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

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

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INTRODUCTION

The map area (fig. 1) encompasses 660 square miles of the southeastern part of the Hualapai Indian Reservation, along with a small portion of the Grand Canyon National Park (western edge of map), and private and state lands that border the southeastern Reservation (fig. 2). The map area is in that 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.

Hundreds of solution collapse breccia pipes are found in the Hualapai Indian Reservation as well as in the canyons and on the plateaus across much of northwestern Arizona. Many of the pipes contain uranium-mineralized rock along with anomalous concentrations of Ag, Co, Cu, Mo, Ni, Pb, and Zn. On this southeastern map, 218 confirmed and suspected breccia pipes and collapse features have been mapped; of these, approximately 8% display surface expression of mineralized rock, (recognizable Cu minerals, principally malachite, azurite, or brochantite), or have gamma radiation 2.5 times above background levels.

This research was funded by the Bureau of Indian Affairs in cooperation with the Hualapai Tribe in the hope of stimulating mining interest on Hualapai lands that might result in additional income for the Hualapai people. The entire 1550 mi^2 Hualapai Reservation has been mapped geologically at a scale of 1:48,000, and has been divided into 4 separate map areas (NE, SE, NW, and SW). Within the Reservation, all breccia pipes and collapse features have been accurately mapped to scale. Outside the Reservation, pipes were not mapped in detail, and these are shown simply as black dots but not to scale (Huntoon and Billingsley, 1981, and this project). Although outside of the Reservation, several collapse features that are particularly well defined were mapped as part of this study, and these have accurately depicted boundaries. Most of the pipes and collapse features are developed in strata that overlie the Mississippian Redwall Limestone.

The escarpment of the Aubrey Cliffs forms the boundary between the Coconino Plateau (north and northeastern sections of map area) and the Aubrey Valley (southeastern map area, fig. 2). The Aubrey Valley, a broad alluviated plain which buries any underlying breccia pipes, is bounded on the west by the Blue Mountain fault. West of the Aubrey Valley is a broad irregular plateau of low relief that breaks off into canyons along the Hurricane Fault. Although few breccia pipes have been mapped east of the fault, this area holds the greatest potential for economic breccia pipes within the southeastern part of the reservation. The Grand Canyon and its tributaries are in the west and northwest sections of the map area. Elevations range from 1340 feet at the Colorado River to 7392 feet at Manzanita on the Aubrey Cliffs north of Diamond Creek, giving a maximum relief of 6,052 feet in the map area.

