Geologic Map of Pipe Spring National Monument and the Western Kaibab-Paiute Indian Reservation, Mohave County, Arizona

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Prepared in cooperation with the
National Park Service and the Kaibab-Paiute Tribe

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INTRODUCTION

This geologic map is a product of a cooperative project between the U.S. Geological Survey, the National Park Service, and the Kaibab-Paiute Indian Tribe to provide a uniform quality geologic database for this part of the Uinkaret Plateau of the Arizona Strip north of Grand Canyon National Park and west of Fredonia, Arizona. The geologic data will be useful for future geologic, biologic, and hydrologic resource studies of this area conducted by the National Park Service, the Kaibab-Paiute Tribe, the citizens of Moccasin, Arizona, the Bureau of Land Management (BLM), the State of Arizona, local private ranching organizations, and individuals.

Sandy Canyon Wash, Bitter Seeps Wash, and Bulrush Wash are the principal drainages in the map area that flow south into Kanab Creek, the principal drainage of this region that flows south toward the Colorado River in Grand Canyon. Moccasin Mountain and Moquith Mountain (Moki Mountain on old maps) form highland plateaus west and north of Moccasin and Kaibab, Arizona. The Vermilion Cliffs are a prominent topographic expression of the landscape that marks the southern and eastern edges of Moccasin and Moquith Mountains. The north edge of the map area abuts the Utah/Arizona State line. Access to the map area is by Arizona State Highway 389 and a short paved road to Pipe Spring National Monument and the towns of Kaibab and Moccasin, Arizona (fig. 1). Several unimproved dirt roads lead from these paved roads to various locations within the map area, but travel on some of these roads requires 4-wheel-drive vehicles. Extra food and water are highly recommended for travelers to this remote area.

The Kaibab-Paiute Tribe manages the reservation lands that encompass most of the map area. Visitors to the Kaibab-Paiute Indian Reservation are required to obtain a permit and permission from the Tribal Offices at the junction of Highway 389 and the road to Pipe Spring National Monument. The Bureau of Land Management (BLM), Arizona Strip Field Office in St. George, Utah, manages BLM lands west and south of the Kaibab-Paiute Indian Reservation area. Part of the BLM Cottonwood Point Wilderness area is included in the northwest corner of the map (fig. 1). There are 22 sections of land belonging to the State of Arizona and 26 sections of private ranch land, which includes the town of Moccasin, Arizona (U.S. Department of the Interior, 1999). Elevations range from about 4,265 ft at Bulrush Wash in the southeast corner of the map area to about 7,042 ft on Moquith Mountain, northeast edge of map area. Elevations below 5,000 ft generally support a sparse growth of sagebrush, cactus, grass, and various high-desert shrubs. Elevations above 5,000 ft commonly support moderate to thick growths of sagebrush and grass in alluvial valleys, while pinion pine, juniper, and oak trees thrive on Moccasin and Moquith Mountains. Salt cedar (tamarisk) and Russian olive trees grow along the banks of local tributary washes east of Kaibab and Moccasin, Arizona.

PREVIOUS WORK

Marshall (1956a, b), Pillmore (1956), and Hemphill (1956) made the earliest photogeologic maps of the area for the U.S. Atomic Energy Commission. Those maps were later compiled onto the state geologic map of Arizona by Wilson and others (1969) and later modified by Reynolds (1988). Geologic maps of adjacent areas (fig. 1) include photogeologic maps of the Short Creek NW quadrangle (now Colorado City quadrangle) by Marshall and Pillmore (1956); the Short Creek SW quadrangle (now Maroney Well quadrangle) by Marshall (1956c); the Heaton Knolls NW quadrangle (now Wild Band Pockets quadrangle) by Marshall (1956d); and the Fredonia NE quadrangle (now Fredonia quadrangle) by Morris (1957). Other nearby geologic maps include Clayhole Wash and vicinity, scale 1:31,680, about 9 mi west of the map area (Billingsley and others, 2002); Upper Clayhole Valley and vicinity about 6 mi southwest of the map area (Billingsley and Priest, 2003); and Jumpup Canyon and Big Springs quadrangles near the southeast edge of the map area (Billingsley, 1992).

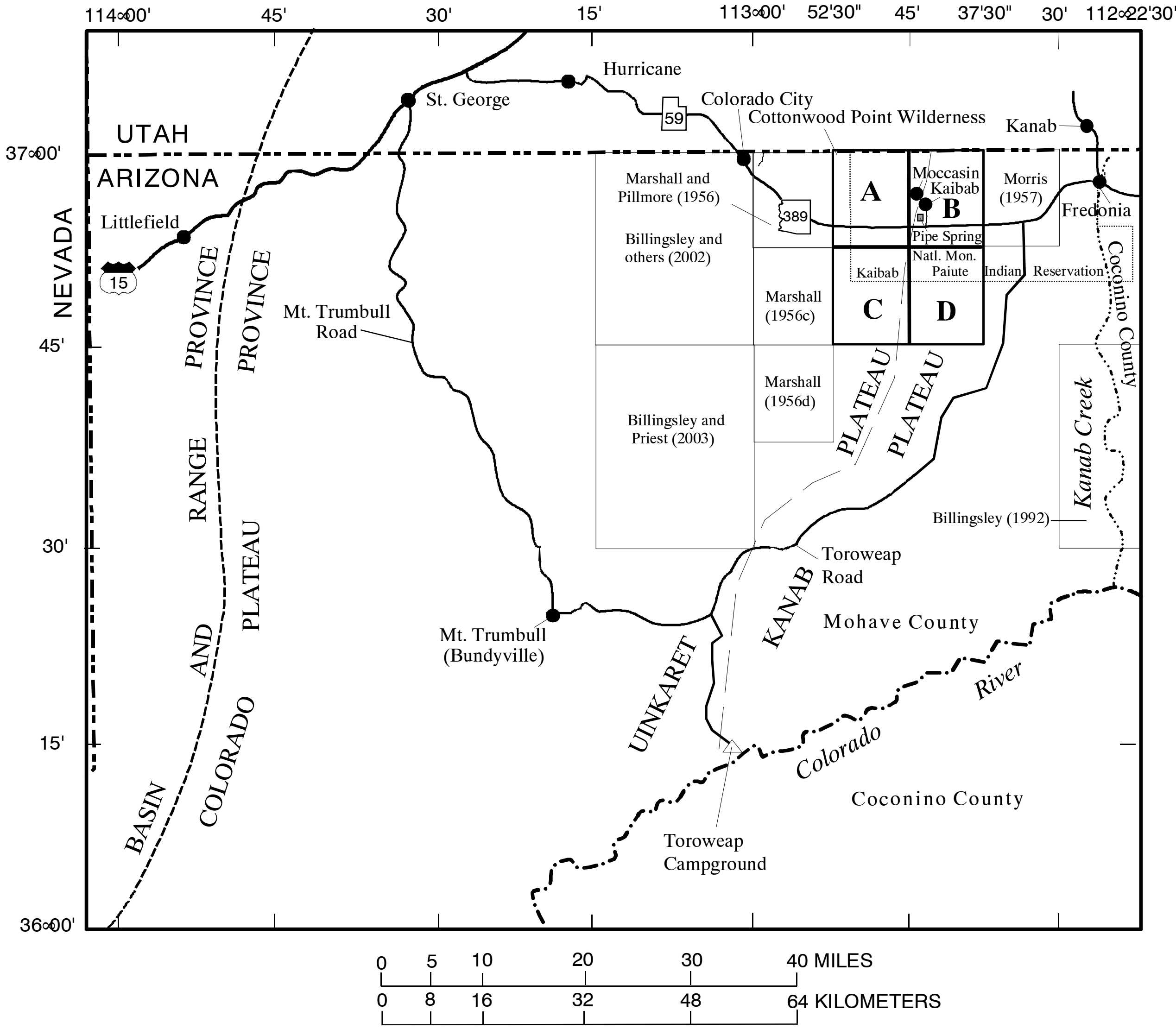

Figure 1. Map showing the Moccasin (A), Kaibab (B), Pipe Valley (C), and Pipe Spring (D) U.S. Geological Survey 7.5-minute quadrangles and adjacent mapped areas, northern Mohave County, northern Arizona.

MAPPING METHODS

The geology was mapped using Bureau of Land Management 1:24,000-scale 1976 aerial infrared photographs and 1:24,000-scale 2002 aerial color photographs followed by extensive field checking. Many of the Quaternary alluvial deposits have similar lithologies but different geomorphic characteristics and were mapped almost entirely by aerial photography. Relative ages of surficial fluvial and eolian deposits were determined using stratigraphic position and the amount of erosional degradation. The map units and geologic structures were field checked to insure accuracy and consistency of map unit descriptions.

