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

Geologic Map of the Fredonia 30´ x 60´ Quadrangle, Mohave and Coconino Counties, Northern Arizona

By George H. Billingsley, Susan S. Priest, and Tracey J. Felger

Pamphlet to accompany

Scientific Investigations Map 3035

View looking south into Kanab Canyon from Gunsight Point, showing lower Permian strata from Esplanade Sandstone to Kaibab Formation at the rim. *Photograph by George H. Billingsley*.

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Introduction

This geologic map is the result of a cooperative effort of the U.S. Geological Survey, the National Park Service, the U.S. Forest Service, and the Bureau of Land Management (BLM) and the Kaibab-Paiute Tribe to provide a regional geologic database for resource management officials of all government and agencies, city municipalities, private enterprises, and individuals of this part of the Arizona Strip. The Arizona Strip is part of northwestern Arizona north of the Colorado River and bounded by the States of Nevada and Utah. Field work on the Kaibab-Paiute Indian Reservation was conducted from 2002 to 2005 with permission from the Kaibab-Paiute Tribal Government of that administration and permission was granted to publish a geologic map of 4 quadrangles online (Billingsley and others, 2004). **The Kaibab-Paiute Tribal government of 2006 to 2008 requested that all geologic information within the Kaibab-Paiute Indian Reservation not be published as part of the Fredonia 30´ x 60´ quadrangle (this publication)**. For further information, contact the Kaibab-Paiute Tribal government at HC 65 Box 2, Fredonia, Arizona, 86022, telephone # (928) 643-7245. Visitors to the Kaibab-Paiute Indian Reservation are required to obtain a permit and permission for access from the Tribal Offices at the junction of State Highway 389 and the paved road leading to Pipe Spring National Monument.

The Fredonia 30´ x 60´ quadrangle encompasses approximately 5,018 km^2 (1,960 mi^2) within Mohave and Coconino Counties, northern Arizona and is bounded by longitude 112° to 113° W., and latitude 36°30´ to 37° N. The map area lies within the southern Colorado Plateaus geologic province (herein Colorado Plateau). The map area is locally subdivided into seven physiographic parts: the Grand Canyon (Kanab Canyon and its tributaries), Kanab Plateau, Uinkaret Plateau, Kaibab Plateau, Paria Plateau, House Rock Valley, and Moccasin Mountains as defined by Billingsley and others, 1997, (fig. 1). Elevations range from 2,737 m (8,980 ft) just west of State Highway 67 on the Kaibab Plateau, southeast corner of the map area to about 927 m (3,040 ft) in Kanab Canyon, south-central edge of the map area.

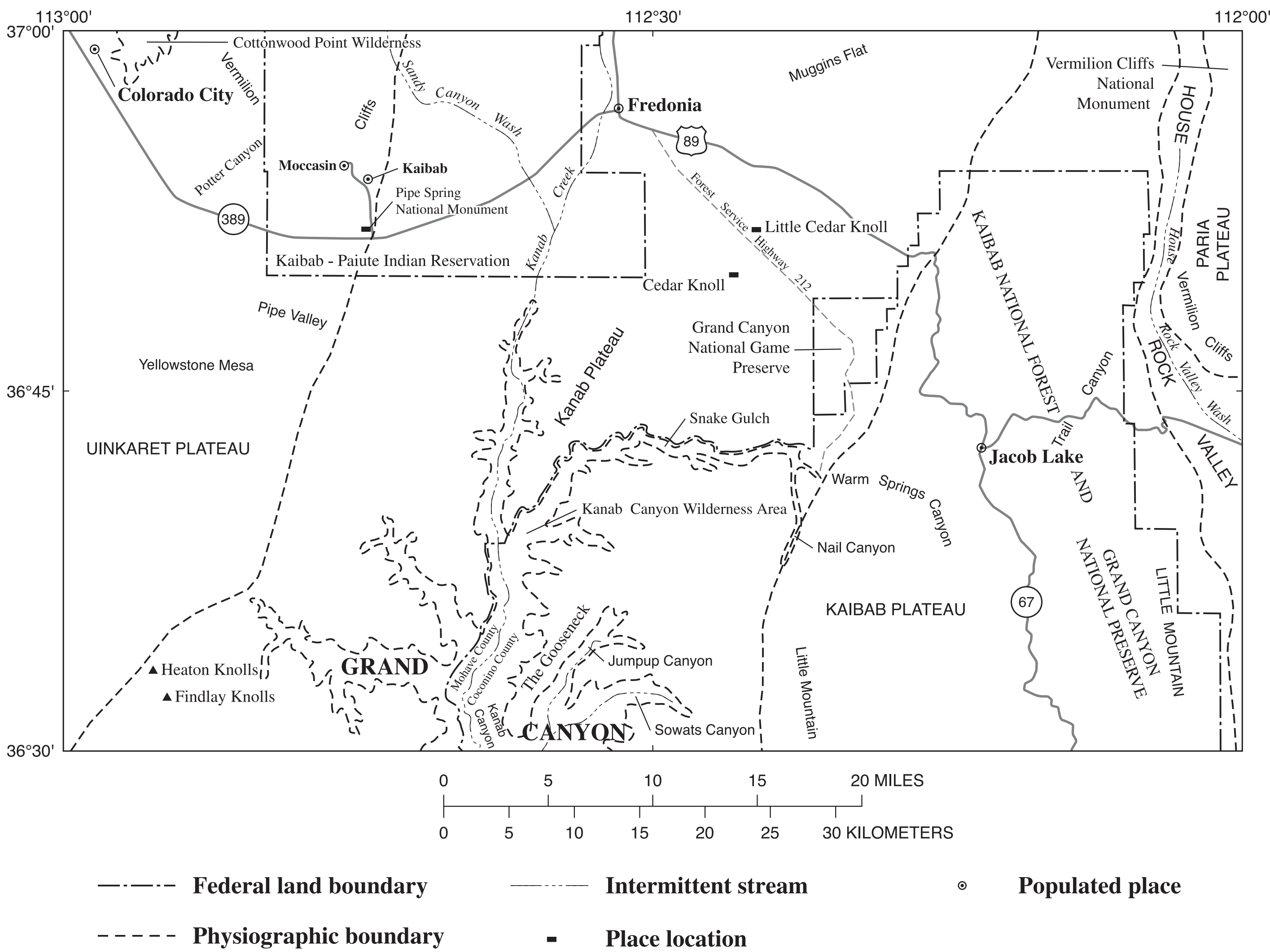

Figure 1. Index map of the Fredonia 30´ x 60´ quadrangle, Arizona showing the physiographic, cultural, and geologic locations mentioned in the text.

The Vermilion Cliffs are a prominent, 457-m (1,500-ft) high feature in the northern part of the map area that mark the southern, western, and eastern edges of the Moccasin Mountains, and the western edge of the Paria Plateau. The north edge of the map area is the Utah/Arizona State line. Settlements within the Fredonia 30´ x 60´ quadrangle include Colorado City, Fredonia, Moccasin, Kaibab, and Jacob Lake, Arizona (fig. 1). U.S. Highway 89A provides access to the northeast quarter of the map area, State Highway 389 provides access to the northwest quarter of the map area, a short paved road from State Highway 389 leads to Pipe Spring National Monument and the towns of Kaibab and Moccasin, Arizona, and State Highway 67 (a one-way in and one-way out access road) provides access to the North Rim of the eastern Grand Canyon about 32 km (20 mi) south of the southeast quarter of the map area.

The Bureau of Land Management Arizona Strip Field Office in St. George, Utah, manages BLM lands in the western, central, and northeastern part of the Fredonia quadrangle that are accessible by several unimproved dirt roads. Gravel roads in this part of the map area are maintained by the BLM but travel on some of these roads requires a 4-wheel-drive vehicle. Access to the Vermilion Cliffs National Monument (BLM) in the northeast corner of the map area is by a gravel road in House Rock Valley that leads north from U.S. Highway 89A; back country hiking or use permits are required from the BLM offices in Fredonia, Arizona, or St. George, Utah. Part of the Cottonwood Point Wilderness area (BLM) is within the northwest corner of the map area just east of Colorado City, Arizona.

U.S. Forest Service graveled roads provide access to the Kaibab National Forest and the Grand Canyon National Game Preserve in the southeastern quarter of the Fredonia quadrangle, but access is often restricted or the areas closed during winter months because of heavy snow accumulations from October through April, including closure of State Highway 67 to the North Rim of Grand Canyon. Access to the Kanab Canyon Wilderness Area and canyon tributaries is by foot trails; back country hiking permits are required and are obtained from the Kaibab National Forest Visitors Center at Jacob Lake, Arizona. Back country hiking permits, obtained from Grand Canyon National Park at Grand Canyon, Arizona, are required for foot travel into Grand Canyon National Park at the south-central edge of the map in Kanab Canyon area. Extra water and food is highly recommended for travel into the remote areas of the Arizona Strip (this map area). There are several small parcels of private and State land scattered throughout the map area, mainly near the settlements of Colorado City and Fredonia, Arizona.

The Fredonia quadrangle is one of the few remaining areas near the Grand Canyon where new geologic mapping is needed for geologic connectivity of the regional geologic framework. This map provides an updated regional geologic database for use by federal, state, and private land resource managers who direct environmental and land management programs such as range management, biological studies, flood control, and water resource investigations. The geologic information will support future and ongoing local geologic investigations and associated scientific studies of all disciplines within the Fredonia quadrangle and the Grand Canyon area.

Kanab Creek, which flows south toward the Colorado River in Grand Canyon, is the principal drainage in the western two-thirds of the map area. House Rock Valley Wash drainage, which flows southeastward toward Marble Canyon of the Grand Canyon about 21 km (13 mi) east of House Rock Valley, drains the eastern third of the map area. Elevations below about 1,525 m (5,000 ft) generally support a sparse growth of sagebrush, cactus, grass, and various high-desert shrubs. Elevations above about 1,525 m (5,000 ft) commonly support moderate to thick growths of sagebrush and grass in alluvial valleys, while woodlands of pinion pine, juniper, and oak trees thrive on hilly terrain between 1,525 to 2,135 m (5,000 to 7,000 ft), and forests of ponderosa pine and douglas fir thrive at elevations above 2,235 m (7,000 ft) on the Kaibab Plateau. Salt cedar (tamarisk) and Russian olive trees grow along the banks of Kanab Creek and its tributary washes.

Previous Studies

Hemphill (1956), Marshall (1956 a–e), Marshall and Phillmore (1956), McQueen (1956; 1957), Minard (1957), Morris (1956; 1957), Pillmore (1956), Pomeroy (1957), and Wells (1958; 1959; 1960) made the earliest photogeologic maps of the area for the U.S. Atomic Energy Commission. Those maps were later compiled onto a geologic map of Coconino County, Arizona, by Wilson and others (1960) and onto a state geologic map of Arizona by Wilson and others (1969). More recent geologic maps within the Fredonia 30´ x 60´ quadrangle include Billingsley and others (1983), Bush (1983), Billingsley (1992), Billingsley and others (2001), Billingsley and others (2004), Billingsley and Hampton (2001), and Billingsley and Wellmeyer (2001). Geologic maps of adjacent areas include the Grand Canyon 30´ x 60´ quadrangle that borders the south edge (Billingsley, 2000), the Littlefield 30´ x 60´ quadrangle that borders the west edge (Billingsley and Workman, 2000), and the Kanab 30´ x 60´ quadrangle that borders the north edge (Sable and Hereford, 2004).

Mapping Methods

The geology was mapped using 1:24,000-scale 2005 color aerial photographs courtesy of the Bureau of Land Management, Arizona Strip Office in St. George, Utah, and 1:24,000-scale 1994 color aerial photographs courtesy of the U.S. Forest Service, North Kaibab Ranger District in Williams, Arizona. The map units and geologic structures were field checked to insure accuracy and consistency of map unit descriptions. Many of the Quaternary alluvial deposits have similar lithology but have different geomorphic characteristics and are mapped almost entirely by aerial photography. Relative ages of surficial fluvial and eolian deposits are approximate and are determined by stratigraphic position and the amount of erosional degradation.

