Prepared in cooperation with the National Park Service and the Navajo Nation

Geologic Map of Wupatki National Monument and Vicinity, Coconino County, Northern Arizona

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Pamphlet to accompany

Scientific Investigations Map 2958

Earth crack in Kaibab Formation. View looking southwest toward the San Francisco Peaks. *Photograph courtesy of National Park Service, Wupatki National Monument*.

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Introduction

The geologic map of Wupatki National Monument is a cooperative effort between the U.S. Geological Survey, the National Park Service, and the Navajo Nation to provide geologic information for resource management officials of the National Park Service, U.S. Forest Service, Navajo Indian Reservation (herein the Navajo Nation), and visitor information services at Wupatki National Monument, Arizona. Funding for the map was provided in part by the Water Rights Branch of the Water Resources Division of the National Park Service. Field work on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for, and receive, a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515, telephone (928)-871-6587.

Wupatki National Monument lies within the USGS 1:24,000-scale Wupatki NE, Wupatki SE, Wupatki SW, Gray Mountain, East of SP Mountain, and Campbell Francis Wash quadrangles in northern Arizona. The map is bounded approximately by longitudes 111°16' to 111°32'30" W. and latitudes 35°30' to 35°37'40" N. The map area is in Coconino County on the southern part of the Colorado Plateaus geologic province (herein Colorado Plateau). The map area is locally subdivided into three physiographic parts, the Coconino Plateau, the Little Colorado River Valley, and the San Francisco Volcanic Field as defined by Billingsley and others (1997) [fig. 1]. Elevations range from 4,220 ft (1,286 m) at the Little Colorado River near the northeast corner of the map area to about 6,100 ft (1,859 m) at the southwest corner of the map area.

The small community of Gray Mountain is about 16 mi (26 km) northwest of Wupatki National Monument Visitor Center, and Flagstaff, Arizona, the nearest metropolitan area, is about

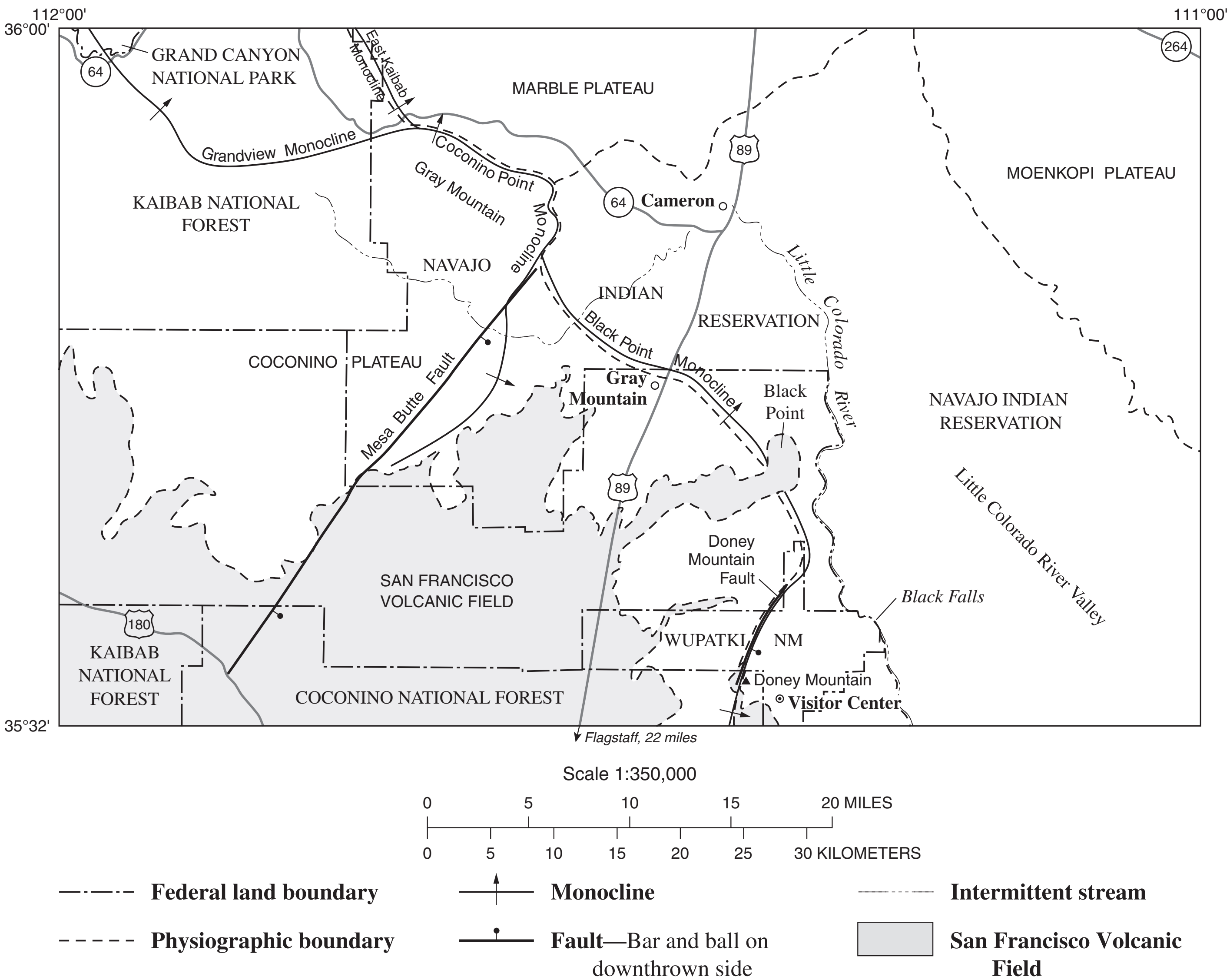

Figure 1. Regional index map showing Wupatki National Monument (NM) in relation to the Grand Canyon area, Coconino County, northern Arizona.

24 mi (38 km) southwest of the Visitor Center (fig. 1). U.S. Highway 89 provides access to the west entrance of Wupatki National Monument. A paved Coconino County road provides a loop from Wupatki National Monument south to Sunset Crater National Monument and back to U.S. Highway 89 about 10 mi (16 km) north of Flagstaff, Arizona. Access to Coconino National Forest is via dirt roads maintained by the National Forest Service. Several unimproved dirt roads on Babbitt Ranch lands provide limited access to remote areas north of Wupatki National Monument. Travel is mostly restricted to paved roads within Wupatki National Monument, and a dirt road that crosses the Little Colorado River provides access to the Navajo Nation area east and northeast of the Little Colorado River. The Little Colorado River crossing is not bridged and can be impassable when the river is flowing. Four-wheel-drive vehicles are recommended but not necessary for travel in remote parts of the Navajo Nation. Extra food and water are highly recommended for travel in this sandy area.

Land ownership north of Wupatki National Monument forms a checkerboard pattern between private and State land. Coconino National Forest manages lands south of Wupatki National Monument and the National Park Service manages Wupatki National Monument. The Leupp and Tolani Lake Chapters of the Navajo Nation manage the area northeast and east of the Little Colorado River (see land management boundaries on map).

The geologic map of Wupatki National Monument provides updated geologic framework information for this part of the Colorado Plateau. The geologic information supports Federal, State, and private land managers when conducting geologic, biologic, and hydrologic investigations and will support future and ongoing geologic and associated scientific investigations of all disciplines within the Wupatki National Monument area.

Previous Work

An early reconnaissance photogeologic map (1:500,000-scale) of this area was compiled by Wilson and others (1969) as part of a geologic map of the State of Arizona. The state map was later recompiled at 1:1,000,000-scale by Richard and others (2000). An excellent photogeologic map of the Navajo Nation area was produced by Cooley and others (1969) but was not registered to topography because a topographic base other than a 1:250,000-scale did not exist at the time. Other geologic maps encompassing the Wupatki National Monument area include a regional geologic map of the Flagstaff 1° x 2° quadrangle by Ulrich and others (1984), a geologic map of the SP Mountain part of the San Francisco Volcanic Field by Ulrich and Bailey (1987), a geologic map of the eastern San Francisco Volcanic Field by Moore and Wolfe (1976), a geologic map of the southwestern Moenkopi Plateau and southern Ward Terrace by Billingsley (1987a), a preliminary map of Wupatki National Monument produced by McCormack (1989), and a regional geologic map of the Cameron 30' x 60' quadrangle (Billingsley and others, unpub. data). The Quaternary and Tertiary geologic map units of this map have been modified and updated from all previous maps to help with biologic and soil studies and geomorphic interpretation of landscape development.

