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Prepared in cooperation with the National Park Service, the Navajo Nation, and the Hopi Tribe

Geologic Map of the Cameron 30′ x 60′ Quadrangle, Coconino County, Northern Arizona

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Pamphlet to accompany

Scientific Investigations Map 2977

Adeii Eechii Cliffs showing Jurassic and Triassic strata. *Photograph by George H. Billingsley.*

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U.S. Geological Survey

Introduction

This geologic map is the result of a cooperative effort of the U.S. Geological Survey and the National Park Service in collaboration with the Navajo Nation and the Hopi Tribe to provide regional geologic information for resource management officials of the National Park Service, U.S. Forest Service, Navajo Indian Reservation (herein the Navajo Nation), the Hopi Tribe, and for visitor information services at Grand Canyon National Park, Arizona as well as private enterprises that have lands within the area. Funding for the map was initiated by the Grand Canyon Science Center, Grand Canyon National Park and provided by the Water Rights Branch of the Water Resources Division of the National Park Service, Ft. Collins, Colorado. 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. Permission to publish a small portion of the Hopi Moenkopi District at the north-central edge of the map was granted by the Department of Natural Resources. Any person wishing to conduct geological investigations within this area, must submit for permission to the Department of Natural Resources, The Hopi Tribe, P.O. Box 123, Kykotsmovi, Arizona 86039, telephone # (928) 734–3601.

The Cameron 30' x 60' quadrangle encompasses approximately 5,018 km^2 (1,960 mi^2) within Coconino County, northern Arizona and is bounded by longitude 111° to 112° W., and latitude 35°30' to 36° N. The map area is within the southern Colorado Plateaus geologic province (herein Colorado Plateau). The map area is locally subdivided into six physiographic areas: the Grand Canyon (including the Little Colorado River Gorge), Coconino Plateau, Marble Plateau, Little Colorado River Valley, Moenkopi Plateau, and the San Francisco Volcanic Field as defined by Billingsley and others, 1997 (fig. 1). Elevations range from about 2,274 m (7,460 ft) at the south rim of Grand Canyon along State Highway 64 to about 994 m (3,260 ft) in the Grand Canyon, northeast quarter of the map area.

Settlements within the map area include Cameron and Gray Mountain, Arizona. The small community of Coal Mine Canyon, Arizona is about 1.5 km (1 mi) east of the northeast corner of the map (fig. 1). U.S. Highway 180 provides access to the southwest corner of the map area, U.S. Highway 89 to the central part, State Highway 64 to the northwest half, and State Highway 264 to the far northeast corner of the map area.

The roads and trails in the Kaibab and Coconino National Forests are maintained by the National Forest Service, and several dirt roads on the Babbitt Ranches provide limited access to remote areas within the central region of the map. Travel is restricted to paved roads in the Wupatki National Monument area. Four-wheel drive vehicles are recommended in the Navajo Nation area northeast of the Little Colorado River due to sandy conditions. Extra water and food is highly recommended for travel in this remote region.

Land ownership forms a checkerboard pattern in the central region of the map area between private and State land. Kaibab National Forest and Grand Canyon National Park manage lands in the northwest third of the map area, the Coconino National Forest manages land in the southwest portion, the National Park Service manages the Wupatki National Monument area, and the Navajo Nation and local Navajo Chapter governments manage lands of the Navajo Nation in the eastern part of the map, and the Hopi Tribe and Moenkopi Village governments manage the Hopi Moenkopi District in the north-central edge of the map (fig. 1).

The Cameron quadrangle is one of the few remaining areas near the Grand Canyon where uniform geologic mapping was needed for geologic connectivity of the regional geologic framework that will be useful to federal, state, and private land resource managers who direct environmental and land management programs such as range management, biological studies, flood control, and water resource investigations. The geologic information presented will support future and ongoing local geologic investigations and associated scientific studies of all disciplines within the Cameron quadrangle area.

Previous Studies

Wilson and others (1969) compiled an early reconnaissance photogeologic map (1:500,000-scale) of this area as part of a geologic map of Coconino County and the State of Arizona. The map was later recompiled at 1:1,000,000 scale by Richard and others (2000). Cooley and others (1969) produced an excellent photogeologic map of the Navajo Nation area but the map was not registered to a topographic database because a topographic base larger than 1:250,000 scale did not exist at the time. A geologic map of the Cameron 15' quadrangle was mapped by Akers and others (1962); a geologic map of the Flagstaff 1° x 2° quadrangle (1:250,000 scale) was produced by Ulrich and others (1984); a geologic map of the Coconino Point and Grandview Point (15') quadrangles was produced by Billingsley and others (1985); a geologic map of the S P Mountain part of the San Francisco Volcanic Field was produced by Ulrich and Bailey (1987); a geologic map of the southwestern Moenkopi Plateau and southern Ward Terrace was produced by Billingsley (1987a); a preliminary map of Wupatki National Monument was produced by McCormack (1989); and a small part of the Grand Canyon in the northwest corner of the map area was mapped by Huntoon and others (1996). The Quaternary geology of all previous maps has been modified and updated for this map to match consistency and detail of the adjoining Valle 30' x 60' quadrangle (Billingsley and others, 2006). A geologic map of the Grand Canyon 30' x 60' quadrangle (Billingsley, 2000), adjoins the northwest corner of this map and a geologic map of the Valle 30' x 60' quadrangle (Billingsley and others, 2006) is adjacent to the west edge of the map.

Mapping Methods

This map was initially compiled at 1:24,000 scale from 1958 and 1968 black and white aerial photographs; the initial

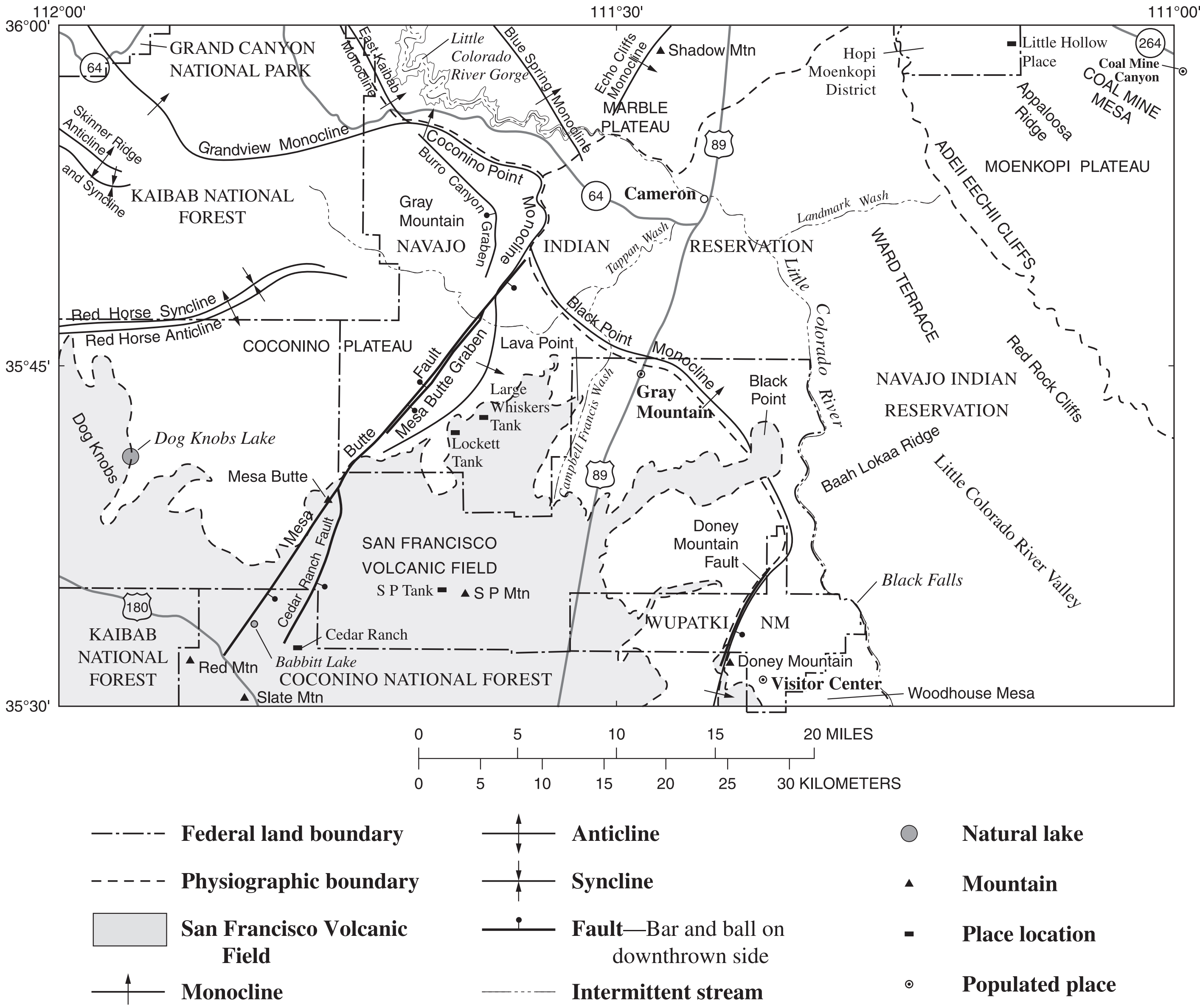

Figure 1. Index map of the Cameron 30’ x 60’ quadrangle showing physiographic, cultural, and geologic locations mentioned in the text.

compilation was extensively field checked. Many of the Quaternary alluvial and eolian deposits, which have similar lithology and geomorphic characteristics, were mapped almost entirely by photogeologic methods. In most areas, the lithology, stratigraphic position, and the amount of erosional degradation were used to correlate relative age of alluvial deposits. Field studies insured accurate location and description of several map units and structures.

Susan S. Priest and Tracey Felger (U.S. Geological Survey), Flagstaff Science Center, compiled the map in digital format using Arc/Map techniques. Thirty-two detailed 1:24,000 scale maps that were initially compiled to produce this map can be seen as view maps in the USGS web site address. This map is the 6th of a series of digital geologic maps of the Grand Canyon region.

Geologic Setting

The map area is characterized by nearly flat-lying to gently dipping Paleozoic, Mesozoic, and Cenozoic strata. Miocene, Pliocene, and Pleistocene volcanic rocks of the San Francisco Volcanic Field form a protective caprock over weak strata of Paleozoic, Mesozoic, and Cenozoic rocks in the southern part of the map area. The southeastern part of the Kaibab upwarp or anticline elevates the northwest part of the Kaibab National Forest. Within elevated highlands, the Grandview and East Kaibab Monoclines extend east and southeast to Gray Mountain, partially within the Navajo Nation. South and southwest of Gray Mountain, the Paleozoic and Mesozoic strata have a regional southwesterly dip averaging 2° toward the Dog Knobs area of the Coconino Plateau (fig. 1). The highlands in the northwestern part of the map are separated from the highlands in the southern part of the map by the northeast-trending Cedar Ranch and Mesa Butte Faults (fig. 1). These closely associated fault structures form a major subsurface divide of the Coconino Plateau between the Little Colorado River to the east and Cataract Canyon of the Grand Canyon west of the map area (Don Bills, oral comun., 2005).

The Mesozoic and Paleozoic strata under the volcanic rocks of the San Francisco Volcanic Field, the eastern part of the Coconino Plateau, Little Colorado River Valley, and the Moenkopi Plateau have an average regional dip of about 2° northeast. The Little Colorado River and its tributary systems eroded much of the Mesozoic strata from the highland areas of the Gray Mountain and Coconino Plateau areas before volcanism began. In the eastern half of the map area, the Little Colorado River is eroding a strike valley parallel to the northeast-dipping Mesozoic strata. The Little Colorado River meandered within this strike valley for much of Miocene to Holocene time and maintained a position mostly on the Triassic Chinle Formation. Along the northern edge of the map area, the Little Colorado River eroded into and became entrenched in the resistant Permian Kaibab Formation and incised a meandering canyon downstream of Cameron, Arizona. Here the valley is subsequent to and controlled by the highland areas of the Coconino Point and East Kaibab Monoclines.

The southern margin of the Marble Plateau is characterized by gently dipping Paleozoic and Mesozoic strata that generally dip less than 2° to the south and east. The Little Colorado River eroded deeply into Paleozoic strata exposing nearly 580 m (1,900 ft) of Mississippian to Permian strata and is physiographically part of the Grand Canyon area, which begins about 11 km (7 mi) west of Cameron, Arizona.

From east of Cameron, Arizona, to the southeast corner of the map area, the Little Colorado River Valley is characterized by gently northeast dipping Paleozoic and Mesozoic strata. These strata form the Ward Terrace and Red Rock Cliffs area below the Adeii Eechii Cliffs of the Moenkopi Plateau. The Adeii Eechii Cliffs form the southwest edge of the Moenkopi Plateau where Jurassic and Cretaceous strata are largely covered by extensive fluvial and eolian surficial sand deposits of Late Cenozoic age.

Paleozoic and Mesozoic Sedimentary Rocks

Paleozoic Rocks

Erosion of the Grand Canyon in the northwest corner of the map area has exposed about 994 m (3,260 ft) of Paleozoic rock strata. The Paleozoic rock strata in the subsurface of the Coconino and Marble Plateaus in the western two-thirds of the map area are, from oldest to youngest, the Muav Limestone (Middle Cambrian), the Temple Butte Formation (Upper and Middle Devonian), the Redwall Limestone (Upper and Lower Mississippian), the lower part of the Supai Group, undivided (Upper, Middle, and Lower Pennsylvanian and Upper Mississippian), the Esplanade Sandstone (Lower Permian) in the upper part of the Supai Group, the Hermit Formation, Coconino Sandstone, Toroweap Formation, and the Kaibab Formation (Lower Permian). These rocks of unknown thickness are likely in the subsurface of northeast third of the map area. The Redwall Limestone, Supai Group of rocks, Hermit Formation, Coconino Sandstone, Toroweap Formation, and the Kaibab Formation are exposed in the Grand Canyon and in the walls of the Little Colorado River Gorge. The Kaibab Formation forms the surface bedrock of most of the western two-thirds of the map area except for a few isolated exposures of the Moenkopi and Chinle Formations (Triassic) beneath volcanic rocks of the San Francisco Volcanic Field and in the Wupatki National Monument area.

Based on exposed rocks in Grand Canyon and in the Verde Valley 65 km (40 mi) south of the map area, the Muav Limestone gradually thins eastward and southeastward in the subsurface of the map area and may locally pinch out onto Precambrian basement rocks. The Temple Butte Formation unconformably overlies the Muav Limestone and is correlative to the Devonian Martin Limestone of the Verde Valley and gradually thins or pinches out east and south of the map area. The Redwall Limestone gradually thins eastward in the subsurface of the map area and unconformably overlies either the Temple Butte Formation or overlies the Muav Limestone where the Temple Butte is locally missing. The Redwall Limestone is 170 m (560 ft) thick in the west part of the map and gradually thins eastward to about 122 m (400 ft) in the subsurface of the eastern part of the map area. The lower Supai Group, undivided, unconformably overlies the Redwall Limestone and thins eastward in the subsurface of the map area but probably maintains a general thickness of about 244 m (800 ft) in the subsurface of the map area. The Esplanade Sandstone of the upper Supai Group gradually thins eastward and southward in the subsurface of the map area averaging about 107 m (350 ft) thick or less. The Hermit Formation unconformably overlies the Esplanade Sandstone in the Little Colorado River Gorge and Grand Canyon area; north and east of the map area, channels have eroded into the Esplanade Sandstone as much as 9 m (30 ft) (Huntoon and others, 1996; Billingsley, 2000). The Hermit Formation is about 25 m (80 ft) thick in Grand Canyon and thins eastward to less than about 6 m (20 ft) in the Little Colorado River Gorge and gradually pinches out under the Cameron area. The Hermit Formation may extend to the southern part of the map area because it is present in the Verde Valley 65 km (40 mi) south of the map area. In the Grand Canyon in the northwest quarter of the map area, a sharp planar erosional contact separates the Hermit Formation from the overlying Coconino Sandstone.

The Coconino Sandstone forms a shear buff-white cliff in the Grand Canyon and Little Colorado River Gorge area and maintains a relatively constant thickness of about 183 m (600 ft) or less in the subsurface throughout most of the map area. Subsurface well logs suggest that the basal part of the Coconino Sandstone is a red sandstone that is likely the northern extent of the Schnebly Hill Formation of the Verde Valley as defined by Blakey (1990; Ronald C. Blakey, oral commun., 2005). The Coconino Sandstone (not the Schnebly Hill Formation) is basically a tongue of the Seligman Member of the Toroweap Formation in the western and northern part of Grand Canyon (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; and Billingsley and others, 2000; Billingsley and Wellmeyer, 2003) but the

Coconino Sandstone is a well established term in Grand Canyon nomenclature and does form a distinct mappable unit throughout the Grand Canyon region. Therefore, the name Coconino Sandstone is herein maintained as a map unit and the lower red sandstone is the Schnebly Hill Formation that thickens southward in the subsurface of the map area to about 60 m (200 ft) along the southwest edge of the map. The Coconino Sandstone gradually thins north, east, and west of the map area but thickens south of the map area, and the Schnebly Hill Formation gradually thickens south and southeast of the map area. Both the Schnebly Hill Formation and the Coconino Sandstone form an important ground water bearing unit in the map area locally known as the "C" aquifer.

The Toroweap Formation unconformably overlies the Coconino Sandstone and undergoes a substantial west to east facies change in the subsurface of the map area. In Grand Canyon, in the northwest corner of map area, the three recognized members of the Toroweap Formation, in ascending order, are the Seligman, Brady Canyon, and Woods Ranch Members but are too thin to show at map scale, thus the Toroweap Formation is mapped as one unit (Sorauf and Billingsley, 1991). These three members change from a thin lower sandstone, middle limestone ledge, and upper gypsiferous siltstone slope to a general cliff-forming calcareous sandstone facies of the Toroweap Formation in the Little Colorado River Gorge, Gray Mountain, and subsurface of the entire map area. The Toroweap Formation gradually thins from about 60 m (200 ft) in the Little Colorado River Gorge to less than about 9 m (30 ft) in the subsurface in the southeast corner of the map based on recent well log interpretations near Leupp, Arizona, about 32 km (20 mi) southeast of the map area (Don Bills, oral commun., 2005).

