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Geologic Map of the Grand Canyon 30′ × 60′ Quadrangle, Coconino and Mohave Counties, Northwestern Arizona

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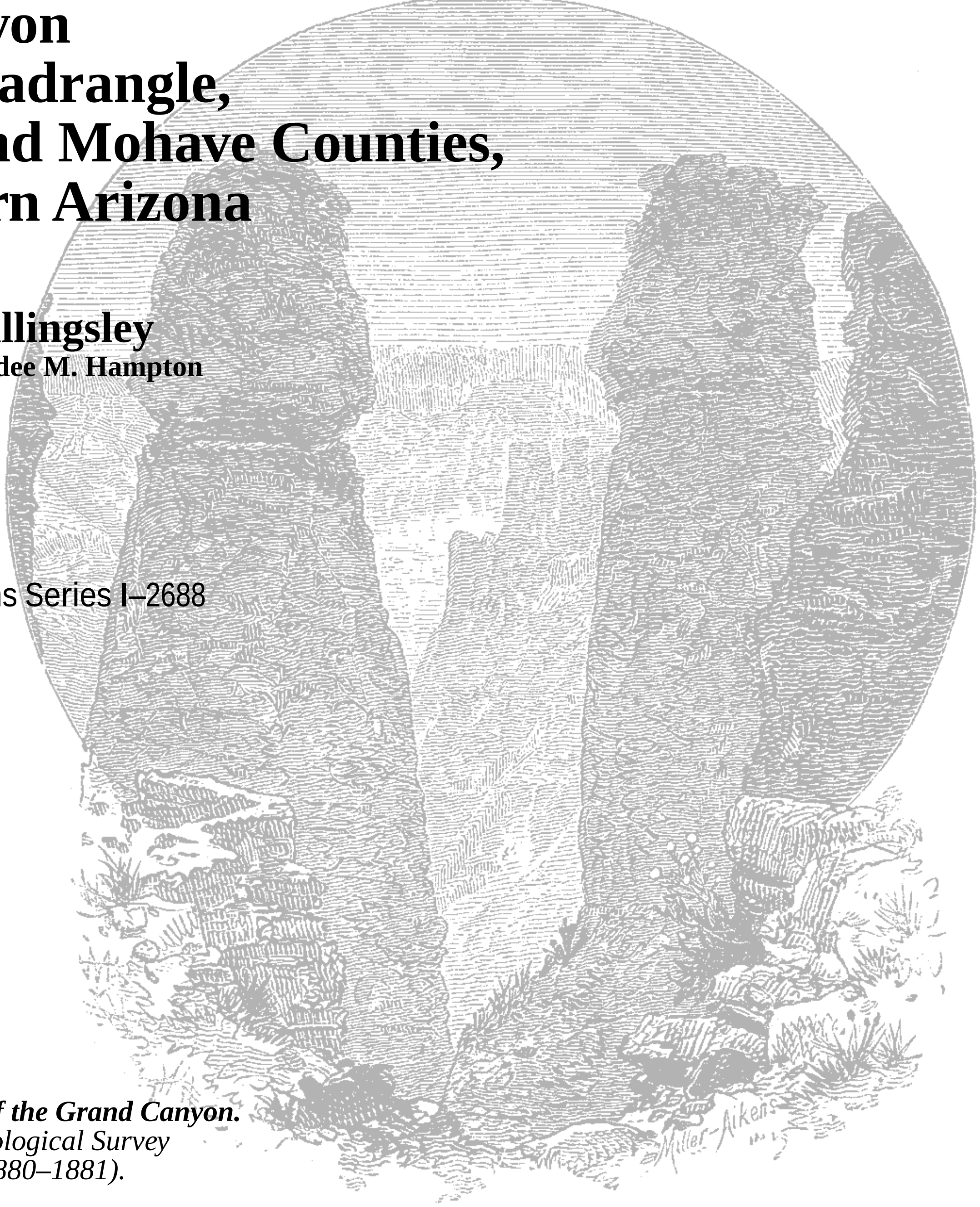
Pamphlet to accompany
Geologic Investigations Series I–2688
Version 1.0



Pinnacles on the brink of the Grand Canyon.
Illustration from U.S. Geological Survey
Second Annual Report (1880–1881).

Prepared in cooperation with the U.S. National Park Service

2000

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

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qr **Colorado River gravel deposits (Holocene)**—Mud, silt, and fine-grained sand transported by the Colorado River; interbedded with poorly sorted, angular to well-rounded, coarse-grained sand, gravel, pebbles, cobbles, and boulders of local alluvial debris fans and flows, partly reworked by the Colorado River. Includes local wind-blown sand sheets and small sand dune deposits derived from local gravel deposits. Only large deposits shown. About 3–80 ft (1–25 m) thick

Qtg **Terrace gravel deposits (Holocene and Pleistocene)**—Light-brown, pale-red, and gray, slope-forming, poorly sorted alluvial mud, silt, sand, coarse gravel, pebbles, cobbles, and boulders. Composed mainly of subangular to well-rounded Paleozoic sandstone and limestone clasts of local origin and some rounded clasts of assorted metamorphic rocks locally derived from inner gorge of Grand Canyon, and well-rounded quartzite and volcanic rocks that originated upstream in Utah, Colorado, and New Mexico. Clasts are partly consolidated by matrix of mud and sand cemented with calcium and gypsum. Thick deposits of mud and silt are preserved on south side of Colorado River just downstream of Tapeats Creek (north-central part of map area). Forms terraced benches about 3–300 ft (1–100 m) above post-Glen Canyon Dam high-water line of Colorado River, and above local tributary stream beds. Deposit is mixed with landslide and talus debris near Fossil Canyon and Tapeats Creek areas and may represent deltaic deposits resulting from temporary ponding of Colorado River by the Surprise Valley landslide near Tapeats Creek, or by volcanic dams farther downstream near western edge of map area. Only largest deposits shown. About 3–300 ft (1–100 m) thick

Qa **Alluvial deposits (Holocene and Pleistocene)**—Brown, red, and gray, slope-forming, unsorted mixture of mud, silt, sand, pebbles, cobbles, and boulders. Clasts are mostly angular, some are rounded; locally consolidated by calcite and gypsum cement. Sandstone, limestone, and chert clasts and gravel are locally derived from Paleozoic rocks. Includes alluvial-fan, floodplain, talus, colluvium, and valley-fill deposits. Subject to extensive sheet wash erosion or deposition, flash-flood debris flows, and arroyo erosion. Only largest deposits shown; most talus deposits are not shown to emphasize the bedrock geology, but are common in headward slopes of local tributary drainages and as talus deposits on slopes of Hermit Formation (Ph). About 3–100 ft (1–30 m) thick

Qt **Travertine deposits (Holocene and Pleistocene)**—Gray, white, and tan, massive, porous, cliff-forming limestone. Includes clasts of talus breccia or stream gravel. Formed as rapid chemical precipitation of calcium carbonate of spring water. Forms massive, rounded mounds or thick, layered encrustations on steep slopes or cliffs at and near active and inactive springs. Forms banded deposits of dripstone, flowstone, and rimstone as porous massive hanging sheets, including stalactites and stalagmites. Thickest deposits are in Havasu Canyon below Supai, and at Royal Arch Creek east of Supai. Forms temporary dams or blockages of Havasu Creek in Havasu Canyon. Only thickest deposits shown. About 3–100 ft (1–30 m) thick

