National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Wupatki National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/416

ON THE COVER
During the 10th century peoples of the Sinagua culture gathered near the current Wupatki Pueblo ruins, gradually building a 100-room pueblo. By 1182, perhaps 85 to 100 people lived at Wupatki Pueblo, the largest building for at least fifty miles. People used stones from the Moenkopi Formation as building blocks for the structures—often utilizing large outcrops as foundations.

THIS PAGE
Citadel Sink, the largest sink in the monument, borders the Citadel and Nalakiku ruins between South Mesa and East Mesa. Sink formation and enlargement is an ongoing process, as water seeps into fractures and fissures and dissolves limestone.

National Park Service photographs by Paul Whitefield (NPS North Central Arizona National Monuments).

Wupatki National Monument

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

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Executive Summary

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

Located approximately 38 km (24 mi) north of Flagstaff, Wupatki National Monument protects 14,334.83 ha (35,422.13 ac) of arid, rugged land in Coconino County, Arizona. Originally established in 1924 to preserve and protect the Citadel and Wupatki pueblos that were built by the Sinagua Indians in the 1100s, the monument's boundaries have expanded through the years, and now include approximately 2,400 archeological sites.

Wupatki National Monument lies within the southwestern part of the Colorado Plateau, a physiographic province composed of broad plateaus and mesas. Lower Permian (299-270 million years ago) and Lower Triassic (251-245 million years ago) sedimentary rocks dominate the monument's landscape. In the eastern portion of the monument, the reddish sandstones and siltstones of the Triassic Moenkopi Formation offer a vivid color contrast to the gray Permian limestone exposed in western Wupatki. Dark-gray to black, 1-million-year-old basaltic lava occurs as caprock to several mesas in the Wupatki National Monument area. Lava flows resulted from volcanic eruptions in the San Francisco Volcanic Field, located south of the monument. The northeast-to-southwest trending Black Point Monocline separates Permian units from Triassic strata and forms the principal geologic structure in Wupatki.

The primary geologic issues affecting resource management at Wupatki National Monument are visitor safety issues, including blowholes and earthcracks. Other geology-related issues include potential development of economic resources, potential seismic hazards, and future volcanic eruptions.

Vertical cracks or fissures in the bedrock and blowholes pose potential safety issues at Wupatki National Monument. Past tectonic activity has opened fractures and joints in the rocks, locally termed "earthcracks." These cracks may be over 100 m (330 ft) deep, and some have developed into sinkholes as the underlying fractured carbonate rock has dissolved. Although the backcountry in the monument is closed to unguided visitors, an inventory of earthcracks may help resource managers monitor these sites for biological diversity and microclimates.

Blowholes are small openings in the ground that connect to an extensive underground fracture system. Some of the blowholes, however, are large enough for a person to squeeze through. Prior to being capped, the blowhole at Wupatki Ruin measured over 5.5 m (18 ft) deep. Because of their potential depth, blowholes present a potential safety hazard in the monument. In the past, many blowholes were used as dumping grounds and are now in need of restoration work.

Water is a precious resource in the arid Southwest, and future uranium mining activities will require water resources to process uranium ore. Although mining is prohibited in Wupatki National Monument, future uranium exploration may occur in the Cameron district, north of the monument. Petroleum is produced from northeastern Arizona. Future exploration for either uranium or petroleum will not cause any direct, internal issues within Wupatki National Monument.

Although Wupatki National Monument lies within the active earthquake zone of northern Arizona, the impact of earthquakes on the park is expected to be minor. Historical earthquakes in the region record magnitudes generally less than 3.0 on the Richter scale.

The last volcanic eruption in the San Francisco Volcanic Field occurred approximately 1,000 years ago and resulted in the formation of Sunset Crater. However, future volcanic eruptions are difficult to predict. The potential interaction between magma and cooler groundwater may produce spectacular displays of gas-propelled ash and glowing rock fragments as well as basaltic lava flows. Eruptions from the eastern section of the San Francisco Volcanic Field may deposit ash and lava within the borders of Wupatki National Monument.

The geologic features and processes at Wupatki National Monument record a geologic history that spans approximately 300 million years. The units of geologic time are identified on the geologic timescale (fig. 23). Carbonate strata and marine invertebrate fossils provide evidence of an extensive inland sea that covered much of Arizona during the end of the Paleozoic approximately 251 million years ago. By the Mesozoic, the sea had retreated from the region and the terrestrial, red-colored beds of the Triassic Moenkopi Formation were deposited in lowland fluvial and tidal flat environments. Millions of years later, the Sinagua Indians would use the reddish Moenkopi sandstone as building blocks for their pueblos.

With the advent of volcanism about 6 million years ago in the San Francisco Volcanic Field, basalt began to flow and volcanic ash inundated the region. The Sunset Crater eruption spread ash and cinders over a broad area and destroyed the Sinagua's farmland, but the ash also retained water. Within a few decades, the Sinagua returned and prospered in the region, during the early-to-mid 1100s.

Quaternary (2.6 million years ago to the present) gravel deposits interbedded with the volcanic flows record vertical erosion rates by the Little Colorado River over the last 2.6 million years. Stream terraces of three different ages are exposed in Wupatki National Monument. Flash floods periodically erode the channel banks of these ephemeral streams, and arroyos have incised into the Doney Cliffs and Black Point Monocline. Precipitation continues to seep into the fractured Paleozoic bedrock, dissolving carbonate rocks, and enhancing the fracture and joint system. Blowholes, associated with the fracture system, continue to be influenced by the air temperature and pressure and remain a curiosity to visitors.

This report includes a Map Unit Properties Table that describes characteristics such as erosion resistance, suitability for infrastructure development, geologic significance, recreation potential, and associated cultural and mineral resources for each mapped geologic unit.

The glossary contains explanations of many technical terms used in this report, including terms used in the Map Unit Properties Table. The geologic timescale (fig. 23) offers a general reference to some of the geologic activity that has occurred over the 4.6 billion years of Earth history.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to: Paul Whitefield, Natural Resource Specialist for the North Central Arizona National Monuments, for providing many photographs and updated information throughout the report; Dave Brumbaugh, Northern Arizona University, for his updated information on seismic activity in the area; Dale Pate and Andrea Croskrey, both from the NPS Geologic Resources Division, for their input and suggestions regarding cave issues in the park; Pat O'Dell, NPS Geologic Resources Division, for providing information regarding economic resources in the area; and Tim Connors, NPS Geologic Resources Division, for providing photographs.

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Introduction

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

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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

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

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

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

Regional Location

Located in Coconino County, Arizona, Wupatki National Monument protects 14,334.83 ha (35,422.13 ac) of high desert grasslands, mesas, buttes, and volcanic hills (fig. 1). The monument was originally established in 1924 to preserve the Citadel and Wupatki pueblos (figs. 2, 3), but the boundaries have been adjusted over the years to include additional pueblos and other archeological resources. Approximately 2,400 archeological sites have been catalogued at Wupatki National Monument (Ort et al. 2008).

Spectacular views within and beyond the monument include outcrops of red sandstone juxtaposed against white limestone, cinder cones and lava flows of the San Francisco Volcanic Field (fig. 4), and the Painted Desert that stretches southeast from Wupatki to Petrified Forest National Park (KellerLynn 2010). Wupatki's Visitor Center lies approximately 38 km (24 mi) northeast of Flagstaff, Arizona, and a paved Coconino County road provides a loop from Sunset Crater National Monument (about 16 km [10 mi] north of Flagstaff) to Wupatki National Monument and back to U.S. Highway 89 (fig. 1). The Little Colorado River forms the eastern border between the monument and the Navajo Indian Reservation.

Without the relatively young volcanoes of the San Francisco Volcanic Field, the region between Flagstaff and the Grand Canyon would be a flat, arid plateau. Humphreys Peak, one of the peaks of San Francisco Mountain, rises to an elevation of 3,850 m (12,633 ft) and is Arizona's highest peak (fig. 3) (Priest et al. 2001). In contrast, the elevation of Wupatki National Monument ranges from 1,500 to 1,800 m (5,000 to 6,000 ft).

Dry, windy summers with brief thunderstorms characterize this high desert region. Most of Wupatki's annual 20 cm (8 in) of precipitation occurs from thunderstorms developing from July to September.

Regional Geology

Wupatki National Monument lies within a large geological province known as the Colorado Plateau, a roughly circular region bordered by the Rocky Mountains and the Basin-and-Range provinces (fig. 5). High plateaus and isolated mountains characterize the Colorado Plateau, which includes parts of Arizona, Utah, Colorado, and New Mexico. The Colorado River, for which the plateau was named, drains at least 90% of the plateau. Buffered from the compressive forces that formed the Rocky Mountains and the extensional (pull-apart) tectonics that produced the distinctive Basin-and-Range topography, the Colorado Plateau experienced subdued structural deformation during the past 65 million years. This deformation resulted in broad, regional uplift, gentle folding, and fractured and jointed rock.

Plateaus and mesas characterize the Colorado Plateau. Wupatki National Monument lies on the Coconino Plateau, a vast tableland within the Colorado Plateau bordered by the Grand Canyon to the north and Little Colorado River to the east. Smaller mesas in the central and western part of the monument include West Mesa, South Mesa, East Mesa, and North Mesa.

Upper Paleozoic and lower Mesozoic sedimentary rock strata dominate the landscape at Wupatki National Monument (fig. 6). Approximately 92 m (300 ft) of Lower Permian (299-270 million years ago) Kaibab Formation (map units Pkh and Pkf in the Map Unit Properties Table) and Toroweap Formation (Pt) form the extensive Antelope Prairie in the western part of the monument (Billingsley et al. 2007A). These Paleozoic rocks form cliffs and ledges of calcareous sandstones and cherty limestones, which contain abundant quartz. Many of the same formations are mapped and exposed within Walnut Canyon National Monument to the south (Graham 2008).

The Antelope Prairie forms the western limb of the Black Point Monocline (fig. 1), a northeast-trending asymmetric fold that bisects the monument (see Geologic Map Data section). Monoclines have one limb of relatively horizontal strata and one limb of more steeply dipping strata. Strata on the western limb of the Black Point Monocline are nearly horizontal whereas strata on the eastern limb of the fold dip as much as 30° to the northeast (Billingsley et al. 2007A; Billingsley et al. 2007B).

Excellent exposures of Paleozoic strata in the Grand Canyon, northwest of Wupatki National Monument, define the subsurface stratigraphy in the region. In the Grand Canyon, the Toroweap Formation overlies the Lower Permian Coconino Sandstone (labeled Pc on the geologic cross-sections in Attachment 1) although there is a substantial break or gap in the stratigraphic record between the two units (this gap is called an "unconformity"). The Coconino Sandstone contains the local aquifer. Subsurface well logs indicate that the Coconino Sandstone is about 183 m (600 ft) thick beneath the Wupatki National Monument area (Billingsley et al. 2007A).

East of the Black Point Monocline, red sandstone and siltstone of the Lower Triassic (251-237 million years ago) Moenkopi Formation (TRmhm, TRmss, and TRmw) dominate the landscape. The Holbrook and Moqui Members (TRmhm) of the Moenkopi Formation may extend into the Middle Triassic. The contact between the gray-white Kaibab Formation and the red Moenkopi Formation represents an unconformity, a geologic feature that denotes a period of erosion and/or nondeposition. As much as 67 m (220 ft) of Moenkopi Formation was eroded from the monument prior to deposition of the Upper Triassic Chinle Formation (229-200 million years ago). Remnants of Chinle Formation sandstones, siltstones, and shale are exposed in the Little Colorado River Valley, northeast of Wupatki National Monument (map units TRcp and TRcs) (Billingsley et al. 2007A).

Pliocene (5.3-2.6 million years ago) and Pleistocene (2.6 million years ago-11,700 years ago) volcanic rocks in the western and southern part of the monument form an erosion resistant caprock over Triassic strata. Most of the volcanic units in the monument are basalt, a dark-colored rock composed primarily of the feldspar mineral plagioclase. Basalt flows (Qmcb, Qb, Qmb, Qmlp, Qwb, QTb, and Tbpb), pumice (Qsfp), basalt dikes (Qmbi), and pyroclastic deposits (Qmp) are part of the San Francisco Volcanic Field, a spectacular landscape covering approximately 4,700 sq km (1,800 sq mi) (fig. 4). The field contains more than 600 volcanoes that have erupted during the past 6 million years (Priest et al. 2001). San Francisco Mountain is the field's only stratovolcano, a type of volcano formed by successive layers of lava and pyroclastic material erupted from a central vent. Many of the Cascade Range volcanoes, such as Mount St. Helens and Mount Rainier, are stratovolcanoes. The youngest volcano in the field, Sunset Crater, erupted less than 1,000 years ago. Southwesterly winds carried sand-sized particles of ash from the Sunset Crater eruption and deposited them in cinder sand sheets (Qsc) and dunes (Qdc) in the monument area. For more information on Sunset Crater Volcano National Monument, see Thornberry-Ehrlich (2005).

The Little Colorado River, the principal stream drainage in the area, provides an abundant supply of sand and silt (Qs, Qf, Qg1, and Qg2) that is transported by southwesterly winds to form extensive sand sheet and dune deposits (Qd, Qes, Qdl, and Qdb) on the northeast side of the river (Billingsley et al. 2007A).

Landslide deposits (Ql), and talus and rockfall deposits (Qtr), form steep slopes below the basalt of Woodhouse Mesa south of the Visitor Center. In the western part of the monument, fresh water sediments (Qps) accumulated in intermittent lakes in Hulls Canyon, near East Mesa, and near Red House Basin. These lakes were most likely important sources of fresh water to the early, prehistoric inhabitants of the Wupatki National Monument area.

The northeast-trending Doney Mountain Fault and Black Point Monocline are the principal structural features in the monument (see the Features and Processes section). Folding and movement along the fault have raised the Coconino Plateau above the adjacent Little Colorado River Valley by 150 to 215 m (500 to 700 ft) (Billingsley et al. 2007A).

Washes and arroyos cut into the Doney Cliffs, and drain to the Little Colorado River. The larger washes contain intermittent (ephemeral) streams that have incised deeply into the Kaibab and Moenkopi Formations.

Cultural History

The intimate relationship between geology and human occupation at Wupatki National Monument spans at least 10,000 years. Two spear points, dating back to 11,000 and 8,000 years ago, are evidence of nomadic hunters and gatherers who roamed the desert region until about 500 CE ("Common Era" [CE] is preferred to "AD"). The gravel terraces along the Little Colorado River provided stones for tool making (fig. 7).

Beginning in the 7th century CE, Sinagua Indians entered the Wupatki area. The Sinagua found water in random depressions and ephemeral lakes in the region and used the water to successfully farm the region between the San Francisco Peaks and the Verde Valley, south of Flagstaff (Noble 1991).

Northern Sinagua sites date from approximately 675 CE. By 900 CE, their population had grown and they had established trading relations with the Kayenta Anasazi people to the north and the Hohokam to the south (Noble 1991). Early communities consisted of pit houses that were subsequently covered by the ash and cinders of the Sunset Crater eruptions between 1100 and 1050 (Self et al. 2010).

Lava flows, cinders, and ash also destroyed the Sinagua's farmland in the vicinity of Sunset Crater. However, a few decades later, the Sinagua discovered that the thin ash layer retained moisture, decreased evaporation, and conserved heat, thus prolonging the growing season. In addition, increased rainfall in the century following 1064 CE brought more water to the region. The Sinagua moved back to the area and were joined by other southwest cultures, including the Kayenta Anasazi, Cohonina, Hohokam, and Cibola people (Noble 1991).

Between 1150 and 1250 CE, large villages were established, and Sinagua settlements extended into the Wupatki and Walnut Canyon areas. Wupatki, the main ruin in Wupatki National Monument, means "long house" in the Hopi language. This pueblo was the tallest, largest, and probably the most important pueblo in the San Francisco Mountain region (fig. 2, cover). The pueblo consisted of 100 rooms with a community room and ballcourt. The Moenkopi Formation provided the red sandstone blocks for their pueblos. By 1182, Wupatki was home to 85 to 100 people and within a day's walk for a population of several thousand (National Park Service 2006).

By 1250, the Sinagua abandoned Wupatki and migrated northeast. By the early 1400s, the Sinagua culture began to blend with the Hopi culture (Nobel 1991). The Hopi consider the ancestral Sinagua who lived and died at Wupatki to be spiritual guardians of the pueblos. In Hopi legend, Wupatki is not abandoned but remembered and cherished (National Park Service 2006).

Looking for an overland route from Santa Fe to California in 1851, Captain Lorenzo Sitgreaves became the first Euro-American to document the ruins at Wupatki. Since Sitgreaves' expedition was not archaeological, he did not spend much time exploring the ruins. He did, however, have the expedition's artist, Richard Kern, make a drawing of Wupatki ruin. Kern's drawing represents the first known depiction of Wupatki Pueblo by Euro-Americans (Northern Arizona University, Department of Anthropology 2010).

Trade opportunities with the Navajo and Hopi in the Wupatki area led to the establishment of two trading posts in the late 1800s and early 1900s. In 1878, John Lorenzo Hubbell purchased a trading post near Ganado, Arizona, approximately 150 km (95 mi) east of Wupatki National Monument. The Hubbell family operated the trading post until the National Park Service purchased it in 1967 and established the Hubbell Trading Post National Historic Site.

The first well-documented expedition to Wupatki came in 1900 when archeologist Jesse W. Fewkes became the first to sketch, map, describe, and possibly excavate portions of Wupatki ruin. His drawing of Wukoki Pueblo is featured on the cover of the January 1904 issue of "Records of the Past" a magazine which also contained an article by Fewkes. In his article, Fewkes advocated for the preservation of the Wupatki ruins.

Beginning in 1916, Harold S. Colton and his wife, Mary Russell-Ferrell Colton, began more than 50 years of archaeological exploration in northern Arizona. Fewkes and the Coltons advocated for national monument status for Wupatki, but little was done to preserve the ruin until 1924 when President Calvin Coolidge granted Wupatki and a few surrounding ruins national monument status.

Since 1924, expeditions to Wupatki Pueblo have collected wood samples for dendrochronology (tree-ring dating), rock samples for paleomagnetic dating, and other artifacts. Dendronchronology and paleomagnetic rock dating have helped establish precise dates for the construction of various ruins at Wupatki National Monument. From 1981 to 1987, archeologist Bruce Anderson photographed, mapped, and analyzed over 2,700 sites within the monument. In 1996, Northern Arizona University's (NAU) Anthropology Laboratories received a grant from the Southwest Parks and Monuments Association (now Western National Parks Association) to map Wupatki pueblo and inventory artifacts using global positioning system (GPS) technology. Wupatki National Monument continues to provide research opportunities for studying ancient pueblo communities.

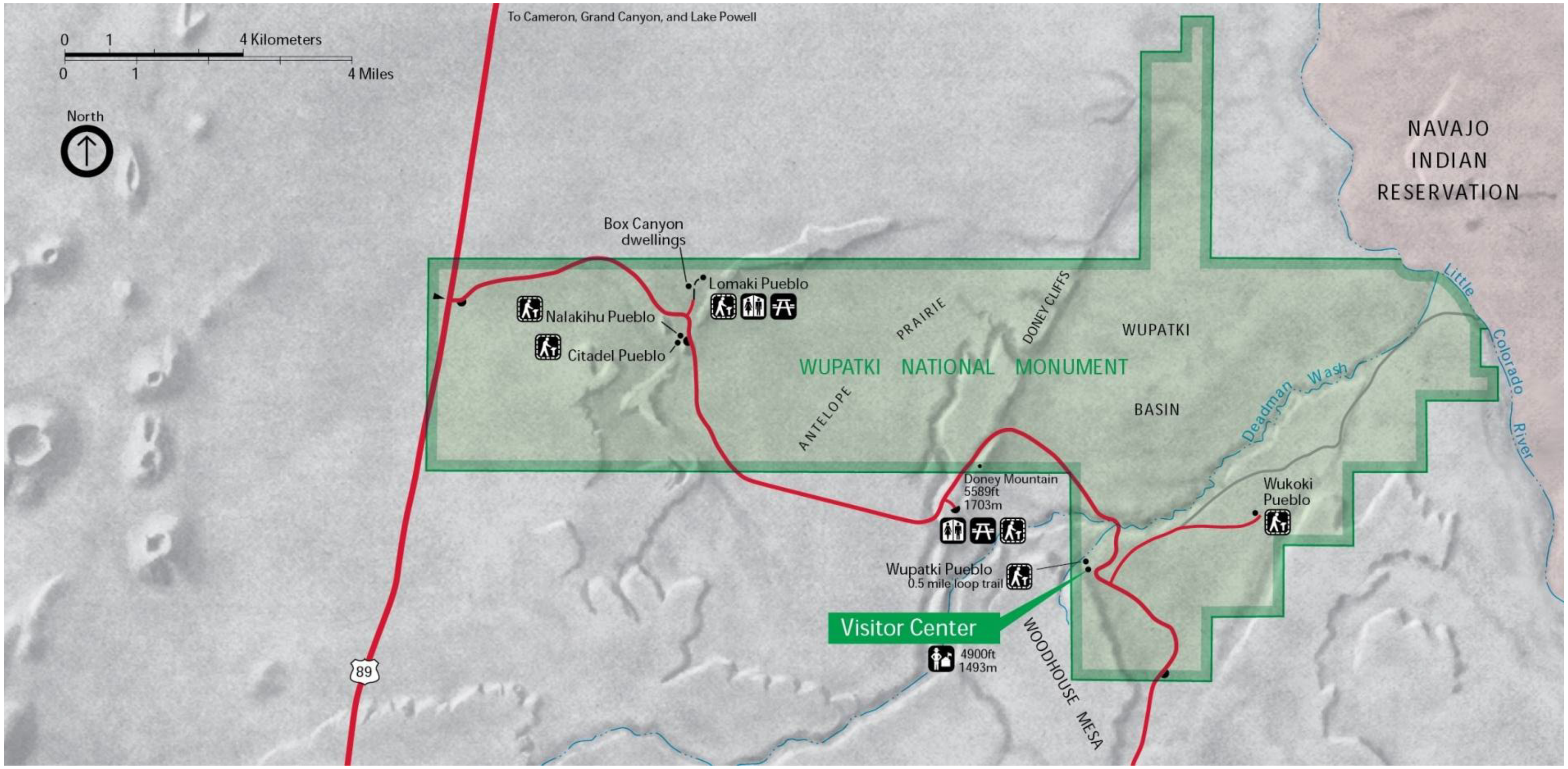


Figure 1. Location map of Wupatki National Monument, Arizona. A Coconino County loop road connects Sunset Crater Volcano National Monument (to the south) with Wupatki National Monument. Note the volcanic cones of the San Francisco Volcanic Field to the west of the monument (fig. 4). National Park Service map.