GEOLOGIC SETTING

The map area lies within the north part of the Uinkaret Plateau, a subplateau of the southwestern part of the Colorado Plateau physiographic province (Billingsley and others, 1997). The area is characterized by nearly flat Paleozoic and Mesozoic sedimentary strata that have an average regional dip of about 1∞to 2∞north-northeast and are gently warped by minor north-south-trending folds and offset by normal faults. About 650 ft of Permian strata and about 3,400 ft of Triassic and Jurassic strata make up the sedimentary section within the map area. The Sevier Fault that offsets all Paleozoic and Mesozoic strata and the Moccasin Monocline are the principal structures in the map area and have a general north-south and northeast strike.

Quaternary deposits are widely distributed in the map area and consist of fluvial alluvium deposits, eolian sand sheets and sand dune deposits, mixed fluvial and eolian deposits, talus, rock fall, and landslide debris. Manmade quarries, drainage diversion dams, and stock tanks are also mapped. Agricultural fields and minor road cut excavations are not mapped. Map contacts between several Quaternary surficial deposits are arbitrarily placed because of intertonguing and gradational facies changes in both the lateral and vertical sense. The information about surficial units strongly influences many resource management decisions for managing rangeland conditions, flood control problems, biological studies, soil erosion and development, and the development of local construction projects. The surficial deposits are Pleistocene or Holocene age (less than 2 m.y.) based on datable volcanic rocks associated with similar surficial deposits mapped in adjacent areas (Billingsley and Workman, 2000; Billingsley and others 2002; Billingsley and Priest, 2003).

STRATIGRAPHY

The Paleozoic and Mesozoic stratigraphic units exposed within the map area include, in order of decreasing age, the Kaibab Formation (Lower Permian), the Moenkopi Formation (Lower and Middle? Triassic), the Chinle Formation (Upper Triassic), the Moenave Formation (Lower Jurassic), the Kayenta Formation (Lower Jurassic), and the Navajo Sandstone (Lower Jurassic). Ages of the Mesozoic strata have been revised to reflect new data described and published by Biek and others, 2000.

Gray cherty limestone and gray, red, and white siltstone and gypsum beds of the Kaibab Formation crop out in the southeast corner of the map area. A complete section of the Kaibab Formation is exposed just southeast of the map area in Kanab Canyon (Billingsley, 1992). About three-fourths of the surface bedrock in the south and east part of the map area is composed of red siltstone and sandstone, gray gypsum, and gray dolomite of the Moenkopi Formation, and white sandstone and multi-colored siltstone and claystone of the Chinle Formation. Red-brown claystone, siltstone, and sandstone of the Moenave and Kayenta Formations form the lower slopes of the Vermilion Cliffs, whereas light-red and white, cross-bedded Navajo Sandstone forms the cliffs of the upper part of the Vermilion Cliffs as well as the highlands of Moccasin and Moquith Mountains in the northwest quarter of the map area. A regional unconformity separates the Permian Kaibab Formation from the Triassic Moenkopi Formation. Another regional unconformity separates the Moenkopi Formation from the Triassic Chinle Formation, and a third regional unconformity separates the Chinle Formation from the Jurassic Moenave Formation.

Light-red, gray, and brown alluvial and eolian surficial deposits that are locally derived from bedrock outcrops cover more than half of the map area. All surficial deposits are generally 3 to 60 ft thick. Most of the fluvial deposits, such as alluvial fans and alluvial terrace deposits, are locally derived from Triassic and Jurassic strata of the Vermilion Cliffs. The eolian deposits are commonly derived from local fluvial deposits below the Vermilion Cliffs and outcrops of the Navajo Sandstone on Moccasin and Moquith Mountains. The thickest and most widespread eolian deposits are on Moccasin and Moquith Mountains. Most of the eolian deposits are stabilized by grassy vegetation during wet climatic conditions but do become active during prolonged dry conditions coupled with extensive overgrazing.

STRUCTURAL GEOLOGY

The Sevier Fault is the principle structural feature in the map area and forms the boundary between the Uinkaret Plateau west of the fault and the Kanab Plateau east of the fault (Billingsley and others, 1997). The Sevier Fault north of Pipe Spring National Monument generally has a north-south strike that extends into Utah. South of the Monument the fault has a slightly southwest-northeast strike and connects to the Toroweap Fault about 13 mi south of the map area. Just north of Pipe Spring National Monument, a short west segment of the Sevier Fault extends northwest toward Moccasin, Arizona, and dies out about 2 mi north of Moccasin. Paleozoic and Mesozoic strata have a north-northeast regional dip about 1∞to 2∞throughout the map area. There are minor faults and folds and a few local collapse structures scattered throughout the map area.

The main segment of the Sevier Fault continues northeast of Pipe Spring National Monument to the Vermilion Cliffs where the fault parallels the east-facing Vermilion Cliffs for about 3 mi to Sand Wash, then continues north into Utah east of the Coral Pink Sand Dunes State Park. A gentle east-dipping monocline is present along the Sevier Fault at the north edge of the map west of the Moquith Mountains. Monoclines on the Colorado Plateau have developed in response to the Laramide orogeny of Late Cretaceous through Eocene time along pre-existing Precambrian fault zones (Huntoon, 2003). Mesozoic strata along the Moccasin Monocline dip east as much as 10ʃ elevating the landscape about 200 to 300 ft west of the Sevier Fault. Extensional stresses from Late Miocene to the present time have resulted in down-to-the-west normal faulting along the Precambrian basement faults effectively reversing part of the Laramide offset of strata by displacing strata down-to-the-west as much as 1,300 ft near Pipe Spring. Most of the fault displacement probably occurred during Pliocene and Pleistocene time and likely continues today, as observed on the Toroweap and Hurricane Faults west and southwest of the map area (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003).

WEST SEGMENT OF THE SEVIER FAULT

The west segment of the Sevier Fault branches from the main segment just north of Pipe Spring National Monument. Associated with the west segment is an east-dipping monocline herein referred to as the Moccasin Monocline. At the base of the Moccasin Monocline is a small syncline that parallels the strike of the monocline. The west segment of the Sevier Fault, Moccasin Monocline, and syncline all gradually die out northward into Moccasin Mountain about 2 mi north of Moccasin, Arizona. The monocline and syncline extend southwest of Pipe Spring National Monument and gradually die. The syncline is subtly visible in the monoclinal flex in the Vermilion Cliffs just west of Pipe Spring. The monocline, syncline, and Sevier Fault all parallel the west side of the paved road between Pipe Spring National Monument and Moccasin, Arizona. The northwest structural trend of the west segment of the Sevier Fault may be continuous as a small fault at depth in the Precambrian basement rocks under Moccasin Mountain and reconnect to the main segment of the Sevier Fault near Sandy Canyon Wash just south of the Arizona/Utah State line.

MAIN SEGMENT OF THE SEVIER FAULT

Fluvial and eolian sand deposits largely cover the main segment of the Sevier Fault north of its junction with the west segment of the Sevier Fault. About 2 mi northeast of the junction, the Sevier Fault displaces the Shinarump Member of the Chinle Formation about 240 ft near South Moccasin Wash. The offset results in a fault scarp that forms a northeast-trending slope of the red Moenkopi Formation capped by a white sandstone of the Shinarump Member of the Chinle Formation. Three miles north of South Moccasin Wash, the Sevier Fault is partly visible in Mesozoic strata between landslide deposits near the base of the Vermilion Cliffs. The fault is mostly covered by landslide debris or surficial deposits for 3 mi along the Vermilion Cliffs to Sandy Canyon Wash. Just southwest of Blue Knolls, the Sevier Fault is poorly exposed in small drainages at the base of the Vermilion Cliffs and the fault plane appears to dip west about 70ʃ to 75ʃ. Surficial deposits largely cover the Sevier Fault from Sandy Canyon Wash north into Utah, but its position is marked by topographic expression where the Sevier Fault separates the higher Moquith Mountains east of the fault from the lower Moccasin Mountains west of the fault.

A monocline is not apparent along the main segment of the Sevier Fault until it reaches the vicinity of the Arizona/Utah State line, but a syncline is present just east of the Vermilion Cliffs for about 3 mi to Sandy Canyon Wash where the syncline dies out. Triassic strata east of and along most the main segment of the Sevier Fault dip about 2ʃ northeast.

