Prepared in cooperation with the National Park Service, the U.S. Forest Service, the Bureau of Land Management, and the Navajo Nation

# Geologic Map of the Glen Canyon Dam 30' x 60' Quadrangle, Coconino County, Northern Arizona

Pamphlet to accompany

Scientific Investigations Map 3268

2013

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

# Contents

# Geologic Map of the Glen Canyon Dam 30' x 60' Quadrangle, Coconino County, Northern Arizona

By George H. Billingsley and Susan S. Priest

## Introduction

This geologic map is a cooperative effort of the U.S. Geological Survey (USGS) in collaboration with the National Park Service, the National Forest Service, the Bureau of Land Management, and the Navajo Nation to provide regional geologic information for resource management officials and for visitor information services at Grand Canyon National Park, Glen Canyon National Recreational Area, Vermilion Cliffs National Monument, the Kaibab National Forest, and the northwestern part of the Navajo Nation. Funding for the map was provided by the U.S. Geological Survey National Geologic Mapping Program, Reston, Virginia. Field work on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for and receive a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515, telephone (928) 871–6587.

The Bureau of Land Management Arizona Field Office in St. George, Utah, manages public lands of the Vermilion Cliffs Natural Area, Paria Canyon Vermilion Cliffs Wilderness Area, House Rock Valley, and Vermilion Cliffs National Monument in the northwestern quarter of the Glen Canyon Dam 30′ x 60′ quadrangle. The North Kaibab Ranger District in Fredonia, Arizona, manages the Kaibab National Forest and House Rock State Buffalo Ranch land along the west edge of the quadrangle. Grand Canyon National Park manages land within the western half of Marble Canyon and along the Colorado River corridor. Glen Canyon National Recreational Area manages lands along the Colorado River from Lake Powell to Lees Ferry. The Navajo Nation and local Navajo Chapter governments (LeChee, Copper ine, Kaibito, Bodaway/Gap, Tonalea, and Navajo Mountain Chapters) manage lands of the Navajo Nation in the eastern two-thirds of the quadrangle.

Other lands within the quadrangle include about 13 sections of Arizona state land and about ¾ section of private land in House Rock Valley and 1½ sections of private land at Cliff Dwellers Lodge, Vermilion Cliffs Lodge, and Marble Canyon, Arizona. The city of Page, Arizona, manages land within the Page Corporate Boundary area east of Glen Canyon Dam in the north-central part of the quadrangle.

The Glen Canyon Dam quadrangle is one of the few remaining areas where uniform new geologic mapping is needed for connectivity to the regional Grand Canyon geologic framework. This information will be useful to Federal, State, and Native American resource managers who direct environmental and land management programs that include issues such as range management, biological studies, climate change assessments, flood control, water resource investigations, and natural hazard assessments associated with floods, rock falls, and sand dune mobility. The geologic information will support future and ongoing geologic investigations and scientific studies of all disciplines within this part of northern Arizona.

## Geography

The Glen Canyon Dam 30' x 60' quadrangle encompasses approximately 5,018 $km^2$ (1,920 $mi^2$) within Coconino County, northern Arizona, and is bounded by lat 37° to 36°30' N., long 111° to 112° W. The map area is within the southern Colorado Plateaus geologic province (herein Colorado Plateau) and includes the eastern part of the Arizona Strip (fig. 1) northwest of the Colorado River and the northwestern portion of the Navajo Indian Reservation (Navajo Nation) east of the Colorado River. The map is locally subdivided into six physiographic areas: The Paria Plateau, House Rock Valley, Marble Canyon, Kaibito Plateau, Rainbow Plateau, and Marble Plateau (fig. 1, map sheet 3). The Colorado River flows from Glen Canyon National Recreational Area (Lake Powell) through Lees Ferry and southwestward into Marble Canyon of the Grand Canyon. Elevations range from about 2,875 ft (876 m) at the Colorado River in the southwest corner of the map to approximately 7,355 ft (2,224 m) on the east rim of Paria Plateau in the northwest third of the quadrangle.

The largest settlement within the Glen Canyon Dam quadrangle is Page, Arizona. Smaller settlements include LeChee, Copper Mine, and Kaibito located south and southeast of Page on the Kaibito Plateau, and Lees Ferry, Marble Canyon, Cliff Dwellers Lodge, Vermillion Cliffs Lodge, and Bitter Springs southwest of Page on the Marble Plateau along U.S. Highway 89A. Lees Ferry is a historical Colorado River crossing and today provides access for Colorado River trips from Glen Canyon Dam to Lees Ferry or as a departure point down through Grand Canyon.

U.S. Highways 89A and 89 provide access to the western half of the quadrangle and State Highway 98 provides access to the eastern half within the Navajo Nation. Roads and trails within the Kaibab National Forest and Grand Canyon National Game Preserve at the west edge of House Rock Valley are maintained by the National Forest Service and the Grand Canyon Trust. Unimproved dirt roads within the Navajo Reservation in the eastern two thirds of the quadrangle are maintained by the Navajo Nation Roads Department in Window Rock, Arizona. Other dirt roads are maintained locally by Chapter governments. Four-wheel drive vehicles are recommended for driving on all dirt roads within the quadrangle due to sand, mud, and snow. Extra water and food is highly recommended for travel in the map area.

# Previous Work

Early reconnaissance photogeologic maps in the northwestern part of the Glen Canyon Dam 30′ x 60′ quadrangle were produced by Detterman (1956a,b), Marshal (1956), McQueen (1956a,b,c,d), Minard (1956a,b,c,d), Petersen (1959, 1961), Petersen and Phoenix (1959), Petersen and Wells (1961), and Phoenix (1963). Early reconnaissance photogeologic mapping by Cooley and others (1969, map 1 of 9) covered the Navajo Indian Reservation in the eastern part of the quadrangle. The geologic map by Cooley and others was not registered to a topographic base larger than 1:250,000-scale because larger base maps of the Navajo Nation did not exist at that time. Wilson and others (1960) compiled a geologic map of Coconino County at 1:375,000-scale using the early reconnaissance maps listed above, and Wilson and others (1969) compiled a geologic map of the State of Arizona (1:500,000 scale) using this data. Detailed 7.5′ geologic maps along the Utah/Arizona border were made by Peterson (1973) and Peterson and Barnum (1973a,b). A geologic map of the Marble Canyon 1° x 2° quadrangle (1:250,000 scale) by Haynes and Hackman (1978) covers the Glen Canyon Dam quadrangle area. Geologic maps by Hackman and Wyant (1973) of the Escalante 1° x 2° quadrangle (1:250,000 scale) and Doelling and Davis (1989) cover the area adjacent to the northern border of this quadrangle.

Hereford and others (2000) and Hereford and Webb (2003) made detailed surficial geologic maps of the local Lees Ferry area. Recent geologic mapping within the southern part of Glen Canyon National Recreational Area was produced by Willis (2012**)**, and a geologic map of the House Rock Valley area was produced by Billingsley and Priest (2010). Huntoon and others (1996) and Timmons and others (2007) produced geologic maps of the eastern part of Grand Canyon National Park along the southwestern edge of the quadrangle. The Quaternary geology of all previous maps has been modified and significantly updated to match adjoining 30′ x 60′ quadrangle maps that include the Valle (Billingsley and others, 2006b), Cameron (Billingsley and others, 2007), Fredonia (Billingsley and others, 2008), Tuba City (Billingsley and others, 2013), and Smoky Mountain (Doelling and Willis, 2006) quadrangles. The Grand Canyon 30' x 60' quadrangle (Billingsley, 2000) adjoins the southwest corner of the Glen Canyon Dam quadrangle and shows mostly the bedrock geology of Huntoon and others (1996), but the Quaternary geology was not mapped in detail.

## Mapping Methods

Geologic mapping of the Glen Canyon Dam quadrangle was produced using 1:54,000- and 1:24,000-scale black and white aerial photographs flown in 1958 and 1968, respectively; 1:24,000- and 1:12,000-scale color aerial photographs flown in 1981 and 1986, respectively, courtesy of the U.S. Forest Service; and 1:24,000-scale color aerial photographs flown in 2005 by the Bureau of Land Management. Aerial geology was compiled onto USGS 1:24,000-scale topographic maps. The map area was field checked to verify bedrock and surficial geology, structure, and map unit descriptions.

Many of the Quaternary alluvial and eolian deposits are lithologically and geomorphically similar to each other and to units in the adjoining Fredonia and Tuba City 30′ x 60′ quadrangles. These units were mapped almost entirely by photogeologic methods. In most areas, lithology, stratigraphic position, and amount of erosional degradation were used to correlate the relative age of the alluvial and eolian deposits. 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. Not all surficial deposits within the quadrangle were field checked. Geologic information along the Colorado River was verified from river rafts on the Colorado River and from canyon-rim viewpoints.

In the eastern half of the quadrangle, not all small eolian and bedrock outcrops were individually mapped, because they are too small to show at map scale. Some eolian deposits were classified into a dominant dune type such as linear dunes that contain linear dunes as well as various other dunes types and sand sheet deposits. All surficial contacts adjacent to alluvial, eolian, and bedrock map units are approximate.

The digital geodatabase was created using ESRI ArcGIS. Field sheets were scanned and then brought into ArcMap for georeferencing. Geologic features were then digitized, symbolized, and cross-checked against the original field sheets. Thirty-two detailed 1:24,000-scale maps were compiled to produce this publication. This map is the ninth in a series of digital 30′ x 60′ geologic maps of the Grand Canyon region.

## Geologic Setting

The Glen Canyon Dam 30′ x 60′ quadrangle is characterized by nearly flat lying to gently dipping Paleozoic and Mesozoic sedimentary strata that overlie tilted Proterozoic strata or metasedimentary and igneous rocks similar to those exposed at the bottom of Grand Canyon southwest of the quadrangle (Timmons and others, 2007; Billingsley and others, 2012). Mississippian to Permian rocks are exposed in the walls of Marble Canyon; Permian strata and minor outcrops of Triassic strata form the surface bedrock of House Rock Valley and Marble Plateau, southwestern quarter of the quadrangle. The Paleozoic strata exposed in Marble Canyon and Grand Canyon south of the map are likely present in the subsurface of the entire quadrangle but with unknown facies and thickness changes.

The Mesozoic sedimentary rocks exposed along the Vermilion and Echo Cliffs once covered the entire quadrangle, but Cenozoic erosion has removed most of these rocks from the House Rock Valley and Marble Plateau areas. Mesozoic strata remain over much of the northern and eastern portions of the quadrangle where resistant Jurassic sandstone units form prominent cliffs, escarpments, mesas, buttes, and much of the surface bedrock of the Paria, Kaibito, and Rainbow Plateaus. Jurassic rocks in the northeastern part of the quadrangle are cut by a sub-Cretaceous regional unconformity that bevels the Entrada Sandstone and Morrison Formation from Cummings Mesa southward to White Mesa near Kaibito. Quaternary deposits, mainly eolian, mantle much of the Paria, Kaibito, and Rainbow Plateaus in the northern and northeastern portion of the quadrangle. Alluvial deposits are widely distributed over parts of House Rock Valley and Marble Plateau in the southwest quarter of the quadrangle.

The east-dipping strata of the Echo Cliffs Monocline forms a general north-south structural boundary through the central part of the quadrangle, separating Marble and Paria Plateaus west of the monocline from the Kaibito Plateau east of the monocline (Haynes and Hackman, 1978; fig. 1, map sheet 3). The Echo Cliffs Monocline continues north of the quadrangle into southern Utah (Doelling and Willis, 2006).

The gentle north- and northeast-dipping Mesozoic strata on the Kaibito and Rainbow Plateaus are partly interrupted by northwest-trending, broad-based, ill-defined synclines and anticlines. These broad-based structures form mesas and buttes near anticlinal crests and deeply incised drainages in synclinal valleys. The 1,300-ft-thick (396-m-thick) Navajo Sandstone erodes into a maze of tributary slot canyons in the northeastern part of the quadrangle. Mesozoic strata in the extreme northeast corner of the quadrangle dip gently southwest due to the influence of the Monument Upwarp in southeastern Utah and by an intrusive uplift (laccolith) that forms Navajo Mountain, a prominent 10,388 ft, (3,166 m) landmark just northeast of the quadrangle.

The quadrangle is located in a high-desert-climate regime where rainfall is generally less than 12 in (30.5 cm) per year. The erosion of thick Jurassic sandstones on the Paria, Kaibito, and Rainbow Plateau surfaces contribute a plentiful sand supply that is readily transported by southwesterly winds that form extensive sand dune and sand sheet deposits over much of these plateaus. The perennial Colorado River constantly transports weathered material out of the quadrangle. Glen Canyon Dam was completed in 1963 and has trapped much of the Colorado River sediment upstream within Lake Powell.

## Paleozoic Rocks

The erosion of Marble Canyon by the Colorado River has exposed about 2,400 ft (732 m) of Paleozoic strata in the southwestern quarter of the Glen Canyon Dam quadrangle. These rocks are likely present in the subsurface in other parts of the quadrangle with variable facies and thickness changes. Overall, most Paleozoic units gradually thin east of Marble Canyon and thicken toward the west. The Paleozoic rocks exposed in Marble Canyon are, in ascending order, the Redwall Limestone (Upper and Lower Mississippian), the Surprise Canyon Formation (Upper Mississippian), the Supai Group (Upper Mississippian, Lower, Middle, and Upper Pennsylvanian and Cisuralian), the Hermit Formation (Cisuralian), the Coconino Sandstone (Cisuralian), the Toroweap Formation (Cisuralian), and the Kaibab Formation (Cisuralian).

### Mississippian

The Redwall Limestone (Mr) forms a large 500 to 550 ft (152 to 168 m) reddish-gray cliff in the narrow depths of Marble Canyon and gradually thins east and thickens west as observed in Grand Canyon exposures south of the quadrangle. The Redwall Limestone unconformably overlies either the Devonian Temple Butte Formation or the Cambrian Muav Limestone where the Temple Butte is locally missing.

Overlying the Redwall Limestone is the Surprise Canyon Formation (Ms) present mainly in shallow (generally less than 40 ft (12 m) deep) paleovalleys eroded into the Redwall Limestone in the Marble Canyon area. The Surprise Canyon Formation thins east and thickens west of the quadrangle. Surprise Canyon sediments commonly fill paleokarst caves eroded into the top part of the Redwall Limestone.

## Pennsylvanian

The lower Supai Group (IPms) includes, in descending order, the Wescogame Formation (Upper Pennsylvanian), the Manakacha Formation (Middle Pennsylvanian), and the Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian). The upper Supai Group is represented by the Esplanade Sandstone (Cisuralian). The Supai Group unconformably overlies the Redwall Limestone or the Surprise Canyon Formation and maintains a general thickness of about 825 ft (252 m) in Marble Canyon. The Supai Group gradually thins eastward and thickens westward in the subsurface of the quadrangle.

## Permian (Cisuralian)

The Esplanade Sandstone (Pe) of the upper Supai Group forms a prominent light-red sandstone cliff, 350 to 400 ft (107 to 122 m) thick in Marble Canyon. It gradually thins east and south and thickens north of the quadrangle area.

