UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Breccia pipe and geologic map of the northwestern Hualapai Indian Reservation and vicinity, Arizona

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Prepared in cooperation with the U.S. Bureau of Indian Affairs and the Hualapai Tribe

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This map is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

The map area encompasses approximately 720 square miles of: (1) the northwestern part of the Hualapai Indian Reservation, (2) the western part of the Grand Canyon National Park (north of the Colorado River), (3) portions of Bureau of Land Management land, (4) private land, and (5) state lands which border the western reservation boundary (fig. 1). The map area is in the part of the southwestern Colorado Plateau physiographic province that is dissected by the Colorado River to form the Grand Canyon and its system of plateaus and tributary canyons.

The Grand Canyon separates the Hualapai Plateau (south of the Colorado River) from the Sanup and Shivwits Plateaus (north of the river). Both the Hualapai and Sanup Plateaus are irregular plateaus of low relief; they are dissected by several deep tributary canyons to the Colorado River, most notably, Spencer, Meriwhitica, Quartermaster and Surprise Canyons. These plateaus are bounded on the west by the Grand Wash Cliffs, which also mark the physiographic break between the Colorado Plateau and the Basin and Range province. The Sanup Plateau was connected to the Hualapai Plateau before Grand Canyon time (Young, 1985), and now occupies a narrow bench land topography between the Colorado River and the topographically higher Shivwits Plateau to the north. An erosional scarp 1,200 feet high separates the Sanup from the higher Shivwits plateau. Mount Dellenbaugh, a low volcanic mountain on the Shivwits Plateau, is a major landmark to air navigation of the western Grand Canyon region (fig. 1). All three plateaus are made up of nearly horizontally bedded Paleozoic rocks with a regional dip averaging 1 degree to the northeast.

Elevations range from 1,157 feet at Lake Mead to 7,072 feet at Mount Dellenbaugh on the Shivwits Plateau. The Grand Canyon has a maximum depth of 4,800 feet (southeastern corner of map) but averages 3,600 feet deep between the Hualapai and Sanup Plateaus. Lake Mead has backed up 42 miles into the western Grand Canyon to Colorado River mile 236 (fig. 1; river mileage begins at mile zero at Lees Ferry, Arizona.)

Thousands of solution-collapse breccia pipes are found on the Hualapai Indian Reservation and adjacent areas in northwestern Arizona. A significant number of the pipes contain U-mineralized rock as well as anomalous concentrations of Ag, Co, Cu, Mo, Ni, Pb, and Zn. On the Hualapai Reservation, 886 confirmed and suspected breccia pipes have been mapped; of these approximately 8% show surface expression of mineralized rock, either recognizable Cu-bearing minerals, most notably malachite, azurite, or brochantite, or gamma radiation in excess of 2.5 times background. On the NW part of the reservation (this map) 224 confirmed and suspected pipes have been mapped. Only 12 of these show gamma radiation in excess of 2.5 times background and none show any signs of Cu-bearing minerals. Elsewhere on the map an additional 217 collapse features have been recognized, but most of these have not been field checked for mineralized rock. This report includes two plates, one showing the geology (plate 1), including the breccia pipes coded into categories, and another (plate 2) showing only the breccia pipes with their respective pipe number and category. All pipes in the mineralized category were sampled, and petrographic, mineralogic, and geochemical studies are in progress. Initial mapping of the pipes and collapse features was done on 1:24,000 color aerial photographs. Each feature mapped was surveyed by

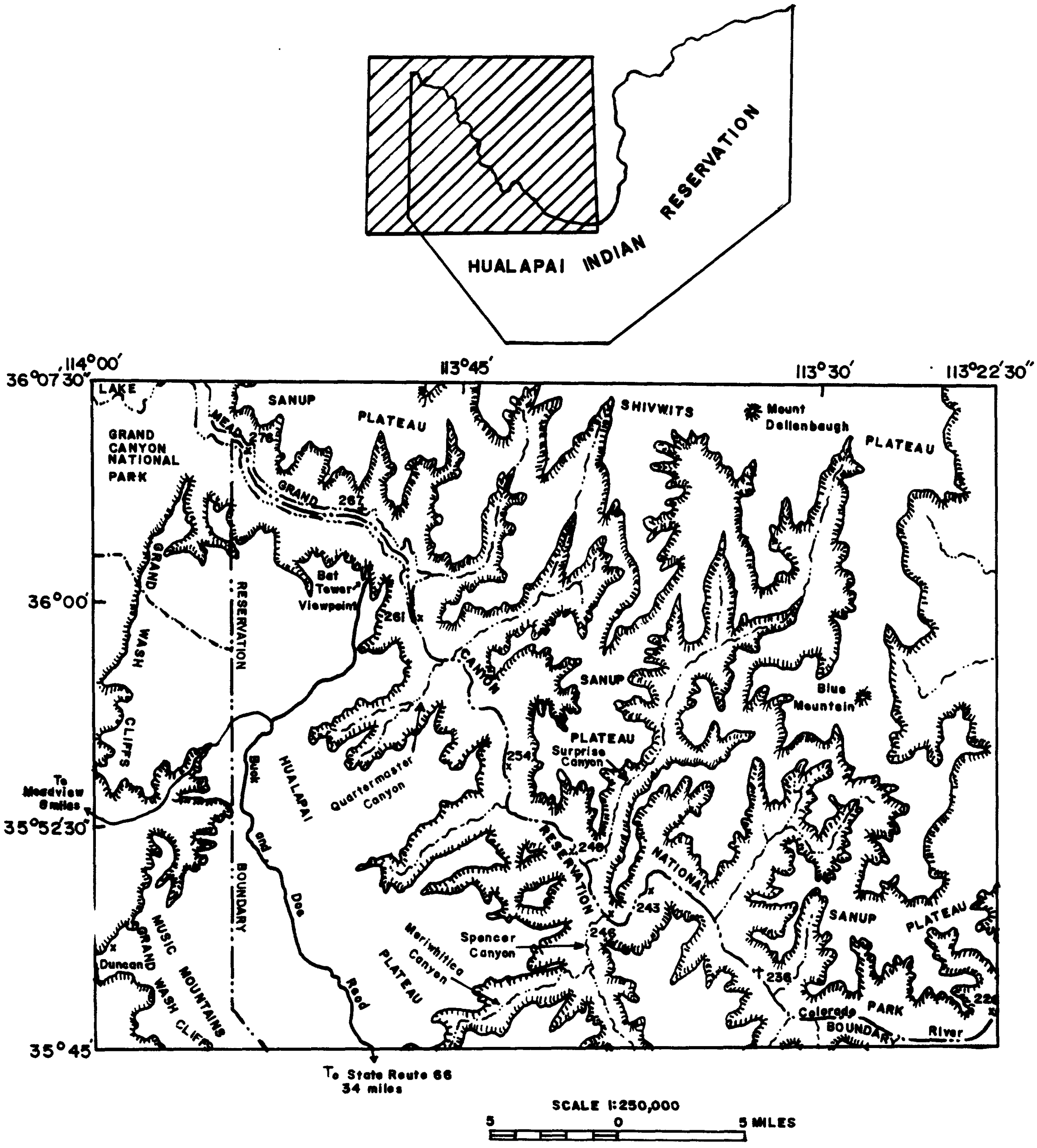


Figure 1. Geographic map of the northwestern part of the Hualapai Indian Reservation, Arizona.

helicopter or 4-wheel drive vehicle; more than 90% of the structures on the Hualapai Reservation were field checked by radiometric traverses.

Because the Paleozoic rocks of northwestern Arizona contain abundant carbonate and gypsiferous rock, numerous karst features have developed since the Mississippian. For our studies of mineralized breccia pipes in Arizona we have defined "breccia pipe" to refer to those solution features which: (1) formed pipe-shaped breccia bodies, (2) have economic potential to host U-ore, (3) bottom in the Redwall Limestone, and (4) stoped upward through the overlying Paleozoic strata. Those dissolution features whose origin or breccia content is unknown we refer to merely as "solution collapses," "solution or collapse structures," or "solution features". Those that are known to only form open holes in the present ground surface, but probably do not go any deeper, we call sink holes.

Despite periods of depressed uranium prices, the breccia pipes have commanded considerable exploration activity in the 1980's because of their high grade uranium deposits. Mining activity in breccia pipes of the Grand Canyon region of northern Arizona began during the nineteenth century, although at that time production was primarily for Cu with minor production of Ag, Pb, and Zn. It was not until 1951 that U was first recognized in the breccia pipes. During the period 1956-1969, the Orphan mine yielded 4.26 million lb of U_3O_8 with an average grade of 0.42% U_3O_8 (Chenoweth, 1986). In addition to uranium, 6.68 million lb of Cu, 107,000 oz of Ag, and 3,400 lb of V_2O_5 were recovered from the ore (Chenoweth, 1986). Between 1980-1986 four breccia pipes were mined for uranium in northern Arizona with grades in excess of 0.4% U_3O_8 and production ranging from 1-7 million lbs of U_3O_8 per pipe.

