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Hubbell Trading Post National Historic Site

Geologic Resources Inventory Report

Photograph taken in 2023 of Hubbell Hill and guest hogan. Hubbell Hill—which is composed of the Chinle Formation—is a distinctive landmark for the historic site. Built in 1934, the guest hogan (stone building) serves as a tribute to John Lorenzo (J. L.) Hubbell's hospitality. It is composed of locally available building stone.

NPS / MARYANN NEUBERT

Hubbell Trading Post National Historic Site: Geologic resources inventory report

Science Report NPS/SR—2024/163

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Acknowledgements

The GRI team thanks the participants at the 2007 scoping meeting and the 2022 follow-up meeting for their assistance in this inventory. In addition, thanks very much to Keith Lyons (NPS stationed at Canyon de Chelly National Monument) and Maryann Neubert (NPS stationed at Hubbell Trading Post National Historic Site) for making the time to discuss reviewers' comments and answer questions as part of the final review process of this report.

Because the GRI does not conduct original geologic mapping, the team is thankful to the US Geological Survey (USGS) for its map of the area. This report and associated GRI GIS data could not have been completed without it.

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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.

Hubbell Trading Post National Historic Site (referred to as the "historic site" throughout this report) is in northeastern Arizona, on the outskirts of Ganado, Apache County, Arizona. It is surrounded by, but not under the jurisdiction of, the Navajo Nation.

Established in 1965 as part of the National Park System, the historic site is the oldest continuously operated trading post (since 1878) in the American Southwest. The historic site preserves, protects, interprets, and operates the trading post and associated homestead in a manner that conserves park resources and reflects an earlier era of cultural and community exchange.

Many park resources such as Hubbell Hill and Pueblo Colorado Wash, which are integral to the historic site's history and cultural identity, are geologic resources. The historic site's bedrock and surficial deposits record 275 million years of Earth's history, including ancient and modern mountain building, widespread deposition of sediment by ancestral rivers, and entrenchment (downward incision by a river through surficial deposits and into bedrock) of the Colorado River system.

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 historic site's significance as expressed in its foundation document.

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

Introduction—This chapter orients readers to the historic site's "sense of place," including location, background, park establishment and operation, and physiographic setting. Additionally, the chapter provides information about the GRI and introduces users to its products. A geologic map in GIS format (referred to as the "GRI GIS data" throughout this report) is the principal deliverable of the GRI. This chapter provides specific information about the use of the GRI GIS data and highlights the source map used to compile these data. The chapter also calls attention to the poster, which displays the GRI GIS data.

Geologic Heritage—This chapter highlights the historic site's geologic heritage, which exists at the overlap of geology and human experiences and values. It makes connections among geologic resources and other park resources, including Pueblo Colorado Wash, Hubbell Hill, building stone, the irrigation system, and the historic site's museum collection.

Geologic History—This chapter describes the chronology of geologic events that led to the present-day landscape. It includes a description of the four main geologic events: development of the Ancestral Rocky Mountains, deposition of the historic site's bedrock (Chinle Formation), the Laramide Orogeny (mountain-building event), and entrenchment of the Colorado River system, which includes Pueblo Colorado Wash. This chapter provides a geologic time scale that organizes these events in a context of geologic time and connects these events to geologic map units in the GRI GIS data as well as to geologic features in and near the historic site.

Geologic Features and Processes—This chapter describes the following geologic features and processes of significance for the historic site: the Chinle Formation; petrified wood and other fossils; unconformity (a significant gap or break in the rock record); the Bidahochi Formation as evidence for the development of the Colorado River system and the existence of ancient Hopi Lake; fluvial features and processes such as alluvium (stream deposits), terraces (former floodplains), and the development of Pueblo Colorado Wash and tributaries; and eolian features and processes (composed of windblown sand and silt). The features and processes are discussed in order of geologic time, oldest to youngest. Notably, the chapter includes a surficial geologic map that provides greater detail than the GRI GIS data.

Geologic Resource Management Issues—This chapter discusses management issues related to the historic site's geologic resources (features and processes). The issues are ordered alphabetically, not by management priority. They are climate change planning; erosion; geologic hazards; geomorphic change of Pueblo Colorado Wash; paleontological resource inventory, monitoring, and protection; and water rights and irrigation.

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 NPS Geologic Resources Division (GRD) can provide technical assistance with many of these issues. Climate change planning is best addressed by the NPS Climate Change Response Program. Erosion-related issues can be addressed by the Natural Resources Conservation Service (NRCS); GRD has a memorandum of understanding with the NRCS that facilitates technical assistance requests. Water rights and irrigation issues are best addressed by the NPS Water Resources Division (WRD). 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 historic site, and "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

This chapter orients readers to the historic site and introduces them to the Geologic Resources Inventory (GRI). The GRI is administered by the Geologic Resources Division (GRD) of the National Park Service (NPS) Natural Resource Stewardship and Science (NRSS) Directorate. The GRI 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 Program.

Park Location

Hubbell Trading Post National Historic Site (referred to as the "historic site" throughout this report) is on the outskirts of Ganado, Arizona (see poster), which is in Apache County. Ganado has a population of 883. The closest city is Gallup, New Mexico (population 21,899). To the north, Chinle, Arizona, hosts a population of 4,573 people (US Census Bureau 2020).

Ganado was formerly known as Pueblo Colorado ("Red Town"), which is a Spanish translation of nearby Kin Dah Lichi′i ("Red House")—now Kin Dah Lichi′i Olta ("Red House School")—in Kinlichee, Arizona, about 8 km (5 mi) northeast of Ganado. While some early maps of the area show "Pueblo Colorado," that name was dropped in the late 19th century to avoid confusion with the town of Pueblo, Colorado. The Navajo refer to Ganado as Lok′aah ("reed") niteel ("it is wide/broad"). The name Ganado honors Ganado Mucho—literally meaning "accumulated much," but the name is understood to mean wealthy in cattle and sheep, hence commonly translated as "Many Cattle." Ganado Mucho or Many Cattle was a Navajo leader during the transition to reservation life (Carey 2009; Steven Semken, Arizona State University, professor, written communication, 25 May 2023).

Ganado is one of 110 chapters (local government subdivisions) of the Navajo Nation (Navajo Nation 2023). In the 1920s, chapters were established throughout the Navajo Reservation (now Navajo Nation) as units of agricultural extension services. Also, the discovery of oil on Diné Bikéyah ("Navajoland") in the early 1920s prompted the need for a more systematic form of government, and, in 1923, a Tribal government that incorporated chapters was imposed to help meet the increasing desires of American oil companies to lease Navajo lands for exploration (Navajo Nation 2022). Over the years, chapter houses became meeting places to gather and discuss issues (Manchester and Manchester 1993). Interestingly, the historic site's visitor center was formerly a chapter house, built in the 1930s (see "Building Stone").

Park Establishment

Leading up to the establishment of the historic site, an act of Congress (Public Law 89-148) in 1965 authorized the purchase of the "site and remaining structures…including the contents of cultural and historical value, together with such additional land and interests in land…as are needed to preserve and protect the post and its environs for the benefit and enjoyment of the public." Unlike other trading posts, Hubbell Trading Post included a homestead with irrigated farmland that was established as part of a self-sustaining business (National Park Service 2016). The 65-ha (160-ac) historic site represents the Hubbell homestead claim. The trading post and associated homestead are unique in being one of very few parcels of land retained in private ownership during the expansion of the Navajo Nation between 1880 and 1934 (Froeschauer-Nelson 1998).

Before its designation as a unit of the National Park System, the trading post was added to the Historic Sites Register in 1960 and then listed as a national historic landmark with the passage of the National Historic Preservation Act of 1966 (Froeschauer-Nelson 1998). That act created the National Register of Historic Places (see “Additional References, Resources, and Websites”), on which Hubbell Trading Post National Historic Site is now listed as a historic district.

Trading Post Operations and Background

Hubbell Trading Post is the oldest continuously operated trading post in the American Southwest and is an outstanding example of the larger trading post system (National Park Service 2016). In accordance with the congressional intent for its authorization and NPS objectives, the trading post has been preserved and managed from the outset as a functional and viable business operation, continuing in a mode similar to an active trading post. Unlike a replicated trading post or a historic site that emphasizes the use of reenactments and static exhibits for interpretation, the trading-post complex and associated farmland are managed as an intact and fully operational trading post reflecting traditional and ongoing trading relationships (National Park Service 2016).

Traditionally associated tribes and pueblos of the historic site include, in alphabetical order: Apache Tribe of Oklahoma; Fort McDowell Yavapai Nation, Arizona; Fort Sill Apache Tribe of Oklahoma; Hopi Tribe of Arizona; Jicarilla Apache Nation, New Mexico; Kaibab Band of Paiute Indians of the Kaibab Indian Reservation, Arizona; Mescalero Apache Tribe of the Mescalero Reservation, New Mexico; Navajo Nation, Arizona, New Mexico, and Utah; Pueblo of Acoma, Pueblo of Jemez, Pueblo of Laguna, Pueblo of Nambe, Pueblo of Pojoaque, Pueblo of San Ildefonso, Pueblo of Santo Domingo, and Pueblo of Tesuque, New Mexico; San Carlos Apache Tribe of the San Carlos Reservation, Arizona; Southern Ute Indian Tribe of the Southern Ute Reservation, Colorado; Ute Mountain Tribe of the Ute Mountain Reservation, Colorado, New Mexico, and Utah; White Mountain Apache Tribe of the Fort Apache Reservation, Arizona; and Zuni Tribe of the Zuni Reservation, New Mexico. This list, which was derived from the NPS Intermountain Region’s Tribal contact database, was compiled in the historic site’s foundation document (National Park Service 2016).

Trading posts brought an opportunity for commerce to newly established reservations, which Congress created by passing the Indian Appropriations Act in 1851. The Navajo Reservation was established in 1868. By 1878, John Lorenzo (J. L.) Hubbell had purchased the trading post from William Leonard and, within a few years, had begun to expand and develop the operation and its adjacent lands. During the 1880s, Hubbell brought in a partner, C. N. Cotton, and by 1885, Cotton had acquired full ownership of the trading post operation. In 1894, however, Hubbell once again purchased the trading post and operated it until his death in 1930.

Hubbell was widely regarded as among the most trusted and respected traders of the region, earning him the name “Don” Lorenzo, a Spanish title of honor. His wire-rimmed glasses gained him the

Navajo name Nak′ee Sinili (“Eyeglasses”; Figure 1). Hubbell admired Navajo and other Tribal arts and crafts, recognizing their increasingly widespread popularity and value (National Park Service 2010). Hubbell’s influence on the local culture was considerable, and many Navajo rugs look the way they do because Hubbell advised the weavers as to which designs would sell. “Ganado Red,” for example, is a style associated with Hubbell Trading Post (Manchester and Manchester 1993).

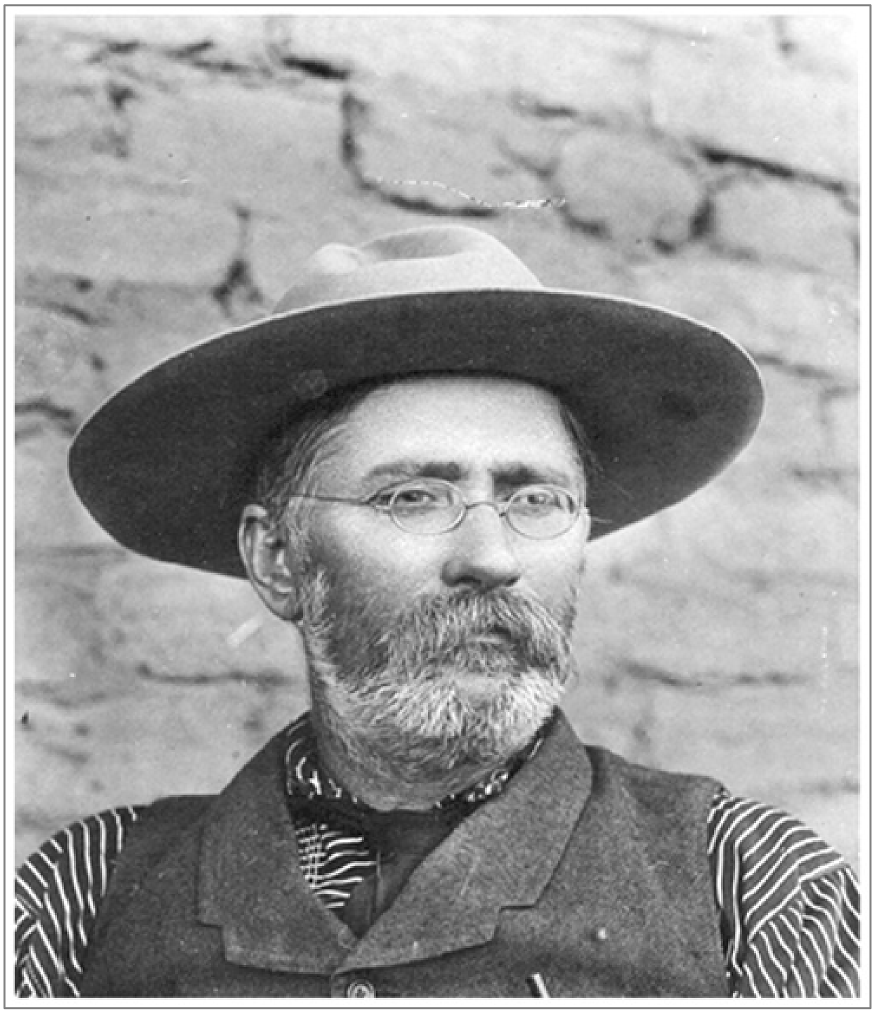


Figure 1. Photograph of John Lorenzo (J. L.) Hubbell. Called Nak'ee Sinili (“Eyeglasses”) by the Navajo with whom he traded, Hubbell was known for his honesty in business dealings and his hospitality. Hubbell’s career as a trader spanned critical years for the Navajo as they adjusted to life on the newly established Navajo Reservation (now, Navajo Nation). NPS photograph, date unknown; available at https://www.nps.gov/hutr/learn/photosmultimedia/photogallery.htm (accessed 13 February 2024).

Hubbell’s hospitality is reflected in the overall informal, relaxed feeling that historically and presently characterizes the trading post (National Park Service 2016). Explorers, artists, writers, scientists, and politicians, including President Theodore Roosevelt, enjoyed the atmosphere of the trading post and the hospitality of the Hubbell family (National Park Service 2010).

Following Hubbell's death, the trading post continued under the ownership and management of the Hubbell family until 1967, when the National Park Service purchased it from J. L. Hubbell's heirs. Dorothy Hubbell, wife of J. L. Hubbell's younger son, Roman, was the last member of the family to live at the trading post.

Today, administrative commitments at the historic site center on the relationship between the NPS and the Western National Parks Association (WNPA), formerly Southwestern Parks and Monuments Association. In this relationship, the business operations of the trading post and visitor center sales are the responsibilities of WNPA, and WNPA staff members are required to operate a viable and accountable business that generates a sustainable income and benefits the nonprofit organization and Indigenous artisans. The NPS provides interpretive and curatorial services, maintains and preserves the structures at the historic site, and ensures public safety and security. The NPS also works cooperatively within the Navajo Nation on issues such as utility provision, conservation, interpretation, historic preservation, and project compliance.

Physiographic Setting

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

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 terminology, "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.

At least two key features define the Colorado Plateau. First, Earth's crust (outermost layer) that underlies the plateau is thick, much thicker than the crust in the adjacent Basin and Range physiographic province (Figure 2). Varying geologic interpretations exist concerning the thickness of the plateau's crust, but Parsons et al. (1996) found that it ranged between about 30 and 48 km (19 and 30 mi), with the thickest area being the Kaibab Plateau on the north rim of the Grand Canyon (see GRI report by Graham 2020). Second, the Colorado Plateau stands high above sea level. Elevations range from 610 m (2,000 ft) above sea level in the western Grand Canyon to 3,700 m (12,000 ft) above sea level in the high plateaus of Utah. The average elevation is 1,900 m (6,200 ft) above sea level (Price 2010). At 1,928 m (6,325 ft) above sea level, the historic site is about average.

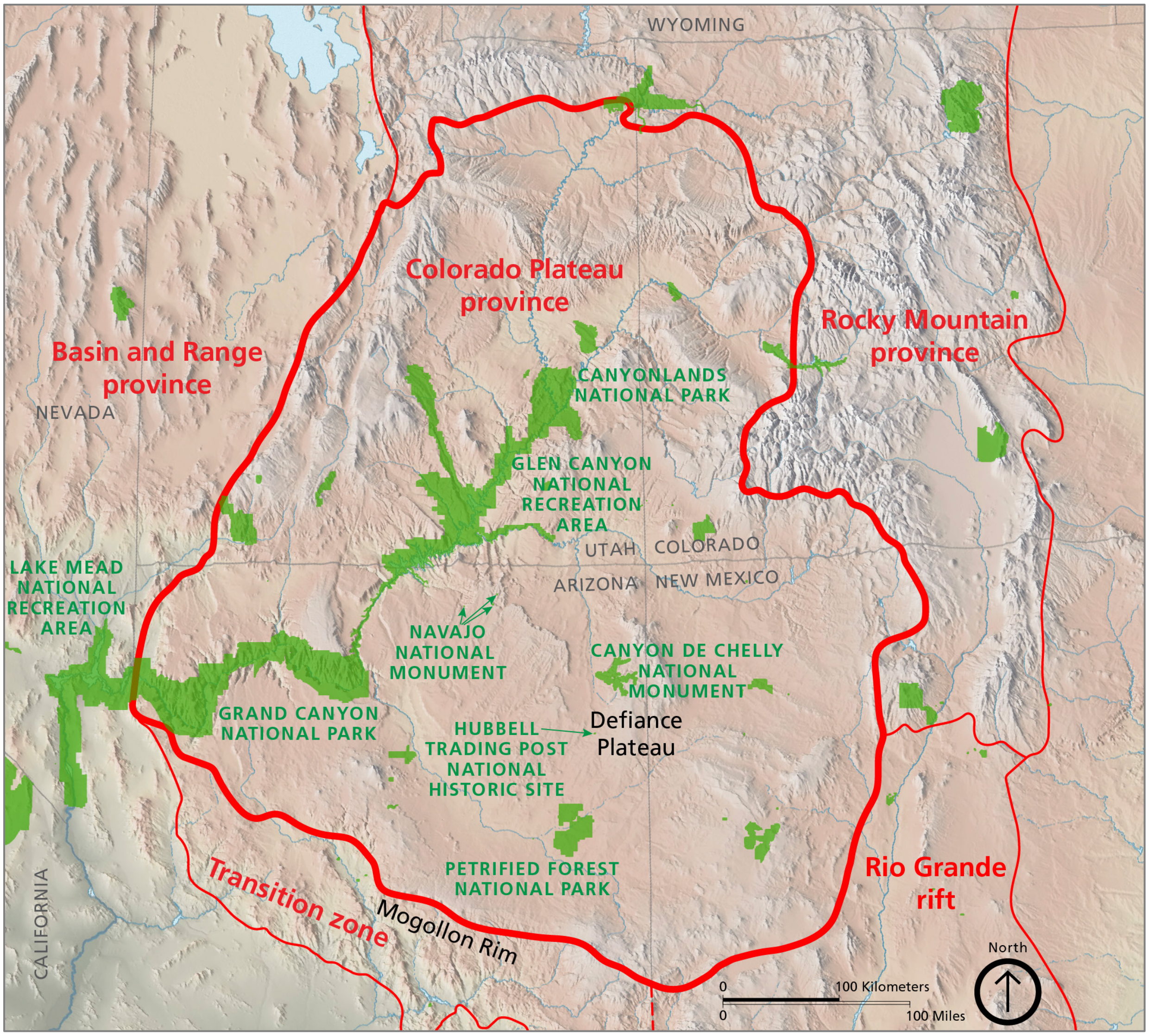


Figure 2. Map of the Colorado Plateau physiographic province. Located in the Four Corners Area of Arizona, Utah, Colorado, and New Mexico, the historic site is one of many NPS areas in the region. The figure shows these areas in green; labels identify a selection of them. Graphic by Trista L. Thornberry-Ehrlich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

The historic site's physiography can be further classified as part of the Defiance Plateau (Figure 2). The Defiance Plateau is essentially an elongated dome (roughly circular upfolded structure) cut by faults. Movement along these faults brought ancient rocks to the surface (Hackman and Olson 1977). Some areas of the Defiance Plateau expose (brought to the surface then eroded) rocks that are more than a billion years old. Near the historic site, however, the oldest exposed rock unit is the De Chelly Sandstone (**Pdc**), which is about 275 million years old (Blakey and Knepp 1989). The sandstone is exposed along Pueblo Colorado Wash, east of the historic site (see poster). The De Chelly Sandstone is named for Canyon de Chelly (Gregory 1915, 1917), north of the historic site (see the GRI report about Canyon de Chelly National Monument by KellerLynn 2024).

In 1916, the USGS named the Defiance Plateau for the military post, Fort Defiance, which was established in 1851 about 40 km (25 mi) east of Ganado. Interestingly, “Hubbell Plateau” is a variant name of the Defiance Plateau (US Board on Geographic Names 2000). The plateau is 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 Defiance Plateau rises 2,389 m (7,838 ft) above sea level (US Board on Geographic Names 2000). In geologic terminology, the plateau is referred to as the Defiance uplift (see “Significant Geologic Events”).

GRI Program

The GRI was established in 1998 by the GRD and the NPS Inventory and Monitoring Program [Division] to meet the NPS need for geologic mapping and related information. Geologic maps were identified as one of 12 natural resource data sets critical for long-term, science-informed park management. From the beginning, the GRI has worked with long-time NPS partner Colorado State University (CSU) to ensure that products are scientifically accurate and utilize the latest in GIS technology. Because NPS units in Alaska are at a much larger scale than the continental United States and have distinctive resource management challenges, the GRI also partners with the NPS Alaska Regional Office and the University of Alaska Museum of the North to develop GRI products in that state. For additional information regarding the genesis of the GRI and its early focus, refer to National Park Service (1992, 1998, 2009).

GRI Products

The GRI team completed the following tasks as part of the GRI for the historic site: (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 through the NPS Integrated Resource Management Applications (IRMA) Data Store (see “Access to GRI Products”).

Information provided in GRI products is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided in GRI products. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data or on the poster. Based on the scale of the source map (Hackman and Olson 1977, scale 1:250,000) and US Map Accuracy Standards (US Geological Survey 1999), geologic features represented in the GRI GIS data and on the poster are horizontally within 127 m (417 ft) of their true locations.

Geologic mapping at 1:24,000 scale, which would be more useful for resource management, is not available for the historic site. However, see the “Hubbell Hill” section in this report for a cross section that shows the historic site’s bedrock (Chinle Formation) in greater detail. In addition, a geologic map by Euge (1983; scale 1:600) provides a more detailed look at surficial deposits (see “Chinle Formation” section in this report).

Scoping Meeting

A geologic scoping meeting took place at the historic site on 16 February 2007. At that time, the GRI was called the Geologic Resource Evaluation (GRE) program but has since changed names. The scoping meeting brought together historic site 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 geologic report. A scoping summary (KellerLynn 2007) summarizes the findings of that meeting.

GRI GIS Data

Following the scoping meeting, the GRE (now GRI) team compiled a digital geologic map in GIS format for the historic site. These data are the principal deliverable of the GRI. The 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 (Figure 3). Scoping participants and the GRI team identified the best available source maps based on coverage (area mapped), map scale, and date of mapping. Compatibility of the mapping with the current geologic interpretation of the area was also considered.

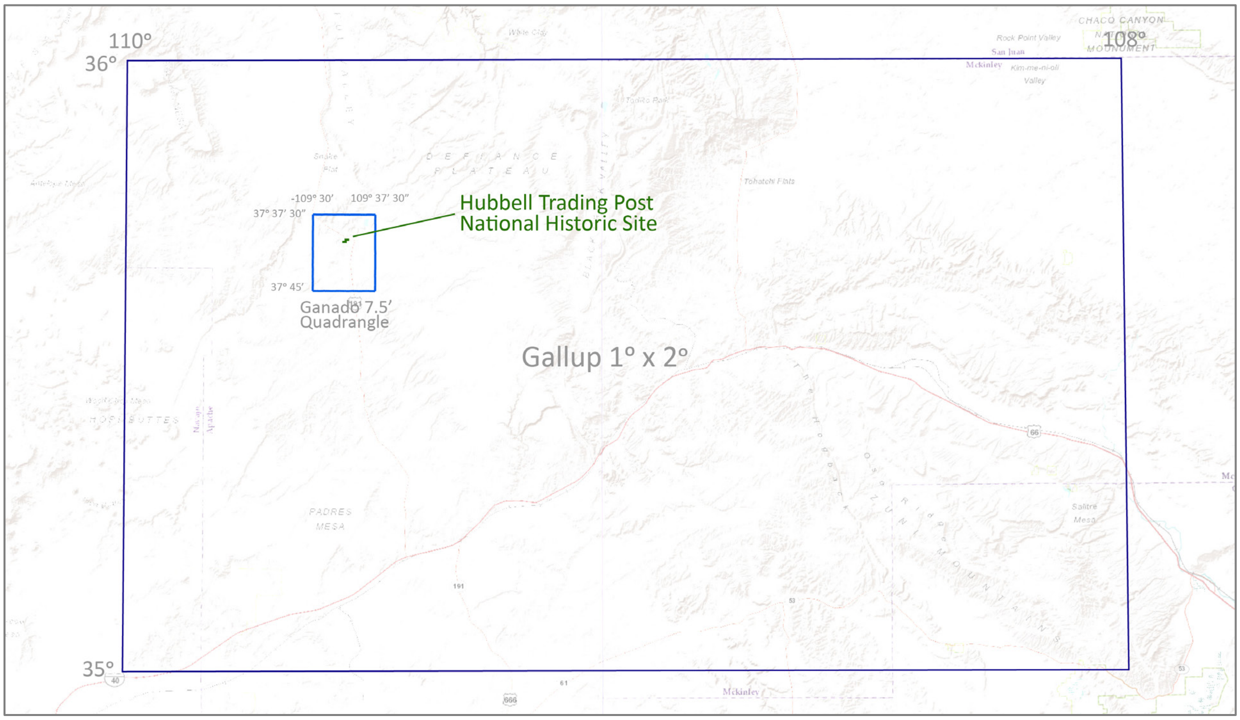


Figure 3. Index map of the GRI GIS data. The historic site lies in the Ganado 7.5' quadrangle, which is also the extent of the GRI GIS data for the historic site. GRI GIS data were extracted from Hackman and Olson (1977), which is a geologic map that covers the entire Gallup 1° × 2° sheet. The boundary for the historic site (January 2022) is shown in green. Terrain data sources: Esri, Garmin, USGS, National Oceanic and Atmospheric Administration, and NPS. Graphic by Jim Chappell (Colorado State University).