Figure 2. Wupatki Pueblo ruins, Wupatki National Monument. This three-story tall pueblo was occupied longer than any of the other ruins of the region. Wood, textiles, and perishable material have been preserved to an unusual extent due to the extreme aridity and excellent drainage of the region. National Park Service photograph courtesy Tim Connors (NPS Geologic Resources Division).

Figure 3. View of San Francisco Mountains from Wupatki National Monument. The Citadel Pueblo, resembling a fortress at the top of a hill, stands in the foreground. San Francisco Mountain is an eroded stratovolcano and includes Humphreys Peak, Arizona's highest point at 3,850 m (12,633 ft). The summit of Humphreys Peak is over 1,800 m (6,000 ft) higher than the topography at Wupatki National Monument. National Park Service photograph by Paul Whitefield (NPS North Central Arizona National Monuments).

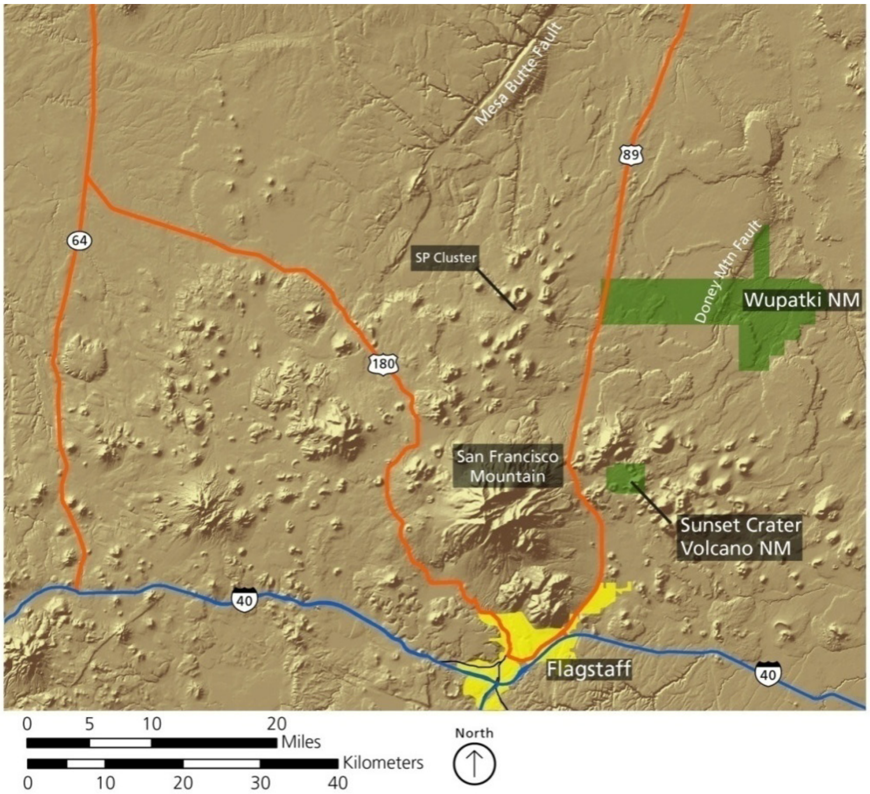


Figure 4. The figure shows many of the more than 600 volcanic vents that have erupted during the past 6 million years in the San Francisco Volcanic Field. Lava flows (flat lobate features) can be recognized by their proximity to vents. Larger tectonic structures such as the northeast-trending Mesa Butte Fault and Doney Fault (which cuts through Wupatki National Monument) are also visible. Map by Philip Reiker (NPS Geologic Resources Division) after Priest et al. (2001).

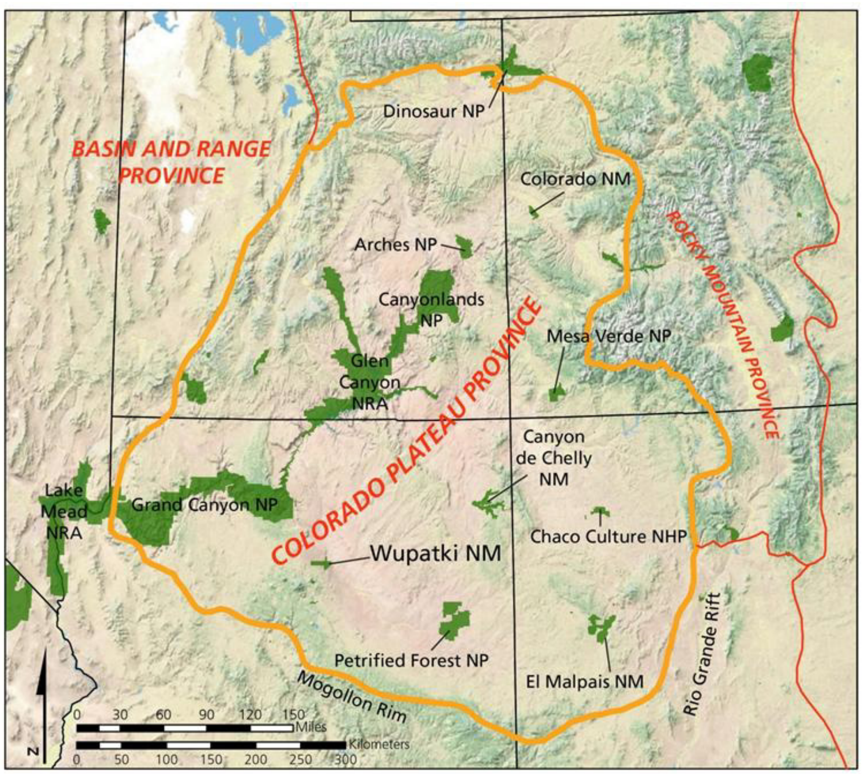


Figure 5. Map of selected National Park Service units on the Colorado Plateau, in green, and the immediate vicinity. Wupatki National Monument lies on the southwestern margin of the Colorado Plateau. The Basin-and-Range Province, with its distinctive topography of narrow, north-south trending mountain ranges and basins, borders the Colorado Plateau to the west, northwest, and southwest. The Rocky Mountain Province borders the Colorado Plateau to the east. Map by Philip Reiker (NPS Geologic Resources Division).

Era	Period (age in millions of years)		Formations/Units		Brief Description
CENOZOIC	Quaternary (2.6 to present)	Holocene (0.117 to present)	Artificial fill		Excavated alluvium and bedrock.
			Alluvial fans, floodplain, dune and sheet sand, and terrace-gravel deposits		Unconsolidated deposits of silt, sand, pebbles, cobbles, and some boulders.
		Holocene and Pleistocene (2.6 to present)	Alluvial fan, alluvium, eolian, and older terrace-gravel deposits		Unconsolidated deposits of clay, silt, sand, and pebbles. Partly cemented with calcite and gypsum.
			Landslide, talus, and rockfall deposits		Unsorted rock debris and angular rocks and boulders of red sandstone and siltstone and gray limestone.
			Valley-fill deposits		Silt, sand, and lenses of gravel.
		Pleistocene (2.6 to 0.11)	Basalt flows, pumice, basalt dike, pyroclastic deposits		Volcanic rocks of the San Francisco Volcanic Field. Basalt in various flows, a dike, and pyroclastic deposits and rhyolite airfall pumice associated with San Francisco Mountain.
	Neogene (23 to 2.6)	Pliocene (5.3 to 2.6)			
		Miocene (23 to 5.3)	Old stream-channel deposits		Interbedded siltstone, sandstone, arkosic granite, and conglomerate.
	Paleogene (66 to 23)	Oligocene (34 to 23)	Regional Unconformity (significant break or gap in the stratigraphic record)		
		Eocene (56 to 34)			
		Paleocene (66 to 56)			
MESOZOIC	Cretaceous (146 to 66)				
	Jurassic (200 to 146)				
	Triassic (251 to 200)	Upper (229 to 200)	Chinle Formation	Petrified Forest Member	Slope-forming mudstone, siltstone, and interbedded sandstone. Petrified logs and wood fragments.
				Shinarump Member	Cliff-forming sandstone and conglomeratic sandstone.
		Middle (246 to 229)	Regional Unconformity		
		Lower (251 to 246)	Moenkopi Formation	Holbrook and Moqui Members	Red-brown, slope-forming claystone, siltstone, and sandstone.
				Shnabkaib Member	Yellowish-brown, cliff-forming calcareous siltstone and sandstone.
				Wupatki Member	Red-brown, slope-forming siltstone, sandstone, and crumbly mudstone.
			Regional Unconformity		
PALEOZOIC	Permian (299 to 251)	Cisuralian (Lower) (299 to 271)	Kaibab Formation	Harrisburg Member	Red to brown, slope-forming gypsum, siltstone, sandstone, and limestone.
				Fossil Mountain Member	Light-gray, cliff-forming fossiliferous, cherty, sandy limestone and minor dolomite.
			Toroweap Formation, undivided		White, cliff-forming, cross-bedded sandstone.

Figure 6. General stratigraphic column for the Wupatki National Monument area. All of these units are exposed within the monument except for the Chinle Formation. Adapted from Billingsley and others (2007A). See the Map Unit Properties Table for more detail.

Figure 7. Artifacts and pottery found in abandoned Pueblos in Wupatki National Monument. National Park Service photographs courtesy Paul Whitefield (NPS North Central Arizona National Monuments).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Wupatki National Monument on June 28-29, 2001, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

The primary geologic issues identified at the scoping session for Wupatki National Monument included visitor safety issues and potential economic resources, specifically uranium and petroleum. In addition, potential seismic and volcanic hazards may impact Wupatki National Monument. The monument lies within the active seismic zone of Northern Arizona, and within the San Francisco Volcanic Field. The Sunset Crater erupted approximately 1,000 years ago, and future eruptions in the San Francisco Volcanic Field are probable. External issues, such as global climate change, may influence the springs and seeps in the monument, which may then lead to ecosystem modifications.

The monument also contains areas where material has been removed for road construction and other purposes. Some of these areas may impact cultural sites in the monument. As an initial step toward restoring all the disturbed areas in the monument, the NPS Geologic Resources Division completed a disturbed land inventory in 2000, and recommended action to restore twelve borrow pits in the monument (Greco et al. 2000). Erosion is the principal geologic issue associated with the borrow pits.

Visitor Safety Issues: Earthcracks and Blowholes

A more complete description of the geologic processes that resulted in earthcracks and blowholes may be found in the Surficial Features subheading of the Features and Processes section. These geologic features present potential safety hazards to monument visitors. The backcountry of Wupatki National Monument is closed to unguided visitors, so access to earthcracks and blowholes away from the designated visitor areas is limited.

Earthcracks

Tectonic activity in the past generated surface cracks, locally called "earthcracks," associated with faults and regional joint fractures in Wupatki's bedrock (fig. 8). Some of the cracks that have been explored are as much as 152 m (500 ft) deep and may pose safety hazards to visitors (Blyth 1995; Billingsley et al. 2007A). All of the earthcracks in the monument are closed to public entry (Paul Whitefield, NPS North Central Arizona National Monuments, Natural Resource Specialist, written communication, January 5, 2011).

Some earthcracks in the Kaibab Formation limestone have widened into 'sinks' and 'sinkholes' along open faults and joints, as water has dissolved the fractured carbonate rock. These features are not true karst dissolution/collapse features that may form in carbonate terrain, but are collapse zones or "mini-basins" that formed along minor faults associated with the larger earthcrack system in Wupatki National Monument (Paul Whitefield, NPS North Central Arizona National Monuments, Natural Resource Specialist, written communication, January 5, 2011).

Citadel Sink, the largest sink in the monument, borders the Citadel and Nalakiku ruins between South Mesa and East Mesa (inside front cover) (Billingsley et al. 2007A). This depression measures approximately 150 m (500 ft) by 200 m (650 ft). Sink formation and enlargement is an ongoing process, as water continues to seep into fractures and fissures and dissolve limestone.

Earthcracks are part of the earthcrack/fissure/blowhole system in the sedimentary rocks of western Wupatki National Monument. The last earthcrack inventory was conducted in 1976. The largest of three surveyed earthcracks was slightly less than 100 m (330 ft). One of the inventoried earthcracks contained two endemic psuedoscorpions and a winter hibernaculum for one sensitive bat species (Paul Whitefield, NPS North Central Arizona National Monuments, Natural Resource Specialist, written communication, January 5, 2011). In 2007, the National Park Service proposed an inventory and video documentation of vertebrate and invertebrate cave-dwelling fauna in the monument to enhance protection of those resources under the Cave Protection Act of 1988 (National Park Service 2007A).

Earthcracks and associated features are non-renewable geological resources. A cave inventory and subsequent monitoring plan may help to preserve these resources. Paul Whitefield, Natural Resource Specialist for North Central Arizona National Monuments, has proposed a new baseline microclimate monitoring and biological inventory for the earthcracks in the monument. Pollen and insect remains that may collect on earthcrack floors may provide information on ecosystem development and regional climatic change (Mike Conway, Arizona Geological Survey, Geologist, written communication, February 6, 2011). In addition, Rickard Toomey describes methods to monitor several parameters, or vital signs, associated with caves in a variety of geological settings (Toomey 2009). These vital signs include: cave meteorology; airborne sedimentation; direct visitor impacts; permanent or seasonal ice; cave drip and pool water; microbiology; stability-breakdown, rockfall and partings; mineral growth; surface expressions and processes; regional groundwater levels and quantity; and fluvial processes. Some of Toomey's parameters may apply to the earthcracks at Wupatki National Monument and provide valuable monitoring information for resource managers.

Blowholes

Blowholes at Wupatki National Monument generate a great deal of interest. These small openings create a natural fan or vacuum as air either blows in or out of the hole. Blowholes are typically only a few centimeters in diameter, but they connect to long, narrow fractures in the subsurface. Some of the blowholes, however, are large enough for a person to squeeze through. Spelunkers were able to descend 5.5 m (18 ft) into the blowhole at Wupatki Ruin before it was capped by a masonry box in 1965 (fig. 9). They found that the opening connected to a large underground fracture, which proved to be too constricted to explore (National Park Service 2007B).

Because of their depth, blowholes at Wupatki National Monument present potential safety issues. According to participants at the scoping workshop in 2001, many of the blowholes were used as dumping grounds in the past, and are now in need of some restoration work.

Economic Resources

During the scoping meeting, participants mentioned that Wupatki National Monument may contain uranium and petroleum potential. When the Federal government established the monument, the mineral rights were not included in the purchase. However, the Mining in Parks Act of September 28, 1976 prohibits active mining in National Park Service units. In addition, according to the Surface Mining Control and Reclamation Act (1977) the NPS does have legal authority to provide input during the permitting process of mining activities within park viewsheds. The Surface Mining Control and Reclamation Act of 1977 controls surface coal mining and reclamation activities on both federal and non-federal lands.

The major metallic mineral mining districts in Arizona form a northwest-trending belt south of the Colorado Plateau. The Colorado Plateau, however, contains abundant reserves of uranium, and the only petroleum production in the state.

From 1950 to 1976, some of the richest helium-bearing gas in the world was produced from pore spaces in the Permian-aged Coconino Sandstone in the Holbrook Basin, southeast of the park (Rauzi and Fellows 2003; Arizona Geological Survey 2010). Helium deposits may also exist in the Coconino Sandstone beneath Wupatki National Monument (Mike Conway, Arizona Geological Survey, Geologist, written communication, February 6, 2011). Coal, potash, and industrial minerals are also produced in northern Arizona, although production and exploration is well beyond the boundaries of the monument.

The eastern portion of the San Francisco Volcanic Field may also contain potential geothermal resources. Specifically, an east-west band of youthful volcanism immediately north of Sunset Crater appears promising as a potential electricity-grade geothermal resource (Duffield et al. 2000; Morgan et al. 2004). Physical manifestations of the deep geothermal system, such as geysers, hot springs, and fumaroles, are missing in the San Francisco Volcanic Field, but recent data suggest that deep geothermal gradients are being masked by a surface groundwater recharge system on the Colorado Plateau (Morgan et al. 2004; Crossey et al. 2006). With regard to Wupatki National Monument, wells drilled through the Kaibab Formation beneath the monument to test geothermal potential may disrupt the complex earthcrack-blowhole system.

Uranium Ore

Uranium exploration poses no immediate internal threat to Wupatki National Monument. In Arizona, uranium deposits occur in both the Basin-and-Range province and the Colorado Plateau. Deposits in the Basin-and-Range are insignificant compared to those on the Colorado Plateau, where over 99% of the uranium has been produced. Uranium on the Colorado Plateau occurs mainly in either: (1) sandstones in the Upper Jurassic Morrison Formation and the Upper Triassic Chinle Formation, or (2) in solution-collapse breccia-pipes formed in the Permian Redwall Limestone (Wenrich et al. 1989; Wenrich 2010).

Breccia pipes are vertical pipe-like columns created when overlying, angular, sedimentary rock fragments (breccia) collapse into a solution cavern formed in underlying massive limestone. Mineralizing fluids pass through the pipes and deposit a variety of metallic minerals, including uranium. Most of the known breccia pipes occur in northwestern Arizona. Many lie in the vicinity of Grand Canyon National Park. Fluids moving upward through the breccia pipes may deposit uranium in overlying sandstones (Wenrich et al. 1989)

The sandstone formations are neither exposed at the surface in Wupatki National Monument, nor in the subsurface beneath the monument (Billingsley et al. 2007A). The Redwall Limestone, however, was deposited across most of northern Arizona, including the area of Wupatki National Monument. In the Grand Canyon, the Redwall Limestone is approximately 150 to 240 m (500 to 800 ft) thick, but the unit thins to approximately 90 to 100 m (295 to 300 ft) thick in the subsurface near Cameron, Arizona, and is absent in the Defiance uplift area, east of the monument near the New Mexico border (McKee 1958; Beus 1990; Billingsley et al. 2007B). In the subsurface north of the monument, the top of the Redwall Limestone is estimated to be at a depth of 700 m (2,300 ft) beneath the Coconino Plateau, and 800 m (2,600 ft) in the Little Colorado River Valley, east of the

Black Point Monocline (figs. 10 and 20) (Billingsley et al. 2007B).

Because the Redwall Limestone may be present beneath Wupatki National Monument, the park may be within or immediately adjacent to northern Arizona's breccia pipe province. The highest-grade uranium ore bodies (over 0.5% U_3O_8) occur in these breccia pipes. Approximately 10% of breccia pipes yield economically viable mineral concentrations of uranium, copper, nickel, gold, or silver (Mike Conway, Arizona Geological Survey, Geologist, written communication, February 6, 2011).

In the Cameron mining district, located approximately 32 km (20 mi) north of Wupatki National Monument, uranium primarily occurs in the Petrified Forest Member of the Chinle Formation. The mining district lies on the southwest flank of the 8,500 sq km (3,300 sq mi) Black Mesa basin where erosion from the Little Colorado River has exposed a broad belt of Chinle Formation approximately 3 to 8 km (2 to 5 mi) wide by 30 km (18 mi) long (Bollin and Kerr 1958; Wenrich et al. 1989). The potential uranium deposit is separated from the monument by the Little Colorado River (Ulrich et al. 1984).

Future exploration may target the foot of Ward Terrace, which is located east of the main mining district. Open-pit uranium mining and processing requires water, and at Cameron, water would also be needed for dust control. The amount of water that would be required is unknown at this time.

No other discoveries of uranium in the Chinle Formation have been as large as those found in the Cameron mining district (Wenrich et al. 1989; Scarborough 1981). One reason the Cameron mining district may be unique is its location on the eastern edge of the breccia-pipe province. Uranium ore bodies may have resulted from fluids moving upward through the breccia pipes and into the Chinle Formation (Wenrich et al. 1989).

Petroleum Exploration

Petroleum exploration also poses no immediate internal threat to Wupatki National Monument. In order to accumulate economic quantities of hydrocarbons (oil and gas) in the subsurface, specific geologic conditions must be met. Organic-rich shale must be buried so that increased temperature and pressure matures the organic material and generates oil and gas. The oil and gas must then migrate out of the shale and into porous and permeable (reservoir) rocks. Migration must then be stopped (trapped) before the oil and gas reaches the surface. Hydrocarbon traps may consist of geologic structures, such as faults that juxtapose porous and permeable units against impermeable rock, or stratigraphic traps in which permeable layers pinch out into impermeable units such as shale.

In Arizona, these conditions may exist in seven basins, and on the northeastern flank of the Defiance Arch, an uplifted area that extends into northeastern Arizona from west-central New Mexico (Butler 1995; Rauzi 2001). Northern Arizona contains four of the seven basins as well as the Defiance Arch (table 1). The Holbrook basin in east-central Arizona lies southeast of Wupatki National Monument.

Table 1. Northern Arizona basins and uplifted areas with hydrocarbon potential (Rauzi 2001).

Basin/Arch	Location
Paradox basin	Northeast Arizona
Black Mesa basin	Northeast Arizona
Holbrook basin	East-central Arizona
Chuar basin	North-central Arizona
Cordilleran shelf	Northwest Arizona
Defiance Arch	East-central Arizona

In Arizona, oil and natural gas production come primarily from the southwestern flank of the Paradox basin, in the extreme northeastern corner of the state approximately 240 km (150 mi) northeast of the monument (Nations et al. 1989; Rauzi 2010). Wupatki National Monument is not located within or on the flank of any of the potential hydrocarbon-producing basins. While Wupatki National Monument may contain the same formations in the subsurface that serve as source and reservoir rocks in the basins, the monument contains no identifiable hydrocarbon trap or evidence, such as oil seeps, that oil has migrated into or through the area. Future drilling activity in the basins or Defiance Arch area of northern Arizona should not affect Wupatki National Monument.

Seismic Activity (Earthquakes)

Most of Arizona's earthquakes occur in northern Arizona, associated with the transition zone between the Colorado Plateau and the Basin-and-Range province (fig. 11). Few of Arizona's recorded earthquakes register over a magnitude (M) 3.0 on the Richter scale. In February 1999, a magnitude 3.1 earthquake was located in Wupatki National Monument (Arizona Earthquake Information Center 2010). Since 1900, five earthquakes with magnitudes greater than 5 have shaken the Flagstaff area. These earthquakes occurred in 1906 (M6.2), 1910 (M6.0), 1912 (M6.2), 1959 (M5.0), and 1993 (M5.4) (Arizona Earthquake Information Center 2010).

