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BRECCIA-PIPE AND GEOLOGIC MAP OF THE SOUTHEASTERN PART OF THE HUALAPAI INDIAN RESERVATION AND VICINITY, ARIZONA

By

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INTRODUCTION

The map area encompasses about 660 mi^2 (1,050 km^2) of the southeastern part of the Hualapai Indian Reservation, a part of Grand Canyon National Park (northwest edge of map area), and private and State lands that border the southeastern and eastern boundaries of the Reservation (fig. 1). The map area is in that part of the southwestern Colorado Plateaus physiographic province that is dissected by the Colorado River to form the Grand Canyon and its system of tributary canyons.

Hundreds of solution-collapse breccia pipes are found in the Hualapai Indian Reservation and adjacent areas in northwestern Arizona. Many pipes contain uranium and copper minerals and anomalous concentrations of Ag, Co, Mo, Ni, Pb, and Zn. In the map area, 231 confirmed and suspected breccia pipes and collapse features have been recognized. Of these, approximately 8 percent have copper or other minerals, or have gamma radiation in excess of 2.5 times background level.

This research was funded by the Bureau of Indian Affairs in cooperation with the Hualapai Tribe to appraise the mineral potential of the Hualapai lands. The entire 1,550 mi^2 (2,465 km^2) Hualapai Reservation has been mapped geologically at a scale of 1:48,000 (Wenrich and others, 1996, 1997; Billingsley and others, 1999). Within the Reservation, all breccia pipes and collapse features have been plotted. Outside the Reservation, several pipes are shown by symbols based on the work of Huntoon and others (1981) and this project. A few well-defined collapse features outside of the Reservation are shown.

The top of the Aubrey Cliffs forms the boundary between the Coconino Plateau in the northern and northeastern parts of the map area and the Aubrey Valley in the southwestern part of the map area (fig. 1). The Aubrey Valley, a broad alluviated plain that conceals any underlying breccia pipes, is bounded on the west by tributary canyons to Peach Springs and Diamond Creek Canyons. The Hualapai Plateau is west of Aubrey Valley and is a broad, irregular-shaped plateau of low relief that breaks off into canyons along the Hurricane Fault. The Grand Canyon and its tributaries are in the western and northwestern parts of the map area. Elevations range from 1,340 ft (408 m) above sea level at the Colorado River to 7,392 ft (2,253 m) at Manzanita (benchmark) on the Aubrey Cliffs north of Diamond Creek, giving a maximum relief of 6,052 ft (1,845 m) in the map area.

This report includes two maps, map A showing geology and breccia pipes coded into categories, and map B showing only the breccia pipes and their respective pipe number and category. Breccia and collapse structures in the extreme northwest corner of the map area are those mapped by Huntoon and others (1981). All pipes in the mineralized category were sampled; petrographic, mineralogic, and geochemical studies are in progress. Initial mapping of the pipes and sinkholes was done using 1976, 1:24,000-scale color aerial photographs. Each collapse feature was visited and examined by helicopter or vehicle. Radiometric traverses were made across all but a few of the pipes and sinkholes. Collapse features not field checked are in the Redwall Limestone and were determined to have little economic potential based on previous field investigations (Billingsley and others, 1986; Wenrich and others, 1996, 1997).

GEOLOGIC SETTING

The oldest rocks in the map area are Early Proterozoic granites, schists, and gneisses exposed along the Colorado River and in the Diamond Creek drainages (northwestern part of map area). The metamorphic rocks are mostly in the middle and upper amphibolite facies. Early Proterozoic pegmatite and diabase dikes intrude these rocks throughout the area (Huntoon and others, 1981).

Exposed in canyon walls and on the plateaus are Paleozoic strata ranging in age from Cambrian to Permian. The youngest exposed Paleozoic unit is the resistant Kaibab Formation of Early Permian age, which forms the surface of the Coconino Plateau. Rocks of Pennsylvanian and Mississippian age crop out locally in Aubrey Valley and in the southwestern part of the map area, although at many places they are covered by Cenozoic deposits. Strata of Ordovician and Silurian age are not present in the region or map area. Their position in the section is marked by a regional disconformity that separates rocks of Cambrian and Devonian age.

Deposits of Late Cretaceous to Holocene age are locally present. The Cenozoic deposits cover much of the Paleozoic rocks on the plateaus, the large upland valleys, and in Aubrey Valley. In the tributary canyons of the Colorado River, Cenozoic rocks are mostly limited to younger landslides, travertine, and talus deposits.

The oldest Cenozoic rocks consist of two units: a consolidated gravel and conglomerate unit that fills a 2-mi (3.2 km) wide paleovalley

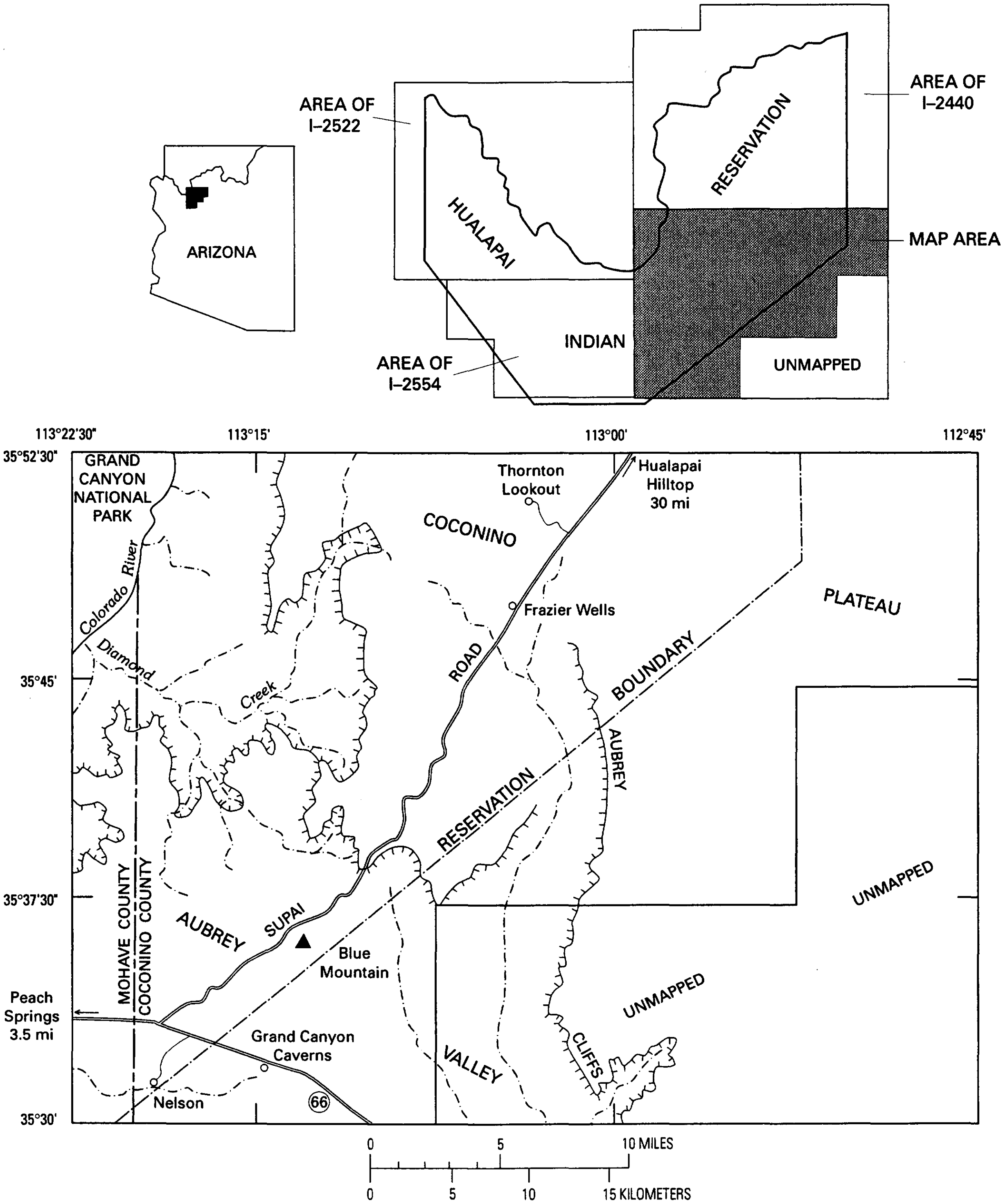


Figure 1. Geographic map of the southeastern part of the Hualapai Indian Reservation, Arizona.

