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Geologic Map of the Peach Springs 30′ x 60′ Quadrangle, Mohave and Coconino Counties, Northwestern Arizona

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Pamphlet to accompany
Scientific Investigations Map 2900

View looking north along the Hurricane Fault (westside down) and Diamond Butte (center of photo), Diamond Creek area of western Grand Canyon. Colorado River is flowing south. *(photograph by G.H. Billingsley, 1988)*.

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Introduction

This map is a product of a cooperative project of the U.S. Geological Survey, the U.S. National Park Service, and the Bureau of Land Management to provide geologic map coverage and regional geologic information for visitor services and resource management of Grand Canyon National Park, Lake Mead National Recreation Area, Grand Canyon-Parashant-National Monument, and adjacent lands in northwestern Arizona. This map is a synthesis of previous and new geologic mapping that encompasses the Peach Springs 30´ x 60´ quadrangle, Arizona. The geologic data will support future geologic, biologic, hydrologic, and other science resource studies of this area conducted by the National Park Service, the Hualapai Indian Tribe, the Bureau of Land Management, the State of Arizona, and private organizations.

Preliminary geologic maps of this area were produced by Young (1966), Huntoon and others (1981), Huntoon (1982), and Billingsley and Huntoon (1983). These maps were modified by Wenrich and others (1996; 1997), Billingsley and others (1999), and Billingsley and others (2000b). A geologic map of the Mount Trumbull 30´ x 60´ quadrangle borders the north edge of this map (Billingsley and Wellmeyer, 2003), and a geologic map of the Grand Canyon 30´ x 60´ quadrangle adjoins the northeast corner (Billingsley, 2000).

Debra L. Block, Flagstaff Science Center, U.S. Geological Survey, used ARC/MAP techniques to compile the map in digital format. This is the 5th map in a series of new digital 1:100,000-scale geologic maps for the Grand Canyon region.

The Peach Springs 30´ x 60´ quadrangle encompasses approximately 604 km^2 (1,980 mi^2) within Mohave and Coconino Counties of northwestern Arizona. The quadrangle is bounded by longitudes 113° to 114° W, and latitudes 35°30´ to 36°00´ N. The map area lies within the southwest edge of the Colorado Plateaus Province (herein Colorado Plateau) and includes a small part of the eastern Basin and Range Province in western Arizona. Billingsley and others (1997) locally subdivide the Colorado Plateau into seven physiographic parts within the map area: the Grand Canyon, Shivwits Plateau, Sanup Plateau, Coconino Plateau, Hualapai Plateau, Truxton Valley, and Aubrey Valley (fig. 1). Hualapai Valley of the Basin and Range Province occupies the southwest corner of the map area. The Basin and Range and Colorado Plateau boundary is along the base of the Grand Wash Cliffs, along which the southern part of the Grand Wash Fault is covered.

The boundary between the Shivwits Plateau and Sanup Plateau occupies a narrow platform bench-land formed by the Esplanade Sandstone and Pakoon Limestone between the north rim and inner gorge of the Grand Canyon (fig. 1). The

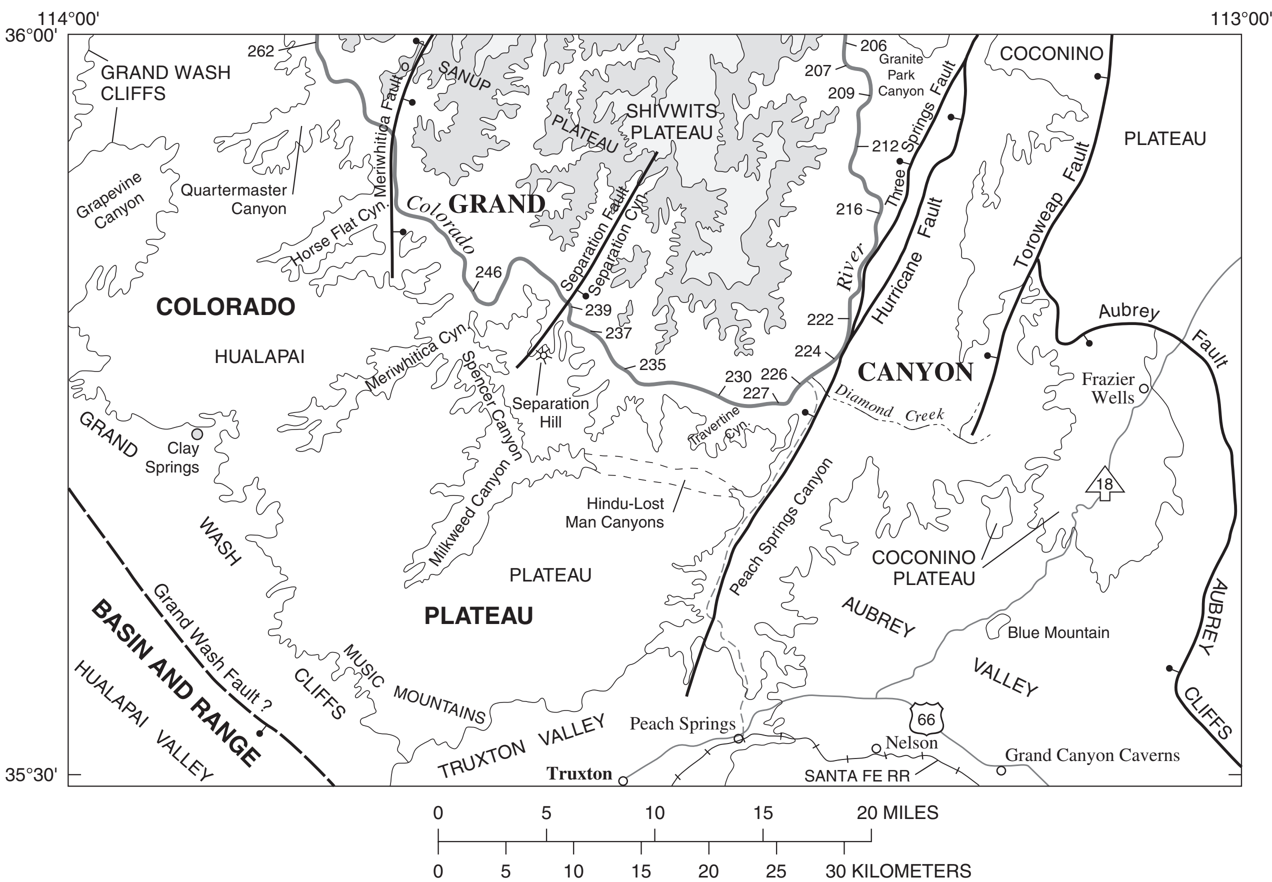

Figure 1. Index map of the Peach Springs 30´ x 60´ quadrangle, Arizona, showing physiogeographical subprovinces and some cultural and structural features. Numbers are Colorado River Miles as measured from Lees Ferry, Arizona.

boundary between the Coconino Plateau and Aubrey Valley east of the Colorado River is arbitrarily marked along the east rim of Grand Canyon down to the top of the Redwall Limestone cliff that forms the south wall of Diamond Creek and the west wall of Peach Springs Canyon about 6.5 km (4 mi) north of Peach Springs, Arizona. Areas southeast of the Redwall Limestone cliff are considered as being in the northwest part of Aubrey Valley. The area from Peach Springs to Truxton, Arizona is part of the Truxton Valley. West and northwest of Truxton Valley are the Music Mountains that form the south boundary of the Hualapai Plateau. The Hualapai Plateau is bounded on the southwest by the top of the Grand Wash Cliffs and on the northeast by the inner gorge of Grand Canyon that is formed by the Redwall Limestone cliff or lower part of the Supai Group.

Elevations within the map area range from about 2,253 m (7,390 ft) on the east rim of Grand Canyon on the Coconino Plateau, northeast quarter of the map area, to 352 m (1,156 ft) at the Colorado River Mile 262 (fig. 1) in the northwest quarter of the map area. Peach Springs, Arizona, is a small settlement within the map area (south-central edge of map) along U.S. Highway 66. Nelson, Arizona, is a limestone quarry mine along the Santa Fe Railroad east of Peach Springs. Grand Canyon Caverns is a small roadside park along U.S. Highway 66 in the southeast corner of the map area. Frazier Wells is an abandoned village along Indian Route 18 on the Coconino Plateau. Public access to the map area is by U.S. Highway 66 along the south edge of the map and Indian Route 18. The Santa Fe Railroad passes through Peach Springs, Arizona, and along part of the south edge of the map area (fig. 1).

