U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science Directorate
Geologic Resources Division

Natural Bridges National Monument

GRI Ancillary Map Information Document

Produced to accompany the Geologic Resources Inventory (GRI) Digital Geologic Data for Natural Bridges National Monument

nabr_geology.pdf

Version: 2/9/2021

Geologic Resources Inventory Map Document for Natural Bridges National Monument

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Geologic Resources Inventory Map Document

Natural Bridges National Monument, Utah

Document to Accompany Digital Geologic-GIS Data

nabr_geology.pdf

Version: 2/9/2021

This document has been developed to accompany the digital geologic-GIS data developed by the Geologic Resources Inventory (GRI) program for Natural Bridges National Monument, Utah (NABR).

Attempts have been made to reproduce all aspects of the original source products, including the geologic units and their descriptions, geologic cross sections, the geologic report, references and all other pertinent images and information contained in the original publication.

This document contains the following information:

1) **About the NPS Geologic Resources Inventory Program** – A brief summary of the Geologic Resources Inventory (GRI) Program and its products. Included are web links to the GRI GIS data model, and to the GRI products page where digital geologic-GIS datasets, scoping reports and geology reports are available for download. In addition, web links to the NPS Data Store and GRI program home page, as well as contact information for the GRI coordinator, are also present.

2) **GRI Digital Map and Source Citation** – The GRI digital geologic-GIS map produced for this project along with the source map used in its completion.

3) **Map Unit List** – A listing of all geologic map units present on maps for this project, listed from youngest to oldest.

4) **Map Unit Descriptions** – Descriptions for all geologic map units.

5) **Ancillary Source Map Information** – Additional source map information from the source map report.

6) **GRI Digital Data Credits** – GRI digital geologic-GIS data and ancillary map information document production credits.

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About the NPS Geologic Resources Inventory Program

Background

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. Geologic resources for management consideration include both the processes that act upon the Earth and the features formed as a result of these processes. Geologic processes include: erosion and sedimentation; seismic, volcanic, and geothermal activity; glaciation, rockfalls, landslides, and shoreline change. Geologic features include mountains, canyons, natural arches and bridges, minerals, rocks, fossils, cave and karst systems, beaches, dunes, glaciers, volcanoes, and faults.

The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. Many additional partners participate in the GRI process by contributing source maps or reviewing products.

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists.

Products

Scoping Meetings: These park-specific meetings bring together local geologic experts and park staff to inventory and review available geologic data and discuss geologic resource management issues. A summary document is prepared for each meeting that identifies a plan to provide digital map data for the park.

Digital Geologic Maps: Digital geologic maps reproduce all aspects of traditional paper maps, including notes, legend, and cross sections. Bedrock, surficial, and special purpose maps such as coastal or geologic hazard maps may be used by the GRI to create digital Geographic Information Systems (GIS) data and meet park needs. These digital GIS data allow geologic information to be easily viewed and analyzed in conjunction with a wide range of other resource management information data.

For detailed information regarding GIS parameters such as data attribute field definitions, attribute field codes, value definitions, and rules that govern relationships found in the data, refer to the NPS Geology-GIS Data Model document available at: https://www.nps.gov/articles/gri-geodatabase-model.htm

Geologic Reports: GRI reports synthesize discussions from the original scoping meeting, follow up conference call(s), and subsequent research. Chapters of each report discuss the geologic setting of the park, distinctive geologic features and processes within the park, highlight geologic issues facing resource managers, and describe the geologic history leading to the present-day landscape. Each report also includes a poster illustrating these GRI digital geologic-GIS data.

For a complete listing of GRI products visit the GRI publications webpage: https://go.nps.gov/gripubs. GRI digital geologic-GIS data is also available online at the NPS Data Store: https://irma.nps.gov/DataStore/Search/Quick. To find GRI data for a specific park or parks select the appropriate park(s), enter “GRI” as a Search Text term, and then select the Search button.

For more information about the Geologic Resources Inventory Program visit the GRI webpage: https://

www.nps.gov/subjects/geology/gri.htm. At the bottom of that webpage is a “Contact Us” link if you need additional information. You may also directly contact the program coordinator:

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The Geologic Resources Inventory (GRI) program is funded by the National Park Service (NPS) Inventory and Monitoring (I&M) Division. Learn more about I&M and the 12 baseline inventories at the I&M webpage: https://www.nps.gov/im/inventories.htm.

GRI Digital Map and Source Map Citation

The GRI digital geologic-GIS map for Natural Bridges National Monument, Utah (NABR):

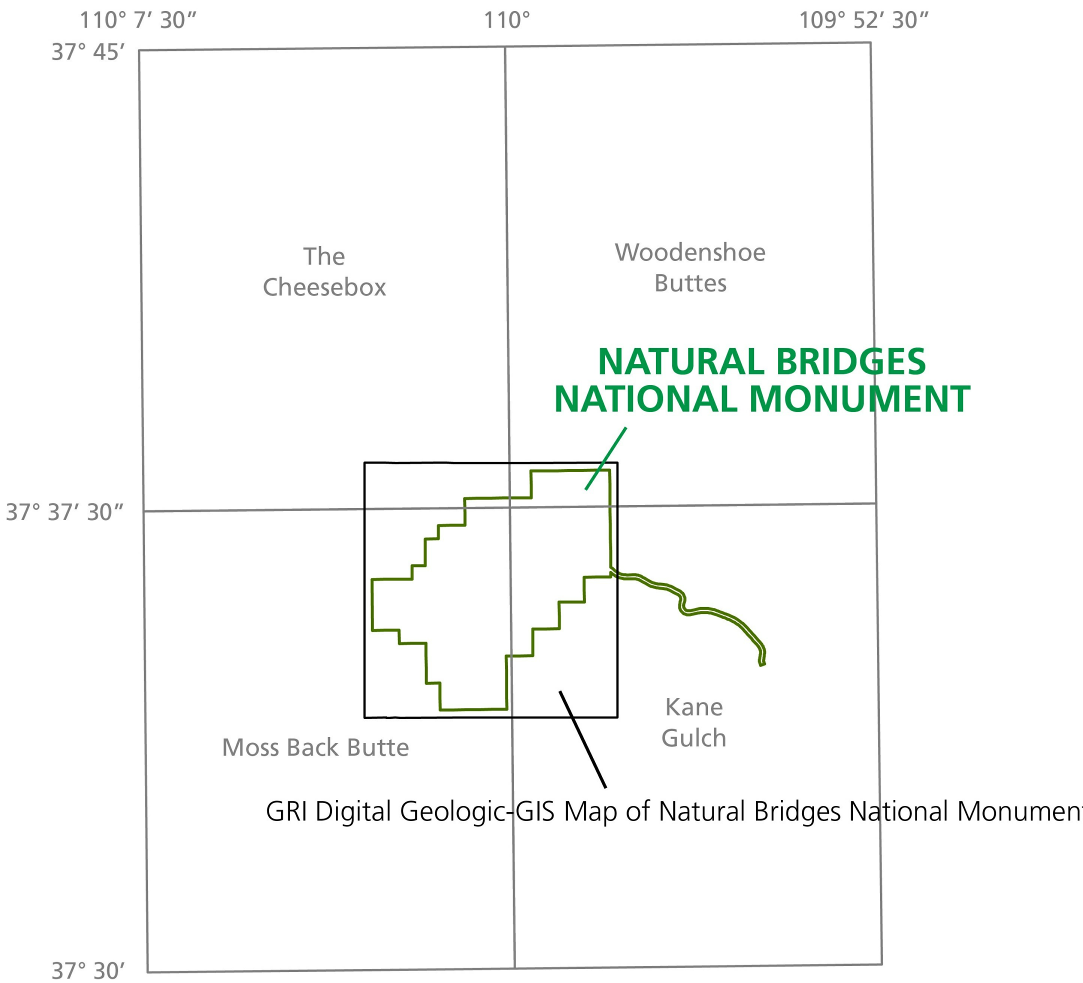
Digital Geologic-GIS Map of Natural Bridges National Monument, Utah (*GRI MapCode NABR*)

Huntoon, Jacqueline E., 2000, Geologic Map of Natural Bridges National Monument and Vicinity, Utah: Michigan Technological University, unpublished digital data and report, scale 1:24,000 (Natural Bridges National Monument). (*GRI Source Map ID 945*).

The full extent of the source map was used, and all geologic features were captured. Additional information pertaining to each source map is also presented in the GRI Source Map Information (NABRMAP) table included with the GRI geologic-GIS data.

Index Map

The following index map displays the extent of the GRI digital geologic-GIS map (in black) produced for Natural Bridges National Monument (NABR). The boundary for Natural Bridges National Monument (as of February, 2021) is outlined in green. The extent of 7.'5 quadrangles that the monument is within are also presented.



Index Map by Stephanie O'Meara (Colorado State University).

Map Unit List

The geologic units present in the digital geologic-GIS data produced for Natural Bridges National Monument, Utah (NABR) are listed below. Units are listed with their assigned unit symbol and unit name (e.g., Qal - Alluvium). Units are listed from youngest to oldest. Information about each geologic unit is also presented in the GRI Geologic Unit Information (NABRUNIT) table included with the GRI geologic-GIS data. Triassic source unit symbols were changed from Tr to TR in this document and in the GRI digital geologic-GIS data.

Cenozoic Era

Quaternary Period
Qal - Shattered sedimentary and igneous rocks

Mesozoic Era

Triassic Period
TRc - Chinle Formation
TRm - Moenkopi Formation

Paleozoic Era

Permian Period
Po - Organ Rock Formation
Pc - Cedar Mesa Formation

Map Unit Descriptions

Descriptions of all geologic map units, listed from youngest to oldest, are presented below. All unit descriptions were taken from the source map Natural Bridges National Monument.

Qal - Alluvium (Quaternary)

No additional unit description present on source map.

TRc - Chinle Formation (Upper Triassic)

The Upper Triassic Chinle Formation unconformably overlies the Moenkopi Formation. The Chinle forms a pastel-colored slope composed of entirely continental deposits along the rim of the mesa that lies to the north of NABR. The Chinle varies in thickness from about 300 to 600 feet (100-200 m) near Natural Bridges. The basal member of the Chinle, the Shinarump Conglomerate Member, contains quartz- and chert-pebble conglomerate deposited by fluvial systems that eroded paleovalleys into the underlying Moenkopi Formation. Above the Shinarump Conglomerate Member, Chinle sediments were deposited in fluvial channel, floodplain, marsh, and lake systems. Fluvial trunk-stream systems flowed mainly to the northwest, toward the shoreline located in western Utah. Chinle sediments were derived from both the Uncompahgre uplift and the interior of North America (Stewart and others, 1972b; Dubiel, 1994. The climate during deposition of the Chinle is interpreted to have been monsoonal with pronounced alternation between wet and dry seasons (Dubiel and others, 1991).

