chapter/front-matter-guide/
- Intergovernmental Panel on Climate Change: https://www.ipcc.ch/
- NPS Climate Change Response Program: https://www.nps.gov/orgs/ccrp/index.htm
- NPS Climate Friendly Parks Program: https://www.nps.gov/subjects/climatechange/cfpprogram.htm
- NPS Policy Memorandum 15-01: Addressing Climate Change and Natural Hazards for Facilities (Jarvis 2015): https://www.nps.gov/policy/PolMemos/policymemoranda.htm
- Secretarial Order 3289: Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources: https://www.usgs.gov/media/files/secretarial-order-no-3289
- US Global Change Research Program: https://www.globalchange.gov/

Earthquakes

- Earthquake monitoring in Arizona occurs at seismograph stations throughout the state. Most of these stations are maintained by two seismograph networks: (1) Northern Arizona Network (https://www.fdsn.org/networks/detail/AR/), operated by Northern Arizona University; and (2) Arizona Broadband Seismic Network (http://www.fdsn.org/networks/detail/AE/), operated by the Arizona Geological Survey.
- Arizona Earthquake Information Center: https://aeic.nau.edu/index.html
- Arizona Geological Survey, information about earthquakes, including time-lapse video of historic earthquake epicenters of Arizona and information about the June 2014, M 5.3 earthquake in Duncan, Arizona: https://azgs.arizona.edu/center-natural-hazards/earthquakes
- *Geological Monitoring* (Young and Norby 2009) chapter about seismic monitoring (Braile 2009): https://www.nps.gov/subjects/geology/geological-monitoring.htm

- Natural Hazards in Arizona (interactive map): https://www.americangeosciences.org/critical-issues/maps/arizona-hazards
- USGS Earthquake Hazards Program: https://earthquake.usgs.gov/
- USGS Earthquake Hazards Program, Unified Hazard Tool: https://earthquake.usgs.gov/hazards/interactive/

Erosion

- NPS Geoconservation—Disturbed Land Restoration: https://www.nps.gov/articles/geoconservation-disturbed-land-restoration.htm
- Arizona Rangeland Management and Grazing (State standards for rangeland health): https://www.blm.gov/programs/natural-resources/rangeland-and-grazing/rangeland-health/arizona
- *Upland Soil Erosion Monitoring and Assessment—An Overview* (Ypsilantis 2011), BLM Technical Note 438: https://www.blm.gov/learn/blm-library/agency-publications/technical-notes. *Note*: Former NPS soil scientist, Pete Biggam, reviewed this document. It provides prudent land management practices that will help reduce erosion, including maintaining adequate plant, litter, and biological soil crust cover; diminishing soil compaction; maintaining soil aggregate stability; applying good road building practices; reducing catastrophic wildfire conditions; and managing off-highway vehicle use. Other practices include concurrent reclamation of areas disturbed by mining and energy development, proper road maintenance, and implementation of sound livestock grazing management practices. The document will aid resource specialists in evaluating and selecting techniques for monitoring and assessing upland soil surface erosion.
- Web Soil Survey (WSS)—a powerful online tool to access and use soil data for all 50 states—hosted by the Natural Resources Conservation Service (NRCS): https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

Floods

- Natural Hazards in Arizona (interactive map): https://www.americangeosciences.org/critical-issues/maps/arizona-hazards
- Federal Emergency Management Agency (FEMA) Flood Maps: https://www.fema.gov/flood-maps
- FEMA Flood Map Service Center: https://msc.fema.gov/portal/home

Geologic Heritage

- *America's Geologic Heritage—An Invitation to Leadership* (National Park Service and American Geosciences Institute 2015): https://www.earthsciweek.org/content/our-shared-geoheritage

- NPS America's Geoheritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- NPS Geologic Type Section Inventory for the Southern Colorado Plateau Inventory & Monitoring Network (Henderson et al. 2022): https://doi.org/10.36967/nrr-2293053
- United Nations Educational, Scientific and Cultural Organization (UNESCO) Global Geoparks: https://en.unesco.org/global-geoparks

Geologic Maps and Nomenclature

- American Geosciences Institute (information about geologic maps and their uses): https://www.americangeosciences.org/environment/publications/mapping
- *General Standards for Geologic Maps* (Evans 2016)
- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): https://ngmdb.usgs.gov/Geolex/search
- National Geologic Map Database (NGMDB): https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Geological Surveys and Societies

- Arizona Geological Survey: https://azgs.arizona.edu/
- American Geophysical Union: https://www.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: https://www.stategeologists.org/
- Geological Society of America: https://www.geosociety.org/
- USGS: https://www.usgs.gov/

NPS Geology

- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Division: https://www.nps.gov/orgs/1088/index.htm
- NPS Geologic Resources Inventory: https://www.nps.gov/subjects/geology/gri.htm
- NPS Geoscience Concepts: https://www.nps.gov/subjects/geology/geology-concepts.htm
- *Parks and Plates: The Geology of Our National Parks, Monuments, and Seashores* (Lillie 2005)

NPS Photogrammetry

- NPS Photogrammetry Applications and Examples: https://www.nps.gov/articles/series.htm?id=4B2E480A-1DD8-B71B-0B41FD201137856F

- NPS Photogrammetry—Fossils in 3D: https://www.nps.gov/subjects/fossils/photogrammetry.htm
- NPS Resource Management Using 3D Photogrammetry: https://www.nps.gov/subjects/geohazards/photogrammetry.htm

NPS Reference Tools

- GeoRef (geologic citation database). The GRI team collaborates with TIC to maintain an NPS subscription to GeoRef via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records. Historic site staff can contact the GRI team or GRD for access.
- Integrated Resource Management Applications (IRMA) portal: https://irma.nps.gov/.
- Technical Information Center (TIC; repository for technical documents and means to receive interlibrary loans): https://www.nps.gov/orgs/1804/dsctic.htm.