During scoping, participants suggested that the *Geologic Map of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah* (plate 1, sheets 5 and 6; scale 1:125,000) by Cooley et al. (1969) be used as the source map. That map and report were prepared by the USGS in cooperation with the Bureau of Indian Affairs and the Navajo Tribe.

The GRI team used that map for compiling the GRI GIS data. However, during the writing of the GRI report for Canyon de Chelly National Monument (see KellerLynn 2024), which also used the map by Cooley et al. (1969) as the source map, GRI team members discovered a spatial "shift" in the data (i.e., geology and topography did not line up). This error was deemed "unfixable," so the GRI team compiled alternative GRI GIS data from a smaller scale USGS map (Hackman and Olson 1977, scale 1:250,000). The current GRI GIS data for the historic site consist of a portion of the map by Hackman and Olson (1977; Figure 3). Notably, although the data are geospatially flawed, information from the original map and report by Cooley et al. (1969) is accurate and was used in preparing this GRI report.

An ancillary map information document (hutr_geology.pdf) accompanies the GRI GIS data and includes essential elements of the source map such as a map unit list, map unit descriptions, map legends, a chart showing the correlation of map units, and references. The ancillary map information document also provides an index map of the GRI GIS data (Figure 3).

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the historic site 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, and 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.

GRI Report

At the beginning of the report-writing process, the GRI team hosted a virtual follow-up meeting for historic site staff and interested geologic experts on 26 January 2022. Because many staff members, including the superintendent and archeologists, have responsibilities at both Canyon de Chelly National Monument and the historic site, a single meeting was held for both parks. The meeting provided an opportunity to reconnect with historic site staff, introduce "new" (since the 2007 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

The GRI report (this document) is a culmination of the GRI process. It synthesizes discussions from the scoping and follow-up meetings, additional geologic research, and input from reviewers (see "Acknowledgments"). The selection of geologic features and processes highlighted in this report was guided by both meetings as well as by the GRI GIS data, which reflect the geologic interpretation of the source map authors (Hackman and Olson 1977) and Cooley et al. (1969). In addition, various NPS documents guided the selection of geologic features, processes, and topics to be discussed in this report. These documents include, from most to least used, the foundation document (National

Park Service 2016), cultural landscape report (Froeschauer-Nelson 1998), administrative history (Manchester and Manchester 1993), cultural landscape inventory (National Park Service 2003), the historic site's soil erosion study (Euge 1983), and the historic site's history of farming (Peterson 1986).

The target audience of GRI reports is park resource managers, but the GRI team hopes that its reports will also be appealing and useful to other audiences such as park interpreters and visitors. To that end, GRI reports attempt to avoid technical terms and strive to be accessible to readers without a background in geology. Nevertheless, like other sciences, geology is full of jargon. GRI reports use geologic terminology, but the terms are defined at their first instance, usually in parentheses following the term. Commonly, graphics are provided to illustrate potentially unfamiliar concepts.

To make connections between the GRI GIS data and this report, the text uses map unit symbols. For example, most of the historic site is covered by alluvial and/or eolian deposits (see poster), which correspond to the map unit symbol **Qae**. "**Q**" stands for the Quaternary Period (deposited during the last 2.6 million years); "**a**" stands for alluvial (deposited by fluvial [river] processes); and "**e**" stands for eolian (deposited by the wind).

The names of geologic map units used in this report follow the interpretation of the source map authors (Hackman and Olson 1977) and reflect the formal nomenclature found in the US Geologic Names Lexicon ("Geolex"), which is a national compilation of names and descriptions of geologic units maintained by the USGS (see "Additional References, Resources, and Websites"). Significantly, the source map of the GRI GIS data (Hackman and Olson 1977) mapped the bedrock at the historic site as the Monitor Butte Member of the Chinle Formation (**TRcmb**); however, these rocks are now recognized as the Bluewater Creek Member of the Chinle Formation (see "Chinle Formation").

Geographic names used in this report follow formally accepted terms recorded in the Geographic Names Information System (GNIS), which is an online database maintained by the USGS (see "Additional References, Resources, and Websites"). The GNIS reflects decisions made by the US Board on Geographic Names, which is a federal body designed to maintain uniform geographic name usage throughout the federal government. 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.

To reflect the historic site's sense of place, Navajo words for placenames, people, and historic events are included in this report. In general, Navajo terms are provided at first instance with an accompanying English translation. Typically, the English word is then used throughout the remainder of the report.

Geologic Heritage

This chapter highlights the geologic heritage of the historic site. Geologic heritage exists at the overlap of geology and human experiences and values.

The following geologic resources are an integral part of the historic site's history and cultural identity; they are also part of its geologic heritage:

Pueblo Colorado Wash

Map unit: **Qae** (see "Fluvial Features and Processes")

Pueblo Colorado Wash drains east to west across the northernmost part of the historic site (see poster). The perennial stream attracted both wildlife and people and encouraged human settlement (Froeschauer-Nelson 1998).

In 1874 or 1875, a trader named William Leonard came down from Fort Defiance and established a trading post on the banks of Pueblo Colorado Wash (Figure 4). Although no primary source documentation has been located that describes Leonard's reasoning behind his site selection, the cultural landscape report (Froeschauer-Nelson 1998) hypothesized that the trader's response to the natural features that surrounded him played a significant role in his selection. For example, the placement of the trading post on the "upper terrace" (a long, narrow, relatively level or gently inclined surface along a stream) of Pueblo Colorado Wash allowed for easy access to water while providing protection from flash floods. In contrast to an agricultural terrace (land leveled by hand to retain water), the "upper terrace" is a natural/geologic feature (see "Fluvial Features and Processes").

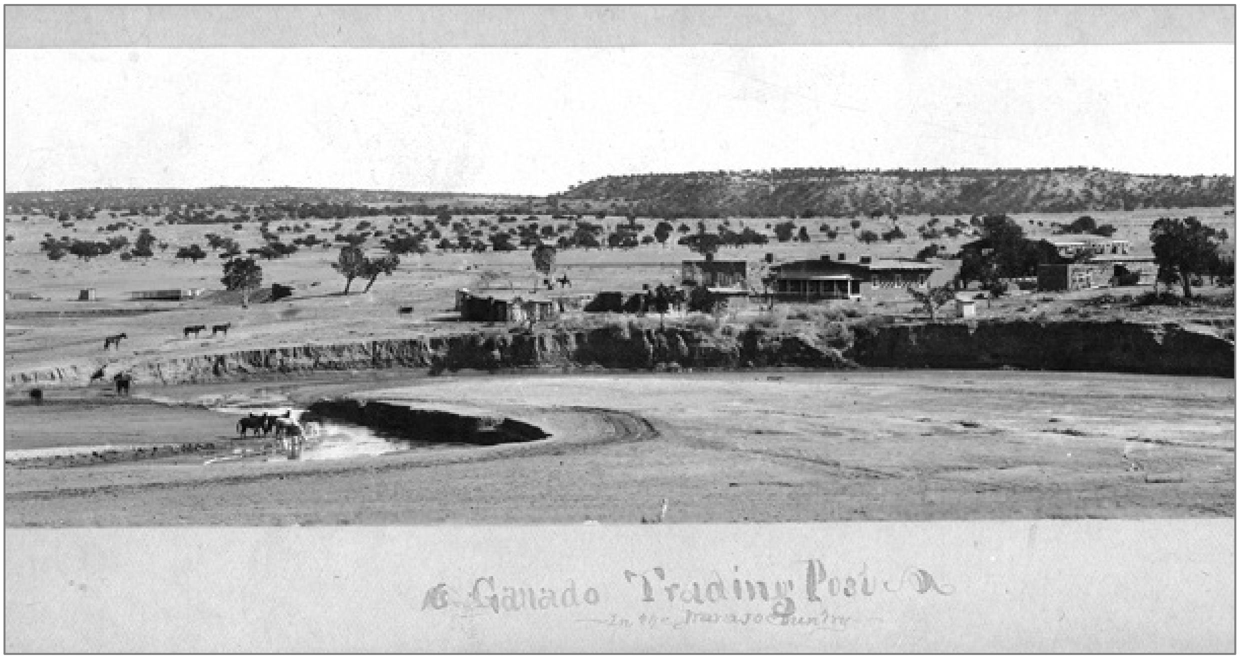


Figure 4. Historical photograph of Hubbell Trading Post and homestead. Taken from Hubbell Hill (looking south), the perennial waters of Pueblo Colorado Wash flow from east to west (left to right) past the trading post. The historic site preserves, protects, interprets, and operates an exceptionally intact late-19th-to-early-20th-century trading post complex. Unlike other trading posts established at that time, this complex included a homestead with livestock and irrigated terraced farmlands. NPS photograph, date unknown; available at https://www.nps.gov/hutr/learn/photosmultimedia/photogallery.htm (accessed 13 February 2024).

Hubbell Hill

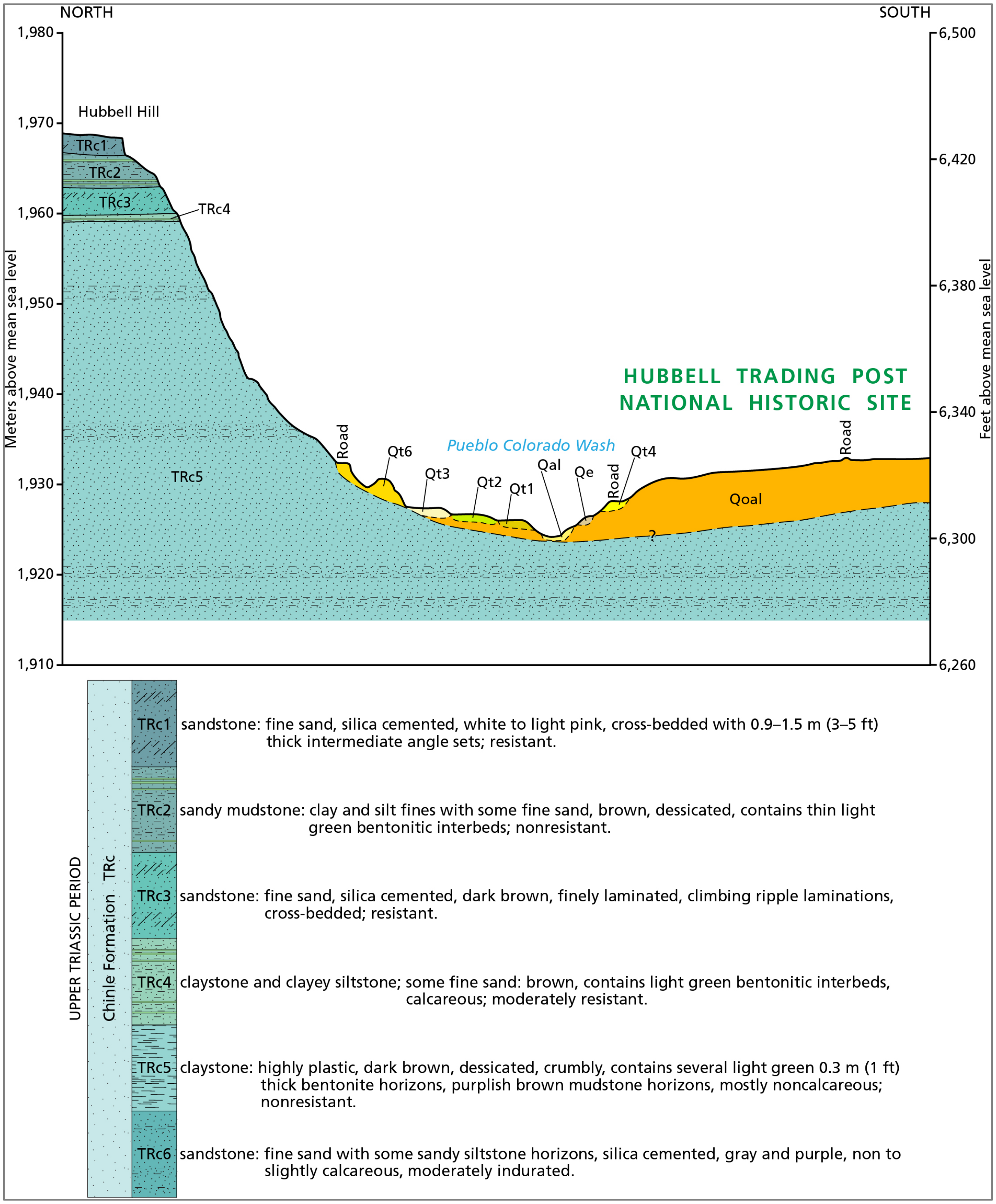
Map unit: **TRcmb** (see "Chinle Formation")

The prominent hillock now known as "Hubbell Hill" (US Board on Geographic Names 1981) likely served as an easily identifiable landmark when William Leonard established his trading post along the banks of Pueblo Colorado Wash (Froeschauer-Nelson 1998). Rising about 33 m (100 ft) above the surrounding landscape and standing 1,960 m (6,431 ft) above sea level, Hubbell Hill still serves as a prominent topographic feature today (National Park Service 2003). Although Hubbell Hill is not within the historic site, the foundation document (National Park Service 2016) identifies it as a fundamental resource and value (i.e., as part of "Trading Post and Homestead") because it is integral to the cultural landscape, which includes far-reaching vistas.

The Hubbell family used Hubbell Hill as a place for contemplation and escape (Froeschauer-Nelson 1998). Seven family members are buried there, in order of burial: (1) Lina Rubi (J. L. Hubbell's wife), (2) J. L. Hubbell, (3) Lorenzo (elder son), (4) Roman (younger son), (5) Adele (elder daughter), (6) LaCharles Eckel (granddaughter of Lina Rubi and J. L. Hubbell, and daughter of Barbara [younger daughter of Lina Rubi and J. L.]), and (7) Dorothy (wife of Roman). In addition, J. L. Hubbell's friend Bi'lii Lani (Many Horses) is buried there. Most of these graves are unmarked, though three are marked by gravestones (see "Building Stone"). Family members would occasionally place cut flowers around the graves, but they generally abided by Roman’s wish to “[not] make this look like a grave yard. Just let it look like a hill and let the native vegetation come back in” (Froeschauer-Nelson 1998, p. 167).

Hubbell Hill is an eroded remnant of an approximately 200-million-year-old floodplain. Erosion took place during development of the Colorado River system, of which Pueblo Colorado Wash is a part (see “Significant Geologic Events”).

The authors of the source map for the GRI GIS data (Hackman and Olson 1977) and a soil survey for the historic site (Euge 1983) identify Hubbell Hill as consisting of the Monitor Butte Member; these rocks are now recognized as the Bluewater Creek Member (see “Chinle Formation”). Locally (as exposed within and in the vicinity of the historic site), Euge (1983) divided the member into six rock layers. Five of these rock layers and an alluvial terrace (see “Fluvial Features and Processes”) make up Hubbell Hill (Figure 5).



TRc1 sandstone: fine sand, silica cemented, white to light pink, cross-bedded with 0.9–1.5 m (3–5 ft) thick intermediate angle sets; resistant.

TRc2 sandy mudstone: clay and silt fines with some fine sand, brown, dessicated, contains thin light green bentonitic interbeds; nonresistant.

TRc3 sandstone: fine sand, silica cemented, dark brown, finely laminated, climbing ripple laminations, cross-bedded; resistant.

TRc4 claystone and clayey siltstone; some fine sand: brown, contains light green bentonitic interbeds, calcareous; moderately resistant.

TRc5 claystone: highly plastic, dark brown, dessicated, crumbly, contains several light green 0.3 m (1 ft) thick bentonite horizons, purplish brown mudstone horizons, mostly noncalcareous; nonresistant.

TRc6 sandstone: fine sand with some sandy siltstone horizons, silica cemented, gray and purple, non to slightly calcareous, moderately indurated.

Figure 5. Cross section of Hubbell Hill and Pueblo Colorado Wash. The historic site's bedrock was mapped as the Monitor Butte Member of the Chinle Formation but is now recognized as the Bluewater Creek Member (see "Chinle Formation"). Euge (1983) describes these rocks in detail and divides them into six units: Triassic Chinle unit 6 (TRc6) to Triassic Chinle unit 1 (TRc1). TRc6 (not shown in cross section) is exposed in the stream channel of Pueblo Colorado Wash (see "Entrenchment of the Colorado River System"). For descriptions of surficial deposits (Qoal, Qt6–Qt1, and Qal) shown on the figure, see "Entrenchment of the Colorado River System." Bentonite (in TRc4 and TRc2) is a type of clay with shrink/swell potential (see "Geologic Hazards"). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Euge (1983, cross section A–A' for plate 1).

Building Stone

The foundation document (National Park Service 2016) identifies buildings and smaller scale structures as a fundamental resource and value (i.e., part of "Trading Post and Homestead") because they provide an intact, tangible record of the development of the trading post. Using historic photographs and tree-ring dating, investigators determined a chronology of construction; the cultural landscape report (Froeschauer-Nelson 1998, p. 133–135) provides a summary. The administrative history (Manchester and Manchester 1993) provides information on individual buildings. By association, the building stone that comprises these structures may be considered a fundamental resource and value.

Historic buildings and structures remain for today's visitor to see, touch, and experience first-hand. These buildings are all in their original locations and retain the building materials selected by the Hubbell family. The stonework found throughout the historic site is "extremely well laid and with a few repairs over the years has been most durable as well as attractively finished" (Froeschauer-Nelson 1998, p. 152). These buildings and materials symbolize the many hands that helped develop the site; the Hubbells hired both Navajo and Hispanic workers to labor on the construction of various structures and buildings. The artistry and skill seen in these features reflects the workers' cultural traditions as well as those of the Hubbell family (Froeschauer-Nelson 1998).

A focused inventory of building stone, including consultation with a geologist, is not known to have taken place at the historic site. The information that follows was gleaned from the administrative history (Manchester and Manchester 1993), cultural resource report (Froeschauer-Nelson 1998), and cultural resource inventory (National Park Service 2003):

- Barn—constructed of locally available stone (see "Source Areas of Building Materials"). Described as "rough rubble" set with adobe clay mortar (Manchester and Manchester 1993, p. 71).
- Bread oven—brick oven structure above the stone; stone foundation up to 1 m (3 ft) above grade.
- Bunkhouse (also referred to as "stone residence")—consists of stone and mortar walls on a shallow foundation (Manchester and Manchester 1993).
- Entrance road—composed of compacted gravel of unknown provenance (see "Source Areas of Building Materials"). Upon crossing the wooden plank-surfaced bridge, visitors experience the crunching sounds and slow speeds of the gravel road that leads to the historic site. For many, this is a distinctive sensory experience, transporting them to and preparing them for the trading-post context (Froeschauer-Nelson 1998).
- Fireplace—The massive central fireplace in the guest hogan contains petrified wood (Figure 6).
- Garden ornaments and decorations—After the original (Leonard) trading post was razed, the area was converted to flower gardens. Roman brought in numerous pieces of petrified wood that were used to define flower beds. Specimens of petrified wood were collected from

throughout the site and surrounding landscape (Froeschauer-Nelson 1998). The cultural landscape report also states that "other minerals" were collected from throughout the site and surrounding landscape and subsequently used for ornamentation and the creation of planting beds for the flower garden (Froeschauer-Nelson 1998, p. 131); these "other minerals" were not identified, however.

- Gravestones—Lina Rubi has a "tall monument" over her grave (Manchester and Manchester 1993, p. 26); the administrative history (Manchester and Manchester 1993) provides no other information, such as dimensions of the monument, rock type, rock formation name, or origin (quarry name and location). Roman Hubbell's grave is marked by a small headstone that "looks as though it could have been carved right down at the trading post" (Manchester and Manchester 1993, p. 26); it was carved by a local Navajo man (name unknown). The most recent headstone was placed over the grave of LaCharles Eckel, who died in 1983 (Manchester and Manchester 1993).
- Grinding wheel—composed of rock of unknown provenance (see "Source Areas of Building Materials").
- Guest hogan—composed of sandstone walls and flagstone floors. Constructed between 1934 and the early 1940s, Roman wanted to have the guest hogan built as a standing memorial to his father, who was known for his hospitality. The builder was Hubbell family friend Emilio Limas. The door was carved by Dorothy Hubbell (Manchester and Manchester 1993).
- Headgates (in the irrigation system)—composed of concrete and stone of unknown provenance (see "Irrigation System").
- Hubbell home—constructed of locally available stone (see "Sources of Building Materials"). The adobe walls—40 to 45 cm (16 to 18 in) thick—were built on a shallow stone and mud mortar foundation (Manchester and Manchester 1993).
- Manager's residence (now ranger's residence)—Older walls are stone and adobe on a shallow foundation; newer walls are stud wall construction (Manchester and Manchester 1993).
- Parking lots—surfaced with compacted gravel of unknown provenance (see "Source Areas of Building Materials"); peeled logs are used as wheel stops for individual parking spaces. The informal character of compacted gravel is compatible with the cultural landscape and allows flexibility for visitors to park oversized recreational vehicles (Froeschauer-Nelson 1998).
- Picnic area—constructed in the early 1940s of rock of unknown provenance (see "Source Areas of Building Materials"); includes a stone picnic table with stone benches, a brick-lined barbecue pit, and a flagstone paving area (Froeschauer-Nelson 1998).
- Pump house (now restrooms)—constructed of random ashlar ("dressed," i.e., cut/worked) stone walls (Manchester and Manchester 1993).
- Root cellar (now library)—small stone structure with the south end built into sloping land (Manchester and Manchester 1993).

- Signage—composed of irregularly shaped and engraved sandstone (Figure 7).
- Sundial—A large piece of petrified wood serves as the base for the sundial (Figure 8).
- Trading post—constructed of locally available stone (see “Source Areas of Building Materials”); sandstone and mortar (Manchester and Manchester 1993). By 1883, Hubbell had begun construction on a new and larger masonry trading post building, beginning with the office and rug room of the existing building. In 1889, the store and wareroom (limestone and adobe mortar; Manchester and Manchester 1993) were added, and the trading post attained its present floor plan (Froeschauer-Nelson 1998). The original Leonard buildings were out in front of the present trading post. In the early 1920s, the deteriorated condition of the old Leonard complex was seen as a potential hazard to the young Hubbell children playing in and around the structures, so the buildings were razed in 1923.
- Visitor center (former Navajo chapter house and school)—constructed of random ashlar stone walls (Manchester and Manchester 1993).

Figure 6. Photograph of fireplace. The massive fireplace in the guest hogan is made of natural stone and petrified wood as well as pottery and other stone items of archeological significance. NPS photograph by Maryann Neubert (Hubbell Trading Post National Historic Site), taken 2023.

Figure 7. Photograph of stone sign. Introduced to the trading post by the Hubbell family, signs made of sandstone are a small-scale feature of geologic interest. NPS photograph by J. Galbraith, taken in 2002; available in National Park Service (2003, p. 75).

Figure 8. Photograph of sundial with petrified wood base. The Chinle Formation is well-known for its fossils. Although the provenance of this piece of petrified wood is not known, it is possible that Roman Hubbell (J. L. Hubbell's younger son) collected it locally. NPS photograph by Maryann Neubert (Hubbell Trading Post National Historic Site), taken 2023.

Types of Building Materials

The barn, Hubbell home, and trading post were identified by the historic site's cultural landscape report (Froeschauer-Nelson 1998) as constructed of "locally available stone." Presumably, locally available stone was also used to construct the other stone buildings at the historic site, though the cultural landscape report does not explicitly state this.

The most likely geologic candidate of "locally available stone" is the Chinle Formation, Monitor Butte Member (**TRcmb**), which is now recognized as the Bluewater Creek Member of the Chinle Formation (see "Chinle Formation"). Hackman and Olson (1977) describe the Monitor Butte Member as a dusky- to grayish-red claystone and sandy siltstone; it also has some grayish-red beds of sandstone and limestone-pebble conglomerate. Clastic sedimentary rocks, such as the Chinle Formation, are categorized by the size of the grains (mineral or rock particles) they contain (Table 1).

Table 1. Grain sizes of sediments.

Sediment Name	Size Range in Millimeters	Size Range in Inches
Boulder	>256	10
Cobble	64–256	2.5–10
Pebble	4–64	0.16–2.5
Granule	2–4	0.08–0.16
Sand [A]	1/16–2	0.0025–0.08
Silt [A]	1/256–1/16	0.00015–0.0025
Clay [A]	<1/256	<0.00015

[A] Sand, silt, and clay may be subdivided into coarse, medium, fine, and very fine.

Flagstone walkways of reddish tan sandstone are located around the old chapter house and along the north and west sides of the Hubbell home, connecting the family house with the guest hogan and the manager's residence (see poster). Another path constructed from the reddish tan sandstone is the path that runs north–south between the trading post building and the Hubbell home; this path is used daily by staff and visitors alike (Froeschauer-Nelson 1998, p. 74). Although verification is needed, this material may be the De Chelly Sandstone (**Pdc**), which is exposed along Fish Wash (Hackman and Olson 1977), east of the historic site (see "Source Areas of Building Materials," below).

Another type of building material used at the historic site is adobe. Adobe was made from soils collected on site; Dorothy Hubbell noted that "we got our adobe right here… I think they were doing it back of the old chapter house" (Froeschauer-Nelson 1998, p. 131). A local source of adobe is unit **Qae**—alluvial and/or eolian deposits (see poster and "Fluvial Features and Processes").

Gravel was also used in construction at the historic site; it composes the entrance road and parking lots. A local source of gravel is unit **Qao**—alluvial and/or eolian deposits on older surfaces such as terraces and pediments (see poster). Terraces are relatively level benches or steplike surfaces that rise above the active stream channel whereas pediments are broad, gently sloping erosion surfaces (see "Fluvial Features and Processes").

Source Areas of Building Materials

Although oral history recounts that some of the building stone in the trading post is from ruins (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), Dorothy Hubbell insisted that J. L. Hubbell never directed his crews to remove stones from the prehistoric Pueblo ruins on the property to use in construction because of Hubbell's respect for the sites and the cultural taboos associated with disturbing abandoned ruins (Froeschauer-Nelson 1998). Nevertheless, the family clearly collected some stone items of archeological significance, for example, those used to decorate the fireplace in the guest hogan (see Figure 6).

Besides locally collected stone, another potential source area of building stone is the Defiance Plateau (see Figure 2). Because most of the building timbers—especially those used for vigas (exposed beams) and larger structural features—were transported from the Defiance Plateau (24 km [15 mi] east of Ganado), obtaining building stone from the Defiance Plateau does not seem outside the realm of possibility, particularly as supplies diminished and "the workers had to travel farther from the property to locate new sources" (Froeschauer-Nelson 1998, p. 130).

