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

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Pamphlet to accompany
Scientific Investigations Map 3227

2012

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square inch (in^2)	0.09290	square meter (m^2)
square foot (ft^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

Introduction

This geologic map is a cooperative effort of the U.S. Geological Survey (USGS) in collaboration with the National Park Service, the U.S. Forest Service, the Navajo Nation, and the Hopi Tribe to provide regional geologic information for resource management officials and for visitor information services of the National Park Service, the U.S. Forest Service, the Navajo Nation, and the Hopi Tribe. Funding for the map was provided by the U.S. Geological Survey National Geologic Mapping Program, Reston, Virginia.

Field work on the Navajo Nation lands was conducted under a permit from the Navajo Nation Minerals Department. Anyone wishing to conduct geologic investigations on the Navajo Nation lands must first apply for, and receive, a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515, (928) 871-6587. Permission to conduct field work on portions of the Hopi Moenkopi District at the south-central edge of the map was granted by the Department of Natural Resources of the Hopi Tribe. Any person wishing to conduct geological investigations within Hopi lands must obtain permission from the Department of Natural Resources, The Hopi Tribe, P.O. Box 123, Kykotsmovi, Arizona 86039, (928) 734-3601.

The Tuba City 30' x 60' quadrangle encompasses approximately 5,018 km^2 (1,920 mi^2) within Coconino County, northern Arizona, and is bounded by lat 36° to 36°30' N., long 111° to 112° W. The map area is within the southern Colorado Plateaus geologic province (herein Colorado Plateau). The map area encompasses the southwest portion of the Navajo Nation, part of the Hopi lands, and eastern Grand Canyon National Park, where new geologic mapping is needed for geologic connectivity to the regional geologic framework. The Tuba City 30′ x 60′ quadrangle will benefit local, federal, state, Navajo, and Hopi resource managers who direct environmental and land management programs such as range management, biological studies, flood control, water resource investigations, and natural hazard assessments associated with sand dune mobility. Our geologic information will support ongoing and future geologic investigations and associated studies within the region.

The west half of the Tuba City quadrangle was mapped primarily by George Billingsley and the east half was mapped primarily by Phil Stoffer. Mapping was compiled at 1:24,000-scale using a combination of aerial photography, digital orthophotos, and field checking. The mapped area is presented as two 1:50,000-scale views, west half (sheet 1) and east half (sheet 2), with related information on a third sheet (sheet 3). This pamphlet contains a description of map units applicable to the entire Tuba City quadrangle.

Geography

The Tuba City quadrangle is locally subdivided into eight physiographic areas: the Grand Canyon (which includes the Little Colorado River Gorge and Marble Canyon), Walhalla Plateau, Kaibab Plateau, the southern part of House Rock Valley (west of Marble Canyon), Coconino Plateau, Moenkopi Plateau, Kaibito Plateau, and Marble Plateau (east of Marble Canyon) as defined by Billingsley and others, 1997 (fig. 1, sheet 3). Shinumo Altar, Blue Moon Bench, Limestone Ridge, Bodaway Mesa, Yon Dot Mountains, Red Point Hills, and the Painted Desert are collectively referred to as part of the Marble Plateau. Landmark features of the Kaibito Plateau east of the Echo Cliffs include Preston Mesa, Middle Mesa, a portion of White Mesa, Tuba Butte, and Wildcat Peak. The Moenkopi Plateau in the southeast corner of the map area includes Coal Mine Mesa. Coal Mine Canyon erodes into Coal Mine Mesa and is a tributary to Moenkopi Wash. Elevation ranges from about 2,480 ft (756 m) at the Colorado River in Grand Canyon, southwest corner of map, to about 8,860 ft (2,700 m) on the Kaibab Plateau, north rim of Grand Canyon near Point Imperial, west-central edge of map.

Settlements within the Tuba City quadrangle area include Tuba City, Moenkopi, Moenave, The Gap, and Cedar Ridge. Not shown are the small communities of Coal Mine Canyon about 1 mi (1.6 km) south of the southeast corner of the map and Tonalea about 1.6 km (1 mi) northeast of the northeast corner of the map.

U.S. Highway 160 and State Highway 264 provide access to the eastern half of the map area, U.S. Highway 89 to the central part, and State Highway 64 to the Grand Canyon and southwest corner. Roads and trails within the Kaibab National Forest are maintained by the National Forest Service, and roads in the Grand Canyon National Game Preserve of House Rock Valley area are maintained by the National Forest Service and the Grand Canyon Trust. Roads on Walhalla Plateau are maintained by Grand Canyon National Park. Unimproved dirt roads provide access to remote parts of the Navajo Nation Reservation. Some are maintained by the Navajo Nation Roads Department in Window Rock, Arizona, and others are maintained locally by chapter governments (Cameron, Coalmine Canyon, Tuba City, Bodaway/Gap, Kaibito, and Tonalea Chapters). Four-wheel drive vehicles are recommended for winter driving on dirt roads of the Navajo Nation areas north and west of Tuba City due to mud and snow. Four-wheel drive is also recommended for all unmaintained dirt roads north and east of Tuba City due to sandy conditions. Extra water and food is highly recommended for travel in this region.

The Kaibab National Forest and Grand Canyon National Park manage lands in the western third of the quadrangle. The Navajo Nation and local Navajo chapter governments manage lands in the eastern two-thirds of the area. The Hopi Tribe and Moenkopi Village manage the Hopi Moenkopi District in the south-central map area.

Previous Work

An early reconnaissance photogeologic map that includes the eastern two-thirds of the Tuba City quadrangle was compiled by Cooley and others (1969, map 1 of 9) for the Navajo and Hopi Reservations of Arizona, New Mexico, and Utah. These maps were not registered to a base because a topographic base larger than 1:250,000-scale did not exist. Wilson and others (1969) compiled an early reconnaissance geologic map of Coconino County and the State of Arizona (1:500,000-scale) using the work of Cooley and others (1969). A geologic map of the Marble Canyon 1° x 2° quadrangle (1:250,000-scale) covers the Tuba City quadrangle (Haynes and Hackman, 1978). Huntoon and others (1996) produced a geologic map of the eastern part of Grand Canyon National Park and vicinity, and Timmons and others (2007) most recently produced a geologic map of the Butte Fault/East Kaibab Monocline area in eastern Grand Canyon. The Precambrian bedrock geology of Timmons and others (2007) in Grand Canyon is reproduced on this map. The Quaternary geology of all previous maps has been modified and significantly updated to match adjoining 30′ x 60′ quadrangle maps, which include Valle (Billingsley and others, 2006), Cameron (Billingsley and others, 2007), and Fredonia (Billingsley and others, 2008). The Grand Canyon 30' x 60' quadrangle (Billingsley, 2000) adjoins the west edge of the Tuba City quadrangle and reflects the bedrock geology of Huntoon and others (1996), but the Quaternary geology was not mapped in detail on that map.

Mapping Methods

Geologic mapping of the Tuba City quadrangle was produced by stereoscopic analysis of aerial photographs augmented by digital orthophotos and extensive field checking. Primary resources include 1:54,000-scale black and white aerial photographs from 1958 and 1968 and 1:24,000-scale and 1:40,000-scale color aerial photographs from 2005. Geologic features were compiled onto 1:24,000-scale topographic maps. Geologic map units were extensively field checked to verify bedrock and surficial units and descriptions. Mapping of the eastern half of the quadrangle was enhanced by using 1:40,000-scale digital color orthophotos. The orthophoto mapping is not quite aligned with the 1:24,000-scale base in some areas.

Many of the Quaternary alluvial and eolian deposits have similar lithology and geomorphic characteristics and were mapped almost entirely by photogeologic methods. Pliocene, Pleistocene, and Holocene surficial deposits are differentiated chiefly on the basis of morphologic character and physiographic position. Older alluvial and eolian deposits generally exhibit extensive erosion whereas younger deposits are actively accumulating material and are slightly eroded. Eolian deposits are stabilized by vegetation in most areas but are partially reactivated during severe drought or storm conditions.

In the eastern half of the quadrangle, small eolian and bedrock outcrops were not individually mapped. Instead, they were lumped into a dominant classification. All surficial contacts adjacent to alluvial, eolian, and bedrock map units are approximate.

Surficial deposits within the Grand Canyon area were not investigated in the field and are largely photo interpretations based on previous field reconnaissance mapping (Huntoon and others, 1996). For a detailed description of surficial deposits and Precambrian rocks within the Grand Canyon area, see Timmons and others (2007).

Mapping was compiled by hand on 1:24,000-scale paper topographic maps. The base maps were then scanned and brought into ArcMap for georeferencing. Geologic features were digitized, symbolized, and cross-checked against the original field sheets in an ArcGIS personal geodatabase. Thirty-two detailed 1:24,000-scale maps were compiled to produce this publication. This map is the eighth in a series of digital 30′ x 60′ geologic maps of the Grand Canyon region.

Geologic Setting

The Tuba City quadrangle is characterized by nearly flat-lying to gently dipping sequences of Paleozoic and Mesozoic strata that overly tilted Precambrian strata or metasedimentary and igneous rocks that are exposed at the bottom of Grand Canyon. The Paleozoic rock sequences from Cambrian to Permian age are exposed in the walls of Grand Canyon, Marble Canyon, and Little Colorado River Gorge, herein collectively referred to as the Grand Canyon. Mesozoic sedimentary rocks are exposed in the eastern half of the quadrangle where resistant sandstone units form cliffs, escarpments, mesas, and local plateaus. A few Miocene volcanic dikes intrude Mesozoic rocks southwest, northwest, and northeast of Tuba City, and Pleistocene volcanic rocks representing the northernmost extent of the San Francisco Volcanic Field are present at the south-central edge of the quadrangle (Ulrich and Bailey, 1987; Billingsley and others, 2007). Quaternary deposits mantle much of the Mesozoic rocks in the eastern half of the quadrangle and are sparsely scattered in the western half. A brief discussion of the surficial deposits is presented later in the text.

Principal folds are the north-south-trending, east-dipping Echo Cliffs Monocline and the East Kaibab Monocline. The East Kaibab Monocline elevates the Kaibab, Walhalla, and Coconino Plateaus and parts of Grand Canyon. Grand Canyon erosion has exposed the Butte Fault beneath the east Kaibab Monocline, providing a window into the structural complexity of monoclines in this part of the Colorado Plateau. Rocks of Permian and Triassic age form the surface bedrock of Marble Plateau and House Rock Valley between the East Kaibab and Echo Cliffs Monoclines (fig. 1, sheet 3).

The Echo Cliffs Monocline forms a structural boundary between the Marble Plateau to the west and the Kaibito and Moenkopi Plateaus to the east. Jurassic rocks of the Kaibito and Moenkopi Plateaus are largely mantled by extensive eolian sand deposits. A small part of the northeast-dipping Red Lake Monocline is present in the northeast corner of the quadrangle.

A broad and gentle elongated anticline, the Limestone Ridge Anticline, forms the crest of Marble Plateau. Here, Paleozoic and Mesozoic strata generally dip less than 1° to 2° in all directions from a central high area along Limestone Ridge north of Bodaway Mesa and east of Cedar Ridge and The Gap (fig. 1, sheet 3). The Limestone Ridge Anticline plunges gently southeast toward the Painted Desert at the south edge of the quadrangle and northward toward Lees Ferry, Arizona, at the north-central edge of the quadrangle. The Tuba City Syncline is a very broad northwest-southeast-oriented synclinal downwarp that parallels the Echo Cliffs Monocline north of Tuba City. The Preston Mesa Anticline is a small fold present on Kaibito Plateau north of Tuba City (fig. 1, sheet 3; Cooley and others, 1969; Haynes and Hackman, 1978).

Precambrian Rocks

At the bottom of Grand Canyon in the western third of the quadrangle, the Colorado River has exposed the oldest rocks of late Precambrian age. Proterozoic rocks of the Grand Canyon form three main packages that record distinct depositional and tectonic episodes in the Paleoproterozoic, Mesoproterozoic, and Neoproterozoic. These rocks, from oldest to youngest, include the Granite Gorge Metamorphic Suite and Zoroaster Complex (Paleoproterozoic), the Unkar Group (Mesoproterozoic), and the Chuar Group (Neoproterozoic).

Paleoproterozoic

The Paleoproterozoic rocks form the basement rocks for the map area and underlie all younger rocks in the region. These metamorphic and igneous rocks are commonly called the Granite Gorge Metamorphic Suite and Zoroaster Complex (Ilg and others, 1996: Karlstrom and others, 2003). Within the quadrangle, these rocks span ages between 1,680 and 1,750±2 Ma (Hawkins and others, 1996); however, some of the oldest rocks are dated at 1,842 Ma southwest of the quadrangle (Ilg and others, 1996). These lithologic units represent a complexly deformed package of metasedimentary and metavolcanic rocks intruded by numerous granitic dikes and plutons. These rocks record the assembly and stabilization of a juvenile continental crust in the southwest during a southward (present coordinates) growth of the Laurentian continent by the accretion of volcanic arc terrains (Hoffman, 1988; Karlstrom and Bowring, 1988). Following continental assembly, the Paleoproterozoic rocks stabilized and remained at middle crustal depths from 1.65 to 1.45 Ga as suggested by the 1.375 Ga age of granite near Quartermaster Canyon in western Grand Canyon (Karlstrom and others, 2003).

Mesoproterozoic

The 1.4 Ga thermal/tectonic events are hypothesized to have been regionally important in driving the uplift and exhumation of middle crustal rocks prior to the deposition of the Mesoproterozoic sediments of the Grand Canyon Supergroup. The beveling of the basement metamorphic and igneous rocks prior to deposition of the Grand Canyon Supergroup is recognized as the Greatest Angular Unconformity (Powell, 1875) marked between basement Paleoproterozoic rocks and the overlying Mesoproterozoic rocks of the Unkar Group. The Great Unconformity separates all Precambrian rocks from the overlying Paleozoic rocks in the Grand Canyon region.

The 1,250 to 1,100 Ma Unkar Group is approximately 6,900 ft (2,100 m) thick and is divided into five formations, in ascending order: the Bass Formation, Hakatai Shale, Shinumo Sandstone, Dox Formation, and Cardenas Basalt as defined by Timmons and others (2007). These five formations reflect nomenclature usage published by Timmons and others (2007) and do not reflect the USGS style as defined by Elston (1979) and Hendricks and Stevenson (2003). The succession contains both fluvial and shallow-marine deposits with one main disconformity below the Shinumo Sandstone. In general, the rocks of the Unkar Group dip northeast (10°–30°) toward normal faults and the normal faults dip 60° southwest (Sears, 1973).

The combined sedimentologic and deformational history of the Unkar Group highlights an important period of geologic history in the U.S. Southwest. Plate tectonic forces at the plate margin (currently west Texas) created massive alpine-scale mountain ranges along the eastern margin of Laurentia (Grenville orogeny). The far field forces related to that collision manifested as deformational features and depositional systems in Grand Canyon (Timmons and others, 2007). Rocks of the lower Unkar Group are involved in northeast-striking monoclines that record northwest-directed crustal shortening (see Red Canyon on map; Timmons and others, 2005, 2007). These monoclines are intimately related to deposition of the lower Unkar Group. The lower Unkar Group and its associated deformation are buried by the upper Unkar Group that records dominantly northeast-directed extension along northwest-striking faults (Timmons and others, 2005).

Neoproterozoic

Deformation of the Unkar Group continued into Nankoweap Formation time as indicated by an unconformity within that formation and an angular unconformity between the Nankoweap and overlying Chuar Group rocks. Rocks of the Chuar Group include, in ascending order, the Galeros Formation and the Kwagunt Formation that are in turn subdivided into four and three members, respectively (Karlstrom and others, 2000). Deposition of the mudstone-dominated Chuar Group began approximately 300 m.y. after the eruption of the Cardenas Basalt and marks a new depositional and deformational episode in the Grand Canyon and adjacent areas. By 800 to 742 Ma, deposition of approximately 5,250 ft (1,600 m) of the Chuar Group of sediments had ended, and deposition of the overlying Sixtymile Formation occurred soon after.

