Prepared in cooperation with the Water Resources Division of the National Park Service

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

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Pamphlet to accompany

Scientific Investigations Map 2895

View looking downstream into Cataract Canyon showing the Lower Permian strata of the Coconino Plateau *(photograph by G.H. Billingsley, 2003)*.

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INTRODUCTION

The geologic map of the Valle 30´ x 60´ quadrangle is the result of a cooperative effort between the U.S. Geological Survey and the National Park Service to provide geologic information for regional resource management and visitor information services for Grand Canyon National Park, Arizona. The map area encompasses approximately 1,960 mi^2 within Coconino County, northern Arizona and is bounded by long 112° to 113° W. and lat 35°30´ to 36° N. and lies within the southern Colorado Plateaus geologic province (herein Colorado Plateau). The map area is locally subdivided into four physiographic parts; (1) the Grand Canyon (Cataract Canyon and extreme northeast corner of the map area), (2) the Coconino Plateau, (3) the Mount Floyd Volcanic Field, and (4) the San Francisco Volcanic Field as defined by Billingsley and others, 1997 (fig. 1). Elevations range from 7,460 ft (2,274 m) on the Coconino Plateau along State Highway 64 northeast corner of the map area, to about 4,200 ft (1,280 m) at the bottom of Cataract Canyon.

Settlements within the map area include Tusayan and Valle, Arizona (fig. 1). State Highway 64 and U.S. Highway 180 provide access to the Tusayan and Valle areas. Indian Route 18 is a paved highway in the northwest corner of the map area that is maintained by the Hualapai and Havasupai Indian Tribes and leads from State Route 66 about 7 mi (11 km) east of Peach Springs, Arizona to Hualapai Hilltop, a parking lot just north of the map area at the rim of Cataract Canyon where visitors begin an 8 mi (13 km) hike into Havasupai, Arizona. Other remote parts of the map are accessed by two dirt roads, which are maintained by Coconino County, and by several unmaintained local ranch roads. Weather conditions restrict travel within the area and visitors must obtain permission to access a few local ranch lands in the

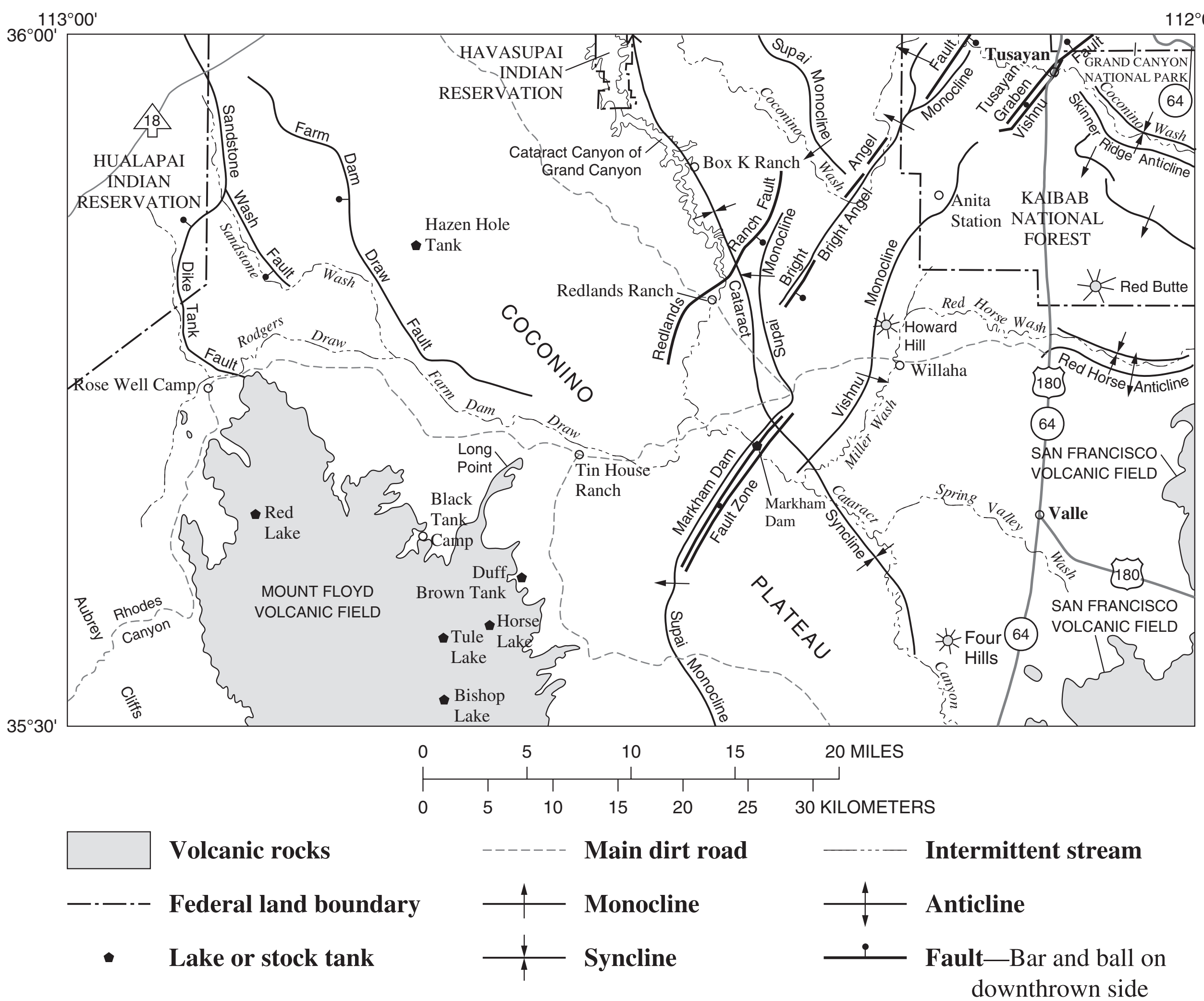

Figure 1. Index map of the Valle 30' x 60' quadrangle showing some locations and geologic and structural features mentioned in the text.

south-central edge of the map area. Extra water and food are highly recommended when traveling in this remote region. Access into Cataract Canyon is restricted to horse or foot travel and visitors must obtain permission from the Havasupai Tribe to hike within the Havasupai Indian Reservation (fig. 1).

In the central part of the map area, most of the land is privately owned and managed by the Babbitt Ranches Inc. in conjunction with the Nature Conservancy and the Navajo Tribe. In the southern half of the map, land alternates between privately owned land and State land forming a checkerboard pattern. The National Park Service manages land in Grand Canyon National Park (extreme northeast edge of map area), the U.S. Forest Service manages lands in the Kaibab National Forest, the Hualapai Tribe manages lands in the northwest quarter of the map area, and the Havasupai Tribe manages lands within Cataract Canyon and adjacent parts of the Coconino Plateau (fig. 1).

PREVIOUS WORK

Wilson and others (1969) compiled an early reconnaissance photogeologic map of this area as part of a geologic map of Coconino County and which was later compiled at 1:500,000 scale for the State of Arizona map. A new 1:1,000,000-scale geologic map of Arizona was recompiled by Reynolds (1988) using the same geologic data. Wenrich and others (1997) and Billingsley and others (2000b) mapped the northeastern part of the Hualapai Indian Reservation, which encompassed the northwest corner of this map. Wolfe and others (1987) mapped the San Francisco Volcanic Field in the southeast corner of this map and Huntoon and others (1996) mapped a portion of the northeast corner of the map area. The Quaternary geology of Wenrich and others (1997), Billingsley and others, (2000b), and Wolfe and others (1987) has been modified and updated (see index to geologic mapping on geologic map).

Geologic maps of adjacent areas include (1) the Grand Canyon 30´ x 60´ quadrangle, which borders the north edge of this map (Billingsley, 2000), (2) the Mount Trumbull 30´ x 60´ quadrangle adjacent to the northwest corner of this map (Billingsley and Wellmeyer, 2003), and (3) the Coconino Point and Grandview Point quadrangles adjacent to the northeast corner of this map (Billingsley and others, 1985). Huntoon (1999) produced a local structural geologic map of the Cataract Basin area.

MAPPING METHODS

The geology was mapped first by photogeologic methods using 1974 black and white 1:24,000-scale stereo aerial photographs and later by extensive field checking. Many of the Quaternary units have similar lithology and geomorphic characteristics and were mapped almost entirely using photogeologic methods. Relative ages of alluvial deposits with similar lithologies were determined on the basis of stratigraphic position and the amount of erosional degradation. Several map units and structures were investigated in the field to insure accuracy of placement. Map contacts between alluvial and eolian units are approximate.

Tracey Felger and Susan S. Priest, Flagstaff Science Center, U.S. Geological Survey, used ARC/MAP techniques to compile the map in digital format. This is the 4th map in a series of new digital 1:100,000-scale geologic maps for the Grand Canyon region.

GEOLOGIC SETTING

The map area is characterized by nearly flat lying to gently dipping Paleozoic, Mesozoic, and Cenozoic strata. Miocene, Pliocene, and Pleistocene volcanic rocks form a protective caprock over most of the Mesozoic and Cenozoic rocks along the south and east margins of the map area. The southwest limb or part of the Kaibab Upwarp or anticline elevates the northeast part of the map area where Paleozoic and Mesozoic strata have a regional southwest dip averaging about 2 degrees toward the broad Cataract Syncline in the vicinity of Cataract Canyon and Valle, Arizona. The regional dip in the southwest half of the map area is about 1 to 2 degrees northeast towards the Cataract Syncline. The Cataract Syncline axis is approximate and closely follows the northwest trend of Cataract Canyon (Huntoon, 2003).

PALEOZOIC AND MESOZOIC SEDIMENTARY ROCKS

Nearly 1,500 ft (460 m) of Lower Permian strata are exposed in the walls of Cataract Canyon. The Paleozoic strata in the map area are, oldest to youngest, the Esplanade Sandstone, the Hermit Formation, the Coconino Sandstone, the Toroweap Formation, the Kaibab Formation.