South of the Pipe Spring National Monument, fluvial and eolian deposits cover the Sevier Fault and Moccasin Monocline. The existence of the Moccasin Monocline south of Pipe Spring is somewhat conjectural and the Sevier Fault trace is approximate marked for about 3 mi south to Pipe Valley Wash. Fault drag on the upthrown side (east) of the fault in a drainage 1 mi south of Pipe Spring shows strata dipping west as much as 45ʃ. South of the map area, the Sevier Fault and a monocline continue for several miles forming a near perpendicular intersection with the Toroweap Fault.

One structural peculiarity within the map area is a local graben in the Vermilion Cliffs 2 mi north of Kaibab, Arizona. The graben, oriented generally north-south, cuts through the southeast tip of Moccasin Mountain then turns sharply east toward the Sevier Fault at its northern extension. The displacement of the Navajo Sandstone into the graben is about 160 ft near the Sevier Fault and about 200 ft at its southern extension. The graben has a U-shaped profile in cross section instead of a typical V-shaped profile. The U-shaped graben is well exposed in the Vermilion Cliffs just west of the Sevier Fault. The Navajo Sandstone is faulted down into the graben and slid southward within the graben as a landslide mass. The sandstone beds within the graben have rotated backward and dip north against the parent wall from which they originated. The landslide mass protrudes out beyond and below the Vermilion Cliffs as a lower broken cliff of the Navajo Sandstone. The base of the graben terminates within the lower part of the Kayenta Formation where the mudstone and siltstone beds provide a surface for the Navajo Sandstone to slide. A minor synclinal fold is present beneath the graben in the lower strata of the Kayenta and Moenave Formations that may reflect a graben structure at depth.

The minor synclines in the south-central part of the map have a general north-south trend and these folds, like others found elsewhere on the Colorado Plateau, are probably related to early Laramide compressional stresses (Huntoon, 2003).

JOINTS

Joints are prominent features visible in the sandstone bedrock units throughout the map area. There are four different orientations of joints in the Moccasin Canyon and Moccasin Mountain area northwest of Pipe Spring National Monument: north-south, northeast, northwest, and east-west. At least two and sometimes three joint sets are present in different parts of the map area, but typically only two sets are commonly present, the northeast and northwest oriented.

Joints are vertically continuous through all hard and soft Paleozoic and Mesozoic rock strata exposed in the Grand Canyon south of the map area. The joints reflect older regional stress patterns from compressional tectonic events of different geologic ages from Proterozoic through Cenozoic time for the Colorado Plateau. The joints are prominently displayed on surface exposures of hard sandstone and sandy limestone bedrock units of the Kaibab Formation, the Shinarump Member of the Chinle Formation, the Springdale Sandstone Member of the Moenave Formation, and the Navajo Sandstone. These rocks units are well-cemented, competent cliff-forming strata that tend to break and fracture rather than bend and flow as the softer interbedded mudstone and siltstone strata that form steep slopes between the cliff-forming sandstones. The northwest- and northeast-orientated joint systems appear to be the most active in the map area because many of the joints are visible as semi-open cracks in the Navajo Sandstone. The cracks are also visible in the surficial eolian sand deposits on Moccasin Mountain as linear vegetation growths, especially in the upper reaches of Moccasin Canyon where the joints are filled with eolian sand deposits and the local vegetation has established a deep roothold. On aerial photographs, the linear vegetation growth patterns are visible in sand sheet or sand dune deposits.

A north-northwest joint zone at Zion National Park, 10 mi northwest of the map area, is documented by Rodgers (2002) as the youngest in the region. Rodgers concluded that the north-northwest trending joint zones and subsequent isolated joints indicate a pervasive extension characteristic of west-southwest extension of the central Basin and Range Province that has affected the western Colorado Plateau since mid-Miocene time. However, the northwest joint system may be as old as Laramide age and may have been reactivated from Miocene time to the present because of the following observation. The abundant northwest- and north-orientated joints form open cracks in the canyon walls of Navajo Sandstone in Moccasin Canyon. The joint planes are parallel to the Moccasin Monocline and dip as much as 8ʃ to 10ʃ west in the middle of the monocline. The Navajo Sandstone and Kayenta Formation strata dip east as much as 8ʃ to 10ʃ. By unfolding the monocline back to its nearly flat-lying position of pre-Laramide time, the joints would be nearly vertical as they are in the nearly flat-lying strata in upper Moccasin Canyon. Thus, the joint systems along the Moccasin Monocline are either pre-Laramide and were tilted by Laramide folding, or if the joints at Zion National Park are Miocene age as suggested by Rodgers (2002), then the Moccasin Monocline would have to be Late Miocene or younger in age because of the tilted joint planes.

COLLAPSE STRUCTURES

Circular bowl-shaped areas with inward-dipping strata are collapse structures that may have developed because of collapse-formed breccia pipes caused primarily by dissolution of the deeply buried Mississippian Redwall Limestone (Wenrich and Huntoon, 1989; Wenrich and Sutphin, 1989). A dot and the letter C on the map mark such features. These collapse features, however, cannot be distinguished with certainty from shallow collapse structures caused by the dissolution of gypsum in the Kaibab or Toroweap Formations. Drilling is required to confirm that breccia pipes do originate in the Redwall Limestone. The deep-seated breccia pipes contain potential economic high-grade ore deposits of copper and uranium minerals (Wenrich, 1985). The primary metal is uranium along with Ag, Pb, Zn, Cu, Co, and Ni (Wenrich and Huntoon, 1989).

A large collapse structure is present in the upper reaches of Cove Canyon about 3 miles east of Kaibab, Arizona. This collapse structure is about 1/8 mi in diameter and is likely a breccia pipe at depth. The smaller breccia pipes marked near Pipe Valley Wash are also probably collapse breccia pipes.

SPRINGS OF THE MAP AREA

Water is a critical natural resource that is responsible for the early pioneer development of this part of the high desert of the Arizona Strip. The historical use of Pipe Spring is the reason for the existence of Pipe Spring National Monument that helps to preserve the historical and natural resources of this unique area. Moccasin Spring, northwest of Pipe Spring, is also a critical natural water resource for the town of Moccasin, Arizona, and it is critical for human and animal habitats of this remote part of northern Arizona (fig. 2).

There are similar structural and bedrock characteristics that control the spring discharges at Pipe Spring and Moccasin Spring. Both springs (1) are on the down-thrown side of either the west segment or main segment of the Sevier Fault, (2) discharge at the bottom of a local syncline at the base of the east-dipping Moccasin Monocline, (3) are at or near the contact of the Navajo Sandstone and the Kayenta Formation, and (4) are associated with north-south and northwest-southeast oriented bedrock joints.

Moccasin Spring is about 3.5 mi northwest of Pipe Spring at elevation 5,170 ft and Pipe Spring is at elevation 4,970 ft, a vertical difference of 200 ft. Thus, the ground-water gradient is about 57 ft/mi from Moccasin Spring to Pipe Spring assuming that both springs have the same ground-water source. The ground-water flow is largely confined to the base of the Navajo

Sandstone and upper part of the Kayenta Formation, mostly within the syncline at the base of Moccasin Monocline. The high-angle, west-dipping fault plane of the west and main segments of the Sevier Fault acts as a partial barrier to the eastward flow of ground water, but most importantly, the impermeable strata of the Chinle and Moenkopi Formations east of the faults forms the impermeable barrier to ground-water leakage through the faults because of the abundant claystone and gypsum content of those formations. Thus, ground water accumulates on the west side of the west segment of the Sevier Fault forming a saturated water zone within the syncline and against the fault plane until the static water level reaches an erosional gap in the bedrock for ground water to overflow the fault. Moccasin Wash has eroded deep enough into the west segment of the Sevier Fault to provide a point of overflow for ground water to flow east into the alluvial deposits of South Moccasin Wash. The discharge for Pipe Spring is similar in that a small drainage has eroded headward into the syncline just northwest of Pipe Spring, allowing water to flow east and southeast over the eroded main segment of the Sevier Fault.

At South Moccasin Wash, ground water flows over the fault barrier into thick sandy alluvial and eolian deposits that overlie impermeable bedrock strata of the Petrified Forest Member of the Chinle Formation, or upper red member of the Moenkopi Formation. The Shinarump Member of the Chinle Formation is porous conglomeratic sandstone that becomes saturated with water as much as the alluvium of South Moccasin Wash and that forms a perched water table in the South Moccasin Wash valley area under the towns of Moccasin and Kaibab, Arizona. The alluvial deposits along South Moccasin Wash are as much as 120 ft thick or more along the drainage.