A dirt road, locally known as the Diamond Creek Road, leads 33.5 km (21 mi) from Peach Springs down into Peach Springs Canyon and to the Colorado River at the mouth of Diamond Creek (Colorado River Mile 226 as measured from Lees Ferry, Arizona). This road is maintained by the Hualapai Tribe and is the only vehicle access to the Colorado River in Grand Canyon for Colorado River raft trips and hiking. Access to the Colorado River is by permit only from the Hualapai Tribe. Access to the remote areas of Grand Canyon-Parashant National Monument of the Shivwits Plateau north of Grand Canyon is by 4-wheel drive on dirt roads from St. George, Utah, by way of Mount Dellenbaugh, 13 km (8 mi) north of the map area to Kelly Point northwest of Diamond Creek (fig. 1). Visitors must obtain hiking permits and information from the backcountry office at Grand Canyon National Park, Grand Canyon Village, Arizona, to hike into the Grand Canyon-Parashant area north of the Colorado River. Access to the Coconino Plateau and Grand Canyon east of the Colorado River is by jeep trails and dirt roads maintained by the Hualapai Tribe and require a permit from the Hualapai Tribe at Peach Springs, Arizona. Access into the depths of Grand Canyon of this region is rather limited and a go-at-your-own-risk type of hiking with a permit from the Hualapai Tribe. Perhaps the most accessible way of seeing the Grand Canyon is by raft down the Colorado River from Lees Ferry, Arizona, to Diamond Creek. Some river trips begin at Diamond Creek and end at South Cove on Lake Mead northwest of the map area. There are several river companies that schedule trips down the Colorado River; trips vary in length of travel days and costs. Check with the National Park Service Backcountry Office at Grand Canyon for information about Colorado River trips. River trip permits from Diamond Creek to Lake Mead are obtained from the Hualapai Tribe at Peach Springs, Arizona.

Geologic Setting

The Colorado River and its tributaries have dissected the southwestern Colorado Plateau into what is now the southwestern part of Grand Canyon. The erosion of Grand Canyon has exposed about 426 m (1,400 ft) of Proterozoic crystalline metamorphic rocks and granite, about 1,450 m (4,760 ft) of Paleozoic strata, and about 300 m (1,000 ft) of Tertiary sedimentary rocks. Outcrops of Proterozoic crystalline rocks are exposed at the bottom of Grand Canyon at Granite Park from Colorado River Mile 207 to 209, at Mile 212, and in the Lower Granite Gorge from Colorado River Mile 216 to 262, and along the Grand Wash Cliffs in the southwest corner of the map area (Karlstrom and others, 2003; fig. 1).

The majority of the map area is characterized by east and northeast gentle dipping Paleozoic strata that overlie Proterozoic crystalline metamorphic and igneous rocks. The Paleozoic rocks form most of the cliffs and slopes in Grand Canyon and display remarkable east-to-west facies changes and thickness changes. Most of the Pennsylvanian strata and all of the Permian strata were eroded from the Hualapai Plateau, Truxton Valley, and Aubrey Valley areas during Late Cretaceous through Eocene time, when tectonic events caused east-northeast crustal contraction and regional uplift of the southwestern Colorado Plateau margin (Young, 1966; 1985; 1987; 2001). North and northeast flowing drainages from higher terrain southwest of the map area removed some of the Permian strata and almost all the Mesozoic strata from the Coconino and Shivwits Plateaus within the map area. Deep paleocanyons, such as Milkweed, Hindu, Lost Man, and Peach Springs Canyons were developed during this early erosional event by northeast flowing streams and are still preserved on the Hualapai Plateau today. These ancient canyons were later filled with sediment during Paleocene through early Miocene time (Young, 1999). These sediments are preserved as alluvial fan, stream, and intermittent lake deposits at various locations on the Hualapai Plateau, Coconino Plateau, Truxton Valley, and Aubrey Valley.

The 19-Ma Miocene basalt flows and 18.5-Ma Peach Springs Tuff provide a regional time break throughout the Hualapai Plateau area (table 1 on map). These volcanic rocks separate the old gravel and sedimentary (Ts1) deposits (Upper Cretaceous, Paleocene, Eocene, and lower Miocene) from the young gravel and sedimentary (Tg) deposits (upper Miocene to Pliocene). Where the volcanic rocks are not present, the separation between old and young gravel and sedimentary deposits is mapped based on composition and degree of weathering of the sediments. Young (1999) summarizes the nomenclature and distribution of these sediments that are widely distributed in the south and west half of the map area.

Some limestone deposits within the old gravel and sedimentary (Ts1) deposits contain late Paleocene to Eocene fossils at some locations on the Hualapai and Coconino Plateaus. These gravel and sedimentary deposits on the Coconino Plateau are preserved under hard volcanic rocks of the Mount Floyd Volcanic Field about 35 km (22 mi) east of the map area. Modern erosion of these early Tertiary deposits has resulted in an extensive cover of lag gravel (QTg) composed mostly of Proterozoic and some Paleozoic clastic material (Young, 1999). The oldest gravel and sedimentary (Ts2) deposits in the map area are preserved in ancient erosional valleys on the Coconino Plateau east of Diamond Creek. For extensive discussions and details on the nomenclature and distribution of the Tertiary gravel and sedimentary deposits (Ts1, Ts2, Tg, and QTg) see Young (1999).

Other Cenozoic deposits include: (1) Miocene basalt flows on the Shivwits Plateau, (2) the Blue Mountain Basalt (Miocene) in Aubrey Valley, which may be associated with basalt outcrops just west and northwest of Grand Canyon Caverns, Arizona, (3) isolated outcrops of Quaternary basalt flows along the Colorado River, (4) late Quaternary fluvial and eolian deposits on the Hualapai Plateau, in Aubrey Valley, and within some tributary canyons in Grand Canyon, and (5) several late Quaternary large landslide deposits in Grand Canyon.

From late Miocene to the present, the tectonic regime has changed from regional contraction and uplift to east-west regional extension that produced normal faults and erosion that accompanied the development of the southwestern part of Grand Canyon. During the past 6 million years (Young and Brennan, 1974; Lucchitta, 1979), the dramatic topographic relief associated with the Grand Canyon led to the development of localized gravity features such as landslides and gravity-glide detachments (Huntoon, 1974).

The landslide debris masses are large-scale gravity landslide blocks within Grand Canyon that are as much as 2.4 km (1.5 mi) in length and involve over 1,067 m (3,500 ft) of Paleozoic strata above the Cambrian Bright Angel Shale. Most of the landslides are along the Colorado River between Colorado River Mile 206 and 224 where the river generally parallels the Hurricane Fault Zone. Earthquake activity along the active Hurricane Fault may have triggered many of the landslides along this reach of the Colorado River. Only the thickest or most extensive Tertiary and Quaternary deposits are shown on the map to place emphasis on the bedrock geology within the Grand Canyon area.

Structural Geology

Highly complex metamorphic and intrusive granitic structures are present in the Lower Proterozoic rocks along the Colorado River from Mile 207 to 262. The characteristic structures in the Paleozoic rocks in the map area are high-angle to nearly vertical normal fault separations and east-dipping monoclinal folds. Contractional folding and regional uplift of the Paleozoic rocks began in Late Cretaceous and early Tertiary time (about 65 Ma) causing erosion of the Mesozoic and Paleozoic strata that once covered the map area (Huntoon, 2003). The principle monoclines in the map area, from east to west, include the Aubrey, Toroweap, Hurricane, Meriwhitica, and Horse Flat Monoclines; the monoclines developed over deep-seated reverse faults that displaced strata up-to-the-west during Late Cretaceous to early Tertiary time. Reverse fault motion along the basement faults caused the faults to propagate variable distances upward into the Paleozoic sedimentary rocks that simultaneously folded and formed the monoclines.

The Hurricane Monocline dies out in Peach Springs Canyon near Diamond Creek and the Hurricane Fault also diminishes and dies out just south of the Truxton Valley area. The Three Springs Fault represents the core of an eroded segment of the Hurricane Monocline that parallels the main segment of the Hurricane Monocline (Billingsley and others, 2000b). The Toroweap Monocline consists of two segments, one north of Diamond Creek and the other southwest of Blue Mountain (southeast corner of map area). Surficial Quaternary deposits cover most of the Aubrey Monocline, but folded bedrock that is exposed in some places along the base of the Aubrey Cliffs demonstrates the monocline's presence. The Meriwhitica Monocline has the greatest displacement of Paleozoic rocks of all the monoclines in the map area with up to 457 m (1,500 ft) in Meriwhitica Canyon. The Meriwhitica Monocline on the Hualapai Plateau surface was beveled to a nearly flat surface expression by early Tertiary erosion, but the monocline is well exposed in deeply eroded Meriwhitica and Milkweed Canyons. The Horse Flat Monocline, which parallels the Meriwhitica Monocline, is the westernmost monocline in the map area with low structural relief and low amplitude dipping beds. All monoclines within the map area have generally east-dipping strata that developed in response to a horizontal east-northeast stress regime during Laramide time (Huntoon, 2003).