Ql **Landslide deposits (Holocene and Pleistocene)**—Unconsolidated to partly consolidated masses of unsorted rock debris. Includes detached blocks that have rotated backward and slid downslope as loose incoherent masses of broken rock and deformed strata, partly surrounded by talus (talus not shown). Includes local talus, rock glaciers, and rock-fall debris. Landslide blocks may be associated with earthquake activity. Some landslide blocks may become unstable in very wet conditions. Only large landslide blocks shown (fig. 5). Many small landslide masses are commonly found below cliffs of Kaibab Formation (Pk), Coconino Sandstone (Pc), Redwall Limestone (Mr), and Tapeats Sandstone (Ꞓt). Variable thickness 10–200 ft (3–60 m)

VOLCANIC DEPOSITS

Quaternary basalts (Pleistocene)—Includes basalt flows, dikes, and pyroclastic deposits in Tuckup Canyon and Kanab Plateau areas, northwestern corner of map area. Divided into Tuckup Canyon Basalt, basalt of Hancock Knolls, Sage Basalt, and units Qi and Qp

Tuckup Canyon Basalt (Pleistocene)—Informally described by Billingsley (1970). Herein formally named for Tuckup Canyon, the type area, central Grand Canyon, northern Mohave County, Arizona (sec. 11, T. 34 N., R. 6 W.). Whole rock K-Ar age is 0.76±0.08 Ma (Wenrich and others, 1995). Divided into units Qti, Qtp, and Qtb

Qti **Intrusive dikes**—Dark-gray, finely crystalline alkali-olivine basalt. Contains augite and olivine phenocrysts in glassy groundmass. Occurs as two dikes in unnamed western tributary of upper Tuckup Canyon that align with trend of 10 Hancock Knolls pyroclastic cones (Qhp) on Kanab Plateau. Alignment reflects prominent northwest strike of near-vertical fractures and joints in Paleozoic strata in Tuckup Canyon area. Dikes are 1–3 ft (0.4–1 m) wide

Qtp **Pyroclastic deposits**—Red and reddish-gray cinders and scoriaceous glassy fragments of basalt; unconsolidated. Forms small cinder cone overlying associated basalt flow (Qtb) and part of Toroweap and Kaibab Formations (Pt, Pk) and Coconino Sandstone (Pc) in an unnamed western tributary of Tuckup Canyon. Also forms small isolated deposit below Qti dike at Coconino Sandstone (Pc) and Hermit Formation (Ph) contact northwest of unnamed western tributary canyon of Tuckup Canyon. Thickness about 200 ft (60 m)

Qtb **Basalt flow**—Dark- to light-gray, finely crystalline alkali-olivine basalt. Most of the basalt came from a fissure-like dike (Qti) and pyroclastic cone (Qtp) vent area in unnamed western tributary of upper Tuckup Canyon (Billingsley, 1970). Basalt flowed into Tuckup Canyon over outcrops of Toroweap and Kaibab Formations, Coconino Sandstone, Hermit Formation, and Esplanade Sandstone (Pe). The basalt flow merged or coalesced with a basalt flow (Qhb) from the Hancock Knolls area and spread out into upper Tuckup Canyon onto alluvium and Esplanade Sandstone. Tuckup Canyon drainage has been diverted around east side of basalt flow in upper Tuckup Canyon. Remnants of basalt flow cascaded over and cling to steep canyon walls of Esplanade Sandstone and Wescogame Formation, undivided (MPu), indicating that Tuckup Canyon had eroded at least as deep as Manakacha Formation, undivided, prior to the flow about 760,000 years ago. Thickness ranges from 3–25 ft (1–7.5 m)

Basalt of Hancock Knolls (Pleistocene)—Informally named for Hancock Knolls, the type area, Kanab Plateau, northern Mohave County, Arizona (sec. 20, T. 35 N., R. 6 W.). May be same eruptive phase as Tuckup Canyon Basalt (0.76±0.08 Ma) based on alignment of Hancock Knolls pyroclastic cones (Qhp) to dikes (Qti) and pyroclastic cone (Qtp) in upper Tuckup Canyon, and the coalescing of basalt flows (Qhb, Qtb) from both areas in upper Tuckup Canyon. Divided into units Qhp and Qhb

Qhp **Pyroclastic deposits**—Red to reddish-black cinder and scoriaceous basaltic fragments, and black cinders; unconsolidated. Forms 10 pyroclastic cones on the Kanab Plateau that align along a strike of N. 30° W. for about 5 mi (8 km) northwest of Tuckup Canyon. Unit overlies associated basalt flows (Qhb) and Harrisburg Member of Kaibab Formation (Pk). Variable thickness 40–350 ft (12–107 m)

Qhb **Basalt flows**—Dark- to light-gray, finely crystalline alkali-olivine basalt. Contains augite and olivine phenocrysts less than 1 mm in diameter in glassy groundmass. Unit overlies Harrisburg Member of Kaibab Formation (Pk). The southernmost basalt flowed about 1 mi (1.5 km) and cascaded down an unnamed western tributary of upper Tuckup Canyon to coalesce with Tuckup Canyon Basalt (Qtb; Billingsley, 1970). Tributary drainage has eroded through this basalt flow. Variable thickness 3–90 ft (1–27 m)

Sage Basalt (Pleistocene)—Formally named for an unnamed cinder cone with a triangulation survey station on top called “Sage” in upper reaches of Toroweap

Valley (sec. 26, T. 36 N., R. 7 W.), the type area, Uinkaret volcanic field, Kanab Plateau, northern Mohave County, Arizona (Billingsley and Workman, 2000). Divided into units Qsp and Qsb

Qsp **Pyroclastic deposits**—Red-brown and reddish-black scoriaceous basalt fragments, ash, and cinder deposits; partly consolidated. Including deposits outside of map area, forms three pyroclastic cones that align along a north-south, near-vertical bedrock fracture or joint system (Billingsley and Workman, 2000). Deposits overlie associated basalt flows (Qsb). Only eastern part of southernmost pyroclastic cone lies within map area. About 200 ft (60 m) thick

Qsb **Basalt flows**—Dark-gray, finely crystalline to glassy alkali-olivine basalt. Groundmass contains plagioclase, olivine, and augite laths. Includes abundant olivine phenocrysts 0.25–5 mm in diameter consisting of about 30 percent basalt in some outcrops. Overlies Harrisburg Member of Kaibab Formation (Pk). Basalt is offset about 110 ft (34 m) by the Toroweap Fault about 2 mi (3 km) west of northwestern corner of map area (Billingsley and Workman, 2000). Thickness ranges from 10 to 60 ft (3 to 18 m)