This research on the Hualapai Indian Reservation was funded by the Bureau of Indian Affairs in cooperation with the Hualapai Tribe in the hope that it would stimulate mining interest in Hualapai lands and would result in additional income for the Hualapai people. The entire 1550 mi^2 Hualapai Reservation has been geologically mapped at a scale of 1:48,000 and has been divided into 4 separately published map areas: NE, SE, NW (plate 1, this map), and SW. Within the reservation the boundaries of all breccia pipes and collapse features (most of which are suspected breccia pipes) have been accurately mapped to scale (plate 2). Outside of the reservation, pipes were not mapped in detail; their locations are based on the work of Huntoon and Billingsley (1981, 1982), and this project, and are shown as black dots, not to scale, whose boundaries were not mapped.

With the exception of the Supai Group, all formations have been mapped as individual units. As can be observed from Plate 1, with the exception of several pipes in the Muav Limestone and an unnamed Cambrian unit in the area of Meriwhitica Canyon, all pipes bottom in the Redwall Limestone and extend into the overlying strata. Most of the pipes in this NW map area have been eroded down to the Esplanade Formation, which caps most of the Sanup Plateau, or to the Redwall Limestone, which caps the Hualapai Plateau along with isolated remnants of the Lower Supai Group. It is impossible to determine if the Cambrian pipes stoped above their host formation because the overlying strata have been eroded in the Meriwhitica Canyon area, the only place where these pipes have been recognized.

GEOLOGIC SETTING

The oldest rocks in the map area are Precambrian granites, schists, and gneisses that are exposed along the Colorado River from Colorado River mile 226 (southeast corner of map) to mile 261, just downstream from Quartermaster Canyon (fig 1). The metamorphic rocks are mostly in the middle and upper amphibolite facies. Pegmatite dikes cut these rocks throughout the area.

Exposed in canyon walls and on plateaus are Paleozoic sandstone, shale, and limestone ranging from Early Cambrian to Early Permian in age. Devonian and Mississippian rocks are the most widely exposed Paleozoic units on the surface of the Hualapai Plateau, although at many places they are covered by Cenozoic deposits. Rocks of Pennsylvanian and Permian age form the surfaces of the Sanup Plateau. The Kaibab Formation (Permian) forms the surface of the Shivwits Plateau that is in turn partially covered by Tertiary basalt flows. Strata of Ordovician and Silurian age are not present in the area of the northwestern Hualapai Reservation. Their anticipated position in the section is marked by a regional disconformity that separates rocks of Cambrian and Devonian age.

Mesozoic rocks are confined to a small erosional channel in upper Surprise Canyon on the Shivwits Plateau. These rocks consist of conglomerates of the Timpoweap Member of the Moenkopi Formation (Early Triassic age).

Cenozoic deposits, ranging from Paleocene to Holocene in age, cover much of the Paleozoic section on the Hualapai Plateau. Late Tertiary basalt and andesite basalts cover large areas of the Shivwits Plateau. In the tributary canyons of the Grand Canyon, Cenozoic rocks are limited to landslides, travertine, talus, and basalt dikes.

The oldest Cenozoic deposit in the map area appears to be a gravel located in paleo-valleys between Quartermaster and Spencer Canyons, east of Spencer Canyon. These ancient valley sediments are partially preserved by Tertiary basalt flows. The Buck and Doe Conglomerate, described by Young (1966, p. 26) consists primarily of Paleozoic clasts. The deposit is considered to be Paleocene or older in age because of its apparent stratigraphic position below gravels that, a few miles east of the map area, contain Eocene gastropods (Young, 1985).

To the south in Peach Springs and Milkweed Canyons, similar conglomerates and fanglomerates occupy a similar stratigraphic position (Young, 1966, Young and Brennan, 1974). Where Cenozoic rocks are clearly exposed in Peach Springs Canyon, the conglomerate interfingers with gravels of similar lithology east of the map area described by Koons (1948, 1964).

Miocene and older deposits are commonly covered with basalt flows and tuff of Miocene age on the Hualapai Plateau. The Peach Springs Tuff (Young, 1966, 1970, and 1979) yields an age of 18.3 million years (Damon, 1968) just south of this map. Basalt flows (Pliocene and younger) spread out over large areas of the Harrisburg Gypsifereous Member of the Kaibab Formation and over some undefined thin gravels on the Shivwits Plateau. Lag gravel deposits, younger than Miocene, consist of mixed Precambrian and Paleozoic clasts, and were formed by erosion, mixing, and redeposition of older gravel deposits as well as local erosion of Paleozoic and Precambrian rocks. These deposits are locally found in small abandoned tributary or "cutoff" drainages on the Hualapai Plateau.

A few remnants of a Pleistocene basalt flow followed the Colorado River for a distance of 74 miles from its source upstream (located at Colorado River miles 243, 246, 249, and 254, fig. 1). The travertine deposits in Meriwhitica, Spencer, and Quartermaster Canyons, and those along the Colorado River (Colorado River mile 267 to 276, fig. 1) are the largest accumulations of travertine in the Grand Canyon except for those at Havasu Canyon, southcentral Grand Canyon, Arizona.

STRUCTURAL GEOLOGY

Tectonic overview

The tectonic history of the southwestern part of the Colorado Plateau can be divided 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. (2) Paleozoic through Cretaceous time was characterized by a minimum 8,000 feet of net regional 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 which was accompanied by widespread erosion. (4) Regional uplift and erosion have continued since the Laramide orogeny, but the tectonic regime was transformed in Miocene time into one of east-west regional extension. (5) Erosion has produced the Grand Canyon during the past five million years; the dramatic topographic relief associated with it led to the development of localized gravity-tectonic features including large landslides, small gravity-glide detachments, and valley anticlines.

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 Precambrian structural setting in the region. The Paleozoic and younger rocks were 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 Late Cenozoic 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 Pleistocene and older volcanic rocks are common 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 the Late Cretaceous and Cenozoic time. Vertical uplift along the southwestern margin of the Colorado Plateau has been between 2 and 3 miles since Cretaceous sedimentation ceased. More than 3,000 feet 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 on the Plateau are spatially restricted and relatively modest in comparison.

The primary result of the uplift has been erosion. A minimum of a mile of rock has been stripped from the Hualapai Plateau since the end of Cretaceous time.

The west-flowing Colorado River was established through the region in Pliocene time (Young and Brennan, 1974). 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 great as 5,000 ft. Thus, The Grand Canyon is a late-stage and modest manifestation of the total volume of rock that has been removed from the region.

The southwest margin of the Colorado Plateau became topographically and structurally differentiated in Miocene time from the Basin and Range Province, located to the south and west (Young and Brennan, 1974). Prior to this differentiation, Mesozoic and Laramide uplift resulted in a northeastward tilting of the region including the Colorado Plateau and the adjacent Basin and Range region 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, 1964; Young, 1966). Early Tertiary arkosic sediments, comprised in part of Precambrian clasts derived from the area south of the plateau margin, cover large areas of the plateau surface east of the Toroweap fault (east of the plate 1 map area) 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 southern part of the reservation (south of the map area). Precambrian rocks were exposed along the southwestern edge of the plateau by Eocene time, indicating that more than 8,000 ft of Paleozoic and Mesozoic sediments had been eroded from that area.

Deformation of the Paleozoic rocks

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. The monoclines and the principal normal faults that dominate the structural fabric of the Hualapai Reservation developed prior to erosion of the Grand Canyon. The Laramide monoclines developed while thousands of feet of Mesozoic and upper Paleozoic rocks still blanketed the region, a conclusion supported by the ductile deformation of the Paleozoic sedimentary rocks 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 (shown on plate 1) monoclines. Laramide flexing across these folds was downward to the east with offsets as much as 2,000 ft. Individual monoclines developed over single, reactivated, west-dipping Precambrian faults. As reverse motion occurred along these basement faults, the faults propagated variable distances upward into the section as the Paleozoic rocks simultaneously folded, forming the monoclines.

Typical monocline geometry is shown on figure 2. The anticlinal and synclinal fold axes 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 exposing the basement fault under a monocline can be found along the Meriwhitica monocline on the south wall of Reference Point Canyon (plate 1).

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 indicate the locations of intersecting Precambrian faults in the underlying basement (fig. 3).

Two north-trending, east-dipping monoclines are located in the area encompassed by Plate 1, the Horse Flat monocline to the west, and the Meriwhitica monocline in the center. The Horse Flat monocline is a minor fold with a few hundred feet of structural offset. The Meriwhitica monocline is unusually well exposed, and has over 1,000 ft of offset in the map area. It is cored by a reactivated Precambrian basement fault that is well exposed along the Colorado River in the vicinity of Reference Point Canyon. The basement fault is a high-angle reverse fault, at this location, which has propagated upward into the Cambrian rocks. The cross-sectional views provided by Reference Point and Clay Tank Canyons reveal that the synclinal and anticlinal axial planes of the fold converge downward on the basement fault. Hence, the monocline is seen to die out with depth. Conversely, its width increases with elevation so that at the level of the top of the Redwall Limestone, the fold is almost 1 mile wide as measured between the anticlinal and synclinal hinges. The rocks involved in the fold deformed ductilely, demonstrating that the Paleozoic rocks were buried under a substantial thickness of overburden at the time the monocline developed. The Meriwhitica and Horse Flat monoclines were not downfaulted to the west in Late Cenozoic time, as were the Hurricane and Toroweap monoclines, to the east of the map area.

