GEOLOGIC SUMMARY

by George H. Billingsley

The geologic map of the Mount Trumbull 30´ x 60´ quadrangle is a cooperative product of the U.S. Geological Survey, the National Park Service, and the Bureau of Land Management that provides geologic map coverage and regional geologic information for visitor services and resource management of Grand Canyon National Park, Lake Mead Recreational Area, and Grand Canyon Parashant National Monument, Arizona. This map is a compilation of previous and new geologic mapping that encompasses the Mount Trumbull 30´ x 60´ quadrangle of Arizona.

Dutton (1882) made the first early reconnaissance geologic map of the Uinkaret Plateau, which is part of this map area. More recently, Huntoon and others (1981, 1982) and Billingsley and Huntoon (1983) produced geologic maps of the south half of this area that were later revised by Wenrich and others (1996, 1997). Geologic maps within the north half of the map area were produced by Lucchitta and Beard (1981a, b), Billingsley (1997a, b, c), Billingsley and others (2000), and Billingsley and others (2001, 2002, unpub. data). A geologic map of the Littlefield 30´ x 60´ quadrangle borders the northern edge of this map (Billingsley and Workman, 2000) and a geologic map of the Grand Canyon 30´ x 60´ quadrangle adjoins the eastern border (Billingsley and Hampton, 2000).

The Mount Trumbull 30´ x 60´ quadrangle encompasses approximately 5,018 km^2 (1,960 mi^2) of land within Mohave and Coconino Counties of northwestern Arizona. The quadrangle is bounded by longitude 113° to 114° and latitude 36°00´ to 36°30´. Elevations within the map area range from 2,447 m (8,028 ft) at Mount Trumbull on the Uinkaret Plateau, northeast quarter of the map area, to 353 m (1,156 ft) at Lake Mead, southwest quarter of the map area.

The map area lies mostly within the southwestern part of the Colorado Plateau and partly within the southeastern edge of the Basin and Range geologic provinces. The Colorado Plateau is locally subdivided into seven physiographic areas as shown by Billingsley and others (1997): the Grand Canyon, the Kanab, Uinkaret, Shivwits, and Sanup Plateaus north of Grand Canyon, and the Coconino and Hualapai Plateaus south of Grand Canyon (fig. 1). The approximate position of the Grand Wash Fault separates the Basin and Range province from the Colorado Plateau province. The northwest part of the map area is referred to as the Grand Wash Trough within the Basin and Range (fig. 1).

The boundary between the Kanab and Uinkaret Plateaus is marked along the Toroweap Fault, which is a geologic and topographic feature. The boundary between

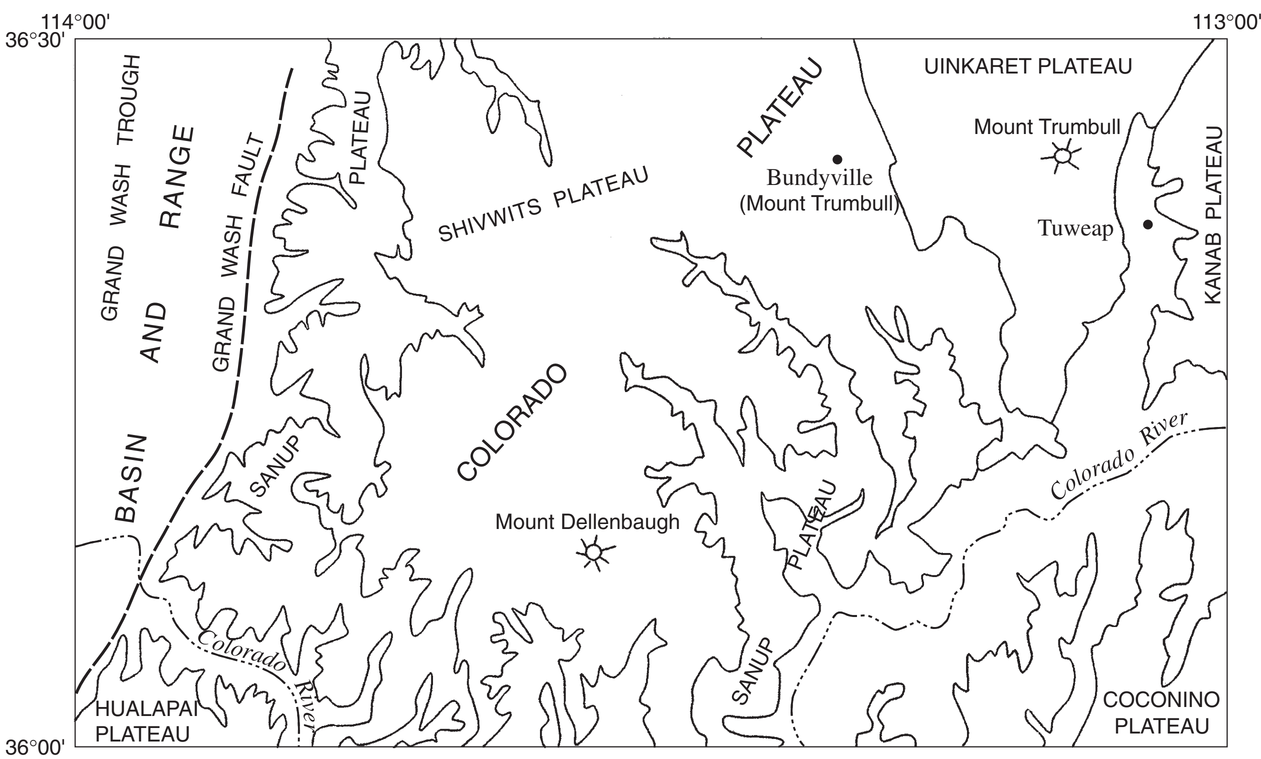

Figure 1. Index map of the Mount Trumbull 30' x 60' quadrangle, Arizona showing the physiographic provinces and subprovinces.

the Uinkaret and Shivwits Plateaus is marked along the Hurricane Fault that forms the Hurricane Cliffs, a prominent west-facing fault scarp. The boundary between the Shivwits Plateau and Sanup Plateau is marked along the north rim of the Grand Canyon and northward along the upper Grand Wash Cliffs to Hidden Canyon. The Sanup Plateau is a narrow flat platform or topographic bench between the north rim and the inner gorge of the Grand Canyon and between the upper and lower Grand Wash Cliffs. The Sanup Plateau extends to the Hurricane Fault at Whitmore Canyon.

The nearest settlements to the map area are Colorado City, Arizona about 58 km (36 mi) north of the northeast corner of the map area, and St. George, Utah about 90 km (56 mi) north of Mount Trumbull. There are two abandoned settlements within the map area, Tuweap and Mount Trumbull (fig. 1). The town of Mount Trumbull, locally known as Bundyville, is near the base of the Hurricane Cliffs on the Shivwits Plateau about 16 km (10 mi) west of Mount Trumbull mountain. Today, Bundyville is little more than a small cluster of local ranches and one abandoned historic schoolhouse. Tuweap is in the upper reaches of Toroweap Valley, a northern tributary to Grand Canyon consisting of a few abandoned ranch buildings. Toroweap Campground is in Grand Canyon National Park in the lower reaches of Toroweap Valley on the rim of the inner gorge of Grand Canyon and provides a spectacular overlook of the Colorado River (Colorado River Mile 174 to 183).

Access to the plateau regions north of Grand Canyon is by dirt roads that are maintained by the Bureau of Land Management of the Arizona Strip Field Office in St. George, Utah. Access to the Coconino and Hualapai Plateaus in the southwestern and southeastern part of the map area is by jeep trails and dirt roads maintained by the Hualapai Tribe and requires permits from the Tribe for access and travel. Access into the depths of Grand Canyon in this map area is rather limited to a few non-maintained trails and a go-at-your-own-risk type of hiking. Visitors north of the Colorado River must obtain hiking permits and information from the backcountry office at Grand Canyon National Park, Grand Canyon Village, Arizona, or from the Toroweap Ranger Station in Toroweap Valley. Visitors south of the Colorado River must obtain permits from the Hualapai Tribe at Peach Springs, Arizona.

GEOLOGIC SETTING

Erosion by earlier Laramide and Tertiary streams and the Colorado River and its tributaries have exposed about 365 m (1,200 ft) of Mesozoic strata, over 1,220 m (4,000 ft) of Paleozoic strata, and about 30 m (100 ft) of Early Proterozoic crystalline metamorphic rock complex within the map area. The Early Proterozoic rocks (Xgr) are exposed at the bottom of Grand Canyon along a one-mile reach of the Colorado River between Miles 189.6 and 190.6 as measured from Lees Ferry, Arizona. The majority of the map area is characterized by gently east and northeast dipping Paleozoic and Mesozoic strata that overlie Early Proterozoic crystalline metamorphic rocks.

Paleozoic rocks comprise most of the cliffs and slopes in the walls of Grand Canyon and display remarkable east-west facies and thickness changes. The Permian Kaibab Formation (Pk) generally forms the rim of Grand Canyon north and east of the Colorado River and the plateau surface of the Shivwits, Uinkaret, Kanab, and Coconino Plateaus because of its resistance to erosion. However, the Kaibab Formation has been removed along the southern part of the Shivwits Plateau due to Laramide uplift and subsequent erosion allowing the Toroweap Formation (Pt) to form the canyon rim in some areas. A significant unconformity separates the Kaibab Formation from the underlying Permian Toroweap Formation. Channels as much as 43 m (140 ft) deep have eroded into the soft strata of the Woods Ranch Member of the Toroweap Formation in Toroweap, Whitmore, and Mohawk Canyon areas. Otherwise, the Toroweap Formation maintains a general overall thickness throughout the map area. The limestone of the Brady Canyon Member of the Toroweap Formation thickens from east to west while sandstone and gypsum of the Seligman Member thins from east to west. The Permian Coconino Sandstone (Pc) intertongues within the lower part of the Seligman Member of the Toroweap Formation (Pt) in the vicinity of Parashant and Whitmore Canyons (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; Billingsley and others, 2000). Because the name Coconino Sandstone is well established in the Grand Canyon nomenclature and it forms a significant mappable cliff unit within the walls of Grand Canyon, the Coconino Sandstone is herein maintained as a separate map unit. The Coconino Sandstone unconformably overlies the Hermit Formation and pinches out in the west third of the map area, which allows the Toroweap Formation to overlie the Hermit Formation. The Permian Hermit Formation (Ph) undergoes a facies change from a deltaic siltstone and sandstone sequence in the east quarter of the map area to a thicker marine-shoreline sandstone and siltstone sequence in the west quarter of the map area. A regional unconformity separates the Hermit Formation from the underlying Esplanade Sandstone, but the unconformity is difficult to locate in the map area because the erosional relief is little more than 3 m (10 ft) at the top of a sandstone ledge about 60 m (200 ft) above the sandstone bench of the Sanup Plateau in the Grand Wash Cliffs area and in Parashant Canyon.

The Supai Group (McKee, 1982) includes, in descending order, the Esplanade Sandstone, Wescogame Formation, Manakacha Formation, and Watahomigi Formation. The Permian Esplanade Sandstone of the Supai

Group (Pe) is composed of an upper siltstone slope unit, a middle sandstone cliff unit, and a lower siltstone and sandstone slope unit near and east of the Hurricane Fault. However, west of the Hurricane Fault, the middle sandstone cliff unit intertongues with marine limestone beds of the Pakoon Limestone between the Grand Wash Cliffs and the Hurricane Fault. The Permian Pakoon Limestone of McNair (1951) contains Early Permian marine fossils that establish a Permian age for the Esplanade Sandstone throughout Grand Canyon. The Permian Esplanade Sandstone and Pakoon Limestone cliff is mapped as one unit (Pep) west of the Hurricane Fault and as part of the upper Supai Group. West of the Grand Wash Cliffs, the Esplanade Sandstone thins and pinches out and the Pakoon Limestone becomes the upper part of the Callville Formation. The Upper Mississippian and Pennsylvanian part of the lower Supai Group, undivided (MIPs), maintains a regional thickness but includes a significant east-west facies change from a deltaic continental deposit along the east edge of the map area to a marine limestone and calcareous sandstone along the Grand Wash Cliffs of the west edge of the map area. The Pennsylvanian Wescogame and Manakacha, and the Mississippian and Pennsylvanian Watahomigi Formations that comprise the lower Supai Group are not subdivided on the map because the individual unconformities that separate these formations are difficult to establish in the field because of their subtle expression. The entire Supai Group becomes the Callville Formation west of the Grand Wash Cliffs. However, the Esplanade Sandstone and Pakoon Limestone are exposed and mapped as such at The Cockscomb, east of the Wheeler Fault southwest edge of the map at Lake Mead, and are not mapped as the Callville Formation for map consistency.

A regional unconformity separates the lower Supai Group (Watahomigi Formation) from either the underlying Surprise Canyon Formation or the Redwall Limestone. The unconformity between the lower Supai Group and the Surprise Canyon Formation and between the Surprise Canyon Formation and the Redwall Limestone often merge at the same horizon to form a more significant erosional unconformity that separates the Supai Group from the underlying Redwall Limestone. The unconformity between the Surprise Canyon Formation and the Redwall Limestone is significantly expressed where river channels as much as 122 m (400 ft) deep have eroded into the Redwall Limestone. These erosion channels are filled with lower conglomerate and sandstone deposits that represent a continental environment that was subsequently buried by upper limestone and sandstone deposits that represent an estuarine marine environment of the Surprise Canyon Formation. The type section and thickest sequence of the Mississippian Surprise Canyon Formation (Ms) is on the Hualapai Plateau in the southwest corner of the map area near Colorado River Mile 264.

The Mississippian Redwall Limestone (Mr) generally maintains a constant thickness throughout the map area except where removed by erosion in Late Mississippian time. The Redwall Limestone consists of marine limestone and dolomite beds that form a major gray cliff throughout the Grand Canyon area. The Devonian Temple Butte Formation (Dtb) forms a distinctive dark-gray band of limestone and dolomite ledges beneath the light-gray Redwall Limestone cliff and generally maintains a uniform thickness of about 138 m (450 ft) from east to west across the map area. The Temple Butte Formation is readily identified in the field by a strong fetid smell when rocks of this unit are freshly broken. The Cambrian Tonto Group (Ꞓm, Ꞓba, and Ꞓt) gradually thickens from east to west across the map area and is composed of the upper Muav Limestone, the middle Bright Angel Shale, and the lower Tapeats Sandstone. These Cambrian units are recognized on the basis of their distinctive rock types: limestone and dolomite lithology form the Muav Limestone; shale and siltstone lithology form the Bright Angel Shale; and sandstone and conglomerate lithology form the Tapeats Sandstone. The map contact between these three units is gradational and lithologically defined in both the vertical and lateral sense. The Muav Limestone forms gray cliffs of limestone and dolomite that are separated by slope-forming tongues of green shale and siltstone of the Bright Angel Shale. But the map contact between the Muav Limestone and Bright Angel Shale is arbitrarily marked at the base of the lowest prominent cliff-forming limestone, the Rampart Cave Member of the Muav Limestone (McKee and Resser, 1945). The Bright Angel Shale slope is composed of green to reddish-green shale and siltstone with minor ledges of limestone typical of Muav Limestone lithology in the upper part and tongues of brown sandstone typical of the Tapeats Sandstone lithology in the lower part. The map contact between the Bright Angel Shale and the Tapeats Sandstone is arbitrarily marked in a transition zone of about 30 m (100 ft) near the bottom of the slope-forming Bright Angel Shale near the top of the cliff-forming Tapeats Sandstone. The Tapeats Sandstone forms a thin-bedded, brownish-red conglomeratic sandstone cliff that unconformably overlies Proterozoic crystalline rocks.

Sedimentary rocks of Mesozoic age once covered the entire map area before Laramide and Tertiary erosion removed most of these rocks. The Mesozoic rocks are generally composed of nonresistant red and white mudstone, siltstone, and sandstone. Most of the Mesozoic rocks are preserved under Tertiary and Quaternary basalt flows on the Shivwits, Uinkaret, and Kanab Plateaus or concealed beneath Quaternary alluvium and landslide deposits. The 365 m (1,200 ft) of the Moenkopi Formation (TRm) at Hells Hole in upper Whitmore Canyon, central part of the map area, is the most complete, thickest, and closest outcrop of the Moenkopi Formation to Grand

Canyon other than at Lees Ferry, Arizona (Colorado River Mile 0). The Mesozoic rocks exposed at Hells Hole include about 122 m (400 ft) of the Chinle Formation (Ꞓc) representing the closest outcrop of this formation to Grand Canyon other than at Lees Ferry, Arizona. Hells Hole also contains the most complete section of the Permian Harrisburg Member of the Kaibab Formation.

Cenozoic deposits include Tertiary and Quaternary basalts, alluvium, and landslides. The youngest volcanic rock is the Little Spring Basalt (this map), dated at about 1,000 years old (Fenton, 1998), consisting of two basalt flows and a pyroclastic cone on the Uinkaret Plateau. Other Quaternary volcanic rocks generally range from about 75 to 400 ka, and Tertiary volcanic rocks range in age from about 3.6 to 17 Ma. The alluvial deposits are composed of fluvial terrace-gravel and alluvial fan deposits. Landslide deposits are most common around and below Tertiary or Quaternary volcanic outcrops. Only the thickest and most extensive Quaternary deposits are shown. Thin veneers over distinct outcrops of bedrock are omitted.