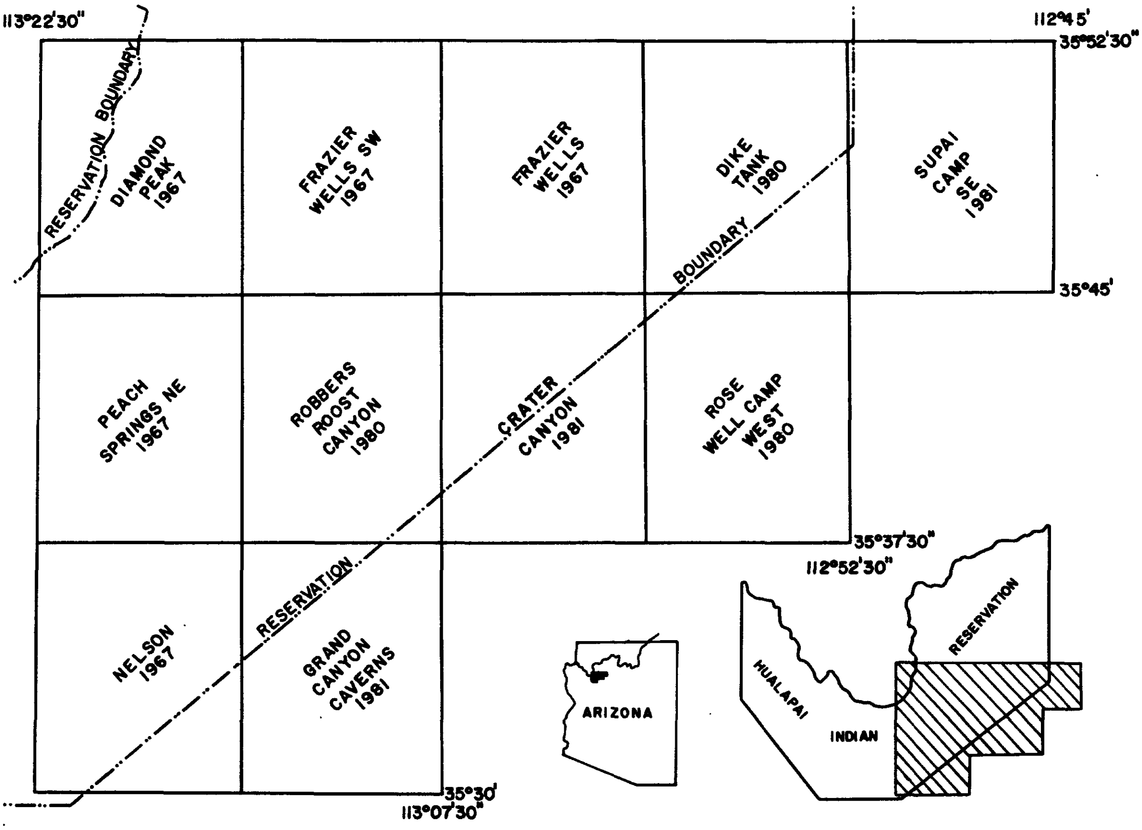

FIGURE 1. Location map of quadrangles mapped for the southeastern Hualapai Indian Reservation, Arizona (all quadrangles are 7-1/2 minute scale).

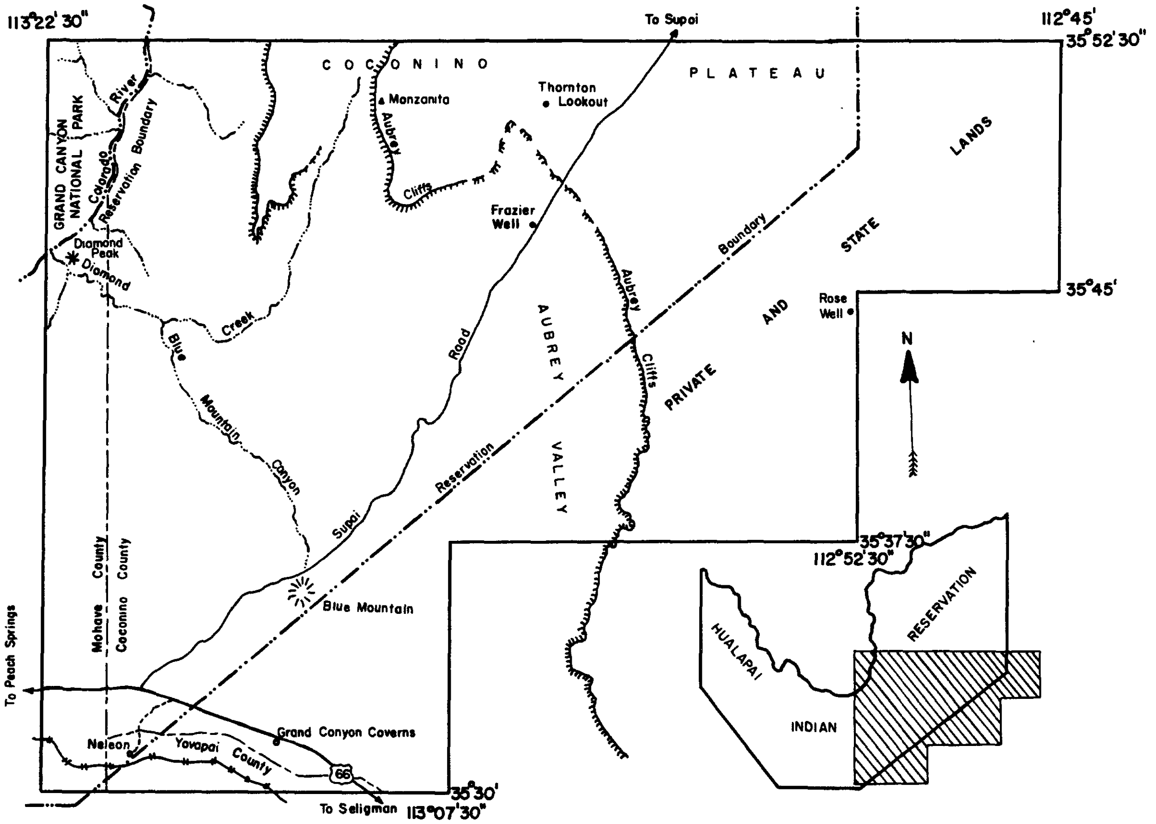

FIGURE 2. Geographic map of the southeastern Hualapai Indian Reservation, Arizona.

This report includes two plates, one with geology, including the breccia pipes coded into categories, and another 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 sinkholes was done on 1:24,000 color aerial photographs. Each feature mapped was surveyed by helicopter or vehicle; more than 90% of the structures were field checked by radiometric traverses. Any features not field checked were those located in the Redwall Limestone that have little economic potential.

GEOLOGIC SETTING

The oldest exposed rocks in the map area are Precambrian granites, schists, and gneisses, that are exposed along the Colorado River and Diamond Creek drainages (west-central map area). These rocks reveal various degrees of metamorphism, mostly in the middle and upper amphibolite facies. Pegmatite dikes are also found, mainly in the Diamond Creek area.