Unconformably overlying the Esplanade Sandstone is the red slope-forming siltstone of the Hermit Formation (Ph). Stream channels as much as 10 ft (3 m) deep eroded into the Esplanade Sandstone are filled with the Hermit Formation. The Hermit Formation thins north to south in Marble Canyon from about 640 ft (195 m) to about 520 ft (158 m). A sharp planar erosional surface and color change separates the red Hermit Formation from the overlying buff-white Coconino Sandstone.

The Coconino Sandstone (Pc) forms a shear, buff-white, 240-ft-high (73-m-high) cliff in the southern part of Marble Canyon and thins rapidly northward to less than 30 ft (9 m) at Marble Canyon Lodge and pinches out in the vicinity of Lees Ferry. The Coconino pinches out in western Grand Canyon region and rapidly thickens south and southeast of the quadrangle.

The Toroweap Formation (Pt) overlies the Coconino Sandstone and undergoes a substantial west-to-east facies change within Marble Canyon. All three members of the Toroweap Formation in ascending order—the Seligman Member, the Woods Ranch Member, and the Brady Canyon Member as defined by Sorauf and Billingsley (1991)—are recognized in the western half of Marble Canyon but become indistinguishable in the eastern half due to rapid facies changes. The west-to-east facies change roughly parallels the trend of the Colorado River in Marble Canyon. Overall, the Toroweap Formation gradually thins east, north, and south of the quadrangle and thickens west. Thickness ranges from 180 to 220 ft (55 to 67 m) in the Marble Canyon area.

The Kaibab Formation forms the rim of Marble Canyon and Grand Canyon southwest of the quadrangle and also forms the surface bedrock for much of House Rock Valley and Marble Plateau where not covered by remnants of Triassic stratum or surficial deposits. The Kaibab Formation is divided into, in ascending order, the Fossil Mountain Member (Pkf) and the Harrisburg Member (Pkh) as defined by Sorauf and Billingsley (1991). A low-relief erosional unconformity commonly separates the lower ledge- and cliff-forming Fossil Mountain Member from the overlying slope- and ledge-forming Harrisburg Member in the walls of Marble 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 a sandy limestone or calcareous sandstone that locally contains mollusk fossils and numerous chert beds in the lower part.

The weathered surface of the Kaibab Formation is often stained dark gray or black by manganese oxide. The Fossil Mountain and Harrisburg Members undergo a west-to-east facies change within the quadrangle area making it increasingly difficult to distinguish them in Marble Canyon and Grand Canyon south of the quadrangle. The Kaibab Formation gradually thins east and thickens northwest and west of the quadrangle and ranges in overall thickness from 240 to 350 ft (73 to 107 m).

A regional unconformity with general relief of less than 10 ft (3 m) separates the gray Permian Kaibab Formation from the overlying red Triassic Moenkopi Formation. Erosional depressions and channels in the upper Kaibab were subsequently filled with angular and subangular chert and sandstone clasts derived from erosion of the Kaibab Formation.

## Mesozoic Rocks

Late Cenozoic erosion has exposed about 3,000 ft (915 m) or more of Mesozoic strata in the northwest quarter and northeast half of the quadrangle and has removed most of these rocks from the southwest quarter. Mesozoic rocks are, in ascending order, the Moenkopi Formation (Middle(?) and Lower Triassic), the Chinle Formation (Upper Triassic), the Glen Canyon Group composed of the Moenave Formation and Wingate Sandstone, undivided (Lower Jurassic), the Kayenta Formation (Lower Jurassic), and the Navajo Sandstone (Lower Jurassic); the San Rafael Group is composed of the Page Sandstone (Middle Jurassic), Carmel Formation (Middle Jurassic), Entrada Sandstone (Middle Jurassic), and Romana Sandstone (Middle Jurassic). Overlying the San Rafael Group is the Morrison Formation (Upper Jurassic). Unconformably overlying Upper Jurassic rocks on high plateaus and mesas within the northeast quarter of the quadrangle are the Dakota Sandstone (Upper Cretaceous) and Mancos Shale (Upper Cretaceous). All Mesozoic strata within the Glen Canyon Dam quadrangle undergo rapid facies and thickness changes northward into Utah. The Dakota Sandstone is called the Dakota Formation in Utah.

### Moenkopi Formation (Lower and Middle(?) Triassic)

Overlying and separated from the underlying Permian beds by the Tr-1 unconformity (Pipiringos and O’Sullivan, 1978) is a sequence of red sandstone ledges and siltstone slopes of the Moenkopi Formation. These rocks occur as scattered outcrops in House Rock Valley and Marble Plateau and as a continuous band of strata along the base of the Vermilion Cliffs from House Rock Valley to Lees Ferry and from Lees Ferry along the base of the Echo Cliffs to the south-central edge of the quadrangle. Prior to Cenozoic erosion, the Moenkopi Formation covering the Permian Kaibab Formation throughout the southwestern quarter of the quadrangle was as much as 1,000 ft (300 m) thick (Billingsley and others, 2006b; Billingsley and Priest, 2010). Limited incomplete outcrops in House Rock Valley and Marble Plateau indicate at least 500 ft (152 m) or more of the Moenkopi Formation was present prior to Cenozoic erosion. The Moenkopi Formation gradually thins east and southeast of the quadrangle and thickens north and northwest.

The Moenkopi Formation is divided into three units, in ascending order: the undivided lower members (Lower Triassic), the Shnabkaib Member (Lower Triassic), and the upper red member (Middle(?) and Lower Triassic). The lower members, undivided, include the lower red member, the Virgin Limestone Member, and the middle red member as defined by Stewart and others (1972) northwest of the quadrangle. The Virgin Limestone Member, separating the lower and middle red members, is less than 2 ft (0.6 m) thick in House Rock Valley and pinches out northward before reaching Lees Ferry. Without the Virgin Limestone marker bed, the lower red and middle red members are too similar in lithology and color to distinguish from each other and all three are herein mapped as the lower members, undivided (Ŧmlm).

Gradationally overlying the undivided lower members, the Shnabkaib Member (Ŧms) undergoes a southeastward facies change from a white, slope-forming siltstone, gypsiferous sandstone, and limestone sequence below the Vermilion Cliffs in House Rock Valley to a yellowish-white, cliff-forming, calcareous sandstone below the Echo Cliffs east of Marble Canyon.

Gradationally overlying the Shnabkaib Member is the upper red member (Ŧmu) consisting of a dark red, intertonguing siltstone and sandstone sequence that forms a series of ledges and slopes along the Vermilion and Echo Cliffs. The unit generally thins northward to Lees Ferry (locally replaced by a Lower Triassic erosional surface, Tr-3), thickens west of the map area, and may thin or pinch out northeast of the quadrangle. The erosional landscape cut into the Moenkopi Formation is known as the

Tr-3 unconformity by Pipiringos and O'Sullivan (1978) and Blakey (1994). The Moenkopi Formation is unconformably overlain by the light-brown, cliff-forming or white, slope-forming conglomeratic sandstone of the Shinarump Member of the Chinle Formation.

The Moenkopi Formation was deposited in shallow tidal flats and floodplains that drained northwest toward southern Utah (Blakey and Ranney, 2008). This coastal setting was followed by a northwest drainage system that deposited the overlying Chinle Formation. Initially, mud, sand, gravel, and conglomerate were deposited to form the basal Shinarump Member of the Chinle Formation. Drainages that eroded into the Moenkopi Formation (Tr-3) were commonly 20 to 60 ft (6 to 18 m) and as much as 100 ft (30 m) deep near Cliff Dwellers Lodge along U.S. Highway 89A.

### Chinle Formation (Upper Triassic)

The Chinle Formation is subdivided into three mappable units, which are exposed along the base of the Echo and Vermilion Cliffs in the southwestern half of the quadrangle. In ascending order, they are the Shinarump Member (₮cs), the Petrified Forest Member (₮cp), and the Owl Rock Member (₮co) as defined by Akers and others (1958) and Repenning and others (1969). Other members of the Chinle Formation described by Woody (2006) are not mapped in order to be consistent with adjacent mapping of the Fredonia and Tuba City 30′ x 60′ quadrangles (Billingsley and others, 2008, 2013).

The Shinarump Member is thickest along U.S. Highway 89A where tan, cliff-forming conglomeratic sandstones are as thick as 180 ft (55 m). The Shinarump forms the first cliff terrace or benchland adjacent to and above U.S. Highway 89A along the Vermilion Cliffs and adjacent to and above U.S. Highway 89 along the Echo Cliffs. The tan cliff of the Shinarump thins to a white slope in some areas above the upper ledges of the upper Moenkopi Formation. The Shinarump Member contains abundant petrified log and wood fragments in gravel lenses. The tan and white sandstone and siltstone sequence of the Shinarump Member grades upward into the multicolored Petrified Forest Member.

The Petrified Forest Member forms the blue, red, white, grayish-green, and purple mud hill slopes below the Shinarump and Owl Rock Members of the Chinle Formation and massive red Jurassic sandstones that form the bulk of the Vermilion and Echo Cliffs. The Petrified Forest Member generally maintains a thickness between 300 and 400 ft (92 and 122 m) throughout the quadrangle and gradually thickens south of the quadrangle.

Gradationally overlying the Petrified Forest Member is the Owl Rock Member of the Chinle Formation with a variable thickness of 150 to 200 ft (46 to 60 m). The contact between the Petrified Forest and Owl Rock Members is generally marked at the lowest gray limestone bed of the Owl Rock that is best exposed at Lees Ferry.

The contact of the Owl Rock Member with the overlying Moenave Formation is unconformable and marked by sharp changes in lithology and color from greenish-gray mudstone, siltstone, and limestone of the Owl Rock to orange-red fluvial sandstone and siltstone of the Moenave. This regional unconformity is known as the Tr-5 unconformity (Lucas, 1993) or the J-0 unconformity of Pipiringos and O'Sullivan (1978) and Peterson and Pipiringos (1979). The Owl Rock gradually thins northward along the Vermilion and Echo Cliffs to Lees Ferry and gradually thickens southeastward in the subsurface.

The Petrified Forest and Owl Rock Members of the Chinle Formation are soft and easily eroded, which allows erosional undercutting of the more resistant cliff-forming Moenave Formation, the Kayenta Formation, and the massive Navajo Sandstone that forms the bulk of the Vermilion and Echo Cliffs. This causes large-scale failure along bedrock joints and fractures resulting in large blocks of sedimentary strata that have gradually moved downward and rotated backward against the parent cliff. These blocks or landslide masses break up into extensive talus and rock-fall (Qtr) deposits on and around the landslides deposits (Ql). This action is amplified during wetter climate conditions. Sand derived from the crushing and breakdown of sandstone provides a source for eolian dune sand and sand sheet (Qd) deposits to accumulate on landslide and talus debris along the base of the Vermilion and Echo Cliffs.

## Glen Canyon Group

In ascending order, the Glen Canyon Group consists of the Moenave Formation and Wingate Sandstone, undivided, the Kayenta Formation, and the Navajo Sandstone. A thin remnant of the Wingate Sandstone, which is thicker to the northeast in Utah, is present within the upper Moenave Formation, but it is too thin to show at map scale. The Kayenta Formation and Navajo Sandstone form the dominant vertical topography of the Vermilion and Echo Cliffs and at Lees Ferry in the southwestern half of the quadrangle. Deep slot canyons have been eroded into the Navajo Sandstone by Navajo Creek and Kaibito Creek and their tributaries in the northeastern quarter of the quadrangle. The Glen Canyon Group was named for exposures in Glen Canyon near the present day Glen Canyon Dam on the Colorado River (Gregory and Moore, 1931; Anderson and others, 2000).

### Moenave Formation and Wingate Sandstone, Undivided (Lower Jurassic)

Overlying the Owl Rock Member of the Chinle Formation is the orange-red sandstone and siltstone sequence of the Moenave Formation (Jm). The Moenave Formation originally included, in ascending order, the Dinosaur Canyon Member and the Springdale Sandstone Member near the type section and community of Moenave, Arizona, just south of this quadrangle (Billingsley and others, 2013). The Dinosaur Canyon Member was defined by Colbert and Mook (1951). The Springdale Sandstone Member was originally defined by Gregory (1950) as part of the Chinle Formation then redefined as the upper member of the Moenave Formation by Harshbarger and others (1958); it has recently been reassigned to the basal part of the Kayenta Formation by Lucas and Milner (2006) and Lucas and Tanner (2006) and as used by Biek and others (2007). For this quadrangle, the Moenave Formation includes only the Dinosaur Canyon Member (not mapped) and the Springdale Sandstone Member (Jks) as the basal member of the Kayenta Formation.

The Moenave Formation is largely covered by talus and rock fall or landslide deposits along the Vermilion and Echo Cliffs. The Moenave gradually thins from about 220 to 180 ft (67 to 55 m) thick northward along the Vermilion and Echo Cliffs to Lees Ferry in the southwestern quarter of the quadrangle. The upper part of the Moenave Formation at Lees Ferry includes tongues of the Wingate Sandstone (not mapped) and, according to Wilson (1965), the Wingate rapidly thickens northeastward in the subsurface into southern Utah. Doelling and Davis (1989) indicate that the Wingate Sandstone intertongues with the Moenave Formation near Kanab, Utah, about 30 mi (48 km) northwest of this quadrangle. Doelling and Davis (1989) also report about 100 ft (30 m) of Wingate Sandstone north of this quadrangle from drilling information (Anderson and others, 2000). Doelling and Willis (2006) map the Wingate Sandstone just a few miles north of the quadrangle in San Juan Canyon and Glen Canyon within the Glen Canyon National Recreation Area of Utah.

### Kayenta Formation (Lower Jurassic)

The Kayenta Formation (Jk) unconformably overlies the Moenave Formation. This unconformity is the (J-sub-K) unconformity marking the beginning of Jurassic rocks as defined by Riggs and Blakey (1993) and Blakey (1994). Erosional relief is generally less than 6 ft (2 m) but can be as much as 50 ft (15 m) in the northern part of the map area (Nation, 1990; Phoenix, 1963). The Kayenta Formation includes, in ascending order, the Springdale Sandstone Member (Jks) and an upper purple-red slope-forming sequence of siltstone and sandstone that forms the bulk of the unit.

The Springdale Sandstone Member forms a dark-orange-red, thick-bedded sandstone cliff about 90 to 220 ft (27 to 67 m) thick. The Springdale Sandstone is overlain by 180 to 225 ft (55 to 68 m) of purplish-red siltstone and sandstone of the upper Kayenta Formation. The upper sequence undergoes an eastward facies change into a series of light-red, calcareous, sandstone cliffs separated by small red siltstone slopes as exposed in Navajo Canyon in the northeastern quarter of the quadrangle.

Overall, the Kayenta Formation is about 240 to 300 ft (73 to 91 m) thick along the Vermilion and Echo Cliffs to Lees Ferry and about 280 ft (86 m) thick in Navajo Canyon. The Kayenta gradually thins southeastward in the subsurface of the eastern half of the quadrangle. Several springs and seeps are associated with the Kayenta-Navajo contact along the Vermilion and Echo Cliffs and in Navajo Canyon. The lowest massive crossbedded sandstone marks the gradational contact between the Kayenta Formation and overlying Navajo Sandstone.