Susan S. Priest and Tracey J. Felger (U.S. Geological Survey), Flagstaff Science Center, compiled the map in digital format using Arc/Map techniques. Twenty-six detailed 1:24,000 scale USGS quadrangles and parts of five other 1:24,000-scale quadrangles (Moccasin, Pipe Valley, Pipe Spring, Clear Water Spring, and Fredonia; fig. 2, map sheet) initially compiled to produce this map can be seen as view maps in the USGS web site address. This map is the 7th of a series of digital geologic maps of the Grand Canyon region.

Geologic Setting

The Fredonia map area is north of the eastern Grand Canyon and within the southern part of the Colorado Plateau physiographic province (Billingsley and others, 1997). The area is characterized by nearly horizontal Paleozoic and Mesozoic sedimentary strata that have an average regional dip of about 1° to 2° north-northeast in the western two-thirds of the map area; the strata are gently warped by minor anticlinal and synclinal folds and are offset by normal faults. The Kaibab Anticline (sometimes referred to as the Kaibab Uplift or Kaibab Arch) is a broad, large scale, north trending, north plunging anticline in the eastern third of the map area; the anticline axial trace is approximately located in the northeast quarter of the map area (see cross-section *A–A´*). The Kaibab Anticline elevates the Paleozoic strata as much as 610 m (2,000 ft) higher than the surrounding plateaus west and east of the structure and forms the Kaibab Plateau, a sub plateau of the Colorado Plateau. The eastern flank of the Kaibab Anticline is marked by the East Kaibab Monocline that is divided into an upper and lower segment in the southeast corner of the map area. The western flank of the Kaibab Anticline is marked by the Muav and North Road Faults that offset Paleozoic strata down-to-the-west. The Big Springs Fault angles southeastward into the Kaibab Plateau towards the north rim of Grand Canyon at the south edge of the map area. Mesozoic strata that once covered the Kaibab Anticline have been removed by Cenozoic erosion. The East Kaibab and Moccasin Monoclines are the principal folds in the map area and all have east-dipping strata and a general north-south axial trend. The Moccasin Monocline is not shown on the map because it lies within the Kaibab-Paiute Indian Reservation. A small part of the Moccasin Monocline is shown within the private town of Moccasin, Arizona.

The Sevier, Toroweap, Big Springs, Muav, and North Road Faults are the principal faults within the map area and have a general north-south strike and offset Paleozoic and Mesozoic strata down-to-the-west. There are several small normal faults and minor folds throughout the map area that commonly parallel the northeast and northwest trending bedrock joints and fractures.

The sedimentary section within the map area consists of about 793 m (2,600 ft) of Paleozoic strata and about 1,035 m (3,400 ft) of Mesozoic strata including some minor Tertiary stream-channel (Ts) deposits. Quaternary deposits are widely distributed and consist primarily of fluvial alluvium and eolian sand deposits. The fluvial and eolian deposits are often intertongued and are mapped as mixed alluvium and eolian deposits. Talus, rock fall, and landslide deposits are also mapped as well as most man made quarries, small open pit mines, drainage diversion dams, large ditches, and stock tanks, but agricultural fields and several minor road cut excavations are not mapped. Map contacts between all Quaternary surficial deposits are approximate and are shown as a solid line where deposits intertongue and exhibit a gradational facies changes in both the lateral and vertical sense. The surficial units are important to local resource managers for helping to base management decisions regarding rangeland conditions, flood control problems, biological studies, soil erosion, and construction and development projects. The surficial deposits are commonly Pleistocene? or Holocene age (less than 2 m.y.) based on K-Ar dates of volcanic rocks associated with similar surficial deposits mapped in the southwest corner of the map area and adjacent parts of the Uinkaret Volcanic Field (Billingsley and Workman, 2000; Billingsley and others 2001; Billingsley and Priest, 2003).

Paleozoic and Mesozoic Sedimentary Rocks

The Paleozoic and Mesozoic stratigraphic units exposed within the map area include, in order of oldest to youngest (bottom to top): Redwall Limestone (Mississippian), Supai Group (Upper Mississippian, Pennsylvanian, and Lower Permian), Hermit Formation (Lower Permian), Coconino Sandstone (Lower Permian), Toroweap Formation (Lower Permian), Kaibab Formation (Lower Permian), Moenkopi Formation (Lower and Middle(?) Triassic), Chinle Formation (Upper Triassic), Moenave Formation (Lower Jurassic), Kayenta Formation (Lower Jurassic), and Navajo Sandstone (Lower Jurassic). The Surprise Canyon Formation (Billingsley and Beus, 1999) is not exposed in the map area but may be present in the subsurface of the map area as a reddish sediment accumulation in local paleovalleys and karst caves eroded into the top part of the Redwall Limestone. The Surprise Canyon Formation, the most fossiliferous rock strata in Grand Canyon, contains numerous shallow water marine fossils and land-based plant fossils. Ages of the Mesozoic strata have been revised on the basis of new data from these strata in southern Utah (Biek and others, 2007).

Gray limestone cliffs of the Redwall Limestone (Mississippian) form narrow canyon walls within the lower part of Kanab Creek and Jumpup Canyon at the south-central edge of the map area and are the oldest exposed rock unit of the map. Devonian and Cambrian rock strata shown on cross-sections *A–A´* and *B–B´* are based on exposures south of the map area in the Grand Canyon. The Surprise Canyon Formation (Upper Mississippian) is likely present in the subsurface of the map area, and it would be a reddish marine stratum that fills erosional valleys, channels, and karst features within the upper part of the Redwall Limestone. The lower part of the Supai Group (Upper Mississippian, Pennsylvanian, to lower Permian) forms the red slopes and cliffs above the Redwall Limestone in lower Kanab Creek and its tributaries; a light-red cliff of the Esplanade Sandstone (Lower Permian) caps the lower part of the Supai Group. The Esplanade Sandstone forms a sandstone bench or platform in the lower reaches of Kanab Creek at about 1,250 m (4,100 ft) elevation which forms the Sanup Plateau in the western Grand Canyon area about 48 km (30 mi) west of the map area. Above the Esplanade Sandstone bench is a 250-m (825-ft) thick dark-red siltstone and sandstone slope of the Hermit Formation (Lower Permian) that is commonly covered by talus and rockslide deposits. A 45-m (150-ft) thick, light-brown to white cliff of the Coconino Sandstone (Lower Permian) overlies the red Hermit Formation in the south half of the map area. Because the Coconino Sandstone pinches out from the south into the central part of the map area, the gray strata of the Toroweap Formation (Lower Permian) unconformably overlies the red Hermit Formation. The Coconino Sandstone pinch out is visible in the upper reaches of Kanab Creek and north of Warm Springs Canyon of the Kaibab Plateau, but most of the pinch-out is in the subsurface of the northern quarter of the map area.

Gray cherty limestone and reddish-gray to white siltstone and gypsum beds of the Toroweap Formation (Lower Permian) overlie the Coconino Sandstone where the Coconino is present, otherwise the Toroweap strata unconformably overlies the Hermit Formation. The gray limestone, siltstone, and gypsum beds of the Kaibab Formation (Lower Permian) form much of the bedrock surface in the southern three-quarters of the map area and the gray rim rock cliffs of Kanab Creek and its tributaries of the Grand Canyon. The reddish siltstone and gray gypsum beds within the Harrisburg Member of the Kaibab Formation thin eastward into the Kaibab Plateau area, whereas the gray sandy and cherty limestone beds within the Harrisburg thicken eastward. The limestone beds are often confused with or mapped as part of the upper Fossil Mountain Member of the Kaibab Formation where lower siltstone and gypsum beds are absent.

A regional unconformity separates the Permian Kaibab Formation from the overlying Triassic Moenkopi Formation. The unconformity is often difficult to distinguish in most areas due to the lack of erosional relief and similarity of lithology and color of both units. The unconformity is marked by wide, shallow, stream-channel valleys eroded into the Kaibab Formation. The deeper channels are identified by deposits of conglomerate composed of well rounded small boulders, cobbles, and pebbles of chert and limestone that are derived from erosion of the underlying Kaibab Formation that forms the basal Timpoweap Member of the Moenkopi Formation.

The term Rock Canyon Conglomerate was proposed and abandoned by Gregory (1948, 1952), used by Nielsen and Johnson (1979), and Nielsen (1986, 1991). But the term Timpoweap Member of the Moenkopi Formation is used in this report as used by Stewart and others (1972); Billingsley and Workman (2000); and Sable and Hereford (2004). The conglomerate forms the lower part of the Timpoweap Member of the Moenkopi Formation, however, where the conglomerate is not present, a yellowish fine-grained limestone and sandstone is commonly present within the shallow paleovalleys and in many places is interbedded with conglomerate. The limestone beds form the upper part of the Timpoweap Member and become very widespread from west to east across the northern part of the map area within shallow paleovalleys eroded into the Kaibab Formation (Billingsley and Workman, 2000; Sable and Hereford, 2004). The limestone beds of the Timpoweap Member have similar characteristics to the limestone beds of the underlying Harrisburg Member of the Kaibab Formation making it difficult in many areas to distinguish them, mainly where the erosional unconformity has low relief; especially along the northern edge of the map area. For this reason, the Timpoweap Member, as mapped by Sable and Hereford (2004) on the north Kaibab Plateau in Utah (northeast edge of map area) cannot be distinguished with certainty from upper limestone beds of the Harrisburg Member of the Kaibab Formation; thus, strata contacts of that area will not match adjoining strata of the Kanab quadrangle in Utah. The lack of chert nodules and the presence of small chert pebble clasts within limestone beds of the Timpoweap generally help to distinguish between limestone beds of the Timpoweap Member of the Moenkopi Formation from those of the Harrisburg Member of the Kaibab Formation, but not consistently.

In the north-central part of the map near Fredonia and Pipe Spring National Monument, Arizona, the surface bedrock is composed of red siltstone and sandstone, gray gypsum, and gray-white dolomite of the Moenkopi Formation (Lower and Middle(?) Triassic). At Colorado City, Moccasin, and Kaibab, Arizona, and along the east side of House Rock Valley, the surface bedrock is mostly white sandstone and multi-colored blue and red siltstone, mudstone, and claystone of the Chinle Formation (Upper Triassic). Above the Chinle Formation, reddish-brown claystone, siltstone, and sandstone beds of the Moenave and Kayenta Formations form the lower cliffs and slopes of the Vermilion Cliffs between Colorado City and Fredonia, Arizona, and on the east side of House Rock Valley in the northeast corner of the map area. Above the red slopes of the Kayenta Formation, light-red and white, large-scale cross-bedded sandstone cliffs of the Navajo Sandstone (Jurassic) form the upper and main part of the Vermilion Cliffs. The Navajo Sandstone is the surface bedrock of the highlands of Moccasin Mountains east of Colorado City in the northwest part of the map area and the Paria Plateau in the northeast corner of the map area.

The surficial deposits are generally 1 to 18 m (3 to 60 ft) thick and are mostly alluvial deposits, such as alluvial fans, alluvial terraces, and mixed alluvium and eolian deposits. Eolian deposits are mainly confined to the Paria Plateau area and are mainly derived from outcrops of the Navajo Sandstone. Most of the eolian deposits are stabilized by grassy vegetation during wet climatic conditions but become locally active during prolonged dry conditions.

The basalt flows and pyroclastic cones in the southwest corner of the map area are part of the eastern extension of the Uinkaret Volcanic Field. The main body of the Uinkaret Volcanic Field is west of the map area (Billingsley and Workman, 2000; Billingsley and others, 2001).