Rocks of the Chuar Group record an important episode of sedimentation and deformation related to the incipient rifting of Laurentia in the Neoproterozoic. Faulting and folding of the Chuar Group and the Sixtymile Mile Formation record east-west extensions along north-striking normal faults (Dehler and others, 2001). The timing of deformation and the marine depositional setting are consistent with an early phase of continental rifting and basin formation as rifting begins along the present day western cordillera.

The Precambrian bedrock presented in this map is that of Timmons and others (2007). Surficial deposits in the Precambrian area have been slightly modified from Timmons and others (2007) to better match and correlate with adjacent 30′ x 60′ maps of the Grand Canyon area (Billingsley and others, 2006, 2007, 2008).

Paleozoic Rocks

The erosion of Grand Canyon by the Colorado River has exposed about 3,300 ft (1,006 m) of Paleozoic strata. These Paleozoic rocks are likely present in the subsurface of Coconino, Marble, Kaibito, and Moenkopi Plateaus with variable facies and thickness changes and an overall gradual thinning of most units toward the east. Paleozoic rocks from oldest to youngest are the Tapeats Sandstone (Lower(?) to Middle Cambrian), the Bright Angel Shale (Middle Cambrian), the Muav Limestone (Middle Cambrian), the Temple Butte Formation (Middle and Upper Devonian), the Redwall Limestone (Lower, Middle, and Upper Mississippian), the Surprise Canyon Formation (Upper Mississippian), the lower part of the Supai Group, undivided (Lower, Middle, and Upper Pennsylvanian and Upper Mississippian), and the Esplanade Sandstone, the Hermit Formation, the Coconino Sandstone, the Toroweap Formation, and the Kaibab Formation (Permian, Cisuralian).

Cambrian

Based on exposures in Grand Canyon and in the Verde Valley 40 mi (65 km) south of the map area, the Tapeats Sandstone and Bright Angel Shale gradually thin south and east of the map area and gradually thicken west and north. Both units locally pinch out on elevated Precambrian monadnocks west of the map area and likely do the same under the plateaus surrounding the Grand Canyon. The Muav Limestone gradually thins east and southeast and thickens west and north of the map area and may locally pinch out onto Precambrian rocks as it does just west of the map area in eastern Grand Canyon (Huntoon and others, 1996; Billingsley, 2000).

Devonian

The Temple Butte Formation includes a purple-red dolomite, siltstone, and conglomerate that fill channels as deep as 120 ft (35 m) in the Marble Canyon area. The unit is locally discontinuous between channels in Marble Canyon and likely east of the Marble Canyon area. The Temple Butte Formation is a continuous unit in the southwest quarter of the map area and gradually thickens to the south and west.

Mississippian

The Redwall Limestone gradually thins eastward and thickens westward as seen in Grand Canyon exposures and unconformably overlies either the Temple Butte Formation or the Muav Limestone where the Temple Butte is locally missing. The Redwall Limestone forms a thick 500 to 550 ft (152 to 168 m) reddish-gray cliff in eastern Grand Canyon. The overlying Surprise Canyon Formation is a discontinuous unit that locally fills shallow channels or caves eroded into the top part of the Redwall Limestone.

Pennsylvanian

The lower Supai Group, undivided, unconformably overlies the Redwall Limestone or the Surprise Canyon Formation (where present) and gradually thins eastward in the subsurface of the map area. The lower Supai Group maintains a general thickness of about 800 ft (244 m) north of the map area and gradually thickens westward.

Permian

The Esplanade Sandstone is the upper part of the Supai Group and forms a prominent sandstone cliff that gradually thins east and south and thickens north of the map area. The Hermit Formation unconformably overlies the Esplanade Sandstone where channels have eroded into the Esplanade as deep as 30 ft (9 m).

The Hermit Formation thins eastward to less than 20 ft (6 m) in the Little Colorado River Gorge and likely pinches out before reaching the Tuba City area. The Hermit Formation thickens north and west of the Grand Canyon in the subsurface 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 is about 600 ft (183 m) thick throughout the southwest half of the map area and thins to the north and west of the quadrangle. The basal part of the Coconino Sandstone includes a red sandstone in the Little Colorado Gorge that is likely the northern extent of the Schnebly Hill Formation exposed in the Verde Valley south of the quadrangle as defined by Blakey (1990; Ronald C. Blakey, oral commun., 2005). The Coconino Sandstone (not the Schnebly Hill Formation) is actually 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; Billingsley and others, 2000; Billingsley and Wellmeyer, 2003) but is a well-established unit in Grand Canyon nomenclature that forms a distinct mappable unit throughout the Grand Canyon region. The Coconino Sandstone and Schnebly Hill Formation gradually thicken south and southeast of the map area. Both the Schnebly Hill Formation and the Coconino Sandstone form an important groundwater bearing unit known as the “C” aquifer.

The Toroweap Formation overlies the Coconino Sandstone and undergoes a substantial west-to-east facies change in the Grand Canyon and in the subsurface of the map area. All three members of the Toroweap Formation, as defined by Sorauf and Billingsley (1991), are recognized in the south and west edges of the map as, in ascending order, the Seligman, Brady Canyon, and Woods Ranch Members. All three members become indistinguishable along the eastern rim of Grand Canyon, Marble Canyon, and the Little Colorado River Gorge owing to a facies change into cliff-forming sandstone and are mapped there as the Toroweap Formation, undivided. The west-to-east Toroweap facies change roughly parallels the Colorado River. The Toroweap Formation gradually thins east, north, and south of the Grand Canyon area and thickens west.

The Kaibab Formation forms the rim of the Grand Canyon and the surface bedrock for much of the Coconino, Walhalla, and Kaibab Plateaus, House Rock Valley, and the western half of Marble Plateau where not covered by remnants of the Moenkopi Formation or surficial deposits. The Kaibab Formation is divided into, in ascending order, the Fossil Mountain and Harrisburg Members as defined by Sorauf and Billingsley (1991). 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 in the walls of Grand Canyon and its tributaries. The Fossil Mountain Member contains brachiopod, sponge, and trilobite fossils and abundant chert beds, lenses, and nodules. The Harrisburg Member is primarily a sandy limestone or calcareous sandstone that locally contains a few mollusk fossils. The Harrisburg Member of the Kaibab Formation forms a ledge-and-slope profile above the cliff-forming Fossil Mountain Member. The Harrisburg Formation is often weathered or stained dark gray or black by manganese oxide. The Fossil Mountain and Harrisburg Members undergo a west-to-east facies change within the map area, making it increasingly difficult to distinguish one member from the other east of the Grand Canyon. The Kaibab Formation gradually thins east of the map area and thickens toward the northwest and west.

Mesozoic Rocks

An unconformity with general relief of less than 10 ft (3 m) separates the Permian Kaibab Formation from the overlying Triassic Moenkopi Formation. This unconformity is commonly recognized by a color change from the grayish-white sandy limestone beds of the Kaibab Formation to the light-red, thin-bedded siltstone and sandstone beds of the Moenkopi Formation. Erosional depressions and channels form the lenticular basal part of the Moenkopi Formation. Channels are filled with angular and subangular chert and sandstone conglomerate or breccia deposits derived from the Kaibab Formation.

Erosion has exposed about 2,300 ft (700 m) of Mesozoic strata in the eastern half of the map area and removed most of these rocks from the western half. In ascending order, Mesozoic rocks present are the Moenkopi Formation (Lower and Middle(?) Triassic); the Chinle Formation (Upper Triassic); the Glen Canyon Group consisting of the Moenave Formation (Upper Triassic(?) to Lower Jurassic), the Kayenta Formation (Lower Jurassic age from Doelling and others, 2000), rocks of the Kayenta Formation-Navajo Sandstone transition zone (Lower Jurassic), and the Navajo Sandstone (Lower Jurassic age from Doelling and others, 2000); and the San Rafael Group consisting of the Carmel Formation (Middle Jurassic) and the Entrada Sandstone-Cow Springs Sandstone, undivided (Middle Jurassic). Unconformably overlying the Jurassic rocks are the Dakota Sandstone (Upper Cretaceous) and the Mancos Shale (Upper Cretaceous age from Doelling and others, 2000). All Mesozoic strata undergo rapid facies and thickness changes in all directions in the Moenkopi and Kaibito Plateau areas.

Moenkopi Formation

Overlying the Kaibab Formation is a sequence of red sandstone ledges and siltstone slopes of the Moenkopi Formation. The Moenkopi Formation forms extensive outcrops on the southern part of the Marble Plateau east of the Little Colorado River Gorge and north-south along the Echo Cliffs to Cedar Ridge and as scattered outcrops on the northern part of Marble Plateau. Prior to Cenozoic erosion, the Moenkopi Formation covered the entire map area as thick as 1,000 ft (300 m) (Billingsley and others, 2006). Deposits gradually thin eastward to about 350 ft (107 m) in the Moenkopi Wash and Echo Cliffs areas (Repenning and others, 1969) and thicken northward to about 460 ft (140 m) northwest of the map area and to less than 220 ft (67 m) at Cedar Ridge at the north-central edge of the map area.

The Moenkopi Formation is subdivided into three members south of the Little Colorado River as described by McKee (1954) and Hager (1922) and mapped by Billingsley and others (2007). In ascending order they are the Wupatki Member, the Shnabkaib Member, and the Holbrook and Moqui Members, undivided. The Moenkopi Formation in northwestern Arizona and southern Utah, as mapped by Billingsley and Workman (2000) and Billingsley and others (2008), used the subdivisions of Stewart and others (1972). North of the map area, the Moenkopi is divided into three parts, in ascending order, as the lower members, undivided, the Shnabkaib Member, and the upper red member as mapped by Billingsley and Priest (2010). The Little Colorado River is a convenient geographic boundary for separating Moenkopi Formation nomenclature south and southeast of Cameron from nomenclature north and northwest of Cameron. Facies changes are numerous and common in all Moenkopi Formation map units along a southeast-northwest direction across the map area. The Wupatki Member southeast of Cameron is the lateral equivalent of the lower members, undivided, northwest of Cameron. The lower massive sandstone is the lateral equivalent of the Shnabkaib Member and the Holbrook and Moqui Members are the lateral equivalent of the upper red member.

The Moenkopi Formation forms a continuous outcrop north of the map area along the Echo Cliffs to Lees Ferry and then west along the Vermilion Cliffs into Utah and northwestern Arizona and south of the map area into the Little Colorado River Valley. The nomenclature of both McKee (1954) and Stewart and others (1972) used for this map is based on tracing and correlating the stratigraphic units of each member across northern Arizona and observing the facies changes from the Little Colorado River Valley to the Vermilion Cliffs and west to Fredonia.

The Wupatki Member is the approximate equivalent of the lower red Virgin Limestone and middle red members of the Moenkopi Formation of northwestern Arizona and is mapped as the lower members, undivided (Ŧmlm), in Billingsley and Priest (2010). The Virgin Limestone Member is present at Cedar Ridge and in the Yon Dot Mountains on Marble Plateau as a light-gray, thin-bedded, fine-grained limestone about 6 in thick but is too thin and discontinuous to show at map scale. It does provide a stratigraphic marker bed between the lower red and middle red members for correlation purposes at the northern edge of the map area.

Mapping along the Vermilion Cliffs northwest of Marble Plateau (Billingsley and Priest, 2010) visibly demonstrates that the Shnabkaib Member undergoes a facies change from a thick white siltstone, gypsiferous sandstone, and limestone sequence to a yellowish-white, crossbedded, ledge-forming, fine- to coarse-grained calcareous sandstone and thin limestone southward along the Echo Cliffs to the Little Colorado River Gorge. The Shnabkaib Member continues a facies change southward to a light-red, fine-grained, cliff-forming, crossbedded fluvial sandstone southeast of the Little Colorado River Gorge and into the Little Colorado River Valley south of the map 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, representing a shoreward facies change from marine to coastal tidal flat from northwestern Arizona southeast to the Little Colorado River Valley.

Southeast of the map area, the Holbrook and Moqui Members (McKee, 1954; Hager, 1922) erode to a uniform, mostly covered slope below the cliff-forming sandstones of the Holbrook Member. A variable and sometimes discontinuous boundary exists between the members. 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 the upper red member of Billingsley and Priest (2010) and may, in part, be Middle(?) Triassic age. The Holbrook and Moqui Member nomenclature (Billingsley and others, 2007) is used on this map because the unit exhibits similar lithology, topographic expression, stratigraphic position, and proximity to the Little Colorado River Valley. The unit undergoes a rapid and complex northward facies change in the eastern part of Marble Plateau between the Little Colorado River Gorge and Cedar Ridge and thins northward along the Echo Cliffs to Lees Ferry.

The Moenkopi Formation was deposited from shallow tidal flats and fluvial floodplains that drained northwest toward southern Utah (Blakey and Ranney, 2008). This coastal setting was followed by a northwest fluvial drainage system that deposited the overlying Chinle Formation. The streams and valleys began to accumulate mud, sand, gravel, and conglomerate deposits of the Shinarump Member of the Chinle Formation. Drainages eroded into the Moenkopi Formation average about 30 ft (10 m) deep and locally as much as 100 ft (30 m). This unconformity is known as the T-3 unconformity (Blakey, 1994). The Moenkopi Formation is unconformably overlain by the light-brown, cliff-forming sandstone and conglomeratic sandstone and purple to light-red siltstone of the Shinarump Member of the Chinle Formation.

Chinle Formation

The Chinle Formation is the most colorful unit in the map area and is subdivided into three members seen along the Echo Cliffs. In ascending order they are the Shinarump Member, the Petrified Forest Member, and the Owl Rock Member as defined by Akers and others (1958) and Repenning and others (1969). The Shinarump Member includes an informal sandstone and siltstone member as defined by Repenning and others (1969). The Shinarump Member is thickest in the Painted Desert along U.S. Highway 89 where accumulations are between 180 and 200 ft (55 and 60 m) thick. Basal, tan, conglomeratic, ledge-forming sandstone beds contain numerous petrified logs and wood fragments and lenses of well-rounded quartzite and chert pebbles. The upper informal sandstone and siltstone sequence is predominantly a lenticular maze of thin to thick interbedded stream-channel and flood-plain deposits of light-brown conglomerate and dark-purple, gray, and dark-red lenticular crossbedded siltstone and sandstone. The sandstone and siltstone member is a transitional unit between the Shinarump Member and the Petrified Forest Member. The sandstone and siltstone member sequence is not as crossbedded or as conglomeratic as the underlying basal Shinarump Member and gradually thins and pinches out northward to Cedar Ridge. The thickness of the Shinarump Member and sandstone and siltstone member, undivided, is variable due to widespread local channel pinch outs and thinning of various lenticular units. The contact between the Shinarump and sandstone and siltstone unit and the overlying Petrified Forest Member is gradational and approximate.

The Petrified Forest Member forms the multicolored blue, red, white, and grayish-green mud hills of the Painted Desert badlands between the Little Colorado River Gorge and Moenkopi Wash and northward along the Echo Cliffs Monocline and U.S. Highway 89. 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 is arbitrary. The three units are, in descending order, a red mudstone and sandstone, a gray mudstone and sandstone, and a blue mudstone. The Petrified Forest Member generally maintains a thickness between 300 and 400 ft (92 and 122 m).

Gradationally overlying the Petrified Forest Member is the Owl Rock Member. The Owl Rock Member consists of an interbedded sequence of gray, ledge-forming, siliceous limestone and light-red to yellowish-gray, slope-forming, calcareous siltstone beds that form Ward Terrace in the southeast corner of the map area (fig. 1, sheet 3). The contact between the Petrified Forest and Owl Rock Members is arbitrary and generally marked about 10 to 15 ft (3 to 4.5 m) below the lowest gray limestone bed of the Owl Rock Member. The contact of the Owl Rock Member with the overlying Moenave Formation is unconformable and marked by a sharp contrast in lithology and color change from gray mudstone, siltstone, and limestone to 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 Triassic strata from the overlying Jurassic rocks. The Owl Rock Member gradually thins northward along the Echo Cliffs Monocline.