east of and between upper Diamond Creek and Blue Mountain (central part of map area), and a consolidated gravel and fanglomerate unit that fills a paleovalley and adjacent erosional scarp just north of Blue Mountain. Both deposits consist of Paleozoic clastic material in a gravelly sandstone matrix described informally and together as the Robbers Roost gravel by Koons (1948a, b, 1964). The deposits are considered to be Late Cretaceous to late Paleocene in age because their stratigraphic position is about equivalent to that of similar Paleozoic clastic gravel deposits below Eocene lacustrine deposits a few miles east of the map area on the Coconino Plateau (Young, 1985, 1999). The Robbers Roost gravel in the higher paleovalley on a ridge east of upper Diamond Creek contains conglomerate clasts from the Coconino Sandstone, the Toroweap Formation, and the Kaibab Formation. This high ridge deposit was not described by Koons (1948a, b, 1964) and is a new discovery in the map area. The lower lying deposits of Robbers Roost gravel include locally eroded talus debris, fanglomerate, and fluvial deposits derived from the Esplanade Sandstone, Hermit Shale, Toroweap Formation, and Kaibab Formation. Based on stratigraphic position and clast lithology, the higher paleovalley Robbers Roost gravel is older than the lower lying talus debris and valley fill Robbers Roost gravel because the lower units partly erode into the upper paleovalley unit. The name "Robbers Roost gravel" is presently retained as an informal name because Koons (1948a, b, 1964) did not designate a type locality or a formal description of these and other gravel deposits. Furthermore, Koons (1948a, b, 1964) used various and conflicting names for the same gravel deposits (Young, 1999).

A younger and unconsolidated gravel deposit consisting of Proterozoic clastic material of granite, schist, gneiss, and quartzite was informally designated as the Frazier Well gravel by Koons (1948a), and later was formally named the Music Mountain Formation (Young, 1999). The name Frazier Well gravel is presently retained as an informal unit on this map, but is equivalent to the Music Mountain conglomerate described by Young (1966) and Young and others (1987). These clastic deposits are widespread, overlie the low-lying Robbers Roost gravel north of Blue Mountain, and are inset against the older paleovalley Robbers Roost gravel west of Frazier Wells (east-central part of map area). The Frazier Well gravel appears to be overlain by a 14.6-Ma basalt flow at Blue Mountain (Damon, 1968), suggesting that the Frazier Well gravel is middle Eocene in age or older. Sediments of similar lithology occur throughout the Hualapai and Coconino Plateaus and have been shown to be no younger than middle Miocene (Young, 1999). In summary, the Blue Mountain gravel and Frazier Well gravel of Koons (1948a, b) and part of the Hindu Canyon Formation of Gray (1959, 1964) are all equated with the Music Mountain conglomerate of Young (1966) just east of this map, which is formally proposed as the Music Mountain Formation (Young, 1999).

Modern erosion of the Robbers Roost gravel, the Frazier Well gravel, and local Paleozoic outcrops have resulted in an extensive cover of younger undifferentiated gravel deposits (Tg). These deposits consists of unconsolidated to partly consolidated mixed lithologies of Proterozoic and Paleozoic clastic material. These Tertiary deposits are middle Miocene to Pliocene in age and are equivalent to the Coyote Spring Formation of Young (1999).

STRUCTURAL GEOLOGY

TECTONIC OVERVIEW

The tectonic history of the southwestern part of the Colorado Plateau can be subdivided into five broad episodes. (1) The Precambrian interval involved a complex succession of crustal accretion, subsidence and sedimentation, and finally uplift accompanied by extensional tectonism that produced a deeply eroded metamorphic complex (Ilg and others, 1996). (2) Paleozoic through Cretaceous time was characterized by 8,000–13,000 ft (2,450–3,950 m) of net regional episodic subsidence and comparable sediment aggradation. (3) The Laramide orogeny, herein used to include Late Cretaceous through Eocene events, resulted in north-northeast crustal compression and regional uplift that was accompanied by widespread erosion. (4) Regional erosion has continued since the end of the Laramide orogeny, but the tectonic regime has transformed from regional uplift into one of east-west regional extension. (5) Erosion has produced the Grand Canyon during the past 5 million years (Young and Brennan, 1974; Lucchitta, 1979) and the dramatic topographic relief associated with it led to the development of localized gravity tectonic features including large landslides and small gravity-glide detachments (Huntoon, 1974).

The Hualapai Reservation contains a remarkable record of reactivated faults caused by successive stress regimes imposed on the crust. Large-displacement, north-, northeast-, and northwest-trending normal faults having offsets measured in thousands of feet dominated the Late Proterozoic structural setting in the region. The Paleozoic and younger rocks are deformed by (1) Laramide monoclines that are cored by reverse faults, and (2) superimposed late Cenozoic normal faults. The Laramide monoclines are crustal-shortening features that generally overlie reactivated Precambrian normal faults, whose sense of motion reversed during Laramide compression. The principal post-Laramide normal faults also followed reactivated Precambrian trends (Walcott, 1890; Huntoon, 1974); however, east-west extension in the region has also produced many new normal faults and complex fault zones. Normal faulting continues in the region today and has resulted in the development of extensional basins. Faulted Quaternary alluvium occurs along the Hurricane and Toroweap Faults, and faulted Pleistocene volcanic rocks occur throughout the region.

CENOZOIC UPLIFT AND EROSION

No activity since the close of Mesozoic time has been as great as the regional uplift that took place during Late Cretaceous and Cenozoic time. Vertical uplift along the southwestern margin of the Colorado Plateau has been between 2 and 3 mi (3 and 5 km) since Cretaceous sedimentation ceased. More than 3,000 ft (915 m) of uplift at the Grand Wash Cliffs has occurred in the last 5 million years (Lucchitta, 1979), indicating that rates of uplift in the area accelerated during late Cenozoic time. Individual offsets along the largest faults and monoclines are spatially restricted and relatively modest in comparison.

The primary result of the uplift has been erosion. Probably a minimum of a mile of sedimentary rock has been stripped from the plateaus since the end of Cretaceous time based on the thickness of Mesozoic and Cenozoic rock strata of extreme southern Utah. The Grand Canyon is a late-stage and modest manifestation of the total volume of rock that has been removed from the region.

The west-flowing Colorado River was established through the region in Pliocene time (Young and Brennan, 1974; Lucchitta, 1979). Continued uplift resulted in its rapid incision and attendant development of the Grand Canyon. Topographic relief between the present plateaus and Colorado River within the Hualapai Reservation is now as much as 7,000 ft (2,150 m).

The southwest margin of the Colorado Plateau became topographically and structurally differentiated in Miocene time from the Basin and Range Province, which is located to the south and west of the map area (Young and Brennan, 1974). Prior to this differentiation, Mesozoic and Laramide uplift resulted in northeastward tilting of the region that includes the Colorado Plateau and the part of the adjacent Basin and Range region that lies to the south. Drainage was toward the northeast across what is now the Colorado Plateau margin (Young, 1982). Large volumes of Cretaceous and older rocks were stripped from the entire region between Late Cretaceous and Oligocene time. The detritus was transported northeastward across the Hualapai Indian Reservation into Utah by a system of incised pre-Colorado River streams (Young, 1982).

Sedimentary and topographic relics of this paleodrainage system are well preserved on the Hualapai Indian Reservation (Koons, 1948a, 1964; Young, 1966). Early Tertiary arkosic sediments, composed in part of Proterozoic clasts derived from the area south of the plateau margin, cover large areas of the plateau surface east of the Toroweap Fault, and floor paleochannels to the west. Remnants of prominent paleovalleys are preserved under a veneer of Eocene and younger sedimentary and volcanic rocks in Hindu, Milkweed, and Peach Springs Canyons in the southwestern part of the Reservation (west of this map area), in two meander loops and older hanging valleys directly east of Peach Springs Canyon (west edge of this map area), and north of Blue Mountain (west-central part of map area). Proterozoic rocks were exposed along the southwestern edge of the plateau by the end of Eocene time, indicating that between 9,000 and 13,000 ft (2,750 to 3,950 m) of Paleozoic and Mesozoic sediments had already been eroded from that area.