Exposed in canyon walls and plateau areas, are Paleozoic sedimentary strata consisting of various deposits of sandstone, shale, and limestone that accumulated from Early Cambrian to Early Permian time. The most widely exposed Paleozoic unit is the resistant Kaibab Limestone of Permian age, which forms the surface of the Coconino Plateau. Rocks of Pennsylvanian and Mississippian age cropout locally in the Aubrey Valley and southwestern part of the map area, although at many places are covered by Cenozoic deposits. Strata of Ordovician and Silurian age are not present in the area of the southeastern Hualapai Reservation. Their anticipated position in the section is marked by a regional disconformity that separates rocks of Cambrian and Devonian age.

Cenozoic deposits, ranging from Paleocene to Holocene in age, cover much of the Paleozoic section on the plateaus and in the large upland valleys. In the tributary canyons of the Grand Canyon, Cenozoic deposits are limited to landslides, travertine, and talus. The oldest Cenozoic deposit in the map area appears to be a gravel located in a mile-wide paleo-valley. This ancient valley is now preserved on a high ridge east of Diamond Creek (center of the map area). This gravel consists of Paleozoic clasts, designated Robbers Roost Gravel as described by Koons (1948, p. 58). The deposit is considered to be Paleocene or older in age because of its apparent stratigraphic position below gravels a few miles east of the map area containing Eocene gastropods (Young, 1985). Other similar Paleozoic clastic deposits of the area described by Koons (1948) lie near headward reaches of Blue Mountain Canyon and Diamond Creek, but are not assigned the name Robbers Roost Gravel on this map, because they are more fanglomeritic than the fluvial deposits on the higher plateau. The gravel clasts near Blue Mountain and Diamond Creek incorporate brecciated talus fragments in fanglomerates that flank ancient plateau escarpments formed by local Paleozoic strata. These fanglomerates accumulated at lower elevations than the fluvial Robbers Roost Gravels on the plateau to the east. Regionally, the fanglomerates and fluvial gravels occur at differing elevations, but they may represent contemporaneous events in a valley-scarp relationship. Just to the west in Peach Springs Canyon, fanglomerates with similar characteristics occupy a similar stratigraphic position (Young, 1966, Young and Brennan, 1974). Where detailed stratigraphy is clearly exposed in Peach Springs Canyon, the fanglomerate invariably interfingers with gravels of similar lithology to the Frazier Wells Gravel described below.

Gravel deposits consisting only of Precambrian clasts, dominated by granite, schist, gneiss, and quartzite, are found north of Blue Mountain, at Frazier Well, and around Thornton Lookout Tower (fig. 2). These deposits were designated Frazier Wells Gravel by Koons (1964, p. 100), and his terminology is adopted on this map. The Frazier Wells Gravel is overlain by basalt flows of the Blue Mountain volcano that are 14.6 million years old (Damon, 1968), suggesting the gravels are Miocene in age, possibly Eocene or Paleocene. Sediments of similar lithology occur throughout the Hualapai and Coconino Plateaus and have been shown to be no younger than Eocene (Young, 1985). The Frazier Wells Gravel north of Blue Mountain interfingers with, and overlies, the unnamed fanglomerates in upper Blue Mountain Canyon drainage, which make the fanglomerates approximately contemporaneous, or slightly older than, the Frazier Wells Gravel. However, Frazier Wells Gravel at Frazier Wells and southwest of Thornton Lookout, are deposited in a wide valley that is inset into the Robbers Roost Gravel. Thus, regionally, the Frazier Wells Gravel is apparently younger as well as approximately equivalent in age to both the Robbers Roost Gravel and related fanglomerates. Extensive lag gravel, deposits younger than Miocene, consist of mixed Precambrian and Paleozoic lithologies, which are formed from erosion, mixing, and redeposition of older pre-existing gravel deposits and local erosion of Paleozoic strata.

STRUCTURAL GEOLOGY

Tectonic Overview:

The tectonic history of the northeastern part of the Colorado Plateau can be subdivided into five broad episodes for the purposes of this report. (1) The Precambrian interval was a very complex period of mountain building that culminated in an uplifted, deeply eroded metamorphic complex. (2) Paleozoic through Cretaceous time was characterized by 8,000 to 13,000 feet of regional subsidence and comparable sediment aggradation in which the land surface fluctuated within a few hundred feet of sea level. (3) The Laramide orogeny, herein used in a broad sense to include Late Cretaceous through Eocene events, resulted in regional uplift and north-northeast crustal compression accompanied by widespread erosion. (4) Regional uplift and erosion have continued since the end of the Laramide orogeny, but the tectonic regime has transformed into one of regional extension. (5) The Grand Canyon has eroded during the past five million years and the dramatic topographic relief associated with it has allowed for the development of localized gravity tectonic features including large landslides, gravity-glide structures, and valley anticlines.