Qi **Basalt dikes and necks (Pleistocene)**—Dark-gray, finely crystalline alkali-olivine basalt with plagioclase laths in glassy groundmass. Intrudes through lower part of Hermit Formation (Ph). Forms small dike in an eastern tributary of Tuckup Canyon, two dikes and a neck just downstream of Havasu Canyon (159-Mile dikes, Wenrick and others, 1995), a dike or neck called “The Cork” on the Esplanade Sandstone just north of the159-Mile dikes, and a neck/dike combination on the Esplanade Sandstone called “Yumtheska Vent West” and “Yumtheska Vent East” below Yumtheska Point (Wenrich and others, 1995), northwestern part of map area. Whole-rock K-Ar age obtained for The Cork is 0.407±0.07 Ma, and for Yumtheska Vent West 0.78±0.15 Ma. The Cork, the 159-Mile dikes, the Yumtheska Vents East and West , and the small dike in unnamed eastern tributary of Tuckup Canyon are aligned along a northwest-trending (N. 45° W.) near-vertical joint and fracture system, suggesting a similar eruptive event between 405,000 and 780,000 years ago. The Cork and the Yumtheska Vents East and West include red pyroclastic deposits and local minor basalt that flowed onto the Esplanade Sandstone surface. The neck associated with the 159-Mile dikes is exposed in upper part of Watahomigi-Manakacha Formations, undivided (MIPu), as a neck of welded pyroclastic tuff. All volcanic rocks in this part of map area suggest that the Colorado River had eroded the Grand Canyon almost down to, but not below, Redwall Limestone (Mr) about 405,000–780,000 years ago

Qp **Pyroclastic deposits (Pleistocene)**—Red and reddish-black, scoriaceous alkali-olivine basalt fragments, cinders, ribbons, and bombs. Thickness about 30 ft (10 m) or more at Yumtheska Vent West; minor accumulations at “The Cork” and Yumtheska Vent West too thin to show at map scale

MESOZOIC AND PALEOZOIC SEDIMENTARY ROCKS

TRm **Moenkopi Formation (Lower Triassic)**—Red, slope-forming, fine-grained, thin-bedded shaley siltstone and sandstone. Unit mostly eroded from map area except for one small outcrop along Bright Angel Fault southwest of Grand Canyon. Only about 20 ft (6 m) of basal part of Moenkopi Formation is present and most certainly represents Lower Triassic strata only. Unit is distinguished from underlying red siltstone of Harrisburg Member of Kaibab Formation (Pk) by its darker red color and thin-bedded, platy sandstone beds as opposed to the massive-bedded, pale-red, undulating, softer siltstone beds of Harrisburg Member. A complete section of the Moenkopi crops out at the Vermilion Cliffs about 24 mi (38 km) northeast of map area, and at Mount Logan in the Sawmill Mountains about 13 mi (21 km) west of map area. About 20 ft (6 m) exposed

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

Harrisburg Member—Reddish-gray and brownish-gray, slope-forming gypsum, siltstone, sandstone, and limestone. Informally subdivided, in descending order, into three units forming an upper slope, middle cliff, and lower slope. Upper slope unit is interbedded red and gray gypsum, sandstone, and siltstone, and yellowish-gray fossiliferous sandy limestone. Middle cliff unit is gray, thin-bedded, fossiliferous cherty limestone and sandy limestone. Lower slope unit is (1) yellowish-gray to pale-red gypsifereous siltstone and calcareous sandstone, (2) gray, thin-bedded sandy limestone, and (3) gray to white, thick-bedded gypsum. Upper, middle, and lower units become inseparable on the Kaibab Plateau, northeastern quarter of map area. Solution weathering within gypsum beds of lower slope unit has resulted in warping and bending of limestone of middle cliff unit, especially in or near local drainages on Kanab and Coconino Plateaus where middle cliff unit forms surface bedrock. Gypsum solutioning is responsible for several sinkhole depressions within Harrisburg Member. Contact with underlying Fossil Mountain Member is gradational and arbitrarily marked at top of cherty limestone cliff of the Fossil Mountain. About 260 ft (80 m) thick in western half of map area, thinning eastward to about 120 ft (36 m) in northeastern quarter of map area. Average thickness about 165 ft (50 m)

Fossil Mountain Member—Light-gray, cliff-forming, fine- to medium-grained, thin- to medium-bedded [1–6 ft (0.3–2 m)], fossiliferous, sandy, cherty limestone. In general, unit weathers dark gray. Unit characterized by gray to white fossiliferous chert nodules and white chert lenses parallel to bedding; chert weathers dark gray to black. Some chert nodules contain concentric black and white bands. Includes brecciated chert beds 4–10 ft (1–3 m) thick in upper part at contact of thin limestone or gypsifereous siltstone of Harrisburg Member. Chert in central and western parts of map area makes up about 20 percent of unit; unit becomes sandy in northeastern quarter of map area. Generally forms cliff at rim of the Grand Canyon. Weathers into pinnacles or "pillars" detached from cliff in western half of map area. Unconformable contact with underlying Woods Ranch Member of Toroweap Formation (Pt) attributed to solution erosion and channel erosion; average relief about 10 ft (3 m). Some channels have eroded as much as 150 ft (45 m) into the Woods Ranch in western half of map area. Erosion channels were filled with sandy cherty limestone typical of the Fossil Mountain, providing an extra thickness of the Fossil Mountain. Thickness about 230–350 ft (70–107 m)

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

Woods Ranch Member—Gray and light-red, slope-forming gypsifereous siltstone and silty sandstone, interbedded with white laminated gypsum and gray thin-bedded limestone. Gypsum beds are as much as 10 ft (3 m) thick. Unit as a whole weathers reddish gray. Bedding locally distorted due to solutioning of gypsum. Contact with underlying Brady Canyon Member is gradational and arbitrarily marked at top of cliff-forming limestone of the Brady Canyon. Variable thickness owing to solution of gypsum and channel erosion in upper part; averages about 65 ft (20 m) thick in southeastern quarter of map area, thickening to as much as 200 ft (60 m) in northwestern half of map area

Brady Canyon Member—Gray, cliff-forming, thin- to medium-bedded [1–5 ft (0.05–1.4 m)], fine- to coarse-grained, fetid, fossiliferous limestone. Weathers dark gray. Includes thin-bedded dolomite in upper and lower parts. 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 cliff-forming limestone of the Brady Canyon. Thickness about 40 ft (12 m) at eastern edge of map area, increasing to about 130 ft (40 m) at western edge of map area

Seligman Member—Gray, light-purple, and yellowish-red, slope-forming, thin-bedded dolomite, sandstone, and gypsum above intertongued Coconino Sandstone, and yellowish-tan, flat-bedded, thin-bedded sandstone below the Coconino. In eastern two-thirds of map area, unit is mostly a purplish to light-red, flat-bedded calcareous sandstone interbedded with gray, thin-bedded limestone. In western third of map area, unit is gray-white gypsum and light-red to yellowish-red, thin-bedded calcareous sandstone and gray dolomite. Forms slope or recess between overlying cliff-forming Brady Canyon Member and underlying cliff-forming Coconino Sandstone (Pc) in southeastern two-thirds of map area; forms a gypsiferous slope similar to that of Woods Ranch Member in northwestern third of map area. Sharp gradational contact with the interbedded Coconino where cross-bedded sand dunes of the Coconino were beveled off and sand was redistributed as flat-bedded sandstone. The Coconino intertongues with lower part of the Seligman in western third of map area (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; and Billingsley and Workman, 2000). Thickness about 30 ft (9 m) in eastern half of map area, increasing to about 55 ft (17 m) in western half