DEFORMATION OF THE PALEOZOIC SECTION

The principal tectonic structures that deform the Paleozoic and younger rocks in the Hualapai Reservation formed during east-northeast Laramide compression and east-west post-Laramide extension. East-west extension is continuing at present. The monoclines and the principal normal faults that dominate the structural fabric on the Hualapai Reservation developed before the erosion of the Grand Canyon. The Laramide monoclines developed while thousands of feet of Mesozoic and upper Paleozoic rocks may have blanketed the region, a conclusion supported by the ductile deformation of the Paleozoic sediments that are now exposed along the monoclines.

LARAMIDE MONOCLINES

The Laramide monoclines developed in response to a stress regime in which the maximum principal stress was horizontal and oriented east-northeast (Reches, 1978). The compression resulted in minor crustal shortening through a series of east-dipping monoclines having sinuous, but generally northerly trends (Davis, 1978). The principal monoclines in the Hualapai Indian Reservation include, from east to west, the Aubrey, Toroweap, Hurricane, and Meriwhitica Monoclines. Laramide displacements across these folds were downward to the east with offsets of as much as 1,500 ft (460 m). Individual monoclines developed over single, reactivated, west-dipping Proterozoic faults. As reverse motion occurred along the basement faults, the faults propagated variable distances upward into the section as the Paleozoic sedimentary rocks simultaneously folded, forming the monoclines.

Typical monocline geometry is shown on figure 2. The anticlinal and synclinal hinges of the fold converge with depth on the underlying fault. The Paleozoic sedimentary rocks become more steeply folded with depth and are overturned against the fault at the base of the Paleozoic section. An ideal vertical profile through the Hurricane Monocline is in the north wall of Three Springs Canyon in the northeastern part of the Reservation (Wenrich and others, 1986).

The Hurricane Monocline dies out in Three Springs Canyon, which lies north of the map area. The monocline is missing along the Colorado River and in Peach Springs Canyon, where minor folding along the superimposed Hurricane Fault is related either to normal west-dipping drag along the Hurricane Fault plane, or to minor changes in dip caused by subsidence that resulted from extension within the fault zone. The Three Springs Fault represents the core of an eroded branch of the Hurricane Monocline. The east-side-down segment of this fault did not undergo sufficient post-Laramide normal displacement to change the sense of Laramide offset across the fault. However, post-Laramide downfaulting to the north was great enough to completely undo the Laramide displacement, thus causing the fault to scissor near 222-Mile Canyon (northwest corner of map area). The Hurricane Monocline is cored by a single reverse fault at the level of the Proterozoic basement and is also severed by a later normal fault that followed the same basement fault surface at all locations on this map. Post-monocline, normal displacements are generally greater than the reverse displacements associated with the monoclinal folding. Proterozoic greenschist that formed along the surface of the Hurricane Fault in small canyons north of Diamond Peak is attributed to Precambrian deformation because post-Precambrian depths of burial and thermal regimes were insufficient to cause this degree of metamorphism. The sinuosity of the monoclines results from selective reactivation of segments of Precambrian faults, where the dip and strike of the reactivated segment was favorably oriented to accommodate Laramide strain (Huntoon, 1981). Abrupt changes in strike and branching of the monoclines reveal the locations of intersecting Precambrian faults in the underlying basement.

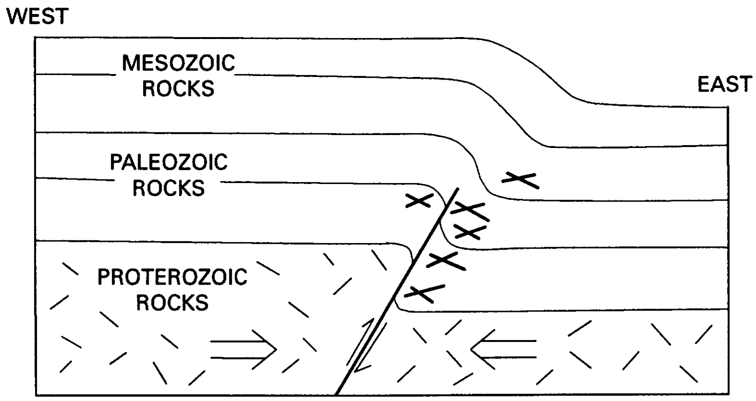
The Toroweap Monocline consists of two aligned segments in the map area, one north of Diamond Creek and the other southwest of Blue Mountain. Post-monocline normal fault patterns having northwest and east-northeast trends here indicate the likely presence of intersecting basement faults lying between these segments. Intersections of such basement faults could have precluded the development of the Precambrian Toroweap Fault in the Blue Mountain/Diamond Creek area, thus preventing development of a monocline here in Laramide time.

LATE CENOZOIC FAULTING AND EXTENSION

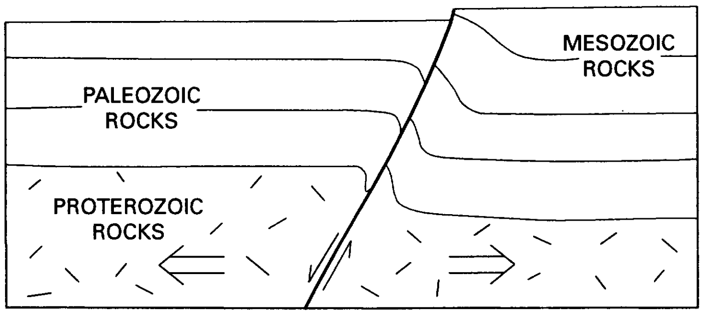
An extensional tectonic stress regime was imposed on the southwestern Colorado Plateau in late Cenozoic time. This regime is still operating and has resulted both in extensive normal faulting of the plateau and tectonic differentiation of the plateau from the adjacent Basin and Range Province to the south and west.

Late Cenozoic faulting on the Hualapai Plateau appears to have commenced after deposition of the early Tertiary arkoses and the Miocene Peach Springs Tuff (Huntoon, 1990) because offsets of these units are the same as offsets of the underlying Paleozoic rocks along the faults. Late Cenozoic east-west extension has produced hundreds of normal faults with offsets of as much as about 2,400 ft (730 m). The initial result of the extension was to fault the monoclines and downdrop the western blocks in a sense opposite to the earlier monoclinal displacement. The late Cenozoic normal displacement across the faults exceeded the Laramide reverse displacement. Also, the late Cenozoic faulting extended greater distances along strike. This resulted in successive stepping down of blocks across the region from east to west.

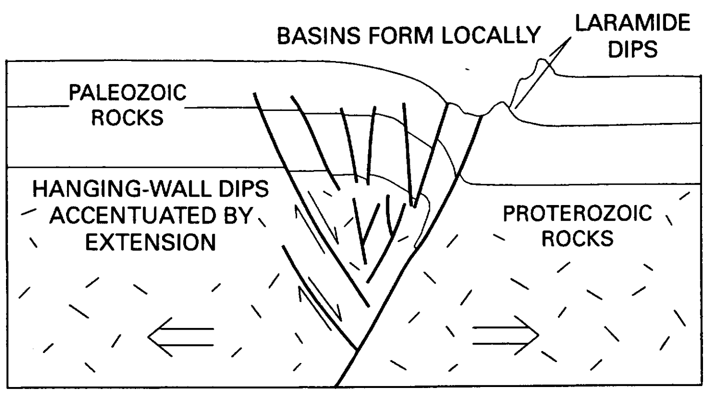
As extension progressed, faulting involved larger areas of the plateau surface. For example,



A. Laramide folding over reactivated Proterozoic fault; original fault was normal.



B. Late Tertiary normal faulting



C. Late Tertiary configuration after continued extension

Figure 2. Diagram showing the development of the Hurricane Fault Zone in the western Grand Canyon, Arizona. Small crosses in figure 2*A* are low-angle conjugate thrust faults.

the Hurricane Fault Zone now occupies a 10-mi (16 km) wide band through part of the Hualapai Reservation, and is characterized by intersecting northeast- and northwest-trending normal faults and grabens (Huntoon and others, 1981). Fault densities and offsets increase with depth, indicating that many of the individual faults have propagated upward from the basement and that they attenuate with increased elevation in the Paleozoic section. Slickenslide striations on the fault surfaces indicate predominant dip-slip displacements and east-west horizontal extension across the region, a conclusion supported by Wong and Humphrey (1986) who concluded that "***based on several recently determined normal focal mechanisms, extensional tectonic stresses appear to have encroached well beyond the physiographic boundaries on all sides of the Plateau."