The distance between the west and main segments of the Sevier Fault along South Moccasin Wash is about 1.5 mi. The perched shallow ground water within the alluvium between the faults is eventually forced over the main Sevier Fault at the lowest eroded part of South Moccasin Wash causing the static water table to become shallow and visible in South Moccasin Wash just west of the fault. East of the main Sevier Fault, bedrock under the alluvium is mostly impermeable gypsum and gypsiferous siltstone and claystone of the Shnabkaib Member and lower red member of the Moenkopi Formation. The ground water is again restricted to the shallow alluvial and eolian deposits of South Moccasin Wash drainage valley forming a perched water zone as far downstream as the alluvial deposits extend. When there is no more alluvium, such as at State Highway 389, water is visibly flowing on bedrock of the Moenkopi Formation in South Moccasin Wash. South Moccasin Wash becomes Twomile Wash just downstream of Highway 389. Some of the water, after evaporation and domestic use, shows up at Twomile Seep in Twomile Wash south of Highway 389 (fig. 2). Tamarisk trees commonly grow where shallow ground water exists due to the close proximity of bedrock in Twomile Wash.

Other springs and seeps within the map area have relatively small discharges, generally less than one gallon per minute, and many become dry during sequential drought year conditions. The next largest springs within the map area is a small cluster of springs collectively known as Upper Moccasin Springs in the upper reaches of Moccasin Canyon (fig. 2). These springs discharge an estimated one or two gallons per minute each, as of spring 2003, a dry year, but discharge will likely increase in wetter climatic conditions.

Joints in the bedrock control the flow of ground water toward most spring outlets in the map area to a certain extent, but it is the bedrock composition and dip of strata of nearly flat-lying or gently folded strata aided by gravity that control the basic ground-water flow. The Navajo Sandstone is commonly a permeable rock unit in which ground water moves and collects within the lower sandstone stratum. Bedding planes and numerous joints within the Navajo Sandstone allow ground water to migrate or flow at a faster rate through the rock unit than within the sandstone itself. The joints and fractures act as direct conduits for ground water flow while the sandstone acts as the reservoir that accumulates and stores ground water and that slowly discharges water into joints and bedding planes to flow toward springs. The most important

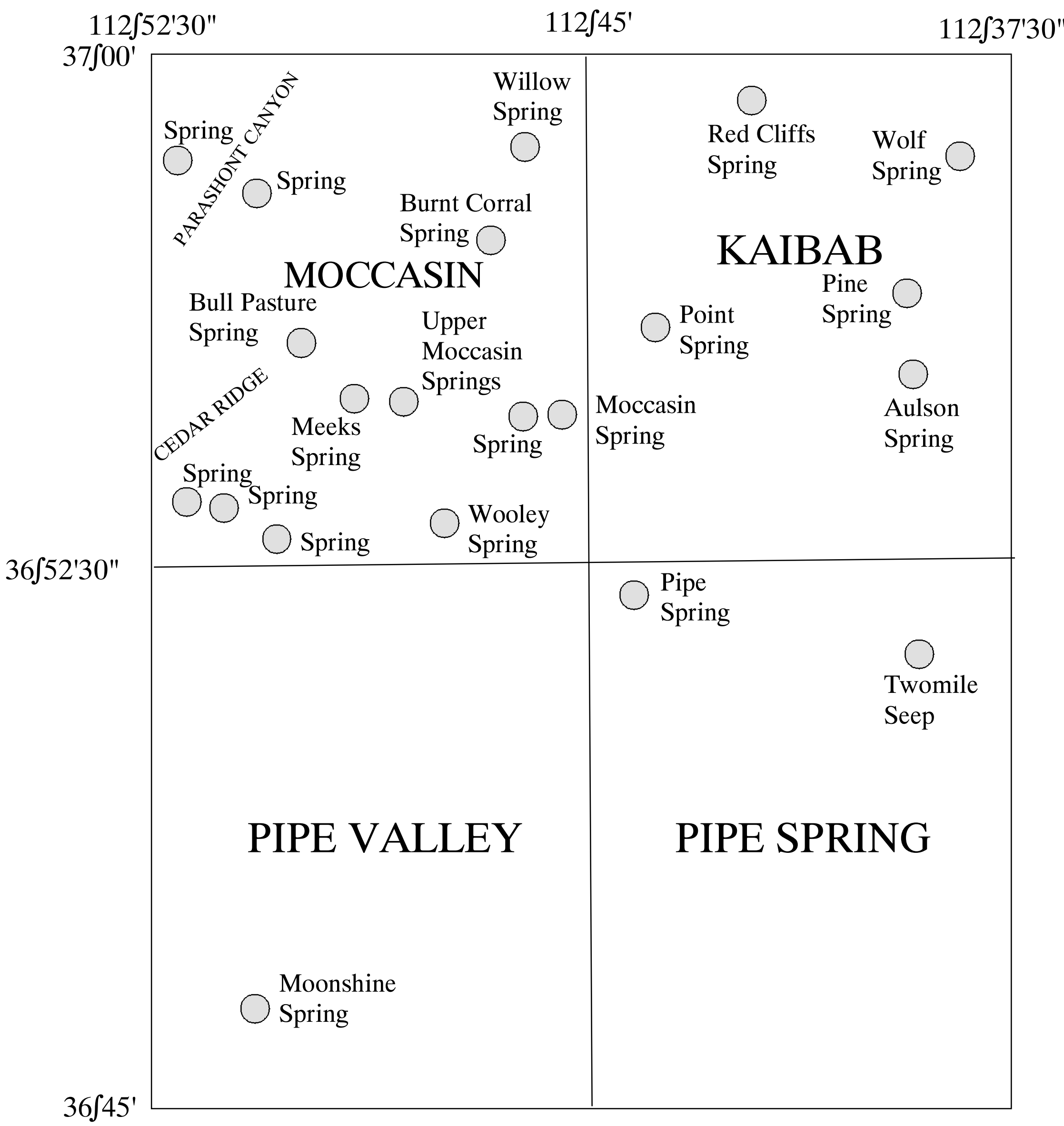

Figure 2. Schematic index map of springs shown on the Moccasin, Kaibab, Pipe Valley, and Pipe Spring U.S. Geological Survey 7.5-minute quadrangles, Mohave County, northern Arizona.

factor is that the Navajo Sandstone overlies the impermeable claystone and siltstone strata of the upper part of the Kayenta Formation, which acts as a barrier to the downward percolation of ground water. The contact between the Navajo Sandstone and Kayenta Formation is gradational and variable throughout the map area as a gradational intertonguing transition zone about 40 to 60 ft thick. This transition zone consists of a sequence of interbedded red sandstone and siltstone beds that form alternating slopes and ledges. The map contacts are approximate and arbitrarily placed at about the lowest red sandstone cliff of the Navajo Sandstone, or near the topmost red siltstone bed within the upper part of the Kayenta Formation that is generally within the Navajo/Kayenta transition zone. In either case, ground water is largely restricted to the base of the Navajo Sandstone and to some extent to permeable sandstone beds within the upper part of the Kayenta Formation. Ground water at or near this contact zone moves down slope through joints or along bedding planes largely controlled by the local or regional dip of strata in the lowest sandstone exposures along the Vermilion Cliffs and in canyon drainages. Springs and seeps commonly located in the Navajo Sandstone/Kayenta Formation transition zone are Pipe Spring, Moccasin Spring, Upper Moccasin Springs, Red Cliffs Spring (Moquith Mountains), Bull Pasture Spring (Bull Pasture, northwest part of map area), Meeks Spring (in upper Potter Canyon), and an unnamed spring in Rosy Canyon, northwest corner of the map area (fig. 2).

A few springs owe their existence, in part, to the permeable Springdale Sandstone Member of the Moenave Formation that is sandwiched between the impermeable strata of the Kayenta Formation above and the Whitmore Point Member of the Moenave Formation below. Two miles north of Kaibab, Arizona, there are three unnamed springs in the Cedar Ridge area (Fig. 2) and Point Spring, two miles north of Kaibab, Arizona, that are usually dry except during wet weather conditions (fig. 2). The recharge for ground water in the Springdale Sandstone is likely limited to surface rainfall collection areas where the Springdale Sandstone is exposed. A likely recharge zone for water at Point Spring is the thick landslide debris masses that overlie the impermeable beds of the Kayenta Formation.

Aulson Spring in Aulson Canyon and Moonshine Spring at Yellowstone Mesa (fig. 2) discharge water at the contact between the Shinarump Member of the Chinle Formation and the upper red member of the Moenkopi Formation. Surface recharge areas of these seep springs are due to extensive exposures of permeable coarse-grained sandstone outcrops of the Shinarump Member of the Chinle Formation that overly impermeable claystone and mudstone beds of the Moenkopi Formation. Large surface exposures of the Shinarump Member above Aulson and Moonshine Springs provide a good surface recharge area for these springs. Often there are other local wet weather seeps at the base of the Shinarump Member outcrops in both areas of the map during wetter climatic conditions.