The Kaibab Formation forms the surface bedrock for much of the Coconino Plateau and the western two-thirds of the map area where not covered by volcanic rocks or surficial deposits. The Kaibab Formation is divided into, in ascending order, the Fossil Mountain Member (lower part) and the Harrisburg Member (upper part) as defined by Sorauf and Billingsley (1991). The Fossil Mountain Member is a gray, cliff-forming, cherty, sandy limestone about 70 m (230 ft) thick in the west half of the map area and forms narrow canyon drainages on the Coconino Plateau and the main cliff at the rim of Grand Canyon and Little Colorado River areas. A gradational and arbitrary boundary separates the ledge- and cliff-forming Fossil Mountain Member from the overlying slope- and ledge-forming Harrisburg Member of the Kaibab Formation. The Fossil Mountain Member contains brachiopod, sponge, and trilobite fossils preserved mostly in chert nodules and chert lenses, whereas the Harrisburg Member contains only a mollusk fossil fauna.

The Harrisburg Member of the Kaibab Formation forms a ledge-slope topography above the cliff-forming Fossil Mountain Member at the rim of Grand Canyon and the rim of the Little Colorado River Gorge where the sandy limestone beds are often weathered or stained dark gray or black by manganese oxide. The Fossil Mountain and Harrisburg Members undergo a west to east facies change from fossiliferous ledges of cherty limestone to cliff-forming, calcareous sandstone that is largely devoid of fossils and becomes increasingly difficult to distinguish one member from the other east of U.S. Highway 89 and are mapped collectively as the Kaibab Formation (Pk) in the southeast corner of the map area. Deposits of gray gypsum and light-red gypsiferous siltstone and sandstone of the Harrisburg Member have been subjected to modern erosion and dissolution weathering resulting in the development of several internal drainage basins and local sinkhole depressions on the Coconino Plateau southwest of Gray Mountain.

A regional unconformity with a general relief of less than 3 m (10 ft) separates the Permian Kaibab Formation from the overlying Triassic Moenkopi Formation. The unconformity is easily recognized by a lithologic and color change from the grayish-white sandy limestone of the Kaibab Formation to the light-red and red, thin-bedded sandstone and siltstone beds of the Moenkopi Formation. The erosional depressions and channels in the upper Kaibab were subsequently filled with angular and subangular chert and sandstone conglomerate deposits derived from the Kaibab Formation that forms the basal part of the Moenkopi Formation. The Kaibab Formation isopachs demonstrate substantial thinning over the Gray Mountain area prior to deposition of the Moenkopi Formation (Barnes, 1989).

Mesozoic Rocks

In the northeast half of the map area, erosion by the Little Colorado River has exposed about 707 m (2,320 ft) of Mesozoic rock strata. The Mesozoic rock strata are in the Little Colorado River Valley and Moenkopi Plateau areas but undergo rapid facies and thickness changes beneath the Moenkopi Plateau. The Mesozoic rocks exposed are, in ascending order, the Moenkopi Formation, (Upper(?) and Lower Triassic), the Chinle Limestone (Upper Triassic), the Moenave Formation (Upper Triassic(?) and Lower Jurassic), the Kayenta Formation (Lower Jurassic), the Kayenta Formation-Navajo Sandstone transition zone (Lower Jurassic), the Navajo Sandstone (Lower Jurassic), the Entrada Sandstone-Cow Springs Sandstone, undivided (Middle Jurassic), the Dakota Sandstone (Upper Cretaceous), and the Mancos Shale (Upper Cretaceous).

Moenkopi Formation

Overlying the Permian Kaibab Formation is a sequence of red sandstone ledges and siltstone slopes of the Triassic Moenkopi Formation that is unconformably overlain by a light-brown cliff of sandstone and conglomerate of the Shinarump Member of the Chinle Formation. The Moenkopi Formation is partly preserved as isolated outcrops under Quaternary and Tertiary volcanic rocks in the western and southern margins of the map area and as extensive outcrops in the Marble Plateau and Little Colorado River Valley. Prior to Cenozoic erosion, the Moenkopi Formation covered the entire map area as much as 300 m (1,000 ft) thick just west of the map area at Red Butte south of Grand Canyon Village (Billingsley and others, 2006). The Moenkopi gradually thins eastward to about 107 m (350 ft) near Cameron, Arizona (Repenning and others, 1969), and thins to less than 67 m (220 ft) at Wupatki National Monument (McKee, 1954). An unknown amount of the upper Moenkopi Formation was eroded prior to deposition of the overlying Triassic Chinle Formation.

The Moenkopi Formation is not subdivided in the Dog Knobs area along the west edge of the map. Elsewhere, there are four members of the Moenkopi Formation as defined by McKee (1954) that are recognized and mapped in the Little Colorado River Valley. In ascending order they are the Wupatki Member, the lower massive sandstone member, and the undivided Holbrook and Moqui Members. The Moenkopi Formation in northwestern Arizona and southern Utah, as defined by Stewart and others (1972), was mapped by Billingsley and Workman (2000). McKee (1954) tentatively correlates all of 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. The nomenclature used for the Moenkopi Formation by McKee (1954) is used for this map area with a proposed new correlation to the Moenkopi Formation in northwest Arizona based on regional mapping, tracing of stratigraphic units, and observation of facies changes over distance. It is proposed here that the Wupatki Member is approximately equivalent to the lower red and middle red members of the Moenkopi Formation of northwestern Arizona; the lower massive sandstone member is correlative to the Shnabkaib Member; and the Holbrook and Moqui 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 from 27 m (90 ft) on the east flank of Gray Mountain and Little Colorado River Gorge west of Cameron, Arizona, to 23 m (75 ft) thick at Wupatki National Monument, and to less than 4.5 m (15 ft) thick in the southeast corner of the map area. South of Leupp, Arizona, about 32 km (20 mi) southeast of the map area, the Wupatki Member gradually pinches out and the lower massive sandstone member of the Moenkopi Formation unconformably overlies the Kaibab Formation. 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. Field mapping observations at the Vermilion Cliffs northwest of Marble Plateau and the Colorado River north show that the Shnabkaib Member undergoes a facies change south and east from a white siltstone, gypsiferous sandstone, and limestone to a yellowish-white crossbedded, ledge-forming, fine-to coarse-grained calcareous sandstone and thin limestone along the Echo Cliffs and Marble Plateau north of the Little Colorado River Gorge, then rapidly continues a facies change to a light red, fine-grained, cliff-forming, crossbedded fluvial sandstone southeast of the Little Colorado River Gorge to the Wupatki National Monument area where McKee (1954) describes the unit as the lower massive sandstone member. Thus, the lower massive sandstone member and the Shnabkaib Member are one and the same at the same stratigraphic horizon and represent a northwest to southeast shoreward facies change.

The lower massive sandstone is 12 to 15 m (40 to 50 ft) thick at the Little Colorado River Gorge and thins to less than 3 m (10 ft) in the vicinity of the town of Gray Mountain, Arizona, and gradually thickens southeast along the Little Colorado River Valley to as much as 26 m (53 ft) in the Wupatki National Monument area.

The Holbrook and Moqui Members of the Moenkopi Formation are defined by McKee (1954) and Hager (1922). The slope-forming Moqui Member is defined by McKee (1954) from exposures along Moqui Wash 13 km (8 mi) west of Winslow, Arizona, and is 26 m (85 ft) thick and is a lighter shade of reddish-brown than the underlying Wupatki or overlying Holbrook Member. The Moqui Member erodes into a uniform, mostly covered slope below the cliff-forming Holbrook Member. The sandstone beds of the Holbrook Member of the Moenkopi Formation were originally defined by Hager (1922) and form an irregular line of bluffs north of the Little Colorado River Valley between Holbrook, Arizona (about 64 km (40 mi) east of the map area) and Cameron, Arizona. The Holbrook and Moqui Members are mapped together as an undivided unit because both members are difficult to identify in some areas of the map. The Holbrook and Moqui 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) and may, in part, be Middle(?) Triassic age. The Holbrook and Moqui Members are unconformably separated from the overlying Triassic Chinle Formation.

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

Chinle Formation

The Triassic Chinle Formation is the most colorful formation in the map area and is subdivided into three mappable units along the Little Colorado River Valley. In ascending order they are the Shinarump Member and sandstone and siltstone member, undivided; the Petrified Forest Member; and the Owl Rock Member as defined by Repenning and others (1969).

The Shinarump Member and sandstone and siltstone member, undivided, is thickest northwest of Cameron in and around Shadow Mountain where accumulations are between 55 and 60 m (180 and 200 ft) thick. The upper sandstone and siltstone sequence of strata is predominantly a lenticular maze of thin to thick interbedded stream channel and flood-plain deposits of light-brown conglomerate, and lenticular crossbedded units of purple, gray, and red siltstone and sandstone. The sandstone and siltstone member as defined by Repenning and others (1969) forms a transitional unit between the Shinarump Member and Petrified Forest Member of the Chinle Formation; the sandstone and siltstone member erodes forming irregular and covered slopes of lenticular beds of mudstone, siltstone and silty sandstone.

Locally and just north of the map area, the sandstone and siltstone member is divided into two conspicuous units (Akers and others, 1958), a lower slope-forming mudstone and siltstone unit and an upper sandstone cliff-forming unit (these subdivisions are not mapped for this map). The sandstone and siltstone member sequence is not as crossbedded or as conglomeratic as the underlying Shinarump Member. The upper cliff-forming sandstone forms an irregular ledge between the lower slope-forming unit and the overlying Petrified Forest Member. The lower slope-forming unit thins southeastward resulting in a pinch out where the upper sandstone combines with the Shinarump Member near Cameron, and is often mistaken for the Shinarump. For this reason and for mapping purposes, the Shinarump Member and sandstone and siltstone member are combined as an undivided map unit. West of Cameron at Red Butte (west of map area) and in a few exposures near the Coconino Point Monocline at the base of Gray Mountain, the sandstone and siltstone member overlies the Moenkopi Formation where the Shinarump Member is absent (Repenning and others, 1969).

The conglomeratic sandstone beds of the Shinarump Member contain numerous petrified logs and wood fragments. Some of the petrified logs and carbonaceous sandstone deposits became enriched with uranium minerals. Several open-pit mines were developed in the 1950's to mine the uranium along the Little Colorado River area. Today all of the mines are abandoned and many have undergone restoration. The thickness of the Shinarump Member and sandstone and siltstone member, undivided, is variable due to widespread local channel erosion and local pinch out and thinning of the siltstone unit. The map unit generally thins southeastward to between 9 and 18 m (30 and 60 ft) thick along the Little Colorado River. The contact between the Shinarump Member and sandstone and siltstone unit, undivided, and the overlying Petrified Forest Member is gradational and highly variable.

The Petrified Forest Member of the Chinle Formation is the colorful middle part of the Chinle Formation and forms the multicolored blue, red, and grayish-green mud hills of the "Painted Desert" badlands along and north of the Little Colorado River and is the most widespread member of the Chinle Formation. The upper and lower parts of the Petrified Forest Member are separated by the Sonsela Sandstone Bed in the upper Little Colorado River Valley east of the map area. In the map area, the upper and lower parts of the Petrified Forest Member cannot be differentiated with certainty because the Sonsela Sandstone Bed is absent; therefore the Petrified Forest Member is mapped as one unit.

Locally, the Petrified Forest Member can be subdivided into three units based on slight lithologic and color differences according to Akers and others (1958), but these units are herein mapped together as the Petrified Forest Member of the Chinle Formation because the gradational boundaries between them are highly variable. The three units are, in ascending order, a blue mudstone, a gray mudstone and sandstone, and a red mudstone and sandstone. The blue mudstone unit is a continuous band of strata within the lower part of the Petrified Forest Member and the two overlying units gradually thin and grade eastward of the map area into the interval occupied by the Sonsela Sandstone Bed and upper part of the Petrified Forest Member. The Petrified Forest Member generally maintains a thickness between 122 and 153 m (400 and 500 ft).

Gradationally overlying the Petrified Forest Member of the Chinle Formation is the Owl Rock Member of the Chinle Formation. The Owl Rock Member consists of a sequence of gray interbedded ledge-forming siliceous limestone and light-red and yellowish-gray, slope-forming, calcareous siltstone beds that form Ward Terrace northeast of the Little Colorado River (fig. 1). The contact between the Petrified Forest and Owl Rock Members is generally marked between the pastel pale-red mudstone and siltstone beds of the lower Owl Rock Member and the lenticular varicolored mudstone, siltstone, and sandstone beds of the Petrified Forest Member about 12 m (40 ft) below the lowest gray limestone bed of the Owl Rock Member. The upper contact of the Owl Rock Member with the overlying Moenave Formation is unconformable and marked by a sharp contrast in color and lithologic change from the blueish-gray mudstone of the Owl Rock to the orange-red fluvial sandstone of the Moenave. This regional unconformity is known as the J-O unconformity (Pipiringos and O'Sullivan, 1978; Peterson and Pipiringos, 1979) and separates the Triassic rocks from the overlying Jurassic rocks. The Owl Rock Member is about 82 m (270 ft) thick north of Cameron, Arizona, and gradually thins southeastward along the Little Colorado River to less than 60 m (200 ft) in the southeast corner of the map area.

Moenave Formation

The Owl Rock Member of the Chinle Formation is overlain by the orange-red sandstone and silty sandstone sequences of the Moenave Formation. The type section of the Moenave Formation is about 13 km (8 mi) north of the map area near the community of Moenave, Arizona. The Moenave Formation includes, in ascending order, the Dinosaur Canyon Member (Colbert and Mook, 1951) that is exposed 30 km (19 mi) south of the type locality and within this map area; and the Springdale Sandstone Member, originally described by Gregory (1950) as part of the Chinle Formation and redefined as the upper member of the Moenave Formation by Harshbarger and others (1958). The Dinosaur Canyon and Springdale Sandstone Members are not mapped separately on this map because the Springdale Sandstone, although present at the north edge of the map, undergoes a facies change from sandstone to siltstone and silty sandstone in the upper part of the Dinosaur Canyon Member. East of the map area, the Moenave Formation intertongues with the Wingate Sandstone. The environmental and regional correlations and paleogeographic reconstructions of the fluvial and eolian systems of the Moenave Formation and the Wingate Sandstone are described by Edwards (1985), Clemmensen and others (1989), Blakey and others (1992), Riggs and Blakey (1993), and Nation (1990). Overall, in the map area the Moenave Formation is between about 84 to 98 m (275 to 320 ft) thick and gradually thins east of the map area.

Cooley and others (1969) mapped the Rock Point and Lukachukai Members of the Wingate Formation (Sandstone) on the Ward Terrace area northeast of the Little Colorado River, as did Billingsley (1987a) using data by Cooley and others (1969). However, the Rock Point and Lukachukai Members of the Wingate Sandstone are not mapped in this map area because of the correlation of these units east of the map area is not stratagraphically correct. The Wingate Sandstone members as mapped by Cooley and others (1969) is between the Moenave Formation and the Chinle Formation, but east and north of the map area, the Wingate Sandstone is correctly mapped between the Moenave Formation and the Kayenta Formation. A thin white sandstone at the top of the Moenave Formation forms a hard caprock at the top of the Red Rock Cliffs resulting in the development of the Red Rock Cliffs (fig. 1). This white sandstone is likely the western extent of the Wingate Sandstone but is not shown on this map because it is too thin (less than 1 m [3 ft]) to show at map scale. The Wingate Sandstone increases to 12 m (40 ft) thick as a light-red and white massive, low-angle crossbedded sandstone in the western part of the Hopi Buttes area about 60 km (37 mi) southeastward into the western part of the Hopi Buttes area southeast of the map area (current mapping by the author). Most of the Moenave Formation, Wingate Sandstone, and Kayenta Formation interval is covered by surficial alluvial and eolian deposits about 72 km (45 mi) east of the map in the Hopi Buttes area. However, regional and local trends suggest that some of the upper fluvial-dominated cycles of the Moenave Formation correlate with eolian-dominated cycles of the Wingate Sandstone east and northeast of the map area (Blakey, 1994). The Rock Point and Lukachukai Members of the Wingate Formation (Sandstone) at the base of the Red Rock Cliffs, as mapped by Cooley and others (1969), are lithologically and locally similar to the overall Moenave Formation and are herein mapped as the basal part of the Moenave Formation.

Kayenta Formation and Navajo Sandstone

Contact of the purplish-red, slope-forming siltstone and sandstone sequence of the Kayenta Formation (Jk) unconformably overlies the brick-red sandstones of the Moenave Formation (Jm) in the Red Rock Cliffs and Ward Terrace areas. The unconformity is marked by a sharp, white to purplish-white silica-cemented sandstone bed that is the western extent of the Wingate Sandstone at the base of the Kayenta Formation. This unconformity is the sub-Kayenta Formation unconformity (J-sub-K) as defined by Riggs and Blakey (1993) and Blakey (1994) and the unconformity extends across the Colorado Plateau wherever the Kayenta Formation and the Springdale Sandstone Member of the Moenave Formation are present. The erosional relief is generally less than 2 m (6 ft) in the map area but the relief is as much as 15 m (50 ft) north of the map area (Nation, 1990).

The Kayenta Formation (Jk) grades upward into a sequence of interbedded red and white crossbedded sandstone ledges and cliffs and purplish-red mudstone and siltstone slopes mapped as the Kayenta Formation-Navajo Sandstone transition zone (Jkn). The white and red crossbedded sandstone ledges and cliffs within the upper Kayenta Formation are tongues of the Navajo Sandstone and the purplish-red mudstone and siltstone slopes are tongues of the Kayenta Formation. North of the map area, the tongues of Navajo Sandstone change southward from cliff-forming eolian deposits to slope-forming fluvial deposits of the “silty facies” of the Kayenta Formation (Blakey, 1994). Blakey (1994) subdivided the Navajo Sandstone of this region into two parts, as suggested by Marzolf (1983); the lower part is equivalent to and intertongues with eolian and fluvial deposits of the Kayenta Formation-Navajo Sandstone transition zone, and the upper part is the eolian cliff-forming Navajo Sandstone above the youngest documentable horizon of intertonguing. This subdivision of the Navajo Sandstone is recognized by Marzolf (1983) as the “wet lower part” and the “dry upper part.”