The Hualapai Reservation contains a remarkable record of reactivated, pre-existing 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, dominate the late Precambrian structural fabric in the region. The Paleozoic and younger rocks are deformed by (1) Laramide monoclines that overlie and are cored by reverse faults, and (2) the superimposed post-Laramide system of normal faults. The Laramide monoclines are crustal shortening features that generally overlie reactivated Precambrian normal faults; the sense of motion along these reactivated faults reversed during Laramide compression. The principal post-Laramide normal faults also faithfully followed reactivated Precambrian trends; however, extension in the region has progressed to such an extent that numerous new normal faults have developed through the section to produce complex extensional fault zones. Normal faulting continues in the region today and has resulted in the development of extensional basins. Faulted Quaternary alluvium is common along the Hurricane and Toroweap Faults, as are faulted Pleistocene and older volcanic rocks throughout the region.

Cenozoic Uplift and Erosion:

When considering the tectonic events in the Hualapai Indian Reservation, one can be overwhelmed by the scale, quality of exposure, and clarity of the record of recurrent movements associated with the monoclines and faults. However, no activity since the close of Mesozoic time has been as important or great as was the regional uplift that took place during the Cenozoic. The vertical uplift has been between 2 and 3 miles since Cretaceous sedimentation ceased, with the greatest elevation occurring along the southwestern margin of the plateau. More than 3,000 feet of uplift at the Grand Wash Cliffs occurred in the last 5 million years (Lucchitta, 1979), indicating that rates of uplift accelerated during late Cenozoic time. Individual offsets along the largest faults and monoclines are spatially restricted and modest in comparison.

The primary result of the uplift has been erosion. A minimum of a mile of rock has been stripped from the plateaus since the end of Cretaceous time. The Grand Canyon is a late stage and rather modest manifestation of the total volume of rock that has been removed from the region.

The west-flowing Colorado River did not develop through the region until Pliocene time (Young and Brennan, 1974). Once it was established, continued uplift resulted in rapid incision of the Colorado River and development of the Grand Canyon topography that dominates the present scene. Topographic relief on the Hualapai Reservation between the present plateaus and Colorado River is now as much as 7,000 feet.

The southwest margin of the Colorado Plateau became topographically and structurally differentiated from the Basin and Range Province, located to the south and west, in Miocene time (Young and Brennan, 1974). Prior to this, the uplift that accompanied the Laramide orogeny resulted in a northeastward tilting of both the Colorado Plateau and the Basin and Range to the south, and drainage was toward the northeast across what is now the Colorado Plateau margin. Large volumes of Cretaceous and older rocks were stripped from the entire region between late Cretaceous and Oligocene time, and the detritus was transported northeastward across the Hualapai Indian Reservation into Utah, in a system of incising pre-Colorado River streams (Young, 1982).

Sedimentary and topographic relicts 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, (northeast and southeast maps) and floor paleochannels to the west. Prominent remnant paleovalleys are preserved under a veneer of Eocene and younger sedimentary and volcanic rocks in Hindu, Milkweed, and Peach Springs Canyons (southwest map), and in two prominent meander loops and older hanging valleys directly east of Peach Springs Canyon (southeast map). The Precambrian rocks were exposed along the southwestern edge of the plateau by the end of Eocene time, indicating that as much as

9,000 to 13,000 feet 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 were imprinted during Laramide compression and post-Laramide extension. Extension is continuing at present. The monoclines and the principal normal faults that dominate the structural fabric on the Hualapai Reservation were emplaced before the Colorado River eroded 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 limestones that are now exposed along the monoclines.

Laramide Monoclines:

The Laramide monoclines developed in response to a stress regime in which the maximum principal stresses were oriented E-NE (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 as much as 1,500 feet. Individual monoclines developed over single, reactivated, west-dipping Precambrian faults. As reverse motion occurred along the basement fault, the fault propagated variable distances upward into the section as the Paleozoic sediments simultaneously folded, forming the monoclines.

Typical monocline geometry is shown on figure 3, in which the anticlinal and synclinal hinges of the fold converge with depth on the underlying fault, and wherein the Paleozoic sediments 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 exists in the north wall of Three Springs Canyon located on the northeast map. The surface expression of the structure cartooned in figure 3 can be seen in the northwest corner of the map, where extensive normal faults lie to the northwest of the Toroweap monocline. In contrast, very little normal faulting occurred on the lower limb of the monocline to the east.