TRm - Moenkopi Formation (Triassic)

In the immediate vicinity of NABR, the Permian-Triassic unconformity separates the Permian Organ Rock Formation from the overlying Lower to early Middle Triassic Moenkopi Formation (Blakey and others, 1993). The unconformity between the Organ Rock and the Moenkopi is difficult to identify near Natural Bridges because Moenkopi red beds directly overlie Organ Rock red beds. The major difference between the two formations is that the lower part of the Moenkopi contains very coarse to medium-sized, well-rounded quartz grains. These grains were likely derived from erosion of the uppermost parts of the White Rim Sandstone and/or De Chelly Sandstone. The White Rim and De Chelly Sandstones are not present in the Natural Bridges area because Natural Bridges lies close to the crest of the Monument upwarp. During development of the Permian-Triassic unconformity these two units were eroded from the crest of the Monument upwarp near Natural Bridges.

The Moenkopi Formation is mainly composed of reddish-brown sandstone, siltstone, and mudstone. Locally it contains chert-pebble conglomerate. The Moenkopi Formation was deposited in a variety of fluvial channel and floodplain, marginal-marine mudflat and tidal channel, sabkha, and marine environments (Stewart and others, 1972a). The Moenkopi along White Canyon varies from about 300 to 400 feet (100-130 m) in thickness, and forms a red-brown slope between the Organ Rock and Chinle Formations. Large-scale wavy bedding is present in the lower part of the Moenkopi (Hoskinnini Member) near Natural Bridges. The wavy bedding is interpreted to be the result of precipitation and dissolution of evaporites in the Hoskinnini.

Like parts of the Cutler Group below, the Moenkopi was deposited by fluvial and floodplain systems that drained the Uncompahgre uplift and other minor positive areas throughout central Utah. These continental systems connected with marginal-marine mudflat and marine depositional settings to the west and northwest. Gypsum is common in the lower members of the formation, indicating arid conditions at the time of deposition. Upsection, the Moenkopi contains fossilized plants and animals that indicate deposition in a warm tropical setting that may have experienced a monsoonal, wet-dry climate (Stewart and others, 1972a; Dubiel and others, 1991).

Po - Organ Rock Formation (Permian)

The Organ Rock Formation is the youngest formation in the Cutler Group in the vicinity of NABR. To the west, along Lake Powell in Glen Canyon National Recreation Area, the White Rim Sandstone of the Cutler Group overlies the Organ Rock. The White Rim was removed from the Natural Bridges area by erosion that occurred at the end of the Permian Period or the beginning of the Triassic Period. To the southeast of NABR, in the vicinity of Monument Valley, the De Chelly Sandstone of the Cutler Group overlies the Organ Rock. Where the White Rim and De Chelly Sandstones are absent, across the crest of the Monument upwarp, the Organ Rock is unconformably overlain by the Lower Triassic Moenkopi Formation. The Organ Rock is thin along the axis of the Monument upwarp, averaging about 300 feet (100 m) thick near NABR. To the east of the Monument upwarp, near Monument Valley, the Organ Rock is over 700 feet (210 m) thick, and to the west of Natural Bridges near Glen Canyon National Recreation Area the Organ Rock is about 400 feet (130 m) thick.

The Organ Rock is a reddish-brown to light-red, slope-forming unit composed of feldspar-rich very fine- to fine-grained sandstone, siltstone, mudstone, and minor carbonate-pebble conglomerate that was deposited primarily in continental fluvial, floodplain, and eolian environments (figure 8c). Marginal-marine mudflat and tidal channel environments are locally present. The lower part of the Organ Rock was deposited by fluvial systems that flowed to the southwest off the Uncompahgre uplift, and by intrabasinal fluvial systems that flowed to the northwest near Monument Valley. Fine-grained floodplain deposits, many exhibiting root casts, trace fossils, and paleosol (ancient soil) development, are interbedded with the fluvial channel deposits.

To the west of Natural Bridges (near Lake Powell), the lower part of the Organ Rock consists of broad, shallow cut-and-fill deposits. The cut-and-fill deposits may represent distal fluvial and floodplain environments on a low-gradient coastal plain, or marginal-marine mudflat and tidal-channel deposits. To date, no definite marine indicators have been identified. Rain-drop impressions, vertical and horizontal burrows, and adhesion ripples are typically associated with the cut-and-fill deposits. Adhesion ripples form when dry sand blows across a damp surface, and adheres to the wet surface in low wrinkled domes that are less than about ¼ inch (6 mm) high.

Also near Lake Powell, the upper part of the Organ Rock contains abundant large-scale cross-bedded sandstone units. These cross-bedded sandstones are interpreted as eolian dune deposits. On the east side of the crest of the Monument upwarp the upper part of the Organ Rock is composed of sandstone beds containing root casts and adhesion ripples. This succession is interpreted as the product of eolian sand sheet deposition. Loess deposits composed of massive very fine-grained sandstones and siltstones that contain root casts are rare within the Organ Rock, but are present in the upper part of the formation. The sedimentary structures within the Organ Rock indicate deposition in an environment that was occasionally flooded, and generally contained sufficient moisture to sustain plant growth.

Pc - Cedar Mesa Formation (Permian)

Almost all of the bedrock exposed within the boundaries of NABR is Cedar Mesa Sandstone (figure 6). White Canyon is named for the light colored sandstone. The contact between the Cedar Mesa and the underlying lower Cutler beds cannot be seen within NABR. In exposures located to the east and west of Natural Bridges the contact is gradational, indicating a gradual change of environments from those represented by the lower Cutler beds. The Cedar Mesa Sandstone's contact with the overlying Organ Rock Formation is well exposed along White Canyon near NABR and is also gradational.

In the Natural Bridges area, the Cedar Mesa consists of three lithofacies (rock assemblages). The dominant facies is a white sandstone. The second facies occurs as thin interbeds of red mudstone that are underlain and overlain by the white sandstone facies. The third facies is a gypsum and limestone facies that is exposed about 20 miles (32 km) to the southeast of Natural Bridges. Only the first two facies are common within NABR (figure 9).

White Sandstone Facies

The white sandstone facies consists of quartz-rich sandstones. Grains are subrounded to well rounded in shape and range from very fine to very coarse in size. Sand-sized marine fossil fragments are rarely present (Stanesco and Campbell, 1989). This facies contains abundant large-scale, high-angle cross-beds (figure 3a). The cross-bedding is interpreted to be the product of deposition by large, migrating eolian dunes. The white sandstone facies contains many other features that are common in modern eolian dunes.

Figure 3b shows a modern sand dune near Hanksville, Utah. The dune is moving toward the area shown in the lower-right corner of the photo. In active dunes the wind blows sand up the windward slope and over the top of the dune. Ripple marks at the top of the dune, in the upper-left corner of the photo, were produced as the sand moved over the crest of the dune. These ripple marks have high ripple indices (length to height ratios). They are generally less than 3/8 of an inch (5 mm) high. If there is sufficient sand supply, the ripples produce inversely graded lamination as they migrate downwind. These coarsening upward laminations that result from wind ripple migration are known as translatent strata.

As sand is blown over the crest of the dune it falls out of suspension on the dune's slipface, producing grainfall stratification. Sand accumulates most rapidly near the top of the slipface. Eventually the slipface becomes oversteepened and sand avalanches down the slope producing grainflow stratification. The toes of the avalanche lobes flow onto the dune apron, another site of ripple formation. Note that the crests of the ripples on the dune apron (figure 3b) run parallel to the direction of dune migration. Wind currents that are deflected by the dune and blow around its sides produce these ripples. In figure 10, wedge-shaped grainflow layers in the Cedar Mesa override and interfinger with translatent strata.

All of the features mentioned above can be seen in the white sandstone facies in Natural Bridges. The Geologic Guide to Sipapu Bridge Trail on the CD-ROM that accompanies this volume contains photographs and descriptions of cross-bedding, ripple marks with high ripple indices, translatent strata, grainflow stratification, as well as grainfall stratification.

The white sandstone facies also contains interdune and sand-sheet deposits. Interdunes are low-lying areas between dunes. Sand-sheets are planar areas that lie adjacent to dune fields. These environments are represented in the white sandstone facies by horizontally laminated units that commonly contain translatent strata but lack abundant cross-beds. The red mudstone facies (described below) is also present in the interdune and sand-sheet environments.

Red Mudstone Facies

Horizontally laminated beds of red mudstone 1 to 10 feet (0.3-3 m) thick separate the much thicker sections of white sandstone in the cliffs of Natural Bridges (figure 11). This facies consists of micaceous mudstone and very fine grained sandstone. Discontinuous unfossiliferous limestones are rarely present. The red mudstone layers are generally massive. Some contain mudcracks filled with sand from overlying units (figure 12), root casts, and burrows. At Natural Bridges some of the red mudstone layers extend laterally for miles. These laterally extensive red beds probably formed during floods that inundated numerous interdune areas and formed a continuous surface. Dunes composed of the white sandstone facies eventually migrated across the flood deposit. In Canyonlands National Park, red mudstones within the Cedar Mesa can be traced toward the northeast into fluvial sandstones and conglomerates of the Cutler Formation undivided (Langford and Chan, 1988). Recent flooding of a dunefield in Peru's altiplano is a modern analogue of the flood events that occurred during deposition of the Cedar Mesa Sandstone. In contrast to the laterally continuous red mudstone layers, some red mudstones pinch out into the white sandstone facies. This type of lateral relationship suggests that some of the red mudstones formed adjacent to active eolian dunes. We interpret these discontinuous red mudstone layers as the product of deposition in isolated interdune ponds that formed during floods or because of rising water tables.

Gypsum and Limestone Facies

Approximately 20 miles (32 km) southeast of Natural Bridges the white sandstone and red mudstone facies interfinger with gypsum and algal limestone in a section almost 1,000 feet (300 m) thick. Some of the gypsiferous layers are massive suggesting they formed from evaporation of ponded surface water. Other gypsum layers displace or deform surrounding sandstone and mudstone layers indicating gypsum grew within the clastic sediment. The algal limestone beds are light gray in color. They contain chert nodules up to 1 foot (30 cm) in diameter. The chert is commonly bright red in color. Many of the limestones exhibit fracturing and brecciation that is interpreted to reflect early, subaerial cementation (Ginsburg, 1957). The characteristics of this facies suggest deposition in a sabkha. Sabkhas form in intertidal or supratidal zones along coastlines under highly evaporative conditions. Results of analysis of carbon, oxygen, and sulfur isotopes, as well as the presence of rare marine fossils, indicate the Cedar Mesa sabkha formed along a marine shoreline that opened to the south (Stanesco and Campbell, 1989; Lock and Pelfrey, 1997).

Ancillary Source Map Information

The following section present ancillary source map information associated with source map used for this project.

Natural Bridges National Monument

The formal citation for this source.

> Huntoon, Jacqueline E., 2000, Geologic Map of Natural Bridges National Monument and Vicinity, Utah: Michigan Technological University, unpublished digital data and report, scale 1:24,000 (*GRI Source Map ID 945*).

Report with text sections and graphics associated with this source map.