The Kayenta Formation thins from about 122 m (400 ft) thick in the northeast corner of the map area to less than about 98 m (320 ft) at the east edge. The Kayenta Formation-Navajo Sandstone transition zone gradually thickens from about 37 m (120 ft) at the northeast corner of the map area to about 73 m (240 ft) thick at the southeast edge. In the zone of facies change, the associated succession of fluvial, eolian, and lacustrine strata become more frequent southeastward of the Adeii Eechii Cliffs, and the Kayenta Formation thins (Middleton and Blakey, 1983; Sargent, 1984). Several springs and seeps are associated with the base of the Navajo Sandstone (Jn) along the Adeii Eechii Cliffs and this horizon is used as the map contact between the Kayenta Formation and Navajo Sandstone transition zone.

The Navajo Sandstone consists of red and white, cliff-forming, crossbedded eolian sandstone and is the upper part of the Navajo Sandstone as proposed by Blakey (1994). The Navajo Sandstone includes several horizons and intervals of local wadi lake deposits as thin-bedded, silica-cemented sandy limestone beds (0.5 to 1.2 m [1 to 2 ft]) thick that are highly lenticular and are of limited lateral extent. These resistant limestone beds are at various levels within the Navajo Sandstone and form local cherty limestone ridges or hills on the Moenkopi Plateau surface. The limestone ledges are frequently exposed along the Adeii Eechii Cliffs and increase in number southeastward as the Navajo Sandstone decreases in thickness from 76 to 48 m (250 to 160 ft) on the Moenkopi Plateau.

The beveled upper surface of the Navajo Sandstone is an erosional unconformity known regionally as the J-1 and J-2 unconformity (Pipiringos and O’Sullivan, 1978; Blakey, 1994). At Appaloosa Ridge and at the west end of Coal Mine Mesa of Moenkopi Plateau, as much as 9 m (30 ft) of erosional relief separates the Navajo Sandstone from the overlying Jurassic Entrada Sandstone-Cow Springs Sandstone, undivided. The erosional channels are filled with conglomerate and sandstone sediment that may be the southernmost extent of the Carmel Formation. At Middle Mesa about 26 km (16 mi) north of the northeast corner of the map area, about 12 m (40 ft) of the Carmel Formation overlies the Navajo Sandstone at Tohnali Mesa and just north of the northeast edge of the map the Carmel Formation is 1.5 to 2 m (5 to 7 ft) thick. The Carmel Formation pinches out in the subsurface of Coal Mine Mesa and is included in the lower part of the Jurassic Entrada Sandstone (Je), but is too thin to show at map scale.

Entrada Sandstone and Cow Springs Sandstone, undivided

The interval of sedimentary strata between the Jurassic Navajo Sandstone (Jn) and the overlying Cretaceous Dakota Sandstone (Kd) consists mostly of white crossbedded sandstone of the Entrada Sandstone (Je) and the yellowish sandstone of Cow Springs Sandstone in the upper part, undivided. This sandstone sequence includes thin red beds of the Carmel Formation at the base of the unit that pinches out southward into the subsurface of Coal Mine Mesa and is too thin to show at map scale. The Carmel Formation thickens north of the map area forming the J-1 and J-2 unconformity (Blakey, 1994) at the top of the Navajo Sandstone.

The lower massive white, very fine-grained cliff- and slope-forming sandstone that weathers steel gray is the Entrada Sandstone (Je) and contains multiple small-scale trough crossbeds. The middle part of the Entrada Sandstone sequence contains a few thin, flat bedded, red siltstone and sandstone beds that may be equivalent to the Summerville Formation at Black Mesa northeast of the map area but pinch out into this part of the map area (Harshbarger and others, 1958). The upper part of the sandstone sequence is yellowish-white, cliff and slope of planar crossbedded sandstone that is a southern extension of the Cow Springs Sandstone (Harsbarger and others, 1958). The Entrada Sandstone and Cow Springs Sandstone, undivided, is unconformably overlain by the Cretaceous Dakota Sandstone (Kd). The Jurassic-Cretaceous unconformity is regionally widespread east and southeast of the map area.

Dakota Sandstone and Mancos Shale

The Cretaceous Dakota Sandstone (Kd) crops out at Appaloosa Ridge and Coal Mine Mesa of the Moenkopi Plateau, northeast corner of the map area. The Dakota Sandstone is subdivided into three units, in ascending order, the lower sandstone member, middle carbonaceous member, and the upper sandstone member; all are present at Coal Mine Mesa and have gradational contacts (O'Sullivan and others, 1972). All three members are too small to show at map scale and are collectively mapped as the Dakota Sandstone.

The lower sandstone member forms a pale-orange lenticular conglomeratic sandstone cliff that occupies shallow channels of a regional unconformity eroded into the underlying Jurassic Entrada Sandstone and contains abundant small iron-rich concretions. The lower sandstone member is generally less than 6 m (20 ft) thick and is missing in parts of the eastern Coal Mine Mesa area where the middle carbonaceous member unconformably overlies the Entrada Sandstone. The middle carbonaceous member is a brown, grayish-black, and black carbonaceous mudstone and siltstone and that averages about 9 m (30 ft) thick. Coal beds are locally several feet thick at the eastern part of Coal Mine Mesa and in the early 1900's coal was mined from this unit at Coal Mine Canyon just north of the northeast corner of the map area for use at Tuba City, Arizona. The Dakota Sandstone has a gradational and arbitrary contact with the overlying Mancos Shale.

Only the lower part of the Mancos Shale is present at Coal Mine Mesa of the Moenkopi Plateau in the northeast corner of the map area. During the Cenozoic, most of the bluish-gray, thin-bedded, slope-forming Mancos Shale was eroded from Coal Mine Mesa; the Mancos Shale is now largely covered by extensive surficial deposits of eolian and fluvial sand, silt, and mud eroded from remnants of the Mancos Shale.

San Francisco Volcanic Field

The Tertiary and Quaternary volcanic rocks of the San Francisco Volcanic Field form a protective caprock over the Permian Kaibab Formation and the Triassic Moenkopi Formation in the southwest quarter of the map area. The volcanic rocks are Pliocene, Pleistocene, and Miocene in age (table 1) as mapped by Ulrich and Bailey (1987) and Wolfe and others (1987). The oldest volcanic rock in the map area is the basalt flow of Cedar Ranch Mesa (K-Ar age, 5.62±0.19 Ma) east of U.S. Highway 180 and the youngest is the basalt flow of Merriam Crater (optical-luminescence age, 19.6±1.2 ka; Duffield and others, 2004) in the Little Colorado River channel, southeast corner of map area. The volcanic rocks range in composition from basalt to rhyolite. The volcanic rocks were mapped on the basis of lithology and morphology and are grouped into map units delineated on the basis of magnetic polarity, radiometric age, and field relations by Ulrich and Bailey (1987) and Wolfe and others (1987). Within these chronostratigraphic units, boundaries 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 as a whole. The K-Ar ages indicated for some of the map units were determined by Paul E. Damon and Edwin H. McKee (Ulrich and Bailey, 1987), and recently by Duffield and others (2004), but most were originally reported by Damon and others (1974).

Surficial Deposits

Quaternary fluvial and eolian deposits cover parts of the southwestern two-thirds of the map area and much of the northeastern third of the map area. Extensive black volcanic cinder ash has been deposited by southwesterly winds as eolian cinder sand sheet and dune deposits in the Wupatki National Monument area and at nearby volcanic pyroclastic cones and basalt flows southwest of Wupatki National Monument. Alluvial deposits are largely unconsolidated thin surface deposits in much of the west and central part of the map area. The Little Colorado River, which flows towards the Grand Canyon northwest of the map area, is the principal drainage in the map area. The Little Colorado River and all of the tributaries on the northeast side of the river are the main source and supply for extensive eolian sand sheet and sand dune deposits that are transported by southwesterly winds to the northeast toward Moenkopi Plateau. Eolian sand sheet and dune deposits have accumulated on Ward Terrace and thick deposits have piled up against the Red Rock Cliffs area (fig.1; fig. 3. on map). These eolian deposits are gradually eroded and transported as sandy alluvium down the tributary drainages back to the Little Colorado River where some of the sand is recycled by the southwesterly winds and blown back to the Red Rock Cliffs to be eroded again. Eventually, the sand is transported down the Little Colorado River to the Colorado River and through Grand Canyon. Extensive and older sand sheet and dune deposits blanket the Moenkopi Plateau northeast of the Adeii Eechii Cliffs (Hack, 1941; Billingsley, 1987b) and are largely stabilized by grassy vegetation. However, in recent years (1990 to 2006) drought has caused some of these deposits to become reactivated and strong

Table 1. *Geochron ages for volcanic rocks within the map area*

Unit label	General geographic locality	Location		Rock type	Calculated age (K-Ar unless noted)	Polarity, Chronozone age	Reference
		Latitude (N)	Longitude (W)				
Qmcb	Merriam Crater flow in Little Colorado River	35.34°	111.28°	Basalt	19.6±1.2 ka (optical-luminescence)	—	Duffield and others (2004)
Qyab	S P Mountain	35.62°	111.61°	Basaltic andesite	0.071±0.004 Ma	Brunhes	Reynolds and others (1986) and Ulrich and Bailey (1987)
Qb	Arrowhead Sink	35.50°	111.55°	Basalt	0.22±0.05 Ma	Brunhes	Ulrich and Bailey (1987)
Qb	S P Tank	35.72°	111.62°	Basalt	0.46±0.05 Ma	Brunhes	Ulrich and Bailey (1987)
Qbt	Tappan Wash	35.89°	111.46°	Basalt	0.53±0.079 Ma	Brunhes	Damon and others (1974)
Qsb	Shadow Mountain	35.99°	111.38°	Basalt	0.649±0.23 Ma	—	Reynolds and others (1986) and Damon and others (1974)
Qb	Southwest of S P Mountain	35.54°	111.74°	Basalt	0.66±0.11 Ma	Brunhes	Ulrich and Bailey (1987)
Qb	Campbell Francis Wash	35.69°	111.55°	Basalt	0.74±0.08 Ma	Brunhes	Ulrich and Bailey (1987)
Qb	S P Tank	35.66°	111.59°	Basalt	0.77±0.04 Ma	Brunhes	Ulrich and Bailey (1987)
Qwb	Southwest of Woodhouse Mesa	35.82°	111.65°	Basalt	0.786±0.14 Ma	Matuyama	Ulrich and Bailey (1987)
Qsfp	San Francisco Mountain	35.51°	111.55°	Pumice	0.80±0.11 Ma (fission-track)	Matuyama	Reynolds and others (1986) and C.W. Naeser and G.A. Izet, *in* Ulrich and Bailey (1987)
Qwb	Woodhouse Mesa, south of map area	35.48°	111.37°	Basalt	0.812±0.059 Ma	—	Reynolds and others (1986)
Qmb	Mesa Butte Fault fissure vent near Lockwood Canyon	35.66°	111.75°	Basalt	0.83±0.04 Ma	Matuyama	Ulrich and Bailey (1987) and Wolfe and others (1987)
Qwb	Kellam Ranch, south of map area	35.37°	111.30°	Basalt	0.874±0.13 Ma	—	Reynolds and others (1986)
Qwb	Wupatki National Monument south of visitor center	35.50°	111.00°	Basalt	0.897±0.14 Ma	—	Reynolds and others (1986)
Qmlp	Lava Point	35.69°	111.53°	Basalt	1.01±0.13 Ma	Matuyama	Ulrich and Bailey (1987)
Qmb	East of Mesa Butte	35.63°	111.74°	Basalt	1.04±0.04 Ma	Matuyama	Ulrich and Bailey (1987)
Qmb	Northeast of S P Mountain	35.66°	111.54°	Basalt	1.04±0.14 Ma	Matuyama	Ulrich and Bailey (1987)
Qmb	Large Whiskers Tanks	35.74°	111.56°	Basalt	1.09±0.03 Ma	Matuyama	Ulrich and Bailey (1987)
Qmbi	East of U.S. Highway 89 and north of S P Mountain	35.64°	111.51°	Basalt	1.20±0.05 Ma	Matuyama	Ulrich and Bailey (1987)
Qmb	East of Mesa Butte	35.68°	111.72°	Basalt	1.38±0.16 Ma	Matuyama	Ulrich and Bailey (1987) and Wolfe and others (1987)
Qslr	Slate Mountain	35.49°	111.84°	Rhyolite dome complex	1.54±0.02 Ma	Matuyama	Reynolds and others (1986) and Wolfe and others (1987)
Tbpb	Black Point	35.63°	111.35°	Basalt	2.43±0.32 Ma	—	Reynolds and others (1986) and Ulrich and Bailey (1987)
Tbi	Dike in ampitheater	35.66°	111.58°	Basalt	3.13±0.39 Ma	Gauss or Gilbert	Ulrich and Bailey (1987)
Tocb	Cedar Ranch Mesa	35.52°	111.75°	Basalt	5.62±0.19 Ma	—	Reynolds and others (1986) and Ulrich and Bailey (1987)

dry winds redeposit the sand as a fresh thin sand veneer over the older deposits in some areas, especially where large stock tanks and windmills are present.

Other surficial deposits are comprised of landslide, talus, and rock fall deposits that are exposed mainly around and below the edges of volcanic rock outcrops such as at Black Point. Several landslide and associated deposits are present on Gray Mountain and in the Little Colorado River Gorge. Man-made diversion dams, stock tanks, gravel pits, and old open-pit uranium mine operations are also mapped to show the human impact on the landscape.

Structural Geology

High-angle to nearly vertical normal-fault separation of Paleozoic and Mesozoic strata and northeast and east-dipping sinuous and intersecting monoclines are the characteristic structures of the map area. Compressional folding of the Paleozoic and Mesozoic rocks along reactivated Proterozoic high-angle faults began in Late Cretaceous and early Tertiary time (about 65 Ma) causing erosion to begin removing Mesozoic strata that once covered the entire map area (Huntoon, 1990). The Laramide erosional period began to transform the landscape to its general configuration, but the late Tertiary and Pleistocene erosion developed the Little Colorado River Valley as a subsequent stream that became an established tributary to the Colorado River in Grand Canyon northwest of the map area (Ranney, 2005). A meandering Little Colorado River appears to have been superimposed as a subsequent stream onto the southern part of Marble Plateau within a synclinal strike valley between the East Kaibab/Coconino Point Monoclines and Marble Plateau. The Little Colorado River and its tributaries became firmly established as an integrated tributary river system to the Grand Canyon sometime in late Miocene or early Pliocene time, between about 6 to 9 million years (Lucchitta, 1979; 1990). Headward erosion of the Little Colorado River, caused by the deepening Colorado River in Grand Canyon, gradually extended the Little Colorado Canyon upstream toward Cameron, Arizona, as demonstrated by the 500 thousand year-old Tappan Basalt flow (Qbt) that forms a ridge or inverted valley within the Little Colorado River drainage downstream of Cameron, Arizona (fig. 2 on map).

The north- and east-dipping monoclines in the map area overlie deep-seated reverse faults that displaced strata up-to-the-west and south during Late Cretaceous and early Tertiary time. During Pliocene and Pleistocene time, east-west extension reactivated the deep-seated faults along parts of some monocline folds, producing normal fault separation that reversed the Cretaceous and Tertiary offset as well as accentuating the dip of the monoclines by reverse drag along the faults (Huntoon, 1990; 2003). Cenozoic extensional faulting that produced many grabens began during late Pliocene time, less than 3 million years ago, based on similar extensional faulting evidence and conditions along the Hurricane and Toroweap Faults west of the map area (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003).

The northwest-trending grabens and faults in the Gray Mountain, S P Mountain, Little Colorado River Gorge, and Wupatki National Monument areas seem to be the most tectonically active structures based on minor offset of Pleistocene and Holocene(?) alluvial deposits and Pleistocene volcanic deposits. Numerous sinkhole depressions have developed along fractures and joints associated with the faults and grabens and have temporarily interrupted runoff in several tributary drainages to the Little Colorado River in the area from the Little Colorado River Gorge southeast to Wupatki National Monument. The basalt flow of Tappan Wash (0.51±0.079 Ma) is offset a few meters by two grabens in two areas along the Little Colorado River below Cameron, Arizona (Rice, 1977), and is offset by minor grabens southwest of Cameron, Arizona, and is offset by the Cedar Ranch Fault at the southwest edge of the map (Shoemaker and others, 1974).

The Coconino Point Monocline is the largest monocline in the map area and it forms the topographic prominent highland of Gray Mountain (fig. 1). Paleozoic and Mesozoic strata dip sharply north, northeast, east, and southeast along the Coconino Point Monocline and at some places on the north side of Gray Mountain, the dip of strata is nearly vertical to slightly overturned. Southwest of the Gray Mountain prominence, the regional dip of strata is generally between 1° and 2° southwest. Small, normal, high-angle, down-to-the-west faults have reversed some of the Laramide offset of strata along short segments of the Coconino Point Monocline on Gray Mountain. The western segment of the Coconino Point Monocline terminates at the T-shaped intersection of the northwest-trending East Kaibab Monocline and the west-trending Grandview Monocline (Doty, 1982).

The East Kaibab Monocline extends northwest into the eastern Grand Canyon area northwest of the map and forms a major structural feature of the eastern Grand Canyon (Huntoon and others, 1996). The East Kaibab Monocline continues northward into Utah. Strata along the East Kaibab Monocline within the map area dip northeast between 20° and 40° with the steepest dip in the lower part of the fold. The vertical relief of Paleozoic strata averages about 305 m (1,000 ft) up-to-the-west.