### Navajo Sandstone (Lower Jurassic)

The Navajo Sandstone (Jn) is a light-red and white, cliff-forming, crossbedded eolian sandstone that maintains a general thickness of about 1,750 ft (534 m) along the Vermilion and Echo Cliffs in the southwestern quarter of the quadrangle and thins eastward to about 1,200 ft (366 m) in the eastern half of the quadrangle. Cenozoic and modern erosion has beveled and removed some of the upper Navajo Sandstone and all of the overlying Jurassic and Cretaceous rocks west of the Red Lake Monocline, southeast corner of the quadrangle, and most of these rocks north of White Mesa to Lake Powell. The Navajo Sandstone forms the surface bedrock for much of the Paria Plateau in the northwest quarter of the quadrangle and most of the Kaibito and Rainbow Plateaus in the northeastern half of the quadrangle. Within the Navajo Sandstone are several thin-bedded, silica-cemented, sandy limestone beds 1 to 2 ft (0.5 to 1.2 m) thick that are lenticular in cross section and have limited lateral extent. These silicified limestone beds are present at various stratigraphic levels within the Navajo Sandstone and locally form flat, cherty limestone ridges, ledges, or flat-topped hills on Kaibito and Rainbow Plateaus. Along the northern border of the quadrangle on Paria Plateau, the upper few tens of feet of the Navajo Sandstone, as mapped, includes the Page Sandstone, tongues of the Page Sandstone, and the Judd Hollow Tongue of the Carmel Formation above the J-2 unconformity, because these units undergo rapid northward facies and thickness changes into Utah (Doelling and Willis, 2006).

## San Rafael Group

The Middle Jurassic rocks of the San Rafael Group consist of, in ascending order, the Page Sandstone, the Carmel Formation, the Entrada Sandstone, and the Romana Sandstone. The formations within this group were deposited in a continental setting that alternated between eolian, fluvial, and marine conditions (Anderson and others, 2000). Descriptions of various lithology and intertonguing relations of the Carmel Formation and Page Sandstone are documented by Doelling and Willis (2006).

### Page Sandstone (Middle Jurassic)

The Page Sandstone (Jp) is very similar in appearance, color, and lithology to the underlying Navajo Sandstone but is separated from it by a major unconformity known as the J-2 unconformity (Pipiringos and O′Sullivan, 1978; Blakey, 1994) but is also identified as the J-1 unconformity by Doelling and Willis (2006). In most places this unconformity may be difficult to identify. It is marked by a lag of angular chert grains and pebbles sparsely dispersed just above the unconformity at the base of the Page Sandstone at and east of Glen Canyon Dam. The erosional relief along the J-2 unconformity separating the Page Sandstone (Jp) from the underlying Navajo Sandstone (Jn) is generally less than 15 ft (5 m) and is located by a topographic and geomorphic expression usually marked by a bench in many places around Lake Powell. Part of the Page Sandstone or the lower tongue of the Page Sandstone (Harris Wash Tongue) is mapped with the upper part of the Navajo Sandstone on the Paria Plateau and Cedar Mountain area west of Glen Canyon Dam. The map contact is approximate.

In the northwestern part of the quadrangle, above the J-2 unconformity, the yellowish-white Page Sandstone and red Carmel Formation consist of, in ascending order, the westward-thinning Harris Wash

Tongue of the Page Sandstone, the eastward-thinning Judd Hollow Tongue of the Carmel Formation, and the westward-thinning Thousand Pockets Tongues of the Page Sandstone, collectively mapped as the Judd Hollow Tongue and Page Sandstone Tongues, undivided (Jcj), which are all overlain by the upper members of the Carmel Formation. These tongues of the Page and Carmel are mapped as separate units north of the quadrangle by Doelling and Davis (1989) and Doelling and Willis (2006). The Judd Hollow Tongue pinches out eastward and is not present in the outcrops at Glen Canyon; therefore, it is simply Page Sandstone (undivided) east of the Echo Cliffs Monocline.

### Carmel Formation (Middle Jurassic)

The Carmel Formation above the Page Sandstone is the lateral equivalent of the Paria River Member and overlying Winsor Member at their type localities in Utah about 50 and 75 mi, respectively, northwest of Page. The Carmel Formation is mapped along the northwestern edge of the quadrangle as the Paria River Member and Winsor Member of the Carmel Formation, undivided (Jcu), because it lacks some of the features that characterize these members farther west.

A few miles east of Glen Canyon Dam on the Kaibito Plateau, the Page Sandstone is mapped to indicate that it is present at most locations but is not mapped where it thins or becomes indistinguishable from the Navajo Sandstone. About 8 mi (13 km) south of Glen Canyon Dam, U.S. Highway 89 cuts through one of the thickest (300 ft [92 m]) and best exposed sections of the Page Sandstone. Farther south towards Copper Mine, Arizona, east-central part of the quadrangle, the Page Sandstone becomes difficult to distinguish from the Navajo Sandstone and the map contact is marked at the J-2 unconformity between the Carmel Formation (Jc) and Navajo Sandstone (Jn).

South and northeast of Glen Canyon Dam and Page, Arizona, a distinct lithology, color, and topography change differentiates the Navajo Sandstone/Page Sandstone from the overlying reddish-brown, slope-forming Carmel Formation. The J-2 unconformity separates the Carmel Formation from the underlying Navajo Sandstone in the south-central part of the quadrangle beyond the wedge edge of the Page Sandstone by a distinct color change from yellowish-white Navajo to red-brown Carmel. The Carmel Formation is 160 to 240 ft (48 to 60 m) thick in the northeastern half of the quadrangle and was largely removed from the southern portion of the Kaibito and Paria Plateaus by Cenozoic erosion. On the Kaibito Plateau, the various tongues and members of the Carmel Formation are not identified and are collectively mapped as the Carmel Formation (Jc).

### Entrada Sandstone (Middle Jurassic)

Overlying the Carmel Formation is the red and white Entrada Sandstone (Je). The Entrada Sandstone is thickest (more than 785 ft [240 m]) at White Mesa, a prominent landmark in the southeast corner of the quadrangle capped by the Cretaceous Dakota Sandstone. The Entrada Sandstone thins northwestward to about 655 ft (200 m) along the northern margin of the quadrangle (Fred Peterson, written commun., 2012).

A quadrangle-wide approach to any of the suggested subdivisions of the Entrada Sandstone is neither consistent nor uniform due to changes in facies, thickness, and intertonguing. Therefore, the Entrada Sandstone is not subdivided on this map. Stratigraphic position and color are helpful for descriptive purposes when correlating White Mesa to geographic areas north and south. For preliminary and informal subdivisions of the Entrada Sandstone, see Doelling and Davis (1989), Doelling and Willis (2006), and Cooley and others (1969). At White Mesa, the Entrada Sandstone (Je) is recognized by color: a lower yellow, a middle red, and an upper white sandstone (not mapped individually).

The Cow Springs Sandstone at Black Mesa southeast of this map is generally a bleached zone at the top of the Entrada Sandstone. Bleaching is caused by seepage of organic fluids into the sandstone from the overlying Dakota Formation (Peterson, 1988). Lack of a distinct layer justifies including the Cow Springs Sandstone as the upper part of the Entrada Sandstone.

The Entrada Sandstone is unconformably overlain by the Cretaceous Dakota Sandstone at White Mesa in the southeastern quarter of the quadrangle. North of White Mesa, the Entrada Sandstone is unconformably overlain by tan sandstone beds of the Salt Wash Member of the Morrison Formation that thickens northward from Tse Esgizii Butte to Cummings Mesa, northeast corner of the quadrangle. The Morrison Formation at Cummings Mesa and Tse Esgizii Butte and the Entrada Sandstone at White Mesa have all been beveled from north to south by an unconformity at the base of the Cretaceous Dakota Sandstone.

### Romana Sandstone (Middle Jurassic)

The Romana Sandstone (Jr) is a white to light-grayish-green unit that locally weathers moderate brown and forms a cliff in most places above the Entrada Sandstone. Because it forms a sheer cliff and cannot be separated from the overlying Salt Wash Member of the Morrison Formation, it is included with the Salt Wash Member as a single map unit. The Romana Sandstone thins eastward across the northern edge of the quadrangle and nearly pinches out at Cummings Mesa. It is present as a darker stained sheer sandstone cliff in isolated buttes between Cummings Mesa and Page, Arizona. The Romana Sandstone at Cummings Mesa is shown on the map but forms such a sheer cliff that it is difficult to map. The Romana Sandstone is considered the stratigraphic equivalent of the Summerville Formation farther north in Utah, because both formations are bounded by the J-3 and J-5 unconformities (Peterson and Pipiringos, 1979).

The Romana Sandstone is lithologically distinctive from the underlying Entrada Sandstone and overlying Salt Wash Member of the Morrison Formation. The Romana Sandstone weathers to a gray-brown cliff that can be distinguished from the underlying, white and red Entrada Sandstone and the overlying, weathered, dark-brown Morrison Formation. The Romana Sandstone unconformably (J-3 unconformity) overlies the Entrada Sandstone in the Lake Powell area of Utah and is beveled out by a low angle erosional surface (J-5 unconformity) east and southeast of Page.

### Morrison Formation (Upper Jurassic)

Unconformably (J-5) overlying the Romana Sandstone are gray and brown, cliff-forming, pebbly to conglomeratic sandstone beds and scarce thin beds of green and red mudstone of the Salt Wash Member (Jms) of the Morrison Formation. The base of the Salt Wash Member of the Morrison Formation may include thin, discontinuous, red mudstone beds of the Tidwell Member of the Morrison Formation in the Cummings Mesa area and buttes farther west on the Rainbow Plateau. Between Cummings Mesa and Page, Arizona, the Morrison Formation thins westward and is unconformably overlain by sandstone beds of the Dakota Sandstone. West of Page on the Paria Plateau, the Entrada Sandstone progressively thins from northeast to southwest by the sub-Cretaceous erosion surface (K-0 unconformity), which is overlain by the Dakota Sandstone. As a result, the Morrison Formation, Romana Sandstone, Entrada Sandstone, and much of the Carmel Formation have largely been removed by the Early Cretaceous erosional event marked by the K-0 unconformity. This beveled surface is described north of the quadrangle in Utah by Anderson and others (2000) and Peterson (1988).

### Dakota Sandstone (Upper Cretaceous)

The Dakota Sandstone or the Dakota Formation of Doelling and Willis (2006) in Utah is present at the top of White Mesa, Tse Esgizii Butte, LeChee Rock, and Cummings Mesa in the northeast quarter of the quadrangle and near U.S. Highway 89 in the northwest quarter. The Dakota Sandstone terminology is used for this quadrangle to match adjoining 30′ x 60′ quadrangles in Arizona. The Dakota Sandstone is subdivided into three informal units by O’Sullivan and others (1972): in ascending order, the lower sandstone member, the middle carbonaceous member, and the upper sandstone member. Peterson (1969) used similar informal member subdivisions: in ascending order, the lower, middle, and upper members. About 10 to 40 ft (3 to 12 m) of the Dakota Sandstone is present at White Mesa with mixed lithology as described by O'Sullivan and others (1972) and collectively mapped as the Dakota Sandstone (Kd). The basal Dakota Sandstone member is a coarse, sandy, pebbly conglomerate that grades upward into the middle member, consisting of mixed sandstone, siltstone, mudstone, and minor thin beds of carbonaceous mudstone and coal. The upper member is chiefly calcareous sandstone with abundant fossil marine clams (Mollusca: Bivalvia). The Dakota Sandstone has a gradational upward contact with the overlying gray mudstone of the Mancos Shale (Km).

#### Mancos Shale (Upper Cretaceous)

The lower part of the Mancos Shale is present on the western third of White Mesa in the southeastern quarter of the quadrangle. Modern erosion has removed most of the bluish-gray, thin-bedded, slope-forming Mancos Shale from the western third of White Mesa and almost all of the shale from the eastern two-thirds of White Mesa east of the quadrangle. Remnants of the Mancos Shale are largely covered by deposits of Pleistocene and Holocene eolian and fluvial sand, silt, mud, and some Tertiary gravel deposits too thin to show at map scale. At the south edge of White Mesa, much of the Dakota Sandstone and Mancos Shale have been removed by Cenozoic erosion and partly overlain by gravels and sedimentary deposits (Tgs).

## Quaternary and Tertiary Surficial Deposits

### Surficial Deposits and Mapping Techniques

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

Surficial sedimentary deposits have accumulated over the last several hundred thousand to about 1 m.y., but most are Pleistocene and Holocene. They generally occur as unconsolidated or weakly consolidated deposits of local extent overlying bedrock. They usually constitute a thin surface veneer but can be as much as several tens of feet thick. Most of the surficial deposits accumulated as a result of running water (fluvial or alluvial deposits), wind (eolian deposits), or a combination of both processes. Some alluvial deposits in valleys, washes, and floodplains are remobilized by wind, forming new sand dune and sand sheet deposits. Landslide, talus, and rock-fall deposits accumulate on steep slopes near buttes and mesas.

Mapping surficial deposits across an area as large as the Glen Canyon Dam 30′ x 60′ quadrangle poses a number of 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 is needed. To accommodate these criteria, the materials are classified using genesis (for example, alluvium, eolian, talus, landslide), geologic age (for example, Pleistocene or Holocene), and lithology (for example, sand, gravel). This strategy has evolved over time from previous surficial mapping in the Grand Canyon region by Billingsley and Workman (2000); Billingsley and Wellmeyer (2003); and Billingsley and others (2006a,b, 2007, 2008, 2013).

Information about surficial deposits was obtained mainly by aerial photo interpretation and field verification. Ages are based mostly on geomorphic criteria, such as relative position in local alluvial terrace sequences, the degree of alluvial fan dissection, and superposition or stabilization of dune and sand sheet deposits. The discontinuous distribution 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 other 30′ x 60′ quadrangles south and west of the Glen Canyon Dam quadrangle were adjusted to a younger age for this publication, based on recent observations with other field geologists.

## Tertiary Gravel Deposits

The oldest gravel and sedimentary deposits (Tgs) cap ridges southwest and east of White Mesa in the southeast corner of the quadrangle. The deposits are as much as 100 ft (30 m) thick and may be as young as early Pleistocene age but are likely Pliocene age pending further study. These deposits unconformably overlie beveled surfaces of east-dipping Jurassic strata along the Red Lake Monocline. These deposits include minor, small, well-rounded chert, quartzite, and granite pebbles within a gray mudstone, siltstone, and sandstone sedimentary deposit. These deposits includes numerous well-rounded pebbles and cobbles of reworked Cretaceous marine sandstone and fossils clasts derived from Jurassic and Cretaceous rocks on White Mesa and perhaps from sources farther east of the quadrangle. Pebble imbrications within these stream sediment deposits indicate a southwesterly current.