Late Cenozoic faulting

A horizontal, east-west, extensional-tectonic-stress regime was imposed

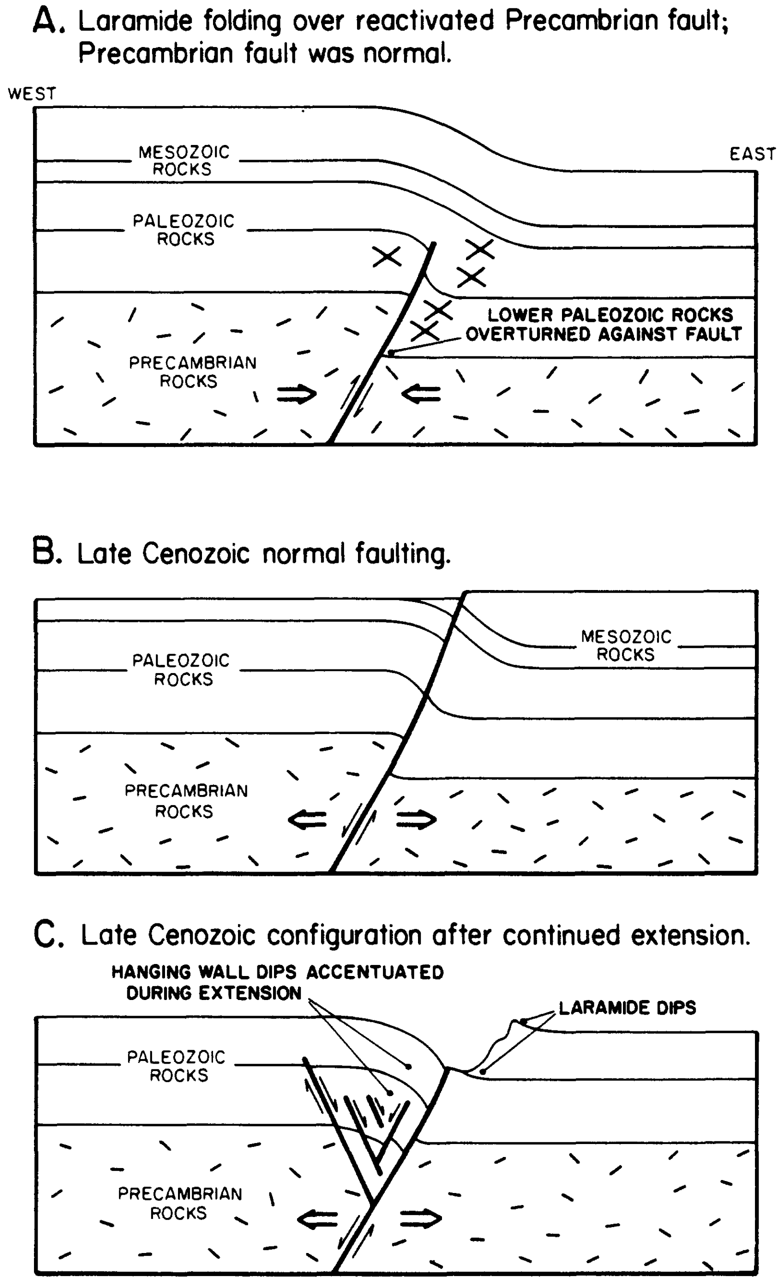


Figure 2. Diagram showing development of the Hurricane Fault Zone in the western Grand Canyon, Arizona. Small crosses in figure 2A are low angle conjugate thrust faults.

on the southwestern Colorado Plateau following Laramide compression. 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.

Cenozoic faulting on the Hualapai Plateau appears to have commenced after deposition of the early Tertiary arkoses and Miocene Peach Springs Tuff, because offsets of these units are the same as offsets of the underlying Paleozoic rocks along the faults. Fault densities increase with depth in the Paleozoic rocks indicating that many of the individual faults have propagated and die out upward from the brittle lower Paleozoic carbonates and the Precambrian basement. Offsets attenuate upward in the Paleozoic section. Slickenslides on the fault surfaces are characterized by dip-slip displacements, revealing generally east-west extension across the region, a view consistent with current fault-plane solutions for the area (Smith and Sbar, 1974).

An extensive record of recurrent movement exists along the principal faults in the region. All of the Cenozoic rock units are faulted. The best known and most complex record of recurrent faulting exists along the Toroweap, Aubrey, and Hurricane faults (east and southeast of this map). 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. For example, successively older strata exposed along the Toroweap fault exhibit progressively greater displacements near the Colorado River in Toroweap and Prospect Canyons (Davis, 1903; McKee and Schenk, 1942). At this location (Colorado River Mile 180 from Lees Ferry, Arizona), late Pleistocene alluvium on the adjacent plateau is displaced as little as 20 ft (Anderson, 1979), the underlying Paleozoic rocks 600 ft, and various Pleistocene and older lavas in Toroweap and Prospect Canyons at variable amounts between these extremes, depending upon their relative ages (Wenrich and others, 1986). Near Frazier Wells, Arizona, southeastern part of the Hualapai Indian Reservation, Paleocene (?) and Eocene gravels are displaced more than 900 feet, west-side down, across the junction of the Toroweap and Aubrey faults (Billingsley and others, 1986).

The normal faults in the map area have north-, northeast-, and northwest-trends. The greatest displacement found in the area occurs along the buried Grand Wash fault in the northwest corner of the map area. The Grand Wash fault displaced the Paleozoic strata as much as 16,000 feet at this location before being buried by the upper part of the synorogenic Miocene-Pliocene Muddy Creek Formation (Lucchitta, 1967). The age of the onset of extensional faulting along the Grand Wash fault appears to be at least as early as Miocene (Young and Brennan, 1974).

Most offsets that occur in the series of north-trending grabens east of the Grand Pipe (#288 - plates 1 and 2) in the northwest corner of the map area attenuate with depth. This relationship is revealed by the fact that the density of faults diminishes at the level of the Cambrian exposures along Lake Mead. The origin of the fault zone is east-west extension, based on the northerly strikes of the faults and vertical slickenslides found along the fault surfaces. The carbonate rocks comprising the plateau surfaces failed through brittle fracturing, whereas the underlying ductile Cambrian rocks deformed through minor attentuation of bed thickness and folding.

The Dellenbaugh fault and other lesser north-trending faults on the Shivwits Plateau are most notable because they displace Pleistocene basalt flows. The Dellenbaugh fault exhibits a record of recurrent displacements because the underlying Paleozoic rocks are is displaced more than the overlying volcanics.

BRECCIA PIPES

Introduction:

This map area of the northwestern Hualapai Reservation includes 453 breccia pipes and solution collapse features (plate 2): (1) 224 mapped collapse features are located within the reservation boundary, (2) 12 mapped collapse features are outside, but adjacent to, the western and southwestern reservation boundary, (3) 61 unmapped breccia pipes (breccia was observed within the feature) are outside of the reservation (designated with a "B"), and (4) 129 unmapped collapse features are outside of the reservation (designated with a "C"). Although the rock exposure is excellent in the map area, the massive nature of the Redwall Limestone commonly makes it difficult to recognize collapse features through inward-tilting beds on the Hualapai Plateau. Of the 453 collapse features, 12 were found to have gamma radiation in excess of 2.5 times background. None were found to have any surface exposure of copper, lead, or zinc minerals. Because all of the 224 collapse features within the reservation boundary are located on that part of the Hualapai Plateau capped primarily by the Mississippian Redwall Limestone, or occasional remnants of the Lower Supai Group, they are by our definition breccia pipes because they bottom in the Redwall Limestone. The same is true for those features mapped on the Sanup Plateau capped by the Permian Esplanade Sandstone. In contrast, some of those located on the Shivwits Plateau may well be shallower collapses that represent gypsum dissolution within the Permian Toroweap or Kaibab Formations. Further discussions on the mineralogy, geochemistry, and origin of the breccia pipes can be found in Wenrich (1985, 1986a) and Wenrich and Sutphin (in press).

Because it is difficult to distinguish breccia pipes from gypsum collapses on the flat, Permian plateau surfaces where little breccia is exposed, all mapped circular features have been placed into categories dependent on such physical characteristics (see collapse feature legend) as: (1) the presence of concentrically inward-dipping beds, (2) altered rocks (specifically, bleached and limonite-stained), (3) brecciated rock, (4) mineralized rock, and (5) circular vegetal or topographic anomalies. Clasts ranging in size from millimeters to boulders, inbedded within a finely comminuted sandstone matrix, comprise the brecciated rock; the clasts are always rock that has been dropped from an overlying stratigraphic horizon. Because the breccia pipes have probably undergone considerable flushing by ground water solutions, the matrix is generally comprised of finely comminuted sand grains with minor carbonate cement.