Extensional basins with as much as several hundred feet of closure have been observed in the normal fault zones. Examples include a depression along the downthrown side of the Aubrey Fault and a young basin developing east of the Toroweap and Aubrey Faults in the northeast corner of the map area. The latter is a closed topographic depression.

An extensive record of recurrent movement exists along the principal faults in the region. All of the Cenozoic units are faulted. The finest known and most complex record of recurrent faulting in the map area exists along the Toroweap, Aubrey, and Hurricane Faults. In fact, so continuous has been late Cenozoic faulting in the region that the number of discernible motions along these faults is limited only by the number of discrete Cenozoic units deposited across the fault surfaces. Early Tertiary fanglomerates are displaced by more than 900 ft (300 m), west block down, across the junction of the Toroweap and Aubrey Faults. Similar rocks are faulted by a north-trending graben along the Aubrey Cliffs at the head of Diamond Creek. Early Tertiary arkoses are downfaulted 200 ft (60 m) to the west along the northern part of the Aubrey Fault. In addition, Quaternary alluvial fans exhibit small west-down displacements along the Aubrey Fault immediately south of the map area, creating fresh-looking fault scarps.

PALEOGEOGRAPHIC RECONSTRUCTIONS

An east-west profile across the center of the map area in Laramide time would not have passed through east-dipping monoclines west of the minor Aubrey fold, because neither the Toroweap nor Hurricane Monoclines developed here. Both were present to the north and would have produced topographic expressions to the north. The post-Laramide surface was not flat however; rather the presence of remnants of early Tertiary canyons and west-dipping early Tertiary fanglomerates reveals that the Mogollon erosional escarpment (defined as the retreating Permian section above the resistant Esplanade Sandstone) occupied virtually its present position through the region.

The west-facing Mogollon escarpment trended north in early Tertiary time along what is now the Aubrey Cliffs and curved northwestward toward the Colorado River at a point north of Diamond Creek. The Aubrey Monocline displaced the Permian strata down to the east. The Hurricane and Toroweap Monoclines had no topographic expression in the Blue Mountain/Diamond Creek area to the west.

North-flowing streams were incising and transporting sediments from elevated terrains south of what is now the Colorado Plateau. These streams were situated on or above the Permian surface east of the Aubrey Cliffs, but were carving canyons into Mississippian rocks west of the cliffs based on the presence of remnants of early Tertiary arkoses. Early Tertiary arkoses are preserved in successively deeper abandoned canyons at the following locations: (1) a shallow west-northwest trending channel eroded in the plateau between Blue Mountain and Peach Springs Canyons, (2) a moderately incised south-southeast oriented channel directly northeast of Hells Canyon, (3) a deeply incised meander loop at Hells Canyon, and (4) the deeply incised Peach Springs Canyon (fig. 1).

The presence of the pre-Colorado river channels has important but subtle structural implications. Specifically, the arkosic sediments that floor them predate late Cenozoic normal faulting in the region, because displacements of the arkoses are everywhere the same as the displacements of the underlying Paleozoic rocks. However, the linearity of Peach Springs Canyon reveals that some structural control existed that allowed the canyon to erode and ultimately capture drainage from the other early Tertiary canyons. The successively lower elevations of the early Tertiary canyon floors reveal that Peach Springs Canyon was the last to be active.

The most likely scenario allowing for the erosion of Peach Springs Canyon involves the presence of fracture weaknesses along the present strike of the Hurricane Fault Zone that predated late Cenozoic normal faulting in the canyon. One reasonable possibility is that the early Tertiary canyons were completely filled with arkoses, which permitted overland spills. These overland spills caused preferential dissection of the surface along fractures across the divides. This capture mechanism implies the presence of fractures in the Paleozoic section, despite the fact that neither the Hurricane Monocline was developed at this location nor normal faulting had commenced in the region. It appears that the Precambrian Hurricane Fault was behaving as a structural hinge that allowed for upward propagation of fractures through the Paleozoic section, even though stratigraphic offsets did not develop at this location. Some of the fractures were probably emplaced during Laramide compression, coincident with development of the Hurricane Monocline farther north along strike. Other fractures in the zone probably developed in the Paleozoic section during Paleozoic and Mesozoic subsidence.

The north-flowing early Tertiary stream in Peach Springs Canyon breached the Mogollon escarpment north of the map area. It discharged into developing sedimentary basins on the Colorado Plateau in Utah. The northward regional dip had to be approximately 1° greater than at present in order for the stream to clear what is now the north rim of the Grand Canyon (Young, 1982, p. 32).

BRECCIA PIPES

INTRODUCTION

The concentration of 231 collapse features within the southeastern part of the Hualapai Reservation is characteristic of their density throughout the Colorado Plateau of northwestern Arizona. Many of these circular features are solution-collapse breccia pipes that bottom in the Mississippian Redwall Limestone, whereas others may be shallower collapses that represent gypsum dissolution within the Permian Toroweap or Kaibab Formations. In addition, numerous sinkholes in the Harrisburg Member of the Kaibab Formation are easily distinguished from the Redwall Limestone collapses by their steep vertical walls and floors covered by large blocks of rubble. The sinkholes appear to be relatively recent in age and are largely the result of modern solution erosion (Billingsley, 1993, 1994).

As the age of the uranium mineralization in some of these pipes is around 200 Ma (Ludwig and Simmons, 1992), and because mineralized rock has only been found in the breccia pipes, gypsum collapse structures do not have any value for mineral exploration. A detailed discussion on the origin of the breccia pipes and the mineralogy and geochemistry of the ore deposits is provided by Wenrich (1985). Because it is difficult to distinguish breccia pipes from gypsum collapse structures, all circular features have been placed into categories based on physical characteristics (see collapse features legend on map B) such as the presence of: (1) concentrically inward-dipping beds, (2) altered rock (specifically bleached and limonite stained), (3) brecciated rock, (4) mineralized rock (total gamma radiation in uranium elements greater than 2.5 times background, or visible copper minerals), and (5) circular vegetation patterns or topographic depressions.

The brecciated rock comprises clasts ranging in size from granules to boulders embedded within a finely comminuted sandstone matrix. The clasts are always from a source rock that has been downdropped from an overlying stratigraphic unit. Because the breccia pipes have probably undergone considerable flushing by ground-water solutions, the matrix is generally composed of finely comminuted quartz with minor calcareous cement.

Delineating the exact outline of any breccia pipe in the field is difficult unless the breccia column itself is exposed, but such exposure is rare in the southeastern part of the map area. The brecciated column of rock within each pipe abuts generally well stratified, relatively undeformed sedimentary rock. The boundary marking this contact is, by definition, a fracture (produced by downward movement of the inner brecciated column of rock). This fracture is referred to here as the ring fracture. More properly, it should be termed the inner ring fracture, as the stratified sedimentary rock surrounding the breccia column commonly contains a series of concentric ring fractures and these are not as well defined as the innermost ring fracture. Because the inner ring fracture is rarely well exposed, and in order to be consistent throughout the map area, the boundaries of the breccia pipes were mapped as the outermost extent of inward-dipping beds or circular features. It should be recognized that the surface area affected by solution collapse can be as much as five times the diameter of the actual breccia column due to lateral dissolution of the Toroweap or Kaibab Formations or both.