Report

GEOLOGY OF THE NATURAL BRIDGES DOCUMENT

Abstract

Natural Bridges National Monument was established to protect three large natural bridges as well as ancient masonry structures constructed by ancestral Puebloan people. Streams in White Canyon and its tributary canyons are primarily responsible for formation of the bridges. Although the bridges are probably less than 30,000 years old, they occur in Permian Cedar Mesa Sandstone. The Cedar Mesa Sandstone was deposited during the Wolfcampian Epoch of the Permian Period (about 270 million years ago). Deposition of the Cedar Mesa Sandstone and the other formations that comprise the Permian Cutler Group occurred along the western margin of North America in a variety of terrestrial and marine environments. After it was deposited, the Cedar Mesa Sandstone was gradually buried to a depth of 5,000 to 10,000 feet (1,500-3,000 m). Some of the overlying rock formations, including the Triassic Moenkopi and Chinle Formations and the Jurassic Wingate Sandstone, are present in the mesas that surround Natural Bridges National Monument. The overlying rocks began to be eroded from the Natural Bridges area sometime between 74 and 65 million years ago, during the Late

Cretaceous to Tertiary Laramide orogeny. Most of the erosion occurred during the last 6 million years, as the Colorado River and its tributaries cut down through the rising Colorado Plateau. Although the ages of the bridges are difficult to determine, they probably began to form during the Pleistocene Epoch of the Quaternary Period (1.64 million-10,000 years before present). At that time the climate in southeastern Utah was considerably wetter than it is today.

Introduction

Natural Bridges National Monument (NABR) is located in southeastern Utah along the northern margin of the physiographic feature known as Cedar Mesa (figure 1). Natural Bridges can be reached via Utah State Route 275, a 4-mile (6.5-km) entry road that connects to Utah Highway 95 between Blanding and Hite Marina. Entry fees are collected at the Visitor Center where exhibits, a bookstore, and a 10-minute video orient visitors and explain the significance of NABR. A 13-site campground is located a short distance from the Visitor Center.

Two steep-sided canyons, Armstrong Canyon and White Canyon, cut through NABR. Three large natural bridges are located within the two canyons. Visitors to NABR can view the bridges from overlooks along Bridge View Drive, a paved 9-mile (14.5-km) loop. From the road, hikers can reach each of the bridges by following well-maintained trails that descend into the canyons. The bridges are linked by a marked but otherwise unmaintained 9-mile (14.5-km) loop hiking route.

The three bridges in NABR are among the ten largest in the world. Sipapu is the largest bridge in NABR and the first bridge that visitors see as they drive along Bridge View Drive. It is considered a mature bridge. Symmetrical in shape with a smooth, rounded opening, Sipapu's abutments lie above the level of the present-day streambed. At 220 feet (67 m) high, with a span of 268 feet (82 m), Sipapu is second only to Rainbow Bridge (located on Lake Powell) in size (see the paper by Chidsey and others in this volume for information about the geology of Rainbow Bridge National Monument). Kachina Bridge is located near the confluence of White and Armstrong Canyons. It is a massive, youthful bridge that is still growing in size. Kachina is 210 feet (64 m) high with a span of 204 feet (62 m). The rock making up the span is 93 feet (28 m) thick, and as recently as June, 1992 a major rockfall occurred as an estimated 4,000 tons (3.6 x 10 6 kg) of sandstone sloughed off the underside of the bridge on its west abutment. The third bridge, Owachomo, is the oldest in NABR and is nearing collapse. It is 106 feet (32 m) high with a span of 180 feet (55 m). Because it is only 9 feet (3 m) thick at the crest of its span, it is very fragile. Located adjacent to Armstrong Canyon, Owachomo lies above and parallel to the present-day streambed.

Geologic Overview

The three bridges are all developed in Lower Permian Cedar Mesa Sandstone. The Cedar Mesa Sandstone was deposited about 270 million years ago (Ma), at a time when the western shoreline of North America trended approximately north-south (in modern coordinates) and ran through the central part of present-day Utah (figure 2). Most of the rocks in the park were deposited by immense windblown sand dunes that migrated inland from the shoreline. The migrating dunes generated cross-bedding, the most prominent sedimentary structure that can be seen in the rocks in NABR (figure 3). As the dunes were buried by other sediments, they were compacted and cemented into rock. Detailed descriptions of the Cedar Mesa Sandstone and the rock units that occur above and below it are included later in this paper.

Although the bridges are carved out of the approximately 270 Ma Cedar Mesa Sandstone, the bridges themselves are likely less than 30,000 years old. Between the time that the Cedar Mesa Sandstone was deposited and the time that the bridges formed, the Cedar Mesa was buried beneath at least 5,000 feet (1,500 m) of overlying rock and sediment. The lower portion of this package of sedimentary rocks is equivalent to the rock units that are exposed in the cliffs and mesas that surround NABR. Most of the overlying rock was probably removed relatively recently, during the last 6 million years (m. y.). Once the Cedar Mesa Sandstone was again exposed at the surface of the Earth, water flowing in White Canyon and Armstrong Canyon began to cut down into it. The natural bridges formed as the canyons cut through necks in the Cedar Mesa Sandstone and channel meanders were abandoned.

Bridges differ from arches in that they are formed by flowing water. The bridges probably began to form during the last glacial stadial, the Pinedale Glacial, that lasted from about 30,000 to12,000 years before present (ybp). Although the Natural Bridges area was not directly in contact with glacial ice, high levels of precipitation during the glacial stadial may have produced large floods that periodically flowed through Armstrong and White Canyons. Thin canyon walls that blocked and diverted the flow into meanders may have been penetrated during the floods. The bridges are the remnants of the thin canyon walls (figure 4). In addition to flowing water, other processes were also instrumental in formation and expansion of the bridges. Development of the bridges is discussed in detail later in this paper.

History of Natural Bridges National Monument and its bridges

In 1883, Cass Hite wandered up White Canyon from the Colorado River searching for gold. He found treasure of a different sort. Three massive stone bridges towered near the head of the White Canyon drainage (figure 5). In the years that followed, cowboys and adventurers found their way to Cedar Mesa to see the unusual spans. In 1904, National Geographic Magazine published a story, "The Colossal Bridges of Utah," that introduced the world to the bridges. A year later a local cowboy named John Scorup led the first scientific expedition to photograph, measure, and study the natural bridges.

United States citizens were extremely interested in the bridges during the first decade of the 20th century, and were equally fascinated with ancient masonry structures found on Cedar Mesa. In 1906 Congress passed the Antiquities Act in an attempt to stem wholesale looting and destruction of the archeological resource. On April 16, 1908, Theodore Roosevelt established Natural Bridges as Utah's first National Monument to protect both the natural bridges and the ruins.

In conducting a survey of the newly created monument the following year, the General Land Office assigned the Hopi names Sipapu, Kachina, and Owachomo to the three bridges that had previously been known as Augusta, Caroline, and Edwin respectively. Sipapu means "the place of emergence," an entryway by which the Hopi believe their ancestors came into this world. Kachina Bridge is named for rock art symbols on the bridge that resemble symbols commonly used on Kachina dolls. Owachomo means, "rock mound," in honor of a feature atop the bridge's east abutment. These Hopi names were chosen because it was at that time widely (and correctly) supposed that the modern-day Hopi (as well as other modern-day Puebloans) are descendents of the people who occupied these remote canyons in ancient times.

Geology of Natural Bridges National Monument

In this section the paleotectonic setting of the Natural Bridges area during deposition of two bedrock formations exposed in NABR (the Cedar Mesa Sandstone and Organ Rock Formation) is first discussed. After the Cedar Mesa and Organ Rock were deposited, they were buried beneath younger rocks, some of which can be seen in the cliffs surrounding NABR. The sedimentology and stratigraphy of the rock units present in and near Natural Bridges are described in the second part of this section. The final part of this section describes the evolution of the natural bridges.

Permian Paleotectonic Elements of Southeastern Utah

Natural Bridges National Monument encompasses an area underlain almost entirely by the Lower Permian Cedar Mesa Sandstone and Organ Rock Formation (figure 6). Deposition of the Cedar Mesa Sandstone occurred during the Wolfcampian Epoch of the Permian Period (270 to 290 Ma), and the Organ Rock Formation was deposited during the Leonardian Epoch (255 to 270 Ma) (Harland and others, 1989; Blakey, 1996; Stanesco and others, this volume). Three major paleotectonic elements (Uncompahgre uplift, Paradox basin, and Monument upwarp) influenced deposition in southeastern Utah during the Early Permian (figure 2). The Uncompahgre uplift was part of the Ancestral Rocky

Mountains. The Ancestral Rockies formed during the Pennsylvanian Period, concurrent with collision of a microcontinent or an island arc and the southern part of North America near Texas and Oklahoma (Ouchita orogeny) (Harry and Mickus, 1998). Stress produced by the collision may have been responsible for development of fault-bounded uplifts and basins across what is now the south-central United States (Kluth and Coney, 1981). The Uncompahgre uplift is bounded by a high-angle reverse fault along its southwestern side (Frahme and Vaughn, 1983). Movement along the Uncompahgre fault resulted in development of a foreland basin, the Paradox basin, adjacent to the uplift. Although the Paradox basin began subsiding during the Pennsylvanian, both the basin and the uplift were still active during the Permian (Huffman and Taylor, 1994).

The third paleotectonic element that influenced deposition in southeastern Utah during the Early Permian is the Monument upwarp. The Monument upwarp is approximately coincident with the southwestern edge of the Paradox basin in southeastern Utah. Isopach maps and correlated sections (for example, Baars, 1962; Blakey, 1996; Condon, 1997) demonstrate that the Monument upwarp influenced deposition during the late Paleozoic and possibly the Early Triassic (Kelley, 1955; Huntoon and others, 1994; Stanesco and others, this volume). During the Permian, the upwarp was a broad, elongate, low-lying topographic high that extended from Monument Valley to approximately the confluence of the Green and Colorado Rivers (figure 2). Blakey (1996) described the effect of the upwarp on deposition of late Paleozoic eolian rocks (including the Cedar Mesa Sandstone). Stanesco and others (this volume) document the Monument upwarp's influence on deposition of the Organ Rock Formation. The Monument upwarp was also active during the Laramide orogeny (late Mesozoic to early Cenozoic). Evidence of this relatively recent activity can be seen at Comb Ridge, where rocks along the upwarp's eastern margin are bent into a steep monocline. Because rocks on the upwarp are bent upward, late Paleozoic and younger rocks are well exposed in cliff faces near the axis of the upwarp where erosion has penetrated into its core.

During the Permian, boulder conglomerates were deposited in proximal alluvial fan environments adjacent to the Uncompahgre fault in the Paradox basin (Campbell, 1980; Mack and Rasmussen, 1984). Feldspar-rich sandstones and silty sandstones were deposited in the distal portions of the fans. Fluvial systems deposited feldspar-rich silty sandstones throughout the Paradox basin and at times prograded from the Paradox basin toward the paleoshoreline. The Organ Rock Formation consists of feldspar-rich rocks that were primarily derived from the Uncompahgre uplift (Stanesco and others, this volume).