Delineating the exact outline of the breccia pipe in the field is difficult unless the breccia column itself is exposed. Such exposure is not uncommon along the cliffs of the Grand Canyon and its tributaries, but is rare on the adjacent plateaus. Because the brecciated column of rock within each pipe abuts against generally well-stratified, relatively undeformed sedimentary rock, the plane demarking this contact is by definition a fracture, 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 inner ring fracture. Because the inner ring fracture is well exposed in less than half of the mapped collapse features, and in order to be consistent throughout the map area, the boundaries of the breccia pipes were mapped as the outer-most extent of the inward-dipping strata.

Large Collapse Features

All known breccia pipes contain a column of breccia that is less than 300 feet in diameter; yet many collapses such as the Shadow Mountain Collapse (located 1 mi. due north of Shadow Mountain, see fig. 2, Wenrich, 1985) on the Marble Plateau and the Grand Pipe, located on the northwest corner of this map, are over one-half mile in diameter. These large collapse features exposed on the plateau surfaces are not uncommon; a good example is the Pigeon Pipe, located east of Kanab Creek on the north rim (see fig. 2, Wenrich, 1985), which is presently an operating uranium mine located on the Kaibab Plateau to the northwest. The collapse feature exposed on the plateau surface at the Pigeon mine is about one-half mile in diameter, yet the actual size of the pipe is less than 300 feet in diameter. This additional collapse above and around the breccia pipes is due to dissolution of Upper Paleozoic soluble units, such as the gypsiferous Woods Ranch Member of the Toroweap Formation and the limestone and gypsum within the Kaibab Formation. This dissolution not only results in solution collapses that may be totally unrelated to breccia pipes, complicating the breccia-pipe mapping process, but it also enhances the surface expression of those features, such as the Pigeon Pipe, that are indeed breccia pipes. Yet, this process can not explain the large collapse features on the Hualapai Plateau, Grand Pipe, or Shadow Mountain Collapse. On the Marble Plateau, where the Shadow Mountain Collapse is located, there are no extensive soluble units in the Toroweap or Kaibab Formations. In the case of the Grand Pipe (Sanup Plateau) and pipes on the Hualapai Plateau, these large collapses are below the soluble upper Paleozoic strata.

In addition to the Grand Pipe there are at least 3 other collapse features shown on Plate 2 that are over one-half mile in diameter: #387, #401, and #714. Perhaps the clue to how such large features formed lies around feature #387; collapse features #388, #389, #390, #391, #414, and #425 form a ring around the larger feature #387 (Plate 2). This same scenario occurs on the NE map (Wenrich and others, 1986) at feature #232. It appears that these large collapse features formed by a coalescing of several small solution features, or breccia pipes. If breccia pipes are present within these large collapse features it is unlikely that they are larger than 300 feet in diameter. All 3 features (#387, #401, and #714, plate 2) lie on the Redwall surface and there has obviously been significant downdropping of the overlying strata, because both #387 and #401 have Pennsylvanian redbeds preserved within their centers.

The Grand Pipe (fig. 4e, Wenrich, 1986b) is one of the best examples of how dissolution of the Redwall Limestone can result in overlying strata forming a closed depression with concentrically inward-dipping beds. Here the Esplanade Sandstone dips 3-7° concentrically inward toward the center of the feature that is filled with downdropped (along a ring fracture--shown on the Plate 1), concentrically inward-dipping (up to 30°) Hermit Shale. In places the rock is extensively bleached and stained with secondary pinkish hematite. On the north-northeast side of the pipe an outcrop with abundant black manganese oxide and limonite staining contains gamma radiation slightly in excess of two and one-half times background. Brecciated rock was also present at this location. Goethite nodules associated with celadonite are exposed within this part of the pipe. Tertiary lavas flowed from a dike down into the depression over the inward-dipping strata on the southwest side of the pipe. This is only one of 3 pipes mapped by the authors observed to have lava associated with them, but the lava is clearly younger than the collapse feature because it flowed into the depression.

Devonian and Cambrian Collapse Features:

Although no breccia pipes are known to go below the base of the Whitmore Wash Member of the Redwall Limestone, 11 collapse features have been observed in the Cambrian Muav Limestone and 7 in the Devonian Temple Butte Formation. Seven of these features contain breccia, and several form distinct brecciated columns of rock, and in fact, look similar in morphology to the Bat Cave breccia pipe (for photograph see fig. 1, Wenrich, 1985). All are located on surfaces that have been eroded below the Redwall Limestone, so it is impossible to ascertain whether they stoped above the Devonian. Nevertheless, because these are not believed at present to be related to breccia pipes that formed the economic uranium deposits they will not be referred to here as breccia pipes.

The breccia in feature #702 is cemented by clear calcite that readily forms float comprised of perfect rhombs of transparent calcite. In some of the features, such as #704 and #718, stalactitic calcite resembling that deposited as travertine from hot springs, but more crystalline, cements the breccia clasts. Neither the stalactitic nor clear calcite varieties appear to be common within the breccia pipes.

Mineralized Breccia Pipes:

None of those 12 pipes that have been labeled as mineralized on this map (Plate 2) of the northwestern Hualapai reservation contain copper, lead, or zinc minerals exposed on the surface. Ten of the 12 are located on the Hualapai Reservation, while the Grand Pipe (#288) is on the north rim along the west edge of the map area and #293 is located just west of the reservation near the top of the Grand Wash Cliffs. All of the "mineralized rock" is restricted to anomalous gamma radiation, which ranges from 15 times background in black shales of the Surprise Canyon Formation along the ring fracture zone of the Bat Cave Pipe (#360), to barely more than two times background in pipes #352 and #345. All but feature #293 have breccia exposed within them and are clearly breccia pipes. Each of these mineralized pipes show some limonite alteration and bleaching of the downdropped Watahomigi or Surprise Canyon Formations.

These mineralized pipes, with the exception of the Grand Pipe, have been stripped of all overlying strata down to the basal Supai Group (the Watahomigi

Formation) or Surprise Canyon Formation. This results in essentially little potential for economic uranium deposits, as all breccia pipes mined to date have their ore within the Permian and upper Pennsylvanian sandstones. In addition, the total volume of rock remaining in the pipe is probably insignificant to provide an economic orebody. It should be noted that none of the collapse features labeled with a "B" or "C", adjacent to a black dot, have been field checked for mineralized rock. Several of these lie on the Shivwits Plateau with a complete section of Paleozoic rocks preserved, but most of the 190 such features lie on the Sanup Plateau capped by the Esplanade Sandstone, which is a good host for uranium mineralization.

Although of little economic value, some of the mineralized pipes on the Hualapai Plateau are of scientific interest. The Bat Cave Pipe (#360) provides one of the best cross sectional views (fig. 1, Wenrich, 1985) of a breccia pipe in the Grand Canyon. Pulverized Surprise Canyon Formation black shales along the south side of the ring fracture emit gamma radiation 8 times background; bleached greenish white sandstone along the north side of the ring fracture emit counts exceeding 15 times background. Pipe #252 is adjacent to the Bat Cave Pipe on the back side of the cliff (plate 2). It almost appears as though the two may be one pipe, but the geometry suggests they are separate, but perhaps related features; most of the Bat Cave Pipe is exposed on the cliff and when its outline is drawn it does not extend through the cliff.

Pipes #340, #349, and #345 (plate 2) have abundant goethite nodules, which on the higher plateaus is a good pathfinder for mineralized breccia pipes. Perhaps these pipes originally were overlain by mineralized sandstones. Downdropped Surprise Canyon Formation in pipe #340 contains abundant limonite pseudomorphs after pyrite, silicified sandstone, bright yellow limonite staining, and anomalous gamma radioactivity associated with iron-rich areas, of 5 times background. The second most radioactive pipe in the map area is #405, which has an unusual host for the anomalous gamma counts. Gamma radioactivity reaches 12 times background along a Mn-stained bed in the Redwall Limestone. These are particularly high counts for the surface exposure of a breccia pipe, and unusual for a limestone.

The anomalous gamma radioactivity within the other mineralized pipes appears to be associated with black and green shales of the Surprise Canyon Formation. Obviously the black shales are more organic-rich than any other rock within the breccia pipes, so it is possible that this anomalous radioactivity is little more than what would be expected for black shales lying in such a permeable zone as afforded by the breccia pipes.

In addition to the 12 breccia pipes that are shown on the map as mineralized, pipe #226 is of interest. Its surface morphology provides an excellent three-dimensional view (from the air--fig. 5, Wenrich, 1985) of a closed circular depression overlying a column of breccia. Unfortunately, there is little exposure of the ring fracture and the highest gamma radioactivity emitted at the surface was only two times background. Alteration and secondary mineralization include bleaching of Watahomigi and Surprise Canyon sandstones, limonite, hematite, and goethite and specular hematite nodules. Calcite crystals and veins are common. The breccia consists of bleached sandstone in a red hematitic sandstone matrix. Fluid inclusion measurements on dolomite crystals provided filling temperatures of

140-161°C (from 5 primary inclusions). This falls within the 86-173°C range of measurements taken from sphalerite found in breccia pipe orebodies.