Structural Geology

Monoclines, such as the Moccasin and East Kaibab Monoclines, developed in response to the Laramide orogeny of Late Cretaceous through Eocene time along pre-existing Proterozoic fault zones (Huntoon, 2003). Extensional stresses from Miocene to the present time have resulted in down-to-the-west normal faulting along these Precambrian basement faults effectively reversing part of the Laramide offset of strata by displacing monoclinal strata down-to-the-west. Most of the normal fault displacements within the map area probably occurred during

Pliocene and Pleistocene time and continue today as observed along parts of the Toroweap Fault in the southwest corner of the map, the Muav, Big Springs, and North Road Faults in the east-central part of the map, and the Hurricane Fault about 23 km (14 mi) west of the map area (Jackson, 1990; Stenner and others, 1999; Billingsley and Workman, 2000; Fenton and others, 2001; Billingsley and Wellmeyer, 2003; Amoroso and others, 2004; Raucci, 2004).

Toroweap and Sevier Faults

The Sevier and Toroweap Faults, the principle structural features in the western half of the map area, form the boundary between the Uinkaret Plateau west of the faults and the Kanab Plateau east of the faults (Billingsley and others, 1997). The Toroweap Fault, southwest corner of the map, has a northeast strike for about 13 km (8 mi), then turns and extends northwest for about 6.5 km (4 mi) and dies out. At the bend in the fault strike, the Toroweap Fault connects to the Sevier Fault (see cross-section *A–A´*). The Sevier Fault continues on a northeast strike for about 8 km (5 mi) and bends to a general north-south strike that eventually passes through Pipe Spring National Monument in the northwest part of the map area. Overall, the Toroweap and Sevier Faults join northeast of Heaton Knolls in the southwest part of map area and are both aligned on a common fault system.

Displacement of strata along the Toroweap Fault is generally about 73 m (240 ft) down-to-the-west in the southwest corner of the map and gradually decreases northeastward. A Pleistocene basalt, which came from Heaton Knolls volcano southeast of and near the fault, flowed over the Toroweap Fault. The basalt flow was partly offset by the Toroweap Fault down-to-the-west about 12 to 18 m (40 to 60 ft) indicating young tectonic activity along this part of the Toroweap Fault. Displacement of strata along the Sevier Fault gradually increases from 14 m (45 ft) down-to-the-northwest at its junction with the Toroweap Fault to as much as 396 m (1,300 ft) at Pipe Spring National Monument and about 366 m (1,200 ft) at the Arizona/Utah State line.

Moccasin Monocline and West Segment of the Sevier Fault

Just north of Pipe Spring National Monument, a short northwestern segment of the Sevier Fault and associated Moccasin Monocline splits off the main segment of the Sevier Fault (Billingsley and others, 2004; Sabol, 2005). Northeast of Pipe Spring National Monument, the Sevier Fault continues north to the Vermilion Cliffs where the fault parallels the east-facing part of the Vermilion Cliffs for about 5 km (3 mi) to Sandy Canyon Wash (not shown on this map) and northward into Utah just east of Coral Pink Sand Dunes State Park about 5 km (3 mi) north of the map area. A gentle east-dipping unnamed monocline is present along the Sevier Fault in Utah north of the map area.

It can be argued that the Moccasin Monocline fold is really an inclined anticline and syncline pair. But the term Moccasin Monocline is used here as in Billingsley and others (2004) and Sabol (2005). West dipping strata as much as 46 degrees is visible on the east side of the Sevier Fault in Pipe Valley drainage southwest of Pipe Spring National Monument and may reflect fault drag along the Sevier Fault in that area.

West Kaibab Fault Zone

The West Kaibab Fault Zone was originally defined by Powell (1875, p. 182–190). Dutton (1882, p. 183–186) described three fault lines which comprised the West Kaibab Fault Zone. Noble (1914) made a detailed study of the southern end of one of the West Kaibab Faults that enters the Grand Canyon. Strahler (1948) named the individual faults of the West Kaibab Fault Zone: Muav Canyon Fault (Muav Fault by Huntoon and others, 1996; Billingsley, 2000), Big Springs Fault, North Road Fault, and LeFevre Graben (spelled Le Fevre on 1988 USGS 7.5’ quadrangle). The term West Kaibab Fault Zone is not used for this map because of the confusion of intersecting faults.

In the east-central part of the map area, the Muav and the North Road Faults form a topographic and structural boundary between the Kaibab and Kanab Plateaus. The Muav Fault, as mapped here, extends southward into the Grand Canyon (Huntoon and others, 1996; Billingsley, 2000) and extends northeastward to the vicinity of U.S. Highway 89A northwest of Jacob Lake, Arizona. Although Strahler (1948) used the name Big Springs Fault from its junction with the Muav Fault in Warm Springs Canyon north to U.S. Highway 89A, the name Muav Fault is used here because it forms a continuous fault line strike northeastward to U.S. Highway 89A and the North Road Fault. Big Springs Fault forms a junction with the Muav Fault at Warm Springs Canyon and angles off southeastward into the Kaibab Plateau to the north rim of Grand Canyon. At the south edge of the map area, the Muav Fault offsets Paleozoic strata down-to-the-west as much as 122 m (400 ft) and is associated with east-dipping strata of the Crazy Jug Monocline in the Grand Canyon just south of the map area (Huntoon and others, 1996; Billingsley, 2000).

Paleozoic and Mesozoic strata dip gently west of the Kaibab Anticline, but the structural trend of the Muav Fault north of U.S. Highway 89A most likely trends northeast in the subsurface for about 5 km (3 mi) to the North Road Fault, described by Strahler (1948), and continues to the Arizona/Utah State line. The North Road Fault offsets Paleozoic and Mesozoic strata down-to-the-west as much as 70 to 80 m (230 to 260 ft). The North Road Fault also forms the east side of Le Fevre Graben; the west-bounding fault of Le Fevre Graben is herein named Le Fevre Ridge Fault.

The Big Springs Fault and Monocline splay south from the Muav Fault near the mouth of Warm Springs Canyon west of Jacob Lake, Arizona. The Big Springs Fault offsets strata about 160 m (525 ft) down-to-the-west near Warm Springs Canyon and extends south and southeastward into the Kaibab Plateau and north rim of the Grand Canyon as offset of strata diminishes (Huntoon and others, 1996; Billingsley, 2000). Paleozoic strata along the Big Springs Monocline west of Big Springs Fault has an easterly dip between 8º and 2º and less than 2º dip east on east side of the fault. Several minor grabens are present throughout the length of the Kaibab Anticline with Le Fevre and Summit Valley Grabens being the largest north of Jacob Lake, Arizona. Many smaller normal faults are shown at map scale with no estimated offsets to help show the structural fabric of the map area. Several smaller faults are not shown at 1:100,000 map scale but are present and are shown on the 1:24,000-scale maps that accompany the digital map database.

East Kaibab Monocline

The East Kaibab Monocline is a prominent structure that forms the eastern limb of the Kaibab Anticline. Powell (1875, p. 182–190) first described the East Kaibab fold; Babenroth and Strahler (1945) renamed the fold the East Kaibab Monocline. The basal part of the East Kaibab Monocline north of Trail Canyon and the lower segment of the East Kaibab Monocline south of Trail Canyon marks the structural boundary between the Kaibab Plateau (anticline) and House Rock Valley. The East Kaibab Monocline is the largest and most pronounced monocline in the map area and splits into an upper and a lower segment (Billingsley and Wellmeyer, 2001; Billingsley and others, 2001; Billingsley and Hampton, 2001). The intermediate bench land between the two monocline segments is called Little Mountain and is part of the Kaibab Plateau. The Upper and Lower East Kaibab Monoclines merge northward to become the East Kaibab Monocline about 6.5 km (4 mi) north of U.S. Highway 89A at Trail Canyon. At Trail Canyon, the Trail Canyon Fault seems to offset the East Kaibab Monocline as a strike-slip fault, but this is interpreted as a strike-slip separation caused by normal fault slip. Trail Canyon Fault bends to an east-west strike south of U.S. Highway 89 A and forms a graben that dies out about 1.5 km (1 mi) east of Jacob Lake, Arizona.

House Rock Valley is at the base of the East Kaibab Monocline and Lower East Kaibab Monocline and is about 1.5 to 3 km (1 to 2 mi) wide in the northeast quarter of the map area and widens southward in the vicinity of U.S. Highway 89A. House Rock Valley is flanked on the east by red cliffs of Mesozoic strata of the Vermilion Cliffs. The Navajo Sandstone forms the bedrock rim of the Vermilion Cliffs, which also marks the western edge of the Paria Plateau. Part of House Rock Valley, the Vermilion Cliffs, and the Paria Plateau are within the new BLM administered Vermilion Cliffs National Monument.

Bedrock Joints and Fractures

Bedrock joints and fractures are prominent surface features visible in the sandstone and limestone bedrock units throughout the map area, such as the Esplanade Sandstone (Permian), Kaibab Formation (Permian), Shinarump Conglomerate Member of the Chinle Formation (Triassic) and the Navajo Sandstone (Jurassic). These rocks units are well-cemented, cliff-forming strata where regional stress patterns are reflected as joints and fractures that are visible on bedrock outcrops. The joint and fracture patterns reflect old and young regional stress patterns from compressional or extensional tectonic events of different ages from Proterozoic through Cenozoic time for the Colorado Plateau. Bedrock joints and fractures are vertically continuous through all hard and soft Paleozoic and Mesozoic rock strata exposed in the map area. Several joint and fracture symbols shown on the Paria Plateau and Moccasin Mountains areas of the map are located in eolian sand sheet and sand dunes but are also visible in small outcrops of the Navajo Sandstone and as lineations of vegetation in thin sand cover.

There are four different joint and fracture systems in the map area: north-south, northeast-southwest, northwest-southeast, and east-west oriented. At least two and sometimes three joint and fracture sets are present in different parts of the map, but typically only two sets are prominent, those oriented northeast-southwest and northwest-southeast. The northwest-southeast and northeast-southwest orientated joint and fracture systems seem to be the youngest in the map area because many of the joints and fractures are visible as semi-open cracks, particularly in the Esplanade Sandstone and Navajo Sandstone. The cracks are also visible as surficial expressions in eolian sand deposits in the Moccasin Mountains above the Vermilion Cliffs and depicted as linear vegetation growths where the joints and fractures are filled with eolian sand deposits allowing local vegetation to established deep rootholds. On aerial photographs, the linear vegetation patterns are visible in sand sheet and dune deposits.

However, northwest of the map area at Zion National Park, the north-northwest oriented joint and fracture zone is documented by Rodgers (2002) as the youngest in the region. Rodgers concluded that the north-northwest oriented joint (fracture) zones and subsequent isolated joints indicate a pervasive extensional feature that is characteristic of west-southwest tectonic extension of the central Basin and Range Province that has affected the western Colorado Plateau Province since mid-Miocene time.

Collapse Structures and Sinkholes

Circular bowl-shaped areas with inward-dipping strata are collapse structures that may have developed because of collapse-formed breccia pipes caused by the dissolution of limestone within the deeply buried Mississippian Redwall Limestone (Wenrich and Huntoon, 1989; Wenrich and Sutphin, 1989). A black dot on the map marks such collapse structures and a red dot marks visible breccia in breccia pipes in Kanab Creek of Grand Canyon. Collapse features in the Kaibab Formation and younger strata, however, cannot be distinguished with certainty from shallow collapse structures that are caused by the dissolution of gypsum in the Kaibab or Toroweap Formations. Drilling is required to confirm that breccia pipes are present at depth in the subsurface of the collapse structure. The deep-seated breccia pipes contain potential economic high-grade ore deposits of copper and uranium minerals (Wenrich, 1985) and some of the breccia pipes in the map area have been mined for uranium and the location is marked on the map with a mine symbol. The primary metal is uranium along with Ag, Pb, Zn, Cu, Co, and Ni (Wenrich and Huntoon, 1989).