The initial mapping of breccia-pipe structures was done using 1976 1:24,000-scale color aerial photographs. Every collapse structure mapped was examined on the ground, and radiometric traverses were made across more than 90 percent of the structures found. The remaining 10 percent of the structures that were not field checked for radioactivity were in the

Redwall Limestone, and have little economic potential because any overlying potentially mineralized sandstones have been removed by erosion.

STRUCTURAL CONTROL OF BRECCIA PIPES

Over 80 percent of the collapse features in the southeastern part of the reservation lie in the Blue Mountain/Diamond Creek area (fig. 3), and are exposed in either the Mississippian Redwall Limestone or the Pennsylvanian and Permian Supai Group and not the Permian Toroweap or Kaibab Formations. Most of the collapse features fall into the C2 category (see collapse features legend on map B) and lack a surface expression of brecciated or mineralized rock. The Blue Mountain/Diamond Creek area (fig. 3) also contains more springs than any other part of the reservation. The Redwall caverns were, and are presently, controlled by the hydraulic gradient, as well as the fractures in the Redwall. If the breccia pipes in the Blue Mountain/Diamond Creek area were formed prior to 200 Ma, as were the ore-grade breccia pipes such as those at the Orphan Mine in eastern Grand Canyon (Ludwig and Simmons, 1992), present ground-water circulation may be similar to that prior to 200 Ma. Within the Blue Mountain/Diamond Creek area several major faults intersect, such as the Toroweap, Diamond Creek, and Blue Mountain Faults (map B). Since ground water tends to follow joints next to major faults, this heavily fractured area has probably always been one of good permeability. Thus, the Blue Mountain/Diamond Creek area has probably experienced enhanced ground-water circulation and attendant limestone dissolution from time to time since Mississippian time. The present high spring discharge certainly indicates that enhanced ground-water circulation occurs in this area today, and the high density of Redwall- and Supai-collared breccia pipes in the same area suggests that this was also true during the Mississippian and Pennsylvanian. Thus, areas of high spring discharge may be good exploration indicators for the discovery of breccia pipes.

Populations of pipes tend to cluster in bands, or, in some cases, in trends containing as many as 12 pipes in straight lines, that follow or parallel existing fault trends or conspicuous lineaments. Some of the breccia pipes in the Blue Mountain/Diamond Creek area are aligned along northwest and northeast trends similar to those shown by Sutphin and Wenrich (1983) on the Marble Plateau. For the most part, though, the alignments are not as numerous and there are several in directions not represented on the Marble Plateau. There are three very convincing alignments similar to those on the Marble Plateau: (1) seven breccia pipes are aligned in a straight row starting with the large mineralized brecciated pipe (819) in Blue Mountain Canyon and trending southwest; (2) approximately 0.75 mi (1.2 km) to the east of the first trend is a parallel but longer trend through another seven pipes, and (3) crossing these two trends, just north of Blue Mountain Canyon, a northwest-southeast trend can be extended through 11 breccia pipes. The first two trends are parallel with the Toroweap lineament, defined both to the north and south by the Toroweap Monocline and Fault Zone. In addition to these three prominent trends, there are at least four north-northwest straight alignments of five to nine pipes, which coincide with the strikes of the many normal faults in the region.

Most of the brecciation and mineralization of the pipes in this area predates the oldest folds and faults that deform the Paleozoic host rocks, specifically late Paleozoic–Triassic pipe-forming events versus Laramide and younger tectonism. However, this does not preclude the possibility of subtle structural influences on pipe localization. The genetic link probably involves periodic reactivation of Precambrian faults in post-Precambrian time.

The mechanism for structural control of breccia-pipe formation envisioned here involves the underlying Precambrian fault zones acting as structural hinges during the long Paleozoic through Cretaceous interval of subsidence and sedimentation. The pre-existing faults were not displaced sufficiently to appreciably deform the overlying Paleozoic and younger rocks. Yet, minor flexing, utilizing the Precambrian faults as hinges, could have allowed for upward propagation of fractures into the overlying section of rocks. This would increase the fracture density in the carbonates along the strikes of the underlying fault zones. Localized dissolution of the carbonates probably took advantage of the joint-enhanced permeability and created sites for the nucleation of future pipes.

The entire process of pipe localization predates the Laramide monoclines. Consequently, the presence of clusters of pipes along Laramide and post-Laramide structures suggests that the Precambrian faults underlying the younger structures aided the upward propagation of fractures important for pipe formation. Such fracturing likely took place long before the basement faults were reactivated to such an extent that the overlying sediments failed through faulting or folding.

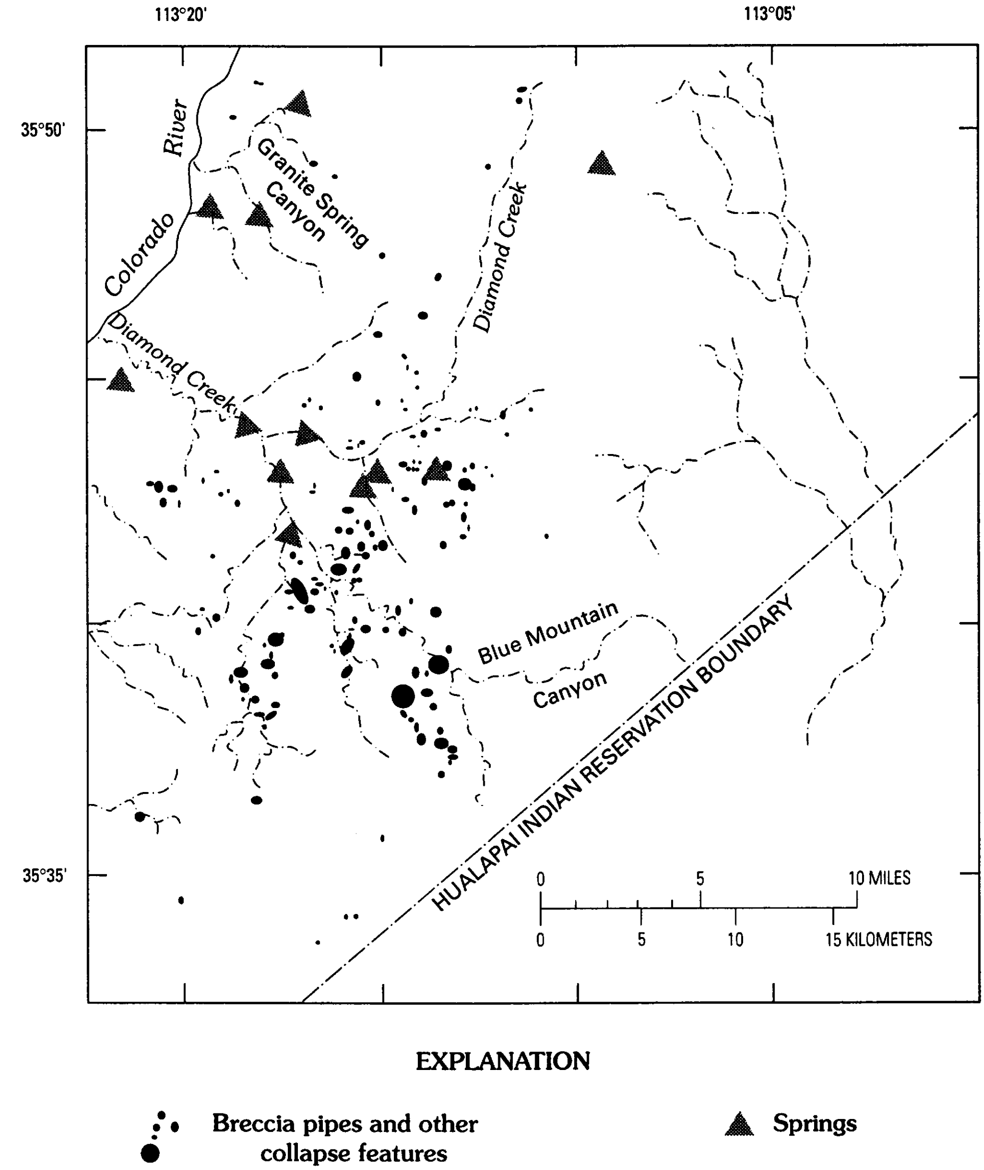


Figure 3. Breccia pipes and springs in the Blue Mountain/Diamond Creek area. All pipes found on the Hualapai Indian Reservation within the boundaries of this figure are shown. Note the concentrations of pipes near the areas of major discharge.