Structural Control of Breccia Pipes:

In contrast to the breccia pipes on the Marble Plateau (Sutphin and Wenrich, 1983) there are virtually no obvious alignments of pipes. There are 3 possible N40°E alignments (plate 1) extending through: (1) 6 features (with 3 or more within one-eighth mile of the alignment) from #324 to #345.5 to a "B" on the north rim; (2) 8 features from #385 to #413 to a "B" on the north rim; (3) 7 features from #702 to #685 to a "C" on the north rim. In addition, there is one possible N50°W alignment of 10 features from #686 to #332 to a "C" just NW of the western reservation boundary. There are two possible short N10°W to N20°W alignments between features #307 to #329 and #345 to $365. The N50°W and N40°E trends are similar in direction to those found on the Marble Plateau. For the most part though, the distribution of breccia pipes in this map area appears to be random.

Joint sets in the Redwall Limestone were found by Huntoon (p. 105, 1970) to consist of a "system of regularly spaced master joints in a rectilinear network that extends up to five miles on either side of major faults". Thus, the major joints within the Redwall along the Bright Angel fault system trend NW and NE. A study of joints on the Redwall Limestone-capped Hualapai Plateau showed that NE- and NW-trending fracture sets may have been imposed upon the Redwall Limestone prior to deposition of the overlying Pennsylvanian Supai Group (Roller, 1987). The northeast set averages approximately N50°E and the northwest set averages N45°W (Roller, 1987). It is interesting to note that those are similar orientations to the few breccia pipe alignments on this map. These northwest and northeast fractures apparently localized ground water movement during the Mississippian and exerted significant control on the development of the Redwall Limestone karst. It is also possible that some of the Redwall karst developed prior to these NW and NE fracture systems. In some breccia pipes, beds of Watahomigi Formation thicken within the pipes indicating that they were deposited into preexisting karst (Billingsley, 1986). Perhaps the dissolution responsible for the upward stoping that created the breccia pipes occurred much later, subsequent to the development of the NW and NE fracture systems. Many of the breccia pipes containing exposed beds of Pennsylvanian Surprise Canyon and Watahomigi Formations do not have obvious thickening of the beds, suggestings that the karst developed subsequent to deposition of these formations. This later development of the breccia pipes would account for why there are so few alignments of collapse features on the Redwall surface, where if anything there should be more, as none are getting "lost" by incomplete stoping to the top of the Kaibab surface. Many of the collapse features on the Hualapai surface may have formed prior to deposition of the Pennsylvanian, and perhaps were choked by Pennsylvanian sediments (Billingsley, 1986), preventing any further stoping.

Although there is not a direct association between breccia pipes and monoclines, the locations of both do appear to be controlled by basement blocks. Shoemaker and others (1978) state that major fault zones and lineaments defined by aligned cinder cones and fault traces on the Colorado Plateau show preferred northeast and northwest directional trends; they believe these observed fault systems probably extend to deep within the crust and have been active since Precambrian time. The monoclines (as stated earlier in the structural section of this report) are Laramide reactivations of such faults. Apparently the stresses exerted, and the resultant fracturing of the rocks that created the monoclines, were consistent across the 75 miles of Colorado Plateau between the Marble Plateau and the Hualapai Plateau. These basement stresses resulted in the creation of very similar shapes to the Coconino Point and Meriwhitica monoclines (fig. 3).

The breccia pipes appear to be most concentrated around the areas where the monoclines bifurcate (fig. 3). As the entire process of pipe localization predates these Laramide monoclines, this clustering of pipes along the Laramide and post-Laramide structures simply suggests that the Precambrian faults underlying and localizing these younger structures, were the same as those that aided the upward propagation of fractures important for pipe formation. Such fracturing took place long before the basement faults were reactivated to such an extent that the overlying sediments failed through faulting or folding. The similar morphology for monoclines throughout the Grand Canyon region is significant because it suggests that whatever structural control was exerted on the breccia pipes by the basement will be the same across the entire province.

Surprise Canyon Formation association with breccia pipes:

The breccia pipes, and particularly mineralized breccia pipes, tend to occur in clusters throughout northern Arizona. Seven of the 12 mineralized pipes shown on Plate 2 occur around the Bat Cave Pipe area. This is also the area of a major ancestral Surprise Canyon Formation valley. The Surprise Canyon Formation appears to be more important to breccia pipe exploration than realized in the past. Unfortunately, the locations of its valleys and tributary channels are hidden beneath most of the plateau surfaces where breccia pipes are presently being mined. More than 40% of the breccia pipes exposed in the Redwall Limestone on the Hualapai Reservation have either Surprise Canyon strata dipping into the pipe, or contain breccia of Surprise Canyon. The association of breccia pipes and Surprise Canyon valleys is probably due to both being dependent on areas of greatest discharge (creating valleys and karst). It is also probable that the solutions which mineralized the breccia pipes used the Surprise Canyon Formation as a channelway once they reached its stratigraphic horizon, migrating into those pipes that were connected by the same Surprise Canyon valley. Thus, a map of Surprise Canyon channels across NW Arizona would provide the exploration geologist with the Upper Mississippian paleogradient, and hence possibly indicate the zones of greatest breccia pipe density.

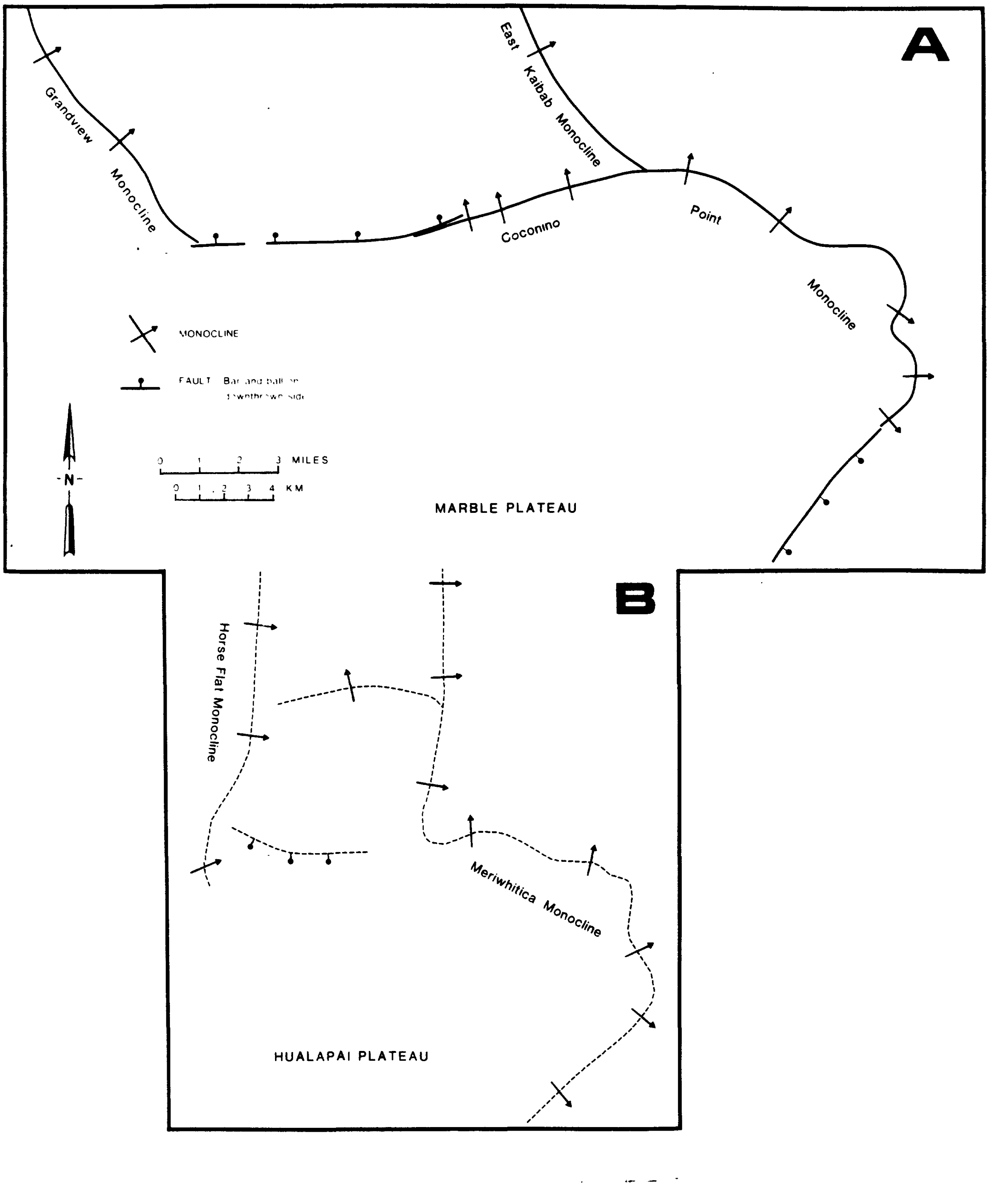


Figure 3. Map showing the similar morphology of the Coconino Point and Meriwhitica Monoclines. The Coconino Point monocline (A) is located on the Marble Plateau 75 miles to east of the map area at the eastern edge of the breccia pipe province and the Meriwhitica monocline (B) is located on the Hualapai Plateau at the western edge of the breccia pipe province (northern end is located on plate 1 and southern end on the SW map of the Hualapai reservation).