Additional stream gravel and sedimentary deposits fill valleys eroded into the Entrada and Dakota sandstones as much as 40 ft (12 m) or more at the northern edge of the quadrangle about 6 mi (9 km) west of Glen Canyon Dam. These deposits fill a wide valley drainage that appears to parallel the base of the Echo Cliffs Monocline. Pebble imbrication within these deposits indicates that the stream flowed from Utah southeast into the abandoned loop of the Colorado River at the north end of Ferry Swale 1 mi (1.5 km) west of Glen Canyon Dam. The gray siltstone and sandstone matrix contains abundant rounded, black pebbles and flat, gray, rounded sandstone pebbles derived from nearby Cretaceous rocks in Utah. Pebbles from younger or older rocks are absent, suggesting that this drainage was likely a strike-valley drainage confined to the base of the Echo Cliffs Monocline in Jurassic and Cretaceous rocks.

## Eolian Deposits

Surficial fluvial deposits (Qs, Qf, Qa1, Qa2, Qa3, Qa4, Qae) are found throughout the map area and tend to be isolated because of steep topography and rapid modern erosion. In contrast, eolian deposits cover large areas of the Paria, Kaibito, and Rainbow Plateaus. The Navajo and Entrada sandstones are the primary source of sand for all eolian sand deposits (Qes, Qd, Qdl, Qdp, Qdb, Qdm, Qdlu) in the northeastern three quarters of the quadrangle. Not all sand deposits are shown because some are too thinly deposited or limited in area to show at map scale. In several areas on the Paria, Kaibito, and Rainbow Plateaus, many of the eolian deposits are collectively mapped by the dominant dune form, such as sand sheet deposits (Qes), linear dune and sand sheets (Qdlu), mixed dune deposits (Qdm), or dune sand and sand sheet deposits (Qd). Some bedrock outcrops within eolian deposits are too small to show at map scale. Eolian sand deposits are transported in a general northeasterly direction across the Paria, Kaibito, and Rainbow Plateaus by southwesterly winds. In many areas, storm runoff erodes eolian sand material into enclosed ponded (Qps) depressions. This sand is often recycled back into nearby eolian deposits during dry conditions, creating a sand conveyor belt. Eventually, much of the sand is transported by fluvial processes down small drainages into the Colorado River where it is carried through the Grand Canyon and out of the region.

## Quaternary Gravel Deposits

Floodplain and terrace-gravel deposits at Lees Ferry are documented by Hereford and others (2000), Hereford and Webb (2003), Cragun (2007), and Hidy and others (2010). This information was helpful in recognizing relatively young floodplain (Qf), lower terrace-gravel (Qg3, Qg4), and upper terrace-gravel (Qg5-18) deposits of Pliocene(?) and Pleistocene age found at various elevations above the Colorado River from Glen Canyon Dam to Colorado River Mile 9 below Badger Creek Rapids in

Marble Canyon (fig. 2, map sheet 3). The floodplain deposits are 0 to 45 ft (0 to 14 m) above the modern Colorado River and the terrace-gravel deposits are 30 to 1,200 ft (9 to 366 m) above the modern Colorado River from Lake Powell to Marble Canyon. The floodplain deposits are composed primarily of silt and sand with minor gravel lenses. The terrace-gravel deposits are primarily silt, sand, pebbles, and cobbles. The upper terrace-gravel deposits along the Colorado River (Qg5-18) provide a unique record of the river's incision into Paleozoic and Mesozoic bedrock across the Echo Cliffs Monocline in the last 500,000 years or more based on the age of river incision into the Lake Powell area of southern Utah by Hanks and others (2000), Davis and others (2000), and Willis and Biek (2000).

The oldest terrace-gravel deposits, undivided (Qg5-18), are in tributaries of the Colorado River, such as Kaibito and Navajo Creeks southeast of Glen Canyon Dam. These deposits are not given a specific terrace-gravel designation, because they are either too isolated or too far from the river for direct correlation.

Assuming that the modern Colorado River gradient of 3.5 ft/mi (1.1 m/km) between Glen Canyon Dam and Badger Creek Rapids, a distance of 25 mi (40 km), has not changed appreciably over the last 500,000 years, the Colorado River has cut 1,200 ft (366 m) into the landscape with an incision rate of about 2.4 ft (0.73 m) per thousand years. This suggests a fairly young and perhaps constant incision of the Colorado River and its tributaries into the landscape of northern Arizona and southern Utah. A close-up of these deposits is shown on figure 2 (map sheet 3). Correlation of these deposits is based on approximate elevation above the present Colorado River at the top of the deposit as derived from Google Earth images.

### Other Surficial Deposits

Other surficial deposits within the quadrangle include landslides (Ql) and talus and rock-fall (Qtr) deposits commonly found below the Vermilion Cliffs, Echo Cliffs, Cummings Mesa, and White Mesa areas. Diversion dams, stock tanks, gravel pits, mines, and man-made landfills and excavations (Qaf) are mapped to show human impact upon the landscape. Not all highway and railway excavations and fills are shown.

## Prospects and Mines

There are seven small abandoned uranium mines and prospects located on the map below the Vermilion and Echo Cliffs. Mines include the Sun Valley, El Pequito, Red Wing, and one that is unnamed; prospects include the Sam, Jasper, and Lehneer (Phoenix, 1963; Haynes and Hackman, 1978; Bush, 1983). All except the Sam Prospect are in the Shinarump Member of the Chinle Formation. The Sam Prospect is in the Petrified Forest Member of the Chinle Formation. According to Bush (1983), some limited production of uranium, gold, and mercury may have occurred from a few of these prospects and mines.

On Kaibito Plateau at the north edge of the community of Copper Mine, Arizona, a copper mine in the Navajo Sandstone produced an unknown amount of copper from small open pits. This mine has been abandoned for several years and the origin of the copper ore is unknown. The mine does not appear to be associated with a collapse-breccia-pipe structure like other copper deposits in the Grand Canyon region and is stratigraphically the highest copper deposit in the Grand Canyon region.

Perhaps the most-sought-after commodity within this quadrangle is quartzite/chert gravel deposits for road and building materials. Other than Colorado River deposits (QTg5-18), this material is very limited and has been quarried in and around Page, Arizona. The gravel and sedimentary deposits elsewhere are mostly of local sedimentary origin and contain very few quartzite/chert clasts.

## Structural Geology

Large-displacement, high-angle to nearly vertical normal faults in Proterozoic basement rocks set the stage for structural deformation of younger Paleozoic and Mesozoic strata exposed in the Grand Canyon southwest of the quadrangle (Huntoon, 1990, 2003). Compressional folding of Paleozoic and Mesozoic rocks along these reactivated Proterozoic high-angle faults peaked at about 65 Ma in Late Cretaceous and early Tertiary time during the Laramide Orogeny. The Echo Cliffs and Red Lake Monoclines are the result of Laramide events (Huntoon, 1990, 2003; Huntoon and others, 1996; Timmons and others, 2005, 2007).

The east-dipping Echo Cliffs Monocline (fig. 1, map sheet 3) is the principle structural feature within the Glen Canyon Dam quadrangle. This north-south-trending fold provides a structural divide through the central part of the quadrangle, separating the Marble and Paria Plateaus west of the monocline from the Kaibito and Rainbow Plateaus east of the monocline (Haynes and Hackman, 1978; Billingsley and others, 2013). The Echo Cliffs Monocline continues northwest of the quadrangle into southern Utah and south of the quadrangle toward Cameron, Arizona. Permian, Triassic, and Jurassic strata along the monocline dip 12° to 23° east. Folding along the Echo Cliffs Monocline has elevated the rocks of Marble Plateau an estimated 1,700 ft (518 m) up to the west in the southern portion of the quadrangle (Billingsley and others, 2013).

The Red Lake Monocline (fig. 1, map sheet 3) trends northward through the community of Kaibito, Arizona, in the southeastern quarter of the quadrangle (Cooley and others, 1969). Kaibito Creek has eroded into Jurassic sandstone that parallels the down-folded limb of the monocline from White Mesa to its junction with Navajo Creek. The monocline gradually dies out northward and does not reach Lake Powell; however, it extends about 60 mi (96 km**)** south of the quadrangle (Billingsley and others, 2013). Light-red Navajo Sandstone is exposed west of the monocline and white to red Entrada Sandstone is exposed to the east. Relief along the monocline is generally less than 200 ft (60 m) and the average dip of strata is about 5° east and as much as 15° to 20° east in the vicinity of White Mesa.

Elsewhere, other gentle northwest-trending, ill-defined, broad folds are approximately located on the quadrangle (fig. 1, map sheet 3): from west to east, Paria Plateau Syncline, Last Chance Anticline, Limestone Ridge Anticline, Tuba City Syncline, Preston Mesa Anticline, Kaibito Syncline, and Cow Springs Syncline. House Rock Valley and the Paria Plateau lie within the structurally ill-defined broad basin of the Paria Plateau Syncline that gently plunges north towards Utah. The Paria Plateau Syncline is approximately located on this quadrangle as referenced on the Marble Canyon 2° quadrangle by Haynes and Hackman (1978), Bush (1983), and Billingsley and Priest (2010).

The Limestone Ridge Anticline is a broad, gentle, doubly-plunging anticline forming the elevated crest of Marble Plateau (Haynes and Hackman, 1978; Billingsley and others, 2013). The anticline plunges north-northwest toward Lees Ferry, nearly parallel to the Colorado River. The Tuba City Syncline is another ill-defined, broad, northwest-trending synclinal depression between the Echo Cliffs Monocline and Preston Mesa Anticline (Cooley and others, 1969; Haynes and Hackman, 1978; Billingsley and others, 2013). Preston Mesa Anticline forms the anticlinal crest west of the Red Lake Monocline. The Cow Springs Syncline forms the synclinal depression east of the Red Lake Monocline.

During the Pliocene and Pleistocene, east-west tectonic extension reactivated deep-seated faults along the Echo Cliffs Monocline and produced normal faults that reversed Cretaceous and Tertiary offset and accentuated the dip of the monocline by reverse fault drag (Huntoon, 1990, 2003). Extensional faulting during the late Pliocene produced numerous grabens throughout the quadrangle. Extension likely began less than 3 Ma and continues to the present based on similar extension west and south of the quadrangle (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003; Billingsley and others, 2006a,b, 2007, 2008, 2013). North- and northeast-trending grabens and faults in the quadrangle appear to be the most recent tectonic structures based on minor offset of Pleistocene and Holocene(?) alluvial deposits and Pleistocene volcanic rocks south of the map (Billingsley and others, 2007, 2013).

Numerous northwest- and northeast-trending joints and fractures are common over the entire quadrangle and provide major hydrologic connections for groundwater transport from the Kaibito Plateau east of the Echo Cliffs Monocline northward towards Lake Powell. West of the Echo Cliffs Monocline, the joints and fractures allow groundwater transfer from Marble Plateau and House Rock Valley to springs along the Colorado River in Marble Canyon. Groundwater from Lake Powell flows along these same joints, fractures, and bedding planes within the Navajo Sandstone toward springs and seeps in Glen Canyon below the dam.

Laramide erosion initiated transformation of the landscape but late Tertiary and Pleistocene erosion has greatly deepened and broadened the canyons of the Colorado River and its tributaries. A precursor Colorado River (?) drainage probably meandered through sediment-filled valleys east of the Echo Cliffs Monocline while eroding a young canyon into Mesozoic rocks southwest of the monocline at some unknown time prior to late Miocene or early Pliocene. These meander patterns have been superimposed on resistant Mesozoic and Paleozoic rocks, preserving the geomorphology of an ancestral Colorado River. Today's Colorado River and its tributaries became well established in late Miocene or early Pliocene time, about 9 to 6 Ma (Lucchitta, 1979, 1990; Ranney, 2005). Headward erosion by the Colorado River tributaries has excavated steep young canyons into the Paria, Kaibito, and Rainbow Plateaus and has greatly enhanced the widening and cliff-retreat process along the Vermilion and Echo Cliffs.

Circular bowl-shaped depressions characterized by inward-dipping strata in the Kaibab and Moenkopi Formations are likely the surface expression of breccia pipes (red dots on map) created by dissolution of the Mississippian Redwall Limestone at depth in the southwestern half of the quadrangle (Wenrich, 1985; Wenrich and Sutphin, 1988). Collapse features (black dots on map) may or may not represent breccia pipes at depth. Drilling is necessary to confirm breccia pipes within collapse structures. Breccia pipes have the potential for concentrating uranium and other minerals at depth, but not all breccia pipes are mineralized (Wenrich and Sutphin, 1989; Wenrich and Huntoon, 1989).

Gypsum dissolution in the Harrisburg Member of the Kaibab Formation has resulted in several sinkholes in House Rock Valley and on Marble Plateau in the southwestern half of the quadrangle. The sinkholes are likely Pleistocene and Holocene in age because they disrupt local drainages and are partially filled with locally produced, fine-grained, unconsolidated sediment and debris.

## Acknowledgments

We appreciate the cooperation and support of the Geologic Division of the National Park Service, Fort Collins, Colorado; the National Park Service of Grand Canyon National Park and Glen Canyon National Recreational Area, Arizona; the Bureau of Land Management, Arizona Strip District, St. George, Utah; and the U.S. Forest Service, North Kaibab Ranger District, Fredonia, Arizona. The North Kaibab Ranger District and the Arizona Strip District provided color aerial photographs of the western half of the quadrangle. Permits to conduct geologic field work on the Navajo Nation were provided by the Navajo Nation Minerals Department, Window Rock, Arizona. Resolutions to conduct local field work were granted by LeChee, Bodaway/Gap, Coppermine, Kaibito, Tonalea, and Navajo Mountain Chapters of the Navajo Nation.

We also appreciate the advice, revisions, and geologic information provided by Fred Peterson of the U.S. Geological Survey, Denver, Colorado, and Grant Willis of the Utah Geological Survey, Salt Lake City, Utah. We are indebted to Charles L. Powell, II, and J.L. 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 on differences in morphology, lithology, and physiographic position as seen on 1968, 1:24,000-scale, black and white aerial photographs; 2005, 1:24,000- and 1:40,000-scale, color aerial photographs; and field observations. Young surficial deposits are actively accumulating material and are vulnerable to wind or water erosion. On the Paria and Kaibito Plateaus, extensive eolian sand sheet and dune deposits are stabilized by vegetation during wet conditions and become destabilized and mobile during severe drought conditions or spring wind events, especially when disturbed by livestock or human activity. Older alluvial and eolian deposits generally exhibit extensive erosion, have greater topographic relief due to deeper incision, are preserved as remnants on elevated benches and mesas, and in some areas have developed a carbonate soil subhorizon. Older terrace-gravel deposits, undivided, are cumulatively labeled Qg5-18 on the geologic map; see figure 2 (map sheet 3) for a detailed view of individual deposits. Eolian and alluvial contacts are provisional and approximate.