Located on the edge of the Colorado Plateau, Wupatki National Monument lies within the northern Arizona active earthquake zone, and may experience low-magnitude earthquakes. For example, an unusual event took place on October 31, 2009, when over 100 earthquakes occurred about 24 km (15 mi) northeast of Flagstaff near Sunset Crater Volcano National Monument. Nicknamed the 'Halloween Swarm,' the earthquakes were triggered within the mid-crust at depths ranging from 17 to 27 km (11 to 17 mi). The largest earthquakes had magnitudes of 2.5, and would not have been felt by local residents (Arizona Earthquake Information Center 2009). Earthquakes of this frequency and depth are uncommon for this area, and research continues on the trigger responsible for the Halloween

Swarm (Dave Brumbaugh, Arizona Earthquake Information Center, Director, written communication, March 6, 2011).

While the Richter magnitude scale measures the seismic energy released by an earthquake, the Modified Mercalli intensity scale attempts to quantify the damage produced by an earthquake. The Modified Mercalli scale has 12 levels with shaking widely felt at level IV and significant damage beginning at level VII. Individuals will feel a level VI earthquake. Heavy furniture might be moved, and some chimneys may be damaged at level VI. At level VII, well-built buildings may experience minor damage, but poorly designed structures will sustain considerable damage. Richter magnitudes of 5.0-5.9 correspond roughly to Modified Mercalli Intensity levels of VI-VII. One level VI earthquake occurred in the Flagstaff area in 1892 (Arizona Earthquake Information Center 2010). Should a level VII earthquake impact the monument, damage may occur to the ruins.

Earthquakes often occur along pre-existing faults. The northeast orientation of the Doney Mountain Fault, however, removes this fault as a likely candidate for any significant movement resulting from an earthquake (Dave Brumbaugh, Arizona Earthquake Information Center, Director, written communication, March 6, 2011).

The National Seismic Network Station site, WUAZ, is located on a hill overlooking Wupatki Pueblo. The National Park Service maintains this site. Information and research on Arizona earthquakes is collected and distributed by the Arizona Earthquake Information Center, which is located in the geology building on the Northern Arizona University campus. Updated information is available on their website: http://www4.nau.edu/geology/aeic/index.html (accessed August 12, 2010). Information concerning earthquakes occurring around the globe may be found at the U. S. Geological Survey's Earthquake Hazards Program at http://earthquake.usgs.gov (accessed August 12, 2010).

Braile (2009) describes methods to monitor several parameters, or vital signs, associated with seismic activity. These vital signs include: monitoring earthquake activity; analysis and statistics of earthquake activity; analysis of historical and prehistoric earthquake activity; earthquake risk estimation; geodetic monitoring, ground deformation; and geomorphic and geologic indications of active tectonics. These parameters may provide additional monitoring information for resource managers.

Disturbed Land

Material removed for road construction and other purposes left twelve borrow pits in the monument (Greco et al. 2000). The sites range from 0.005 ha (0.012 ac) (site #3) to 2.1 ha (5.2 ac) (site #12). Damage to cultural sites, but not to any pueblo ruins, may occur from erosion at four of the twelve borrow pits that were inventoried in 2000. These four sites are located primarily along access roads and are generally out of sight of the pueblos.

Most of the sites assessed in 2000 are recovering and do not require active management treatments. Because archeological resources are either exposed or at risk of eroding near quarries 2, 6, and 7, park management has requested funding for cultural resource stabilization work at these sites. Funding for minor remediation work at quarries 4 and 5, and for less intensive work than originally described for quarry 12, has also been requested. Funds have yet to be allocated for any of this work (Paul Whitefield, NPS North Central Arizona National Monuments, Natural Resource Specialist, written communication, April 5, 2011).

The site closest to any ruin is site #6, this 0.3 ha (0.7 ac) site lies approximately 610 m (2,000 ft) from an unnamed ruin (fig. 12). The site is off the mesa upon which the ruins rest, and is separated from the ruins by an ephemeral stream. Although archeological resources may be at risk from erosion, no pueblo ruins will be impacted by the minor erosion described in the inventory (Greco et al. 2000).

Erosion at the very small borrow pit site #3 may cause maintenance problems for the Hull's Canyon Road. Vegetation recovery is ranked as "good" at this site (Greco et al. 2000).

In 2000, the U.S. Forest Service was using a site, called Heiser Dump, to store rock material for a repaving project. The roughly 0.8 ha (2 ac) site was located adjacent to the "New Heiser" park administrative and operations area in the western part of the monument. Because the site was still being used, the Heiser Dump was not mapped or surveyed in 2000. The project was completed in 2005. The debris was hauled away, and the area was recontoured and scarified with a road grader. Further vegetation management will include the control of *Halogetom glomeratus* (salt lover) and re-seeding to re-establish native vegetation (Paul Whitefield, NPS North Central Arizona National Monuments, Natural Resource Specialist, written communication, April 5, 2011).

Detailed descriptions of each site, as well as recommended action, are available from the Geologic Resources Division (Greco et al. 2000).

Volcanic Eruptions

Sections of the San Francisco Volcanic Field remain active, so that sometime in the future, volcanic eruptions may again deposit volcanic ash over Wupatki National Monument. Over the last 780,000 years, volcanic activity has primarily occurred in locations adjacent to the monument: the eastern part of the field, in a group of volcanic cones called the "SP cluster", and a cluster of cones around Sunset Crater (figs. 4 and 18). Since about 2.5 million years ago, volcanism in the San Francisco Volcanic Field has migrated from west-to-east at a rate of about 2.9 cm (1.1 in) per year, the approximate rate and direction of the North American plate (Tanaka et al.

1986). However, exceptions to this trend exist on an individual volcano-by-volcano basis. For example, older volcanoes exist east of Sunset Crater, the youngest volcano in the San Francisco Volcano Field (Wolfe et al. 1987; Morgan et al. 2004). Volcanic eruptions may yet occur to the west and south of the monument. The volcano that created Sunset Crater erupted about 1,000 years ago. The San Francisco Peaks volcanic system was active until about 90,000 years ago (Morgan et al. 2004). The SP cluster, located immediately west of the monument (fig. 4), consists of 67 basaltic cinder cones, tuff rings, spatter cones, and lava flows that formed within the last 1.7 million years (Ulrich and Bailey 1987; Conway et al. 1998). Based on the age and frequency of past events, scientists estimate that there is a 90% chance of an eruption in the SP cluster within the next 22,000 to 26,000 years, and a 13% chance that an eruption will occur within the next 1,000 years (Conway et al. 1998).

Most of the volcanoes in the San Francisco Volcanic Field are cinder cones composed of basalt; one example is Doney Mountain (fig. 13). Volcanic cinders (fig. 19), like pumice, contain abundant bubble-like cavities. Cinder cones are relatively small, usually less than 300 m (1,000 ft) tall, and form within months to years (Priest et al. 2001). They are also associated with basaltic lava flows. About two-thirds of the past events in the SP cluster resulted in lava flows (Conway et al. 1998). Lava flows extend from both SP Crater and Sunset Crater cinder cones (figs. 4, 14).

In contrast to the smaller cinder cones, a catastrophic eruption produced San Francisco Mountain, the only stratovolcano in the field, between 1.2 million and 400,000 years ago. Explosive volcanic eruptions that form a stratovolcano may cause a significant amount of destruction, as witnessed by the 1980 eruption of Mount St. Helens in the Pacific Northwest.

Predicting the next eruption and what type of impact it will have on Wupatki National Monument is difficult. A blanket of ash and larger volcanic rock fragments from the Sunset Crater eruption covered an area of more than 2,100 km^2 (810 mi^2) (Luedke and Smith 1991). The distribution of volcanic cinders and lava fragments indicate that gas and ash were blasted high into the stratosphere while cinders, lapilli (pebble-size fragments), and lava bombs (material greater than 65 mm [2.5 in]) were ejected to altitudes of tens to hundreds of meters (Self et al. 2010).

According to the U.S. Geological Survey, future eruptions will probably occur in the eastern part of the field and will likely be small (Priest et al. 2001). Because of their size and the remoteness of the area, they should not pose a significant hazard to the monument. However, as Conway and others (1998) have discussed, the SP cluster remains active. In the SP cluster, magma may mix with groundwater to produce an explosive eruption of ash, tuff, and other volcanic clasts (Mike Conway, Arizona Geological Survey, Geologist, written communication, February 6, 2011). Although unpredictable, volcanic eruptions remain a potential hazard to Wupatki National Monument (Mike Conway, Arizona Geological Survey, Geologist, written communication, February 6, 2011).

Global Climate Change

Water is a precious resource in Arizona. Since 1862, major statewide droughts have occurred from 1932 to 1936, 1942 to 1964, and 1973 to 1977, which was most severe in eastern Arizona (US Geological Survey 2004). The impact of future climate change on the state's groundwater and surface water remains uncertain. Climate change may alter seasonal precipitation patterns (e.g., rain versus snow), reduce snowpack, decrease spring runoff, and reduce the water available for stream flow and groundwater recharge (Environmental Protection Agency 2010; NPS Sonoran Desert Network 2010). Precipitation changes and warmer temperatures have unknown implications for vegetation ecosystems and animal habitats, which may subsequently impact water infiltration properties of soil.

In Arizona, groundwater provides the principal source for surface water bodies (NPS Sonoran Desert Network 2010). On a local level, resource managers may address reductions in groundwater storage and infiltration caused by drought and human development by implementing soil conservation and recharge enhancement projects. However, changes in precipitation and recharge due to climate change become more problematic. The National Park Service's Sonoran Desert Network and Arizona's Water Resources Development Commission continue to monitor climate change and Arizona's water resources.

Refer to Karl et al. (2009) for additional information regarding climate change impacts throughout the United States. The NPS Climate Change Response Program addresses science, adaptation, mitigation and communication for climate change issues throughout the National Park System (http://www.nature.nps.gov/climatechange/index.cfm, accessed June 10, 2011).

Potential Geologic Projects

The following topics were presented at the scoping meeting as potential projects applicable to Wupatki National Monument:

- An earthcrack inventory of the area.
- An evaluation of the blowholes with regard to potential safety hazards.
- An evaluation of the uranium and petroleum potential in Wupatki National Monument. Mineral rights belong to the Arizona land office.
- Mapping the gravel deposits, and evaluating their commercial value.
- A description of the provenance of the various clays and rocks that have been used in mortars over the years, and how these materials reflect the interrelationship between the cultural and geologic resources of the area.

Figure 8. An earthcrack near Lomaki Pueblo, Wupatki National Monument. The crack has formed in Permian Kaibab Formation. The person (for scale) stands on the contact between the relatively horizontal strata of the cliff forming Fossil Mountain Member (map unit Pkf) and the overlying, slope-forming Harrisburg Member (map unit Pkh) of the Kaibab Formation. The San Francisco Mountain can be seen in the distance. Photograph courtesy Dr. Sarah Hanson (Adrian College). Available online: http://www.adrian.edu/earthscience/SW_USspr08/SW_USSpring08.htm, accessed February 25, 2011

Figure 9. Blowhole near Wupatki Ruin. The blowhole was capped in 1965. Blowholes in the monument connect to an extensive underground fracture system. National Park Service photograph courtesy Tim Connors (NPS Geologic Resources Division).

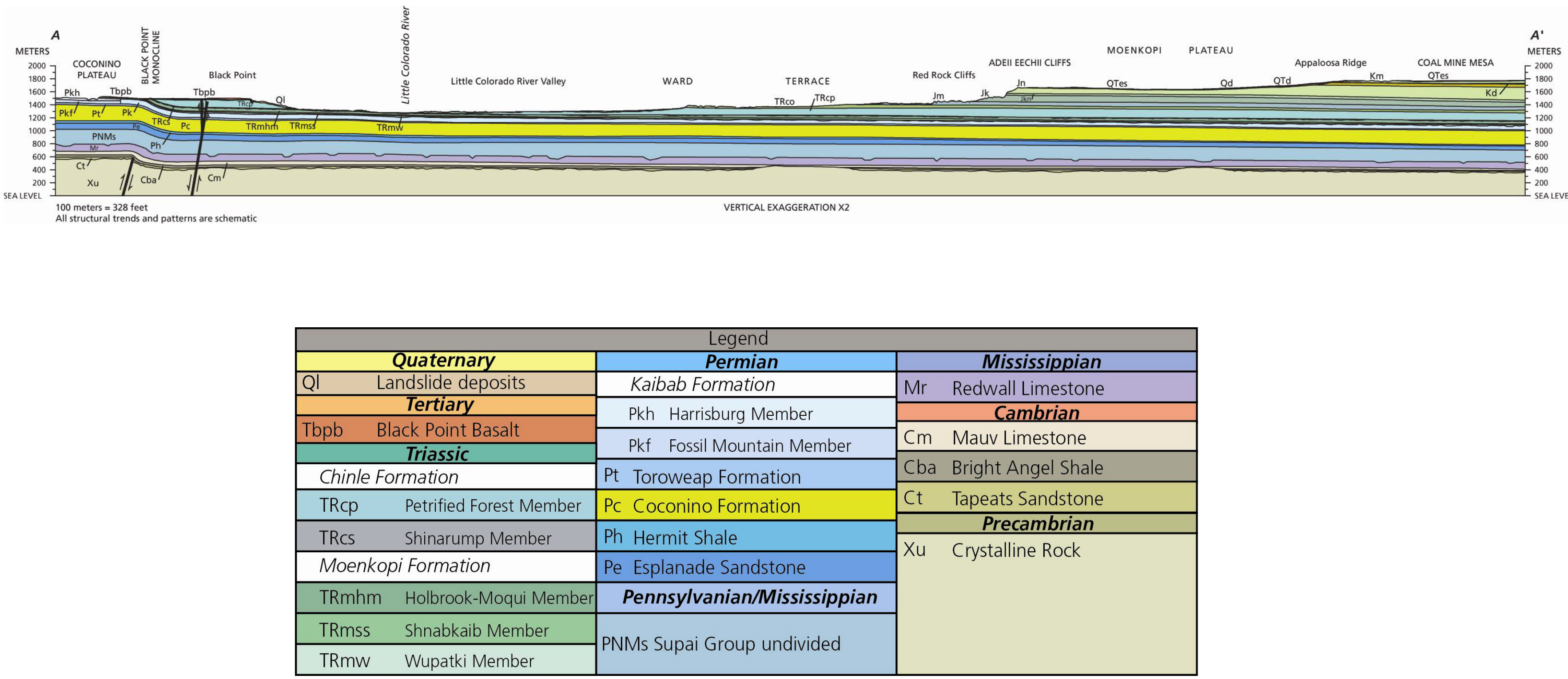


Figure 10. Southwest (A) to northeast (A') geologic cross-section showing the Redwall Limestone (unit Mr) in the subsurface. The cross-section is located north of the monument and is extracted from Billingsley and others (2007B). The Chinle Formation, although included in this cross-section, has been eroded from Wupatki National Monument. Breccia pipes and associated uranium deposits may be present in the Redwall Limestone. Note also how the strata fold over faults in the subsurface to form the Black Point Monocline. Cross section graphic extracted from Billingsley et al. (2007B). Available in the "wupa_geology.hlp" file in the included digital geology (GIS) data (Geologic Map Data section; Attachment 1).

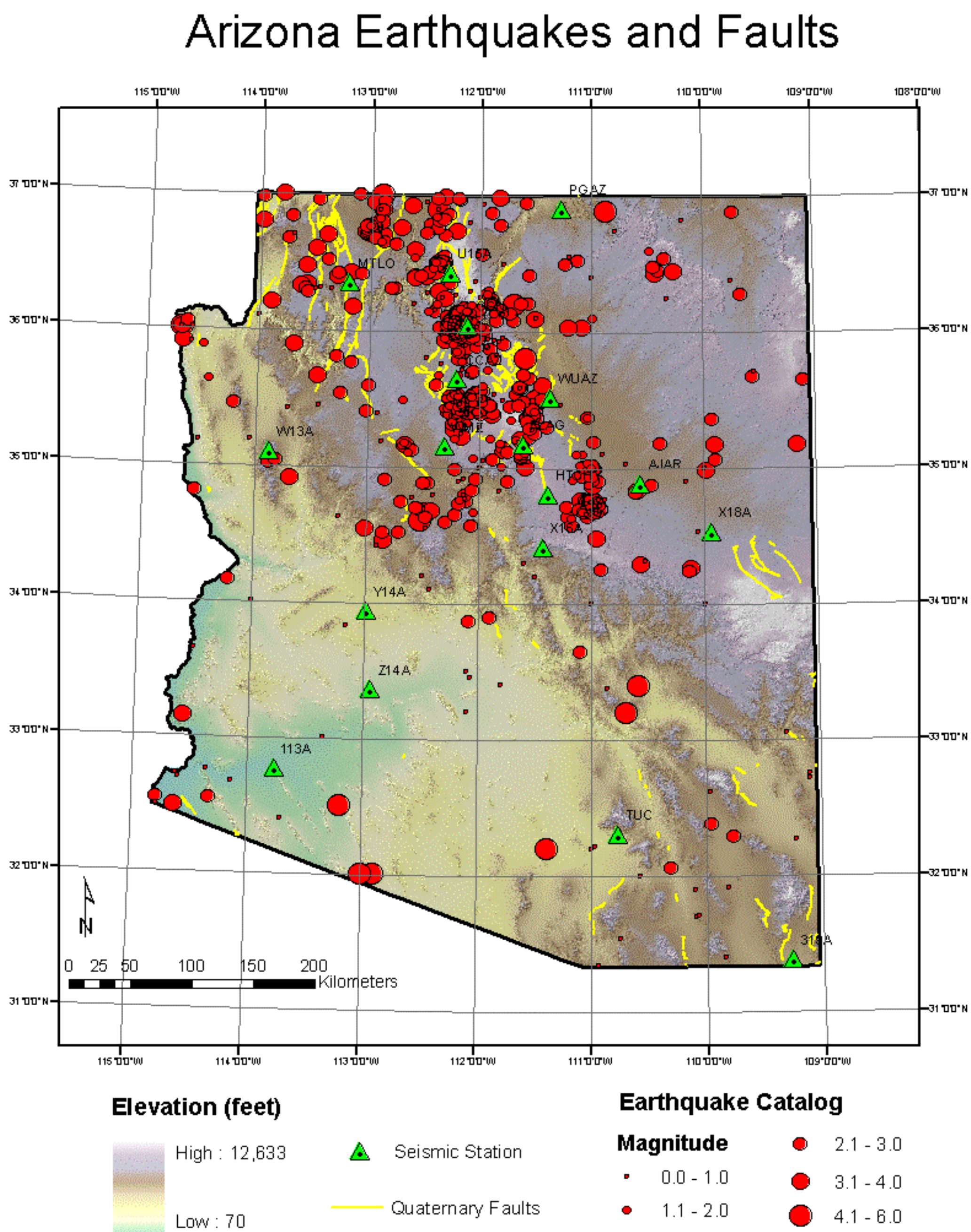


Figure 11. Arizona earthquakes (red circles) and Quaternary-age faults (yellow lines). Seismic station WUAZ is located on a hill overlooking the Wupatki Pueblo. Map courtesy of the Arizona Earthquake Information Center, http://www4.nau.edu/geology/aeic/eq_fault_maps.html, accessed February 24, 2011.

Figure 12. Borrow pit site #6, Wupatki National Monument. Erosion has carved small gullies into the quarry banks and threatens cultural sites in this area. Funding for cultural resource stabilization work has been requested for this site. National Park Service photograph courtesy Deanna Greco (Grand Canyon National Park).

Figure 13. Doney Mountain is an extinct volcano with a rounded summit formed of red and black ash. One of over 600 volcanic features in the surrounding area, it offers vistas of the San Francisco Peaks to the west, the Painted Desert to the north, and the Little Colorado River valley to the east. A small plateau capped with Moenkopi Sandstone lies in the foreground. National Park Service photograph by Paul Whitefield (NPS North Central Arizona National Monuments).

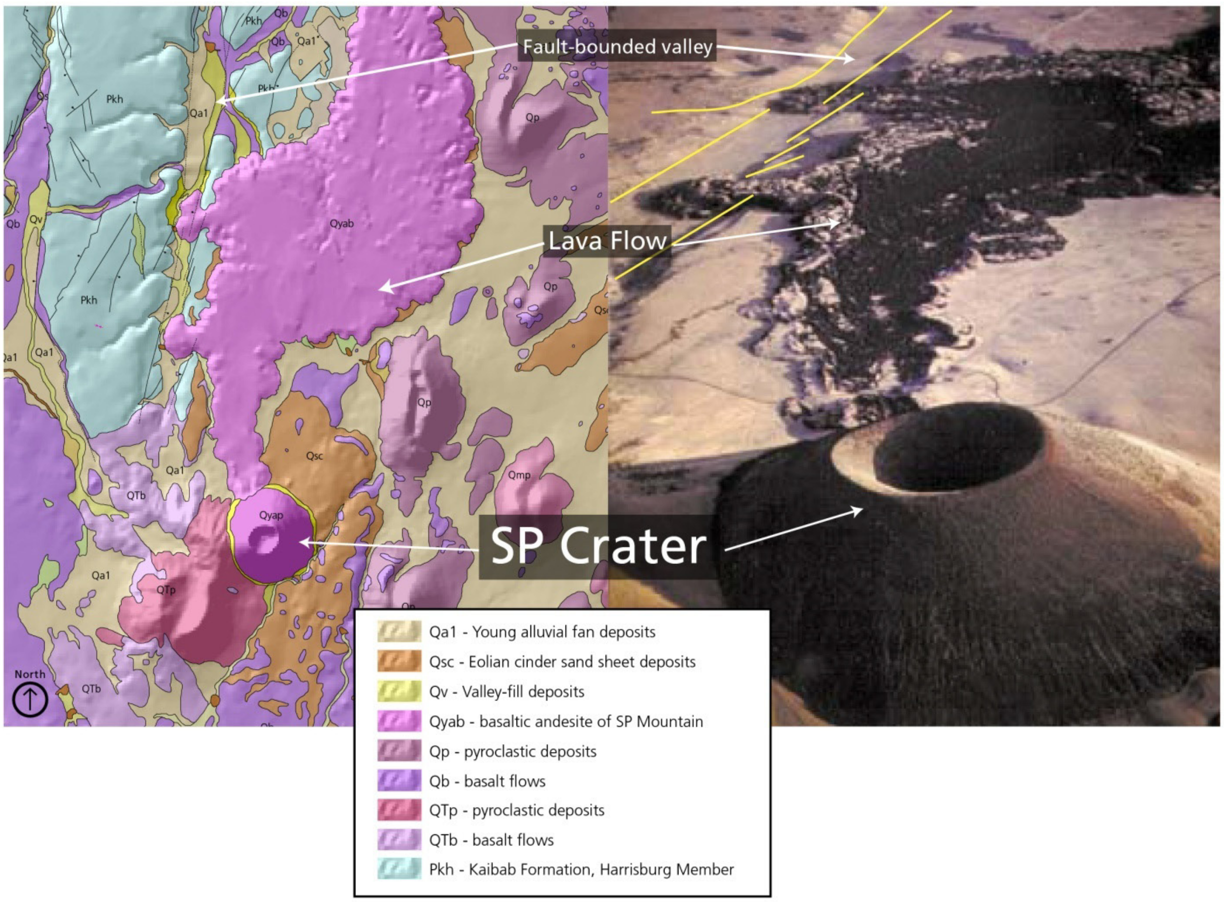


Figure 14. Geologic map and aerial view of SP Crater. This excellent example of a cinder cone lies approximately 5 km (3 mi) west of the monument's western boundary and 32 km (20 mi) north of Flagstaff in the San Francisco Volcanic Field. Associated with the cinder cone is a lava flow that extends approximately 6 km (4 mi) from the cone and is about 30 m (100 ft) thick. The cone and lava flows are mapped as geologic map unit Qyab, basaltic andesite of SP Mountain. Geologic map image extracted from GRI digital geologic data (GIS) by Philip Reiker (NPS Geologic Resources Division); see Geologic Map Data section and included GIS data. Aerial image is a U.S. Geological Survey photograph from Priest et al. (2001).