Pc **Coconino Sandstone (Lower Permian)**—Tan to white, cliff-forming, fine-grained, well-sorted, cross-bedded quartz sandstone. Contains large-scale, high-angle, planar cross-bedded sandstone sets that average about 35 ft (11 m) thick. Locally includes poorly preserved fossil tracks and low-relief wind ripple marks on cross-bedded planar sandstone surfaces. Lower 5–20 ft (2–6 m) is intertongued, thin-bedded, partly calcareous, flat-bedded sandstone of Seligman Member of Toroweap Formation (Pt). Unconformable contact with underlying Hermit Formation (Ph) is sharp planar, with relief generally less than 3 ft (1 m) but locally as much as 8 ft (2.5 m). Desiccation cracks in the Hermit, as much as 2 ft (0.05 m) wide and 12 ft (4 m) deep, are filled with tan sandstone of the Toroweap or Coconino, mainly in eastern third of map area. Thickness of the Coconino decreases east to west, whereas Brady Canyon and Seligman Members of Toroweap Formation increase proportionally in thickness. Forms a 500-ft (154-m) thick cliff in southeast corner of map area, thinning northward to about 350 ft (122 m) and westward to about 150 ft (45 m) at western edge of map area

Ph **Hermit Formation (Lower Permian)**—Red, slope-forming, fine-grained, thin-bedded siltstone and sandstone. Upper part contains red and white, massive, low-angle cross-bedded calcareous sandstone and siltstone beds in western one-quarter of map area. Siltstone beds are dark red and crumbly, and fill shallow erosion channels that are widespread. Siltstone beds form recesses between thicker sandstone beds; locally contains poorly preserved plant fossils in channel fills in lower part of formation. Sandstone beds thicken and thin laterally either as channel fill or low sand dune accumulations. Sandstone bleaches to yellow-white color in vicinity of breccia pipes throughout map area, and at upper contact with Coconino Sandstone (Pc) or Toroweap Formation (Pt) in western half of map area. Unconformably overlies Esplanade Sandstone (Pe). Dark-red, platy, thin-bedded siltstone of Hermit Formation fills channels as much as 60 ft (16 m) deep eroded into the underlying Esplanade in eastern part of map area, and as much as 130 ft (40 m) deep in Havasu Canyon area, south-central part of map area. Erosional relief is generally less than 10 ft (3 m) in northeastern part of map area. About 260 ft (80 m) thick along eastern edge of map area, increasing to about 850 ft (260 m) at western edge of map area

Supai Group (Lower Permian, Pennsylvanian, and Upper Mississippian)—Includes, in descending order, Esplanade Sandstone (Lower Permian), Wescogame Formation (Upper Pennsylvanian), Manakacha Formation (Middle Pennsylvanian), and Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian) as defined by McKee (1975, 1982). Age of Watahomigi redefined by Martin and Barrick (1999). Divided into Esplanade Sandstone (Pe) and Wescogame, Manakacha, and Watahomigi Formations, undivided (MIPu)

Pe **Esplanade Sandstone (Lower Permian)**—Light-red and pinkish-gray, cliff-forming, fine- to medium-grained, medium-bedded [3–10 ft (1–3 m)], well-sorted calcareous sandstone. Includes intrabedded dark-red, thin-bedded, crumbly, slope-forming siltstone in upper and lower parts. Consists of an upper cliff and slope unit in western two-thirds of map area, and a middle cliff unit and a lower slope unit throughout map area.

In western two-thirds of map area, the upper cliff and slope unit contains thin-bedded slope-forming sandstone and siltstone similar to Hermit Formation (Ph) capped by cliff of thick-bedded, low-angle cross-bedded, red and white sandstone; entire unit thins and pinches out eastward in eastern third of map area. Maximum thickness of upper cliff and slope unit about 220 ft (67 m), western edge of map. Middle cliff unit forms a prominent cliff whose upper surface forms the "Esplanade Bench" in western two-thirds of map area, and a prominent cliff in eastern third of map area. Unit consists of light-red, medium-grained, medium- to thick-bedded sandstone and calcareous sandstone in upper half, and mostly flat, massive, low-angle cross-bedded sandstone sets and calcareous sandstone beds in lower half. Cross beds are small- to medium-scale, planar low-angle and high-angle sets. Cross-bedded calcareous sandstone is most common in western half of map area, lesser calcite in eastern half. Middle cliff unit averages about 250 ft (75 m) thick in western half of map area, thinning to about 200 ft (60 m) in eastern half. Lower slope unit consists of alternating layers of light-red, flat-bedded sandstone interbedded with dark-red siltstone and mudstone and gray, thin-bedded limestone. Lower slope unit averages about 80 ft (25 m) thick in western half of map area, thickening to about 100 ft (30 m) in eastern half.

Unconformable contact with underlying Wescogame Formation marked by erosion channels as much as 50 ft (15 m) deep filled with limestone conglomerate; average channel depth about 35 ft (11 m). Overall, the Esplanade averages about 550 ft (167 m) thick in western half of map area, thinning to less than 300 ft (90 m) in eastern half

MIPu **Wescogame (Upper Pennsylvanian), Manakacha (Middle Pennsylvanian), and Watahomigi Formations (Lower Pennsylvanian and Upper Mississippian), undivided**

Wescogame Formation—Light-red, pale-yellow, and light-gray upper slope unit and lower cliff unit. Upper slope unit consists mainly of dark-red, fine-grained siltstone and mudstone interbedded with light-red, coarse-grained, calcareous sandstone and dolomitic sandstone, siltstone, mudstone, and conglomerate. Lower cliff unit consists mainly of light-red to gray, high-angle, large- and medium-scale, tabular-planar, cross-bedded sandstone and calcareous sandstone sets as much as 40 ft (12 m) thick. Includes interbedded dark-red, thin-bedded siltstone in upper part of cliff. Cross-bed sets contain large footprints of four-footed vertebrate animals in eastern part of map area. Unconformable contact with underlying Manakacha Formation marked by unconformity of erosion channels as much as 80 ft (24 m) deep in western part of map area, and less than 30 ft (10 m) deep in eastern part of map area. Channels commonly filled with limestone/chert conglomerate. The Wescogame thickens slightly from west to east, averaging about 130 ft (40 m) in western part of map area and about 150 ft (45 m) in eastern part

Manakacha Formation—Light-red, white, and gray upper slope unit and lower cliff unit of sandstone, calcareous sandstone, dark-red siltstone, and gray limestone. Upper slope unit consists mainly of shaley siltstone and mudstone with minor interbedded, thin-bedded limestone and sandstone. Carbonate content of upper slope unit increases westward to form numerous ledge-forming, thin- and medium-bedded limestone beds. Upper slope unit is about 100 ft (30 m) thick in eastern half of map area, decreasing to less than 60 ft (18 m) thick in western half. Lower cliff unit is dominated by grayish-red, medium- to thick-bedded, cross-bedded calcareous sandstone, dolomite, and sandy limestone. Lower cliff unit is about 60 ft (18 m) thick in eastern part of map area, thickening to about 100 ft (30 m) in western part. Carbonate content of lower cliff unit increases westward across map area, forming numerous gray limestone ledges. Unconformable erosional contact between the Manakacha and underlying Watahomigi Formation approximately marked at base of lower sandstone cliff of the Manakacha; erosional relief generally less than 3 ft (1 m) and wavy unconformable surface. Overall thickness averages about 200 ft (60 m) throughout map area