Mapping Methods

This geology was mapped using 1958 and 1968 black and white 1:24,000-scale aerial photographs followed by extensive field checking. Many of the Quaternary alluvial and eolian deposits have similar lithology and geomorphic characteristics and were mapped almost entirely by photogeologic methods. Lithology, stratigraphic position, and the amount of erosional degradation were used to determine relative age correlations of alluvial deposits on this map and adjoining geologic maps. Geologic map units and structural features were field checked to ensure accuracy of location and description. Susan S. Priest and Tracey Felger (U.S. Geological Survey) used ArcGIS to compile the digital database.

Geologic Setting

The map area is characterized by nearly flat lying to gently dipping Paleozoic and Mesozoic rock strata partly covered by younger volcanic rocks, alluvium, and eolian deposits. Pliocene and Pleistocene volcanic rocks of the San Francisco Volcanic Field form a protective caprock over the softer Triassic strata of the Moenkopi Formation in the southern and western parts of the map area. Triassic strata in the Little Colorado River Valley area are partly covered by Pleistocene and Holocene fluvial sand and gravel deposits and Holocene eolian sand sheet and dune deposits. The eolian deposits are derived from abundant sand supplies in and along the Little Colorado River and its tributaries and partly transported in a northeasterly direction by seasonal southwesterly winds. In the western part of the map area, the northeast trending Doney Mountain Fault and Black Point Monocline (fig. 1) have raised the Coconino Plateau about 500 to 700 ft (150 to 215 m) higher in elevation than the Little Colorado River Valley.

The Little Colorado River was established as a tributary to the Colorado River in Grand Canyon about 6 million years ago (Ranney, 2005). The Little Colorado River developed within a strike valley of northeast-dipping Triassic Chinle and Moenkopi Formations between Cameron and Winslow, Arizona. The river has meandered within this strike valley for much of late Miocene through Holocene time.

The Tertiary and Quaternary volcanic rocks of the San Francisco Volcanic Field form a protective caprock over Triassic and Permian strata in the southwest quarter of the map area. Many of the lava flows in this field traveled northeast down tributary drainages toward the Little Colorado River Valley through parts of Wupatki National Monument. Prevailing southwesterly winds at the time of volcanic eruptions distributed cinders over much of the area, but only the thickest and most widespread deposits are mapped.

Paleozoic and Mesozoic Sedimentary Rocks

Paleozoic rocks

Late Miocene through Holocene erosion along the Doney Mountain Fault and Black Point Monocline in the central part of the map area has exposed about 300 ft (92 m) of Lower

Permian Kaibab and Toroweap Formations in the bottom of Antelope Wash and Citadel Wash on the upthrown side of the monocline and fault. The Kaibab Formation forms the surface bedrock for most of the western half of the map area except where covered by a few isolated exposures of Moenkopi Formation and volcanic rocks of the San Francisco Volcanic Field. The cliff- and ledge-forming, sandy, cherty limestone and sandstone of the Kaibab Formation are about 280 ft (85 m) thick in the map area.

The Kaibab Formation is divided into the Harrisburg Member (upper part) and the Fossil Mountain Member (lower part) as defined by Sorauf and Billingsley (1991). The Fossil Mountain Member is a gray, cliff-forming, cherty, sandy limestone that averages about 180 ft (55 m) thick in the map area and locally forms narrow canyons on Antelope Prairie and White Mesa area. A gradational boundary separates the Fossil Mountain Member from the overlying Harrisburg Member of the Kaibab Formation. The Fossil Mountain Member, 80 to 120 ft (25 to 37 m) thick, contains a few fossil brachiopods, crinoids, and trilobites preserved as a sandy limestone and a few fossil sponges and bryozoans preserved within chert nodules and chert beds. The Harrisburg Member contains scattered rare mollusks preserved in calcareous sandstone in the top part of the unit.

Based on rocks exposed in local wells about 30 mi (48 km) east of the map area near Leupp, Arizona, (Don Bills, oral commun., 2005) and exposures along the Doney Mountain Fault, the Toroweap Formation is about 50 to 70 ft (15 to 21 m) thick in the western part of the map area and less than 30 ft (9 m) thick in the southeast corner of the map area. The Toroweap Formation unconformably overlies the Coconino Sandstone and forms a cliff of calcareous sandstone at the bottom of Citadel Wash and Antelope Wash at Doney Mountain Fault.

Paleozoic rocks in the subsurface of the map area are based on exposures and correlations to Paleozoic rocks in the Grand Canyon northwest of Wupatki National Monument and in the Verde Valley southwest of the monument. Beneath the Toroweap Formation, the Lower Permian Coconino Sandstone forms a shear buff-white cliff in the Grand Canyon and Little Colorado River Canyon east of Cameron, Arizona, and is about 600 ft (183 m) thick in the subsurface of the Wupatki National Monument area. Subsurface well logs suggest that the basal part of the Coconino Sandstone is a fine-grained red sandstone that is likely the northern extent of the Lower Permian Schnebly Hill Formation of the Verde Valley as defined by Blakey (1990; Ronald C. Blakey, oral commun., 2005).

The Coconino Sandstone and the Schnebly Hill Formation contain the local aquifer for this area known as the “C” aquifer. The Coconino Sandstone gradually thins north, east, and west of the map area but thickens to the south. The Schnebly Hill Formation thins north and west and gradually thickens south and southeast of the map area.

In the subsurface, the Coconino Sandstone and Schnebly Hill Formation are, in descending order, the Permian Hermit Formation, the Pennsylvanian and Permian Supai Group, the Mississippian Redwall Limestone, the Devonian Temple Butte Formation, and the Cambrian Muav Limestone, Bright Angel Shale, and Tapeats Sandstone.

Mesozoic Rocks

Erosion by the Little Colorado River and its tributaries in the northeast half of the map area has exposed about 280 ft (85 m) of Triassic rock strata. Triassic rocks are, in ascending order, the Lower and Middle(?)Triassic Moenkopi Formation, and the Upper Triassic Chinle Formation. Northeast of the Little Colorado River and above the Chinle Formation are red rocks of the Upper Triassic(?) and Lower Jurassic Moenave Formation, purple rocks of the Lower Jurassic Kayenta Formation, red and purple rocks of the Lower Jurassic Kayenta Formation-Navajo Sandstone transition zone, and white rocks of the Lower Jurassic Navajo Sandstone.

A regional unconformity separates the Permian Kaibab Formation from the overlying Triassic Moenkopi Formation with typical relief of less than 10 ft (3 m). The unconformity is easily recognized by a color contrast from the gray-white Kaibab Formation to the red Moenkopi Formation. Erosional depressions and channels in the upper Kaibab Formation were filled with a sandy conglomerate that contains angular and subangular fragments of chert derived from the Kaibab Formation, which forms the basal part of the Moenkopi Formation.

Moenkopi Formation

Overlying the Kaibab Formation is the sequence of red sandstone ledges and siltstone slopes of the Triassic Moenkopi Formation. The Moenkopi Formation is preserved in isolated outcrops beneath Quaternary and Tertiary volcanic rocks near the western and southern margins of the map area and is extensively exposed in the eastern part of Wupatki National Monument and Little Colorado River Valley area. The Moenkopi Formation once covered the entire map area as much as 220 ft (67 m) thick (McKee, 1954). An unknown amount of the upper Moenkopi Formation was removed by erosion prior to deposition of the overlying Triassic Chinle Formation.

The Moenkopi Formation in the map area is subdivided into three units on the basis of stratigraphic definitions of McKee (1954) in the Little Colorado River Valley. In ascending order, they are the Wupatki Member, the lower massive sandstone member, and the Moqui and Holbrook Members, which are undivided. McKee (1954) tentatively correlates the Moenkopi Formation in the Little Colorado River Valley to parts of the middle red member, Shnabkaib Member, and upper red member of the Moenkopi Formation of northwestern Arizona and southern Utah as defined by Stewart and others (1972) and mapped by Billingsley and Workman (2000). The nomenclature used for the Moenkopi Formation by McKee (1954) is used for this map with a proposed new correlation to the Moenkopi Formation in northwest Arizona based on regional mapping, regional tracing of stratigraphic units, and observation of facies changes over distance. The Wupatki Member is approximately equivalent to the lower red and middle red members of the Moenkopi Formation; the lower massive sandstone member is correlative to the Shnabkaib Member; and the Moqui and Holbrook Members are approximately correlative to an undetermined amount of the upper red member that may be Middle(?) Triassic age.