STRUCTURAL GEOLOGY

Minor east-dipping Laramide monoclines and late Tertiary and Quaternary normal faults are the characteristic structures found in the Paleozoic and Mesozoic rocks. East northeast-west southwest Laramide compressional folding caused gentle regional warping of the crust and significant regional uplift. This activity began in Late Cretaceous time and continued into early Tertiary time. The uplift caused erosion of most of the Mesozoic strata from the region, as well as deep dissection of the Paleozoic rocks in the vicinity of what is now the Grand Canyon. This erosion produced a step-bench topography that persists to the present. The south-facing, 610-m-high (2,000-ft-high) erosional escarpment comprised of Pennsylvanian and Permian rocks north of the Colorado River and the beveled surface across older rocks on the Hualapai Plateau were essentially eroded to their present position by the close of Laramide time. Early Tertiary, north-flowing, pre-Colorado River streams eroded canyons as deeply as the Precambrian basement on the east side of the Hualapai Plateau immediately south of this map. Their presence reveals that deep canyons containing northerly and easterly flowing streams were present before the west-flowing Colorado River became integrated from east to west across the region in Pliocene time (Young, 1999).

As Laramide compression took place, buried, generally north-trending, pre-existing Precambrian faults were reactivated, giving rise to reverse faulting in the metamorphic basement complex along structural trends that now define the physiographic subdivisions within the map area. The offsets at the Precambrian-Paleozoic contact produced east-dipping monoclines in the overlying Paleozoic strata (Huntoon, 1993). Examples, from west to east, were monoclinal segments along the Main Street, Hurricane, and Toroweap Fault zones, the largest being the Hurricane Monocline in the southeastern part of the map.

According to Huntoon (1990), late Cenozoic extension supplanted Laramide compression and caused reactivation of the same ancient basement faults that had already been reactivated by Laramide compression. However, the motions along the basement faults were opposite to those in Laramide time. Late Tertiary movements were mostly down-to-the west in normal faulting in contrast to Laramide up-to-the-west reverse faulting. The first sense of displacement on the monoclines began to reverse as normal faulting propagated upward into Paleozoic and younger rocks. As normal faulting progressed, faults propagated along the strikes of the basement faults beyond the limits of the Laramide monoclines producing the generally north-trending, now-continuous, down-to-the-west fault escarpments such as the Hurricane Cliffs. By late Pliocene and Quaternary time, extension progressed to such a degree that new normal faulting began to fragment the basement blocks lying between the reactivated basement faults giving rise to the multiple parallel, en echelon, and intersecting normal fault patterns and grabens shown on the map. The density of the normal faults increases with depth as revealed by the greater numbers of faults on the Esplanade surface compared to the Kaibab surface throughout the map area. This reveals that the faults are propagating upward from the basement. In the extreme, the most densely faulted areas have undergone regional extensional sagging such as the area centered on the mouth of Parashant Canyon.

Reverse drag along the principal normal faults is common throughout the map area. Reverse drag along normal faults is defined by Hamblin (1965) as a sag-induced infolding of the rocks toward the fault plane within the hanging wall. The infolding fills space created at depth as displacement occurs along normal fault surfaces that dip less steeply with increasing depth. The result is that reverse drag exacerbates the displacement along those faults. It also accentuates pre-existing monoclinal dips on the downdropped western blocks within the fault zones. Reverse drag is prevalent in the Paleozoic and Mesozoic strata along the Dellenbaugh, Main Street, Hurricane, and Toroweap Faults (Billingsley and others, 2000, 2001).

Cenozoic faulting on this part of the Colorado Plateau began to manifest itself as offsets at the surface in late Pliocene time, about 3.6 to 2.5 Ma (Billingsley and Workman, 2000). Faulting has been an ongoing process shown by the fact that vertical offsets between successively younger late Tertiary and Quaternary units diminish across several faults in the map area. This relation is well expressed along the Hurricane and Toroweap Faults, which displace multiple basal flows and alluvium of differing ages (Jackson, 1990). The faults in the map area are currently active as revealed by offsets of alluvium deposited across them (Huntoon, 1977) and are indicated as solid fault traces across alluvial deposits.

Basalts erupted through joints and fractures onto the plateaus and within Grand Canyon in the map area. Best and Brimhall (1970) note the following relation between volcanism and structure on the Uinkaret Plateau. (1) Normal faulting and volcanism have operated simultaneously throughout most of late Cenozoic time although the inception of faulting predates basaltic volcanism. (2) A shift in fault activity from the Grand Wash to the Hurricane-Toroweap zones has been paralleled in time by an eastward shift in volcanism. (3) Vents throughout the region lie between fault lines and are independent of them with few exceptions. (4) Many of the basalts carry mantle-derived olivine inclusions, indicating that the magma originated from the upper mantle. Dutton (1882) and Koons (1945) observed the tendency for cones on the Uinkaret Plateau to align parallel to faults but to occur in the areas between them.

Deeply eroded outcrops of dike swarms on or below the Esplanade Sandstone surface indicate that the dikes are localized along fractures, joints, and minor faults that parallel nearby normal faults. Examples include the Whitmore dike swarm (Twi) about 1.6 km (1 mi) west of the Hurricane Fault and south of Whitmore Canyon; the dikes of Parashant Canyon and Hundred and Ninetysix Mile Creek (Tp6i) in Parashant Canyon, Colorado River Mile 196 and in Hundred and Ninetysix Mile Canyon; the dikes of Colorado River Mile 202 (T2i) about 1.5 km (1 mi) west of Colorado River Mile 202; and several dikes (Tsgi) in the walls of Tincanebitts and Dry Canyons in the southwest quarter of the map area. The fact that vents do not preferentially occur along the principal late Cenozoic faults indicates that, in general, upward movement of magma was independent of the faults at great depths. The dikes and vents tended to localize on extended fractures in the Paleozoic section in close proximity to the surface. The parallelism between the intruded fractures and nearby faults implies that late Cenozoic extension either created or opened the fractures.

Many bowl-shaped depressions in the Harrisburg Member of the Kaibab Formation and Woods Ranch Member of the Toroweap Formation characterized by inward dipping strata are the surface expressions of breccia pipes that have propagated upward from the Mississippian Redwall Limestone (Wenrich and Huntoon, 1989). Breccia pipes within the Grand Canyon are easily identified in the Permian and Pennsylvanian strata as columns of downward displaced, brecciated rock surrounded by a yellowish-white bleached zone containing ring fractures. Breccia pipes with exposed breccia are indicated on the map by red dots. Collapse features that are probably breccia pipes are indicated by black dots.

Sinkholes, minor folds, and other surface irregularities on the Uinkaret and Shivwits Plateaus are caused by dissolution of gypsum and gypsiferous siltstones within the Harrisburg Member of the Kaibab Formation and the Woods Ranch Member of the Toroweap Formation. The youth of many sinkholes is revealed by their sheer walls, freshness of collapse debris within them, and disrupted local drainage.

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qs **Stream-channel alluvium (Holocene)**—Light-gray to light-brown and reddish-brown, unconsolidated mud, sand, gravel, pebbles and boulders. Subject to flash flood debris flows. Thickness, 0.5 to 2 m (2 to 6 ft)

Qf **Floodplain deposits (Holocene)**—Light-gray to light-brown mud and fine- to coarse-grained, unconsolidated silt and sand and lenses of pebble to cobble gravel; unconsolidated. Locally includes cinder and basalt fragments. Intertongue or overlap valley-fill alluvium (Qv) or young alluvial fan (Qay) deposits. Form relatively flat surfaces having little or no vegetation. Subject to frequent flooding or ponding. Thickness, 1 to 3 m (3 to 10 ft)

Qd **Sand sheet and sand dune deposits (Holocene)**—Grand Wash Trough area: Light-red and tan, fine- to medium-grained, well-sorted wind-blown quartz sand. Sand material derived from erosion of local red siltstone and sandstone outcrops of Rocks of the Grand Wash Trough (Tgr) and redeposited as stream-channel alluvium (Qs), then redeposited as wind-blown sand sheet and small sand dune deposits along wide drainages in Grand Wash Trough area.

Commonly form local climbing or falling dunes over young and older alluvial terrace (Qgy and Qgo) embankments and steep nearby talus slopes. Support moderate grass vegetation. Only thick or large sand sheet or dunes shown. Several smaller drainages have sand sheet or dune deposits that are too small to show at map scale. Thickness, 0.5 to 5 m (2 to 15 ft)

Qr **Colorado River terrace and gravel deposits (Holocene and Pleistocene)**—Mud, silt, and fine- to coarse-grained sand and gravel interbedded with poorly sorted, angular- to well-rounded pebbles, cobbles, and boulders adjacent to Colorado River. Overlap and intertongue with local alluvial debris fans and flows. Young (Qgy) and old (Qgo) alluvial terrace-gravel deposits are mapped as one unit (Qr) along Colorado River because map scale is too small to separate them. Include local wind-blown sand sheet and small sand dune deposits. Clasts are primarily comprised of sandstone, limestone, chert, basalt and well-rounded quartzite and volcanic rocks that have originated upstream from distant upper basin uplifts. Terrace gravels underlie and overlie local basalt flows 3 to 122 m (10 to 400 ft) above Colorado River, southeast quarter of map area. Higher terrace-gravel deposits are partly consolidated by calcium and gypsum. Age of terrace deposits commonly between 0.100 to 0.150 Ma (Fenton, 1998). Deposits are interbedded with local landslide and talus debris. Thickest deposits, downstream from the Toroweap and Hurricane Faults, as much as 60 m (200 ft)

Qgy **Young alluvial terrace deposits (Holocene and Pleistocene)**—In Grand Wash Trough, include lower three terraces along streams as mapped by Billingsley and others (unpub. data). Unit consists of light-brown, pale-red and gray silt, sand, pebbles, cobbles, and boulders, partly consolidated by calcium and gypsum. Composed mostly of well-rounded to sub-angular limestone, sandstone, chert, and basalt clasts as large as 1 m (3 ft) in diameter. Unit is locally inset and overlaps old terrace-gravel (Qgo) deposits and interbedded with young alluvial fan (Qay) deposits. Terraces are 2 to 30 m (6 to 100 ft) above local streambeds. Only thick or large deposits shown. Thickness, 3 to 30 m (6 to 100 ft)

Qay **Young alluvial fan deposits (Holocene and Pleistocene)**—Brown, red, and gray slope-forming, unsorted mix of mud, silt, sand, pebbles, cobbles, and boulders. Clasts are mostly angular but some are rounded; locally consolidated by calcite and gypsum cement. Sandstone, limestone, chert, and gravel are derived locally from Paleozoic and Mesozoic outcrops in Grand Canyon and Grand Wash Trough areas. Include alluvial fan debris flows, sheet wash alluvium, minor aeolian sand deposits, and alluvial valley-fill (Qv) deposits. Subject to extensive sheet wash erosion, flash flood debris flows, and arroyo erosion. Only largest or thickest deposits shown. Most talus deposits on canyon slopes are not shown to emphasize bedrock geology. Thickness, 1 to 30 m (3 to 100 ft)

Qv **Valley-fill alluvium, undivided (Holocene and Pleistocene)**—Gray and light-brown silt, sand, and lenses of pebble to small-boulder gravel; partly consolidated by gypsum cement. Includes well-rounded clasts of limestone, sandstone, subrounded to angular chert fragments, and subrounded to subangular basalt clasts near volcanic outcrops. Arbitrary map contact with young alluvial fan (Qay), young alluvial terrace (Qgy), stream-channel alluvium (Qs), and floodplain (Qf) deposits. Represents less active, low-gradient, alluvial stream-channel or shallow-valley deposits. Alluvial valleys subject to sheetwash flooding or temporary ponding; often cut by arroyos as much as 3 m (10 ft) deep. Supports moderate growth of sagebrush, grass, and cactus on Colorado Plateau and mostly cactus and grass in Grand Wash Trough. Thickness, 1 to 6 m (3 to 20 ft)

Qt **Travertine deposits (Holocene and Pleistocene)**—Gray, white, tan, massive, porous, cliff-forming carbonate deposits. Formed by chemical precipitation of calcium carbonate from springs. Form massive, rounded mounds or thick-layered encrustations on steep slopes or cliffs downslope of spring outlets. Several deposits represent spring discharges that were probably active during Pleistocene time but are currently dry. Travertine incorporates angular clasts and boulders of talus and rounded Colorado River gravel. Only thickest deposits shown along Colorado River, southeast and southwest corner of map area. Several minor deposits in Grand Wash Trough area are too small to show at map scale. Thickness, about 1 to 25 m (3 to 80 ft)

Ql **Landslide deposits (Holocene and Pleistocene)**—In Grand Canyon, form large unconsolidated to partly consolidated masses of Paleozoic rock debris. Include detached blocks of strata that have rotated backward and slid downslope against parent wall as loose incoherent masses of broken rock and deformed strata, partly surrounded by local talus, rock glaciers, and rock-fall debris. Some large landslides in Grand Canyon were likely triggered by earthquakes along the major faults in the area. Landslide masses are common around Tertiary volcanic mountains on the Colorado Plateau and around basalt flows in the Grand Wash Trough area. Landslide masses in Grand Wash Trough are unstable where overlying red siltstone and sandstone of the Grand Wash Trough (Tgr), especially during wet conditions. Only large or significant landslide deposits are shown. Thickness, 10 to 60 m (30 to 200 ft)

Qgo **Older alluvial terrace deposits (Holocene(?) and Pleistocene)**—Similar to young alluvial terrace (Qgy) deposits and partly consolidated by calcite and gypsum cement. Surface has developed a thin soil that forms a smooth surface texture compared to younger terrace surfaces. Commonly overlapped by or interbedded with talus and landslide (Ql) debris deposits and older alluvial fan (Qao) deposits. Include abundant basaltic clasts that form thin desert pavement near landslide deposits. In Grand Wash Trough, support moderate growth of grass, cactus, and desert shrubs. On Colorado Plateau, support moderate growth of grass, cactus, and sagebrush, juniper trees and pinyon pine trees. Thickness, 2 to 5 m (6 to 15 ft)

Qao **Older alluvial fan deposits (Holocene(?) and Pleistocene)**—Similar to young alluvial fan (Qay) deposits, partly consolidated and commonly capped by calcrete soil 1 to 2 m (3 to 6 ft) thick. On plateaus, composed mainly of gray to brown, fine-grained sand and silt matrix mixed with subangular to rounded pebbles and boulders of basalt, limestone, sandstone, and chert. Some basalt boulders are 1 m (3 ft) in diameter. In Grand Wash Trough, composed mainly of gray, coarse-grained sand and gravel matrix containing subangular to rounded pebbles and boulders of limestone, sandstone, and chert derived from Grand Wash Cliffs east of Grand Wash. West of Grand Wash, composed of coarse-grained sand and gravel mixed with subangular to rounded pebbles and boulders of Proterozoic schist, gneiss, and granite mixed with Paleozoic limestone and sandstone clasts. Surfaces are hard and rocky and eroded by arroyos as much as 10 m (30 ft) deep in some areas of the Grand Wash Trough and Colorado Plateau. Support moderate growth of sagebrush, cactus, grass, pinyon pine and juniper trees on Colorado Plateau and sparse growth of cactus, grass, and desert shrubs in Grand Wash Trough. Thickness, 3 to 30 m (9 to 100 ft) or more

QTa **Old alluvium (Pleistocene and Pliocene)**—On Shivwits Plateau, composed of white, gray, and reddish-brown slope-forming siltstone, coarse-gravel, and conglomerate, partly unconsolidated, capped by calcrete soil. Overlies basalt of the Shivwits Plateau (Tsb). White and gray angular chert pebbles are dominant clasts averaging about 5 cm in diameter derived from the Kaibab Formation (Pk). Includes lag gravel of yellow, brown, white, and red, well-rounded, multicolored quartzite pebbles 2.5 to 19 cm (1 to 8 in) in diameter, and small petrified wood fragments derived from the Shinarump Member of the Chinle Formation. Locally includes small basalt fragments derived from underlying basalt of the Shivwits Plateau. Discontinuous calcrete beds form thin, lumpy surface producing white patches of calcrete gravel and alluvium on weathered surface of basalt flows that are easily recognized on aerial photographs. Unconformable contact with underlying basalt of the Shivwits Plateau (Tsb). Unit may have formed an extensive deposit over northern extent of the basalt of the Shivwits Plateau now heavily eroded