ESPLANADE SANDSTONE

The Esplanade Sandstone is incompletely exposed at the bottom of Cataract Canyon but based on exposures in Grand Canyon just north of the map and in the Verde Valley southeast of the map, the Esplanade Sandstone maintains a relatively uniform thickness of about 400 to 450 ft (123 to 137 m) thick throughout the subsurface of the Coconino Plateau. Regionally, the Esplanade Sandstone gradually thins to the east, south, and southwest but thickens slightly to the north and northwest. The Esplanade represents a coastal and near coastal deltaic, eolian sand dune, and nearshore fluvial environments. The highlands that may have supplied most of the sediment were generally south and east of the map area, while shallow seas were present to the west and northeast. An erosional unconformity separates the Esplanade Sandstone from the overlying Hermit Formation; channels eroded into the Esplanade are as much as 130 ft (40 m) deep in Cataract Canyon just north of the map area (Billingsley, 2000).

HERMIT FORMATION

The Hermit Formation is a fluvial deposit of fine-grained sand and silt that filled channels eroded into the Esplanade Sandstone and eventually covered the entire Esplanade. Based on exposures surrounding the map area, the Hermit Formation in the subsurface is about 260 ft (80 m) thick in the east part of the map, thickens to about 850 ft (260 m) in the northwest part, and thins to less than 80 ft (25 m) thick near the southwest and south edge of the map. The clastic sediments of the Hermit Formation accumulated as lowland deltaic deposits from meandering fluvial streams and overbank floodplain deposits. A few low-amplitude eolian sand dunes intertongue with the fluvial deposits.

COCONINO SANDSTONE

The Coconino Sandstone, a crossbedded eolian sandstone, generally thickens from west to east across the map area. The Coconino is about 160 ft (50 m) thick in the northwest corner of the map, about 250 to 280 ft (76 to 85 m) thick at the southeast edge, and thickens to about 500 ft (153 m) or more near the east edge of the map area. The base of the Coconino Sandstone intertongues within the Seligman Member of the Toroweap Formation along the west edge of the map and overlies the Hermit Formation in the central and eastern portions of the map area (see discussion in Toroweap Formation section below). The Coconino Sandstone is buff-white along the north edge of the map area and light red to brown in the southwest corner of the map. Fossil amphibian footprints and wind ripple marks are commonly found within the crossbedded sets.

TOROWEAP FORMATION

Shallow seas west and north of Grand Canyon began to gradually transgress across the Hermit Formation and deposited beach and coastal sand dune deposits above the disconformity. The transgressive phase of the Toroweap Formation, represented by the sandstone and limestone deposits of the Seligman and Brady Canyon Members of the Toroweap Formation, was followed by a regressive phase that deposited the siltstones and gypsum beds of the Woods Ranch Member of the Toroweap Formation. These three members of the Toroweap Formation are undivided on the map because they are too thin to show at map scale but are shown on the Littlefield (Billingsley and Workman, 2000) and the Mount Trumbull (Billingsley and Wellmeyer, 2003) geologic maps northwest of the map area. The Seligman Member is an accumulation of nearshore beach sandstone and shallow marine limestone deposits that are about 55 ft (17 m) thick in the northwest corner of the map, and gradually thins southeastward to less than 30 ft (9 m) thick. Onshore winds supplied abundant sand from the beaches inland to the east and southeast to form coastal and inland sand dunes comprising the Coconino Sandstone. The Coconino Sandstone forms a tongue within the Seligman Member of the Toroweap Formation (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; and Billingsley and others, 2000a) in the western Grand Canyon area but overlies the Hermit Formation in the central and eastern part of the map area. The Coconino Sandstone forms a mappable unit about 200 ft (60 m) thick in the Cataract Canyon area, thickens to more than 400 ft (122 m) in the subsurface in the southeast corner of the map and is about 500 ft (153 m) thick in the northeast part of the map, based on exposures southeast and northeast of the map area (Billingsley, 2000; Billingsley and others, 2000b).

The Brady Canyon Member of the Toroweap Formation consists of thin beds to moderately thick beds of limestone deposited in a shallow sea that covered much of the Coconino Sandstone on the Coconino Plateau and Grand Canyon area. The Brady Canyon Member thins from 250 ft (76 m) along the west edge of the map to about 40 ft (12 m) along the east edge. The Brady Canyon thins eastward across the Coconino Plateau almost proportionally to the thickening of the underlying Coconino Sandstone.

Evaporite deposits of gypsum, gypsiferous siltstone, and gypsiferous sandstone of the Woods Ranch Member of the Toroweap Formation overlie the Brady Canyon Member. The Woods Ranch Member represents a northwestward regressive phase of the Late Permian Toroweap sea. Sediments of the Woods Ranch Member accumulated to about 65 ft (20 m) thick in the southeast half of the map area and about 200 ft (60 m) thick in the northwest half grading into thin deposits of calcareous sandstone and gypsiferous sandstone in the northeast and southwest corners of the map area. The configuration of the marine deposits of the Woods Ranch Member reflects the overall northwest-southeast axis of a marine embayment between the Kaibab Plateau and Aubrey Cliffs suggesting that the Kaibab Plateau and Aubrey Cliffs areas may have been slightly elevated during or before deposition of the Woods Ranch Member. Massive gypsum beds, as much as 30 ft (9 m) thick, accumulated within the central part of the map area conforming to the general configuration of the present Cataract Syncline. After withdrawal of the sea, dissolution and erosion of the Woods Ranch Member sediments produced an eroded surface with 30 to 100 ft (9 to 30 m) of relief that was subsequently buried by the Kaibab Formation (Billingsley, 2000; Billingsley and Wellmeyer, 2003).

KAIBAB FORMATION

The Kaibab Formation forms the surface bedrock of much of the Coconino Plateau map within and surrounding the map area. These deposits are partly covered by younger Mesozoic or Cenozoic strata and Tertiary to Pleistocene volcanic rocks in the southwest and southeast part of the map. The Kaibab Formation has two mappable members, the Harrisburg Member (Pkh) (upper part) and the Fossil Mountain Member (Pkf) (lower part). The Fossil Mountain Member is a cliff-forming cherty limestone about 350 ft (107 m) thick along the west edge of the map and thins to 300 ft (92 m) where it forms a limestone cliff at the rim of Cataract Canyon, and thins to about 230 ft (70 m) at the east edge of the map area. The Fossil Mountain Member represents a transgression of the Early Permian sea that encroached from northwest to southeast over eroded deposits of the Toroweap Formation of the Coconino Plateau. A gradational boundary separates the cliff-forming Fossil Mountain Member from the overlying slope-forming Harrisburg Member of the Kaibab Formation.

Deposits of the Harrisburg Member of the Kaibab Formation form much of the surface bedrock within the map area. Recessive slope-forming beds of the Harrisburg Member overlie cliff-forming beds of the Fossil Mountain Member throughout most of the map area. The Harrisburg Member consists of evaporite and tidal-flat deposits left by the regressive phase of the Kaibab-age sea as it retreated west and northwest. The configuration of the regressive phase of the Kaibab-age sea embayment, which is parallel to the Cataract Syncline, is remarkably similar in aerial extent to the regressive phase of the Woods Ranch Member of the Toroweap Formation sea embayment. The main difference is that the Harrisburg Member sediments extended farther southeast to at least Flagstaff, Arizona (Sorauf and Billingsley, 1991). Erosion and dissolution of gray gypsum and light-red gypsiferous siltstone and sandstone deposits of the Harrisburg Member have resulted in the development of several internally drained karstic depressions on the Coconino Plateau, especially near Cataract Canyon (Huntoon, 2000).

Region-scale erosion followed the withdrawal of the Kaibab-age sea; stream channels eroded as much as 60 ft (18 m) deep into the Harrisburg Member. The stream channels were subsequently filled with fluvial conglomerate and sandstone deposits derived from erosion of the Harrisburg Member deposits. The channel-fill deposits comprise the basal Timpoweap Member of the Moenkopi Formation (not shown at map scale) at scattered locations throughout the map area, particularly near Redlands Ranch and Red Butte. Because many of the members of the Moenkopi Formation are not conclusively identified within the map area, individual members are not mapped separately on this map; they are, however, mapped separately northwest of the map area (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003).

The Toroweap and Kaibab Formations as they relate to regional structure

Early Permian seas encroached and withdrew twice from northwestern Arizona, Nevada, and Utah; the cycles deposited the Toroweap and Kaibab Formations, respectively. The Brady Canyon Member of the Toroweap Formation and the Fossil Mountain Member of the Kaibab Formation represent the shallow marine transgressions. The Woods Ranch Member of the Toroweap Formation and the Harrisburg Member of the Kaibab Formation represent the marine regressions. All members of each formation undergo a facies change from shallow marine conditions west of the Kaibab Anticline to nearshore and tidal flat coastal marine conditions east and southeast of the Kaibab Anticline. The facies change is nearly parallel to the axis of the Kaibab Anticline suggesting that minor uplift along this structure may have influenced both the Toroweap and Kaibab Formations facies change during Early Permian time.

MOENKOPI AND CHINLE FORMATIONS

The Triassic Moenkopi Formation is comprised of a sequence of red sandstone ledges and sandy siltstone slopes. Overlying the Moenkopi Formation at Red Butte is a white conglomeratic sandstone cliff of the Shinarump Member of the Chinle Formation. The Moenkopi Formation is partly preserved under Quaternary and Tertiary volcanic rocks along the east and south edges of the map, but was mostly eroded during the Cenozoic from the central and northwest half of the map area. The Moenkopi Formation once covered all of the Coconino Plateau area and ranged in thickness from about 1,000 ft (305 m), as preserved at Red Butte along the north edge of the map, to about 800 ft (244 m) along the south and southeast edge.

About 80 ft (25 m) of the Triassic Shinarump Member of the Chinle Formation is preserved beneath a 165 ft-thick (50 m) caprock of Tertiary (9 Ma) olivine basalt at Red Butte, which is a prominent landmark on the Coconino Plateau that owes its existence to the basalt caprock. Remnants of the Chinle Formation preserved at Mount Logan 25 mi (40 km) northwest of the map area and at Cedar Ranch Mesa 10 mi (16 km) southeast of the map area, reveal that at least the lower part of the Chinle Formation may have covered the entire map area before Cenozoic erosion.