The Hurricane monocline dies out in Three Springs Canyon, which lies north of this map. This 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-down segment of this fault did not undergo sufficient post-Laramide normal displacement to change the sense of throw across the fault. However, this post-Laramide downfaulting to the north was great enough to completely undo the Laramide displacement, thus causing the fault to scissor near 122-Mile Canyon. The Hurricane Monocline is cored by a single reverse fault at the level of the Precambrian basement and is also severed by a later normal fault that utilized the same basement fault

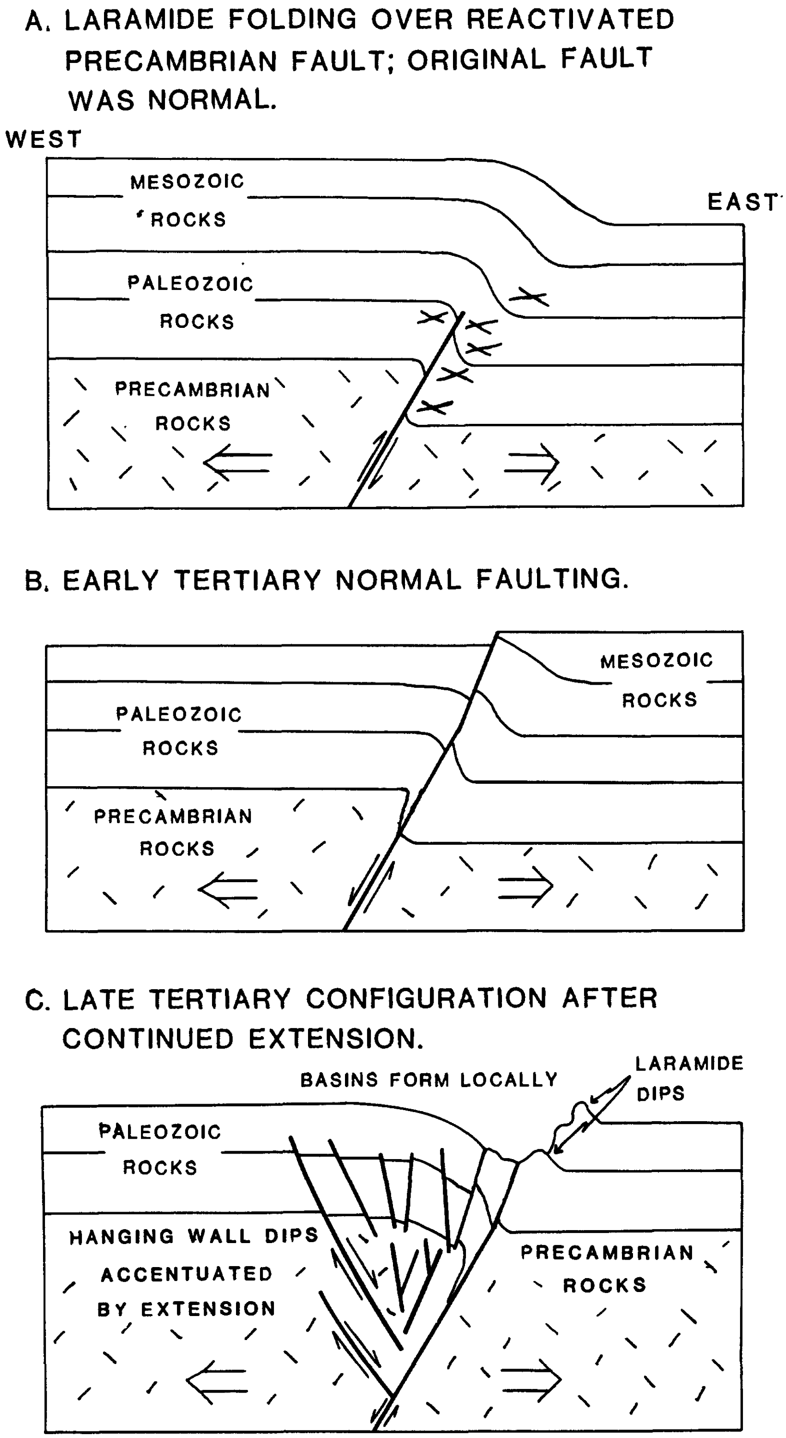

FIGURE 3. Structural cartoon of cross sections showing the stages in the development of the Hurricane Fault zone in the western Grand Canyon, Arizona. Small crosses in figure 3A are low angle conjugate thrusts.

plane at all locations on this map. Post-monocline, normal displacements are generally greater than the reverse displacements associated with the monoclinal folding. Precambrian green schists that formed in the plane of the Hurricane fault in small canyons north of Diamond Peak reveal a Precambrian history of 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 the Laramide strain (Huntoon, 1981). An abrupt change in strike and branching of the monoclines reveals the locations of intersecting Precambrian faults in the underlying basement. Such locations may well be good exploration targets for breccia pipes. An example located in the southeastern Hualapai Reservation is the Blue Mountain/Diamond Creek area, which contains an unusually dense concentration of breccia pipes.