Tay **Alluvium and calcrete soil deposits (Pliocene and Miocene)**—Gray and light-brown, slope-forming, silt, sand, coarse gravel in coarse-grained gravely matrix alluvium; includes subangular to well-rounded limestone and dolomite pebbles, cobbles, and boulders up to 1 m (3 ft) in diameter. Include basalt clasts derived from basalt flows (Tb) of the Grand Wash Trough; partly consolidated by calcium and gypsum cement. Form cliffs or weathers to rounded resistant hills. Unit overlain by thin to thick calcrete soil deposits, 1 to 8 m (3 to 25 ft) thick. Unit is poorly sorted to moderately sorted. Calcrete soil deposits that cover basalt flows form thin, rough, and discontinuous beds averaging about 1.2 m (5 ft) thick and contain scattered cobbles of basalt up to 30 cm (12 in) in diameter. Pebble imbrications show southward flow of depositing streams in Grand Wash Trough area. Unit is strongly dissected by modern erosion. East of Grand Wash drainage, unit is composed of gray and light-brown, poorly sorted, consolidated, silt, sand, gravel, cobbles, and boulders derived from Paleozoic rocks in the Grand Wash Cliffs; clasts are composed of about 80 percent limestone and dolomite, and 10 percent chert in gray gypsiferous siltstone and sandstone matrix, all capped by calcrete soil 3 to 4 m (10 to 12 ft) thick; weathers light brown. Rounded and subrounded limestone and chert clasts are strongly pitted and etched on weathered surfaces and often coated by calcrete rind on underside. Unconformably overlie red siltstone and sandstone (Tgr) and unmapped conglomerate deposits west of Wheeler Fault. Unconformably overlies older gypsum and limestone sediment facies (Tgg and Tgl) between Grand Wash drainage and Grand Wash Cliffs. Support sparse growths of desert vegetation, mainly cactus of various types and creosote bush. Thickness, 15 to 60 m (50 to 200 ft)

Tao **Alluvial deposits (Pliocene and Miocene)**—Gray to dark-gray, slope-forming schist, granite, gneiss, and amphibole clasts derived from Proterozoic outcrops of the Virgin Mountains about 9 to 11 km (6 to 7 mi) northwest of map area. Include clasts composed of white and gray angular chert, subrounded to rounded gray and dark-gray limestone and dolomite clasts averaging about 5 cm (3 in) in diameter derived from Paleozoic rock outcrops of the Virgin Mountains (Bohannon and Lucchitta, 1991; Beard, 1996). Poorly sorted to moderately sorted. Unconformably overlie red siltstone, sandstone, and conglomerate facies (Tgr) and strata of the Kaibab and Moenkopi Formations. Unit is strongly dissected by modern erosion. Support sparse growth of desert vegetation, mainly cactus of various types and creosote bush. Thickness, 60 m (200 ft) or more

Tg **Undifferentiated gravel deposits of the Hualapai Plateau (Pliocene to lower Paleocene(?))**—Gray and light-brown silt, sand, pebbles, cobbles, and small boulders consisting mostly of Paleozoic clasts mixed with Proterozoic clasts in some locations. Clasts are angular to well rounded in sandy matrix; partly consolidated by calcite. Deposits commonly covered by thick alluvium, lag gravel, calcrete soil, or volcanic rocks (Tv). Include the Buck and Doe Conglomerate and Coyote Spring Formation of Young (1999), undivided. Lag gravel makes it difficult to distinguish the stratigraphic sequence in areas of low relief. Fill older drainages and paleovalleys on the Hualapai Plateau, southwest quarter of map area. Thickness, 1 to 30 m (3 to 100 ft)

VOLCANIC ROCKS

Quaternary volcanic deposits (Holocene, Pleistocene, and Pliocene(?))—Includes basalt flows, dikes, and pyroclastic deposits in the Uinkaret Volcanic Field and Shivwits Plateau areas (Billingsley and others, 2000, 2001, 2002, unpub. data). Pyroclastic cones typically overlie basalt flow, but are closely associated in time. Although the cones are generally younger than the basalt flows, some basalt flows may have flowed out from under pyroclastic cones while others may have built up on top of the flows. Described from youngest to oldest:

Little Spring Basalt (Holocene)—Informally named by Billingsley (1997a) and Billingsley and others (2001). Herein formally named for Little Spring (SE1/4 sec. 16, T. 34 N., R. 8 W.) just west of Arkansas Ranch, Uinkaret Plateau, Mohave County, Arizona. The olivine basalt and associated cinder cone represent the youngest volcanic rocks in the Uinkaret Volcanic Field and the map area. Based on cosmogenic ^{3}He dating (Fenton, 1998), the Little Spring Basalt is about 1,000 years old, similar in age to basalt flows at Sunset Crater near Flagstaff, Arizona. Divided into:

Qlsp **Pyroclastic deposits**—Red-brown, gray, and reddish-black basaltic scoria, bombs, cinder, and other scoriaceous ejecta deposits. Consist of two deposits that are part of a single pyroclastic cone formed from two closely spaced vent areas. Cone is about 41 m (135 ft) high on basalt flow surface (elev. 2,138 m [7,015 ft]). Only east half and southwest part of cone is preserved; rest of cone has been rafted away on lava flows toward the northwest and southeast, suggesting that the cone is older than the flow. Support growths of a few ponderosa pine trees and oak trees. Thickness, 41 m (135 ft)

Qlsb **Basalt flows**—Dark-gray, finely crystalline to glassy, alkali-olivine basalt. Groundmass composed of glass, plagioclase, and olivine. Forms clinkery aa surface. Basalt flowed northwest about 1.8 km (1 mi) and southeast about 2.4 km (1.5 mi). Support sparse ponderosa and oak trees. Overlie older Quaternary basalt flows (Qb), pyroclastic deposits (Qp), and young alluvial fan (Qay) deposits. Thickness, 3 to 7 m (10 to 21 ft)

Basalt of Larimore Tank (Pleistocene)—Informally named for Larimore Tank, a stock tank on U.S. Geological Survey Hat Knoll 7.5´ quadrangle (sec. 16, T. 37 N., R. 7 W.), Uinkaret Volcanic Field, Mohave County, Arizona (Billingsley and others, 2001). Incorrectly named Cave Basalt by Billingsley (1994) and Billingsley and Workman (2000) before it was known the name Cave Basalt was already in use

Qltb **Basalt flows**—Dark-gray to black, finely crystalline, alkali-olivine basalt. Basalt has coalesced from five pyroclastic vent areas just north of map area aligned along northwest-southeast-trending fractures in underlying Permian strata. Contains abundant olivine phenocrysts 0.25 to 1 mm in diameter. Overlain by young alluvial fan (Qay) deposits. Dissolution sinkholes associated with karstification of the Harrisburg Member of the Kaibab Formation have formed under basalt flows allowing basalt to collapse as much as 18 m (60 ft). Sinkholes are partly filled with ponded alluvium. Basalt flowed into upper part of Toroweap Valley but mostly north towards Clayhole Valley north of map area (Billingsley, 1994). Thickness, 1 to 12 m (3 to 40 ft)

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 and Hampton (2000) before it was know that the name Sage Basalt was already in use. Includes three unnamed pyroclastic cones and associated basalt flows in the upper reaches of Toroweap Valley. Divided into:

Qgrp **Pyroclastic deposits**—Red-brown and reddish-black scoriaceous basalt fragments, ash, and cinder deposits; partly consolidated. Include three pyroclastic cones aligned along north-south, near vertical bedrock fracture system. Deposits overlie associated basalt flows. Only western part lies within map area. Toroweap Fault offsets north cone 26 m (85 ft). North cone is about 134 m (440 ft) high, central cone about 70 m (230 ft) high, and south cone about 60 m (200 ft) high

Qgrb **Basalt flows**—Dark-gray, finely crystalline to glassy, alkali-olivine basalt. Groundmass contains plagioclase, olivine, and augite laths. Includes abundant olivine phenocrysts 0.25 to 5 mm in diameter composing about 30 percent of basalt in some outcrops. Overlie Harrisburg Member of the Kaibab Formation (Pk). Northern part of basalt of Graham Ranch flow and pyroclastic cone is offset about 26 m (85 ft) down-to-the-west by the Toroweap Fault; southern part is offset about 34 m (110 ft) down-to-the-west, about half of total offset of Toroweap Fault, 67 m (220 ft) in underlying Paleozoic strata. Thickness, 3 to 18 m (10 to 60 ft)

Basalt of the Uinkaret Plateau (Pleistocene)—Informally named and include several pyroclastic cones and associated basalt flows of similar age north and south of Mount Trumbull. Basalts are assumed to have erupted during a similar eruptive phase throughout the map area north and south of Mount Trumbull. Several flows have coalesced from numerous vent areas to form a single massive basalt flow that cascaded into Toroweap Valley and Whitmore Canyon. Basaltic units north of Mount Trumbull are designated with a number (Qi1, Qb1, Qp1) because stratigraphic relations in upper Toroweap Valley suggest that these basalt flows may be slightly older than basalt deposits (Qi, Qp, and Qb) south of Mount Trumbull. Other Quaternary basalt flows and associated pyroclastic deposits that have mappable boundaries are informally designated on the map with an elevation number (Qp6375) representing the highest associated pyroclastic cone or informally named for a nearby ranch shown on U.S. Geological Survey 7.5´ quadrangles

Qi/Qi1 **Intrusive rocks**—Dark-gray to black alkali-olivine basalt dikes and necks. Form nearly vertical dikes or necks that commonly protrude above surrounding volcanic or bedrock deposits. Variable widths range from 0.5 to 6 m (1 to 18 ft). Neck or plug in Kaibab Formation southeast of Mount Trumbull is partly covered. Best examples are near Paws Pocket, east side of Whitmore Canyon, east-central part of map

Qp/Qp1 **Pyroclastic deposits**—Reddish-gray, black, and red to gray tuff, ash, scoriaceous ejecta, bombs, and cinder deposits; partly consolidated. Include about 17 pyroclastic deposits north of Mount Trumbull (Qp1) such as Craigs Knoll and about 36 pyroclastic vents south of Mount Trumbull (Qp) such as Mount Emma, Slide Mountain, and Petty Knoll in the Uinkaret Mountains between Whitmore Canyon and Toroweap Valley. Deposits are associated with coalescing basalt flows that issued from several vents. Locally form fine- to coarse-grained cinder sheet deposits on basalt flows near cones. Map contacts are approximate and show only the thickest deposits, not entire pyroclastic blanket deposit. No K-Ar ages are available, but cosmogenic ^{3}He ages at scattered locations indicate an age of 0.100 to 0.200 Ma (Fenton, 1998). Thickness, 6 to 180 m (18 to 600 ft)

Qb/Qb1 **Basalt flows**—Dark-gray to black, finely crystalline, alkali-olivine basalt. Olivine and plagioclase phenocrysts common. Include scoriaceous material from pyroclastic deposits. Basalt flows north of Mount Trumbull originated from several pyroclastic vents and generally flowed east into upper Toroweap Valley. Basalt flows overlie the Moenkopi Formation near pyroclastic cones and the Kaibab Formation farther away from the cones. Flows went down alluviated valleys before reaching Toroweap Valley. Basalt flows in upper Toroweap Valley (Qb1) are mostly covered with young alluvial fan (Qay) deposits and basalt flows (Qb) that originated south of Mount Trumbull. South of Mount Trumbull, basalt cascaded into Whitmore Canyon and Toroweap Valley from higher terrain of the Uinkaret Mountains. Basalt cascades are steep where they flowed over the Hurricane Fault scarp at Hells Hollow drainage in upper Whitmore Canyon and over cliffs of the Kaibab and Toroweap Formations in Whitmore Canyon and Toroweap Valley. Basalt flowed over the Moenkopi, Kaibab, and Toroweap Formations south of Mount Trumbull. Cosmogenic ^{3}He dating of basalt surfaces in upper Whitmore Canyon indicate an average age of about 0.100 Ma, and flow surfaces in lower Whitmore Canyon and Toroweap Valley have an average age of about 0.150 to 0.200 Ma (Fenton, 1998). Thickness, 6 to 91 m (18 to 300 ft)

Basalt of Kenworthy Ranch (Pleistocene)—Informally named for the Kenworthy Ranch in Sink Valley, Uinkaret Plateau, Mohave County, Arizona (sec. 1, T. 35 N., R. 9 W.; Billingsley, 1997b; Billingsley and others, 2001). Divided into:

Qkrp **Pyroclastic deposits**—Reddish-black and red tuff, ash, scoriaceous ejecta, and cinders overlie associated basalt flows. Map contact is approximate. Include three unnamed cinder cones that align north-south. North pyroclastic cone just west of Kenworthy Ranch is about 49 m (160 ft) high, middle cone is about 24 m (80 ft) high, and south cone about 24 m (80 ft) high

Qkrb **Basalt flows**—Light- to dark-gray, finely crystalline, alkali-olivine basalt. Include small phenocrysts of augite and olivine in glassy groundmass. Flows radiate from all three pyroclastic cones coalescing to form large elongated north-south oval flow mass. Overlie Harrisburg Member of the Kaibab Formation (Pk). Thickness, 15 m (50 ft)

Basalt of Marshall Ranch (Pleistocene)—Informally named for Marshall Ranch about 2.5 km south of Kenworthy Ranch, Uinkaret Plateau, Mohave County, Arizona (sec. 13, T. 35 N., R. 9 W.; Billingsley, 1997b; Billingsley and others, 2001). Divided into:

Qmrp **Pyroclastic deposits**—Reddish-black and red tuff, ash, scoriaceous ejecta, and cinders overlie associated basalt flows. Include two unnamed pyroclastic cones and three smaller secondary spatter cones. Secondary cones appear to have erupted from basalt flows that came from south pyroclastic cone. North pyroclastic cone is about 73 m (240 ft) high and south cone is about 85 m

(280 ft) high

Qmrb **Basalt flows**—Gray-black, finely crystalline, alkali-olivine basalt. Majority of basalt flowed in radial pattern from south pyroclastic cone. Basalt also flowed west about 3 km (2 mi). Partly overlie the basalt of Potato Valley (Qpvb) at south margin and overlie Harrisburg Member of the Kaibab Formation elsewhere. Thickness, 12 to 36 m (40 to 120 ft)

Basalt of hill 6375 (Pleistocene)—Informally named for unnamed pyroclastic cone (hill 6375) at the north end of Sink Valley, Uinkaret Plateau, Mohave County, Arizona (sec. 31, T. 35 N., R. 8 W.; Billingsley, 1997b; Billingsley and others, 2001). Divided into:

Qp6375 **Pyroclastic deposits**—Reddish-black cinder and scoriaceous ejecta overlie associated basalt flow. Include small cone at the north end of associated basalt flow that may be local splatter cone deposit derived from basalt flow. Main cone deposit, hill 6375, is about 64 m (290 ft) thick

Qb6375 **Basalt flows**—Dark-gray alkali-olivine basalt. Basalt flowed west 0.8 km (0.5 mi) and north about 1.5 km (1 mi). Overlies Harrisburg Member of the Kaibab Formation (Pk). Thickness, 1 to 12 m (3 to 40 ft)

Basalt of hill 6646 (Pleistocene)—Informally named for unnamed pyroclastic cone (hill 6646) at northwest end of Sink Valley, Uinkaret Plateau, Mohave County, Arizona (sec. 35, T. 36 N., R. 9 W.; Billingsley, 1997b; Billingsley and others, 2001). Divided into:

Qp6646 **Pyroclastic deposits**—Red and black cinder and scoriaceous deposits overlie associated basalt flow. Include one large pyroclastic cone and two adjacent small cones. There are three eruptive vent areas that formed the main cone aligned along a north-south strike, similar to north-south strike of basaltic cones in Kenworthy Ranch area. Main pyroclastic cone is about 76 m (250 ft) thick

Qb6646 **Basalt flows**—Dark-gray alkali-olivine basalt. Basalt flowed north about 3 km (2 mi). Overlies Harrisburg Member of the Kaibab Formation (Pk). Thickness, 10 to 30 m (30 to 100 ft)

Basalt of hill 6457 (Pleistocene)—Informally named for unnamed cinder cone (hill 6457) north of and below Mount Trumbull, Uinkaret Plateau, Mohave County, Arizona (sec. 16, T. 35 N., R. 8 W.; Billingsley and others, 2001). Divided into:

Qp6457 **Pyroclastic deposits**—Reddish-black cinder and scoriaceous deposits. Include two smaller cones that partly overlie associated basalt flow from cone 6457. North cone may have erupted from the basalt flow. Pyroclastic cone (hill 6457) is 36 m (120 ft) thick, and north cone about 24 m (80 ft) thick

Qb6457 **Basalt flows**—Dark-gray alkali-olivine basalt. Basalt flowed north from hill 6457 about 0.8 km (0.5 mi) onto young alluvial fan (Qay) and floodplain (Qf) deposits. Thickness, 36 m (120 ft)

Basalt of Potato Valley (Pleistocene)—Informally named from Potato Valley, Uinkaret Plateau, Mohave County, Arizona (sec. 25, T. 35 N., R. 9 W.; Billingsley, 1997b; Billingsley and others, 2001). Includes several pyroclastic cones and associated basalt flows along north and west edge of Potato Valley. Divided into:

Qpvp **Pyroclastic deposits**—Red and black cinder, tuff, ash, and scoriaceous ejecta. Include two main pyroclastic cones on north and west sides of Potato Valley and five small pyroclastic vents. The two main cones appear to be the main sources for associated basalt flows that ring the north and west side of Potato Valley. Several small cones on basalt flows appear to have erupted from the flow as secondary eruptions. Dikes in Hells Hole (QTi) south of Potato Valley may be associated with Potato Valley cones. Thickness, 106 m (350 ft) on west side of Potato Valley and 85 m (280 ft) on north side