During the late Miocene, Pliocene, and Pleistocene, east-west extension reactivated the deep-seated faults of the monocline folds, which produced normal down-to-the-west fault separation of rock strata along and near monoclines and reversed the sense of Paleozoic and Mesozoic offset (Huntoon, 2003). The Hurricane Fault offsets Miocene deposits in the upper Diamond Creek area as much as the underlying Paleozoic strata making the Hurricane Fault younger than Miocene age in this area. However, age constraints along the Hurricane Fault north of the map area confirms that faulting in that area began less than 3.6 Ma ago and continues to the present time (Billingsley and Workman, 2000; Billingsley and others, 2001; Billingsley and others, 2002). It is assumed that a late Pliocene age applies to most of the Hurricane Fault in the map area and possibly to other faults in the central and eastern part of the map area. Many of the north-south striking faults in the east half of the map are currently tectonically active because they offset young alluvial deposits along various segments of the faults. Faults in the northwest part of the map may be slightly older in age as they are likely to be connected to the Miocene Grand Wash Fault Zone that separates the Basin and Range from the Colorado Plateau northwest of the map area (Billingsley and Wellmeyer, 2003).

Laramide erosion shaped much of the modern landscape but it is uncertain when the Colorado River and its tributaries became firmly established as an integrated through-flowing stream in Grand Canyon (Young, 1985; 1987; Young and Spamer, 2004). Most certainly the Colorado River was present sometime during the late Miocene or early Pliocene, the last 6 to 10 million years (Lucchitta, 1990) and Grand Canyon erosion has greatly increased the relief since that time. Volcanic dikes 9 Ma in age are present on both sides of the Colorado River in the walls of Grand Canyon and on the Sanup and Hualapai Plateaus about 5 km (3 mi) north of the northwest corner of the map (Colorado River Mile 264; Wenrich and others, 1997). The 9-Ma dikes may indicate that this part of the Grand Canyon, which is about 914 m (3,000 ft) deep, was not cut by the Colorado River below the Esplanade Sandstone-Pakoon Limestone level of the Hualapai and Sanup Plateaus prior to 9 Ma (Billingsley, 2004).

Circular collapse structures, 92 to 300 m (300 to 1,000 ft) in diameter, in the Grand Canyon and on the Hualapai and Sanup Plateaus are the result of collapse-formed breccia pipes originating from the dissolution of the Mississippian Redwall Limestone (Wenrich, 1985). Within the Grand Canyon, breccia pipes are recognized in the Permian and Pennsylvanian rocks as visible columns of brecciated rock often surrounded by a yellowish-white bleached zone and ring fractures. Breccia pipes with exposed breccia are indicated on the map by a red dot, and collapse features that are probable breccia pipes at depth are indicated by a black dot (Billingsley and others, 1999; Billingsley and others, 2000b; Wenrich and others, 1996; 1997).

Acknowledgments

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qs **Stream-channel deposits (Holocene)**—Light-gray to light-brown and reddish-brown, unconsolidated mud, sand, gravel, pebbles and boulders. Subject to flash flood debris flows. Thickness, 0.5 to 3 m (2 to 10 ft)

Qf **Flood-plain deposits (Holocene)**—Light-gray to light-brown mud and fine- to coarse-grained, unconsolidated silt and sand and lenses of pebble to cobble gravel; unconsolidated. Intertongue or overlap valley-fill alluvium (Qv) or young alluvial fan (Qay) deposits in Aubrey Valley. Form relatively flat surfaces; support little vegetation except grass. Subject to occasional flooding or ponding of water. Similar deposits in Hualapai Valley are commonly overlapped by or interbedded with valley-fill (Qv) and young alluvial fan (Qay) deposits too thin to show at map scale. Thickness, 1 to 3.5 m (3 to 12 ft)

Qd **Sand sheet and sand dune deposits (Holocene)**—Aubrey Valley area; tan, fine- to coarse-grained, well-sorted wind-blown quartz sand. Sand is derived from erosion of locally old gravel (QTg) and young gravel and sedimentary (Tg) deposits of upper Aubrey Valley. Sand is transported as stream-channel (Qs) deposits and redistributed as wind-blown sand sheet and sand dune (Qd) deposits along drainages. In Hualapai Valley area; southwesterly wind deposits of sand sheet and dune deposits derived from young alluvial fan (Qay) and stream-channel (Qs) deposits near base of Grand Wash Cliffs. All units support thin to moderate grassy vegetation. Only thickest or largest sand sheet and sand dune deposits shown; smaller sand sheet and sand dune deposits are present in the map area but are too small to show at map scale. Thickness, 0.5 to 6 m (2 to 20 ft)

Qr **Colorado River gravel and silt deposits (Holocene and Pleistocene(?))**—Mud, silt, and fine- to coarse-grained sand and gravel interbedded with poorly sorted, angular to well-rounded pebbles, cobbles, and boulders adjacent to the Colorado River. Include local alluvial debris fans and flows and eolian sand sheet and small dune deposits. Composed of silt, sand, in a gravelly matrix with small sandstone, limestone, chert, basalt, and well-rounded quartzite rocks and volcanic rocks that originate from Utah, Colorado, and New Mexico. Unit is mostly mud and fine-grained sand and silt in backwaters of Lake Mead area (Colorado River Mile 237–262). Include older terrace deposits that overlie basalt flows 3 to 30 m (10 to 100 ft) above post Glen Canyon Dam high-water line of Colorado River, partly consolidated by calcium, mud, and gypsum. Deposits often include landslide and talus debris. Thickness, 3 to 30 m (10 to 100 ft)

Qay **Young alluvial fan deposits (Holocene and Pleistocene(?))**—On Colorado Plateau, composed of brown, red, and gray, slope-forming, unsorted mix of mud, silt, sand, gravel, pebbles, cobbles, and boulders. Clasts are mostly angular but some are rounded where derived locally from young gravel and sedimentary (Tg) deposits and old gravel (QTg) deposits; locally consolidated by calcite and gypsum cement. Southwest of Grand Wash Cliffs, composed of coarse-grained quartz and feldspar sand and gravel mixed with subangular to rounded pebbles and boulders of Proterozoic schist, gneiss, and granite mixed with Paleozoic clasts of limestone and sandstone and Cenozoic clasts of basalt. Include alluvial fan debris flows, sheet wash alluvium, and fluvial valley-fill (Qv) deposits; partly covered by eolian sand sheet and sand dune (Qd) deposits. Subject to extensive sheet wash erosion, minor arroyo erosion, and flash flood debris flow accumulations. Only largest or thickest deposits shown. Thickness, 1 to 30 m (3 to 100 ft). May be as much as 92 m (300 ft) thick or more in Hualapai Valley

Qv **Valley-fill deposits (Holocene and Pleistocene)**—Brown or reddish-gray, slope-forming, unsorted mixture of mud, silt, sand, pebbles, cobbles and boulders. Clasts are angular to rounded and locally consolidated by calcite and gypsum cement. Sandstone, limestone, and chert clasts in gravelly sandy matrix are derived locally from nearby Paleozoic and Cenozoic outcrops. Unit is similar to stream-channel (Qs) deposits but occupy low gradient, low energy drainages. Subject to extensive sheet wash and arroyo erosion and flash flood debris flows. Most extensive and thickest deposits are in Aubrey and Hualapai Valleys and commonly interbedded with local stream-channel (Qs) and sand sheet and sand dune (Qd) deposits. Thickness, about 60 m (200 ft) in Aubrey Valley; about 60 to 92 m (200 to 300 ft) or more in Hualapai Valley

Qt **Travertine deposits (Holocene and Pleistocene)**—Gray, white, tan, massive, porous, cliff-forming freshwater limestone. Include angular clasts of local talus breccia or gravel. Formed by rapid chemical precipitation of calcium carbonate of spring water. Form massive, rounded mounds or thick-layered encrustations on steep slopes or cliffs below active and non-active spring outlets in Grand Canyon. Thickest deposits are in Meriwhitica, Spencer, Travertine, and Quartermaster Canyons and form thick "travertine dams" within these canyons. Thickness, 2 to 60 m (6 to 200 ft)

Ql **Landslide deposits (Holocene and Pleistocene)**—Unconsolidated to partly consolidated masses of unsorted rock debris and blocks of sedimentary strata. Detached sedimentary strata has rotated backward against parent outcrop and slid downward as loose incoherent masses of broken rock and deformed strata, partly surrounded by talus debris (talus not shown). Include local talus debris, rock glacier, and rock-fall debris. Largest landslides are commonly found along either side of Colorado River from Mile 207 to 222, involving as much as 1,067 m (3,500 ft) of vertical Paleozoic strata. Landslide masses are likely associated with earthquake activity along Hurricane and Meriwhitica Faults. Landslide deposits may become unstable in wet climatic conditions. Thickness, 9 to 183 m (30 to 600 ft)