Moenave Formation

The type section of the Moenave Formation is near the community of Moenave, west of Tuba City. The Moenave

Formation originally included, in ascending order, the Dinosaur Canyon Member (Colbert and Mook, 1951) 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). More recently, the Springdale Sandstone Member was reassigned to the basal part of the Kayenta Formation (Beik and others, 2007). Thus, the Dinosaur Canyon Member represents the entire Moenave Formation within this quadrangle. The Moenave Formation is a red, slope-forming unit that gradually thins north and northeast of the map area and is removed by modern erosion southwest of the map area.

Kayenta Formation

The Kayenta Formation unconformably overlies the Moenave Formation. This unconformity is the sub-Kayenta Formation unconformity (J-sub-K) as defined by Riggs and Blakey (1993) and Blakey (1994). Erosional relief is generally less than 6 ft (2 m) in the map area but can be as much as 50 ft (15 m) north of the map area (Nation, 1990). The Kayenta Formation includes, in ascending order, the Springdale Sandstone Member and an upper slope-forming sequence of siltstone and sandstone. The Springdale Sandstone forms an orange-red, thick-bedded sandstone cliff overlain by the purple-red, slope-forming siltstone and sandstone of the upper Kayenta Formation from southwest of Tuba City and northwest along the Echo Cliffs. The upper sequence undergoes a facies change northward to a series of light-red sandstone ledges and small, red siltstone slopes at Cedar Ridge.

Kayenta Formation-Navajo Sandstone Transition Zone

The Kayenta Formation grades upward into a sequence of interbedded red and white crossbedded sandstone ledges and purple-red mudstone and siltstone slopes mapped as the Kayenta-Navajo transition zone. The crossbedded sandstone cliffs within the transition zone in the map area grade northward into the Navajo Sandstone. The purple-red mudstone and siltstone slopes grade southward into the Kayenta Formation. 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-Navajo transition zone and the upper part is the eolian cliff-forming Navajo Sandstone found 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-Navajo transition zone is about 240 ft (73 m) thick in the map area and grades laterally northwestward to become the basal part of the Navajo Sandstone near Cedar Ridge. The succession of fluvial, eolian, and lacustrine strata become more frequent as the Kayenta Formation thins in the zone of facies change southeast of the map area (Middleton and Blakey, 1983; Sargent, 1984; Long, 2008). Several springs and seeps are associated with the basal Navajo Sandstone tongues within the Kayenta-Navajo transition zone in the Tuba City, Moenave, and Moenkopi areas. The lowest sandstone cliff marks the approximate contact between the Kayenta Formation and the Kayenta-Navajo transition zone. The upper contact of the Kayenta-Navajo transition zone is marked at the base of the massive overlying Navajo Sandstone.

Navajo Sandstone

The Navajo Sandstone consists of red and white, cliff-forming, eolian, crossbed sets and is the upper part of the Navajo Sandstone as proposed by Blakey (1994). The Navajo Sandstone includes several shallow lake horizons represented as thin-bedded, silica-cemented sandy limestone 1 to 2 ft (0.5 to 1.2 m) thick that are highly lenticular and have limited lateral extent. These resistant limestone beds are at various stratigraphic levels within the Navajo Sandstone and locally form cherty limestone ledges, ridges, or small hills on the Kaibito and Moenkopi Plateaus. The number of limestone ledges increases southeast of the map area. The Navajo Sandstone thins south and east of the map area and is gradually removed by Cretaceous erosion southeast of the map area.

Carmel Formation

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 Coal Mine Mesa in the southeast corner of the quadrangle, as much as 30 ft (9 m) 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 that are likely correlative to the southernmost extent of the Carmel Formation (Jc) at Middle Mesa north of Coal Mine Mesa (east-central edge of the quadrangle) where about 30 ft (9 m) of the Carmel Formation overlies the Navajo Sandstone. The Carmel Formation is also present northeast of the Red Lake Monocline in the northeast corner of the quadrangle. The Carmel Formation has been removed from much of the Kaibito Plateau by modern erosion.

Entrada Sandstone-Cow Springs Sandstone

Strata overlying the Navajo Sandstone in the southeast corner of the map area consists mostly of white and interbedded, red and white, crossbedded Entrada Sandstone overlain by a yellowish, crossbedded cliff of Cow Springs Sandstone, undivided (Je). This sandstone sequence includes thin red beds of the Carmel Formation at the base that extend a short distance southward into the subsurface of Coal Mine Mesa and then pinch out. The upper part of the sandstone sequence, above the interbedded red and white sunstone beds, is a yellowish-white, cliff and slope of planar crossbedded sandstone that is a southern extension of the Cow Springs Sandstone (Harshbarger and others, 1958).

The lower part of the Entrada Sandstone consists of massive, white, very fine grained, cliff- and slope-forming sandstone that weathers steel gray and contains multiple small-scale, low-angle trough crossbeds at Moenkopi Plateau, southeastern quarter of the map. In the northeast quarter of the quadrangle, a red and white, flat-bedded sequence of cliff-forming sandstone makes up a middle red sandstone sequence of the Entrada Sandstone. These red siltstone and sandstone beds increase to more reddish sandstone north of the quadrangle and pinch out south of Coal Mine Mesa on Moenkopi Plateau in the southeast quarter of the quadrangle.

The Entrada Sandstone-Cow Springs Sandstone, undivided, is unconformably overlain by the Cretaceous Dakota Sandstone in the eastern Coal Mine Mesa area and northeast of the quadrangle and are overlain by Tertiary gravels (Tgs) in the western part of Moenkopi Plateau. The Jurassic-Cretaceous unconformity is widespread east, northeast, and southeast of the map area.

Dakota Sandstone

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

A coal bed, locally several feet thick, was mined from this unit at Coal Mine Canyon for use at Tuba City in the early 1900s. The Dakota Sandstone has a gradational and arbitrary contact with the overlying Mancos Shale.

Mancos Shale

The lower part of the Mancos Shale is present at Coal Mine Mesa on the Moenkopi Plateau. Modern erosion has removed most of the bluish-gray, thin-bedded, slope-forming Mancos Shale from Coal Mine Mesa and White Mesa. Remnants of the Mancos Shale are now largely covered by extensive deposits of Pleistocene and Holocene eolian and fluvial sand, silt, and mud. At White Mesa, much of the Dakota Sandstone and Mancos Shale deposits have been removed by Tertiary erosion. What remains is partly overlain by gravels and sedimentary deposits of Tertiary age.

Cenozoic Volcanic Rocks

Shadow Mountain, located about 1 km south of the south-central edge of the map, is an isolated Pleistocene pyroclastic cone with associated basalt flows that are chemically and petrologically similar to rocks of the San Francisco volcanic field. This cone represents the northernmost extent of this volcanic field. Shadow Mountain has a K-Ar age of 0.649±0.23 Ma (Damon and others, 1974; Condit, 1974; Ulrich and Bailey, 1987; Wolfe and others, 1987). These deposits (Qi, Qsb, Qsp) adjoin those of the Cameron 30′ x 60′ quadrangle (Billingsley and others, 2007) at the south-central edge of the map area.

Older intrusive dikes (Ti) are oriented generally north-south in Moenkopi Wash southwest of Tuba City, in Hamblin Wash south of The Gap, at Tuba Butte northwest of Tuba City, and at Wildcat Peak northeast of Tuba City. A new $^{40}Ar/^{39}Ar$ age from a dike at Wildcat Peak yields an age of 19.05±Ma (Peters, 2011). This north-south dike is similar in composition and orientation to the other three dike locations mentioned above and are all assumed to be a similar Miocene age. This age may reflect the southernmost extent of the 21 to 26 Ma volcanic laccolithic mountains in southern Utah, Navajo Mountain, and the Henry Mountains. The 19 Ma age also explains why there are no volcanic surface flows associated with these dikes, because any flows that may have occurred have been eroded away during Late Tertiary and Quaternary erosion along with much of the upper bedrock that exposes these dikes today.

Pliocene-Pleistocene Gravel Deposits

The oldest gravel and sediment deposits (Tgs) cap mesas or ridges as much as 50 ft (17 m) thick, mainly in the eastern part of the quadrangle. These deposits commonly form a cap-rock deposit on Middle Mesa, on Coal Mine Mesa, and at Crooked Ridge. The deposits rest unconformably on beveled surfaces of the Navajo Sandstone and the Carmel Formation. Gravel clasts within the sandstone and siltstone sediments are composed of well-rounded pebbles and cobbles of chert, quartzite, sandstone, limestone, some fossil wood fragments, and reworked marine fossils derived mainly from Cretaceous rocks and perhaps some Jurassic rocks east of the map area.

Younger old terrace gravel deposits (QTg5, QTg6, QTg7) are present at three different levels above Moenkopi Wash and below the oldest gravel and sediment deposits (Tgs) capping Middle Mesa and Moenkopi Plateau east of Tuba City. These deposits reflect various stages of incision into the Navajo Sandstone by an ancestral Moenkopi Wash probably within the last few hundred thousand years. In the Grand Canyon, gravel (QTg5) and sediment deposits of Quaternary age, but with a different lithology, form isolated, well-consolidated terrace deposits about 400 to 450 ft (122 to 137 m) above the Colorado River.

Quaternary Surficial Deposits

Surficial Mapping Technique

Surficial deposits on the Colorado Plateau have largely been ignored because their role on the landscape was not recognized. Today we are learning how significant these deposits are on biology, soil science, and climate studies as well as on the evolutionary development of the landscape.

Surficial sedimentary deposits have accumulated over the last several hundred thousand years. They generally occur as unconsolidated or weakly consolidated deposits of local extent overlaying bedrock. They are usually a thin veneer but can be as much as several tens of meters thick. Surficial deposits have accumulated mainly as a result of running water (fluvial or alluvial deposits), wind (eolian deposits), or a combination of both. Steep slopes near buttes and mesas often have landslide, talus, and rockfall deposits. Deposits in alluvial valleys, washes, and floodplains are often remobilized by wind forming adjacent sand dune and sand sheet deposits.

Mapping surficial deposits across an area as large as the Tuba City 30′ x 60′ quadrangle poses unique challenges. Although a fairly recent age is obvious, very little data is available to confidently assign the deposits to Holocene, Pleistocene, or older. A map-unit naming scheme that combines information about lithology and genesis was needed. To accommodate these criteria, the materials are classified and named using genesis (for example, alluvium, eolian, talus, landslide), geologic age (for example, Holocene, Pleistocene), and lithology (for example, sand, gravel). This strategy has evolved from previous surficial mapping in the Grand Canyon region (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003; Billingsley and others, 2006, 2007, 2008).

Information about surficial deposits was obtained mainly by aerial photo interpretations. Ages are based mostly on geomorphologic criteria, such as relative position in local alluvial-terrace sequences, degree of alluvial fan dissection, and superposition or stabilization of dune and sand sheet deposits. The discontinuous aspect of surficial deposits does not lend itself to easy correlation. Therefore, all age assignments for surficial materials are provisional and the age of a specific unit in one area may not be correlative to the same unit in another area. Unit names with time implications, such as young, intermediate, old, and older, are intended only to indicate local relative stratigraphic position, not age uniformity, throughout the map area. A few eolian units common to both the Cameron and Tuba City 30′ x 60′ quadrangles were adjusted to a younger age for this publication and, therefore, are not the same color as on the Cameron 30′ x 60′ quadrangle (Billingsley and others, 2007).

Local Surficial Deposits

Surficial fluvial deposits are found throughout parts of the western map area and tend to be isolated because of steep topography and rapid modern erosion. In contrast, extensive eolian deposits cover large areas of the Kaibito and Moenkopi Plateaus in the eastern part of the map, where the Navajo Sandstone is the primary source for surficial sand sheet and sand dune deposits. Not all sand deposits are individually shown. In several areas, such as north and east of Tuba City, sand deposits are mapped as an undifferentiated unit consisting of various dune types and small pockets of bedrock. These extensive eolian deposits are transported northeastward across Moenkopi and Kaibito Plateaus by southwesterly winds. In many areas, these eolian deposits are continually recycled; storm runoff erodes then redeposits them in enclosed ponded (Qps) depressions, where wind moves them back onto and across the plateau. Eventually, much of the eolian sand is fluvially transported by fluvial processes into main drainages, such as Moenkopi Wash and Hamblin Wash, that drain into the Little Colorado River, through the Grand Canyon, and out of the region.

Other surficial deposits include travertine deposits that originate from springs in the Grand Canyon and form travertine dams in the bed of the Little Colorado River Gorge that are too small to show at map scale. Numerous landslide (Ql) and talus and rockfall (Qtr) deposits are below the rims of the Little Colorado River Gorge, Marble Canyon, and Grand Canyon and along the Echo Cliffs east of U.S. Highway 89. Diversion dams, stock tanks, gravel pits, and a landfill east of Tuba City are mapped to show the human impact upon the landscape.

Structural Geology

Structural deformation of the Paleoproterozoic (X), Mesoproterozoic (Y), and Neoproterozoic (Z) rocks at the bottom of Grand Canyon are well illustrated by Timmons and others (2007) showing the multiple extensional and folding events of Mesoproterozoic and Neoproterozoic time that largely corresponds with the deposition of Unkar and Chuar Group rocks. Rocks of the Unkar Group were faulted and slightly tilted as coherent blocks then were beveled by a period of erosion that lasted nearly 300 million years. Deposition of the overlying Chuar Group resulted in an angular unconformity between the Unkar and Chuar Groups (Timmons and others, 2007). During Neoproterozoic time, the Chuar Group was subjected to additional folding and, most importantly, west-down normal slip on Butte Fault formed a deep Chuar Group depocenter; drag along this fault produced the Chuar Syncline of Neoproterozoic age (Timmons and others, 2007).

Large high-angle to nearly vertical normal-fault separations in Proterozoic basement rocks set the stage for structural deformation of younger Paleozoic and Mesozoic strata. Compressional folding of Paleozoic and Mesozoic rocks along reactivated Proterozoic high-angle faults began in Late Cretaceous and early Tertiary time—a period known as the Laramide Orogeny that peaked about 65 Ma. Numerous northeast- to east-dipping sinuous monoclines in the western half of the map area are the result of Laramide compression along Proterozoic faults. Concurrent and subsequent erosion has removed much of the Mesozoic strata that once covered the entire map area (Huntoon, 1990, 2003; Huntoon and others, 1996; Timmons and others, 2007).

The East Kaibab Monocline has elevated the landscape to the west forming the topographic highlands of the Walhalla and Kaibab Plateaus (fig. 1, sheet 3). The East Kaibab Monocline extends northwestward into Utah and forms the structural boundary between the Kaibab Plateau and House Rock Valley to the east (Billingsley and others, 2008). The monocline also extends southeast of the map area to Gray Mountain (Billingsley and others, 2007). Strata along the East Kaibab Monocline dip northeast between 20° and 80° with the steepest dip in the lower part of the fold in Grand Canyon (Timmons and others, 2007). Vertical relief of Paleozoic strata along the East Kaibab Monocline and Butte Fault in Grand Canyon averages about 1,000 ft (305 m) up to the west.

The Echo Cliffs Monocline, another major fold, extends from Cedar Ridge at the north-central edge of the map southeastward along U.S. Highway 89 and the Echo Cliffs to about Hidden Springs northwest of Moenave. From Hidden Springs, the Echo Cliffs Monocline bends southwest into the Painted Desert, where it gradually broadens and terminates just south of the south-central edge of the map. In this area, the southwest trend of the Echo Cliffs Monocline is structurally aligned with the northeast trend of the Mesa Butte Fault located about 12 mi (19 km) south of the map edge (Billingsley and others, 2007). The Echo Cliffs Monocline continues north of the quadrangle to Lees Ferry and then northwest into southern Utah. Permian, Triassic, and Jurassic strata that outcrop along the Echo Cliffs Monocline dip east 12° to 18° along the north half of the structure and southeast 3° to 4° along the south half.