The Wupatki Member thins east and southeast in the map area from 75 ft (23 m) thick at Wupatki National Monument to less then 15 ft (4.5 m) in the southeast corner of the map area. The Wupatki Member gradually pinches out east of the map area, where the lower massive sandstone member of the Moenkopi Formation unconformably overlies the Kaibab Formation about 20 mi (32 km) southeast of the map area. The lower massive sandstone member, according to McKee (1954), is stratagraphically above the Shnabkaib Member of the Moenkopi Formation of northwestern Arizona and southern Utah. However, field observations show that the Shnabkaib Member undergoes a facies change from white siltstone, gypsiferous sandstone, and limestone in northwest Arizona to a yellow-white crossbedded, ledge-forming, fine-to coarse-grained calcareous sandstone and thin limestone along the Echo Cliffs and Marble Plateau north of Cameron, Arizona, and the Little Colorado River Canyon to a light red, fine-grained, cliff-forming, crossbedded fluvial sandstone near Gray Mountain, Arizona, and finally to Wupatki National Monument where it is described as the lower massive sandstone member by McKee (1954). Thus, the lower massive sandstone member and the Shnabkaib Member are at the same stratigraphic horizon and form a marker bed that represents a northwest to southeast marine shoreward facies change.

The lower massive sandstone is less than 10 ft (3 m) thick near Gray Mountain, Arizona, and gradually thickens southeast along the Little Colorado River Valley to as much as 53 ft (26 m) in the Wupatki National Monument area. The lower massive sandstone forms a continuous cliff or ledge that gradually thins south and east of Wupatki National Monument to less than 11 ft (3 m) and unconformably overlies the Kaibab Formation about 20 mi (32 km) southeast of Leupp, Arizona.

The Moqui and Holbrook Members of the Moenkopi Formation are defined by McKee (1954). The slope-forming Moqui Member is defined from exposures along Moqui Wash 8 mi (13 km) west of Winslow, Arizona. It is 85 ft (26 m) thick and a lighter shade of reddish-brown than the underlying Wupatki or overlying Holbrook Members. The Moqui Member erodes into a uniform, mostly covered slope below the cliff-forming Holbrook Member. Sandstone beds of the Holbrook Member of the Moenkopi Formation form an irregular line of bluffs along the Little Colorado River Valley between Holbrook and Cameron, Arizona. The Moqui and Holbrook Members are mapped as undivided because they are difficult to distinguish individually in some areas of the Little Colorado River Valley within the map area. The Moqui and Holbrook Members are approximately correlative to the upper red member of the Moenkopi Formation in northwestern Arizona and southern Utah (McKee 1954; Repenning and others, 1969). It is possible that the Holbrook Member is part of the Shinarump Member of the Chinle Formation in the map area, but this idea needs further investigation. The Moqui and Holbrook Members are unconformably separated from the overlying Triassic Chinle Formation.

Regional uplift terminated deposition of the Moenkopi Formation and caused general withdrawal of the Triassic marine tidal flats and continental river floodplains northwestward into Utah followed by development of a northwest-flowing drainage system toward the sea. Drainages that eroded into the Moenkopi Formation averaged about 30 ft (10 m) deep and locally as much as 150 ft (46 m) deep. This unconformity is known as the T-3 unconformity (Blakey, 1994). The eroded stream valleys began accumulating mud, sand, and gravel and formed the basal deposits of the Shinarump Member of the Chinle Formation.

Chinle Formation

The Chinle Formation is subdivided into three mappable units along the Little Colorado River Valley. In ascending order they are the Shinarump Member, the Petrified Forest Member, and the Owl Rock Member as defined by Repenning and others (1969).

The conglomeratic sandstone beds of the Shinarump Member contain numerous petrified log and wood fragments. Some of the petrified logs and associated carbonaceous sandstone deposits became enriched with uranium minerals shortly after deposition. Several open-pit mines were developed along the Little Colorado River in the late 1950's to mine the scattered pockets of uranium ore. Today, all of the uranium mines are abandoned and many have undergone landscape restoration.

The thickness of the Shinarump Member is variable owing to widespread erosion, local channel incision into the Moenkopi Formation, and local pinch out and thinning of sandstone and siltstone. The Shinarump Member generally thins from about 200 ft (60 m) northwest of Cameron, Arizona, to 30 to 60 ft (9 to 18 m) thick along the Little Colorado River in the map area. The contact between the Shinarump Member and the overlying Petrified Forest Member is gradational and highly variable, and this contact reflects a lithologic change from brown and purple sandstone and siltstone to fine-grained multicolored mudstone and siltstone.

The Petrified Forest Member of the Chinle Formation forms the multicolored blue, red, and gray-green soft hills of the "Painted Desert" badlands along and northeast of the Little Colorado River. The Petrified Forest Member generally maintains a thickness between 400 and 500 ft (122 and 153 m) northeast of Wupatki National Monument and was likely that thick in the Monument area before removal by erosion.

Cenozoic Rocks

San Francisco Volcanic Field

Volcanic rocks of the San Francisco Volcanic Field are Miocene, Pliocene, and Pleistocene in age as mapped by Moore and Wolfe (1976; 1987), Ulrich and Bailey (1987), and Wolfe and others (1987). The oldest volcanic rock within the map area is the Black Point Basalt (K-Ar age, 2.43±0.32 Ma; Ulrich and Bailey, 1987) and it forms West, East, South, and North Mesas in the west part of Wupatki National Monument. The youngest volcanic rock is the basalt flow of Merriam Crater (optical-luminescence age, 19.6±1.2 ka; Duffield and others, 2006) in the Little Colorado River channel, northeast corner of the map area. The rocks range in composition from basalt to andesite to rhyolite. The volcanic rocks are delineated on the basis of magnetic polarity, isotopic age, and field relations. Within these chronostratigraphic units, contacts are shown between adjacent basalt flows because their individual lithologic characteristics and stratigraphic relations are important to the magnetic history of the individual units of the field. K-Ar ages were determined by Paul

E. Damon and Edwin H. McKee (in Ulrich and Bailey, 1987), Duffield and others (2006), and Damon and others (1974).

The Black Point Basalt (formally named by Ulrich and Bailey, 1987) originated near San Francisco Mountain about 2.4 million years ago. This basalt flowed northeast down a tributary drainage eroded into the Moenkopi Formation and into the Little Colorado River channel and floodplain. The basalt traveled a short distance upstream and about 2 mi (3 km) downstream within the Little Colorado River channel and floodplain. Since emplacement of the Black Point Basalt, the Little Colorado River has eroded down about 680 ft (207 m). This value suggests that the Little Colorado River has downcut approximately 315 ft (96 m) per million years, or about 3 ft (1 m) per thousand years (Damon and others, 1974; Billingsley, 1987b). The basalt, which is more resistant to erosion than the underlying Moenkopi and Chinle Formations and sediments of the Little Colorado River, now forms a mesa known as Black Point about 11 mi (18 km) north of the Wupatki National Monument Visitor Center.

A segment of the Black Point Basalt split from the main flow and traveled down another tributary drainage toward the Little Colorado River through what is now the western part of Wupatki National Monument, but it did not reach the river. This flow arm forms a series of inverted valleys called West Mesa, South Mesa, East Mesa, and North Mesa. These mesas are about 40 to 50 ft (12 to 15 m) above the surrounding flatlands of Antelope Prairie, White Mesa, and the Citadel Ruins area (fig. 2).

Younger basalts from volcanoes south of the map area erupted about 800,000 years ago (K-Ar age, 0.786±0.14 Ma, 0.84±0.13 Ma, and 0.87±0.14 Ma; Damon and others, 1974). The basalts flowed north toward the Little Colorado River Valley but stopped before reaching the river. This series of basalt flows is collectively and informally called the basalt flows of Woodhouse Mesa (Wolfe and others, 1987) that form black basalt cliffs over red sediments of the Moenkopi Formation just south of the Visitor Center at Wupatki National Monument. Other informal and younger basalt flows came from the southwest and flowed into the western part of Wupatki National Monument several hundred thousand years ago (Ulrich and Bailey, 1987). About this same time, a fissure eruption along the Doney Mountain Fault just west of the Visitor Center at Wupatki National Monument formed Doney Mountain, an elon-