Pine Spring and Wolf Spring discharge small amounts of water at the contact between alluvium and the Petrified Forest Member of the Chinle Formation. These seep springs are the result of ground water collected from rainfall on alluvial fan deposits uphill of the spring outlets. The impermeable claystone and siltstone beds of the Chinle Formation effectively prevents the downward percolation of ground water at the base of the alluvial fans and forces most of the local perched accumulated ground water to flow down to exposures of the Chinle bedrock.

Wooley Spring west of Pipe Spring discharges below a large landslide debris mass that overlies impermeable siltstone and claystone strata of the Kayenta Formation. The large landslide mass is an excellent recharge zone for Wooley Spring during wet weather years because of the fractured nature of the landslide. Willow Spring and Burnt Corral Spring on Moccasin Mountain are wet weather springs within the Navajo Sandstone. These springs discharge from minor impermeable cherty limestone beds that have limited lateral extent within the Navajo Sandstone. As a result, these springs are short lived because they are largely restricted to the extent of the cherty limestone beds within the Navajo Sandstone.

The swamp in Parashont Canyon is a perched water zone in the surficial valley alluvium that fills a canyon drainage eroded into the impermeable Kayenta Formation. This shallow perched ground water is dependent on local runoff into the canyon drainage. The alluvial filled valleys of Rosy Canyon, Parashont Canyon, Bull Pasture, and Woodberry Canyon, in the northwest quarter of the map area, all have potential shallow well water producing capabilities that may be limited in volume and restricted to the alluviated valleys.

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits are differentiated from one another chiefly on the basis of difference in morphologic character and physiographic position observed on 1976 aerial photographs and field observations. Older alluvial and eolian deposits generally exhibit extensive erosion, whereas younger deposits are actively accumulating material or are lightly eroded. Salt is a common constituent in all alluvial deposits derived from the Chinle and Moenkopi Formations in the south and east part of the map area.

Qaf **Artificial fill and quarries (Holocene)**ó Alluvium and bedrock material removed from quarries and trench excavations to build stock tanks, drainage diversion dams, roads, or other manmade construction projects other than modern highways. No map distinctions between cut or fill excavations. Agricultural fields are not shown

Qs **Stream-channel alluvium (Holocene)**ó White to light-red interbedded silt, sand, gravel, and pebbles; unconsolidated and poorly sorted. Pebbles and some cobbles are mostly sandstone above the topographic position of the Shinarump Member of the Chinle Formation; below the Chinle, clasts are dominated by black, well-rounded pebbles of quartzite or chert of volcanic origin. Locally overlaps or is deposited adjacent to young and intermediate alluvial terrace-gravel deposits (Qg1, Qg2) and commonly overlaps young and intermediate alluvial fan (Qa1, Qa2) deposits. Gradational and arbitrary contacts with other surficial alluvial or eolian deposits are approximate and subject to change. Stream channels are subject to intermittent high-energy flash floods that can produce local sediment accumulation on floodplain (Qfp) and young terrace alluvial (Qg1) deposits and widespread sediment accumulations on young alluvial fan (Qa1) deposits. Stream-channel alluvium is a common source for local sand dune or sand sheet accumulations in Pipe Valley and Sandy Canyon Wash areas. Little or no vegetation in stream channels except for occasional tamarisk trees or willow trees and grass. Thickness, 3 to 12 ft

Qfp **Floodplain deposits (Holocene)**ó Light-red or tan silt, fine- to coarse-grained sand, and lenses of pebble gravel; partly consolidated by gypsum or calcite cement. Gravel locally contains yellow, red, black, and white subrounded to subangular chert fragments, well-rounded white quartzite, and gray-blue, rounded limestone pebbles º to æ inch in diameter. Seasonal floods may produce fresh deposits that generally accumulate temporary deposits on point bars of drainages, on young alluvial terrace-gravel (Qg1) deposits, and on flatland areas adjacent to young alluvial fan (Qa1) deposits when drainages area clogged by debris flows or man-made obstructions. Gradational and arbitrary contact both laterally and vertically between stream-channel (Qs), floodplain (Qfp), and young alluvial fan (Qa1) deposits. Support thick growth of tamarisk trees and other water-dependent plants where stream bedrock is very shallow, usually less than 10 ft to bedrock. Dense growths of tamarisk often help trap and accumulate sediment to form floodplain deposits within and along drainages. Deposits are generally 3 to

6 ft above stream-channel (Qs) deposits and often grade laterally into stream-channel deposits. Thickness, 3 to 20 ft

Qps **Ponded sediments (Holocene)**ó Light-red to white clay, mud, silt, and fine-grained sand. Locally include small angular to subrounded fragments of bedrock from nearby rock outcrops. Sediment accumulates in temporarily ponded areas on young and intermediate alluvial terrace-gravel (Qg1, Qg2) deposits due to temporary sand dune accumulations or overbank sand levee deposits that prevent sediments from eroding back into local drainages for an extended amount of time. Includes ponded deposits consisting mostly of sand and silt on Moccasin Mountain where widespread sand sheet and sand dunes form temporary dams across local drainages or as internal dunal depressions formed within dunes. South of Pipe Spring National Monument, ponded deposits accumulate in lowland areas where artificial diversion dams, stock tanks, or small sand dunes block drainage. Desiccation cracks often form on dry hardpan surfaces. Clay and fine silt largely restrict plant growth. Thickness, 1 to 6 ft

Qes **Eolian sand sheet deposits (Holocene)**ó On Moccasin and Moquith Mountains above Vermilion Cliffs, light-red to white silt and fine- to coarse-grained eolian sand derived from the Navajo Sandstone (Jn). Forms thick deposits over gently sloping terrain of Navajo Sandstone where sand fills large cracks and joints on the surface of Navajo allowing deep-rooted vegetation to develop linear growths on sand sheet or sand dune (Qd) deposits. Only most extensive and thickest deposits on Moccasin Mountain are shown; map contacts are arbitrary and gradational between sand sheet (Qes), sand dune (Qd), and mixed eolian and fluvial (Qae) deposits and are based on morphologic interpretation on aerial photos. Below Vermilion Cliffs, deposits accumulate along local stream drainages and on gentle slopes of young and intermediate alluvial fan (Qa1, Qa2) deposits. Unit forms coarse-grained sand ramps on gentle slopes of the Shinarump Member of the Chinle Formation where the Shinarump is the sand source. Deposit often leads to fine-grained climbing or falling sand dune (Qd) accumulations on steep bedrock or landslide (Ql) deposits along Vermilion Cliffs and other small isolated mesas and buttes where wind speed is reduced to allow sand accumulation. In Pipe Valley south of State Highway 389, sand sheet deposits are thin, widespread, and partly stabilized by grass and small high-desert shrubs during wet conditions on young alluvial fan (Qa1) deposits; also stabilized by lag gravel consisting mostly of black pebbles derived from the Shinarump Member of the Chinle Formation of Yellowstone Mesa. Sand sheet veneer deposits are widespread and common through the map area but most are too thin to show. Support moderate growths of grass, black brush, and other small high-desert shrubs above Vermilion Cliffs, mostly grass below Vermilion Cliffs. Thickness, 0.5 to 3 ft in south half of map; as much as 9 to 15 ft in large valleys on Moccasin Mountain and within tributary canyons eroded into Moccasin Mountain

Qd **Eolian sand dune deposits (Holocene)ó** Light-red to white, fine- to coarse-grained sand. Form complex lumpy dune shapes and random dune accumulations on variable sloping topography. Include climbing or falling dunes on steep sloping topography along Vermilion Cliffs. Arbitrary and gradational contact with sand sheet (Qes) and mixed eolian and fluvial (Qae) deposits are based on aerial photography interpretation. Dune surfaces are commonly active in large open valley areas that support sparse growth of grass or small shrubs and on steep topography. Unit is partly stabilized by grassy vegetation or by crypto-organic soil growths in local canyon drainage areas below Vermilion Cliffs. Thickness, 12 to 35 ft