Karst sinkholes are the result of gypsum dissolution within the Woods Ranch Member of the Toroweap Formation and

Harrisburg Member of the Kaibab Formation and are common in the map area. Sinkhole depressions are most common at higher elevations of the Kaibab Plateau and may reflect a higher precipitation rate than at lower elevations of the Uinkaret and Kanab Plateaus. The largest and deepest karst sinkholes are on the Kaibab Plateau and are likely the result of dissolution of gypsiferous strata in the Woods Ranch Member of the Toroweap Formation because the sinkholes are more than 12 to 30 m (40 to 100 ft) deep, are steep sided or cliff walled, and nearly extend through the Kaibab Formation. The shallower karst sinkhole depressions throughout the map are most likely the result of dissolution of gypsiferous strata in the Harrisburg Member of the Kaibab Formation because these sinkholes are usually only a few meters deep and do not have steep-sided or shear rock walls. Most of the shallower sinkholes are associated with the Harrisburg Member of the Kaibab Formation in the western half of the map area because the gypsiferous sediments within the Harrisburg Member are thickest in that part of the map.

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DESCRIPTION OF MAP UNITS

[Some unit exposures on the printed map are too small to distinguish the color for unit identification. These units are labeled where possible, and unlabeled units are attributed in the geodatabase.]

SURFICIAL DEPOSITS

Holocene, Pleistocene, and Pliocene(?) surficial deposits are differentiated from one another chiefly on the basis of difference in morphologic character and physiographic position observed on 1976 and 2002 aerial photographs and by field observations. Older alluvial and eolian deposits generally exhibit extensive erosion and surface soil development, whereas younger deposits are actively accumulating material or are lightly eroded. Salt and gypsum are common constituents in all alluvial deposits derived from the Kaibab, Moenkopi, and Chinle Formations in the map area. Contacts with adjacent surficial deposits and bedrock deposits are gradational and locations are approximate.

Qaf **Artificial fill and quarries (Holocene)**—Alluvium and bedrock material removed from quarries and trench excavations used to build stock tanks, drainage diversion dams, roads, or other manmade construction projects; not all modern highways cuts are shown. Include uranium and copper mine excavations. No map distinctions between cut or fill excavations. Agricultural fields are not shown

Qs **Stream-channel deposits (Holocene)**—White to light-red interbedded silt, sand, gravel, and pebbles; unconsolidated and poorly sorted. Pebbles and some cobbles are mostly sandstone above the stratigraphic position of the Shinarump Member of the Chinle Formation; below the Chinle, clasts are dominated by black, well-rounded pebbles of quartzite or chert derived from the Shinarump Member of the Chinle Formation. Intertongue with or inset against young alluvial fan (Qay), young terrace-gravel (Qgy), and upper part of valley alluvial (Qv) deposits, overlaps flood-plain (Qf) and ponded sediment (Qps) deposits. Stream channels subject to intermittent high-energy flash floods that produce local sediment accumulation on flood-plain (Qf), young terrace-gravel (Qgy), and young alluvial fan (Qay) deposits. Little or no vegetation in stream channels except for occasional tamarisk trees, willow trees, and grass. About 1 to 4 m (3 to 12 ft) thick

Qt **Travertine deposits (Holocene)**—Gray and tan, massive, porous, cliff-forming fresh water limestone. Include angular clasts of local talus breccia or gravel. Formed by rapid chemical precipitation of calcium carbonate of spring water. Form encrustations on steep slopes or cliffs below active and non-active spring outlets. Thickest deposits are at Slide Spring in Slide Canyon, an eastern tributary to Snake Gulch in upper Kanab Canyon. Thickness, 2 to18 m (6 to 60 ft)

Qf **Flood-plain deposits (Holocene)**—Light-red or gray silt, fine- to coarse-grained sand, and gravel lenses; partly consolidated by gypsum or calcite cement. Gravel locally contains yellow, red, black, and white subrounded to subangular chert and quartz, well-rounded red sandstone, and gray-blue rounded limestone fragments and pebbles 0.5 to 1 cm (0.25 to 0.75 in) in diameter. Gradational lateral and vertical contact between stream-channel (Qs), flood-plain (Qf), and young alluvial fan (Qay) deposits. Support thick growths of tamarisk trees and other water-dependent plants where stream bedrock is very shallow, usually less than 3 m (10 ft) below floodplain surface. Dense growths of tamarisk help trap and accumulate sediment that develops flood-plain deposits within and along drainages. Deposits are generally 1 to 2 m (3 to 6 ft) above stream-channel (Qs) deposits and often grade laterally into stream-channel deposits. About 1 to 6 m (3 to 20 ft) thick

Qps **Ponded sediments (Holocene)**—Light-red to white clay, mud, silt, and fine-grained sand. Locally include small angular to subrounded fragments of bedrock clasts from nearby outcrops. Deposits are common sediment in sinkhole depressions. Sediment accumulates in temporary ponded areas on young terrace-gravel (Qgy) deposits due to sand dune accumulations or overbank sand and mud that form levee deposits preventing sediments from eroding back into local drainages for an extended amount of time. Include ponded deposits consisting of sand and silt on Moccasin Mountains and Paria Plateau where widespread sand sheet and sand dunes form temporary dune blockage across local drainages, or as blowout depressions formed within sand dunes. Youngest deposits accumulate in lowland areas where artificial diversion dams, stock tanks, or roads block drainages. Desiccation cracks often form on dry hardpan surfaces. Clay and fine silt content of sediment largely restricts plant growth except in sandy areas above Vermilion Cliffs. About 0.5 to 2 m (1 to 6 ft) thick

Qd **Dune sand and sand sheet deposits (Holocene)**—On Moccasin Mountains and Paria Plateau above Vermilion Cliffs; consists of light-red to white silt and fine- to coarse-grained eolian sand derived from the Navajo Sandstone (Jn). Only most extensive and thickest deposits are shown. Gradational contacts between young mixed alluvium and eolian (Qae) deposits based on geomorphologic interpretation on aerial photos. Below Vermilion Cliffs, deposits accumulate along local stream drainages and on gentle slopes of young alluvial fan (Qay) deposits. Deposit often leads to fine-grained climbing dunes or falling dunes of dune sand and sand sheet (Qd) accumulations on steep topography along base of Vermilion Cliffs on west side of Paria Plateau. In Pipe Valley south of State Highway 389 and in House Rock Valley along U.S. Highway 89A, white to light-brown and light-red, fine- to coarse-grained quartz sand partly stabilized by grass and small high-desert shrubs during wet conditions. Support moderate growths of grass, black brush, and other small high-desert shrubs above Vermilion Cliffs; mostly grass below Vermilion Cliffs. Unit partly stabilized by grassy vegetation or crypto-organic soil growths in local stream drainage areas below Vermilion Cliffs. About 1 to 2 m (0.5 to 6 ft) thick near and below Vermilion Cliffs; about 3 to 11m (9 to 35 ft) thick on Moccasin Mountains and Paria Plateau

Qae **Young mixed alluvium and eolian deposits (Holocene)**—Composed of gray, light-red, and white silt and fine- to coarse-grained, eolian and fluvial sand lenses; includes interbedded reddish-brown and gray silt and clay. Include a few coarse-grained gravel lenses composed primarily of angular chert fragments and red to white sub-rounded sandstone pebbles on Moccasin Mountains and Paria Plateau. Below Vermilion Cliffs in House Rock Valley and south and west of Yellowstone Mesa, includes multicolored and black, well-rounded chert pebbles derived from Shinarump Member of the Chinle Formation. Commonly occupies upper slopes of young alluvial fan (Qay) deposits. Below Vermilion Cliffs west of Colorado City, unit mostly composed of white and light-red sand and red silt that intertongues with young alluvial fan (Qay) deposits. Unit often overlapped by dune sand and sand sheet (Qd) deposits. Support thick to moderate growths of grass, cactus, and sagebrush; thick sagebrush, cliff rose bush, and pinion pine, oak, and juniper trees above Vermilion Cliffs. About 1.5 to 18 m (5 to 60 ft) thick

Qc **Colluvial deposits (Holocene)**—Gray to light-brown, poorly sorted, fine- to coarse-grained, slope-forming mixed silt, sand, gravel, and small, well-rounded pebbles. Include angular fragment clasts of petrified wood, sub-rounded sandstone, and small well-rounded black, red, yellow, and brown quartz and chert pebbles derived from Shinarump Member of the Chinle Formation; partly consolidated. Form pediment slopes below Yellowstone Mesa and southwest of Colorado City, west quarter of map area. Small well-rounded pebbles form a partial desert pavement cover on some surfaces. Unit intertongues with young alluvial fan (Qay) deposits and is partly eroded by arroyos as much as 3 m (10 ft) deep. Surfaces are moderately vegetated and stabilized by grasses and small pebble desert pavement. About 3 to 12 m (10 to 40 ft) thick

Qv **Valley-fill deposits (Holocene)**—Gray to light-red, slope-forming, unsorted mixture of mud, silt, sand, gravel, small pebbles, and cobbles. Partly consolidated by calcite and gypsum cement. Include sandstone, limestone, and chert clasts in sandy matrix locally derived from nearby Paleozoic and Mesozoic sedimentary rock outcrops in northwestern third of map area. On Kaibab Plateau; composed mostly of gray silt, sand, and numerous white to yellow chert fragments. Similar to stream-channel (Qs) deposits but occupies low-gradient drainages that deposit mostly fine-grained sand or silt in flat drainage floors, especially in Nail Canyon and Snake Gulch west of Jacob Lake, Arizona. Similar to or interbedded with flood-plain (Qf) deposits in Pipe Valley area. Subject to extensive sheet wash erosion, deposition, flash flood debris flows, temporary ponding of floods, sheet wash and arroyo erosion. Commonly interbedded with stream-channel (Qs), dune sand and sand sheet (Qd), and ponded sediment (Qps) deposits. About 1 to 6 m (3 to 20 ft) thick

Qtr **Talus and rock fall deposits (Holocene)**—Along Vermilion Cliffs; consists of red to yellow silt and sand mixed with angular rocks and boulders of light-red sandstone and dark-red siltstone; partly cemented by calcite. Form talus debris slopes in steep-walled canyons and on lower slopes of Vermilion Cliffs; often associated with and adjacent to or below landslide (Ql) deposits. Include some boulders of Navajo Sandstone or Shinarump Member of the Chinle Formation larger than 3 m (10 ft) near landslide (Ql) deposits near base of Vermilion Cliffs. In Kanab Creek drainages; consists of gray to yellow silt, sand, gravel mixed with small to large angular rocks and boulders of gray limestone, white chert, and white to tan sandstone derived from the Kaibab and Toroweap Formations and Coconino Sandstone; partly cemented by calcite and gypsum. Form talus debris cover on red slopes of Hermit Formation; associated with and below landslide (Ql) deposits. Unit often grades down slope into young or old alluvial fan (Qay, Qao) deposits or young or old terrace-gravel (Qgy, Qgo) deposits. About 1.5 to 14 m (5 to 45 ft) thick

Qgy **Young terrace-gravel deposits (Holocene and Pleistocene(?))**—Below Vermilion Cliffs; consists of red, white, and gray interbedded fine- to coarse-grained sand and thinly laminated silt; partly consolidated by clay and calcite cement. Include interbedded thin beds of gray or red mud and clay and interbedded lenses of gravel composed of gray subangular chert fragments. Unit cut by modern erosion as much as 9 m (30 ft) deep in Kanab Creek near Fredonia, and other drainages eroded into the Vermilion Cliffs.