Geologic Features and Processes

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

Geologic features at Wupatki National Monument represent a variety of past depositional environments, ranging from marine ecosystems to river systems. Processes involving tectonic deformation, uplift, and erosion have exposed these ancient environments to today's visitors.

The Sinagua Indians used sandstone of the Moenkopi Formation in Wupatki National Monument to build their multi-storied pueblos. Resting on bedrock, the uniform slabs of sandstone were reinforced with local clay-based mortar. The geologic features in the monument provide a window through which to view what the world was like millions of years ago. These features today have changed very little from when the Sinagua occupied the region.

Bedrock Features

Like much of the stratigraphy on the Colorado Plateau, the layers of rock in Wupatki National Monument are relatively horizontal. The oldest bedrock unit in the monument is the Permian Toroweap Formation. The Permian Kaibab Formation, common throughout northern Arizona, overlies the Toroweap Formation and forms the youngest Paleozoic formation in the monument (figs. 6, 15, and 16). Excellent exposures of older Paleozoic and Precambrian rock units may be found at Grand Canyon National Park, northwest of the monument.

Mesozoic rocks overlie Paleozoic strata. The Triassic Moenkopi Formation (fig. 17) is the youngest bedrock in the monument (Billingsley et al. 2007A). The Upper Triassic Chinle Formation overlies the Moenkopi Formation east of the Little Colorado River, but the formation has been eroded from Wupatki National Monument (McCormack 1989). The Moenkopi, less resistant to erosion than the Kaibab Formation, has been eroded from the uplands in the western part of the monument, and is restricted to structurally low areas.

Permian Toroweap Formation (map unit Pt)

Exposed at the bottom of Citadel Wash and Antelope Wash along the Doney Mountain Fault, the 15 to 21 m (50 to 70 ft) thick Toroweap Formation in Wupatki National Monument makes a dramatic departure from exposures in the Grand Canyon. In the Grand Canyon, the Toroweap is subdivided into three distinct members that represent tidal-flat, sabkha, and eolian depositional environments. However, in the monument area, the Toroweap cannot be subdivided into individual members (Turner 1990; Billingsley et al. 2007A). Exposed as a cliff of low-angle, calcareous, cross-bedded sandstone, the Toroweap at Wupatki has been interpreted as coastal, eolian deposits similar to the sand dunes of the underlying Coconino Sandstone (labeled 'Pc' on the geologic cross-sections in Attachment 1).

Permian Kaibab Formation (map units Pkh and Pkf)

The Kaibab Formation forms the bedrock surface in the central part of the monument, as well as the Coconino Plateau. It is the youngest Paleozoic unit on the southern Colorado Plateau, and forms the caprock of the Grand Canyon (fig. 16). The Kaibab contains the Fossil Mountain Member (Pkf) and the younger Harrisburg Member (Pkh). In Wupatki National Monument, most of the surface exposures of the Kaibab Formation consist of the Harrisburg Member (Billingsley et al. 2007A).

Approximately 55 m (180 ft) of Fossil Mountain Member form the gray cliffs and ledges in the narrow canyons on Antelope Prairie, and along the Doney Mountain Fault (Billingsley et al. 2007A). The lithology of the unit changes from west-to-east, from sandy limestone to calcareous sandstone. This change results from a shift in Permian depositional environments from a more offshore environment to one that is more shoreward. Fossiliferous chert nodules and chert breccias, which may have formed from settling of suspended siliceous sponge spicules into topographic depressions, occur in the upper part of the member. Fossils in the chert nodules and sandy limestone include brachiopods, crinoids, trilobites, sponges, and bryozoans indicative of a subtidal, shallow-marine environment. Evaluation of the Fossil Mountain Member across the Coconino Plateau and in the Grand Canyon records an overall west-to-east transgressive episode of sedimentation during this time (McCormack 1989; Hopkins 1990). During a "transgression," sea level rises, and as the sea advances onto the continent, the coastline moves inland. In this case, sea level rose, and shoreline sedimentation migrated from west-to-east across northern Arizona.

The thin- to medium-bedded (0.3 to 2 m [1 to 6 ft]) Fossil Mountain Member gradually transforms to the thin-bedded Harrisburg Member (fig. 16). The contact between the two members is commonly placed at the topographic break where cliff-forming, cherty limestone changes to the slope- and ledge-forming gypsum, siltstone, sandstone, and sandy limestone of the Harrisburg Member (Billingsley et al. 2007A). In the top part of the unit, mollusks may be found in calcareous sandstone. The gastropods, pelecypods, scaphopods, and ostracods are able to tolerate a greater range of environmental conditions than the normal-marine organisms common to the Fossil Mountain Member.

In the monument, the Harrisburg Member is only about 25 to 37 m (80 to 120 ft) thick, but the unit thickens westward to about 90 m (300ft) in northwestern Arizona and southern Nevada. For example, at Blue Diamond Hill, west of Las Vegas, the Harrisburg Member is so thick that gypsum is mined from the unit (Hopkins 1990). Gypsum, formed from evaporation of sea water, and the molluscan fauna found at Wupatki National Monument and throughout the Coconino Plateau, suggest that the Harrisburg Member represents a partially to highly restricted, shallow-marine environment that resulted from the westward regression of the shallow sea at the end of the Permian (see the Geologic History section).

Triassic Moenkopi Formation (map units TRmhm, TRmss, and TRmw)

The eastern half of Wupatki National Monument contains extensive exposures of red sandstone ledges and siltstone slopes of the Lower and perhaps Middle Triassic Moenkopi Formation (fig. 17). An easily recognizable regional unconformity (a break in the geologic record that represents an interruption in deposition) separates the red Moenkopi Formation from the underlying, gray-white Kaibab Formation (fig. 17). As much as 67 m (220 ft) of Moenkopi Formation once covered Wupatki National Monument, but erosion removed an unknown amount of Moenkopi Formation prior to deposition of the Upper Triassic Chinle Formation, which is exposed northeast of the monument (Billingsley et al. 2007A).

In contrast to the marine environments of the Permian, the members of the Triassic Moenkopi Formation in Wupatki National Monument contain geologic features indicative of terrestrial deposition. The Wupatki Member (TRmw), the oldest member of the Moenkopi Formation, displays ripple-marked mudstone, salt crystal casts, and raindrop impressions like those found in tidal flats today. Its red colored beds are typical of terrestrial sediments that develop a ferric (iron) oxide (hematite) coating on individual grains. Cross-bedded sandstones and calcareous siltstones in the overlying Shnabkaib Member (TRmss) represent continental lowland fluvial and tidal flat environments. Trough-crossbedding and ripple marks resulting from fluvial processes and fossil casts of reptile tracks characterize the reddish-brown claystone, siltstone, and sandstone layers in the Holbrook and Moqui Members (TRmhm).

The Lower Triassic Wupatki Member (TRmw) consists of sandstone ledges protruding from red to red-brown siltstone and mudstone slopes. Exposures range in thickness from 6 to 10 m (20 to 35 ft) and can be found from the Black Point Monocline to the southeast border of the monument, south of the Wukoki Ruin (Billingsley et al. 2007A). A massive yellow-white to light-brown cliff-forming sandstone layer at the base of the 15 m (50 ft) thick Shnabkaib Member marks the contact with the Wupatki Member. More resistant to erosion than the mudstones and siltstones of the Wupatki Member and the overlying Holbrook and Moqui Members, the Shnabkaib sandstone forms prominent mesas or ridges shaped like antique flatirons along the Black Point Monocline (Billingsley et al. 2007A).

The Holbrook and Moqui Members, which are collectively mapped as one unit in the monument, may be partly Middle Triassic in age. The most prominent unit of the Moenkopi Formation in the monument, the Holbrook and Moqui Members, form 25 to 37 m (80 to 120 ft) thick exposures of slope-forming layers of claystone, siltstone, and sandstone. Beyond the monument's boundaries, abundant vertebrate fossils have been discovered in the Holbrook Member, and are listed below in the Paleontological Resources subheading (Tweet et al. 2009).

Volcanic Rocks of the San Francisco Volcanic Field

Volcanic rocks, ranging in composition from basalt (low silica content) to rhyolite (high silica content), form a myriad of volcanic landforms in the San Francisco Volcanic Field. In general, magma that is rich in silica is more viscous and its eruptions are more explosive than magma containing less silica. More than 500 individual vents spewed basaltic lavas throughout the volcanic field (Newhall et al. 1987). The SP cluster contains basaltic cinder cones, tuff rings, spatter cones, and basaltic lava flows (fig. 4). In contrast, large, long-lived eruptions of high-silica magma produced the domes of Mount Elden, Kendrick Peak, Sugarloaf Mountain, Bill Williams Mountain, and Sitgreaves Mountain (Moore and Wolfe 1976; Newhall et al. 1987; Wolfe et al. 1987; Holm 1988; Conway et al. 1998; Priest 2001).

The San Francisco Mountain complex, which can be seen from the monument (fig. 3), formed from countless eruptions of lava and pyroclastic material, through a central vent, over hundreds of thousands of years (Holm 1988). The 3,850 m (12,633 ft) summit of this stratovolcano was once at nearly 4,900 m (16,000 ft). Prior to the formation of the Sugarloaf volcanic dome about 100,000 years ago, the summit collapsed, forming a massive debris avalanche that filled the valley immediately west of Sunset Crater (Mike Conway, Arizona Geological Survey, Geologist, written communication, February 6, 2011).

Most of the more than 600 volcanoes in the San Francisco Volcanic Field, however, resulted from eruptions of low-viscosity, basaltic lava that formed cinder cones. Cinder cones form when gas-charged frothy blobs of basalt magma erupt as an upward spray, or lava fountain. The ejected lava blobs cool and fall back to the ground, accumulating as relatively symmetrical, cone-shaped hills of dark volcanic rock. Small fragments of basalt are called 'cinders' and larger fragments, 'bombs.' When the gas pressure has been sufficiently released from the magma, lava oozes from the vent to form a lava flow. (Priest et al. 2001). South of Wupatki National Monument, two impressive lava flows, the Bonito Lava Flow and the Kana-A Flow, are exposed in Sunset Crater Volcano National Monument and adjacent Coconino National Forest.

In the monument, basaltic lava flows form the majority of volcanic rocks of the San Francisco Volcanic Field. In 2006, Geologist-in-the-Park Sarah Hanson identified as many as eight distinct basalt lava flows in Wupatki National Monument (Hanson 2006; Hanson 2007). Hanson's detailed examination found that each of the flows had a unique geochemical signature. On the GIS map included with this report, volcanic rocks of the San Francisco Volcanic Field were mapped based on magnetic polarity, isotopic age, and field relations (Billingsley et al. 2007A). Table 2 correlates Hanson's flows with those on the enclosed map.

Table 2. Volcanic lava flows in Wupatki National Monument.

Hanson's Flows	Corresponding Map Unit
Western Section	
Black Point Flow	Tbpb: Black Point Basalt
Citadel Flow	
Gem City Flow	Qb: Basalt flows
Arrowhead Sink Flow	Qmb: Basalt flows
Red House Basin Flow	
	Qmlp: Lava Point Basalt
Central Section	
Doney Mountain Flows	Qmp: Pyroclastic deposits Qmb: Basalt flows Qmbi: Basalt dike
Woodhouse Mesa Flow	Qwb: Woodhouse Mesa basalt flows
Eastern Section	
Wukoki Flow	Qwb: Woodhouse Mesa basalt flows
Grand Falls Flow	Qmcb: Merriam Crater basalt flows

In western Wupatki, the Black Point and Citadel basalt flows (map unit Tbpb), the oldest flows in the park (about 2.43 million years old), contain similar minerals and geochemistry (Hanson 2007). They represent two separate lobes from the same lava flow that entered the area from the southwest (Ulrich and Bailey 1987; Billingsley et al. 2007A). The dark-gray to black basalt contains plagioclase phenocrysts (larger, easily recognizable crystals set within a finer-grained groundmass) as large as 1 cm (0.4 in) and averages 12 m (40 ft) thick.

The Black Point Basalt (Tbpb) is an excellent example of inverted topography. Originally, the basalt flowed down tributary drainages, to the Little Colorado River that had eroded into the Moenkopi Formation. Less resistant to erosion than the hard basalt, the Moenkopi eroded more quickly from the surrounding area. Once deposited in valleys, the hard Black Point Basalt now caps West Mesa, South Mesa, East Mesa, and North Mesa in the western part of Wupatki National Monument. Today, these mesas rise approximately 12 to 15 m (40 to 50 ft) above the surrounding Antelope Prairie, White Mesa, and the Citadel Ruins area (Billingsley et al. 2007A).

The Gem City basalt flows (Qb) that outcrop along present stream drainages in the southwestern part of western Wupatki are some of the youngest flows in the monument. Their ages range from 770,000 to 220,000 years old (Ulrich and Bailey 1987; Billingsley et al. 2007A). Older basalt that forms the Arrowhead Sink and Red House Basin flows (Qmb) (1.38-0.83 million years old) is primarily exposed south of the monument, and shares similar southwest flow directions with the Black Point and Citadel basalt flows (Hanson 2007; Billingsley et al. 2007A).

South of the Visitor Center at Wupatki National Monument, Woodhouse Mesa basalt forms black cliffs rising above the red sediments of the Moenkopi Formation. The Woodhouse Mesa Flow (Qwb) and Wukoki Flow (Qwb) are geochemically distinct, but both are mapped as the (0.87-0.79 million year old) basalt flows of Woodhouse Mesa (Billingsley et al. 2007A). The basalt contains phenocrysts of olivine, clinopyroxene, and plagioclase. Field evidence indicates that the basalt flowed into the monument from the south.

Several flows combine to form the Doney Mountain Flow (Qmp, Qmb, Qmbi) in the south-central part of the monument. Doney Mountain is an elongated north-trending cinder cone that formed about 68,000 to 70,000 years ago, when a fissure eruption opened along the Doney Mountain Fault, which is within the boundaries of the monument. Two basalt flows erupted from Doney Mountain and flowed about 0.8 km (0.5 mi) downhill toward the current location of the Visitor Center. The principal unit in the Doney Mountain Flow consists of up to 92 m (300 ft) of dark-gray to red-brown pyroclastic deposits, (Qmp) that form 5 small cinder cones at the south-central border of the monument and 17 fissure vents that parallel the trend of the Doney Mountain Fault (Billingsley et al. 2007A).

The youngest basalt flow in Wupatki National Monument is the Grand Falls Flow (Qmcb) (Moore and Wolfe 1976; Hanson 2007; Billingsley et al. 2007A). About 19,000 years ago, lava flowed from Merriam Crater, located 17.5 km (11 mi) southeast of the map area, and formed a lava dam across the Little Colorado River canyon at the east edge of the monument. Stream flow diverted around the north side of the basalt flow, and then returned to its 60-m-(200-ft)-deep canyon, at what is now called Grand Falls (Moore and Wolfe 1976; Billingsley et al. 2007A). Currently, the Little Colorado River forms a small rapid called Black Falls as it flows over the Merriam Crater basalt.

Cinders and Sinagua Culture

Ground cover of black, gray, and red cinders occurs over large areas near Wukoki Ruin; on the slopes of Woodhouse Mesa, near Wupatki Ruin and the Visitor Center; and in western Wupatki National Monument on West Mesa, South Mesa, and East Mesa (Billingsley et al. 2007A). Southwesterly winds have shaped the deposits into dunes (Qdc) and sand sheets (Qsc).

Cinders and ash from the Sunset Crater eruption have long played a prominent role in the archaeology of the

Sinagua culture in Wupatki National Monument. In the early-to-mid 12th century (approximately 1130-1160 CE), several generations after the initial eruption, the Wupatki area experienced its greatest population increase (Noble 1991; Hooten et al. 2001). One reason for this population growth, proposed in 1932, could be that the water-retention capacity of the cinders allowed previously unfertile land to be farmed (Colton 1932; Hooten et al. 2001). It was thought that, for this to happen, the Sunset Crater eruption must have been responsible for the cinders at Wupatki National Monument. Comparison between the cinders at Wupatki National Monument and those known to have originated from the Sunset Crater eruption did not occur until 2001 (Hooten et al. 2001).

Hooten and others (2001) found two types of cinders in Wupatki National Monument. Each type came from a very different source. The most abundant type of cinder is a black, glassy cinder exposed over much of the southern end of the monument. The geochemical signature of this black cinder matches the geochemistry of cinders from Sunset Crater, thus proving that the cinders had been blown into the monument area approximately 1,000 years ago. The eruption deposited a minimum of 5 to 10 cm (2 to 4 in) of ash over the entire Wupatki National Monument area, a thickness ideal for a water-retaining mulch (Hooten et al. 2001).

The second variety of cinder is a red, oxidized tephra (pyroclastic material ejected by an explosive volcanic eruption) limited to the area around Doney Mountain. These cinders are geochemically distinct from the Sunset Crater material and represent an earlier phase of volcanic activity in the monument region (Hooten et al. 2001).

Surficial Features

Earthcracks and Sinks

Pleistocene (and perhaps even Holocene) east-to-west extensional (pull-apart) stress fractured the bedrock beneath Wupatki National Monument, and opened earthcracks along regional joint fractures. As mentioned in the Geologic Issues section, earthcracks may be 150 m (500 ft) deep (fig. 8). The cave mentioned at the scoping meeting in 2001 referred to one of these large, vertical earthcracks, which was entered by spelunkers (Paul Whitefield, NPS North Central Arizona National Monuments, Natural Resource Specialist, written communication, January 5, 2011).

In the western third of the monument, water percolating through fractured Kaibab Formation limestone (map unit Pkh) has dissolved some of the carbonate rock to form sinks and sinkholes. The most notable sink in the monument is the roughly circular Citadel Sink, that measures 152 m (500 ft) by 198 m (650 ft) (inside cover). Sinks also exist at Arrowhead Sink, along the southern border of the monument, and in the Red House Basin, located in the Coconino National Forest south of the monument (Billingsley et al. 2007A; U.S. Geological Survey Wupatki Southwest topographic quadrangle).

Blowholes

The Sinagua people, like today's visitors, probably were intrigued by the holes in the ground that blew air out and sucked air back in. They likely noticed that air coming from the holes was cool in summer and warm in winter. Archaeologists have noted that many blowholes are associated with habitation sites of prehistoric people. This association is probably not a coincidence (National Park Service 2007B).

The blowholes in Wupatki National Monument connect to underground fracture systems in the Kaibab Formation. The extent and design of these fracture systems, however, is not well known. The amount of air blowing in and out of the blowhole near Wupatki Pueblo suggests that a substantial amount of air space exists in the area's subsurface fracture system. Researchers estimate that the fracture system contains 200 million cu meters (7 billion cu ft) of air space, which is equivalent to a tunnel measuring 50 m (165 ft) wide, 50 m (165 ft) high, and 80 km (50 mi) long (National Park Service 2007B). Air exiting a blowhole may reach velocities of up to 56 km per hour (35 mi per hour) (Blyth 1995).

Air temperature and pressure drive the operation of the blowholes. Air travels from areas of high density to areas of lower density. Cool night and early morning air is denser than the warmer air in the blowhole system, so cool air rushes into the holes. The density difference diminishes as the outside air heats up during the day. Eventually the density of the outside air equals the density of the underground air, and air flow into the blowhole stops. If the outside air continues to warm, the cooler subsurface air begins to rush out of the blowhole (National Park Service 2007B).

Atmospheric pressure also affects the blowholes. Air flows from high pressure to low pressure, so if a low pressure system moves into the area, the pressure of the underground air will be higher and air will flow out of the blowhole (like air rushing from a tire when the tire valve is pushed). If a high pressure system moves into the area, the opposite will occur.

Whether air will be flowing into or out of a blowhole at any specific time is difficult to determine, due to the complex interactions between temperature and pressure. One of the more popular blowholes in the monument is found at the end of the Wupatki Pueblo interpretive trail (fig. 9).

Stream Terraces

Holocene and Pleistocene terrace deposits of three different ages (mapped as Qg1, Qg2, and Qg3) are exposed in Wupatki National Monument. Most terraces lie east of the Black Point Monocline and Doney Mountain Fault (the region known as the Wupatki Basin) (Billingsley et al. 2007A). The youngest terrace deposits (Qg1) in the Wupatki Basin lie along the north-to-northeast trending Doney Mountain Wash and

Deadman Wash. These arroyos contain ephemeral streams that drain to the Little Colorado River. Younger terrace deposits may be eroded by flash floods or sheet wash erosion.