CENOZOIC ROCKS

Laramide erosion uncovered progressively older rocks to the south and west of the map area, including Precambrian basement rocks along the southwestern edge of the Colorado Plateau region. North-flowing paleovalley and tributary drainages eroded into the Moenkopi and Kaibab Formations of the Coconino Plateau and were subsequently filled with late Paleocene and early Eocene fluvial conglomerate, sandstone, gravel, and silt deposits interbedded with local freshwater limestone deposits (Young and Hartman, 1984; Young, 2001). These Tertiary sediments (Ts) accumulated to an unknown thickness on the Coconino Plateau before the erosion of Grand Canyon. Remnants of these sedimentary rocks are preserved beneath the Tertiary (6.5 Ma) volcanic rocks of the Mount Floyd Volcanic Field in the southwest quarter of the map area. Erosion of these Tertiary sediments left behind a significant accumulation of scattered quartzite lag gravel deposits on the Coconino Plateau surfaces, especially near and around Rose Well Camp, Black Tank Camp, and upper Cataract Canyon (fig. 1).

Clasts from these lag gravels are extremely durable and some have been transported down Cataract Canyon into the Colorado River and beyond. Clasts from these gravels are well-rounded pebbles, cobbles and boulders of Precambrian quartzite, granite, metamorphic crystalline rocks, and Cretaceous volcanic rocks derived from south and southwest of the map area near Prescott, Bagdad, and Kingman, Arizona (Young, 2001). The Tertiary sediments here are very similar to Tertiary sediments of the Clarion Formation in southern Utah, but there is no evidence that these deposits once extended across the Grand Canyon into Utah. However, similar stratigraphy and fossils between the Tertiary deposits north and south of Grand Canyon strongly suggest the deposits were continuous and were deposited within a Laramide basin across the Grand Canyon and have since been removed by Grand Canyon erosion (Young, 1985, 1999, 2001; Billingsley and others, 1999, 2000b; Huntoon, 2003).

The Tertiary sediments at the northern end of Long Point have a slightly different composition than other Tertiary sediments preserved beneath the Mount Floyd Volcanic Field south and southeast of Long Point. At Long Point, the sediments contain several rhyolitic volcanic clasts and petrified wood fragments that may have been transported down paleovalleys from the west. Some of the boulders within the gravelly sediments are as much as 15 inches (36 cm) in diameter. The rhyolite volcanic clasts are common in similar sediments at Thornton Lookout 4 mi (6.5 km) west of the map area.

VOLCANIC ROCKS

The Quaternary and Tertiary basalt flows of the San Francisco Volcanic Field formed a protective caprock over the Moenkopi Formation and Harrisburg Member of the Kaibab Formation along the east and southeast part of the map area. K/Ar ages from the San Francisco Volcanic Field rocks are generally Pleistocene and Pliocene with most of the cinder cone deposits being less than 1 Ma. A 2-Ma basalt flow forms Howard Mesa at the southeast edge of the map. The oldest basalt flow, about 9 Ma, is at Red Butte (Wolfe and others, 1987).

The volcanic rocks in the Mount Floyd Volcanic Field have not been studied in detail and this map is the first attempt to map these rocks. Further study of these rocks is required to better understand the timing of volcanic eruption events and rock types in relation to landscape development. McKee and McKee (1972) conducted the first dating of these rocks and obtained K-Ar ages of 7.03±0.4 and 14.4±0.5 Ma from a basalt flow at Long Point southwest of Tin House Ranch. However, there is only one basalt flow at Long Point. An $^{40}Ar/^{39}Ar$ age of 6.76±0.13 Ma was obtained for this project from a basalt sample near Duff Brown Tank (sec. 26, T. 26 N., R. 3 W.) just south of Long Point and an $^{40}Ar/^{39}Ar$ age of 6.38±0.04 was obtained from an obsidian flow that overlies the basalt flow southwest of Black Tank Camp (sec. 18, T. 26 N., R. 4 W.; Peters, 2002). These two ages conform to the 7.03±0.4 Ma obtained by McKee and McKee (1972).

Weathering of the volcanic rocks of the Mount Floyd Volcanic Field area produces a fine-grained decomposed volcanic soil deposit over extensive surficial basalt flows. This fine-grained material washed into lowland streams and valleys or into natural ponded basins and is the source for a distinctive variety of silt dune (Qsd) deposits. The silt dunes have formed downwind on the northeast side of dry valleys and local lakebeds.

Other surficial deposits in the map area are comprised of landslide and associated talus deposits around and below the volcanic outcrops of the Mount Floyd Volcanic Field and at Red Butte. Quaternary fluvial and eolian deposits cover much of the map area as thin alluvial fan, terrace-gravel, sand dune, sand sheet, and mixed fluvial and eolian deposits. The alluvial deposits are largely unconsolidated and are the source for extensive, thin eolian sand dune and sand sheet deposits that cover much of the west and central part of the Coconino Plateau. These eolian deposits are stabilized by grassy vegetation during normal and wet years but during the recent drought (2000–2003), extensive sand dune and sand sheet deposits have become mobilized, especially west of Cataract Canyon.

STRUCTURAL GEOLOGY

High-angle fault separation to nearly vertical normal-fault separation of Paleozoic and Mesozoic strata and monoclines of variable dip annotations are the characteristic structures in the map area. The tectonic structures deformed the Paleozoic and younger rocks. There are two primary classes of tectonic structures: (1) compressional folds in the form of broad warping of the crust and localized monoclines, and (2) extensional high-angle normal faults.

The regional warping that caused the Kaibab Anticline northeast of the map area, Cataract Syncline through the center, and the Hualapai uplift to the west and southwest occurred during the Laramide orogeny dating from late Eocene to Late Cretaceous time (Naeser and others, 1989). This period of northeast-southwest compression also coincided with uplift of the Colorado Plateau. Erosion, rather than deposition, has been the dominant process since the onset of Laramide uplift.

Laramide northeast-southwest compression reactivated deeply buried favorably oriented faults in the Precambrian basement (Huntoon, 2003). Reverse displacements along the generally north and northwest trending Precambrian faults produced localized monoclines—sharp step-like folds—in the Paleozoic and Mesozoic overburden as it folded above the faults. The Supai Monocline is the principle monocline that developed in the Cataract Basin area but is considered a minor monocline owing to the small offset across it. Surface strata of the Kaibab Formation dip west an average of 8° and as much as 20° in some areas. The Supai Monocline is unusual in that the east side is displaced up, opposite to most of the monoclines in the western Colorado Plateau. Its profile indicates that the fault in the Precambrian basement was reactivated as an east-dipping instead of west-dipping fault.

There are several fold structures within the map area that are likely to influence surface and ground water circulation. Red Horse Anticline and Syncline south of Red Butte are east-west oriented folds that are largely responsible for the development and control of Red Horse Wash. The Red Horse Syncline has accumulated a general thickness of alluvium up to about 140 ft (43 m) thick over the Moenkopi Formation that has the potential to contain perched shallow water accumulations. This structure likely controls ground water flows to parallel the structure from east to west along its length.

North of Red Butte, the east-west trending Skinner Ridge Anticline and Syncline, a structure similar to the Red Horse Anticline and Syncline, is likely responsible for the early development of the east-west trending Coconino Wash because Coconino Wash parallels these structures for several miles.

The south limbs of the Red Horse and Skinner Ridge Anticlines have a low dip that closely reflects the regional dip of the Kaibab Anticline. If the stratum were tilted back to a horizontal position, both folds would reflect that of a monocline. However, it is not certain if these folds occurred before uplift of the Kaibab Anticline, which would make them a monocline, or as they are now, the surface expression of an anticline and syncline.

East-west extensional stresses supplanted Laramide compression in mid-Tertiary time, coinciding with major extensional tectonism in the Basin and Range Province to the west. The result was normal faulting throughout the map area during Miocene(?) to Holocene (Huntoon, 2003). Late Tertiary faulting commenced along the Laramide monoclines where reactivated Precambrian faults caused down faulting along the monoclines opposite in offset to Laramide folding. As extension continued, faulting spread to areas between the monoclines. The Supai Monocline did not experience sufficient extension to down fault to the east; however, rifting of the area west of the monocline was extreme for the region.

Between the east-dipping Vishnu Monocline and west-dipping Supai Monocline south of Howard Hill, a 2-mi-wide (3-km-wide) structural horst has a topographic relief of about 500 ft (153 m). This horst is about 8 to 10 mi (13 to 16 km) long and gradually diminishes at its south end near Cataract Canyon. The horst structure in the subsurface would likely form a barrier for northwest flowing ground water in all aquifers for most of its length, but ground-water flows are likely to concentrate and pass through this structure along the northwest-orientated joints and faults (cross section C–C´) termed the Markham Dam Fault Zone by Huntoon (2003).

The Markham Dam Fault Zone in the center of Cataract Basin is one of the most extensive and most active of all extensional fault zones on the southern Colorado Plateau (fig. 1). Huntoon (2003) states that this fault zone is broken by northwest-trending faults and grabens that are intersected by a few northeast-trending grabens. There are minor separations of Holocene(?) and Pleistocene alluvial deposits and numerous sinkholes that have developed along joints associated with the faults. In addition, a cluster of northwest-trending faults, most that are down-to-the-west, also occur in the vicinity of Rose Well Camp, 10 mi (16 km) west of the Markham Dam Fault Zone. The fluvial sediments in Farm Dam Draw and Sandstone Wash are likely to contain local perched shallow water within the alluvial deposits. The youthfulness of both the Markham Dam and Rose Well faulting is partly expressed by closed basin sediment accumulation along the downthrown side of some of the faults. Many of the closed topographic basins on the Coconino Plateau in this region are also the result of minor faults and fractures and the resulting dissolution of gypsum migrating down the fractures and faults in the Toroweap and Kaibab Formations. Low intensity earthquakes reflect continued faulting in this region.

Extension associated with normal faults accounts for much of the late Tertiary subsidence in the center of the Cataract Syncline. Open earth cracks and sinkholes, which capture significant volumes of surface runoff, have developed along normal faults in the Kaibab Formation. The extent of topographically closed subsidence depressions on the downthrown sides of normal faults is revealed by the fact that of the 3,020 sq mi surface area of the Cataract Basin, 209 sq mi drains internally (Melis and others, 1996).