Watahomigi Formation—Gray and purplish-red, slope-forming limestone, siltstone, mudstone, and conglomerate. Forms an upper ledge/slope unit and a lower slope unit. Upper ledge/slope unit consists of alternating gray, thin-bedded cherty limestone ledges interbedded with purplish-gray siltstone and mudstone; limestone beds contain Lower Pennsylvanian conodont fossils (Martin and Barrick, 1999); red chert lenses and nodules common. Includes limestone chert-pebble conglomerate at base, locally containing Lower Pennsylvanian fossils. Upper ledge/slope unit averages about 70 ft (21 m) thick throughout map area. Lower slope unit consists mainly of purplish-red mudstone and siltstone, interbedded with thin-bedded, aphanitic to granular limestone in upper part with red chert veins and nodules. Conodonts in lower thin limestone beds are Upper Mississippian (Martin and Barrick, 1999). Unit includes purple siltstone and gray limestone interbedded with conglomerate that fill small erosion channels cut into either Surprise Canyon Formation (Ms) or Redwall Limestone (Mr). Purple shale and mudstone of lower slope unit unconformably overlies the gray Redwall in majority of map area. Contact with the Surprise Canyon is often based on color change from purple mudstone of the Watahomigi to dark-red mudstone of the Surprise Canyon. Unit averages about 100 ft (30 m) thick along eastern edge of map area, thickening to about 200 ft (60 m) along western edge

Ms **Surprise Canyon Formation (Upper Mississippian)**—Dark-reddish-brown siltstone and sandstone, gray limestone and dolomite, and grayish-white chert conglomerate in dark-red or black sandstone matrix. Formation locally absent throughout map area; present only in paleovalleys and karst caves eroded into top half of Redwall Limestone (Mr). Consists of an upper slope unit, a middle cliff unit, and a lower slope unit in western half of map area; forms slope in eastern half of map area.

Upper slope unit consists of red-brown, thin-bedded siltstone, calcareous sandstone, and reddish-gray, thin-bedded sandy limestone. Contains numerous ripple marks and marine fossils. Thickness ranges from about 50 to 75 ft (15 to 23 m). Middle cliff unit consists of a reddish-gray, thin-bedded, coarse-grained silty and sandy limestone containing numerous marine fossils. Average thickness about 50 ft (15 m) in western third of map area, thinning and pinching out eastward in eastern two-thirds of map area. Lower slope unit consists of dark-red-brown to black, iron-stained, thin-bedded, coarse- to medium-grained siltstone, sandstone, limestone, and conglomerate. Sandstone and siltstone beds contain numerous plant fossils, bone fossils, mudcracks, and ripplemarks. Sandstone is coarse grained and thin bedded with some low-angle, cross-beds. Conglomerate beds consists of white and gray chert clasts supported in dark-red to black, coarse-grained chert sandstone or gravel matrix, all derived from the Redwall. Thickness of lower unit about 3–60 ft (1–18 m), averaging about 25 ft (8 m). In eastern half of map area, the Surprise Canyon consists mainly of dark-red-brown, slope-forming, massive to thin-bedded, poorly sorted siltstone and sandstone, containing localized plant fossils.

The Surprise Canyon is the most fossiliferous rock unit in the Grand Canyon. Overall, thickness averages about 145 ft (45 m) in western half of map area, thinning to less than 50 ft (15 m) in eastern half

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

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

Mooney Falls Member—Light-gray, cliff-forming, fine- to coarse-grained, thick-bedded to very thick bedded [4–20 ft (1–6 m)], fossiliferous limestone. Limestone weathers dark gray; chert beds weather black. Includes dark-gray dolomite beds in lower part in western quarter of map area; oolitic limestone and chert beds restricted to upper part throughout map area. Contains large-scale, tabular and planar, low-angle cross-stratified limestone beds in upper third of unit in western half of map area. Disconformable contact with the underlying Thunder Springs distinguished by lithology; massive-bedded, gray limestone of the Mooney Falls overlies thin-bedded, dark-gray to brown dolomite and white chert beds of the Thunder Springs. Member thickens from about 250 ft (75 m) in southeast quarter of map area to about 400 ft (122 m) in northwest quarter

Thunder Springs Member—About half of member is gray, cliff-forming, fossiliferous, thin-bedded limestone and about half is brownish-gray, cliff-forming, thin-bedded [1–5 in. (2–12 cm)], finely crystalline dolomite and fine- to coarse-grained limestone interbedded with white beds of chert lenses. Limestone is common in northern half of map area, dolomite is more common in southern half. Weathers into distinctive prominent band of black and light-brown bands on cliff face. Locally includes large-scale cross-bedding and irregularly folded beds in northern half of map area. Fossil content increases from east to west across map area. Disconformable planar contact with underlying Whitmore Wash Member distinguished by distinct lack of chert in the Whitmore Wash. Member is about 100 ft (30 m) thick in south half of map area, increasing to about 150 ft (45 m) thick in north half

Whitmore Wash Member—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 limestone in western and northern part of map area. Unconformable contact with underlying Temple Butte Formation (Dtb) marked by erosion channels of low relief about 5–10 ft (2–3 m) in depth. Contact generally recognized where major cliff of the Redwall overlies stair-step ledges of the Temple Butte. Uniform thickness throughout map area, about 80 ft (25 m)

Dtb **Temple Butte Formation (Upper and Middle Devonian)**—Purple, reddish-purple, dark-gray, and light-gray, ledge-forming dolomite, sandy dolomite, sandstone, mudstone, and limestone as defined by Beus (1990). Purple, reddish-purple, and light-gray, fine- to coarse-grained, thin- to medium-bedded, ripple-laminated ledges of mudstone, sandstone, dolomite, and conglomerate fill channels eroded into the underlying Cambrian strata; channels are as much as 100 ft (30 m) deep in eastern half of map area, and about 40 ft (12 m) deep in western half of map area. Channel deposits are overlain by dark-gray to olive-gray, medium- to thick-bedded dolomite, sandy dolomite, limestone, and sandstone. Unit as a whole forms sequence of dark-gray ledges. Unconformity at base of unit represents major stratigraphic break in Paleozoic rock record in the Grand Canyon, spanning part of Late Cambrian, all of Ordovician and Silurian, and most of Early and Middle Devonian time, about 100 million years. Dark-gray Devonian rocks are distinguished from underlying light-gray Cambrian rocks by color contrast. Unit thickens from about 50 ft (15 m) in eastern half of map area to as much as 275 ft (84 m) in western half of map area, excluding local channel deposit thickness