The Toroweap Monocline consists of two aligned segments in the map area, one north of Diamond Canyon and the other southwest of Blue Mountain. The fact that the exposed Laramide monoclines in the region generally overlie reactivated Precambrian faults reveals that Precambrian basement complexities precluded development of the fold in the Blue Mountain/Diamond Creek area. Post-monocline normal fault patterns having northwest and east-northeast trends at this location indicate the likely presence of intersecting basement faults with identical trends. 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. On the southwest side of this area the Toroweap fault changes strike.

Post-Laramide Faulting:

An extensional tectonic stress regime was imposed on the southwestern Colorado Plateau following Laramide compression. This regime is still operating and has resulted in extensive normal faulting of the plateau, and tectonic differentiation of the plateau from the adjacent Basin and Range Province to the west.

Normal faulting in the map area appears to have commenced after deposition of the early Tertiary arkoses and Miocene Peach Springs Tuff based on the displacement of these units along the faults. Outcrop relationships revealing the lack of pre-Miocene faulting are particularly well exposed along the Hurricane Fault zone in the headward reaches of Peach Springs Canyon (southwest map).

Extension on the Hualapai Reservation has produced hundreds of normal faults, primarily located west of the Aubrey Monocline, with displacement ranging up to about 2,400 feet. The initial result of the extension was to fault the monoclines and downdrop the western blocks in a sense opposite to the monoclinal displacement. In each case, the post-Laramide normal displacement across the faults exceeded the Laramide reverse displacement. Also, the post-Laramide faulting extended greater distances along strike. This resulted in successive stepping down of blocks across the region from east to west (fig. 3c).

As extension progressed, faulting involved larger areas of the plateau surface. For example, the Hurricane Fault zone now occupies a 10-mile wide band, through the center of the Hualapai Reservation, and is characterized by intersecting northeast- and northwest-trending normal faults and grabens. Fault densities 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. Slickensides on the fault planes reveal dominant dip-slip displacements. They generally reveal east-west extension across the region. This is supported by Wong and Humphrey (1986) who state 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. 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 and most complex records of recurrent faulting in the map area exist along the Toroweap, Aubrey, and Hurricane Faults. In fact, so continuous has been post-Laramide faulting in the region that the number of discernable motions along these faults is limited only by the number of discrete Cenozoic units deposited across the fault planes.

Early Tertiary fanglomerates are displaced by more than 900 feet, 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 Canyon. Similarly, early Tertiary arkoses are downfaulted to the west as much as a 200 feet along the northern part of the Aubrey Fault. In addition, Quaternary alluvial fans exhibit small west-down displacements along the Aubrey Fault immediately south the map area, creating rather fresh looking fault scarps.

Paleogeographic Reconstructions:

An east-west profile across the center of the map area in Laramide time would have passed through no 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. However the post-Laramide surface was not flat. Rather, the presence of partially buried 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 northward along what is now the Aubrey Cliffs and curved northwestward toward the Colorado River at a point north of Diamond Canyon. The Aubrey Monocline stepped the Permian surface down to the east. To the west the Hurricane and Toroweap Monoclines had no topographic expression in the Blue Mountain/Diamond Creek area.

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

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

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. The early Tertiary canyons were filled with arkoses which permitted overland spills. These overland spills caused dissection of the Redwall surface along the fractures across the divides. This capture mechanism implies the presence of fractures in the Paleozoic section, despite the fact that neither the 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, which was coincident with development of the Hurricane Monocline farther to the north along strike. Other fractures were probably emplaced during Paleozoic and Mesozoic subsidence.

The north-flowing early Tertiary drainage through Peach Springs Canyon had to breach the Mogollon escarpment north of the map area. Those streams discharged into developing sedimentary basins on the Colorado Plateau in Utah. The northward region dip had to be approximately one degree 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 218 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, while others may be shallower collapses that represent gypsum dissolution within the Permian Toroweap Formation or Kaibab Limestone. In addition, there are numerous sink holes in the Kaibab surface that are readily discernable in the field from both the Redwall Limestone collapses (referred to here as breccia pipes) and the gypsum collapses by their steep vertical walls and floors covered by large blocks of rubble. The sink holes appear to be relatively recent, probably less than 2.4 m.y. (Wenrich and Billingsley, 1986). Because the age of the uranium mineralization is around 200 m.y. (Ludwig and others, 1986), and because mineralized rock has only been found in the breccia pipes, these other features appear to have no value for 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 the gypsum collapses, all circular features have been placed into categories dependent on such physical characteristics (see collapse features legend) as the presence of: (1) concentrically inward-dipping beds, (2) altered rock (specifically bleached and limonite stained), (3) brecciated rock, (4) mineralized rock (defined here as anomalous gamma radiation in excess of 2.5 times background or visible Cu minerals), and (5) circular vegetation patterns or topographic depressions. The brecciated rock is comprised of clasts ranging in size from millimeters to boulders embedded within a finely comminuted sandstone matrix. The clasts are always from a source rock which has been downdropped 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 quartz with minor calcareous cement.