Qaf **Artificial fill and quarries (Holocene)**—Alluvium and bedrock material removed from borrow pits and trenches to build stock tanks, drainage diversion dams, landfills, roads, railroads, and projects related to the city of Page, Arizona, Glen Canyon Dam, and the Arizona Public Service Power Plant east of Page (not all road and railroad excavations are shown)

Qs **Stream-channel deposits (Holocene)**—Poorly sorted, unconsolidated, 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-fill (Qv) deposits in House Rock Valley and Marble Plateau areas. Overlaps and intertongues with floodplain (Qf), ponded sediment (Qps), and mixed alluvium and eolian (Qae) deposits on Paria and Kaibito Plateau areas. Little or no vegetation in stream channels, except for some salt cedar (tamarisk), Russian olive, and cottonwood trees and grass. Contacts with adjacent alluvial or eolian deposits are approximate. Thickness, 3 to 30 ft (1 to 9 m)

Qf **Floodplain deposits (Holocene)**—Gray, brown, and light-red interbedded lenses of clay, mud, silt, and sand; include minor lenticular gravel deposits. Intertongue with or overlap stream-channel (Qs), valley-fill (Qv), young terrace-gravel (Qg1), young alluvial fan (Qa1), and mixed alluvium and eolian (Qae) deposits. Subject to stream-channel erosion or overbank flooding in lateral and vertical sense. Similar to valley-fill (Qv) deposits in small tributary drainages and in shallow valleys on Paria and Kaibito Plateaus; subject to widespread and frequent overbank flooding along Colorado River, Paria River, and local drainages in House Rock Valley and in deep tributary drainages to Lake Powell in northeastern half of quadrangle. Subject to temporary ponding; unit is often mixed or intertongues with ponded sediments (Qps) or mixed alluvium and eolian (Qae) deposits in shallow wide drainages on Paria and Kaibito Plateaus. Support moderate growths of sagebrush, grass, tumbleweed, desert shrubs, and tamarisk trees. Thickness, 3 to 30 ft (1 to 9 m) or more

Qes **Sand sheet deposits (Holocene)**—Gray-white to light-red, fine- to coarse-grained, windblown sand composed mainly of quartz and chert grains derived primarily from Jurassic formations. Form extensive cover over gently sloping terrain on Paria and Kaibito Plateaus and upper House Rock Valley. Include thin deposits on alluvial fan slopes below Echo Cliffs and Vermilion Cliffs. Commonly intertongue with mixed alluvial and eolian (Qae) deposits and all eolian sand deposits

(Qd, Qdp, Qdl, Qdb, Qdm, Qdlu) that share gradational and approximate contacts, both lateral and vertical. Support moderate growth of grass, small desert shrubs, and juniper and pinyon woodlands. Thickness, 1 to 18 ft (0.3 to 6 m)

Qd **Dune sand and sand sheet deposits, undivided (Holocene)**—Echo and Vermilion Cliffs area: White, gray, and light-red, fine- to coarse-grained quartz, feldspar, and chert sand grains locally derived from Paleozoic and Mesozoic sedimentary rocks; especially on or near talus and rock-fall (Qtr) and landslide (Ql) deposits below Vermilion and Echo Cliffs. Unconsolidated stream-channel (Qs) or valley-fill (Qv) deposits are transported by wind to form lumpy, undefined, geometric sand dune or sand sheet deposits over alluvial fan (Qa1, Qa2, Qa3) and young terrace-gravel (Qg1) deposits near washes in southwest quarter of quadrangle. Support moderate growths of grass and sagebrush.

Paria and Kaibito Plateaus areas: White, gray, and light-red, fine- to coarse-grained sand composed mainly of quartz, chert, and minor feldspar derived from nearby Jurassic sedimentary rocks. Include topographically controlled climbing and falling dunes, mixed dune (Qdm) and sand sheet (Qes) deposits that mantle bedrock slopes and shallow valleys on Paria and Kaibito Plateaus. Navajo Sandstone (Jn) is the primary source of sand on Paria 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 northeasterly by southwesterly winds. Support moderate growth of grass, Mormon Tea, high desert shrubs, and scattered pinyon and juniper woodlands. Thickness, 3 to 200 ft (1 to 61 m)

Qdl **Linear dune deposits (Holocene)**—Gray-white, light-red, fine- to medium-grained, well-sorted, unconsolidated linear sand accumulations aligned northeasterly across relatively flat terrain on Kaibito Plateau. Unit often merges with sand sheet (Qes), dune sand and sand sheet (Qd), mixed dune (Qdm), and parabolic dune (Qdp) 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 extend over 1 mi (1.5 km) or more in length. Individual linear dunes are mapped where they form prominent features on Kaibito Plateau. Linear dunes that are not as well defined are mapped as linear dune and sand sheet deposits (Qdlu). Thickness, 6 to 40 ft (2 to 12 m)

Qdp **Parabolic dune deposits (Holocene)**—Gray-white, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand. Ponded sediments (Qps) commonly form on upwind (southwest) side between parabolic dune horns and within parabolic and mixed dune (Qdm) deposits. Bedrock often exposed at southwest interior of parabolic dunes. Contact merges with adjacent dune sand and sand sheet (Qd), sand sheet (Qes), and mixed alluvium and eolian (Qae) deposits. Support little to sparse grassy vegetation. Thickness, 6 to 30 ft (2 to 9 m)

Qdb **Barchan dune deposits (Holocene)**—Light-red, fine- to medium-grained, well-sorted, unconsolidated quartz sand. Form isolated cluster northeast of State Highway 98 northeast of Kaibito on Kaibito Plateau. Dunes are actively forming and expanding as of 2011. Sand is derived mainly from nearby outcrops of Entrada Sandstone (Je) and Carmel Formation (Jc). Subject to changes in extent and shape due to seasonal storms and sand mobility. Support little to no vegetation. Thickness, 6 to 30 ft (2 to 9 m)

Qdm **Mixed dune deposits (Holocene)**—Gray-white, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand derived primarily from the Navajo Sandstone (Jn) and Entrada Sandstone (Je). Parabolic and linear dunes are dominant and are often interconnected or associated with extensive sand sheet deposits. On Kaibito Plateau, linear dunes often form on downwind side of parabolic dunes. Parabolic dunes often form adjacent to and as part of linear dunes. Include Navajo Sandstone (Jn) outcrops and ponded sediment (Qps) deposits too small to show at map scale. Frequently reactivated northwest of Kaibito and northeast of Page near Lake Powell. Thickness, 6 to 40 ft (2 to 12 m)

Qdlu **Linear dune and sand sheet deposits, undivided (Holocene)**—Gray-white, light-red, fine- to coarse-grained, well-sorted, unconsolidated quartz sand derived primarily from the Navajo Sandstone (Jn) and Entrada Sandstone (Je) on Kaibito Plateau. Unit often forms clusters of closely spaced deposits that often merge and separate as an interconnecting mass of dune forms and abundant sand sheet deposits. Support sparse grassy vegetation and small high desert brush. 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 exotic boulders that came from as far away as Colorado, Utah, and New Mexico along Colorado and Paria Rivers. Include well-rounded clasts of quartzite, quartz, chert, sandstone, and limestone in many large tributaries to the Colorado River throughout the quadrangle. Locally overlap young alluvial fan (Qa1), floodplain (Qf), and valley-fill (Qv) deposits below Vermilion and Echo Cliffs and House Rock Valley and on Marble Plateau. Unit often covered by dune sand and sand sheet (Qd) and sand sheet (Qes) deposits in east half of quadrangle. Form benches about 3 to 12 ft (1 to 3.5 m) above stream-channel (Qs) or floodplain (Qf) deposits along Colorado River, Paria River, Navajo Creek, and Kaibito Creek. Subject to frequent flash-flood erosion and overbank flooding. Support light vegetation, mainly grass, and a few desert shrubs. Thickness, 6 to 20 ft (2 to 6 m)

Qa1 **Young alluvial fan deposits (Holocene)**—Base of Vermilion and Echo Cliffs, House Rock Valley, and Marble Plateau: Reddish gray to light-brown silt, sand, gravel, pebbles, cobbles, and boulders; partly consolidated by calcite and gypsum cement. Pebbles, cobbles, and boulders are subangular to round. Unit is subject to widespread flash-flood debris flows. Subject to temporary cover by dune sand and sand sheet (Qd) and sand sheet (Qes) deposits. Support light growths of sagebrush, cactus, and grass. Thickness 10 to 30 ft (3 to 9 m).

Paria and Kaibito Plateaus: Gray, light-brown, and light-red clay, silt, sand, and minor pebbles of chert, limestone, and sandstone; unconsolidated. Unit often overlapped by stream-channel (Qs), ponded sediments (Qps), floodplain (Qf), dune sand and sand sheet (Qd), sand sheet (Qes), valley-fill (Qv), young terrace-gravel (Qg1), and mixed alluvium and eolian (Qae) deposits. Clay, silt, and sand are primarily derived from local Jurassic and Cretaceous outcrops. Subject to widespread 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 but stratigraphically higher. Form benches about 15 to 30 ft (4.5 to 9 m) above modern streambeds and about 6 to 25 ft (2 to 7.5 m) above young terrace-gravel (Qg1) deposits in upper reaches of Colorado River tributaries. 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 rock-fall (Qtr), and landslide (Ql) deposits throughout quadrangle. Subject to severe cut-bank erosion. Support growths of grass and a variety of high desert shrubs, tamarisk, and cottonwood trees. Thickness, 6 to 30 ft (2 to 9 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 sheet wash erosion with arroyos that have incised as much as 3 to 10 ft (1 to 3 m) below Vermilion and Echo Cliffs. Subject to partial coverage by dune sand and sand sheet (Qd) and sand sheet (Qes) deposits. Unit commonly overlapped by young alluvial fan (Qa1) deposits; intertongues with or overlaps valley-fill (Qv), talus and rock-fall (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)**—House Rock Valley and Marble Plateau: Gray and red-brown clay, silt, sand, and gravel; partly consolidated by calcite and or gypsum cement. Locally include minor lenses of angular to subrounded chert and limestone fragments or pebbles in sandy matrix derived from nearby Permian, Triassic, and Jurassic strata. Similar to floodplain (Qf) deposits but occupy natural internal drainage depressions created by sinkhole development or man-made containment structures in southwestern half of quadrangle.

Paria and Kaibito Plateaus: Gray, brown, and light-red clay, silt, sand, and minor chert gravel. Chert gravel is often locally derived from thin silicified limestone beds within the Navajo Sandstone (Jn). Ponded sediments are commonly formed in depressions caused by sand dune blockage or in small wind deflation hollows within extensive dune sand and sand sheet (Qd), parabolic dune (Qdp), and mixed dune (Qdm) deposits. These deposits are likely temporary but are important as watering places during human and animal migration across the dry sandy areas of the plateaus. Thickness, 5 to 20 ft (1.5 to 6 m)

Qae **Mixed alluvium and eolian deposits (Holocene)**—Gray-white, light-red, fine- to coarse-grained interbedded sand, brown clay and silt, and lenses of subrounded pebbles or angular gravel fragments. Include angular white chert fragments locally derived from Permian and Triassic strata in House Rock Valley and on Marble Plateau. On Paria and Kaibito Plateaus, unit consists of white to gray chert fragments and small black sandstone concretions derived from Navajo Sandstone. Deposits accumulated by alluvial and (or) eolian processes result in an interbedded sequence of mixed mud, silt, sand, and gravel. Deposit subject to sheet wash erosion and arroyo cutting during wet conditions and wind-blown sand accumulation during dry conditions. Support light to moderate growth of grass, cactus, sagebrush, and high desert shrubs. Thickness, 3 to 40 ft (1 to 12 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. Similar to young and intermediate terrace-gravel (Qg1, Qg2) deposits. Form terrace deposits adjacent to and 80 to 100 ft (24 to 30 m) above the Colorado and Paria Rivers and within narrow tributaries of Kaibito and Navajo Creeks. Include abundant rounded and well-rounded clasts of quartzite, quartz, chert, sandstone, and limestone along the Colorado and Paria Rivers. Thickness, 6 to 35 ft (2 to 10 m)

Qa3 **Old alluvial fan deposits (Holocene)**—Gray and light-brown, unsorted silt, sand, and gravel mixed with angular and subrounded pebbles and cobbles of red and white sandstone, gray limestone, and gray chert; partly consolidated by calcite and gypsum cement. Unit partly overlain by dune sand and sand sheet (Qd) deposits below White Mesa in southeastern quarter of quadrangle. Include large boulders, cobbles, and pebbles of sedimentary rocks derived from nearby talus and rock-fall (Qtr) and landslide (Ql) deposits below Vermilion and Echo Cliffs in southwestern half of quadrangle. Support moderate growths of grass, sagebrush, cactus, and various desert shrubs. Thickness, 5 to 25 ft (1.5 to 7.5 m)

Qv **Valley-fill deposits (Holocene and Pleistocene(?))**—Gray and light-brown silt, sand, and lenses of gravel; partly consolidated by gypsum and calcite below Vermilion and Echo Cliffs. Include occasional rounded clasts of limestone, sandstone, and subrounded to angular chert derived from nearby outcrops of Kaibab Formation and Shinarump Member of the Chinle Formation in House Rock Valley and on Marble Plateau. Intertongue with or overlain by young and intermediate alluvial fan (Qa1, Qa2) and young and intermediate terrace-gravel (Qg1, Qg2) deposits. Subject to sheet wash flooding or arroyo cutting. Reflects low-gradient, low-energy sediment accumulation in shallow drainages in all areas of quadrangle. Thickness, 3 to 30 ft (1 to 9 m)

Qtr **Talus and rock-fall deposits (Holocene and Pleistocene(?))**—In Marble Canyon: Gray to yellowish-red silt, sand, and gravel mixed with abundant small to large angular limestone, sandstone, and chert rocks and boulders derived from Paleozoic strata; cemented or partly cemented by calcite and gypsum. Below Vermilion and Echo Cliffs: Red to yellow silt, sand, and gravel mixed with angular rocks and boulders of light-red or white sandstone and red to dark-red siltstone derived from Triassic and Jurassic strata; partly cemented by calcite. Below Cummings Mesa and White Mesa, eastern quarter of quadrangle: Gray siltstone and sandstone derived from Jurassic and Cretaceous strata. Most units are often associated with, adjacent to, or part of landslide (Ql) deposits that commonly grade downslope into young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3) or young, intermediate, or old terrace-gravel (Qg1, Qg2, Qg3) deposits. Thickness, 5 to 80 ft (1.5 to 24 m)

Ql **Landslide deposits (Holocene and Pleistocene)**—Unconsolidated to partly consolidated masses of angular unsorted rock debris. Include large slump blocks of rock sediments that have rotated backward against the parent outcrop and slid downslope as a loose mass of rock fragments and deformed strata; often associated with talus and rock-fall (Qtr) deposits. Include individual car- and house-size boulders. Unit partly covered by dune sand and sand sheet (Qd) and sand sheet (Qes) deposits below Vermilion and Echo Cliffs, White Mesa, and Cummings Mesa. Gradational contact with young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3) and young, intermediate, and old terrace-gravel (Qg1, Qg2, Qg3) deposits near base of deposits. Subject to extensive sheet wash erosion, flash-flood debris flows, rock fall, and arroyo erosion. Thickness, 10 to 200 ft (3 to 61 m)