Qao **Old alluvial fan deposits (Holocene(?) and Pleistocene)**—Similar to young alluvial fan (Qay) deposits, partly consolidated and commonly covered by calcrete soil 1 to 2 m (3 to 6 ft) thick. On plateaus, composed mostly of gray to brown, fine-grained sand and silt matrix mixed with subangular to rounded pebbles and boulders of basalt, limestone, sandstone, quartzite, and chert. In Aubrey Valley, composed mainly of gray, coarse-grained sand and gravel matrix containing rounded pebbles and small boulders of limestone, sandstone, quartzite, and chert derived from Aubrey Cliffs and upper Aubrey Valley. Support moderate growth of sagebrush, cactus, grass, pinyon pine and juniper trees on Colorado Plateau and sparse cactus and grass in Aubrey Valley. Thickness, 3 to 30 m (9 to 100 ft) or more

QTg **Old gravel deposits (Pleistocene, Pliocene, and middle Miocene)**—Gray and light-brown silt, sand, gravel, pebbles, and small boulder conglomerate of mixed Paleozoic and Proterozoic lithologies; consolidated to partly consolidated by gypsum and calcite cement. Include calcrete soil deposits in upper 1 to 2 m (3 to 6 ft) of surface on Hualapai Plateau and in Aubrey and Truxton Valleys. Include Coyote Spring Formation of Young (1999). Constituents are reworked from young and old gravel sedimentary (Tg and Ts1) deposits, volcanic units (Tv, Tbmb), and local Paleozoic bedrock outcrops. Clasts are matrix supported and cemented with calcium carbonate as calcrete. Quartzite clasts, eroded from old gravel (QTg) and young gravel and sedimentary (Tg) deposits, form a thin lag gravel cover, too thin to show at map scale, throughout the south and east half of the map area. Unit is present on Coconino Plateau northeast quarter of map area but not mapped because it is difficult to distinguish from old gravel and sedimentary (Ts1) deposits due to lag gravel cover composed of a similar lithology. Unit in

Truxton Valley overlies old gravel and sedimentary (Ts1) deposits and is difficult to distinguish from young gravel and sedimentary (Tg) deposits. Thickness, 20 to 200 ft or more

Tg **Young gravel and sedimentary deposits (Pliocene to upper Miocene)**—Post-volcanic (Tv, Tbmb) deposit of gray and light-brown silt, sand, pebbles, cobbles, and small boulders consisting of either all Proterozoic clasts or mixed Proterozoic and Paleozoic clasts; poorly sorted, partly consolidated to consolidated. Clasts are angular to well rounded in light-red sandy matrix. Poor exposures make it difficult to distinguish from overlying younger deposits of old gravel (QTg) that include some volcanic clasts. Unit may be equivalent, in part, to Paleozoic-clast conglomerate (Tgc) west of and along Grand Wash Cliffs. Weathers to rounded hills. Deposit commonly covered by thin surficial alluvium, lag gravel, or calcrete soil. Thickness, 3 to 80 m (10 to 260 ft)

VOLCANIC ROCKS

Qb **Basalt flows along the Colorado River (Pleistocene)**—Dark-gray alkali-olivine basalt. Consist of at least one flow known as the Black Ledge flow (Hamblin, 1994). Thickness, 3 to 9 m (10 to 30 ft)

Shivwits basalt (upper Miocene)—Informally named by Best and others (1980) for the Shivwits Plateau, northern Mohave County, Arizona. Includes a widespread mass of basaltic flows and associated pyroclastic vents and dikes at Blue Mountain and Price Point on Shivwits Plateau of this map area. Mount Dellenbaugh is the type section for the Shivwits basalt (sec. 2, T. 31 N., R.12 W.), the highest point on Shivwits Plateau (elev. 7,072 ft) that forms a regional landmark 19 km (12 mi) north of the map area. K/Ar ages include 7.06±0.49 Ma and 4.75±0.26 Ma (Best and others, 1980); 6.2±0.30 Ma and 7.64±0.30 Ma (Lucchitta and McKee, 1975); 6.78±0.15 Ma (Reynolds and others, 1986); and 8.2±0.1 Ma (Wenrich and others, 1995)

Tsi **Intrusive rocks**—Gray-black, finely crystalline, alkali-olivine basalt. Approximate map contact. Source for extensive basalt flows and pyroclastic deposits on the southern Shivwits Plateau west of Grand Canyon (average elev. 1,829 m [6,000 ft]). Dikes align about N. 30° W., similar to the 202-Mile dikes north of the map area. Average widths of dikes, about 2 m (6 ft)

Tsb **Basalt flows**—Gray-black, finely crystalline, alkali-olivine basalt. Groundmass contains olivine phenocrysts and plagioclase laths. Consist of one or more thin basalt flows overlying red and white mudstone, siltstone, sandstone, and gypsifereous siltstone beds of the Moenkopi Formation and gray siltstone and limestone of the Kaibab Formation. Form composite volcano of Blue Mountain and Price Point, Shivwits Plateau. Thickness, 2.5 to 122 m (8 to 400 ft)

T227i **227-Mile intrusive (Miocene)**—Informally named by Wenrich and others (1995). Gray alkali-olivine basalt dikes and sills exposed in Watahomigi Formation of the Supai Group, undivided (PMs) about 4 km (2.5 mi) north of Colorado River Mile 227. K/Ar age of sill, 13.5±0.3 Ma (Wenrich and others, 1995). Dike and sill thickness, 1 to 3.5 m (3 to 12 ft)

Blue Mountain Basalt (Miocene)—Forms Blue Mountain in Aubrey Valley (not Blue Mountain on Shivwits Plateau), the type locality (secs. 26 and 35, T. 26 N., R. 9 W.) K/Ar age is 14.63±1.10 Ma (Damon, 1968)

Tbmi **Dikes and necks**—Dark-gray alkali-olivine basalt. Forms two small dikes, plugs, or necks southwest of basalt flow on top of unnamed mesa 6.5 km (4 mi) north of Blue Mountain in Aubrey Valley. Highest elevation dike intrudes upper part of the Hermit Formation (Ph); lowest elevation dike intrudes base of the Esplanade Sandstone (Pe). Dike widths, 0.5 to 3.5 m (2 to 12 ft)

Tbmb **Basalt flows**—Dark-gray alkali-olivine basalt. Include small basalt flow on top of unnamed mesa 6.5 km (4 mi) north of Blue Mountain of Aubrey Valley. Overlies old gravel and sedimentary (Ts1) deposits and young gravel and sedimentary (Tg) deposits. Source for basalt on unnamed mesa is likely from one of two dikes (Tbmi) just southwest of mesa. Blue Mountain Basalt is offset by three small normal faults. Thickness, 76 m (250 ft) at Blue Mountain; 6 m (20 ft) thick on top of unnamed mesa

Volcanic rocks of the Hualapai Plateau, undivided (middle to lower Miocene)

Tv **Andesite flows and basalt flows, undivided**—Volcanic deposits on the Hualapai Plateau are alkali-olivine basalt and andesitic basalt flows, agglomerate, volcanogenic fluvial sediments, and rhyolite ash flows derived from local and distant sources. Deposits include the Separation Hill basalt near the upper reach of south Separation Canyon on the Hualapai Plateau, K/Ar age, 19.0±0.44 Ma (Wenrich and others, 1995); the Peach Springs basalt at the town of Peach Springs, Arizona, K/Ar age 19.9±0.4 Ma (Wenrich and others, 1995); the Peach Springs Tuff, a gray welded rhyolitic ash-flow tuff that occupies Tertiary paleovalleys in Milkweed and Peach Springs Canyons; K/Ar age 18.5±0.2 Ma (Neilson and others, 1990) average thickness, about 9 m (30 ft); the Iron Mountain basalt, northwest corner of map, K/Ar age 17.4±0.9 Ma (Wenrich and others, 1995); and the Grapevine Canyon volcanics at Grapevine Canyon, northwest corner of map, K/Ar age 15.3±0.3 Ma (Wenrich and others, 1995). Variable thickness, 1 to 73 m (3 to 240 ft)

Ti **Dikes, plugs, and necks**—Alkali-olivine basalt and andesitic basalt plugs, necks, or dikes in Milkweed and Horse Flat Canyons and on Hualapai Plateau. Includes dikes associated with unnamed dome near Nelson, Arizona (southeast corner of map area)