The Organ Rock's feldspar-rich composition contrasts with the high quartz content of the Cedar Mesa Sandstone. The Cedar Mesa Sandstone, like other Permian sandstones on the Colorado Plateau, was probably derived from a source area other than the Uncompahgre uplift (Scott, 1965; Irwin, 1976; Campbell and Stanesco, 1985). Paleocurrent data from the Cedar Mesa Sandstone suggest that it was deposited by northwesterly winds. Poole (1962) suggested that the Cedar Mesa, as well as other late Paleozoic sandstones on the Colorado Plateau, were derived from recycling of older eolian sandstones. Based on paleogeographic and paleoclimatic reconstructions (Parrish, 1985), paleocurrent data (Poole, 1962), and composition data (Scott, 1965; Campbell and Stanesco, 1985), the Cedar Mesa is interpreted to have been primarily derived from the shallow-marine shelf environment located to the northwest (in terms of modern latitude and longitude) of NABR (Stanesco and Campbell, 1989). Sediments were made available for transport from the shelf to the Natural Bridges area during times of lowered sea level when the shelf was subaerially exposed (Loope, 1984; Peterson, 1988).

Regional Stratigraphy and Sedmentology

In the Natural Bridges region, the Organ Rock Formation is the top of the Permian System. Triassic and Jurassic rocks that overlie the Organ Rock Formation are exposed along the skyline that is visible from NABR. These rocks include the Lower Triassic Moenkopi Formation, the Upper Triassic Chinle Formation, and the Lower Jurassic Wingate Sandstone. The Organ Rock, along with the underlying Cedar Mesa Sandstone and the informally named lower Cutler beds, are part of the Cutler Group. The lower Cutler beds are the oldest Permian rocks exposed on Cedar Mesa. Toward the north and northeast, the Cutler Group grades into the coarser Cutler Formation undivided. The Cutler Formation undivided consists of sandstones and conglomerates deposited in fluvial and alluvial fan environments adjacent to the Uncompahgre uplift. The Cutler Group and the Triassic and Jurassic formations that can be seen from Natural Bridges are described in this section (figure 7).

Lower Cutler Beds

The lower Cutler beds are not exposed in Natural Bridges, but they are present elsewhere on Cedar Mesa. The lower Cutler beds consist of interlayered sandstones, mudstones, and limestones. Tidal flats, deltas, coastal sand dunes, fluvial systems, and shallow-marine shelf environments are all represented in the lower Cutler beds (Loope, 1984; Campbell, 1987; Condon, 1997). Lateral shifts in the location of these environments resulted in interbedding of rock types in the lower Cutler beds. Figure 8a depicts the geography of southeastern Utah during deposition of the lower Cutler beds. Feldspar-rich sediment was shed from the Uncompahgre uplift. Some of this sediment was transported by fluvial systems to a shallow sea whose shoreline fluctuated back and forth across the present-day location of Natural Bridges. Sand and dust were blown through the Natural Bridges region when relative sea level was low and the marine shelf to the northwest was exposed (Campbell, 1987). Southeast of Natural Bridges, the upper part of the lower Cutler beds grades into the thickly bedded red siltstones and very fine-grained sandstones of the Halgaito Formation. The Halgaito is interpreted as loess deposits that formed downwind of sand dunes located in the Natural Bridges area (Murphy, 1987).

Cedar Mesa Sandstone

Almost all of the bedrock exposed within the boundaries of NABR is Cedar Mesa Sandstone (figure 6). White Canyon is named for the light colored sandstone. The contact between the Cedar Mesa and the underlying lower Cutler beds cannot be seen within NABR. In exposures located to the east and west of Natural Bridges the contact is gradational, indicating a gradual change of environments from those represented by the lower Cutler beds. The Cedar Mesa Sandstone's contact with the overlying Organ Rock Formation is well exposed along White Canyon near NABR and is also gradational.

In the Natural Bridges area, the Cedar Mesa consists of three lithofacies (rock assemblages). The dominant facies is a white sandstone. The second facies occurs as thin interbeds of red mudstone that are underlain and overlain by the white sandstone facies. The third facies is a gypsum and limestone facies that is exposed about 20 miles (32 km) to the southeast of Natural Bridges. Only the first two facies are common within NABR (figure 9).

White Sandstone Facies

The white sandstone facies consists of quartz-rich sandstones. Grains are subrounded to well rounded in shape and range from very fine to very coarse in size. Sand-sized marine fossil fragments are rarely present (Stanesco and Campbell, 1989). This facies contains abundant large-scale, high-angle cross-beds (figure 3a). The cross-bedding is interpreted to be the product of deposition by large, migrating eolian dunes. The white sandstone facies contains many other features that are common in modern eolian dunes.

Figure 3b shows a modern sand dune near Hanksville, Utah. The dune is moving toward the area shown in the lower-right corner of the photo. In active dunes the wind blows sand up the windward slope and over the top of the dune. Ripple marks at the top of the dune, in the upper-left corner of the photo, were produced as the sand moved over the crest of the dune. These ripple marks have high ripple indices (length to height ratios). They are generally less than 3/8 of an inch (5 mm) high. If there is sufficient sand supply, the ripples produce inversely graded lamination as they migrate downwind. These coarsening upward laminations that result from wind ripple migration are known as translatent strata.

As sand is blown over the crest of the dune it falls out of suspension on the dune's slipface, producing grainfall stratification. Sand accumulates most rapidly near the top of the slipface. Eventually the slipface becomes oversteepened and sand avalanches down the slope producing grainflow stratification. The toes of the avalanche lobes flow onto the dune apron, another site of ripple formation. Note that the crests of the ripples on the dune apron (figure 3b) run parallel to the direction of dune migration. Wind currents that are deflected by the dune and blow around its sides produce these ripples. In figure 10, wedge-shaped grainflow layers in the Cedar Mesa override and interfinger with translatent strata.

All of the features mentioned above can be seen in the white sandstone facies in Natural Bridges. The Geologic Guide to Sipapu Bridge Trail on the CD-ROM that accompanies this volume contains photographs and descriptions of cross-bedding, ripple marks with high ripple indices, translatent strata, grainflow stratification, as well as grainfall stratification.

The white sandstone facies also contains interdune and sand-sheet deposits. Interdunes are low-lying areas between dunes. Sand-sheets are planar areas that lie adjacent to dune fields. These environments are represented in the white sandstone facies by horizontally laminated units that commonly contain translatent strata but lack abundant cross-beds. The red mudstone facies (described below) is also present in the interdune and sand-sheet environments.

Red Mudstone Facies

Horizontally laminated beds of red mudstone 1 to 10 feet (0.3-3 m) thick separate the much thicker sections of white sandstone in the cliffs of Natural Bridges (figure 11). This facies consists of micaceous mudstone and very fine grained sandstone. Discontinuous unfossiliferous limestones are rarely present. The red mudstone layers are generally massive. Some contain mudcracks filled with sand from overlying units (figure 12), root casts, and burrows. At Natural Bridges some of the red mudstone layers extend laterally for miles. These laterally extensive red beds probably formed during floods that inundated numerous interdune areas and formed a continuous surface. Dunes composed of the white sandstone facies eventually migrated across the flood deposit. In Canyonlands National Park, red mudstones within the Cedar Mesa can be traced toward the northeast into fluvial sandstones and conglomerates of the Cutler Formation undivided (Langford and Chan, 1988). Recent flooding of a dunefield in Peru’s altiplano is a modern analogue of the flood events that occurred during deposition of the Cedar Mesa Sandstone. In contrast to the laterally continuous red mudstone layers, some red mudstones pinch out into the white sandstone facies. This type of lateral relationship suggests that some of the red mudstones formed adjacent to active eolian dunes. We interpret these discontinuous red mudstone layers as the product of deposition in isolated interdune ponds that formed during floods or because of rising water tables.

Gypsum and Limestone Facies

Approximately 20 miles (32 km) southeast of Natural Bridges the white sandstone and red mudstone facies interfinger with gypsum and algal limestone in a section almost 1,000 feet (300 m) thick. Some of the gypsiferous layers are massive suggesting they formed from evaporation of ponded surface water. Other gypsum layers displace or deform surrounding sandstone and mudstone layers indicating gypsum grew within the clastic sediment. The algal limestone beds are light gray in color. They contain chert nodules up to 1 foot (30 cm) in diameter. The chert is commonly bright red in color. Many of the limestones exhibit fracturing and brecciation that is interpreted to reflect early, subaerial cementation (Ginsburg, 1957). The characteristics of this facies suggest deposition in a sabkha. Sabkhas form in intertidal or supratidal zones along coastlines under highly evaporative conditions. Results of analysis of carbon, oxygen, and sulfur isotopes, as well as the presence of rare marine fossils, indicate the Cedar Mesa sabkha formed along a marine shoreline that opened to the south (Stanesco and Campbell, 1989; Lock and Pelfrey, 1997).

Organ Rock Formation

The Organ Rock Formation is the youngest formation in the Cutler Group in the vicinity of NABR. To the west, along Lake Powell in Glen Canyon National Recreation Area, the White Rim Sandstone of the Cutler Group overlies the Organ Rock. The White Rim was removed from the Natural Bridges area by erosion that occurred at the end of the Permian Period or the beginning of the Triassic Period.

To the southeast of NABR, in the vicinity of Monument Valley, the De Chelly Sandstone of the Cutler Group overlies the Organ Rock. Where the White Rim and De Chelly Sandstones are absent, across the crest of the Monument upwarp, the Organ Rock is unconformably overlain by the Lower Triassic Moenkopi Formation. The Organ Rock is thin along the axis of the Monument upwarp, averaging about 300 feet (100 m) thick near NABR. To the east of the Monument upwarp, near Monument Valley, the Organ Rock is over 700 feet (210 m) thick, and to the west of Natural Bridges near Glen Canyon National Recreation Area the Organ Rock is about 400 feet (130 m) thick.

The Organ Rock is a reddish-brown to light-red, slope-forming unit composed of feldspar-rich very fine- to fine-grained sandstone, siltstone, mudstone, and minor carbonate-pebble conglomerate that was deposited primarily in continental fluvial, floodplain, and eolian environments (figure 8c). Marginal-marine mudflat and tidal channel environments are locally present. The lower part of the Organ Rock was deposited by fluvial systems that flowed to the southwest off the Uncompahgre uplift, and by intrabasinal fluvial systems that flowed to the northwest near Monument Valley. Fine-grained floodplain deposits, many exhibiting root casts, trace fossils, and paleosol (ancient soil) development, are interbedded with the fluvial channel deposits.

To the west of Natural Bridges (near Lake Powell), the lower part of the Organ Rock consists of broad, shallow cut-and-fill deposits. The cut-and-fill deposits may represent distal fluvial and floodplain environments on a low-gradient coastal plain, or marginal-marine mudflat and tidal-channel deposits. To date, no definite marine indicators have been identified. Rain-drop impressions, vertical and horizontal burrows, and adhesion ripples are typically associated with the cut-and-fill deposits. Adhesion ripples form when dry sand blows across a damp surface, and adheres to the wet surface in low wrinkled domes that are less than about ¼ inch (6 mm) high.