The flagstone used on the property in pathways and floors is said to be from a wash called "Where the Mexicans Weep" and was hauled in by wagons (Froeschauer-Nelson 1998, p. 131). "Where the Mexicans Weep" is a tributary of Fish Wash, which, in turn, is a tributary of Kinlichee Creek, about 9 km (6 mi) northeast of the historic site. The name "Where the Mexicans Weep" was established because Mexicans commonly got their wagons stuck in this wash. Notably, Fish Wash is thought to have easier access and better quality, flatter stone than "Where the Mexicans Weep" (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). Though field verification is needed, the source of the flagstone at "Where the Mexicans Weep" and Fish Wash may be the De Chelly Sandstone (**Pdc**; see poster). This sandstone makes up the stunning walls of Canyon de Chelly (see GRI report about Canyon de Chelly National Monument by KellerLynn 2024).

Fluted Rock (south of Canyon de Chelly National Monument) is a possible source area of stone found at the historic site (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). Notably, Fluted Rock is composed of minette (Hackman and Olson 1977), which is the major rock type in the Navajo volcanic field (Semken 2010). Minette is typically friable and crumbles into sand-sized particles as it weathers, so its use as a building stone is unlikely. However, dikes of aphanitic (fine-grained) minette—which has the same chemical composition as friable minette but consists of individual crystals that are so small, they form a denser, harder, dark-colored rock—cut across the interior rocks of volcanoes in the Navajo volcanic field. Aphanitic minette is used for making flaked stone tools and is consequently a potential source material for stone tools found at the historic site.

The Bidahochi Formation (**Tbu**), which tops the mesas surrounding the historic site, is another potential source of building stone. The Bidahochi Formation weathers into ledges, alternating with steep white slopes. Because the Bidahochi Formation consists of poorly cemented, clay-rich sandstone, however, its use as "locally available stone" seems less likely than the Chinle Formation (see "Types of Building Materials").

Irrigation System

In response to the lay of the land—rising gently north to south—and its relationship to Pueblo Colorado Wash, Hubbell decided to use check (or terrace) irrigation methods for agricultural development (Figure 9). The system was in good company; local Navajo and Hopi farmers used variations of check irrigation as far back as the Ancestral Puebloan period (about 1,250 years ago). The terraces held water at many levels and provided a way to control the degree of fall between the fields and Pueblo Colorado Wash, thereby avoiding major erosion problems caused by water discharge (National Park Service 2003).

The irrigation system, which Hubbell built and then sold to the federal government (Nancy Stone, Hubbell Trading Post National Historic Site, superintendent, personal communication, 2002, *in* National Park Service 2003, p. 57), consisted of the following: a dam/reservoir at Ganado Lake, an irrigation reservoir or holding pond referred to as "Hubbell Reservoir" adjacent to the historic site's southern border (Bureau of Reclamation 2003), a main irrigation canal that divided into north and south canals, laterals (irrigation ditches leading from the main canals), checks/terraces, and leveled land (Peterson 1986). Ganado dam/reservoir; Hubbell Reservoir; and the main, north, and most of the south irrigation canals were outside the original homestead claim and are outside the historic site boundary (Figure 9).

Once established, check irrigation was relatively simple. Water was let into each agricultural terrace (not natural/alluvial terrace; see "Fluvial Features and Processes") and allowed to run on it until the terrace was completely flooded (Peterson 1986). The terraces were "twelve to fifteen yards [11 to 14 meters] wide…each dropping from top to bottom (generally east to west) but maintained grade between borders (generally south to north) and then dropped a foot or so to the next terrace. This process was repeated on down the [irrigation] ditch" (Peterson 1986, p. 76).

Only vague evidence of the terraces (i.e., recognized by their borders) remains on the landscape (Peterson 1986). By contrast, numerous stone headgates (composed of concrete and stone of unknown provenance) within long remnant ditches are located throughout the agricultural fields today. Headgates, which turned water from the laterals into the checks, are perhaps the most impressive physical remains of the entire system. About 185 remain, and their existence is reflective of their sturdiness and minimal need for repair. Headgates exemplify a "build to last" approach (Froeschauer-Nelson 1998, p. 152).

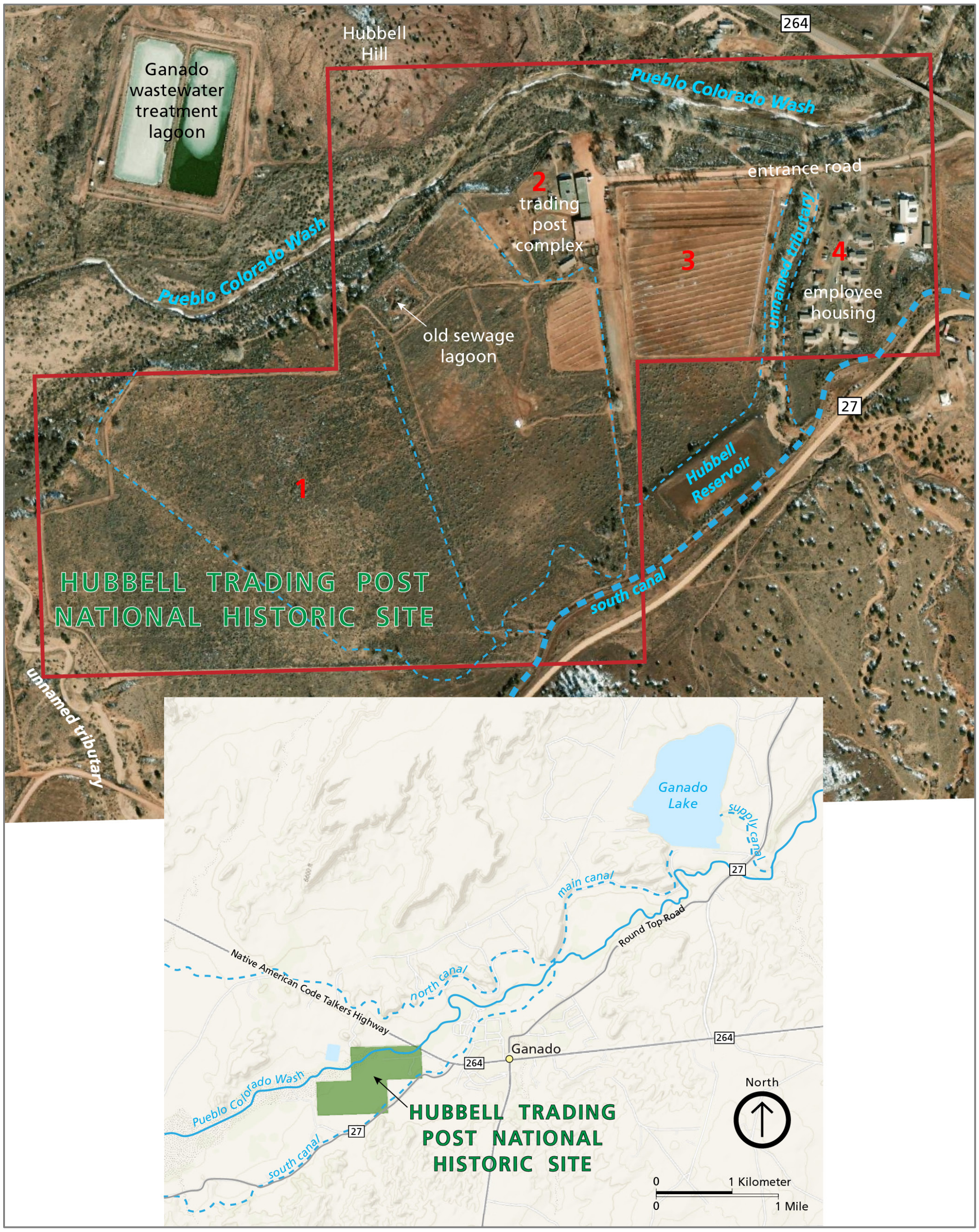


Figure 9. Map of irrigation system and farm fields. Hubbell transported water via irrigation canals and laterals from Ganado Lake (northeast of the trading post) to cultivate his fields, which covered a total of about 45 ha (110 ac). 1—The largest field or fields covered about 32 ha (80 ac). 2—The Hubbell family grew corn and other vegetables in a 0.1-ha (0.25-ac) field. 3—A 6-ha (16-ac) field was east of the trading-post complex and north of Hubbell Reservoir; a portion of this field as well as Hubbell Reservoir were outside the homestead claim and are outside of the historic site's boundary. 4—The easternmost field encompassed 5 ha (13 ac) and was irrigated by a lateral that fed directly off the main canal; the housing area now occupies this field. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Froeschauer-Nelson (1998, figure 53) and National Park Service (2003, site plan on p. 3). Base imagery by Esri World Imagery. Inset map: Base map by Esri World Hillshade.

Museum Collection

The historic site's museum collection contains more than 350,000 items, including the Hubbell family archive of 264,000 business records that document the history of exchange at the trading post. In addition, prehistoric objects, art, furnishings, household odds and ends, farm equipment, and oral histories are part of the museum collection. The museum collection also contains items of geologic heritage value, including the following:

- Natural history items—Most of the specimens in the museum collection that are referenced as "natural history" are geologic specimens or mounted heads (hunting trophies). Most of the geologic specimens were collected by the Hubbell family, and many were used as decoration in the buildings (Manchester and Manchester 1993).
- Fossils—The paleontological resource inventory and monitoring report for the Southern Colorado Plateau Network (Tweet et al. 2009) documents 47 catalog numbers for paleontological objects in the historic site's museum collection. Most of these (n = 42) are pieces of petrified wood identified as *Araucarioxylon arizonicum* (see "Petrified Wood and Other Fossils"). Three of the other five specimens are bones: one unidentified mineralized bone, a domestic sheep (*Ovis* sp.) horn, and a bone piece. The other two specimens are pieces of a different type of petrified wood (*Woodworthia*). In addition, Tweet et al. (2009) documents some geologic specimens of unknown origin and formations that could be fossiliferous as well as items in the historic site's archeological collection that are made from fossils. Furthermore, in 2015, Justin Tweet (NPS Geologic Resources Division, associate) inventoried additional paleontological specimens at the NPS Western Archeological and Conservation Center (WACC); these specimens (i.e., shells, fossil bone, and petrified wood) were collected at the historic site or in the vicinity.
- Rock specimens, mineral specimens, and surface process materials—The NPS Museum Collection (online database; see "Additional References, Resources, and Websites") records 28,250 objects from the historic site's museum collection. Of these, 79 are related to geology—62 rock specimens, 15 mineral specimens, and two surface process materials (i.e., rounded river rocks).

Geologic History

This chapter describes the geologic events that led to the historic site'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 chronology of geologic events (bottom to top).

Geologists have been interpreting and reinterpreting the geologic story of the Colorado Plateau for more than 100 years (e.g., Gregory 1916b), and some details are still hotly debated. However, agreement about environmental origins as well as correlation of rock units across the region is now widespread. The geologic interpretation provided in this GRI report follows the source map (Hackman and Olson 1977) that was used in compiling the GRI GIS data, as well as Cooley et al. (1969), which scoping participants identified as having an accurate interpretation of the historic site's geology. Guidance was also taken from more-recent geologic mapping of the Chinle Formation at Petrified Forest National Park (Martz et al. 2012) and input from William G. Parker (Petrified Forest National Park, program manager, email communications, November 2023 and January 2024).

Three paleogeographic maps help illustrate the geologic events discussed in this chapter. Two of these maps are snapshots of geologic time: one for the Pennsylvanian Period at about 300 million years ago when the Ancestral Rocky Mountains dominated the scene and one for the Triassic Period about 220 million years ago when the historic site's bedrock—the Chinle Formation—was being deposited. The third paleogeographic map shows the supercontinent Pangea. As a point of reference, the historic site's bedrock (the Chinle Formation) was deposited when Earth's crust (outermost layer or shell) was configured into Pangea (Figure 10). The configuration of Pangea began about 335 million years ago (Middle Mississippian Period), reaching its greatest extent about 250 million years ago (Early Triassic Period). The Chinle Formation was deposited about 230 million–210 million years ago (Richard et al. 2000). Breakup of the supercontinent began about 200 million years ago (Early Jurassic Period).

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 historic site, the Ancestral Rocky Mountains were at the western edge of this transcontinental mountain belt.

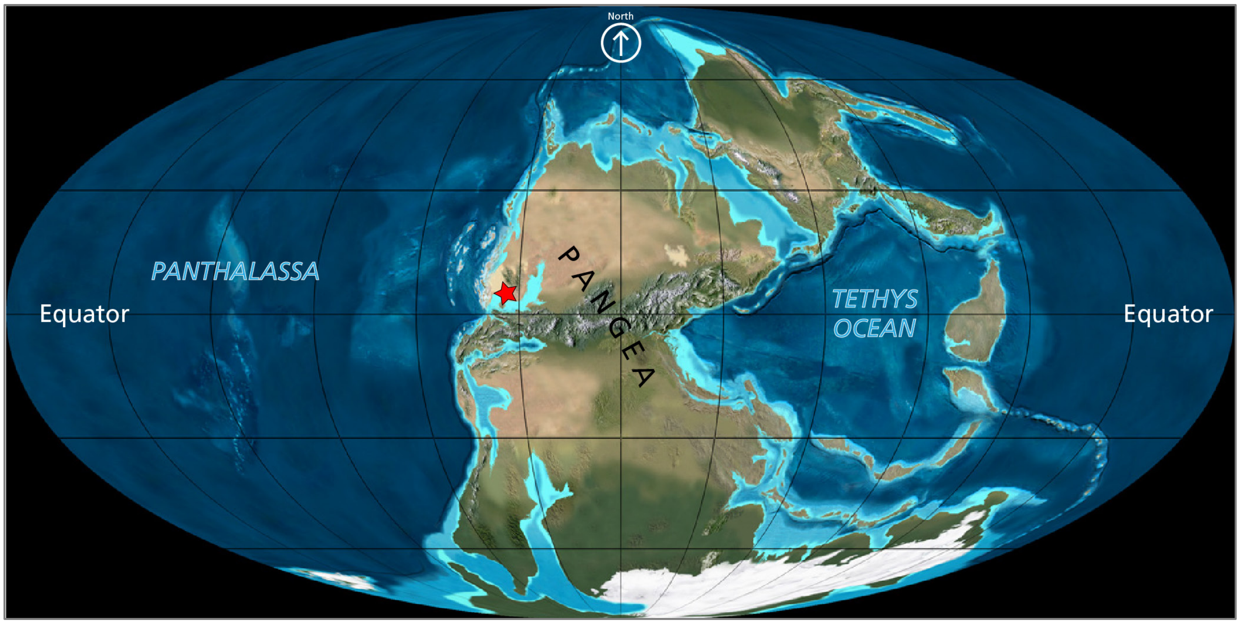


Figure 10. Paleogeographic map of Pangea. The supercontinent Pangea reached its greatest extent during the Permian Period. It spanned from pole to pole and was shaped like a huge letter "C," which cupped the Tethys Ocean. The remainder of Earth's surface was covered by the super-ocean Panthalassa. Arizona (red star) was on the western edge of Pangea near the equator. The Ancestral Rocky Mountains system was on the western edge of the mountain chain—sometimes referred to as the "Central Pangean Mountains" (e.g., Scotese et al. 1979)—that spanned the continent. Base paleogeographic map by Ron Blakey, "Paleogeography of Southwest North America," © 2012 Colorado Plateau Geosystems Inc, used under license; see https://deeptimemaps.com/ (accessed 13 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

Significant Geologic Events

The following geologic events are significant for the historic site:

Development of the Ancestral Rocky Mountains

During the Pennsylvanian and Permian Periods, the Defiance uplift (see "Physiographic Setting") was an island in the Ancestral Rocky Mountains system (Figure 11). The Ancestral Rocky Mountain system comprised a group of highlands (rising above sea level) and adjacent basins (below sea level) at the western margin of Laurentia (proto-North America). Today, remnants of the Ancestral Rocky Mountains (uplifts and basins) are concentrated in a northwest–southeast-oriented swath across the Four Corners Area (see Figure 2), Oklahoma, and Texas (Figure 11).

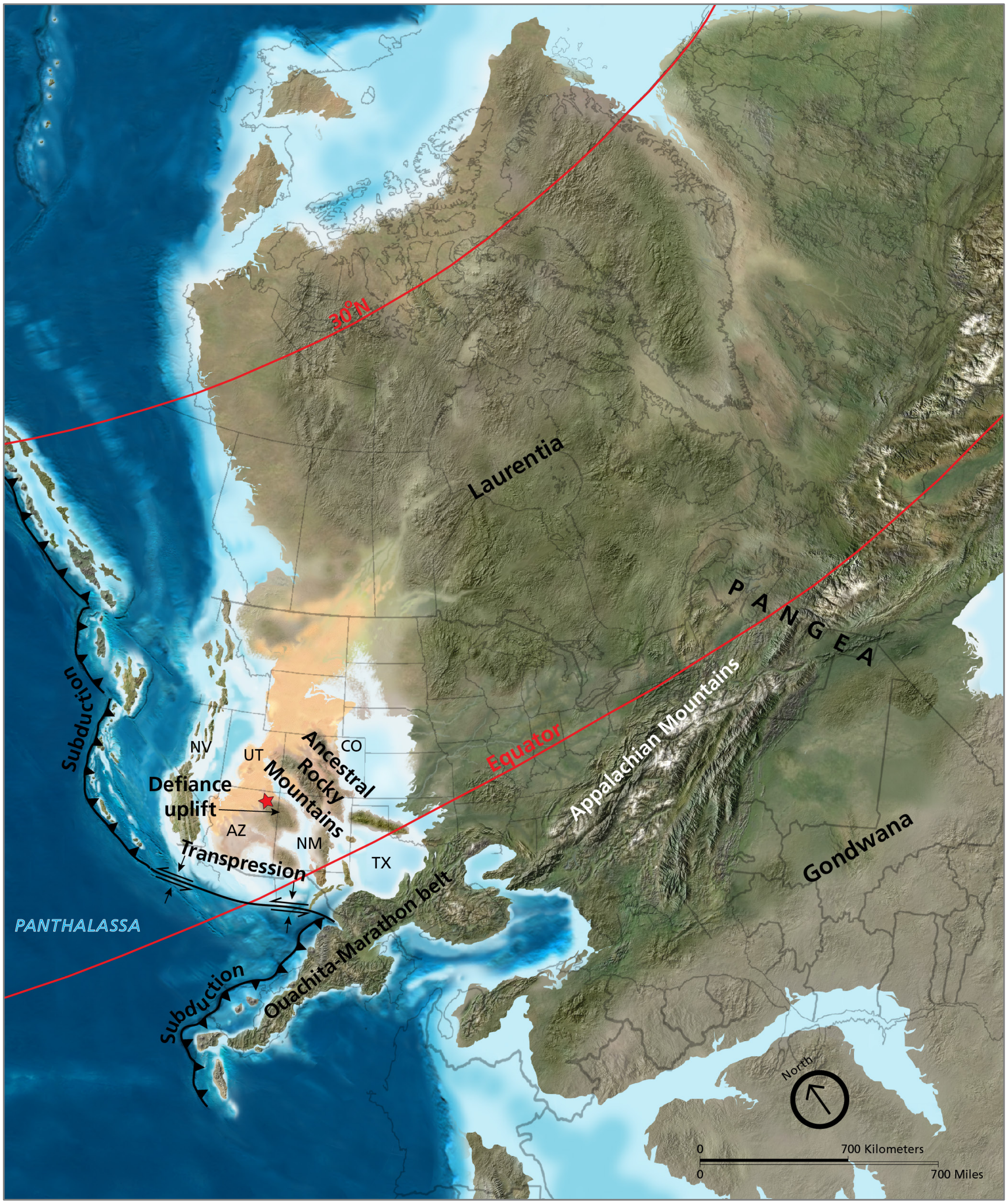


Figure 11. Paleogeographic map of the Late Pennsylvanian Period (about 300 million years ago). The Ancestral Rocky Mountains system dominates the western margin of Laurentia. Tectonic stresses—including the convergence to the WNW in Nevada, transpression to the SW in present-day Sonora, and the suturing between Laurasia and Gondwana in the Ouachita-Marathon belt to the SSE—drive uplift and basin development. A red star marks the location of the historic site. Base paleogeographic map by Ron Blakey, “Paleogeography of Southwest North America,” © 2012 Colorado Plateau Geosystems Inc, used under license; see https://deeptimemaps.com/ (accessed 13 February 2024). Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

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 11) 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 a combination of compression and horizontal plate motion when two plates meet (see areas of subduction and transpression labeled on Figure 11). Interestingly, no evidence exists of magmatism or volcanism related to the development of the Ancestral Rocky Mountains system.

Deposition of the Chinle Formation

The clastic detritus (fragments of preexisting rocks) that eroded from highlands and accumulated in adjacent basins of the Ancestral Rocky Mountains system formed Pennsylvanian and Permian bedrock such as the Supai Formation and De Chelly Sandstone, which are exposed in Canyon de Chelly National Monument (north of the historic site). By the time the historic site's bedrock (Chinle Formation) was deposited, however, the Ancestral Rocky Mountains were no longer the dominant source of sediment.

The Chinle Formation was deposited between about 230 million and 210 million years ago (Richard et al. 2000). 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 12). The Chinle Formation was deposited in an elongated basin that 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 continent about 230 million years ago (i.e., when deposition of the Chinle Formation started). 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 12). Deposition of the Chinle Formation ushered in the continental sedimentation that has dominantly characterized the region ever since (Riggs et al. 2016).

Figure 12. Paleogeographic map of the Late Triassic Period (about 220 million years ago). The supercontinent Pangea is still intact, and the Chinle Formation is being deposited by rivers flowing across the continent toward Panthalassa. The source of river sediment is primarily the Cordilleran arc, but the Ouachita-Marathon belt and the Appalachian Mountains also are sources. A red star marks the location of the historic site. Base paleogeographic map by Ron Blakey, "Paleogeography of Southwest North America," © 2012 Colorado Plateau Geosystems Inc, used under license; see https://deeptimemaps.com/ (accessed 13 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 in the Late Cretaceous Period (about 80 million years ago), 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 1875; Tweto 1975). Over the years, however, uplifted mountain ranges have become the most recognizable Laramide feature (Blakey and Ranney 2018). A commonly cited plate tectonics mechanism for the Laramide Orogeny is shallow-slab or flat-slab (low-angle) subduction (Saleeby 2003; Figure 13).

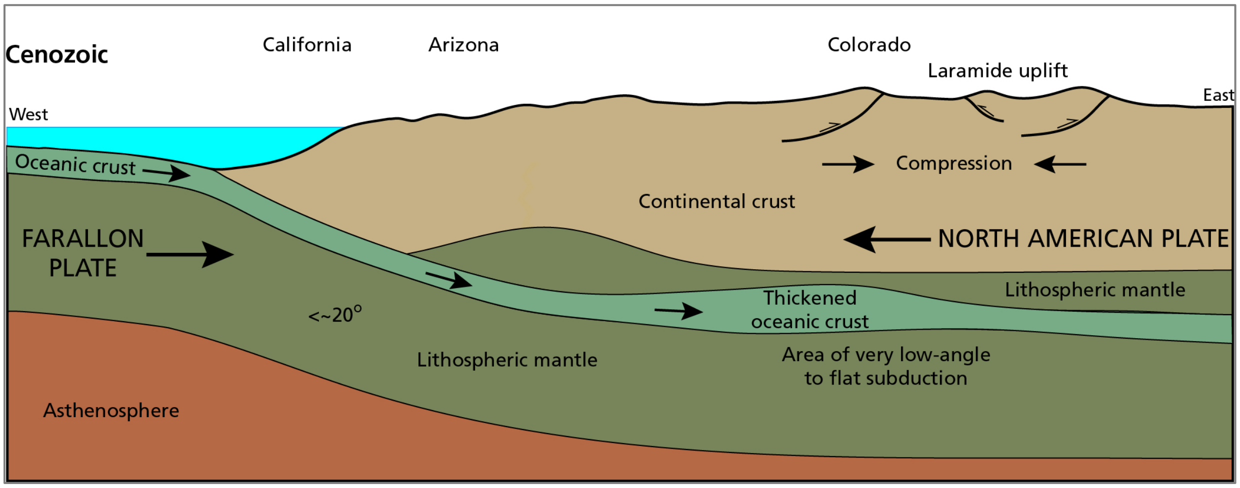


Figure 13. Schematic cross section of flat-slab subduction. A commonly cited plate tectonics mechanism for the Laramide Orogeny is flat-slab subduction, which is also called “shallow-slab” or “low-angle” subduction. About 80 million years ago (Cretaceous Period), as the Farallon oceanic plate slid beneath 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).

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, compression caused westward tilting, created significant folds, and reactivated the Defiance uplift during the orogeny. Large folds, such as the Defiance uplift, appear to be associated with ancient, steeply dipping fault zones (Davis 1984).

Inclined layers of rock are representative of the folding caused by the Laramide Orogeny. On a geologic map (see poster), symbols that show strike (trend of the strata across the landscape) and dip (direction the rocks are dipping) depict these inclined beds. Near the historic site, the general strike of the rocks is north-northwest–south-southeast; dip is to the southwest. Strike and dip, referred to as "geologic attitudes," reflect the uplifted Defiance uplift as well as the core of the Rocky Mountains northeast of the historic site.

Entrenchment of the Colorado River System

During the early Neogene Period (Miocene Epoch, 23 million–5.3 million years ago), streams predating the Colorado River system flowed across the surface of the Colorado Plateau. No integrated outlet off the elevated region existed yet. Streams may have drained into internal basins where they formed ephemeral lakes, but evidence is lacking and makes this interpretation speculative. The one possible exception, however, is "Hopi Lake" (also referred to as "Lake Bidahochi"), which is represented by the Bidahochi Formation. The Bidahochi Formation rests atop mesas in the vicinity of the historic site (see "Bidahochi Formation").

Pueblo Colorado Wash and its tributaries are part of the Colorado River system (see "Fluvial Features and Processes"), and drainage development at the historic site is connected to this system. The timing of initial downcutting by the Colorado River system is uncertain but is known to predate initial 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). Notably, the lower Colorado River drainage became established when the San Andreas Fault ripped open the Gulf of California. This 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 (lowest level toward which erosion of Earth's surface progresses, ultimately sea level) would have caused the Colorado River on the plateau 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 vicinity of the historic site took place during four erosional events that correspond to four widespread erosion surfaces. These surfaces were not mapped on the source map (Hackman and Olson 1977), so they do not appear in the GRI GIS 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). The four erosional events are as follows:

1. Miocene Epoch: Valencia cycle—Streams that flowed on the Valencia surface initiated the Colorado River system (Cooley et al. 1969). The Valencia cycle is named from the Valencia surface (Cooley and Akers 1961).
2. Pliocene Epoch: Hopi Buttes-Zuni cycle, undifferentiated—During the early part of the Hopi Buttes-Zuni cycle, accelerated downcutting entrenched the ancestral Colorado and Little Colorado River systems 300–460 m (1,000–1,500 ft) below the level of the Valencia surface. In the ancestral valley of the Little Colorado River, the lower member of the Bidahochi Formation was deposited on the Hopi Buttes surface (see poster and Figure 14); the upper

member (**Tbu**) was deposited on the Zuni surface (Cooley et al. 1969). The Hopi Buttes-Zuni cycle is named from the Hopi Buttes (Gregory 1917) and Zuni (McCann 1938) surfaces.