In fact, basement control is strongly suggested by the cluster of pipes in the Blue Mountain/Diamond Creek area. The cluster begins where the southwesternmost surface expression of the Toroweap Monocline disappears. The cluster ends where the Toroweap Monocline begins again toward the southwest corner of the map. It is important to note that the monocline changes direction by about 30° when it begins again. This is suggestive that the Blue Mountain/Diamond Creek breccia pipe cluster lies at the intersection of several basement blocks that coincide with greatest spring discharges. Thus, if areas of intersecting basement blocks can be outlined in northwestern Arizona, areas of significant clusters of breccia pipes may be located.

One of the major problems in uniform mapping of collapse features is the contrasting vegetation density and types across the Reservation. From the Toroweap Monocline to the Aubrey Cliffs, the vegetation is dense, particularly around Frazier Well where tall Ponderosa pines dominate the landscape. This region of the map contains no mapped collapse features, but that does not preclude their presence, although their detection can probably only be made through geophysical methods. In the Aubrey Valley and vicinity, breccia pipes may be present, but, if so, they are covered by Cenozoic gravel deposits and alluvium. Farther east the landscape is dominated by junipers and grasslands and few collapse features were found there. This may be attributed to the few major structural features in that area.

The southeastern part of the Reservation contains seven breccia pipes with exposed mineralized rock. Of these, six are in the Blue Mountain/Diamond Creek area; the seventh, the Blue Mountain Pipe, is discussed in the following section. All six in the Blue Mountain/Diamond Creek area contain anomalous gamma radiation greater than 2.5 but less than 5 times background. No copper minerals were observed on the surface, although some have significant alteration and goethite nodule accumulations. Pipe 874 contains so much goethite that in places it forms the clasts of the breccia. All six of the mineralized pipes in this area are exposed in the lower Supai Group or Redwall Limestone, and thus have low potential for any significant uranium tonnage. Pipe 842 contains a silicified plug. Such silicification is not common in breccia pipes, although there are four such features on the Hualapai Reservation. Other than the Orphan Pipe (eastern Grand Canyon area), none of the other known orebodies have such features; on the other hand, none of the others are exposed at the level of the Coconino Sandstone, which is the host rock for these silicified breccias.

THE BLUE MOUNTAIN PIPE

The seventh mineralized pipe in the map area is the Blue Mountain Pipe (287), which was drilled from 1976 to 1978 by Western Nuclear and in 1984 by the U.S. Geological Survey (Van Gosen and Wenrich, 1985). The potential for an orebody is excellent, although no drill holes have delineated more than low-grade (greater than 0.02 percent U_3O_8) uranium, which was encountered at a depth of about 400 ft (120 m) below the Coconino Sandstone–Hermit Shale contact. The drill cuttings revealed extensive reduction of the Hermit Shale and abundant pyrite associated with the uranium-mineralized zones. The pipe consists of a silicified breccia column of Coconino Sandstone blocks and fragments that protrude as a 130-ft (40 m) high spire above the canyon floor. Malachite, azurite, and chrysocolla can be observed on the spire, as can liesegang-banded sandstone blocks.

COLLAPSE FEATURES HAVING ECONOMIC POTENTIAL

One collapse feature, 562, mapped in 1982, but located east of and off the Reservation, was drilled in 1984 and 1985 by Rocky Mountain Energy. Similar features with a raised slightly bleached rim of the Harrisburg Member of the Kaibab Formation surrounding a soil-covered low center are found in the northeastern part of the map area (Wenrich and others, 1986). Features 564 (on this map, but off the Reservation next to 562), 534, 569, and 570 (all three are just north of this map and on the Reservation) appear to be similar features (Wenrich and others, 1997; photos of these features are shown in Wenrich and others, 1992). Although all four of these features are in the C4 category (see collapse features legend on map B) with little exposed rock, they appear to have a moderate potential for ore and further study of them is merited.

Several other features in the C4 category are worthy of note. Feature 523 is represented by a circular patch of tall trees. This is in contrast to many features, such as 522, which are circular grass- or shrub-covered clearings among the surrounding terrain of trees. The Canyon Pipe [southeast of Grand Canyon Village about 35 mi (56 km)], a known orebody, is expressed on the surface as a circular patch of grass and shrubs surrounded by Ponderosa pines. Perhaps this suggests that mineralized pipes produce a trace-metal halo above the orebody sufficient to prevent the growth of trees. Likewise, it is possible that those circular features with increased vegetation growth (specifically trees) may merely represent sinkholes or unmineralized collapse features that increase the permeability of the rock and hence permit more water movement and increased vegetation growth. If this is true, then feature 522 may not be of further interest. Feature 1129 is another grassy patch surrounded by trees, but is elongate in contrast to the more circular nature of such features as the Canyon Pipe. Perhaps this elongation resulted from the coalescing of two breccia pipes. Collapse feature 1104 forms a circular reddish soil patch, which may represent alteration at the surface, or downdropping of the redder Harrisburg Member of the Kaibab Formation into cream- to white-colored units. Feature 1117, a C2 category feature (Aubrey Cliffs), is off the Reservation and is an area of inward-dipping beds. The breccia contains abundant pyrolusite, but no other breccia pipes are known to contain significant manganese anomalies.

Few favorable features on this map are collared in rock above the Supai Group. Most of the other features shown on the map are in the C? category, which are questionable at best. They represent features that were thought by one member of the mapping team to possibly be a circular feature, but not by the other member.

Perhaps one of the better features shown on this map, besides 562 and 564, is feature 587 in the southeastern part of the map area. It too is off of the Reservation, but only by 0.5 mi (0.8 km). It represents a circular grassy patch surrounded by inward-dipping beds of the Toroweap Formation and by trees.

CONGLOMERATE CAVE

Feature 1103 is a sinkhole in the Robbers Roost gravel herein informally referred to as Conglomerate cave (north of Blue Mountain). A funnel-shaped hole descends vertically through 220 ft (70 m) of conglomerate of the Robbers Roost gravel cemented by calcite. These gravels unconformably overlie the Esplanade Sandstone, so a hole of this magnitude suggests dissolution within the underlying Redwall Limestone. The vertical, open nature of the hole also suggests that at least some of the collapse must have been recent because the walls within the cave are well-cemented conglomerate of the Robbers Roost gravel.

CONCLUSIONS

The southeastern part of the Hualapai Reservation contains some collapse features that may have economic potential, specifically those on the eastern side of the map area that are mapped in the C4 category. Most pipes within the cluster on the western side are collared in the Redwall Limestone or formations of the Supai Group and have little overlying host rock that might contain a uranium orebody. The Blue Mountain Pipe (287), which is east of the main cluster of pipes, is probably worthy of further exploration, although future drill holes should probably be drilled into the hillslope away from the breccia plug.