Also near Lake Powell, the upper part of the Organ Rock contains abundant large-scale cross-bedded sandstone units. These cross-bedded sandstones are interpreted as eolian dune deposits. On the east side of the crest of the Monument upwarp the upper part of the Organ Rock is composed of sandstone beds containing root casts and adhesion ripples. This succession is interpreted as the product of eolian sand sheet deposition. Loess deposits composed of massive very fine-grained sandstones and siltstones that contain root casts are rare within the Organ Rock, but are present in the upper part of the formation. The sedimentary structures within the Organ Rock indicate deposition in an environment that was occasionally flooded, and generally contained sufficient moisture to sustain plant growth.

Moenkopi Formation

In the immediate vicinity of NABR, the Permian-Triassic unconformity separates the Permian Organ Rock Formation from the overlying Lower to early Middle Triassic Moenkopi Formation (Blakey and others, 1993). The unconformity between the Organ Rock and the Moenkopi is difficult to identify near Natural Bridges because Moenkopi red beds directly overlie Organ Rock red beds. The major difference between the two formations is that the lower part of the Moenkopi contains very coarse to medium-sized, well-rounded quartz grains. These grains were likely derived from erosion of the uppermost parts of the White Rim Sandstone and/or De Chelly Sandstone. The White Rim and De Chelly Sandstones are not present in the Natural Bridges area because Natural Bridges lies close to the crest of the Monument upwarp. During development of the Permian-Triassic unconformity these two units were eroded from the crest of the Monument upwarp near Natural Bridges.

The Moenkopi Formation is mainly composed of reddish-brown sandstone, siltstone, and mudstone. Locally it contains chert-pebble conglomerate. The Moenkopi Formation was deposited in a variety of fluvial channel and floodplain, marginal-marine mudflat and tidal channel, sabkha, and marine environments (Stewart and others, 1972a). The Moenkopi along White Canyon varies from about 300 to 400 feet (100-130 m) in thickness, and forms a red-brown slope between the Organ Rock and Chinle Formations. Large-scale wavy bedding is present in the lower part of the Moenkopi (Hoskinnini Member) near Natural Bridges. The wavy bedding is interpreted to be the result of precipitation and dissolution of evaporites in the Hoskinnini.

Like parts of the Cutler Group below, the Moenkopi was deposited by fluvial and floodplain systems that drained the Uncompahgre uplift and other minor positive areas throughout central Utah. These continental systems connected with marginal-marine mudflat and marine depositional settings to the west and northwest. Gypsum is common in the lower members of the formation, indicating arid conditions at the time of deposition. Upsection, the Moenkopi contains fossilized plants and animals that indicate deposition in a warm tropical setting that may have experienced a monsoonal, wet-dry climate (Stewart and others, 1972a; Dubiel and others, 1991).

Chinle Formation

The Upper Triassic Chinle Formation unconformably overlies the Moenkopi Formation. The Chinle forms a pastel-colored slope composed of entirely continental deposits along the rim of the mesa that lies to the north of NABR. The Chinle varies in thickness from about 300 to 600 feet (100-200 m) near Natural Bridges. The basal member of the Chinle, the Shinarump Conglomerate Member, contains quartz- and chert-pebble conglomerate deposited by fluvial systems that eroded paleovalleys into the underlying Moenkopi Formation. Above the Shinarump Conglomerate Member, Chinle sediments were deposited in fluvial channel, floodplain, marsh, and lake systems. Fluvial trunk-stream systems flowed mainly to the northwest, toward the shoreline located in western Utah. Chinle sediments were derived from both the Uncompahgre uplift and the interior of North America (Stewart and others, 1972b; Dubiel, 1994. The climate during deposition of the Chinle is interpreted to have been monsoonal with pronounced alternation between wet and dry seasons (Dubiel and others, 1991).

Wingate Sandstone

The Lower Jurassic Wingate Sandstone unconformably overlies the Chinle Formation in the area surrounding NABR. The Wingate forms the massive to jointed reddish-orange cliff that rims the highest mesas seen from NABR. The Wingate is composed of fine- to medium-grained quartz and feldspathic sandstones. It is characterized by large-scale cross-bedding. The Wingate was deposited by eolian dunes in an arid climate setting. The Wingate Sandstone averages 300 to 400 feet (100-130 m) in thickness along White Canyon.

Development of Bridges

At one time all of the rocks described above (with the exception of the lower Cutler beds) were present above the Cedar Mesa Sandstone in the vicinity of NABR. Other, younger rocks, that range in age from Jurassic to Cretaceous, were also present. The maximum depth of burial of the Cedar Mesa Sandstone was between 5,000 to 10,000 feet (1,500-3,000 m). Depth of burial estimates are based on the present-day thickness in nearby areas of the formations that once existed above the Cedar Mesa Sandstone (Hintze, 1993). Because the Cedar Mesa was deposited at or near sea level during the Permian, the Natural Bridges region must have subsided from the Permian to the Cretaceous to accommodate deposition of all of the overlying sedimentary rock.

Regional subsidence apparently ended in the Late Cretaceous. The effects of the Laramide orogeny were first expressed during the Maastrichtian (74-65 Ma) (Dickinson and others, 1987). This orogeny probably resulted from shallowing of the angle of subduction along the west coast of North America (Dickinson, 1981). The Natural Bridges area lies near the crest of the Monument upwarp, and rocks on this structure were bent into a broad, approximately north-south trending arch during the Laramide orogeny.

Removal of extensive amounts of rock from above the Cedar Mesa Sandstone did not occur until the entire Colorado Plateau began to rise during the Cenozoic. Uplift of about 6,000 feet (2,000 m) occurred in the eastern part of the plateau during the late Eocene (Gregory and Chase, 1992; Parsons and McCarthy, 1995), approximately 39 to 35 Ma (Harland and others, 1989). As the land surface rose, rivers began to cut down through the rock. When the rivers cut through soft, easily eroded rocks (like the Organ Rock Formation) they established meandering patterns and flowed through relatively wide, gentle valleys. When the rivers cut down into resistant rocks (like the Cedar Mesa Sandstone), the meandering channel paths that were established in a non-resistant overlying layer were superimposed on the resistant rock. The amount of downcutting in the Natural Bridges area was controlled by the elevation of the Colorado River's channel. Until as recently as 6 Ma, the Colorado River had not cut through the Grand Canyon and its channel's elevation was about 0.6 miles (1 km) higher than it is today (Parsons and McCarthy, 1995). During the last 6 m.y. the Colorado River cut through the Grand Canyon (Lucchitta, 1989), lowering local base level for rivers throughout southeastern Utah. The rate of downcutting by the Colorado River was rapid, and the rivers that drained into it cut down into the rocks beneath their beds faster than they cut into the rock on the sides of their channels. The meandering streams that cut into the Cedar Mesa Sandstone became entrenched in the rock (Stokes, 1969).

The natural bridges in NABR began to form after the streams were entrenched in the Cedar Mesa Sandstone. At some locations along the streams' paths thin walls separated the cut-bank side of one meander bend from the cut-bank side of another meander (figure 4). At these locations, the river eroded both sides of the thin walls. Erosion by the river, alone or in concert with other processes (described below), eventually produced a break in the wall. Once the wall was penetrated, the stream flowed through the wall, widening and smoothing the hole. The result was a natural bridge.

At the present time, the climate in southeastern Utah is arid, and streams in the canyons in NABR only rarely carry large volumes of water. It is likely that the natural bridges formed at a time high runoff events were more common than they are today. During the Pleistocene Epoch of the Quaternary Period the climate in Utah was significantly wetter than it is today. The Pinedale Stadial glacial period (30,000-12,000 ybp) is one of the last glacial advances that occurred during the Pleistocene. Although NABR was not directly in contact with ice, most of Utah experienced relatively wet conditions during the Pinedale Stadial. The natural bridges probably began to form at that time.

Although river flows were instrumental in development of the bridges, other processes such as frost wedging (Gregory, 1938), plant root growth, ground-water seeps (Culmer, 1908; Gregory, 1917, 1938), stress-release exfoliation (Gregory, 1938), and wind all weakened the Cedar Mesa before and after the bridges formed. Most visitors to NABR arrive during the summer months, and do not experience the freezing temperatures that affect NABR during winter. Precipitation or ground water that flows into cracks along exposed rock faces may freeze during winter, resulting in an increase in volume that breaks the rock apart. Plant roots pry rock apart along existing joints or fractures in the same way.

Ground-water seeps are common in White and Armstrong Canyons, and ground water preferentially migrates laterally along the top of the relatively fine-grained red layers within the Cedar Mesa Sandstone. Ground water exiting the formation at a seep carries dissolved minerals with it. Through time these seeps substantially weaken the rock and if they occur on a cliff, the cliff face retreats faster around the seep than elsewhere. Overhanging cliffs are therefore common above seeps.

The relatively fine-grained red layers are efficient at retaining the water that enters them due to capillary effects. Plant roots penetrating into the red layers are able to utilize the moisture and survive dry periods. These plant roots change the chemical conditions in the rock and their presence speeds the rate of erosion. In addition, the plant roots mechanically break apart the rock, also leading to accelerated erosion rates.

Because the Cedar Mesa was deeply buried until relatively recently, it is still responding to the change in stress at free surfaces. In the canyons, cliff walls respond to the drop in stress by developing fractures that are nearly parallel to the trend of the canyon. The fractures are widened by frost wedge action or plant root growth until the rock breaks and the canyon is enlarged by a small amount. Finally, wind in the canyons carries abundant quartz grains that sandblast and erode all surfaces they encounter.

Currently there are three large natural bridges in NABR (figures 4 and 5). Sipapu bridge was produced as the stream in White Canyon cut off a meander bend. The abandoned meander can be seen from the Sipapu Bridge Trail (see the Geologic Guide to Sipapu Bridge Trail on the CD-ROM that accompanies this volume). Kachina Bridge formed when the stream in White Canyon broke through a wall just upstream of its original junction with Armstrong Canyon (Barnes, 1987). Owachomo Bridge formed when the stream in a Tuwa Canyon (a tributary to Armstrong Canyon) twice cut through meander bends into Armstrong Canyon (Barnes, 1987). The bridge is now isolated from the main channel, because the second cutting event resulted in abandonment of the part of Tuwa Canyon that passed under the bridge. Several smaller unmarked spans are present in White and Armstrong Canyons. All of the bridges are temporary and will eventually collapse. Remnants of older, collapsed bridges can also be observed within the canyons (figure 6a). New bridges will form in the future. On figure 6a, three sites are indicated where the walls separating upstream and downstream parts of meanders are thin and are currently being eroded. At some time in the future, the walls will be penetrated by the streams in White or Armstrong Canyons, and new bridges will probably be formed as a result.

Conclusion

The natural bridges in NABR are the result of Quaternary erosion of Permian bedrock. Hikers in NABR will find their access routes into the canyons controlled by geology. Like the ancestral-Puebloan people who occupied this area over 1,000 years ago, modern visitors will make use of the ledges formed at the contact between the white sandstone facies (below the ledges) and the red mudstone facies (above the ledges) of the Cedar Mesa Sandstone to travel through the region. The exposures of the Cedar Mesa Sandstone and Organ Rock Formation contained within NABR are excellent and indicate that the bedrock in this area was deposited in an arid environment with a climate similar to that experienced by the region today.