On Kanab Plateau, Uinkaret Plateau, and Kanab Canyon areas; consists of gray and light-brown, fine- to coarse-grained silt, sand, and gravel; partly consolidated by gypsum and calcite cement. Include gray-blue subrounded limestone and light-red sandstone clasts, in matrix of mostly white angular and subangular chert gravel. Deposits commonly intertongue with or overlapped by young alluvial fan (Qay) and mixed alluvium and eolian (Qae) deposits and inset against old terrace-gravel (Qgo) deposits. Subject to flash flood erosion or overbank accumulations of flood-plain (Qf) sediments in upper Kanab Creek drainage and its northeastern tributaries in Muggins Flat, north-central part of map area. Terraces are generally 1.2 to 9 m (4 to 30 ft) above local streambeds and as much as 18 m (60 ft) above stream channel in upper reaches of Kanab Creek and some of its tributaries. Unit often cut by arroyo erosion as much as 6 m (20 ft) in south-central part of map and as much as 18 m (60 ft) above stream channels in upper reaches of Kanab Creek and some of its tributaries. Moderately vegetated by sagebrush, grass, cactus, tamarisk trees, willow trees, juniper and pinion pine trees at elevations above 1,525 m (5,000 ft); mostly vegetated by grass, thick growths of cactus, sagebrush, desert shrubs, and some cottonwood trees in lower reaches of Kanab Creek. About 1 to 18 m (3 to 60 ft) thick or more

Qay **Young alluvial fan deposits (Holocene and Pleistocene(?))**—Vermilion Cliffs area; consists of light-red and brown silt and fine- to coarse-grained sand and gravel; partly consolidated by calcite and clay. Include subangular red and white chert fragments and small red and white sandstone and gray limestone clasts generally less than 5 cm (2 in) in diameter derived locally from nearby Vermilion Cliff outcrops. Include large boulders of the Shinarump Member of the Chinle Formation as much as 2 m (6 ft) in diameter below Yellowstone Mesa area. Clay content greatest below or in outcrops of Petrified Forest Member of the

Chinle Formation. Include numerous black, brown, yellow, red, and gray, very well rounded quartzites and chert pebbles 1.5 to 5 cm (0.5 to 2 in) in diameter and occasional rounded, gray-white petrified wood fragments down slope of Vermilion Cliffs areas. Locally covered by thin eolian dune sand and sand sheet (Qd) deposits, young mixed alluvium, and eolian (Qae) deposits at distal ends of alluvial fan deposits.

On Kanab Plateau, Uinkaret Plateau, and in Kanab Creek drainages; gray, light-red, and light-brown silt, sand, and white cherty gravel, partly consolidated by gypsum and calcite. Include lobes of flash flood debris flows of unsorted angular boulders in sandy matrix that often form temporary dams that block principal drainages, primarily in Kanab Creek, Nail Canyon, and Snake Gulch, central part of map area. Surfaces are generally gullied as much as 3 m (10 ft) or partly covered by desert pavement of small gravel or pebbles in northwest quarter of map area; partly consolidated by calcite, clay, and gypsum cement below stratigraphic level of the Chinle Formation; mostly unconsolidated above Chinle below Vermilion Cliffs. Commonly overlapped by or intertongue with stream channel (Qs) deposits in upper Kanab Creek drainages and Muggins Flat area. Intertongue with landslide (Ql) and talus and rock fall (Qtr) deposits at upper reaches of alluvial fans below Vermilion Cliffs where unit is heavily dissected by erosion. Subject to extensive sheet wash erosion or sediment accumulation during heavy storms. Support moderate growths of grass, sagebrush, cactus, juniper, pinion pine, and various small high-desert shrubs. About 2 to 18 m (6 to 60 ft) thick

Ql **Landslide deposits (Holocene and Pleistocene)**—Vermilion Cliffs area; consists of unconsolidated masses of unsorted rock debris that include detached blocks of Mesozoic strata that have rotated backward and slid down slope against parent cliff as loose incoherent masses of broken rock and deformed strata, often surrounded by talus and rock fall (Qtr) deposits. Parallel to the Vermilion Cliffs, landslide masses are as large as 3 km (2 mi) in length. Out from the Vermilion Cliffs, landslide masses are 0.8 km (0.5 mi) in width and have slid down slope 153 to 213 m (500 to 700 ft) or more. Unit often partly covered by eolian dune sand and sand sheet (Qd) deposits. Individual landslides may become unstable during wet conditions and creep down slope where unit is underlain by claystone or siltstone bedrock of Kayenta Formation or Petrified Forest Member of the Chinle Formation.

Kanab Creek and tributary canyon drainages; consists of partly consolidated masses of unsorted rock debris that include detached blocks of Permian strata that have either fallen or slide down soft gypsiferous slopes of the Woods Ranch Member of the Toroweap Formation. Support sparse growth of sagebrush, cactus, grass, juniper trees, and pinion trees. About 8 to 60 m (25 to 200 ft) thick

Qgo **Old terrace-gravel deposits (Pleistocene)**—Gray, light-brown to light-red clay, silt, sand; partly consolidated by calcite and gypsum cement in tributaries of Kanab Creek drainages. Locally contain lenses of small rounded to subrounded pebble gravel and conglomerate composed of white and red sandstone, blue-gray limestone, abundant subrounded or angular white chert, and scattered, well rounded, multicolored quartzite pebbles in fine- to coarse-grained gravel matrix. Down slope of Vermilion Cliffs, include well rounded quartz, chert, or quartzite pebbles of various sizes derived from Shinarump Member of the Chinle Formation. In eastern tributary drainages of Kanab Creek and Muggins Flat west of Kaibab Plateau, include occasional well-rounded pebbles and small cobbles of brown, purple, and gray quartzite clasts derived from old gravel and sedimentary (Ts) deposits. Unit forms terraces about 9 to 37 m (30 to 120 ft) above stream channel (Qs) deposits along Kanab Creek and its tributaries and often covered by thin eolian dune sand and sand sheet deposits or lag gravel deposits too thin to show at map scale. Support sparse growth of sagebrush, black brush, cactus, and grass. About 2 to 6 m (6 to 20 ft) thick

Qao **Old alluvial fan deposits (Pleistocene and Pliocene(?))**—Red, gray, and brown poorly sorted mixture of mud, silt, sand, and gravel derived from the Kaibab Formation on the west side of Kaibab Plateau, and angular to subrounded fragments of chert, limestone, and sandstone derived from the Hermit Formation, Coconino Sandstone, Toroweap Formation, and Kaibab Formation on east side of Kaibab Plateau. Partly consolidated by calcite and gypsum cement. Include scattered, well rounded, brown, black, gray, and purple quartzite pebbles and cobbles derived from old stream-channel (Ts) deposits. Stony surface where not covered by dune sand and sand sheet (Qd) deposits along base of Vermilion Cliffs; surface often exhibits desert pavement composed mainly of black, well rounded pebbles in northwest quarter of map area. Unit is extensively eroded and contributes material to young alluvial fan (Qay) deposits. Oldest deposits form elevated and isolated alluvial fan slopes that overlie bedrock strata of the Moenkopi Formation or Kaibab Formation. Unit is about 9 to 37 m (30 to 120 ft) above young alluvial fan (Qay) deposits in north-central part of map area. Surface is consolidated by calcite and gypsum cement forming a rocky calcrete soil zone 0.5 to 1.2 m (2 to 4 ft) thick; extensively gullied and eroded near fan edges. Cobbles and boulders on fan surface are encased in calcite rinds and caliche detritus material common. Intertongue with talus and rock fall (Qtr) and landslide (Ql) deposits. Support pinion pine, juniper, and oak woodlands with grass, cactus, and sagebrush. Adjacent to or overlapped by young alluvial fan (Qay) and dune sand and sand sheet (Qd) deposits. About 1.5 to 15 (5 to 50 ft) thick

QTg **Terrace-gravel deposits (Pleistocene and Pliocene(?))**—Gray and light-brown, mud, silt, sand, gravel, and cobbles; poorly sorted and partly consolidated by calcite, gypsum, and clay cement. Pebbles and boulders are rounded clasts of gray limestone and white chert derived from local outcrops of Kaibab Formation (Pkh and Pkf), scattered brown and purple-brown quartzite cobbles reworked from old stream-channel (Ts) deposits, and multicolored, mostly black well rounded pebbles from Shinarump Member (ŦRcs) of the Chinle Formation. Form isolated deposits in upper Kanab Creek and in some tributaries as much as 92 m (300 ft) above modern drainages, particularly in upper Jumpup Canyon. Deposits are partially preserved in abandoned cutoff meander loops or in isolated abandoned point bars in upper Kanab Creek canyon. In Jumpup Canyon, a tributary to Kanab Creek, unit fills 170 m (560 ft) deep ancestral Jumpup Canyon drainage that had previously eroded through Kaibab and Toroweap Formations, Coconino Sandstone, and into upper part of Hermit Formation. About 5 to 8 m (15 to 25 ft) thick; about 170 m (560 ft) thick in Jumpup Canyon

VOLCANIC ROCKS

Heaton Knolls Basalt (Pleistocene)—Herein formally defined as the Heaton Knolls Basalt named for Heaton Knolls, the type area that forms a series of linear Pleistocene volcanic cinder cones on U.S. Geological Survey 7.5’ Heaton Knolls quadrangle (sec. 3, T. 36 N., R. 6 W., and sec. 34, T. 37 N., R. 6 W.), Kanab Plateau, Mohave County, Arizona (fig. 1). Heaton Knolls and associated Findlay Knolls volcanoes represent the northeastern extent of the Uinkaret Volcanic Field (Billingsley and others, 2001)

Qhkp **Pyroclastic deposits (Pleistocene)**—Light-red, grayish-black, and brown olivine basalt fragments of mixed cinder, scoria, volcanic bombs, and volcanic ribbons. Forms 91 m (300 ft) high Heaton Knolls and Findlay Knolls pyroclastic cones that overlies associated basalt flows (Qhkb) that are aligned in north-northwest trend for 2.5 km (1.5 mi) reflecting the north-northwest trend of bedrock joints and fractures in southwest corner of map area. Unit also partly overlies Harrisburg Member of the Kaibab Formation on northeast flank of Heaton Knolls. About 91 m (300 ft) thick

Qhkb **Basalt flows**—Dark-gray, finely crystalline, alkali olivine basalt. Include fine-grained groundmass of plagioclase, olivine, augite, and glass of which olivine is most common constituent. Basalt overlies strata of Harrisburg Member of the Kaibab Formation (Pkh) that straddle Toroweap Fault and is overlain by associated pyroclastic (Qhkp) deposits. Lavas flowed out in radial pattern from several eruptive centers along north-northwest fissures southeast of Toroweap Fault and part of basalt flowed northwestward over the Toroweap Fault scarp. Offset of Paleozoic strata along this segment of the Toroweap Fault before eruption of Heaton Knolls was offset about 49 m (160 ft) down-to-the-northwest and subsequent offset of the Heaton Knolls Basalt is about 12 m (40 ft) down-to-the-northwest for total offset of about 60 m (200 ft) near Heaton Knolls. About 2 to 73 m (6 to 240 ft) thick

Qgrb **Basalt of Graham Ranch (Pleistocene)**—Informally named for Graham Ranch in upper Toroweap Valley, the type area (sec. 3, T. 35 N., R. 7 W.), Uinkaret Volcanic Field, Uinkaret Plateau, Mohave County, Arizona (Billingsley and others, 2001). Incorrectly named the Sage Basalt by Billingsley and Workman (2000) and Billingsley (2000) before it was known that the name Sage Basalt was already in use. Includes four unnamed pyroclastic cones and associated basalt flows in upper reaches of Toroweap Valley just southwest of map area. Dark-gray finely crystalline to glassy alkali olivine basalt; vuggy with calcite fillings. Includes altered olivine in glassy groundmass with abundant olivine phenocrysts 0.25 to 1 mm in diameter. K-Ar age, 0.63±0.24 Ma, obtained by Jackson (1990) from basalt of Graham Ranch about 3 km (2 mi) south of southwest corner of map area. Lavas emerged from fissures in bedrock in Harrisburg Member of the Kaibab Formation and coalesced into radial patterns from each fissure. Much of the basalt flowed north and west into upper reaches of Toroweap Valley and into southwest corner of map area. The basalt and one associated pyroclastic cone is offset by the Toroweap Fault about 26 m (85 ft) down-to-the-west; underlying Kaibab Formation is offset about 67 m (220 ft) down-to-the-west for total offset of 93 m (305 ft) just southwest of map area (Billingsley and others, 2001; Billingsley and Wellmeyer, 2003). Basalt in southwest corner of map area is offset by Toroweap Fault about 26 m (85 ft) down-to-the-west; underlying Kaibab Formation is offset about 74 m (240 ft) down-to-the-west for a total offset of about 99 m (325 ft). About 3 to 60 m (10 to 200 ft) thick