HOWARD HILL DOME

Howard Hill is a stratigraphic dome about 1 mi in diameter, as expressed in strata of the Harrisburg Member of the Kaibab Formation, which rises about 200 ft (60 m) above the surrounding plateau surface. Howard Hill Dome is herein named for Howard Hill (sec 22, T. 28 N., R. 1 E.) in Coconino County, 2 mi (3 km) north of Willaha, Arizona, a railroad siding of the Grand Canyon railway. Strata around the base of the dome dip between 7° and 10°. A high-angle normal ring fault offsets strata down around the outside of the dome as much as 70 ft (22 m). The ring fault does not completely circumvent the dome but is present on the north, east, and south side where the stratigraphic dip is the greatest. A few minor normal faults strike northeast across the dome with less than 5 ft (1.5 m) of offset.

The dome is probably a basaltic laccolith, as shown on cross section A–A´, although it hasn't been drilled. The interpretation is justified because a few laccoliths of similar size are present in the San Francisco Volcanic Field southeast of the map area and the ring fault is similar to ring faults in several small laccoliths in the Henry Mountains in southeast Utah (Hunt and others, 1953). The intrusion at Howard Dome probably dates from the 9 Ma activity that produced the lava cap at Red Butte, 10 mi (16 km) east of Howard Hill.

INTERNAL DRAINAGES

Several areas west of Cataract Canyon have internal surface drainage, such as at Hazen Hole Tank (fig. 1). The primary cause of the internal drainage is extensional faulting and development of structural depressions along grabens. The secondary cause of internal drainage is the dissolution of gypsum in the Toroweap and Kaibab Formations. The gypsum is transported down numerous joints and small faults forming surficial sinkhole depressions on the Coconino Plateau. The aerial distribution of sinkholes shown on the map generally delineates the extent of the Permian embayment during the regressive phase of the Toroweap and Kaibab-age seas discussed earlier. The modern gypsum karst developed in the Harrisburg Member of the Kaibab Formation, indicated by sinkholes on the map, is among the best developed on the southern Colorado Plateau owing to the presence of thick deposits of gypsum. The northwestward extension of the Permian depocenter is also indicated by the distribution of sinkholes in the Harrisburg Member on the Littlefield 30´ x 60´ quadrangle northwest of this map area (Billingsley and Workman, 2000). The internal drainage depressions are likely excellent fracture zones for ground water recharge to the lower aquifers.

In the southwest quarter of the map area, other internal drainage basins developed in volcanic rocks and formed intermittent lakes such as Tule Lake, Red Lake, Bishop Lake, and Horse Lake. These enclosed depressions result from minor tectonism as the primary process followed by some probable dissolution of the Tertiary limestone under the volcanic rocks of the Mount Floyd Volcanic Field.

REDLANDS RANCH BASIN

The Redlands Ranch Fault and the Supai Monocline are about 3 mi apart in the central part of the map area. Redlands Ranch is situated in a basin between these two structures and is the lowest structural part of the Coconino Plateau. Remnants of the Moenkopi Formation are preserved at Redlands Ranch due, in part, to a large half-mile diameter collapse structure within the basin where the Moenkopi Formation has downdropped an additional 200 ft (60 m) into the collapse. The static water level at Redlands Ranch should be higher in the Paleozoic section than at any other part of the Coconino Plateau.

COLLAPSE STRUCTURES

Inward-dipping strata characterize circular bowl-shaped depressions in the Kaibab and Moenkopi Formations. Breccia pipes underlie many such surface depressions. Breccia pipes are collapse structures caused primarily by dissolution of the deeply buried Mississippian Redwall Limestone. The dissolution of gypsum in the Woods Ranch Member of the Toroweap Formation within these collapse structures enhances their surface bowl-shaped expression (Wenrich and Huntoon, 1989). Drilling is required to confirm that the breccia pipes do originate in the Redwall Limestone rather than from dissolution of gypsum in the Toroweap and Kaibab Formations. Large-scale collapse depressions ½ to 1 mi (0.8 to 1.6 km) in diameter that are likely breccia pipes at depth are at Redlands Ranch, Box K Ranch, in Coconino Wash east of Cataract Canyon, and in Farm Dam Draw west of Tin House Ranch. There are 100 collapse structures plotted on the Valle quadrangle. The surface expression of a collapse structure on the Coconino Plateau is a large circular patch of alluvium about a third of a mile in diameter supporting a moderate growth of sagebrush and grass in a subtle depression surrounded by ponderosa pine, pinion pine and juniper forest.

Five collapse structures were drilled by Energy Fuels Nuclear Inc. in the Red Butte area confirming each structure is a breccia pipe at depth (Wenrich, 1992). One of these drilled breccia pipes contains a significant uranium ore deposit. High-grade ore deposits have been mined from breccia pipes elsewhere near the Grand Canyon area. The primary metal is uranium along with Ag, Pb, Zn, Cu, Co, and Ni (Wenrich and Huntoon, 1989). Several suspect features identified by Wenrich (1992) are not plotted on the Valle 30´ x 60´ map because they cannot be verified in the field. Only collapse features with inward dipping strata are shown.

Minor folds, sinkholes, enclosed surface drainage basins, and other surface irregularities on the Coconino Plateau are largely due to the dissolution of gypsum and gypsiferous siltstone within the Harrisburg Member of the Kaibab Formation and to some extent, the dissolution of gypsum within the Woods Ranch Member of the Toroweap Formation. The sinkholes are likely Holocene and Pleistocene age because they disrupt local surface drainages and are commonly filled with ponded fine-grained sediments. The deposits of gypsum in the Kaibab and Toroweap Formations are thickest along a northwest-southeast axial trend in the vicinity of Cataract Canyon of the ancient embayment of the Kaibab and Toroweap Formation-age sea, as discussed earlier. As a result, many of the largest depressions occur near and west of Cataract Canyon.

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Holocene, Pleistocene, and Pliocene(?) surficial deposits are differentiated from one another chiefly on the basis of differences in morphologic character and physiographic position observed on 1974 black and white aerial photographs and from field observations. Older alluvial and eolian deposits generally exhibit extensive erosion and have greater topographic relief, whereas younger deposits are either actively accumulating material or are lightly eroded

Qaf **Artificial fill and quarries (Holocene)**—Alluvium and bedrock material excavated from bar-pits and trenches to build livestock tanks, drainage diversion dams, roads, and other construction projects. Include copper mine excavations and mine dumps southwest of Tusayan and west of State Highway 64. Does not include all highway road cuts and roadbed fill

Qf **Flood-plain deposits (Holocene)**—Gray, brown, and light-red clay, silt, sand, and some lenticular gravel; partly consolidated by gypsum and calcite cement. Intertongue or overlap young terrace-gravel (Qgy), valley-fill (Qv), and young alluvial fan (Qay) deposits. Subject to lateral stream-channel erosion or overbank flooding. Similar to valley-fill deposits but form broad, flat, valley floors subject to widespread frequent overbank flooding. In broad floodplains, minor arroyo development may occur near downstream drainage outlets. Support thick growths of grass, cliffrose bush, and sagebrush that help to trap and accumulate fine-grained sediment. Subject to temporary ponding in broad drainage floodplains. Thickness, 6 to 20 ft (1.8 to 6 m)

Qd **Dune sand and sand sheet deposits (Holocene)**—White to gray, fine- to coarse-grained, wind-blown sand. Composed of quartz and chert sand of the Harrisburg Member of the Kaibab Formation that accumulates from young terrace-gravel (Qgy) or valley-fill (Qv) sources. Form shallow sand dune or thick sand sheet deposits. Commonly occur as lumpy, undefined sand dune shapes or thick to thin sand sheet deposits on floodplain (Qf) and young terrace-gravel (Qgy) deposits along Sandstone Wash, Rodgers Draw, and Farm Dam Draw in west-central part of map area, and minor deposits along Coconino Wash and Red Horse Wash in northeast part of map area. Include climbing and falling dunes or thick sand accumulations on gentle slopes of bedrock outcrops adjacent to large drainages. Sand locally transported northeast by southwesterly winds, especially along Sandstone Wash and Farm Dam Draw where stream channels are wide and sandy. Include sand dune or sand levees along southwest edge of extensive sand sheet (Qss) deposits and along southwest edge of extensive young mixed alluvium and eolian (Qae) deposits where topography flattens to prairie-like conditions. Sand dune and sand sheet deposits are mostly hidden or covered by forest growths in the forested lands near Tusayan, Arizona, Coconino Wash, and Red Butte areas. Deposits largely absent in southeast third of map area due to volcanic rock outcrops. Support moderate growth of grass in southwest part of map area and sagebrush, pinion pine, juniper, and ponderosa pine woodlands in northeast map area. Thickness, 3 to 20 ft (1 to 6 m)

Qgy **Young terrace-gravel deposits (Holocene)**—Light-brown, pale-red, and gray, poorly sorted fluvial mud, silt, sand, gravel, pebbles, cobbles, and boulders. Composed mainly of subangular to well-rounded Paleozoic sandstone, limestone, and chert clasts of local origin. Include well-rounded clasts of quartzite, quartz, assorted metamorphic crystalline rocks, and well-rounded volcanic rocks derived from Tertiary sediments (Ts), southwest and southeast part of map area. Interbedded silt, sand, gravel, and pebbles to boulders are partly consolidated by gypsum and calcite cement. Locally overlap young alluvial fan (Qay) and valley-fill (Qv) deposits. Little to moderate vegetation in terrace-gravel deposits; primarily grass and sagebrush. Contact with adjacent alluvial and eolian deposits is approximate. Subject to flash flood and sheet wash erosion. Form fluvial terrace benches about 3 to 40 ft (1 to 12 m) above stream drainages. Deposit intertongues with landslide (Ql) and talus and rock fall (Qtr) deposits in Cataract Canyon. Unit fills erosion channels cut into bedrock and young alluvial fan (Qay) deposits. Support moderate growth of local shrubs, sagebrush, and grass. Thickness, 3 to 40 ft (1 to 12 m)