Acknowledgements

The reviews of this manuscript provided by Paul Anderson, Ron Blakey, Jack Campbell, and Tom Chidsey, Jr. contributed to its improvement. We thank them for taking the time to read and comment on this paper.

We also appreciate the computer-assisted drafting performed by Dave Linari, an undergraduate student at Michigan Technological University.

Preparation of this paper was partially supported by the National Science Foundation (Grant Number: DUE-9950213), and by the National Park Service, Geologic Resources Division.

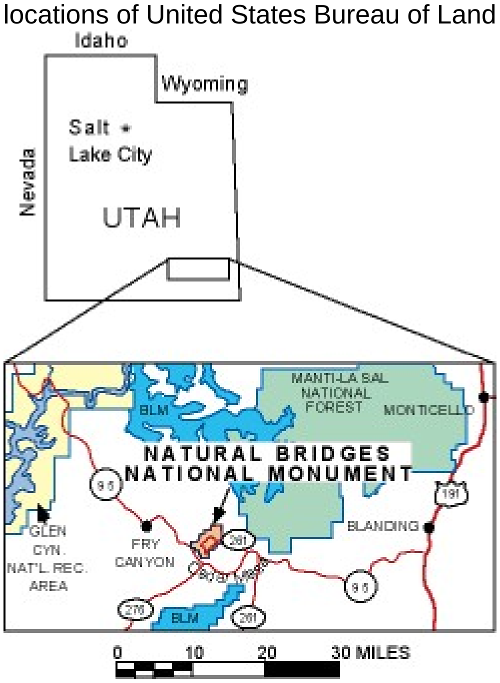
We also thank the staff at Natural Bridges for making our time in the field as enjoyable as possible.

Text from source map report Natural Bridges National Monument.

List of Figures

Figure 1. Location of Natural Bridges National Monument in Utah

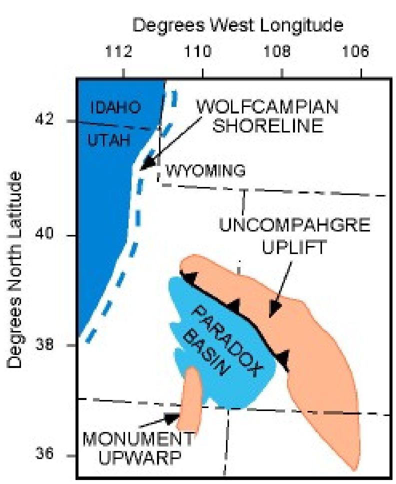
Natural Bridges National Monument is located on top of the Cedar Mesa plateau. BLM indicates the locations of United States Bureau of Land Management Primitive Areas.



Graphic from source map [Natural Bridges National Monument](#).

Figure 2. Early Permian paleotectonic elements of southeastern Utah

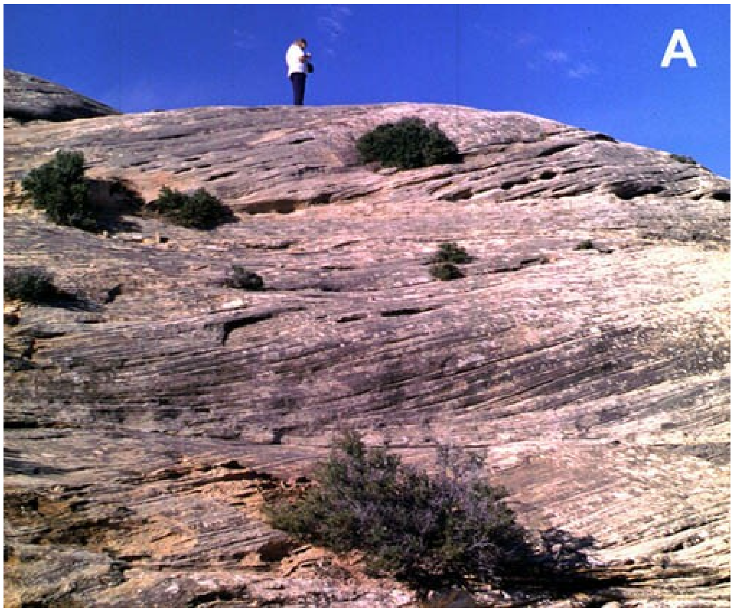
The Permian shoreline position fluctuated to the east and west parallel to the line shown on the map.



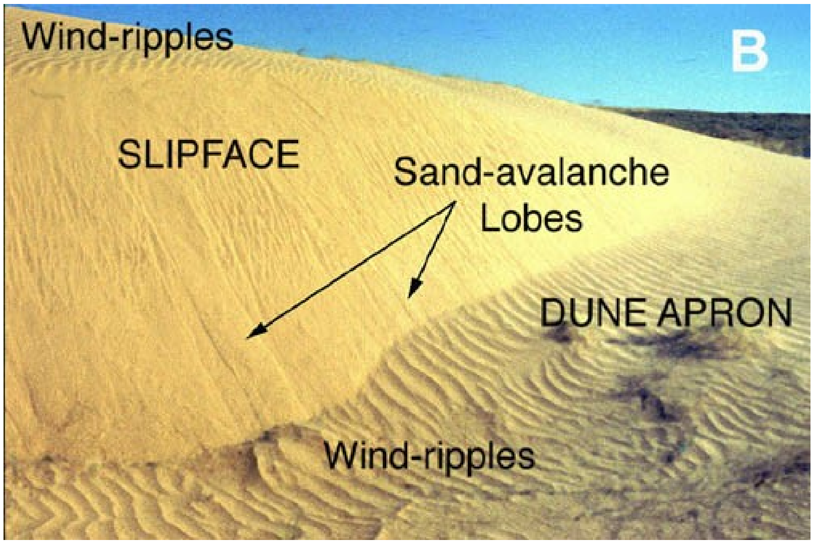
Graphic from source map [Natural Bridges National Monument](#).

Figure 3. Eolian features

A) Cross-bedding in the Cedar Mesa Sandstone in Natural Bridges National Monument.



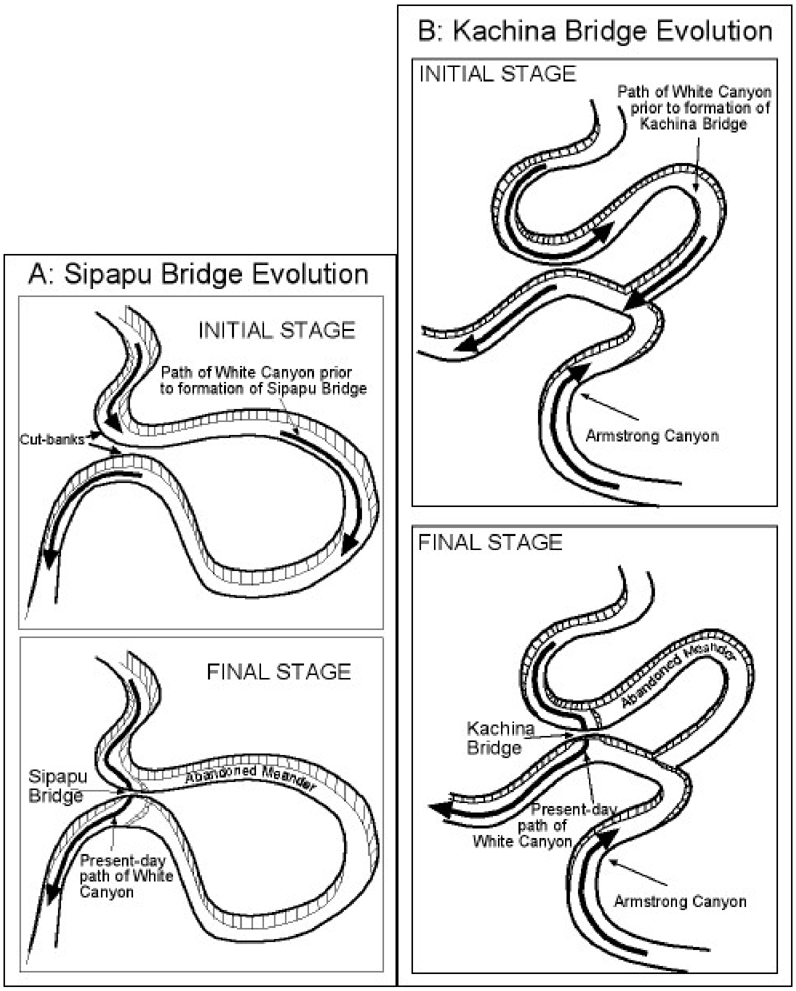
B) A modern dune located near Hanksville, Utah. Wind blew from the upper left toward the lower right of the photo during formation of this dune.

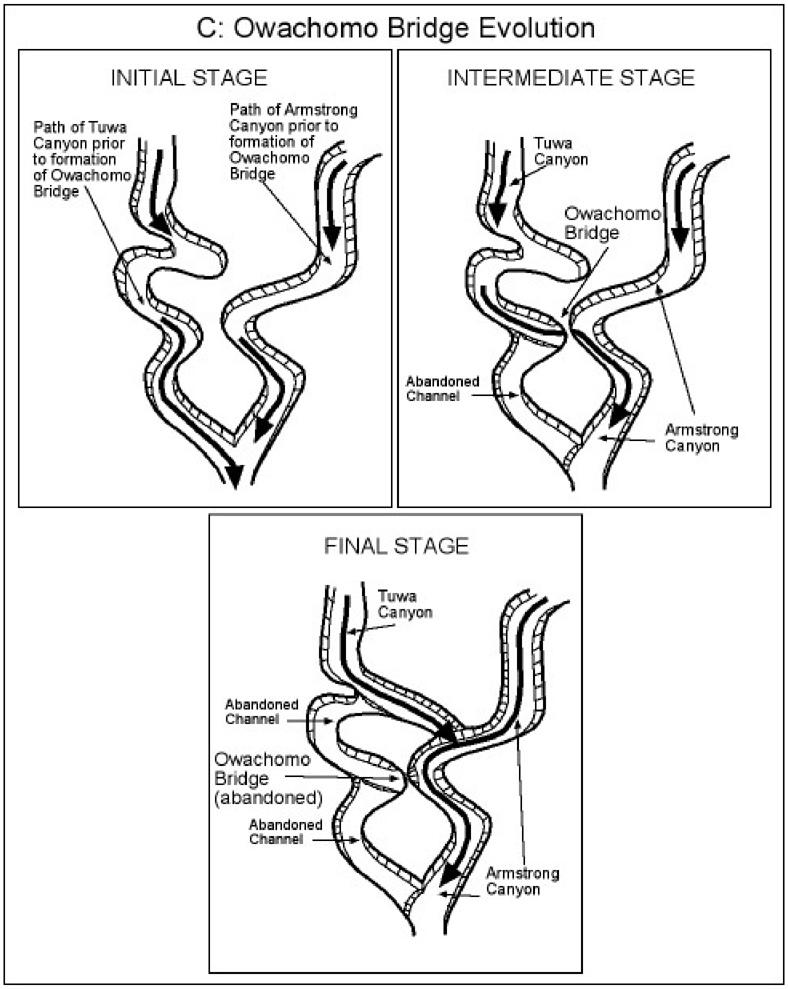


Graphics from source map [Natural Bridges National Monument](#).