Qg4 **Older terrace-gravel deposits (Pleistocene)**—Gray and light-brown silt, sand, gravel, and well-rounded flat pebbles and cobbles; poorly sorted and partly consolidated by calcrete in top 3 ft (1 m) along Colorado and Paria Rivers. Similar to young, intermediate, and old terrace-gravel (Qg1, Qg2, Qg3) deposits. Form isolated deposits 110 to 130 ft (34 to 39 m) above Colorado and Paria Rivers. Support minor growths of grass and low desert shrubs. Thickness, 2 to 15 ft (1 to 4.5 m)

Qa4 **Older alluvial fan deposits (Pleistocene and Pliocene(?))**—Gray, sandy and gravelly fluvial debris-flow deposits. Unit is part of a more extensive alluvial fan deposit in House Rock Valley derived from Kaibab Plateau west of map area. Include clasts and boulders eroded from the Hermit Formation, Coconino Sandstone, Toroweap Formation, Kaibab Formation, and Moenkopi Formation from the Kaibab Plateau in

House Rock valley. Unit is extensively eroded and gullied; eroded material is redeposited onto adjacent younger alluvial fans. Unit forms protective surface over Moenkopi Formation in western House Rock Valley. Support light to moderate growth of grass, cactus, and various high desert shrubs and bushes. Thickness, 10 to 25 ft (3 to 7.5 m)

Qg5-18 **Oldest terrace-gravel deposits, undivided (Pleistocene and Pliocene(?))**—See figure 2 (map sheet 3) for maps showing detailed locations of separate deposits. Gray and light-brown clay, silt, sand, and gravel, poorly sorted; partly cemented by calcite. Include numerous subrounded to rounded chert, limestone, and sandstone pebbles locally derived from nearby rock outcrops. Include many well-rounded clasts of quartzite, sandstone, and chert from the Claron Formation transported by an ancestral Paria River in Utah, northwest of the quadrangle, and well-rounded exotic volcanic and metamorphic rocks from Colorado and New Mexico transported by an ancestral Colorado River and its tributaries. The oldest terrace-gravel deposits have been correlated by stratigraphic position above the Colorado River from Marble Canyon to Lake Powell based on aerial photographs and elevations derived from Google Earth images and 7.5′ quadrangles (table 1, map sheet 3). Unit is partly covered by eolian sand (Qd, Qes) deposits near Glen Canyon Dam. Support sparse growths of grass and low desert shrubs. Thickness, 6 to 30 ft (2 to 9 m)

Tgs **Gravel and sedimentary deposits (Pliocene(?) or Miocene(?))**—Gray, brown, and white mudstone, sandstone, siltstone, and minor gravel deposits, poorly sorted and partly consolidated. Unit consists mainly of gray, fine-grained, fluvial silt and sand that contains scattered pebbles and cobbles of well-rounded gray sandstone and limestone clasts derived from Jurassic and Cretaceous rocks (Kd, Km) of White Mesa east of Kaibito Monocline. Contains numerous rounded and a few well-rounded granite, quartzite, and chert clasts whose origin is not certain (possibly reworked from gravels in the Chuska Mountains of northeastern Arizona). Also well-rounded Cretaceous fossil fragments, sandstone, and limestone pebbles and cobbles locally derived from underlying bedrock. Unit overlies beveled Jurassic rocks of Navajo Sandstone (Jn) west of Kaibito Monocline and Carmel Formation (Jc), Entrada Sandstone (Je), and Dakota Sandstone (Kd), east of Kaibito Monocline in southeast corner of quadrangle. Age may be Pliocene(?) as mapped by Billingsley and others (2012) or Miocene(?) as suggested by Lucchitta (2011).

West of Glen Canyon Dam: Poorly sorted and partly consolidated gray clay, silt, sand, and gravel. Includes well-rounded, black, brown, and minor red chert pebbles and small gray limestone pebbles. Pebbles are generally 0.5 to 3 in (1.2 to 7.5 cm) in diameter. Black pebbles make up about 75% of pebble distribution, gray and white about 24%, brown and red less than 1%. Form gray rounded outcrops in channels eroded into underlying Entrada Sandstone (Je) about 1 mi (1.6 km) south of U.S. Highway 89, north-central edge of quadrangle. Thickness, 30 to 100 ft (9 to 30 m)

## SEDIMENTARY ROCKS

Cretaceous rocks were deposited in mixed continental and marine environments. During this time, the Western Interior Seaway transgressed and regressed into and out of the Glen Canyon Dam quadrangle.

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 thin-bedded limestone. Unit is largely covered by dune sand and sand sheet (Qd) deposits on White Mesa. Locally fossiliferous with cephalopods and other marine fossils that date unit as Late Cretaceous. Deposited on a shallow sea floor that transgressed southwest from the midcontinent. Unit is laterally equivalent to the Tropic Shale of lower part of Mancos Shale in southern Utah (Doelling and others, 2000; Anderson and others, 2000). Gradational contact with underlying Dakota Sandstone (Kd). Unit is partially preserved on White Mesa, southeast corner of quadrangle, and mostly removed by Tertiary erosion elsewhere. Thickness, 60 ft (18 m)

Kd **Dakota Sandstone (Upper Cretaceous)**—Described as Dakota Formation in Utah (Doelling and Davis, 1989), referred to as Dakota Sandstone in Arizona to match nomenclature of the Cameron 30′ x 60′ quadrangle (Billingsley and others, 2007), the Tuba City 30′ x 60′ quadrangle (Billingsley and others, 2012), and the Winslow 30′ x 60′ quadrangle (Billingsley and others, 2013). Medium- to light-gray, slope-forming, laminated to thin-bedded mudstone, siltstone, and sandstone. Locally includes a lower conglomerate to conglomeratic sandstone member, a middle carbonaceous mudstone to coal member, and an upper sandstone member as defined by O’Sullivan and others (1972) in the northeast and southeast corners of quadrangle.

Lower sandstone member: Light-orange to light-gray silty sandstone and conglomeratic sandstone that forms a cliff as much as 20 ft (6 m) thick. Occupies channels eroded into underlying Entrada Sandstone (Je) at White Mesa and into Salt Wash Member of the Morrison Formation on Cummings Mesa that marks the regional angular Cretaceous (K-0) unconformity (Pipiringos and O’Sullivan, 1978; Peterson and Turner-Peterson, 1987). Clasts in sandstone are composed of red and gray, well-rounded chert and quartzite typically less than 2 in (5 cm) in diameter. Base of Dakota Sandstone locally overlies younger strata from Cummings Mesa south to White Mesa owing to beveling of underlying Jurassic rocks southwestward across the quadrangle and younger rocks north of the quadrangle in Utah (Doelling and Willis, 2006; Doelling and Davis, 1989; Doelling and others, 2000; Anderson and others, 2000; Peterson, 1988). Overlies progressively older rocks south and southeast of the quadrangle (Harshbarger and others, 1958; Cooley and others, 1969; Billingsley and others, 2012). Although these relations establish the angularity of the Cretaceous pre-Dakota Sandstone unconformity (K-0), the angularity is so small that it is not apparent at most outcrops within the Glen Canyon quadrangle.

Middle carbonaceous member: Dark-grayish-brown, carbonaceous, flat-bedded mudstone, siltstone, coal, and interbedded brown, conglomeratic, crossbedded lenticular sandstone. Coal beds are generally less than 1 ft (0.3 m) thick on White Mesa. Gypsum is a common constituent in siltstones appearing as thin veins and isolated crystals. The upper sandstone member is not present in the quadrangle. Unit is mostly covered by dune sand and sand sheet (Qd) deposits at White Mesa and Cummings Mesa.

The upper sandstone member of the Dakota Sandstone may be partly present on White Mesa but was not verified in the field and is included with the middle carbonaceous member. Overall thickness, 10 to 40 ft (3 to 12 m)

**Morrison Formation (Upper Jurassic)**—The Morrison Formation consists of two members in the Glen Canyon Dam quadrangle. They are, in ascending order, the Salt Wash Member and Brushy Basin Member. The basal Tidwell Member is thin and discontinuous and, where present, is included with the Salt Wash Member for mapping purposes (Peterson, 1973, 1988; Peterson and Barnum, 1973a,b)

Jms **Salt Wash Member (Upper Jurassic)**—Light-brown to gray, cliff-forming, thick-bedded, fluvial and conglomeratic, coarse-grained sandstone. Forms massive upper sandstone cliffs on Cummings Mesa and most other buttes and mesas farther west. Unit weathers to light-brown or gray cliffs and is unconformably overlain by patches of Dakota Sandstone (Kd) on Cummings Mesa and at the top of Tse Esgizii Butte and LeChee Rock (K-0 unconformity). The J-5 unconformity marks the basal contact of the Salt Wash Member with the underlying Romana Sandstone (Jr). Erosion of the Salt Wash Member beneath the regional K-0 unconformity accounts for the westward thinning of the Salt Wash Member of the Morrison Formation. Thickness, 0 to 380 ft (0 to 116 m)

**San Rafael Group (Middle Jurassic)**—The San Rafael Group includes, in ascending order, the Page Sandstone (Jp), the Carmel Formation (Jc), the Entrada Sandstone (Je), and the Romana Sandstone (Jr) that overly the Navajo Sandstone (Jn) at the J-2 unconformity. The eolian Page Sandstone and shallow marine to sabkha Carmel Formation were deposited marginal to a seaway that advanced southward into southwestern Utah and northwestern Arizona (Peterson, 1994). The Carmel Formation and Entrada Sandstone extended to the Moenkopi Plateau south of the quadrangle (Billingsley and others, 2012). Overlying the Carmel, the Entrada (Je) and Romana (Jr) Sandstones were deposited in eolian shoreline and marginal marine environments (Peterson, 1988). The Page Sandstone is included within the San Rafael Group because it intertongues with the Carmel Formation, and both units unconformably overlie the Navajo Sandstone where they are present directly on top of the Navajo Sandstone

Jr **Romana Sandstone (Middle Jurassic)**—Brown to gray, cliff-forming, thick-bedded, eolian, flat-bedded, fine- to medium-grained sandstone containing scattered grit and granules; weathers to a shear brown cliff that overlies white and red cliffs of Entrada Sandstone. Contact with Entrada Sandstone (Je) is visibly identifiable in several small buttes between Page, Arizona, and Cummings Mesa along northern border of quadrangle based on weathered color differences and local access. Lithologically, the Romana Sandstone is somewhat more coarse grained then the underlying Entrada Sandstone. Unit pinches out southwards, thins northeast and east of Cummings Mesa, and has been removed by Cretaceous erosion south of Cummings Mesa and west of Page, Arizona. Thickness, 0 to 175 ft (0 to 53 m)

Je **Entrada Sandstone (Middle Jurassic)**—White, light-red, yellow-white, and white cliff-forming, crossbedded, fine-grained sandstone and siltstone in northeast half of quadrangle. Includes, in ascending order, a basal sandy member, a middle silty member, and an upper sandy member as informally defined by Cooley and others (1969). The Entrada Sandstone gradationally overlies the Carmel Formation (Jc).

Basal sandy member: Composed of light-red and white steep slope or weak cliff of very fine grained, trough-crossbedded sandstone that partially intertongues with thin, flat-bedded, red siltstone of upper Carmel Formation between White Mesa and Cummings Mesa. Otherwise, forms gradational boundary with underlying Carmel Formation with visible color change from red siltstone of Carmel to light-red and white sandstone of Entrada.

Middle silty member: Consists of prominent light-red, cliff-forming, silty sandstone at White Mesa; undergoes thickness and facies change north and south of

White Mesa into red- and white-banded, fine-grained, cliff-forming sandstone that becomes mostly white, low-angle-crossbedded sandstone north and south of White Mesa. Unit forms prominent red and white banded sandstone cliff at Cummings Mesa that is likely equivalent to the middle white and orange-red banded member of Doelling and Davis (1989) in Utah.

Upper sandy member: Composed of white to tan, cliff-forming, low-angle-crossbedded sandstone. Unit forms prominent white sandstone cliff at Cummings Mesa and on several small buttes west of Cummings Mesa capped by brown-weathered Romana Sandstone (Jr). Unit is equivalent, in part, to white, fine-grained, crossbedded sandstone of the Cow Springs Sandstone southeast of quadrangle where the Cow Springs Sandstone is considered an upper part of the Entrada Sandstone (Cooley and others, 1969; Peterson, 1988; Billingsley and others, 2013).

Entrada Sandstone forms a sandstone cliff overlain by a thin sheer cliff of the Romana Sandstone (Jr) that is overlain by a conglomeratic, coarse-grained sandstone cliff of the Salt Wash Member of the Morrison Formation. Conglomerate lenses of Dakota Sandstone (Kd) locally and unconformably overlie the Salt Wash Member of the Morrison. Unit thins southwest of the quadrangle and thins north into Utah. Maximum thickness is at White Mesa, about 785 ft (240 m)

Jc **Carmel Formation, undivided (Middle Jurassic)**—Kaibito Plateau area: Red, slope-forming siltstone, claystone, and silty calcareous and gypsiferous sandstone. Includes white, flat-bedded, low-angle-crossbedded calcareous sandstone interbedded with numerous flat-bedded red silty sandstones. Red silty sandstone contains ripple marks and abundant rounded sandy fecal pellets about 0.5 in (1 cm) in diameter. North of Paria River along Utah-Arizona border, unit includes light-gray sandstone beds as much as 3 ft (1 m) thick containing white and red calcite and white barite crystals. Correlative to and intertongues with members of the Page Sandstone in northern half of quadrangle. Unconformably overlies crossbedded Navajo Sandstone (Jn) in southeast quarter of quadrangle on Kaibito Plateau. Erosional relief at base is generally less than 15 ft (4.5 m). The Carmel Formation pinches out south of the quadrangle in the subsurface of the Moenkopi Plateau (Billingsley and others, 2013). Unit is locally removed from most of the southern Kaibito and Paria Plateaus by Cenozoic erosion. The Carmel Formation gradually thickens west and northwest of the quadrangle (Doelling and others, 2000; Anderson and others, 2000; Doelling and Willis, 2006).