The Grandview Monocline extends west from the intersection of the East Kaibab and Coconino Point Monoclines to a northwest bend in the structural trend and continues into the Grand Canyon at the northwest corner of the map. The Permian and Triassic strata along the east trending segment of the Grandview Monocline are mostly Permian age, highly folded to a near vertical position, and partly faulted, generally with less than 30 m (100 ft) of offset. The folding has elevated the Coconino Plateau an average of 275 m (900 ft) up-to-the-south. South of the Grandview Monocline the elevated highlands form the western part of Gray Mountain of the Coconino Plateau. From the northwest bend of the Grandview Monocline to the Grand Canyon, the dip of Paleozoic and Mesozoic strata in the upper part of the monocline averages 20° to 30° northeast, and the dip of strata increases to as much as 75° northeast in the lower part of the fold. West and southwest along the northwest segment of the Grandview Monocline to the Grand Canyon, the elevated highlands are between 122 and 153 m (400 and 500 ft) high.

West of the bend in the Grandview Monocline, a small east striking scissors fault indicates a probable structural connection at depth with the Skinner Ridge Anticline 3 km (2 mi) farther west. The east trending Skinner Ridge Anticline and associated syncline is a similar structure north of the Red Horse Anticline and Red Horse Syncline.

The Red Horse Anticline and Red Horse Syncline are generally east trending and parallel to Red Horse Wash southwest of Gray Mountain. Between the anticlinal and synclinal hinges the Paleozoic and Mesozoic strata dip as much as 7° north with an average dip of 3° to 4° north. Strata on the south limb of the Red Horse Anticline dip less than 2° south. The Red Horse Anticline and Syncline gradually terminate southwest of Gray Mountain and west of the Mesa Butte Fault and appear to control the stream patterns in their vicinity.

South of Gray Mountain, the Coconino Point Monocline extends to what was mapped as the Additional Hill Monocline described by Barnes (1974) and mapped by Billingsley and others (1985). Upon closer inspection of aerial photographs and additional field checking, it is determined that the Coconino Point Monocline and the Additional Hill Monocline are really one and the same structure that makes a southeasterly bend at its intersection with the Mesa Butte Fault. The Coconino Point Monocline gradually turns to a southwesterly trend parallel to the Mesa Butte Fault (fig. 1). The name Additional Hill Monocline is herein dropped from usage and is replaced by the Coconino Point Monocline on this map.

Gray Mountain

The trapezoidal shape of Gray Mountain northeast of the Burro Canyon Graben System is the highest block of Gray Mountain; its surface is cut by three prominent joint sets that form perfect equilateral triangles. This area is also distinguished by two dome structures separated by a sharp synclinal flexure. This structurally complex area has produced an epidermal landslide block (labeled as Ql, cross section B–B') that consists of a relatively coherent sheet of the Kaibab Formation derived from a steeply dipping source near the crest of Gray Mountain. This landslide block horizontally preserves the synclinally folded younger Triassic strata at the base of the northeast face of Gray Mountain (Marshall, 1972).

Southwest of Gray Mountain, the Burro Canyon Graben System parallels the regional joint pattern and other north-by-northwest oriented grabens exposed on the top of Gray Mountain and are parallel to the north on the upper limb of the East Kaibab Monocline. The East Kaibab Monocline intersection with Coconino Point Monocline marks an abrupt shift from monoclinal folding to marked extension along the trend of the East Kaibab Monocline axis southeast across Gray Mountain, forming the Burrow Canyon Graben System (Barnes, 1974; Lufholm, 1975).

On the southwest face of Gray Mountain the intersection of the East Kaibab-Burro Canyon structures with the Coconino Point Monocline marks an abrupt shift from extension across Gray Mountain back to monoclinal folding along the Coconino Point Monocline. The area of strain transfer coincides with the intersection of the Mesa Butte Fault (a graben in this area). Offset along the Mesa Butte Fault is right oblique slip, southeast side down. These geometric relations suggest that a northeasterly oblique shift in the strain pattern along the Mesa Butte Fault formed the Gray Mountain Prominence (Pettengill, 1970; Barnes, 1974).

The Coconino Point Monocline extends southwest and parallel to the southwest strike of the Mesa Butte Fault and Mesa Butte Graben for about 19 km (12 mi) and dies out near the Mesa Butte volcano about 3 km (2 mi) north of Mesa Butte. The Mesa Butte Fault and the Cedar Ranch Fault intersect at the north side of Mesa Butte volcano. The Cedar Ranch Fault offsets Paleozoic and Mesozoic strata down-to-the-southeast about 85 m (280 ft). The Mesa Butt Fault combines with the Cedar Ranch Fault for a short distance for a total offset of strata about 110 m (360 ft) down-to-the-southeast. East and south of Mesa Butte, the Cedar Ranch Fault strikes southwest east of and parallel to the Mesa Butte Fault. The Cedar Ranch Fault continues southwest to Cedar Ranch where the fault is buried by large landslide deposits and Tertiary basalt flows. The Cedar Ranch Fault likely extends to the south edge of the map, but extensive basalt flows of the San Francisco Volcanic Field cover the fault trace.

The Mesa Butte Fault offsets strata generally less than 30 m (100 ft) down-to-the-southeast along the Mesa Butte Graben section that forms a linear depression along the southeast side of Mesa Butte Fault. However, southwest of Gray Mountain, Permian strata has been down-dropped into the graben as much as 80 m (260 ft) and forms an impressive linear feature about 0.5 km (0.25 mi) wide and about 20 km (12 mi) long. This linear feature forms a prominent "crack" or linear depression on the landscape that is easily seen on aerial photographs and satellite images. The Mesa Butte Fault and Graben intersect the northeast structural trend of the Coconino Point Monocline along its eastern face; oblique shift along that fault progressively elevated Paleozoic and Mesozoic strata up-to-the-northwest forming a hinge-faulted monocline along its trend northeast of the Mesa Butte Graben. This structural pattern of northeasterly oblique slip, up-to-the-northwest is paralleled by a similar but smaller scale fault, the Doney Mountain Fault in the south-central part of the map area (Barnes, 1974).

The Coconino Point Monocline, a short segment of the Mesa Butte Fault, and the Cedar Ranch Fault, form a major structural barrier to ground water flow between groundwater flowing west to Havasu Spring in the central Grand Canyon region and groundwater flowing north into Blue Spring about 14.5 km (9 mi) north of the map area in the Little Colorado River Gorge. The divide between east and west flowing surface drainages is generally a few miles west of the Mesa Butte and Cedar Ranch Faults. Dog Knobs Lake is an area of internal drainage within the southwest part of the map, but in general the surface runoff west of the Dog Knobs and Gray Mountain areas flows west to Cataract Canyon and into the central part of Grand Canyon, and the surface runoff east of the Dog Knobs and Gray Mountain areas flows northeast toward the Little Colorado River.

The Black Point Monocline and Coconino Point Monocline intersect about 6.5 km (4 mi) south of the Gray Mountain Prominence (fig. 1). The Black Point Monocline is a broad northeast-dipping structure where Permian and Triassic strata dip between 15° and 30° northeast and the fold averages about

1.6 km (1 mi) wide. The Black Point Monocline trends southeast from its intersection with the Coconino Point Monocline at Gray Mountain to Black Point (fig. 1 on the map) and to about 8 km (5 mi) southeast of Black Point where it intersects the northeast strike of Doney Mountain Fault. The Black Point Monocline abruptly bends to the southwest in a series of right-stepping en echelon faults and parallels the Doney Mountain Fault southwest to the Wupatki National Monument area (McCormack, 1989). The Black Point Monocline gradually dies out south of Wupatki National Monument and is offset down-to-the-southeast by the Doney Mountain Fault. The Doney Mountain Fault offsets Permian and Triassic strata as much as 67 m (220 ft) north of Doney Mountain and 92 m (300 ft) at Doney Mountain volcano. Doney Mountain volcano erupted along the east side of and parallel to the strike of the Doney Mountain Fault in Wupatki National Monument. The Black Point Monocline and Doney Mountain Fault gradually die out just southwest of Wupatki National Monument and are covered by basalt flows of the San Francisco Volcanic Field.

The Echo Cliffs Monocline is a broad southeast-dipping monocline that forms the eastern boundary of Marble Plateau where the dip of Permian and Triassic strata is generally less than 3° to 4° southeast in the vicinity of Shadow Mountain and where the monocline gradually terminates. This monocline forms a prominent structural fold north of the map area and parallels U.S. Highway 89 for several miles. The southern terminus of the monocline seems to intersect a structurally complex area where the Little Colorado River Gorge begins. The southwesterly trending Echo Cliffs Monocline intersects a northeasterly trending syncline that may be a continuation of the northeast strike of the Mesa Butte Fault at depth. The syncline and Mesa Butte Fault are separated by a nearly perpendicular structure called the Blue Spring Monocline.

The Blue Spring Monocline just north of Gray Mountain is a northwest trending structure of northeast-dipping Paleozoic and Mesozoic strata. The relief along this monocline is generally less than 60 m (200 ft) and the average dip of strata is about 5° northeast. Several collapse breccia pipe structures are generally aligned along the northwest trend of the Blue Spring Monocline. The Blue Spring Monocline is perhaps the most important hydrological structure in the map area. Its northwesterly trend gradually terminates into a down-to-the-northeast fault that extends to Blue Spring in the bottom of the Little Colorado River Gorge just northwest of the map area. Associated with the Blue Spring Monocline and Fault are numerous northwest trending joints and fractures from which Blue Spring and several smaller springs issue at the top of the Redwall Limestone. The structural faults, fractures, and joints associated with the Blue Spring Monocline form a major hydrological avenue for ground water transport; groundwater from most regions northeast, east, southeast, and south of Gray Mountain flows through karst caverns and open joints in the Redwall Limestone to Blue Spring north of the map area. Blue Spring is the largest natural flowing spring in Arizona; daily discharge is nearly 200 cubic feet per second.

Circular bowl-shaped depressions in the Kaibab Formation, characterized by inward-dipping strata, are likely to be the surface expression of collapse-formed breccia pipes that originate from the dissolution of limestone of the deeply buried Mississippian Redwall Limestone. The dissolution of gypsum in the Woods Ranch Member of the Toroweap Formation may enhance some of these collapse features (Wenrich and Huntoon, 1989). Collapse features are indicated by a black dot on the map and may or may not represent breccia-pipe structures at depth. Exposed breccia in breccia pipes are indicated by a red dot. Drilling methods are needed to confirm breccia pipes that originate at depth in the Redwall Limestone. Large-scale collapse depressions may be the result of several interconnecting smaller collapse features or breccia pipes, such as the depressions north of the Little Colorado River on Marble Plateau and on the Coconino Plateau southwest of Gray Mountain. Breccia pipes have the potential for uranium-mineralization and other minerals at depth, but not all breccia pipes are mineralized (Sutphin and Wenrich, 1989; Wenrich, 1992). Only circular collapse features that have inward dipping strata are marked on the map as potential breccia pipes at depth.

Gypsum dissolution within the Harrisburg Member of the Kaibab Formation has resulted in several sinkholes on the Coconino Plateau. The sinkholes are likely Pleistocene and Holocene age because they disrupt local drainages and are commonly filled with local ponded fine-grained sediments. The deposits of gypsum in the Kaibab and Toroweap Formations are thickest along the west edge of the map area as reflected by the numerous sinkholes.

Internal drainage areas in the volcanic rocks of the San Francisco Volcanic Field may reflect large sinkhole depressions in the underlying Harrisburg Member of the Kaibab Formation in the southwest quarter of the map area. During wet climatic conditions these depressions form intermittent lakes such as Dog Knobs Lake and Babbitt Lake, southwest quarter of map area (fig.1). However, because Dog Knobs Lake is underlain by a small graben structure along which small sinkholes have developed that quickly drain any water, the lake is almost always dry.

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DESCRIPTION OF MAP UNITS

[Some unit exposures on the printed map are too small to distinguish the color for unit identification. These units are labeled where possible, and unlabeled units are attributed in the geodatabase.]

SURFICIAL DEPOSITS

Holocene, Pleistocene, and Pliocene(?) surficial deposits are differentiated from one another chiefly on the basis of differences in morphologic character and physiographic position illustrated 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. On Moenkopi Plateau, extensive sand sheet and dune deposits are relatively stabilized by vegetation and are the oldest eolian deposits within the map area (Billingsley 1987a; Hack, 1941). These deposits are partially reactivated on surfaces during severe drought or storm conditions, especially along the Adeii Eechii Cliffs of the Moenkopi Plateau. Surficial map contacts of eolian units are provisional and arbitrary. Young surficial deposits are actively accumulating material and often subject to moderate erosion.

Qaf **Artificial fill and quarries (Holocene)**—Excavated alluvium and bedrock material removed from bar-pits and trenches to build livestock tanks, drainage diversion dams, roads, and other construction projects (not all highway road excavations are mapped). Include uranium mine excavations, tailing deposits, and mine restoration sites in the Little Colorado River Valley area

Qs **Stream-channel deposits (Holocene)**—Poorly sorted, interlensing silt, sand, pebbles, and gravel. Intertongue with or inset against young alluvial fan (Qay), young terrace-gravel (Qgy), and upper part of valley alluvial (Qv) deposits, overlaps 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. Contact with other alluvial deposits merge laterally and are approximate. Stream-channel deposits of Little Colorado River mapped as shown on 1968 black and white aerial photographs and do not necessarily reflect stream-channel deposits of today due to extensive low-gradient channel changes caused by yearly flooding events. Little Colorado River stream channel meanders within its wide valley from upstream of Cameron to southeast corner of map area where the channel is confined within bedrock strata of Kaibab Formation. Downstream of Cameron, the Little Colorado River is largely confined within alternating hard and soft rocks of the Moenkopi and Kaibab Formations for about 11 km (7 mi), then becomes confined and strikingly meandering within narrow walls of Permian and older Paleozoic strata that form the Little Colorado River Gorge (fig. 1) and is part of the Grand Canyon physiographic area. About 2 to 9 m (6 to 30 ft) thick

Qf **Flood-plain deposits (Holocene)**—Gray, brown, and light-red clay, silt, sand. Include some lenticular gravel. Unit is partly consolidated by gypsum and calcite cement. Intertongue or overlap stream-channel (Qs), valley alluvial (Qv), young terrace-gravel (Qgy), and young alluvial fan (Qay) deposits. Subject to stream-channel erosion or overbank flooding in lateral and vertical sense. Similar to valley alluvial (Qv) deposits in small tributary drainage valleys that form broad, flat, valley floors subject to widespread and frequent overbank flooding along Little Colorado River and in highland valleys west of Gray Mountain. Tamerisk trees in Little Colorado River valley commonly occupy floodplain or low-lying terrace areas. In broad floodplains on Coconino Plateau and northeast of Little Colorado River, minor arroyo development may occur at downstream drainage outlets due to headward erosion of streams. Support thick growths of sagebrush, grass, cliffrose bush, and sagebrush at high elevations over 1,524 m (5,000 ft) that help trap and accumulate fine-grained sediment on floodplains of Coconino Plateau; sagebrush, tumble weed plants, 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 broad drainage floodplains on Coconino Plateau. About 2 to 9 m (6 to 30 ft) thick

Qd **Dune sand and sand sheet deposits (Holocene)**—Coconino Plateau and Gray Mountain area: White, gray, fine- to coarse-grained, wind-blown sand composed mainly of quartz and chert grains derived from Harrisburg Member of the Kaibab Formation west and south of Gray Mountain; accumulates on stream-channel (Qs) or valley alluvial (Qv) deposits. Form lumpy, undefined geometric sand dunes or sand sheet deposits on flood-plain (Qf) and young terrace-gravel (Qgy) deposits of local washes in west and southwest quarter of map area. Small sand sheet and dune deposits are mostly hidden or covered by forest growth in Kaibab National Forest south of Grand Canyon; support moderate growth of grass, sagebrush, pinion pine, juniper, and ponderosa pine woodlands. Little Colorado River and Moenkopi Plateau area: White, gray to light-red, fine- to coarse-grained sand composed mainly of quartz, chert, and minor feldspar grains derived from pre-existing Triassic and Jurassic sedimentary strata east of Little Colorado River. Include topographically controlled climbing and falling dunes and sand sheets that mantle gentle slopes of bedrock at Ward Terrace and Red Rock Cliffs and within tributary drainages northeast and east of Little Colorado River below Moenkopi Plateau. Sand is originally transported by fluvial erosion down tributary drainages from southwestern edge of Moenkopi Plateau to Little Colorado River is re-transported upstream by southwesterly winds onto Triassic and Jurassic bedrock surfaces forming significant deposits on Ward Terrace and against Red Rock Cliffs (Billingsley, 1987a), but does not reach Moenkopi Plateau except in the southeast corner of map area; includes topographically controlled climbing and falling dunes, complex dunes, parabolic dunes, and barchan dunes as mapped by Billingsley (1987a). Arbitrary and gradational lateral and vertical contacts between other alluvial or eolian deposits, especially along southwestern edge of Moenkopi Plateau at Adeii Eechii Cliffs where southwesterly winds actively erode bedrock of Navajo Sandstone and distribute sand as a thin veneer of white quartz sand over red old dune (QTd) and old eolian sand sheet and dune (QTes) deposits. Support moderate growth of grass and high desert shrubs that stabilize extensive sand sheet and dune deposits on Moenkopi Plateau. About 1 to 61 m (3 to 200 ft) thick

Qps **Ponded sediments (Holocene and Pleistocene(?))**—Gray or brown clay, silt, sand, and some lenses of gravel; partly consolidated by calcite and or gypsum cement. Locally include small chert and limestone fragments or pebbles. Similar to flood-plain (Qf) deposits but occupy man-made drainage depressions or natural internal drainage depressions caused by sinkhole development, and most commonly caused by sand dune blockages. Larger internal drainage basins, such as Dog Knobs Lake and Babbitt Lake, or smaller sinkhole depressions are common in west half of map area. Eolian blowout depressions, common in dune sand and sand sheet (Qd) deposits on Ward Terrace and below Red Rock Cliffs northeast of Little Colorado River area, and in old eolian sand sheet and dune (QTes) deposits on Moenkopi Plateau, accumulate temporary ponded sediments due to temporary sand-formed dams, many of which are too small to show at map scale. Desiccation cracks often develop in dry conditions on hardpan surfaces of larger accumulations that often restrict plant growth because of excessive clay content. Northeast and east of Little Colorado River and on Moenkopi Plateau, sandy ponded areas do support growths of seasonal grass and often develop a parabolic dune complex downwind (northeast) of sediment area. About 1.5 to 9 m (5 to 30 ft) thick