3. Late Pliocene and early Pleistocene Epochs: Black Point cycle—On mesa tops near the historic site, remnants of the early Black Point surface (late Pliocene) and late Black Point surface (early Pleistocene) cut across the Bidahochi Formation (**Tbu**). As mapped by Hackman and Olson (1977), alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) cover the Black Point surface (see poster). The Black Point cycle was named from the Black Point surface (Gregory 1917).
4. Middle and late Pleistocene Epoch: Wupatki cycle—Canyon cutting continued during this cycle, for example, at Canyon de Chelly National Monument (see GRI report by KellerLynn 2024). The Wupatki cycle is named from the Wupatki surface (Childs 1948).

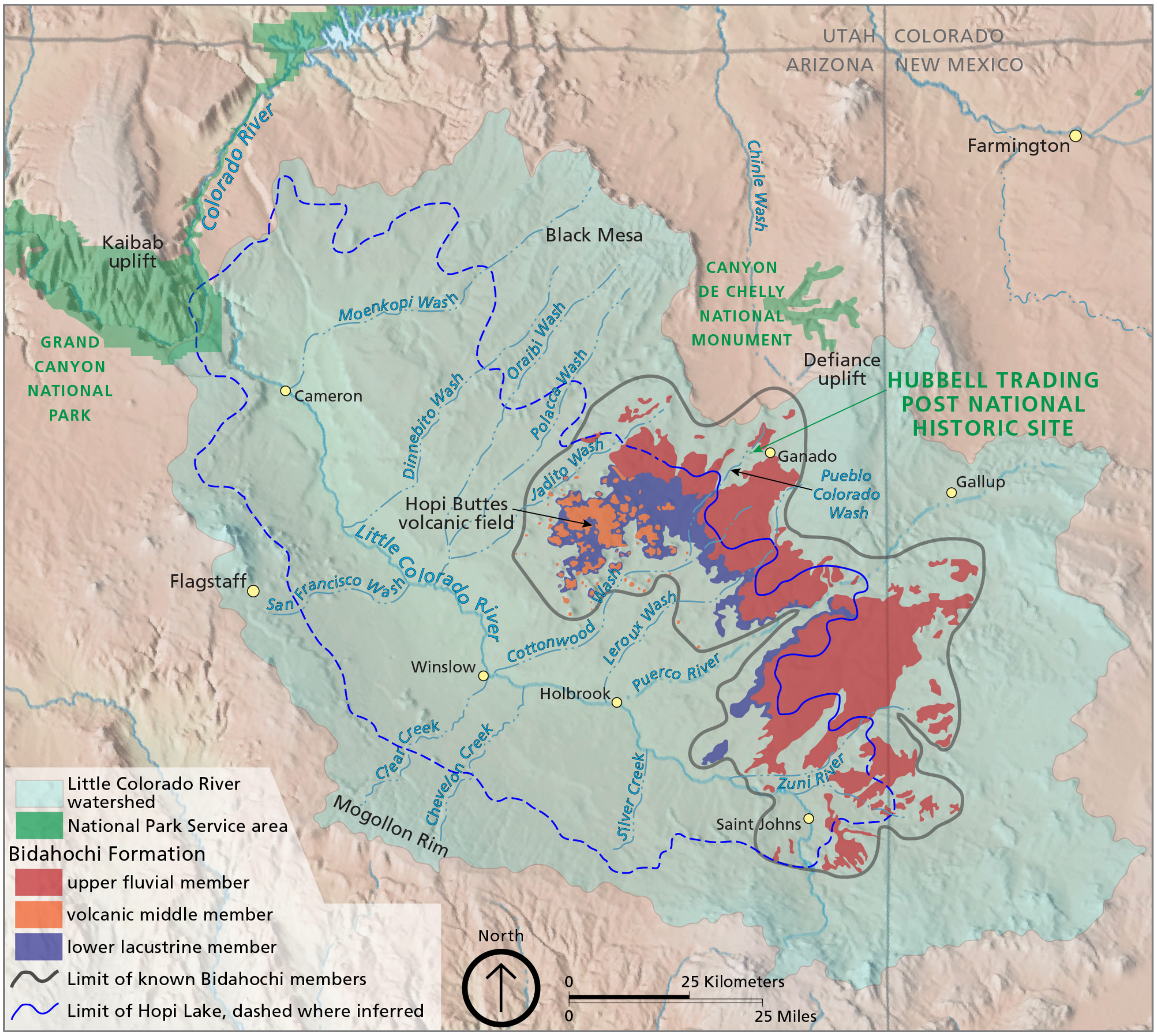


Figure 14. Map of the Little Colorado River watershed and the Bidahochi Formation. The Little Colorado River, a tributary from the southeast, empties into the Colorado River at the head of the Grand Canyon. Between 16 million and 6 million years ago (Miocene–Pliocene Epochs), the Bidahochi Formation was deposited in the ancestral Little Colorado River valley. The map shows the three informal members of the Bidahochi Formation as well as the limit of Hopi Lake. Arrows point to the historic site, Pueblo Colorado Wash, and the Hopi Buttes volcanic field. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Repenning et al. (1958, figure 3), Dallegge et al. (2003, figure 1), and Dickinson (2013, figure 2). NPS base map by Tom Patterson.

Entrenchment (the downward incision of a river through surficial deposits and into bedrock) of the Colorado River system was at its maximum during the late Pliocene and Pleistocene Epochs (Cooley et al. 1969), or about 3.6 million–11,700 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). Along the Little Colorado River (into which Pueblo Colorado Wash drains), entrenchment between Cameron and Winslow (Figure 14) was about 300 m (1,000 ft). In the upper reaches of Chinle Wash (north of the historic site), the Chaco River (in New Mexico), and the south-flowing tributaries of the Little Colorado River, including Pueblo Colorado Wash, entrenchment was generally less than 180 m (600 ft).

Regional downcutting continued intermittently throughout the Pleistocene Epoch and is recorded by several levels of terraces (former valley floors or floodplains) preserved along large streams (Cooley et al. 1969) such as the Little Colorado River. Changes in the stream regimen since the Pleistocene Epoch are indicated by alternating periods of erosion and deposition in all canyons and valleys in the Little Colorado River watershed, though the number, magnitude, and duration of events differ from drainage to drainage and along reaches of the same drainage. These differences are indicated by the distribution of terraces and local areas of alluviation (deposition of alluvium) along the present main drainageways (Cooley et al. 1969). The alluvial terraces along Pueblo Colorado Wash (see Figure 5), which are natural and not to be confused with the agricultural terraces constructed by the Hubbell family, are part of the drainage development of the Little Colorado River and its tributaries during the Holocene Epoch and historic times (see "Fluvial Features and Processes").

Geologic Time Scale

The geologic time scale (Table 2) is divided into the following columns:

Period/Eon and Epoch—The first two columns show the divisions of geologic time, which are in stratigraphic order; that is, the oldest divisions and rock units are at the bottom, and the youngest are at the top.

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 regional or specific age for a rock unit or geologic event is known, that age and a citation are included on the table.

Geologic Map Unit—All map units in the GRI GIS data are included on the table, but only the following two map units occur within the historic site: (1) the Chinle Formation, Monitor Butte Member (**TRcmb**) (now correlated with the Bluewater Creek Member; see "Chinle Formation"), and (2) alluvium and/or eolian deposits (**Qae**).

Geologic Event—By reading the geologic events from bottom to top, a geologic history is provided. Detailed descriptions of geologic events and associated geologic features are given in this chapter and in the "Geologic Features and Processes" chapter. In general, timing of geologic events follows interpretations from the geologic source map (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 within and/or near the historic site.

Items in parentheses in the geologic time scale (Table 2) include GRI map abbreviations for geologic time units such as era, period, and epoch. For example, "**TR**" in a map unit symbol indicates that these rocks were deposited during the Triassic Period (251.9 million–201.3 million years ago). "**Q**" stands for the Quaternary Period (the past 2.6 million years). In a map unit symbol, lowercase letters represent the name of a map unit; for example, "**cmb**" in **TRcmb** stands for the Chinle Formation ("**c**"), Monitor Butte Member ("**mb**"). In **Qae**, "**a**" stands for alluvial deposits (sediments deposited in stream channels), and "**e**" stands for eolian deposits (sediments deposited by the wind).

"**T**" in a map unit symbol—for example, the Bidahochi Formation, upper member (**Tbu**)—stands for "Tertiary," which is no longer a formally accepted period of geologic time by the International Commission on Stratigraphy (2023). However, Tertiary is still commonly used in geologic mapping projects in the United States, and because the source map and GRI GIS data use this term, so does this GRI report. Two periods—the Paleogene (66.0 million–23.0 million years ago) and Neogene (23.0 million–2.6 million years ago)—have formally replaced the Tertiary. These two periods are further divided into five epochs, oldest to youngest: Paleocene, Eocene, Oligocene, Miocene, and Pliocene.

Table 2. Geologic time scale.

Period/Eon	**Epoch**	**Boundary Age**	**Geologic Map Unit**	**Geologic Event**	**Location**
Quaternary (Q)	Holocene (H) and Pleistocene (PE)	Less than 2.6 million years ago	Alluvial and/or eolian deposits (**Qae**)	• Winds erode, transport, and deposit sediments. • Fluvial development includes narrowing and deepening of channels, changes in the length of perennial reaches of streams, and the general decline of streamflow (Cooley et al. 1969). • Changes in the stream regime create terraces (mapped by Euge 1983; see Figure 5).	• **Qae** covers most of the historic site's surface. • Pueblo Colorado Wash
Quaternary (Q)	Holocene (H) and Pleistocene (PE)	Less than 2.6 million years ago	Alluvial and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**)	Deposition of sediments on the Black Point erosion surface	• None within the historic site • Atop dissected surfaces of **Tbu** on mesa tops near the historic site
Tertiary (T) or Neogene (N)	Pliocene (PL)	5.3 million–2.6 million years ago	Bidahochi Formation (**Tbu**) provides evidence for the entrenchment of the Colorado River system	• The Colorado and Little Colorado Rivers join. • The Gulf of California opens (between 4.8 million and 4.63 million years ago; Crow et al. 2021). • Incision of the Grand Canyon starts about 6 million years ago.	Mesa tops near the historic site

Table 2 (continued). Geologic time scale.

Period/Eon	Epoch	Boundary Age	Geologic Map Unit	Geologic Event	Location
Tertiary (T) or Neogene (N) and Quaternary (Q)	Miocene (MI)–Pleistocene (PE)	23.0 million–11,700 years ago	Erosion surfaces of Cooley et al. (1969)	Drainage development of the Colorado River system creates four erosion surfaces.	• None within the historic site • The Black Point surface cuts across the Bidahochi Formation near the historic site.
Tertiary (T) or Neogene (N)	Pliocene (PL) and Miocene (MI)	23.0 million–2.6 million years ago *Note*: Deposition of the Bidahochi Formation begins about 16 million years ago and ends about 6 million years ago (Dallegge et al. 2003; Douglass et al. 2020; Heizler et al. 2021).	Bidahochi Formation, upper member (**Tbu**)	The upper fluvial member of the Bidahochi Formation is deposited in the ancestral valley of the Little Colorado River (Figure 14).	• None within the historic site • Mesa tops near the historic site
Tertiary (T) or Paleogene (PG) Cretaceous (K) Jurassic (J)	Oligocene (OL), Eocene (E), and Paleocene (EP) Late/Upper Early/Lower Late/Upper Middle Early/Lower	201.4 million–23.0 million years ago *Note*: The Laramide Orogeny occurs 80 million–50 million years ago.	• Inclined beds • Unconformity	Laramide Orogeny: • Compressive forces create an assortment of folds; faults occur locally. • Reactivation of the Defiance uplift. • Initial uplift of the Colorado Plateau.	Inclined beds are exposed west of the historic site (see poster).

Table 2 (continued). Geologic time scale.

Period/Eon	**Epoch**	**Boundary Age**	**Geologic Map Unit**	**Geologic Event**	**Location**
Triassic (TR)	Late/Upper	251.9 million–201.4 million years ago *Note*: The Chinle Formation was deposited about 230 million–210 million years ago (Richard et al. 2000).	Chinle Formation: • Owl Rock Member (**TRco**) • Petrified Forest Member, upper part (**TRcpa**) • Petrified Forest Member, Sonsela Sandstone Bed (**TRcps**) • Petrified Forest Member, lower part (**TRcpb**) • Monitor Butte Member (**TRcmb**) *Notes*: Following Lucas and Hayden (1989), **TRcmb** is now correlated with the Bluewater Creek Member. Following Martz et al. (2012), **TRcps** is now recognized as the Sonsela Member.	• Pangea starts splitting apart about 200 million years ago. • The Colorado Plateau is near sea level. • A widespread river system spreads sediments across the continent (see Figure 12). • **TRco**—mostly lacustrine in origin; forms ledgy slopes • **TRcpa**—fluvial; forms badlands and rolling slopes • **TRcps**—fluvial; forms ledges and benches • **TRcpb**—fluvial; forms badlands and rolling slopes • **TRcmb**—mostly fluvial in origin; forms irregular ledges and slopes	• **TRcmb** crops out at the southeastern tips of the historic site (see poster). • Hubbell Hill (northwest of the historic site) is composed of **TRcmb** (see poster).
Triassic (TR) Permian (P)	Middle Early/Lower Lopingian Guadalupian	273.0 million–~237 million years ago	Unconformity—a gap of about 50 million years in the rock record of the Colorado Plateau	The supercontinent Pangea reaches its greatest extent about 250 million years ago.	None within the historic site
Permian (P)	Cisuralian	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 (e.g., at Canyon de Chelly National Monument).	• None within the historic site • Exposed northeast of the historic site (see poster)
Pennsylvanian (PN)	Late/Upper Middle Early/Lower	323.2 million–298.9 million years ago	n/a	Newly uplifted mountains (i.e., Ancestral Rocky Mountains) supply abundant sediments to depositional environments.	None within the historic site

Table 2 (continued). Geologic time scale.

Period/Eon	Epoch	Boundary Age	Geologic Map Unit	Geologic Event	Location
Mississippian (M) Devonian (D) Silurian (S) Ordovician (O) Cambrian (C)	Not used in this report; see International Commission on Stratigraphy (2023) for a breakdown.	538.8 million–323.2 million years ago	n/a *Note*: Neither Ordovician nor Silurian rocks are found on the Colorado Plateau.	Starting about 335 million years ago, the supercontinent Pangea starts assembling from existing continental crust.	None within the historic site
Proterozoic (Z, Y, or X)	Not used in this report; see International Commission on Stratigraphy (2023) for a breakdown.	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. • Earth's nascent crust assembles, and an early system of faults forms.	• Arizona's oldest rocks form about 1.75 billion years ago. • None within the historic site
Archean	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 in Arizona. • None within the historic site
Hadean	n/a	4.6 billion–4.0 billion years ago	n/a	Planet Earth forms.	No representative Earth rocks

Geologic Features and Processes

This chapter highlights the geologic features and processes of significance for the historic site's landscape and history. Selection of these features and processes was based on input from scoping and follow-up meeting participants, 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).

Chinle Formation

Map unit: **TRcmb**

The bedrock at the historic site is the Chinle Formation (see poster), which was named for the beautiful exposures in the Chinle Valley (Gregory 1916a, 1916b, 1917), north of the historic site. The Chinle Formation was deposited about 230 million–210 million years ago (Richard et al. 2000).

The Chinle Formation is a fluvial deposit that records a range of environment settings that formed along and within rivers. These environments include solitary channels, levees along riverbanks, crevasse splays that form when a sediment-laden stream breaches a levee and deposits its material on the floodplain, local alluvial fans, floodplains, backswamps, ponded floodplain lakes, and local lacustrine deltas. These depositional settings have been documented by various researchers (Stewart et al. 1972; Blakey and Gubitosa 1983; Lupe and Silberling 1985; Dubiel 1991; Therrien et al. 1999).

In geologic terminology, a formation—such as the Chinle "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 (surface between two types or ages of rocks). A formation can be formally divided into "members" or combined into a "group." Depending on location, "Chinle rocks" are either recognized as a formation or a group. In Arizona, Colorado, New Mexico, Nevada, Texas, and Utah, these rocks are primarily mapped as a formation. In parts of New Mexico and Texas, however, they are mapped as the Chinle Group (Geolex, accessed 22 March 2023).

Since the early 1990s, the stratigraphic nomenclature of the Chinle Formation has been undergoing revision. Geologic correlation and reinterpretation of the formation at Petrified Forest National Park (south of the historic site) have received widespread recognition (Raucci et al. 2006; Martz and Parker 2010; Martz et al. 2012). Table 3 shows the current "working" stratigraphy at Petrified Forest National Park with correlation to western New Mexico and northeastern Arizona as well as to the historic site.

Table 3. 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**	**Hubbell Trading Post National Historic Site**
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).
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 Monitor Butte Member (as mapped by Hackman and Olson 1977).
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 historic site.

Source map authors (Hackman and Olson 1977) mapped the historic site’s bedrock as the Monitor Butte Member of the Chile Formation (**TRcmb**); Euge (1983) did likewise. However, the Monitor Butte Member is 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). Lucas and Hayden (1989) propose 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 north end of Monitor Butte is the type section (place where a formation is most clearly revealed and, typically, where it was originally described; 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 is dominantly gray-red and red-brown sandstone, silty mudstone, and sandy siltstone (Lucas and Hayden 1989).

Euge (1983) subdivided the so-called “Monitor Butte Member” (p. 10) into six beds: three sandstones, a claystone, a claystone/clayey siltstone, and a sandy mudstone (see Figure 5; for an explanation of rock types, see Table 1). That mapping effort provides greater detail than the source map (Hackman and Olson 1977). The claystone, mudstone, and clayey siltstone beds of Euge (1983) are the loose, non-resistant, nearly level deposits that weather to rounded buttes and smooth slopes common in the Ganado area. These sediments were deposited in lakes and on floodplains. The thin, resistant cap rocks near the top of Hubbell Hill are composed of sandstone as is one location in Pueblo Colorado Wash (Figure 15). The sandstone cap on Hubbell Hill is probably a stream channel deposit. The climbing ripple laminations in the sandstone, a short distance below the top of Hubbell Hill, indicate a floodplain environment (Euge 1983).

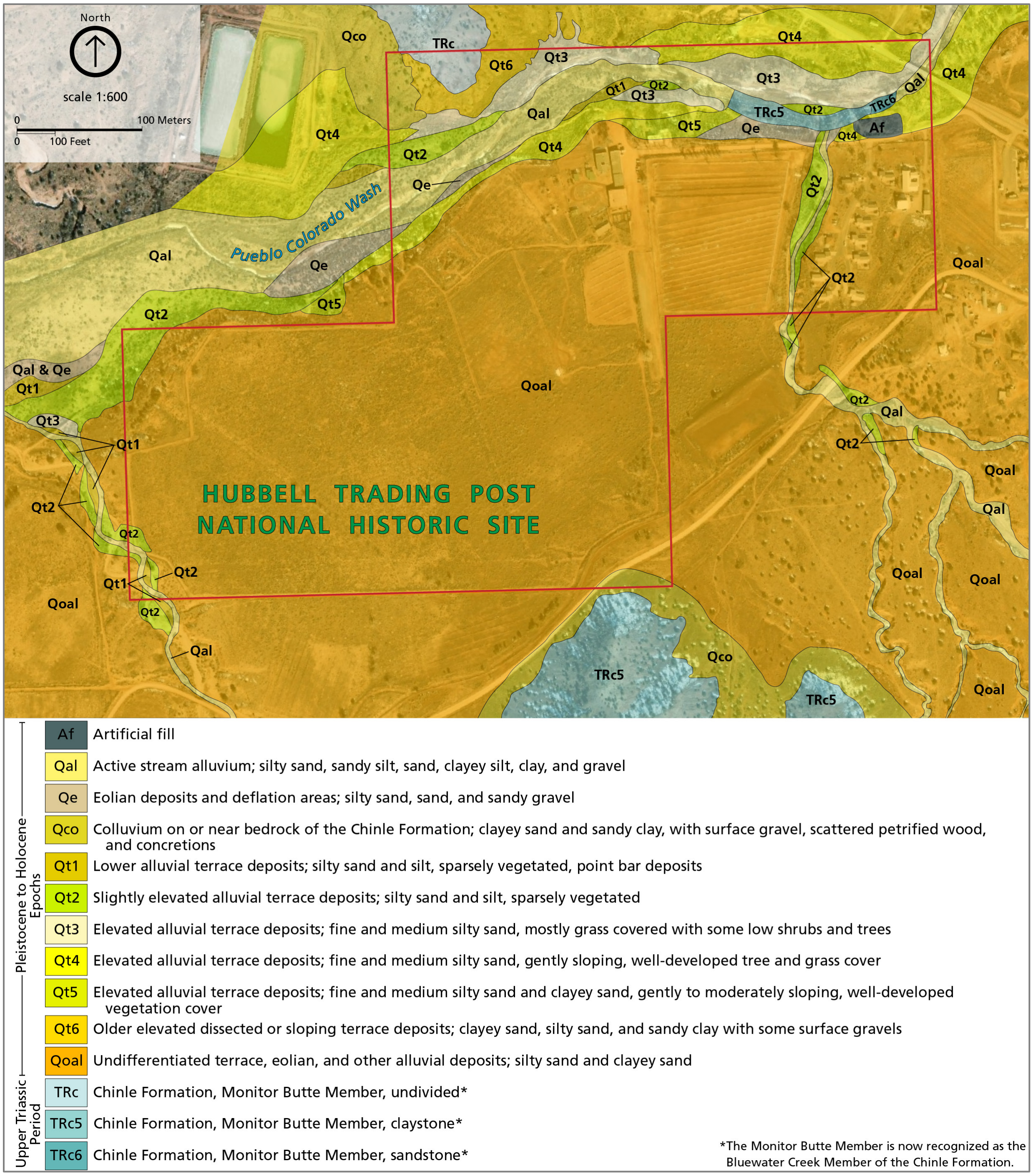


Figure 15. Geologic map by Euge (1983). Most of the historic site, including gently sloping previously cultivated farm fields, is underlain by unit Qoal, which is undifferentiated terrace, eolian, and alluvial deposits. Also, a series of six alluvial terraces, from oldest to youngest, Qt6–Qt1, step up from the active stream channel (unit Qal). Bedrock—the Monitor Butte Member of the Chinle Formation (now recognized as the Bluewater Creek Member of the Chinle Formation)—is exposed at Hubbell Hill (unit TRc), at the southern boundary (TRc5), and in the stream channel (TRc5 and TRc6). See Figure 5 of this report for descriptions of the Chinle Formation as mapped by Euge (1983). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Euge (1983, plate 1). Base imagery by Esri World Imagery.

Petrified Wood and Other Fossils

Near the historic site, the most notable fossils are petrified wood, which are the fossilized remains of conifer trees (Figure 16). Petrified wood is formed by minerals replacing the original organic material of the plant. In other words, these fossils are trees that have turned to stone (Santucci et al. 2021b). The petrified wood near the historic site has been recognized as part of the Monitor Butte Member of the Chinle Formation (Ash 1972a, 1972b, 1972c; 1980; 1996), which is now correlated with the Bluewater Creek Member of the Chinle Formation (see "Chinle Formation").

Figure 16. Photograph of petrified wood. When the Hubbells lived at the trading post, large specimens of petrified wood were used as garden ornaments, including borders for flower beds, and elsewhere as decorative elements. This tradition continues today. NPS photograph by Maryann Neubert (Hubbell Trading Post National Historic Site), taken 2023.

The taxonomy of the petrified wood is a vexing problem because many specimens—including those in the historic site's museum collection—are called by the venerable name *Araucarioxylon arizonicum* or, more recently, *Agathoxylon arizonicum* (see National Park Service 2012). Indeed, the state fossil of Arizona is *Araucarioxylon arizonicum*. However, to accurately identify a genus or species, microscopic examination of a thin section of the tree's xylem (plant tissue that transfers water and nutrients throughout the entire plant) is required. Unless a thin section was used for identification, a given specimen should probably just be called "petrified wood" (Justin Tweet, GRD, associate, email communication, 31 October 2023). Furthermore, based solely on the xylem structure (including resin canals, rays, and tracheid pitting), and without seed cones or DNA evidence, it is difficult to be certain of a plant's taxonomy. Complicating this problem is that the majority of this wood has been almost completely agatized, obliterating the cellular structures used to make taxonomic assignments (National Park Service 2012).

Fossils have yet to be documented in the rocks or unconsolidated deposits at the historic site, but specimens of petrified wood are thought to have been collected "from throughout the site and surrounding landscape" (Froeschauer-Nelson 1998, p. 131). Colluvium (e.g., talus and cliff debris), which occurs on or near bedrock of the Chinle Formation, is known to contain petrified wood (Euge 1983). As mapped by Euge (1983), colluvium (unit Qco) consists of clayey sand and sandy clay, with surface gravel, scattered petrified wood, and concretions (hard, compact aggregate of mineral matter, commonly rounded in shape). Sizeable deposits of unit Qco of Euge (1983) occur at the southeastern corner of the historic site and on the western side of Hubbell Hill (see Figure 15). Whether the petrified wood used as garden ornaments and other decorations at the historic site came from these deposits is unknown.

While plants are the best-known fossils from this Late Triassic stratigraphic interval, other types of fossils are known, including unionid bivalves (freshwater mussels; McRoberts and Good 1993); conchostracans (clam shrimp; Tasch 1978); coelacanths and other fish (Lucas and Hayden 1989; Parrish 1989; Murry and Kirby 2002); metoposaurid amphibians (highly flattened, mostly aquatic animal with small, weak limbs, sharp teeth, and a large, flat head); phytosaurs (semiaquatic crocodile-like carnivorous reptiles); aetosaurs (heavily armored herbivorous crocodile relatives); other reptiles (Heckert 1999); various other invertebrate and tetrapod (four-footed animal) tracks and traces (Hasiotis et al. 1994); and coprolites (fossil dung) (Heckert 1999). No such fossils have been found at the historic site to date.

Typical Quaternary fossils in the region include isolated bones of large mammals (such as sloths, proboscideans, equids, bison, and camelids) and fossil material useful for paleoecologic and paleoclimatologic studies (such as pollen and packrat [*Neotoma* spp.] middens). Given the geography of the historic site, however, isolated mammal bones, plant fragments, and pollen would be more likely than packrat middens (Tweet et al. 2009), which are typically preserved in rock shelters (a type of cave). In addition, fluvial deposits—which are made up of clasts (fragments of preexisting rocks) eroded from whatever geologic units are drained by the watercourse—commonly include fossiliferous clasts if the watercourse passes through fossiliferous rocks. However, these are usually of limited scientific value and are usually only a minor component of deposits.