Paria Plateau area: Includes, in ascending order, the Harris Wash Tongue of the Page Sandstone (Jp), the Judd Hollow Tongue of the Carmel Formation (Jcj), and the Thousand Pockets Tongue of the Page Sandstone, undivided (Jp), as well as the Paria River Member and Winsor Members, undivided (Jcu). Members and tongues of the Carmel Formation are described by Doelling and others (2000) and mapped by Peterson (1973), Peterson and Barnum (1973a,b), Doelling and Davis (1989), and Doelling and Willis (2006) along the northern margins of the quadrangle and northward into Utah. Various tongues of the Page Sandstone as described by Peterson (1988) and Blakey and others (1983, 1996) pinch out or intertongue with other members of the Page Sandstone or Carmel Formation along northern margin of Paria Plateau and Cedar Mountain west and northwest of Glen Canyon Dam. Thickness, 165 to 240 ft (48 to 73 m)

Jcu **Paria River Member and Winsor Member, undivided (Middle Jurassic)**—White, red, and brown, ledge- and cliff-forming, low-angle-crossbedded, thin-bedded, silty sandstone and sandstone in lower part; gray-white, thin-bedded, sandy limestone in upper part. Form white- and red-banded sequence on small mesas and buttes along northern edge of Paria Plateau, Cedar Mountain, and upper reach of Paria River canyon. An unknown thickness of upper part has been removed by modern erosion on the Paria Plateau. Unit thickens northwest of the quadrangle toward the southern end of a shallow seaway in southwestern Utah (Doelling and Willis, 2006). Thickness, 5 to 40 ft (1.5 to 12 m)

Jcj **Judd Hollow Tongue and Page Sandstone Tongues, undivided (Middle Jurassic)**—Red-brown and yellowish-white, slope- and cliff-forming, thin, interbedded siltstone, crossbedded sandstone, and silty limestone sequence on Paria Plateau, northwestern edge of quadrangle. Thickens north and northwest of Paria Plateau; thins or pinches out rapidly east and south. Sequence includes the Harris Wash Tongue of the Page Sandstone (lower part), the Judd Hollow Tongue of the Carmel Formation (middle part), and the Thousand Pockets Tongue of the Page Sandstone (upper part) collectively mapped as one unit (Jcj). Sequence undergoes west to east facies and thickness changes from Paria Plateau to Glen Canyon Dam and intertongues with the Page Sandstone (Jp).

Harris Wash Tongue: Yellowish-white, cliff-forming, fine- to medium-grained, crossbedded sandstone. Unconformably overlies similar-appearing Navajo Sandstone.

Judd Hollow Tongue: Dark-brown, slope-forming sandstone and siltstone. Identifiable where red siltstone and sandstone beds intertongue with white sandstone of the Page Sandstone on small buttes and mesas near the Paria River.

Thousand Pockets Tongue: Yellow, white, or brown, massive, cliff-forming, crossbedded sandstone with thin, red siltstone partings. Unconformably overlies Judd Hollow Tongue of Carmel Formation. Forms a thick sandstone bed over the Judd Hollow Tongue where the Judd Hollow is present; pinches out eastward into Page Sandstone southwest of Glen Canyon Dam.

Overall thickness, 10 to 40 ft (3 to 12 m)

Jp **Page Sandstone (Middle Jurassic)**—Kaibito Plateau: Light orange-red, cliff-forming, crossbedded, fine- to medium-grained sandstone, locally with thin, dark-red, basal siltstone that unconformably overlies similar-appearing Navajo Sandstone east, south, and southwest of Glen Canyon Dam. Basal unconformity locally contains angular fragments of white chert at the J-2 unconformity, representing a period of erosion (Pipiringos and O'Sullivan, 1978; Peterson and Pipiringos, 1979). Weathers slightly darker orange than the Navajo Sandstone on the Kaibito Plateau and is locally absent or difficult to identify along southern margins of the quadrangle beneath red siltstone and sandstone of the Carmel Formation (Jc).

Paria Plateau: Light-orange-red, cliff-forming, crossbedded, fine- to medium-grained sandstone interbedded with dark-red, thin-bedded silty sandstone. Includes three undifferentiated crossbedded sandstone tongues, in ascending order: the Harris Wash, Thousand Pockets, and Leche-e, as described by Peterson and Pipiringos (1979) and Blakey and others (1983, 1996), and the Judd Hollow Tongue of the Carmel Formation (between the Harris Wash and Thousand Pockets Tongues) as mapped by Doelling and Willis (2006). The Page Sandstone and Carmel Formation intertongue and grade into marine rocks northwest of Paria Plateau. See Peterson and Pipiringos (1979), Doelling and others (2000), and Doelling and Willis (2006) for detailed descriptions, intertonguing relations, and facies relations for the Page

Sandstone and Carmel Formation along northern margin of Paria Plateau and north of the quadrangle. The Page Sandstone is present in the upper reaches of Paria Canyon as light-purple-red sandstone but is included as uppermost part of Navajo Sandstone in this quadrangle due to difficulties of access and uncertainties of contact with the Navajo. Thickness, 0 to 300 ft (0 to 92 m)

**Glen Canyon Group** (**Lower Jurassic**)—The Glen Canyon Group includes, in ascending order, the Moenave Formation and Wingate Sandstone, undivided (Jm); the Springdale Sandstone Member of the Kayenta Formation (Jks); the Kayenta Formation, undivided (Jk); and the Navajo Sandstone (Jn). The red siltstone and sandstone of the Lower Jurassic Moenave Formation and Wingate Sandstone, undivided, unconformably (Tr-5; Lucas and Tanner, 2006) overlies the purple and white mudstone, sandstone, and gray limestone of the Upper Triassic Owl Rock Member of the Chinle Formation (Ꞧco) primarily on the basis of differences in lithology, topography, vertebrate fossils, and color.

The Rock Point Member of the Jurassic Wingate Sandstone, as mapped by Cooley and others (1969), is included within the Moenave Formation and Wingate Sandstone, undivided. The Moenave Formation and Wingate Sandstone are lithologically and stratigraphically equivalent in the Lees Ferry area. Facies changes and thinning of the Wingate Sandstone from the Four Corners area westward along the Arizona/Utah boundary is attributed to intertonguing within the upper part of the Moenave Formation at Lees Ferry.

In the northern quarter of the quadrangle, the upper boundary of the Glen Canyon Group is marked by the J-2 unconformity between the Navajo Sandstone and Page Sandstone, or the Navajo Sandstone and Carmel Formation where the Page Sandstone is missing (Doelling and others, 2000; Doelling and Willis, 2006**;** and this report). At the southern edge of the quadrangle, where the Page Sandstone is not present, the J-2 unconformity is between the Navajo Sandstone (Jn) and Carmel Formation (Jc) and is easily recognized by color and lithology differences

Jn **Navajo Sandstone (Lower Jurassic)**—Red, white, and light-reddish-brown, cliff-forming, high-angle-crossbedded, fine- to medium-grained, well-sorted sandstone. Includes scattered horizontal thin siliceous limestone and dolomite lenses at various levels between crossbed sets throughout the unit. The sand grains consist of rounded to subrounded, frosted quartz grains, cemented by calcite with some secondary silica and iron oxide. Displays elaborate array of high-angle-crossbed sets as much as 35 ft (11 m) thick. Flat, interbedded, gray- to light-purple, siliceous limestone, dolomite, or dark-red sandy siliceous mudstone form resistant ledges as flat-topped ridges or small mesas on Kaibito Plateau. The limestone and dolomite beds formed in playas or ponds between dunes and are somewhat more abundant southward on the Kaibito Plateau and south of the quadrangle. Sandstone beds contain numerous small, rounded, black and reddish-black, pea-size hematite concretions on the Kaibito Plateau and larger, avocado-shaped, iron-oxide concretions, as much as 3 in (7.5 cm) in diameter on the Paria Plateau. Crossbed dip directions in the map area indicate paleowinds were generally from the northwest (Peterson, 1988). Gradational contact with underlying Kayenta Formation (Jk) is marked at the lowest white or light-red massive sandstone cliff. Unit thins east and southeast of the quadrangle and thickens north and northwest. Modern erosion of the sandstone provides a rich source of loose sand for eolian transport over much of the Paria and Kaibito Plateaus. Thickness, 1,200 to 1,750 ft (366 to 534 m)

Jk **Kayenta Formation, undivided (Lower Jurassic)**—Upper slope- and ledge-forming unit: Light-red, dark-orange, light-purple, and gray, flat-bedded, moderately sorted, subrounded to subangular, fine- to medium-grained, crossbedded sandstone and fine-grained, flat-bedded mudstone, siltstone, and silty sandstone is about 240 to 300 ft (73 to 91 m) thick along the base of the Vermilion and Echo Cliffs to Lees Ferry; about 280 ft (86 m) is exposed in Navajo Canyon in northeastern quarter of quadrangle. Ripple laminations, current ripples, and small-scale trough crossbeds indicate that depositing streams flowed toward the northwest. Upper slope-forming unit undergoes a northward facies change from mostly slope forming siltstone, mudstone, and sandstone to cliff-forming, red sandstone and minor siltstone from the southern part of Echo Cliffs and Vermilion Cliffs to Lees Ferry, southwest half of quadrangle. Unit commonly covered by landslide (Ql) and talus and rock-fall (Qtr) deposits caused by the erosion of the upper Kayenta Formation undercutting overlying cliffs of Navajo Sandstone, allowing large blocks of both Navajo Sandstone and upper Kayenta Formation to fail as landslide masses, especially where joints and fractures are nearly parallel to Echo and Vermilion Cliffs. Gradational contact with underlying cliff-forming Springdale Sandstone Member (Jks). Thickness, 180 to 225 ft (55 to 68 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 crossbedding interbedded with fluvial conglomeratic sandstone lenses containing dark-red mudstone, siltstone rip-up clasts, and poorly preserved petrified plant remains north of quadrangle in Utah (Biek and others, 2000). Crossbeds are separated by thin-bedded to laminated, dark-red siltstone and mudstone that locally contain mudstone pellets. Deposited in braided streams and minor floodplains of northward-flowing streams (Biek and others, 2007).

The Springdale Sandstone was originally described as an 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; Biek and others, 2007; Tanner and Lucas, 2007). This unconformity is the sub-Kayenta unconformity (J-sub-K) as defined by Riggs and Blakey (1993) and Blakey (1994). Erosional relief is generally less than 6 ft (2 m) along the Vermilion and Echo Cliffs but as much as 50 ft (15 m) near Lees Ferry (Nation, 1990). Light-red, fine-grained, crossbedded sandstone at the top of the Springdale Sandstone Member may represent the southern extent of the Wingate Sandstone (not mapped separately). The Early Jurassic age is documented by Peterson and Pipiringos (1979). Unconformable contact with underlying Moenave Formation is known as the J-sub-K unconformity (Blakey, 1994). Thickness, 90 to 220 ft (27 to 67 m)

Jm **Moenave Formation and Wingate Sandstone, undivided (Lower Jurassic)**—Reddish-brown slopes and ledges of thin-bedded, flat-bedded, and crossbedded, fine- to coarse-grained fluvial siltstone and silty sandstone. Includes the Dinosaur Canyon Member of the Moenave Formation as redefined by Blakey (1994), Marzolf (1991), Lucas and Tanner (2006), Tanner and Lucas (2007), and Biek and others (2007). The age of unit was documented by Peterson and Pipiringos (1979). The unconformable contact with the underlying Owl Rock Member of the Chinle Formation is 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, fine- to coarse-grained sandstone of Moenave Formation. Commonly covered by landslide (Ql) or talus and rock-fall (Qtr) deposits and minor eolian sand deposits along the base of the Echo and Vermilion Cliffs to Lees Ferry. Thickness, 80 to 140 ft (25 to 43 m)

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

Ƭco **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 small, resistant benches or ledges along base of Echo and Vermilion Cliffs. Number of limestone beds within unit averages three to four. Contains abundant mud pellets, silicified clay, and concretionary chert nodules. Gradually thins northward from south-central edge of quadrangle along Echo Cliffs to Lee Ferry; thins slightly from Lees Ferry west along base of Vermilion Cliffs; gradually thickens southeast of quadrangle. Gradational contact with underlying Petrified Forest Member placed at lowest laterally continuous nodular limestone bed. Thickness, 100 to 200 ft (30 to 60 m)

Ƭcp **Petrified Forest Member (Upper Triassic)**—Purple, blue, light-red, greenish-gray, and grayish-blue, slope-forming mudstone and siltstone. Includes interbedded white to yellowish-white, coarse-grained, lenticular, low-angle trough crossbeds of siltstone and sandstone in lower part. Petrified logs and wood fragments common in lower part may be within upper part of Shinarump Member. Gradational contact with underlying Shinarump Member approximately marked at change from slope-forming multicolored mudstones of Petrified Forest Member to brown, yellowish-white cliffs and purple slopes of coarse-grained conglomeratic sandstone of Shinarump Member. Weathers into rounded hills or slopes with a rough, puffy, popcorn surface due to swelling of clay when wet. Sandstones are uranium- and copper-bearing in some places and contain traces of gold and mercury in others (Bush, 1983). Thickness, 400 to 500 ft (122 to 153 m)

Ƭcs **Shinarump Member (Upper Triassic)**—Brown and (or) tan, cliff- and slope-forming, coarse-grained, low-angle-crossbedded sandstone and conglomeratic sandstone. Includes interbedded slope-forming, poorly sorted, purple, light-red, and blue siltstone and mudstone lenses. Lithology is highly variable locally but regionally homogeneous consisting of about 75% sandstone, 20% conglomerate, and 5% mudstone. Pebbles are well rounded, brown to black, siliceous composition and light-colored, well-rounded quartz. Petrified logs and wood fragments are common and scattered throughout unit. Unconformable contact with underlying red siltstone and sandstone of Moenkopi Formation is known as the Tr-3 unconformity by Pipiringos and O'Sullivan (1978) and as the Tr-3 unconformity by Blakey (1994). Unit is thickest just northeast of Cliff Dwellers Lodge at base of Vermilion Cliffs. Thickness, 60 to 200 ft (18 to 60 m)

**Moenkopi Formation (Middle(?) and Lower Triassic)**—Includes, in descending order, the upper red member (Ƭmu), the Shnabkaib Member (Ƭms), and the lower red member, Virgin Limestone Member, and middle red member, undivided (Ƭmlm) as defined by Stewart and others (1972). The basal Timpoweap Member of the Moenkopi

Formation is present in some areas but too thin and limited in extent to show as a separate unit. Where present, it is included within the lower red member.