SEDIMENTARY ROCKS

Ts **Old stream-channel deposits (Pliocene and Miocene(?))**—Red, gray, and light-brown, poorly sorted, partly consolidated, matrix-supported pebbles and boulders of well-rounded red, brown, gray, and purple quartzite or chert up to 48 cm (20 in) in diameter. Matrix consists of red, brown, and gray, partly consolidated, coarsely textured arkosic fluvial sandstone and siltstone. Form isolated sediments in early Tertiary paleodrainage of ancestral Kanab Creek system that eroded into the Moenkopi and Kaibab Formations on the Kanab Plateau. Only three deposits are preserved. Two deposits form small reddish hills; Cedar Knoll (sec. 4, T. 39 N., R. 1 W.) and Little Cedar Knoll (secs. 13 and 24, T. 39 N. R. 2 W.) about 17.5 km (11 mi) southeast of Fredonia, Arizona, near Forest Service Highway 212 at about 1,707 m (5,600 ft) elevation. Deposits are about 304 m (1,000 ft) above present level of Kanab Creek 13 km (8 mi) west of Cedar Knoll and Little Cedar Knoll. Unit is currently being mined for road gravel at Little Cedar Knoll. A third deposits fills a paleovalley channel eroded 3 to 5 m (10 to 15 ft) deep into Harrisburg Member of the Kaibab Formation between Jumpup and Sowats Canyons 3 km (2 mi) northeast of The Gooseneck (sec. 29, T. 37 N., R. 2 W.) at elevation 1,828 m (6,000 ft), south-central part of map area. Distance between Little Cedar Knoll south to The Gooseneck locality is about 22 km (14 mi); elevation drops about 183 m (600 ft) suggesting a southward paleogradient of about 13 m/km (43 ft/mi). Quartzite pebbles, cobbles, and boulders commonly form surface pavement or lag gravel in vicinity of Cedar Knoll, Little Cedar Knoll, and near The Gooseneck area. Quartzite pebbles and cobbles from Cedar Knoll and Little Cedar Knoll are commonly reworked into young, and old alluvial fan (Qay, Qao) deposits toward Kanab Creek and into young and old terrace-gravel (Qgy, Qgo) deposits. Quartzite pebbles and cobbles form minor patches of desert pavement or lag gravel surfaces down slope of Cedar Knoll and Little Cedar Knoll on bedrock surfaces. Quartzite gravels are present in old terrace-gravel (Qgo) deposits on southeast side of Muggins Flat area indicating that quartz gravels were derived from other outcrops in southern Utah. A minor quartzite lag gravel deposit is present near U.S. Highway 89A about 8 km (6 mi) northwest of Jacob Lake, Arizona, and does not represent a sedimentary deposit, but is indicated on the map to illustrate highest elevation 2,300 m (7,545 ft) for this type of lag gravel on Kaibab Plateau. Isolated remnants of quartzite lag gravels are scattered on several ridges on east side of Kaibab Plateau near 2,300 m (7,545 ft) elevation in the vicinity of U.S. Highway 89A, but are too thin and widely scattered to show on map. Thickest deposits are at Cedar Knoll, about 14 m (45 ft) thick and at Little Cedar Knoll, about 20 m (65 ft) thick

Jn **Navajo Sandstone (Lower Jurassic)**—White, light-red, and yellowish-gray, cliff-forming, medium crossbedded to thickly crossbedded, well-sorted, fine- to coarse-grained eolian quartz sandstone; lower part is interbedded with dark-red, flat-bedded, coarse-grained sandstone and siltstone of Kayenta Formation. Age determination is by Peterson and Pipiringos (1979) and Biek and others (2000). Lower part is commonly red; upper part is commonly white but can be either all red or all white. Includes lenses of interbedded dark purple-gray, thin-bedded, calcareous sandstone or siliceous limestone formed by freshwater deposits within and between sand dunes. High-angle, crossbedded sandstone sets are interbedded with low-angle, crossbedded sandstone sets and thin flat-bedded sandstone sets. Unit commonly covered by thin to thick eolian dune sand and sand sheet (Qd) deposits or young mixed alluvium and eolian (Qae) deposits. Unit is highly fractured by near vertical northeast-, northwest-, and north-oriented bedrock joints and fractures.

Paria Plateau area; unit is highly fractured by near vertical joints and fractures and a few high angle normal faults with northwest strike. Gradational and intertonguing contact with underlying sandstone facies of Kayenta Formation along Vermilion Cliffs, northeast quarter of map area. Unit supports moderate growths of pinion and juniper trees, cliff-rose bush, sagebrush, and various high-mountain shrubs. Incomplete section in map area due to modern erosion of top part of unit. Thickens north of map to as much as 610 m (2,000 ft). About 457 m (1,500 ft) thick in Moccasin Mountains area; about 330 m (1,080 ft) thick in Paria Plateau area

Jk **Kayenta Formation (Lower Jurassic)**—Includes an upper slope-forming siltstone, and a basal cliff of the Springdale Sandstone Member. The Springdale Sandstone Member was originally described as the upper member of the underlying Moenave Formation (Averitt and others, 1955; Stewart and others, 1972; Sargent and Philpott, 1987; Billingsley and others, 2004) and has been reassigned to the basal part of the Kayenta Formation on the basis of paleontological data and a prominent Jurassic unconformity at the base of the Springdale (Blakey, 1994; Marzolf, 1994; Lucas and Tanner, 2006; Tanner and Lucas, 2007; Biek and others, 2007). Upper slope-forming unit is dark-red and light reddish-brown, calcareous mudstone, siltstone, and cliff-forming sandstone that undergo a facies change eastward from mostly slope-forming siltstone and mudstone at Moccasin Mountains to a mostly cliff-forming sandstone at Paria Plateau, northeast corner of map area. Age of unit determined by Peterson and Pipiringoes (1979) and Biek and others (2000). Along Vermilion Cliffs, unit often covered by landslide debris (Ql) and talus and rock fall (Qtr) deposits caused by erosion of soft sediments of Kayenta Formation that undercuts resistant overlying cliff of Navajo Sandstone allowing large sections of both Navajo Sandstone and upper Kayenta Formation to fail as landslide masses, especially where the bedrock joints and fractures parallel Vermilion Cliffs. Kayenta Formation is deposited in river floodplains, river channels, playas, and shallow lake environments (Blakey, 1994; Peterson, 1994). Unconformable contact with underlying Moenave Formation (Jm). Thickness increases from 143 m (470 ft) at Ed Lamb Point westward to nearly 183 m (600 ft) in Potter Canyon southwest of Moccasin Mountains and thickness of intertonguing Lamb Point Tongue of Navajo Sandstone decreases in northwest quarter of map area. About 143 to 183 m (470 to 600 ft) thick

Jks **Springdale Sandstone Member (Lower Jurassic)**—Light-red to reddish-brown, cliff-forming, thin- to thick-bedded sandstone and conglomeratic lenses. Includes low-angle trough crossbedded sets of fluvial sandstone that contain dark-red mudstone and siltstone rip-up clasts and poorly preserved petrified and carbonized fossil plant remains within crossbedded sets (Peterson and Pipiringos, 1979; Biek and others, 2000). Crossbeds are separated by thin-bedded to laminated dark-red siltstone and mudstone beds that locally contain mudstone pellets (Wilson, 1967). Unconformable contact with underlying Dinosaur Canyon Member of the Moenave Formation. Unit deposited by northeast to southwest flowing streams based on crossbedding studies by Wilson (1967). Thickens north and east of map area to about 60 m (200 ft) in Utah. Forms light-red sandstone cliffs that weather dark red on east side of House Rock Valley, northeast quarter of map area. Thickness ranges from about 37 to 60 m (120 to 200 ft)

Jm **Moenave Formation (Lower Jurassic)**—Includes, in descending order, the Dinosaur Canyon Member and Whitmore Point Member, undivided as redefined by Blakey, 1994; Marzolf, 1994; Lucas and Tanner, 2006; Tanner and Lucas, 2007; Biek and others, 2007. Originally defined as the upper Member of the Moenave Formation by Averitt and others (1955), Stewart and others (1972), and Sargent and Philpott (1987). Age determination after Peterson and Pipiringos (1979) and Biek and others (2000)

Dinosaur Canyon Member (Lower Jurassic)—Reddish-brown, slope- and ledge-forming, thin-bedded, very fine-grained sandstone and silty sandstone. Gradational contact with underlying Whitmore Point Member of the Moenave Formation west of Fredonia area, marked by distinct color contrast between blue-green, green, and yellow mudstone and siltstone of Whitmore Point Member to reddish-brown siltstone and sandstone of Dinosaur Canyon Member; unconformable contact with Owl Rock Member of the Chinle Formation in House Rock Valley area where Whitmore Point Member is missing. Unit commonly covered by landslide (Ql) and talus and rock fall (Qtr) deposits. Thickness ranges from about 37 to 60 m (120 to 200 ft)

Whitmore Point Member (Lower Jurassic)—Type section is near Potter Canyon at southwest point of Moccasin Mountains (elev. 2,013 m [6,603 ft]) at Radio Towers). Named for Whitmore Point by Wilson (1967) 5.6 km (3.5 mi) west of Pipe Spring National Monument, but the name Whitmore Point is not on 1988 USGS 7.5' Moccasin quadrangle. Composed of reddish-brown sandstone and siltstone interbedded with reddish-purple to greenish-gray and blue mudstone and claystone, and thin gray dolomitic limestone. Limestone contains small reddish-brown chert nodules and poorly preserved fossil algal structures and fish scales and bones near Zion National Park north of map area (Biek and others, 2000; 2007). Unconformable contact with underlying Chinle Formation in west half of map area; unit thins eastward to less than 12 m (40 ft) at Vermilion Cliffs on east side of House Rock Valley, northeast quarter of map area. Thickness ranges from about 12 to 24 m (40 to 80 ft)

Chinle Formation (Upper Triassic)—Includes, in descending order, the Owl Rock Member, Petrified Forest Member, and Shinarump Member as used by Stewart and others, 1972; Sargent and Philpott, 1987; Biek and others, 2000; 2007. Owl Rock is mapped as part of Petrified Forest Member (Ŧcp) below Vermilion Cliffs west of Fredonia, Arizona, because it is too thin to show, but is mapped separately near Colorado City, Arizona, and in House Rock Valley area

Ŧco **Owl Rock Member (Upper Triassic)**—Light-red and blueish-white coarse-grained sandstone, gray, fine-grained sandstone and siltstone interbedded with thin-bedded, 12 cm to 0.5 m (5 in to 2 ft) thick grayish-white siliceous limestone beds. Limestone contains red and white chert nodules and lenses. Gradational contact with underlying Petrified Forest Member. About 9 to 18 m (30 to 60 ft) thick

Ŧcp **Petrified Forest Member (Upper Triassic)**—Gray, light-purple, blue, to light-red, slope-forming claystone, siltstone, and white, coarse-grained sandstone. Mudstone weathers to frothy popcorn surface. Includes petrified wood and calcite nodules. Unit is mostly covered by eolian sand sheet (Qes), dune sand and sand sheet (Qd), and young mixed alluvium and eolian (Qae) deposits, and young, intermediate, and old alluvial fan (Qay and Qao) deposits. Contact with underlying Shinarump Member is gradational in vertical and lateral extent because of intertonguing and phases changes. Thickness ranges from about 183 to 213 m (600 to 700 ft)