Unconformity

Layers of rocks are said to be "conformable" when 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. Throughout Earth's history, the deposition of sediment has been interrupted again and again. All such breaks in the rock record are termed "unconformities" and represent long periods of time when deposition ceased and/or erosion removed previously formed rocks.

Unconformities are important because they represent significant geologic events in Earth's history, and their identification helps geologists recognize what intervals of geologic time are not represented by the strata (Lutgens and Tarbuck 1992). Unconformities are intriguing because the infinitesimal surface (contact) between adjacent rock units covers thousands, millions, or even billions of years. Many major geologic events—mountain building, regional uplift, or rise and fall of sea level—may be "collapsed" into a single horizontal surface. The layers of the Grand Canyon, which are full of "geologic gaps," illustrate the significance of unconformities. "In the Grand Canyon, much more time is absent than is represented. If a gap of five hundred million years were the right five hundred million years, it could erase the Grand Canyon" (McPhee 1999, p. 441).

Near the historic site, an unconformity encompassing 194 million years occurs between the Chinle and Bidahochi Formations (see Table 2). This gap in the rock record encompasses the Jurassic and Cretaceous Periods when one event after another—multiple orogenies, continental-scale deserts, a seaway, and regional uplift—impacted the Colorado Plateau.

Bidahochi Formation

Map unit: **Tbu**

The Bidahochi Formation was named for the settlement of Bidahochi, near Indian Wells, Arizona (Regan 1924, 1932). Bidahochi is in the Hopi Buttes volcanic field (Tsézhin Bii') southwest of the historic site (see Figure 14).

Regan (1924, 1932) did not designate a type section for the Bidahochi Formation, but later, Repenning and Irwin (1954) did. Of interest for the historic site, the type section is along Pueblo Colorado Wash. It is 24 km (15 mi) east of Bidahochi or an estimated 30 km (20 mi) downstream from the monument.

Sediments that compose the Bidahochi Formation accumulated 16 million–6 million years ago (Miocene to Pliocene Epochs; Dallegge et al. 2003), that is, while the Colorado River system was entrenching the landscape (see "Entrenchment of the Colorado River System"). Ancestral tributaries deposited Bidahochi sediments on the Zuni surface (Pliocene Epoch). Later, the Black Point surface (Pleistocene–Holocene Epochs) cut across the Bidahochi Formation. Now, the Bidahochi Formation comprises the broad, slightly dissected uplands—also called "tablelands" or referred to as "mesas"—between tributary drainages in the vicinity of the historic site (see poster).

Although the Bidahochi Formation does not occur within the historic site, the upper member (**Tbu**) tops surrounding mesas. It is the uppermost bedrock unit in the area and, as such, is significant as part of "far-reaching vistas," which are a fundamental resource and value of the historic site (i.e., part of "Trading Post and Homestead"; National Park Service 2016).

The upper member is as much as 240 m (790 ft) thick (Love 1989) and consists of predominantly white to very pale brown, poorly cemented, medium- to fine-grained argillaceous (clay-rich) sandstone (Hackman and Olson 1977). It is mostly fluvial in origin (Hackman and Olson 1977), forming in ancestral tributaries to the Little Colorado River, including the ancestral Pueblo Colorado Wash. During deposition, the upper member (**Tbu**) spread across gently sloping, pediment-like surfaces—the Zuni surface (Cooley et al. 1969; see "Entrenchment of the Colorado River System")—that were carved across interfluves (uplands) separating paleovalleys (Dickinson 2013).

A few ash beds of rhyolite (volcanic equivalent of granite) occur in the lower part of the upper member (**Tbu**). Interestingly, these ash beds are not related to the Hopi Buttes volcanic field but are interpreted as originating from distal volcanic sources (Dallegge et al. 2003), including the Heise volcanic field, which is one of seven volcanic fields along the Yellowstone hot-spot track (Figure 17). The Heise volcanic field erupted about 6.5 million–4.3 million years ago when the Yellowstone hot spot was situated under what is now Craters of the Moon National Monument and Preserve (see GRI report by KellerLynn 2018).

In addition to the upper fluvial member (**Tbu**), the Bidahochi Formation consists of two other informal members: the lower lacustrine member and the middle volcanic member (see Figure 14). The lower lacustrine member is interesting because of the role it has played in helping geologists decipher the timing of incision of the Grand Canyon (e.g., see Scarborough 1985; Love 1989; White 1991; Vazquez 1998; Dallegge 1999; Dallegge et al. 2000, 2003; Meek and Douglass 2001; Karlstrom et al. 2011; Dickinson 2013; Douglass et al. 2020; Anderson et al. 2021; Potochnik et al. 2022). The middle volcanic member is interesting because of its connection to the Hopi Buttes volcanic field (e.g., see White 1991; Amoroso et al. 2013). In contrast to the rhyolitic (light-colored, rich in potassium and sodium) ash beds in the upper member (Tbu), which came from a distal source, the ashes in the middle member are mafic (dark-colored, rich in magnesium and iron) and originated in the Hopi Buttes volcanic field. Eruptions of the Hopi Butte volcanic field were phreatomagmatic (also referred to as "hydrovolcanic"), resulting from the interaction among lava, magmatic heat, or gases and water at or near Earth's surface.

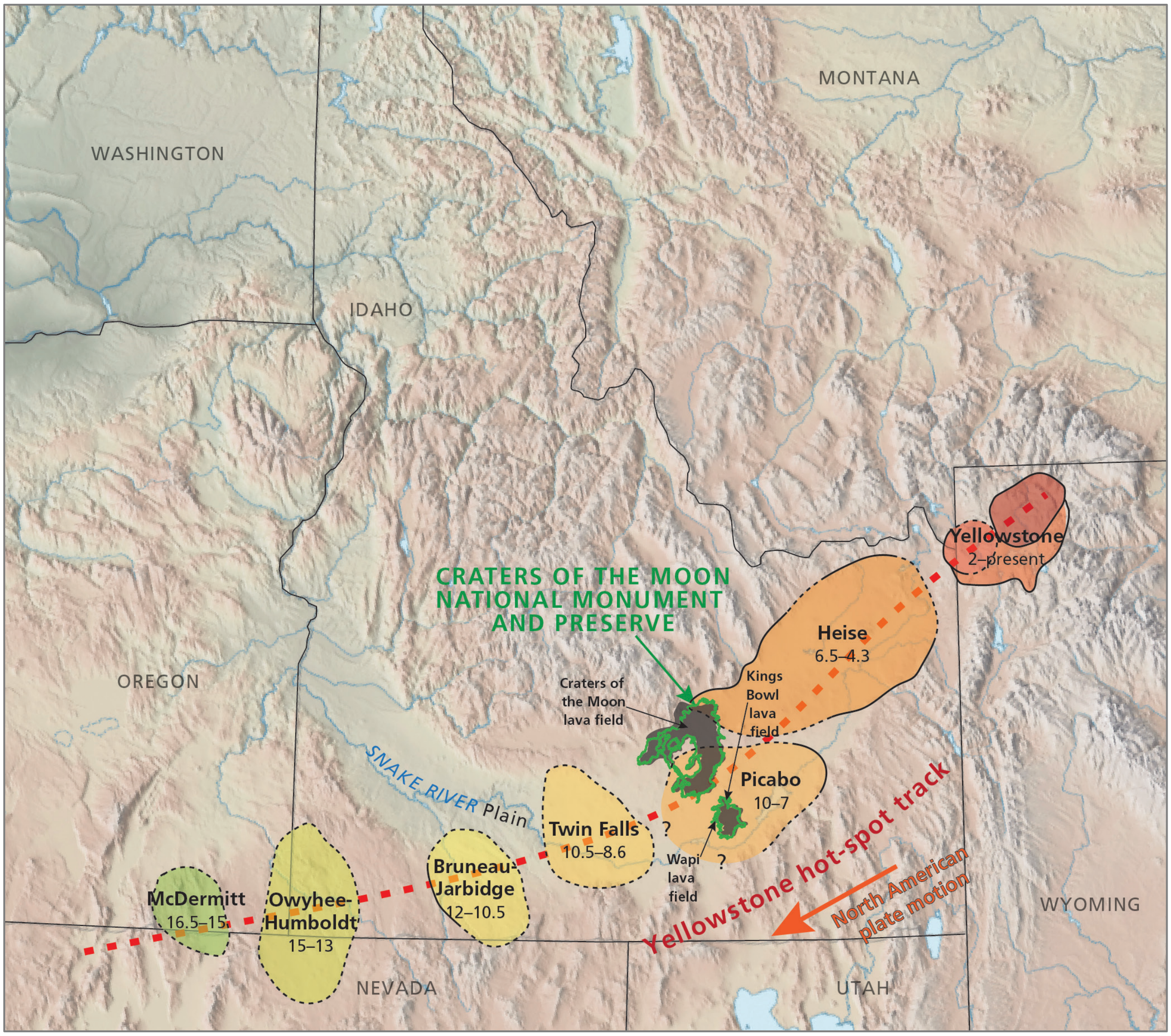


Figure 17. Map of the Yellowstone hot-spot track. The Yellowstone hot-spot track is composed of seven volcanic fields. When the Heise volcanic field was erupting between 6.5 million and 4.3 million years ago, rhyolitic ash from this and other distal sources became incorporated into the lower part of the upper member of the Bidahochi Formation (Tbu). At that time, the hot spot was situated under Craters of the Moon National Monument and Preserve, which is about 240 km (150 mi) southwest of where the hot spot now lies below Yellowstone National Park. The hot spot has remained stationary as the North American plate has moved to the southwest (arrow). On the figure, ages in millions of years of the various volcanic fields indicate this progression, starting with the McDermitt volcanic field (approximately 16.5 million–15 million years ago). Ages from Smith and Siegel (2000). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University). NPS base map by Tom Patterson.

Fluvial Features and Processes

Map units: **Qao**, **Qae**

In places, uplands composed of the Bidahochi Formation are covered by alluvial and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**). These deposits consist of brown clay and silty sand and gravel; they are commonly cemented by caliche (calcium carbonate [$CaCO_3$] on or near the surface in arid and semiarid regions) and veneered with eolian deposits (Hackman and Olson 1977). Deposition of this material began in the Pleistocene Epoch (2.6 million–11,700 years ago).

Starting in the Pleistocene Epoch and continuing to the present day, unit **Qae** (alluvial and/or eolian deposits) represents modern fluvial activity. Except for a couple exposures of the Chinle Formation, this material covers the surface of the historic site (see poster). These deposits consist of windblown silt and sand (see "Eolian Features and Processes") on mesas, benches, and in broad valleys that are reworked, in part, by running water.

The principal drainage through the historic site is Pueblo Colorado Wash. Pueblo Colorado Wash and other large tributaries of the Little Colorado River occupy alluviated (characterizing deposition of alluvium) valleys between bluffs composed of the Bidahochi Formation. Draining southwestward from the Defiance Plateau, Pueblo Colorado Wash is a tributary of the Little Colorado River that is, in turn, a tributary of the Colorado River (see Figure 14). Pueblo Colorado Wash is approximately 130 km (81 mi) long (Esri 2020) and has both intermittent and perennial segments (US Geological Survey 2015). A perennial segment—790 m (2,600 ft) long—is within the historic site.

In addition, two unnamed, intermittent tributaries cross the historic site; one lies west of the employee housing area, and the other is at the southwest corner of the historic site (see Figure 15). The streams are generally dry, and they respond to runoff-producing storm activity with a rapid rise in discharge followed by a rapid decline in flow after cessation of rainfall. Intermittent streams have the capability of transporting significant quantities of bedload and suspended sediment during storm events (Euge 1983).

A geologic map by Euge (1983; scale 1:600) provides a more detailed look at the historic site's surficial deposits than the source map (Hackman and Olson 1977, scale 1:250,000). The map by Euge (1983), which was associated with a soil survey, is not part of the GRI GIS data, but Figure 15 provides a picture. As mapped by Euge (1983), most of the historic site is underlain by unit Qoal, which consists of undifferentiated terrace, eolian, and other alluvial deposits composed of silty sand and clayey sand on gently sloping, previously cultivated farmland. In addition, Euge (1983) mapped six alluvial terraces (units Qt1–Qt6), which step up from the active channel (unit Qal) to the base of Hubbell Hill (see Figure 5 and Figure 15). Overall, the terraces at the historic site indicate a history of valley filling, followed more recently by episodes of stream downcutting. Unit Qoal and terrace units Qt6 and Qt5 formed during a period of aggradation ("valley filling") between 2000 BCE and 900 to 1200 CE. Terrace unit Qt4 also formed during a period of aggradation between 1100 and 1300 CE. Terrace units Qt1, Qt2, and Qt3 developed as a result of downcutting between 1950 and 1920 CE (Euge 1983).

The unnamed tributary at the southwest corner of the historic site has as many as three terraces (units Qt1, Qt2, and Qt3 of Euge 1983). Three terraces indicate a longer development history than the unnamed tributary west of the housing area, which has only two terraces (units Qt1 and Qt2; see

Figure 15). Based on mapping and historic photographs, the two unnamed tributaries did not exist before 1920, at least not in their present incised form (Euge 1983). The unnamed tributary west of the housing area occupies an area that historically supported an irrigation lateral for the 6-ha (16-ac) field to the west (Froeschauer-Nelson 1998; see Figure 9).

Eolian Features and Processes

Map units: **Qae**, **Tbu**, **Pdc**

Based on the extent of **Qae** (see poster)—which Hackman and Olson (1977) describe as windblown silt and sand reworked by running water—eolian deposits may be widespread in the historic site and across the surrounding landscape. However, because the source map (Hackman and Olson 1977; scale 1:250,000) combined alluvial (stream) and eolian (windblown) deposits into a single map unit, the relative significance is unclear.

More detailed mapping by Euge (1983; scale 1:600) shows separate eolian deposits and deflation areas (unit Qe) along Pueblo Colorado Wash (see Figure 15). Eolian deposits are also present in the two tributary drainages at the historic site. The source of the windblown materials is likely local; wind action removed sediment from the floodplain area and reworked some of the terrace deposits at the historic site (Euge 1983). This activity is ongoing.

Larger eolian features are shown on a sketch map by Cooley et al. (1969, figure 14 [in that report]), including longitudinal dunes in the vicinity of the historic site. Longitudinal dunes are long and narrow, usually symmetrical in cross profile, and characteristically wider and steeper on the windward side and tapering to a point on the leeward side. The orientation of longitudinal dunes is parallel with the direction of the prevailing wind. Because the prevailing wind direction is southwesterly, the orientation of the dunes in the vicinity of the historic site is northeast. These dunes are Holocene and late Pleistocene in age and, therefore, considered active. In addition, eroded longitudinal dunes of Pleistocene age are located atop mesas in the vicinity of the historic site (i.e., on the Black Point surface that overlies the Bidahochi Formation). These dunes have been eroded considerably and are distinguishable from the younger, well-formed longitudinal dunes in this area.

Cross-beds (inclined sedimentary layers) in the Bidahochi Formation, which was deposited 16 million–6 million years ago, indicate that prevailing wind direction at that time was from the southwest. Farther back in time—during the early Oligocene Epoch (33.9 million–27.8 million years ago) and possibly the Eocene Epoch (approximately 56.0 million–33.9 million years ago)—cross-beds in the Chuska Sandstone, which is exposed in the Chuska Mountains east of the historic site, indicate that the prevailing wind direction also was from the southwest. Thus, possibly as far back as 56 million years ago, wind direction and transport, at least during times of preserved eolian deposition, are generally the same as the present wind pattern (Wright 1956; Cooley et al. 1969). However, about 275 million years ago, the Permian sand dunes of the De Chelly Sandstone (**Pdc**; see poster) were deposited by northeasterly winds (Blakey and Knepp 1989; Blakey 1990, 1996). These winds created the stunning cross-beds now displayed in the walls of Canyon de Chelly (see the GRI report about Canyon de Chelly National Monument by KellerLynn 2024).

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 provides technical and policy assistance for these issues (see “Guidance for Resource Management”). The issues are ordered alphabetically, not with respect to management priority.

Climate Change Planning

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.

The following three documents provide climate change information specific to the historic site: (1) weather and climate inventory (Davey et al. 2006), (2) climate change resource brief (Monahan and Fisichelli 2014), and (3) park-specific resource brief about how future warming might alter visitation (Fisichelli and Ziesler 2015).

The Southern Colorado Plateau Inventory & Monitoring Network monitors climate at the historic site (e.g., see Southern Colorado Plateau Network 2022b). Several vital signs (measurable parameters of the overall condition of natural resources) will likely show the effects of climate change; some of these vital signs include geologic indicators of change, for example, upland vegetation and soil, and groundwater and spring ecosystems.

The historic site’s foundation document (National Park Service 2016) identifies a climate change vulnerability assessment as a data need; it also identifies adaptation to climate change as a planning need. Park managers are directed to the NPS Climate Change Response Program (see “Additional References, Resources, and Websites”) to address climate change planning. Also, discussions with the Navajo Nation Climate Change Program (see “Additional References, Resources, and Websites”) seems warranted because applying traditional knowledge to climate change planning has the potential to enhance and improve the planning process and outcomes.

The foundation document (National Park Service 2016) states that information regarding resources susceptible to anticipated climate change impacts should be collected. As such, the following list of geologic features and processes, which is ordered alphabetically, may be of use:

- Colorado River system. Higher temperatures are amplifying drought in the Colorado River basin. Since 2000, Lake Mead on the Colorado River has fallen 40 m (130 ft) and lost 60% of its volume, a result of the ongoing drought and continued water withdrawals by cities and agriculture (Gonzalez et al. 2018).
- 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, building facades, 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. Also, prolonged drought may increase the number and magnitude of dust storms, which cause lower visibility and safety hazards for drivers.

- Erosion. Climate change may induce changes in dominant processes (e.g., snowmelt, rainfall, and growth of vegetation), resulting in new patterns of erosion and deposition (Brazier et al. 2012). An increase in storm frequency and intensity, which is projected (Wuebbles et al. 2017), could accelerate current erosion rates. Also, increases in mean annual temperature and extreme heat events projected for the region could impact fundamental resources and values (e.g., "Trading Post and Homestead") through erosion. While increased erosion may destroy geologic heritage features and change the dynamics of geomorphic processes, new exposures of geologic heritage significance may also be revealed (Gordon et al. 2022).
- Groundwater. Future climate scenarios predict declines in the recharge of varying magnitudes of groundwater in the US Southwest (Meixner et al. 2016). Declines in recharge could lower the groundwater table and decrease discharge at springs and in wells. Changes in groundwater may affect preservation of organic deposits (Gordon et al. 2022).
- Landforms and geomorphic processes. Understanding landscape history and learning from past changes recorded in landforms will help to indicate how geomorphic systems will adapt to the speed and scale of projected climate change. Direct impacts from climate change will principally arise through changes in geomorphic processes and in vegetation cover. Geologic features may be lost to greater erosion or become obscured by sediment deposition and increased vegetation cover. Geomorphic processes may become either more or less dynamic, change entirely, or cease to operate. Some geologic features (e.g., sand dunes and stream channels) may shift location, including migrating outside NPS boundaries. Because many changes in geomorphic processes will also impact biodiversity, climate change action plans for nature conservation require an integrated approach (Gordon et al. 2022).
- Pueblo Colorado Wash. The channel of Pueblo Colorado Wash widens, steepens, and straightens during summer monsoonal flood events and narrows, flattens, and lengthens (becomes more sinuous) during snowmelt discharge in the spring (Zeedyk 2004). Climate change-induced changes to storm and snowmelt patterns will change the fluvial behavior of Pueblo Colorado Wash. As the magnitude and frequency of storms increase, river systems may become more dynamic, resulting in more erosion, channel changes, and changes in sediment transport. More frequent or intense storms could increase the vulnerability of park infrastructure, resources, and archeological sites (e.g., on alluvial terraces along Pueblo Colorado Wash). Also, increasing numbers of small events have the capacity to transfer large volumes of sediment from tributary channels to the main channel of Pueblo Colorado Wash (Zeedyk 2004).
- Runoff and sediment loading. An increase in the relative amount of snowmelt runoff, compared to that derived from summer storm events, could induce channel entrenchment in Pueblo Colorado Wash because of the different sediment loads associated with runoff from

each source. The sediment loading of snowmelt runoff is generally less than that of rainstorm runoff because, for example, a more erosion-resistant vegetation cover tends to exist in upland areas where snow accumulates. A reduction in the sediment loading of flow into Pueblo Colorado Wash could increase its erosive capacity and lead to erosion and incision (Euge 1983).

- Wildfire, slope movements, and soil erosion. The area burned by wildfire across the western United States from 1984 to 2015 was twice what would have burned had climate change not occurred (Gonzalez et al. 2018). Moreover, fire frequency on a global scale may increase by as much as 25% 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 2015 and 2021b, respectively). Where droughts persist, loss of vegetation cover from increased wildfires will increase the risk of soil erosion.

Erosion

Erosion is the wearing away of the land surface by water, wind, ice, or other natural or anthropogenic agents that abrade, detach, or remove geologic parent material or soil from one point on Earth's surface and transport it to another (Soil Science Society of America 2022). Accelerated erosion is erosion in excess of natural rates, usually as a result of anthropogenic activities (Soil Science Society of America 2022), such as over tillage of farm fields or garden plots; concentrated runoff from paved or other hard-packed surfaces; and surface water "speedways" created during the burial of cable, phone, and fiberoptic lines. In general, erosion is distinct from weathering, which involves no movement, and from mass wasting (e.g., landslides or debris flows), which involves movement under the force of gravity.

Heavy rainfall—including associated runoff and heavy raindrop impacts—is a primary agent of erosion at the historic site (National Park Service 2016). Also, strong winds are an agent of erosion. In addition, human activities, including past attempts at controlling erosion, are responsible for erosion damage.

The following examples of erosion have taken place at the historic site:

- Archeological sites. Erosion results in the easy identification and degradation of archeological sites. Structural features at the site known as Wide Reed Ruin have been exposed as a result of slumping soil and illegal collection activities.
- Entrance road. Runoff from roads is a disturbance that causes erosional gullies (see the scoping summary by KellerLynn 2007). Historic site staff require technical assistance for implementing proper drainage from roads.
- Former farm fields. As evidence of wind erosion, nebkas (windblown mounds of soil) have built up around shrubs in former farm fields. Also, heavy summer rains cause some erosion in the fields because only a sparse cover of native plants provides protection (Regenesis Collaborative Development Group, Inc. 2005). As a protective measure, an unnamed

archeological site (in a former farm field) was backfilled and stabilized using a filter fabric material in 1984. As the loose sandy soils have been displaced by the winds that buffet the site, areas of the filter fabric are now exposed to ultraviolet radiation, which degrades the efficacy of the material (Froeschauer-Nelson 1998).

- Former floodplain (terrace) of Pueblo Colorado Wash. Many areas on the former floodplain that are isolated behind a heavily vegetated sequence of inner terraces, including several containing archeological sites, are undergoing erosion by discontinuous gullies. These gullies are not related to the base level of the major streams, nor do they form an integrated network. Most result from the localized concentration of runoff from roadways or from remnants of the irrigation network (Euge 1983).
- Gabions (metal cages filled with rocks; Figure 18). Installed in the 1970s and redone in the 1980s (Manchester and Manchester 1993), gabions were placed in Pueblo Colorado Wash as an attempt to control streambank erosion and protect archeological sites. No comprehensive study of the effectiveness of gabions is known to have taken place within the National Park System (Hal Pranger, NPS Geologic Resources Division, Geologic Features & Systems Branch, manager, email, 12 October 2022), but the value of using gabions as erosion control structures is under question (KellerLynn 2007). The construction of gabions in 1974—perhaps in combination with channel modifications such as the construction of the State Route 264 bridge—is suspected of causing increased erosion along the main wash (Euge 1983). Also, a project manual to rehabilitate the road, parking lot, and bridge at the historic site (National Park Service 1983) proposed that the installation of gabions in Pueblo Colorado Wash to protect the Wide Reed Ruin may have accelerated bank cutting downstream from the site, particularly at another archaeological site where considerable bank sloughing is taking place. Observations elsewhere in the region show that channel aggradation occurs rapidly upstream of gabions, but the apparent dampening of sediment transport by structures leads to less aggradation and even incision immediately downstream of structures (Henderson and DeLong 2012).
- Parking lot. Sudden rain events have resulted in sheet flow (overland flow, not in a channel) at the historic site (see scoping summary by KellerLynn 2007). On one occasion, the flow was great enough to transport a large log—estimated to be about 2 m (6–8 ft) long and 20–25 cm (8–10 in) in diameter (Ailema Benally, Canyon de Chelly National Monument, interpreter, email communication, 20 April 2007)—through the trading post's parking lot.
- Pueblo Colorado Wash. Erosion is taking place in the "wash along the west edge of the historic site" (National Park Service 2016, p. 12), that is, Pueblo Colorado Wash (Maryann Neubert, Hubbell Trading Post National Historic Site, museum curator/cultural resources specialist, personal communication, 27 October 2023). The wash was described as "inching closer to the boundary fence" and "widening" (National Park Service 2016, p. 12 and 13). Moreover, erosion in Pueblo Colorado Wash associated with heavy rainfall has "uncovered archeological resources and human remains. Erosion matting has been compromised, but vegetation in these areas provides some stabilization and protection from erosion" (National Park Service 2016, p. 22).

- State Route 264 bridge. The bridge over Pueblo Colorado Wash allows access to the historic site via the entrance road (see poster). The bridge restricts streamflow, which in turn increases stream energy and velocity, resulting in incision and bank erosion. Gabions near the bridge further restrict flow and increase stream velocities (Euge 1983). Erosion at this location is an ongoing concern. In winter 2022–2023, for example, erosion was notable from the bridge to down behind the visitor center. Willows held the west bank, but erosion took place in other spots between willow stands. The cottonwoods became islands (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).
- Unnamed tributary west of the housing area. The west side of the drainage has experienced some slumping and erosion. Historically, the area supported the irrigation lateral for the 6-ha (16-ac) field to the west (see Figure 9). Several of the historic stone headgates have fallen or are in the process of falling into the drainage as a result of slumping (Froeschauer-Nelson 1998).
- Visitor center (former chapter house). Following the removal of a post and wire fence that ran along the top of an embankment above the visitor center, years of uncontrolled visitor circulation caused trampling and compaction of soil around tree roots, as well as the proliferation of informal trails, which perpetuate erosion. As visitors scrambled up and down the embankment, eroding unstable soils, the exposure of the tree roots increased, degrading their overall condition and posing safety (tripping) hazards to visitors (Froeschauer-Nelson 1998).

Figure 18. Photograph of Pueblo Colorado Wash. The photograph provides a sense of Pueblo Colorado Wash and its floodplain in the historic site. Hubbell Hill is in the background. Note the gabions (bundles of rocks) that line the nearside of the wash and cut perpendicular toward it. The NPS initially installed gabions in the 1970s. Photograph by Katie KellerLynn (Colorado State University), taken 2007.