Tb **Basalt flow of Nelson**—Alkali-olivine basalt associated with intrusive laccolith or dome at Nelson, Arizona, and an unnamed hill 1.5 km (1 mi) northwest of Grand Canyon Caverns, Arizona

Tc **Pyroclastic deposits**—Red basaltic pyroclastic cinder cone deposits at Grapevine Canyon, northwest corner of map area, west edge of Hualapai Plateau. Overlie Devonian and Mississippian strata on rim and within Grapevine Canyon and overlain by thick alkali-olivine basalt flows (Tv). Pyroclastic deposits and basalt flows within Grapevine Canyon indicate that Grapevine Canyon is older then 15.3 Ma. Include deposits on rim of upper Meriwhitica Canyon west of Meriwhitica Monocline. Thickness, 9 to 60 m (30 to 200 ft)

Tp **Quartz monzonite pluton (Upper Cretaceous)**—Gray-brown, coarsely crystalline plagioclase-hornblende-biotite-bearing pluton about 0.8 km (½ mi) in diameter. K/Ar age 65.5±3.5 Ma. Pluton intrudes Cambrian sedimentary rocks of Grand Wash Cliffs, near Clay Springs, northwestern Hualapai Plateau (Young, 1979). Unconformably overlain by 19-Ma basalt flows (Tv)

SEDIMENTARY ROCKS

Tgc **Paleozoic-clast conglomerate (Miocene)**—Light-gray, brown, ledge- and slope-forming, poorly sorted, poorly bedded alluvial fan debris flows derived from Paleozoic strata in the Grand Wash Cliffs; clasts dominantly limestone and dolomite. Unit thins west and southwest of Grand Wash Cliffs. Thickness, 677 m (2,220 ft)

Ts1 **Old gravel and sedimentary deposits (lower Miocene, Oligocene, Eocene, Paleocene, and Upper Cretaceous)**—Include, undivided, the Music Mountain Formation, West Water Formation, Hindu Fanglomerate, Buck and Doe Conglomerate of Young (1999) on the Hualapai Plateau. Include the Frazier Wells gravel of Koons (1964) on Coconino Plateau and upper Aubrey Valley formally renamed the Music Mountain Formation by Young (1999). Composed of poorly sorted, partly consolidated, matrix-supported pebbles and boulders of well-rounded granite, gneiss, schist, and red and white quartzite, as much as 48 cm (20 in) in diameter. Matrix consists of brown to red, partly unconsolidated, coarsely textured arkosic sandstone and siltstone. Form gravely sediments in early Tertiary paleocanyon drainages eroded into Hualapai Plateau, and form widespread alluvial fan deposits in upper Aubrey Valley and on Coconino Plateau. Form rounded hills and slopes where weathered; produce extensive lag gravel deposits. Quartzite pebbles and cobbles commonly reworked into young gravel and sedimentary (Tg) deposits or old gravel (QTg) deposits on Hualapai and Coconino Plateaus and in Aubrey and Truxton Valleys. Quartzite pebbles, cobbles, and boulders commonly form surface pavement or lag gravel making it difficult to distinguish younger sediments from older sediments

Ts2 **Oldest gravel and sedimentary deposits (Paleocene(?) and Upper Cretaceous)**—Include Robbers Roost gravel of Koons (1948a, b) on Coconino Plateau and upper Aubrey Valley east of Toroweap Fault; composed primarily of sandstone clasts derived from the Coconino Sandstone and limestone and chert clasts derived from the Toroweap and Kaibab Formations as mapped by Billingsley and others (2000b). Unit is well consolidated in cherty, coarse-grained sandy gray matrix cemented by calcium. Clasts are well rounded, well sorted; clast imbrication indicates deposition by north-flowing drainage. Deposit fills ancient drainage valley eroded into Toroweap and Kaibab Formations east of Diamond Creek on Coconino Plateau. Deposit is partly eroded and inset by younger drainage filled with old gravel and sedimentary deposits (Ts1), called Frazier Wells gravel of Koons (1964); renamed Music Mountain Formation by Young (1999). Thickness, 12 to 67 m (40 to 220 ft).

A second and similar deposit occupies a lower elevation north-south paleovalley southeast of Diamond Creek; deposit composed of red-gray silt, sand, gravel, pebbles, and boulders of limestone, sandstone, and chert derived from local Permian outcrops of Esplanade Sandstone, Hermit Formation, Coconino Sandstone, Toroweap Formation, and Kaibab Formation. Unit is well consolidated by calcite and gypsum cement and forms resistant rounded hills or cliffs. Clasts are rounded to angular and include talus debris from local paleovalley walls. Deposit occupies bottom of paleovalley eroded into Hermit Formation; paleovalley is widest at southern extension near Blue Mountain and narrows northward toward Tower of Babylon in upper Diamond Creek. The lower elevation paleovalley is likely younger than the similar Paleozoic higher elevation clastic paleovalley southeast of the Toroweap Fault. Thickness, 60 m (200 ft)

Ʀm **Moenkopi Formation (Lower Triassic)**—Includes only the basal Timpoweap Member (Lower Triassic) as defined by Stewart and others (1972). In general, Moenkopi Formation is mostly eroded from map area except for an isolated outcrop north of Granite Park, northeast edge of map. Unit is likely covered by Shivwits basalt flows on Shivwits Plateau (Billingsley and Wellmeyer, 2003). Timpoweap Member consists of light reddish-gray, cliff-forming conglomerate in lower part and light-gray to light-red, slope-forming calcareous sandstone in upper part. Conglomerate composed of subangular to rounded pebbles and cobbles of gray and dark-gray limestone, white and brown chert, and gray sandstone in matrix of gray to brown, coarse-grained sandstone. Consolidated by calcite and gypsum. All detritus in Timpoweap Member is derived from erosion of the Kaibab Formation. Fills paleovalley about 40 m (130 ft) deep eroded into Kaibab Formation. Imbrication of pebbles in conglomerate shows general northeast flow of depositing stream. Thickness, 0 to 40 m (0 to 130 ft)

Pk **Kaibab Formation, undivided (Lower Permian)**—Includes, in descending order, the Harrisburg and Fossil Mountain Members as defined by Sorauf and Billingsley (1991), undivided.

Harrisburg Member consists of red-gray, yellow-gray, and blue-gray, slope-forming gypsum, gypsiferous siltstone, sandstone, calcareous sandstone; and gray, ledge-forming limestone, sandy limestone; and capped by yellow-gray, thin-bedded, fossiliferous sandy limestone. Includes silicified fossiliferous chert breccia beds near base of unit, particularly along Aubrey and Toroweap Faults. Forms surface bedrock of Coconino Plateau where not covered by Cenozoic deposits. Unit is partly removed by modern erosion along higher terrain of Aubrey Cliffs and Coconino Plateau. Unit is totally removed by Laramide erosion on Shivwits Plateau of map area. Unit is partly covered by old gravel and sedimentary (Ts1) deposits on Coconino Plateau, northeast quarter of map area. Contact with underlying Fossil Mountain Member is gradational and arbitrary contact is marked at top of cherty limestone cliff of Fossil Mountain Member. Harrisburg Member thickens northeast and east of map area, thins southwest and southeast. Unit is beveled and removed by early Tertiary erosion prior to deposition of the Shivwits basalt (Tsb) on Shivwits Plateau of map area. Thickness, 38 to 50 m (125 to 165 ft).

Fossil Mountain Member consists of light-gray, cliff-forming, fine- to medium-grained, thin- to medium-bedded (0.5 to 2 m [1 to 6 ft]), fossiliferous, sandy, cherty limestone. Weathers dark gray. Unit is characterized by numerous gray to white chert nodules and chert lenses in limestone beds; chert weathers dark gray to black. Some chert nodules contain spherical black and white bands. Breccia chert beds (1.5 to 3 m [4 to 10 ft] thick) are common in upper part near contact with overlying Harrisburg Member of the Kaibab Formation. Chert composes about 20 percent of unit and limestone beds become sandier east and southeast of map area. Fossil Mountain Member generally forms upper cliff of the Aubrey Cliffs and upper cliff of Shivwits Plateau. Also forms east rim of the Grand Canyon and Coconino Plateau. Most of Fossil Mountain Member is beveled and removed by early Laramide erosion prior to deposition of the Shivwits basalt (Tsb) on Shivwits Plateau in map area. Unconformable contact with underlying Toroweap Formation characterized by dissolution of gypsum and erosion channels with average relief of about 3 m (10 ft). Thickness, 40 to 107 m (130 to 350 ft)

Pt **Toroweap Formation, undivided (Lower Permian)**—Includes, in descending order, Woods Ranch, Brady Canyon, and Seligman Members as defined by Sorauf and Billingsley (1991).