Qae **Mixed eolian and fluvial deposits (Holocene)**ó Composed of gray, light-red, and white silt and fine- to coarse-grained eolian and fluvial sand lenses interbedded with red-brown and gray silt and clay. Include some coarse-grained gravel composed of angular chert fragments and red to white sub-rounded sandstone pebbles on Moccasin Mountain. Below Vermilion Cliffs, southeast half of map area, include multicolored, well-rounded quartzite pebbles derived from the Shinarump Member of the Chinle Formation. Commonly occupy upper slopes of young and intermediate alluvial fan (Qa1, Qa2) deposits. Below Vermilion Cliffs, northwest quarter of map area, mostly composed of white and light-red sandstone and red siltstone that forms young alluvial fan deposits but deposits are dominated by interbedded mixed fluvial and eolian deposits in Parashont and Woodberry Canyons. Often overlapped by surficial sand sheet (Qes) or sand dune (Qd) deposits with arbitrary or approximate map contacts based on aerial photo interpretations. Support thick to moderate growths of grass, cactus, and some sagebrush below Vermilion Cliffs; sagebrush, oak brush, cliffrose bush, pinion pine, oak, and juniper trees above Vermilion Cliffs. Thickness, 5 to 60 ft

Qv **Valley fill alluvial deposits (Holocene)**ó Gray to light-red, slope-forming, unsorted mixture of mud, silt, sand, gravel, small pebbles, and cobbles. Partly consolidated by calcite and gypsum cement. Sandstone, limestone, and chert in sandy matrix is locally derived from nearby Paleozoic and Mesozoic sedimentary rock outcrops in southeast quarter of map area. Similar to stream-channel (Qs) deposits but occupy low-gradient drainages that deposit mostly fine-grained sand or silt over nearly flat drainage floor. Similar to or interbedded with floodplain (Qfp) deposits in Pipe Valley area. Subject to extensive sheet wash erosion, deposition, flash flood debris flows, and arroyo erosion. Commonly interbedded with local stream-channel alluvium (Qs) and sand sheet (Qes) or sand dune (Qd) deposits. Contacts with other alluvial deposits are arbitrary and approximate. Thickness, 3 to 20 ft

Qtr **Talus and rock fall deposits (Holocene)**ó Include silt, sand, and large to small broken rocks and boulders that form talus debris slopes in steep-walled canyons and lower part of Vermilion Cliffs. Some boulders of Navajo Sandstone or sandstone of the Shinarump Member of the Chinle Formation are as large as vehicles and up to house size near landslide debris (Ql) deposits below Vermilion Cliffs. Arbitrary and gradational contact between landslide debris (Ql) deposits, talus and rock fall debris (Qtr), young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3) deposits as determined by aerial photo interpretation. Unit grades downslope into young, intermediate, or old alluvial fan (Qa1, Qa2, Qa3) deposits. Thickness, 5 to 45 ft

Qg1 **Young alluvial terrace-gravel deposits (Holocene)**ó Red, white, and gray interbedded fine- to coarse-grained sand and thinly laminated silt; partly consolidated by gypsum and calcite cement. Include interbedded thin beds of gray or red mud and clay and some interbedded lenses of gravel composed of gray subangular chert fragments above outcrops of the Chinle Formation. Include gray-blue subrounded limestone pebbles, and red, yellow, black, or white, well-rounded quartzite pebbles below outcrops of the Shinarump Member of the Chinle Formation. Deposits are inset against intermediate alluvial terrace-gravel (Qg2) deposits and young and intermediate alluvial fan (Qa1, Qa2) deposits. Subject to erosion by flash floods or overbank floodplain (Qfp) sediment accumulation in lower reaches of drainages. Moderately vegetated by sagebrush, grass, cactus, tamarisk trees, willow trees, juniper trees, and some pinion pine trees in canyons eroded into Vermilion Cliffs. Terraces are generally 4 to 10 ft above stream-channel (Qs) deposits and as much as 40 ft above stream channels in lower reaches of Bulrush Wash and Bitter Seeps Wash. Unit cut by modern arroyos as much as 30 ft deep in Moccasin Canyon and in other unnamed canyons eroded into Vermilion Cliffs. Thickness, 4 to 50 ft or more

Qa1 **Young alluvial fan deposits (Holocene)**ó Light-red, gray, and brown silt, fine- to coarse-grained interbedded sand and gravel; partly consolidated by gypsum, calcite, and clay. Contain light-red to brown silt, red and white chert fragments and small red and white sandstone pebbles locally derived from outcrops of the Kayenta Formation and Navajo Sandstone below the Vermilion Cliffs. Locally include boulders of the Shinarump Member of the Chinle Formation as much as 6 ft in diameter near outcrops of the Shinarump below Yellowstone Mesa and Bitter Seeps Wash areas. Clay content greatest near outcrops of Petrified Forest Member of the Chinle Formation in Sandy Canyon Wash, and Pipe Valley areas. Include numerous black, brown, yellow, red, and gray, very well rounded quartzite and chert pebbles 0.5 to 2 inches in diameter and rare, rounded, gray-white petrified wood fragments derived from Shinarump Member of the Chinle Formation. Locally covered by thin sand sheet (Qes) and mixed eolian and fluvial (Qae) or sand dune (Qd) deposits at distal ends of alluvial fan deposits. Commonly overlapped by or intertongue with stream (Qs) deposits. Subject to extensive sheet wash erosion or sediment accumulation during heavy storms. Support moderate growths of grass, sagebrush, and various small high-desert shrubs. All deposits below Vermilion Cliffs are composed of sediment derived locally from Triassic and Jurassic sedimentary strata. Thickness, 5 to 40 ft

Qg2 **Intermediate alluvial terrace-gravel deposits (Holocene and Pleistocene(?))ó** Gray, light-red to brown, thin- to massive-bedded, interbedded clay, silt, and fine-to coarse-grained sand similar to young alluvial terrace-gravel (Qg1) deposits; partly consolidated by clay and gypsum. Unit intertongues with young and intermediate alluvial fan (Qa1, Qa2) deposits along Bulrush Wash. Map contact is arbitrary between alluvial units. Deposit forms terraces generally 8 to 20 ft above local streambeds in upper reaches of drainages near Vermilion Cliffs and as much as 60 ft above stream channels in lower Bulrush Wash and Bitter Seeps Wash. Intertongue with young and intermediate alluvial fan (Qa1, Qa2) deposits in upper Pipe Valley Wash, Twomile Wash, and Sandy Canyon Wash. Arbitrary and gradational contact with young and intermediate alluvial fan deposits. Support moderate growth of grass, cactus, black brush, and sparse sagebrush. Thickness, 8 to 30 ft

Qa2 **Intermediate alluvial fan deposits (Holocene and Pleistocene(?))**ó Similar to young alluvial fan (Qa1) deposits; partly consolidated by calcite, clay, and gypsum cement below stratigraphic level of the Chinle Formation; mostly unconsolidated above Chinle Formation. Commonly overlapped by young alluvial fan (Qa1) and stream-channel (Qs) deposits. Intertongue with intermediate alluvial terrace-gravel (Qg2) deposits near distil ends of fans. Intertongue with landslide (Ql) deposits and talus and rock fall (Qtr) deposits at upper reaches of alluvial fans below Vermilion Cliffs where unit is heavily dissected by erosion. Support moderate growths of sagebrush, cactus, and grass. Thickness, 6 to 45 ft

Ql **Landslide debris deposits (Holocene and Pleistocene)**ó Unconsolidated masses of unsorted rock debris typically along lower slopes of Vermilion Cliffs. Include detached blocks of strata that have rotated backward and slid downslope as loose incoherent masses of broken rock and deformed strata, often surrounded by talus and rock fall (Qtr) debris. Often covered in part by sand sheet (Qes) and sand dune (Qd) deposits. Individual landslides may become unstable during wet conditions and creep downslope where unit overlies claystone or siltstone bedrock of Petrified Forest Member of the Chinle Formation or lower part of the Kayenta Formation. Support sparse growth of sagebrush, cactus, grass, juniper trees, and pinion trees. Thickness, 25 to 200 ft

Qg3 **Old alluvial terrace-gravel deposits (Pleistocene)ó** Gray and light-brown to light-red clay, silt, and sand similar to young and intermediate alluvial terrace-gravel (Qg1, Qg2) deposits. Locally contain lenses of small pebble gravel and conglomerate composed of white and red, rounded sandstone, blue-gray rounded limestone, sub-rounded white chert, and scattered well rounded multicolored quartzite pebbles in fine- to coarse-grained gravel matrix. Unit preserved as scattered deposits along lower reaches of Bulrush Wash and Bitter Seeps Wash, southeast corner of map area. Form terraces about 30 to 120 ft above stream (Qs) deposits. Unit often covered by thin sand sheet deposits too thin to show at map scale. Support sparse growth of sagebrush, black brush, cactus, and grass. Thickness, 10 to 20 ft