Figure 4. Intrepreted evolution of the three natural bridges

In each part of this figure, the Initial Stage corresponds to time prior to formation of the bridge. The Final Stage corresponds to the present-day configuration of the canyons.

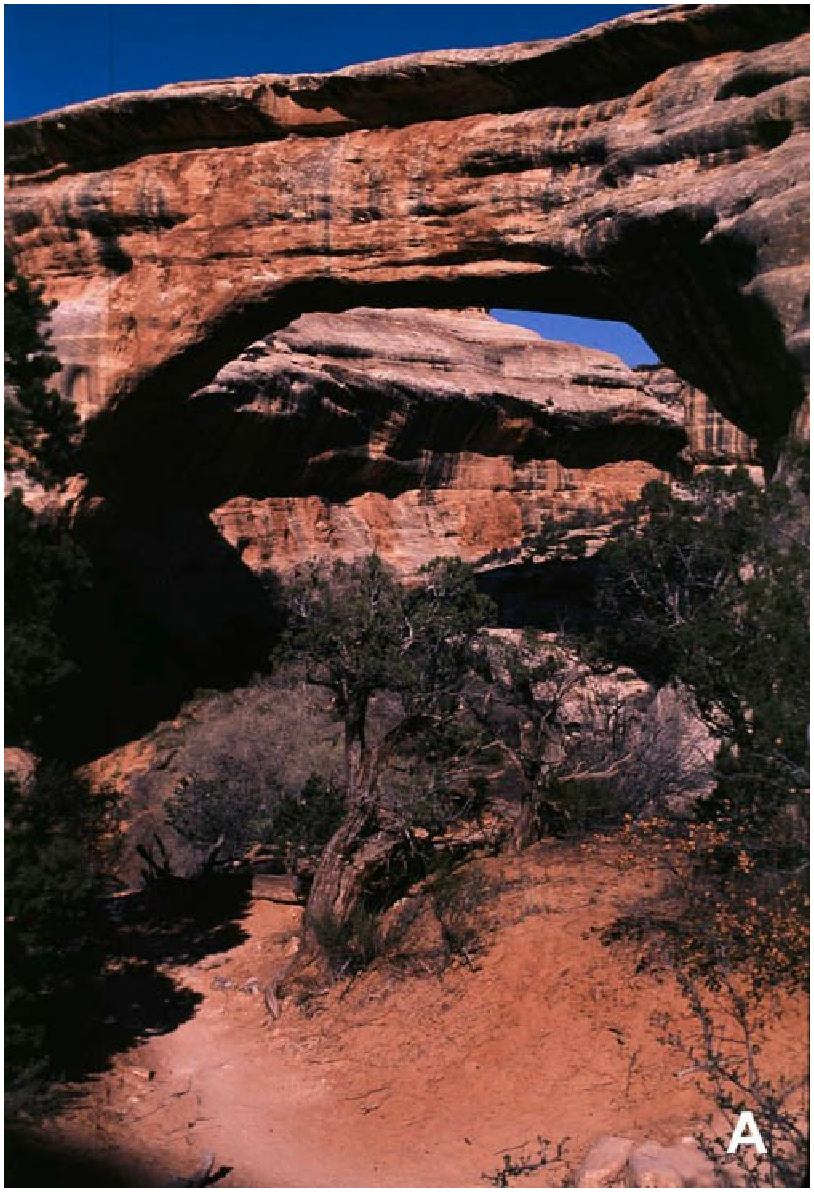




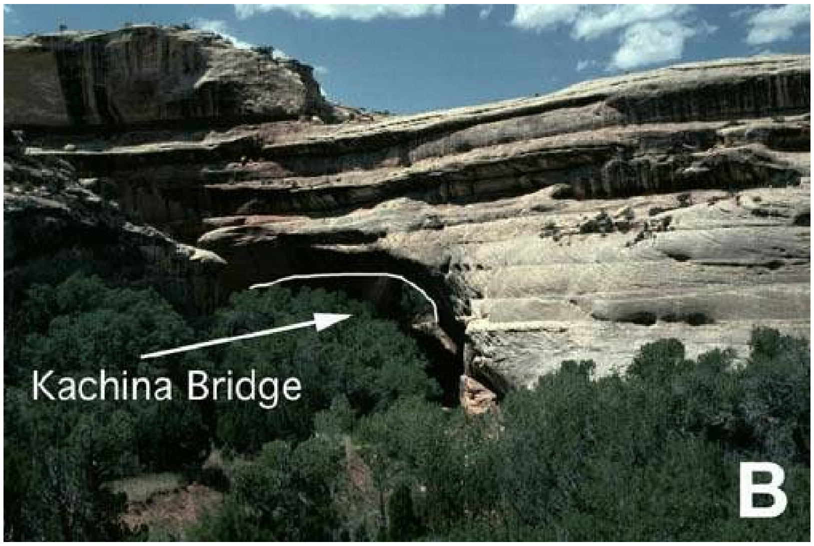
Graphics from source map Natural Bridges National Monument.

Figure 5. The natural bridges

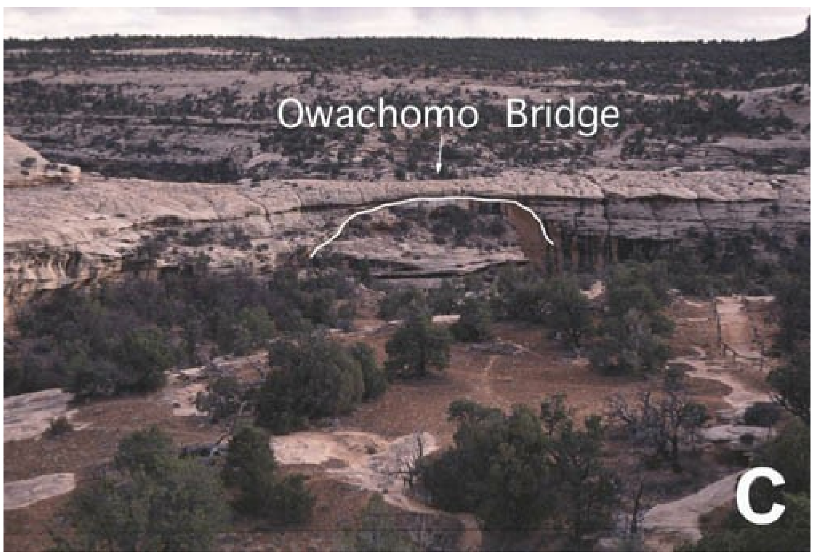
A) Sipapu Bridge.



B) Kachina Bridge as viewed from Armstrong Canyon. Kachina Bridge is partly hidden by vegetation in the photo and its location is highlighted with a white line.



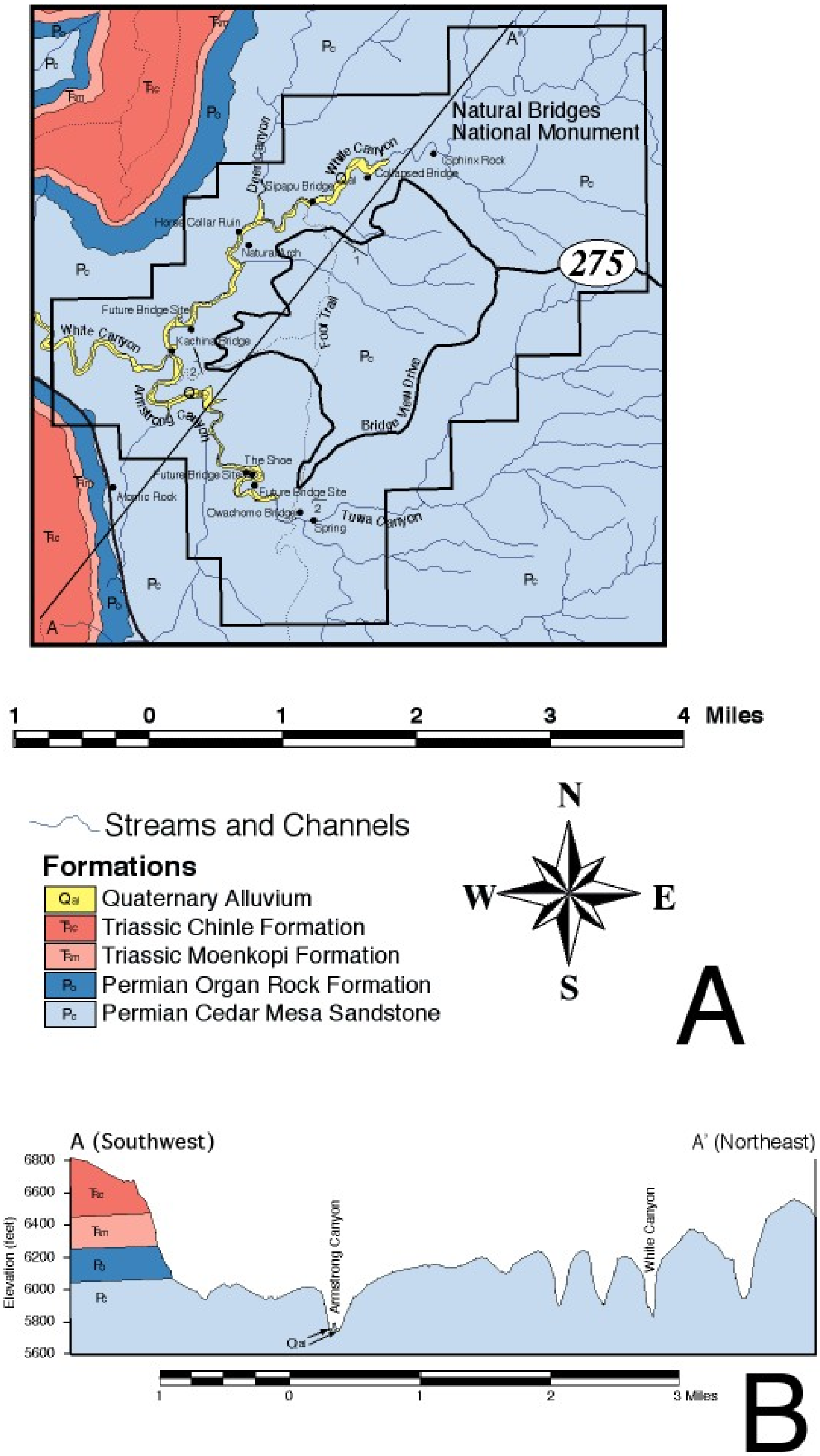
C) Owachomo Bridge as viewed from the overlook on the Owachomo Bridge trail. Owachomo Bridge's opening is highlighted with white in the photo so that it can be seen more easily.



Graphics from source map Natural Bridges National Monument.