Northeast-trending high-angle normal faults intersect the Echo Cliffs Monocline just south of Cedar Ridge where strata is folded to a near vertical position and partially faulted as much as 100 ft (30 m). Folding along the Echo Cliffs Monocline has elevated Marble Plateau an estimated 1,700 ft (518 m) up to the west at Cedar Ridge in the north half of the quadrangle and less than 500 ft (152 m) west of Moenkopi Wash in the south half of the quadrangle. Oddly enough, the average elevation of Marble Plateau west of the Echo Cliffs Monocline is nearly at the same average elevation, about 6,200 ft (1,890 m), as the Moenkopi and Kaibito Plateaus east of the monocline.

Blue Spring Monocline is a small northwest-trending fold displaying northeast-dipping Paleozoic and Mesozoic strata in the southwest quarter of the map area. Relief along this monocline is generally less than 200 ft (60 m) and the average dip of strata is about 5°. Several collapse structures align along the northwest trend of the Blue Spring Monocline, suggesting enhanced karst solutioning of the Redwall Limestone (Wenrich and Huntoon, 1989; Wenrich and Sutphin, 1989). The Blue Spring Monocline is one of the most important hydrological structures within the map area because Blue Spring and several associated springs issue from the top part of the Redwall Limestone at the northwest extent of the Blue Spring Monocline at the bottom of the Little Colorado River Gorge. Numerous northwest-trending joints, fractures, and small faults associated with the Blue Spring Monocline form a major hydrologic avenue for groundwater transport from regions southeast of the map area to Blue Spring. Blue Spring is the largest natural flowing spring in Arizona. Daily discharge is nearly 200 ft^3/s (Don Bills, oral commun., 2012).

On the eastern side of the quadrangle, a few broad north-northwest-trending folds roughly parallel the Echo Cliffs Monocline. The Tuba City Syncline extends from Coal Mine Mesa north to and beneath Crooked Ridge and north of the map area. The White Point Fault (Cooley and others, 1969) is not very evident in the crossbedded Navajo Sandstone where reverse fault drag along the fault makes it difficult to locate strata, which may dip west as much as 22° between White Point Mesa and Preston Mesa. The White Point Fault gradually disappears beneath sand deposits north and south of White Point. Northeast of White Point is the Preston Mesa Anticline (Cooley and others, 1969). This anticline trends northwest-southeast through Preston Mesa with strata dipping less than 5°. The Red Lake Monocline trends northwest-southeast at the northeast corner of the quadrangle between Wildcat Peak and White Mesa. Strata along Red Lake Monocline dip 15° to 20° east in the vicinity of Kaibito just north of the map area.

During the Miocene, Pliocene, and Pleistocene, east-west extension reactivated deep-seated faults along some monoclines, producing normal faults that reversed Cretaceous and Tertiary offset, as well as accentuated the dip of the monoclines by reverse drag along the faults (Huntoon, 1990, 2003). Extensional faulting during the late Pliocene produced many graben structures. A time frame of less than 3 m.y. is inferred, based on similar extensional fault evidence along the Hurricane and Toroweap Faults west and south of the map area (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003; Billingsley and others, 2006, 2007, 2008), but this is not well constrained. North- and northeast-trending grabens and faults in the Little Colorado River Gorge and Marble Plateau areas appear to be the most recent tectonic structures in the area based on minor offset of Pleistocene and Holocene(?) alluvial deposits and Pleistocene volcanic rocks south of the map (Billingsley and others, 2007). Several sinkholes have developed along fractures and joints associated with the faults and grabens. These sinkholes have temporarily interrupted runoff to some small tributaries of the Little Colorado River.

The Laramide erosional period starting about 60 Ma began to transform the landscape to its current configuration, but Neogene Tertiary and Quaternary erosion greatly deepened and broadened the Grand Canyon. The meandering Little Colorado River occupied a strike valley in soft Mesozoic rocks between the East Kaibab Monocline and Marble Plateau and has been superimposed as a subsequent stream into the resistant rocks of the Kaibab Formation in the southern part of Marble Plateau, preserving the older meander pattern. At about the same time, an unnamed drainage from the northeast was meandering on the Navajo Sandstone along a strike valley that parallels the Echo Cliffs Monocline in the vicinity of The Gap. This drainage system is responsible for at least two of the topographic gaps in the Echo Cliffs. Well-rounded sandstone and chert pebbles and cobbles of Jurassic and Cretaceous age suggest that the Crooked Ridge drainage originated from the Black Mesa area east or northeast of the quadrangle and that pebble imbrication of the gravels in the sandy sediment indicate a southwest-flowing stream that deposited the Crooked Ridge stream sediments toward the Echo Cliffs Monocline, then meandered southeast along a monoclinal strike valley towards the Tuba City area. Lag gravels scattered on the Kaibito Plateau northeast and near Tuba City are evidence of this drainage.

The Little Colorado River and its tributaries became integrated with the Colorado River sometime in late Miocene or early Pliocene time after about 6 to 9 Ma (Lucchitta, 1979, 1990; Ranney, 2005). Continued headward erosion of the Little Colorado River, caused by erosional deepening of the Colorado River in Grand Canyon, has gradually extended the Little Colorado River Gorge upstream toward Cameron and into the eastern half of the map area. Headward erosion from the Colorado River continues westward into the Kaibab and Walhalla Plateaus and has greatly enhanced the widening process of eastern Grand Canyon along the East Kaibab Monocline.

Circular bowl-shaped depressions in the Kaibab and Moenkopi Formations, characterized by inward-dipping strata, are likely to be the surface expression of collapse-formed breccia pipes created by dissolution of the Mississippian Redwall Limestone at depth. Collapse features are indicated by a black dot on the map and may or may not represent breccia pipes at depth. Drilling is needed to confirm breccia pipes within collapse structures. Exposed breccia pipes are indicated by red dots.

Large-scale collapse depressions may be the result of several interconnecting smaller collapse features or breccia pipes, such as the Shadow Mountain collapse on the Marble Plateau at the south-central portion of the quadrangle (fig. 1, sheet 3). The Shadow Mountain collapse is a circular, alluvial-filled structural basin about 0.6 mi (1 km) in diameter. The Chinle Formation dips between 5° and 18° toward the center of the collapse. Breccia pipes have the potential for uranium and other minerals at depth, but not all breccia pipes are mineralized (Wenrich and Sutphin, 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 in the Harrisburg Member of the Kaibab Formation has resulted in several sinkholes on the Kaibab Plateau. The sinkholes are likely Pleistocene and Holocene in age because they disrupt local drainages and are commonly filled with locally derived, fine-grained sediments. Gypsum deposits within the Kaibab and Toroweap Formations are thickest along the west edge of the map as evidenced by the increase in sinkholes of that area.

Acknowledgments

We appreciate the cooperation and support of the Water Resource Division and the Geologic Division of the National Park Service, Fort Collins, Colorado, and the Grand Canyon Science Center, National Park Service, Grand Canyon National Park, Arizona. We appreciate the Navajo Nation Minerals Department and the Hopi Tribe for permission to publish those portions of this map involving Navajo Nation and Hopi Tribal lands. We also appreciate the advice, revisions, and geologic information provided by Mark Timmons of New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico, and Karl Karlstrom of the University of New Mexico, Albuquerque, New Mexico. We are indebted to Dr. Charles L. Powell, II, and Jan Zigler of the U.S. Geological Survey, Menlo Park, California, for their technical advice and assistance in the preparation of this map and report.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Pliocene(?), Pleistocene, and Holocene surficial deposits are differentiated from one another chiefly based on differences in morphologic character and physiographic position on 1:24,000-scale, 1968, black and white; 1:24,000-scale, 2005, color; and 1:40,000-scale, 2005, color aerial photographs and on field observations of the lithology. Older alluvial and eolian deposits generally exhibit extensive erosion, have greater topographic relief, and in some areas have developed a carbonate soil subhorizon. Younger deposits are actively accumulating material or are lightly eroded. On Moenkopi and Kaibito Plateaus, extensive eolian sand sheet and dune deposits are stabilized by vegetation during wet conditions and become destabilized and mobile when disturbed by livestock or human activity. These deposits are also partially reactivated during severe drought conditions or spring wind events. Young surficial deposits are actively accumulating material and are vulnerable to wind or water erosion. Eolian and alluvial contacts are provisional and arbitrary.

Qaf **Artificial fill and quarries (Holocene)**—Excavated alluvium and bedrock material removed from barrow pits and trenches to build livestock tanks, drainage diversion dams, landfills, roads, and other construction projects (not all road and construction excavations are shown)

Qs **Stream-channel deposits (Holocene)**—Poorly sorted, interbedded mud, silt, sand, pebbles, and gravel. Intertongue with or inset against young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3), young, intermediate, and old terrace-gravel (Qg1, Qg2, Qg3), and upper part of valley alluvial (Qv) deposits; overlaps and intertongues with 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 some salt cedar (tamarisk), Russian olive, and cottonwood trees. Contacts with adjacent alluvial or eolian deposits are approximate. Stream-channel deposits of Moenkopi and Hamblin Washes do not necessarily reflect stream-channel deposits of today owing to low-gradient channel changes caused by yearly fluctuations in stream levels and flooding events. Thickness, 3 to 30 ft (1 to 9 m)

Qf **Flood-plain deposits (Holocene)**—Gray, brown, to light-red interbedded lenses of clay, mud, silt, and sand. Include minor lenticular gravel deposits, partly consolidated by gypsum and calcite cement. Intertongue with or overlap stream-channel (Qs), valley-fill (Qv), young terrace-gravel (Qg1), and young alluvial fan (Qa1) deposits. Subject to stream-channel erosion or overbank flooding in lateral and vertical sense. Similar to valley-fill (Qv) deposits in small tributary drainages; subject to widespread and frequent overbank flooding along Colorado River, Little Colorado River, Moenkopi Wash, and Hamblin Wash areas. Support thick growths of sagebrush and grass, tumble weed, desert shrubs, and tamarisk trees. Subject to temporary ponding and often mixed with ponded sediments (Qps) or mixed alluvium and eolian (Qae) deposits in broad drainages on Moenkopi and Kaibito Plateaus. Thickness, 3 to 30 ft (1 to 9 m)

Qes **Sand sheet deposits (Holocene)**—White, gray, fine- to coarse-grained, windblown sand composed mainly of quartz and chert grains derived primarily from the Navajo Sandstone and Moenave Formation. Deposits form extensive cover over gently sloping terrain on Moenkopi and Kaibito Plateaus in eastern third of map. Also form thin sand sheets on alluvial fan slopes below the Echo Cliffs parallel to U.S. Highway 89. Commonly intertongue with mixed alluvial and eolian (Qae) deposits that share a gradational lateral and vertical contact. Support moderate growths of grass and small high-desert shrubs that tend to stabilize the deposits. Thickness, 1 to 15 ft (0.3 to 4.5 m)

Qd **Dune sand and sand sheet deposits (Holocene)**—Grand Canyon, Coconino Plateau, and Marble Plateau areas: White, gray, and light-red, fine- to coarse-grained, windblown sand composed mainly of quartz, feldspar, and chert grains derived from Proterozoic, Paleozoic, and Mesozoic sand and gravel deposits that accumulate in stream-channel (Qs) or valley-fill (Qv) deposits and are transported by wind to form lumpy, undefined geometric sand dunes or sand sheet deposits on flood-plain (Qf) and young terrace-gravel (Qg1) deposits near washes in west half of map. Support moderate growths of grass and sagebrush

Moenkopi and Kaibito Plateau areas: White, gray to light-red, fine- to coarse-grained sand composed mainly of quartz, chert, and minor feldspar derived from nearby Triassic and Jurassic sedimentary rocks east of U.S. Highway 89. Include topographically controlled climbing and falling dunes, complex dunes, parabolic dunes, barchan dunes, and sand sheets that mantle bedrock slopes north and south of Moenkopi Wash, along the Echo Cliffs, and within drainages on Moenkopi and Kaibito Plateaus. Navajo Sandstone (Jn) is the primary source of sand on Moenkopi and Kaibito Plateaus. Unit has arbitrary and gradational contacts, in the lateral and vertical sense, with adjacent surficial deposits and bedrock outcrops. Sand is generally transported northeast by southwesterly winds that erode local Triassic sandstone units and older sand deposits. Unit distributes a fresh veneer of sand over bedrock and older eolian deposits on Coal Mine Mesa. Support moderate growth of grass, Mormon tea, and high desert shrubs. Wet conditions stabilize all eolian deposits on Moenkopi and Kaibito Plateaus. Thickness, 3 to 200 ft (1 to 61 m)

Qdl **Linear dune deposits (Holocene)**—White, gray, light-red, fine- to medium-grained, well-sorted, unconsolidated sand accumulations that are aligned and generally trend northeast. Often merge with dune sand and sand sheet (Qd), sand sheet (Qes), parabolic dune (Qdp), and barchan dune (Qdb) deposits. Linear dunes are generally 40 to 80 ft (12 to 24.5 m) wide and less than 0.5 mi (0.8 km) long but can reach over 3 mi (5 km) or more in length on Moenkopi and Kaibito Plateaus. Individual linear dunes are mapped where they form prominent landscape features on Moenkopi and Kaibito Plateaus. Groups of linear dunes are mapped as linear dune and sand sheet deposits (Qdlu). Thickness, 6 to 40 ft (2 to 12 m)

Qdp **Parabolic dune deposits (Holocene)**—White, gray, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand arranged most commonly in complex interconnecting parabolic dune deposits or occasionally in individual parabolic dunes. Sandy ponded sediments (Qps) are commonly formed on upwind (southwest) side of dune complex. Bedrock or older sand accumulation is often exposed at southwest side of parabolic dunes. Contact merges with adjacent dune sand and sand sheet (Qd) and sand sheet (Qes) deposits, mixed alluvial and eolian (Qae) deposits, and local Mesozoic bedrock outcrops on Moenkopi and Kaibito Plateaus. Support little to sparse grassy vegetation. Thickness, 6 to 30 ft (2 to 9 m)

Qdb **Barchan dune deposits (Holocene)**—White, gray, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand that forms isolated barchan dunes or a cluster of interconnecting barchan dunes mainly northeast of Tuba city, on Kaibito Plateau. Subject to yearly change in extent and shape due to seasonal storms and sand mobility. Support little to sparse grassy vegetation. Thickness, 6 to 40 ft (2 to 12 m)

Qdm **Mixed dune deposits (Holocene)**—White, gray, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand derived primarily from the Navajo Sandstone (Jn). Parabolic and linear dunes are the dominant dune types and are often interconnected and associated with massive sand sheet (Qes) deposits. Linear dunes often form as downwind extension of parabolic dunes on Moenkopi and Kaibito Plateaus and parabolic dunes often attach to or are part of linear dunes. Include quite a few Navajo Sandstone (Jn) and ponded sediment (Qps) deposits too small to show at map scale. Often covered annually by active dune sand and sand sheet (Qd) deposits. Thickness, 6 to 40 ft (2 to 12 m)

Qdlu **Linear dune and sand sheet deposits (Holocene)**—White, gray, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand derived primarily from the Navajo Sandstone (Jn) on Moenkopi and Kaibito Plateaus. Unit is often a cluster or group of closely spaced linear dune and sand sheet deposits. Individual linear dunes often merge and separate as an interconnecting mass of dune forms with abundant sand sheet deposits between. Support little to sparse grassy vegetation. Thickness, 9 to 40 ft (3 to 12 m)

Qg1 **Young terrace-gravel deposits (Holocene)**—Light-brown, pale-red, and gray, well-sorted, interbedded clay, silt, sand, gravel, pebbles, cobbles, and some boulders. Include well-rounded clasts of quartzite, quartz, chert, sandstone, and limestone. Support light to moderate growths of grass, cactus, and desert shrubs. Subject to flash-flood erosion and overbank flooding. Locally overlap young alluvial fan (Qa1), flood-plain (Qf), and valley-fill (Qv) deposits. Often covered by dune sand and sand sheet (Qd) and sand sheet (Qes) deposits in east half of quadrangle. Support light vegetation, mainly grass, and a few desert shrubs. Form benches about 3 to 12 ft (1 to 3.5 m) above stream-channel (Qs) or flood-plain (Qf) deposits. Subject to frequent flash flood erosion. Thickness, 6 to 20 ft (2 to 6 m)