Tonto Group (Middle and Lower Cambrian)—Includes, in descending order, Muav Limestone, Bright Angel Shale, and Tapeats Sandstone as defined by Noble (1922) and modified by McKee and Resser (1945). These Cambrian units are recognized on the basis of distinct rock types: limestone and dolomite lithologies belong to the Muav; shale and siltstone lithologies belong to the Bright Angel; and sandstone and conglomerate lithologies belong to the Tapeats. Tonto Group overlies tilted strata of Grand Canyon Supergroup of Middle to Late Proterozoic (1.4–1.1 billion years) age in eastern and central parts of map area, and igneous and metamorphic rocks of Early Proterozoic (1.7–1.6 billion years) age in western part of map area. This hiatus is known regionally as the Great Unconformity

Ꞓm **Muav Limestone (Middle Cambrian)**—Dark-gray, light-gray, brown, and orange-red, cliff-forming limestone, dolomite, and calcareous mudstone. Includes, in descending order, unclassified dolomites, and Havasu, Gateway Canyon, Kanab Canyon, Peach Springs, Spencer Canyon, and Rampart Cave Members of McKee and Resser (1945). These members consist of fine- to medium-grained, thin- to thick-bedded, mottled, fossiliferous, silty limestone, limestone, and dolomite. Three unnamed slope-forming siltstone and shale units of Bright Angel Shale (Ꞓba) lithology are intertongued between cliff-forming members of Muav Limestone. These unnamed siltstone and shale units are green and purplish-red, micaceous siltstone, mudstone, and shale, and thin brown sandstone. Contact with the underlying Bright Angel is gradational and lithology dependent. Contact is arbitrarily marked at base of lowest prominent cliff-forming limestone of Rampart Cave Member of the Muav in western half of map area, and of Peach Springs–Kanab Canyon Members of the Muav in eastern half of map area. All members of the Muav thicken from east to west across map area. However, the Peach Springs, Spencer Canyon, and Rampart Cave change to purple-red and green siltstone/shale facies of the Bright Angel in eastern half of map area, where they are included as part of the Bright Angel . Intertonguing and facies change relationships between the Muav and Bright Angel produce variable thickness trends. Overall, the Muav thickens from about 350 ft (107 m) in eastern part of map area to about 600 ft (183 m) in western part

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purple-red, slope-forming siltstone and shale, and interbeds of red-brown to brown sandstone of Tapeats Sandstone lithology. Includes ledge-forming red-brown sandstone member of McKee and Resser (1945). Consists of green and purple-red, fine-grained, micaceous, ripple-laminated, fossiliferous siltstone and shale; 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 upper part of unit in western quarter of map area. Intertonguing and facies change relationships with the underlying Tapeats produce variable thickness trends. Contact with the Tapeats is arbitrarily marked at lithologic vertical and lateral transition from predominantly green siltstone and shale to predominantly brown sandstone in slope above the Tapeats cliff. Thickness is about 350 ft (107 m) in eastern quarter of map area, thickening to about 500 ft (150 m) in western quarter

Ꞓt **Tapeats Sandstone (Middle and Lower Cambrian)**—Brown and red-brown, cliff-forming sandstone and conglomerate. Includes an upper slope-forming transition zone of nearly equal distribution of brown sandstone of Tapeats Sandstone lithology and green siltstone and shale of Bright Angel Shale lithology, and a lower unit of cliff-forming sandstone and conglomeratic sandstone. Lower cliff unit consists mainly of medium- to coarse-grained, thin-bedded, low-angle planar and trough cross-bedded sandstone and conglomeratic sandstone; sandstone beds 6–24 in. (15–60 cm) thick. Unconformable contact with underlying Middle and Late Proterozoic surface that forms the Great Unconformity. The Tapeats fills in lowland areas and thins across or pinches out against young Proterozoic highlands. Variable thickness 0–400 ft (0–122 m)

MIDDLE PROTEROZOIC SEDIMENTARY ROCKS

Grand Canyon Supergroup—As mapped by J.W. Sears (Huntoon and others, 1996)

Unkar Group (Middle Proterozoic)—Includes, in descending order, unnamed diabase sills and dikes, Cardenas Basalt, Dox Formation, Shinumo Quartzite, Hakatai Shale, and Bass Formation. The Cardenas and upper part of the Dox are not exposed in map area, but complete sections are present about 6 mi (9.5 km) east of map area. There, the Cardenas is about 900 ft (300 m) thick and the Dox is about 1,280 ft (390 m) thick

Yi **Unnamed diabase sills and dikes**—Black, medium- to coarse-grained, olivine-rich diabase. Contains plagioclase, olivine, clinopyroxene, magnetite-ilmenite, and biotite. Diabase sills and dikes intrude all rocks within Unkar Group below Cardenas Basalt. Chemical variation diagrams indicate a potential common parentage between dikes and sills and the overlying Cardenas, but direct physical connection has not been observed, although isochron ages are basically identical at 1,070±70 Ma (Hendricks and Stevenson, 1990). Sills range in thickness from about 65 ft (20 m) in Clear Creek at eastern edge of map area to more than 655 ft (200 m) near Bass Rapids in central part of map area. Dike widths range from 3 to 12 ft (1 to 4 m)

Yd **Dox Formation**—Includes, in descending order, Ochoa Point, Comanche Point, Solomon Temple, and Escalante Creek Members as defined by Stevenson and Beus (1982). Of these, only part of the Escalante Creek is exposed in map area. Upper two-thirds or more of the Dox is removed by erosion and subsequently covered by Paleozoic rocks. The Escalante Creek is exposed in upper Bright Angel Creek and Shinumo Creek, eastern quarter of map area

Escalante Creek Member—Gray, light-brown to dark-brown, cliff-forming, fine- to medium-grained sandstone and interbedded dark-brown to green, slope-forming shale and mudstone. Includes gray contorted sandstone beds in lower part similar to those in underlying Shinumo Quartzite and small-scale, tabular-planar cross-bedded and graded-bedding sets. Conformable contact with the underlying Shinumo marked at lowest shaley slope of the Dox. Incomplete exposure due to erosion of upper part. Exposed thickness about 200 ft (60 m)

Ys **Shinumo Quartzite**—Red-brown, purple, and gray, cliff-forming sandstone. Includes four undivided informal members as defined by Daneker (1975). In descending order, they are upper, upper middle, lower middle, and lower sandstone members. Upper member consists of red-brown and purple, fine- to coarse-grained, well-sorted, highly contorted, gnarly bedded sandstone capped by nondisrupted, flat-bedded, gray sandstone. Upper middle member consists of rusty-red, fine- to coarse-grained, highly contorted, gnarly bedded sandstone. Lower middle member consists of purple "freckled" (reduction spots), fine-grained, well-sorted, low-angle cross-bedded sandstone with local contorted beds in upper part. Lower member consists of purplish-red, coarse-grained, flat-bedded, arkosic conglomeratic sandstone. All members cemented with silica, making sandstone as hard as metamorphic quartzite, but unit is not metamorphosed. Angular unconformity separates cliff of red-brown Shinumo Quartzite from underlying slope of red Hakatai Shale, marked at truncated beds of the Hakatai. The Shinumo increases in thickness from 1,132 ft (345 m) at eastern edge of map area to 1,540 ft (470 m) at Shinumo Creek, central part of map area