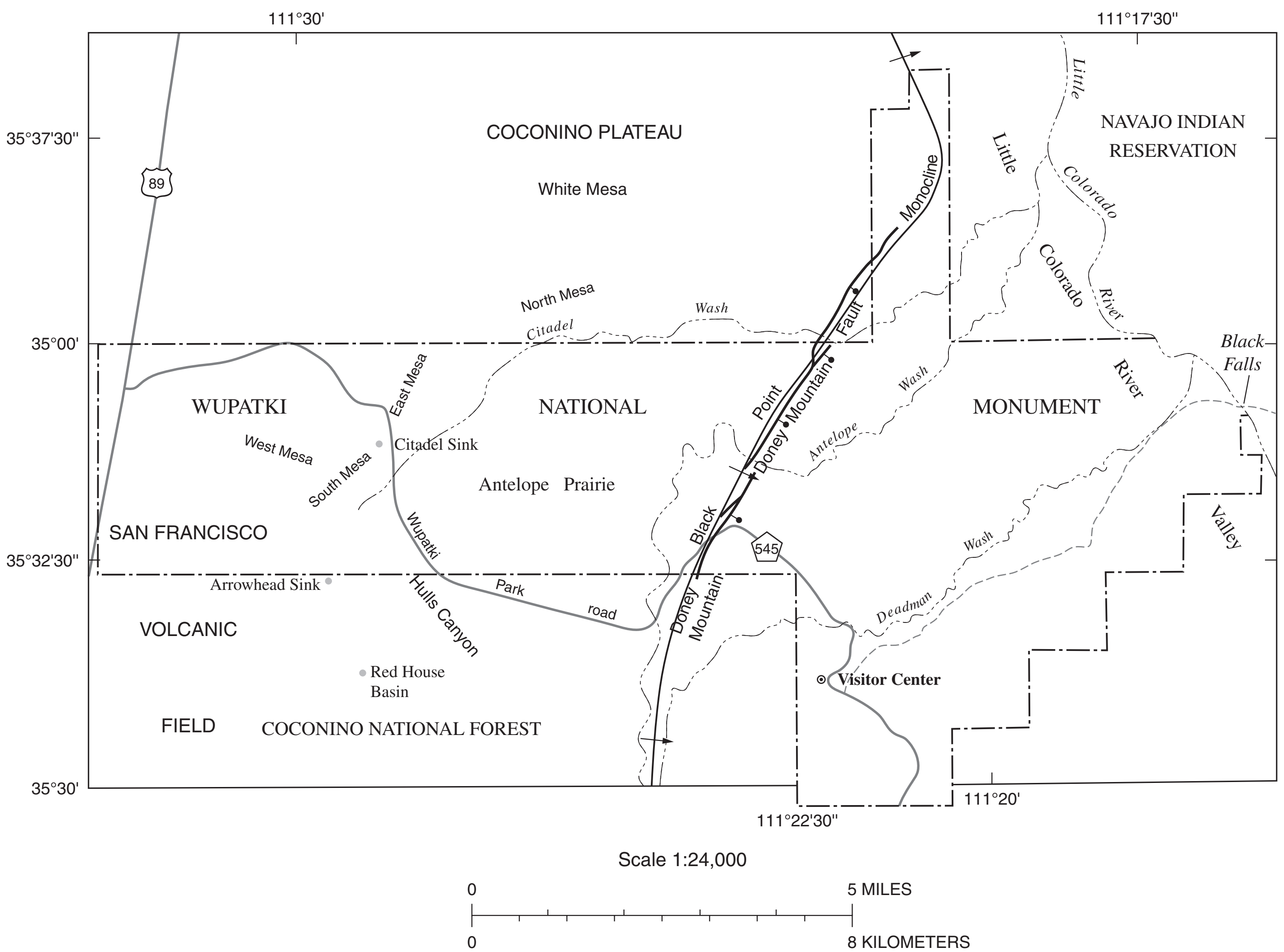

Figure 2. Index map of the Wupatki National Monument, area showing physiographic, cultural, and geologic locations mentioned in the text.

gated north-trending cinder cone. Two basalt flows erupted from Doney Mountain and flowed about a half mile east and downhill towards the future Visitor Center of Wupatki National Monument. A preliminary optical-luminescence age for Doney Mountain is about 68 to 70 thousand years, plus or minus 5 thousand years (Cassandra Fenton, written commun., July 2006).

The youngest basalt in the Wupatki National Monument area is a flow that originated from Merriam Crater about 19,000 years ago (optical-luminescence age, 19.6±1.2 ka; Duffield and others, 2006). The flow traveled north into the Little Colorado River about 6.2 mi (10 km) at the east edge of Wupatki National Monument and formed a lava dam across the Little Colorado River canyon. Stream flow has since been diverted around the north side of the basalt and then returns back into the original 200-ft-(60 m)-deep canyon at what is now called Grand Falls. The basalt flow continued down the canyon of the Little Colorado River to the eastern boundary of Wupatki National Monument, where the river spreads out onto a small floodplain. The river now flows over the basalt flow of Merriam Crater and forms a small rapid called Black Falls. The flow provides for a solid vehicle crossing of the Little Colorado River from Wupatki National Monument to Navajo Nation lands when the river is not flowing. Downstream of Black Falls, the basalt flow of Merriam Crater spread to about a half mile wide within the Little Colorado River floodplain and terminated 4 mi (6.5 km) below Black Falls. The Little Colorado River, below Black Falls, flows along the west edge of the basalt.

Surficial Deposits

Quaternary alluvial and eolian deposits cover parts of the western and eastern thirds of the map area. Black volcanic cinders were transported by southwesterly winds from the Sunset Crater eruption 10 mi (16 km) southwest of Wupatki National Monument about 1,000 years ago and form extensive eolian cinder sand sheets (Qsc) and dune deposits (Qdc) in the Wupatki National Monument area (Hooten and others, 2001; Breternitz, 1967). The Little Colorado River is the principal stream drainage. Alluvial (Qs, Qf, Qg1, and Qg2) deposits associated with the Little Colorado River and its tributaries provide an abundant supply of silt and sand subsequently transported by southwesterly winds to develop extensive eolian sand sheet and dune (Qd, Qes, Qdl, and Qdb) deposits on the northeast side of the Little Colorado River. The eolian deposits are gradually eroded by southwesterly flowing tributary drainages and transported back to the Little Colorado River where the process can repeat itself (Billingsley, 1987b). Eventually, the sand is transported down the Little Colorado River to the Colorado River and through Grand Canyon.

Other surficial units include landslide (Ql) and talus and rockfall (Qtr) deposits exposed mainly around and below the edges of the basalt flows of Woodhouse Mesa of Wolfe and others (1987; QTwb) south of the Visitor Center at Wupatki National Monument. In the western part of the map area, several Pleistocene and Holocene grabens and sinkholes accumulated fresh water sediments (Qps) from small intermittent lakes. There were three lakes in Hulls Canyon, four near East Mesa, and two near Red House Basin (fig. 2). These small lakes were likely an important intermittent water source for the prehistoric inhabitants of the Wupatki National Monument area. Manmade diversion dams, stock tanks, gravel pits, and open-pit uranium mines are mapped as artificial fill (Qaf).

Structural Geology

Paleozoic and Mesozoic strata within the map area have an average regional dip of about 1° northeast, except along the Black Point Monocline where dips are as much as 12° to 14° northeast at Black Point (just north of the map area) and 7° to 12° east along the Doney Mountain Fault segment of the monocline. Northwest and north of the map area, the Black Point Monocline is a broad, mile-wide (1.6 km) northeast-dipping structure where Permian and Triassic strata dip between 15° and 30° northeast.

The Doney Mountain Fault and associated Black Point Monocline are the principal structures within the map area (fig. 1). Compressional folding of Paleozoic and Mesozoic rocks along reactivated Proterozoic high-angle faults began in Late Cretaceous and early Tertiary time (about 65 Ma). The Laramide erosional period began removing Mesozoic strata that once covered the entire map area (Huntoon, 2003). Today's landscape took shape during late Tertiary and Pleistocene time when the Little Colorado River drainage system developed (Ranney, 2005). The Little Colorado River and its tributaries became firmly established and integrated with the Colorado River in the Grand Canyon sometime in late Miocene time, about 6 to 9 million years ago (Lucchitta, 1979; 1990).

The northeast- and east-dipping Black Point Monocline overlies a deep-seated reverse fault that displaced strata up-to-the-west during Late Cretaceous and early Tertiary time (Huntoon, 2003). During Pliocene and Pleistocene time, east-west extension reactivated the deep-seated faults of northwest-trending monoclines. Normal fault separations reversed some of the Cretaceous and early Tertiary offset and accentuated the dip of monoclines by reverse drag along the faults. Cenozoic extensional faulting produced many grabens beginning in late Pliocene time, less than 3 million years ago; this observation is based on similar extensional faulting evidence along the Hurricane and Toroweap Faults west of the map area (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003).