The Qg1 terrace benches form 1 to 3.6 m (3 to 12 ft) above stream-channel (Qs) deposits, and 1.5 to 2 m (4 to 6 ft) above Little Colorado River channel and flood-plain (Qf) deposits (Billingsley et al. 2007A). Older terrace benches near the eastern border of the monument (Qg2 and Qg3) rise 4.5 to 12 m (15 to 40 ft) above modern streambeds, and about 43 m (140 ft) above the Little Colorado River (Billingsley et al. 2007A).

The terrace deposits contain similar lithology, primarily unconsolidated silt, sand, pebbles, cobbles, and some boulders from local Permian and Triassic formations, as well as rounded basalt clasts from the San Francisco Volcanic Field. The clasts are unconsolidated in Qg1 and Qg2, but clasts in Qg3 are partly cemented by calcite and gypsum cement.

Terrace and fluvial deposits have been used to reconstruct the landscape evolution of the Little Colorado River drainage basin in Wupatki National Monument (Blyth 1995). Intermediate and older terrace deposits (Qg2 and Qg3) correspond to once-continuous floodplain deposits that capped the Triassic Moenkopi Formation from the late Pliocene to late Pleistocene (see the Geologic History section). With uplift of the Colorado Plateau, the Little Colorado River eroded vertically through these floodplain deposits, forming a terraced landscape.

Springs and Seeps

Water is as precious a resource today in Arizona as it was when the Sinagua occupied Wupatki National Monument. In the eastern part of the monument, east of the Black Point Monocline, groundwater seeps from interbedded sandstones and shales of the Triassic Moenkopi Formation. At Wupatki Spring, near Wupatki Ruin, groundwater emerges from young alluvial fan deposits (Qa1) that overlie the Shnabkaib and Wupatki Members of the Moenkopi Formation (TRmss and TRmw) (Billingsley et al. 2007A). Heiser Spring, located in Heiser Wash in the southern part of the monument, discharges groundwater from the Wupatki Member as well. Discharge rates are low at Heiser Spring, ranging from 1.8 to 1.9 liters per minute (0.48 to 0.50 gallons per minute) (Blakemore 2003). Flow continues throughout the year, and collects in concrete spring boxes. Throughout their existence, the springs have been a welcomed resource for both humans and wildlife.

Recharge begins in the higher elevations to the west and southwest of the monument. Precipitation percolates through thin regolith and volcanic rocks of the San Francisco Volcanic Field, and through fractures in underlying Paleozoic strata (Blakemore 2003).

Geologic Structures

The northeast-to-southwest trending Black Point Monocline and associated Doney Mountain Fault, which parallels the monocline, form the principal geologic structures in Wupatki National Monument. Typical of the many monoclines on the Colorado Plateau, the Black Point Monocline extends for kilometers, beginning north of Gray Mountain and disappearing beneath basalt flows in the San Francisco Volcanic Field, south of the monument (Billingsley et al. 2007A; Billingsley et al. 2007B). The monocline forms a broad, 1.6 km-wide (1 mi) structure, in which relatively horizontal strata on the west limb of the monocline fold over the Doney Mountain Fault, tilting between 7° and 12°, before returning to relatively flat-lying beds in the Wupatki Basin, east of the monocline (figs. 4, 13, and 20) (Huntoon 2003; Billingsley et al. 2007A; Billingsley et al. 2007B).

Fault movement on the Doney Mountain Fault has uplifted the older Permian limestone relative to the younger Triassic sandstones and shales. The prominent Doney Cliffs separate the uplifted Kaibab Formation from the Triassic Moenkopi Formation in Wupatki National Monument. (Billingsley et al. 2007A).

The Doney Mountain Fault began as a reverse fault (fig. 21) caused by the collision between the North American plate and the tectonic plate to the west, called the Kula plate, approximately 80 to 75 million years ago. The compressive energy from the collision reactivated much older, high-angle Precambrian faults that resulted in reverse faults like the Doney Mountain Fault, as well as the great monoclinal folds on the Colorado Plateau. This same collision also produced the Rocky Mountains.

In late Pliocene time, less than 3 million years ago, the crust was pulled apart in the Wupatki National Monument area. This extensional stress caused normal fault movement (fig. 21) along the same ancient fault planes that had been reactivated during the collision that caused the reverse faulting 80 to 75 million years ago. Normal fault movement along the Doney Mountain Fault dragged down the strata along the Black Point Monocline, accentuating the dip of the rock layers (Billingsley et al. 2007A).

In addition to the prominent Black Point Monocline and Doney Mountain Fault, Wupatki National Monument contains northwest- and north-trending normal faults and structural basins, called grabens, that developed due to east-west extensional stress since the Pleistocene (2.6 to 0.01 million years ago) (Billingsley et al. 2007A). The majority of these younger, normal faults within Wupatki National Monument trend to the northwest and may be relatively young. For example, these faults vertically offset some basalt flows that are approximately 510,000 years old. The association of these faults in the Citadel Wash area suggests that graben development began less than 500,000 years ago (Billingsley et al. 2007A). Extension has also contributed to the relatively recent earthcracks in the monument.

Recent extension along the edge of the Colorado Plateau may also be responsible for the apparent horizontal offsets along the Doney Mountain Fault, and the change of direction of the Black Point Monocline. In the northern part of the monument, the Black Point Monocline turns abruptly to the southwest, along short, staggered, northwest-trending, normal faults (see Digital Geologic Data Overview). From Doney Mountain to north of Antelope Wash, the Doney Mountain Fault is also offset by northwest-trending faults (Billingsley et al. 2007A).

In summary, the structures in Wupatki National Monument reflect processes primarily at work during three tectonic episodes during Earth's history. First, compression about 80 to 75 million years ago caused reverse faulting (Doney Mountain Fault) and the development of the Black Point Monocline. Approximately 3 million years ago, crustal extension reversed the movement on the Doney Mountain Fault. Most recently, continued east-west extension has generated northwest-trending normal faults, earthcracks, and sinks in the monument.

Paleontological Resources

Throughout the Colorado Plateau, fossils can be found in the Permian Kaibab and Toroweap Formations, and in the Triassic Moenkopi Formation. Limestones in the Paleozoic formations contain mostly marine invertebrate remains. The primary fossils in the Moenkopi Formation outside of the monument include vertebrate body fossils and trace fossils (trails, tracks, and burrows of organisms) of fish, amphibians, and reptiles (Tweet et al. 2009).

No fossils have been documented from the limited exposures of the Toroweap Formation in Wupatki National Monument. In Wupatki, the Toroweap consists of a single cliff-forming sandstone, but in Grand Canyon National Park, the Toroweap includes three members. One of these members, the Brady Canyon Member, contains open-marine invertebrate fossils in its limestone beds, including brachiopods, bryozoans, crinoids, and horn corals (Turner 1990).

The Kaibab Formation contains an abundant array of fossils of marine organisms, including foraminifera, sponges, corals, bryozoans, brachiopods, bivalves, cephalopods, gastropods, scaphopods, trilobites, ostracods, crinoids, conodonts, algae, and trace fossils (Hopkins 1990). The formation also contains chondrichthyan (cartilaginous fish) teeth, spines, dermal denticles, and ray-finned fish teeth and tooth plates (Hunt et al. 2005; Tweet et al. 2009).

In the Wupatki National Monument area, a few brachiopods, trilobites, and crinoids have been collected from sandy limestone in the Fossil Mountain Member of the Kaibab Formation, and sponges and bryozoans have been collected from chert nodules and beds. Outside of the boundaries of the monument, fossils common to the Fossil Mountain Member include sponges, rugose corals, bryozoans, brachiopods, bivalves, trilobites, crinoids, echinoids, and shark teeth.

Calcareous sandstone in the top part of the Harrisburg Member contains scattered mollusk fossils (Billingsley et al. 2007A). Gastropods and scaphopods are the most common fossils found in the region, but the unit also contains bryozoans, brachiopods, bivalves, cephalopods, trilobites, crinoids, conodonts, and shark teeth. In Wupatki National Monument, a gastropod (genus *Bellerophon*) and an unidentified mollusk have been collected and catalogued from the Kaibab Formation. These now reside in the Walnut Canyon National Monument collections (Tweet et al. 2009).

The Museum of Northern Arizona in Flagstaff houses the Moenkopi Formation fossils collected from Wupatki National Monument. The specimens include vertebrate trace fossils, an ammonite fragment, and fragments of preserved plants. *Chirotherium* ("hand beast") tracks, named because the foot print resembles a human hand, have been found within the monument (McCormack 1989; Tweet et al. 2009). Chirotheriid tracks in the Wupatki Member of the Moenkopi consist of four toes, three in front and one to the rear, that are 1 to 3 cm (0.4 to 1.2 in) long (McCormack 1989). Paleontologists believe these trackways may represent an archosaur, an early predatory ancestor of the dinosaurs. In recent years, geosciences interns in the GeoCorps America program have also discovered amphibian swimming tracks, an archosauromorph-like trackway, and tetrapod tracks within the monument (Tweet et al. 2009). The group of archosauromorphs includes crocodilians, dinosaurs, and birds.

Although Cenozoic fossils have not been found in bedrock units in Wupatki National Monument, Cenozoic rocks and sediments within approximately 100 km (60 mi) of the monument have yielded isolated bones of large mammals, including sloths, proboscideans (elephants), equids (horses), bison, and camelids (Tweet et al. 2009). Mammoth remains have been reported from the Wupatki National Monument vicinity (Agenbroad and Mead 1989). In addition, pollen and plant material discovered from as many as 22 packrat middens in the monument have helped to reconstruct the late Pleistocene and Holocene ecology and climate of the southwestern United States (Tweet et al. 2009).

Known for its archaeology, Wupatki National Monument also contains fossils among its cultural resources. Petrified wood and chert were used by prehistoric people to make tools and weapons. Parrot bones and shell jewelry have been found among the Wupatki ruins (Tweet et al. 2009). The Western Archeological and Conservation Center collections contain a number of artifacts constructed from fossils or petrified wood, such as a chert or fossil sponge projectile point, a petrified wood fragment from Wupatki Ruin that was used as a bead, and petrified wood projectile points from Nalakihu and Citadel Ruins (Tweet et al. 2009).

A detailed summary of the fossils collected from Wupatki National Monument and the surrounding area may be found in Tweet et al. (2009) (an internal NPS document).

The 2009 Paleontological Resources Preservation Act directs the National Park Service to manage and protect paleontological resources using science-based principles and expertise. It also calls for inventory, monitoring, and scientific and educational use of fossil resources. Protection of associated location information is also required, as fossils are non-renewable resources. The National Park Service and other federal land management agencies are currently (June 2011) developing joint regulations associated with the Act.

Santucci et al. (2009) outlines potential threats to in situ paleontological resources and suggested monitoring "vital signs" to qualitatively and quantitatively assess the potential impacts of these threats. Paleontological vital signs include: erosion (geologic factors); erosion (climatic factors); catastrophic geohazards; hydrology/bathymetry; and human access/public use. Santucci et al. (2009) also presents detailed methodologies for monitoring each vital sign.

Cultural Connections to Geology

The geology of Wupatki National Monument and vicinity helped the Sinagua carve a life out of the desert of the southern Colorado Plateau. With exposure to surface conditions, the Moenkopi Formation fractured and broke along flat edges, making excellent building blocks for Sinagua pueblos (figs. 17, 22). Erosion and weathering of Moenkopi Formation rocks produced clay, which was used as mortar to hold the pueblo walls together. Chert from river gravel deposits was used for arrow heads and cutting tools (fig. 7). Volcanic ash and cinders provided valuable, moisture-retaining mulch for crops (fig. 19).

The natural springs in the monument provided water to the early inhabitants and wildlife. About 800 years ago, Ancestral Puebloan peoples even built catchment basins below the springs.

Blowholes may have also been important to early inhabitants of the region. Wupatki Pueblo was built near a blowhole, as were many large pueblo sites in northern Arizona (National Park Service 2007B). The Hopi considered these openings to be the source of the wind and home of the wind god, Yaponcha. Prehistoric people may have built their homes near blowholes for spiritual reasons. They may also have used blowholes to predict the weather. For example, when atmospheric pressure is low, air blows out of the blowholes and there is a chance of rain. The Sinagua may have also appreciated the cool air from the blowholes in the summer and the warm air in the winter (National Park Service 2007B).

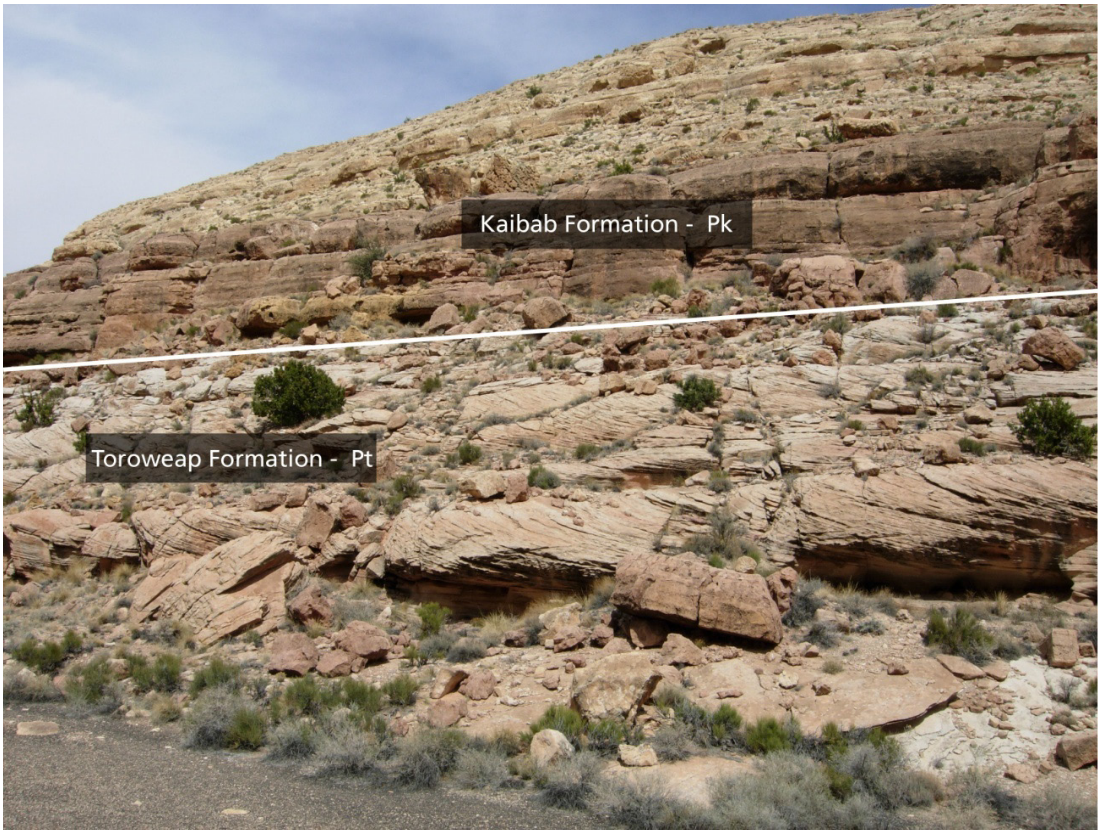


Figure 15. Contact between the Toroweap and Kaibab Formations. Notice the typical cross bedding (angled layers) in the Toroweap. National Park Service photograph by Paul Whitefield (NPS North Central Arizona National Monuments).

Figure 16. Exposure of the Kaibab Formation. The relatively horizontal strata forming the cliffs are the Fossil Mountain Member of the Kaibab Formation (map unit Pkf) and the beveled slope is the Harrisburg Member (map unit Pkh). The view is towards the west at Cathedral Canyon near the Doney Mountain Fault. U.S. Geological Survey photograph by G.H. Billingsley in 2004; extracted from from Billingsley et al. (2007A).

Figure 17. The Triassic Moenkopi Formation in Wupatki National Monument forms distinctive reddish slopes commonly covered by eroded slabs of red sandstone. Moenkopi sandstone was used by Sinagua Indians to build their pueblos and other structures. The Permian Kaibab Formation underlies the Moenkopi, while cinders (black) fill valley floors and depressions. The contact between the Moenkopi and the Kaibab is an unconformity (white line). National Park Service photograph by Paul Whitefield (NPS North Central Arizona National Monuments).

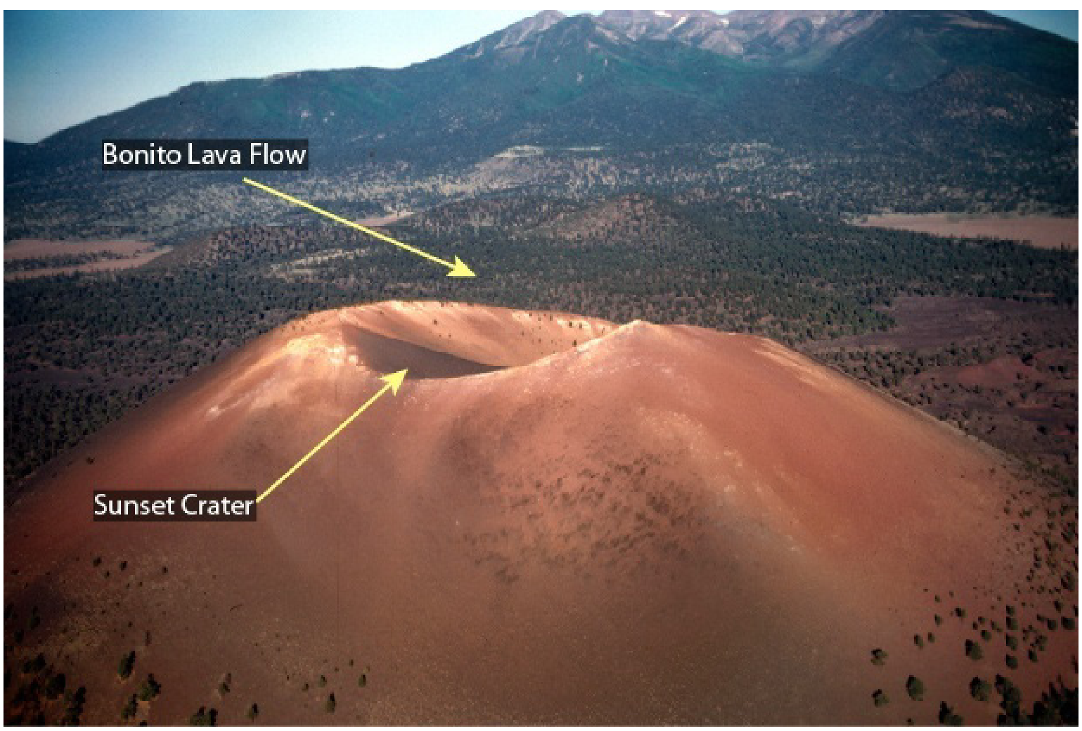


Figure 18. Aerial view of Sunset Crater cinder cone in Sunset Crater Volcano National Monument, viewed from the east. Sunset Crater stands 340 m (1,100 ft) tall. Its crater measures 122 m (400 ft) deep and 686 m (2,250 ft) from rim to rim. The dark landscape beyond the crater is part of the Bonita Lava Flow. U.S. Geological Survey photograph by Edwin McKee, available at http://libraryphoto.cr.usgs.gov/htmllib/batch57/batch57j/batch57z/med00711.jpg, accessed December 22, 2010.

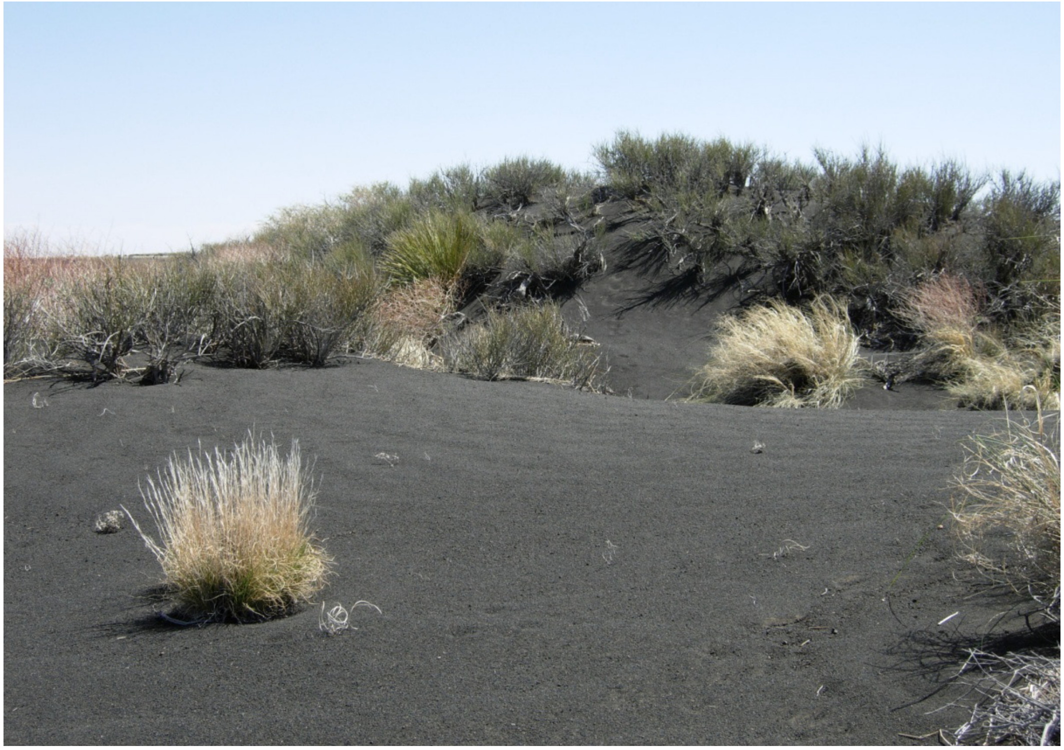


Figure 19. Eolian cinder dune (Qdc) in Wupatki National Monument, displaying wind ripples. The black cinders may acted as a moisture-holding mulch for crops, possibly influencing people to move to the Wupatki area around CE 1100. National Park Service photograph by Paul Whitefield (NPS North Central Arizona National Monuments).