Qay **Young alluvial fan deposits (Holocene)**—Gray-brown silt, sand, gravel, and some boulders. Clasts are subangular to rounded limestone, chert, and sandstone locally derived from Mesozoic and Paleozoic outcrops of the Moenkopi and Kaibab Formations. Include medium- to coarse-grained sand and gravel to well-rounded pebbles of quartzite and quartz derived from Tertiary sediments (Ts); basalt, andesite, rhyolite, and obsidian clasts and fragments from the Mount Floyd Volcanic Field in southwest part of map area and rounded to subrounded clasts and fragments of basalt from the San Francisco Volcanic Field in southeast part of map area. Include subrounded to angular basalt clasts from Red Butte in northeast quarter of map area. Partly consolidated by silt, gypsum, and calcite. Overlapped by ponded sediments (Qps), floodplain (Qf), sand sheet and dune (Qd), and sand sheet (Qss) deposits. Intertongue with upper part of valley-fill (Qv) and young terrace-gravel (Qgy) deposits. Surfaces are partly eroded and cut by small arroyo erosion. Surface has thin sandy calcrete soil mixed with large cobbles and boulders of basalt near Mount Floyd Volcanic Field. Subject to extensive sheet-wash erosion and flash flood debris flows. Support moderate growth of high desert shrubs, sagebrush, cactus, and grass. Thickness, 3 to 25 ft (1 to 7.5 m)

Qps **Ponded sediments (Holocene and Pleistocene(?))**—Gray to brown clay, silt, sand, and lenses of gravel. Locally include small chert and limestone fragments or pebbles. Similar to floodplain (Qf) deposits but occupy natural internal drainage depressions and man-made stock tank areas. Internal drainage sinkhole ponded sediments are common in northwest quarter of map area. Accumulate in several small areas within sand dune and sand sheet deposits near Farm Dam Draw, many too small to show at map scale. Desiccation cracks common on dry playa-like hardpan surfaces restrict plant growth. Lake beds in the Mount Floyd Volcanic Field area are dry most of the time and are source areas of silt for silt dune (Qsd) deposits. Support little or no vegetation or minor growths of seasonal grass. Thickness, 5 to 35 ft (1.5 to 11 m)

Qss **Sand sheet deposits (Holocene and Pleistocene(?))**—White, brown, and gray, fine- to coarse-grained wind-blown sand. Composed primarily of quartz and feldspar grains derived from erosion of Tertiary sediments (Ts) in southwest half of map area. Composed of quartz grains and small chert fragments derived from Harrisburg Member of the Kaibab Formation in central part of map area. Form extensive deposits over gently sloping terrain of flat prairieland topography downwind (northeast) of sand dune deposits in southwest and central part of map area. Intertongue with young mixed alluvium and eolian (Qae) deposits and old mixed alluvium and eolian (QTae) deposits. Arbitrary and gradational lateral and vertical contact between sand sheet (Qss) and sand sheet and dune (Qd) deposits based on morphologic interpretation of aerial photographs. Only most extensive deposits shown. Support moderate growth of grass and small high-desert shrubs. Thickness, 1 to 10 ft (0.3 to 3 m)

Qsc **Eolian and fluvial silt deposits (Holocene and Pleistocene(?))**—Brown to medium-gray clay, silt, and fine-grained sand composed of decomposed and weathered volcanic rock. Similar to eolian silt dune (Qsd) deposits except they are thinner, widespread, and restricted to the Mount Floyd Volcanic Field area. Silt and clay matter is primarily derived from weathered volcanic rock that has accumulated as fine-grained silt and sand in young terrace-gravel (Qgy), valley-fill (Qv), ponded sediments (Qps), and silt dune (Qsd) deposits transported downwind (northeasterly) onto nearby slopes of basaltic and andesitic pyroclastic deposits. Gradational and arbitrary contact with adjacent alluvial or eolian deposits. Include unsorted fragments of small pebbles and cobbles derived from local basalt, rhyolite, or obsidian, and pyroclastic deposits. Partly consolidated by calcite and clay cement. Form extensive thin deposits downwind of young alluvial fan (Qay) deposits. Form thin veneer over most volcanic rocks in the Mount Floyd Volcanic Field area where only thickest and most extensive deposits are shown. Support moderate to thick growth of grass, sagebrush, some cactus, and scattered pinion/juniper woodlands. Thickness, 1 to 25 ft (0.3 to 7.5 m)

Qae **Young mixed alluvium and eolian deposits (Holocene and Pleistocene(?))**—Gray, light-red and brown clay, silt, and fine- to coarse-grained sand interbedded with lenses of coarse-grained gravel. Include white angular chert fragments. Formed by wind- and water-transported sediment by fluvial or eolian processes resulting in an interbedded accumulation of alluvial and eolian deposits. Deposit subject to sheet wash erosion in wet conditions, eolian sand accumulation in dry conditions. Commonly occupy broad flatland or gently sloping topography downwind (northeast) of tributary drainages and valleys in northwest two-thirds of map area. Often overlapped by sand sheet (Qss) or sand sheet and dune (Qd) deposits. Support thick to moderate growth of grass, cactus, and local high desert shrubs. Thickness, 1 to 6 ft (0.3 to 1.8 m)

Qao **Old alluvial fan deposits (Holocene and Pleistocene)**—Lithologically similar to young alluvial fan (Qay) deposits; partly consolidated by calcite and gypsum cement. Surface has thin upper calcrete soil that forms flat rocky and sandy surface near Mount Floyd Volcanic Field outcrops. Include numerous basalt clasts from Mount Floyd Volcanic Field in southwest quarter of map area. Commonly overlapped by or intertongue with talus and rock fall (Qtr), landslide (Ql), and young alluvial fan (Qay) deposits. Support moderate growth of grass, sagebrush, cactus, cliffrose bush, and some scattered pinyon and juniper trees. Thickness, 5 to 25 ft (1.5 to 7.5 m)

Qtr **Talus and rock fall deposits (Holocene and Pleistocene)**—Brown, gray, slope-forming, unsorted mixture of mud, silt, sand, pebbles, cobbles, and very large broken boulders. Form talus debris slopes in Cataract Canyon and below volcanic outcrops of the Mount Floyd Volcanic Field and Red Butte. Include individual car- and house-size basalt boulders at Red Butte and Long Point areas. Clasts are mostly angular to subangular. Gradational and arbitrary contact with landslide (Ql), young alluvial fan (Qay), floodplain (Qf), young terrace-gravel (Qgy), and valley-fill (Qv) deposits. Subject to extensive sheet-wash erosion, flash-flood debris flows, and arroyo erosion. Only thick or extensive deposits shown. Thickness, 1 to 25 ft (0.3 to 7.5 m)

Ql **Landslide deposits (Holocene and Pleistocene)**—Unconsolidated to partly consolidated masses of unsorted rock debris. Include detached blocks that have rotated backward and slid downslope as loose incoherent masses of broken rock and deformed strata. Include talus debris, rock glaciers, and rock-fall debris on lower slopes, adjacent to, and below landslide masses. Some landslide blocks may become unstable in very wet conditions. Only large landslide blocks are shown. Many small landslide masses commonly found below cliffs of volcanic rock of the Mount Floyd Volcanic Field, Red Butte, and around edges of the San Francisco Volcanic Field. Thickness, 10 to 200 ft (3 to 60 m)

Qsd **Silt dune deposits (Holocene and Pleistocene)**—Brown and medium-gray clay, silt, and fine-grained sand composed of decomposed and weathered volcanic rock. Include subrounded to angular fragments of pebbles and cobbles of local basalt rocks about 4 to 6 inches (9.6 to 14.5 cm) in diameter and as much as 1 ft (0.3 m) in diameter. The basaltic rocks are randomly scattered within and on silt dunes. High winds during wet conditions may have blown basalt rocks across flat slick muddy lake surfaces and up onto slick muddy dune surfaces. Source for silt dunes is locally derived from dry lake surfaces of ponded sediments (Qps), such as Red Lake, Tule Lake, Bishop Lake, Horse Lake, and several unnamed dry lakes and ponds in the Mount Floyd Volcanic Field and transported by southwesterly winds to accumulate on northeast shores of lakes and ponds. Support little to no vegetation due to heavy silt and clay content. Thickness, 6 to 80 ft (1.8 to 25 m)

Qv **Valley-fill deposits (Holocene and Pleistocene)**—Gray and light-brown silt, sand, and lenses of gravel; partly consolidated by gypsum and calcite cement. Include occasional rounded clasts of limestone, subrounded to angular chert, and subrounded to angular basalt. Intertongue or overlap young alluvial fan (Qay) deposits and young terrace-gravel (Qgy) deposits. Sediment accumulation is the result of low-energy and low-gradient stream flows. Subject to sheet-wash flooding and temporary ponding where vegetation is thickest. Support moderate growth of grass in lower elevations in central area of map, and heavy sagebrush, grass, cactus, and some juniper trees at higher elevations, generally above 6,000 ft (1,830 m). Thickness, 3 to 12 ft (1 to 3.7 m)

QTae **Old mixed alluvium and eolian deposits (Pleistocene and Pliocene(?))**—Lithologically similar to young mixed alluvium and eolian (Qae) deposits, but often capped by thin poorly developed calcrete soil; forms thicker deposits than young mixed alluvium and eolian (Qae) deposits. Include small cobbles and boulders. Form flat mesa-like benches about 30 to 120 ft (9 to 37 m) above modern drainage erosion in central part of map area. Unit is overlain in part by sand sheet and dune (Qd) and sand sheet (Qss) deposits in central and west half of map area. Thickness, 10 to 20 ft (3 to 6 m)

QTg **Old terrace-gravel deposits (Pleistocene and Pliocene(?))**—Lithologically similar to young terrace-gravel (Qgy) deposits but dominated by well-rounded quartzite pebble and cobble clasts. Form isolated outcrops or small mesas about 30 ft (9 m) above young terrace-gravel (Qgy) deposits and about 120 ft (37 m) above modern drainage of Cataract Canyon near Redlands Ranch. Deposits near Redlands Ranch were once part of thicker and more widespread deposits along Cataract Canyon, now largely removed by modern erosion. Thickness, 10 to 20 ft (3 to 6 m)

VOLCANIC ROCKS

Volcanic rocks of the San Francisco Volcanic Field (Pleistocene, Pliocene, and Miocene)—Volcanic rocks of the San Francisco Volcanic Field are defined, in part, by Wolfe and others (1987)