Delineating the exact outline of the breccia pipe in the field is difficult unless the breccia column itself is exposed. Such exposure is rare in the southeastern map area. 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 (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 inner ring fracture. Because this 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 outer-most extent of inward-dipping beds or circular feature. It should be recognized that the surface area affected by solution collapse can be as much as 5 times the diameter of the actual breccia pipe due to lateral dissolution of the Toroweap and Kaibab.

The initial mapping was done on 1:24,000 color aerial photographs. Every feature mapped was surveyed by helicopter, or field vehicle if accessible within a mile from a road; over 90% of the structures were field checked by radiometric traverses across the feature. All of the 10% that were not field checked were collared in the Redwall Limestone, and hence have little economic potential because the overlying sandstones that commonly host the ore deposits were removed by erosion.

Structural Control of Breccia Pipes Located on the Southeastern Map:

Over 80% of the collapse features in the southeastern part of the reservation lie in the Blue Mountain/Diamond Creek area (fig. 4), and are exposed in either the Redwall Limestone or Supai Group and thus cannot be Toroweap or Kaibab collapses. Most of these collapse features fall into the C2 category (inward dipping beds) and lack a surface expression of brecciated or mineralized rock. The Blue Mountain/Diamond Creek area (fig. 4) 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 these breccia pipes in the Blue Mountain/Diamond Creek area were formed prior to 200 m.a., as are the ore grade breccia pipes (Ludwig, 1986), then it appears that present areas of major ground water circulation may be similar to those prior to 200 m.a. Many structures within the Hualapai Reservation, such as the Hurricane and Toroweap Faults, have been active since the Precambrian. Within the Blue Mountain/Diamond Creek area several major faults intersect, such as the Toroweap, Diamond Creek, and Blue Mountain Faults. Since ground water tends to follow extended 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 since the Precambrian. 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 it was true during the Mississippian and Pennsylvanian. Thus, areas of high spring discharge may well be good exploration areas for the discovery of large concentrations of breccia pipes.

No perfect correlation exists between the locations or alignments of breccia pipes and the principal faults and folds which deform the Paleozoic host rocks in the map area. However, populations of pipes tend to cluster in bands, or in some cases trends containing up to 12 pipes in straight lines, that follow or parallel existing fault trends or prominent lineaments. Some of the breccia pipes located in the Blue Mountain/Diamond Creek area are aligned along NW and NE 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 3 very convincing alignments similar to those on the Marble Plateau: (1) 7 breccia pipes are aligned in a perfectly straight row starting with the large mineralized brecciated pipe at the Blue Mountain Arch and trending SW; (2) Approximately 0.75 mi to the E of the first trend is a parallel, but longer, trend through another 7 pipes, and (3) crossing these two trends, just N of the Blue Mountain Arch, at about 70°, a NW-SE trend can