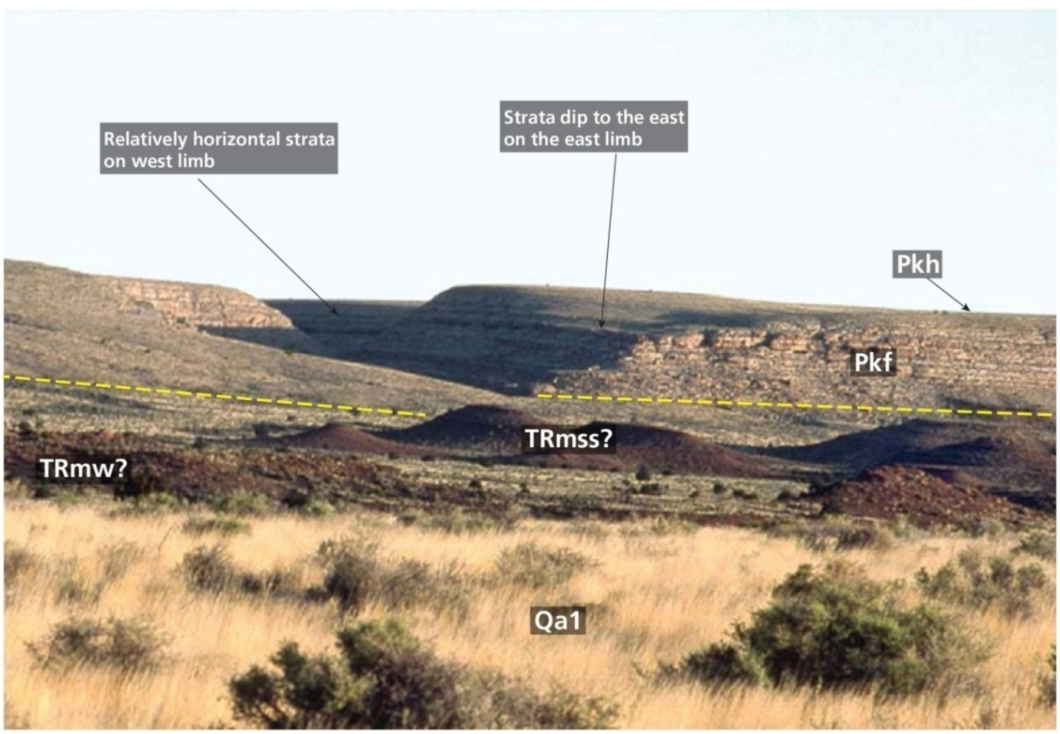


Figure 20. A view of Black Point Monocline and Doney Mountain Fault, looking west at Antelope Wash, which has carved a canyon through the monocline. Strata on the west limb of the monocline are relatively horizontal while the strata on the east limb tilt to the east. The dashed yellow lines approximate the surface trace of the Doney Mountain Fault that offset the monocline. The Harrisburg Member of the Kaibab Formation (Pkh) caps the monocline. The steep cliffs are composed of the Fossil Mountain Member of the Kaibab Formation (Pkf). The dark hills in the center of the photograph may be composed of the Shnabkaib Member of the Triassic Moenkopi Formation (TRmss) that overlies the Wupatki Member of the Moenkopi Formation (map unit TRmw). Grasses and sagebrush grow on alluvial fan deposits (Qa1) in the foreground. National Park Service photograph extracted from Billingsley and others (2007A).

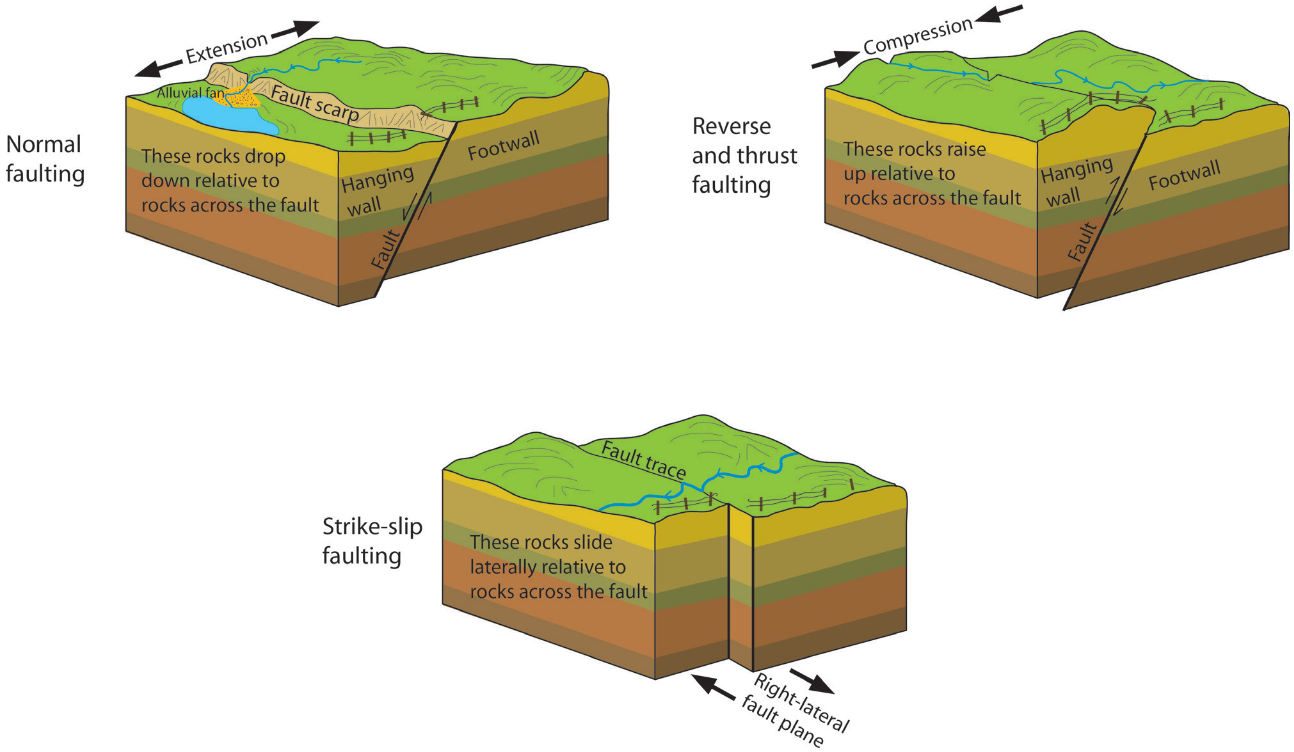


Figure 21. Schematic graphics illustrating different fault types. As a way of orientation, if you walked down a fault plane, your feet would be on the "footwall," and the rocks over your head would form the "hanging wall." In a normal fault the hanging wall moves down relative to the footwall. Normal faults result from extension (pulling apart) of the crust. In a reverse fault the hanging wall moves up relative to the foot wall. A thrust fault is similar to a reverse fault only the dip angle of a thrust fault is less than 45°. Reverse faults occur when the crust is compressed. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. If the movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. If movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Figure 22. Pueblos in Wupatki National Monument were often constructed around rock outcrops, taking advantage of the natural heating and cooling effects of the rocks. In Wupatki Pueblo, the Moenkopi Formation is also used for building blocks. National Park Service photograph by Paul Whitefield (NPS North Central Arizona National Monuments).

Geologic History

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

The geologic features and processes at Wupatki National Monument record a geologic history that spans approximately 300 million years. Permian rocks (figs. 6 and 23) are the oldest rocks exposed in Wupatki National Monument. However, the 1,840 million year old Elves Chasm pluton, the oldest rock unit known in the southwestern United States, is exposed in Grand Canyon National Park to the north. Prior to 1,400 million years ago, during the Precambrian, the southwestern continental margin of proto-North America may have looked like today's western Pacific, with numerous offshore volcanic islands, and oceanic crust being subducted beneath the Asian continent (Hoffman 1989; Pallister et al. 1997). Precambrian subduction compressed the ocean basin sediments and attached them to the proto-North American continent (Conway and Silver 1989; Hoffman 1989). By 1,400 million years ago, most of present-day Arizona had been added to the proto-North American continent (fig. 24).

Cambrian rocks in Arizona record a major advance of the sea into the area about 520 million years ago, at the initiation of the Paleozoic era (fig. 25). Throughout the Paleozoic, epicontinental seas advanced (transgressed) and retreated (regressed) across Arizona, depositing sediment on the sea floor that would eventually lithify into thick layers of limestone and sandstone.

Permian Period (299-251 million years ago)

As the Paleozoic era came to a close, subduction of the oceanic plate beneath the proto-North American continent caused west-to-east directed thrust faulting that added continental shelf and slope rocks to the western margin. The South American tectonic plate collided with the proto-North American plate and closed the proto-Gulf of Mexico ("proto" refers to a landmass or ocean that existed prior to the current feature). The collision caused the uplift of the northwest-southeast-trending Ancestral Rocky Mountains in Colorado, the northeast-southwest-trending Sedona Arch in central Arizona, and the Mogollon Rim, an uplift in east-central Arizona. South and west of the Mogollon Rim, an offshore continental shelf became an ideal environment for carbonate production in Arizona (Blakey 1980; Peterson 1980).

About 275 million years ago, the western margin of Pangaea, the supercontinent that formed as the globe's landmasses sutured together, was oriented along the equator (Biek et al. 2000; Morris et al. 2000). A dry, high pressure climatic belt prevailed in this western part of Pangaea, and resulted in restricted marine, evaporitic conditions over much of the continental shelf and coastal areas (Peterson 1980).

The high-angle, sweeping sets of cross-beds in the early Permian (Cisuralian) Coconino Sandstone record the southerly advance of an eolian sand sea (erg) composed of exceptionally large sand dunes (Middleton et al. 1990). The Coconino Sandstone is exposed on the Colorado Plateau, but is not exposed in the monument (Billingsley et al. 2007A). An island arc system lay to the west, where the margin of proto-North America continued to be compressed against the subducting oceanic plate. Northeast of Wupatki National Monument, the dune sand mingled with coarser sediment eroding from the Ancestral Rocky Mountains (Peterson, 1980).

The Permian Toroweap (Pt) and Kaibab Formations (Pkh and Pkf) represent an overall transgressive episode in which the sea advanced from the west to drown the dune field of the Coconino Sandstone. Wave erosion from the advancing sea beveled the Coconino sand dunes and redistributed the sand into the flat-bedded or low-angle cross-bedded sandstone of the Toroweap Formation (fig. 15) at Wupatki National Monument (Turner 1990; Billingsley et al. 2007).

The regionally extensive Kaibab Formation contains a myriad of rock types and fossils that attest to the ancient seaway (called the Kaibab Sea) that covered most of Arizona in the Permian (fig. 26). The west-to-east transition of fossiliferous limestone to dolomitic mudstone and sandstone in the Fossil Mountain Member represents an overall transgressive phase of deposition (Cheevers and Rawson 1979; Cheevers 1980; McCormack 1989; Hopkins 1990). At Wupatki National Monument, the open-marine fauna, sandy limestone, and minor amounts of dolomite represent subtidal, shallow-marine environments (Hopkins 1990).

The overlying Harrisburg Member of the Kaibab Formation (Pkh) records the westward regression, or retreat, of the Kaibab Sea. Massive gypsum deposits in the unit, especially in western Arizona and southern Nevada, formed in hypersaline basins or lagoons bordered by coastal mudflat and sabkha environments (Hopkins 1990). In the Wupatki area, molluscan fauna, gypsum, and sandy limestone represent restricted, shallow-marine environments that developed as the sea retreated westward.

The boundary between the Permian and Triassic periods (and Paleozoic and Mesozoic eras) is marked by the most severe mass extinction event in the last 542 million years.

Up to 96% of marine species, including some of those found in the Permian bedrock of Wupatki National Monument, and 70% of terrestrial vertebrates, may have perished (Raup 1991). The only known mass extinction of insects occurred at this time. The loss of biodiversity is recorded in the extinction of 57% of all families and 83% of all genera. Thousands of species of insects, reptiles, and amphibians died on land while in the oceans, rugose corals and the once prolific trilobites vanished, as did many species of snails, urchins, sea lilies (crinoids), and some fish. Five million years later, at the dawn of the Mesozoic Era, the oceans' chemistry began evolving into the chemistry of modern oceans, and on land, the first mammals and dinosaurs evolved.

Triassic Period (251-200 million years ago)

From the middle of the Paleozoic through the Mesozoic, the western margin of North America was an active plate margin where dense, oceanic crust subducted beneath lighter continental crust. At an active plate tectonic margin, pressure and heat from convergence melts some of the asthenosphere and generates magma above the downgoing (subducting) plate. Magma rises to form plutons and active volcanoes, such as those found in today's Cascade Range. During the Mesozoic, an arcuate-shaped 'magmatic arc' (also called a 'volcanic arc') formed along the western margin of North America (figs. 27, 28) (Oldow et al. 1989; Christiansen et al. 1994; Dubiel 1994; Lawton 1994; Peterson 1994). Some of the magma erupted onto the surface, while some of the magma solidified beneath the surface to form the plutons and batholiths of the Sierra Nevada, some of which are exposed in Yosemite National Park.

During the Triassic, the supercontinent Pangaea reached its greatest areal extent. All the continents had converged to form a single landmass that was located symmetrically about the equator (Dubiel 1994). As the Kaibab Sea withdrew, fluvial, mudflat, sabkha, and shallow marine environments of the Moenkopi Formation developed in what is now the Great Basin region of the United States (fig. 27) (Stewart et al. 1972; Christiansen et al. 1994; Morales 2003). The fossilized plants and animals in the Moenkopi are evidence of a climate shift to a warm tropical setting that may have experienced monsoonal, wet-dry conditions (Stewart et al. 1972; Dubiel 1994).

In the Wupatki National Monument area, reddish mudstones interbedded with sandstones and sedimentary structures, such as small-scale ripple marks, salt crystal casts, and rain drop impressions in the Wupatki Member (TRmw), suggest deposition in near-shore, shallow marine and tidal flat environments. The cross-bedding, scour marks, and channel-fill features in the massive sandstone in the overlying Shnabkaib Member have been interpreted as eolian deposits interbedded with ephemeral stream systems (McCormack, 1989; Billingsley et al. 2007A). Features such as cusp-shaped ripple marks, trough-shaped cross-bedding, which formed when sand filled in stream channels, as well as tracks of reptiles, confirm continued fluvial deposition in the Holbrook and Moqui Members (TRmhm) (Blakey 1988; Billingsley et al. 2007A).
A regional unconformity separates the Moenkopi Formation from the Upper Triassic Chinle Formation (TRcp and TRcs). Terrestrial plants (such as those preserved in Petrified Forest National Park), fresh water invertebrate fossils, and lake sediments attest to continued terrestrial deposition during Chinle time.

Jurassic Period (200-145 million years ago)

Any rocks deposited during the Jurassic and Cretaceous periods have been eroded from the Wupatki National Monument landscape. In the Jurassic, the Farallon Plate and the North American Plate converged at an oblique angle to one another, and created a northwest-trending volcanic island arc along the southwestern margin of North America, southwest of today's Colorado Plateau and Mogollon Rim in Arizona (fig. 28) (Tosdal et al. 1989). Locally, crustal extension occurred within the volcanic arc. Quartz-rich eolian sand blew into the region from extensive dune fields located on the southern Colorado Plateau (Bilodeau et al. 1987; Tosdal et al. 1989). Voluminous pyroclastic rocks and volcanic flows erupted across most of the Sonoran Desert region of Arizona during the Early Jurassic. For approximately 35 million years, into the Middle and perhaps early Late Jurassic period, explosive volcanism continued to dramatically modify the southern Arizona landscape.

In the Middle Jurassic (175-161 million years ago), Wrangellia, a collection of islands in the Pacific, collided with North America, initiating volcanic activity along the west coast, from Mexico to Canada (fig. 28). The collision resulted in west-to-east directed thrust faulting that formed mountains in Nevada. A shallow sea encroached into Utah from the north. About 165 million years ago, catastrophic volcanic eruptions occurred in southeastern Arizona, producing bowl-shaped depressions called calderas. Calderas form when overlying rocks collapse into an emptied magma chamber. Calderas in the southern Huachuca and Dragoon Mountains record this violent volcanic activity. Coronado National Memorial in southeastern Arizona, for example, lies within the Montezuma caldera, estimated to be 16 to 18 km (10 to 11 mi) in diameter (Lipman and Hagstrum 1992).

By mid-Late Jurassic time, approximately 150 million years ago, strike-slip faulting (fig. 21) related to the opening of the Gulf of Mexico generated large-scale, high-angle, northwest-trending faults in southern Arizona (Tosdal et al. 1989). A large strike-slip fault zone, called the Mojave-Sonora megashear, truncated the southwestern continental margin of North America. Regional extension stretched the crust of southeastern Arizona, opening a series of pull-apart basins (Kluth 1983; Elder and Kirkland 1994; Anderson and Nourse 2005; Anderson and Silver 2005; Stevens et al. 2005). The northwest-southeast trending megashear accommodated approximately 800 to 1,000 km (500 to 600 mi) of displacement (Anderson and Silver 2005; Haenggi and Muehlberger 2005).

At the end of the Jurassic, volcanism waned and finally ended. Rift (pull-apart) tectonics formed the Bisbee trough that extended into southeastern Arizona from the Gulf of Mexico.

Cretaceous Period (145-65 million years ago)

During the Early Cretaceous in southern Arizona, rifting along the northwest-southeast-trending Bisbee basin dominated the tectonic regime. Rather than accreting land to the continent, tectonic forces were pulling the land apart. Rifting tilted the Mogollon slope towards the northeast.

Approximately 90 million years ago, in the Late Cretaceous, renewed oceanic-continental plate convergence along the western margin of North America caused sedimentary strata to be folded and thrust eastward over Precambrian basement rocks in a mountain-building episode called the Sevier Orogeny. Rising mountains in the developing fold-and-thrust belt extended from Canada to Mexico. Abundant sediment was eroded from the mountains and deposited in an adjacent basin (called a 'foreland basin').

The Gulf of Mexico continued opening as South America moved away from North America, and seawater encroached northward into the subsiding basin. Marine water also began to transgress southward from the Arctic region. The seas advanced and retreated many times during the Cretaceous until a seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 5,000 km (3,000 mi) (Kauffman 1977). Northeastern Arizona formed part of the western border of this Western Interior Seaway, the most extensive interior seaway ever recorded in North America (fig. 29).

Approximately 75 million years ago, the Western Interior Seaway began to retreat, following the advent of the Laramide Orogeny. Unlike the steeper angle of subduction thought to be responsible for the thrust faulting of the Sevier Orogeny, the Laramide Orogeny involved relatively low angle subduction (fig. 30). Because the angle was so low, the compressive stress was transferred farther inland. Reverse faults transported deeply buried Precambrian rock units to the surface, where they are now exposed in the Rocky Mountains. The Laramide Orogeny, which lasted from roughly 75 to 35 million years ago (Late Cretaceous to the Eocene epoch in the Paleogene), is not only responsible for the modern Rocky Mountains, but also for most of the copper, silver, and gold ore deposits in the southwestern United States (Pallister et al. 1997).

Paleogene and Neogene (Tertiary) Periods (65-2.6 million years ago)

At the beginning of the Cenozoic, about 1.6 km (1 mi) of terrestrial and marine rock layers covered the Permian Kaibab Formation (Billingsley 1989; Morales 2003). The Laramide Orogeny caused the uplift of the southwestern Colorado Plateau, and subsequent erosion of most of the Mesozoic strata from the Wupatki area. North-flowing, sediment-choked streams dominated the landscape and covered parts of northern Arizona with 100 to 200 m (330 to 650 ft) of gravelly sediments.

The Laramide Orogeny also reactivated ancient, north-trending Precambrian faults. Reverse and thrust fault movement along these Precambrian fault planes horizontally shortened the western margin of North America (Marshak et al. 2000; Huntoon 2003). On the Colorado Plateau, compression during the orogeny resulted in east-dipping monoclines that overlie deep-seated, west-dipping reverse faults. The Black Point Monocline and Doney Mountain Fault formed during the orogeny. Intervening strata between monoclines were gently warped into broad, north-trending arches and basins. Subsequent erosion removed approximately 235 million years of geologic history, between the Triassic rocks and the late Pliocene or early Pleistocene Black Point Basalt, in Wupatki National Monument.

About 45 million years ago (Eocene epoch), plate movement along the west coast subduction zone slowed. As a consequence, deformation caused by plate convergence ceased in the Wupatki National Monument area (Dickinson 1981; Huntoon 2003).

Volcanism returned to Arizona approximately 26.9 million years ago (Oligocene epoch) when a large magma chamber formed beneath the Chiricahua Mountains of southeastern Arizona. When the overlying rock eventually ruptured, more than 417 cu km (100 cu mi) of magma blew out of the volcano and buried a region of at least 3,108 sq km (1,200 sq mi) under a thick blanket of ash and pumice. The roof of the magma chamber collapsed and produced the Turkey Creek Caldera (Pallister et al. 1997). This giant crater-like depression is preserved in Chiricahua National Monument (Graham 2009).

When subduction off the southwestern coast of North America ceased about 20 million years ago, volcanism waned in Arizona. The motion of the plates changed from compression to strike-slip, initiating the San Andreas Fault System and crustal extension that would result in the normal faulting that characterizes the Basin-and-Range province. During the Miocene-Pliocene epochs, the Colorado Plateau was uplifted as much as 3 to 4 km (1.8 to 2.5 mi) (Oldow et al. 1989).

About 6 million years ago (Miocene epoch), the San Francisco Volcanic Field, south of Wupatki National Monument, became a major volcanic center on the southwestern margin of the Colorado Plateau (Luedke and Smith 1991; Priest et al. 2001). Some geologists believe that a localized zone of melting, or "hot spot," in the mantle beneath Arizona, is responsible for the volcanism in the San Francisco Volcanic Field. Periodically, eruptions occur above this hot spot. Because the North American Plate moves slowly westward over this stationary source of magma, the most recent volcanoes, such as the Sunset Crater that erupted 1,000 years ago, are found in the eastern part of the volcanic field. Volcanic activity was almost continuous during the late Cenozoic, particularly in the Pliocene and Pleistocene.

The Colorado River began eroding the Grand Canyon about 5 million years ago (or less) (Spencer et al. 2001; Lucchitta 2003). By 3.8 million years ago (Pliocene epoch), the Colorado River had established its current course in the upper Lake Mead area, and by 1 million years ago (middle Pleistocene), it had carved its present path in the western Grand Canyon (Lucchitta and Jeanne 2001; Hamblin 2003; Lucchitta 2003). As the Colorado River incised into the Colorado Plateau, its tributaries did the same, including the Little Colorado River.