Qa1 **Young alluvial fan deposits (Holocene)**—In Grand Canyon: Reddish-gray to light-brown silt, sand, gravel, pebbles, cobbles, and boulders; partly consolidated by calcite and gypsum cement. All material is derived primarily from Precambrian and Paleozoic rocks and subject to flash-flood debris flows. Pebbles, cobbles, and boulders are subangular to rounded. Little to no vegetation cover. Thickness 10 to 30 ft (3 to 9 m)

On Marble Plateau: Gray-brown to red silt, sand, gravel, pebbles, cobbles, and boulders; partly consolidated by gypsum and calcite cement. Local outcrops of the Kaibab and Moenkopi Formations provide silt and sand and also supply calcite, gypsum, and some salt as cementing agents for most alluvial deposits on Marble Plateau. Support light growths of sagebrush, cactus, and grass. Thickness 3 to 20 ft (1 to 6 m)

In eastern third of map area: Gray, light-brown, and light-red, clay, silt, sand, pebbles, and cobbles of chert, limestone, and sandstone; unconsolidated. Unit often overlapped by stream-channel (Qs), ponded sediments (Qps), flood-plain (Qf), dune sand and sand sheet (Qd), and sand sheet (Qes) deposits. Intertongue with upper part of valley-fill (Qv), young terrace-gravel (Qg1), and mixed alluvium and eolian (Qae) deposits. Clay, silt, and sand are primarily derived from local outcrops of Triassic, Jurassic, and Cretaceous rocks. Subject to extensive sheet-wash erosion, wind erosion, flash flood debris flows, and arroyo erosion. Thickness, 3 to 30 ft (1 to 9 m)

Qg2 **Intermediate terrace-gravel deposits (Holocene)**—Gray and brown silt, sand, gravel, and lenses of pebbles or conglomerate; partly consolidated. Lithologically similar to young terrace-gravel (Qg1) deposits. Siltstone and fine-grained sandstone matrix is mixed with subangular to rounded pebbles and boulders derived from nearby bedrock. Form benches about 15 to 30 ft (4.5 to 9 m) above modern streambeds and about 6 to 20 ft (2 to 6 m) above young terrace-gravel (Qg1) deposits in upper reaches of tributary streams. Support growths of grass and a variety of high-desert shrubs. Subject to cutbank erosion. Locally intertongue with, overlain by, or inset into young and intermediate alluvial fan (Qa1, Qa2), valley-fill (Qv), mixed alluvium and eolian (Qae), talus and rockfall (Qtr), and landslide (Ql) deposits. Thickness, 6 to 25 ft (2 to 7.5 m)

Qa2 **Intermediate alluvial fan deposits (Holocene)**—Lithologically similar to young alluvial fan (Qa1) deposits; partly cemented by calcite, gypsum, and clay. Surface of unit is partly eroded by sheetwash erosion that incises as much as 3 to 10 ft (1 to 3 m). In eastern third of quadrangle, unit is often covered by dune sand and sand sheet (Qd) and sand sheet (Qes) deposits. Unit is commonly overlapped by young alluvial fan (Qa1) deposits and intertongues or overlaps with valley-fill (Qv), talus and rockfall (Qtr), and young and intermediate terrace-gravel (Qg1, Qg2) deposits. Support light to moderate growths of grass, sagebrush, and cactus. Thickness, 6 to 50 ft (2 to 15 m)

Qps **Ponded sediments (Holocene)**—Gray or red-brown clay, silt, sand, and gravel; partly consolidated by calcite and or gypsum cement. Locally include small lenses of angular to subrounded chert and limestone fragments or pebbles in sandy matrix. Similar to flood-plain (Qf) deposits but occupy man-made ponded areas or natural internal drainage depressions caused by sinkhole development on plateau surfaces in western half of quadrangle. Deposits on Moenkopi and Kaibito Plateaus are commonly formed in depressions created by temporary sand dune dams or in wind deflation hollows of dune sand and sand sheet (Qd) and parabolic dune (Qdp) deposits. Desiccation cracks often develop on hardpan surfaces during dry conditions. Thickness, 5 to 30 ft (1.5 to 9 m)

Qg3 **Old terrace-gravel deposits (Holocene)**—Gray and light-brown, clay, silt, sand, gravel, cobbles, and boulders partly consolidated by clay, calcite, and gypsum cement; poorly sorted. Include abundant rounded and well-rounded clasts of quartzite, quartz, chert, sandstone, and limestone in Grand Canyon. Form terrace deposits adjacent to and as much as 400 ft (122 m) above the Colorado River. Thickness, 25 to 80 ft (7.5 to 24 m)

Qa3 **Old alluvial fan deposits (Holocene)**—Gray and light-brown, unsorted silt, sand, and gravel mixed with brecciated and subrounded pebbles and cobbles of red sandstone and gray limestone and chert; partly consolidated by calcite and gypsum cement. Unit often overlain by sand sheet (Qes) and mixed alluvium and eolian (Qae) deposits in eastern half of quadrangle. Include large boulders, small cobbles and pebbles of sedimentary rocks derived from nearby talus and rockfall (Qtr) and landslide (Ql) deposits in western half of map. Support moderate growths of grass, sagebrush, cactus, and various desert shrubs. Thickness, 5 to 25 ft (1.5 to 7.5 m)

Qae **Mixed alluvium and eolian deposits (Holocene)**—Gray, light-red, fine- to coarse-grained interbedded sand, brown clay and silt, and lenses of pebbly or brecciated gravel. Include angular white chert fragments locally derived from Permian strata on Kaibab and Marble Plateaus; white, gray, brown, and red chert fragments derived from members of the Chinle Formation in Painted Desert area; and white to gray chert fragments and concretionary sandstone pebbles derived from Navajo Sandstone on Moenkopi and Kaibito Plateaus. Deposits accumulate by combinations of alluvial or eolian processes resulting in an interbedded sequence of mixed mud, silt, sand, and gravel. Deposit subject to sheetwash erosion and arroyo cutting during wet conditions and wind-blown sand accumulations during dry conditions. Sediments commonly accumulate on broad sandy flatlands or on gently sloping alluvial fans. Support light to moderate growth of grass, cactus, sagebrush, and high desert shrubs. Thickness, 3 to 40 ft (1 to 12 m)

Qv **Valley-fill deposits (Holocene)**—Gray and light-brown silt, sand, and lenses of gravel; partly consolidated by gypsum and calcite. Include occasional rounded clasts of limestone, sandstone, and subrounded to angular chert derived from nearby bedrock; include abundant rounded chert or quartz pebbles derived from Shinarump Member of the Chinle Formation in Painted Desert area. Intertongue or overlap young and intermediate alluvial fan (Qa1, Qa2) deposits and young terrace-gravel (Qg1) deposits. Commonly reflect low-gradient, low-energy sediment accumulation in shallow drainages in all areas of the map area. Subject to sheetwash flooding and temporary ponding due to grasses at lower elevations; sagebrush, grass, cactus, and some forest trees at elevations above 6,000 ft (1,830 m); sagebrush and temporary blockage by eolian sand accumulation on Moenkopi and Kaibito Plateaus. Thickness, 3 to 30 ft (1 to 9 m)

Qt **Travertine deposits (Holocene and Pleistocene(?))**—Gray and tan, stained light-red, massive, porous, cliff-forming freshwater limestone. Include angular clasts of local talus breccia or stream gravel. Formed by rapid chemical precipitation of calcium carbonate from springwater discharge as encrustations on steep slopes or cliffs. Deposits are primarily near base of Cambrian Muav Limestone along east side of Colorado River and north side of Little Colorado River in Grand Canyon. Include numerous dams in bed of Little Colorado River too small to show at map scale. Include minor deposits at seeps along contact between Kayenta Formation-Navajo Sandstone transition zone (Jkn) and underlying Kayenta Formation (Jk) in Moenkopi Wash area that are too thin to show at map scale. Thickness, 6 to 60 ft (2 to 18 m)

Qtr **Talus and rockfall deposits (Holocene and Pleistocene(?))**—In Grand Canyon: Gray to yellowish-red silt, sand, and gravel mixed with abundant angular limestone, sandstone, and chert rocks and boulders derived from steep-walled areas of Proterozoic and Paleozoic strata; partly cemented by calcite and gypsum.

Along Echo Cliffs: Red to yellow, silt and sand mixed with angular rocks and boulders of light-red or white sandstone and red to dark-red siltstone derived from Mesozoic outcrops along Echo Cliffs and Moenkopi wash; partly cemented by calcite. Unit often associated with or adjacent to landslide (Ql) deposits. Unit commonly grades downslope into young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3) deposits or young and intermediate terrace-gravel (Qg1, Qg2) deposits. Thickness, 5 to 45 ft (1.5 to 14 m)

Ql **Landslide deposits (Holocene and Pleistocene)**—Landslides are unconsolidated to partly consolidated masses of angular unsorted rock debris. Include stratified blocks (slumps) that rotated backward against parent outcrop and slid downslope as loose incoherent masses of broken rock fragments and deformed strata; often form talus and rockfall (Qtr) deposits adjacent to and below landslide masses. Include individual car- and house-size boulders. Gradational and arbitrary contact with young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3) and young, intermediate, and old terrace-gravel (Qg1, Qg2, Qg3) deposits. Subject to extensive sheetwash erosion, flash-flood debris flows, and arroyo erosion. Thickness, 10 to 200 ft (3 to 61 m)

QTg4 **Older terrace-gravel deposits (Pleistocene and Pliocene(?))**—Gray and light-brown silt, sand, gravel and well-rounded flat pebbles and cobbles along higher beveled terraces of Navajo Sandstone (Jn) along Moenkopi Wash. Unit contains mud, silt, and sandy gravel derived from Cretaceous outcrops east of map area. Form terraced benches or ridges on Navajo Sandstone about 30 to 45 ft (9 to 14 m) above Moenkopi Wash. Unit is mainly exposed in cliff areas and commonly covered by thin dune sand and sand sheet (Qd) deposits. Thickness, 2 to 10 ft (0.5 to 3 m)

QTg5 **Youngest old terrace-gavel deposits (Pleistocene and Pliocene(?))**—Gray and light-brown clay, silt, sand, and gravel, poorly sorted; cemented by calcite on higher terrace levels along Moenkopi Wash. Contain rounded fragments of Cretaceous fossils and well-rounded flat quartzite, chert, sandstone, and limestone pebbles. Fossil fragments are derived from Cretaceous rocks east of the map area. Include iron-rich sandstone concretions probably derived from underlying Navajo Sandstone (Jn). Unit is covered by dune sand and sand sheet (Qd) deposits. Support moderate growths of grass and low desert shrubs. Thickness, 3 to 60 ft (1 to 18 m)

QTg6 **Intermediate old terrace-gravel deposits (Pleistocene and Pliocene(?))**—Gray and light-brown clay, silt, sand, and gravel, poorly sorted; cemented by calcite. Contain angular to subrounded chert, limestone, and sandstone pebbles derived from Cretaceous rocks east of the map area. Form isolated outcrops north of Moenkopi Wash and along U.S Highway 160 east of Tuba City. Unit is mostly covered by extensive eolian sand deposits (Qd, Qes). Thickness, 6 to 30 ft (2 to 9 m)

QTg7 **Oldest old terrace-gravel deposits (Pleistocene and Pliocene(?))**—Gray and light-brown clay, silt, sand, and gravel, poorly sorted; cemented by calcite. Lithology similar to youngest and intermediate old terrace-gravel deposits (QTg5, QTg6) at highest levels north of Moenkopi Wash and east of Tuba City. Unit may represent part of an extensive pediment surface that drained from Black Mesa area east of map and formed before incision of Moenkopi Wash. Thickness, 6 to 18 ft (2 to 6 m)

Tgs **Gravel and sedimentary deposits (Pliocene(?) and Miocene(?))**—Gray, brown, and white clay, sand, silt, and gravel, poorly sorted; consolidated. Unit consists mostly of fine-grained gray silty sand that includes scattered pebbles and cobbles of well-rounded gray sandstone and limestone derived from Jurassic and Cretaceous rocks east and northeast of the map area. Forms extensive thin veneer on Moenkopi Plateau that overlies beveled Jurassic and Cretaceous rocks of the Navajo Sandstone (Jn), Entrada Sandstone (Je), Dakota Sandstone (Kd), and Mancos Shale (Km), in southeast quarter of map. Forms consolidated caprock deposit on Middle Mesa that overlies beveled Jurassic rocks of the Carmel Formation (Jc) and Navajo Sandstone (Jn), east edge of map. Forms partly consolidated mixed sandstone, siltstone, mudstone, and minor pebble sediments on Crooked Ridge in northeast corner of map. Unit at all three localities forms the highest surficial fluvial deposits, have a similar lithology, and are at approximate similar elevations that may be Pliocene (?) age based on relevant elevations above younger fluvial deposits of Moenkopi Wash. Age may be Miocene(?) as suggested by Lucchitta (2011). Thickness, 6 to 100 ft (2 to 30 m)

VOLCANIC ROCKS

Shadow Mountain is an isolated pyroclastic cone with associated basalt flows and dikes at the south-central edge of the map area. These volcanic rocks are chemically and petrologically similar to rocks of the San Francisco volcanic field, representing the northernmost volcanic rocks of that field, and have a K-Ar age of 0.649±0.23 Ma (Damon and others, 1974; Condit, 1974). Miocene dikes are exposed in Moenkopi Wash, in Hamblin Wash, at Tuba Butte, and at Wildcat Peak. A recent $^{40}Ar/^{39}Ar$ age from a dike at Wildcat Peak is 19.05±0.10 Ma (Peters, 2011).

Qi **Intrusive dikes of Shadow Mountain (Pleistocene)**—Black olivine-labradorite basalt dikes, 1 to 3 ft (0.5 to 1 m) wide

Qsp **Pyroclastic deposits of Shadow Mountain (Pleistocene)**—Black and red scoria, cinder, and ash of olivine-labradorite basaltic composition. Overlie associated basalt flows (Qsb) and the Petrified Forest and Shinarump Members (₸cp, ₸cs) of the Chinle Formation. Thickness, 3 to 135 ft (1 to 40 m)

Qsb **Basalt flows of Shadow Mountain (Pleistocene)**—Black olivine-labradorite basalt largely covered by associated pyroclastic (Qsp) deposits. Basalts flowed into small graben north of main cone, providing evidence that the graben is older than the flow. Flow is offset by a fault suggesting that faulting has occurred within the last 65 k.y. Thickness, 40 ft (12 m)

Ti **Intrusive dikes (Miocene)**—Dark-gray basalt composed of plagioclase, clinopyroxene, olivine, and opaque oxides. Dikes occur in Moenkopi Wash southwest of Tuba City, in Hamblin Wash south of The Gap, at Tuba Butte northwest of Tuba City, and at Wildcat Peak northeast of Tuba City. Dikes are extensively weathered and are 2 to 6 ft (0.05 to 2 m) wide and 15 to 33 ft (5 to 10 m) in height

SEDIMENTARY ROCKS

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 cephalopods that are laterally equivalent to those in the Tropic Shale in the lower part of Mancos Shale in southern Utah. Age as defined by Doelling and others (2000). Deposited on a shallow sea floor that transgressed southwest from the midcontinent. Gradational and arbitrary contact with underlying Dakota Sandstone (Kd). Deposit is mostly removed by Tertiary erosion on Moenkopi Plateau south of Moenkopi Wash. Erosion channels as deep as 20 ft (6 m) are filled with Tertiary gravel and sedimentary deposits (Tgs) and probably represent widespread alluvial pediment and stream-channel deposition. Largely covered by sand sheet (Qes) and dune sand and sand sheet (Qd) deposits at Coal Mine Mesa on Moenkopi Plateau in southeast corner of map (sheet 2) and on White Mesa in northeast corner of map (sheet 2). Thickness, 140 ft (43 m)

Kd **Dakota Sandstone (Upper Cretaceous)**—Medium- to light-gray, slope-forming, laminated to thin-bedded mudstone, siltstone, and sandstone. Locally includes lower sandstone, middle carbonaceous, and upper sandstone members as defined by O'Sullivan and others (1972; northeast and southeast corners of map). Age as defined by Doelling and others (2000)