Model for Breccia Pipe Formation and Mineralization:

The breccia pipe forming process began as early as Late Mississippian time (Billingsley, 1986), shortly after deposition of the Redwall Limestone, but was completed by early Jurassic, the age of the uraninite ore (200-220 Ma, Ludwig and others, 1986). These U, Cu, Pb, Zn, Ni, Co, Ag-bearing breccia pipes may have been produced by the following sequence of events (events with the same number may have been concurrent, or their sequence is not obvious):

1a. Development of karst in the Redwall Limestone shortly after its deposition (Billingsley, 1986).

1b. Fracturing of the Redwall Limestone by two joint sets averaging N50°E and N45°W (Roller, 1987). Because ancient karst features presently exposed on the Redwall surface (Hualapai Plateau) do not form obvious NE and NW alignments, it is possible that the early Redwall karst formed prior to the development of these NE and NW joint sets.

2. Deposition of the Upper Mississippian and Lower Pennsylvanian (?) Surprise Canyon and Lower Pennsylvanian Watahomigi Formations on and within the karst surface. Much of this sediment clogged the cave passages (Billingsley, 1986) and perhaps prevented upward stoping of many filled karst features.

3a. Deposition of the overlying Paleozoic and Triassic strata up through the Chinle Formation. During the Upper Paleozoic, northwestern Arizona remained tectonically stable and flat-lying. This provided a very low hydraulic gradient and probably permitted little movement of connate waters within the sediments. Streams flowed approximately northwestward or southwestward across northwestern Arizona during parts of the late Mississippian through Permian time (Fred Peterson, written communication, 1986).

3b. Upward stoping of the Redwall Limestone caverns causing collapse and brecciation of the overlying strata. This process could have begun shortly after the close of the Mississippian and continued to stope upward throughout the Upper Paleozoic and Triassic periods; it is more likely though, that stoping did not occur until after lithification of the overlying sediment, as there is no obvious evidence for soft-sediment deformation. Thus, this upward stoping may have occurred as late as the Triassic.

(1) Joint control of the karst. The extent of the joint control on breccia pipe formation is not, as yet, clear. It has been shown that breccia pipes on the Marble Plateau are reasonably well aligned in NE and NW trends (Sutphin and Wenrich, 1983). Yet, on the Hualapai Plateau (this map) no such alignments are obvious. It is possible that much of the early karst (event #1a, above) in the Redwall may have been clogged with sediments of the Surprise Canyon and never stoped its way upward. If the NE and NW fracture pattern developed subsequent to this early karst (event #1b), then the breccia pipes might indeed align in NE and NW trends in contrast to the karst on the Redwall surface that never stoped upward. That is,

dissolution of karst features located at intersections of NE and NW fractures, might have been later reactivated. Such fractures must have localized ground water movement and exerted significant, but by no means total, control on the breccia pipe stoping process. Major faults in northern Arizona that have been periodically reactivated since the Precambrian (Huntoon, 1970), are generally oriented in the same NW and NE directions; a good example is the Mesa Butte Fault which trends NE across the Marble Plateau. Such prominent NW and NE trends suggest that the basement-induced fractures in the Redwall Limestone exerted control on the location of breccia pipes.

(2) Breccia pipe development prior to jointing in strata overlying the Redwall Limestone. A detailed joint study at the Ridenour Mine, located to the east on the NE map of the Hualapai Reservation (Wenrich and others, 1986), revealed that the breccia pipe ring fracture formed prior to any jointing in the Lower Permian Esplanade Sandstone (E.R. Verbeek, written communication, 1987). This observation was supported by work of J.A. Roller (1987) who established "that the NE- and NW-trending fracture sets (F1 and F2) in the Redwall Limestone do not have correlatives in the Supai Group." Although only studied at one location, she found that the "one station studied in the Surprise Canyon Formation suggests the possibility that the Surprise Canyon Formation contains the early F1 and F2 sets of the Redwall Limestone." If all of the above observations are correct then the sequence of events would have been as described in events #1a and #1b, and the later breccia pipe stoping (event #3b) would have been influenced by NE and NW fractures while the early karst-filled by Surprise Canyon Formation (Billingsley, 1986) would not have been. The lack of jointing in the Supai and younger rocks accounts for the circular nature to the breccia pipes rather than an elliptical morphology elongated along fractures.

4. Uplift of sediments during the Triassic. In the Triassic Period, a magmatic arc formed across southwestern Arizona and extended northwestward into southeastern California and western Nevada. Large quantities of gravel and sand were transported northwestward across northwestern Arizona by streams that originated in the uplifted flank of Precambrian and Paleozoic rocks (Mogollon Highlands) on the back or northeast side of the magmatic arc (Bilodeau, 1986). This provided a steep hydraulic gradient, for the first time since the Upper Paleozoic strata were deposited, so that any brine fluids trapped there since the beginning of the Pennsylvanian could migrate toward the center of the developing basin.

5. Development of a basin in northwestern Arizona. "There was a significant fluvial and deltaic basin in the Cameron area during deposition of the [Triassic] Shinarump, Mudstone/Sandstone, and Petrified Forest Members of the Chinle Formation. Significant fluctuations in lake level, and associated ground water level, occurred in response to both seasonal and longer-term climatic fluctuations, in part due to the tropical monsoonal climate and its long-term intensity variations. These hydrologic fluctuations resulted in significant "pumping" in the system" (Russell F. Dubiel,

written communication, 1986). This "pumping" of the hydrologic system is known to accentuate karst development today in northern Florida.

The migration of brine fluids may have also been accelerated by sudden development or enlargement of the breccia pipes during the Triassic. It is possible that there may not have been any large province of breccia pipes until the Triassic. Thus, it is possible that the sudden brecciation of the pipes during the Triassic, coupled with the uplift and steepened hydraulic gradient, provided fluids from several sources, with a highly permeable conduit for fluid movement. The hydraulic gradient would have been upward within the basin (Huntoon, 1986). The breccia pipes undoubtedly formed excellent conduits for upward movement of previously trapped connate waters from any of the Upper Paleozoic aquifers within this northern Arizona basin environment. In fact, metal-rich fluids could have also migrated upward from the Precambrian through major NE and NW fractures, into those pipes that intersect such structures--perhaps explaining the clustering of mineralized pipes. Alternatively, the Redwall Limestone and other Paleozoic aquifers were in contact with the Precambrian in the Mogollon Highlands, so that Precambrian rocks could have been the source for metal-rich fluids that migrated through the Paleozoic aquifers.

The location of the ore within the breccia pipes may well have been controlled by the local hydraulic gradient. This might explain why the ore in the Orphan mine (South Rim), located primarily in the Supai Group, is stratigraphically lower than most North Rim ores that are present near the Coconino-Toroweap contact. Perhaps the North Rim ore deposition was located more toward the center of the basin, and thus stratigraphically higher, but topographically lower.

6. Mineralization. Mississippi Valley-type deposits formed in the matrix between the breccia fragments. Metals from connate waters that were released during tilting of the rock surrounding northern Arizona, probably formed these orebodies. Depositon of the first and second stages (events #6a and #6b) of mineralization is clearly prior to uraninite deposition (Wenrich and Sutphin, in press) around 200 Ma (Ludwig and others, 1986).

a. The first stage of mineralization. Deposition of coarsely crystalline calcite, dolomite, and barite preceeded all ore mineralization

b. The second stage of mineralization. Minerals rich in Ni, Co, As, Fe, and S: siegenite, bravoite, pyrite, millerite, Fe-siegenite, cobaltian pyrite, niccolite, rammelsbergite, pararammelsbergite, gersdorffite, Co-gersdorffite, arsenopyrite, and marcasite predate the uraninite (Wenrich and Sutphin, in press). It was during this stage that the "pyrite cap" over the orebody probably formed; this cap has been instrumental in the preservation of the orebodies for the past 200 Ma.

c. The third stage of mineralization. Fe-Zn-Pb sulfides and Cu sulfides: galena, sphalerite, pyrite, lautite, chalcopyrite, enargite, and tennantite formed next. More calcite was deposited and the first signs of uraninite mineralization can be observed. Uraninite was generally precipitated later than most minerals of this stage.