Northwest- and north-trending grabens and faults in the Wupatki National Monument area appear to be tectonically young and perhaps slightly active on the basis of small separations of Pleistocene and Holocene(?) alluvial deposits, especially in the western third of Wupatki National Monument. A few sinkholes have developed along open fractures and joints associated with graben faults, as demonstrated by runoff in several minor drainages that have been temporarily interrupted by recent earth-crack and sinkhole development. The most notable sinkholes are Citadel Sink at East Mesa, Red House Basin, an unnamed sink near Red Basin, and Arrowhead Sink (fig. 2). About 13 mi (21 km) north of the map area, the basalt flow of Tappan Wash (0.51±0.079 Ma) is offset by a few meters of displacement in two grabens along the Little Colorado River below Cameron, Arizona (Rice, 1977). These faulted basalts suggest that much of the graben development in the Citadel Wash area probably began less than 500,000 years ago. However, open bedrock cracks along regional joint fractures reflect a more recent tensional stress of the landscape. Cracks as much as 500 ft (152 m) deep have been explored (Peter Huntoon, oral commun., 2005).

West of the Black Point Monocline, Paleozoic and Mesozoic strata form the topographic highlands of White Mesa and Antelope Prairie on the Coconino Plateau where strata have a regional dip between 1° and 2° northeast. On older geologic maps (Cooley and others, 1969; Wilson and others, 1969), the Black Point Monocline was terminated at its junction with the northeast-trending Doney Mountain Fault. Upon closer inspection of aerial photographs and additional field checking, the Black Point Monocline abruptly bends southwest in a series of right-stepping en-echelon faults at its intersection with the Doney Mountain Fault and continues southwest and parallel to the strike of the Doney Mountain Fault into Wupatki National Monument as expessed by southeast-dipping Paleozoic and Mesozoic strata (McCormack, 1989). The Doney Mountain Fault offsets Permian and Triassic strata as much as 220 ft (67 m) north of Doney Mountain and 300 ft (92 m) at Doney Mountain. The Black Point Monocline and Doney Mountain Fault gradually die out south of Wupatki National Monument and are covered by basalt flows of the San Francisco Volcanic Field.

Acknowledgments

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits are differentiated from one another chiefly on the basis of differences in morphologic character and physiographic position observed on 1:24,000-scale 1968 black and white aerial photographs and from field observations. Older alluvial and eolian deposits generally exhibit extensive erosion and have greater topographic relief, whereas younger deposits are either actively accumulating material or are moderately eroded.

Qaf **Artificial fill and quarries (Holocene)**—Alluvium and bedrock material excavated from borrow-pits and trenches to build livestock tanks, drainage diversion dams, roads, and other construction projects (not all road excavations are mapped)

Qs **Stream-channel deposits (Holocene)**—Poorly sorted, interlensing silt, sand, and coarse gravel. Intertongues with or is inset against young and intermediate alluvial fan (Qa1, Qa2), young and intermediate terrace-gravel (Qg1, Qg2), and upper parts of valley-fill (Qv) deposits, overlap flood-plain (Qf) and ponded sediment (Qps) deposits. Stream channels subject to high-energy flows and flash floods. Little or no vegetation in stream channels, except for salt cedar (tamerisk), russian olive, and cottonwood trees along Little Colorado River and some of its tributaries. Intertongues with other alluvial deposits and contacts are approximate but not dashed. Stream-channel deposits of Little Colorado River are mapped as shown on 1968 black and white aerial photographs and do not necessarily reflect stream-channel deposits of today due to extensive lateral and low-gradient channel changes caused by yearly flood events. Thickness, 6 to 30 ft (2 to 9 m)

Qf **Flood-plain deposits (Holocene)**—Gray, brown, and light-red clay, silt, sand, and some lenticular gravel; partly consolidated by gypsum and calcite cement. Intertongue with or overlap stream-channel (Qs), valley-fill (Qv), young terrace-gravel (Qg1), and young alluvial fan (Qa1) deposits. Subject to lateral stream-channel erosion or overbank flooding. Similar to valley-fill (Qv) deposits in small tributary drainage valleys. Form broad, flat valley floors subject to widespread and frequent overbank flooding along Little Colorado River and in highland graben valleys in west part of Wupatki National Monument. Tamarisk trees in Little Colorado River Valley commonly occupy floodplain or low-lying terrace areas. On floodplains of Cedar Canyon on Coconino Plateau, minor arroyo development may occur owing to headward erosion of streams. Support thick growth of sagebrush, grass, and some cliffrose bush that help trap and accumulate fine-grained sediment on floodplains; sagebrush, tumble weed, desert shrubs, and grass in and along Little Colorado River area. Subject to temporary ponding and often mixed with ponded sediments (Qps) or young mixed alluvium and eolian (Qae) deposits in Little Colorado River area. Thickness, 6 to 30 ft (2 to 9 m)

Qd **Dune sand and sand sheet deposits (Holocene)**—White to gray to light-red, fine- to coarse-grained sand composed mainly of quartz, chert, and minor feldspar grains derived from Triassic and Jurassic sedimentary strata east of Little Colorado River. Form lumpy, undefined geometric sand dunes or sand sheet deposits on flood-plain (Qf), young terrace-gravel (Qg1), and young alluvial fan (Qa1) deposits of Little Colorado River and local tributary washes in northeast quarter of map area. Support moderate growth of grass, sagebrush, and various small desert shrubs. Include complex dunes, parabolic dunes, dome dunes, and sand sheets. Arbitrary and gradational contacts (not dashed) with other alluvial or surficial deposits. Thickness, 3 to 60 ft (1 to 18 m)

Qes **Young eolian sand sheet deposits (Holocene)**—White to gray, fine- to coarse-grained, wind-blown sand composed of quartz and chert grains derived from Little Colorado River stream-channel (Qs) deposits. Deposits formed northeast and east of Little Colorado River over gently sloping terrain. Intertongue with young mixed alluvium and eolian (Qae) deposits. Arbitrary and gradational lateral and vertical map contacts (not dashed) that intertongue with dune sand and sand sheet (Qd) deposits and other surficial deposits. Support moderate growth of grass and small high-desert shrubs. Thickness, 1 to 15 ft (0.3 to 4.5 m)

Qdl **Young linear dune deposits (Holocene)**—White, gray, and light-red, fine- to medium-grained, well sorted, unconsolidated quartz sand accumulation aligned in general northeast direction. Associated with young eolian sand sheet deposits (Qes) northeast of Little Colorado River on pediment slopes in southeast corner of map area. Only one linear dune is shown in map area, but linear dunes are common northeast of map area; generally 40 to 80 ft (12 to 24.5 m) in width and commonly less than ½ mi (0.8 km) in length, but dunes can reach to over 3 mi (5 km) in length northeast of map area on Moenkopi Plateau. Thickness, 6 to 20 ft (2 to 6 m)

Qdb **Young barchan dune deposits (Holocene)**—White, gray, light-red, fine- to coarse-grained, well-sorted quartz sand that forms an isolated barchan dune along a tributary northeast of the Little Colorado River. Arbitrary and gradational contacts (not dashed) with other eolian, alluvial, or bedrock deposits; subject to change on yearly basis due to seasonal storms. Support little or no vegetation. Thickness, 8 ft (2.4 m)

Qg1 **Young terrace-gravel deposits (Holocene)**—Light-brown, pale-red, and gray well-sorted, interbedded mud, silt, sand, pebbles, cobbles, and some boulders; partly consolidated by matrix of mud and sand cemented by calcium carbonate and gypsum. Composed mainly of subangular to well-rounded Paleozoic and Mesozoic sandstone, limestone, and chert clasts of local origin. Include well-rounded clasts of quartzite, quartz, and assorted metamorphic crystalline rocks reworked from Tertiary conglomerates southeast and south of map area. In south and southwest part of map area, unit includes well-rounded volcanic clasts derived from San Francisco Volcanic Field. Locally overlaps young alluvial fan (Qa1), flood-plain (Qf), and valley-fill (Qv) deposits. Subject to flash flood and sheet wash erosion. Support little to no vegetation, mainly grass and some cottonwood trees along Little Colorado River. Contacts with adjacent alluvial and eolian deposits is approximate (not dashed on map). Form terraced benches about 3 to 12 ft (1 to 3.6 m) above stream-channel (Qs) deposits on Coconino Plateau and 4 to 6 ft (1.5 to 2 m) above Little Colorado River channel and flood-plain (Qf) deposits. Fill erosion channels cut into bedrock, young alluvial fan (Qa1), and flood-plain (Qf) deposits. Thickness, 6 to 20 ft (2 to 6 m)

Qa1 **Young alluvial fan deposits (Holocene)**—West and southwest of Little Colorado River: Gray-brown silt, sand, pebbles, cobbles, and boulders. Composed mainly of subangular to rounded limestone, chert, and sandstone clasts derived from Permian and Triassic strata of the Coconino Plateau area. Include medium to small, subrounded to rounded pebbles and cobbles of basalt and andesite and pyroclastic fragments of the San Francisco Volcanic Field. Partly consolidated by gypsum and calcite cement. Support light to moderate growth of sagebrush, cactus, juniper, and grass.