Lower sandstone member: Light-orange to light-gray silty sandstone and conglomeratic sandstone that forms cliffs as much as 20 ft (6 m) thick seen in channels eroded into underlying Entrada Sandstone-Cow Springs Sandstone, undivided (Je). Unit pinches out or thins in short lateral distance within channels. Clasts in sandstone are composed of red and gray, well-rounded chert and quartzite typically less than 2 in (5 cm) in diameter. The regional angular unconformity between the Dakota Sandstone and underlying Jurassic-Cretaceous rocks is based on the Dakota Sandstone overlying younger rocks north of the map area and overlying older rocks south and southeast of the quadrangle. Although these relations establish the angularity of the pre-Dakota Sandstone age unconformity, the dip is so small that it is not apparent at most outcrops within the area (Harshbarger and others, 1958)

Middle carbonaceous member: Dark-grayish-brown, carbonaceous, flat-bedded mudstone, siltstone, and coal and interbedded brown, conglomeratic, crossbedded lenticular sandstone. Coal beds are generally less than 2 ft (0.5 m) thick at east end of Coal Mine Mesa on Moenkopi Plateau (southeast corner of map). Coal was mined from thicker coal beds at the rim of Coal Mine Canyon. Coal-seam fires in the recent past add vibrant red color (baked clay) in upper cliffs of Coal Mine Canyon. Gypsum is a common constituent in the siltstones, appearing as thin veins and isolated crystals. The upper sandstone member is not present in the map area

Unit unconformably overlies Entrada Sandstone-Cow Springs Sandstone, undivided (Je), in eastern part of Coal Mine Mesa where lower sandstone member is not present (J-2 unconformity of Pipiringos and O'Sullivan, 1978). Mostly covered by extensive dune sand and sand sheet (Qd) deposits. Overall thickness, 10 to 40 ft (3 to 12 m)

San Rafael Group (Middle Jurassic)—The San Rafael Group (Middle Jurassic) includes, in ascending order, the Carmel Formation (Jc) and the Entrada Sandstone (Je) that overlies beveled crossbeds of the Navajo Sandstone (Jn), known as the J-2 unconformity that is recognized primarily on differences in lithology and color change from white sandstone of the Navajo to red siltstone of the Carmel. The Carmel Formation represents a shallow marine environment within a seaway that moved southward from Canada into northern Arizona and extended to and pinches out in the subsurface of Coal Mine Mesa. Overlying the Carmel Formation are white and red sandstone deposits of the Entrada Sandstone-Cow Springs Sandstone, undivided (Je), that represent a coastal beach and marine tidal flat

Je **Entrada Sandstone-Cow Springs Sandstone, undivided (Middle Jurassic)**—White, light-gray, and yellowish, very fine grained, trough crossbedded sandstone. Includes interbedded (5 to 7 ft [1.5 to 2 m]) thick beds of red siltstone and sandstone representing southern extent of reddish Entrada Sandstone units just north of quadrangle that thin rapidly southward and pinch out near and just south of Coal Mine Mesa. Interval of uppermost red, flat-bedded siltstone and sandstone is likely equivalent to the Summerville Formation north of map area. Uppermost interval of yellowish-white, fine-grained, crossbedded sandstone is equivalent to the Cow Springs Sandstone northeast and east of quadrangle area. The Summerville Formation and Cow Springs Sandstone are equivalent to lower part of Morrison Formation north of the map area (Doelling and others, 2000) and east of the map area at Black Mesa (Cooley and others, 1969). Unit as a whole forms a cliff where overlain by resistant conglomeratic, coarse-grained sandstone lenses of Dakota Sandstone (Kd), or Tertiary conglomeratic gravel and sedimentary (Tgs) deposits. Unit thins south and southeast of map area and thickens rapidly north. Thickness, 115 to 250 ft (35 to 76 m)

Jc **Carmel Formation (Middle Jurassic)**—Red and light-gray, slope-forming sandstone, siltstone, claystone, and silty calcareous and gypsiferous sandstone at Middle Mesa (east edge of quadrangle), along Red Lake Monocline (northeast corner of quadrangle), and as isolated outcrops (northwest quarter of quadrangle). Unit thins southward and pinches out south and east of the Moenkopi Plateau. Present as dark red silty sandstone interval between base of Entrada Sandstone (Je) and top of Navajo Sandstone (Jn) at the east end of Coal Mine Mesa and is locally absent at west end of Coal Mine Mesa. Unconformably overlies upper beveled surface of Navajo Sandstone (Jn), known regionally as the J-2 unconformity; erosional relief is generally less than 15 ft (4.5 m) but can be as much as 30 ft (9 m). Ripple marks and abundant rounded sandy fecal pellets about 0.5 in (1 cm) diameter are found in lenticular, light-gray sandstone beds as much as 3 ft (1 m) thick. Locally contains white and red calcite and white barite crystals. Unit pinches out southward into subsurface of Moenkopi Plateau; locally removed by modern erosion from most of Kaibito Plateau. Unit gradually thickens north and northeast of quadrangle. Thickness, 0 to 30 ft (0 to 9 m)

Glen Canyon Group (Lower Jurassic)—Includes, in ascending order, Moenave Formation (Jm), Springdale Sandstone Member of Kayenta Formation (Jks), 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 unconformity between the Triassic and Jurassic is based primarily 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 (ŦRco) is overlain by red mudstone, siltstone, and sandstone of the Moenave Formation (Jm). The basal light-red sandstone of the Moenave Formation may be a lateral equivalent of the Lukachukai Member of the Wingate Formation as mapped by Cooley and others (1969) but is herein included within the lower part of the Moenave Formation, because it is lithologically the same as the overlying beds of the Moenave Formation and because the Wingate Sandstone thins southward from Utah and does not appear to reach the map area

About 20 mi (32 km) north of the map area, the upper boundary of the Glen Canyon Group is the J-2 unconformity between the Navajo Sandstone (Jn) and Page Sandstone (Doelling and others, 2000). At Middle Mesa, east central edge of the map area, the J-2 unconformity is between the Navajo Sandstone and Carmel Formation (Jc), and in the extreme southeast corner of the map area, it is between the Navajo Sandstone and the Entrada Sandstone-Cow Springs Sandstone, undivided (Je)

Jn **Navajo Sandstone (Lower Jurassic)**—Red, white, and tan, cliff-forming, high-angle crossbedded, fine- to medium-grained, well-sorted sandstone. Includes massive horizontal or planar bedding. Quartz grains are frosted. Crossbeds are as much as 35 ft (11 m) thick. Includes many discontinuous thin beds of gray to light-purple siliceous limestone, dolomite, or dark-red sandy siliceous mudstone that form resistant ledges and flat-topped ridges or small mesas on surface of Moenkopi and Kaibito Plateaus. Siliceous beds were formed in playas or ponds between sand dunes and become increasingly common on Moenkopi Plateau. Crossbeds contain numerous small, rounded, black and reddish-black, pea-size hematite concretions as much as 3 in (7.5 cm) in diameter. Crossbed dip direction indicates paleowinds were generally from the north and northwest. Gradational and arbitrary contact with underlying Kayenta Formation-Navajo Sandstone transition zone (Jkn) marked at lowest white or red massive sandstone cliff. Unit rapidly thins east and southeast of map area and thickens north and northwest. Unit is removed by erosion in west half of map. Thickness, 400 to 600 ft (122 to 183 m)

Jkn **Kayenta Formation-Navajo Sandstone transition zone (Lower Jurassic)**—Light-red and white, fine- to medium-grained, massive to crossbedded, cliff-forming beds of Navajo Sandstone lithology that intertongue with purple and light-red, slope-forming mudstone, siltstone, and sandstone beds of Kayenta Formation lithology. Forms sequence of red and white sandstone cliffs that alternate with purple and light-red mudstone and siltstone slopes resulting in arbitrary map contact. This zone is considered to be the lower “wet part” of the Navajo Sandstone by Marzolf (1983, 1991) and Blakey (1994). Gradually thins northward and becomes basal part of the Navajo Sandstone near Cedar Ridge. Individual red and white sandstone units thin or lens out into purplish siltstones of the Kayenta Formation south of the map area. Several springs and seeps issue from base of Navajo Sandstone along Echo Cliffs from Cedar Ridge to Tuba City and Moenkopi. Thickness, 0 to 240 ft (0 to 73 m)

Jk **Kayenta Formation (Lower Jurassic)**—Includes an upper slope-forming light-purple, siltstone and sandstone and the basal orange-brown, cliff-forming Springdale Sandstone Member. The Springdale Sandstone was originally described as the upper member of the underlying Moenave Formation (Averitt and others, 1955; Stewart and others, 1972; Sargent and Philpott, 1987; Billingsley and others, 2004) but has since been reassigned as the basal part of the Kayenta Formation based on paleontological data and a prominent Jurassic unconformity at its base (Blakey, 1994; Marzolf, 1991; Lucas and Tanner, 2006; Tanner and Lucas, 2007; Biek and others, 2007)

Upper slope-forming unit: Purple, lavender, and light-red fluvial, crossbedded, fine-grained mudstone, siltstone, and silty sandstone that undergo a northward facies change from mostly slope-forming siltstone, mudstone, and sandstone at Moenkopi Wash to mostly cliff-forming red sandstone and minor siltstone along Echo Cliffs at Cedar Ridge. Age is determined by Peterson and Pipiringoes (1979) and Biek and others (2000). Along Echo Cliffs, often covered by landslide (Ql) and talus and rockfall (Qtr) deposits caused when erosion of underlying Kayenta Formation undercuts overlying Navajo Sandstone cliffs allowing large blocks of both Navajo Sandstone and upper Kayenta Formation to fail as landslide masses; especially prevalent where joints and fractures nearly parallel Echo Cliffs (fig. 1). Unit is unconformable with underlying cliff-forming Springdale Sandstone Member (Jks). Thickness, 300 to 470 ft (92 to 143 m)

Jks **Springdale Sandstone Member (Lower Jurassic)**—Light-red to reddish-brown and dark-red, cliff-forming, thin- to thick-bedded sandstone. Includes low-angle trough crossbed sets with fluvial conglomeratic sandstone lenses containing dark-red mudstone and siltstone rip-up clasts and poorly preserved petrified and carbonized fossil plant remains north of map area (Peterson and Pipiringos, 1979; Biek and others, 2000). Crossbeds are separated by thin-bedded to laminated dark-red siltstone and mudstone that locally contain mudstone pellets. Unconformable contact with underlying Moenave Formation (Jm). Light-red, fine-grained, crossbedded sandstone filling channels eroded into top of Springdale Sandstone may represent southern extent of Wingate Sandstone. Thickness, 100 to 140 ft (30 to 43 m)

Jm **Moenave Formation (Lower Jurassic)**—Includes only the Dinosaur Canyon Member as redefined by Blakey (1994), Marzolf (1991), Lucas and Tanner (2006), Tanner and Lucas (2007), and Biek and others (2007) in the map area. Age is after Peterson and Pipiringos (1979) and Biek and others (2000, 2007). Forms reddish-brown slopes and ledges of thin-bedded, flat-bedded, and crossbedded, fine- to coarse-grained fluvial siltstone and silty sandstone. Unconformable contact with underlying Owl Rock Member of the Chinle Formation, known as the J-O unconformity separating Triassic rocks from overlying Jurassic rocks. Commonly covered by landslide (Ql) or talus and rockfall (Qtr) deposits. Thickness, 80 to 140 ft (25 to 43 m)

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

ŦRco **Owl Rock Member (Upper Triassic)**—Grayish-red and light-purple, slope- and ledge-forming, nodular siliceous limestone interbedded with purple, light-blue, and light-red calcareous siltstone and sandstone. Limestone beds are gray, cherty, lenticular, silty, irregular bedded, 1 to 5 ft (0.5 to 1.5 m) thick; extend laterally for several miles and form resistant benches or ledges along Echo Cliffs and Ward Terrace (fig. 1, sheet 3). Number of limestone beds decreases northward from several at Ward Terrace to two at Cedar Ridge. Contains abundant mud pellets and silicified clay and concretionary chert nodules. Gradually thins northward along Echo Cliffs and thickens slightly southeast of map area. Unconformable contact between Owl Rock Member of the Chinle Formation and overlying Moenave Formation commonly marked by a distinct lithologic and color change from purple and white calcareous siltstone and sandstone and gray limestone of Owl Rock to dark-red and orange-red, coarse-grained sandstone of Moenave Formation. Gradational contact with underlying Petrified Forest Member placed at lowest laterally continuous limestone bed or at nodular calcareous grayish-yellow siltstone slope about 10 to 15 ft (3 to 4.5 m) below lowest prominent limestone bed. Thickness, 100 to 200 ft (30 to 60 m)

ŦRcp **Petrified Forest Member (Upper Triassic)**—Purple, blue, light-red, greenish-gray, and grayish-blue, slope-forming mudstone and siltstone. Includes interbedded white, coarse-grained, lenticular, channel-fill sandstone. Includes three informal units of Akers and others (1958), in descending order: red mudstone and sandstone, gray mudstone and sandstone, and blue mudstone. Includes large lenticular erosion channels and large-scale, low-angle trough crossbeds. Petrified logs and wood fragments common in lower white or yellowish-white sandstone; alternately may be within upper part of Shinarump and sandstone and siltstone member, undivided. Gradational contact with underlying Shinarump Member and sandstone and siltstone member, undivided, at change from slope-forming multicolored mudstones of Petrified Forest Member to tan cliffs and purple slopes of coarse-grained sandstone of Shinarump Member. Weathers into rounded hills or slopes with a rough, puffy, popcorn surface caused by swelling of clay when wet. Thickness, 400 to 500 ft (122 to 153 m)

ŦRcs **Shinarump Member and sandstone and siltstone member, undivided (Upper Triassic)**—White, light-brown, tan, 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 locally but regionally homogeneous, consisting of about 75% sandstone, 20% conglomerate, and 5% mudstone. Pebbles are generally brown, black, or light-colored, well-rounded quartz and siliceous composition. Petrified logs and wood fragments are generally scattered throughout unit but common at some localities. Unconformable contact with underlying red siltstone and sandstone of Moenkopi Formation. Unit is thickest in Painted Desert area; thins north along Echo Cliffs and thins south of map area. Thickness, 60 to 200 ft (18 to 60 m)

Moenkopi Formation (Middle(?) and Lower Triassic)—Includes, in descending order, the Holbrook and Moqui Members, undivided, Shnabkaib Member, and Wupatki Member. The basal Timpoweap Member of the Moenkopi Formation is present but too thin and limited in extent to show at map scale so is included in the Wupatki Member

The Moenkopi Formation is mostly eroded in the Grand Canyon area, but remnants form Cedar Mountain, Gold Hill, Yon Dot hills, Shinumo Altar (fig. 1, sheet 3), and several isolated outcrops on Marble and Coconino Plateaus

Ꞧmhm **Holbrook and Moqui Members, undivided (Middle(?) and Lower Triassic)**—Reddish-brown and tan, slope-forming, alternating sequence of claystone, siltstone, and sandstone (McKee, 1954). Unit is equivalent to upper red member of Stewart and others (1972) in northwestern Arizona. Siltstone and sandstone beds include large- to medium-scale trough crossbedding and abundant cusp-type ripple marks, interbedded thin limestone, lenses of conglomeratic sandstone, chert nodules, and thin veins of gypsum. Gradational contact with underlying Shnabkaib Member. Unit undergoes rapid facies change from red siltstone-sandstone sequence in northern part of map area to mostly tan sandstone sequence in the south. Tan sandstone beds increase in thickness north to south across the map and become similar to conglomeratic beds of the overlying Shinarump Member and sandstone and siltstone member, undivided (Ꞧcs). Include numerous channel lenses that are often confused with the Shinarump. Thus, uncertainties exist in the central part of the map where unconformities between similar sandstones are numerous and difficult to differentiate. Typically, small pebbles within a sandstone lens or bed denotes the Shinarump Member and sandstone and siltstone members, undivided, of the Chinle Formation. Thickness, 80 to 120 ft (25 to 37 m)