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 Gray Mountain area; white, gray, brown, and red chert fragments derived from Owl Rock Member of the Chinle Formation east of the Little Colorado River in the Ward Terrace area, and chert fragments derived from the Navajo Sandstone on Moenkopi Plateau. Deposits have accumulated by combinations of alluvial or eolian processes resulting in an interbedded sequence of thin-bedded, mixed mud, silt, sand, and gravel deposits. Deposit subject to sheetwash erosion during wet conditions and wind-blown sand accumulations during dry conditions. Commonly accumulate on broad flatlands or gently sloping alluvial fans 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. About 1 to 12 m (3 to 40 ft) thick

Qgy **Young terrace-gravel deposits (Holocene and Pleistocene)**—Light-brown, pale-red, and gray, poorly sorted fluvial mud, silt, sand, gravel, pebbles, cobbles, and boulders. Composed primarily of subangular to well-rounded Paleozoic sandstone, limestone, and chert clasts of local origin. Include well-rounded clasts of quartzite, quartz, and assorted metamorphic crystalline rocks derived from terrains far south of the map area. Include well-rounded volcanic rocks that originate from the San Francisco Volcanic Field and may include some quartzite and chert clasts derived from the Shinarump Member of the Chinle Formation. Include flood-plain (Qf) deposits and various terrace-gravel deposits in narrow canyon drainages too small to show at map scale. Clasts are partly consolidated by matrix of mud and sand cemented with calcium and gypsum. Form terraced benches about 1 to 12 m (3 to 40 ft) above stream-channel (Qs) deposits. Deposits are mixed with landslide, talus, and rock fall (Qtr) deposits in Little Colorado River Gorge. Unit fills erosion channels cut into bedrock, young alluvial fan (Qay), and flood-plain (Qf) deposits. Support moderate growth of local high-desert shrubs, sagebrush, and grass. About 1 to 12 m (3 to 40 ft) thick

Qay **Young alluvial fan deposits (Holocene and Pleistocene)**—Grayish-brown silt, sand, gravel, and some boulders. Pebbles, cobbles and boulders are subangular to rounded clasts of limestone, chert, and sandstone derived from local Paleozoic and Mesozoic strata of the Moenkopi and Kaibab Formations. Include medium- to coarse-grained sand and scattered well-rounded pebbles of quartzite and quartz and subrounded clasts and fragments of basalt derived from the San Francisco Volcanic Field. Unit is partly consolidated by silt, gypsum, and calcite and partly overlapped by ponded sediments (Qps), flood-plain (Qf), dune sand and sand sheet (Qd) deposits. Intertongue with upper part of valley alluvial (Qv), stream-channel (Qs), and young terrace-gravel (Qgy) deposits. Surfaces are partly eroded and cut by arroyo erosion. Surface has thin calcrete soil development that forms a sandy surface mixed with large cobbles and boulders of basalt near the Dog Knobs area of the San Francisco Volcanic Field. Extensively eroded and cut by arroyos in lowland areas northeast and east of Little Colorado River. Include coarse gravel, subangular to rounded pebbles and cobbles of limestone, chert, and sandstone derived from local Paleozoic and Mesozoic outcrops on Coconino Plateau. Subject to extensive sheetwash erosion and flash flood debris flows. Support moderate growths of sagebrush, cactus, and grass. About 1 to 12 m (3 to 40 ft) thick

Qec **Eolian cinder 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 from nearby pyroclastic volcanic centers; airborne ash and cinders were deposited within a few miles of local volcanic eruptions in the San Francisco Volcanic Field in south part of map area, and from eruptions south and southwest edge of map area. Pyroclastic fragments are commonly vesicular ash fall deposits that have been transported by southwesterly winds and that have accumulated against or downslope of local topographic obstructions such as basalt flows, steep-walled drainages, rock ledges, and local fault scarps, especially in Wupatki National Monument area. Form extensive cover of eolian cinder sheet deposits over all terrain in south-central part of map area; many deposits too thin to show at map scale. Cinder fragments become smaller and more subrounded farther downwind (northeast) of eruptive centers. About 1.5 to 12 m (5 to 40 ft) thick

Qtr **Talus and rock fall deposits (Holocene and Pleistocene)**—Along Adeii Eechii Cliffs area; red to yellow, silt and sand mixed with angular rocks and boulders of light-red sandstone and dark-red siltstone; partly cemented by calcite. Form talus debris slopes in steep-walled canyons and lower slopes of Adeii Eechii Cliffs; often associated with, adjacent to, or below landslide (Ql) deposits. In Little Colorado River Gorge and Gray Mountain area; gray to yellow silt, sand, gravel mixed with small to large angular rocks and boulders of gray limestone, white chert, and white to tan sandstone derived from the Kaibab and Toroweap Formations and Coconino Sandstone; partly cemented by calcite and gypsum. Form talus debris cover on slopes below landslide (Ql) deposits. Unit often grades down slope into young alluvial fan (Qay) deposits or young terrace-gravel (Qgy) deposits. About 1.5 to 14 m (5 to 45 ft) thick

Ql **Landslide deposits (Holocene and Pleistocene)**—Landslides are unconsolidated to partly consolidated masses of unsorted rock debris. At northeast base of Gray Mountain, includes a horizontally bedded gravity-glide mass of Kaibab Formation that overlies Triassic beds of the Shinarump Member of the Chinle Formation. Include detached stratified blocks that rotated backward against parent outcrop and slid downslope as loose incoherent masses of broken rock fragments and deformed strata; often form talus and rock fall (Qtr) deposits adjacent to and below landslide masses on Gray Mountain, Little Colorado River Gorge, and Black Point areas. Some landslide blocks below edges of basalt flows at Black Point are unstable during wet conditions (fig. 1 on map). Landslide masses at Black Point are commonly associated with soft siltstone and claystone strata of Petrified Forest Member of the Chinle Formation. Include individual car- and house-size basalt boulders near base of Gray

Mountain and in Little Colorado River Gorge. Clasts are mostly angular and unsorted; partly cemented by calcium. Gradational and arbitrary contact with young alluvial fan (Qay), flood-plain (Qf), young terrace-gravel (Qgy), and valley alluvial (Qv) deposits. Subject to extensive sheetwash erosion, flash-flood debris flows, and arroyo erosion. About 3 to 61 m (10 to 200 ft) thick

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; unconsolidated east and northeast of Little Colorado River. Include occasional rounded clasts of limestone, subrounded to angular chert, and subrounded to angular basalt southwest of Little Colorado River. Intertongue or overlap young alluvial fan (Qay) deposits and young terrace-gravel (Qgy) deposits. Commonly reflect low energy, low-gradient, shallow drainages. Subject to sheetwash flooding and temporary ponding due to vegetation growths of grass at lower elevations in central area of map, and sagebrush, grass, cactus, and some juniper trees at higher elevations above 1,830 m (6,000 ft) in west half of map area. About 1 to 9 m (3 to 30 ft) thick

QTd **Old dune deposits, undivided (Pleistocene and Pliocene(?))**—White, light-red to light-brown, coarse- to very fine-grained sand and silt; partly consolidated beneath veneer of active, reworked sand cover. Form base or internal cores of younger, reactivated linear dunes immediately downwind (northeast) of Adeii Eechii Cliffs (shown as active linear dunes by Billingsley, 1987a), on Moenkopi Plateau, Appaloosa Ridge, and Coal Mine Mesa. Contain at least 25% to 35% gray, fine-grained silt and clay content on Coal Mine Mesa from erosion of underlying Dakota Sandstone (Kd) and Mancos Shale (Km). Unit often forms complex linking sets of parabolic dunes along edge of Adeii Eechii Cliffs and Appaloosa Ridge of Moenkopi Plateau. Several individual dunes on Moenkopi Plateau have developed downwind of ponded sediments and are younger than adjacent old eolian sand sheet and dune (QTes) deposits. Bedrock or ponded sediments (Qps) are often exposed within interior of parabolic dunes. Include combinations of parabolic, barchan, dome, and dune-like thick sand sheet deposits that frequently coalesce downwind (northeast) to form old linear dunes (old dune deposits, undivided [QTd]) or old eolian sand sheet and dune (QTes) deposits northeast of Adeii Eechii Cliffs on Moenkopi Plateau. Linear dune traces are often longer than 3 km (2 mi) and as long as 10 km (6 mi). Some linear dunes merge with other linear dunes and form a linear complex of parabolic or barchanoid dune trains within a short length of linear dune (not shown). Include topographically controlled climbing or falling dunes and short linear dunes below Appaloosa Ridge. Unit commonly stabilized by moderate growth of grass and mormon tea bush. Gradational and approximate contact with adjacent surficial deposits. About 2 to 12 m (6 to 40 ft) thick

QTes **Old eolian sand sheet and dune deposits (Pleistocene and Pliocene(?))**—Light-red to light-brown, very fine-grained to medium-grained sand and silt. Form widespread deposits on Moenkopi Plateau that merges with old dune (QTd) and old mixed alluvium and eolian (QTae) deposits. Contacts with other map units are gradational and arbitrary based on morphologic characteristics observed on 1968 aerial photographs. Unit is overlapped by young mixed alluvium and eolian (Qae), stream-channel (Qs), and young alluvial fan (Qay) deposits below Appaloosa Ridge (southwest of ridge) and at Little Hollow Place, northeast corner of map area. Below Appaloosa Ridge, on Coal Mine Mesa, and at Little Hollow Place unit contains abundant gray clay and silt derived from underlying Dakota Sandstone (Kd) and Mancos Shale (Km). Unit is stabilized by thick growth of grass and mormon tea brush. Deposits cover Jurassic and Cretaceous bedrock and form protective cover against wind deflation of bedrock; where not covered, bedrock units are extensively eroded by wind deflation, especially along Adeii Eechii Cliffs. Unit is locally disturbed at stock tanks and windmill watering holes for livestock where fresh sand is actively forming new sand sheet and dune deposits (not mapped). About 1 to 3.6 m (3 to 12 ft) thick

QTae **Old mixed alluvium and eolian deposits (Pleistocene and Pliocene(?))**—Lithologically similar to young mixed alluvium and eolian (Qae) deposits but often capped or covered by poorly sorted sand, gravel, and small cobbles and boulders consolidated by calcrete soil development. Form flat mesa-like benches about 9 to 36.5 m (30 to 120 ft) above surrounding plateau surfaces along east-central edge of map area. About 3 to 6 m (10 to 20 ft) thick

QTg4 **Older terrace-gravel deposits (Pleistocene and Pliocene(?))**—Gray and light-brown silt, sand, gravel, cobbles, and boulders up to 30 cm (1 ft) in diameter along Tappan Wash southwest of

Cameron; consists mostly of sand and gravel material derived from the Kaibab and Moenkopi Formations. Includes some volcanic clasts from the San Francisco Volcanic Field that may be older than 1 million years. Form terrace benches or ridges about 9 to 14 m (30 to 45 ft) above Tappan Wash where Tappan Wash meanders over soft strata of lower Moenkopi Formation.

Form terrace benches about 45 to 60 m (150 and 200 ft) above modern Little Colorado River between Cameron, Arizona, and Black Point. Unit is extensively eroded and stratigraphically below oldest terrace-gravel (QTg5) deposits. Unit forms Baah Lokaa Ridge east of and lower than Black Point and an unnamed ridge northeast of Little Colorado River below Ward Terrace that fills 3 km (2 mi) wide old Little Colorado River channel with sandy gravely sediment as much as 30.5 m (100 ft) thick. Include calcrete soil horizon in upper 1 m (3 ft) of unit. Supports light vegetation cover, mostly grass and small desert shrubs. Unit is extensively eroded and gullied. About 3 to 55 m (10 to 180 ft) thick

QTa **Older alluvial fan deposits (Pleistocene and Pliocene)**—Gray and light-brown clay, silt, sand, and gravel, poorly sorted, partly consolidated by calcrete soil in top 1 m (3 ft). Material is mostly reworked older terrace-gravel (QTg4) deposits and erosional debris from Petrified Forest Member (₸cp) and Owl Rock Member (₸co) of the Chinle Formation, southeast quarter of map area. Contain angular fragments of petrified wood and well-rounded quartzite and chert pebbles in fluvial and eolian sandy matrix. Form stabilized cover over remaining older terrace-gravel deposits (QTg4). Unit has a gentle surface gradient toward Little Colorado River and is extensively eroded. Support moderate cover of grasses and low desert shrubs. About 1 to 4.5 m (3 to 15 ft) thick

QTg5 **Oldest terrace-gravel deposits (Pliocene and Miocene)**—Gray to light-brown silt, sand, gravel, pebbles and cobbles. Contain well rounded pebbles and cobbles of gray limestone and chert derived from Kaibab Formation, red sandstone clasts derived from Moenkopi Formation, and dominated by quartzite and a few granite and metamorphic clasts derived from older gravel deposits of the Mogollon Rim southeast of the map area. Unit is 79 m (260 ft) above present Little Colorado River at Cameron, Arizona, (elevation 1,341 m [4,400 ft]). Unit may, in part, be equivalent to old stream-channel (Ts) deposits at Black Point because the Little Colorado River gradient between these high level gravels is 3 m/km (9 ft/mi), comparable to the modern day Little Colorado River gradient between Cameron and Black Point. About 2 to 4.5 m (6 to 15 ft) thick

VOLCANIC ROCKS

[See table 1 for ages of volcanic rocks in the map area.]

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

Volcanic rocks of the San Francisco Volcanic Field (Pleistocene, Pliocene, and Miocene)

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 originated from Merriam Crater 17.5 km (11 mi) southeast of the southeast corner of map area and flowed north to a small 60 m (200 ft) deep canyon of the Little Colorado River and formed a lava dam across the canyon. The lava dam diverted the Little Colorado River stream flow around the north side of the basalt flow and back into 60 m (200 ft) deep canyon downstream of the lava dam that forms Grand Falls (8 km [5 mi]) southeast of map area (Moore and Wolfe, 1976, 1987). Basalt of Merriam Crater flowed downstream of Grand Falls in the Little Colorado River channel into the map area east of Wupatki National Monument. The river overflows the basalt flow and forms rapids known as Black Falls (fig. 1). Downstream of Black Falls, the Little Colorado River flows adjacent to basalt flow, but most of the basalt flow spread out onto abandoned stream-channel (Qs) and low flood-plain (Qf) deposits and terminates just south of Black Point. Optical-luminescence age, 19.6±1.2 ka (Duffield and others, 2004). About 2 to 4 m (6 to 13 ft) thick

Qyap **Pyroclastic deposits of S P Mountain (Pleistocene; Brunhes age)**—Dark-gray to reddish-gray basaltic andesite. Contain phenocrysts of clinopyroxene, olivine, and intensely corroded plagioclase in hypocrystalline groundmass of the same minerals, plus opaque oxide and glass. Same composition as basaltic andesite flow (Qyab), but less crystalline. Contains abundant large volcanic bombs that help form sharp rims of uneroded crest of cone (Hodges, 1962; Ulrich and Bailey, 1987). Pyroclastic cone partially overlies older cone on west side and has a circular plan view; forms 287-m- (940-ft-) high cone with 60-m- (200-ft-) deep interior crater. About 287 m (940 ft) thick

Qyab **Basaltic andesite flow of S P Mountain (Pleistocene; Brunhes age)**—Dark-gray basaltic andesite. Flow is more crystalline than associated basaltic pyroclastic deposits of S P Mountain (Qyap). Flow has rough blocky surface and steep flow fronts. Basalt flowed northward about 6.5 km (4 mi) over Harrisburg Member of the Kaibab Formation and into local graben structures (fig. 4 on map). K-Ar age determined by Baksi (1974) is 0.071±0.004 Ma (Ulrich and Bailey, 1987). About 6 to 40 m (20 to 130 ft) thick

Qyp **Pyroclastic deposits of five young cinder cones (Pleistocene; Brunhes age)**—Grayish-black porphyritic basalt with abundant 1- to 3-mm phenocrysts of corroded tabular plagioclase, scattered olivine, and sparse clinopyroxene in a hyalophitic groundmass. Forms five young cinder cones overlying older cinder cones; 200 to 800 m (200 to 2,625 ft) in diameter and 25 to 165 m (80 to 540 ft) high at south-central edge of map area. Thickness, 25 to 165 m (80 to 540 ft)

Qyb **Basalt flow of five young cinder cones (Pleistocene; Brunhes age)**—Grayish-black porphyritic basalt flow with same composition as pyroclastic deposits of five young cinder cones (Qyp). Consists of one small flow 700 m (2,297 ft) long and 400 m (1,315 ft) wide. About 5 to 10 m (16 to 33 ft) thick

Shadow Mountain is an isolated pyroclastic cone with associated basalt flows about 19 km (12 mi) northwest of Cameron, Arizona (fig. 1). These volcanic rocks are chemically and petrographically similar to rocks of the San Francisco Volcanic Field and represent the northern-most volcano of the field. The polarity of these rocks has not been determined. K-Ar age, 0.649±0.23 Ma (Damon and others, 1974; Condit, 1974).