Prudent land management practices will help reduce erosion. Many state and federal documents provide guidelines (see "Guidance for Resource Management"). Past failed attempts at controlling erosion—including the installation of gabions in Pueblo Colorado Wash and the introduction of tamarisk (e.g., *Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) in the 1930s and 1940s (see "Geomorphic Change of Pueblo Colorado Wash")—should serve as cautionary tales for present-day resource managers.

Geologic Hazards

The dynamic landscapes preserved in 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 volcanoes). 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.

Table 4 summarizes the geologic hazards at the historic site. 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 4.

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 historic site. The "sources of information" listed in the table are the primary resources used to make the "best professional judgement" determination.

Explanation of hazard ratings (i.e., Best Professional Judgement in Table 4):

- Known hazard: Conditions that cause the hazard are well documented at the historic site. 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 historic site. 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 historic site. Note this is a coarse filter evaluation; local knowledge of a hazard(s) should be used when available.

Table 4. Geologic hazards checklist.

Potential Hazard	Best Professional Judgement	Risk or Secondary Hazard	Sources of Information
Active faults/earthquakes	Potential hazard	• Seismic hazard is low (Figure 19). • Natural Hazards in Arizona (online map viewer) shows three earthquakes that have occurred in Ganado: (1) magnitude (M) 5.0 in 1937 with Modified Mercalli Scale intensity (MMI) VI (i.e., felt by all, many frightened; some heavy furniture moved, a few instances of fallen plaster, damage slight); (2) M 2.6 in 1986; and (3) M 1.6 in 2008. The M 2.6 and 1.6 earthquakes correlate to MMI Scale I, which are not felt except by very few under especially favorable conditions.	• No active faults near the historic site (see poster) • Natural Hazards in Arizona (Arizona Geological Survey 2024a)
Cave/karst (e.g., contamination and sinkholes)	Not applicable	Not applicable	Not applicable
Coastal storm surge/ sea or lake level change/ shoreline erosion	Not applicable	Not applicable	Not applicable
Dust/sandstorms	Potential hazard	• Blowing sand may cause pitting on cultural features. • Dune migration may negatively affect farming. • High-velocity winds causing sandstorms often stop traffic along US Highway 66 (now Interstate 40) between Holbrook and Winslow and elsewhere in many parts of the Navajo Nation (Cooley et al. 1969). • Sandstorms are frequent in all areas that do not have forest cover. • Called “chindi” in Navajo, dust devils or whirlwinds are commonly seen on broad treeless flats on summer days when the wind velocity is low. On days with generally high winds, the air is full of dust and sand.	• Alluvial and/or eolian deposits (**Qae**) • Alluvium and/or eolian deposits on older surfaces such as terraces and pediments (**Qao**) • Cooley et al. (1969) • Although not specific to the historic site, work by Sweeney et al. (2011), McDonald and Sweeney (2017), and Sweeney and McDonald (2017) influenced the decision to include dust storms as a potential hazard.

Table 4 (continued). Geologic hazards checklist.

Potential Hazard	**Best Professional Judgement**	**Risk or Secondary Hazard**	**Sources of Information**
Flooding: Flash floods	Known hazard	• Sudden, heavy rains cause flash floods. Little of this precipitation goes into the ground, and the runoff is great. During flash flood events, a broad floodplain may become covered with water within minutes. In less than an hour, the floodplain may be visible again, and the channel may carry a small stream. • Sudden rain events have resulted in significant sheet flow at the historic site.	• Alluvium (**Qae**) • Web Soil Survey (Natural Resources Conservation Service 2022) indicates that building site development on certain soils is very limited due to flooding potential (Figure 20). • Euge (1983) • Zeedyk (2004) • Geologic scoping summary (KellerLynn 2007)
Flooding: Riverine floods (referred to as "regional floods" by the Arizona Geological Survey)	Known hazard	• Snowmelt or rainfall may cause flooding. • Flooding may cause destruction of infrastructure, stream channel migration, and stream bank erosion	• Alluvium (**Qae**) • Web Soil Survey (Natural Resources Conservation Service 2022) indicates that building site development on certain soils is very limited due to flooding potential (Figure 20). • USGS stream gage 354236109331400 PUEBLO COLORADO WASH NR GANADO is in the historic site. Online data are available from 1998 onward. Data allow for calibration of discharge and design of in-stream infrastructure. • Euge (1983) calculated flood discharge and produced 100-year and 500-year floodplain maps for the historic site (see Table 2 in Euge 1983). • Zeedyk (2004) • Geologic scoping summary (KellerLynn 2007)
Hydrothermal activity	Not applicable	Not applicable	Not applicable
Permafrost	Not applicable	Not applicable	Not applicable

Table 4 (continued). Geologic hazards checklist.

Potential Hazard	Best Professional Judgement	Risk or Secondary Hazard	Sources of Information
Radon	Potential hazard—Radon levels in Arizona are generally low, but the following hot spots are known: (1) Tucson (the area around Cardinal Avenue), (2) the Cave Creek area, (3) parts of the Verde Valley, and (4) the Granite Dells near Prescott (Arizona Geological Survey 2024b).	• Health hazard • Most homes in the Navajo Nation do not have high indoor radon concentrations. The Navajo Nation has average indoor radon levels that are comparable to the estimated national average and to the average for the state of Arizona. Fewer than 10% of homes are likely to contain radon concentrations greater than 4 pCi/l, the level at which remediation is recommended (Spencer 1993). • Elevated levels of radon are found in both new and old buildings as well as 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 into a building. • Radon levels in Arizona can be higher during summer/air-conditioning months than during months with milder temperatures.	• The Chinle and Bidahochi Formations are known for uranium deposits and associated radon. • Spencer (1992, 1993) • Spencer et al. (1990) • EPA Map of Radon Zones (Environmental Protection Agency 1993)
Shrink/swell soils	Potential hazard	• Shrink/swell soils are widespread on the Colorado Plateau in northern Arizona and are notable for their popcorn textures; they also may exhibit polygonal soil cracks (mud cracks). • Hazards include cracking of foundations, walls, sidewalks, and roads; slippery trail conditions; and damage to plant roots. • Ground heaving and foundation cracks in the housing area at the historic site are probably the result of “overexcavating” and/or building on improperly compacted fill, not a consequence of shrink/swell soils (KellerLynn 2007).	• The Chinle Formation contains clays (e.g., montmorillonite and bentonite) known for shrinking and swelling. • Web Soil Survey (Natural Resources Conservation Service 2022) indicates that building site development on certain soils is either somewhat limited or very limited due to shrink/swell potential (Figure 20). • Geologic scoping summary (KellerLynn 2007)

Table 4 (continued). Geologic hazards checklist.

Potential Hazard	**Best Professional Judgement**	**Risk or Secondary Hazard**	**Sources of Information**
Subsidence, fissures, and (non-karstic) sinkholes	Known hazard—sinkholes are forming in fields northeast of the historic site; they are thought to be the result of groundwater pumping (KellerLynn 2007).	• Subsidence can cause serious problems to infrastructure such as irrigation canals, storm drainage systems, and sewage systems, which depend on gravity flow. • Because subsidence can change carefully engineered slopes, flow can speed up, stop, or even reverse in extreme cases. • Gradients of streams flowing into a subsiding basin become steeper and cause increased erosion. • Storm runoff may flood areas that have sunk and are lower than their surroundings. • Farm fields that are flood-irrigated may need constant re-leveling to ensure that water flows in the right direction. • Land elevation surveys and contour lines on topographic maps are rendered obsolete when surface elevations change due to subsidence.	• Alluvium (**Qae**) • Geologic scoping summary (KellerLynn 2007) • Natural Hazards in Arizona (Arizona Geological Survey 2024a) maps no earth fissures in the vicinity of the historic site, but they are occurring locally (KellerLynn 2007). • Although not specific to the historic site, work by Slaff (1993) and Harris and Pearthree (2002) influenced the decision to include subsidence as a potential hazard at the historic site.
Slope movements	Potential hazard—no landslide deposits are mapped in the historic site, but the Chinle Formation has potential	• The Chinle Formation is known for its landslide potential; for example, the Bitter Springs landslide closed US-89 south of the town of Page, Arizona, for more than a year. • Hubbell Hill is composed of the Chinle Formation.	• Steven Semken (Arizona State University, professor, written communication, 26 May 2023) • Petley (2013)
Tsunami	Not applicable	Not applicable	Not applicable

Table 4 (continued). Geologic hazards checklist.

Potential Hazard	Best Professional Judgement	Risk or Secondary Hazard	Sources of Information
Volcanic eruptions	Potential hazard	Arizona has three active volcanic fields: (1) San Francisco, (2) Uinkaret, and (3) Pinacate, which are 175 km (110 mi) southwest, 330 km (200 mi) west, and 540 km (340 mi) southwest of the historic site, respectively. Notably, prevailing winds are from the southwest, and the historic site is downwind from these volcanic fields. The chief hazards are from cinder- and ash-fall downwind of an erupting vent (opening at Earth's surface through which magma erupts or volcanic gases are emitted). Lava flows are a hazard proximal to a vent, potentially causing wildfires, damage to infrastructure, and road closures.	Arizona Geological Survey (2024c)

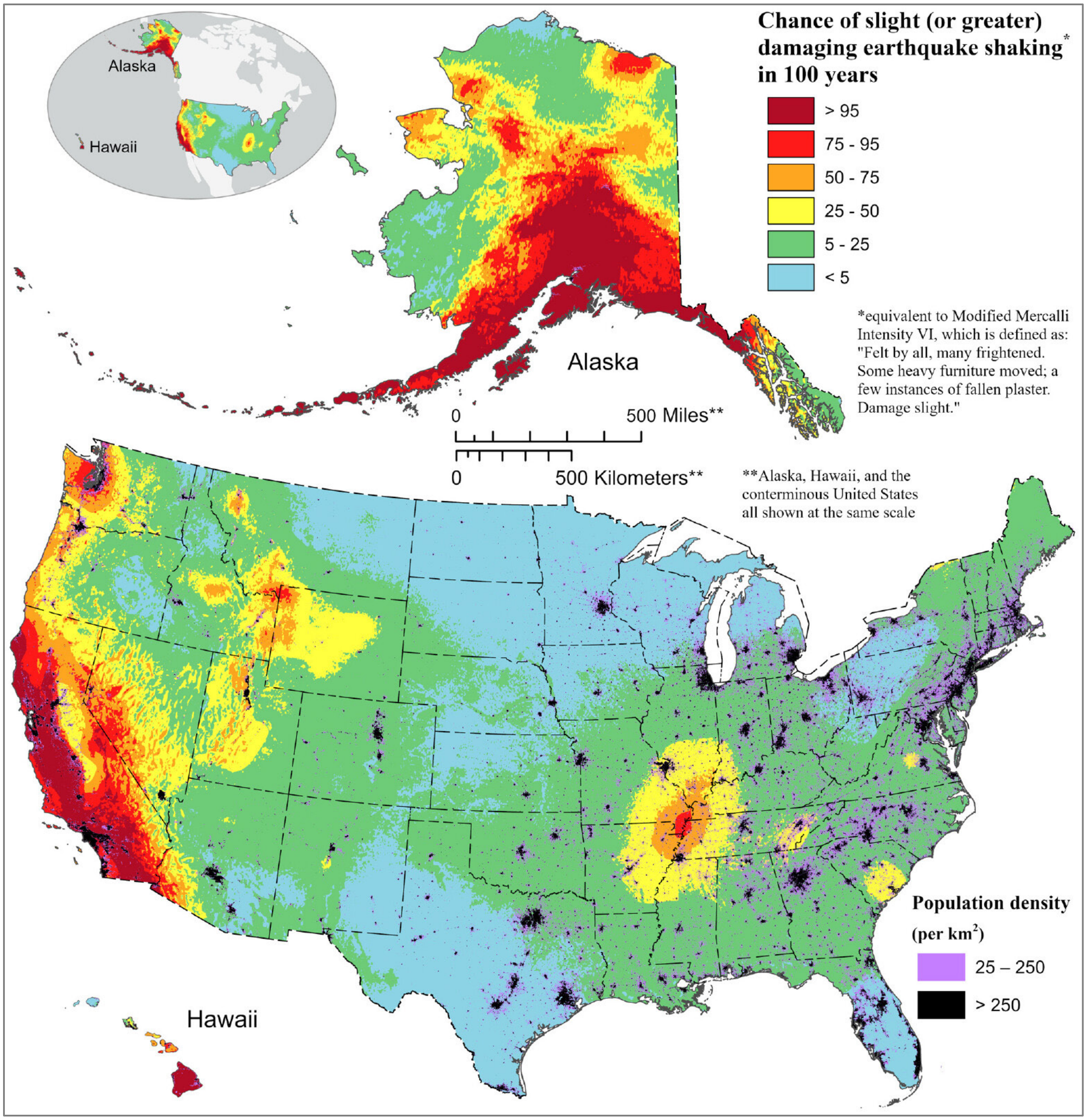
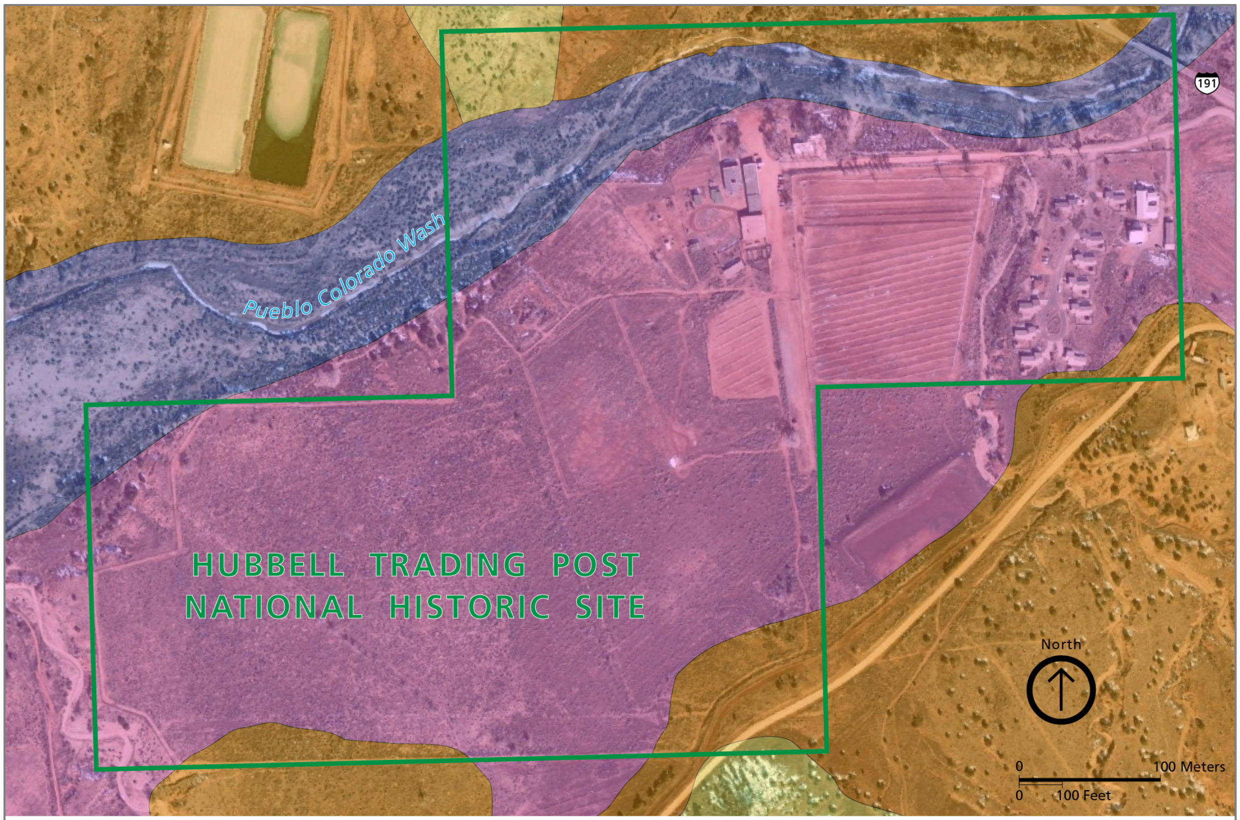


Figure 19. National seismic hazard map. The map shows the chance of any level of damaging earthquake shaking in 100 years from the 2023 50-State National Seismic Hazard Model. The shaking is equivalent to Modified Mercalli Intensity VI and higher and is based on the average peak ground acceleration and 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 Petersen et al. (2024, figure 3) available at https://doi.org/10.1177/87552930231215428 (accessed 13 February 2024).



	Soil unit	Slope %	Acres in Area of Interest (AOI)	Percent of AOI	Building Site Development
🟧	Aquima-Hawaikuh complex	1–5%	97.9	33.0%	Somewhat limited due to shrink/swell potential
🟨	Rizno-Tekapo family-Rock outcrop complex	2–45%	6.2	2.1%	Very limited due to shrink/swell potential
🟪	San Mateo-Wenota-Radnik complex	0–3%	150.9	50.8%	Very limited due to flooding and/or shrink/swell potential
🟦	Trail-Riverwash association	0–1%	41.9	14.1%	Very limited due to flooding potential
	Totals for AOI		296.8	100%	

Figure 20. Soil map of Hubbell Trading Post National Historic Site. Four different soils occur at the historic site. Each has limitations with respect to building site development due to shrink/swell potential and/or flooding potential. “Somewhat limited” indicates that the soil has features that are moderately favorable for the specified use; the limitations can be overcome or minimized by special planning, design, or installation. “Very limited” indicates that the soil has one or more features that are unfavorable for the specified use; the limitations generally cannot be overcome without major soil reclamation, special design, or expensive installation procedures. Poor performance and high maintenance can be expected. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using map generated from Web Soil Survey (https://websoilsurvey.nrcs.usda.gov/app/; accessed 13 February 2024).

Geomorphic Change of Pueblo Colorado Wash

Since the early 1900s, Pueblo Colorado Wash has changed from a wide, shallow wash to a narrow, deeply incised wash with low sinuosity (Froeschauer-Nelson 1998; Zeedyk 2004). This is a common theme of washes in the southwestern United States, including those in the National Park System such as Dinosaur National Monument (see Scott et al. 2018) and Canyon de Chelly National Monument (see GRI report by KellerLynn 2024). Geomorphic change is a management concern because it impacts archeological resources along the banks of Pueblo Colorado Wash, hinders the development of a healthy riparian ecosystem, and causes erosion (see "Erosion").

Investigators and resource managers have considered many possible factors contributing to geomorphic change in Pueblo Colorado Wash. Factors include the following: the presence of an upstream dam and the development of an irrigation system that altered natural hydrology and sediment processes; year-round grazing by trespass livestock inhibiting the establishment of native, riparian vegetation; ditching and straightening of the channel for flood control purposes; climate cycles and variations in precipitation; and natural arroyo processes that can move sediment downstream in pulses through alternating episodes of channel filling and incision (Euge 1983; Wagner and Inglis 2010). However, the planting and subsequent spread of tamarisk and Russian olive is deemed the primary cause of geomorphic change. The planting and spread of Russian olive and tamarisk narrow and deepen channels by stabilizing banks and inducing floodplain aggradation (Birken and Cooper 2006; Manners et al. 2014; Scott et al. 2018).

Russian olive was probably introduced to the trading post in the early to mid-1940s, that is, at the time the barbecue pit and picnic area were constructed; tamarisk was also introduced at that time (Froeschauer-Nelson 1998). Another invasive species, silver-leaved poplar (*Populus alba*), was introduced in the mid-1930s as part of the site improvement project by the Bureau of Indian Affairs. Notably, the use of this invasive species continued into the late 1990s, when the NPS transplanted numerous saplings of a large poplar tree near the visitor center. These extremely invasive trees make them "a highly undesirable choice" in landscaping and restoration (Froeschauer-Nelson 1998, p. 75).

By about 1990, invasive shrubs (i.e., tamarisk and Russian olive) had formed dense thickets along Pueblo Colorado Wash and other natural drainages, crowding out native vegetation and creating a fire hazard that threatened the historic site's invaluable cultural features. Moreover, a deep gully had formed in the wash, further diminishing its natural and cultural resource functions and values (Wagner and Inglis 2010).

By the late 1990s, these threats prompted resource management action (National Park Service 2003; Wagner and Inglis 2010). Much of the invasive exotic vegetation was removed from the floodplain and native cottonwoods (*Populus* spp.), willows (*Salix* spp.), reeds (species unknown), and grasses (species unknown) were planted along the banks and floodplain. Also, livestock was excluded from the wash. Moreover, small instream structures were installed to encourage the development of a more stable channel form; an induced meandering technique was implemented to improve the hydrologic balance in the channel (see Zeedyk 2004).

Resource management efforts were meant to help establish a healthy, native, riparian–wetland plant community (National Park Service 2003; Wagner and Inglis 2010). Conclusions from a study in Canyon de Chelly National Monument (Reynolds and Cooper 2017) may be applicable, or at least illuminating, for the historic site. Namely, recovery of native riparian plant communities may not be possible (Reynolds and Cooper 2017). Because of downcutting and lack of flooding on the old floodplains, riparian and wetland plants can no longer persist in those locations. Following the removal of tamarisk and Russian olive, study sites in Canyon de Chelly National Monument are transitioning to dry grasslands, as indicated by an increased abundance of native upland species (Reynolds and Cooper 2011). Where sites have dried due to stream downcutting and lack of flooding, target species should be native, upland plants (Reynolds and Cooper 2017).

Lessons learned from past studies are notable for future resource management at the historic site. These include the following: (1) hydrologic conditions should be considered when restoring riparian sites (Reynolds and Cooper 2017), and (2) some level of ongoing mechanical control will be necessary to keep exotic species from re-spreading and to preserve the historic character of the site (National Park Service 2003; Bankhead et al. 2017).

In the past, the historic site received funding from the Arizona Water Protection Fund (AWPF) for stream restoration, exotic species control, and native-species revegetation under AWPF grant 97-029 (completed in May 2001), AWPF grant 00-104 (completed in August 2004), and AWPF grant 00-105 (completed in December 2005). Annual reports, for example Arizona Water Protection Fund Commission (2005), provide progress updates. At present, no active restoration is taking place in Pueblo Colorado Wash (GRI follow-up meeting, 22 January 2022).

The Southern Colorado Plateau Network (SCPN) conducts riparian monitoring in Pueblo Colorado Wash, which may provide information useful for future restoration efforts. The following vital signs and metrics used by SCPN are associated with geomorphic processes: floodplain width and elevation, channel width and depth, channel plan form, channel slope, and composition of bed material. Specific objectives of monitoring include determining the status and trends in geomorphic processes (as reflected in channel and floodplain form), groundwater dynamics, and vegetation dynamics. These objectives are applicable and significant for the proper functioning of Pueblo Colorado Wash (Southern Colorado Plateau Network 2022a).

Paleontological Resource Inventory, Monitoring, and Protection

Potential sources of in situ fossils include the Triassic Chinle Formation and Quaternary deposits (see “Petrified Wood and Other Fossils”). Fossils have yet to be discovered from these sources within the historic site.

A baseline paleontological resource inventory (Tweet et al. 2009) provides recommendations for park managers, including future field inventories to discover in situ paleontological resources. Such inventories have revealed previously undiscovered fossil resources (e.g., see GRI report about Aztec Ruins National Monument by KellerLynn 2016). Such an inventory could be conducted by a Scientists in Parks (SIP) participant (see “Guidance for Resources Management”). The historic site’s foundation document (National Park Service 2016) identifies a “resurvey” of archeological resources as a data need. Park managers may wish to consider coordinating a reconnaissance-level, field-based paleontological inventory with that resurvey. Any paleontological inventory should also document the use of petrified wood for building and ornamental stone at the historic site.

Another recommendation is that historic site staff should be encouraged to observe exposed sedimentary rocks and associated eroded deposits for fossil material while conducting their usual duties. Staff should photodocument and potentially monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts (Tweet et al. 2009).

If fossil localities are identified, monitoring of significant sites should be undertaken at least once a year. "Monitoring In Situ Paleontological Resources" (Santucci et al. 2009) in *Geological Monitoring* (Young and Norby 2009) provides a list of vital signs for monitoring.

The recommendations by Tweet et al. (2009) highlight the significance of coordination between paleontological and archeological studies because fossils can be both geologic and cultural resources. Fossils found in a cultural context should be documented as a paleontological resource but also will 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 staff members can coordinate additional documentation and research of such material. Likewise, archeological excavations or infrastructure developments should consider scheduling site monitoring by a trained paleontologist to document and protect fossil resources.

Among other recommendations, Tweet et al. (2009) suggests a multi-park, cooperative research effort to study the ancient ecosystems preserved in the Chinle Formation. The Chinle Formation is exposed in five SCPN parks: Canyon de Chelly National Monument, Glen Canyon National Recreation Area, Grand Canyon National Park, Hubbell Trading Post National Historic Site, and Petrified Forest National Park. A previous multi-agency study (Turner et al. 1998; Turner and Peterson 2004), which investigated the ancient ecosystems of the Jurassic Morrison Formation, could serve as a guide. 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 contexts in these SCPN parks (Tweet et al. 2009), a network-wide investigation into the provenance of the wood may yield information regarding the original source locations of lithics (stone tools) and subsequent trade routes.

Water Rights and Irrigation

A key issue at the historic site is water rights and irrigation, and the historic site's foundation document (National Park Service 2016) identifies an irrigation/water use plan and analysis of water rights as data needs. Addressing these needs is beyond the scope of the GRI, but because of the connection between this issue and geologic resources such as Pueblo Colorado Wash, it warrants mention in the GRI report. Park managers are encouraged to request assistance from the NPS Water Resources Division, Water Rights Program (see "Guidance for Resource Management").

Homestead and Farm: A History of Farming at Hubbell Trading Post National Historic Site (Peterson 1986) provides a historical context and other potentially pertinent information about J. L. Hubbell's water rights, which are worthy of consideration. At present, water use at the historic site is provided through a utilities service agreement with the Navajo Tribal Utility Authority. The agreement was last renewed in 2014 and expires in 2024. All water is metered and paid for by tenants (National Park Service 2016).

An understanding of existing water rights would help historic site staff effectively irrigate agricultural fields, trees, and other vegetation that contribute to the site's cultural landscape and historic setting. An analysis of water rights and usage requirements would also help historic site staff determine the acreage of fields and pastures that can be sustainably irrigated and the feasibility of future development opportunities such as a community demonstration farm on the site (National Park Service 2016).