Ꞧms **Shnabkaib Member (Lower Triassic)**—Yellowish-white and light-brown, cliff-forming, crossbedded, fine-grained, calcareous siltstone and coarse-grained sandstone. Unit is equivalent to lower massive sandstone member of the Moenkopi Formation as defined by McKee (1954) south of the map area (Billingsley and others, 2007). Lowermost ledge-forming sandstone undergoes a facies change from light-red calcareous sandstone south of map area to yellowish-white calcareous gypsiferous sandstone and dolomite north of map area. Gradational contact with underlying Wupatki Member marked at base of lowest tan or light-red sandstone cliff. Thickness, 50 to 100 ft (15 to 30 m)

Ꞧmw **Wupatki Member (Lower Triassic)**—Red and red-brown, slope-forming, thin-bedded, mudstone, siltstone, and sandstone as defined by McKee (1954). Interbedded sandstones as thick as 1 to 3 ft (0.5 to 1 m) form resistant ledges within crumbly red-brown mudstone/siltstone slopes. Bedding surfaces often contain small-scale ripple marks, salt crystal casts, mud cracks, and rain-drop impressions. Unit is equivalent to lower red member, Virgin Limestone Member, and middle red member of Stewart and others (1972) in northwestern Arizona. Virgin Limestone Member is present at Cedar Ridge and in Yon Dot Mountains on Marble Plateau but is too thin to show at map scale. Virgin Limestone beds consist of yellowish-white, thin, platy, silty limestone and siltstone about 1 to 3 ft (0.3 to 1 m) thick and about 15 to 20 ft (4.5 to 6 m) above Harrisburg Member of the Kaibab Formation (Pkh); represent the regional Permian/Triassic unconformity. Unit includes basal Timpoweap Member of the Moenkopi Formation. Timpoweap Member is composed of subangular to subrounded conglomerate in calcareous sandstone matrix; small, white, angular chert pebbles and fragments derived from Kaibab Formation occupy shallow depressions and channels eroded into underlying Harrisburg Member of the Kaibab Formation in western half of map. Thickness, 30 to 85 ft (9 to 26 m)

Kaibab Formation (Cisuralian)—Includes, in descending order, the Harrisburg Member and Fossil Mountain Member as defined by Sorauf and Billingsley (1991)

Pkh **Harrisburg Member (Cisuralian)**—Reddish-gray and brownish-gray, ledge- and slope-forming, gypsiferous siltstone, calcareous sandstone, and thin-bedded sandy limestone. Top of unit near Little Colorado River Gorge includes white, low-angle, crossbedded, calcareous sandstone with mollusk fossils; elsewhere, upper part is primarily sandy, cherty limestone. Forms surface of Kaibab, Coconino, and Marble Plateaus and House Rock Valley in west half of quadrangle. Contact with underlying Fossil Mountain Member is gradational and marked at topographic break between grayish-white, slope- and ledge-forming sandy limestone and sandstone sequence of Harrisburg Member and underlying cliff-forming, gray to light-brown, thick-bedded, cherty limestone and sandy limestone of Fossil Mountain Member. Unit gradually thins west to east and undergoes shoreward facies change from mostly cliff- and slope-forming limestone and siltstone marine sediments in west half of quadrangle to mostly sandy marine calcareous sandstone east of Grand Canyon. Difficult to distinguish members in subsurface of eastern half of quadrangle. Thickness, 120 to 80 ft (37 to 25 m)

Pkf **Fossil Mountain Member (Cisuralian)**—Light-gray, cliff-forming, fine- to medium-grained, thin- to medium-bedded (1 to 6 ft [0.3 to 2 m]), fossiliferous, cherty (25% to 30%), sandy limestone and dolomite. Weathers dark gray; cliff surfaces often stained by black magnesium oxide. Includes abundant gray and white, fossiliferous chert nodules and white chert breccia beds. Chert nodules may contain concentric black and white bands or fossil sponges. White, cliff-forming, chert breccia beds 4 to 10 ft (1 to 3 m) thick commonly present in uppermost part help establish contact between Harrisburg (Pkh) and Fossil Mountain (Pkf) Members. Unit gradually thins eastward and undergoes a shoreward facies change from limestone, dolomite, and sandy limestone to calcareous sandstone and sandy limestone similar in texture, composition, and appearance to overlying Harrisburg Member. Unit commonly forms cliff below slopes and ledges of Harrisburg Member along rim of Grand Canyon, Marble Canyon, and Little Colorado River Gorge. Unconformable contact with underlying Toroweap Formation (Pt) attributed in part to solution and erosion of gypsiferous siltstone in Toroweap but mostly to channel erosion; average erosional relief about 10 ft (3 m). Unit gradually thins east and southeast in subsurface of map area, becoming indistinguishable from upper Harrisburg Member. Thickness, 230 to 180 ft (70 to 55 m)

Pt **Toroweap Formation, undivided (Cisuralian)**—Includes, in descending order, the Woods Ranch, Brady Canyon, and Seligman Members, undivided, as defined by Sorauf and Billingsley (1991). All three members are present on western side of Marble Canyon and Grand Canyon. All three members undergo a rapid shoreward (eastward) facies change from cliff and slope units west of Colorado River to cliff units east of Colorado River. Unit gradually thins east and southeast in subsurface of map area and thickens west (Billingsley, 2000; Billingsley and Wellmeyer, 2003; Billingsley and others, 2007). Eastern extent is unknown but likely extends to or pinches out at eastern margin of map. Thickness, 200 to 250 ft (60 to 76 m)

Ptw **Woods Ranch Member (Cisuralian)**—Grand Canyon and Marble Canyon areas: gray and light-red, slope-forming gypsiferous siltstone, gray gypsum, and gray sandstone interbedded with gray, thin-bedded limestone. Weathers to reddish-gray slope. Bedding locally distorted due to dissolution of gypsum and gypsiferous siltstone. Erosional undercutting of overlying Kaibab Formation results in numerous landslides and large open cracks near canyon rims that tend to be accentuated along pre-existing joint and fracture systems. Unit undergoes shoreward (eastward) facies change to mostly brown, cliff-forming, calcareous sandstone and dolomite that weathers dark brown. Contact with underlying Brady Canyon Member is gradational and marked at lithologic and topographic break between slope-forming gypsiferous siltstone and sandstone of Woods Ranch and cliff-forming limestone of Brady Canyon in western two-thirds of Marble Canyon and Grand Canyon area; becomes indistinguishable from underlying Seligman and Brady Canyon Members in eastern third of Marble Canyon, southeastern Grand Canyon, and Little Colorado River Gorge and subsurface of Marble Plateau. Thickness, 100 to 180 ft (30 to 55 m)

Ptb **Brady Canyon and Seligman Members, undivided (Cisuralian)**—

Brady Canyon Member: Gray to brown, cliff-forming, thin- to medium-bedded (1 to 5 ft [0.05 to 1.4 m]), fine- to coarse-grained, limestone and sandy limestone. Weathers light gray. Contains white and gray chert nodules that make up less than 5% of unit. Gradational contact with underlying Seligman Member marked at base of limestone cliff in western part of quadrangle. Becomes indistinguishable from other Toroweap Members east of Marble Canyon, Grand Canyon, and Little Colorado River Gorge. Thickness, 20 to 30 ft (6 to 9 m)

Seligman Member: Gray, light-purple, and yellowish-red, slope-forming, thin-bedded dolomite, sandstone, gypsum, and calcareous sandstone. Forms slope or recess between overlying Brady Canyon Member and underlying Coconino Sandstone (Pc) in Marble Canyon and Grand Canyon. Undergoes easterly shoreward facies change similar to Brady Canyon and Woods Ranch Members; pinches out before reaching Little Colorado River Gorge. Sharp unconformable contact with underlying white, cliff-forming Coconino Sandstone. Coconino Sandstone intertongues with lower part of Seligman Member west and north of map area (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; Billingsley and Wellmeyer, 2003; Billingsley and others, 2006). Undergoes gradual shoreward (eastward) facies change along with overlying Brady Canyon and Woods Ranch Members, making all indistinguishable from one another east of Colorado River where they are mapped as Toroweap Formation, undivided (Pt). Thickness, 10 to 20 ft (3 to 6 m)

Pc **Coconino Sandstone (Cisuralian)**—Tan to white, cliff-forming, fine-grained, well-sorted, cross-bedded quartz sandstone. Thin red sandstone beds at base of Coconino Sandstone in Little Colorado River Gorge are likely the northern edge of the Schnebly Hill Formation as defined by Blakey (1990) in the Verde Valley south of the quadrangle. Contains large-scale, high-angle, planar crossbeds that average about 11 m (35 ft) thick. Locally includes amphibian trackways and low-relief wind ripple marks on crossbed surfaces. Unconformable contact with underlying Hermit Formation (Ph) is sharp and planar with relief generally less than 3 ft (1 m) but locally as much as 8 ft (2.5 m); marked by distinct color and topographic change between white, cliff-forming sandstone of Coconino Sandstone and dark-red, slope-forming siltstone of Hermit Formation. Unit is exposed only in walls of the Grand Canyon but is present in the subsurface of eastern half of map. Unit gradually thickens east and southeast of map area and significantly thins to the north and west. Thickness, 200 to 600 ft (60 to 183 m)

Ph **Hermit Formation (Cisuralian)**—Red, slope-forming, fine-grained, thin- to medium-bedded siltstone and sandstone. In Little Colorado River Gorge, upper part contains red, massive, low-angle, cross-stratified calcareous sandstone and siltstone beds that may be equivalent, in part, to Schnebly Hill Formation in Verde Valley south of map area (Blakey, 1990). Siltstone beds throughout unit weather dark red and crumbly and fill widespread shallow erosion channels; form recesses between thicker sandstone beds. Contains poorly preserved plant fossils in channel-fill deposits in lower part of unit at Grand Canyon. Red cliffs and ledges of sandstone immediately below contact with Coconino Sandstone (Pc) are often bleached yellowish-white color owing to groundwater seepage from Coconino Sandstone. Unconformably overlies Esplanade Sandstone (Pe) with erosional relief generally less than 10 ft (3 m). Unit thins southeast of Grand Canyon to less than 40 ft (12 m) at Little Colorado River Gorge and may extend into subsurface of eastern part of map area. Unit thickens north and west of map area. Thickness, 40 to 360 ft (12 to 110 m)

Supai Group (Cisuralian, Pennsylvanian, and Upper Mississippian)—Includes in descending order, the Esplanade Sandstone and Wescogame, Manakacha, and Watahomigi Formations, undivided

Pe **Esplanade Sandstone (Cisuralian)**—Light-red and pinkish-gray, cliff-forming, fine- to medium-grained, medium- to thick-bedded (3 to 10 ft [1 to 3 m]), well-sorted calcareous sandstone. Includes interbedded dark-red, thin-bedded, crumbly, recessive and slope-forming siltstone beds in upper and lower part. Crossbeds are small to medium scale, low- and high-angle planar. Unconformable contact with underlying Pennsylvanian and Upper Mississippian rocks (PMs) marked by erosion channels as much as 30 ft (9 m) deep in Grand Canyon and Little Colorado River Gorge area. Thickness, 350 to 400 ft (107 to 122 m)

PMs **Wescogame (Upper Pennsylvanian), Manakacha (Moscovian), and Watahomigi (Bashkirien and Serpukhovian) Formations, undivided**—Includes, in descending order, the Wescogame, Manakacha, and Watahomigi Formations as defined by McKee (1982). Individual formations are difficult to identify because of similar lithology and topographic expression; unconformable contacts are shallow, difficult-to-find erosion channels. Herein, the three formations are shown as one map unit

Wescogame Formation: 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, 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 as much as 40 ft (12 m) thick. Unconformable contact with underlying Manakacha Formation marked by erosion channels 3 to 6 ft (1 to 2 m) deep in Grand Canyon area. Channels commonly filled with limestone/chert conglomerate west of map area. Thickness, 130 to 150 ft (40 to 45 m)

Manakacha Formation: Light-red, white, and gray upper slopes and ledges of sandstone, calcareous sandstone, dark-red siltstone, and thin gray limestone. Upper slope consists mainly of shaley siltstone and mudstone with minor interbedded, thin-bedded limestone and sandstone. Carbonate content increases west of map area forming numerous ledge-forming, thin and medium limestone beds at west edge of map. Upper slope is about 75 to 100 ft (23 to 30 m) thick in Grand Canyon. Lower cliff is dominated by reddish-gray, medium- to thick-bedded, crossbedded, calcareous sandstone and sandy limestone. Lower cliff is about

60 ft (18 m) thick. Carbonate content increases west of map area, forming numerous gray limestone ledges (McKee, 1982). Unconformable contact between Manakacha Formation and underlying Watahomigi Formation marked at base of lower red sandstone cliff; erosional relief nearly flat, generally less than 3 ft (1 m). Thickness, 200 ft (60 m)

Watahomigi Formation: Gray and purple, slope-forming limestone, siltstone, mudstone, and minor conglomerate. Minor red chert lenses and nodules in lower limestone beds. Includes alternating gray, thin-bedded cherty limestone ledges interbedded with purplish-gray siltstone and mudstone in upper part. Upper ledge/slope averages about 70 ft (21 m) thick. Lower slope consists mainly of purplish-red mudstone and siltstone, interbedded with thin-bedded, aphanitic to granular limestone with red chert veins and nodules. Fossil conodonts in lower thin limestone beds west of map area are Late Mississippian age (Martin and Barrick, 1999). Unit includes purple siltstone and gray limestone interbedded with reddish conglomeratic sandstone that fills small erosion channels cut into underlying Surprise Canyon Formation (Ms) or into Redwall Limestone (Mr). Lower Supai Group gradually thins eastward and gradually thickens westward in west half of map. Thickness, 100 to 120 ft (30 to 37 m)

Ms **Surprise Canyon Formation (Serpukhovian)**—Dark-reddish-brown, massive to thin-bedded, poorly sorted siltstone, sandstone, thin-bedded gray limestone, dolomite, and a basal gray and white conglomerate of subrounded chert clasts derived from Redwall Limestone in dark-red or black sandstone matrix. Unit is locally absent throughout map area and limited to deposits within paleovalley and karst caves eroded into top half of underlying Redwall Limestone (Billingsley and Beus, 1999). Unit is likely present in subsurface of eastern part of map area. Sandstone and siltstone beds contain plant and bone fossils, mud cracks, and ripple marks. Thickness, 0 to 100 ft (0 to 30 m)

Mr **Redwall Limestone, undivided (Mississippian)**—Includes, in descending order, Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members, with no middle Mississippian as defined by McKee (1963) and McKee and Gutschick (1969). Members are too small to show at map scale because of steep topography in Grand Canyon. Unit overall is light- to dark-gray, cliff-forming, thin- to thick-bedded, fine- to coarse-grained, fossiliferous limestone and dolomite. Includes thin-bedded gray and white chert beds, lenses, and nodules. Exposed mainly as sheer cliff in Grand Canyon; gradually thins eastward in subsurface. Is an important aquifer because of solution caverns and joint and fracture systems. Thickness, 400 to 450 ft (122 to 137 m)

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, platy limestone beds that form recess about 3 to 9 ft (1 to 3 m) thick near top of Mooney Falls Member cliff. Fossils locally common. Includes distinctive ripple-laminated limestone, oolitic limestone, and some chert lenses. Unit locally absent in Paleozoic section where removed by Late Mississippian paleovalley erosion. Thickness, 50 to 100 ft (15 to 30 m)

Mooney Falls Member: Light-gray, cliff-forming, fine- to coarse-grained, thick-bedded to very thick bedded (4 to 20 ft [1 to 6 m]), fossiliferous limestone. Limestone weathers dark gray; chert beds weather black. Upper part includes dark-gray dolomite beds, oolitic limestone, and chert beds. Karst caves in upper part contain red sandstone and siltstone deposits of Surprise Canyon Formation (Ms) in Marble Canyon. Disconformable contact with underlying Thunder Springs Member is distinguished by lithology; massive-bedded, gray limestone of the Mooney Falls Member overlies thin-bedded, dark-gray to brown dolomite and white chert beds of Thunder Springs Member. Thickness, 300 ft (75 m)