East and northeast of Little Colorado River: Gray, light-brown, and light-red mud, silt, sand, as well as cobble and pebble clasts of chert, limestone, and sandstone. Overlapped by ponded sediments (Qps), flood-plain deposits (Qf), and dune sand and sand sheet (Qd) deposits. Intertongued with young terrace-gravel (Qg1) and young alluvial fan (Qae) deposits. Surface subject to extensive sheet-wash erosion, flash flood debris flows, and small arroyo erosion. Support growth of cottonwood trees, camel thorn bush, salt bush, and a variety of high desert shrubs. Thickness, 3 to 20 ft (1 to 6 m)

Qg2 **Intermediate terrace-gravel deposits (Holocene and Pleistocene(?))**—Southwest of Little Colorado River: Gray and brown silt, sand, and gravel; unconsolidated. Lithologically similar to young terrace-gravel (Qg1) deposits. Composed mainly of gray and brown siltstone and fine-grained sandstone matrix mixed with subangular to rounded pebbles and boulders of local Permian limestone and Triassic sandstone. Include well-rounded basalt clasts derived from the San Francisco Volcanic Field. Locally intertongue with or inset into young and intermediate alluvial fan (Qa1, Qa2) deposits. Form terrace benches about 15 to 30 ft (4.5 to 9 m) above modern streambeds and about 5 to 20 ft (1.5 to 6 m) above young terrace-gravel (Qg1) deposits. Support minor growth of high desert shrubs and grass.

Northeast and east of Little Colorado River: Form isolated deposits of gray and red silt, sand, and multi-colored, angular cherty fragments. Form terrace benches 10 to 50 ft (3 to 15 m) above modern Little Colorado River bed. Thickness, 6 to 100 ft (2 to 30 m)

Qa2 **Intermediate alluvial fan deposits (Holocene and Pleistocene(?))**—Lithologically similar to young alluvial fan (Qa1) deposits; partly cemented by calcite and gypsum, but surfaces are more gravelly and often cut by arroyos as much as 10 ft (3 m) deep southwest of Little Colorado River area. Northeast of Little Colorado River, surfaces are sandy and often covered by young sand sheet deposits too thin to show at map scale. Commonly overlapped by young alluvial fan (Qa1) deposits near the Little Colorado River area and intertongued or overlapped valley-fill (Qv), talus and rock fall (Qtr), and young and intermediate terrace-gravel (Qg1, Qg2) deposits west and southwest of Little Colorado River. Include abundant subrounded to subangular basalt clasts in southwest quarter of map area and abundant subangular chert clasts northeast of Little Colorado River. Support moderate growth of grass, sagebrush, and cactus southwest of Little Colorado River and little to no vegetation except some grass northeast of Little Colorado River. Thickness, 6 to 50 ft (2 to 15 m)

Qps **Ponded sediments (Holocene and Pleistocene(?))**—Gray to brown clay, silt, sand, and minor lenses of gravel; partly consolidated by calcite and or gypsum cement. Locally include small chert, limestone, and sandstone fragments or pebbles. Similar to flood-plain (Qf) deposits but occupy manmade or natural internal drainage depressions. Internal drainage basins and sinkholes in the western part of Wupatki National Monument and Coconino National Forest formed intermittent shallow freshwater ponds that were likely an important water source for early human inhabitants of this area. Dessication cracks often develop in dry conditions on hardpan surfaces and clay content often restricts plant growth. Thickness, 5 to 40 ft (1.5 to 12 m)

Qae **Young mixed alluvium and eolian deposits (Holocene and Pleistocene(?))**—Gray, light-red, and brown clay, silt, and fine- to coarse-grained sand interbedded with lenses of pebbly gravel. Include white angular chert fragments locally derived from Permian strata on Coconino Plateau and white, gray, brown, and red chert fragments derived from Owl Rock Member of the Chinle Formation east of the Little Colorado River. Deposits accumulated by combination of alluvial and eolian processes resulted in an interbedded sequence of thin-bedded, mixed mud, silt, sand, and gravel. Unit subject to sheet wash erosion during wet conditions and often covered by windblown sand accumulation in dry conditions. Commonly occupies broad flatland or gently sloping topography downwind (northeast) of local drainage valleys. Often overlapped by dune sand and sand sheet (Qd) deposits. Support light to moderate growth of grass, cactus, and high desert shrubs. Thickness, 3 to 40 ft (1 to 12 m)

Qdc **Eolian cinder dune deposits (Holocene and Pleistocene)**—Black, gray, and red coarse-grained fragments of angular to subangular, glassy basaltic and andesitic cinders and scoria. Material is derived primarily from Sunset Crater eruption 10 mi (16 km) southwest of map area about 1,000 years ago (Hooten and others, 2001: Breternitz, 1967). Include pyroclastic deposits from other volcanic vents in the San Francisco Volcanic Field in west part of map area and near Doney Mountain. Pyroclastic fragments are commonly vesicular fallout deposits transported by southwesterly winds; particles accumulated against or downslope of local topographic obstructions such as basalt flows, steep-walled drainages, rock ledges, and fault scarps. Form extensive thin cover of eolian cinder deposits over all terrain in southwest part of map area. Cinder fragments become smaller and more rounded farther downwind (northeast) of eruptive centers. Thickness, 5 to 40 ft (1.5 to 12 m)

Qsc **Eolian cinder sand sheet deposits (Holocene and Pleistocene)**—Sand sheets composed of black, gray, and red coarse-grained fragments of angular to subangular, glassy, basaltic cinders and scoria. Similar to eolian cinder dune (Qdc) deposits but form extensive surface deposits of volcanic particles downwind (northeast) of eruptive centers in south part of map area. Volcanic cinder fragments become smaller and more rounded farther downwind (northeast) of eruptive centers. Form discontinuous cinder ground cover over south-central part of map area within and near Wupatki National Monument. Northeast of Wupatki National Monument, cinder sand sheet deposits are present as detected on aerial photos and in the field but are too discontinuous to show at map scale. Volcanic cinders are commonly mixed with quartz sand. Thickness, 1 to 5 ft (0.3 to 1.5 m)

Qtr **Talus and rock fall deposits (Holocene and Pleistocene)**—Brown, gray, slope-forming, unsorted mixture of mud, silt, sand, pebbles, cobbles, and large angular boulders. Form talus debris slopes in steep-walled canyons near base of Doney Mountain Fault and below basalt flows near Wupatki National Monument Visitor Center. Include individual car- and house-size basalt boulders. Clasts are mostly angular and unsorted; partly cemented by calcium carbonate. Gradational and arbitrary contacts with landslide (Ql), young and intermediate alluvial fan (Qa1, Qa2), young and intermediate terrace-gravel (Qg1, Qg2), and valley-fill (Qv) deposits. Subject to extensive sheet-wash erosion, flash-flood debris flows, and arroyo erosion. Only thick or extensive deposits shown. Thickness, 3 to 25 ft (1 to 7.5 m)

Ql **Landslide deposits (Holocene and Pleistocene)**—Unconsolidated to partly consolidated masses of unsorted rock debris. Include detached blocks that have rotated backward and slid down slope as loose masses of broken rock and deformed strata. Include talus and rockfall debris on lower slopes adjacent to and below landslide masses. Some landslide blocks may become unstable in wet conditions below edges of basalt flows south of the Wupatki National Monument Visitor Center. Gradational and arbitrary map contacts (not dashed) with young and intermediate alluvial fan (Qa1, Qa2) and young and intermediate terrace-gravel (Qg1, Qg2) deposits. Subject to extensive sheet wash erosion, flash-flood debris flows, and arroyo erosion. Thickness of landslides, 10 to 120 ft (3 to 36 m)

Qv **Valley-fill deposits (Holocene and Pleistocene)**—Gray and light-brown silt, sand, and lenses of gravel; partly consolidated by gypsum and calcite cement west and southwest of Little Colorado River. Include minor rounded clasts of limestone and sandstone, subrounded to angular chert, and subrounded to angular basalt southwest of Little Colorado River. Intertongued with or overlapped by young and intermediate alluvial fan (Qa1, Qa2) deposits and young and intermediate terrace-gravel (Qg1, Qg2) deposits. Commonly reflects low energy and low-gradient shallow drainages. Subject to sheet-wash flooding and temporary ponding owing to growth of sagebrush, grass, cactus, and some juniper trees in west half of map area. Thickness, 3 to 30 ft (1 to 9 m)