Qpvb **Basalt flows**—Dark-gray alkali-olivine basalt. Flows on north side of Potato Valley erupted from unnamed cinder cone and flowed northwest about 3 km. Flow appears to have merged or coalesced with flows from two cones on west side of Potato Valley forming a basalt dam responsible for the accumulation of alluvial sediments in Potato Valley. Basalt flows on west side of Potato Valley flowed mostly north about 5 km (3 mi). Thickness, 2 to 25 m (6 to 85 ft)

Basalt of hill 6588 (Pleistocene)—Informally named for highest of four pyroclastic cones on east flank of Mount Trumbull, the type area, Uinkaret Volcanic Field, Mohave County, Arizona (sec. 36, T. 35 N., R. 8 W.; Billingsley and others, 2001). Includes pyroclastic deposits and associated basalt flows. Divided into:

Qp6588 **Pyroclastic deposits**—Reddish-black to mostly black and gray ash, cinder, scoriaceous fragments, and basaltic boulders; partly consolidated. Include four pyroclastic cones aligned in 2-km-long (1-mi-long) northwest-southeast trend. Deposits mostly overlie associated basalt flows and landslide deposits (Ql); often incorporated into basalt flows on steep east slopes of hill 6588. Variable thickness because of steep terrain, 2 to 55 m (6 to 180 ft)

Qb6588 **Basalt flows**—Dark-gray and light-gray, finely crystalline, alkali-olivine basalt. Include interbedded scoriaceous pyroclastic deposits. Basalt cascaded down steep slope into Toroweap Valley over landslide deposits (Ql) and lower strata of the Moenkopi Formation (T̶Rm) and Harrisburg Member of the Kaibab Formation (Pk). Flows partly buried by undivided basalt flows (Qb) and young alluvial fan (Qay) deposits in Toroweap Valley. Thickness, 2 to 10 m (6 to 30 ft)

Basalt of Craigs Knoll and Berry Knoll (Pleistocene)—Informally named for Craigs Knoll (sec. 4, T. 35 N., R. 8 W.), and Berry Knoll (sec. 24, T. 36 N., R. 9 W.), Uinkaret Plateau, Mohave County, Arizona (Billingsley, 1997b; Billingsley and others, 2001; Billingsley and Workman, 2000). Includes dikes, pyroclastic deposits, and basalt flows that appear to have erupted simultaneously at Craigs Knoll and Berry Knoll and at unnamed pyroclastic cone between Craigs Knoll and Berry Knoll. Divided into:

Qcbi **Intrusive dikes or necks**—Greenish-black olivine basalt. Widths of dikes shown on map are approximate

Qcbp **Pyroclastic deposits**—Gray and reddish-gray to black cinder, tuff, ash, and scoriaceous ejecta; mostly consolidated into welded tuff. Form cliff on east side of Craigs Knoll and steep slope on south and west side. Deposits mostly covered by dark-gray basalt on north flank of Craigs Knoll. Include small secondary pyroclastic deposit on south flank of Craigs Knoll. Deposits overlie associated basal basalt flow exposed on south flank of Craigs Knoll, and an upper associated basalt flow overlies pyroclastic deposits, mostly on north and west flanks of Craigs Knoll. Thickness, 183 m (600 ft)

Qcbb **Basalt flows**—Light-gray and dark-gray alkali-olivine basalt. Include lower and upper basalt flows separated by pyroclastic deposits (Qcbp). No K-Ar age available. Lower basalt accumulated on Harrisburg Member of the Kaibab Formation (Pk) and lower strata of the Moenkopi Formation (T̶Rm). Estimated thickness of lower flow, about 40 m (130 ft). Upper basalt erupted near top of Craigs Knoll and flowed west, north, and east about 8 km (5 mi). Estimated thickness of upper flow, 3 to 20 m (10 to 65 ft)

Little Tanks Basalt (Pleistocene)—Formally named for a local stock tank labeled "Little Tanks reservoir" in the type area just north of map area, Mohave County, Arizona (sec. 5, T. 36 N., R. 10 W.). Basalt and associated pyroclastic deposits form Cinder Knoll (sec. 29, T. 36 N., R. 10 W.), north-central edge of map. K-Ar age, 1.0±0.4 Ma (Billingsley, 1993; Billingsley and Workman, 2000). Divided into:

Qlp **Pyroclastic deposits**—Red-brown and reddish-black basaltic scoria and cinder deposits; partly consolidated. Unit forms Cinder Knoll, a 15-m-high (50-ft-high) pyroclastic cone capped by basalt flow

Qlb **Basalt flows**—Dark-gray, finely crystalline to glassy, alkali-olivine basalt. Groundmass composed of plagioclase, olivine, and augite. Unit contains abundant olivine phenocrysts 0.25 to 1 mm in diameter. Unit unconformably overlies Harrisburg Member of the Kaibab Formation (Pk) and Timpoweap Member and lower red member of the Moenkopi Formation (T̶Rm). Thickness, 1 to 3 m (3 to 10 ft)

QTi **Hells Hole dikes (Pleistocene or Pliocene(?))**—Dark-gray alkali-olivine basalt. Include three dikes in the Kaibab and Moenkopi Formations in Hells Hole. Form nearly vertical walls that stand out in relief in some places as much as 3 to 4 m (10 to 12 ft) high and about 0.5 to 2 m (2 to 6 ft) wide. Dikes are aligned in general north-south trend and appear to connect to pyroclastic vents on west side of Potato Valley (Qpvp); also may be source for basalt of Mount Logan (Tmlb) due to close proximity to Mount Logan. Vertical exposure is nearly 610 m (2,000 ft)

Tertiary volcanic deposits (Pliocene and Miocene)—Include basalt flows, dikes, and pyroclastic deposits in the Uinkaret Volcanic Field on the Shivwits Plateau, and the Grand Wash Trough of the Basin and Range area

Basalt north of Mount Emma (Pliocene)—Gray-black alkali-olivine basalt; includes several basalt flows, pyroclastic deposits, and intrusive rocks. Unit largely covered by Quaternary pyroclastic (Qp) deposits at Mount Emma and other north-south-aligned pyroclastic cones and associated basalt flows (Qb). Unit is offset down-to-the-west about 250 m (820 ft) by southern splay of the Hurricane Fault. There are no K-Ar ages available, but age estimated to be about 2.6 to 3.6 Ma based on stratigraphic position, elevation, and flow direction of basalt of Mount Logan (Tmlb) and basalt of Mount Trumbull (Tmb). Divided into:

Tei **Intrusive rocks**—Gray-black alkali-olivine basaltic plug or dike. Unit partly exposed and offset by the Hurricane Fault. Most of unit covered by landslide deposits (Ql). Width of plug is probably in excess of 90 m (300 ft) and appears to be source of Tertiary basalt flows north of and under Mount Emma pyroclastic deposits. Plug does not protrude above ground surface; highly altered and weathered

Tep **Pyroclastic deposits**—Reddish-black cinder, scoria, ash, and other scoriaceous ejecta; deeply eroded. Associated with intrusive plug (Tei) on downthrown side of Hurricane Fault north of Mount Emma. Thickness, 12 m (40 ft)

Teb **Basalt flows**—Near Mount Emma, gray-black alkali-olivine basalt; plagioclase laths common in glassy groundmass. Consist of several basalts that flowed east and south from plug (Tei) area. Underlying strata concealed, but because of similar elevation as basalt of Mount Logan, it is assumed basalt overlies the Chinle Formation (T̵Rc) or upper Moenkopi Formation (T̵Rm). Thickness, 122 m (400 ft)

Basalt of Mount Logan (Pliocene)—Informally named Mount Logan basalt for Mount Logan (Reynolds and others, 1986). Forms prominent Mount Logan (elev. 2,398 m [7,866 ft]) on Uinkaret Plateau, Mohave County, Arizona (sec. 12, T. 34 N., R. 9 W.; Billingsley and others, 2000, 2001). K-Ar age, 2.63±0.34 Ma obtained from a basalt flow on Mount Logan, but a specific location was not disclosed. New age determinations are needed to determine the sequence of events between the basalt of Mount Logan and the basalt of Bundyville, which appear to be the same age (3.6 Ma) based on close proximity to each other (about 3.5 km [2 mi] apart), stratigraphic position where both units overlie the same 122-m-thick (400-ft-thick) section of the Chinle Formation (T̵Rc), and similar thickness

Tmlb **Basalt flows**—Light-gray, finely crystalline, alkali-olivine basalt; contains red and green olivine phenocrysts 1 mm in diameter in glassy groundmass; includes plagioclase laths in glassy groundmass. Plagioclase masses form white spotted blotches in some areas. Basalt flow(s) overlie Petrified Forest Member of the Chinle Formation (T̵Rc) east side of Hells Hole (sec. 12, T. 34 N., R. 9 W.). Eastern extent of basalt may overlie upper red member and Shnabkaib Member of the Moenkopi Formation (T̵Rm). Basalt dikes (QTi) may be source for basalt of Mount Logan below the summit of Mount Logan in Hells Hole. Basalt flowed east about 5.3 km (3 mi) from near the summit of Mount Logan, descending about 335 m (1,100 ft). Average thickness, about 67 m (220 ft)

Basalt of Bundyville (Pliocene)—Informally named the Bundyville basalt for the abandoned settlement of Mt. Trumbull (Bundyville; Hamblin and Best, 1970; Hamblin, 1970), Shivwits Plateau, Mohave County, Arizona, (secs. 23, 24, 25, and 26, T. 35 N., R. 10 W.). Exposed on downthrown side of Hurricane Fault in northwest quarter of map area (Billingsley and others, 2000). K-Ar age, 3.6±0.18 Ma (Reynolds and others, 1986). Divided into:

Tbi **Intrusive dikes**—Dark-gray alkali-olivine basalt. Dikes are nearly vertical and oriented N. 40° W. and nearly parallel to the Hurricane Fault. Widths, 1 to 3 m (2 to 10 ft)

Tbb **Basalt flows**—Dark-gray, finely crystalline, olivine basalt. Groundmass contains olivine. Include one to three basalt flows that form a caprock overlying purple and white mudstone and sandstone beds of the Petrified Forest Member of the Chinle Formation (T̵Rc). Flow surfaces locally distorted by landslide and soft sediment deformation of underlying soft mudstone that has been caused by earthquakes related to the Hurricane Fault. Basalt predates any offset of strata along Hurricane Fault implying that the fault is younger than 3.6 Ma. Flows assumed to have originated from local dikes (Tbi) that are largely covered by basalt, landslide, or talus debris. Thickness, 30 to 55 m (100 to180 ft)

Basalt of Mount Trumbull (Pliocene)—First described by Koons (1945), informally named Mount Trumbull basalt for Mount Trumbull by Hamblin and Best (1970) and Hamblin (1970), Uinkaret Plateau, Mohave County, Arizona, (sec. 27, T. 35 N., R. 8 W.; southeast quarter of map area; Billingsley and others, 2001). Forms prominent landmark on Uinkaret Plateau. K-Ar age, 3.6±0.18 and 3.67±0.09 Ma (Reynolds and others, 1986). Divided into:

Tmi **Intrusive rocks**—Gray-black, finely crystalline, alkali-olivine basalt. Forms highest point on north side of Mount Trumbull (elev. 2,447 m [8,029 ft]). Source for Tertiary basalt flows on Mount Trumbull. Width, 120 m (400 ft) or more

Tmb **Basalt flows**—Gray-black, finely crystalline, alkali-olivine basalt. Groundmass contains olivine phenocrysts and plagioclase laths. Consist of one or more thin basalt flows that form caprock overlying concealed purple and white mudstone and sandstone beds of the Petrified Forest Member of the Chinle Formation (T̵Rc) on west side of mountain (exposed in landslide float material) that overlie upper red member and possible Shnabkaib Member of the Moenkopi Formation (T̵Rm) on east side of mountain (exposed as landslide blocks). Partly covered by Quaternary pyroclastic (Qp) deposits. Thickness, 30 to 60 m (100 to 200 ft)

Basalt of the Grand Wash Trough (Pliocene)—Include intrusive dikes and necks (Ti), basalt flows derived from north of map area and from Olaf Knolls (Tb), and interbedded fluvial sediments (not shown on map) between basalt flows (Billingsley and others, unpub. data)

Ti **Dikes and necks**—At Olaf Knolls, consists of light-gray alkali-olivine basalt dike that intrudes red sandstone and siltstone (Tgr) rocks of the Grand Wash Trough. Form highest part of Olaf Knolls volcanic area (elev. 985 m [3,232 ft]). Hachured symbol on map marks possible small mar or caldera depression on north flank of Olaf Knolls. Age of Olaf Knolls assumed to be about 4 to 4.5 Ma based on relation to nearby basalt flows derived north of the map area (Qb) in Cottonwood and Grand Wash drainages. Include dikes or necks of dark-gray alkali-olivine basalt on east side of Cottonwood Wash, south of Pakoon Springs that intrude gray gypsum, gypsiferous siltstone, and red siltstone and sandstone (Tgr). Pyroclastic deposits not present. Widths, as much as 30 m (100 ft)

Tb **Basalt flows**—Consist of two or more basalt flows (Damon and others, 1996). Light-gray to medium-gray alkali-olivine basalt. Age of upper flow at Pakoon Springs, 3.99±0.06 to 4.70±0.07 Ma. Age of lower basalt at Grand Wash Bay, Lake Mead, that may have originated from dikes or necks (Ti) along east side of Cottonwood Wash (southwest edge of map area), 3.24±0.05 Ma (Damon and others, 1996). Include interbedded alluvial sediments between basalt flows along Cottonwood, Grand, and Pakoon Wash drainages in upper part. Source of upper basalt flows appears to have originated from pyroclastic vents and dikes in northern part of Grand Wash Trough (north of map area) that occupy Grand, Cottonwood, and Pakoon Wash paleodrainages. Interbedded alluvial sediments are composed of gray and light-brown, poorly sorted, slope-forming, consolidated conglomerate, gravel, sand, and silt. Contain Proterozoic and Paleozoic clasts derived from the Virgin Mountains northwest of map area. Thickness of intrabasaltic sediments are as much as 90 m (300 ft; Lucchitta and others, 1995a, b), but average about 24 m (80 ft) thick in map area and thin southward. Lower basalt flow contains calcite-filled veins and vugs. Basalt at Olaf Knolls (sec. 1, T. 35 N., R. 15 W.) is light- to medium-gray alkali-olivine basalt. Majority of basalt flowed in radial pattern from highest point of Olaf Knolls approximately 2.5 km (1.5 mi) to southwest, 1.5 km (1 mi) to northeast, and 1.5 km (1 mi) to west. Flows occupy Grand Wash paleodrainage and unconformably overlie red siltstone and sandstone (Tgr) deposits. All basalt flows overlain by conglomerate and calcrete (Tay) deposits and partly overlain by young and old alluvial fan (Qay and Qao) deposits. Basalt flows exposed 1.5 km (1 mi) southeast of Olaf Knolls near Grand Wash Cliffs may have originated from another source north of map area or possibly Olaf Knolls. Combined thickness of upper basalt and interbedded sediments, 2 to 140 m (6 to 460 ft). Thickness of lower basalt, 2 to 10 m (6 to 30 ft)

Whitmore dike swarm (Pliocene)

Twi **Intrusive dikes**—Dark-gray to black alkali-olivine basalt. K-Ar age, 4.56±0.12 Ma (Wenrich and others, 1995). Form nearly vertical dikes eroded down to bedrock surface of Esplanade Sandstone and Pakoon Limestone (Pep) about 2 km (1.3 mi) southwest of Whitmore Canyon and 3 km (1.5 mi) west of Colorado River Mile 188. Dikes parallel joints and nearly vertical fractures in bedrock for about 3.3 km (2 mi) along north-south trend. Dikes exposed in the Esplanade Sandstone and Pakoon Limestone (Pep) and lower part of the Hermit Formation (Ph) 1.6 km (1 mi) west of Colorado River Mile 188 only produced one basalt flow (Twb). Dike widths, 0.5 to 1.2 m (2 to 3.5 ft)

Twb **Basalt flow**—Dark-gray to black alkali-olivine basalt. Includes small olivine phenocrysts and plagioclase laths in glassy groundmass. Basalt emerged from dike (Twi) in lower part of Hermit Formation (Ph) and flowed down steep debris slope descending about 60 m (200 ft) onto upper part of Esplanade Sandstone and Pakoon Limestone (Pep). Basalt preserves soft strata of the Hermit Formation as a basalt-capped hill informally called “Whitmore Hill” (sec. 26, T. 32 N., R. 9 W.; elev. 1,161 m [3,808 ft]). Basalt flow implies that erosion exposed at least the Esplanade Sandstone at this location by 4.5 Ma. Thickness, 18 m (60 ft)

Basalt of Poverty Knoll (Pliocene)—Informally named for Poverty Knoll, a 245-m-high (800-ft-high) mesa or flat-topped knoll on Shivwits Plateau, north-central part of map area (sec. 2, T. 35 N., R. 11 W.; Billingsley and others, 2000). Divided into:

Tpki **Intrusive dike**—Light-gray, finely crystalline, alkali-olivine basalt. Forms small knoll, center-top of Poverty Knoll

Tpkb **Basalt flow**—Light-gray, finely crystalline, alkali-olivine basalt containing plagioclase laths and olivine phenocrysts 1 mm in diameter in glassy groundmass; contains about 35 percent olivine phenocrysts. Flow emerged from central dike and flowed in radial pattern over Shnabkaib Member of the Moenkopi Formation. Thickness averages about 37 m (120 ft)

Poverty Mountain Basalt (Pliocene)—Informally named Shivwits basalt by Best and others (1980) and Reynolds and others (1986) in conjunction with the basalt of the Shivwits Plateau flows south of map area. Formally named Poverty Mountain Basalt for Poverty Mountain, the type area, Shivwits Plateau, west-central edge of map area (secs. 29 and 32, T. 35 N., R.11 W.; Billingsley and others, 2000). K-Ar age, 4.75±0.26 Ma (Reynolds and others, 1986). Divided into:

Tpi **Intrusive neck**—Medium-gray, finely crystalline, alkali-olivine basalt. Forms small dike associated with basalt flows and pyroclastic deposits near eastern part of mountain. Dike and nearby small pyroclastic vents are aligned northwest-southeast and are main sources for basalt flows (Tpb) on Poverty Mountain

Tpp **Pyroclastic deposits**—Reddish-black and red fragments of scoria, cinders, and small ribbons overlie basalt flows at and near vent areas. Interbedded with basalt flows near dike (Tpi) and pyroclastic cone areas. Largest cone is about 25 m (80 ft) thick

Tpb **Basalt flows**—Medium-gray to light-gray, finely crystalline, alkali-olivine basalt. Include augite and olivine phenocrysts less than 1 mm in diameter in glassy groundmass. Basalt overlies gently east-northeast-dipping (2° average) upper red member and Shnabkaib Member of the Moenkopi Formation and the Harrisburg Member of the Kaibab Formation. Basalt flowed in radial pattern from three vent areas over upper strata of the Moenkopi Formation. Basalt flows coalesced and flowed west and down across east-dipping Triassic strata into upper reaches of Hidden Canyon paleodrainage. Thickness, 30 to 92 m (100 to 300 ft)

Grassy Mountain Basalt (Pliocene)—Formally named Grassy Mountain Basalt for Grassy Mountain, the type area, Shivwits Plateau (secs. 3, 4, 9, 10, T. 33 N., R. 11 W.; Billingsley and others, 2000). Divided into:

Tgi **Intrusive dikes**—Dark-gray, finely crystalline, alkali-olivine basalt. Source areas for associated basalt flows and pyroclastic deposits on Grassy Mountain. Dikes are aligned with nearly vertical east-west bedrock joints and fractures of this area. Widths, 0.5 to 2 m (1 to 6 ft)

Tgp **Pyroclastic deposits**—Red to reddish-black, angular, scoriaceous cinder fragments and ash deposits; unconsolidated. Spatially associated with intrusive dikes; interbedded with local basalt flows (Tgb). Thickness, 1 to 6 m (3 to 20 ft)

Tgb **Basalt flows**—Dark-gray, finely crystalline, alkali-olivine basalt; olivine phenocrysts averaging 1 mm in diameter form about 25 percent of rock sample from interior of basalt flow. One or more flows interbedded with pyroclastic deposits near dikes. Basalts flowed generally west and northwest and overlie upper red member and Shnabkaib Member of the Moenkopi Formation (₮m). Thickness, 12 to 60 m (40 to 200 ft)

Tp6i **Dikes of Parashant Canyon and Hundred and Ninetysix Mile Creek (Miocene)**—Dark-gray, fine-grained to coarsely crystalline, olivine-augite basalt. Dikes commonly form recessive cracks in limestone rocks of canyon walls that appear as open eroded joints. Commonly eroded and chemically altered or decomposed, especially near Colorado River Mile 197 and in Hundred and Ninetysix Mile Creek. Several dikes parallel or occupy faults, but most parallel or occupy northwest-southeast-trending joints and fractures in bedrock for 25 km (15 mi) distance. No associated basalt flows are present. Dikes intrude Cambrian through Permian rocks from Colorado River Mile 197 to north rim of Parashant Canyon on the Shivwits Plateau and southeast of Colorado River into upper reaches of Hundred and Ninetysix Mile Creek. K-Ar age, 6.34±0.1 Ma from dike on Sanup Plateau, north side of Parashant Canyon (Wenrich and others, 1995). Other dikes near Colorado River are too chemically altered or decomposed for K-Ar age dating techniques. Dikes at Colorado River Mile 197 extend upward over 1,050 m (3,450 ft) into Esplanade Sandstone and Pakoon Limestone (Pep) where inner gorge is 3 km (2 mi) wide. Dike widths, 0.3 to 3 m (1 to 10 ft)

T2i **Dikes of Colorado River Mile 202 (Miocene)**—Light-gray, coarsely to finely crystalline, olivine-augite basalt. Include three to four dikes that parallel and occupy northwest-trending joints, fractures, and minor faults in Paleozoic bedrock. Composition is basalt and andesite. K-Ar age is 5.76±0.26 (Wenrich and others, 1995). There appear to be no flows associated with dikes of Colorado River Mile 202, but some basalt flows on the Shivwits Plateau east of Mollies Nipple may be associated with dikes of Colorado River Mile 202. Dikes extend from the Muav Limestone (Ꞓm) up almost into the lower Toroweap Formation (Pt) near Mollies Nipple, east edge of Shivwits Plateau. Dikes are aligned to similar northwest-trending dikes at Yellow John Mountain on nearby Shivwits Plateau. Widths, 0.1 to 3 m (1 to 10 ft)

Basalt of the Shivwits Plateau (Miocene)—Informally named for Shivwits Plateau, Mohave County, Arizona. Mount Dellenbaugh is highest point (elev. 2,155 m [7,072 ft]) that forms a regional landmark on the southern Shivwits Plateau; type section for basalt of the Shivwits Plateau (sec. 2, T. 31 N., R.12 W.). Includes the 6.2±0.30 Ma and 7.64±0.30 Ma Shivwits basalt of Lucchitta and McKee (1974), 6.78±0.15 Ma Dellenbaugh basalt (Reynolds and others, 1986), 7.06±0.49 Ma Mt. Dellenbaugh basalt of Best and others (1980), 8.2±0.1 Ma Price Point basalt of Wenrich and others (1995). Includes numerous dikes, necks, pyroclastic deposits, and extensive basalt flows. Divided into:

Tsi **Intrusive rocks**—Gray-black, finely crystalline, alkali-olivine basalt. Approximate map contacts. Source for extensive basalt flows and minor pyroclastic deposits on Shivwits Plateau (average elev. 1,829 m [6,000 ft]). Dikes trend about N. 30° W., similar to dikes of Colorado River Mile 202 (T2i) east of Shivwits Plateau. Dike widths, 0.1 to 2 m (1 to 6 ft)

Tsp **Pyroclastic deposits**—Reddish-black scoria and cinder fragments, partly consolidated. Form small pyroclastic cones, heavily eroded and partly covered by basalt flows. Often interbedded with basalt flows near vent areas. Thickness, 12 m (40 ft)

Tsb **Basalt flows**—Gray-black, finely crystalline, alkali-olivine basalt. Includes one or more thin basalt flows that overlie red and white mudstone, siltstone, and gypsum of the lower Moenkopi Formation (₮m) and gray siltstone, gypsum, and cherty limestone of the Kaibab Formation (Pk). Groundmasses commonly contain olivine phenocrysts and plagioclase laths. Form composite volcanoes of Blue Mountain, south of map area, Yellow John Mountain and Mount Dellenbaugh on Shivwits Plateau. Partly covered by Quaternary and Tertiary alluvium (QTa) east of Wildcat Ranch at northern reaches of basalt flow. Basalt generally flowed in radial patterns from prominent mountain volcanic centers onto relatively flat eroded surface of east- and northeast-dipping Moenkopi and Kaibab Formations. Longest basalt flows generally flowed northwest. Thickness, 3 to 122 m (10 to 400 ft)

Snap Point Basalt and Garrett dikes (Miocene)—Includes basalt flow on Snap Point, upper Grand Wash Cliffs, and at Nevershine Mesa, Grand Wash Trough (Billingsley and others, unpub. data). Includes associated dikes (Garrett dikes) in Sanup Plateau and at Colorado River Mile 264 in Grand Canyon. Informally named Snap Point basalt in Reynolds and others (1986) and Wenrich and others (1995). Because of the isolation and mappable occurrence of basalt flows and associated dikes, the Snap Point Basalt is herein formally named Snap Point Basalt for Snap Point, the type area, Shivwits Plateau, Mohave County, Arizona (sec. 16, T. 32 N., R. 14 W.). K-Ar age is 9.07±0.80 Ma at Snap Point (Reynolds and others, 1986) and 9.2±0.13 Ma for Garrett dikes on Sanup Plateau (Wenrich and others, 1995). Divided into:

Tsgi **Intrusive dikes**—Dark-gray, greenish, finely crystalline, alkali-olivine basalt. Contain phenocrysts of augite and olivine less than 1 mm in diameter. Form near-vertical dikes orientated in north-south alignment parallel to local joints and fractures in Paleozoic bedrock units. Include dikes in Pigeon Canyon north of Snap Point that lie on similar north-south trend of Garrett dikes south of Fort Garrett Point. Intrude all Paleozoic rocks in walls of Grand Canyon on both sides of Colorado River Mile 264 and in tributaries of Tincanebitts and Dry Canyons. Exposed dikes in canyon walls reveal that Grand Canyon was not as deep or wide 9 m.y. ago as it is today. Dike widths, 0.5 m (1 to 2 ft)

Tsgb **Basalt flows**—Dark-gray alkali-olivine basalt. Basalt originates from dike source near highest part of Snap Point. Consists of two separate basalt flows, one flowed east about 2.4 km (1.5 mi) down drainage eroded into Fossil Mountain Member of the Kaibab Formation (Pk) on the Shivwits Plateau and another flowed west down steep erosional escarpment of upper Grand Wash Cliffs into Snap Canyon drainage and into Grand Wash Trough below lower Grand Wash Cliffs. Snap Canyon was filled to a depth of several hundred meters by alluvial deposits (Tgc) at time of Snap Point flow. Alluvial deposit forms large alluvial debris fan at the mouth of Snap Canyon (Billingsley and others, unpub. data). Snap Point Basalt flowed into Grand Wash Trough and was subsequently buried by younger alluvial fan deposits. Modern erosion has removed most of the alluvial deposits (Tgc) from around the Snap Point Basalt to form an inverted topographic feature called Nevershine Mesa. Thickness, 3 to 10 m (10 to 30 ft)

Volcanic rocks of the Hualapai Plateau, undivided (Early to middle Miocene)—Deposits include scattered remnants of basalt flows in southwest corner of map area that appear to have originated from the 17.4±0.9 Ma Iron Mountain basalt southwest of the map area and the 15.3±0.3 Ma Grapevine Canyon volcanic rocks south of the map area (Wenrich and others, 1995). Includes the 17.4±0.3 Ma plug of The Grand Pipe, a breccia pipe named by Wenrich and others (1996), Sanup Plateau, 3 km (2 mi) north of Colorado River Mile 275

Tvi **Plug of The Grand Pipe**—Alkali-olivine basalt plug or dike in ring fracture of The Grand Pipe of Wenrich and others (1996) on the Sanup Plateau. K-Ar age, 17.4±0.3 Ma (Wenrich and others, 1996). Plug is about 10 m (30 ft) in diameter and is the source for remnants of eroded basalt flow on small hill on south side of The Grand Pipe

Tv **Basalt flows**—Alkali-olivine basalt flows. Scattered remnants of basalt are part of extensive flows that flowed north down drainages from Iron Mountain about 11 km (7 mi) southwest of map area and flows from the Grapevine Canyon volcanic area south of the map. Basalt overlies Tertiary gravel deposits that may be part of the Buck and Doe Conglomerate of Young (1999). No age or chemical studies have been done on these basalts. Thickness, 2 to 4 m (6 to 12 ft)

SEDIMENTARY ROCKS

Rocks of the Grand Wash Trough (Pliocene and Miocene)—The Tertiary and Quaternary alluvial rocks in the Grand Wash Trough were collectively called the Muddy Creek Formation by Lucchitta (1979), but recent studies by Bohannon (1984, 1991, 1992), Bohannon and others (1993), and Beard (1996) have determined that these sedimentary rocks are not connected to the Muddy Creek Formation of the Muddy River area farther west but are rocks that have formed in separate basins at about the same time as the Muddy Creek. The Hualapai Limestone of Lucchitta (1979) is equivalent to sediments of gypsum and gypsiferous siltstone facies (Tgg) and limestone and siltstone facies (Tgl) north of Lake Mead. Tertiary sediments, alluvial rocks (Tgx, Tgg, Tgl, Tgc, Tgr, Tao, Tay), and volcanic rocks (Tb) of the Grand Wash Trough unconformably overlie the Horse Spring Formation (Ths; Billingsley and others, unpub. data). Divided into:

Tgr **Red siltstone, sandstone, and conglomerate facies (Pliocene and Miocene)**—Dark-red to orange-red, slope-forming, medium- to fine-grained, gypsiferous siltstone and sandstone overlain by cliff-forming, gray to light-orange-brown, coarse- to fine-grained, poorly sorted, consolidated silt, sand, gravel, and conglomerate. Clasts in upper conglomerate consist of about 90 percent limestone and dolomite, 5 percent sandstone, and 5 percent chert in gray gypsiferous siltstone and sandstone gravel matrix. Base of unit not exposed but assumed to unconformably overlie rocks of the Grand Wash Trough (Tgl, Tgg, and Tgx) and Mesozoic and Paleozoic rocks along basin margins. Conglomerate beds contain small subrounded to angular clasts of Proterozoic crystalline rocks along Pakoon Wash, northwest edge of map area. About 130 m (425 ft) of unit exposed along Grand Wash and Pakoon Wash drainages, increasing to about 450 to 470 m (1,475 to 1,550 ft) or more north of map area (Lucchitta and others, 1995a, b; Billingsley and Workman, 2000)

Tgc **Paleozoic-clast conglomerate facies (Miocene)**—Gray, cliff-forming, rounded to subrounded clasts of Paleozoic limestone and sandstone from 1 to 70 cm (1 to 28 in) in diameter mixed with coarse gravel and conglomerate derived from Paleozoic rocks of the Colorado Plateau. Consolidated by calcium and gypsum cement. Forms alluvial debris fans at the mouths of Pigeon, Pearce, and Snap Canyons and several small unnamed drainages from the Grand Wash Cliffs. Lower part of unit includes lenses of reddish and red-brown sandstone gravel and conglomerate, poorly sorted and consolidated by calcite and gypsum cement. Gradational and intertonguing vertical and horizontal contact arbitrarily marked between lithologic change at bottom of conglomeratic facies (Tgc) and top of underlying limestone and siltstone facies (Tgl), and gypsum and gypsiferous siltstone facies (Tgg). Unit gently folded and highly fractured near base of Grand Wash Cliffs. Unit thins rapidly west from Grand Wash Cliffs, thickest near mouths of Snap, Pigeon, and Pearce Canyon drainages. Thickest section, about 760 m (2,500 ft)

Tgl **Limestone and siltstone facies (Miocene)**—Gray, silty, crystalline limestone, light-red, gray, and greenish-gray gypsiferous siltstone, gray to reddish-gray calcareous sandstone, and gray to white gypsum. Limestone beds are vuggy, irregularly bedded, 1 to 10 m (3 to 30 ft) thick. Contain abundant plant and algae fossils indicative of freshwater inland basin deposits. Include interbedded gray, greenish-gray, and reddish-gray gypsiferous mudstone and siltstone that grade into underlying gypsum and gypsiferous siltstone facies (Tgg). Siltstone and sandstone beds thin or thicken laterally at expense of equivalent limestone beds. Sandstone beds are conglomeratic in places with small, rounded clasts of chert, quartzite, and carbonate fragments. Gradational and arbitrary vertical and horizontal contact with underlying gypsum and gypsiferous siltstone facies (Tgg). Intertongues laterally into Proterozoic-clast conglomerate facies (Tgx) in lower part of unit and unconformably overlies Proterozoic-clast conglomerate facies (Tgx) in upper part of unit east of Wheeler Fault. Limestone beds are moderately folded as much as 13° in upper part of basin near Grand Wash. Includes one white and one light-brown (0.5 to 1 m [1 to 3 ft]) thick tuff bed between limestone beds. Limestone beds are likely the equivalent of the Hualapai Limestone of Lucchitta (1979) south of Lake Mead. Thickens south to as much as 305 m (1,000 ft) at Lake Mead. Thickness in map area, 60 to 70 m (200 to 230 ft)