Thunder Springs Member: Roughly half of member is gray, cliff-forming, fossiliferous, thin-bedded limestone and half is brownish-gray, cliff-forming, thin-bedded (1 to 5 in [2 to 12 cm]), finely crystalline dolomite and fine- to coarse-grained limestone interbedded with thin beds of white chert. Locally includes large-scale crossbedding and irregular gently folded beds. Nautiloid fossils are common in upper 10 ft (3 m) of unit. The disconformable planar contact with the underlying Whitmore Wash Member is distinguished by a distinct lack of chert in Whitmore Wash Member. Thickness, 100 ft (30 m)

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) or Muav Limestone (Ꞓm) marked by low-relief erosion channels about 5 to 10 ft (2 to 3 m) deep. Contact generally recognized where major cliff of light-gray Redwall Limestone overlies stair-step ledges of dark-gray Devonian Temple Butte Formation in Grand Canyon, Little Colorado River Gorge, and Marble Canyon; locally overlies channel filled with reddish-purple mudstone and dark-gray contorted limestone beds of Temple Butte Formation within Marble Canyon. Otherwise unit most commonly overlies flat ledges of light-gray to greenish-gray, thin-bedded limestone of Cambrian Muav Limestone in Marble Canyon area. Thickness, 80 to 100 ft (25 to 30 m)

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 the underlying Cambrian Muav Limestone; channels are as much as 40 to 120 ft (12 to 37 m) deep in Marble Canyon. Carbonate ledges weather to dark gray. Unconformity at base represents major stratigraphic break spanning about 100 m.y. in the Grand Canyon that includes part of Late Cambrian, all of Ordovician and Silurian, and most of Early and Middle Devonian. Unit thins east and north of the map area, thickens west and south, and is likely intermittent or discontinuous in the subsurface of the northeastern two-thirds of the map. Thickness, 0 to 120 ft (0 to 37 m)

Tonto Group (Middle and Lower(?) Cambrian)—Includes, in descending order, the Muav Limestone, Bright Angel Shale, and Tapeats Sandstone as defined by Noble (1922) and modified by McKee and Resser (1945). The age and depositional history of Cambrian rocks in Grand Canyon are explained by Rose (2003). Tonto Group overlies tilted strata of the Grand Canyon Supergroup of Mesoproterozoic age (1.4 to 1.1 Ma). Grand Canyon Supergroup rocks may be present only in the western part of the map. Otherwise, Tonto Group overlies igneous and metamorphic rocks of Paleoproterozoic age (1.7 to 1.6 Ma). This hiatus is known regionally as the Great Unconformity

Ꞓm **Muav Limestone (Middle Cambrian)**—Dark-gray to light-greenish-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 underlying Bright Angel Shale is gradational and lithology dependent; marked at base of lowest prominent limestone cliff. Unit gradually thins west to east, thinning to an unknown thickness in subsurface of eastern two-thirds of quadrangle. Thickness, 320 to 380 ft (97 to 115 m)

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purple-red, slope-forming siltstone, shale, and red-brown to brown sandstone. Includes abundant 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 marked at top of transition from dominantly green siltstone slopes to dominantly brown sandstone ledges above Tapeats Sandstone cliff. Unit generally maintains a uniform thickness across western part of map area based on exposures in Grand Canyon; gradually thins eastward in subsurface. Thickness, 200 to 300 ft (60 to 90 m)

Ꞓt **Tapeats Sandstone (Middle and Lower(?) Cambrian)**—Brown and red-brown, cliff-forming, coarse-grained sandstone and conglomerate. Unconformable contact with the underlying Proterozoic surface is called the Great Unconformity. Tapeats Sandstone fills lowland areas between Proterozoic highlands and is locally absent on Proterozoic highlands. Variable thickness, 0 to 300 ft (0 to 91 m)

NEOPROTEROZOIC ROCKS

Neoproterozoic igneous and sedimentary rocks, as mapped by Timmons and others (2007), are exposed in the Grand Canyon and are likely present in the subsurface in the eastern part of the quadrangle.

Zs **Sixtymile Formation, undivided (Neoproterozoic)**—Informally divided into, in descending order, the lower, middle, and upper members (Elston, 1979). Lower member is composed of slumped blocks of dolomite surrounded by black shale exposed mainly in Sixtymile Canyon in eastern Grand Canyon. Middle member is thick sequence of white to red, laminated and thinly bedded siltstone, locally disrupted by intraformational brecciation and folding. Upper member contains intraformational breccias and red fluvial sandstones derived from the middle siltstone member. Unit unconformably overlain by Tapeats Sandstone. Thickness, 196 ft (60 m)

Chuar Group (Neoproterozoic)—Includes, in descending order, the Kwagunt Formation and Galeros Formation as defined by Ford and Dehler (2003), modified by Timmons and others (2007). A correlation by long-distance lithologic comparison, micropaleontologic assemblages, paleomagnetism, and very limited isotopic dating suggests the Nankoweap Formation, Chuar Group, and Sixtymile Formation were deposited within the 1,000 to 700 m.y. period. The Cambrian Tonto Group overlies these tilted strata in the subsurface west and east of Grand Canyon in the Tuba City quadrangle (sheet 1); this hiatus is known regionally as the Great Unconformity

Kwagunt Formation (Neoproterozoic)—Includes, in descending order, the Walcott, Awatubi, and Carbon Butte Members as mapped by Timmons and others (2007)

Zkw **Walcott Member (Neoproterozoic)**—Black to gray mudstone, gray dolomitic sandstone (12 to 31 ft [4 to 9.5 m] thick), brecciated dolomite and sandstone. A thin tephra deposit yielded a U-Pb zircon age of 742±6 Ma, providing an upper age limit for the Chuar Group (Karlstrom and others, 2000). Thickness, 838 ft (255 m)

Zka **Awatubi Member (Neoproterozoic)**—Red, green, blue, and light-brown mudstone, siltstone, and sandstone. A basal tan to light-brown stromatolite carbonate bed contains fossil biohermal dome features. Thin-bedded sandstone and siltstone contain ripple foreset beds and mud-crack casts. Near top of member, organic shale preserves the macroalgal fossil, Chuaria circularis, first described by Ford and Breed (1973). Thickness, 823 to 1,128 ft (252 to 344 m)

Zkcb **Carbon Butte Member (Neoproterozoic)**—Interbedded sandstone and siltstone. Basal sandstone is brown, medium- to fine-grained, thick sandstone, forming a distinctive marker bed approximately 252 ft (76 m) thick, and includes abundant soft-sediment deformation features, interference ripple marks, and mud-crack casts (Ford and Breed, 1973). Above basal sandstone unit are thin, interbedded, multicolored, mudstone, siltstone, and sandstone. Thickness, 112 to 223 ft (34 to 68 m)

Galeros Formation (Neoproterozoic)—Includes, in descending order, the Duppa, Carbon Canyon, Jupiter, and Tanner Members as mapped by Timmons and others (2007)

Zgd **Duppa Member (Neoproterozoic)**—Fine-grained siliciclastic unit dominated by shale and interbedded thin-bedded siltstone. Includes interbedded calcareous siltstone beds about 3 ft (1 m) thick. Variable thickness, 571 to 2,050 ft (174 to 625 m)

Zgcc **Carbon Canyon Member (Neoproterozoic)**—Fine-grained, interbedded siliciclastic mudstone, siltstone, and sandstone. Includes several thin dolomite and sandstone marker beds, 3 to 6 ft (1 to 2 m) thick. Sandstone beds contain symmetric and interference ripple marks, low-angle crossbeds, and mud-crack casts. Stromatolite fossils become more common toward top of unit. Thickness, 1,546 ft (471 m)

Zgj **Jupiter Member (Neoproterozoic)**—Fine-grained, interbedded siliciclastic mudstone, siltstone, sandstone, and dolomite. Dolomite and some sandstone beds form several marker beds throughout unit. Base of unit is stromatolitic dolomite, 40 ft (912 m) thick. Interbedded sandstone beds contain symmetric ripple marks, mud-crack casts, and raindrop impressions. Thickness, 868 to 1,516 ft (264 to 462 m)

Zgt **Tanner Member (Neoproterozoic)**—Very fine grained siliciclastic siltstone, sandstone, and thin dolomite. Include dark-brown dolomite at base of unit that unconformably overlies sandstone beds of the Nankoweap Formation. Thickness, 20 to 80 ft (6 to 24 m)

YZn **Nankoweap Formation, undivided (Neoproterozoic to latest Mesoproterozoic)**—Unconformity-bounded Nankoweap Formation separates rocks of the Neoproterozoic Chuar Group and Late Mesoproterozoic Unkar Group. Includes an upper and lower member, undivided (Gebel, 1978). Upper member is composed of siltstone and thick-bedded, fine-grained, red sandstone at base and more massive 3-ft-thick (1-m-thick) sandstone bed toward top of section, capped by white, fine-grained quartz sandstone. Unit contains trough crossbeds, ripple marks, mud cracks, soft-sediment deformation, and rare salt casts. Lower member is dominated by hematite-cemented quartzite sandstone and siltstone with lenses of lithic sandstone derived from underlying Cardenas Basalt. Thickness, 330 ft (100 m)

MESOPROTEROZOIC ROCKS

Mesoproterozoic igneous and sedimentary rocks, as mapped by Timmons and others (2007), are exposed in the Grand Canyon and are likely present in the subsurface in the eastern part of the quadrangle.

Unkar Group (Mesoproterozoic)—Includes, in descending order, Cardenas Basalt and the Dox Formation as defined by Hendricks and Stevenson (2003) and modified by Timmons and others (2007). Unkar Group rocks have been correlated to mafic intrusions of similar age and type in the southwestern United States (Howard, 1991). Cambrian Tonto Group overlies these tilted strata in the subsurface west and east of eastern Grand Canyon

Yc **Cardenas Basalt (Mesoproterozoic)**—Includes informal members, in descending order: the lapillite, fan-jointed, and bottle-green members (Lucchitta and Hendricks, 1983). Lapillite member is composed of scoriaceous fragments of volcanic bombs and ash matrix interbedded in massive basalt flows a few meters to several tens of meters thick (Lucchitta and Hendricks, 1983). Includes diabase intrusions that intrude both the Unkar Group and crystalline basement rocks as dikes and sills from a few tens of meters to 981 ft (300 m); dikes are thinner and locally utilize fault planes; similar in texture, mineralogy, and chemistry to Cardenas Basalt, suggesting a shared and common source. Thickness, 163 to 294 ft (50 to 90 m). Fan-jointed member is composed of porphyritic and vesicular basaltic andesite, approximately 163 ft (50 m) thick (Hendricks and Lucchitta, 1974). The bottle-green member consists of thin, discontinuous sequences of interbedded basalt flows and sandstone beds, highly altered, and contains secondary chlorite, epidote, talc, and zeolites; approximately 294 ft (90 m) thick

Dox Formation (Mesoproterozoic)—Includes, in descending order, the Ochoa Point, Comanche Point, Solomon Temple, and Escalante Creek Members as mapped by Timmons and others (2007) and described by Hendricks and Stevenson (2003). Contacts between members of Dox Formation are gradational and based mainly on topographic expression, depositional environments, and color change

Ydo **Ochoa Point Member (Mesoproterozoic)**—Red slope- and cliff-forming micaceous mudstone that grades upward into red quartz sandstone and silty sandstone. Includes salt-crystal casts in mudstone and asymmetrical ripple marks and small-scale crossbeds in sandstone. Thickness, 250 to 300 ft (976 to 91 m)

Ydc **Comanche Point Member (Mesoproterozoic)**—Light-red, pale-green to white, slope-forming, mudstone and siltstone and minor thin-bedded sandstone. Includes mud cracks, ripple marks, salt casts, wavy to irregular bedding, and stromatolitic dolomite beds within or adjacent to white siltstone beds. Thickness, 508 ft (155 m)

Yds **Solomon Temple Member (Mesoproterozoic)**—Cyclical sequence of red mudstone, siltstone, and quartz sandstone. Includes thin beds of argillaceous dolomite or calcareous siltstone. Mud cracks and ripple marks are common. Thickness, 920 ft (280 m)

Yde **Escalante Creek Member (Mesoproterozoic)**—Light-brown to greenish-brown sandstone, calcareous sandstone, and arkosic sandstone. Includes an upper dark-brown to green shale and mudstone. Thickness, 1,278 ft (390 m)

Ys **Shinumo Sandstone, undivided (Mesoproterozoic)**—Includes five informal members, in descending order: the Seventy Five Mile Rapid, Cottonwood Camp, Papago Creek, Ribbon Falls, and Surprise Valley Members, undivided (Timmons and others, 2007). Consists of red, brown, purple and white, cliff-forming, fine- to coarse-grained, well-sorted quartz arenite and subarkose sandstone with siliceous cement. Upper massive sandstone shows dramatic contorted bedding. Unconformable contact with underlying Hakatai Shale truncates crossbeds and alluvial channel deposits. Thickness, 1,132 ft (345 m)

Yh **Hakatai Shale, undivided (Mesoproterozoic)**—Includes three informal members, in descending order: the Stone Creek, Cheops Pyramid, and Hance Rapids members based on lithology of Beus and others (1974) and Reed (1976). The Cheops and Hance Rapids members are red to bright-red, slope-forming, highly fractured, argillaceous mudstones and shale. Upper Hance Rapids member is purple and red, cliff-forming, medium-grained sandstone. Unit contains mud cracks, ripple marks, and tabular-planar crossbed structures. Gradational contact with underlying Bass Formation. Thickness, 448 to 981 ft (137 to 300 m)

Yb **Bass Formation (Mesoproterozoic)**—Gray and reddish-gray dolomite interbedded with arkose and sandy dolomite and siltstone interbedded with intraformational breccias and conglomerates throughout sequence. Interbedded with dolomite and mudstone beds. Beds of white, very fine grained tephra deposits with a U-Pb zircon age of 1254±2 Ma (Timmons and others, 2007) toward base of section. The basal Hotauta Conglomerate Member (Noble, 1922) consists of rounded, gravel-sized clasts of chert, granite, quartz, plagioclase crystals, and micropegmatites in quartz sand matrix (Dalton, 1972). Contains biscuit-form and biohermal stromatolite beds (Nitecki, 1971). Unconformable contact with underlying Paleoproterozoic granites and schists. Thickness, 196 to 327 ft (60 to 100 m)

PALEOPROTEROZOIC ROCKS

Paleoproterozoic intrusive igneous and metasedimentary rocks, as mapped by Timmons and others (2007), are exposed in Grand Canyon and are likely present in the deep subsurface of the eastern part of the quadrangle.

Xg **Granite (Paleoproterozoic)**—Unfolded to weakly foliated, medium- to fine-grained muscovite-biotite, granitic pegmatite and aplite dikes, sills, and small plutons. U-Pb zircon ages range from 1,685 to 1,680±1 Ma (Hawkins and others, 1996)

Xgd **Granodiorite-gabbro-diorite and granodiorite complexes (Paleoproterozoic)**—Weakly to well-foliated, medium- to coarse-grained quartz-plagioclase and diorite-hornblende-bearing granitoids of probable volcanic arc origin (1.74 to 1.71 Ga)

Xv **Vishnu Schist of Granite Gorge Metamorphic Suite (Paleoproterozoic)**—Quartz-mica schist, pelitic schist, and meta-arenites of probable volcanic arc basin origin. Locally contains graded bedding and turbidite layering. Strongly foliated with multiple generations of folds and foliations (Ilg and others, 1996)

Xr **Rama Schist and Gneiss of Granite Gorge Metamorphic Suite (Paleoproterozoic)**—Quartz-ofeldspathic schist and gneiss of probable felsic to intermediate metavolcanic origin; strongly foliated; yields a U-Pb zircon age of 1,741±1 Ma (Hawkins and others, 1996)

Xbr **Brahma Schist of Granite Gorge Metamorphic Suite (Paleoproterozoic)**—Amphibolites, biotite-hornblende schist and biotite schist of probable mafic volcanic origin. Local metafelsite interbeds contain phenocrysts of quartz and feldspar; beds yield a U-Pb zircon age of 1,750±2 Ma (Hawkins and others, 1996)

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