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DESCRIPTION OF MAP UNITS

SURFICIAL AND IGNEOUS DEPOSITS

Qal **Alluvial deposits (Holocene)**—Unconsolidated fluvial deposits of silt, sand, gravel, and boulders; includes eolian and floodplain deposits. Faults shown bounding alluvium do not offset alluvium

Qd **Dune sand (Holocene and Pleistocene(?))**—Light-red to light-brown, coarse-grained to very fine grained sand, stabilized by grassy vegetation. Includes parabolic or complex linear dunes and sand-sheet deposits. Thickness 3–20 ft (1–6 m)

Qc **Colluvium (Holocene and Pleistocene(?))**—Consists of brecciated rock fragments, boulders, gravel, sand, and silt; partly consolidated; contains gypsiferous or calcareous cement. Includes alluvial-fan deposits, talus, and landslide debris. Faults shown bounding colluvium do not offset colluvium. Thickness 5–80 ft (1–25 m)

Qt **Travertine deposits (Holocene and Pleistocene)**—Spring deposits of gray calcium carbonate. Includes angular boulders, gravel, sand, and silt of adjacent colluvial deposits. Mostly restricted to Diamond Creek in west-central part of map area. As much as 50 ft (15 m) thick

Qg **Older terrace-gravel deposits (Holocene and Pleistocene)**—Well-rounded gravel, sand, and silt. Fluvial Colorado River deposits interbedded with Quaternary basalt flows several tens of feet above the Colorado River at junction of Colorado River and Granite Spring Canyon; not all deposits shown because too small to show at map scale. Thickness 10–20 ft (3–5 m)

Qb **Basalt flows (Pleistocene)**—Olivine basalt; exhibits radial and columnar cooling joints along the Colorado River. Described as the "black ledge flow" by Hamblin (1994). As much as 30 ft (10 m) thick

QTl **Landslides (Holocene, Pleistocene, and Pliocene(?))**—Unsorted and unconsolidated material. In Grand Canyon, consists mainly of large blocks of Paleozoic sedimentary rock that have slid downward and rotated backwards toward base of parent wall. Along Aubrey Cliffs, consists of a jumbled unconsolidated mixture of Permian strata and minor Tertiary gravel (Tg). As much as 60 ft (18 m) thick

Tlp **Long Point basalt flows of McKee and McKee (1972) (Pliocene and Miocene)**—Dark-gray, fine-grained alkali olivine basalt (McKee and McKee, 1972). Limited to east-central edge of map area where unit unconformably overlies Frazier Well gravel (Tfw). McKee and McKee (1972) described two flows separated by gravel deposits; K-Ar age of lower flow is 14±0.4 Ma, and upper flow is 7.03±0.4 Ma. Not certain which flow is represented on this map. Thickness 40–130 ft (12–40 m)

Ti **Intrusive volcanic rocks (Miocene)**—Dark-gray alkali olivine basalt dikes; one near Nelson (southwest corner of map area), one in southeast corner of map area, and two on west side of unnamed mesa about 7 mi (11 km) north of Blue Mountain

Tb **Basalt (Miocene)**—Includes dark-gray alkali olivine basalt flows of Blue Mountain (Damon, 1968), and light-gray andesitic basalt flows just northwest of Grand Canyon Caverns (southwest corner of map area). Basalt at Blue Mountain has K-Ar whole-rock age of 14.63±1.10 Ma (Damon, 1968), and overlies Robbers Roost and Frazier Well gravel deposits (Trr, Tfw) and possibly younger unnamed Tertiary gravel deposits (Tg). Stratigraphic relations of gravel deposits (Tg) in vicinity of Blue Mountain is unclear. As much as 250 ft (75 m) thick

Tg **Undifferentiated gravel deposits (Pliocene to lower Paleocene(?))**—Gray and light-brown, silt, sand, pebbles, cobbles, and small boulders consisting of either all Paleozoic clasts, or all Proterozoic clasts, or mixed lithologies. Clasts are angular to well rounded in sandy matrix; consolidated by calcium carbonate cement in southwest corner of map area, partly consolidated in northeastern part of map area. Difficult to distinguish from Robbers Roost and Frazier Well gravels (Trr, Tfw); needs further study. Includes Cataract Creek gravel, which was informally introduced and described by Koons (1964) as reworked Frazier Well gravel in northeastern part of map area. Deposits appear to be old alluvial fans that include reworked gravel from Robbers Roost and (or) Frazier Well gravels. Deposits commonly covered by thin alluvium, lag gravel, or caliche (not mapped). Thickness 4–100 ft (1–30 m) or more

Tfw **Frazier Well gravel of Koons (1964) [middle Eocene to upper Paleocene (Young, 1999)]**—Originally called Blue Mountain gravel by Koons (1948a, p. 58); renamed Frazier Well gravel by Koons (1964, p. 100); correlative to Music Mountain Formation of Young (1999).

Consists of unconsolidated, well-rounded boulders, cobbles, and pebbles of granite, gneiss, schist, and red and white quartzite. Includes boulders as much as 20 in. (48 cm) in diameter; matrix supported, consisting of uncemented, coarsely textured, arkosic sandstone and siltstone. Forms gently rounded hills and slopes. Near Rose Well Camp (east edge of map area), includes conglomerate, sandstone, siltstone, and silty limestone exposed under Long Point basalt flows (Tlp) of McKee and McKee (1972). Unconformably overlies or inset against Robbers Roost gravel (Trr) and Paleozoic strata west of Frazier Wells in north-central part of map area. Variable thickness 5–140 ft (2–43 m)

Trr **Robbers Roost gravel of Koons (1948a) [middle Eocene to lower Paleocene (Young, 1999)]**—Originally defined by Koons (1948a, p. 58); correlative to Music Mountain Formation of Young (1999). Includes undivided upper (here recognized as a new unit) and lower deposits.

Upper deposit is gray conglomerate that fills a 2-mi (6.5 km) wide paleovalley on high ridge east of upper Diamond Creek. Considered the oldest gravel deposit in map area. Consists of well-rounded to subrounded conglomeratic clasts of Coconino Sandstone, Toroweap Formation, Kaibab Formation, and some Moenkopi Formation; clasts average about 2–3 in. (5–9 cm) in diameter, some as large as 15 in. (36 cm). Clasts are matrix supported with calcium carbonate cement. Forms resistant rounded hills.

Lower deposit is gray to reddish-gray fanglomerate and gravel that fills a paleovalley and overlies adjacent paleoslopes north of Blue Mountain (central part of map area). Consists of rounded to subangular fanglomerate and colluvial clasts locally derived from outcrops of Esplanade Sandstone, Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Formation; includes boulders as much as 2 ft (0.5 m) in diameter in paleovalley, and much larger on paleoslopes. Clasts are matrix supported with calcium carbonate cement. Forms resistant rounded hills or cliffs.

Maximum thickness of unit 200 ft (60 m)

SEDIMENTARY ROCKS

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

Harrisburg Member—Yellowish-gray to pale-red shale; fine- to medium-grained, thin-bedded, ledge- and slope-forming sandstone; gypsiferous siltstone; thin-bedded, fossiliferous limestone; and dolomitic sandstone. Includes silicified fossiliferous chert breccia beds near base of unit particularly along Aubrey and Toroweap Faults. Forms bedrock surface of Coconino Plateau where not covered by Cenozoic deposits. Gradational and arbitrary contact at top of chert limestone cliff of underlying Fossil Mountain Member. Average thickness 125 ft (38 m)

Fossil Mountain Member—Light-gray, fine- to medium-grained, thin-bedded, fossiliferous, cliff-forming, sandy, chert limestone. Commonly erodes into pillars or cone-shaped pinnacles in cliff outcrops. Unconformable contact with underlying Woods Ranch Member of Toroweap Formation (Pt) marked by solution and channel erosion with relief as much as 20 ft (6 m); contact is approximated on map where locally obscured by talus and minor landslide debris. Average thickness 250 ft (75 m)

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

Woods Ranch Member—Slope-forming, gypsiferous, pale-red silty sandstone; gray, gypsiferous siltstone; and dark-gray, thin-bedded, fossiliferous, sandy limestone. Beds locally distorted or absent along canyon walls where dissolution has occurred. Gradational and arbitrary contact between slope-forming Woods Ranch Member and cliff-forming Brady Canyon Member. Variable thickness 60–100 ft (18–30 m)

Brady Canyon Member—Cliff-forming, dark- to light-gray, fine- to medium-grained, medium-bedded, fossiliferous limestone; weathers dark gray. Individual limestone beds average about 2 ft thick (0.5 m); includes minor chert lenses and nodules. Gradational and arbitrary contact between cliff-forming limestone of Brady Canyon Member and slope-forming sandstone of Seligman Member. Thickness 250 ft (75 m)

Seligman Member—Slope-forming, yellow to yellowish-white to pale-red, fine-grained, thin planar-bedded sandstone. Includes minor thin beds of dolomite and gypsum. Sandstone mostly derived from underlying Coconino Sandstone (Pc). Sharp, planar contact with underlying Coconino Sandstone. Thickness 30–40 ft (10–3 m)