Tgg **Gypsum and gypsiferous siltstone facies (Miocene)**—Gray and gray-white gypsum, greenish-gray, light-red, and reddish-gray gypsiferous siltstone and mudstone. Upper 15 to 20 m (50 to 65 ft) consists mostly of multicolored, banded, thin-bedded mudstone and gypsiferous siltstone interbedded with thin-bedded (0.5 to 1 m [1 to 3 ft]), dark-gray limestone beds. Includes beds of pinkish-white to light-gray, cliff-forming tuffaceous limestone and white tuff beds, 0.5 to 1 m (1 to 3 ft) thick in upper part. Forms Gyp Hills badlands area east of Wheeler Fault. Upper siltstone and mudstone beds grade downward into gray silty gypsiferous siltstone and massive gray gypsum. Unit gently folded except along trace of Wheeler Fault where beds dip west as much as 65°. Base of unit not exposed. Intertongues with Proterozoic-clast conglomerate facies (Tgx). Thickness, 120 m (400 ft) or more

Tgx **Proterozoic-clast conglomerate facies (Miocene)**—Dark-gray to reddish-brown, cliff- to resistant slope-forming conglomerate. Includes interbedded lenses of gravel and sandstone, poorly sorted and moderately well bedded; consolidated. Clasts are composed of reddish-brown, brown, red, grayish-green, and light-green, well-rounded rhyolite, black biotite schist, gneiss, gabbro, diorite, red pegmatite, granite, white quartz, gray limestone and dolomite, and red sandstone derived from the Jumbo Peak about 19 km (12 mi) west of map area. Include large boulders as much as 1.5 m (5 ft) in diameter that were probably carried in by large debris flows. Base of unit not exposed. About 675 m (2,275 ft) exposed near east side of Wheeler Fault

Horse Spring Formation (Miocene and Oligocene)—Named the Cottonwood Wash Formation by Moore (1972), but these rocks have close lithologic and stratigraphic similarity to the Rainbow Gardens Member of the Horse Spring Formation as proposed by Bohannon (1984) and formally defined by Beard (1996)

Ths **Rainbow Gardens Member**—Includes basal conglomerate and middle limestone and sandstone unit. Consists of complex intertonguing sequence of clastic and carbonate lithofacies. Upper unit of the Rainbow Gardens Member is not exposed within map area but is assumed to be present in subsurface where it is covered by younger rocks of the Grand Wash Trough. The Thumb Member of the Horse Spring Formation may be present in subsurface. Age of Rainbow Gardens Member of the Horse Spring Formation is bracketed between 26 Ma and 18.8 Ma (Beard, 1996). Only one outcrop is exposed in map area just east of Tassi Spring on upthrown side of Wheeler Fault (southwest corner of map area). Unconformable contact with underlying Kaibab Formation and both units dip 24° to 34° east-southeast. Unconformably overlain by Proterozoic-clast conglomerate facies (Tgx) of rocks of the Grand Wash Trough. Incomplete section, 132 m (435 ft) exposed

Ꞓc **Chinle Formation, undivided (Upper Triassic)**—Includes the Shinarump and Petrified Forest Members. Shinarump Member locally missing or has undergone local facies change to sandstone lithology similar to sandstones in Petrified Forest Member. The Chinle Formation at Hells Hole is 21 km (13 mi) north of Colorado River Mile 188 and is the thickest Chinle Formation deposit nearest to the Colorado River of Grand Canyon other than at Lees Ferry, Arizona. Petrified Forest Member is white, blue-gray, pale-red and purple, slope-forming mudstone, siltstone, and coarse-grained sandstone; contains small, very well rounded pebbles of black, yellow, brown, and red quartzite. Includes white, coarse-grained, ledge-forming sandstone at base that may be equivalent to the Shinarump Member of the Chinle Formation; contains brown, yellow, white, and red petrified wood fragments. Unit contains bentonitic clays derived from decomposition of volcanic ash. Unconformable contact with overlying basalt of Bundyville (Tbb) west of Hurricane Fault and basalt of Mount Logan (Tmlb) east of Hurricane Fault. Erosion has removed an unknown thickness of upper part of the Chinle Formation. Unit is mostly covered by landslide debris (Ql). Unconformable contact with underlying slope-forming upper red member of the Moenkopi Formation; erosional relief less than 2 m (6 ft) at Hells Hole marked by color contrast between red Moenkopi Formation and purple-white Chinle Formation in slope. Thickness, 122 m (400 ft)

Ꞓm **Moenkopi Formation, undivided (Middle(?) and Lower Triassic)**—Includes, in descending order, the upper red member, Shnabkaib Member, middle red member, Virgin Limestone Member, lower red member, and the Timpoweap Member as defined by Stewart and others (1972). In general, Moenkopi Formation is mostly eroded from map area except for isolated outcrops beneath Tertiary volcanic rocks at Mount Trumbull, Mount Logan, Poverty Knoll, Poverty Mountain, Grassy Mountain, and Yellow John Mountain. A complete section of the Moenkopi Formation crops out at Hells Hole 21 km (13 mi) north of Colorado River Mile 188, upper Whitmore Canyon. Total thickness of the Moenkopi Formation at Hells Hole, 365 m (1,200 ft).

Upper red member consists of red, thin-bedded, cliff- and slope-forming siltstone and sandstone. Gradational lower contact placed at uppermost thick white or light-gray calcareous siltstone and dolomite of Shnabkaib Member. Unit thins south and east, thickens north. Thickness, 122 m (400 ft).

Shnabkaib Member is white, laminated to thin-bedded, slope- and ledge-forming, aphanitic dolomite interbedded with light-gray, calcareous, silty gypsum. Gradational lower contact at lowest thick white or light-gray, calcareous, silty dolomite of middle red member. Unit thins south and west, thickens north. Thickness, 135 m (440 ft).

Middle red member consists of red-brown, thin-bedded to laminated, slope-forming siltstone and sandstone. Includes white and gray gypsum beds, minor white platy dolomite, green siltstone, and gray-green to red gypsiferous mudstone. Gradational lower contact about 10 m (30 ft) above gray limestone bed of Virgin Limestone Member. Unit thins west, south, and east, thickens north. Thickness, 122 m (400 ft).

Virgin Limestone Member consists of one light-gray, thin-bedded to thinly laminated, ledge-forming limestone bed, 0.5 to 2 m (1 to 6 ft) thick, and overlying pale-yellow, red, and bluish-gray, thin-bedded, slope-forming gypsiferous siltstone. Pinches out south and west in map area, thickens north and includes two limestone beds at north edge of map area and as many as four limestone beds near St. George, Utah. Unconformable contact at base of limestone bed with underlying lower red member; erosional relief as much as 2 m (6 ft) just north of map area (Billingsley and Workman, 2000). Thickness, 20 m (65 ft).

Lower red member consists of red, fine-grained, thin-bedded, sandy siltstone; and gray, white, and pale-yellow laminated gypsum and minor sandstone. Lower part contains redeposited gypsum and siltstone of Harrisburg Member of the Kaibab Formation. Gradational contact with underlying conglomerates of the Timpoweap Member; locally, unconformably overlies Harrisburg Member of the Kaibab Formation where Timpoweap is absent. Thickens in paleovalleys and pinches out onto eroded paleohills of underlying Harrisburg Member. Unit distinguished from red siltstone of Harrisburg Member of the Kaibab Formation by dark-red color and thin-bedded, platy beds of the lower red member as opposed to massive-bedded, pale-red, undulating siltstone and gray limestone beds of Harrisburg Member. Thickness, 0 to 20 m (0 to 65 ft).

Timpoweap Member consists of light-gray, slope- and cliff-forming conglomerate in lower part and light-gray to light-red, slope-forming calcareous sandstone in upper part. Conglomerate composed of subangular to rounded pebbles and cobbles of gray and dark-gray limestone, white and brown chert, and gray sandstone in matrix of gray to brown, coarse-grained sandstone. Consolidated by calcite and gypsum. All detritus in Timpoweap Member derived from Kaibab Formation. Fills paleovalleys about 1,500 m (5,000 ft) wide and as much as 70 m (230 ft) deep eroded into Harrisburg Member of the Kaibab Formation. Imbrication of pebbles in conglomerate show general northeastward flow of depositing streams. Thickness, 0 to 70 m (230 ft)

Pk **Kaibab Formation, undivided (Lower Permian)**—Includes, in descending order, the Harrisburg and Fossil Mountain Members as defined by Sorauf and Billingsley (1991). Entire unit is removed by modern erosion from some areas of the north rim of Grand Canyon. Thickness of Kaibab Formation, 0 to 160 m (0 to 530 ft), but as much as 198 m (650 ft) in channel areas.

Harrisburg Member consists of reddish-gray and brownish-gray, slope-forming gypsum, siltstone, sandstone, and limestone. Includes, in descending order, an upper slope, middle cliff, and lower slope unit.

Upper slope unit: red and gray, interbedded gypsum, sandstone, siltstone, capped by yellowish-gray, fossiliferous sandy limestone. Middle cliff unit: gray, thin-bedded, cherty limestone that weathers dark gray and yellowish-gray sandy limestone. Lower slope unit: yellowish-gray to pale-red, gypsiferous siltstone and calcareous sandstone; gray, thin-bedded sandy limestone; and gray to white, thick-bedded gypsum. Dissolution within lower gypsum beds has resulted in local warping and bending of middle limestone beds, especially at or near local drainages. Dissolution of gypsum in the Harrisburg Member is responsible for many collapse sinkholes on Shivwits, Uinkaret, and Kanab Plateaus. Gradational contact marked at top of cherty limestone cliff of Fossil Mountain Member. Thickness, 0 to 80 m (0 to 265 ft) in north half of map, beveled and removed by erosion along south edge of the Shivwits Plateau area.

Fossil Mountain Member is light-gray, cliff-forming, fine- to medium-grained, thin- to medium-bedded (0.3 to 2 m [2 to 6 ft]), fossiliferous, sandy, cherty limestone. Unit characterized by gray and white chert nodules and chert lenses parallel to bedding; chert weathers dark gray to black. Unit in general weathers medium gray. Several chert nodules contain concentric black and white bands and or fossil sponges. Brecciated chert beds 1 to 3 m (0.5 to 10 ft) thick common in upper part at contact with overlying Harrisburg Member. Unit generally forms cliff rim of Grand Canyon. Weathers into pinnacles or detached pillars or spires. Unconformable contact with underlying Woods Ranch Member of the Toroweap Formation characterized by channel erosion averaging about 3 m (10 ft) in relief, but in some areas large erosion channels or valleys are as much as 45 m (145 ft) in depth and as much as 2 km (1.3 mi) in width between lower Whitmore and Parashant Canyons and in upper Toroweap Canyon. Thickness of Fossil Mountain Member, 70 to 120 m (240 to 385 ft)

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

Woods Ranch Member consists of gray and light-red, slope-forming, gypsiferous siltstone and silty sandstone interbedded with white laminated gypsum and gray thin-bedded limestone. Gypsum beds are as much as 3 to 5 m (10 to 15 ft) thick. Unit as a whole weathers as reddish-gray slope. Bedding locally deformed due to subsidence caused by dissolution of gypsum. Contact with underlying Brady Canyon Member is gradational and marked at top of underlying limestone cliff of Brady Canyon Member. Unit in general thins southward and thickens northward. Variable thickness owing to local channel erosion in upper part. Thickness, 18 to 60 m (60 to 200 ft).

Brady Canyon Member is gray, cliff-forming, thin- to medium-bedded (0.05 to 1.4 m [1 to 5 ft]) fine- to coarse-grained, fetid, fossiliferous limestone. Weathers dark gray. Includes thin-bedded dolomite in upper and lower part. Contains white and gray chert nodules that make up less than 8 percent of unit. Contact with underlying Seligman Member is gradational and placed at lithologic break at base of limestone cliff and top of sandstone-gypsum slope. Thickness, 40 m (130 ft) at east edge of map area, increasing to as much as 137 m (450 ft) along upper Grand Wash Cliffs.

Seligman Member consists of light-purple, yellowish-red, and gray, slope-forming, thin-bedded dolomite interbedded with calcareous sandstone and gypsum. In northeastern third of map area, unit is gray to white, light-red gypsum and silty gypsum interbedded with yellowish-red, thin-bedded, calcareous sandstone and gray dolomite. Forms recess between the cliff-forming Brady Canyon Member of the Toroweap Formation and the cliff-forming Coconino Sandstone in southwestern two-thirds of map area. Forms a gypsiferous slope similar to the Woods Ranch Member of the Toroweap Formation in northwestern third of map area. The Coconino Sandstone intertongues with lower part of the Seligman Member of the Toroweap Formation as crossbedded sandstone set between flat-bedded sandstone beds. The near-shore crossbedded sandstone has an upper and lower gradational contact within the flat-bedded marine sandstone of the lower Seligman Member (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; Billingsley and others, 2000). Where Coconino Sandstone forms a cliff in central and eastern Grand Canyon, flat-bedded sandstone beds of the lower part of the Seligman Member of the Toroweap Formation are present at the base of the cliff in most areas. Upper crossbedded sand dune sets of the Coconino Sandstone were beveled off and redistributed as flat-bedded sandstone of the Seligman Member of the Toroweap Formation. Thickness, about 10 m (30 ft) in southern two-thirds of map area, increasing to about 17 m (55 ft) in northern third

Pc **Coconino Sandstone (Lower Permian)**—Tan to white, cliff-forming, fine-grained, well-sorted, crossbedded quartz sandstone. Contains large scale, high-angle, planar crossbedded sandstone sets as large as 11 m (35 ft) thick, and low-angle crossbedded sets less than 2 m (6 ft) thick in upper and lower part of cliff. Locally includes low-relief wind ripple marks on crossbedded planar sandstone surfaces. Unit intertongues with marine sandstone and gypsum beds in lower part of the Seligman Member of the Toroweap Formation in northeastern two-thirds of map area (Fisher, 1961; Schleh, 1966; Rawson and Turner, 1974; Billingsley and others, 2000). Crossbedded sets thin and thicken laterally in upper Grand Wash Cliffs and Pakoon Ridge areas. Sharp planar, unconformable contact with underlying Hermit Formation; erosional relief generally less than 1 m (3 ft) but locally as much as 2.5 m (8 ft). Thickness, 47 m (155 ft), eastern third of map area, thins west and pinches out between Parashant Canyon and Snap Point along south edge of Shivwits Plateau. In northwest part of map area, 3 to 9 m (10 to 30 ft) thick

Ph **Hermit Formation (Lower Permian)**—Red, slope-forming, fine-grained, thin-bedded siltstone and sandstone. Includes red and white, massive to low-angle crossbedded, calcareous sandstone ledges in upper part, northwest quarter of map area. Majority of unit is interbedded, slope-forming sandstone and siltstone. Unit often bleached white or yellow near breccia pipes and at upper contact with the Coconino Sandstone due to reducing effect of ground water in the Coconino Sandstone. Base of unit unconformably overlies massive-bedded, red and white sandstone of Esplanade Sandstone (Pe and Pep) throughout map area. The deep erosion channels as much as 16 m (50 ft) deep at the unconformity are most pronounced in northeastern part of map area. Depth of channels decreases westward to generally less than 3 m (10 ft) deep along the Grand Wash Cliffs, and the contact between the Hermit Formation and Esplanade Sandstone/Pakoon Limestone is difficult to determine in the field. Along the Grand Wash Cliffs, contact between the Hermit Formation and Esplanade Sandstone/Pakoon Limestone is marked at the top of the first red or white cliff-forming, massive, sandstone bed. Dark-red, crumbly, thin-bedded siltstone that contains poorly preserved plant fossils forms recesses between thicker sandstone beds in lower 60 m (200 ft) of unit along the Grand Wash Cliffs. Similar plant fossils are also present in dark-red siltstone deposits within deep erosion channels cut into the Esplanade Sandstone (Pe) in eastern part of map area. Thickens from 213 m (700 ft), east edge of map area, to 244 to 260 m (800 to 860 ft) along the Grand Wash Cliffs

Supai Group (Lower Permian, Upper, Middle, and Lower Pennsylvanian, and Upper Mississippian)—Includes, in descending order, the Esplanade Sandstone east of Hurricane Fault (Pe), the Esplanade Sandstone and Pakoon Limestone west of Hurricane Fault (Pep), and the Wescogame, Manakacha, and Watahomigi Formations, undivided (MIPs) as defined by McKee (1975, 1982). Age of the Watahomigi Formation is Lower Pennsylvanian and Upper Mississippian by Martin and Barrick (1999). Divided into:

Pe **Esplanade Sandstone east of Hurricane Fault (Lower Permian)**—Includes, in descending order, an upper cliff and slope, a middle cliff, and lower slope unit. Upper cliff and slope unit includes an upper, light-red or white sandstone cliff and a lower, dark-red siltstone, sandstone, and gypsum slope that visually resemble that of the Hermit Formation in eastern third of map area (Hurricane Fault and east of Hurricane Fault). In western two thirds of map area, the upper cliff and slope undergoes a gradual facies change west of the Hurricane Fault to a light-red and white, low-angle crossbedded and massive calcareous sandstone along Grand Wash Cliffs and at Pakoon Ridge, which forms the upper part of the Esplanade Sandstone and Pakoon Limestone west of the Hurricane Fault (Pep) unit. Maximum thickness of upper unit, about 67 m (220 ft) along east edge of map area, thinning westward to about 15 m (50 ft) in Grand Wash Cliffs area. Middle cliff unit is composed of light-red, cliff-forming, fine- to medium-grained, medium-bedded 1 to 3 m (3 to 10 ft) thick, well-sorted, calcareous sandstone east of Hurricane Fault. Includes gray, thin-bedded sandy limestone of the Pakoon Limestone interbedded in lower half of Esplanade cliff west of Hurricane Fault. Pakoon Limestone pinches out eastward about the Hurricane Fault area, but thickens rapidly westward towards Grand Wash Cliffs and Pakoon Ridge where the Esplanade Sandstone and Pakoon Limestone of McNair (1951) are undivided (Pep). Middle cliff unit averages about 75 m (250 ft) thick at east edge of map area, thickening to about 91 m (300 ft) along Grand Wash Cliffs area. Lower slope unit is composed of a basal limestone pebble conglomerate that grades upward into slope-forming, interbedded dark-red siltstone, light-red sandstone, and gray, thin-bedded limestone that fills channels eroded as much as 10 m (30 ft) into underlying Wescogamie Formation of the undivided Supai Group (MIPs). Unconformable contact between the Permian and Pennsylvanian strata in east two-thirds of map area and a disconformity between the Permian and Pennsylvanian strata along the Grand Wash Cliffs and in the Pakoon Ridge area. Thickness of lower slope unit, about 25 m (80 ft) at east edge of map area, thins westward and pinches out near Grand Wash Cliffs. Overall, Esplanade Sandstone (Pe) and Esplanade Sandstone and Pakoon Limestone (Pep) are about 167 m (550 ft) thick in east half of map area, decreasing to about 107 m (350 ft) in west half

Pep **Esplanade Sandstone and Pakoon Limestone west of Hurricane Fault (Lower Permian)**—Esplanade Sandstone defined by McKee (1975, 1982); Pakoon Limestone defined by McNair (1951). Light-red and pinkish-gray, cliff-forming, fine- to medium-grained, medium-bedded (1 to 3 m [3 to 10 ft]), well-sorted, calcareous sandstone and interbedded, dark-red, slope-forming siltstone. Includes an upper cliff and slope unit, a middle cliff unit, and a lower slope unit as described for Esplanade Sandstone (Pe).