Sources for Park-Specific Documents

- NPS History eLibrary hosts historical information and management documents: http://www.npshistory.com/
- IRMA is a repository of park-specific documents: https://irma.nps.gov/DataStore/
- NPS Planning, Environment and Public Comment (PEPC) provides information about park planning: https://parkplanning.nps.gov/parks.cfm
- TIC is a repository for technical documents: https://www.nps.gov/orgs/1804/dsctic.htm
- *Park Science*: https://www.nps.gov/subjects/parkscience/index.htm
- Western Archeological and Conservation Center (WACC): https://www.nps.gov/orgs/1260/library.htm

Relevancy, Diversity, and Inclusion

- Elements of Indigenous Style: A Guide for Writing By and About Indigenous Peoples (Younging 2018)
- NPS Office of Relevancy, Diversity, and Inclusion: https://www.nps.gov/orgs/1244/index.htm

Rock Art Documentation

- Arizona State Historic Preservation Office: https://azstateparks.com/SHPO
- Colorado Rock Art Association: https://coloradorockart.org/
- NPS Podcast 013: 3D Digital Rock Art Documentation and Preservation: https://www.nps.gov/articles/000/podcast-013-3d-digital-rock-art-documentation-and-preservation.htm

Rockfall and Other Slope Movements

- The GRD employs three rockfall management strategies: (1) unstable slope management program (USMP) for risk reduction within transportation corridors, (2) quantitative risk estimation for specific rockfall hazards, and (3) monitoring of potential rockfall areas. Park managers can contact the GRD to discuss these options and determine if submitting a technical request is appropriate.
- *Geological Monitoring* (Young and Norby 2009) chapter about monitoring slope movements (Wieczorek and Snyder 2009): https://www.nps.gov/subjects/geology/geological-monitoring.htm
- NPS Geohazards: https://www.nps.gov/subjects/geohazards/index.htm
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): https://pubs.usgs.gov/circ/1325/
- Natural Hazards in Arizona (interactive map): https://www.americangeosciences.org/critical-issues/maps/arizona-hazards
- USGS Landslide Hazards Program: https://www.usgs.gov/programs/landslide-hazards
- US Landslide Inventory Web Application, includes landslides and other slope movements mapped by the Arizona Geological Survey: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=ae120962f459434b8c904b456c82669d

Soils

- Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey: https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. The most up-to-date soils information is available via WSS. Derivative maps can be created from the WSS including maps relevant for facilities siting or improvements. The data include "ecological sites" such as sedimentary cliffs, uplands (sandstone, mudstone/sandstone, sandy, loamy, sandy loam, and clay loam), terraces (clay loam), and bottoms (loamy and sandy). Please contact the GRI program for assistance in obtaining and using soils data.
- WSS_four_steps (PDF/guide for how to use WSS): https://irma.nps.gov/DataStore/Reference/Profile/2190427. Note: The PDF is contained within SRI_Detailed_Soils.zip, which also contains an index map of parks where an SRI has been completed. Download and extract all files.

US Geological Survey Reference Tools

- Geographic Names Information System (GNIS; official listing of place names and geographic features): https://www.usgs.gov/us-board-on-geographic-names
- National Geologic Map Database (NGMDB): https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

- US Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): https://ngmdb.usgs.gov/Geolex/search
- USGS Publications Warehouse: http://pubs.er.usgs.gov
- USGS Store (find maps by location or by purpose): https://store.usgs.gov/
- Tapestry of Time and Terrain (descriptions of physiographic provinces; Vigil et al. 2000): https://pubs.usgs.gov/imap/i2720/

Watershed Management

- Arizona Water Atlas: https://infoshare.azwater.gov/docushare/dsweb/View/Collection-19396
- Case Studies of Riparian and Watershed Restoration in the Southwestern United States—Principles, Challenges, and Successes (Ralston and Sarr 2017): https://doi.org/10.3133/ofr20171091
- Navajo Nation, Division of Natural Resources: https://dnr.navajo-nsn.gov/Departments
- Navajo Nation Integrated Weed Management Plan: https://www.bia.gov/regional-offices/navajo/navajo-nation-integrated-weed-management-plan/draft-iwmp
- NPS Natural Resource Condition Assessments (NRCA) Program: https://www.nps.gov/subjects/science/nrca.htm
- NRCA Drivers and Stressors (forces contributing to ecosystem change): https://www.nps.gov/subjects/science/nrca_drivers.htm
- US Army Corps of Engineers, Hydrologic Engineering Center (CEIWR-HEC), River Analysis System (HEC-RAS): https://www.hec.usace.army.mil/software/hec-ras/. This software allows the user to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling.
- USGS National Water Information System: https://waterdata.usgs.gov/nwis
- USGS National Water Information System—streamflow data at Chinle Creek stream gage (9379025) at Chinle, Arizona: https://waterdata.usgs.gov/az/nwis/uv/?site_no=09379025&PARAmeter_cd=00065,00060
- USGS Science in Your Watershed: https://water.usgs.gov/wsc/index.html. Provides USGS scientific information, such as real-time streamflow, water quality samples, groundwater sites, and additional hydrologic science information, organized by hydrologic unit codes (HUC). The HUC for the Lower San Juan River basin is 140802. Canyon del Muerto is HUC 1408020404. Canyon de Chelly is HUC 1408020405.
- USGS Streamgaging Network: https://www.usgs.gov/mission-areas/water-resources/science/usgs-streamgaging-network
- USGS Water Resource Links for HUC 14080204 (Chinle Creek): https://water.usgs.gov/lookup/getwatershed?14080204/www/cgi-bin/lookup/getwatershed

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Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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