Ŧcs **Shinarump Member (Upper Triassic)**—White to yellowish-brown, cliff-forming, thin- to thick-bedded, coarse-grained, low-angle crossbedded sandstone, gravel, and conglomeratic sandstone. Includes numerous small channel lenses and pockets of small pebble conglomerate composed of well rounded to subrounded, multicolored quartz, quartzite, and black chert pebbles in gravely sandstone matrix. Black chert pebbles are dominant clasts. Pebbles average about 2.4 to 4.8 cm (1 to 2 in) in diameter and include some well-rounded quartzite cobbles as large as 24 cm (10 in) in diameter and numerous angular petrified wood fragments and segments of petrified logs. Black pebbles eroded from Yellowstone Mesa area form desert pavement of lag gravel on all alluvial fan and colluvial surfaces down slope of mesa, southwest quarter of map area. Unit is source area for well rounded, multicolored quartz, quartzite, and chert pebbles in all surficial units below outcrops of the Shinarump Member of the Chinle Formation. Weathered sand from the Shinarump Member provides source for local eolian sand sheet (Qes) and dune sand and sand sheet (Qd) deposits that are transported by southwesterly winds up and over Petrified Forest Member. Unit fills broad channels that are as much as 9 m (30 ft) deep and 0.8 to 1.5 km (0.5 to 1 mi) wide eroded into underlying upper red member of Moenkopi Formation (Ŧmu). Thickness ranges from about 6 to 38 m (20 to 125 ft)

Moenkopi Formation (Middle(?) and Lower Triassic)—Includes, in descending order, upper red member, Shnabkaib Member, middle red member, Virgin Limestone Member, lower red member and Timpoweap Member, as used by Stewart and others (1972). Boundary between Middle(?) and Lower Triassic lies within the upper red member (Morales, 1987). Formation as a whole gradually thickens northwesterly across map area. (Timpoweap Member is partly redefined because of west to east facies change within map area)

Ŧm **Moenkopi Formation, undivided (Middle(?) and Lower Triassic)**—Light-red and dark-red, slope-forming siltstone and sandstone and minor gray gypsum. Exposed as isolated outcrops in House Rock Valley along lower limb of East Kaibab Monocline and on Little Mountain of the Kaibab Plateau between the west and east segments of the East Kaibab Monocline. Units are likely equivalent to the lower red and middle red members, minus the Virgin Limestone Member of the Moenkopi Formation. Units are often capped by older alluvial sediments except along State Highway 89A near House Rock Valley. Thickness, about 6 to 14 m (20 to 45 ft

Ћmu **Upper red member (Middle(?) and Lower Triassic)**—Light-red and dark-red, slope- and ledge-forming sequence of siltstone, sandstone, and conglomerate interbedded with minor gray gypsum. Includes small dark-red and brown resistant sandstone cliffs in upper part that exhibits minor unconformity at bottom of lowest dark-red sandstone cliff (middle part of unit, not shown on map) that may represent boundary between Early and Middle Triassic age (Moralas, 1987; Billingsley and Workman, 2000). Gradational contact with underlying Shnabkaib Member approximately placed at top of highest thick white siltstone and dolomite bed of Shnabkaib Member. About 49 m (160 ft) thick

Ћms **Shnabkaib Member (Lower Triassic)**—Interbedded and intertonguing, white to light-gray, laminated to thinly bedded, slope-forming, aphanitic dolomite and light-gray, calcareous siltstone and silty gypsum. Includes some light-red, thin-bedded mudstone, siltstone, and sandstone in lower and upper part. Gradational contact with underlying middle red member; map contact placed at lowest thick white or light-gray calcareous siltstone and dolomite bed of the Shnabkaib Member. Unit thickness is variable within map area because of approximate upper and lower contacts; unit thickens northwestward and thins eastward and southeastward. Thickness ranges from about 27 to 114 m (90 to 375 ft)

Ћmm **Middle red member (Lower Triassic)**—Reddish-brown, thin-bedded to laminated, slope-forming gypsiferous siltstone and sandstone, white and gray gypsum, minor white platy dolomite, green siltstone, and gray-green to red gypsiferous mudstone. Includes abundant thin veinlets and stringers of gypsum deposited in fractures and cracks throughout unit. Includes minor beds of white laminated dolomite, green siltstone, and gray-green to red gypsiferous mudstone. Mud cracks and ripple marks common throughout. Gradational contact with underlying Virgin Limestone Member at top of highest light-gray limestone bed of Virgin Limestone Member in Fredonia and Muggins Flat, north-central part of map; gradational lower contact with lower red member in House Rock Valley marked by color contrast between dark-red lower red member and light-red middle red member, northeast quarter of map area. Unit gradually thickens northeasterly across map area. Thickness ranges from about 55 to 92 m (180 to 300 ft)

Ћmv **Virgin Limestone Member (Lower Triassic)**—Includes two light-gray, thin-bedded to laminated, ledge-forming limestone beds [0.3 to 1 m (1 to 3 ft)] thick, separated by pale-yellow, light-red, and blue-gray, thin-bedded slope-forming gypsiferous siltstone that makes up bulk of unit. Lower limestone bed contains star-shaped crinoid plates and poorly preserved *Composita* brachiopods in upper part 14.5 km (9 mi) east of map area. Lower limestone bed thickens and thins due to channel fill cut as much as 1.3 m (4 ft) deep into underlying dark-red siltstone and sandstone of lower red member of the Moenkopi Formation south of Fredonia, Arizona, near Kanab Creek. Upper limestone bed contains abundant fossil algae and pinches out a few kilometers east of Fredonia, Arizona; whereas lower limestone bed thins eastward to western edge of Kaibab Plateau and is not present in House Rock Valley east of Kaibab Plateau. Unit as a whole thickens west and north, thins south and east of Fredonia, Arizona. Forms small mesas near Kanab Creek and thin white ledges in Muggins Flat area, north-central part of map. Thickness ranges from 0 to 25 m (0 to 80 ft)

Ћml **Lower red member (Lower Triassic)**—Dark-red, slope-forming, thin-bedded, fine-grained, gypsiferous, sandy siltstone, sandstone, and pale-yellow to gray laminated silty gypsum. Ledge-forming light red sandstone beds become more numerous in upper reaches of Kanab Creek and Fredonia areas. Gypsum, siltstone, and sandstone in lower part are derived from erosion of Harrisburg Member of the Kaibab Formation. Includes prominent ledge-forming, red-gray to light purple-red, coarse-grained to conglomeratic, thin-bedded, low-angle cross-bedded calcareous sandstone marker bed, 2 to 4 m (6 to 13 ft) thick in lower part that forms resistant sandstone surface of Kanab Plateau west of Kanab Creek and south of Pipe Spring National Monument area. Marker bed includes raindrop impressions and rare carbonaceous plant fossils in Short Creek 5 km (3 mi) west of map area (Billingsley and Workman 2000; Billingsley and others, 2002). Interbedded or gradational contact with underlying limestone, sandstone, or conglomerate of the Timpoweap Member, otherwise unconformable contact with Harrisburg Member of the Kaibab Formation. Locally fills paleovalleys eroded into Harrisburg Member of the Kaibab Formation or pinches out onto paleohills of the Kaibab in southwest quarter of map area. Thickness ranges from about 36 to 76 m (120 to 250 ft)

Ћmt **Timpoweap Member (Lower Triassic)**—Includes an upper and lower part: Upper part consists of gray to yellow-gray, cliff-forming, fine-grained, thick-bedded sandy limestone as much as 3 m (10 ft) thick. Locally includes gray, interbedded, coarse-grained, low-angle crossbedded calcareous sandstone containing small, rounded chert pebbles. Gradationally overlies conglomerate or thin-bedded sandy yellowish limestone of lower part except where unit unconformably overlies Harrisburg Member of the Kaibab Formation. Unit is difficult to distinguish from Harrisburg Member of the Kaibab Formation at north edge and is mapped as Harrisburg Member of the Kaibab Formation in that area, whereas adjoining geologic map of Kaibab Plateau in Utah is mapped, in part, as Timpoweap Member of the Moenkopi Formation (Sable and Hereford, 2004).

Lower part consists mainly of cliff- and slope-forming, gray, dark-gray, white and reddish-brown chert conglomerate in gray gravel sandstone matrix. Includes yellow, reddish-brown, interbedded, calcareous, thin-bedded, cross-stratified, sandstone, siltstone, gray gypsiferous siltstone, and yellow to gray, thin-bedded sandy limestone. Conglomerate clasts are subangular to rounded pebbles and cobbles of limestone and chert derived from erosion of nearby and underlying Kaibab Formation. Conglomerate is pebble-supported in most outcrops with pebbles compressed into one another; where matrix-supported, matrix is gray limestone and coarse-grained cherty sandstone. Conglomerate clasts are as much as 30 cm (12 in) in diameter. Imbrication of pebbles in conglomerate indicates northeasterly flow of depositing streams. Unconformable contact with underlying Harrisburg Member of the Kaibab Formation in paleovalleys. Rock Canyon Conglomerate was proposed and abandoned by Gregory (1948, 1952), used by Nielsen and Johnson (1979), and Nielsen (1986, 1991). Timpoweap Member of the Moenkopi Formation is used in this report as used by Stewart and others (1972) and Sable and Hereford (2004). Unit gradually thins west to east across map area and is largely confined to shallow wide paleovalleys in upper reaches of Kanab Creek and Muggins Flat area. Thickness ranges from 0 to 30 m (0 to 100 ft)

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

Pkh **Harrisburg Member (Lower Permian)**—Includes an upper, middle, and lower part in the western two-thirds of map area; due to facies changes, all three parts merge into one sandy limestone lithology eastward. In western two-thirds of map area, upper part consists of slope-forming, red and gray, interbedded gypsiferous siltstone, sandstone, gray gypsum, and thin-bedded gray limestone. Uppermost pale-yellow or light-gray, fossiliferous (mollusks and algae) sandy limestone, 1 to 2 m (2 to 6 ft) thick weathers yellowish-gray, brown, and reddish-gray; forms resistant caprock of Harrisburg Member in south-central half of map area around Kanab Creek drainages. Gradational contact with middle part. Unit is very similar in content, color, and weathering characteristics as limestone of the Timpoweap Member of the Moenkopi Formation. Some Timpoweap Member limestone beds contain small well-rounded chert or quartzite pebbles, whereas Harrisburg Member upper limestone beds contain scattered angular white chert fragments.

Middle part consists of two cliff-forming limestone beds that together gradually increases in thickness eastward across map area from 6 m (20 ft) to as much as 14 m (46 ft). Upper limestone bed is gray, thin-bedded, irregularly bedded cherty limestone that weathers dark brown or black. Lower limestone bed is light-gray, light-brown, and white, thick-bedded, sandy limestone separated from upper cherty limestone by about 3 m (10 ft) of thin-bedded gypsiferous sandstone and siltstone that thins eastward and northeastward to less than 1 m (3 ft). Both limestone beds and intervening gypsiferous sandstone and siltstone beds increase and decrease in thickness at expense of each other. Both limestone beds merge to form ledges and cliffs in small tributary canyons of the northern Kaibab Plateau and is difficult to distinguish from cherty limestone cliffs and ledges of the Fossil Mountain Member of the Kaibab Formation. Erosional unconformity separates middle part of Harrisburg Member from lower part where the lower sandy limestone bed fills erosion channels that are as much as 4 m (14 ft) deep in west half of map area and are less than 1 m (3 ft) deep in east half.