Qa3 **Old alluvial fan deposits (Pleistocene)**ó Similar to young and intermediate alluvial fan (Qa1, Qa2) deposits; stony surface where not covered by sand dune (Qd) deposits along base of Vermilion Cliffs in northeast quarter of map area. Contribute material to young and intermediate alluvial fan deposits. Composed mainly of silt, sand, gravel, cobbles, and boulders of sandstone locally derived from the Kayenta Formation or Navajo Sandstone. Intertongue with talus and rock fall (Qtr) and landslide debris (Ql) deposits. Adjacent to or overlapped by young and intermediate alluvial fan (Qa1, Qa2), sand sheet (Qes), and sand dune (Qd) deposits. Thickness, 10 to 50 ft

QTg4 **Oldest alluvial terrace-gravel deposits (Pleistocene and Pliocene**(?))ó Lithologically similar to young, intermediate, and old alluvial terrace-gravel (Qg1, Qg2, Qg3) deposits as isolated deposits in Bulrush Wash about 120 to 180 ft above modern drainage. Deposits are partially preserved in abandoned cutoff meander loops or isolated abandoned point bars in southeast quarter of map area. Thickness, 6 to 20 ft

SEDIMENTARY ROCKS

Jn **Navajo Sandstone (Lower Jurassic)—**White to light-red and yellow-gray, cliff-forming, medium-crossbedded to thickly-crossbedded, well-sorted, fine- to coarse-grained eolian quartz sandstone interbedded with dark-red, coarse-grained sandstone and siltstone in lower part. Age determination by Peterson and Pipiringos (1979) and Biek and others (2000). Lower part is commonly red, upper part commonly white. Includes lenses of interbedded dark purple-gray, thin-bedded, calcareous sandstone beds that formed freshwater deposits within and between coastal sand dunes. High-angle, crossbedded sandstone sets interbedded with low-angle, crossbedded sandstone and thin flat-bedded sandstone sets. Unit commonly covered by thin to thick sand sheet (Qes), sand dune (Qd), or mixed eolian and fluvial (Qae) deposits. Unit is highly fractured by near vertical northeast-, northwest-, and north-south-oriented bedrock joints. Joints that parallel the Moccasin Monocline dip west or southwest as much as 82∫ and strata of the Navajo Sandstone and Kayenta Formation dip east 8∫ at Moccasin Canyon and just northwest of Pipe Spring National Monument. Joints are near vertical in upper Moccasin Canyon where strata are nearly horizontal verifying that the joints likely developed prior to development of the Moccasin

Monocline. Gradational but sharp contact with underlying Tenney Canyon Tongue of the Kayenta Formation placed at base of Navajo Sandstone cliff at Moquith Mountains and the Kayenta Formation elsewhere. Supports moderate growth of pinion and juniper trees, cliff-rose bush; thick growths of sagebrush, various high-mountain shrubs and grasses on Moccasin and Moquith Mountains. Incomplete section due to removal of top part by modern erosion. Unit thickens north of map area to as much as 2,000 ft. Thickness, about 1,500 ft

Jkt **Tenney Canyon Tongue of the Kayenta Formation (Lower Jurassic)**ó Age as described by Biek and others (2000). Dark-red to light red-brown, slope-forming, very fine-grained, thin-bedded to laminated, fluvial siltstone and sandstone. Includes dark-red sandstone lenses that form ledges in upper part. Gradational southwesterly facies change from fine-grained, ledge- and slope-forming sequence to alternating slope-forming, fine- to coarse-grained, mudstone, siltstone, and sandstone sequence. Unit intertongues laterally with underlying Lamb Point Tongue (Jnl) of the Navajo Sandstone. Forms sharp local horizontal contact at top of Lamb Point Tongue cliff marked by color contrast of dark-red siltstone and sandstone of Tenney Canyon Tongue to white and light-red sandstone of Lamb Point Tongue at Moquith (Moki) Mountain area. Unit thickens from 120 ft at Kanab, Utah, to 220 ft at Ed Lamb Point, Moquith Mountains 8 miles northeast of Kaibab and Moccasin, Arizona. Tenney Canyon Tongue becomes upper part of Kayenta Formation where Lamb Point Tongue of Navajo Sandstone pinches out west and south of Moquith Mountains. Thickness at Moquith Mountain area, 220 ft

Jnl **Lamb Point Tongue of the Navajo Sandstone (Lower Jurassic)**ó Age as described by Biek and others (2000). Type locality is Ed Lamb Point on USGS 7.5í Kaibab quadrangle, Vermilion Cliffs of Moquith Mountains, 8 miles northeast of Moccasin and Kaibab, Arizona (Wilson, 1967). Gray-white to orange-brown, cliff-forming, very fine-grained to fine-grained, crossbedded quartz sandstone of eolian origin. Top 10 to 15 ft east of Ed Lamb Point locally shows penecontemporaneous deformed beds that are beveled by overlying Tenney Canyon Tongue (Jkt) of the Kayenta Formation. Forms gradational and sharp contact with underlying Kayenta Formation (Jk) marked at base of white and red sandstone cliff of the Lamb Point Tongue. Forms cliff of white and red cross-bedded Navajo Sandstone within upper part of Kayenta Formation along Vermilion Cliffs from Moquith Mountains east to Kanab, Utah. Unit is 400 ft thick near Kanab, Utah, thins south and west to 140 ft thick at Moquith Mountains; is mostly a red sandstone cliff about 100 ft thick near Point Spring of Vermilion Cliffs 2 mi north of Moccasin and Kaibab, Arizona. Unit forms an elongated 1-mi-wide tongue of sand that extends southwest from Ed Lamb Point to Moccasin Mountains 2 mi north of Kaibab, Arizona and pinches out as a red sandstone ledge in Vermilion Cliffs 1 mi west of Pipe Spring National Monument. Thickness, 0 to 140 ft

Jk **Kayenta Formation (Lower Jurassic)**ó Dark-red and light red-brown, slope-forming calcareous mudstone, siltstone, and sandstone. Unit deposited in river floodplains, river channels, playas, and shallow lake environments (Blakey, 1994; Peterson, 1994). Age of unit determined by Peterson and Pipiringoes (1979) and Biek and others (2000). Unit often covered by landslide debris (Ql) and talus and rockfall (Qtr) deposits along lower part of Vermilion Cliffs. Erosion of soft sediments of the Kayenta Formation undercuts the resistant overlying Navajo Sandstone causing large sections of Navajo and upper Kayenta units to fail as landslide blocks along Vermilion Cliffs, especially where local joints parallel Vermilion Cliffs. Thickness increases from 270 ft at Ed Lamb Point to nearly 400 ft at Potter Canyon at the expense and loss of the Lambs Point Tongue of the Navajo Sandstone southwest of Moccasin Mountain. Thickness, 270 to 400 ft

Moenave Formation (Lower Jurassic)ó Includes, in descending order, the Springdale Sandstone Member, Whitmore Point Member, and Dinosaur Canyon Member as defined 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)

Jms **Springdale Sandstone Member (Lower Jurassic)**ó Light-red to red-brown, cliff-forming, thin- to thick-bedded sandstone and lenses of conglomerate. 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). Gradational contact with underlying Whitmore Point Member. Unit deposited by northeast to southwest flowing streams based on crossbedding studies by Wilson (1967). Thickens north and east of map area to about 200 ft at Kanab, Utah, thins southward and intertongues with lower part of the Kayenta Formation. Thickness, 120 to 170 ft

Jmw **Whitmore Point Member (Lower Jurassic)**ó Type section is near Potter Canyon at southwest point of Moccasin Mountains (elev. 6,603 ft at Radio Towers, left end of cross section B-Bí). Named for Whitmore Point by Wilson (1967) 3.5 mi west of Pipe Spring National Monument, but the name Whitmore Point is not on the current USGS 7.5í Moccasin quadrangle. Composed of red-brown sandstone and siltstone interbedded with red-purple to green-gray and blue mudstone and claystone and thin gray dolomitic limestone. Limestone contains small red-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). Gradational contact with underlying Dinosaur Canyon Member (Jmd) marked by distinct color contrast of blue-green, green, and yellow mudstone and siltstone of Whitmore Point Member to red-brown siltstone and sandstone of underlying Dinosaur Canyon Member. Thickness, 60 to 80 ft

Jmd **Dinosaur Canyon Member (Lower Jurassic)**ó Red-brown, slope and ledge-forming, thin-bedded, very fine-grained sandstone and silty sandstone. Unconformable contact with underlying undivided Owl Rock and Petrified Forest Members of the Chinle Formation. Unit gradually thickens west to east and is about 200 ft thick at Kanab, Utah (Wilson, 1967). Thickness, 120 to 200 ft

Chinle Formation (Upper Triassic)ó 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)