Woods Ranch Member consists of gray and light-red, slope-forming gypsiferous siltstone, silty sandstone, white laminated gypsum, and gray to dark-gray, thin-bedded, fossiliferous sandy limestone. Gypsum beds are as much as 3 m (10 ft) thick on Coconino Plateau. Unit as a whole weathers red-gray. Bedding locally distorted due to dissolution of gypsum. Contact with underlying Brady Canyon Member is gradational and arbitrarily marked at top of limestone cliff of Brady Canyon Member. Unit thickens north and northwest and thins south and southeast of map area. Variable thickness owing to dissolution of gypsum and channel erosion in upper part; 18 to 30 m (60 to 100 ft) thick.

Brady Canyon Member consists of dark- to light-gray, cliff-forming, thin- to medium-bedded (0.5 to 1.5 m [1 to 5 ft]), fine- to coarse-grained, fetid, fossiliferous limestone; weathers dark gray. Includes thin-bedded dolomite in upper and lower part; average thickness of limestone beds, 0.5 to 1 m (2 to 3 ft). Contains white and gray chert nodules that make up less than 8 percent of unit. Contact with underlying Seligman Member is gradational and arbitrarily placed at base of limestone cliff of Brady Canyon Member. Unit thickens west and northwest, thins southeast and east of map area. Thickness, 76 m (250 ft) at Coconino Plateau area, 110 m (360 ft) at Shivwits Plateau area.

Seligman Member consists of gray, light-purple, and yellow-red, slope-forming, thin-bedded dolomite, sandstone, and gypsum. In Coconino Plateau area, unit is mostly purple, light-red and gray flat-bedded, calcareous sandstone interbedded with gray, thin-bedded limestone. In Shivwits Plateau area, unit is gray to white gypsum and light-red to yellow-red, thin-bedded, calcareous flat-bedded sandstone and thin-bedded gray dolomite. Forms recess between overlying cliff-forming Brady Canyon Member of the Toroweap Formation and underlying cliff-forming Coconino Sandstone. Unit thickens north and northwest, thins east and southeast of map area. Sharp planar and undulate contact with underlying Coconino Sandstone where crossbedded sand dunes of Coconino Sandstone were beveled off and sand was redistributed as planar-bedded sandstone. The Coconino Sandstone (Pc) intertongues within the lower part of the Seligman Member of the Toroweap Formation (Pt) north and west of the map area (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; Billingsley and others, 2000a; Billingsley and Wellmeyer, 2003). Because the name Coconino Sandstone is well established in the Grand Canyon nomenclature and it forms a significant mappable cliff unit within the walls of Grand Canyon, the term Coconino Sandstone is herein maintained as a separate map unit from the Toroweap Formation. The Coconino Sandstone pinches out in the west half of the map area allowing the Toroweap Formation to overlie the Hermit Formation. Thickness, 4.5 to 12 m (15 to 40 ft)

Pc **Coconino Sandstone (Lower Permian)**—Light-brown, yellow-red, and light-red, cliff-forming, fine-grained, well-sorted, cross-stratified quartz sandstone. Forms resistant slope along north margin of Aubrey Valley. Contains large scale, high-angle, planar crossbedded sandstone sets that average about 10.5 m (35 ft) thick. Locally includes poorly preserved fossil tracks and low-relief wind ripple marks on crossbedded planar sandstone surfaces. Lower 1.5 to 6 m (5 to 20 ft) is thin-bedded, partly calcareous, flat-bedded sandstone of Seligman Member of the Toroweap Formation that forms a sharp planar unconformable contact with underlying Hermit Formation with relief generally less than 1 m (3 ft), but locally as much as 2.5 m (8 ft). Unit thins west and southwest and pinches out in central part of map area where Toroweap Formation overlies the Hermit Formation; unit thickens southeast, east and northeast of map area. Thickness, 0 to 52 m (0 to 170 ft)

Ph **Hermit Formation (Lower Permian)**—Red to red-brown, slope-forming, fine-grained, thin-bedded siltstone and sandstone; mostly covered by surficial deposits in Aubrey Cliffs area. Includes red, thick-bedded, massive to low-angle crossbedded, calcareous sandstone beds in upper part below Shivwits Plateau area. Siltstone beds are dark red, crumbly, and fill erosional channels or form widespread flat-bedded units that form recesses between thicker sandstone beds throughout unit. Sandstone beds thicken and thin laterally either as channel fill or low-angle crossbedded sandstone sets. Sandstone beds often bleach to white in or near vicinity of breccia pipes and at upper contact with the Coconino Sandstone (Pc) in east half of map area. Locally contains poorly preserved plant fossils in channel fill siltstone beds eroded into underlying Esplanade Sandstone and Pakoon Limestone, undivided (Pep). Unconformable contact with underlying Esplanade Sandstone and Pakoon Limestone, undivided (Pep) and Esplanade Sandstone (Pe), erosional relief generally less than 3 m (10 ft) deep. West of Hurricane Fault, channels have eroded into light-red, cliff-forming sandstone beds of the Esplanade Sandstone and Pakoon Limestone, undivided. This sandstone cliff overlies 60 m (200 ft) of red, thin-bedded slope-forming siltstone beds that visually resembles strata of the Hermit Formation on Sanup Plateau north of Colorado River. Erosional unconformity is difficult to locate in some areas due to low relief. Unit thickens northwest, north, and northeast; thins east, southeast, and south of map area. Thickness, 30 to 213 m (100 to 700 ft)

Supai Group (Lower Permian, Upper, Middle, and Lower Pennsylvanian, and Upper Mississippian)—Includes, in descending order, Esplanade Sandstone, east of the Hurricane Fault (Lower Permian, Pe); Esplanade Sandstone and Pakoon Limestone, undivided, west of the Hurricane Fault (Lower Permian; Pep); Wescogame Formation (Upper Pennsylvanian), Manakacha Formation (Middle Pennsylvanian), and Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian (ℙMs), undivided as defined by McKee (1975; 1982). Upper Mississippian age for Watahomigi Formation is defined by Martin and Barrick (1999). Pakoon Limestone as defined by McNair (1951)

Pe **Esplanade Sandstone (Lower Permian)**—Consists of an upper cliff and slope, a middle cliff, and lower slope unit.

Upper cliff and slope unit is composed of an upper, light-red or white sandstone cliff and a lower, dark-red siltstone, sandstone and gypsum slope. The lower siltstone and sandstone slope visually resembles strata of overlying Hermit Formation. Erosional unconformity separates Esplanade Sandstone from overlying Hermit Formation as shallow channels eroded into sandstone cliff of upper cliff and slope unit (Pe). Maximum thickness of upper cliff and slope unit, about 67 m (220 ft), thins westward.

Middle cliff unit is composed of light-red, cliff-forming, fine- to medium-grained, low-angle, crossbedded, well-sorted, calcareous sandstone beds 1 to 3 m (3 to 10 ft) thick. Includes a few interbedded gray, thin-bedded sandy limestone units of the Pakoon Limestone in lower half of middle cliff unit that pinch out east and southeast of the Hurricane Fault area, but thicken west and northwest of the Hurricane Fault toward the Shivwits Plateau, northwest corner of map where Esplanade Sandstone (McKee, 1963) and Pakoon Limestone (McNair, 1951) are undivided (Pep). Middle cliff unit averages about 76 m (250 ft) thick at east edge of map area.

Lower slope unit is composed of a basal limestone pebble conglomerate that grades upward into slope-forming, interbedded dark-red siltstone, light-red sandstone, and gray, thin-bedded limestone that fills channels eroded as much as 9 m (30 ft) into underlying Wescogame Formation of the Supai Group, undivided (ℙMs). Forms unconformable contact between Permian and Pennsylvanian strata in northeastern two-thirds of map area. Thickness of lower slope unit, about 24.5 m (80 ft) at east edge of map area, thins northwest and pinches out beneath Shivwits Plateau and northwest corner of map area. Thickness, about 152 m (500 ft)

Pep **Esplanade Sandstone and Pakoon Limestone, undivided (Lower Permian)**—Light-red and red-gray, cliff-forming, fine- to medium-grained, medium-bedded (1 to 3 m [3 to 10 ft]), well-sorted calcareous sandstone; interbedded, dark-red, slope-forming siltstone, and light-gray sandy limestone and limestone. Includes an upper cliff and slope unit, middle cliff unit, and lower slope unit.

Upper cliff and slope unit consists of thin-bedded, slope-forming, sandstone and siltstone about 60 m (200 ft) thick capped by 6 to 12 m (20 to 40 ft) cliff of light-red, thick-bedded, low-angle, crossbedded sandstone; forms upper cliff and lower slope at base of Hermit Formation often mistaken for strata of Hermit Formation on Sanup Plateau; unit gradually thins west and northwest of map area. Thickness, 73 m (240 ft).