In western two-thirds of map area, the upper cliff and slope undergoes a gradual facies change west of the Hurricane Fault to a light-red and white, low-angle crossbedded and massive calcareous sandstone along Grand Wash Cliffs and at The Cockscomb, southwest corner of map area, which forms the upper part of the Esplanade Sandstone and Pakoon Limestone west of the Hurricane Fault (Pep) unit. Maximum thickness of upper unit, about 67 m (220 ft) along east edge of map area at Lake Mead, thinning westward to about 15 m (50 ft) in Grand Wash Cliffs area.

Middle cliff unit is composed of an upper, light-red to white, fine- to medium-grained, thick-bedded calcareous sandstone and flat, massive, low-angle crossbedded sandstone and calcareous sandstone in lower half that intertongue with gray limestone beds of the Pakoon Limestone. Small- to medium-scale, planar low-angle, calcareous sandstone crossbeds that include some high-angle sets throughout compose nearly half of the Esplanade Sandstone and Pakoon Limestone cliff along the Grand Wash Cliffs. Pakoon Limestone beds are gray to pinkish-gray, fine-to medium-grained, thin- to medium-bedded limestone and oolitic limestone along Grand Wash Cliffs and The Cockscomb areas. Pakoon Limestone contains numerous Early Permian marine fossils throughout unit in west half of map area, which establish Early Permian age (McNair, 1951) for Esplanade Sandstone east of Hurricane Fault (Pe), and Esplanade Sandstone and Pakoon Limestone west of Hurricane Fault (Pep). Pakoon Limestone thins eastward and pinches out in the vicinity of the Hurricane Fault in eastern part of map area. Pakoon Limestone beds form topographic bench of Sanup Plateau along Grand Wash Cliffs area. Thickness of middle cliff unit averages about 91 m (300 ft) in west half of map area and thins to about 76 m (250 ft) in east half.

Lower slope unit consists of alternating layers of light-red sandstone, dark-red siltstone and mudstone, and gray thin-bedded limestone of the Esplanade Sandstone (Pe). Unconformable contact with underlying Wescogame Formation of the Supai Group undivided (MIPs) marked by erosion channels of as much as 10 m (30 ft) deep; channels contain limestone pebble conglomerate. Lower slope unit, about 25 m (80 ft) thick in eastern part of map area, thins and pinches out near Grand Wash Cliffs area. Overall thickness of Esplanade Sandstone and Pakoon Limestone west of Hurricane Fault, about 107 m (350 ft) along Grand Wash Cliffs

MIPs **Wescogame Formation (Upper Pennsylvanian), Manakacha Formation (Middle Pennsylvanian), and Watahomigi Formation (Lower Pennsylvanian and Upper Mississippian), undivided**—Supai Group as defined by McKee (1975, 1982). Age of the Watahomigi Formation is Lower Pennsylvanian and Upper Mississippian as defined by Martin and Barrick (1999). All three formations are equivalent to the Callville Limestone (not exposed in map area) of the Basin and Range west of the Grand Wash Cliffs.

Wescogame Formation forms an upper slope and lower cliff. Upper slope is composed of dark-red, fine-grained siltstone, mudstone, and interbedded light-red sandstone. Lower cliff is composed of light-red to gray, high-angle, large- and medium-scale, tabular-planar, crossbedded sandstone sets as much as 10 m (30 ft) thick. Includes interbedded dark-red, thin-bedded siltstone beds in upper part of cliff. Unconformable contact with underlying Manakacha Formation marked by erosion channels as much as 24 m (80 ft) deep in western part of map area, less than 10 m (30 ft) deep in eastern part of map area. Channel deposits commonly composed of limestone chert conglomerate. Thickness, 40 to 64 m (130 to 210 ft).

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

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

Ms **Surprise Canyon Formation (Upper Mississippian)**—Dark reddish-brown cliff- and slope-forming siltstone and sandstone; gray limestone and dolomite; and white conglomerate in dark-red or black sandstone matrix (Billingsley and Beus, 1999). Formation is present only as sedimentary deposits in erosion channels and infillings of karst features dissolved from the upper part of Redwall Limestone (Mr). Includes an upper slope, middle cliff, and lower slope unit.

Upper slope unit includes red-brown, thin-bedded siltstone, calcareous sandstone, and reddish-gray, thin-bedded, sandy limestone. Contains numerous ripple marks and marine fossils. Thickness, about 15 to 23 m (50 to 75 ft).

Middle cliff unit consists of reddish-gray, thin-bedded, coarse-grained, silty sandy limestone. Contains numerous marine fossils distinguishing it as the most fossiliferous rock unit in Grand Canyon. Thickness, 15 to 60 m (50 to 200 ft).

Lower slope unit consists of dark red-brown to black, iron-stained, thin-bedded, coarse- to medium-grained siltstone, sandstone, limestone, and conglomerate; includes minor coal beds. Thin, low-angle crossbedded sandstone sets and siltstone beds contain numerous plant and bone fossils, mudcracks, and ripple marks. Conglomerate beds consist of white and gray chert clasts supported in coarse-grained chert sandstone or gravel matrix, all derived from Redwall Limestone (Mr). Conglomerate beds average about 8 m (25 ft) thick. Includes local coal beds 1 m (3 ft) thick in black shale slope in southwest corner of map area. The Redwall Limestone surface was a tropical sinkhole plain drained by west-trending, low-gradient channels. The channels developed into major drainage valleys with depths reaching up to 122 m (400 ft) cutting out 2/3 of the thickness of the Redwall Limestone. The depth of karstification exceeded that of nearby channels. This environment was drowned by a marine transgression from the west that deposited carbonate sediments of the Surprise Canyon Formation in the channels, valleys, and karst, but did not cover the entire Redwall Limestone surface. Maximum thickness, 122 m (400 ft), unit thins eastward

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

Horseshoe Mesa Member is light olive-gray, ledge- and cliff-forming, thin-bedded, fine-grained limestone. Weathers to form receding ledges. Gradational and disconformable contact with underlying massive-bedded limestone of Mooney Falls Member marked by thin-bedded, platy limestone beds that form recess about 1 to 3 m (3 to 10 ft) deep at base of unit near top of Redwall Limestone cliff. Fossils not common except locally. Includes distinctive ripple-laminated limestone beds, oolitic limestone, and some chert. Member thickens slightly from east to west across map area, highly karstified with laterally extensive karst breccia, locally absent where removed by Late Mississippian paleovalley erosion. Thickness, 15 to 30 m (50 to 100 ft).

Mooney Falls Member is light-gray, cliff-forming, fine- to coarse-grained, thick to very thick bedded (3 to 6 m [10 to 20 ft]), fossiliferous limestone. Highly karstified with laterally extensive karst breccias in upper part. Includes dark-gray dolomite beds in lower part, west quarter of map area; oolitic limestone and chert beds are restricted to upper part. Contains large-scale, tabular and planar, low-angle cross-stratified limestone beds in upper third of unit. Limestone weathers dark gray. Disconformable contact with underlying Thunder Springs Member distinguished by weathered color change and lithology; massive bedded, gray limestone of Mooney Falls Member overlies thin-bedded, dark-gray to brown dolomite and chert beds of Thunder Springs Member. Thickness, 158 m (520 ft).

Thunder Springs Member consists of about 50 perecent white, cliff-forming, fossiliferous, thin-bedded, alternating bands of white chert and about 50 percent brownish-gray, thin-bedded (2 to 12 cm [1 to 7 in]) finely crystalline dolomite and fine- to coarse-grained limestone. Limestone is most common lithology in north half of map area, dolomite more common in south half. Weathers into distinctive prominent black and light-brown bands on cliff face. Locally, includes large-scale crossbedding and irregularly folded beds in north half of map area. Fossil content increases from east to west across map area. Disconformable planar contact with underlying Whitmore Wash Member distinguished by distinct lack of chert in Whitmore Wash Member. Thickness, 30 m (100 ft) in south half of map area, increasing to 45 m (150 ft) in north half.

Whitmore Wash Member is yellowish-gray and brownish-gray, cliff-forming, thick-bedded, fine-grained limestone. Weathers dark gray. Fossiliferous in northwest quarter of map area. Unit is mostly dolomite east and northeast of map area. Unconformable contact with underlying Temple Butte Formation (Dtb) at erosion channels of low relief, about 2 to 3 m (6 to 10 ft) in depth. Contact generally recognized where major cliff of gray Redwall Limestone overlies stair-step ledges of dark-gray Temple Butte Formation. Uniform thickness throughout map area, 25 m (80 ft). Overall, Redwall Limestone increases in thickness east to west from about 183 m (600 ft) to 243 m (800 ft)

Dtb **Temple Butte Formation (Upper and Middle Devonian)**—Purple, reddish-purple, dark-gray, and light-gray, ledge-forming dolomite, sandy dolomite, sandstone, mudstone, and limestone as defined by Beus (1990). Purple, reddish-purple, and light-gray, fine- to coarse-grained, thin- to medium-bedded, ripple-laminated ledges of mudstone, sandstone, dolomite, and conglomerate fills channels eroded as much as 15 m (50 ft) into the underlying Cambrian strata in east half of map area. Channel deposits are overlain by dark to olive-gray, medium- and thick-bedded dolomite, sandy dolomite, limestone, and sandstone that form a sequence of dark-gray ledges. Unconformity at base of Temple Butte represents major stratigraphic break in the Paleozoic record in Grand Canyon that represents erosion or non-deposition during part of the Late Cambrian, all of the Ordovician and Silurian, and most of the Early and Middle Devonian, representing a hiatus of about 100 m.y. Dark-gray rocks of the Temple Butte Formation are distinguished from underlying, light-gray rocks of Cambrian age by color contrast. Unit thickens from 84 m (275 ft) in eastern part of map area to as much as 140 m (460 ft) in western part

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). For this map, all limestone and dolomite lithologies in the Cambrian sequence are assigned to the Muav Limestone; all shale and siltstone lithologies to the Bright Angel Shale; and all sandstone and conglomerate lithologies to the Tapeats Sandstone in the lateral and vertical sense. However, the Muav Limestone map unit includes tongues of Bright Angel Shale, the Bright Angel Shale map unit contains tongues of the Muav Limestone and Tapeats Sandstone, and the Tapeats Sandstone map unit contains tongues of Bright Angel Shale. The Tonto Group overlies Early Proterozoic (1.7 to 1.6 Ma) igneous and metamorphic rocks above what is regionally known as the Great Unconformity

Ꞓm **Muav Limestone (Middle Cambrian)**—Dark-gray, light-gray, brown, and orange-red, cliff-forming limestone, dolomite, and interbedded thin calcareous mudstone. Includes, in descending order, the unclassified dolomite member, the Havasu Member, Gateway Canyon Member, Kanab Canyon Member, Peach Springs Member, Spencer Canyon Member, and Rampart Cave Member as defined by McKee and Resser (1945) and three unnamed Bright Angel Shale lithologic units between limestone members. Carbonate beds are composed of fine- to medium-grained, thin- to thick-bedded, mottled, fossiliferous, silty limestone, limestone, and dolomite. Unnamed Bright Angel Shale beds are composed of green and purplish-red, micaceous, siltstone, mudstone, shale, and thin brown sandstone beds. Contact between Muav Limestone and underlying Bright Angel Shale is lithology dependent and placed at the base of lowest prominent cliff-forming limestone of the Rampart Cave Member of the Muav Limestone. Intertonguing relations between Muav Limestone and Bright Angel Shale produce variable thicknesses of limestone and shale units. Limestone units thicken from east to west across the map area. Overall, the Muav Limestone thickens from 185 m (600 ft) in eastern part of map area to 425 m (1,400 ft) in western part

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purple-red, slope-forming siltstone and shale and red-brown to brown sandstone. Includes interbedded limestone of the Flour Sack Member of McKee and Resser (1945) in upper part and ledge-forming, red-brown sandstone member in middle part. Includes interbedded, dark-green, medium- to coarse-grained, thin-bedded glauconitic sandstone; and purplish-red and brown, thin-bedded, fine- to coarse-grained, ripple-laminated sandstone in lower part. Intertonguing relations produce variable thicknesses and lithologies. Contact with Tapeats Sandstone is arbitrarily marked at lithologic change from dominantly green shale and siltstone of the Bright Angel Shale to dominantly brown sandstone of the Tapeats Sandstone, generally about 10 m (30 ft) above Tapeats Sandstone cliff. Thickness, 150 m (500 ft)

Ꞓt **Tapeats Sandstone (Middle and Lower(?) Cambrian)**—Brown and red-brown, cliff-forming sandstone and conglomerate. Includes an upper slope-forming transition zone of nearly equal distribution of brown sandstone and green shale beds and lower cliff-forming sandstone and conglomeratic sandstone. Lower cliff is composed mostly of medium- to coarse-grained, thin-bedded, low-angle planar and trough crossbedded sandstone and conglomeratic sandstone beds 15 to 60 cm (6 to 24 in) thick. Silica cement gives appearance of quartzite. Unconformable contact with underlying Early Proterozoic surface forms the Great Unconformity. Tapeats fills lowland areas and thins across or pinches out against Proterozoic highlands. Thickness, 0 to 122 m (0 to 400 ft)

EARLY PROTEROZOIC CRYSTALLINE ROCKS

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

Xgr **Granite, granitic pegmatite, and aplites**—Granite plutons and stocks and pegmatite and aplite dikes emplaced synchronously with peak metamorphism. One small outcrop in map area is at Colorado River Mile 190 just south of Whitmore Canyon junction with Colorado River. About 1.7–1.66 Ma (Ilg and others, 1996; Hawkins and others, 1996)

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APPENDIX

DIGITAL DATABASE DESCRIPTION

By

Jessica L. Wellmeyer

INTRODUCTION

This map, compiled from previously published and unpublished data and new mapping by the authors represents the general distribution of bedrock and surficial deposits in the Mount Trumbull quadrangle. The associated database delineates map units that are identified by general age and lithology following the spatial resolution (scale) of the database to 1:100,000 or smaller. The content and character of the database, as well as methods of obtaining the database, are described below.

FOR THOSE WHO DON'T USE DIGITAL GEOLOGIC MAP DATABASES

Two sets of plot files containing images of much of the information in the database are available to those who do not use an ARC/INFO compatible Geographic Information System (GIS). Each set contains an image of a geologic map sheet and the accompanying explanatory pamphlet. There is a set available in PostScript format and another in Acrobat PDF format (see sections below). Those who have computer capability can access the plot file packages online at http://geopubs.wr.usgs.gov/i-map/i2766. Requests for a tape copy of the digital database or plot files can be made by sending a tape with request and return address to: Database Coordinator, U.S. Geological Survey, 345 Middlefield Road, M/S 975, Menlo Park, CA 94025.

DATABASE CONTENTS

The digital database package consists of the geologic map database and supporting data including base maps, map explanation, geologic description, and references. A second package consists of PostScript plot files of a geologic map sheet and a pamphlet containing a geologic description.