ꞆRcp **Owl Rock and Petrified Forest Members, undivided (Upper Triassic)**ó The Owl Rock Member of the Chinle Formation, (not mapped separately) is present at the south end of the Moquith Mountains, northeast corner of the map area and gradually thins to the west and southwest and overlies the Petrified Forest Member. The Owl Rock is composed of light-red and white, coarse-grained sandstone, gray, fine-grained sandstone and siltstone interbedded with thin-bedded (5 in to 2 ft) gray-white siliceous limestone beds. Limestone contains red and white chert nodules. The Owl Rock is 40 ft thick at Kanab, Utah, and thins to less than 30 ft at Ed Lamb Point and grades into the upper part of the Petrified

Forest Member throughout the map area. The Petrified Forest Member is composed of gray, light-purple, blue, light- to dark-red, slope-forming claystone, siltstone, and white, coarse-grained sandstone. Weathers to frothy popcorn surface. Includes petrified wood and calcite nodules at the Blue Knolls area. Unit is mostly covered by sand sheet (Qes) and sand dune (Qd) and mixed fluvial and eolian (Qae) deposits, and young, intermediate, and old alluvial fan (Qa1, Qa2, Qa3) deposits. Contact with underlying Shinarump Member is gradational in the vertical and lateral extent because multicolored mudstone and siltstone intertongue with white gritty sandstone and conglomerate of the Shinarump Member. Thickness, 600 to 700 ft

TRcs **Shinarump Member (Upper Triassic)**ó White to yellow-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 the dominant pebble. Pebbles average 1 to 2 inches in diameter and include some well-rounded quartzite cobbles as much as 10 inches in diameter and numerous petrified wood fragments and segments of petrified logs. Black pebbles eroded from the Yellowstone Mesa area form a desert pavement of lag gravel on all alluvial fan surfaces around Yellowstone Mesa, southwest quarter of map area. Unit is the common source for 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 is a source for local sand sheet (Qes) and sand dune (Qd) deposits that overlie the Petrified Forest Member east of the Vermilion Cliffs. Unit overlies and fills broad erosion channels that are as deep as 30 ft and Ω to 1 mi wide eroded into underlying upper red member of the Moenkopi Formation. Thickness, 20 to 125 ft

Moenkopi Formation (Middle(?) and Lower Triassic)ó Includes, in descending order, upper red member, Shnabkaib Member, middle red member, Virgin Limestone Member, lower red member and Timpoweap Member, undivided, as used by Stewart and others (1972). (Timpoweap Member is redefined for this map area due to facies changes of the Timpoweap Member from that defined by Stewart and others [1972])

TRmu **Upper red member (Middle(?) and Lower Triassic)**ó Light-red and dark-red, slope- and ledge-forming sequence of siltstone and sandstone. Forms small cliffs in upper part. Gradational contact with underlying Shnabkaib Member placed arbitrarily at top of highest thick white siltstone and dolomite bed of Shnabkaib Member. Thickness, 160 ft

TRms **Shnabkaib Member (Lower Triassic)**ó White to light-gray, laminated to thinly bedded, slope-forming, aphanitic dolomite interbedded with light-gray, calcareous silty gypsum. Includes some thin light red mudstone, siltstone, and sandstone beds in lower and upper part. Gradational contact with underlying middle red member placed at lowest thick white or light-gray calcareous siltstone and dolomite bed of the Shnabkaib Member. Unit thickens northwest of map area, thins southeast. Thickness, 90 to 110 ft

TRmm **Middle red member (Lower Triassic)**ó Red-brown, thin-bedded to laminated, slope-forming gypsiferous siltstone and sandstone. Includes 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. Mudcracks and ripple marks common throughout.

Gradational lower contact with Virgin Limestone Member placed at top of highest gray limestone bed of Virgin Limestone Member. Thickness, 280 to 300 ft

Ŧmv **Virgin Limestone Member (Lower Triassic)**ó Includes two light-gray, thin-bedded to laminated, ledge-forming limestone beds (1 to 3 ft thick), separated by pale-yellow, light-red, and bluish-gray, thin-bedded to massive, slope-forming gypsiferous siltstone that makes up the bulk of the unit. Lowest limestone bed contains star-shaped crinoid plates and poorly preserved Composita brachiopods in upper part 18 mi east of map area; locally, upper limestone bed contains fossil algae. Erosional unconformity separates lower gray limestone from underlying dark red siltstone and sandstone of lower red member of the Moenkopi Formation with erosional relief as much as 4 ft. Lower limestone bed thickens and thins as shallow channel-fill deposit. Forms small mesas near Bitter Seeps Wash and Pipe Valley Wash. Thickness, 120 ft

Ŧml **Lower red member and Timpoweap Member, undivided (Lower Triassic)**ó Dark-red, slope-forming, thin-bedded, fine-grained, gypsiferous, sandy siltstone, sandstone, and pale-yellow to gray laminated silty gypsum. Gypsum, siltstone, and sandstone in lower part are derived from erosion of Harrisburg Member of the Kaibab Formation. Includes a prominent ledge-forming red-gray to light purple-red, coarse-grained, low-angle crossbedded calcareous sandstone marker bed in lower part 3 to 7 ft thick that often forms resistant sandstone surface of Kanab Plateau near Bulrush Wash and Bitter Seeps Wash. Marker bed includes raindrop impressions and rare carbonaceous plant fossils 18 mi east of map area (Billingsley and others, 2002). Has unconformable contact with underlying gray limestone and red sandstone and siltstone of Harrisburg Member of the Kaibab Formation at southeast edge of map area. Thickness, 120 to 180 ft

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

Pkh **Harrisburg Member**ó Red and gray, slope-forming, interbedded gypsiferous siltstone, sandstone, gypsum, and gray, cliff-forming, thin-bedded limestone. Yellow-gray to light-red alternating slope and ledge-forming calcareous sandstone and sandy limestone in upper part; contains calcite and gypsum cement. Upper part includes thin beds of low-angle crossbedded, calcareous sandstone, conglomerate, and minor siltstone that form small ledges in Burnt Canyon Point area, southeast corner of map area. Limestone beds are as much as 14 ft thick consisting of a gray, thin-bedded, cherty limestone that weathers dark brown or black and a light-gray, thin-bedded, sandy limestone. Limestone beds thicken and thin laterally and form small cliffs in the Bulrush and Sandy Canyon Wash areas. Dissolution of gypsum in lower part has locally distorted some limestone beds causing them to slump or bend into local drainages. Contact with underlying Fossil Mountain Member is gradational and marked at top of cherty limestone bed of the Fossil Mountain Member of the Kaibab Formation. Thickness, 160 ft

Pkf **Fossil Mountain Member**ó Light-gray, fine- to medium-grained, thin-bedded, fossiliferous, cliff-forming, sandy, cherty limestone. Unit characterized by thin bedded, white chert beds and nodules in sandy cliff-forming limestone. Contact with underlying Woods Ranch Member of the Toroweap Formation is not exposed in map area but is exposed 3 mi southeast of map area in Kanab Canyon where contact is an unconformity caused by a combination of dissolution of gypsum and channel erosion with relief as much as 6 to 15 ft. Thickness, 250 ft

UNITS SHOWN ONLY IN CROSSSECTION

Toroweap Formation (Lower Permian)ó Includes, in descending order, Woods Ranch, Brady Canyon, and Seligman Members, as defined by Sorauf and Billingsley (1991) and described by Billingsley and Priest (2003) adjacent to southwest corner of map area. Units are exposed in Kanab Canyon just south of the map area

Ptw **Woods Ranch Member**ó Gray, slope-forming gypsiferous siltstone and pale-red silty sandstone interbedded with white laminated gypsum. Beds are locally distorted because of the dissolution of gypsum. Lower contact gradational. Thickness varies from 180 to 265 ft because of the dissolution of gypsum

Ptb **Brady Canyon Member**ó 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 1 to 2 ft thick and include chert lenses and nodules. Lower gradational contact with underlying Seligman Member of the Toroweap Formation. Contact commonly covered by minor slump or talus debris. Thickness, 230 ft

Pts **Seligman Member**ó Gray, thin-bedded, slope-forming dolomite and gypsiferous sandstone. Middle part includes gray to red, thinly interbedded siltstone, sandstone, and gypsum; includes interbedded, crossbedded sandstone of the Coconino Sandstone in the middle part. Lower part includes brown, purple, and yellow, fine- to medium-grained, thin-bedded, low- to high-angle crossbedded and planar-bedded sandstone that is mostly covered by talus debris. Contact with underlying Hermit Formation is unconformable with erosional relief as much as 3 ft; contact mostly covered by talus and alluvial deposits. Thickness, 170 ft

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