Qsp **Pyroclastic deposits of Shadow Mountain (Pleistocene)**—Black and red scoria, cinder, and ash deposits of olivine-labradorite basaltic composition. Deposits overlie associated basalt flows and strata of Petrified Forest and Shinarump Members of the Chinle Formation. About 183 m (600 ft) thick

Qsb **Basalt flows of Shadow Mountain (Pleistocene)**—Black olivine-labradorite basalt flows that are largely covered by associated pyroclastic (Qsp) deposits. Basalts flowed into one small graben north of main cone making that graben older than the basalt flow. The basalt was down-faulted into another graben 0.8 km (½ mi) east of the main cone suggesting this graben developed after the eruption (within the last half million years). This graben is aligned with the southwest-northeast strike of Mesa Butte Fault southwest of Shadow Mountain and is likely a northern extension of that structural trend. About 3 to 14 m (10 to 45 ft) thick

Qp **Pyroclastic deposits (Pleistocene; Brunhes age)**—Dark-gray, black, and reddish-brown indurated and oxidized pyroclastic deposits. Include ribbon and tear-shaped volcanic bombs in welded tuffaceous scoria and cinder deposits. Contains microscopic crystals of clinopyroxene, olivine, plagioclase, abundant clasts of vesicular basalt with dark-gray or reddish-brown glassy matrix, and occasional sedimentary xenoliths. Includes several eruptive vents that built pyroclastic or splatter cones on associated basalt flows. About 5 to 260 m (15 to 850 ft) thick

Qb **Basalt flows (Pleistocene; Brunhes age)**—Dark-gray and black porphyritic and aphyric, clinopyroxene-olivine and alkali-olivine basalt. Flows occur locally within present stream drainages, are moderately young in appearance, are locally covered by thin alluvium, eolian sand, or air-borne 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). About 1 to 20 m (3 to 65 ft) thick

Qbt **Basalt flow of Tappan Wash (Pleistocene; Brunhes age)**—Dark-gray and black, dense, aphyric, clinopyroxene-olivine and alkali-olivine basalt. Conspicuously rich in black glassy plagioclase groundmass. Flow originated from Crater Lake volcano (N4536 of Wolfe and others, 1987); a vent 9.5 km (6 mi) south of the map area on the east side of Kendrick Mountain and flowed down various tributary drainages to Tappan Wash, then down Tappan

Wash to the Little Colorado River, a distance of 88 km (55 mi); then down Little Colorado River another 11 km (7 mi) to the beginning of the Little Colorado River Gorge (see fig. 2 on map). Geomorphology of basalt flow of Tappan Wash is described by Rice (1977) as the Tappan Lava Flow and mapped by Ulrich and Bailey, (1987). K-Ar age, 0.53±0.19 Ma (Damon and others, 1974). The flow averages about 2 m (6 ft) thick for much of its length and accumulated to as much as 40 m (130 ft) in the Little Colorado River where it forms an inverted valley within Little Colorado drainage (fig. 2 on map). Basalt flow is cut by several faults that form grabens north of S P Mountain and at Little Colorado River; fault offset generally less than about 1.5 m (5 ft). About 1 to 40 m (3 to 130 ft) thick

Qbf **Fissure deposits of Lockett Tank (Pleistocene; Brunhes age)**—Dark-gray to black linear extrusion of aphyric basalt along fault at Lockett Tank about 14 km (9 mi) north of S P Mountain. About 3 to 6 m (10 to 20 ft) thick

Qbmp **Pyroclastic deposits (Pleistocene; Brunhes or Matuyama age)**—Dark-gray to red pyroclastic cones and small rounded spatter cones on basalt flows (Qbmb). Weathers yellowish brown and reddish brown. Largest deposit forms Red Mountain (fig. 1). Unit is superficially gullied; consists of bedded cinders, agglutinated spatter with volcanic ribbon and tear-shaped bombs. About 60 to 292 m (200 to 960 ft) thick

Qbmb **Basalt flows (Pleistocene; Brunhes or Matuyama age)**—Dark-gray to black aphyric alkali basalt composed of plagioclase, clinopyroxene, olivine, and magnetite. Weathers yellowish brown to reddish brown. Surface of flows are relatively smooth, flat and undissected. About 10 to 60 m (30 to 200 ft) thick

Qsfp **Pumice of San Francisco Mountain (Pleistocene; Matuyama age)**—White to light-gray, poorly sorted, mantle bedding of rhyolite pumice fall. Unit is matrix free except for locally reworked zone in upper 1 m (3 ft). Lapilli range from several millimeters to several centimeters in size, are colorless vesicular glass, and lack visible crystals. Contains xenoliths of greenschist and blueish-gray dense rhyolite with feldspar and quartz phenocrysts. Unit overlies older basalt flows (Qmb) near US Highway 89 at south-central edge of map along Deadman Wash 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). About 3 to 5 m (10 to 15 ft) thick

Qmbi **Basalt dike (Pleistocene; Matuyama age)**—Dark-gray to black plagioclase-aphyric 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). Includes three dikes just east of US Highway 89 about 16 km (10 mi) north of south-central edge of map area. Dike widths, 0.3 to 0.5 m (1 to 1.5 ft)

Qmp **Pyroclastic deposits (Pleistocene; Matuyama age)**—Dark-gray to reddish-brown plagioclase-aphyric and porphyritic basalt. Consist of intergranular groundmass of plagioclase, clinopyroxene, olivine, and magnetite. Contain scattered olivine and clinopyroxene phenocrysts. Include several cones of Mesa Butte volcano that are aligned with and overlie Mesa Butte Fault (fig. 1). Cones are in early stage of erosion, slightly eroded and gullied. About 25 to 230 m (80 to 750 ft) thick

Qmb **Basalt flows (Pleistocene; Matuyama age)**—Dark-gray plagioclase-aphyric and porphyritic basalt of similar composition to pyroclastic (Qmp) deposits. Weather yellow or brown. Surfaces are weathered and slightly eroded and gullied. K-Ar age of various flows, 0.83±0.04 Ma, 1.04±0.04 Ma, 1.09±0.03 Ma, 1.20±0.05 Ma, and 1.38±1.01 Ma (Ulrich and Bailey, 1987; Wolfe and others, 1987). Flows generally follow older drainage areas that are above present drainages. About 5 to 45 m (15 to 159 ft) thick

Qmlp **Basalt flow of Lava Point (Pleistocene; Matuyama age)**—Dark-gray to black plagioclase-aphyric basalt. Similar composition to (Qmb) basalt flows. Mapped as Lava Point flow (Qmb) by Ulrich and Bailey (1987) east of U.S Highway 89 but not mapped separately from other basalt flows of similar composition and age. Mapped herein as separate unit because unit forms an inverted valley for several kilometers north of an unknown source in south part of map area that is similar to an inverted valley formed by adjacent Black Point Basalt flow (Tbpb). K-Ar age, 1.01±0.13 Ma (Ulrich and Bailey, 1987). About 6 to 15 m (20 to 50 ft) thick

Qslr **Rhyolite dome complex of Slate Mountain (Pleistocene; Matuyama age)**—Light-gray aphanitic rhyolite. Rare microphenocrysts of pale-brown amphibole, biotite, and altered fayalite(?) occur in a felsic cryptocrystalline groundmass (Wolfe and others, 1987). Unit forms the north flank of a 1.5 km (1 mi) diameter cluster of domes that form Slate Mountain; summit of Slate Mountain is south of map area. Uplifted sedimentary rocks of Lower Permian age are exposed adjacent to east and south edge of rhyolite just south of map boundary. K-Ar age, 1.54±0.02 Ma (Wolfe and others, 1987). About 92 m (300 ft) thick

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. Contain minor gabbro xenoliths. K-Ar age, 0.786±0.14 Ma (Ulrich and Bailey, 1987), and south of map area 0.874±0.13 Ma; 0.897±0.14 Ma; 0.812±0.059 Ma (Reynolds and others, 1986; Damon and others, 1974). About 2 to 15 m (6 to 50 ft) thick

QTi **Intrusive dike or plug (Pleistocene or Pliocene; Matuyama age)**—Dark-gray aphyric basalt and microporphyritic olivine basalt. Includes pyroclastic fragments. Source for pyroclastic cones (QTp) and basalt flows (QTb); Dog Knobs, southwest quarter of map area. Widths, 1.5 to 4.5 m (5 to 15 ft)

QTp **Pyroclastic deposits (Pleistocene or Pliocene; Matuyama age)**—Dark-gray to red cinders, agglutinated spatter, bomb and ribbon fragments; yellowish brown to reddish brown where weathered. Form several rounded, little dissected, superficially gullied pyroclastic cones of Dog Knobs area, southwest quarter of map area. About 60 to 120 m (200 to 400 ft) thick

QTb **Basalt flows (Pleistocene or Pliocene; Matuyama age)**—Dark-gray, yellowish-brown to brown, aphyric and slightly porphyritic basalt and microporphyritic olivine basalt; surfaces mostly smooth, relatively flat, undissected. Includes thin, interbedded pyroclastic deposits near pyroclastic cones of Dog Knobs area. Unit is thickest near flow margins in some areas. Thickness ranges from about 10 to 60 m (30 to 200 ft)

QTap **Basalt and andesite pyroclastic deposits (Pleistocene or Pliocene; Matuyama age)**—Dark-gray, glassy, basaltic andesite. Weather yellowish brown to brown, locally gullied. Cones composed of cinders, scoria, and spatter, southwest corner of map area. About 25 to 122 m (80 to 400 ft) thick

QTab **Basalt and andesite flows (Pleistocene or Pliocene; Matuyama age)**—Dark-gray basaltic andesite; partly blocky, hummocky surfaces, locally gullied. Weather yellowish brown to brown. Contain abundant phenocrysts of clinopyroxene and plagioclase, subordinate phenocrysts of orthopyroxene, sparse phenocrysts of olivine and hornblende and scattered rounded quarts grains with clinopyroxene reaction rims. Groundmass is mostly fine-grained or glassy and contains plagioclase microlites, opaque oxide, and small crystals of clinopyroxene and orthopyroxene. About 18 to 67 m (60 to 220 ft) thick

Tbi **Dike in amphitheater (Pliocene; Gauss or Gilbert age)**—Dark-gray plagioclase-phyric basalt and mixed pyroclastic dikes and necks. Composed of plagioclase, clinopyroxene, olivine, and opaque oxides. Crystal-rich basalt; occurs in 2.7 km (1.5 mi) wide basalt- and tuff-rimmed depression informally named the "Amphitheater" by Ulrich and Bailey (1987), 10 km (6 mi) east of U.S. Highway 89 and about 8 km (5 mi) northeast of S P Mountain. Dike is 2 to 6 m (4 to 20 ft) wide and 5 to 10 m (15 to 33 ft) in height. K-Ar age, 3.13±0.39 Ma (Ulrich and Bailey, 1987). Coarse pyroclastic debris is scattered on surrounding surface of Wupatki Member of the Moenkopi Formation. Thickness, 5 to 10 m (15 to 33 ft)

Tp **Pyroclastic deposits (Pliocene; Gauss or Gilbert age)**—Dark-gray to red cinder and spatter fragments; weathers yellowish brown, brown, or reddish brown. Composed of clinopyroxene and olivine phenocrysts, plagioclase, opaque oxides, and glass; partly decomposed and weathers light red. Mass wasting has diminished slope angles of pyroclastic cones; flanks are gullied to extensively eroded. Cones are elongated and aligned along a northwest trend north in Dog Knobs area indicating the influence of bedrock faults, fractures, and joints on vent positions and orientation. About 1.5 to 12 m (5 to 40 ft) thick

Tb **Basalt flows (Pliocene; Gauss or Gilbert age)**—Medium- to dark-gray plagioclase-phyric, aphyric, and slightly porphyritic basalt. Smooth surfaced, partly dissected north of Dog Knobs area and about 10 km (6 mi) northeast of S P Mountain. Composed of plagioclase, clinopyroxene, olivine, and opaque oxides. Less than 30 m (90 ft) thick

Tbpb **Black Point Basalt flows (Pliocene)**—Dark-gray to black plagioclase-aphyric basalt; surface weathers smooth and locally dissected. Contain scattered to abundant tabular plagioclase phenocrysts as large as 1 cm in diameter and includes abundant olivine microphenocrysts in feldspathic groundmass with intergranular to ophitic intergrowth of brown pyroxene and plagioclase. K-Ar age, 2.43±0.32 Ma (Ulrich and Bailey, 1987). Basalt flows form two lobes in map area; one extends northeast from south-central edge of map area for 26 km (16 mi) to the Little Colorado River, and the other lobe extends east-northeastward from Wupatki National Monument for 14 km (8.5 mi) referred to as the Citadel flow by Cooley (1962), but is mapped as the Black Point basalt flows (Ulrich and Bailey, 1987) because both lobes emerge from a single flow southwest of Wupatki National Monument. Basalt flows average about 12 m (40 ft) thick at Black Point where basalt filled a low-relief channel of Little Colorado River 1.5 km (1 mi) wide and extended down river about 5 km (3 mi). About 6 to 40 m (20 to 132 ft) thick

Tocb **Basalt flow of Cedar Ranch Mesa (Miocene)**—Dark-gray, massive, olivine-phyric basalt; weathers brown and has a smooth surface. Contains abundant 1- to 3-mm subhedral to euhedral olivine phenocrysts rimmed with iddingsite in a distinctive holcrystalline groundmass of intergranular to subophitic clinopyroxene and plagioclase. K-Ar age, 5.62±0.19 Ma (Ulrich and Bailey, 1987). Unit overlies Petrified Forest Member of the Chinle Formation and is susceptible to landslide mass wasting along northern edges of flow near Cedar Ranch. Partly buried by younger basalt flow (Qb). About 20 to 32 m (65 to 110 ft) thick

SEDIMENTARY ROCKS

Ts **Oldest stream-channel deposits (Pliocene(?) and Miocene)**—Black Point area: Light-red, gray, and brown interbedded siltstone, sandstone, arkosic gravel, and lenticular conglomerate. Sediments are well sorted and consolidated beneath the Black Point Basalt flows (Tbpb) at Black Point, center of map area. Unconsolidated gravel sediments form rounded hill of Little Colorado River terrace and tributary alluvial fan deposit surrounded by the Black Point Basalt flows at Black Point. The Black Point Basalt (Tbpb) flowed northeast and east from the San Francisco Volcanic Field area down tributary drainage eroded into the lower half of the Moenkopi Formation to the Little Colorado River and flowed onto and around a stream delta or river terrace deposit and onto floodplain and channel of the Little Colorado River (fig. 1 on map). Basalt flowed a short distance upstream (south) and across river floodplain (east) about 1.5 km (1 mi) and downstream (north) about 3.5 km (2 mi); 2.43±0.51 Ma (Damon and others, 1974). Unit is the oldest Little Colorado terrace-gravel deposit in the map area. Base of deposit is 174 m (570 ft) above present Little Colorado River bed at Black Point at elevation 1,463 m (4,800 ft). The 207 m (680 ft) river down cutting estimate by Billingsley (1987b) from top the Black Point Basalt flow, not base of map unit. Similar and unconsolidated deposits cover floor of ancient meander channel of Little Colorado River superimposed and eroded into Harrisburg Member of the Kaibab Formation on Black Point Monocline about 1.5 km (1mi) south of Black Point; 174 m (570 ft) above present Little Colorado River. Sediments in small channel are mostly covered by quartzite lag gravel as is small terrace or alluvial fan hill surrounded by the Black Point Basalt flow. Conglomerate consists primarily of well-rounded quartzite, chert, and minor clasts of granite and metamorphic rocks derived from older gravel deposits of the Mogollon Rim southeast of the map area; and local gray limestone clasts derived from Kaibab Formation; and red sandstone derived from Moenkopi Formation.

East of Gray Mountain area: Light-gray to reddish-gray silt, sand, gravel, pebbles, cobbles, and small boulder detritus derived from erosion of local Kaibab and Moenkopi Formation outcrops; unsorted and partly consolidated. Clasts of gray limestone, white chert, red sandstone, and grayish-black basalt are subrounded to well rounded; pebble imbrications indicating a general flow from southwest to northeast. Meander loops are superimposed into Harrisburg Member of the Kaibab Formation south of Gray Mountain prominence. Includes some well rounded basalt clasts from San Francisco Volcanic Field area that are likely older than basalt flow of Tappan Wash (Qbt) because the basalt of Tappan Wash is stratagraphically below most of the channel fill deposits. Fills old abandoned meander loops of an ancient tributary canyon drainage to the Little Colorado that meandered across the Kaibab and Moenkopi Formations, perhaps as old as Miocene age (Charles Barnes, oral commun., 2005). About 3 to 18 m (10 to 60 ft) thick

Km **Mancos Shale (Upper Cretaceous)**—Bluish-gray to light-gray, thinly laminated to thin-bedded, slope-forming, carbonaceous claystone, siltstone, and mudstone with interbedded light-gray, fine- to medium-grained sandstone. Includes bentonitic claystone, siltstone, and some thin-bedded limestone. Locally fossiliferous with cephalopod faunas that are laterally equivalent to the Tropic Shale Formation in the lower part of the Mancos Shale in southern Utah. Sediments were deposited on shallow sea floor that transgressed westward from the mid-continent area. Gradational and arbitrary contact with underlying Dakota Sandstone (Kd). Sediments are mostly removed by Cenozoic erosion and largely covered by old eolian sand sheet and dune (QTes) deposits at Coal Mine Mesa on Moenkopi Plateau, northeast corner of map area. About 43 to 60 m (140 to 200 ft) thick

Kd **Dakota Sandstone (Upper Cretaceous)**—Medium- to light-gray, slope-forming, laminated to thin-bedded mudstone, siltstone, and sandstone. Locally includes the lower sandstone and middle carbonaceous members as defined by O'Sullivan and others (1972). The upper sandstone member is not present in the map area.

Lower sandstone member is light-orange to light-gray silty sandstone and conglomeratic sandstone in lower part. Unit is well cemented and forms a cliff that fills erosional channels as much as 6 m (20 ft) thick and locally pinches out laterally in short distances. Pebble clasts in conglomeratic sandstone lenses are composed of red and gray, well-rounded chert and quartzite typically less than 5 cm (2 in) in diameter. Unit unconformably overlies white sandstone beds of the Entrada Sandstone (Je). The regional unconformity between the Dakota Sandstone and underlying Jurassic-Cretaceous rocks has been established as an angular regional unconformity, based on the Dakota Sandstone overlying younger rocks north of the map area and overlying older rocks south and southeast of the map area. Although these relationships establish the angularity of the pre-Dakota Sandstone age unconformity, the angularity is so small that it is not apparent at most outcrops within the Navajo Country (Harshbarger and others, 1958).