Guidance for Resource Management

This chapter provides information to assist park 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), NPS 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Access to GRI Products

- GRI products (scoping summaries, GIS data, posters, and reports): http://go.nps.gov/gripubs
- GRI products 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.
- GRI GIS data model: http://go.nps.gov/gridatamodel
- 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&

Four Ways to Receive Geologic Resource Management Assistance

- Contact the NPS Geologic Resources Division (GRD): https://www.nps.gov/orgs/1088/contactus.htm. The GRI is administered by the GRD. In addition, the GRD provides 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.
- Formally request assistance through Solution for Technical Assistance Requests (STAR): https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only). 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 from NRSS divisions and programs.
- Submit a proposal to receive geologic expertise through the Scientists in Parks (SIP) program. General information is available at https://www.nps.gov/subjects/science/scientists-in-parks.htm. The internal NPS site is https://doimspp.sharepoint.com/sites/nps-scientistsinparks (available on the DOI network only). Formerly the Geoscientists-in-the-Parks (GIP) program, the SIP program places scientists (typically undergraduate students) in parks to complete science-related projects. Proposals may be for assistance with research, resource management, interpretation, public education, inventories, and/or monitoring. GRD

can provide guidance and assistance with submitting a proposal. The Geological Society of America and Environmental Stewards are partners of the SIP program.

- Refer to *Geological Monitoring* (Young and Norby 2009), which provides guidance for monitoring vital signs. 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.

Assistance with Water-Related Issues

Although water is a geologic agent, some water-related issues are best addressed by WRD staff rather than GRD staff. Such issues include water quality, water supply, floodplains, wetlands, and water rights. Park managers are directed to WRD webpages for program specifics (https://www.nps.gov/orgs/1439/index.htm) and contact information (https://home.nps.gov/orgs/1439/contactus.htm). Park managers can formally request assistance from WRD through STAR (see "Four Ways to Receive Geologic Resource Management Assistance").

Assistance with Erosion and Other Soils Related Issues

Although geology (i.e., parent material) is a soil-forming factor (see Jenny 1941), soil-related issues are best addressed by a soil scientist. Resource managers are encouraged to contact the Office of the Arizona State Soil Scientist for assistance (see "Additional References, Resources, and Websites"). This office is part of the Natural Resources Conservation Service (NRCS). As an alternative, park managers may submit a technical assistance request through STAR (see "Four Ways to Receive Geologic Resource Management Assistance"). GRD has a memorandum of understanding with the NRCS for providing technical assistance throughout the National Park System. Historic site staff could consider collaboration with the Navajo Nation to mitigate erosion (National Park Service 2016).

NPS Natural Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/policy/index.cfm
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- Natural Resources Inventory and Monitoring Guideline (NPS-75): https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural Resource Management Reference Manual #77 (NPS-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 includes 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 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 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, 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.

Paleontological Resources

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.

<u>Federal Mineral Leasing (Oil, Gas, and Solid Minerals)</u>

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 GLCA, which is the only park unit that contains a STSA.
- **Exceptions:** Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration.
- **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 § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, 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.

Recreational Collection of Rocks and Minerals

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.
- **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 (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** require 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: https://azgs.arizona.edu/
- 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

Climate Change

- *A Record of Change—Science and Elder Observations on the Navajo Nation* (Redsteer and Wessells 2017): https://doi.org/10.3133/gip181
- Fourth National Climate Assessment (Reidmiller et al. 2018): https://nca2018.globalchange.gov/. *Note*: Chapter 25 (Gonzalez et al. 2018) provides information about the US Southwest: https://nca2018.globalchange.gov/chapter/25/.
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- Navajo Nation, Climate Change Program: https://www.navajoclimatechange.org/
- NPS Climate Change Useful Resources: http://www.nps.gov/subjects/climatechange/resources.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: 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
- Southern Colorado Plateau Inventory& Monitoring Network, Climate Monitoring: https://www.nps.gov/im/scpn/climate.htm
- US Global Change Research Program: http://www.globalchange.gov/home

Earthquakes

- Arizona Earthquake Information Center: https://aeic.nau.edu/index.html
- Arizona Geological Survey, Earthquakes: https://azgs.arizona.edu/center-natural-hazards/earthquakes
- *Arizona is Earthquake Country* (Conway and Young 2012): https://repository.arizona.edu/handle/10150/629330
- 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, operated by Northern Arizona University (https://www.fdsn.org/networks/detail/AR/); and (2) Arizona Broadband Seismic Network, operated by the Arizona Geological Survey (http://www.fdsn.org/networks/detail/AE/)
- “Seismic Monitoring” (Braile 2009) in *Geological Monitoring* (Young and Norby 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
- US Geological Survey (USGS), Earthquake Hazards Program: https://earthquake.usgs.gov/
- USGS Earthquake Hazards Program, Unified Hazard Tool: https://earthquake.usgs.gov/hazards/interactive/

Erosion and Soils

- “Aeolian Features and Processes” (Lancaster 2009) in *Geological Monitoring* (Young and Norby 2009): https://www.nps.gov/subjects/geology/geological-monitoring.htm
- *Cultural Landscape Report for Hubbell Trading Post National Historic Site, Ganado, Arizona* (Froeschauer-Nelson 1998) provides recommendations, site plans, and construction details for erosion control measures in Pueblo Colorado Wash and the unnamed wash west of the housing area.
- GRI reports for Petroglyph National Monument (KellerLynn 2017) and John Muir National Historic Site (KellerLynn 2021a) provide information about gully erosion at those parks, which may be applicable to the historic site: https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm.
- GRI report for Little Bighorn Battlefield National Monument (KellerLynn 2011) provides information about successful efforts to control off-trail use and mitigate erosion associated with compaction of soils, trampling, and the proliferation of social trails: https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm.
- NPS efforts (e.g., trail building, education and outreach) in Canyonlands National Park to protect biological soils crusts from trampling may be applicable; see https://www.nps.gov/cany/learn/photosmultimedia/inside_soilcrust.htm. Work by USGS scientist Jayne Belnap is notable.

- *Gully Erosion* (Harvey et al. 1985): https://openlibrary.org/books/OL25190981M/Gully_erosion
- Natural Resources Conservation Service: https://www.nrcs.usda.gov/
- Natural Resources Conservation Service, State Soils Scientists: https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/state-soil-scientists
- NPS Geoconservation—Disturbed Land Restoration: https://www.nps.gov/articles/geoconservation-disturbed-land-restoration.htm
- *Soil Erosion Study: Hubbell Trading Post National Historic Site* (Euge 1983): https://irma.nps.gov/DataStore/DownloadFile/145570
- *Upland Soil Erosion Monitoring and Assessment: An Overview* (Ypsilantis 2011): https://archive.org/details/uplandsoilerosio00ypsi. *Note*: This is BLM Technical Note 438. Former NPS soil scientist, Pete Biggam, reviewed this document, which provides prudent land management practices that will help reduce erosion. Information in the document will also aid resource specialists in evaluating and selecting techniques for monitoring and assessing upland soil surface erosion.
- Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS): https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

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
- International Union of Geological Sciences (IUGS), International Commission on Geoheritage: https://iugs-geoheritage.org/. *Note*: The Great Unconformity at Grand Canyon, Arizona, for example, is a geological heritage site. It is one of the most profound unconformities (break in the rock record) on Earth, with as much as 1.3 billion years of Earth's history removed by erosion.
- National Register of Historic Places: https://www.nps.gov/subjects/nationalregister/index.htm
- NPS America's Geologic Heritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- NPS Museum Collection (online database): https://museum.nps.gov/ParkPList.aspx

Fossils in Cultural Contexts

- "A Preliminary Inventory of National Park Service Paleontological Resources in Cultural Resource Contexts, Part 1: General Overview" (Kenworthy and Santucci 2006): https://irma.nps.gov/DataStore/Reference/Profile/2195223
- "An Overview of Paleontological Resources Preserved within Prehistoric and Historic Structures" (Santucci et al. 2021a): https://irma.nps.gov/DataStore/Reference/Profile/2283741
- "The Intersecting Crossroads of Paleontology and Archeology: When Are Fossils Considered Artifacts? Chaco Culture National Historical Park, Mesa Verde National Park, Pecos National Historical Park, Petrified Forest National Park, Salinas Pueblo Missions National Monument, White Sands National Park, Wupatki National Monument" (Santucci 2021b): https://home.nps.gov/articles/000/the-intersecting-crossroads-of-paleontology-and-archeology-when-are-fossils-considered-artifacts.htm

Geologic Maps

- American Geosciences Institute (information about geologic maps and their uses): http://www.americangeosciences.org/environment/publications/mapping
- *General Standards for Geologic Maps* (Evans 2016)
- National Geologic Map Database: https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Flooding

- *A Home Buyer's Guide to Geologic Hazards in Arizona* (Harris and Pearthree 2002): https://repository.arizona.edu/handle/10150/629464
- Arizona Geological Survey, Floods: https://www.azgs.arizona.edu/center-natural-hazards/floods
- "Fluvial Geomorphology: Monitoring Stream Systems in Response to a Changing Environment" (Lord et al. 2009) in *Geological Monitoring* (Young and Norby 2009): https://www.nps.gov/subjects/geology/geological-monitoring.htm
- Navajo Nation Flooding History: Flooding in the Desert (DRAFT): https://storymaps.arcgis.com/stories/fa0a1056b3364cda96a248bae2a265c8

Geological Surveys and Societies

- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: https://www.stategeologists.org/
- Arizona Geological Survey: https://azgs.arizona.edu/
- Geological Society of America: http://www.geosociety.org/
- US Geological Survey: http://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: http://go.nps.gov/gri
- 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 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/. *Note*: The GRI team uploads scoping summaries, maps, and reports to the NPS DataStore (https://irma.nps.gov/DataStore/) on IRMA. Enter "GRI" as the search text and select a park from the unit list.
- 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/
- NPS Integrated Resource Management Applications (IRMA) is a repository of park-specific documents: https://irma.nps.gov/
- NPS Planning, Environment and Public Comment (PEPC) provides information about park planning: https://parkplanning.nps.gov/parks.cfm
- *Park Science*: https://www.nps.gov/subjects/parkscience/index.htm
- Western Archeological and Conservation Center (WACC): https://www.nps.gov/orgs/1260/index.htm

US Geological Survey Reference Tools

- Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- US Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search

- USGS Publications Warehouse: http://pubs.er.usgs.gov
- USGS Store (find maps by location or by purpose): http://store.usgs.gov
- Tapestry of Time and Terrain (descriptions of physiographic provinces; Vigil et al. 2000): http://pubs.usgs.gov/imap/i2720/

Literature Cited

These references are cited in this report. If park managers are interested in other investigations and/or a broader search of the scientific literature, the GRD has collaborated with—and funded—the NPS Technical Information Center (TIC) to maintain a subscription to GeoRef (the premier online geologic citation database). Multiple portals are available for NPS staff to access this database. Historic site staff may contact the GRI team or GRD staff for instructions on how to access GeoRef.

Amoroso, L., S. S. Priest, and M. Hiza-Redsteer. 2013. Bedrock and surficial geologic map of the Satan Butte and Greasewood 7.5′ quadrangles, Navajo and Apache Counties, northern Arizona. Open-File Report 2013-1007. Prepared in cooperation with the Navajo Nation. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/ofr20131007

Anderson, J. C., K. E. Karlstrom, and M. T. Heizler. 2021. Neogene drainage reversal and Colorado Plateau uplift in the Salt River area, Arizona, USA. Geomorphology 395, article 107964. https://doi.org/10.1016/j.geomorph.2021.107964

Arizona Geological Survey. 2024a. Natural hazards in Arizona. Online map viewer. Arizona Geological Survey, Tucson, Arizona. https://www.americangeosciences.org/critical-issues/maps/arizona-hazards (accessed 13 February 2024).

Arizona Geological Survey. 2024b. Radon. Online information. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/center-natural-hazards/radon (accessed 13 February 2024).

Arizona Geological Survey. 2024c. Volcanism. Online information. Arizona Geological Survey, Tucson, Arizona. https://www.azgs.arizona.edu/center-natural-hazards/volcanism (accessed 13 February 2024).

Arizona Water Protection Fund Commission. 2005. Arizona water protection fund: protecting Arizona’s river & riparian resources. Annual report 2004–2005. Arizona Water Protection Fund Commission, Phoenix, Arizona. https://www.azwpf.gov/documents-and-reports

Ash, S. R. 1972a. Late Triassic plants from the Chinle Formation in north-eastern Arizona. Palaeontology 15(4):598–618.

Ash, S. R. 1972b. Plant megafossils of the Chinle Formation. Pages 23–44 *in* C. S. Breed and W. J. Breed, editors. Investigations in the Triassic Chinle Formation. Bulletin 47. Museum of Northern Arizona, Flagstaff, Arizona.

Ash, S. R. 1972c. The search for plant fossils in the Chinle Formation. Pages 45–58 *in* C. S. Breed and W. J. Breed, editors. Investigations in the Triassic Chinle Formation. Bulletin 47. Museum of Northern Arizona, Flagstaff, Arizona.

Ash, S. R. 1980. Upper Triassic floral zones of North America. Pages 153–170 *in* D. L. Dilcher and T. M. Taylor, editors. Biostratigraphy of fossil plants. Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania.

Ash, S. R. 1996. Evidence of arthropod-plant interactions in the Upper Triassic of the Southwestern United States. Lethaia 29(3):237–248.

Baars, D. L. 1983. The Colorado Plateau. University of New Mexico Press, Albuquerque, New Mexico.

Bankhead, N. L., R. E. Thomas, and A. Simon. 2017. A combined field, laboratory and numerical study of the forces applied to, and the potential for removal of, bar top vegetation in a braided river. Earth Surface Processes and Landforms 42:439–459.

Barthelmes, M. 2020. Horseshoe Bend National Military Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2020/2158. National Park Service. Fort Collins, Colorado. http://go.nps.gov/gripubs

Birken, A. S., and D. J. Cooper. 2006. Processes of Tamarix invasion and floodplain development along the lower Green River, Utah. Ecological Applications 16:1103–1120.

Blakey, R. C. 1990. Stratigraphy and geologic history of Pennsylvanian and Permian rocks, Mogollon Rim region, central Arizona and vicinity. Geological Society of America Bulletin 102(9):1189–1217.

Blakey, R. C. 1996. Permian eolian deposits, sequences, and sequence boundaries, Colorado Plateau. Pages 405–426 *in* M. W. Longman and M. D. Sonnenfeld, editors. Paleozoic systems of the Rocky Mountain region. SEPM (Society of Sedimentary Geology), Rocky Mountain Section, Denver, Colorado.

Blakey, R. C., and R. Gubitosa. 1983. Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona. Pages 57–76 *in* M. W. Reynolds and E. D. Dolly, editors. Mesozoic paleogeography of west-central United States. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Denver, Colorado.

Blakey, R. C., and R. Knepp. 1989. Pennsylvanian and Permian geology of Arizona. Pages 313–347 *in* J. P. Jenney and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona. https://www.arizonageologicalsoc.org/InPrintPublications

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

Blakey, R. C., and W. D. Ranney. 2018. Ancient landscapes of western North America: a geologic history with paleogeographic maps. Springer International Publishing, Cham, Switzerland.

Braile, L. W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm

Brazier, V., P. M. C. Bruneau, J. E. Gordon, and A. F. Rennie. 2012. Making space for nature in a changing climate: the role of geodiversity in biodiversity conservation. Scottish Geographical Journal 128:211–233. https://doi.org/10.1080/14702541.2012.737015

Bureau of Reclamation. 2003. Hubbell Reservoir: 2001 joint National Park Service and Bureau of Reclamation literature search and review and site visit report. US Department of the Interior, National Park Service, Hubbell Trading Post National Historic Site, Arizona, maintenance, operation, and safety of dams program. Prepared by Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Carey, H. Jr. 2009. Navajo leader Ganado Mucho (Many Cattle). Online information. Association unknown. http://navajopeople.org/blog/navajo-leader-ganado-mucho-%E2%80%9Cmany-cattle%E2%80%9D/ (accessed 13 February 2024).

Childs, O. E. 1948. Geomorphology of the valley of the Little Colorado River, Arizona. Geological Society of America Bulletin 59(4):353–388.

Coney, P. J. 1978. The plate tectonic setting of southeastern Arizona. Pages 285–290 *in* J. F. Callender, J. C. Wilt, and R. E. Clemons, editors. Land of Cochise (Southeastern Arizona). Fall Field Conference Guidebook 29. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/29/

Conway, F. M., and J. J. Young. 2012. Arizona is earthquake country. Down-To-Earth 21. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629330

Cooley, M. E. 1968. Physiographic map of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah (scale 1:316,800). Plate 3 of Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, with a section on vegetation. Professional Paper 521-A. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp521A

Cooley, M. E., and J. P. Akers. 1961. Ancient erosion cycles of the Little Colorado River, Arizona and New Mexico. Pages 244–248 *in* Short papers in the geologic and hydrologic sciences. Professional Paper 424-C. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp424C

Cooley, M. E., J. W. Harshbarger, J. P. Akers, W. F. Hardt, and O. N. Hicks. 1969. Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, with a section on vegetation. Professional Paper 521-A. Prepared in cooperation with the Bureau of Indian Affairs and the Navajo Tribe. US Geological Survey, Washington, DC. https://pubs.usgs.gov/publication/pp521A. Note: Sheet 6 of Plate 1 (scale 1:125,000) covers the historic site.

Crow, R., J. Schwing, K. E. Karlstrom, M. Heizler, P. Pearthree, P. K. House, S. Dulin, S. U. Janeke, M. Stelten, and L. J. Crossey. 2021. Refining the age of the Colorado River, southwestern United States. Geology 49(6):635–640. https://doi.org/10.1130/G48080.1

Dallegge, T. A. 1999. Correlation and chronology of the Miocene-Pliocene Bidahochi Formation, Navajo and Hopi Nations, northeastern Arizona. Thesis. Northern Arizona University, Flagstaff, Arizona.

Dallegge, T. A., M. H. Ort, W. C. McIntosh, and M. E. Perkins. 2000. Age and deposition basin morphology of the Bidahochi Formation and implications for the ancestral upper Colorado River. Pages 47–51 (Chapter 6) *in* R. A. Young and E. E. Spamer, editors. Colorado River: origin and evolution. Proceedings of a symposium held at Grand Canyon National Park in June 2000. Grand Canyon Association, Grand Canyon, Arizona.

Dallegge, T. A., M. H. Ort, and W. C. Mcintosh. 2003. Mio-Pliocene chronostratigraphy, basin morphology and paleodrainage relations derived from the Bidahochi Formation, Hopi and Navajo Nations, northeastern Arizona. The Mountain Geologist 40(3):55–82.

Dana, J. D. 1895. Manual of geology. 4th edition. American Book Company, New York, New York.

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2006. Weather and climate inventory, National Park Service, Southern Colorado Plateau Network. Natural Resource Technical Report NPS/SCPN/NRTR—2006/007. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/DownloadFile/147107

Davis, G. H. 1984. Structural geology of rocks and regions. John Wiley & Sons, New York, New York.

De Harport, D. L. 1959. Archeological survey of Canyon de Chelly, northeastern Arizona: a Puebloan community through time. Dissertation. Harvard University, Department of Anthropology, Cambridge, Massachusetts.

Dickinson, W. R. 2013. Rejection of the lake spillover model for initial incision of the Grand Canyon, and discussion of alternatives. Geosphere 9(1):1–20. https://doi.org/10.1130/GES00839.1

Dobson, J. E., E. A. Bright, P. R. Coleman, R. C. Durfee, B. A. Worley. 2000. LandScan: a global population database for estimating populations at risk. Photogrammetric Engineering and Remote Sensing 66(7):849–857.

Douglass, J. E., B. F. Gootee, T. Dallegge, A. Jeong, Y. B. Seong, and B. Y. Yu. 2020. Evidence for the overflow origin of the Grand Canyon. Geomorphology 369, article 107361. https://doi.org/10.1016/j.geomorph.2020.107361

Dubiel, R. F. 1991. Architectural-facies analysis of nonmarine depositional systems in the Upper Triassic Chinle Formation, southeastern Utah. Pages 103–110 *in* A. D. Miall and N. Tyler, editors. The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery. Concepts in Sedimentology and Paleontology 3. SEPM (Society for Sedimentary Geology), Claremore, Oklahoma.

Environmental Protection Agency. 1993. EPA map of radon zones. EPA 402-F19-004. US Environmental Protection Agency, Washington, DC. https://www.epa.gov/radon/epa-map-radon-zones

Esri. 2020. USA rivers and streams. ArcGIS Hub [online data]. Esri, Redlands, California. https://hub.arcgis.com/datasets/esri::usa-rivers-and-streams/explore?location=39.846334%2C-104.941074%2C9.52 (accessed 13 February 2024).

Euge, K. M. 1983. Soil erosion study: Hubbell Trading Post National Historic Site. Earth Technology Corporation (Ertec Western, Inc.), Phoenix, Arizona. https://irma.nps.gov/DataStore/DownloadFile/145570

Evans, T. J. 2016. General standards for geologic maps. Section 3.1 *in* M. B. Carpenter and C. M. Keane, compilers. The geoscience handbook 2016. AGI Data Sheets, 5th edition. American Geosciences Institute, Alexandria, Virginia.

Fisichelli, N. A., and P. S. Ziesler. 2015. Hubbell Trading Post National Historic Site: how might future warming alter visitation? Park visitation and climate change: park-specific brief. National Park Service, Climate Change Response Program, Fort Collins, Colorado. https://irma.nps.gov/DataStore/DownloadFile/524463

Frisch-Gleason, R. 1998. Highlights of northern Arizona geology. Arizona Geological Survey Down-To-Earth 7. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629405

Froeschauer-Nelson, P. 1998. Cultural landscape report for Hubbell Trading Post National Historic Site, Ganado, Arizona. US Department of the Interior, National Park Service, Intermountain Support Office, Santa Fe, New Mexico. http://npshistory.com/publications/hutr/clr/index.htm

Gonzalez, P., G. M. Garfin, D. D. Breshears, K. M. Brooks, H. E. Brown, E. H. Elias, A. Gunasekara, N. Huntly, J. K. Maldonado, N. J. Mantua, H. G. Margolis, S. McAfee, B. R. Middleton, and B. H. Udall. 2018. Southwest. Pages 1101–1184 *in* D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. Impacts, risks, and adaptation in the United States. Fourth national climate assessment, volume II. US Global Change Research Program, Washington, DC. https://nca2018.globalchange.gov/downloads/

Gordon, J. E., D. Tormey, R. Wignall, V. Brazier, and R. Crofts. 2022. Climate change will challenge the management of geoheritage in protected and conserved areas. Parks Stewardship Forum 38(1):56–63. https://escholarship.org/uc/item/3v15v033

Graham, J. P. 2020. Grand Canyon National Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2020/2195. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

Gregory, H. E. 1915. The igneous origin of the “glacial deposits” of the Navajo Reservation, Arizona and Utah. American Journal of Science, Series 4, 40(236):97–115 (article 8).

Gregory, H. E. 1916a. Geologic map of the Navajo country Arizona, New Mexico, Utah (scale 1:500,000). Plate II *in* Geology of the Navajo country: a reconnaissance of parts of Arizona, New Mexico, and Utah. Professional Paper 93. US Geological Survey, Washington, DC. https://ngmdb.usgs.gov/Prodesc/proddesc_4665.htm. Note: The report in which this map appears has a publication date of 1917.

Gregory, H. E. 1916b. The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah. Water-Supply Paper 380. US Geological Survey, Washington, DC. https://doi.org/10.3133/wsp380

Gregory, H. E. 1917. Geology of the Navajo country: a reconnaissance of parts of Arizona, New Mexico, and Utah. Professional Paper 93. US Geological Survey, Washington, DC. https://doi.org/10.3133/pp93

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). Miscellaneous Investigations Series Map I-981, sheet 1 (of 2): geology. US Geological Survey, Washington, DC. https://ngmdb.usgs.gov/Prodesc/proddesc_9849.htm. Note: Sheet 2 is structure and uranium deposits.

Harris, R. C., and P. A. Pearthree. 2002. A home buyer’s guide to geologic hazards in Arizona. Down-To-Earth 13. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629464

Harvey, M. D., C. C. Watson, and S. A. Schumm. 1985. Gully erosion. Prepared for Bureau of Land Management, contract number YA558-CT4-0011; order number BLM-YA-PT-85-002-4340. Water Engineering and Technology, Inc., Fort Collins, Colorado. https://openlibrary.org/books/OL25190981M/Gully_erosion

Hasiotis, S. T., R. F. Dubiel, K. L. Conrad, and M. G. Lockley. 1994. Footprint evidence of North America's earliest dinosaur, Upper Triassic Chinle Formation, Fort Wingate, New Mexico. Geological Society of America Abstracts with Programs 26(6):17.

Heath, D. C., D. J. Wald, C. B. Worden, E. M. Thompson, and G. M. Smoczyk. 2020. A global hybrid VS30 map with a topographic slope–based default and regional map insets. Earthquake Spectra 36(3):1570–1584.

Heckert, A. B. 1999. Upper Triassic tetrapods from the Lucero uplift, central New Mexico. Pages 311–315 *in* F. J. Pazzaglia and S. G. Lucas, editors. Albuquerque geology. Fall Field Conference Guidebook 50. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/50/

Heizler, M. T., K. E. Karlstrom, M. Albonico, R. Hereford, L. S. Beard, S. M. Cather, L. J. Crossey, and K. E. Sundell. 2021. Detrital sanidine 40Ar/39Ar dating confirms <2 Ma age of Crooked Ridge paleoriver and subsequent deep denudation of the southwestern Colorado Plateau. Geosphere 17(2):438–454. https://doi.org/10.1130/GES02319.1

Henderson, W. M., and S. DeLong. 2012. Evaluating dryland ecological and river restoration using repeat LiDAR and hydrological monitoring. Abstract EP31C-0831. American Geophysical Union Fall Meeting, 3–7 December 2012, San Francisco, California.

Hilario, A., A. Asrat, B. van Wyk de Vries, D. Mogk, G. Lozano, J. Zhang, J. Brilha, J. Vegas, K. Lemon, L. Carcavilla, and S. Finney, editors. 2022. The first 100 IUGS geological heritage sites. International Union of Geological Sciences. First published in Spain (October 2022). https://iugs-geoheritage.org/

Humphreys, E., E. Hessler, K. Dueker, G. L. Farmer, E. Erslev, and T. Atwater. 2003. How Laramide-age hydration of North American lithosphere by the Farallon slab controlled subsequent activity in the western United States. International Geology Review 45:575–595.

International Commission on Stratigraphy. 2023. International chronostratigraphic chart (v2023/09). Drafted by K. M. Cohen, D. A. T. Harper, P. L. Gibbard, and N. Car. International Union of Geological Sciences, International Commission on Stratigraphy (ICS), Durham, England [address of current ICS chair]. https://stratigraphy.org/chart

Jarvis, J. E. 2015. Addressing climate change and natural hazards for facilities. Policy Memorandum 15-01, 20 January 2015. Washington DC Support Office, Washington DC. https://www.nps.gov/policy/PolMemos/policymemoranda.htm

Jenny, H. 1941 [reprinted with forward by Ronald Amundson, University of California, Berkeley in 1994]. Factors of soil: a system of quantitative pedology formation. Dover Publications, Inc., New York, New York.