QTi **Intrusive dike or plug (Pleistocene and Pliocene; Matuyama age)**—Dark-gray aphyric basalt and microporphyritic olivine basalt. Includes welded pyroclastic fragments. Source for pyroclastic cones (QTp) and basalt flows (QTb). Specific dikes or plugs are 5 to 15 ft (1.5 to 4.5 m) wide

QTp **Pyroclastic deposits (Pleistocene and Pliocene; Matuyama age)**—Dark-gray to red cinders, agglutinated spatter, bomb and ribbon fragments; yellow-brown to red-brown where weathered. Cones rounded, somewhat subdued, little dissected although superficially gullied. Thickness, 200 to 400 ft (60 to 122 m)

QTb **Basalt flows (Pleistocene and Pliocene; Matuyama age)**—Dark-gray, yellow-brown to brown, aphyric and slightly porphyritic basalt and microporphyritic olivine basalt; surfaces mostly smooth, relatively flat, undissected. Includes thin, interbedded pyroclastic deposits near pyroclastic cone areas. Thickest near flow margins in some areas. Thickness, 30 to 200 ft (9 to 60 m)

QTai **Basalt and andesite dikes and necks (Pleistocene and Pliocene; Matuyama age)**—Dark-gray intersertal to subophitic basalt with abundant phenocrysts of clinopyroxene, plagioclase, and sparse olivine and hornblende. Source for Quaternary/Tertiary basaltic and andesite flows and pyroclastic deposits. Dikes and necks are 1 to 4 ft (0.5 to 1.3 m) wide

QTap **Basalt and andesite pyroclastic deposits (Pleistocene and Pliocene; Matuyama age)**—Dark-gray intersertal to subophitic pyroclastic deposits. Weathers light yellow-brown. Contain abundant phenocrysts of clinopyroxene and plagioclase in glassy groundmass. Form small pyroclastic cones and isolated pyroclastic deposits. Thickness, 20 to 200 ft (6 to 60 m)

QTab **Basalt and andesite flows (Pleistocene and Pliocene; Matuyama age)**—Dark-gray intersertal to subophitic basalt, with or without glass; partly blocky, hummocky, locally gullied. Weathers yellow-brown to brown. Contains abundant phenocrysts of clinopyroxene and plagioclase, subordinate phenocrysts of orthopyroxene, sparse phenocrysts of olivine and hornblende and scattered rounded quartz grains with clinopyroxene reaction rims. Groundmass is mostly fine grained or glassy and contain plagioclase microlites, opaque oxide, and small crystals of clinopyroxene. Thickness, 80 to 300 ft (25 to 92 m)

Thma **Andesite flows of Howard Mesa (Pliocene)**—Dark-gray to gray-black andesite; includes two lobes extending into map area from the south. Contains scattered phenocrysts of plagioclase and quartz 1/8 inch in diameter. Plagioclase is intensely corroded; quartz is less abundant, is corroded and has pyroxene reaction rims. Groundmass is hyalocrystalline consisting of glass, plagioclase microlites, hornblende prisms altered to opaque oxide, and other opaque grains. K/Ar age, 2.06±0.18 Ma, polarity reversed (Wolfe and others, 1987). Thickness, 200 ft (60 m) or more

Tyi **Young intrusive rocks (Pliocene; Gauss or Gilbert age)**—Dark-gray basalt and mixed pyroclastic dikes and necks. Composed of plagioclase, clinopyroxene, olivine, and opaque oxides. Intrusives from 4 to 20 ft (1.2 to 6 m) wide

Typ **Young pyroclastic deposits (Pliocene; Gauss or Gilbert age)**—Dark-gray to red cinder and spatter fragments; weather yellowish-brown, brown, or reddish-brown. Composed of clinopyroxene and olivine phenocrysts, plagioclase, opaque oxides, and glass. Mass wasting has diminished slope angles of pyroclastic cones; flanks are gullied to extensively eroded. Cones are elongated and aligned along a northwest trend in the Four Hills area indicating the influence of bedrock fractures and bedrock joints on vent position and orientation. Thickness, 30 to 200 ft (9.2 to 60 m)

Tyb **Young basalt flows (Pliocene; Gauss or Gilbert age)**—Medium- to dark-gray basalt; includes plagioclase-phyric, aphyric, and slightly porphyritic basalt. Smooth surfaced, partly dissected. Composed of plagioclase, clinopyroxene, olivine, and opaque oxides. Thickness less than 90 ft (28 m)

Trb **Basalt flow of Red Butte (Miocene)**—Dark-gray olivine basalt. Weathers brown; massive flow. K/Ar age, 8.92±0.23 Ma (Wolfe and others, 1987), 9.73±0.91 Ma and 8.78±0.22 Ma (Reynolds and others, 1986). Forms basalt caprock over thin soil deposit 3 to 5 ft (1 to 1.5 m) thick that was baked to a bright red; also partly overlies Shinarump Member of the Chinle Formation where soil is not present. Source of basalt is not present in the immediate vicinity of Red Butte and is assumed to be a dike under the basalt flow or is covered by surrounding landslide (Ql) deposits. Thickness, 165 ft (50 m)

Volcanic rocks of the Mount Floyd Volcanic Field (upper Miocene)—Volcanic rocks in the southwest part of the map area represent the northern part of the Mount Floyd Volcanic Field and have not been studied in detail. Paleomagnetic ages have not been determined. Hand specimens have been identified in the field during the course of this mapping project and are assigned temporary rock unit descriptions that are subject to change pending future investigations. A suggested general $^{40}Ar/^{39}Ar$ age for the northern part of the Mount Floyd Volcanic Field is 6.76±0.13 Ma and 6.38±0.04 Ma (Peters, 2002)

Tri **Rhyolite, rhyodacite, and obsidian dikes, necks, and vent areas (upper Miocene)**—Red, gray, and black rhyolite and rhyodacite. Rhyolite exhibits convoluted and twisted thin platy flow patterns; weathered outcrops resemble roof shingles. Map contacts are approximate because erosion has not fully exposed extent of these intrusive features. Vent area is source for extensive rhyolite, rhyodacite, and obsidian flows that overlie older basalt flows east of Red Lake. Include dikes and flows of black, gray, and red obsidian within vent areas

Tr **Rhyolite, rhyodacite, and obsidian flows (upper Miocene)**—Light gray, dark red, and grayish-black. Obsidian flows are mostly black obsidian but often contain black and gray-banded obsidian or red to red and black obsidian east of Red Lake and southwest of Black Tank Camp (sec. 18, T. 26 N., R. 4 W.). $^{40}Ar/^{39}Ar$ age, 6.38±0.04

Ma (Peters, 2002). Flows overlie one or more olivine basalt flows (Tba). Thickness, 30 to 200 ft (9.2 to 60 m)

Ti **Basalt and andesite dikes, plugs, and necks (upper Miocene)**—Dark-gray, finely crystalline alkali-olivine basalt. Contains augite and olivine phenocrysts in glassy groundmass. Intrusive units align in north or northwest trend, which parallel local prominent north and northwest strike of near-vertical fractures, joints, and faults in bedrock strata of the Coconino Plateau area. Dikes are 2 to 30 ft (0.6 to 9.2 m) wide; necks are as much as 100 ft (30 m) in diameter. Includes hypothetical laccolithic intrusion beneath Howard Hill as shown on cross section A–A´

Tp **Pyroclastic deposits (upper Miocene)**—Red and reddish-gray cinders, scoria, ash, and glassy fragments of basalt, partly unconsolidated. Form pyroclastic cones that overlie associated basalt and andesite flows (Tba). Cones are extensively eroded and gullied. Thickness, 20 to 400 ft (6 to 122 m)

Tba **Basalt and andesite flows (upper Miocene)**—Dark- to light-gray, finely crystalline alkali-olivine basalt. Most of the basalt came from elongated fissure dikes (Ti) and vent areas beneath pyroclastic cone deposits (Tp). Basalt flowed onto flat, partly eroded Tertiary sedimentary rocks of freshwater limestone, sandstone, and siltstone (Ts). Several basalt flows merge or coalesce into one large flow suggesting an eruptive phase of a similar time; $^{40}Ar/^{39}Ar$ age, 6.76±0.13 Ma (Peters, 2002) at Duff Brown Tank (sec. 28, T. 26 N., R. 3 W.). Thickness, 25 to 300 ft (7.5 to 92 m)

SEDIMENTARY ROCKS

Cenozoic, Mesozoic, and Paleozoic sedimentary rock. Tertiary rocks include siltstone, sandstone, and freshwater limestone (Ts) deposits beneath the volcanic rocks of the Mount Floyd Volcanic Field and areas west of Rose Well Camp, southwest third of map area. The Tertiary age sedimentary rocks are not formally named.