The Moenkopi Formation forms a continuous outcrop along and near U.S. Highway 89A at base of Vermilion and Echo Cliffs to Lees Ferry. Unit is mostly eroded from House Rock Valley and Marble Plateau and partly covered by large landslides, talus and rock fall, and other surficial deposits. Overall thickness before Cenozoic erosion, about 500 ft (152 m) or more

Ŧmu **Upper red member (Middle(?) and Lower Triassic)**—Reddish-brown and dark-red alternating sequence of slope- and ledge-forming claystone, siltstone, and sandstone. Thin, laminated mudstone and siltstone beds fill minor channels between thin to thick massive sandstone beds (1 to 10 ft [0.3 to 3 m]) thick. Sandstone beds include large- to medium-scale trough crossbedding, abundant cusp-type ripple marks, interbedded thin limestone beds, and lenses of conglomeratic sandstone, chert nodules, and thin veins of gypsum. Gradational contact with underlying Shnabkaib Member. Unit undergoes rapid facies change southward along Echo Cliffs from red siltstone-sandstone near Lees Ferry to mostly tan and gray-white sandstone at south edge of quadrangle. Includes white-gray, coarse-grained, calcareous sandstone and red siltstone channel lenses similar in lithology and appearance to underlying sandstone and siltstone beds of Shnabkaib Member of the Chinle Formation. Unit is totally removed by Triassic stream-channel erosion at several locations along base of Echo and Vermillion Cliffs to Lees Ferry where channels are instead filled with conglomeratic sandstone of Shinarump Member of the Chinle Formation. Thickness, 0 to 120 ft (0 to 37 m)

Ŧms **Shnabkaib Member (Lower Triassic)**—Yellowish-white and light-brown, cliff-forming, crossbedded, fine-grained, calcareous and gypsiferous siltstone and dolomite and coarse-grained sandstone. Forms prominent white slope or ledge at south end of Vermilion Cliffs near U.S. Highway 89A south of Cliff Dwellers Lodge and yellow-brown calcareous sandstone ledges or cliff east of U.S. Highway 89A and 89 along Echo Cliffs to south edge of quadrangle. Shnabkaib Member thins and undergoes a northward facies change to yellow-brown and light-red calcareous sandstone ledges that weather dark red and black. The Shnabkaib Member is locally removed by Middle(?) Triassic channel erosion in several areas below Echo and Vermilion Cliffs to Lees Ferry. Channels are filled with conglomeratic sandstone of Shinarump Member of the Chinle Formation. Unit gradually thickens south of quadrangle (Billingsley and others, 2013) and northwest of quadrangle (Billingsley and others, 2008). Gradational contact with underlying lower red member, Virgin Limestone Member, and middle red member, undivided (Ŧmlm) marked at base of lowest tan or light-red sandstone cliff. Thickness, 0 to 100 ft (0 to 30 m)

Ŧmlm **Lower red member, Virgin Limestone Member, and middle red member, undivided (Lower Triassic)**—Red and red-brown, slope-forming, thin-bedded, mudstone, siltstone, and sandstone. Bedding surfaces often contain small-scale ripple marks, salt crystal casts, mudcracks, and rain-drop impressions. Lower and middle red members are separated by thin discontinuous bed of yellowish-white, thin, platy, silty limestone and siltstone of the Virgin Limestone Member less than 2 ft (0.6 m) thick and about 15 to 20 ft (4.5 to 6 m) above Harrisburg Member of the Kaibab Formation (Pkh). Virgin Limestone pinches out along southern edge of quadrangle and is not present in the Lees Ferry area. Where the Virgin Limestone is absent, that horizon is marked by color change from light-red siltstone and sandstone of lower red member to a darker red siltstone and sandstone of middle red member. Unit includes basal Timpoweap Member of the Moenkopi Formation composed of subangular to subrounded, small, white, angular chert pebbles and fragments and limestone clasts in calcareous sandstone matrix derived from underlying Harrisburg Member in House Rock Valley and on Marble Plateau, western half of quadrangle. Unconformable erosional contact with underlying Harrisburg Member of the Kaibab Formation in the western half of quadrangle represents regional Permian/Triassic boundary. Thickness, 375 to 400 ft (114 to 122 m)

**Kaibab Formation (Cisuralian)**—Includes, in descending order, the Harrisburg Member (Pkh) and Fossil Mountain Member (Pkf) as defined by Sorauf and Billingsley (1991). Please note that lower Permian is now referred to as Cisuralian

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 south edge of quadrangle includes white, low-angle-crossbedded calcareous sandstone with fossil mollusks; elsewhere, upper part is primarily sandy, cherty limestone beds separated by gray calcareous and gypsiferous siltstone. Forms surface of Marble Plateau and House Rock Valley, southwest part of quadrangle. Contact with underlying Fossil Mountain Member is gradational and marked at topographic break between grayish-white, slope- and ledge-forming sandy limestone, sandstone, and siltstone sequence of Harrisburg Member and underlying gray to light-brown, cliff-forming, thick-bedded cherty limestone and sandy limestone of Fossil Mountain Member. Unit gradually thins west to east across quadrangle and undergoes a shoreward facies change from marine cliff- and slope-forming limestone and siltstone in west half of quadrangle to mostly sandy, cliff-forming calcareous marine sandstone east of Colorado River and Marble Plateau. Thickness, 80 to 120 ft (25 to 37 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, sandy limestone and dolomite. Weathers dark gray; cliffs often stained by black magnesium oxide. Includes abundant gray and white chert nodules and white breccia chert beds. Chert makes up about 25% to 30% of Fossil Mountain Member. Some chert nodules exhibit concentric black and white bands or contain fossil sponges. White, cliff-forming, brecciated chert beds, 4 to 10 ft (1 to 3 m) thick in uppermost part, help establish visible contact between Harrisburg and Fossil Mountain members. Unit gradually thins and undergoes a shoreward (eastward) facies change from limestone, dolomite, and sandy limestone to calcareous sandstone and sandy limestone with similar surface texture, composition, and appearance to overlying Harrisburg Member. Unit commonly forms cliff below slopes and ledges of Harrisburg Member along rim of Marble Canyon. Unconformable contact with underlying Toroweap Formation attributed in part to dissolution of gypsiferous siltstone in upper Toroweap but mostly caused by channel erosion; average erosional relief about 10 ft (3 m). Unit gradually thins east and southeast in subsurface of map area, becoming indistinguishable from overlying Harrisburg Member. Thickness, 160 to 230 ft (48 to 70 m)

Pt **Toroweap Formation, undivided (Cisuralian)**—Includes, in descending order, the Woods Ranch, Brady Canyon, and Seligman Members as defined by Sorauf and Billingsley (1991). All three members are present in tributary canyons on western side of Marble Canyon. All three members undergo a rapid shoreward (eastward) facies change from cliff and slope west of Colorado River to all cliffs 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 quadrangle. Thickness, 180 to 220 ft (65 to 67 m).

Woods Ranch Member, west side of Marble Canyon: 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 cliff results in numerous landslides and large open cracks near canyon rims that trend along pre-existing joint and fracture systems. 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 Member and cliff-forming limestone of Brady Canyon Member in western two-thirds of Marble Canyon.

Woods Ranch Member, east side of Marble Canyon: Brown, cliff-forming, thin-bedded calcareous sandstone and dolomite. Woods Ranch Member undergoes shoreward (eastward) facies change to cliff-forming sequence that weathers dark brown. Contact with underlying Brady Canyon Member becomes indistinguishable in eastern third of Marble Canyon and subsurface of Marble Plateau. Thickness, 140 to 200 ft (43 to 60 m).

Brady Canyon Member: Yellowish-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 dolomitic sandy limestone in western half of Marble Canyon area. Becomes sandy dolomite and sandy limestone cliff in eastern half of Marble Canyon area. Weathers light to dark 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 half of Marble Canyon area, becomes indistinguishable from other Toroweap Members east of Marble Canyon. Thickness, 10 to 30 ft (3 to 9 m).

Seligman Member: Gray, light-purple, and yellowish-red, slope-forming, thin-bedded dolomite, sandstone, some gypsum, and calcareous sandstone. Forms slope or recesses between overlying Brady Canyon Member and underlying Coconino Sandstone in western two-thirds of Marble Canyon. Undergoes easterly shoreward facies change similar to Brady Canyon and Woods Ranch Members. Sharp unconformable contact with underlying white to tan, cliff-forming Coconino Sandstone. Coconino Sandstone intertongues with lower part of Seligman Member west and north of quadrangle (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; Billingsley and Wellmeyer, 2003; Billingsley and others, 2000). Gradual shoreward (eastward) facies change of all three members makes them indistinguishable from one another east of the Colorado River. Thickness, 10 to 20 ft (3 to 6 m)

Pc **Coconino Sandstone (Cisuralian)**—Tan to white, cliff-forming, fine-grained, well-sorted, high-angle-crossbedded quartz sandstone. Large-scale, high-angle-planar crossbeds 6 to 15 ft (3 to 4.5 m) thick. Locally includes large and small amphibian trackways and low-relief wind ripple marks on planar surfaces. Unconformable planar erosional contact with underlying Hermit Formation (Ph) with relief generally less than 3 ft (1 m) but locally as much as 8 ft (2.5 m). Contact is marked by distinct color and topographic change between overlying white, cliff-forming Coconino Sandstone and underlying dark-red, slope-forming Hermit Formation. Unit is exposed only in walls of Marble Canyon; gradually thickens east and southeast of quadrangle and thins rapidly north and west of quadrangle. Thickness, 30 to 400 ft (9 to 122 m)

Ph **Hermit Formation (Cisuralian)**—Red, slope-forming, fine-grained, thin- to medium-bedded siltstone and sandstone. Siltstone beds throughout unit are dark red and crumbly and fill widespread shallow erosional channels that form recesses between thicker sandstone beds. Ledges of siltstone and sandstone immediately below contact with Coconino Sandstone (Pc) are often bleached yellowish white by groundwater seepage from Coconino Sandstone. Weathers to dark-red slope. Unconformably overlies Esplanade Sandstone (Pe) with erosional relief generally less than 10 ft (3 m). Hermit Formation thins southeast of quadrangle and may extend into subsurface of eastern quarter of quadrangle; thickens north and west of quadrangle. Thickness, 520 to 640 ft (158 to 195 m)

**Supai Group (Cisuralian, Pennsylvanian, Upper Mississippian)—**Includes, in descending order, the Esplanade Sandstone (Pe) and Wescogame, Manakacha, and Watahomigi formations, undivided (ⅡPms) as defined by McKee (1982). Overall thickness of Supai Group, 825 ft (252 m)

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 sets. Unconformable contact with underlying Pennsylvanian and Upper Mississippian rocks (ⅡPMs) marked by erosion channels as much as 15 ft (4.5 m) deep filled with conglomerate that is well displayed in Marble Canyon. Thickness, 350 to 400 ft (107 to 122 m)

ⅡPMs **Wescogame (Upper Pennsylvanian), Manakacha (Middle Pennsylvanian), and Watahomigi (Lower Pennsylvanian and Upper Mississippian) 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 between them are shallow and difficult to find.

Wescogame Formation (Upper Pennsylvanian): Light-red, pale-yellow, and light-gray upper slope unit and lower cliff unit. Upper slope unit consists mainly of dark-red, fine-grained siltstone and mudstone interbedded with light-red, coarse-grained, calcareous sandstone, dolomitic sandstone, siltstone, mudstone, and conglomerate. Lower cliff unit consists mainly of light-red to gray, high-angle, large- and medium-scale, tabular- to planar-crossbedded sandstone and calcareous sandstone as much as 20 ft (6 m) thick. Unconformable contact with underlying Manakacha Formation marked by erosion channels 3 ft (1 m) deep in Marble Canyon. Channels commonly filled with limestone/chert conglomerate. Thickness, 110 to 130 ft (34 to 40 m).

Manakacha Formation (Middle Pennsylvanian): 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 southwest of map area forming numerous ledge-forming, thin- to medium-bedded limestone beds. Lower cliff is dominated by reddish-gray, medium- to thick-bedded, crossbedded, calcareous sandstone and sandy limestone. Carbonate content increases west of quadrangle forming numerous gray limestone ledges (McKee, 1982). Unconformable contact between Manakacha Formation and underlying Watahomigi Formation marked at base of lower red sandstone cliff of Manakacha; erosional relief generally less than 3 ft (1 m). Thickness, 175 ft (53 m).

Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian): Gray and purple, slope-forming limestone, siltstone, mudstone, and some conglomerate. Lower limestone beds contain red chert lenses and nodules. Includes alternating gray, thin-bedded cherty limestone ledges interbedded with purplish-gray siltstone and mudstone in upper part. 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 limestone beds west of quadrangle indicate Upper Mississippian age (Martin and Barrick, 1999). Includes purple siltstone and gray limestone interbedded with reddish conglomeratic sandstone that fill small erosion channels cut into underlying Surprise Canyon Formation (Ms) or into Redwall Limestone (Mr). Supai Group gradually thins eastward and gradually thickens west of quadrangle. Thickness, 100 to 120 ft (30 to 37 m). Overall thickness of Supai Group, 825 ft (252 m)

Ms **Surprise Canyon Formation (Upper Mississippian)**—Dark-reddish-brown, massive to thin-bedded, poorly sorted siltstone, sandstone, thin-bedded gray limestone, and dolomite, and a basal conglomerate containing gray and white, subrounded chert clasts derived from Redwall Limestone in dark-red or black sandstone matrix. Unit is limited to deposits within paleovalleys 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 quadrangle. Sandstone and siltstone beds contain plant and bone fossils, mudcracks, and ripple marks. Thickness, 0 to 40 ft (0 to 12 m)

Mr **Redwall Limestone, undivided (Upper and Lower Mississippian)**—Includes, in descending order, Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members, as defined by McKee (1963) and McKee and Gutschick (1969). Members are not shown at map scale because of sheer cliff topography in Marble Canyon. Unit overall is light- to dark-gray, cliff-forming, thin- to thick-bedded, fine- to coarse-grained, fossiliferous limestone and dolomite. Includes gray and white thin-bedded chert beds, lenses, and nodules. Unit gradually thins eastward and thickens westward in subsurface of quadrangle. Solution-eroded caverns and caves along joint and fracture systems make it an important groundwater transporting aquifer. Thickness, 500 to 550 ft (152 to 167 m).

Horseshoe Mesa Member: Light-olive-gray, ledge- and cliff-forming, thin-bedded, fine-grained limestone. Includes distinctive ripple-laminated limestone, oolitic limestone, and some bedded chert lenses. Fossils are locally common. Weathers to receding ledges. Gradational and disconformable contact with underlying massive-bedded limestone of Mooney Falls Member marked by thin-bedded platy limestone beds that form receding ledges near top of Mooney Falls Member cliff. Unit locally absent 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 (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. In Marble Canyon, karst caves in upper part contain red sandstone and siltstone deposits of Surprise Canyon Formation. Disconformable contact with underlying Thunder Springs Member marked by lithology change between massive gray limestone of the Mooney Falls Member and thin-bedded, dark-gray to brown dolomite and white chert beds of Thunder Springs Member. Thickness, 300 ft (75 m).

Thunder Springs Member: Beds of gray, cliff-forming, thin-bedded, fossiliferous limestone and 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. Weathers dark gray with bands of white chert. Locally includes large-scale crossbedding and irregular gently folded beds. Nautiloid (Mollusca: Cephalopoda) fossils are common in upper 10 ft (3 m) of unit. Disconformable planar contact with underlying Whitmore Wash Member distinguished by a distinct lack of chert beds in Whitmore Wash Member. Thickness, 100 ft (30 m).

Whitmore Wash Member: Not exposed in quadrangle but lies beneath the Colorado River at southern edge of quadrangle. Consists of yellowish-gray and brownish-gray, cliff-forming, thick-bedded, fine-grained dolomite. Unit mostly overlies flat ledges of light-gray to greenish-gray, thick-bedded limestone and dolomite of Muav Limestone, or locally overlies reddish-purple mudstone and dark-gray contorted limestone of Temple Butte Formation that fills channels eroded into Muav Limestone in Marble Canyon just south of quadrangle. Unconformable contact with underlying Devonian Temple Butte Formation or Cambrian Muav Limestone marked by low-relief (5 to 10 ft [2 to 3 m]) erosion channels just south of quadrangle along Colorado River. Thickness, 80 ft (25 m)

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