Lower part is slope-forming, light-red, fine- to medium-grained gypsiferous siltstone and sandstone interbedded with gray, medium-grained, thin-bedded limestone and gray to white, massive-bedded gypsum. West of Kaibab Plateau, lower part maintains uniform thickness of about 40 m (130 ft) and thins eastward and southeastward across Kaibab Plateau. Dissolution of gypsum in lower part has locally distorted limestone beds of middle part causing them to slump or bend into local tributary drainages of Kanab Creek area in west half of map area. Gradational contact between slope-forming Harrisburg Member and underlying cliff-forming Fossil Mountain Member of the Kaibab Formation is marked at top of upper cherty limestone bed of Fossil Mountain Member. Harrisburg Member gradually thins eastward across map area and undergoes an eastward facies change to mostly white and gray sandy limestone and calcareous sandstone. Thickness ranges from about 30 to 52 m (100 to 170 ft)

Pkf **Fossil Mountain Member (Lower Permian)**—Light-gray, fine- to medium-grained, thin-bedded, fossiliferous, cliff-forming, sandy, cherty limestone. Unit characterized by thin bedded, white chert beds and chert nodules in cliff-forming sandy limestone. Weathered chert bands are stained black or dark gray. Unconformable contact with underlying Woods Ranch Member of the Toroweap Formation is caused by combination of dissolution of gypsum in the Woods Ranch Member and channel erosion with relief as much as 2 to 4.5 m (6 to 15 ft). Thickness ranges from about 61 to 80 m (200 to 265 ft)

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

Ptw **Woods Ranch Member (Lower Permian)**—Gray, slope-forming gypsiferous siltstone and pale-red silty sandstone interbedded with white, laminated gypsum. Beds are locally distorted because of dissolution of gypsum in upper part. At higher elevations of the Kaibab Plateau, dissolution of gypsum produces large sinkholes into overlying Kaibab Formation. Gradational contact with underlying Brady Canyon Member marked at top of limestone cliff of Brady Canyon unit. Variable thickness due to dissolution of gypsum beds, about 49 to 81 m (160 to 265 ft)

Ptb **Brady Canyon and Seligman Members, undivided (Lower Permian)**—Units are mapped as one because the Seligman Member is too thin to show at map scale in most areas. Brady Canyon Member; gray, cliff-forming, medium-bedded, fine- to coarse-grained, fetid, fossiliferous limestone; weathers dark gray. Includes thin-bedded dolomite in upper and lower parts. Limestone beds average about 0.3 to 1m (1 to 3 ft) thick and contain chert lenses and nodules. Limestone beds undergo eastward facies change from limestone to sandy limestone to calcareous sandstone and become less fossiliferous. Unit is about 55 m (180 ft) thick in Kanab Creek area, thins eastward and northward to about 40 m (130 ft) in House Rock Valley. Gradational contact between cliff-forming Brady Canyon and slope-forming Seligman Members.

Seligman Member; gray to purple-red, slope-forming, thin-bedded dolomite and limestone beds interbedded with reddish gypsiferous siltstone and sandstone and gray gypsum. Unconformable contact with underlying Coconino Sandstone in southern two-thirds of map area and with underlying Hermit Formation in northern third; mostly flat plannar contact in most areas; erosional relief less than 1 m (3 ft). Contact mostly covered by talus and alluvial deposits in Kanab Creek drainage area. Seligman Member thins eastward from about 22 m (70 ft) in Kanab Creek area to less than 6 m (20 ft) on east side of Kaibab Plateau. Brady Canyon and Seligman Members combined gradually thin eastward across map area from about 67 to 40 m (220 to 130 ft) thick

Pc **Coconino Sandstone (Lower Permian)**—Light-brown, yellow-red, and tan, cliff-forming, fine-grained, well-sorted, cross-stratified quartz sandstone. Contains large scale, high-angle, planar crossbedded sandstone sets that average about 6 m (20 ft) thick or less. Lower 1.5 m (5 ft) is thin-bedded, partly calcareous, flat-bedded sandstone of Seligman Member of the Toroweap Formation that forms a sharp planar unconformable contact with underlying Hermit Formation with relief generally less than 1 m (3 ft). Unit gradually thickens from northwest to southeast in southeastern two-thirds of map area; unit pinches out in northwest and north-central part of map where Toroweap Formation (Ptb) overlies the Hermit Formation. Thickness ranges from about 0 to 52 m (0 to 170 ft)

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 interbedded with siltstone where sandstone beds gradually thin or pinch out from north to south across map area. Dark-red crumbly siltstone beds fill shallow erosion channels and form recesses between thick, light-red sandstone beds in upper part; lower part contains more siltstone. Unit locally contains poorly preserved plant fossils within channel-fill siltstone deposits in lower part. Sandstone bleaches to yellowish-white in upper 1 to 3.5 m (3 to 12 ft) of contact with overlying Coconino Sandstone or Toroweap Formation. Base of unit unconformably overlies Esplanade Sandstone (Pe) with erosion channels generally less than 3 m (10 ft) deep. Just south of map area, some erosion channels are as much as 40 m (130 ft) wide and 9 m (30 ft) deep (Billingsley, 2000). Unit thins southward and southeastward of map area and thickens westward and northward. In southwest quarter of map area, lower 18 m (60 ft) of unit is equivalent to upper slope unit of Esplanade Sandstone of McKee (1982), (Billingsley, 2000), but is included as part of Hermit Formation in this map area because upper Esplanade Sandstone units thin northward and pinch out along and in south edge of map area making this upper slope unit of the Esplanade Sandstone indistinguishable from the Hermit Formation slope. Hermit Formation gradually thins eastward and southward, thickens westward and northward across subsurface of map area. Approximate map contact between the Hermit Formation and Esplanade Sandstone at lowest red siltstone bed of Hermit Formation on surface of light-red, thick bedded sandstone of Esplanade Sandstone. Thickness ranges from about 150 to 340 m (500 to 800 ft)

Supai Group (Lower Permian, Upper, Middle, and Lower Pennsylvanian, and Upper Mississippian)—Includes, in descending order, Esplanade Sandstone (Lower Permian); and Wescogame Formation (Upper Pennsylvanian), Manakacha Formation (Middle Pennsylvanian), and Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian), undivided, as defined by McKee (1975; 1982). Upper Mississippian and Lower Pennsylvanian age for Watahomigi Formation is defined by Martin and Barrick (1999)

Pe **Esplanade Sandstone (Lower Permian)**—Light-red, white, and pinkish-gray, cliff-forming, fine- to medium-grained, medium- to thick-bedded [1 to 3 m (3 to 10 ft)], 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 3 to 12 m (10 to 40 ft) thick. Unconformable contact with underlying Wescogame Formation is marked by erosion channels as deep as 15 m (50 ft) filled with calcareous sandstone and limestone conglomerate; average channel depth about 11 m (35 ft) in lower reaches of Kanab Creek area. About 122 to 137 m (400 to 450 ft) thick

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

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

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

Watahomigi Formation consists of gray and purplish-red, slope-forming limestone, siltstone, mudstone, and conglomerate. Forms an upper ledge and slope unit and lower cliff unit. Upper ledge and slope unit is sequence of alternating gray, thin-bedded cherty limestone ledges and purplish-gray siltstone and mudstone slopes; limestone beds contain Early Pennsylvanian conodont fossils (Martin and Barrick, 1999); red chert lenses and nodules are common in limestone beds. Includes limestone chert pebble conglomerate at base; upper ledge and slope unit locally contains Pennsylvanian fossils and averages about 21 m (70 ft) thick. Lower cliff unit consists of a basal, purplish-red mudstone and siltstone overlain by thin-bedded aphanitic to granular limestone cliff with red chert nodules and chert veins. About 30 to 40 m (100 to 130 ft) thick

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

Horseshoe Mesa Member consists of light olive-gray, ledge- and cliff-forming, thin-bedded, fine-grained limestone. Weathers to receding ledges. Gradational and disconformable contact with underlying massive-bedded limestone of Mooney Falls Member marked by thin-bedded, platy limestone beds that form 1 to 3 m (3 to 10 ft) thick recess at base of member near top of Redwall Limestone cliff. Fossils are not common except locally. Includes distinctive ripple laminated limestone beds and oolitic limestone and some chert. Thickness ranges from about 14 to 30 m (50 to 100 ft).

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

Thunder Springs Member consists of about 50 percent white, cliff-forming, fossiliferous, thin-bedded, alternating bands of white chert, and about 50 percent brownish-gray, thin-bedded (2.4 to 12 cm [1 to 5 in]), finely crystalline dolomite and fine- to coarse-grained limestone. Weathers into distinctive prominent band of black and light-brown bands on cliff face. Disconformable planar contact with underlying Whitmore Wash Member distinguished by distinct lack of chert in Whitmore Wash Member. About 30 to 46 m (100 to 150 ft) thick.

Whitmore Wash Member consists of yellowish-gray and brownish-gray, cliff-forming, thick-bedded, fine-grained dolomite that is partly exposed within map area in lower reach of Kanab Creek. Weathers dark gray. West and north of map area, unit is mostly limestone. Unconformable contact with underlying Temple Butte Formation marked by erosional channels of low relief, about 1.5 to 3 m (5 to 10 ft) deep just south of map area (Billingsley, 2000). About 24.5 m (80 ft) thick

UNITS SHOWN ONLY IN CROSS SECTION

[Based on exposures in Grand Canyon (Billingsley, 2000; Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003)]

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). The unconformity at base of Temple Butte Formation represents a major stratigraphic break in Paleozoic rock record in Grand Canyon that includes part of the Late Cambrian, all of the Ordovician and Silurian, and most of the Early and Middle Devonian, representing about 100 m.y. Dark-gray Devonian strata are distinguished from underlying light-gray Cambrian rocks by color contrast. Unit thickens westward, thins southward. Thickness ranges from about 24 to 106 m (80 to 350 ft)

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

Ꞓm **Muav Limestone (Middle Cambrian)**—Dark-gray, light-gray, brown, and orange-red, cliff-forming limestone, dolomite, and calcareous mudstone. Contact with underlying Bright

Angel Shale is gradational and lithology dependent and marked at base of lowest prominent cliff-forming limestone. Muav Limestone generally thins from west to east in subsurface of map area. Intertonguing and facies change relations between Muav Limestone and Bright Angel Shale produce variable thickness trends. Thickness ranges from about 24 to 213 m (80 to 700 ft)

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purple-red, slope-forming siltstone, shale, and reddish-brown to brown sandstone. Includes the ledge-forming reddish-brown sandstone member of McKee and Resser (1945). Consists of green and purplish-red, fine-grained, micaceous, ripple-laminated, fossiliferous shale and siltstone; dark-green, medium- to coarse-grained, thin-bedded, glauconitic sandstone; and interbedded purplish-red and brown, thin-bedded, fine- to coarse-grained, ripple laminated sandstone. Contact with Tapeats Sandstone is approximately marked at top of vertical transition zone from predominantly green shale and siltstone to predominantly brown sandstone above Tapeats Sandstone cliff. About 60 to 90 m (200 to 300 ft) thick

Ꞓt **Tapeats Sandstone (Middle and Lower(?) Cambrian)**—Brown and reddish-brown, cliff-forming, coarse-grained sandstone and conglomerate. Unconformable contact with underlying Statherian Paleoproterozoic surface forms the Great Unconformity. Tapeats Sandstone fills lowland areas and thins across or pinches out against Proterozoic highlands. Variable thickness from 0 to 60 m (0 to 200 ft)

PROTEROZOIC CRYSTALLINE ROCKS

The intrusive and metamorphic rocks are as defined by Ilg and others (1996), Hawkins and others (1996), and Karlstrom and others (2003). There is at least a 50 percent chance that younger Proterozoic sedimentary rocks of the Grand Canyon Supergroup exposed in the eastern Grand Canyon area (Huntoon and others, 1996) may be present in the eastern subsurface of this map area.

Xu **Crystalline rocks, undivided (Statherian, Paleoproterozoic)**—Undivided intrusive and metamorphic rocks. Includes granite plutons, stocks, and pegmatite and aplite dikes, gabbro-diorite, and granodiorite rocks, garnet schist, hornblende-biotite schist, orthoamphibole-bearing schist and gneiss, and probable felsic metavolcanic rocks

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