Ts **Sedimentary rocks (lower Eocene and upper Paleocene)**—Light-red, gray, and white interbedded siltstone, sandstone, arkosic gravel, lenticular conglomerate, and gray, thin-bedded [1 to 3 ft (0.5 to 1 m)] freshwater limestone. Limestone beds contain long vertical tubular structures generally ½ inch (0.12 cm) in diameter and 2 ft (1.3 m) in length and early Eocene to late Paleocene snail fossils (Young and Hartman, 1984; Young, 2001). Thickest limestone beds are near Black Tank Camp (sec. 3, T. 26 N., R 4 W.) and at Duff Brown Tank (sec. 28, T. 26 N., R. 3 W.). Conglomerate beds are thickest at the base of sedimentary rocks and are partly consolidated thin units within the sedimentary sequence. Conglomerate clasts consist primarily of quartzite, chert, and minor granite or metamorphic crystalline rocks derived from sources south of map area as far away as Prescott and Kingman, Arizona. Clasts are well rounded and weather out of the general slope deposit and form extensive lag gravel deposits within several miles of outcrop. Several outlying hills are covered by lag gravel conglomerate derived from the erosion of Tertiary sedimentary rocks north of the Mount Floyd Volcanic Field. Extensive conglomerate and sandstone deposits form rounded hills or ridges in the Rose Well Camp vicinity. Rocks of the Mount Floyd Volcanic Field form a protective caprock over these Tertiary sedimentary rocks throughout the southwest quarter of the map area. Thickness, 60 to 180 ft (18 to 55 m)

Ŧcs **Shinarump Member of the Chinle Formation (Upper Triassic)**—White, coarse-grained, cliff-forming, low-angle crossbedded sandstone and pebble conglomerate. Unit is overlain by thin soil that is baked brick red by overlying basalt flow at Red Butte. Sandstone and conglomerate is partly baked red by basalt flow where basalt is in direct contact. Disconformable contact with underlying red siltstone and sandstone beds of the Moenkopi Formation. Unit is likely part of a paleovalley filled with fluvial deposits that make up the Shinarump Member of the Chinle Formation. Thickness, 85 ft (26 m)

Ŧm **Moenkopi Formation (Upper(?) and Lower Triassic)**—Red, slope-forming, fine-grained, thin-bedded shaley siltstone and sandstone. Includes a white, cliff-forming, coarse-grained, low-angle crossbedded sandstone in lower quarter of unit that may be equivalent to the Moki Member of the Moenkopi Formation east of the map area, or the Shnabkaib Member of the Moenkopi Formation north of the map area. Unit is mostly eroded from map area except for outcrops beneath volcanic rocks in southeast quarter, isolated outcrops in southwest part of map in the vicinity of Valle, Arizona, and at Red Butte. A complete section of the Moenkopi Formation is present only at Red Butte. The basal Timpoweap Member of the Moenkopi Formation (unit not mapped) is a conglomeratic limestone or calcareous sandstone with small chert-conglomerate pebbles that occupy shallow Triassic channels eroded into underlying Harrisburg Member of the Kaibab Formation in eastern quarter of the map area (mapped as Moenkopi Formation ₸m). Channels that are too small to show at map scale are exposed along Spring Valley Wash and on private ranch lands just east of State Highway 64 and are as much as 50 ft (15 m) deep. Other channel exposures are east of Red Butte, along Red Horse Wash on U.S. Forest Service lands southeast of Red Butte, along State Highway 64 southwest of Red Butte just north of Red Horse Wash, and southwest of Redlands Ranch. Unit is distinguished from underlying red siltstone and sandstone beds of the Harrisburg Member of the Kaibab Formation (Pkh) by its darker red color and thin-bedded, platy, coarse-grained sandstone beds as opposed to massive-bedded, pale-red, undulating, siltstone and sandstone beds of the Harrisburg Member of the Kaibab Formation. Forms unconformable contact with underlying Harrisburg Member of the Kaibab Formation representing the regional Permian/Triassic boundary. Thickness, 1,000 ft (305 m)

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

Pkh **Harrisburg Member**—Reddish-gray and brownish-gray, slope-forming gypsum, siltstone, sandstone, and thin-bedded limestone. Includes yellowish-gray fossiliferous sandy limestone at top of unit that is eroded from much of the map area. A gray, thin-bedded, fossiliferous cherty limestone and sandy limestone in middle part of unit form much of the surface bedrock in the central map area. Calcareous sandstone beds west of and near Cataract Canyon have large-scale dessication cracks up to 2 ft (0.6 m) wide filled with reworked calcareous sandstone that form resistant polygon patterns averaging about 14 ft (4.3 m) in diameter; the patterns on aerial photos resemble the surface of a golf-ball. These dessication cracks represent a shallow marine tidal flat subject to extensive dry conditions during the late part of Kaibab Formation deposition. Lower part is yellowish-gray to pale-red gypsiferous siltstone and calcareous sandstone; gray thin-bedded sandy limestone; and gray to white, thick-bedded gypsum in the vicinity of Cataract Canyon and northwest half of map area. Dissolution weathering of gypsum beds within lower part has resulted in warping and bending of limestone beds in middle part into or near local drainages on the Coconino Plateau. Gypsum dissolution within the Harrisburg Member of the Kaibab Formation is also responsible for the development of several large-scale sinkhole depressions and internal drainage basins such as Hazen Hole Tank, northwest half of map area. Dissolution of gypsum beds in underlying Toroweap Formation may be partly responsible for several internal drainage basin depressions in northwest half of map area, especially in the vicinity of collapse structures. Contact with underlying Fossil Mountain Member of the Kaibab Formation is gradational and arbitrarily marked at top of thick, white, cherty limestone zone near top of limestone cliff in canyon profile. Thickness, 120 ft (37 m) in northeast quarter of map thickening to about 260 ft (80 m) in west half of map

Pkf **Fossil Mountain Member**—Light-gray, cliff-forming, fine- to medium-grained, thin- to thick-bedded [1 to 6 ft (0.3 to 1.8 m)], fossiliferous, sandy, cherty limestone. Weathers dark gray. Unit characterized by gray to white fossiliferous chert nodules and white chert lenses parallel to limestone bedding; chert weathers dark gray to black. Some chert nodules contain concentric black and white bands. Includes brecciated chert beds 4 to 10 ft (1.2 to 3 m) thick in upper part near contact of overlying Harrisburg Member of the Kaibab Formation. Chert makes up about 20 percent of unit and becomes sandier in northeast quarter of map area. Generally forms cliff at rim of Grand Canyon (Cataract Canyon) overlain by thin cover of gray to red siltstone and sandy limestone beds of Harrisburg Member. Unconformable contact with underlying Woods Ranch Member of the Toroweap Formation (Pt) attributed to solution erosion and channel erosion; average channel relief about 10 ft (3 m). Some channels have eroded as much as 150 ft (46 m) into Woods Ranch Member just north of map area at National and Mohawk Canyons (Billingsley, 2000). Erosion channels are filled with sandy cherty limestone typical of the Fossil Mountain Member strata, which provides an extra thickness of the Fossil Mountain section. Thickness, 230 ft (70 m) in east half of the map, thickening to about 300 ft (92 m) in west half

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

Woods Ranch Member is gray and light-red, slope-forming gypsiferous siltstone and silty sandstone, interbedded with white laminated gypsum beds and thin-bedded gray limestone. Gypsum beds are as much as 10 ft (3 m) thick. Unit as a whole weathers reddish gray. Bedding locally distorted due to dissolution of gypsum. Contact with underlying Brady Canyon Member is gradational and arbitrarily marked at top of cliff-forming limestone beds of Brady Canyon. Unit commonly thins to less than 20 ft (6 m) thick in vicinity of large collapse structures due to dissolution of gypsum. Variable thickness owing to dissolution of gypsum and channel erosion in upper part; average thickness, 65 ft (20 m) in north-central part of map, thickens to 200 ft (60 m) in west half of map, thins to less than 50 ft (15 m) in southeast quarter of map.

Brady Canyon Member is gray, cliff-forming, thin- to medium-bedded [1 to 5 ft (0.5 to 1.5 m)], fine- to coarse-grained, fetid, fossiliferous limestone. Weathers dark gray. Includes thin-bedded dolomite in upper and lower part. 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 Brady Canyon. Thickness, 40 ft (12 m) in northeast half of map area, increasing to about 130 ft (40 m) at northwest edge of map as exposed in Grand Canyon (Billingsley, 2000; Billingsley and Wellmeyer, 2003).

Seligman Member is gray, light-purple, yellowish-red, slope-forming, thin-bedded dolomite, limestone, sandstone, gypsum, and calcareous sandstone. Includes a unit of crossbedded sandstone equivalent to the Coconino Sandstone, which is mapped separately. Includes yellowish-gray to red, thin-bedded sandstone below Coconino Sandstone tongue in the western Grand Canyon area; these beds thin eastward across the map area allowing the Coconino Sandstone to unconformably overlie the Hermit Formation in the central and eastern Grand Canyon areas. Forms slope or recess between cliff-forming Brady Canyon Member and cliff-forming Coconino Sandstone (Pc) in west half of map area, and slight recess at base of Coconino Sandstone at contact of red sandstone and siltstone of the Hermit Formation. Coconino Sandstone intertongues within lower part of Seligman Member (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; and Billingsley and others, 2000a). Thickness, 30 ft (9.2 m) in east half of map, increasing to 55 ft (17 m) in west half

Pc **Coconino Sandstone (Lower Permian)**—Tan to white or pale-red, cliff-forming, fine-grained, well-sorted, crossbedded quartz sandstone. Contains large-scale, high-angle, planar crossbedded sandstone sets that average about 35 ft (11 m) thick. Locally includes small and large fossil footprints and low-relief wind ripple marks on crossbedded planar sandstone surfaces. The lower and upper [5 to 20 ft (1.5 to 6 m)] intertongues with thin-bedded, partly calcareous, flat-bedded sandstone beds of Seligman Member of the Toroweap Formation in western Grand Canyon area (Billingsley and others, 2000a; Billingsley, 2000; Billingsley and others, 2001; Billingsley and Wellmeyer, 2003). Coconino Sandstone is mapped separately from Toroweap Formation because it forms a mappable unit and is an established unit of the Grand Canyon nomenclature. Unconformable contact with underlying Hermit Formation (Ph) in the central and eastern Grand Canyon area as a sharp planar contact with erosional relief less than 3 ft (1 m) but locally as much as 8 ft (2.5 m). Thickness of Coconino increases from 150 (46 m) to over 500 ft (153 m), west to east in subsurface of map area according to exposures in Grand Canyon north of map area and several miles south of map area

Ph **Hermit Formation (Lower Permian)**—Red, slope-forming, fine-grained, thin-bedded siltstone and sandstone. Upper part contains red, massive, low-angle crossbedded calcareous sandstone and siltstone beds. Dark-red crumbly siltstone beds fill shallow erosion channels. Siltstone beds form recesses between thicker light-red sandstone beds. Unit locally contains poorly preserved plant fossils within channel fill deposits in lower part of formation. Sandstone beds thicken and thin laterally either as channel fill or low-angle crossbedded sand dune or stream channel accumulations. Sandstone bleaches to yellowish-white at upper contact with Coconino Sandstone (Pc). Unconformably overlies Esplanade Sandstone (Pe) with erosion channels generally less than 10 ft (3 m) in depth. Some channels are as much as 130 ft (40 m) and commonly 30 ft (9.2 m) deep in lower Cataract Canyon area just north of map area (Billingsley, 2000). Otherwise, erosional relief is generally less than 10 ft (3 m) between channel areas. Unit thins south and east of Cataract Canyon to less than 260 ft (80 m) in southeast part of map based on thinning of unit in Grand Canyon (Billingsley, 2000); thickens west and north of Cataract Canyon to 850 ft (260 m); Billingsley and others, 2000b; Billingsley and Wellmeyer, 2003)