Middle carbonaceous member is dark-grayish-brown, carbonaceous, flat-bedded mudstone, siltstone, coal, and interbedded brown, conglomeratic, crossbedded lenticular sandstone. Coal beds are generally less than 0.5 m (2 ft) thick and present only at east end of Coal Mine Mesa of map area. Coal was mined from thicker coal beds at the rim of Coal Mine Canyon just north of the northeast corner of map area. Gypsum is common constituent as thin stringers and as isolated crystals. Unit unconformably overlies the Entrada Sandstone in east part of Coal Mine Mesa where lower sandstone member is not present (J-2 unconformity of Pipiringos and O'Sullivan, 1978). Unit is mostly covered by extensive old dune deposits, undivided (QTd). Best exposures are southwest of Coal Mine Mesa at Appaloosa Ridge, northeast corner of map area. Overall thickness, about 3 to 12 m (10 to 40 ft)

Je **Entrada Sandstone-Cow Springs Sandstone, undivided (Middle Jurassic)**—Includes a lower interval of white, very fine-grained, trough crossbedded sandstone equivalent to Entrada Sandstone north of map area; a middle interval of interbedded red, flat-bedded siltstone and sandstone equivalent to Summerville Formation north of map area; and an upper interval of white, fine-grained crossbedded sandstone equivalent to Cow Springs Sandstone north of map area. The Summerville Formation and Cow Springs Sandstone are equivalent to the lower Morrison Formation farther north of map area at Black Mesa. Unit as a whole forms a cliff where protected by resistant conglomeratic, coarse-grained sandstone lenses of the overlying Dakota Sandstone. The Carmel Formation is 1.5- to 2-m- (5- to 7-ft-) thick lenses of red siltstone and sandstone near the base of the Entrada Sandstone at the west end of Appaloosa Ridge and is locally absent at the east end of Coal Mine Mesa; Carmel Formation is too thin to show at map scale. Entrada Sandstone-Cow Springs Sandstone, undivided, unconformably overlies the upper beveled surface of Navajo Sandstone known regionally as the J-2 unconformity; erosional relief is generally less than about 4.5 m (15 ft) but is as much as 9 m (30 ft). The unit as a whole thins from 60 m (200 ft) at the west end of Coal Mine Mesa and Appaloosa Ridge to less than 35 m (115 ft) at northeast corner of map area

GLEN CANYON GROUP

The Glen Canyon Group includes, in ascending order, the Jurassic Moenave Formation (Jm), the Kayenta Formation (Jk), the Kayenta Formation-Navajo Sandstone transition zone (Jkn), and the Navajo Sandstone (Jn). The Moenave Formation unconformably overlies the Triassic Chinle Formation. The boundary between the Triassic and Jurassic units is based on differences in lithology, topography, and color change. The purple and white mudstone, sandstone, and gray limestone of the Owl Rock Member of the Chinle Formation (T̅Rco) is overlain by the red mudstone, siltstone, and sandstone of the Moenave Formation (Jm). The basal red siltstone of the Moenave Formation may be the lateral equivalent of the Rock Point Member of the Wingate Formation as mapped by Cooley and others (1969), but is likely the lateral equivalent of the Church Rock Member of the Chinle Formation north and northeast of the map area as suggested by Repenning and others (1969); Cooley and others (1969) also mapped an orange-red silty ledge-forming sandstone on Ward Terrace as a tongue of the Lukachukai Member of the Wingate Formation (Sandstone) as did Billingsley (1987a) as suggested by Cooley and others (1969). The basal red siltstone (Rock Point Member of the Wingate Formation) and orange-red sandstone (Lukachukai Member of the Wingate Formation) is herein mapped as the lower part of the Moenave Formation because both units are lithologically the same as several overlying siltstone and sandstone units within the Moenave Formation and because the Wingate Sandstone is stratigraphically above the Moenave Formation at the New Mexico/Arizona State line. Furthermore, the Wingate Sandstone is stratigraphically between the Moenave and Kayenta Formation in the Hopi Buttes about 72 km (45 mi) east of the map area.

North of the map area 80 km (50 mi), the upper boundary of the Glen Canyon Group is an unconformity between the Navajo Sandstone and the Page Sandstone, but in the northeast corner of map area, the upper boundary of the Glen Canyon Group is an unconformity between the Navajo Sandstone (Jn) and Entrada Sandstone (Je) in the map area; old dune (QTd) and old eolian sand sheet and dune (QTes) deposits obscure the contact.

Jn **Navajo Sandstone (Lower Jurassic)**—Red, white, and tan, cliff-forming, high-angle crossbedded and massive horizontal or planar bedded, fine- to medium-grained, well-sorted, well-rounded frosted quartz sandstone. Crossbedded sets are as much as 11 m (35 ft) thick. Includes several thin lenses or beds of gray siliceous limestone, dolomite, or dark-red sandy siliceous mudstone that weather out as resistant ledges that form flat-topped ridges or hills on eroded surface of Moenkopi Plateau. These siliceous beds were formed in oases, playas, or ponds between eolian sand dunes and become increasingly common in southeast part of Moenkopi Plateau. Sandstone beds contain numerous small rounded black and reddish-black, pea-size hematite concretions in upper part near Appaloosa Ridge on Moenkopi Plateau and are similar to pumpkin-size concretions [25 cm to 1 m (10 in to 3 ft)] in diameter along Adeii Eechii Cliffs. Gradational and arbitrary contact with underlying Kayenta Formation-Navajo Sandstone transition zone (Jkn) at lowest white or red sandstone cliff of Navajo Sandstone. Several springs and seeps issue from the base of the Navajo Sandstone along the Adeii Eechii Cliffs. Unit rapidly thins eastward from Adeii Eechii Cliffs to the subsurface of Moenkopi Plateau. About 48 to 76 m (160 to 250 ft) thick

Jkn **Kayenta Formation-Navajo Sandstone transition zone (Lower Jurassic)**—Light-red and white, fine- to medium-grained, massive to crossbedded, cliff-forming sandstone beds of Navajo Sandstone lithology that intertongue with purple and light-red, slope-forming mudstone, siltstone, and sandstone beds of underlying Kayenta Formation that forms a sequence of red and white sandstone cliffs that alternate with purple and light-red mudstone and siltstone slopes. This interval is considered to be the lower “wet part” of the Navajo Sandstone by Marzolf (1983) and Blakey (1994). Unit gradually thins southeastward along Adeii Eechii Cliffs and in subsurface of the Moenkopi Plateau based on lithologic map contacts. Individual lower red sandstone units either pinch out or thicken resulting in variable thicknesses of unit and arbitrary contact with the underlying Kayenta Formation. About 37 to 73 m (120 to 240 ft) thick

Jk **Kayenta Formation (Lower Jurassic)**—Purple, lavender, and light-red fluvial, crossbedded, fine-grained mudstone, siltstone, and silty sandstone. Weathers to steep slope. Upper part intertongues with Navajo Sandstone north and east of map area, but forms a mappable transition zone of intertonguing units within map area. Unit includes some lenticular, medium-grained sandstone ledges in middle and lower part. Lower part forms resistant ledgy interbedded siltstone and sandstone sequence commonly 6 to 12 m (20 to 40 ft) thick that forms a protective white cliff over Moenave Formation in the Red Rock Cliffs area. This white sandstone gradually thickens eastward and is correlative to the Wingate Sandstone (too thin to show at map scale) of the Hopi Buttes about 72 km (45 mi) east of the map area. Contact with underlying Moenave Formation is unconformable; erosional relief generally less than 2 m (6 ft) in map area and marked by lithology and color changes; the J-sub-K unconformity as defined by Riggs and Blakey (1993) and Blakey (1994). Laterally, the contact is slightly higher or lower in stratigraphic position over several kilometers accounting for variable thickness differences between the Kayenta and Moenave Formations. Overall the unit rapidly thins east and southeast of map area. About 122 m (400 ft) thick in the west to 98 m (320 ft) thick in the east

Jm **Moenave Formation (Lower Jurassic and Upper Triassic(?))**—Red and light-red, flat-bedded and crossbedded, fine- to coarse-grained fluvial siltstone and silty sandstone. Unit is divided into the Springdale Sandstone Member (upper part) and the Dinosaur Canyon Member (lower part) north of the map area near the town of Moenave, Arizona, the type section. The Springdale Sandstone Member type locality is in Springdale, Utah, and pinches out at the northeast edge of map area. The Dinosaur Canyon Member is informally named from an unnamed tributary (not shown on USGS topographic maps to help protect the fossil dinosaur track ways) to the Little Colorado River below the Adeii Eechii Cliffs. Within the map area the entire sequence of red fluvial sandstones of the Moenave Formation represents the Dinosaur Canyon Member. Formation as a whole generally weathers to form a slope except where overlain by resistant beds of the lower Kayenta Formation that form the Red Rock Cliffs. Unconformable contact with underlying Owl Rock Member of the Chinle Formation is known as the J-O unconformity and separates the Triassic rocks from the overlying Jurassic rocks. About 84 to 98 m (275 to 320 ft) thick

Chinle Formation (Upper Triassic)—Includes the Owl Rock Member; Petrified Forest Member; Shinarump Member and the sandstone and siltstone member, undivided (Repenning and others, 1969)

Ѣco **Owl Rock Member**—Grayish-red and light-purple, slope- and ledge-forming nodular limestone interbedded with purple, light-blue, and light-red calcareous siltstone and sandstone. Limestone beds are gray, cherty, lenticular, silty, irregular bedded 0.5 to 1.5 m (1 to 5 ft) thick and extend laterally for several miles to form resistant ledges of Ward Terrace (fig. 1). Black petrified logs form a unique petrified forest on Ward Terrace south of Landmark Wash. Unit contains abundant mud pellets and silicified clay and concretionary chert nodules and generally maintains constant thickness from Cameron to southeast edge of map area. Unconformable contact between Owl Rock Member of the Chinle Formation and overlying Moenave Formation commonly marked by distinct lithology and color change from purple and white calcareous siltstone and sandstone and limestone of the Owl Rock to dark-red or orange-red coarse-grained sandstone of the Moenave. Gradational and arbitrary contact with underlying Petrified Forest Member placed at lowest laterally continuous limestone or nodular calcareous grayish-white siltstone in slope generally about 18 to 25 m (60 to 80 ft) below lowest prominent limestone caprock of Ward Terrace. About 82 m (270 ft) thick in southeast part of map to 60 m (200 ft) thick in northeast part

Ѣcp **Petrified Forest Member**—Purple, blue, light-red, reddish-purple, grayish-blue, slope-forming mudstone and siltstone and interbedded white, coarse-grained lenticular sandstone. Includes three informal units of Akers and others (1958), in ascending order: blue mudstone, gray mudstone and sandstone, and red mudstone and sandstone (not mapped). Includes large lenticular erosional channel structures and large-scale low-angle trough crossbedding. Petrified logs and wood fragments common in white or yellowish-white sandstone in lower part that may be within upper part of sandstone and siltstone member, undivided, of the Chinle Formation. Gradational and arbitrary contact with underlying Shinarump Member and sandstone and siltstone member, undivided, at lithologic and topographic change from sloping multicolored mudstone of Petrified Forest Member to coarse-grained, light-brown sandstone ledges and purple slopes of Shinarump Member. Weathers into rounded hills or slopes with a rough, puffy, popcorn texture surface due to swelling of clay content when wet. Thickness, 122 to 153 m (400 to 500 ft)

Ѣcs **Shinarump Member and sandstone and siltstone member, undivided**—White, light-brown, and yellowish-pink, cliff-forming, coarse-grained sandstone and conglomeratic sandstone. Includes cliff-forming, low-angle crossbedded sandstone interbedded with slope-forming, poorly sorted, purple, light-red, and blue siltstone and mudstone. Lithology is highly variable but is relatively homogeneous from a regional viewpoint; consists of about 75% sandstone, 20% conglomerate, and 5% mudstone. Pebbles are generally brown to light-colored, well-rounded quartzite and 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 for uranium along Little Colorado River valley during the 1950's. All open-pit mines (Qaf) are abandoned and most have undergone landscape reclamation. Unconformable erosional contact with underlying red siltstone and sandstone of Moenkopi Formation. Thickest exposures of unit is northwest of Cameron, thinning southeastward along Little Colorado River Valley. About 18 to 60 m (60 to 200 ft) thick

Ѣm **Moenkopi Formation, undivided (Middle(?) and Lower Triassic)**—Red, slope-forming, fine-grained, thin-bedded, shaly siltstone and sandstone. Includes, in ascending order, the Wupatki Member, the Shnabkaib Member and lower massive sandstone member, and the Holbrook and Moqui Members, undivided. White, cliff-forming, coarse-grained, low-angle, crossbedded sandstone in lower part of unit in Dog Knobs area may be equivalent to the lower massive sandstone (Ѣmss) member of the Moenkopi Formation east of Dog Knobs area. Unit is mostly eroded from southwest part of map area and commonly buried by volcanic rocks of the San Francisco Volcanic Field in Dog Knobs area. The basal Timpoweap Member of the Moenkopi Formation (not mapped) is composed of conglomeratic limestone or calcareous sandstone with small white, angular chert pebbles and fragments that occupy shallow depressions and channels eroded into underlying Harrisburg Member of the Kaibab Formation in western half of map area. Unit is distinguished from underlying red siltstone and sandstone beds of Harrisburg Member of the Kaibab Formation (Pkh) by its darker red color, thin-bedded, platy, coarse-grained, conglomeratic sandstone beds as opposed to massive-bedded, pale-red and gray, undulating, soft siltstone and sandstone beds of Harrisburg Member. Forms unconformable contact with underlying Harrisburg Member of the Kaibab Formation (Pkh) representing the regional Permian/Triassic unconformity. Overall thickness before Cenozoic erosion, about 300 m (1,000 ft) along west edge of map area, thins eastward to about 107 m (350 ft) near Cameron, Arizona, and to about 67 m (220 ft) at Wupatki National Monument area

Moenkopi Formation

Ѣmhm **Holbrook and Moqui Members, undivided (Middle(?) and Lower Triassic)**—Reddish-brown, slope-forming, alternating sequence of claystone, siltstone, and sandstone (McKee, 1954). Includes 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. About 25 to 37 m (80 to 120 ft) thick

Ѣmss **Shnabkaib Member and lower massive sandstone member, undivided (Lower Triassic)**—Yellowish-white and light-brown, cliff-forming, crossbedded, fine-grained, calcareous siltstone and sandstone. Shnabkaib Member and lower massive sandstone member is undivided on Marble Plateau north of Little Colorado River Gorge and intertongues or overlaps lower massive sandstone member in the vicinity of the Little Colorado River west of Cameron, Arizona. Unit is the Shnabkaib Member of the Moenkopi Formation on Marble Plateau north of map area. Unit is lower massive sandstone member of the Moenkopi Formation as defined by McKee (1954) from Cameron, Arizona south to southeast edge of map. Unit is thickest at Wupatki National Monument (15 m [50 ft]) consisting of two or more sandstone beds that form prominent isolated mesas or ridges in Wupatki National Monument area. Unit gradually thins in all directions from Wupatki and the lowermost ledge-forming sandstone is the most widespread part of unit. Gradational contact with underlying Wupatki Member marked at base of lowest sandstone cliff. About 3 to 26 m (10 to 53 ft) thick

Ѣmw **Wupatki Member (Lower Triassic)**—Red and red-brown, slope-forming, thin flat-bedded, siltstone and sandstone and interbedded crumbly red-brown mudstone (McKee, 1954). Thin sandstone beds (0.5 to 1 m [1 to 3 ft]) form resistant ledges. Bedding surfaces often contain small-scale ripple marks, salt crystal casts, or rain drop impressions. Unconformably overlies Kaibab Formation on a regional Permian-Triassic boundary. Unit generally maintains constant thickness from Little Colorado River Gorge to Cameron, Arizona, then gradually thins southwest and southeast of Gray Mountain, Arizona. About 6 to 26 m (20 to 85 ft) thick

Pk **Kaibab Formation, undivided (Lower Permian)**—Includes, in descending order, Harrisburg and Fossil Mountain Members as defined by Sorauf and Billingsley (1991). Mapped as Kaibab Formation, undivided, east of Doney Mountain Fault and Wupatki National Monument along the Little Colorado River because of eastward shoreward facies change in both members that collectively forms gray to light-brown, cliff-forming, calcareous sandstone and sandy limestone beds that are indistinguishable from each other. Unit gradually thins southeastward. About 92 m (300 ft) thick in western part of map area, thinning to about 76 m (250 ft) thick in eastern part

Kaibab Formation

Pkh **Harrisburg Member (Lower Permian)**—Reddish-gray and brownish-gray, slope-forming gypsum, siltstone, sandstone, and thin-bedded limestone. Includes yellowish-gray fossiliferous sandy limestone at top of unit that is mostly eroded from much of the map area; forms surface bedrock in west half of map area. Contact with underlying Fossil Mountain Member is gradational and arbitrarily marked at topographic break between the grayish-white, slope and ledge forming sandy limestone and sandstone sequence of Harrisburg Member and the gray, cliff-forming white to light-brown, cherty limestone of Fossil Mountain Member. Unit gradually thins west to east and undergoes shoreward facies change from limestone and sandy limestone to calcareous sandstone. About 25 to 37 m (80 to 120 ft) thick

Pkf **Fossil Mountain Member (Lower Permian)**—Light-gray, cliff-forming, fine- to medium-grained, thin- to medium-bedded (0.3 to 2 m [1 to 6 ft]), fossiliferous, cherty, sandy limestone and dolomite. Weathers dark gray to black. In west half of map area unit characterized by abundance of gray and white, fossiliferous, chert nodules and white chert breccia beds. Some chert nodules contain concentric black and white bands. Breccia chert beds (1 to 3 m [4 to 10 ft]) thick commonly form uppermost part of Fossil Mountain Member in west half of map area that helps establish contact between Harrisburg (Pkh) and Fossil Mountain (Pkf) Members of the Kaibab Formation. Chert makes up about 25% of unit in west half of map area, less than 5% in east half. Unit gradually thins eastward and undergoes a shoreward facies change from sandy marine limestone and limestone to calcareous sandstone similar to texture, composition, and appearance of Harrisburg Member. Generally forms cliff at rim of Grand Canyon and Little Colorado River Gorge overlain by ledges of sandy limestone of Harrisburg Member. Unconformable contact with underlying Toroweap Formation (Pt) attributed partly to solution erosion and mostly channel erosion; average erosional relief, about 3 m (10 ft). Thickness, 60 m (200 ft) in northwest quarter of map area and gradually thins east and southeast in subsurface of map area. About 70 m (230 ft) thick in northwest part of map area, thinning to about 55 m (180 ft) thick in southeast part