Pc **Coconino Sandstone (Lower Permian)**—Light-brown, yellowish-red, and light-red, fine-grained, cliff-forming, large-scale cross-stratified sandstone. Forms resistant slope along margins of Aubrey Valley. Thickens from 100 ft (30 m) in western part of map area to more than 200 ft (60 m) in eastern part. Sharp planar erosional contact at base. Thickness averages 170 ft (50 m)

Ph **Hermit Shale (Formation) (Lower Permian)**—Red-brown, thin-bedded, fine-grained, slope-forming siltstone and sandstone; mostly covered by colluvium. Gradational and arbitrary contact with underlying Esplanade Sandstone and Pakoon Limestone (Pep) marked at top of cliff formed by Esplanade and Pakoon; unconformable contact north of map area. Unit thins from about 700 ft (215 m) in northern part of map area to less than 100 ft (30 m) a few miles south of map area. Average thickness 500 ft (150 m)

Supai Group (Lower Permian to Upper Mississippian)—Includes, in descending order, Esplanade Sandstone and Pakoon Limestone undivided as defined by McNair (1951), and Wescogame, Manakacha, and Watahomigi Formations undivided as defined by McKee (1982)

Pep **Esplanade Sandstone and Pakoon Limestone, undivided (Lower Permian)**—Pale-red to reddish-orange, cross-stratified, medium- to fine-grained, medium-bedded, cliff-forming sandstone of Esplanade Sandstone; upper part includes light-gray, fine-grained, thin-bedded, cliff-forming limestone beds of Pakoon Limestone (McNair, 1951) interbedded with Esplanade Sandstone. Unit includes dark-red, fine-grained, thin- to thick-bedded, slope-forming sandy siltstone in upper and lower parts. Interbedded tongues of Pakoon Limestone locally thin and pinch out eastward, but thicken westward. Unconformity separates lower slope-forming part from underlying Upper Pennsylvanian Wescogame Formation; erosional relief as much as 20 ft (6 m); channel fill includes local limestone conglomerate. Thickness 450 ft (140 m)

PMwmw **Wescogame, Manakacha, and Watahomigi Formations, undivided (Upper Pennsylvanian to Upper Mississippian)**

Wescogame Formation (Upper Pennsylvanian)—Red to pale-red, slope-forming siltstone and shale interbedded with grayish-red calcareous sandstone in upper part; includes gray, brown, and reddish-gray, medium-grained, thin-bedded, cliff-forming, calcareous sandstone and dolomitic sandstone in lower part. Dolomitic sandstone contains individual low-angle crossbedded sets as thick as 3 ft (1 m). Unconformable contact at base with channeled relief as much as 4 ft (1 m). Thickness 150 ft (45 m)

Manakacha Formation (Middle Pennsylvanian)—Reddish-brown, fine-grained, thin- to medium-bedded, ledge-forming sandstone, and thick-bedded, low-angle cross-bedded sandstone; interbedded with gray, thin-bedded, medium- to coarse-grained limestone and dolomite, and red-brown shale. Overall, unit forms slope-and-ledge sequence. Unconformable contact at base with relief generally less than 3 ft (1 m). Thickness 200 ft (60 m)

Watahomigi Formation (Lower Pennsylvanian to Upper Mississippian)—Gray and purplish-gray, calcareous, slope-forming siltstone and fine-grained sandstone interbedded with gray, thin- to medium-bedded [less than 2 ft (0.5 m) thick] limestone. Limestone beds commonly contain red and white chert lenses or bands. Limestone units form small cliff in lower part of unit that thickens westward and contains Lower Pennsylvanian fossils. Purple siltstone, conglomerate, and thin-bedded gray limestone containing Upper Mississippian fossils near base of unit. Unconformity of low relief between Pennsylvanian and Mississippian strata in lower third of

Watahomigi slope. Unconformable contact with Surprise Canyon Formation (**Ms**) or Redwall Limestone (**Mr**); relief as much as 5 ft (2 m). Thickness 150 ft (45 m)

Ms **Surprise Canyon Formation (Upper Mississippian)**—Includes upper dark-red-brown, thin-bedded, fine-grained, slope-forming siltstone, sandstone, and thin laminated beds of silty limestone; middle yellowish-gray, coarsely crystalline, silty, crumbly, thin-bedded, fossiliferous, cliff-forming limestone; and lower dark-red to reddish-gray and brown, ledge-forming, chert-pebble conglomerate, clast supported in dark-red-brown to black, iron-stained, coarse-grained sandstone matrix. Unit not present everywhere in map area owing to unconformity at top. Fills paleovalleys and karst caves that were eroded into underlying Redwall Limestone (**Mr**). Overall dark-reddish-brown color of unit helps locate its presence. Variable thickness 0–300 ft (0–90 m)

Mr **Redwall Limestone (Upper and Lower Mississippian)**—Includes, in descending order, Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members undivided as described by McKee (1963). Together, all members form sheer cliff with slight recess between Horseshoe Mesa and Mooney Falls Members. All four members consist of a light-gray, thick-bedded, aphanitic, cliff-forming limestone and dolomite; marine fossils abundant throughout. White chert lenses and beds, which weather dark gray or black, common in Thunder Springs Member. Unconformity at base with relief as much as 5 ft (2 m). Thickness 400–650 ft (120–200 m)

Dtb **Temple Butte Formation (Upper and Middle(?) Devonian)**—Dark-gray to purple-gray, medium-grained, medium-bedded, ledge-forming dolomite, dolomitic sandstone, sandy limestone, reddish-brown siltstone, and gray siltstone; weathers dark gray. Disconformably overlies Muav Limestone (**Ꞓm**). Thickness 400 ft (120 m)

Tonto Group (Middle and Lower Cambrian)—As defined by McKee and Resser (1945)

Ꞓm **Muav Limestone (Middle Cambrian)**—Mottled gray and purple, thin-bedded, cliff-forming dolomitic limestone; weathers rusty gray or dark gray. Includes white to light-gray beds of unnamed dolomite unit at top above the highest Muav Limestone bed. Limestone ledges and low cliffs are separated by beds of slope-forming, green shale lithologically similar to underlying Bright Angel Shale (**Ꞓba**). Base of unit placed at base of Rampart Cave Member of Muav Limestone, which has a disconformable contact with Bright Angel Shale. Thickness 700–900 ft (215–275 m)

Ꞓba **Bright Angel Shale (Middle Cambrian)**—Green and purplish-red, fissile shale interbedded with light-brown to reddish-brown, coarse-grained, thin-bedded, slope-forming sandstone beds of Tapeats Sandstone (**Ꞓt**) lithology. Also interbedded with rusty-brown, ledge-forming dolomitic tongues of Muav Limestone (**Ꞓm**). Includes a purple-red, coarse-grained, thin-bedded, cliff-forming sandstone unit (red-brown sandstone member of McKee and Resser, 1945). Lower contact is gradational and arbitrarily marked at or near top of Tapeats Sandstone cliff. Lower part contains abundant light-brown, thin sandstone beds of Tapeats lithology. Overall, unit forms slope. Thickness 380 ft (90 m)

Ꞓt **Tapeats Sandstone (Middle and Lower Cambrian)**—Light-gray to light-brown and red-purple, medium- to coarse-grained, medium-bedded, cliff-forming sandstone and small-pebble conglomerate. Silica cement gives appearance of quartzite. Includes low-angle crossbeds and thin green shale partings between beds in upper part. Unconformably overlies Proterozoic rocks. Thickness 100–200 ft (30–60 m)

METAMORPHIC AND IGNEOUS ROCKS

Vishnu Schist (Group) (Early Proterozoic)—As defined by Malcolm D. Clark in Huntoon and others (1981)

Xgr **Nonfoliated granitic plutons**—Brown to light-red, holocrystalline and coarse-grained, quartz-bearing, plutonic granite; contains mainly feldspar and mafic minerals

Xvs **Mica schist**—Mica and quartz schist; contains mainly muscovite and biotite

Xva **Mafic schist and amphibolite**—Dark gray or black, very fine grained, foliated; contains amphibole minerals, plagioclase, and sparse quartz

Xvm **Paragneiss**—Granular feldspar and quartz alternating with lenticular micaceous layers and fine-grained amphibole minerals

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