Yh **Hakatai Shale**—Orange-red, purple, and red mudstone, shale, and sandstone. Forms an upper cliff unit, a middle slope unit, and a lower slope unit. Upper cliff unit consists of pale-purple or lavender, fine- to coarse-grained, thin- to medium-bedded, cross-bedded sandstone. Forms gradational contact with underlying middle slope unit at distinct color change from purple to bright red. Middle slope unit is the most distinctive red-bed unit in the Grand Canyon, consisting of reddish-orange, thin-bedded, fine-grained mudstone, siltstone and sandy siltstone; includes nonred, spherical reduction spots ("freckles") less than 10 cm in diameter. Gradational contact with underlying lower slope unit arbitrarily placed at red to purple color change. Lower slope unit consists of purple to reddish-purple, thin-bedded to laminated, fine-grained mudstone, siltstone, and sandy siltstone. Mudcracks, ripple marks, and tabular-planar cross-bedding are common in all units. Gradational contact with underlying Bass Formation in eastern part of map area; sharp but conformable contact in central part of map area. Overall thickness varies from about 445 ft (135 m) in eastern part of map area to nearly 985 ft (300 m) in Hakatai Canyon, central part of map area

Yb **Bass Formation**—Red-brown and reddish-gray, ledge-forming dolomite, silty sandstone, and conglomerate. Includes basal Hotauta Conglomerate Member as defined by Dalton (1972). Consists of fine- to coarse-grained, thin- to medium-bedded dolomite, fine- to coarse-grained, thin-bedded sandstone, silty sandstone, conglomerate, and breccia. Dolomite is most common lithology in Shinumo Creek area (central part of map area), becoming mostly sandstone, siltstone, and conglomerate in Bright Angel Canyon and eastern part of map area. Dolomite beds contain biscuit-shaped biohermal stromatolite fossils and red chert; sandstone beds contain ripple marks, desiccation cracks, and intraformational breccia and conglomerate. The Hotauta is considered part of the Bass in most map areas because of its lensing characteristics. The Bass, including the Hotauta, gradually thickens from southeast to northwest across map area from about 260 to 300 ft (80 to 91 m)

Hotauta Conglomerate Member—Red-brown and gray conglomerate of well-rounded to subangular pebbles and boulders of granite, gneiss, and schist derived from underlying Early Proterozoic igneous and metamorphic rocks. Clasts are cemented in red-brown, coarse-grained, gravelly sandstone matrix. Unconformable contact with underlying Early Proterozoic rocks called the "Greatest Angular Unconformity" (Noble, 1922), a hiatus lasting about 450 million years (Hendricks and Stevenson, 1990). Unit does not include diabase sills. Variable thickness 0–30 ft (0–10 m)

EARLY PROTEROZOIC CRYSTALLINE ROCKS

Intrusive and metamorphic rocks as defined and mapped by Ilg and others (1996), Hawkins and others (1996), and Karlstrom and others (2001)

Intrusive rocks

Xg **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. About 1.7–1.66 Ga

Xgd **Granodiorite complexes**—Gabbro-diorite-granodiorite complexes of probable volcanic arc origin. About 1.74–1.71 Ga

Xum **Ultramafic rocks**—Probable cumulate origin as supracrustal rocks

Metamorphic rocks

Xv **Vishnu Schist**—Quartz-mica schist, pelitic schist, and meta-arenites of metamorphosed, arc-basin, submarine sedimentary rocks. About 1.75 Ga. Locally interlayered with Brahma Schist (Xbr) and Rama Schist (Xr)

Xbr **Brahma Schist**—Consists of amphibolite, hornblende-biotite-plagioclase schist, biotite-plagioclase schist, orthoamphibole-bearing schist and gneiss, and metamorphosed sulfide deposits. Mafic to intermediate-composition metavolcanic rocks. About 1.75 Ga. Locally interlayered with Rama Schist (Xr) and Vishnu Schist (Xv)

Xr **Rama Schist**—Massive, fine-grained quartzofeldspathic schist and gneiss of probable felsic metavolcanic rocks. About 1.75 Ga. Locally interlayered with Brahma Schist (Xbr) and Vishnu Schist (Xv)

Xo **Orthoamphibole-bearing gneiss**—Regolith. An interval several meters thick of weathered detritus eroded from older plutonic rocks. Metamorphic monazite from pelitic schist containing garnet, kyanite, gedrite, sillimanite, and cordierite. Very small outcrops along Colorado River within Granite Gorge

Xec **Elves Chasm pluton**—Oldest plutonic rocks, possible "basement" substrate. Contains mafic (hornblende-biotite tonalite) and intermediate-composition plutonic units (quartz diorite), including tabular amphibolite bodies that may be dikes. About 1.84 Ga

INTRODUCTION

This map is a cooperative effort of the U.S. Geological Survey and the U.S. National Park Service to provide geologic map coverage and regional geologic information for visitor services and Park Service management of the Grand Canyon National Park and vicinity, Arizona. This map is a synthesis of previously published geologic mapping and some new geologic mapping that encompasses the Grand Canyon 30 × 60 minute quadrangle of Arizona. The geologic information presented may be useful to other agencies such as the State of Arizona, the National Forest Service, the Bureau of Land Management, and the Bureau of Indian Affairs, as well as private enterprises that have lands within or near the map area.

Previous geologic mapping of this area was originally done by Maxson (1967a, b, and 1969). The compilation of this digital map incorporates modifications of Maxson's maps and geologic mapping by Huntoon and others (1996), Billingsley and Huntoon (1983), Wenrich and others (1997), and new mapping by Billingsley along a 2-mi (3.2-km) wide band along the northern edge of the quadrangle area. The map was compiled in digital form by Hampton at the U.S. Geological Survey Flagstaff Field Center using ARC/INFO and is the first digital geologic map of any part of the Grand Canyon.

The Grand Canyon 30 × 60 minute quadrangle encompasses approximately 1,960 mi^2 (5,018 km^2) within Mohave and Coconino Counties of northern Arizona. The quadrangle is bounded by longitudes 112°–113° W., and latitudes 36°–36°30' N. The map area lies within the southern part of the Colorado Plateaus geologic province (herein referred to as the Colorado Plateau). The map area is locally subdivided into four physiographic parts: the Grand Canyon, the Kanab Plateau and Kaibab Plateau (north of the Grand Canyon), and the Coconino Plateau (south of the Grand Canyon). The arbitrary boundary between the Kanab and Kaibab Plateaus is marked along the Muav Fault, a physiographic, geologic, and topographic feature (Billingsley and others, 1997). Elevations range from about 9,200 ft (2,805 m) on the Kaibab Plateau, northeast quarter of the map area, to about 1,710 ft (521 m) at the Colorado River, west edge of the map.