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 in Grand Canyon, northwest corner of map area but too small to show at map scale and are mapped as the Toroweap Formation, undivided. All three members undergo a rapid shoreward facies change eastward from a general slope unit of siltstone, gypsiferous sandstone, and limestone to an indistinguishable cliff unit of calcareous sandstone and sandy limestone in Little Colorado River Gorge and Gray Mountain area. From Little Colorado River Gorge in subsurface of map area to southeast corner of map. Unit gradually thins eastward in subsurface of map from Little Colorado River Gorge and Gray Mountain areas to southeast corner of map where drill holes near Leupp, Arizona (southeast of map area) indicate that only 6 to 9 m (20 to 30 ft) of Toroweap Formation is present in that area (Don Bills, oral commun., July 2005). About 55 m (180 ft) thick in western part of map area, thinning to about 9 m (30 ft) thick in eastern part

Woods Ranch Member—In the Grand Canyon area unit is gray and light-red, slope-forming gypsiferous siltstone and silty sandstone, interbedded with thin, white laminated gypsum and gray thin-bedded limestone. Weathers to reddish-gray slope. Bedding locally distorted due to dissolution of gypsiferous siltstone. Unit undergoes shoreward facies change eastward becoming mostly cliff-forming calcareous sandstone. Contact with underlying Brady Canyon Member at Grand Canyon is gradational and marked at topographic break between slope-forming siltstone of Woods Ranch Member and cliff-forming limestone of Brady Canyon Member. About 20 m thick (65 ft) thick in western part of map area, thinning to about 6 m (20 ft) thick in eastern part

Brady Canyon Member—In the Grand Canyon area unit is gray, cliff-forming, thin- to medium-bedded (0.05 to 1.4 m [1 to 5 ft]), fine- to coarse-grained, sandy limestone. Weathers light-gray. Contains white and gray chert nodules that make up less than 5% of unit. Unit undergoes gradual shoreward facies change eastward along with overlying Woods Ranch Member and underlying Seligman Member making all three units indistinguishable from one another. Contact with underlying Seligman Member is marked at base of limestone cliff in Grand Canyon area. About 6 to 9 m (20 to 30 ft) thick

Seligman Member—In the Grand Canyon area unit is gray, light-purple, and yellowish-red, slope-forming, thin-bedded dolomite, sandstone, gypsum, and calcareous sandstone. Forms slope or recess between overlying cliff-forming Brady Canyon Member and underlying cliff-forming Coconino Sandstone (Pc) in Grand Canyon area. Unit undergoes eastward shoreward facies change similar to overlying Brady Canyon Member and appears to thin and pinch out before reaching Little Colorado River Gorge area. Sharp unconformable contact with underlying Coconino Sandstone where crossbedded sand dunes of Coconino were beveled off by marine wave erosion and sand was redistributed as flat-bedded beach sandstone within Seligman Member of the Toroweap Formation west of map area (Billingsley, 2000; Billingsley and others, 2006). Coconino Sandstone intertongues with lower part of Seligman Member west and north of map area (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; and Billingsley and others, 2003). About 3 to 6 m (10 to 20 ft) thick

Pc **Coconino Sandstone and Schnebly Hill Formation, undivided (Lower Permian)**—Tan to white, cliff-forming, fine-grained, well-sorted, cross-bedded quartz sandstone. Includes the Schnebly Hill Formation of Blakey (1990) in subsurface of map area. Thin red sandstone beds at base of Coconino Sandstone cliff in Little Colorado River Gorge is likely the northern feather edge of the Schnebly Hill Formation (Ronald C. Blakey, oral commun., July 2005). Contains large-scale, high-angle, planar cross-bedded sandstone sets that average about 11 m (35 ft) thick. Locally includes poorly preserved amphibian fossil track ways and low-relief wind ripple marks on crossbedded planar sandstone surfaces. Lower part of Coconino Sandstone intertongues or grades southward into Schnebly Hill Formation in subsurface of southern two-thirds of map area. Type section of Schnebly Hill Formation (Blakey, 1990) is in Verde Valley, 80 km (50 mi) south of map area. Unit intertongues with lower part of Seligman Member of the Toroweap Formation west of map area (Billingsley, 2000; Billingsley and Wellmeyer, 2003; Billingsley and others, 2006). Coconino Sandstone is a well established part of Grand Canyon nomenclature and is retained as a mappable unit because it forms a thick, regional, white sandstone cliff in Grand Canyon and Little Colorado River Gorge that is easily recognized and mappable. Unconformable contact with underlying Hermit Formation (Ph) is sharp, planar, with relief generally less than 1 m (3 ft) but locally as much as 2.5 m (8 ft) marked by distinct color and topographic change between white, cliff-forming Coconino Sandstone, light-red Schnebly Hill Formation, and dark-red, slope-forming Hermit Formation. Unit decreases slightly from west to east in subsurface of the map area. Unit is an important water-bearing sandstone east and south of map area (Don Bills, Water Resources Division of the U.S. Geological Survey, oral commun., 2005). About 183 m (600 ft) thick

Ph **Hermit Formation (Lower Permian)**—Red, slope-forming, fine-grained, thin-bedded siltstone and sandstone. Upper part contains red massive, low-angle crossbedded calcareous sandstone and siltstone beds in Little Colorado River Gorge that may be equivalent, in part, to Schnebly Hill Formation. Siltstone beds are dark red and crumbly and fill widespread, shallow erosion channels. Siltstone beds form recesses between thicker sandstone beds; locally contains poorly preserved plant fossils in channel fill deposits in lower part of unit in Grand Canyon area. Sandstone is partly bleached to yellowish-white at upper contact with Coconino Sandstone (Pc). Unconformably overlies Esplanade Sandstone (Pe). Dark-red, platy, thin-bedded siltstone of Hermit Formation fills erosional channels as much as 9 m (30 ft) deep eroded into underlying Esplanade Sandstone in Grand Canyon area (Billingsley, 2000). Otherwise, erosional relief is generally less than 3 m (10 ft). Unit thins south and east of Grand Canyon to less than 12 m (40 ft) in Little Colorado River Gorge; may thicken southward in subsurface of map based on exposures in Verde Valley 80 km (50 mi) south of map area (Blakey, 1990). About 25 m (80 ft) thick in northwestern part of map area, thins to 12 m (40 ft) thick in southeast part

Supai Group (Lower Permian, Pennsylvanian, and Upper Mississippian)—Includes in descending order, the Esplanade Sandstone (Pe); Wescogame Formation, Manakacha Formation, and Watahomigi Formation, undivided (ℙMs)

Pe **Esplanade Sandstone (Lower Permian)**—Light-red and pinkish-gray, cliff-forming, fine- to medium-grained, medium- to thick-bedded (1 to 3 m [3 to 10 ft]), well-sorted calcareous sandstone. Includes intrabedded dark-red, thin-bedded, crumbly, recessive and slope-forming siltstone beds in upper and lower part. Crossbeds are small- to medium-scale, planar low-angle and high-angle sets. Unit gradually thins eastward and southeastward in subsurface of map area based on limited exposures in northwest quarter of map. Unconformable contact with underlying rocks (ℙMs) is marked by erosion channels as much as 9 m (30 ft) deep in

Grand Canyon and Little Colorado River Gorge area. Variable thickness, about 122 to 107 m (400 to 350 ft) thick

PMs **Wescogame (Upper Pennsylvanian), Manakacha (Middle Pennsylvanian), and Watahomigi (Lower Pennsylvanian and Upper Mississippian) Formations, undivided**—Includes, in descending order, Wescogame, Manakacha, and Watahomigi Formations as defined by McKee (1982). Separate formations are difficult to identify in the field and due to limited exposures in northwest corner of map area and in the Little Colorado River Gorge

Wescogame Formation (Upper Pennsylvanian)—Light-red, pale-yellow, and light-gray upper slope unit and lower cliff unit. Upper slope unit consists mainly of dark-red, fine-grained siltstone and mudstone interbedded with light-red, coarse-grained, calcareous sandstone and dolomitic sandstone, siltstone, mudstone, and conglomerate. Lower cliff unit consists mainly of light-red to gray, high-angle, large- and medium-scale, tabular-planar, crossbedded sandstone and calcareous sandstone sets as much as 12 m (40 ft) thick. Unconformable contact with underlying Manakacha Formation marked by erosion channels as much as 4.5 m (15 ft) deep in Grand Canyon part of map area. Channels commonly filled with limestone/chert conglomerate. About 45 m (150 ft) thick

Manakacha Formation (Middle Pennsylvanian)—Light-red, white, and gray upper slope and lower cliff of sandstone, calcareous sandstone, dark-red siltstone, and gray limestone. Upper slope consists mainly of shaly siltstone and mudstone with minor interbedded, thin-bedded limestone and sandstone. Carbonate content of upper slope increases westward to form numerous ledge-forming, thin- and medium-bedded limestone beds. Upper slope is about 30 m (100 ft) thick in Grand Canyon area of map. Lower cliff is dominated by grayish-red, medium- to thick-bedded, crossbedded calcareous sandstone, dolomite, and sandy limestone. Lower cliff is about 18 m (60 ft) thick. Carbonate content increases west of map area forming numerous gray limestone ledges. Unconformable contact between the Manakacha Formation and underlying Watahomigi Formation marked at base of lower red sandstone cliff of Manakacha; erosional relief generally less than 1 m (3 ft) as wavy unconformable surface. About, about 60 m (200 ft) thick

Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian)—Gray and purplish-red, slope-forming limestone, siltstone, mudstone, and conglomerate. Forms an upper ledge/slope and lower slope. Upper ledge/slope consists of alternating gray, thin-bedded cherty limestone ledges interbedded with purplish-gray siltstone and mudstone; limestone beds contain Lower Pennsylvanian conodont fossils in western Grand Canyon area (Martin and Barrick, 1999); red chert lenses and nodules common. Includes limestone chert-pebble conglomerate at base, locally containing Lower Pennsylvanian fossils. Upper ledge/slope averages about 21 m (70 ft) thick throughout Grand Canyon area. Lower slope consists mainly of purplish-red mudstone and siltstone, interbedded with thin-bedded, aphanitic to granular limestone in upper part with red chert veins and nodules. Conodonts in lower thin limestone beds are Upper Mississippian (Martin and Barrick, 1999). Unit includes purple siltstone and gray limestone interbedded with conglomerate that fills small erosion channels cut into either the Surprise Canyon Formation (Ms) north and west of map area or into Redwall Limestone (Mr). Purple shale and mudstone of lower slope unconformably overlies gray Redwall Limestone in Grand Canyon and Little Colorado River Gorge area. Surprise Canyon Formation (Ms) is not present within map area but is present just north of map in Grand Canyon (Billingsley, 2000) and may be present in subsurface of map area. About 30 m (100 ft) thick. Supai Group gradually thins eastward in subsurface of map area. Overall thickness of Supai Group ranges from about 244 to 274 m (800 to 900 ft)

Mr **Redwall Limestone, undivided (Upper and Lower Mississippian)**—Includes, in descending order, Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members, as defined by McKee (1963) and McKee and Gutschick (1969), but these members are too small to show at map scale because of the sheer cliff outcrops of the Redwall Limestone in general. Unit overall is light-gray to dark-gray, cliff-forming, thin- to thick-bedded, fine- to coarse-grained, fossiliferous limestone and dolomite. Includes thin-bedded gray and white chert lenses and nodules. Unit is exposed as sheer cliff in Grand Canyon, and just the top part of the Redwall Limestone is exposed in Little Colorado River Gorge but is too thin to show at map scale. Unit gradually thins eastward in subsurface of map area and is an important subsurface aquifer because of solution-eroded caverns and bedrock joint systems. Variable thickness, about 137 to 122 m (450 to 400 ft)

Horseshoe Mesa Member—Light-olive-gray, ledge- and cliff-forming, thin-bedded, fine-grained limestone. Weathers to receding ledges. Gradational and disconformable contact with underlying massive-bedded limestone of Mooney Falls Member marked by thin-bedded, platy limestone beds of Horseshoe Mesa Member that form recess about 1 to 3 m (3 to 9 ft) thick near top of cliff. Fossils are locally common. Includes distinctive ripple-laminated limestone and oolitic limestone beds and some chert lenses. Unit locally absent where removed by Late Mississippian paleovalley erosion. About 15 to 30 m (50 to 100 ft) thick

Mooney Falls Member—Light-gray, cliff-forming, fine- to coarse-grained, thick-bedded to very thick bedded [1 to 6 m (4 to 20 ft)], fossiliferous limestone. Limestone weathers dark gray; chert beds weather black. Includes dark-gray dolomite beds; oolitic limestone and chert beds restricted to upper part. Disconformable contact with underlying Thunder Springs Member distinguished by lithology; massive-bedded, gray limestone of Mooney Falls Member overlies thin-bedded, dark-gray to brown dolomite and white chert beds of Thunder Springs Member. About 75 m (300 ft) thick

Thunder Springs Member—About half of member is gray, cliff-forming, fossiliferous, thin-bedded limestone and about half is brownish-gray, cliff-forming, thin-bedded [2 to 12 cm (1 to 5 in)], finely crystalline dolomite and fine- to coarse-grained limestone interbedded with lenses of white chert beds. Locally includes large-scale crossbedding and irregularly folded beds north of map area. Disconformable planar contact with underlying Whitmore Wash Member distinguished by distinct lack of chert in Whitmore Wash Member. About 30 m (100 ft) thick

Whitmore Wash Member—Yellowish-gray and brownish-gray, cliff-forming, thick-bedded, fine-grained dolomite. Weathers dark gray. Unconformable contact with underlying Temple Butte Formation (Dtb) marked by erosion channels of low relief about 2 to 3 m (5 to 10 ft) in depth. Contact generally recognized where major cliff of the light-gray Redwall Limestone overlies stair-step ledges of dark-gray Temple Butte Formation in Grand Canyon. About 25 m (80 ft) thick

Dtb **Temple Butte Formation (Upper and Middle Devonian)**—Purple, reddish-purple, dark-gray, and light-gray, ledge-forming dolomite, sandy dolomite, sandstone, mudstone, and limestone, as defined by Beus (2003). Purple and light-gray, fine- to coarse-grained, thin- to medium-bedded, ripple-laminated ledges of mudstone, sandstone, dolomite, and conglomerate fill channels eroded into underlying Cambrian Muav Limestone; channels are as much as 12 m (40 ft) deep in Grand Canyon area in northwest corner of map. Channel deposits are overlain by dark-gray to olive-gray, medium- to thick-bedded dolomite, sandy dolomite, limestone, and sandstone. Ledges weather to dark gray. Unconformity at base represents major stratigraphic break spanning about 100 million years in Grand Canyon that includes part of the Late Cambrian, all of the Ordovician and Silurian, and most of Early and Middle Devonian time. Dark-gray Devonian rocks are distinguished from underlying light-gray Cambrian rocks by color contrast. Unit thins eastward from Grand Canyon and is likely intermittent or discontinuous in the subsurface of the eastern two-thirds of map area. About 0 to 30 m (0 to 100 ft) thick

Tonto Group (Middle and Lower(?) Cambrian)—Includes in descending order, Muav Limestone, Bright Angel Shale, and Tapeats Sandstone as defined by Noble (1922) and modified by McKee and Resser (1945). Only the Muav Limestone is exposed in the northwest corner of the map in Grand Canyon; the other Cambrian units are present in the subsurface of the map area. The age and depositional history of the Cambrian rocks in Grand Canyon are revised by Rose (2003). Tonto Group may overlie tilted strata of Grand Canyon Supergroup of Mesoproterozoic (1.4 to 1.1 billion years) age in subsurface of west and central part of map area and igneous and metamorphic rocks of Paleoproterozoic (1.7 to 1.6 billion years) elsewhere within the map area; this hiatus is known regionally as the Great Unconformity

Ꞓm **Muav Limestone (Middle Cambrian)**—Dark-gray, light-gray, brown, and orange-red, cliff-forming, fine- to medium-grained, thin- to thick-bedded, mottled, fossiliferous, silty limestone, limestone, dolomite, and calcareous mudstone. Includes unnamed siltstone and shale beds of green and purplish-red, micaceous siltstone, mudstone, and thin beds of brown sandstone. Contact with the underlying Bright Angel Shale is gradational and lithology dependent, arbitrarily marked at base of lowest prominent limestone of Muav Limestone in Grand Canyon just north of map area. Muav Limestone gradually thins from 107 m (360 ft) in west part of map area to an unknown thickness in subsurface of eastern two-thirds of map area

UNITS SHOWN ONLY IN CROSS SECTION

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purple-red, slope-forming siltstone, shale, and red-brown to brown sandstone. Consists of green and purple-red, fine-grained, micaceous, ripple-laminated, fossiliferous shale and siltstone; dark-green, medium- to coarse-grained, thin-bedded, glauconitic sandstone; and interbedded purplish-red and brown, thin-bedded, fine- to coarse-grained, ripple laminated sandstone. Contact with underlying Tapeats Sandstone is gradational and arbitrarily marked at top of vertical transition zone from dominantly green siltstone to dominantly brown sandstone above Tapeats Sandstone cliff. About 60 to 90 m (200 to 300 ft) thick

Ꞓt **Tapeats Sandstone (Middle and Lower(?) Cambrian)**—Brown and red-brown, cliff-forming, coarse-grained sandstone and conglomerate. Unconformable contact with underlying Lower Proterozoic surface forms the Great Unconformity. Tapeats Sandstone fills lowland areas and thins across or pinches out against Proterozoic highlands. Variable thickness, 0 to 60 m (0 to 200 ft)

PROTEROZOIC CRYSTALLINE ROCKS

Intrusive and metamorphic rocks as defined by Ilg and others (1996), Hawkins and others (1996), and Karlstrom and others (2003). There is at least a 50 to 75 percent chance that younger Proterozoic sedimentary rocks of the Grand Canyon Supergroup exposed in the eastern Grand Canyon area (Huntoon and others, 1996) may be present in the southern and eastern subsurface of this map area.

Xu **Crystalline rocks, undivided**—Undivided intrusive and metamorphic rocks. Includes granite plutons, stocks, and pegmatite and aplite dikes, gabbro-diorite, and granodiorite rocks, garnet schist, hornblende-biotite schist, orthoamphibole-bearing schist and gneiss, and probable felsic metavolcanic rocks

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