Digital Database Package

The first package is composed of geologic map database files for the Mount Trumbull quadrangle. The coverages and their associated INFO directory have been converted into ARC/INFO export files. These export files are uncompressed and are easily handled and compatible with some Geographic Information Systems other than ARC/INFO. The export files included are:

ARC/INFO export file	Resultant Coverage	Description
mtr_anno.e00	mtr_anno/	Unit annotation, fault and fold names, fault separation values, point data and annotation
mtr_dip.e00	mtr_dip/	Strike and dip information
mtr_poly.e00	mtr_poly/	Faults, depositional contacts, and geological units
mtr_fold.e00	mtr_fold/	Fold axes and basal flow direction arrows
pls_cov.e00	pls_cov/	Public Land Survey grid with section boundaries
hypso_cov.e00	hypso_cov/	Hypsography DLG

The database package also contains the following other export files with extraneous data used in the construction of the database:

ARC/INFO export file	Resultant File	Description
geo1001.lin.e00	geo1001.lin	Lineset
geo100.mrk.e00	geo100.mrk	Markerset
wpgcmyk.shd.e00	wpgcmyk.shd	Shadeset
geolin.lut.e00	geolin.lut	Line lookup table
geomrk.lut.e00	geomrk.lut	Marker lookup table
polycolor.lut.e00	polycolor.lut	Color lookup table

PostScript Plot file Package

The second digital data package available contains the PostScript images described below:

mtrmap.eps	Encapsulated PostScript plottable file containing complete map composition with geology, symbology, annotation, and base map of the Mount Trumbull quadrangle
mtrgeo.doc	A Word document file of this report and the report containing detailed unit descriptions and geological information, plus sources of data and references cited

PDF Plot file Package

The package contains the Adobe Acrobat (.pdf) portable document format files described below:

mtrmap.pdf	A PDF file of the Mount Trumbull quadrangle map sheet
mtrgeo.pdf	A PDF file of this report, including the full geologic report

The Adobe Acrobat files were created from corresponding .eps files and are compatible with Adobe Acrobat version 3.0 and higher.

ACCESSING DATABASE CONTENTS

ARC/INFO Export Files

ARC export files are converted to their proper ARC/INFO format using the ARC command 'import' with the option proper for the format desired. To ease conversion and preserve naming convention, an AML is enclosed that will convert all the export files in the database to coverages and graphic files and that will also create an associated INFO directory. From the ARC command line type:

Arc: &run import.aml

ARC export files can be read by other Geographic Information Systems. Refer to your documentation for proper procedure for retrieval of data.

PostScript and Portable Document Format Files

These files are packaged separately. PDF files come as is and can be downloaded or copied directly to your hard drive with no conversion aside from opening the file from Adobe Acrobat. The PostScript documents are zipped and compressed to a smaller file size. They can be decompressed using WINZIP.

DATABASE SPECIFICS

Procedure Used

Stable-base maps were scanned at the Flagstaff U.S. Geological Survey Field site using the Optronics 5040 raster scanner at a resolution of 50 microns (508 dpi). The resulting raster file was in RLE format and converted to the RLC format using the “rle2rlc” program written by Marilyn Flynn. The RLC file was subsequently converted to an ARC/INFO Grid in ARC/INFO. The linework was vectorized in bulk using the ARC command gridline. A tic file was created in lat/long and projected into the base map projection (Transverse Mercator) using a central meridian of –113.50W. Tics are defined in a 5-minute grid of latitude and longitude in the geologic coverages corresponding with quadrangle corners both in base maps and digital maps. The tic file was used to transform the grid to Universal Transverse Mercator (UTM). ARC/INFO generated a RMS report after transforming the original grid to UTM.

Scale (X,Y) = (5.003,5.001)
Skew (degrees) = (0.008)
Rotation (degrees) = (–1.564)
Translation = (222692.085,3975993.211)
RMS Error (input,output) = (1.729,8.650)

Affine $X = Ax + By + C$
$Y = Dx + Ey + F$
A = 5.001 B = 0.137 C = 222692.085
D = -0.137 E = 4.999 F = 3975993.211

tic id	input x output x	input y output y	x error	y error
1	19334.976	2449.985		
	319729.063	3985597.750	–4.402	2.957
2	1309.199	2418.860		
	229572.203	3987911.500	–0.834	–5.104
3	1349.961	13519.731		
	231291.531	4043393.000	6.547	1.375
4	19262.079	13541.953		
	320874.438	4041066.250	7.288	–6.551
5	17083.956	2437.910		
	308460.563	3985836.250	4.829	11.450
6	14830.807	2423.889		
	297191.781	3986089.250	3.423	–3.987
7	12575.379	2417.995		
	285922.688	3986356.750	–7.948	7.011
8	10323.882	2411.610		
	274653.313	3986638.750	0.547	0.516
9	8069.997	2412.013		
	263383.563	3986935.250	–1.587	13.780
10	5817.939	2409.646		
	252113.484	3987246.250	5.357	–1.552
11	3560.990	2415.001		
	240843.047	3987571.750	–10.735	7.888
12	1320.077	5193.187		
	230000.109	4001781.500	6.251	–7.660
13	1332.091	7967.923		
	230429.297	4015651.750	17.797	–8.568
14	1339.500	10743.234		
	230859.781	4029522.250	5.090	–6.231
15	3588.051	13512.951		
	242490.547	4043051.000	–0.453	3.888
16	5825.796	13508.981		
	253689.203	4042723.750	–8.428	5.742
17	8065.505	13507.507		
	264887.500	4042411.250	–5.876	5.061
18	10305.215	13509.472		
	276085.500	4042113.000	–2.556	7.317
19	12547.252	13515.253		
	287283.156	4041829.500	13.272	13.581
20	14782.670	13520.769		
	298480.531	4041560.500	–3.761	4.928
21	17021.397	13530.592		
	309677.625	4041306.250	–3.368	2.604
22	19279.771	10768.284		
	320586.813	4027198.750	2.893	–7.113
23	19298.435	7996.152		
	320300.031	4013331.500	2.726	–0.373
24	19318.081	5223.528		
	320014.125	3999464.500	6.529	3.529
25	17067.817	5208.030		
	308763.469	3999703.500	1.223	–5.693
26	14817.261	5198.388		
	297512.531	3999956.750	–4.458	0.154
27	12568 .986	5189.377		
	286261.281	4000224.500	1.673	–5.658
28	10318.483	5184.929		
	275009.750	4000507.000	–2.440	—

tic id	input x output x	input y output y	x error	y error
29	8068.721 263757.875	5181.342 4000803.750	–2.379	—
30	5819.601 252505.656	5185.985 4001115.250	2.363	—
31	3567.904 241253.063	5187.798 4001441.250	–5.791	—
32	3574.673 241664.328	7963.100 4015311.000	–2.483	—
33	3580.674 242076.828	10735.693 4029180.750	–4.616	—
34	5823.526 253293.516	10732.584 4028854.000	–4.968	—
35	8066.975 264509.844	10733.541 4028541.750	–1.409	—
36	10308.511 275725.844	10733.492 4028244.000	–7.235	—
37	12551.625 286941.531	10736.793 4027961.000	–4.393	—
38	14794.358 298156.906	10745.737 4027692.250	–2.372	—
39	17035.413 309372.000	10755.589 4027438.250	–8.332	—
40	17053.446 309067.281	7982.144 4013570.750	6.100	–3.110
41	14807.019 297834.219	7970.093 4013824.500	2.864	–10.371
42	12560.736 286600.906	7963.444 4014092.750	1.340	–5.149
43	10313.341 275367.250	7960.335 4014375.500	–4.916	3.426
44	8068.696 264133.281	7956.796 4014672.750	2.836	–5.028
45	5822.617 252898.984	7960.909 4014984.500	4.792	10.468

Lines, points, polygons, and annotation were edited using ARCEDIT.

Following editing and annotation, the individual coverages were projected into UTM projection.

Map Projection

Parameter	Description
Projection	UTM
Units	Meters on the ground
Zone	12
Datum	NAD27

The content of the geologic database can be described in terms of the lines and the areas that compose the map. Descriptions of the database fields use the terms explained below:

Database Fields

Parameter	Description
Item name	name of database field
Width	maximum number of characters or digits stored
Output	output width
Type	B — binary integer; F — binary floating point number, I — ASCII integer, C — ASCII character string
N.dec.	number of decimal places maintained for floating point numbers

LINES

The arcs are recorded as strings of vectors and described in the arc attribute table (AAT). They define the boundaries of the map units, faults, and map boundaries in MTR_POLY. These distinctions and the geologic identities of the boundaries are stored in the LTYPE field according to their line type.

Arc Attribute Table Definition

DATAFILE NAME: MTR_POLY.AAT

COLUMN	ITEM NAME	WIDTH	OUTPUT	TYPE	N. DEC
1	FNODE#	4	5	B	—
5	TNODE#	4	5	B	—
9	LPOLY#	4	5	B	—
13	RPOLY#	4	5	B	—
17	LENGTH	4	12	F	3
21	MTR_POLY#	4	5	B	—
25	MTR_POLY-ID	4	5	B	—
39	LTYPE	35	35	C	—
64	PTTYPE	35	35	C	—

The AAT defined above represents the AAT in MTR_POLY.

DATAFILE NAME: MTR_FOLD.AAT

COLUMN	ITEM NAME	WIDTH	OUTPUT	TYPE	N. DEC
1	FNODE#	4	5	B	—
5	TNODE#	4	5	B	—
9	LPOLY#	4	5	B	—
13	RPOLY#	4	5	B	—
17	LENGTH	4	12	F	3
21	MTR_FOLD#	4	5	B	—
25	MTR_FOLD-ID	4	5	B	—
39	LTYPE	35	35	C	—
64	PTTYPE	35	35	C	—
99	PLUNGE	3	3	I	—

The AAT defined above represents the AAT in MTR_FOLD.

Description of AAT Item Names

Item Name	Description
FNODE#	Starting node of the arc
TNODE#	Ending node of the arc
LPOLY#	Polygon to the left of the arc
RPOLY#	Polygon to the right of the arc
LENGTH	Length of the arc in meters
MTR_POLY#	Unique internal number
MTR_POLY-ID	Unique identification number
LTYPE	Line type
PTTYPE	Point type
PLUNGE	Value of plunge of fold axis

The geologic line types relate to geologic line symbols in the line set GEO1001.LIN according to the lookup table GEOLIN.LUT.

Domain of Line Types recorded in LTYPE field

MTR_POLY
- contact_certain
- contact_river
- fault_underwater
- high_angle_flt_approx
- high_angle_flt_certain
- high_angle_flt_concealed
- low_angle_norm_flt_certain
- map_boundary
- volcanic_mar

MTR_FOLD
- anticline_certain
- basalt_flow_direction
- monocline_certain
- monocline_concealed
- plunging_anticline
- plunging_syncline
- syncline_certain
- underwater_fold

Domain of Markers recorded in PTTYPE field

MTR_POLY
- fault_ball_fill
- xx

MTR_FOLD
- anticline
- syncline
- monocline
- xx

Arcs with a PTTYPE value of ‘xx’ indicate that there is no symbol attached to the arc.

POLYGONS

Map units (polygons) are described in the polygon attribute table (PAT). This identifies the map units recorded in the PTYPE field by map label. Individual map units are described more fully in the accompanying text.

Polygon Attribute Table Definition

DATAFILE NAME: MTR_POLY.PAT

COLUMN	ITEM NAME	WIDTH	OUTPUT	TYPE	N. DEC
1	AREA	4	12	F	3
5	PERIMETER	4	12	F	3
9	MTR_POLY#	4	5	B	—
13	MTR_POLY-ID	4	5	B	—
17	PTYPE	8	8	C	—

Description of Polygon Attribute Table Item Names

Item Name	Description
AREA	Area of polygon in square meters
PERIMETER	Perimeter of polygon in meters
MTR_POLY#	Unique internal number
MTR_POLY-ID	Unique identification number
PTYPE	Unit label

Domain of PTYPE (map units)

		Qb6588	
		Qb6646	
€ba	Pep	Qb6375	Qi
€m	Ph	Qb6457	Qi1
€t	Pk	Qltb	Qkrb
Dtb	Pt	Qcbb	Qkrp
H2O	QTa	Qcbi	Ql
MIPs	QTi	Qcbp	Qlb
Mr	Qao	Qd	Qlp
Ms	Qay	Qf	Qlsb
Pc	Qb	Qgo	Qlsp
Pe	Qb1	Qgy	Qmrb
Qmrp	Qv	Tgg	Tpi
Qp	T2i	Tgi	Tpkb
Qp1	₮c	Tgl	Tpki
Qp6375	₮m	Tgp	Tpp
Qp6457	Tao	Tgr	Tsb
Qp6588	Tay		Tsgb
Qp6646	Tb	Tgx	Tsgi
Qpvb	Tbb	Ths	Tsi
Qpvp	Tbi	Ti	Tsp
Qr	Teb	Tmb	Tv
Qs	Tei	Tmi	Tvi
Qgrb	Tep	Tmlb	Twb
Qgrp	Tg	Tp6i	Twi
Qt	Tgb	Tpb	Xgr
	Tgc		

€ represents Cambrian strata, D represents Devonian strata, IP represents Pennsylvanian strata, P represents Permian strata, ₮ represents Triassic strata, T represents Tertiary strata, and Q represents Quaternary strata. Polygons were assigned colors based on their geologic unit. The colors were assigned from the shadeset

WPGCMYK.SHD and are related to the lookup table POLYCOLOR.LUT

POINTS

Strike and dip information is recorded as coordinate data with related information. This information is described in the Point Attribute Table (PAT). ARC/INFO coverages cannot hold both point and polygon information, thus MTR_DIP has only a point attribute table, and MTR_POLY has only a polygon attribute table.

Point Attribute Table Definition

DATAFILE NAME: HR_DIP.PAT

COLUMN	ITEM NAME	WIDTH	OUTPUT	TYPE	N.DEC.
1	AREA	4	12	F	3
5	PERIMETER	4	12	F	3
9	MTR_DIP#	4	5	B	-
13	MTR_DIP-ID	4	5	B	-
17	PTTYPE	35	35	C	-
52	DIP	3	3	I	-
55	STRIKE	3	3	I	-

Description of item names

Item Name	Description
AREA	
PERIMETER	
MTR_DIP#	Unique internal number
MTR_DIP-ID	Unique identification number
PTTYPE	Point type
DIP	Dip angle in azimuth degrees
STRIKE	Strike angle in degrees

The coverage MTR_DIP contains strike and dip data and other pertinent structural data represented by point symbology, including collapses, sinkholes, and domes. MTR_FOLD and MTR_POLY have point types defined in the AAT, which correspond with the defined linetype for an arc. These point types are related to the lookup table GEOMRK.LUT and are from the symbolset GEO.MRK.

Domain of PTTYPE

bedding
exposed_breccia_pipe
dome
probable_breccia_pipe
sinkhole
vertical_joint
volcanic_vent

ANNOTATION

The coverage MTR_ANNO is strictly annotation to the polygon coverage. It is defined somewhat differently from the fold, polygon, and dip coverages. The arc attribute table is of negligible importance. Arcs in this coverage are merely leaders from a unit annotation to the related polygon. MTR_ANNO contains annotation with unit labels, fault separation, and monocline names. All annotation was in feature subclass anno.unit.

The textset used for all annotation was geofont.txt, specifically symbolset 30. Use of this textset allows for proper symbol notation for unit symbols. The default ARC/INFO textset does not allow for a proper geologic symbol indicating 'Triassic.' By using this alternate textset, the character pattern '^m' prints instead as Ꞓm. The only nonconventional text symbol used, was the '^' (carat) indicating Triassic.

BASE MAP PROCEDURE

The base map image was prepared from a Digital Line Graph (DLG) obtained online from the U.S. Geological Survey. While DLGs are available for many themes, I chose to only use hypsography and public land survey layers for the base of this map to decrease clutter and preserve legibility of features.

SPATIAL RESOLUTION

Use of the digital geologic map database should not violate the spatial resolution of the data. Although the digital form of the data removes the constraint imposed by the scale of a paper map, the detail and accuracy inherent in map scale are also present in the digital data. The database was created and edited at a scale of 1:100,000 which means that higher resolution data is generally not present. Plotting at scales larger than 1:100,000 will not yield greater real detail, but may reveal fine-scale irregularities below the intended resolution.

OTHER FILES

The lineset used to display the appropriate line weight and symbology is GEO1001.LIN. It is related to the database by a lookup table called GEOLIN.LUT. Similarly, the markerset for this database is GEO100.MRK, and its lookup table is GEOMRK.LUT. Colors in the polygon coverage (MTR_POLY) are assigned based on the PTYPE and were chosen from a shadeset called WPGCMYK.SHD and a lookup table POLYCOLOR.LUT. Annotation (unit labels, text labels, and printed numerical values) was displayed using a font entitled GEOFONT.TXT which has capabilities for displaying proper notation of geologic text symbols.

Also enclosed in the database package is MTR.MET, the FGDC standard metadata for the database and MTR.REV, a revision list with current information on the status of all files in the database.