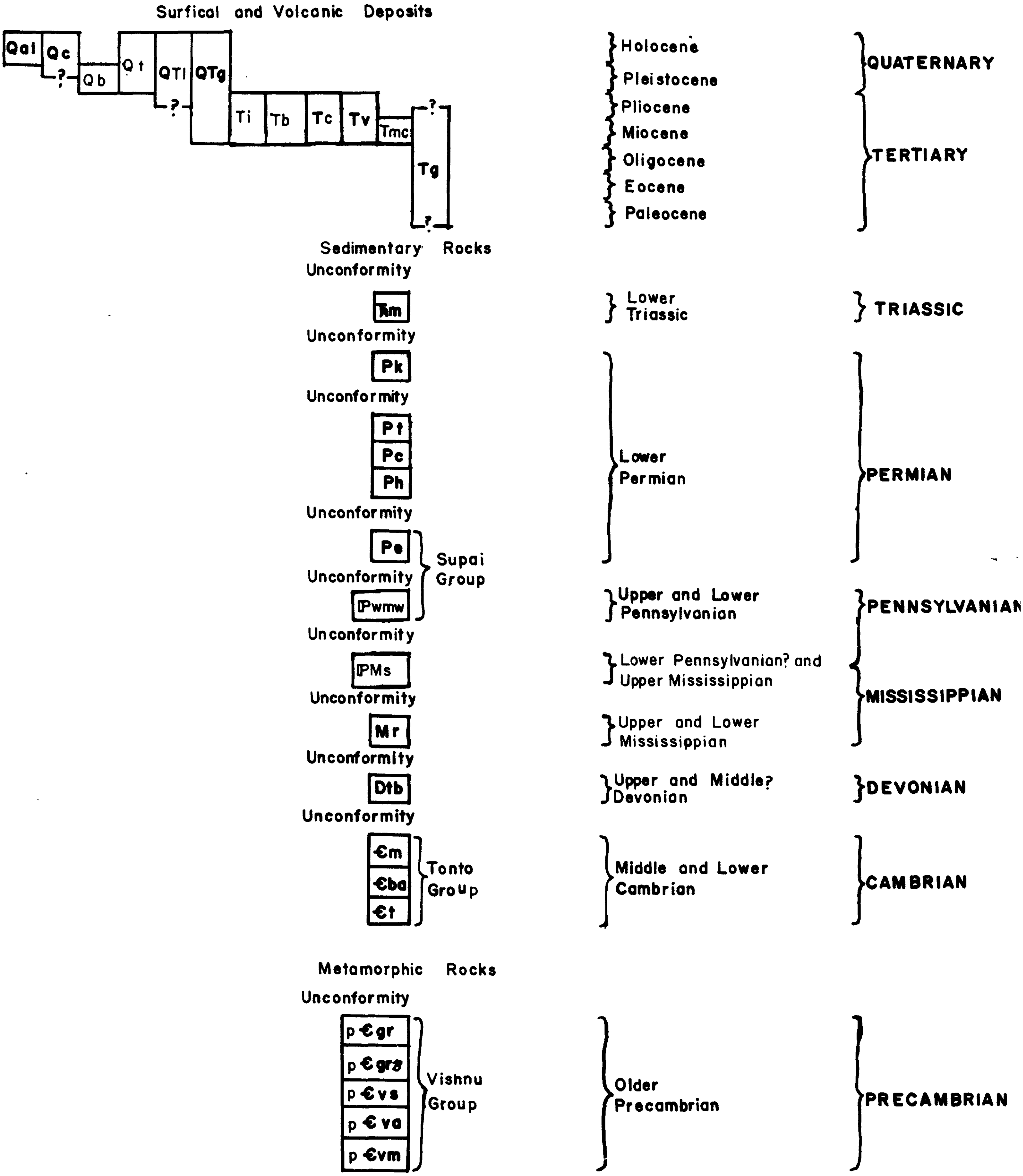
In some pipes a phase of pyrobitumen (85.6% carbon, 3.74% sulfur, and hydrogen) was introduced prior to the deposition of the sphalerite and uraninite (Wenrich and Sutphin, in press). The sulfide-rich Mississippi Valley-type ore already present in the breccia pipes would have provided an excellent reductant for any uranium being transported in oxidizing ground water. Alternatively, although hydrocarbons are well known to be poor reductants for uranium, it is possible that H_2S associated with the pyrobitumen might have been the uranium reductant as well as the reducing medium that so commonly bleached the Hermit and Supai redbeds within, or adjacent to, the breccia pipes. In any event, H_2S is convenient to appeal to as the reductant to form the barite, pyrite, Ni-Co sulfides, etc. (Gornitz and others, 1987). If so, it is peculiar that some of the pipes, such as the Orphan mine, are virtually barren of pyrobitumen. It is more likely that these hydrocarbons merely migrated from the marine sediments, as did the connate waters, subsequent to uplift, into the center of the basin and up some of the breccia pipe conduits. The pyrobitumen may well have had little to do with the uraninite precipitation, because the Mississippi Valley-type ores are more abundant and consistently available as a reductant within all uranium-mineralized pipes.

The uraninite age of 200-220 Ma (Ludwig and others, 1986) suggests a possible Jurassic or Triassic source rock. Although no Triassic or Late Permian volcanic rocks have been identified in the region that now makes up the ancestrial Mogollon highlands, much mapping and age determinations need to be made on rocks from this part of Arizona. It is possible that the uranium source rocks were Precambrian granites exposed in the Mogollon highlands. As with the connate waters, movement of ground water from these highlands through any of the aquifers would have been toward the center of the basin and then up the breccia pipes.

7. <u>Oxidation of some of the orebodies.</u> Later oxidation of the breccia pipe orebodies occurred, particularly along the edge of the Colorado Plateau, such as at the Grand Gulch mine (located about 10 mi. NNE of the Grand Pipe), and in the Basin-and-Range at breccia pipes such as the Apex mine (located in the Beaver Dam Mountains of SW Utah). It appears that the uraninite and sulfide-rich orebody remained intact until the pyrite cap was destroyed. This occurred most extensively along the western edge of the breccia-pipe province, the Grand Wash Cliffs. Canyon dissection during the past several million years has permitted downward percolation of oxidizing ground water removing the pyrite cap and oxidizing the orebody. Such minerals as malachite, azurite, brochantite, cyanotrichite, chrysocolla, hemimorphite, smithsonite, metazeunerite, and goethite formed in these secondary zones of mineralization.

Regions farthest from the margin of the Colorado Plateau, particularly those on the high plateaus capped by the Kaibab, Moenkopi, or Chinle Formations, such as the Coconino Plateau on the NE and SW maps of the Hualapai Reservation (Wenrich and others, 1986, Billingsley and others, 1986), appear to have better preservation of uranium orebodies. Thus, even if the orebodies of breccia pipes on the Hualapai Plateau had not been eroded away, chances are that the ore would have been oxidized and the uranium carried away by ground water.

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Surficial and Volcanic Deposits

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

Qc **Colluvium (Holocene and Pleistocene?)**--Consists of brecciated rock fragments, boulders, gravel, sand, and silt; partially consolidated with a gypsiferous or calcareous cement; includes alluvial fan deposits; intertongues with landslide debris. Faults shown bounding colluvium do not offset colluvium

Qb **Basalt flows (Pleistocene)**--Olivine basalt, exhibits radial and columnar cooling joints along the Colorado River (Colorado River mile 243, 246, 249, and 254)

Qt **Travertine deposits (Holocene and Pleistocene)**--Spring deposits of calcium carbonate with incorporated angular boulders, gravel, sand, and silt of adjacent talus deposits

QTl **Landslides (Holocene, Pleistocene, and Pliocene?)**--Unsorted and unconsolidated material; consists mainly of large blocks of Paleozoic sedimentary rock that have rotated and presently dip toward the base of the parent wall. On the Shivwits Plateau, consists of a jumbled, unconsolidated mixture of basalt, andesite, and beds of the Harrisburg Gypsiferous Member of the Kaibab Formation

QTg **Younger Gravels (Miocene? and Younger)**--Well rounded gravel, sand, and silt from older gravel deposits of Precambrian and Paleozoic clastic material mixed with angular chert and limestone clasts derived from local outcrops of Cambrian to Pennsylvanian rocks. Clasts are matrix supported with some calcium cement. Includes the Willow Springs Formation of Young (1966, p. 26). Commonly covered by thin colluvium or caliche

Ti **Intrusive volcanics (Miocene and Pliocene)**--Alkali olivine basalt and andesitic dikes and plugs

Tb **Basalt and andesitic basalt flows (Miocene and Pliocene)**--Basalt and andesite flows on the Shivwits Plateau surrounding the Blue Mountain and Mount Dellenbaugh areas

Tc **Basaltic cinders (Miocene and Pliocene)**--Basalt cinder cones on the Shivwits and Hualapai Plateaus

Tv **Volcanic deposits (Miocene and Pliocene)**--All volcanic deposits on the Hualapai Plateau; includes the Peach Springs Tuff of Young (1966 and 1979); basalt flows, agglomerate, fluvial volcanic-bearing sediments, and coarse-grained pyroclastics near vent areas

Tmc **Muddy Creek Formation (Miocene)**--Poorly consolidated to well-consolidated, poorly bedded deposits of light gray conglomerate, fanglomerate, interbedded with pinkish-tan siltstone, mudstone, and sandstone. Thickness unknown, probably several thousand feet