Karlstrom, K. E., J. P. Lee, S. A. Kelley, R. S. Crow, L. J. Crossey, R. A. Young, G. Lazear, L. S. Beard, J. W. Ricketts, M. Fox, and D. L. Shuster. 2014. Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons. Nature Geoscience 7:239–244. https://www.nature.com/articles/ngeo2065

Karlstrom, K. E., R. A. Young, L. S. Beard, G. H. Billingsley, K. P. House, A. Aslan, and J. Pederson. 2011. Summary report: CRevolution 2—origin and evolution of the Colorado River system. Pages 3–16 *in* L. S. Beard, K. E. Karlstrom, R. A. Young, and G. H. Billingsley, editors. CRevolution 2—origin and evolution of the Colorado River system, workshop abstracts. Open-File Report 2011–1210. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2011/1210/

KellerLynn, K. 2007. Geologic resource evaluation scoping summary, Hubbell Trading Post National Historic Site, Arizona. Natural National Park Service, Geologic Resources Division, Lakewood, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2011. Little Bighorn Battlefield National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2011/407. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2015. Bandelier National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/1036. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2016. Aztec Ruins National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1245. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2017. Petroglyph National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2017/1547. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2018. Craters of the Moon National Monument and Preserve: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/1783. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2021a. John Muir National Historic Site: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2021/2333. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2021b. Redwood National and State Parks: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2021/2314. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs

KellerLynn, K. 2024. Canyon de Chelly National Monument: geologic resources inventory report. Science Report NPS/SR—2024/159. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2305015

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary inventory of National Park Service paleontological resources in cultural resource contexts, part 1: general overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. Fossils from federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://irma.nps.gov/DataStore/Reference/Profile/2195223

Lancaster, N. 2009. Aeolian features and processes. Pages 1–25 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm

Leary, R. J., P. Umhoefer, M. E. Smith, and N. Riggs. 2017. A three-sided orogen: A new tectonic model for Ancestral Rocky Mountain uplift and basin development. Geology 45(8):735–738.

Lillie, R. J. 2005. Parks and plates: the geology of our national parks, monuments, and seashores. W. W. Norton and Company, New York, New York, and London, England.

Liu, L., and M. Gurnis. 2010. Dynamic subsidence and uplift of the Colorado Plateau. Geology 38(7):663–666. https://doi.org/10.1130/G30624.1

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm

Love, D. W. 1989. Bidahochi Formation: an interpretative summary. Pages 273–280 *in* O. J. Anderson, S. G. Lucas, D. W. Love, and S. M. Cather, editors. Southeastern Colorado Plateau, New Mexico. Fall Field Conference Guidebook 40. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/40/

Lucas, S. G., and S. N. Hayden. 1989. Triassic stratigraphy of west-central New Mexico. Pages 191–211 *in* O. J. Anderson, S. G. Lucas, D. W. Love, and S. M. Cather, editors. Southeastern Colorado Plateau. Fall Field Conference Guidebook 40. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/40/

Lupe, R., and N. J. Silberling. 1985. Genetic relationships between lower Mesozoic continental strata of the Colorado Plateau and marine strata of the western Great Basin: significance for accretionary history of Cordilleran lithotectonic terranes. Pages 263–271 *in* D. G. Howell, editor. Tectonostratigraphic terranes of the circum-pacific region. Earth Science Series 1. Circum-Pacific Council for Energy and Mineral Resources, Santa Cruz, California.

Lutgens, F. K., and E. J. Tarbuck. Essentials of geology. Fourth edition. Macmillan Publishing Company, New York, New York.

Manchester, A., and A. Manchester. 1993. Hubbell Trading Post National Historic Site: an administrative history. Professional Papers No. 46. National Park Service, Southwest Cultural Resources Center, Santa Fe, New Mexico. http://npshistory.com/publications/hutr/index.htm

Manners, R. B., J. C. Schmidt, and M. L. Scott. 2014. Mechanisms of vegetation-induced channel narrowing of an unregulated canyon river: results from a natural field-scale experiment. Geomorphology 211:100–115.

Martz, J. W., and W. G. Parker. 2010. Revised lithostratigraphy of the Sonsela Member (Chinle Formation, Upper Triassic) in the southern part of Petrified Forest National Park, Arizona. PLoS One 5(2):e9329. https://doi.org/10.1371/journal.pone.0009329

Martz, J. W., W. G. Parker, L. Skinner, J. J. Raucci, P. Umhoefer, and R. C. Blakey. 2012. Geologic map of Petrified Forest National Park, Arizona (scale 1:50,000). Contributed Map CM-12-A. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/630688

McCann, F. T. 1938. Ancient erosion surface in the Gallup-Zuni area, New Mexico. American Journal of Science, Series 5, 36(214):260–278.

McDonald, E. V., and M. R. Sweeney. 2017. Blowing dust and a dangerous highway: evaluating the sources of dust along Interstate 10 between Phoenix and Tucson, Arizona. Geological Society of America Abstracts with Programs 49(6), paper number 24-9. https://www.doi.org/10.1130/abs/2017AM-304507

McPhee, J. 1999. Annals of the former world. Farrar, Straus, and Giroux, New York, New York.

McRoberts, C. A., and S. C. Good. 1993. Diversity of some marine and nonmarine bivalves across the Late Triassic Carnian–Norian interval, western North America. Geological Society of America Abstracts with Programs 25(6):332.

Meek, N., and J. Douglass. 2001. Lake overflow: an alternative hypothesis for Grand Canyon incision and development of the Colorado River. Pages 199–204 *in* R. A. Young and E. E. Spamer, editors. Colorado River: origin and evolution. Monograph 12. Grand Canyon Association, Grand Canyon, Arizona.

Meixner, T., A. H. Manning, D. A. Stonestrom, D. M. Allen, H. Ajami, K. W. Blasch, A. E. Brookfield, C. L. Castro, J. F. Clark, D. J. Gochis, A. L. Flint, K. L. Neff, R. Niraula, M. Rodell, B. R. Scanlon, K. Singha, and M. A. Walvoord. 2016. Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology 534:124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

Monahan, W. B., and N. A. Fisichelli. 2014. Recent climate change exposure of Hubbell Trading Post National Historic Site. National Park Service, Inventory & Monitoring Division and Climate Change Response Program, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2212637

Moritz, M. A., M. A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere 3(6): article 49. https://doi.org/10.1890/ES11-00345.1

Murry, P. A., and R. E. Kirby. 2002. A new hybodont shark from the Chinle and Bull Canyon Formations, Arizona, Utah, and New Mexico. Pages 87–106 *in* A. B. Heckert and S. G. Lucas, editors. Upper Triassic stratigraphy and paleontology. Bulletin 21. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

National Park Service. 1983. Project manual, rehabilitate road, parking and bridge, Hubbell Trading Post National Historic Site. IFB [invitation for bid] 7420-83A. US Department of Interior, National Park Service, Denver Service Center, Denver, Colorado.

National Park Service. 1992. Natural resources inventory and monitoring guideline. NPS-75. National Park Service, Washington, DC. https://irma.nps.gov/DataStore/Reference/Profile/622933

National Park Service. 1998. NPS Geologic Resources Inventory Plan. National Park Service, Lakewood, Colorado.

National Park Service. 2003. Cultural landscapes inventory: Hubbell Trading Post NHS landscape, Hubbell Trading Post National Historic Site. National Park Service, Santa Fe Support Office, Santa Fe, New Mexico. https://irma.nps.gov/DataStore/Reference/Profile/2205055. Note: Access to this file is limited to NPS staff.

National Park Service. 2009. Strategic plan for natural resource inventories: FY 2008–FY 2012. Natural Resource Report NPS/NRPC/NRR—2009/094. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/663022

National Park Service. 2010. Hubbell Trading Post National Historic Site, Arizona. Official park brochure. US Department of the Interior, National Park Service, Washington, DC. http://npshistory.com/publications/hutr/index.htm

National Park Service. 2012. What's in a name? The Araucarioxylon problem. Online information. Petrified Forest National Park, Petrified Forest, Arizona. https://www.nps.gov/pefo/whatname.htm (accessed 31 October 2023).

National Park Service. 2015. Addressing climate change and natural hazards: facility planning and design considerations. Level 3 Handbook. National Park Service, Park Planning Facilities and Lands, Construction Program Management Division, Denver, Colorado.

National Park Service. 2016. Foundation document: Hubbell Trading Post National Historic Site, Arizona. HUTR 433/133305. Intermountain Region, Denver, Colorado, and Hubbell Trading Post National Historic Site, Ganado, Arizona. http://npshistory.com/publications/hutr/index.htm

National Park Service and American Geosciences Institute. 2015. America's geologic heritage: an invitation to leadership. NPS 999/129325. National Park Service, Denver, Colorado. https://www.earthsciweek.org/content/our-shared-geoheritage

Natural Resources Conservation Service. 2022. Custom soil resource report for Fort Defiance area, parts of Apache and Navajo Counties, Arizona, and McKinley and San Juan Counties, New Mexico. Online information (report generated at Web Soil Survey). US Department of Agriculture, Natural Resources Conservation Service, Washington, DC. https://websoilsurvey.nrcs.usda.gov/app/ (accessed 13 February 2024).

Navajo Nation. 2022. History. Online information. Navajo Nation, Window Rock, Arizona. https://www.navajo-nsn.gov/History (accessed 13 February 2024).

Navajo Nation. 2023. Navajo Nation chapters. Online information. Navajo Nation, Window Rock, Arizona. http://www.navajo-nsn.gov/Navajo-Government/Navajo-Nation-Chapters (accessed 13 February 2024).

Oberling, Z. A. 2015, Petrogenesis and provenance of volcanic clasts in the Upper Triassic Shinarump Member, Chinle Formation, and equivalents: implications for Early Triassic Cordilleran arc magmatism. Thesis. Northern Arizona University, Flagstaff, Arizona.

Oberling, Z. A., N. R. Riggs, A. P. Barth, and J. D. Walker. 2010. Major and trace element geochemistry and 87Sr/86Sr and ƐNd isotopic compositions of volcanic clasts from the Shinarump Member, Upper Triassic Chinle Formation. Geological Society of America Abstracts with Programs 42(5):646.

Parrish, J. M. 1989. Vertebrate paleoecology of the Chinle Formation (Late Triassic) of the Southwestern United States. Palaeogeography, Palaeoclimatology, Palaeoecology 72(3–4):227–247.

Parsons, T., J. McCarthy, W. M. Kohler, C. J. Ammon, H. M. Benz, J. A. Hole, and E. E. Criley. 1996. Crustal structure of the Colorado Plateau, Arizona: application of new long-offset seismic data analysis techniques. Journal of Geophysical Research: Solid Earth 101(B5):11,173–11,194.

Petersen, M. D., A. M. Shumway, P. M. Powers, E. H. Field, M. P. Morgan, P. Moschetti, K. S. Jaiswal, K. R. Milner, S. Rezaeian, A. D. Frankel, A. L. Llenos, A. J. Michael, J. M. Altekruse, S. K. Ahdi, K. B. Withers, C. S. Mueller, Y. Zeng, R. E. Chase, L. M. Salditch, N. Luco, K. S. Rukstales, J. A. Herrick, D. L. Girot, B. T. Aagaard, A. M. Bender, M. L. Blanpied, R. W. Briggs, O. Ss Boyd, B. S. Clayton, C. B. DuRoss, E. L. Evans , P. J. Haeussler, A. E. Hatem, K. L. Haynie, E. H. Hearn, K. M. Johnson, Z. A. Kortum, N. S. Kwong, A. J. Makdisi, H. B. Mason, D. E. McNamara, D. F. McPhillips, P. G. Okubo, M. T. Page, F. F. Pollitz, J. L. Rubinstein, B. E. Shaw, Z-K Shen, B. R. Shiro, J. A. Smith, W. J. Stephenson, E. M. Thompson, J. A. Thompson Jobe, E. A. Wirth, and R. C. Witter. 2024. The 2023 US 50-State National Seismic Hazard Model: overview and implications. Earthquake Spectra 40(1):5–88. https://doi.org/10.1177/87552930231215428

Peterson, C. S. 1986. Homestead and farm: a history of farming at Hubbell Trading Post National Historic Site. Prepared for Southwest Parks and Monument Association. Utah State University, Logan, Utah. http://npshistory.com/publications/hutr/index.htm

Petley, D. 2013. The Bitter Springs landslide in Arizona, USA. Online information. The landslide blog. American Geophysical Union, Washington, DC. https://blogs.agu.org/landslideblog/2013/02/22/the-bitter-springs-landslide-in-arizona-usa/ (accessed 13 February 2024).

Potochnik, A. R., J. E. Faulds, and S. J. Reynolds. 2022. Cenozoic drainage reversal on the southern margin of the Colorado Plateau, east-central Arizona, USA. Geomorphology 411, article 108286. https://doi.org/10.1016/j.geomorph.2022.108286

Price, G. L. 2010. The geology of northern New Mexico’s parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Raucci, J. J., R. C. Blakey, and P. J. Umhoefer. 2006. A new geologic map of Petrified Forest National Park with emphasis on members and key beds of the Chinle Formation. Pages 157–159 *in* W. G. Parker, S. R. Ash, and R. B. Irmis, editors. A century of research at Petrified Forest National Park 1906–2006. Bulletin 62. Museum of Northern Arizona, Flagstaff, Arizona.

Redsteer, M. H., and S. M. Wessells. 2017. A record of change—science and elder observations on the Navajo Nation. General Information Product 181 (video, available in English and Navajo). US Geological Survey, Reston, Virginia. https://doi.org/10.3133/gip181

Regan, A. B. 1924. Stratigraphy of the Hopi Buttes volcanic field, Arizona. Pan-American Geologist 41(5):355–366.

Regan, A. B. 1932. The Tertiary-Pleistocene of the Navajo country in Arizona with a description of some its fossils. Kansas Academy of Science Transactions 35:253–259.

Regenesis Collaborative Development Group, Inc. 2005. Hubbell Trading Post farm plan. Prepared for the National Park Service, Hubbell Trading Post National Historic Site. Regenesis Collaborative Development Group, Inc., Santa Fe, New Mexico. https://irma.nps.gov/DataStore/Reference/Profile/2203902. Note: Access to this file is limited to NPS staff.

Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. 2018. Fourth national climate assessment, volume II: impacts, risks, and adaptation in the United States. US Global Change Research Program, Washington, DC. https://www.doi.org/10.7930/NCA4.2018

Repenning, C. A., and J. H. Irwin. 1954. Bidahochi Formation of Arizona and New Mexico. American Association of Petroleum Geologists Bulletin 38(8):1821–1826.

Repenning, C. A., J. F. Lance, and J. H. Irwin. 1958. Tertiary stratigraphy of the Navajo country. Pages 123–129 *in* R. Y. Anderson and J. W. Harshbarger, editors. Black Mesa Basin, Northeastern Arizona. Fall Field Conference Guidebook 9. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/9/

Reynolds, L. V., and D. J. Cooper. 2011. Ecosystem response to removal of exotic riparian shrubs and a transition to upland vegetation: Plant Ecology 212(8):1243–1261. https://www.doi.org/10.1007/s11258-011-9901-7

Reynolds, L. V., and D. J. Cooper. 2017. Riparian restoration following tamarisk and Russian olive control in Canyon de Chelly National Monument, Arizona. Pages 32–36 *in* B. E. Ralston and D. A. Sarr, editors. Case studies of riparian and watershed restoration in the southwestern United States—principles, challenges, and successes. Open-File Report 2017-1091. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/ofr20171091

Reynolds, S. J. 1998. Geologic features of northern Arizona. Pages 1–11 (chapter 1) in R. Frisch-Gleason, editor. Highlights of northern Arizona geology. Down-to-Earth 7. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629405

Richard, S. M., S. J. Reynolds, J. E. Spencer, and P. A. Pearthree. 2000. Geologic map of Arizona (scale 1:1,000,000). Map 35. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/photo/geologic-map-arizona

Riggs, N. R., Z. A. Oberling, E. R. Howell, W. G. Parker, A. P. Barth, M. R. Cecil, and J. W. Martz. 2016. Sources of volcanic detritus in the basal Chinle Formation, southwestern Laurentia, and implications for the Early Mesozoic magmatic arc. Geosphere 12(2):439–463. https://doi.org/10.1130/GES01238.1

Saleeby, J. 2003. Segmentation of the Laramide slab—evidence from the southern Sierra Nevada region. Geological Society of America Bulletin 115(6):655–668. https://doi.org/10.1130/0016-7606(2003)115%3C0655:SOTLSF%3E2.0.CO;2

Santucci, B. A., C. A. Moneymaker, J. F. Lisco, and V. L. Santucci. 2021a. An overview of paleontological resources preserved within prehistoric and historic structures. Pages 347–356 *in* S. G. Lucas, A. P. Hunt, and A. J. Lichtig, editors. Fossil record 7. Bulletin 82. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://irma.nps.gov/DataStore/Reference/Profile/2283741

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm

Santucci, V. L., D. Weeks, and R. Thornburg. 2021b. The intersecting crossroads of paleontology and archeology: when are fossils considered artifacts? Chaco Culture National Historical Park, Mesa Verde National Park, Pecos National Historical Park, Petrified Forest National Park, Salinas Pueblo Missions National Monument, White Sands National Park, Wupatki National Monument. Intermountain Park Science 2021, online article. https://home.nps.gov/articles/000/the-intersecting-crossroads-of-paleontology-and-archeology-when-are-fossils-considered-artifacts.htm (accessed 13 February 2024).

Scarborough, R. B. 1985. Cenozoic erosion and sedimentation in Arizona. Open-File Report OFR-85-3. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/635651

Scotese, C. R., R. K. Bambach, C. Barton, R. Van DerVoo, and A. M. Ziegler. 1979. Paleozoic base maps. The Journal of Geology 87:217–277. https://doi.org/10.1086/628416

Scott, M. L., D. W. Perkins, D. M. Merritt, J. A. Scott, and D. J. Cooper. 2018. Big rivers monitoring within Dinosaur National Monument: a summary of monitoring results to detect change in channel condition. Natural Resource Report NPS/NCPN/NRR—2018/1635. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2253155

Semken, S. 2010. Ship Rock and the Navajo volcanic field, Navajo Nation. Pages 85–91 *in* L. G. Price, editor. The geology of northern New Mexico's parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Slaff, S. 1993. Land subsidence and earth fissures in Arizona. Down-To-Earth 3. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629605

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

Soil Science Society of America. 2022. Glossary of soil science terms. Online information. Soil Science Society of America, Madison, Wisconsin. https://www.soils.org/publications/soils-glossary# (accessed 13 February 2024).

Southern Colorado Plateau Network. 2022a. Riparian ecosystems monitoring. Online information. National Park Service, Southern Colorado Plateau Inventory & Monitoring Network, Flagstaff, Arizona. https://www.nps.gov/im/scpn/riparian-ecosystems.htm (accessed 13 February 2024).

Southern Colorado Plateau Network. 2022b. What we monitor. Online information. National Park Service, Southern Colorado Plateau Inventory & Monitoring Network, Flagstaff, Arizona. https://www.nps.gov/im/scpn/what-we-monitor.htm (accessed 13 February 2024).

Spencer, J. E. 1992. Radon gas: a geologic hazard in Arizona. Down-To-Earth 2. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/628821

Spencer, J. E., editor. 1993. Radon in Arizona. Bulletin 199. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629494

Spencer, J. E., J. D. Shenk, and J. T. Duncan. 1990. Map showing areas in Arizona with elevated concentrations of uranium (scale 1:1,000,000). Open-File Report OFR-90-05. Arizona Geological Survey, Tucson, Arizona. https://repository.arizona.edu/handle/10150/629490

Sweeney, M. R., and E. V. McDonald. 2017. Dust emission potential along the Interstate 8 corridor, southern California and Arizona. Geological Society of America Abstracts with Programs 49(6), paper number 24-8. https://www.doi.org/10.1130/abs/2017AM-298753

Sweeney, M. R., E. V. McDonald, V. Etyemezian. 2011. Quantifying dust emissions from desert landforms, eastern Mojave Desert, USA. Geomorphology 135:21–34.

Stewart, J. H., F. G. Poole, and R. F. Wilson. 1972. Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region. Professional Paper 690. US Geological Survey, Washington, DC. https://pubs.usgs.gov/publication/pp690

Tasch, P. 1978. Paleoecology of a conchostracan-bearing lacustrine deposit (Chinle Formation, New Mexico). Geological Society of America Abstracts with Programs 10(1):26.

Therrien, F., M. M. Jones, D. E. Fastovsky, A. S. Herrick, and G. D. Hoke. 1999. The oldest Triassic strata exposed in Petrified Forest National Park revisited. Pages 101–108 *in* V. L. Santucci and L. McClelland, editors. National Park Service Paleontological Research, Volume 4. National Park Service Technical Report NPS/NRGRD/GRDTR-99/3. National Park Service, Geologic Resources Division, Lakewood, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2239628

Turner, C. E., and F. Peterson. 2004. Reconstruction of the Upper Jurassic Morrison Formation extinct ecosystem—a synthesis. Sedimentary Geology 167(3–4):309–355.

Turner, C. E., F. Peterson, D. J. Chure, T. M. Demko, G. F. Engelmann, S. R. Ash, B. B. Britt, E. H. Christiansen, A. L. Deino, S. P. Dunagan, F. G. Ethridge, E. Evanoff, A. R. Fiorillo, S. C. Good, S. T. Hasiotis, B. J. Kowallis, M. J. Kunk, J. S. McIntosh, D. L. Newell, J. D. Obradovich, J. T. Parrish, M. E. Schudack, G. L. Skipp, W. D. Tidwell. 1998. Final report: the Morrison Formation extinct ecosystems project. Interagency agreement 1443-IA-1200-94-003. Technical Information Center number D-737. US Geological Survey, Denver, Colorado and Reston, Virginia; US National Park Service, Jensen, Utah; University of Nebraska, Omaha, Nebraska; New Mexico Museum of Natural History and Science, Albuquerque, New Mexico; Museum of Western Colorado, Grand Junction, Colorado; Brigham Young University, Provo, Utah; Berkeley Geochronology Center, Berkeley, California; Austin Peay State University, Clarksville, Tennessee; Colorado State University, Fort Collins, Colorado; University of Colorado, Boulder, Colorado; Dallas Museum of Natural History, Dallas, Texas; West Chester University, West Chester, Pennsylvania; Exxon Production Research Co., Houston, Texas; Brigham Young University, Provo, Utah; Wesleyan University, Middletown, Connecticut; Los Alamos National Laboratory, Los Alamos, New Mexico; University of Arizona, Tucson, Arizona; Freie Universitat, Berlin, Germany.

Tweet, J. S., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring—Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. National Park Service, Fort Collins, Colorado.

Tweto, O. 1975. Laramide (Late Cretaceous-Early Tertiary) orogeny in the southern Rocky Mountains. Pages 1–44 *in* B. F. Curtis, editor. Cenozoic history of the southern Rocky Mountains. Memoir 144. Geological Society of America, Boulder, Colorado. https://doi.org/10.1130/MEM144-p1

US Board on Geographic Names. 1981. Summary report, feature details [for] Hubbell Hill, Apache County, Arizona. Feature ID: 6091. Online information. Geographic Names Information System (GNIS), maintained by the US Geological Survey, Washington, DC. https://edits.nationalmap.gov/apps/gaz-domestic/public/search/names (accessed 13 February 2024).

US Board on Geographic Names. 2000. Summary report, feature details [for] Defiance Plateau, Apache County, Arizona. Feature ID: 1675454. Online information. Geographic Names Information System (GNIS), maintained by the US Geological Survey, Washington, DC. https://edits.nationalmap.gov/apps/gaz-domestic/public/search/names (accessed 13 February 2024).

US Census Bureau. 2020. Decennial census of population and housing. Online information. US Census Bureau, Washington, DC. https://www.census.gov/en.html (accessed 13 February 2024).

US Geological Survey. 1999. Map accuracy standards. Fact Sheet 171-99. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/fs17199

US Geological Survey. 2015. Streamer. Online information. US Geological Survey, Texas Water Science Center, Austin, Texas. https://txpub.usgs.gov/DSS/streamer/web/ (accessed 13 February 2024).

US Geological Survey. 2023. Volcano hazards. Online information. US Geological Survey, Volcano Hazards Program, Reston, Virginia. https://www.usgs.gov/programs/VHP (accessed 13 February 2024).

Vazquez, J. A. 1998. Maar volcanism in the Wood Chop Mesa area, Hopi Buttes volcanic field, Navajo Nation, Arizona: Thesis. Northern Arizona University, Flagstaff, Arizona.

Vigil, J. R., R. J. Pike, and D. G. Howell. 2000. A tapestry of time and terrain. Geologic Investigations Series 2720. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/imap/i2720/

Wagner, J. I., and R. Inglis. 2010. Assessment of riparian-wetland conditions and recommendations for management: Pueblo Colorado Wash, Hubbell Trading Post National Historic Site, Arizona. Natural Resource Report NPS/NRPC/NRR—2010/213. National Park Service, Water Resources Division, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2124850

White, J. D. L. 1991. Maar-diatreme phreatomagmatism at Hopi Buttes, Navajo Nation (Arizona), USA. Bulletin of Volcanology 53:239–258.

Witkind, I. J., R. E. Thaden, H. E. Malde, and D. H. Johnson. 1963. Geologic map of the Monument Valley area, Arizona (scale 1:62,500). Plate 1 of Geology and uranium-vanadium deposits of the Monument Valley area, Apache and Navajo Counties, Arizona, with sections on Serpentine and Garnet Ridge and mineralogy and paragenesis of the ore deposit at the Monument No. 2 and Cato Sells mines. Bulletin 1103. US Geological Survey, Reston, Virginia. https://www.doi.org/10.3133/b1103

Worden, C. B., M. C. Gerstenberger, D. A. Rhoades, D. J. Wald. 2012. Probabilistic relationships between ground motion parameters and modified Mercalli intensity in California. Bulletin of the Seismological Society of America 102(1):204–221.

Wright, H. E. Jr. 1956. Origin of the Chuska Sandstone, Arizona–New Mexico: a structural and petrographic study of a Tertiary eolian sediment. Geological Society of America Bulletin 67(4):413–434.

Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. 2017. Climate science special report, fourth national climate assessment, volume I. US Global Change Research Program, Washington, DC. https://science2017.globalchange.gov/

Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm

Ypsilantis, W. G. 2011. Upland soil erosion monitoring and assessment: an overview. Technical Note 438. Bureau of Land Management, National Operations Center, Denver, Colorado. https://archive.org/details/blmlibrary

Zeedyk, W. 2004. Geomorphological monitoring and instream structure installations: final report, July 2004. Submitted to Hubbell Trading Post National Historic Site, Ganado, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/652277

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