Qg3 **Old terrace-gravel deposits (Pleistocene)**—Gray and light-brown silt, sand, pebbles, cobbles, and boulders composed primarily of local Permian and Triassic clasts; partly consolidated by calcite and gypsum cement; unsorted. Lithologically similar to young and intermediate terrace-gravel (Qg1, Qg2) deposits, but unit includes abundant rounded volcanic clasts and some well-rounded quartzite clasts. Basalt clasts as much as 1 ft (0.3 m) in diameter; smaller basalt cobbles form desert pavement surface in southeast quarter of map area. Form terraces about 12 to 40 ft (3.7 to 12 m) above modern streambeds; about 140 ft (43 m) above Little Colorado River. Thickness, 2 to 20 ft (0.6 to 6 m)

Qa3 **Old alluvial fan deposits (Pleistocene)**—Gray and light-brown, silt, sand and gravel. Lithologically similar to young and intermediate alluvial fan (Qa1, Qa2) deposits, but unit extensively eroded by arroyos; partly consolidated by calcite and gypsum cement. Surface has thin calcrete soil that forms resistant rocky surface east of Doney Mountain Fault and Black Point Monocline. Support moderate growth of grass, sagebrush, and cactus. Thickness, 5 to 25 ft (1.5 to 7.6 m)

VOLCANIC ROCKS

Volcanic rocks of the San Francisco Volcanic Field (Miocene, Pliocene, and Pleistocene) were originally mapped and defined by Moore and Wolfe (1976; 1987), Ulrich and Bailey (1987), and Wolfe and others (1987). For a complete history of magnetic polarity determinations, analytical data, and classification of basalt types in this map area, see Ulrich and Bailey (1987).

Qmcb **Basalt flow of Merriam Crater (Pleistocene; Brunhes age)**—Dark-gray alkali olivine basalt. Contains scattered phenocrysts of olivine, clinopyroxene, and rare plagioclase in groundmass of the same minerals plus opaque oxides. Basalt flow occupies valley of the Little

Colorado River in northeast part of map area where the river flows over the basalt flow and forms a rapid called Black Falls (fig. 1). Downstream of Black Falls, the Little Colorado River flows adjacent to basalt flow where it had spread out onto stream-channel (Qs) and low flood-plain (Qf) deposits of the Little Colorado River. Optical-luminescence age, 19.6±1.2 ka (Duffield and others, 2006). Thickness, 6 to 13 ft (2 to 4 m)

Qb **Basalt flows (Pleistocene; Brunhes age)**—Dark-gray and black porphyritic and aphyric, clinopyroxene-olivine and alkali-olivine basalt. Flows occur locally adjacent to present stream drainages; are moderately young in appearance; are locally covered by thin alluvium, eolian sand, or airborne cinder deposits; and have been little dissected. K-Ar age of various flows are; 0.22±0.05 Ma, 0.46±0.05 Ma, 0.66±0.11 Ma, 0.74±0.08 Ma, and 0.77±0.04 Ma (Ulrich and Bailey, 1987). Thickness, 3 to 65 ft (1 to 20 m)

Qsfp **Pumice of San Francisco Mountain (Pleistocene; Matuyama age)**—White to light-gray, poorly sorted, massive bedding of rhyolite airfall pumice. Unit is matrix-free, except for locally reworked zone in upper 3 ft (1 m) of unit. Lapilli range from several millimeters to several centimeters in size, are colorless vesicular glass, and lack visible crystals. Contains xenoliths of greenschist and blue-gray dense rhyolite with feldspar and quartz phenocrysts. Unit overlies older basalt flows (Qmb) and is correlated with lower aphyric pumice deposits on San Francisco Mountain (Dennis, 1981) south of map area because of similarities in petrography, composition, and xenoliths. Fission-track age on zircons is 0.80±0.11 Ma (C.W. Naeser and G.A. Izett, in Ulrich and Bailey, 1987). Thickness, 10 to 15 ft (3 to 5 m)

Qmbi **Basalt dike (Pleistocene; Matuyama age)**—Dark-gray to black plagioclase-phyric basalt with abundant 1- to 3-cm plagioclase laths in groundmass of olivine, clinopyroxene, plagioclase, and magnetite. Contains baked xenoliths of sandstone of the Moenkopi Formation (Ulrich and Bailey, 1987). Dike is 1 to 1.5 ft (0.3 to 0.5 m) wide

Qmp **Pyroclastic deposits (Pleistocene; Matuyama age)**—Dark-gray to red-brown plagioclase-phyric and porphyritic basalt. Consists of granular groundmass of plagioclase, clinopyroxene, olivine, and magnetite. Scattered olivine and clinopyroxene phenocrysts may be present. Include five small cones at south-central edge of map area and 17 fissure vents of Doney Mountain aligned with strike of Doney Mountain Fault. Cones are in early stage of erosion, slightly eroded, and gullied. Thickness, 3 to 300 ft (1 to 92 m)

Qmb **Basalt flows (Pleistocene; Matuyama age)**—Dark-gray plagioclase-aphyric and porphyritic basalt of similar composition to pyroclastic (Qmp) deposits. Weathers yellow or brown. Surfaces are subdued and slightly eroded and gullied. K-Ar age of various flows outside of map area, 0.83±0.04 Ma, 1.04±0.04 Ma, 1.20±0.05 Ma, and 1.38±1.01 Ma (Ulrich and Bailey, 1987; Wolfe and others, 1987). Flows generally followed older drainages and now represent inverted topography above present drainages. Thickness, 15 to 160 ft (4.5 to 48 m)

Qmlp **Basalt flow of Lava Point (Pleistocene; Matuyama age)**—Dark-gray to black plagioclase-phyric basalt. Similar composition to (Qmb) basalt flows. Mapped as Lava Point flow by Ulrich and Bailey (1987) east of U.S Highway 89. Unit flowed north for several kilometers from an unknown source southwest of map area; similar to and adjacent to the Black Point Basalt (Tbpb). K-Ar age, 1.01±0.13 Ma (Ulrich and Bailey, 1987). Thickness, 20 to 50 ft (6 to 15 m)

Qwb **Basalt flows of Woodhouse Mesa (Pleistocene; Matuyama age)**—Dark-gray, alkali olivine basalt and minor alkali-rich-alumina basalt. Contain phenocrysts of olivine, clinopyroxene, and plagioclase in fine- to medium-grained matrix of same minerals. K-Ar age, 0.786±0.14 Ma, 0.84±0.13 Ma, and 0.87±0.14 Ma (Damon and others, 1974). Form basalt-capped mesas southeast and south of Wupatki National Monument Visitor Center. Thickness, 6 to 50 ft (2 to 15 m)

QTb **Basalt flows (Pleistocene(?) or Pliocene; Matuyama age)**—Dark-gray, yellow-brown to brown, aphyric and slightly porphyritic basalt and microporphyritic olivine basalt; surfaces mostly smooth, relatively flat, and undissected. Includes thin, interbedded pyroclastic deposits near pyroclastic cones. Unit is thickest near flow margins and filled ancestral Deadman Wash drainage southwest of Wupatki National Monument Visitor Center. Thickness, 30 to 200 ft (10 to 60 m)

Tbpb **Black Point Basalt (Pliocene)**—Dark-gray to black plagioclase-aphyric basalt; surface weathers smooth and is locally dissected. Contains scattered to abundant tabular plagioclase phenocrysts as large as 1 cm in diameter and includes abundant olivine microphenocrysts in feldspathic groundmass with granular to ophitic intergrowth of brown pyroxene and plagioclase. K-Ar age, 2.43±0.32 Ma (Ulrich and Bailey, 1987). Forms two flow lobes in map area; one flow in northwest corner of map area extends northeast to the Little Colorado River to form Black Point; another lobe extends northeast into the western part of Wupatki National Monument for 8.5 mi (14 km) and is referred to as the Citadel flow by Cooley (1962), but it is mapped as one of the flows of the Black Point Basalt because both flow lobes emerge from a single flow source southwest of Wupatki National Monument. Basalt flows average about 40 ft (12 m) thick and flowed down tributary drainages to the Little Colorado River that were eroded into the Moenkopi Formation 2.4 million years ago. The basalt flows now form inverted valleys on Coconino Plateau (named West Mesa, South Mesa, East Mesa, and North Mesa) in the western part of Wupatki National Monument. Thickness 20 to 132 ft (6 to 40 m)