Settlements within the map area include Grand Canyon on the south rim of the Grand Canyon (southeastern corner of map area), and the village of Supai in Havasu Canyon of Havasu Creek (south-central part of map area; fig. 1). The North Rim lodge on the North Rim of the Grand Canyon (east edge of map) is open from May 15 to October 15 each year. Phantom Ranch campground is open all year and lies at the bottom of Grand Canyon in Bright Angel Canyon near the Colorado River between the North Rim and Grand Canyon. State Highway 64 provides access to Grand Canyon, and U.S. Highway 67 provides access to the North Rim from Jacobs Lake, Arizona. Indian Route 18 is a paved road belonging to the Hualapai and Havasupai Tribes leading from State Route 66 east of Peach Springs, Arizona, to Hualapai Hilltop, a parking lot where visitors begin an 8-mi (12.9-km) long horse or foot trail to the village of Supai. The North Kaibab, South Kaibab, and Bright Angel Trails lead into the Grand Canyon and provide access to Phantom Ranch campground and the only footbridges that span the Colorado River within the Grand Canyon.

Access to the plateau regions of the map area is by dirt roads that are not regularly maintained, and access into the depths of the Grand Canyon (other than by trails already mentioned) is by unmaintained foot trails that require a permit from the National Park Service at the National Park Headquarters at Grand Canyon. Visitors must check with the National Park Service Backcountry Office to obtain permits and information before traveling into remote areas of the Grand Canyon. Perhaps the most exciting way of seeing the Grand Canyon area is by raft down the Colorado River. There are several river companies that schedule river trips down the Colorado that vary in length of travel and cost. Check with the National Park Service Backcountry Office for information about Colorado River trips.

GEOLOGIC SETTING

The map area is characterized by gently dipping Paleozoic strata and a small patch of Mesozoic strata that overlie northeast-tilted Middle Proterozoic strata and Early Proterozoic crystalline metamorphic rocks. The Paleozoic rock layers form most of the cliffs and slopes in the walls of Grand Canyon throughout the map area (fig. 2). Tilted strata of the Middle Proterozoic Grand Canyon Supergroup are exposed in the depths of the inner gorge at Tapeats Creek, Shinumo Creek, Crystal Creek, and Bright Angel Canyon areas in the eastern half of the map area (fig. 3 and 4). Early Proterozoic crystalline rocks are exposed along the Colorado River corridor in the eastern half of the map area (fig. 4). The Paleozoic rocks display east-to-west facies changes and overall westward thickening of most formations of about 1,000 ft (300 m).

The Colorado River and its tributaries have dissected the map area, exposing a thin section of Mesozoic strata just southwest of Grand Canyon, about 4,000 ft (1,220 m) of Paleozoic strata in the eastern part of the map area to about 4,800 ft (1,460 m) in the western part, about 4,100 ft (1,250 m) of Proterozoic strata in the eastern and central part of the map area, and an unknown thickness of Early Proterozoic crystalline metamorphic rocks within the 1,300-ft (400-m) deep inner gorge. The Mesozoic rocks, perhaps in excess of 2,500 ft

(760 m), once covered the entire map area but have been removed by erosion except for the small patch along the Bright Angel Fault, southwest of Grand Canyon. A few thin Quaternary volcanic rocks were deposited on the Kanab Plateau and within the central Grand Canyon area (northwestern quarter of the map area). The Tuckup Canyon Basalt, informally named and mapped by Billingsley (1970), is formally named here as a mappable alkali-olivine basalt that outcrops entirely within Tuckup Canyon, the type area, central Grand Canyon, northern Mohave County, Arizona (sec. 11, T. 34 N., R. 6 W.). The whole rock K-Ar age of the basalt is 0.76±0.08 Ma (Wenrich and others, 1995). Quaternary surficial deposits consist mainly of alluvial terrace-gravel, Colorado River alluvium, landslide, talus, and travertine deposits scattered throughout the map area. Only the thickest and largest Quaternary deposits are shown so as to place emphasis on the bedrock geology. The Surprise Valley landslide is the largest landslide in the map area (fig. 5).

STRUCTURAL GEOLOGY

Highly complex metamorphic structures are common in the Early Proterozoic rocks of the inner gorge in the Grand Canyon (Karlstrom and others, 2001), and complex high-angle and low-angle, reverse, normal, and thrust faults and monoclinal folds are typical structures found in the Middle Proterozoic strata (Sears, 1973). High-angle to nearly vertical normal-fault separation of Paleozoic strata and east-dipping monoclines are the characteristic structures found in the Paleozoic rocks. Compressional folding of the Paleozoic rocks began in Late Cretaceous and early Tertiary time (about 65 Ma), causing erosion to begin removing Mesozoic strata that once covered the map area (Huntoon, 1990). The Laramide erosional period developed the landscape to its present configuration, but it is not certain when the Colorado River was established as a through-flowing stream in the area. The best consensus among geologists is that highland areas of the Grand Canyon, such as the Kaibab Plateau, began eroding into canyon drainages of unknown depth during the Paleocene (70–55 Ma; Elston and others, 1989), but the Colorado River and its tributaries became firmly established as an integrated system through the Grand Canyon sometime in late Miocene or early Pliocene time, the last 6–9 million years (Lucchitta, 1990). The time interval between 55 and 9 million years ago is thought to have experienced minor uplift and erosion interspersed with significant accumulations of Cenozoic gravel and stream deposits. During this time an unknown amount of erosion may have partly eroded into the Paleozoic strata to an unknown depth before the Colorado River became established. But most of the Grand Canyon erosion most likely happened within the last 6–9 million years.

The east-dipping monoclines on the Colorado Plateau overlie deep-seated reverse faults that displaced strata up-to-the-west during Late Cretaceous and early Tertiary time. The Supai Monocline is the only southwest-dipping monocline in the Grand Canyon area. During Pliocene and Pleistocene time, east-west extension reactivated the deep-seated faults in monocline folds, producing normal down-to-the-west fault separation along monoclines, reversing the Cretaceous and Tertiary offsets as well as accentuating the easterly dip by reverse drag along the faults (Huntoon, 1990).

Cenozoic extensional faulting probably began during late Pliocene time about 3 million years ago, producing normal fault separations with west-facing fault scarps, such as the Muav Fault. The north-south-trending faults in the western half of the map area appear to be the most active based on minor offset of alluvial and volcanic deposits just west of the map area (Billingsley and Huntoon, 1983; Wenrich and others, 1997).

Circular collapse structures, minor folds, and other surface irregularities on the Kanab, Kaibab, and Coconino Plateaus are due to dissolution of gypsum and gypsifereous siltstone within the Harrisburg Member of the Kaibab Formation and within the Woods Ranch Member of the Toroweap Formation. Some bowl-shaped depressions in the Kaibab Formation, characterized by inward-dipping strata, may be the surface expressions of collapse-formed breccia pipes originating from dissolution of the deeply buried Mississippian Redwall Limestone or dissolution of gypsum in the Woods Ranch Member of the Toroweap Formation (Wenrich and Huntoon, 1989). Within the Grand Canyon, breccia pipes are recognized in the red Permian and Pennsylvanian rocks as visible columns of brecciated rock often surrounded by a yellowish-white bleached zone with ring fractures. Breccia pipes with exposed breccia are indicated on the map by a red dot, and collapse features that are probable breccia pipes are indicated by a black dot.

Gypsum dissolution within the Kaibab and Toroweap Formations has resulted in several sinkholes and caves on the Kanab, Kaibab, and Coconino Plateaus. The sinkholes are Holocene and Pleistocene in age because they disrupt local drainages and are most active where precipitation is the greatest.

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