Middle cliff unit forms “Esplanade Bench” of Sanup Plateau north of Colorado River, a prominent cliff throughout map area. Consists of light-red to white, fine- to medium-grained, thick-bedded, crossbedded sandstone and calcareous sandstone in upper half, and flat, massive, low-angle crossbedded sandstone and calcareous sandstone in the lower half separated by sandy limestone and limestone beds of intertonguing Pakoon Limestone. Some calcareous sandstone beds have small- to medium-scale, planar, mixed low-angle and high-angle crossbedded sets throughout. Beds of Pakoon Limestone intertongue within sandstone lower half of middle cliff unit; limestone beds increase in thickness toward western half of map area and form nearly half of the Esplanade Sandstone and Pakoon Limestone undivided cliff in western Grand Canyon. Pakoon Limestone beds thin and pinch out eastward near Hurricane Fault vicinity, but some thin limestone beds of the Pakoon Limestone extend into the Aubrey Valley southeast of the map area.

Pakoon Limestone is gray to pinkish-gray, fine-to medium-grained, thin- to medium-bedded limestone, oolitic limestone, and sandy limestone in northwest quarter of map area, becoming increasingly sandy and silty toward southeast and east part of map area. Pakoon Limestone contains numerous Lower Permian marine fossils in western half of map area, which establishes the Lower Permian age for the Esplanade Sandstone (Pe) east and north of map area. Thickness of middle cliff unit, 107 to 137 m (350 to 450 ft).

Lower slope unit is composed of alternating light-red sandstone, dark-red siltstone, dark-red mudstone, and gray thin-bedded limestone. Unconformable contact with underlying Wescogame Formation of Supai Group, undivided (ℙMs) is marked by erosional channels as much as 15 m (50 ft) deep. Most erosion channels average about 10.5 m (35 ft) in depth and often contain limestone pebble conglomerate in light-purple calcareous sandstone matrix. Thickness, 24.5 to 30 m (80 to 100 ft).

Overall, Esplanade Sandstone and Pakoon Limestone, undivided, thickens northwest and north of map area, thins east and southeast. Thickness, 167 to 183 m (550 to 600 ft)

ℙMs **Wescogame Formation (Upper Pennsylvanian), Manakacha Formation (Middle Pennsylvanian), and Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian), undivided**—Supai Group as defined by McKee (1982). Watahomigi Formation is Upper Mississippian and Lower Pennsylvanian age as defined by Martin and Barrick (1999).

Wescogame Formation consists of light-red, pale-yellow, and light-gray upper slope and lower cliff, composed of fine- to coarse-grained gray sandstone, dolomitic sandstone, siltstone, mudstone, and conglomerate. Upper slope is composed mostly of light-red, fine-grained siltstone, mudstone, and interbedded light-red sandstone. Lower cliff is composed mainly of light-red to gray, high-angle, large-and medium-scale, tabular-planar, crossbedded sandstone sets as much as 12 m (40 ft) thick. Includes interbedded dark-red, thin-bedded siltstone in upper part. Unconformable contact with underlying Manakacha Formation marked by erosion channels as much as 24.5 m (80 ft) deep in western part of map area; less than 9 m (30 ft) deep in eastern part. Erosional channels commonly filled with limestone/chert pebble conglomerate. Uniform thickness, 40 m (130 ft).

Manakacha Formation consists of light-red, white, and gray upper slope and lower cliff of sandstone, calcareous sandstone, dark-red siltstone, and gray limestone. Upper slope is composed mainly of shaley siltstone and mudstone with minor amounts of interbedded, thin-bedded limestone and sandstone. Carbonate content in upper slope increases westward to form numerous ledge-forming, thin- and medium-bedded sandy limestone beds. Thickness of upper slope is about 18 m (60 ft). Lower cliff unit is dominantly a crossbedded, calcareous sandstone, dolomite, and sandy limestone, about 30 m (100 ft) thick. Carbonate content increases westward across map area forming numerous gray limestone ledges. Unconformable erosional contact between Manakacha and underlying Watahomigi Formations marked at base of lower sandstone cliff of Manakacha Formation. Erosional relief is generally less than 1 m (3 ft), and is mostly a wavy unconformable surface. Thickness, 55 m (180 ft).

Watahomigi Formation consists of gray and purplish-red, slope-forming limestone, siltstone, mudstone, and conglomerate. Forms an upper ledge and slope unit and lower cliff unit. Upper ledge and slope unit is sequence of alternating gray, thin-bedded cherty limestone ledges and purplish-gray siltstone and mudstone slopes; limestone beds contain Early Pennsylvanian conodont fossils (Martin and Barrick, 1999); red chert lenses and nodules are common in limestone beds. Includes limestone chert pebble conglomerate at base of upper ledge and slope unit that locally contain Pennsylvanian fossils. Upper ledge and slope unit average about 21 m (70 ft) thick. Lower cliff unit consists of a basal, purplish-red mudstone and siltstone overlain by thin-bedded aphanitic to granular limestone cliff with red chert nodules and chert veins. Conodonts in lower thin limestone beds are Late Mississippian (Martin and Barrick, 1999). Include purple siltstone and gray limestone interbedded with conglomerate that fill small erosion channels eroded into either the Surprise Canyon Formation (Ms) or Redwall Limestone (Mr). In majority of map area, purple shale and mudstone of the Watahomigi Formation unconformably overlies gray limestone beds of the Redwall Limestone. Contact with the Surprise Canyon Formation is often based on color change from purple mudstone of the Watahomigi Formation to dark-red mudstone of Surprise Canyon Formation. Unit averages about 30 m (100 ft) thick along east edge of map area thickening to about 60 m (200 ft) along Grand Wash Cliffs

Ms **Surprise Canyon Formation (Upper Mississippian)**—Dark reddish-brown cliff and slope-forming siltstone, sandstone, gray limestone, dolomite, and white conglomerate in dark-red or black sandstone matrix as defined by Billingsley and Beus (1999). Formation is locally absent throughout map area and present only as sediment accumulations in paleovalleys and karst caves eroded into top part of the Redwall Limestone (Mr). The Surprise Canyon Formation is the most fossiliferous rock strata in Grand Canyon. Deepest channel deposits are in northwest quarter of map area (up to 122 m [400 ft] deep), unit gradually thins east and south across map area. Forms an upper slope, middle cliff, and lower slope, undivided.

Upper slope includes red-brown, thin-bedded siltstone, calcareous sandstone, and reddish-gray, thin-bedded sandy limestone. Contains numerous ripple marks and tidal flat to shallow water marine fossils. Thickness, 14 to 23 m (50 to 75 ft). Middle cliff consists of reddish-gray, thin-bedded, coarsely-grained silty/sandy limestone. Contains numerous shallow water marine fossils. Thickness, 14 to 60 m (50 to 200 ft). Lower slope consists of dark red-brown to black, iron-stained, thin-bedded, coarse- to medium-grained fluvial and marine siltstone, sandstone, limestone, and conglomerate. Sandstone and siltstone beds contain numerous plant fossils, bone fossils, mudcracks, ripplemarks, and thin low-angle crossbedded sandstone sets. Conglomerate consists of white and gray chert clasts supported in a coarse-grained chert sandstone or gravel matrix all derived from the Redwall Limestone. Conglomerate beds average about 7.5 m (25 ft) thick. Includes local coal beds about 1 m (3) ft thick in black shale beds, northwest corner of map area. Thickness of lower slope, 23 to 38 m (75 to 125 ft). Overall thickness, 0 to 122 m (0 to 400 ft)

Mr **Redwall Limestone, undivided (Upper and Lower Mississippian)**—Includes, in descending order, the Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members as defined by McKee (1963), and McKee and Gutschick (1969).

Horseshoe Mesa Member consists of light olive-gray, ledge- and cliff-forming, thin-bedded, fine-grained limestone. Weathers to receding ledges. Gradational and disconformable contact with underlying massive-bedded limestone of Mooney Falls Member marked by thin-bedded, platy limestone beds that forms recess about 1 to 3 m (3 to 9 ft) thick at base of member near top of Redwall Limestone cliff. Fossils not common except locally. Include distinctive ripple laminated limestone beds and oolitic limestone and some chert. Member thickens slightly from east to west across map area, locally absent where removed by Late Mississippian paleovalley erosion. Thickness, 14 to 30 m (50 to 100 ft).

Mooney Falls Member consists of light-gray, cliff-forming, fine- to coarse-grained, thick to very thick bedded (1.5 to 6 m [4 to 20 ft]) fossiliferous limestone. Includes dark-gray dolomite beds in lower part; oolitic limestone and chert beds are restricted to the upper part. Contains large-scale, tabular and planar, low-angle cross-stratified limestone beds in upper third of unit in western half of map area. Limestone weathers dark gray, chert beds weather black. Disconformable contact with underlying Thunder Springs Member distinguished mainly by lithology; massive bedded gray limestone of Mooney Falls Member overlies thin-bedded dark-gray to brown dolomite and chert beds of Thunder Springs Member. Unit thickens from about 92 m (300 ft) in southeast corner of map area to about 122 m (400 ft) in northwest corner.