Tg **Unnamed fanglomerate and undifferentiated gravels, undivided (Paleocene? through Pliocene?)**--Conglomerate, breccia, fanglomerate, gravel, sand, and silt. Fills older drainages and valleys on the Hualapai Plateau. Includes the Music Mountain Conglomerate and Buck and Doe Conglomerate, undivided of Young (1966, p. 26). The lag gravels make it difficult to distinguish the correct stratigraphic sequence in areas of low relief. Unconformable on Cambrian, Devonian, Mississippian, and Pennsylvanian rocks

Sedimentary Rocks

TRm **Moenkopi Formation (Lower Triassic)**--Timpoweap Member - Light gray and pale reddish-gray conglomerate; consists of reddish-gray siltstone and sandstone matrix with light gray, rounded, fossiliferous limestone and chert cobbles up to 5 inches diameter. Clasts are derived locally from the Kaibab Limestone and are matrix supported; occupies erosional channels within the Kaibab Limestone, forms a cliff up to 100 feet thick

Unconformity

Pk **Kaibab Formation (Lower Permian)**--Harrisburg Gypsiferous and Fossil Mountain Members undivided. The Harrisburg is a yellowish-gray to pale-red shale, red sandstone and gypsiferous gray siltstone interbedded with gray to yellow-gray fossiliferous limestone, dolomitic sandstone and silicified chert beds; and thick layers of gray-white gypsum; forms alternating cliffs and slopes where exposed, forms a slope covered by landslide blocks of Tertiary basalt along the eastern edge of the Shivwits Plateau; ranges from zero to just over 350 ft thick. The underlying Fossil Mountain Member consists of a light-gray, cherty limestone and sandy dolomite and limestone forming a cliff averaging 250 ft in thickness

Unconformity

Pt **Toroweap Formation (Lower Permian)**--Woods Ranch, Brady Canyon and Seligman Members undivided. Top to bottom, the Woods Ranch consists of 90 to 100 ft of slope forming, gypsiferous, pale-red and gray siltstone and sandstone with some thin-bedded dark-gray limestone; locally absent along canyon walls of the Shivwits Plateau where dissolution has occurred. The Brady Canyon Member is a cliff forming, medium-bedded, dark- to light-gray fossiliferous limestone averaging just over 200 ft in thickness. The Seligman Member is a 30 to 70 ft thick, thin-bedded, yellowish-white to pale-red, sandstone, that forms a slope or recess in cliff

Pc **Coconino Sandstone (Lower Permian)**--Light-brown to yellowish-red, fine-grained, large-scale cross-stratified sandstone; forms a small cliff or ledge, locally absent or discontinuous in western half of map area but averages 100 ft thick along the southeastern edge of the Shivwits Plateau

Ph **Hermit Shale (Lower Permian)**--Slope forming, red-brown and white, thin-bedded, fine-grained, siltstone and sandstone; mostly covered by colluvium. Average thickness is 700 ft in eastern half of map increasing to nearly 1,000 ft along western edge of map

Unconformity

Supai Group (Permian and Pennsylvanian)

Pe **Esplanade Sandstone - Pakoon Limestone (Lower Permian)**--The basal Esplanade is a slope forming, pale-red to reddish-orange, thin-bedded siltstone and sandstone, less than 50 ft thick followed by a middle cliff of pale-red, cross-stratified, medium- to fine-grained, medium-bedded sandstone that intertongs with thick-bedded gray, fossiliferous limestone of the Pakoon Limestone. The Pakoon Limestone beds, eastern edge of map area, are commonly 10 ft thick interbedded with cross-bedded sandstone and becomes thicker towards the north-west edge of map forming a sheer cliff about 200 ft thick. The Pakoon is overlain by nearly 100 ft of ledge forming sandstone followed by about 200 ft of slope forming, red siltstone capped with a white to pale-red, fine-grained sandstone ledge of the upper Esplanade Sandstone. Thickness averages 400 ft along eastern edge of map, increasing to just over 500 ft along northwestern edge of map

Unconformity

Ꝑwmw Lower part of Supai Group: Wescogame, Manakacha, and Watahomigi Formations, undivided (Upper, Middle, and Lower Pennsylvanian)

Wescogame Formation (Upper Pennsylvanian)--Pale-red to gray siltstone, shale, and limestone interbedded with grayish-red calcareous sandstone; forms a slope in upper part, cliff in lower part. Average thickness is 130 ft

Unconformity

Manakacha Formation (Middle Pennsylvanian)--Reddish-brown, fine-grained, thick-bedded, cross-bedded sandstone interbedded with gray, medium-grained, cross-bedded dolomite and thin-bedded gray limestone; contains a few thin red-brown shales. Forms a sequence of slopes and ledges upper part and a cliff in lower part. Thickness is about 200 ft east edge of map, increasing to about 250 ft northwest edge of map

Unconformity

Watahomigi Formation (Lower Pennsylvanian)--A purple-gray to gray siltstone and fine-grained sandstone interbedded with gray, thin- to medium-bedded limestone with red chert lenses that forms a series of ledges in a slope. A purple siltstone with a few conglomerates and thin-bedded limestone beds occur near the base. A thick-bedded gray fossiliferous limestone in the lower part thickens westward and forms a cliff. Average thickness is 200 ft

Unconformity

ⅣMs **Surprise Canyon Formation (Lower Pennsylvanian? and Upper Mississippian)**--Consists of an upper slope and ledge forming dark red-brown, thin-bedded, fine-grained siltstone and sandstone and laminated thin beds of silty limestone; a middle cliff forming yellowish-gray, coarsely crystalline silty, crumbly, thin-bedded, fossiliferous limestone; a basal ledge or slope of chert pebble conglomerate, clasts supported with a dark red-brown to black iron-stained sandy matrix; deposited within caves and stream-eroded valleys on the underlying Redwall Limestone. Thickness ranges from a few feet to 400 ft

Unconformity

Mr **Redwall Limestone (Upper and Lower Mississippian)**--From top to bottom, Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members undivided. All members form a continuous sheer cliff with a slight recess at the contact between the Horseshoe Mesa and Mooney Falls Members. All four members consists of a light-gray, thick-bedded, aphanitic limestone and dolomite; contains marine fossils throughout. White chert bands are common in the Thunder Springs Member. Thickness ranges from about 300 to as much as 700 ft

Unconformity

Dtb **Temple Butte Formation (Upper and Middle? Devonian)**--Interbedded dark-gray to purple-gray, medium-bedded dolomite, dolomitic sandstone, sandy limestone, reddish-brown siltstone, and gray siltstone; forms a series of ledges averaging 450 ft in thickness

Unconformity

Tonto Group (Cambrian)

€m **Muav Limestone (Middle Cambrian)**--Mottled gray and purple dolomitic thin-bedded limestone that weathers a rusty gray. Includes white to light-gray beds of unclassified dolomites between Muav Limestone and Temple Butte Formation. Limestone ledges and small cliffs are separated by tongues of slope-forming green shale lithologically similar to underlying Bright Angel Shale. Lower contact with Bright Angel Shale is at base of Rampart Cave Member of Muav Limestone (McKee and Resser, 1945). Averages 900 to as much as 1,200 ft in thickness

Ꞓba **Bright Angel Shale (Middle Cambrian)**--Green and purplish-red fissile siltstone interbedded with light-brown to reddish-brown, coarse-grained, thin-bedded sandstone beds of Tapeats lithology and rusty-brown dolomitic tongues of the Muav Limestone. A very coarse-grained, purple-red sandstone (redbrown sandstone member of McKee and Resser, (1945), forms a cliff about the middle of the unit. Lower contact with the Tapeats Sandstone is arbitrarily placed at or near the top of Tapeats Sandstone cliff. Lower part contains abundant thin beds of light-brown, sandstone of Tapeats lithology. Forms a slope nearly 350 ft thick

Ꞓt **Tapeats Sandstone (Middle and Lower Cambrian)**--Light-gray to light-brown, and red-purple, medium- to coarse-grained, medium-bedded sandstone and small-pebble conglomerate. Silica cement gives appearance of quartzite; has low-angle crossbedding and thin green-shale partings between beds in upper part; forms a cliff that ranges in thickness from 100 to as much as 200 ft

Unconformity

Metamorphic Rocks

Vishnu Group (Older Precambrian)

pꞒgr Nonfoliated granitic plutons -- brown to light-red holocrystalline, quartz-bearing granite pluton

pꞒgr Foliated granitic plutons -- light colored, coarse-grained plutonic granite with feldapar and mafic minerals

pꞒvs Mica schist -- mica and quartz, schistose foliation, mainly muscovite and biotite

pꞒva Mafic schist and amphibolite -- very fine grained, foliated dark-colored minerals; also amphibole and plagioclase with little or no quartz

pꞒvm Paragneiss -- granular feldspar and quartz alternating with lenticular micaceous layers and fine-grained amphibole minerals

pꞒu Precambrian undivided -- brown to reddish-brown, holocrystalline, quartz-bearing granite plutons, very fine-grained foliated schist, gneiss, and quartz-feldspar pegmatites

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