Figure 6. Geologic map and cross section for Natural Bridges National Monument

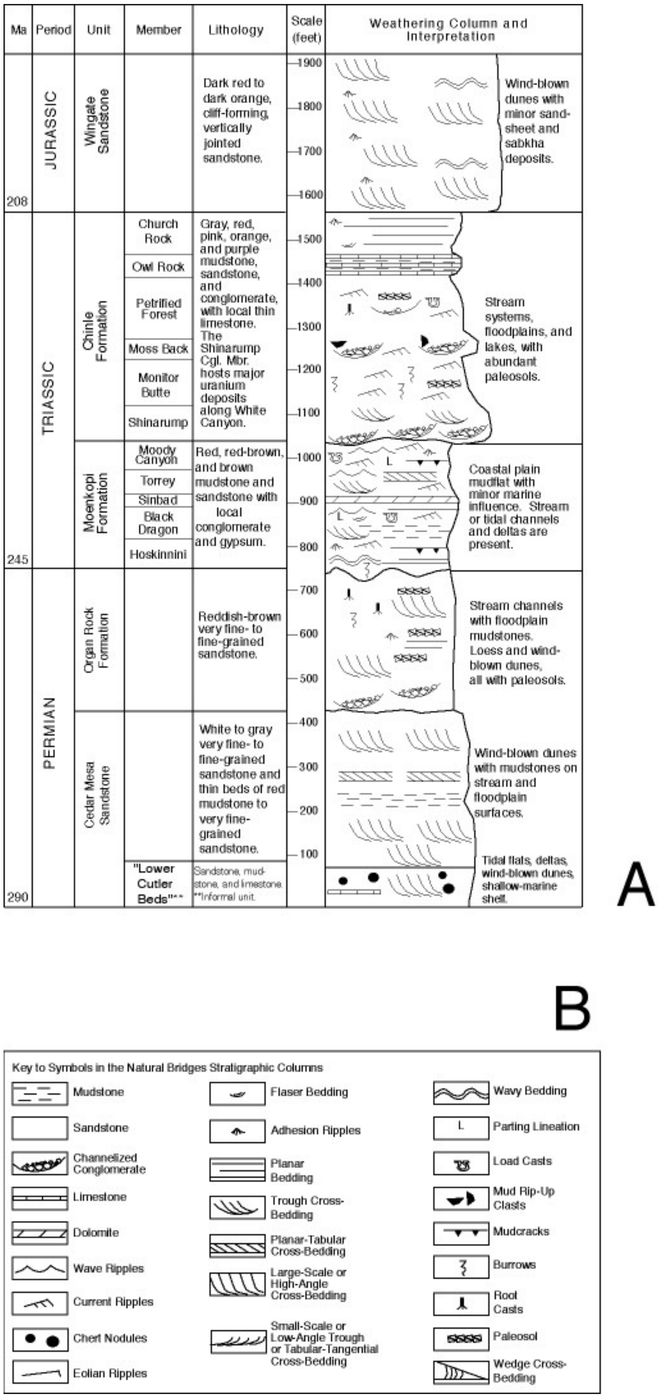
Geologic map (6A) and cross section (6B) for Natural Bridges National Monument.



Graphics from source map Natural Bridges National Monument.

Figure 7. Generalized stratigraphy (7A) of the Paleozoic and Mesozoic rock units

Generalized stratigraphy (7A) of the Paleozoic and Mesozoic rock units exposed on Cedar Mesa. 7B is a key to the symbols used in figures 7A and 9.

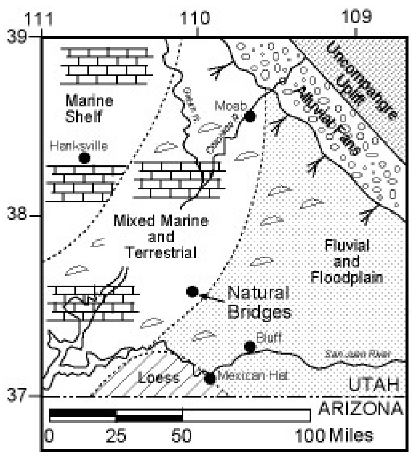


Graphics from source map Natural Bridges National Monument.

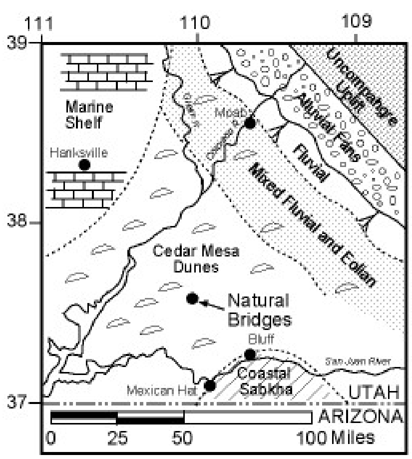
Figure 8. Early Permian depositional environments in southeastern Utah

Early Permian depositional environments in southeastern Utah during the:

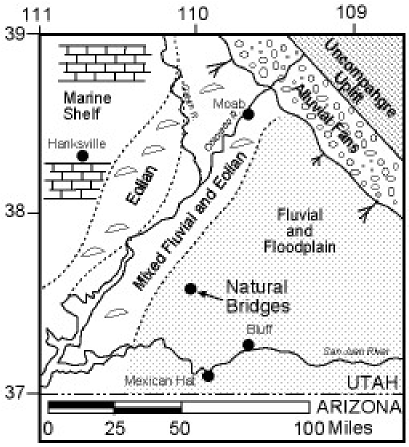
A) Early Wolfcampian (lower Cutler beds).



B) Wolfcampian (Cedar Mesa Sandstone).



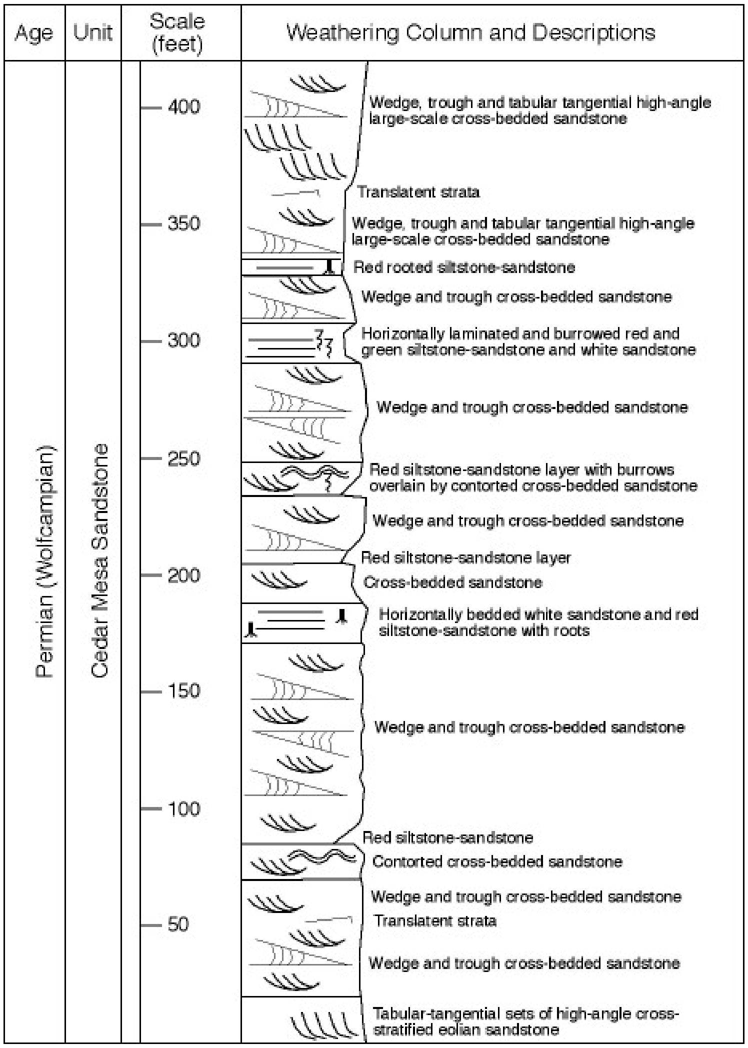
C) Leonardian (Organ Rock Formation).



Graphics from source map [Natural Bridges National Monument](#).

Figure 9. Detailed stratigraphy of the Cedar Mesa Sandstone

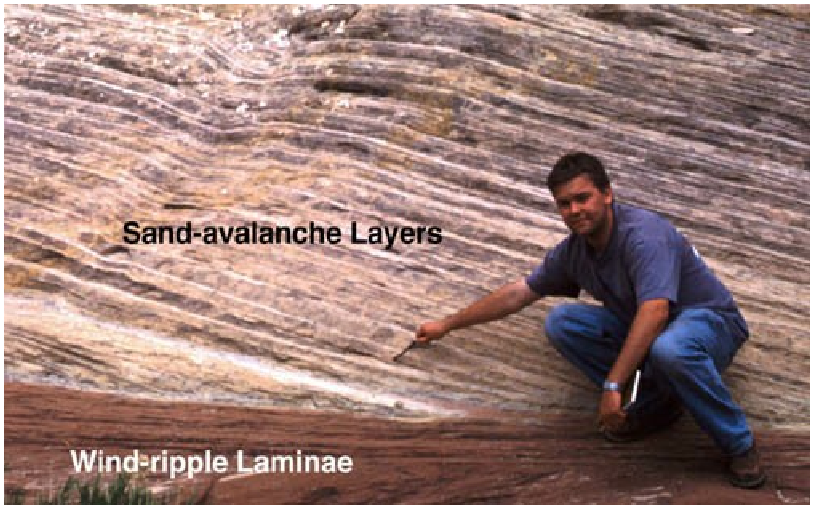
Stratigraphic section was measured along the Sipapu Bridge Trail. The top and base of the formation are not present along the trail and are not included in this section.



Graphic from source map Natural Bridges National Monument.

Figure 10. Sand avalanche layers

Sand avalanche layers (grainflow strata) overlying and interfingering with wind-ripple laminae (translatent strata) in the Cedar Mesa Sandstone.



Graphic from source map Natural Bridges National Monument.

Figure 11. A red mudstone layer underlain and overlain by the white sandstone facies

A red mudstone layer underlain and overlain by the white sandstone facies of the Cedar Mesa Sandstone at the Sipapu Bridge overlook along Sipapu Bridge Trail. At this location the white sandstone directly above the mudstone layer is contorted. This suggests the red mudstone was still wet when the white sandstone dune migrated onto it.

Graphic from source map Natural Bridges National Monument.

Figure 12. Sand-filled mudcrack in the red mudstone facies of the Cedar Mesa Sandstone

Sand-filled mudcrack in the red mudstone facies of the Cedar Mesa Sandstone in Natural Bridges.

Graphic from source map Natural Bridges National Monument.

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The information in this document was compiled from GRI source map, and is intended to accompany the GRI digital geologic-GIS map and other digital data for Natural Bridges National Monument, Utah (NABR) developed by Stephanie O'Meara (see the GRI Digital Map and Source Map Citation section of this document for the source map used by the GRI in the completion of this document and the related GRI digital geologic-GIS map).

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GRI program coordination and scoping provided by Bruce Heise and Tim Connors (NPS GRD, Lakewood, Colorado).