SEDIMENTARY ROCKS

Ts **Oldest stream-channel deposits (Pliocene or Miocene(?))**—Light-red, gray, and brown interbedded siltstone, sandstone, arkosic gravel, and lenticular conglomerate. Unsorted and partly consolidated deposits cover part of floor of incised meander channel of Antelope Wash west of Doney Mountain. Antelope Wash, an ancestral Deadman Wash drainage, was superimposed onto the Kaibab Formation west of Doney Mountain Fault and onto the Moenkopi and Chinle Formations east of Doney Mountain Fault. Pebbles and cobbles in channel are composed mostly of well-rounded quartzite, chert, and minor clasts of granite and metamorphic rocks derived from older gravel deposits southwest of the map area; includes abundant gray limestone clasts derived from the Kaibab Formation and red sandstone clasts derived from the Moenkopi Formation. Well-rounded quartzite clasts form a lag gravel deposit in floor of Antelope Wash. The ancestral Deadman Wash (Antelope Wash) is likely Miocene age, similar to abandoned Little Colorado River channel on Black Point Monocline at north edge of map area where unit is 550 ft (168 m) above the Little Colorado River (elevation 4,800 ft [1,463 m]). Thickness, 1 to 12 ft (0.6 to 3.6 m)

Chinle Formation (Upper Triassic)

ꞦTcp **Petrified Forest Member (Upper Triassic)**—Purple, blue, light-red, red-purple, and gray-blue, slope-forming mudstone and siltstone and interbedded white, coarse-grained lenticular sandstone. Includes large erosional channel structures and large-scale low-angle trough crossbedding. Petrified logs and wood fragments common in white or yellow-white sandstone in lower part that may be within upper part of Shinarump Member of the Chinle Formation. Contact with underlying Shinarump Member marked at lithologic and topographic change from sloping multicolored mudstone of Petrified Forest Member to coarse-grained, light-brown sandstone ledges of Shinarump Member. Weathers into rounded hills or slopes with a rough, puffy, popcorn surface owing to swelling of clay content when wet. Thickness northeast of map area, 400 to 500 ft (122 to 153 m). Thickness, 10 to 30 ft (3 to 9 m)

ꞦTcs **Shinarump Member (Upper Triassic)**—White, light-brown, and yellow-pink, cliff-forming, coarse-grained sandstone and conglomeratic sandstone. Includes low-angle crossbedded sandstone interbedded with purple, light-red, and blue poorly sorted siltstone and mudstone. Lithology is highly variable laterally but relatively homogeneous from a regional viewpoint; unit consists of about 75 percent sandstone, 20 percent conglomerate, and 5 percent mudstone (Repenning and others, 1969). Pebbles are generally brown to light-colored, well-rounded quartzite and a black siliceous composition. Petrified logs and wood fragments common at some localities but generally scattered throughout unit. Some petrified wood and associated sandstone include uranium mineral deposits that were mined along Little Colorado River Valley during the 1950's just north of map area. Forms resistant caprock of Tse Lichii Point, northeast corner of map area. Unconformable erosional contact with underlying red siltstone and sandstone of Moenkopi Formation. Thickness, 40 to 100 ft (12 to 30 m)

Moenkopi Formation (Middle(?) and Lower Triassic)—Red, slope- and cliff-forming, fine-grained, thin-bedded siltstone and sandstone. Unconformable contact with underlying Harrisburg Member of the Kaibab Formation represents the regional Permian/Triassic unconformity. Erosional relief is generally less than 10 ft (3 m). Unit includes, in descending order, the Holbrook Sandstone and Moqui Members, undivided; the lower massive sandstone member, undivided; and the Wupatki Member as defined by McKee (1954). Overall thickness before Cenozoic erosion at Wupatki National Monument, 220 ft (67 m)

Ʀmhm **Moqui and Holbrook Members, undivided (Middle(?) and Lower Triassic)**—Red-brown, slope-forming, alternating sequence of claystone, siltstone, and sandstone. Include large to medium-scale trough crossbedding and abundant cusp-type ripple marks that testify to fluvial origin. Fossil casts of reptile tracks are often preserved on bottom surfaces of sandstone beds. Include interbedded, thin-bedded limestone and lenses of conglomeratic sandstone, and some lenses, nodules, veins, and thin-bedded gypsum. Thickness, 80 to 120 ft (25 to 37 m)

Ʀmss **Lower massive sandstone member (Lower Triassic)**—Yellow-white and light-brown, cliff-forming, crossbedded, fine-grained, calcareous siltstone and sandstone. Consists of two or more sandstone beds that form prominent isolated mesas or flatiron ridges along the Black Point Monocline. Lowermost ledge-forming sandstone is most widespread part of unit. Represents a tidal flat and continental lowland fluvial environment in the Wupatki National Monument area. Unit thins in all directions from Wupatki National Monument and correlates to the Shnabkaib Member of the Moenkopi Formation in northwestern Arizona. Minor erosional contact with underlying Wupatki Member of the Moenkopi Formation marked at base of lowest sandstone cliff. Thickness, 50 ft (15 m)

Ʀmw **Wupatki Member (Lower Triassic)**—Red and red-brown, slope-forming, thin-bedded siltstone and sandstone and interbedded crumbly red-brown mudstone. Thin, flat sandstone beds (1 to 3 ft [0.5 to 1 m]) form resistant ledges within slopes. Bedding surfaces often contain small-scale ripple marks, salt crystal casts, or rain drop impressions. Unconformably overlies the Kaibab Formation and forms the regional Permian-Triassic boundary. Unit gradually thins southwest and southeast of Wupatki National Monument. Thickness, 20 to 35 ft (6 to 10 m)

Kaibab Formation (Lower Permian)—Includes, in descending order, Harrisburg and Fossil Mountain Members as defined by Sorauf and Billingsley (1991). East of Doney Mountain Fault and Black Point Monocline, unit members are difficult to separate because of similar lithology owing to facies changes of both units that collectively form a gray to light-brown, cliff-forming, calcareous sandstone and sandy limestone. Unit gradually thins in southeasterly direction across Wupatki National Monument area from about 300 ft (92 m) west of Wupatki National Monument to less than 250 ft (76 m) a few kilometers east of map area

Pkh **Harrisburg Member (Lower Permian)**—Red-gray to brownish-gray, slope-forming gypsum, siltstone, sandstone, and thin-bedded limestone. Includes yellowish-gray fossiliferous sandy limestone at top of unit that is largely removed by erosion from parts of map area. Forms surface bedrock in central part of map area. Contact with underlying Fossil Mountain Member is gradational and placed at topographic break between white-gray, slope- and ledge-forming sandy limestone and sandstone sequence of Harrisburg Member and cliff-forming white to light-brown, cherty limestone of Fossil Mountain Member. Unit gradually thins from west to east and undergoes a shoreward (eastward) facies change from limestone and sandy limestone to calcareous sandstone and sandstone. Thickness, 80 to 120 ft (25 to 37 m)

Pkf **Fossil Mountain Member (Lower Permian)**—Light-gray, cliff-forming, fine- to medium-grained, thin- to medium-bedded (1 to 6 ft [0.3 to 2 m]), fossiliferous, cherty, sandy limestone and minor dolomite. Weathers dark gray or brown, often stained by black magnesium oxide. Unit characterized by gray to white fossiliferous chert nodules and chert breccias. Chert breccia beds are less than 3 ft (1 m) thick and commonly mark uppermost part of Fossil Mountain Member in west half of map area. Unit gradually thins from west to east and undergoes a shoreward (eastward) facies change from sandy limestone to calcareous sandstone, similar in texture, composition, and appearance to Harrisburg Member. Typically forms cliff or series of ledges along Doney Mountain Fault overlain by ledges of sandy limestone and sandstone of Harrisburg Member. Unconformable contact with underlying Toroweap Formation (Pt) attributed mostly to shallow channel erosion; average erosional relief, about 10 ft (3 m). Thickness, 180 ft (55 m)

Pt **Toroweap Formation, undivided (Lower Permian)**—Includes, in descending order, Woods Ranch, Brady Canyon, and Seligman Members, undivided, as defined by Sorauf and Billingsley (1991). All three members are present at Grand Canyon northwest of the map area, but all three members undergo a rapid shoreward eastward and southeastward facies change from Grand Canyon to Wupatki National Monument to form a white, low-angle, crossbedded sandstone cliff unit in Citadel Wash and Antelope Wash along Doney Mountain Fault. Unit gradually thins southeast of the map area in the subsurface where drill holes near Leupp, Arizona, indicate that only 20 to 30 ft (6 to 9 m) of the Toroweap Formation is present in that area (Don Bills, oral commun., July 2005). In the subsurface, on the basis of exposures west of Cameron, Arizona, the Toroweap Formation has a sharp unconformable contact with the underlying Coconino Sandstone, a high-angle, crossbedded sandstone. Dunes of the Coconino Sandstone were beveled off by marine wave erosion and sand was redistributed as flat-bedded or low-angle crossbedded sandstone within the lower part of Toroweap Formation (Billingsley and Workman, 2000; Billingsley and others, 2006). Thickness northwest to southeast, 80 to 30 ft (24 to 9 m)

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