Supai Group (Lower Permian, Upper, Middle, and Lower Pennsylvanian, and Upper Mississippian)—Only the Esplanade Sandstone of the Supai Group is exposed in map area. Units beneath the Esplanade Sandstone are exposed in Grand Canyon north of the map area. The Supai Group 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 Formation is defined by Martin and Barrick (1999). Divided into Esplanade Sandstone (Pe); and Wescogame, Manakacha, and Watahomigi Formations, undivided (PMs)

Pe **Esplanade Sandstone (Lower Permian)**—Light-red and pinkish-gray, cliff-forming, fine- to medium-grained, medium- to thick-bedded [3 to 10 ft (1 to 3 m)], well sorted calcareous sandstone. Includes interbedded dark-red, thin-bedded, crumbly recesses of slope-forming siltstone between sandstone beds in upper and lower part. Crossbeds are small- to medium-scale, planar low-angle and high-angle sets. Unconformable contact with underlying Wescogame Formation marked by erosion channels as much as 50 ft (15 m) deep filled with calcareous sandstone and limestone conglomerate; average channel depth about 35 ft (11 m) in Cataract Canyon, north of map area. Erosion of Cataract Canyon has not extended completely through Esplanade Sandstone. Total thickness in Cataract Canyon north of map area is 400 to 450 ft (122 to 137 m); Billingsley, 2000). Incomplete exposure in map area; thickness, 120 ft (37 m)

UNITS SHOWN ONLY IN CROSS SECTION

[Based on exposures in Grand Canyon ½ to 20 mi north of the map area (Billingsley, 2000), northwest of map area (Billingsley and Wellmeyer, 2003), and west of map area (Billingsley and others, 2000b]

PMs **Wescogame (Upper Pennsylvanian), Manakacha (Middle Pennsylvanian), and Watahomigi Formations (Lower Pennsylvanian and Upper Mississippian), undivided**—Wescogame Formation is light-red, pale-yellow, and light-gray upper slope unit and lower cliff unit. Upper slope consists mainly of dark-red, fine-grained siltstone and mudstone interbedded with light-red, coarse-grained calcareous sandstone and dolomitic sandstone and conglomerate. Lower cliff consists mainly of light-red to gray, high-angle, large- and medium-scale, tabular-planar crossbedded 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. Unconformable contact with underlying Manakacha Formation marked by unconformity of erosion channels as much as 80 ft (25 m) deep in western part of map area and less than 30 ft (9 m) deep in eastern part of map area. Channels commonly filled with limestone/chert conglomerate. The Wescogame Formation thickens slightly from west to east, averaging about 130 ft (40 m) thick in west part of map area to about 150 ft 46 m) in east part.

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

Watahomigi Formation is gray and purplish-red, slope-forming limestone, siltstone, mudstone, and conglomerate. Forms an upper ledge/slope and a lower slope. Upper ledge/slope consists of alternating gray, thin-bedded cherty limestone ledges interbedded with purplish-gray siltstone and mudstone. 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, locally containing Early Pennsylvanian fossils. Upper ledge and slope averages about 70 ft (22 m) thick throughout map area. Lower slope consists 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 Late Mississippian (Martin and Barrick, 1999). Unit includes purple siltstone and gray limestone interbedded with conglomerate that fills small erosion channels cut into either the Surprise Canyon Formation (Ms) or Redwall Limestone (Mr). Purple shale and mudstone of lower slope unconformably overlies gray Redwall Limestone in majority of map area and unconformably overlies the Surprise Canyon Formation where present. Contact with the Surprise Canyon Formation is often based on color change from purple mudstone of Watahomigi Formation to dark-red mudstone of Surprise Canyon Formation. Unit averages about 100 ft (30 m) thick along east edge of map area thickening to 200 ft (60 m) along west 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 and present only in paleovalleys and karst caves eroded into top half of the Redwall Limestone (Mr). Consists of an upper slope, a middle cliff, and lower slope in west half of map area; forms slope in east half of map area.

Upper slope consists of reddish-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 consists of a reddish-gray, thin-bedded, coarse-grained silty and sandy limestone containing numerous marine fossils. Average thickness about 50 ft in (15 m) west third of map area, thins and pinches out in east two-thirds of map area based on exposures in Grand Canyon north of map area (Billingsley, 2000). Lower slope consists of dark reddish-brown to black, iron-stained, thin-bedded, coarse- to medium-grained siltstone, sandstone, limestone, and conglomerate. Sandstone and siltstone beds contain numerous plant fossils and bone fossils, mudcracks, and ripplemarks. Sandstone is coarse grained and thin bedded with some low-angle, crossbedded sets. Conglomerate beds consist of white and gray chert clasts supported in dark-red to black, coarse-grained chert sandstone or gravel matrix, all derived from erosion of the Redwall Limestone. Thickness of lower slope, about 3 to 60 ft (1 to 18 m), averages about 25 ft (7.5 m). In east half of map area, the Surprise Canyon Formation consists mainly of dark reddish-brown, slope-forming, massive to thin-bedded, poorly sorted siltstone and sandstone containing plant fossils.

The Surprise Canyon Formation is the most fossiliferous rock unit in the Grand Canyon. Overall, thickness averages about 145 ft (44 m) in west half of map area, thinning to less than 50 ft (15 m) in east half

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

Horseshoe Mesa Member is light-olive-gray, ledge- and cliff-forming, thin-bedded, fine-grained limestone. Weathers to form receding ledges. Gradational and disconformable contact with underlying massive-bedded limestone of Mooney Falls Member marked by thin-bedded platy limestone beds of Horseshoe Mesa Member that form recess about 3 to 9 ft (1 to 3 m) thick near top of Mooney Falls cliff. 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 to 100 ft (15 to 30 m).

Mooney Falls Member is light-gray, cliff-forming, fine- to coarse-grained, thick-bedded to very thick bedded [4 to 20 ft (1.2 to 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 underlying Thunder Springs Member 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. Unit thickens from about 250 ft (76 m) in southeast quarter of map 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 to 5 in (2.4 to 12 cm)], finely crystalline dolomite and fine- to coarse-grained limestone interbedded with white chert beds. Limestone common in north half of map area; dolomite is common in south half. Locally includes large-scale crossbedding and irregularly folded beds in north half of map area. Fossil content increases from east to west across map area. Disconformable planar contact with underlying Whitmore Wash Member is 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 (46 m) thick in north half.

Whitmore Wash Member is yellowish-gray and brownish-gray, cliff-forming, thick-bedded, fine-grained dolomite. 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 to 20 ft (1.5 to 6 m) in depth. Contact generally recognized where major cliff of the Redwall Limestone overlies stair-step ledges of the Temple Butte Formation in Grand Canyon. 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 (2003). 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 east half of map area, and about 40 ft (12 m) deep in west 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 weathers to dark-gray sequence of ledges. Unconformity at base represents major stratigraphic break in the Paleozoic rock record in Grand Canyon, spanning part of the Late Cambrian, all of the 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 east half of map area to as much as 275 ft (84 m) in west half of map area, excluding extra channel fill 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 basis of distinct rock types: limestone and dolomite lithologies belong to the Muav Limestone; shale and siltstone lithologies belong to the Bright Angel Shale; and sandstone and conglomerate lithologies belong to the Tapeats Sandstone (Rose, 2003). Tonto Group may overlie tilted strata of Grand Canyon Supergroup of Middle Late Proterozoic (1.4 to 1.1 billion years) age in east part of map area and igneous and metamorphic rocks of Early Proterozoic (1.7 to 1.6 billion years) age in central and west 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, 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 positioned 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 Shale is gradational and lithology dependent. Contact is arbitrarily marked at base of lowest prominent limestone of Rampart Cave Member of the Muav Limestone in west quarter of map area, and at base of limestone of Peach Springs-Kanab Canyon Members of the Muav Limestone in east three-quarters of map area. All members of the Muav Limestone thicken from east to west across map area and thin south to the south edge of map area. However, the Peach Springs, Spencer Canyon, and Rampart Cave Members change to purplish-red and green siltstone/shale facies of the Bright Angel Shale in east quarter of map area where they are included as part of the Bright Angel Shale map unit. Intertonguing and facies change relations between the Muav Limestone and Bright Angel Shale produce variable thickness trends. Overall, the Muav Limestone thickens from about 359 ft (107 m) in east part of map area to about 600 ft (183 m) in west part

Ꞓba **Bright Angel Shale (Middle and Lower(?) Cambrian)**—Green and purple-red, slope-forming siltstone and shale, and interbeds of reddish-brown to brown sandstone of Tapeats Sandstone lithology. Includes ledge-forming red-brown sandstone member of McKee and Resser (1945). Consists of green and purplish-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 in western quarter of map area. Intertonguing and facies change relations with the underlying Tapeats Sandstone produce variable thickness trends. Contact with Tapeats Sandstone is arbitrarily marked at lithologic vertical and lateral transition from predominantly green siltstone and shale to predominantly brown sandstone above Tapeats Sandstone cliff. About 350 ft (107 m) thick in east quarter of map area, thickening to about 500 ft 153 m) in northwestern quarter, thinning to about 150 ft (46 m) in southwest quarter

Ꞓt **Tapeats Sandstone (Middle and Lower(?) Cambrian)**—Brown and reddish-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 sandstone and conglomeratic sandstone. Lower cliff consists mainly of medium- to coarse-grained, thin-bedded, low-angle planar and trough crossbedded sandstone and conglomeratic sandstone; sandstone beds are 6 to 24 in (14 to 58 cm) thick. Unconformable contact with underlying Early Proterozoic rocks that form the Great Unconformity. The Tapeats Sandstone fills lowland areas and thins across or pinches out against Proterozoic highlands. Variable thickness, 0 to 400 ft (0 to 122 m)

Xu **Crystalline rocks, undivided (Early Proterozoic)**—Includes various types of igneous and metamorphic granite, and crystalline schist and gneiss. Thickness unknown

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