The siltstone, sandstone, limestone clasts, and conglomerate that cover the floor of an incised meander channel in Antelope Wash, west of Doney Mountain, probably were deposited in a Miocene or Pliocene channel that drained to the Little Colorado River (Breed 1969; Blyth 1995). Known as the Doney Channel, the former stream is approximately 13 km (8 mi) long, with a gradient that indicates flow was to the north. Carved into the underlying Kaibab Formation, Doney Channel sediments consist of clasts derived from the Kaibab Formation and from older gravel deposits southwest of Wupatki National Monument (Billingsley et al. 2007A).

Quaternary Period (2.6 million years ago to present day)

Pleistocene Epoch (2.6-0.0117 million years ago)

Approximately 2.4 million years ago, basaltic lava from the volcanic activity in the San Francisco Volcanic Field first reached Wupatki National Monument when two lobes of the Black Point Basalt (map unit Tbpb) flowed into the area. One lobe flowed northwest of the monument, forming Black Point, while the other lobe, which is referred to as the Citadel flow by Cooley (1962) and Hanson (2007), can be found on West Mesa, South Mesa, and East Mesa in Wupatki National Monument (Moore and Wolfe 1976; Billingsley et al. 2007A). Basalt flowed down tributary drainages to the Little Colorado River that had been eroded into the Moenkopi Formation. The surrounding sedimentary rocks of the Moenkopi Formation eroded more rapidly than the basalt, so that the topography became inverted. What were once valleys became mesas capped with the more-resistant basalt.

Basalt (QTb) also filled the ancestral Deadman Wash (Antelope Wash) drainage southwest of the Visitor Center, and approximately 1 million years ago, a basalt similar to the Black Point Basalt flowed north from an unknown source southwest of the monument. Called the Lava Point flow (Qmlp), the unit is exposed in the far northwestern corner of the monument (Billingsley et al. 2007A). Basalt flows erupted 1 to 1.4 million years ago, and followed older drainages that now represent inverted topography above present ephemeral stream channels near Doney Mountain.

Approximately 790,000 years ago, about the same time that pumice erupted from San Francisco Mountain and was deposited into the area, the Woodhouse Mesa basalt flow (Qwb) entered the monument (Ulrich and Bailey 1987; Billingsley et al. 2007). Various, local basalt flows in the monument occurred between 770,000-220,000 years ago, and are exposed adjacent to present stream drainages. Fissure eruptions (eruptions along elongate fractures rather than a central vent), about 68,000-70,000 years ago, formed Doney Mountain. Two basalt flows from the eruption flowed downhill towards the future site of the Visitor Center. The youngest basalt flows in Wupatki National Monument resulted from the Merriam Crater eruption approximately 19,000 years ago, when lava flowed into the Little Colorado River along the eastern border of Wupatki National Monument (Qmcb).

Fluvial and stream terrace deposits in the Wupatki Basin record a Cenozoic history of uplift and erosion. These deposits document two successive periods of erosion that beveled the surface to Cretaceous, Triassic, and Permian rocks. One surface, known as the Black Point pediment, developed in the late Pliocene and early Pleistocene. The other surface formed in the middle to late Pleistocene (Wupatki pediment). Younger, late Pleistocene fluvial deposits that underlie the Merriam Crater basalt flow document a low sinuosity, ephemeral Little Colorado River that occupied channels approximately 33 m (10 ft) and 65 m (21 ft) above the modern floodplain (Blyth 1995).

As many as seven Pleistocene stream terraces occupied the landscape between Cameron and Winslow, Arizona during the Black Point and Wupatki erosion cycles. Four of these terrace deposits have been mapped in Wupatki National Monument (Blyth 1995). These older terrace deposits are identified as Pleistocene (Qg3) and Pleistocene/Holocene (Qg2) (Billingsley et al. 2007A).

Holocene Epoch (11,700 years ago to present day)

Downcutting continued into the Holocene, resulting in younger alluvial fan (Qa1) and terrace deposits (Qg1) in the monument. Many intermittent, ephemeral streams cross the Wupatki Basin and Antelope Prairie. The main streams include the Kana'a, Heiser, Deadman, Doney Mountain, Antelope and Citadel washes. Wind distributed sand and volcanic ash into dunes and sand sheets that today spread across the surface northeast of the Little Colorado River.

Dissolution by groundwater, and continued erosion along faults and joints in the Kaibab Formation, have created deep fissures, or earthcracks, and depressions associated with tectonic grabens (Blyth 1995; Billinngsley et al. 2007A). The distinctive blowholes in Wupatki National Monument connect to fissures and solution caves in the Kaibab Formation.

Volcanic eruptions from the stationary hot spot beneath the San Francisco Volcanic Field continued into the Holocene, as well. The most recent eruptive activity took place about 1,000 years ago and formed Sunset Crater, Arizona's youngest volcano (Priest et al. 2001).

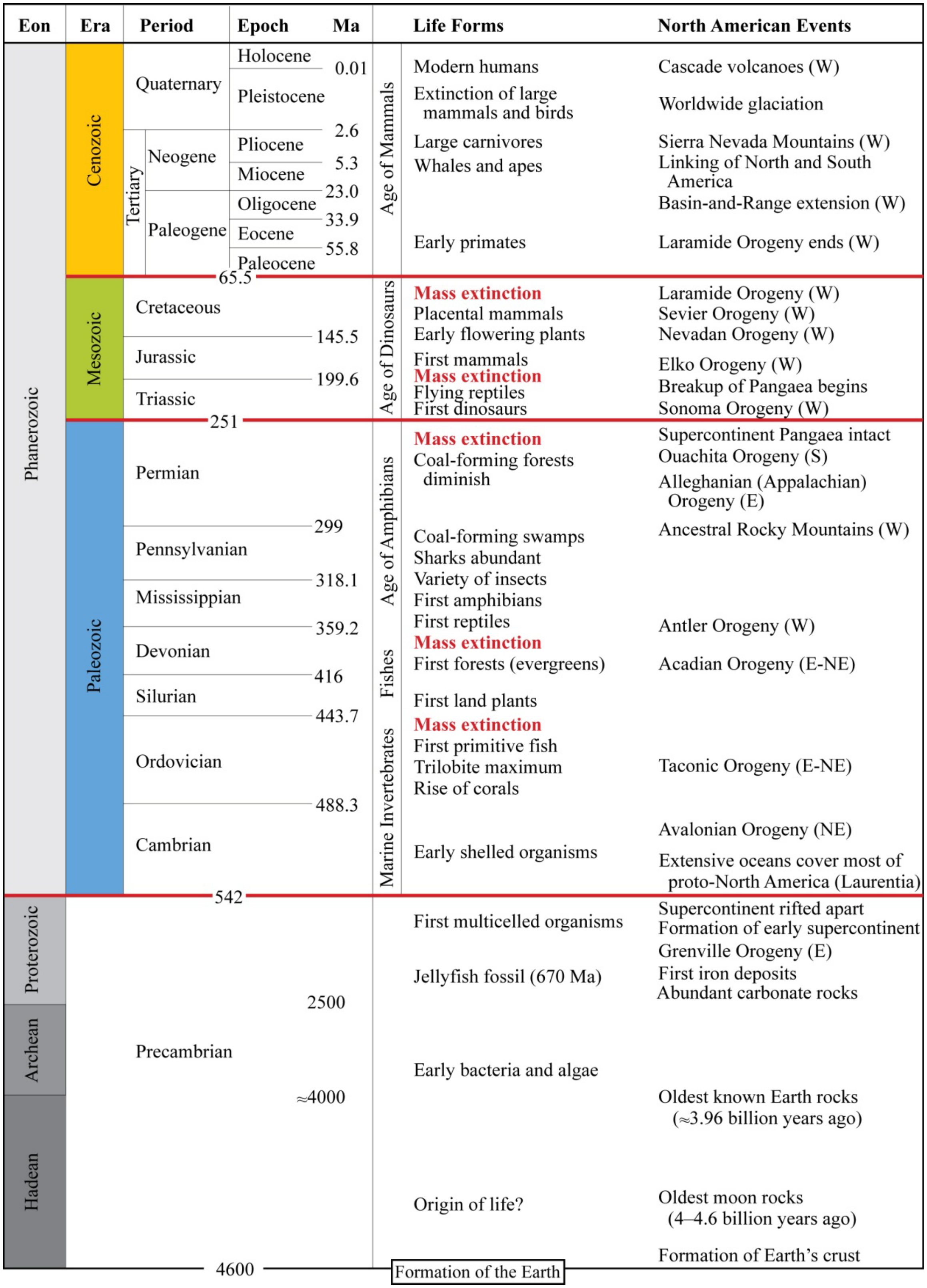


Figure 23. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015 with additional information from the International Commission on Stratigraphy, http://www.stratigraphy.org/view.php?id=25.

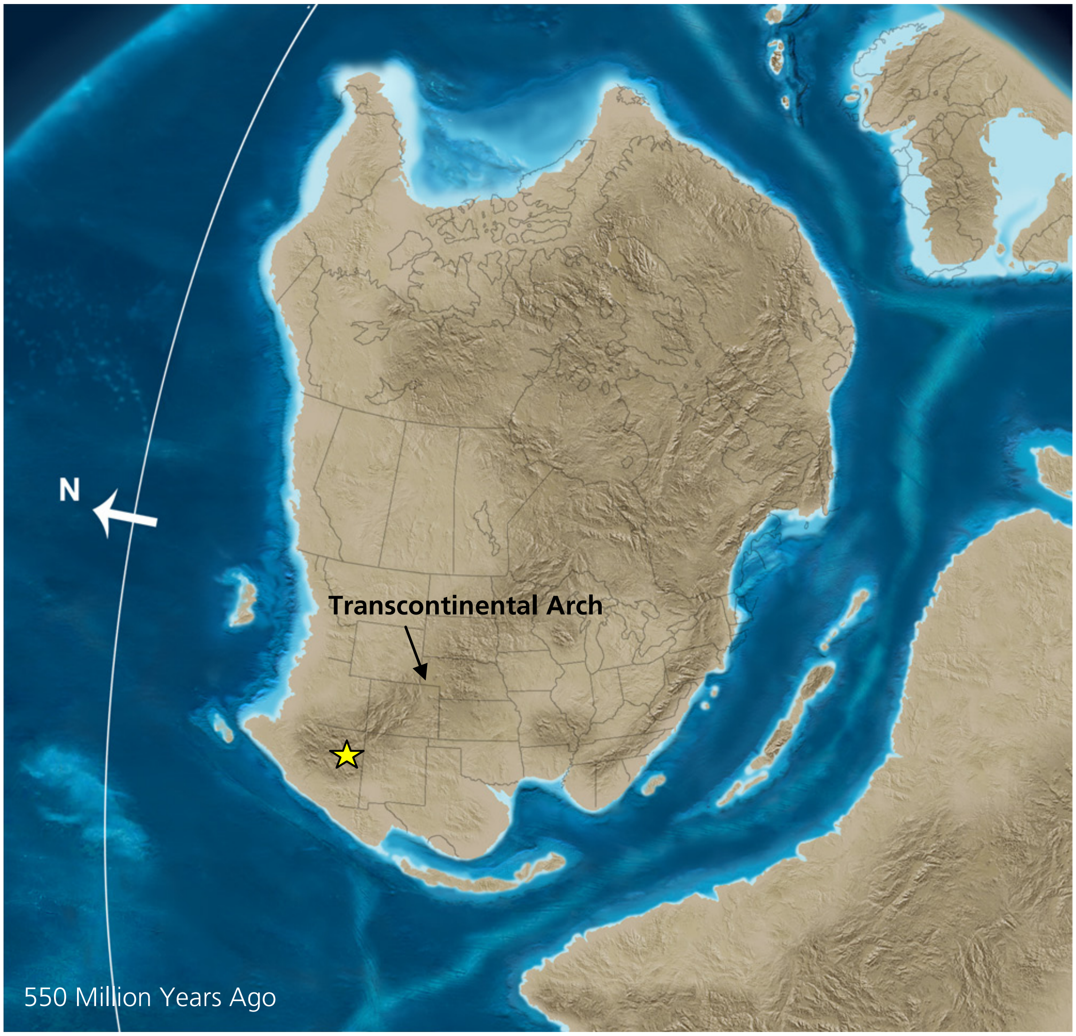


Figure 24. Late Precambrian paleogeography of North America. Approximately 550 million years ago, most of what is now Arizona had been attached to the proto-North American continent, which lay south of the equator (white line). The Transcontinental Arch remained a prominent structural feature well into the early Paleozoic. The yellow star (not to scale) represents the approximate location of today's Wupatki National Monument. Brown colors represent land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base map by Dr. Ron Blakey (Northern Arizona University Department of Geology), available online: http://jan.ucc.nau.edu/rcb7/namPC550.jpg, accessed December 27, 2010. Annotations by the author.

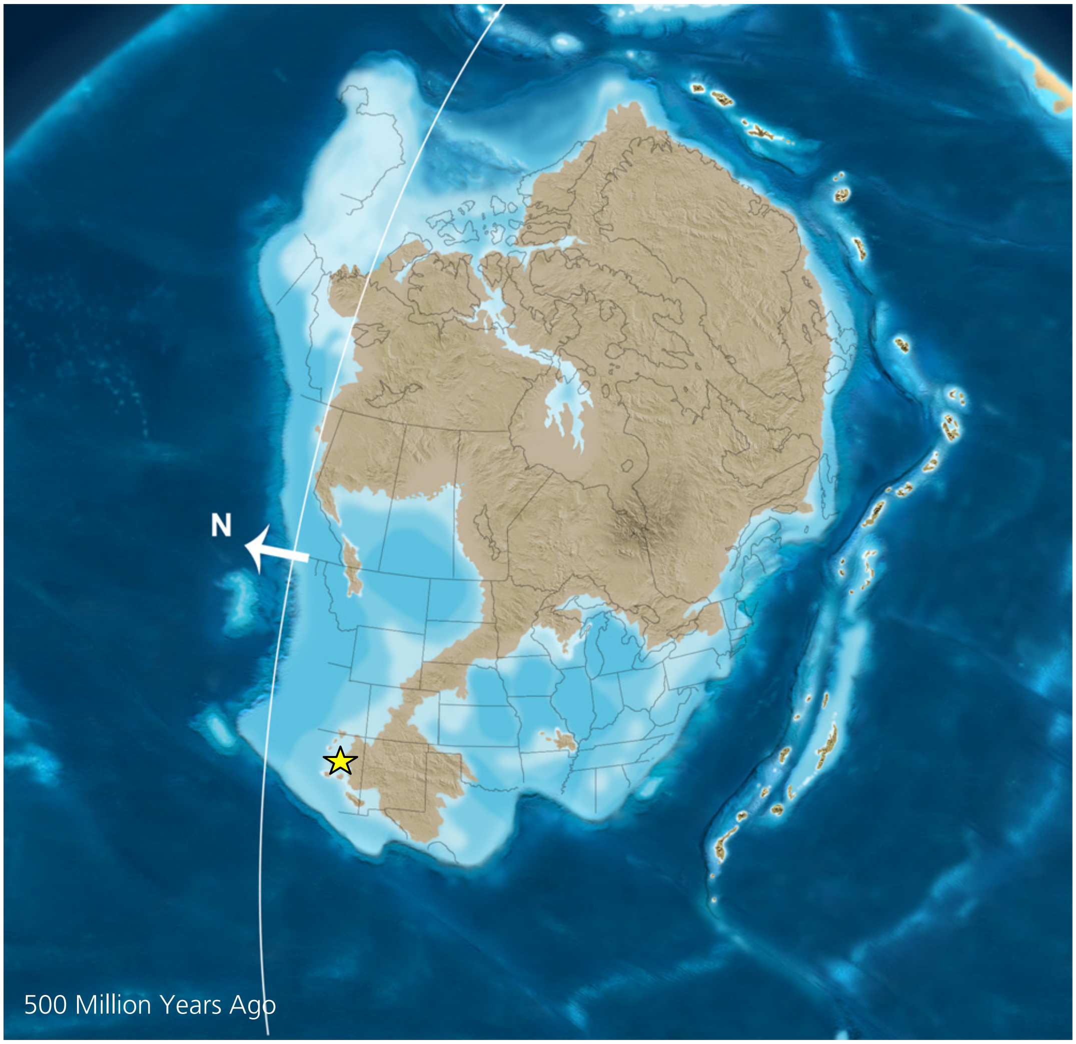
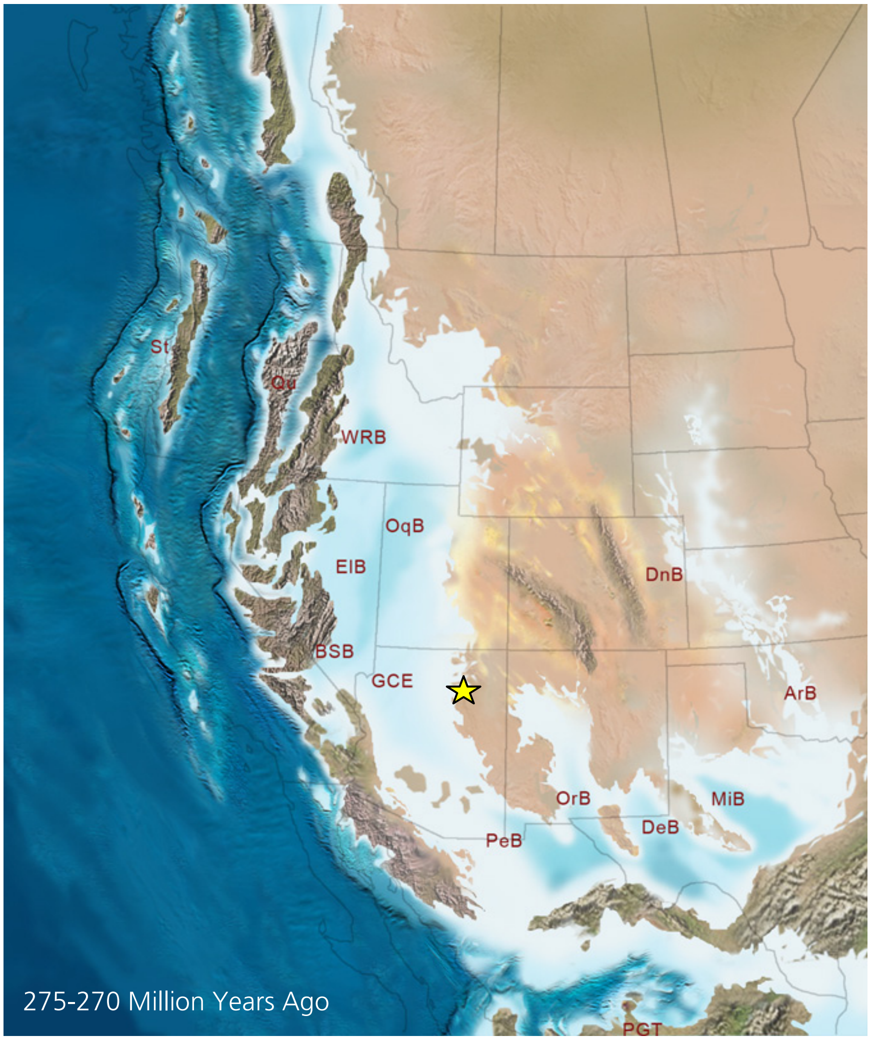


Figure 25. Late Cambrian paleogeography of North America. By approximately 500 million years ago, a major sea level rise had inundated most of the continental area that is now the United States. The white line represents the equator. The yellow star (not to scale) represents the approximate location of today's Wupatki National Monument. Brown colors represent land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base map by Dr. Ron Blakey (Northern Arizona University Department of Geology), available online: http://jan.ucc.nau.edu/rcb7/namC500.jpg, accessed December 27, 2010. Annotations by the author.



<u>Actively Subsiding Sedimentary Basins during the Permian</u>

ArB: Arbuckle Basin
BSB: Bird Springs Basin
DeB: Delaware Basin
DnB: Denver Basin
ElB: Ely Basin
GCE: Grand Canyon Embayment
MiB: Midland Basin
OqB: Oquirrh Basin
OrB: Orogrande Basin
PeB: Pedrogosa Basin
WRB: Wood River Basin

<u>Other Terranes Accreting to Ancestral North America</u>

PGT: Peri-Gondwanan Terranes
Qu: Quesnell
St: Stikine

Figure 26. Permian paleogeography of southwestern North America during deposition of the Kaibab Formation, approximately 275-270 million years ago. Remnants of the northwest-southeast trending Ancestral Rocky Mountains can still be seen in Colorado. The Pedregosa Basin (PeB) in southeastern Arizona and southwestern New Mexico is closing as South America (part of the PGT) collides with North America. An active subduction zone lies along the western margin of the landmass that will soon become the supercontinent, Pangaea. The yellow star represents the approximate location of today's Wupatki National Monument. Brown colors represent land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base map by Dr. Ron Blakey (Northern Arizona University Department of Geology), available online: http://jan.ucc.nau.edu/rcb7/garm270.jpg, accessed September 13, 2010. Annotations by the author.

Figure 27. Early Triassic paleogeography of southwestern North America during deposition of the Moenkopi Formation approximately 240 million years ago. The Permian sea had withdrawn from Arizona. A subduction zone continued to be active along the western margin of North America (thick black line), and the Gulf of Mexico began to open. The yellow star represents the approximate location of today's Wupatki National Monument. Brown colors represent land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base map by Dr. Ron Blakey (Northern Arizona University Department of Geology), available online: http://jan.ucc.nau.edu/rcb7/garm240.jpg, accessed September 13, 2010. Annotation by the author.