Thunder Springs Member consists of about 50 percent white, cliff-forming, fossiliferous, thin-bedded, alternating bands of white chert, and about 50 percent brownish-gray, thin-bedded (2.4 to 12 cm [1 to 5 in]), finely crystalline dolomite and fine- to coarse-grained limestone. Limestone is most common in northwest half of map area, dolomite more common in southeast half. Weathers into distinctive prominent band of black and light-brown bands on cliff face. Disconformable planar contact with underlying Whitmore Wash Member distinguished by distinct lack of chert in Whitmore Wash Member. Unit increases in thickness from east to west across map area. Thickness, 30 to 46 m (100 to 150 ft).

Whitmore Wash Member consists of yellowish-gray and brownish-gray, cliff-forming, thick-bedded, fine-grained dolomite. Weathers dark gray. Fossiliferous in northwestern quarter of map area. Unit is mostly a limestone west and north of map area. Unconformable contact with underlying Temple Butte Formation marked by erosional channels of low relief, about 1.5 to 3 m (5 to 10 ft) in depth. Contact generally recognized where major cliff of light-gray Redwall Limestone overlies dark-gray stair-step ledges of Temple Butte Formation. Thickness, 24.5 m (80 ft)

Dtb **Temple Butte Formation (Upper and Middle Devonian)**—Purple, reddish-purple, dark-gray, and light-gray, ledge-forming dolomite, sandy dolomite, sandstone, mudstone, and limestone as defined by Beus (2003). Purple, reddish-purple, and light-gray, fine- to coarse-grained, thin- to medium-bedded, ripple-laminated ledges of mudstone, sandstone, dolomite, and conglomerate fills channels eroded into the underlying Cambrian strata as much as 30 m (100 ft). Channel deposits are overlain by dark olive-gray, medium- and thick-bedded dolomite, sandy dolomite, limestone, and sandstone forming a sequence of dark-gray ledges. Unconformity at base of Temple Butte Formation represents major stratigraphic break in Paleozoic rock record in Grand Canyon that includes part of the Late Cambrian, all of the Ordovician and Silurian, and most of the Early and Middle Devonian time, representing about 100 m.y. Dark-gray Devonian strata are distinguished from underlying light-gray Cambrian rocks by color contrast. Unit thickens east to west, thins south. Thickness, 122 to 140 m (400 to 460 ft)

Tonto Group (Middle and Lower(?) Cambrian)—Includes, in descending order, Muav Limestone, Bright Angel Shale, and Tapeats Sandstone as defined by Noble (1922), modified by McKee and Resser (1945); recognized on the basis of distinct lithologies. All limestone and dolomite in the Cambrian sequence belong to the Muav Limestone; shale and siltstone belong to the Bright Angel Shale; and sandstone and conglomerate belong to the Tapeats Sandstone. The Tonto Group strata unconformably overlie Lower Proterozoic (1.7 to 1.6 billion years) igneous and metamorphic rocks; this hiatus is known as the Great Unconformity. See Rose (2003) for a revised age and depositional history of Cambrian rocks in the Grand Canyon

Ꞓm **Muav Limestone (Middle Cambrian)**—Dark-gray, light-gray, brown, and orange-red, cliff-forming limestone, dolomite, and calcareous mudstone. Includes, in descending order, unclassified dolomites, the carbonate units Havasu, Gateway Canyon, Kanab Canyon, Peach Springs, Spencer Canyon, and Rampart Cave Members (McKee and Resser, 1945), and three unnamed, slope-forming siltstone and shale of Bright Angel shale type lithologic units between carbonate members. Carbonate members are fine- to medium-grained, thin- to thick-bedded, mottled, fossiliferous, silty limestone, limestone, and dolomite. Unnamed shale and siltstone units are green and purplish-red, micaceous siltstone, mudstone, shale, and thin brown sandstone beds. Contact with underlying Bright Angel Shale is gradational and lithology dependent and marked at base of lowest prominent cliff-forming limestone, the Rampart Cave Member. Muav Limestone Members thicken from east to west across the map area, but the Spencer Canyon and Rampart Cave Members change facies to a purple-red and green siltstone/shale of Bright Angel Shale lithology in northeast half of map area where they are included as part of Bright Angel Shale. Intertonguing and facies change relations between Muav Limestone and Bright Angel Shale produce variable thickness trends. Thickness, 365 to 427 m (1,200 to 1,400 ft)

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purple-red, slope-forming siltstone, shale, and red-brown to brown sandstone. Includes the ledge-forming red-brown sandstone member of McKee and Resser (1945). Consists of green and purple-red, fine-grained, micaceous, ripple-laminated, fossiliferous shale and siltstone; dark-green, medium- to coarse-grained, thin-bedded, glauconitic sandstone; and interbedded purplish-red and brown, thin-bedded, fine- to coarse-grained, ripple laminated sandstone. Includes gray, thin-bedded, fine-grained, micaceous silty dolomite in the upper part of west quarter of map area. Intertonguing and facies change relations produce variable thickness trends. Contact with Tapeats Sandstone is arbitrarily marked at top of vertical transition zone from dominantly green shale and siltstone to dominantly brown sandstone in slope above Tapeats Sandstone cliff. Thickness, 92 to 107 m (300 to 350 ft)

Ꞓt **Tapeats Sandstone (Middle and Lower(?) Cambrian)**—Brown and red-brown, cliff-forming, coarse-grained sandstone and conglomerate. Includes an upper slope-forming transition zone of nearly equal distribution of brown sandstone and green shale, and a lower cliff-forming sandstone and conglomeratic sandstone. Lower cliff unit consists mainly of a medium- to coarse-grained, thin-bedded, low-angle planar and trough crossbedded sandstone and conglomeratic sandstone; sandstone beds 14 to 57 cm (6 to 24 in) thick. Unconformable contact with underlying Lower Proterozoic surface forming the Great Unconformity. Tapeats Sandstone fills in lowland areas, and thins across or pinches out against Proterozoic highlands between Colorado River Mile 230 and 235. Variable thickness, 0 to 60 m (0 to 200 ft)

PROTEROZOIC CRYSTALLINE ROCKS

Intrusive and metamorphic rocks as defined by Ilg and others (1996), Hawkins and others (1996), and Karlstrom and others (2003)

Yd **Diabase intrusive rocks**—Black sills and dikes intruded into granitic rocks. Unit is shown as dark line with hatchers on map, Colorado River Mile 237 to 239. About 1.1 Ga (billion years old)

Yg **Young granite and pegmatite**—Granite plutons, stocks, dikes, and pegmatite. About 1.4 Ga (billion years old)

Xgr **Granite, granitic pegmatite and aplite**—Granite plutons, stocks, and pegmatite and aplite dikes emplaced synchronously with peak metamorphism. Contains abundant biotite, muscovite, and garnet. About 1.7 to 1.68 Ga

Xgd **Granodiorite complexes**—Gabbro-diorite-graniodiorite complexes of probable volcanic arc origin. Includes hornblende-biotite granodiorite, and tonalite. About 1.74 to 1.72 Ga

Xdg **Diorite, gabbro, and anorthosite**—About 1.74 to 1.72 Ga

Xs **Schist**—Quartz-mica, schist, and pelitic schist

Xv **Intermediate metavolcanic rocks**—Massive, fine-grained quartzo-feldspatic schist and gneiss of probable felsic metavolcanic rocks. Equivalent to the Rama Schist of eastern Grand Canyon as defined by Ilg and others (1996). About 1.75 Ga

Xm **Mafic metavolcanic rocks**—Biotite hornblende schist and amphibolite. Contains abundant biotite and garnet. Equivalent to Brahma Schist of eastern Grand Canyon

Xo **Orthoamphibole schist**—Regolith. An interval several meters thick of weathered detritus eroded from older plutonic rock

Xc **Carbonate and chert**—A few meters thick interval of carbonate rock and chert nodules within an orthoamphibole schist, one location only, below Colorado River Mile 237

Xu **Crystalline rocks, undifferentiated**—Undivided intrusive and metamorphic rocks. Includes granite plutons, stocks, and pegmatite and aplite dikes, gabbro-diorite, and granodiorite rocks, garnet schist, hornblende-biotite schist, orthoamphibole-bearing schist and gneiss, and probable felsic metavolcanic rocks. Unit is not mapped in detail and needs future study. Probably same age range as similar rocks along Colorado River

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