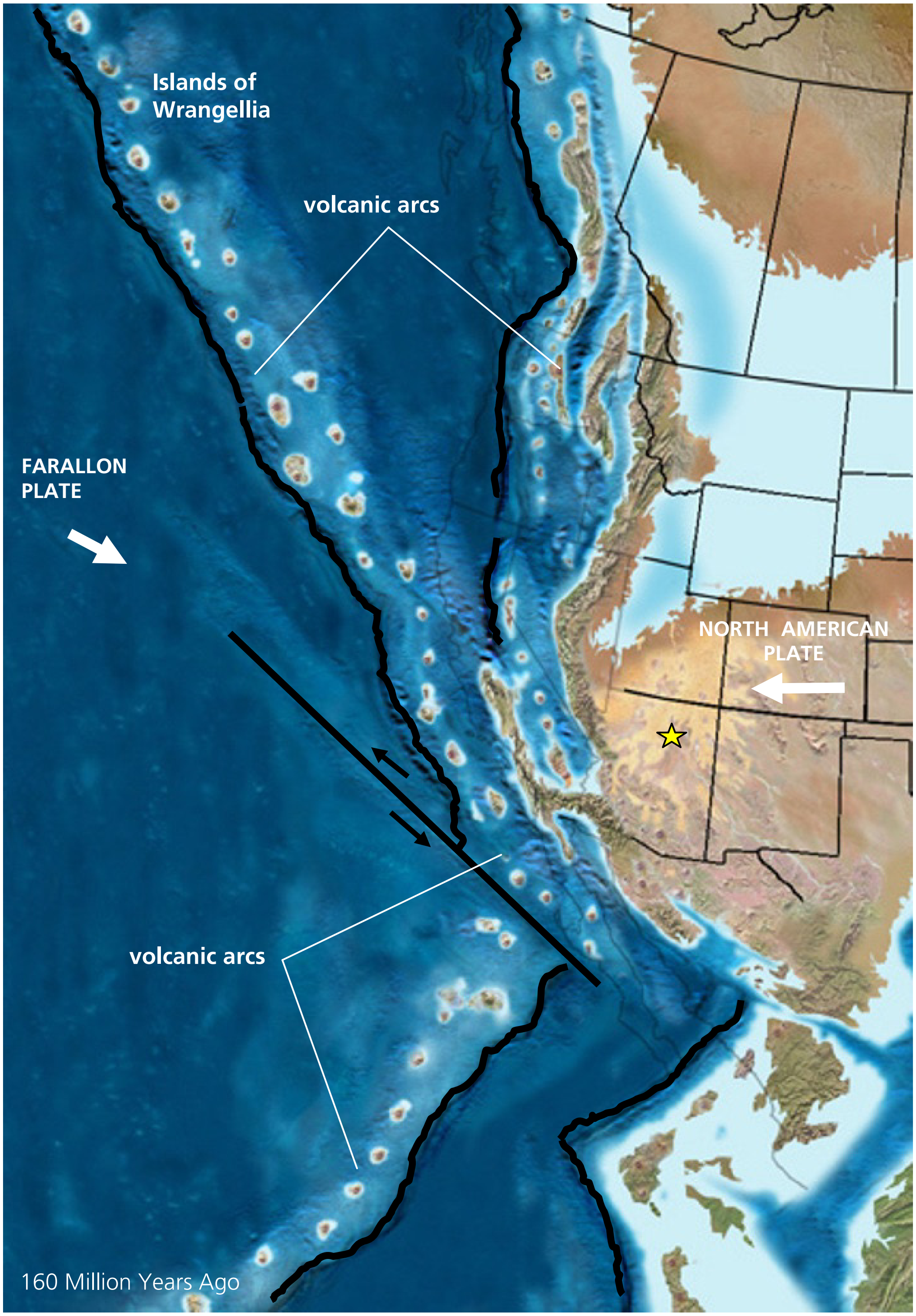


Figure 28. Middle Jurassic paleogeography of western North America. Approximately 160 million years ago, oblique convergence between the North American Plate and the Farallon Plate has created a transform (strike-slip) fault along the southwestern margin of North America. Volcanic islands (volcanic arc) form above subduction zones. White arrows indicate the general direction of plate movement. Black arrows indicate movement along the transform fault. In this case, movement is left-lateral (sinistral). The yellow star represents the approximate location of today's Wupatki National Monument. Brown colors represent land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base map by Dr. Ron Blakey (Northern Arizona University Department of Geology), available online: http://jan.ucc.nau.edu/rcb7/jur160seattle.html, accessed December 28, 2010. Annotation by the author.

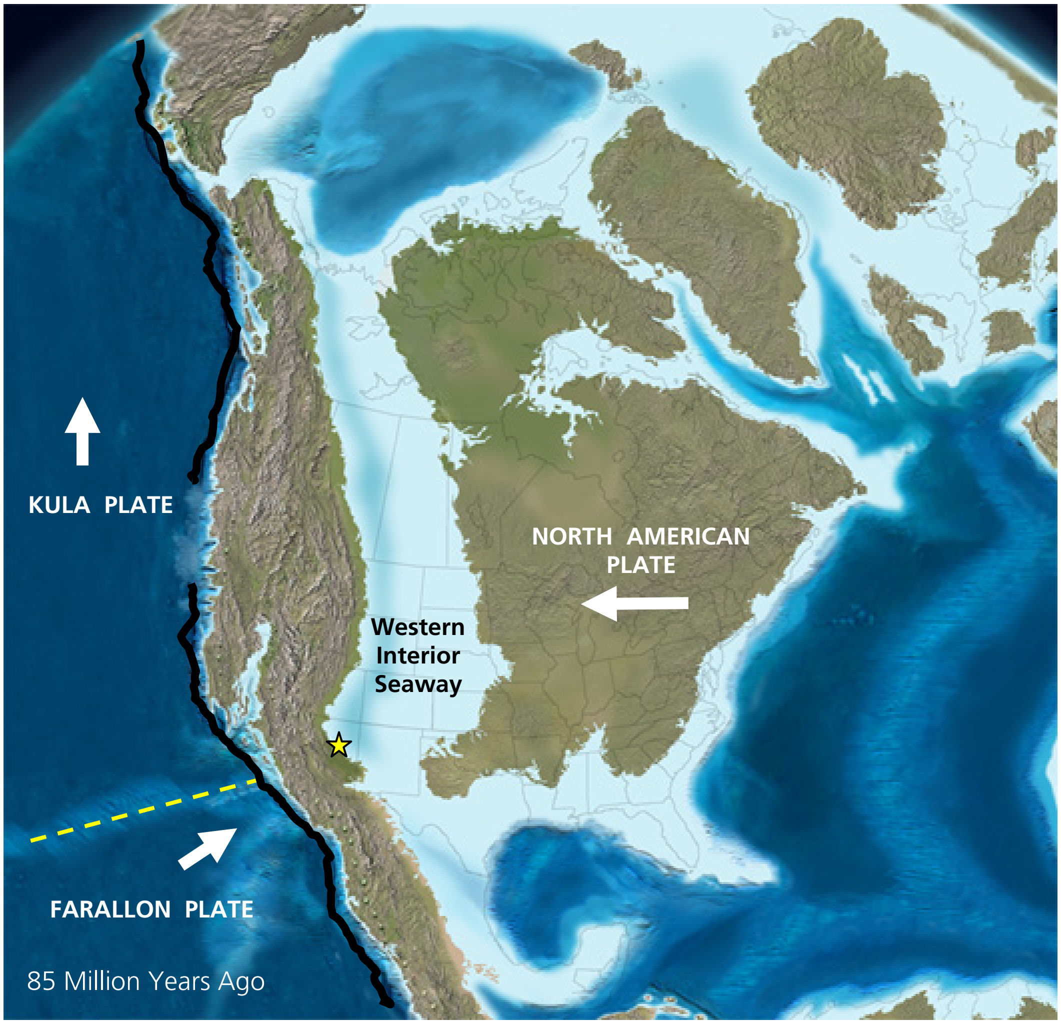


Figure 29. Late Cretaceous paleogeography of North America. Approximately 85 million years ago, the Western Interior Seaway spread from the Gulf of Mexico to the Arctic Ocean. The Sevier Orogeny, generated by tectonic plate collision, produced fold-and-thrust belt mountains along the western continental margin. Regional metamorphism affected western Arizona and eastern California. Paleozoic and Mesozoic sandstone, mudstone, and limestone were metamorphosed to quartzite, schist, and marble. The yellow star marks the approximate location of today's Wupatki National Monument. Arrows indicate the general direction of plate movement. Dashed line marks the approximate contact between the Farallon Plate and Kula Plate. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base map by Dr. Ron Blakey (Northern Arizona University Department of Geology), available online: http://jan.ucc.nau.edu/rcb7/namK85.jpg, accessed September 13, 2010. Annotation by the author.

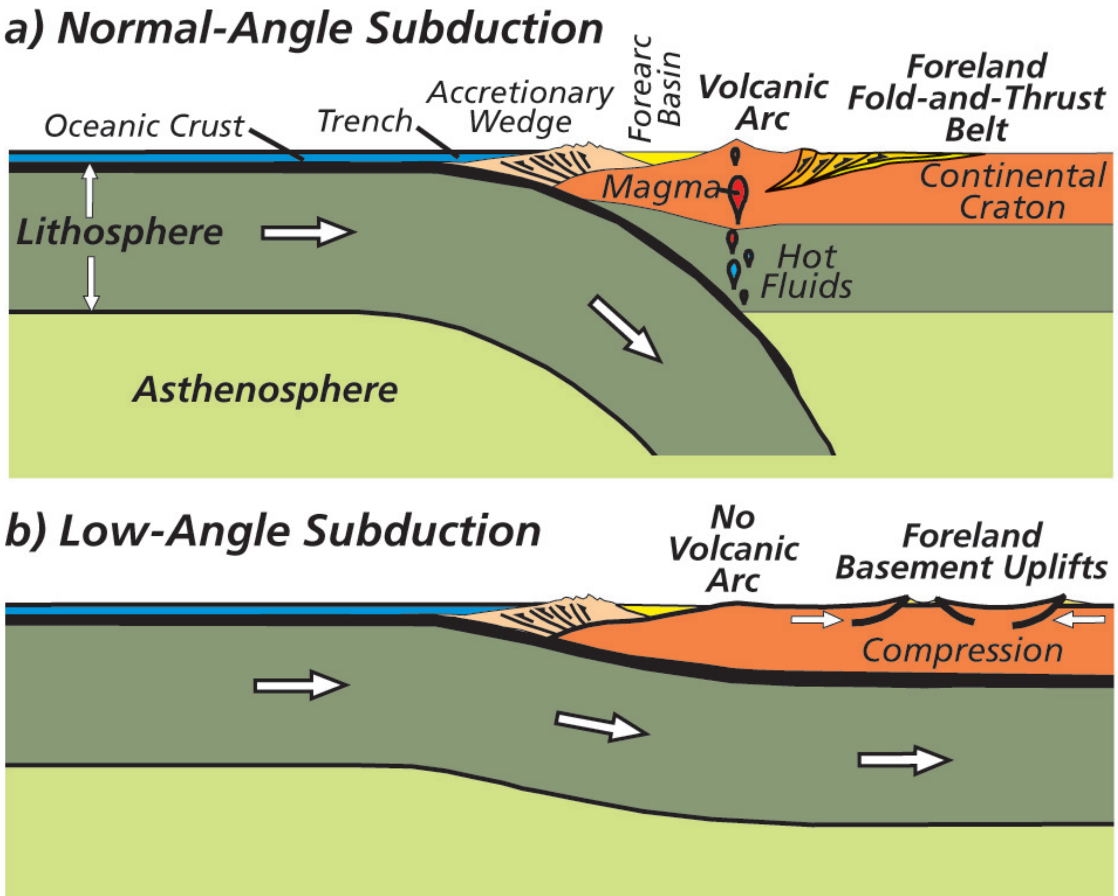


Figure 30. Normal-angle and low-angle subduction diagrams. A) In a normal plate-tectonic setting, a relatively steep angle of subduction causes melting above the downgoing slab. Magma rises to the surface and erupts, forming a chain of volcanoes (volcanic arc) along the continental margin, similar to the present Andes Mountains of South America. Sedimentary strata are folded and thrust toward the continental craton in a "foreland fold-and-thrust belt." In the Triassic, oceanic-oceanic plate convergence caused the volcanic arc to form offshore. During the Jurassic, the oceanic plate collided with the North American continent and the volcanic arc formed along the western margin of North America, as depicted in this diagram. B) During the Laramide Orogeny, the subducting slab flattened out, and deformation occurred farther inland. The downgoing slab in low-angle subduction does not extend deep enough to heat up and produce magma so volcanism ceases or migrates toward the craton. The subducting slab transmits stress farther inland, causing hard rock in the crust to compress and break along reverse faults, forming basement uplifts such as those in today's Rocky Mountains. Diagram by Dr. Robert J. Lillie (Oregon State University).

Geologic Map Data

This section summarizes the digital geologic data available for Wupatki National Monument. It includes an overview graphic of the GIS data and a summary table that lists each map unit displayed on the digital geologic map for Wupatki National Monument. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Wupatki National Monument:

Billingsley, G. H., S.S. Priest., and T.J. Felger. 2007, Geologic map of the Cameron 30' x 60' quadrangle, Coconino County, northern Arizona (scale 1:100,000). Scientific Investigations Map 2977. U.S. Geological Survey, Denver, Colorado, USA.

Billingsley, G. H., S.S. Priest., and T.J. Felger. 2007, Geologic map of Wupatki National Monument and Vicinity, Coconino County, northern Arizona (scale 1:24,000). Scientific Investigations Map 2958. U.S. Geological Survey, Denver, Colorado, USA.

These source map(s) provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Wupatki National Monument using data model version 2.0.

GRI digital geologic data for Wupatki National Monument are included on the attached CD and are available through the NPS Natural Resource Information Portal (https://nrinfo.nps.gov/Reference.mvc/Search). Enter "GRI" as the search text and select Wupatki National Monument from the unit list. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.hlp) that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data

Geology data layers in the Wupatki National Monument GIS data

Data Layer	*Code*	*On Overview?*
Geologic attitude observation localities	*ATD*	*No*
Folds	*FLD*	*Yes*
Faults	*FLT*	*Yes*
Geologic Line Features	*GLF*	*No*
Geologic units	*GLG*	*Yes*
Geologic contacts	*GLGA*	*Yes*
(Non–attitude) Geologic Measurement Localities	*GML*	*Yes*
Geologic Point Features	*GPF*	*No*
Hazard Point Features	*HZP*	*No*
Mine (and mine related) Point Features	*MIN*	*No*
Geologic Cross Section Lines	*SEC*	*No*
Map Symbology	*SYM*	*Yes*
Volcanic Line Features	*VLF*	*Yes*
Volcanic Point Features	*VPF*	*No*

Note: All data layers may not be visible on the overview graphic.

Overview Graphic of Digital Geologic Data

The overview graphic on the following page displays the GRI digital geologic data draped over a shaded relief image of Wupatki National Monument and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview graphic. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for Wupatki National Monument, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the map unit properties table (fold-out pages after the overview graphic) correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The arrangement of the units in the table—from youngest (top) to oldest (bottom)—indicates a sequence of geologic events and the spatial and temporal relationships among the units. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 24) for the geologic period and age associated with each unit.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters /40 feet (horizontally) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

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

abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

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

alluvium. Stream-deposited sediment.

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

aphyric. Describes the texture of fine-grained or aphanitic igneous rocks that lack coarse (large) crystals.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

arc. See "volcanic arc" and "magmatic arc."

arenite. A general term for sedimentary rocks composed of sand-sized fragments with a pure or nearly pure chemical cement and little or no matrix material between the fragments.

arkose. A sandstone with abundant feldspar minerals, commonly coarse-grained and pink or reddish.

arroyo. A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.

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

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

barchan dune. A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

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

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

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

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

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block (fault). A crustal unit bounded by faults, either completely or in part.

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

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

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

calcrete. Pedogenic calcareous soil, e.g., limestone consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution.

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

carbonate. A mineral that has CO_3^- as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

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

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

chert. An extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz. Also called "flint."

cinder cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

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

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

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

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

clinopyroxene. A group name for pyroxene minerals crystallizing in the monoclinic system. Important rock-forming minerals; common in igneous and metamorphic rocks.

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

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

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

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

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

convergent boundary. A plate boundary where two tectonic plates are colliding.

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

core. The central part of Earth, beginning at a depth of about 2,900 km (1,800 mi), probably consisting of iron-nickel alloy.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

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

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

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

cryptocrystalline. Describes a rock texture where individual crystals are too small to be recognized and separately distinguished with an ordinary microscope.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

cutbank. A local term in the western U.S. for a steep bare slope formed by lateral erosion of a stream.

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

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

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

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

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

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a dolomite-bearing rock, or a rock containing dolomite.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

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

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

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

epicenter. The point on Earth's surface that is directly above the focus (location) of an earthquake.

epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

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

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

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

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

flat slab subduction. Refers to a tectonic plate being subducted beneath another tectonic plate at a relatively shallow angle.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

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

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

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

fracture. Irregular breakage of a mineral; also any break in a rock (e.g., crack, joint, or fault).

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

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

greenschist. A metamorphic rock, whose green color is due to the presence of the minerals chlorite, epidote, or actinolite, corresponds with metamorphism at temperatures in the 300–500°C (570–930°F) range.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

gypsum. The most common sulfate mineral (calcium sulfate). Frequently associated with halite and anhydrite in evaporites.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

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

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

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

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

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

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

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

lag gravel. An accumulation of coarse material remaining on a surface after the finer material has been blown away by winds.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lapilli. Pyroclastics in the general size range of 2 to 64 mm (0.08 to 2.5 in.).

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.

limb. Either side of a structural fold.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

lithification. The conversion of a newly deposited, unconsolidated sediment into a coherent, solid rock, involving processes such as cementation, compaction, desiccation, crystallization. It may occur concurrent with, soon after, or long after deposition.

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

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

longitudinal dune. Dune elongated parallel to the direction of wind flow.

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.

mantle. The zone of Earth's interior between the crust and core.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.
meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.
mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."
member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.
mesa. A broad, flat-topped erosional hill or mountain bounded by steeply sloping sides or cliffs.
metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.
mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage, meaning that it forms flat sheets.
microcrystalline. A rock with a texture consisting of crystals only visible with a microscope.
mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.
monocline. A one-limbed fold in strata that is otherwise flat-lying.
monument. An isolated pinnacle, column, or pillar of rock resulting from erosion and resembling an anthropogenic monument or obelisk.
mud cracks. Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.
muscovite. A mineral of the mica group. It is colorless to pale brown and is a common mineral in metamorphic rocks such as gneiss and schist, igneous rocks such as granite, pegmatite, and sedimentary rocks such as sandstone.
normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.
oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.
oil field. A geographic region rich in petroleum resources and containing one or more wells that produce, or have produced, oil and/or gas.
olivine. An olive-green mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.
orogeny. A mountain-building event.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.
paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.
parabolic dune. Crescent-shaped dune with horns or arms that point upwind.
parent material. Geologic material from which soils form.
parent rock. Rock from which soil, sediments, or other rocks are derived.
passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").
pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.
pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.
permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.
phenocryst. A coarse (large) crystal in a porphyritic igneous rock.
plagioclase. A feldspar mineral containing various proportions of sodium and calcium. A common rock-forming mineral.
plastic. Capable of being deformed permanently without rupture.
plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.
plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.
pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.
porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.
porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.
porphyritic. Describes an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.
potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).
pumice. Solidified "frothy" lava. It is highly vesicular and has very low density.
pumiceous. Volcanic vesicular texture involving tiny gas holes such as in pumice. Finer than scoriaceous.
pyroclast. An individual particle ejected during a volcanic eruption.
pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.
pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.
quartzite. Metamorphosed quartz sandstone.
radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.
radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.
recharge. Infiltration processes that replenish groundwater.

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

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

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

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

rock. A solid, cohesive aggregate of one or more minerals.

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

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sabkha. A coastal environment in an arid climate just above high tide. Characterized by evaporate minerals, tidal-flood, and eolian deposits. Common in the Persian Gulf.

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

sand sheet. A large irregularly shaped plain of eolian sand, lacking the discernible slip faces that are common on dunes.

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

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.

scoriaceous. Volcanic igneous vesicular texture involving relatively large gas holes such as in vesicular basalt. Coarser than pumiceous.

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

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

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

sheetwash (sheet erosion). The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water rather than by streams flowing in well-defined channels.

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

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

sill. A tabular igneous intrusion that parallels the bedding or foliation of sedimentary and metamorphic country rock, respectively.

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

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

sinkhole. A circular depression in a karst area with subterranean drainage; is commonly funnel-shaped.

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

spatter cone. A low, steep-sided cone of spatter built up on a fissure of vent, usually composed of basaltic material.

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

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

strata. Tabular or sheet-like masses or distinct layers of sedimentary rock. Plural of *stratum*.

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

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

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills.

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

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

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

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.
subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.
subsidence. The gradual sinking or depression of part of Earth's surface.
syncline. A downward curving (concave up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.
talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.
tectonic. Relating to large-scale movement and deformation of Earth's crust.
terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").
terrane. A large region or group of rocks with similar geology, age, or structural style.
terrestrial. Relating to land, Earth, or its inhabitants.
terrigenous. Derived from the land or a continent.
thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.
tongue (stratigraphy). A member of a formation that extends and wedges out away from the main body of a formation.
topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.
trace (fault). The exposed intersection of a fault with Earth's surface.
trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.
transform fault. A strike-slip fault that links two other faults or two other plate boundaries.
transgression. Landward migration of the sea as a result of a relative rise in sea level.
transverse dune. Dune elongated perpendicular to the prevailing wind direction. The leeward slope stands at or near the angle of repose of sand whereas the windward slope is comparatively gentle.
tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.
type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.
unconfined groundwater. Groundwater that has a water table; i.e., water not confined under pressure beneath a confining bed.
unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.
undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.
uplift. A structurally high area in the crust, produced by movement that raises the rocks.
vent. An opening at Earth's surface where volcanic materials emerge.
vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.
vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was still molten.
volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).
volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.
volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.
volcanogenic. Describes material formed by volcanic processes.
wash. A term used especially in the southwestern United States for the broad, gravelly dry bed of an intermittent stream, generally in the bottom of a canyon; it is occasionally swept by a torrent of water.
water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.
weathering. The physical, chemical, and biological processes by which rock is broken down.
xenolith. A rock particle, formed elsewhere, entrained in magma as an inclusion.

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of June 2011.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado). http://nature.nps.gov/geology/

NPS Geologic Resources Inventory. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

National Fossil Day (annually; the Wednesday of Earth Science Week). http://nature.nps.gov/geology/nationalfossilday/.

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NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf.

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

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NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

State Geological Survey Websites

Arizona Geological Survey: http://www.azgs.state.az.us/

Association of American State Geologists: http://www.stategeologists.org/

Geological Society Resources

Geological Society of America: http://www.geosociety.org/

American Geological Institute (AGI): http://www.agiweb.org/

AGI Earth Science Week: http://www.earthsciweek.org/

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United States Geological Survey (USGS)

U.S. Geological Survey: http://www.usgs.gov/

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”).

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.usgs.gov

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Wupatki National Monument, held on June 28-29, 2001. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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