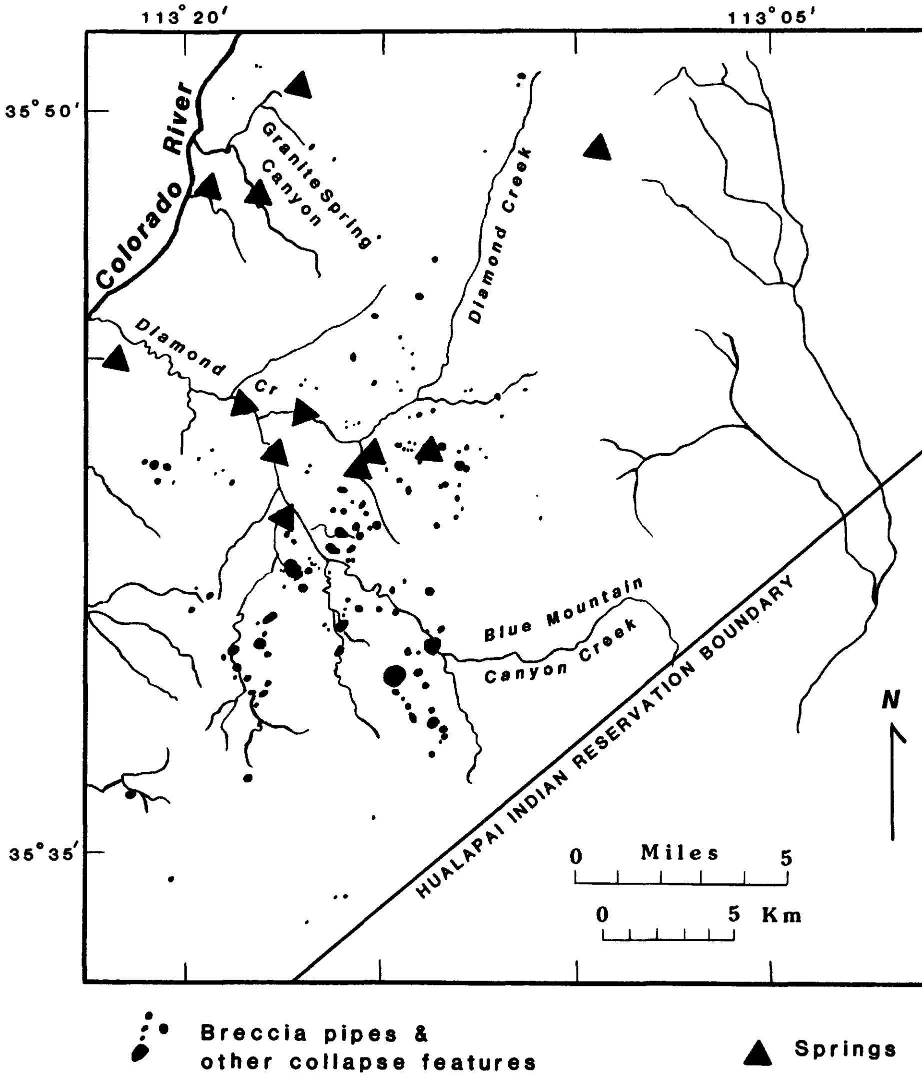

FIGURE 4 Breccia pipes and springs located in the Blue Mountain/Diamond Creek area. This map shows all pipes found on the reservation within the boundaries of this diagram. Note the concentration of most pipes in the area of major discharge.

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 4 NNW perfectly straight alignments of 5 to 9 pipes, which coincide with the strikes of the numerous normal faults in the region.

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

The mechanism for this structural control of the breccia pipes involves the underlying Precambrian fault zones acting as structural hinges during the long Paleozoic through Cretaceous interval of subsidence and sedimentation. Specifically, 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. 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 even the Laramide monoclines. Consequently, the presence of clusters of pipes along Laramide and post-Laramide structures simply suggests that the Precambrian faults underlying and concentrating those younger structures probably 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.

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

One of the major problems in uniform mapping of collapse features is contrasting vegetation density and types across the reservation. From the Toroweap Monocline across to the Aubrey Cliffs the vegetation is dense, particularly around Frazier Wells where tall Ponderosa Pines dominate the landscape. This region of the map contains no mapped collapse features, but this 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 are covered by Cenozoic gravel deposits and alluvium. Further to the east the landscape becomes dominated by junipers and grasslands. Still there are few collapse features. On the other hand, there are also few major structural features here.

The SE part of the reservation contains 7 breccia pipes with exposed mineralized rock. Of these, 6 are located in the Blue Mountain/Diamond Creek area. All 6 contain anomalous gamma radiation >2.5, but <5, times background. No Cu 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 6 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 4 such features on the Hualapai Reservation. Other than the Orphan Pipe, none of the known orebodies have such features; on the other hand, none of the others are exposed at the Coconino level, which is the host rock for these silicified breccias.

The Blue Mountain Pipe:

The seventh mineralized pipe on the SE map is the Blue Mountain Pipe which was drilled from 1976-1978 by Western Nuclear and in 1984 by the U.S. Geological Survey (Van Gosen and Wenrich, 1985). The potential for sufficient uranium reserves for an orebody is excellent, although no drill holes have delineated more than low grade (<0.02% U_3O_8) uranium, which was encountered at a depth of about 400 feet below the Coconino-Hermit Shale contact at the surface. 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 protrudes as a 130′ spire above the canyon floor. Malachite, azurite and chrysocolla can be observed on the spire, as can strikingly attractive liesegang-banded sandstone blocks. Additional drilling might reveal an orebody.

Collapse Features with Economic Potential on the Southeastern Map:

One collapse feature, #562, mapped in 1982, but located off of the reservation, was drilled in 1984 and 1985 by Rocky Mountain Energy. Similar features with a raised slightly bleached rim of Harrisburg Member of the Kaibab Limestone surrounding a soil covered low center, are found to the north on the NE map of the reservation. Features #564 (on this map, but off the reservation next to #562), #534, #569, and #570 appear similar (photos of these features are shown in Wenrich and others, in press). Although all 4 of these features are in the C4 category (circular topographic or vegetation anomalies) 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, 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 sufficient trace metal halo above the ore body to prevent the growth of trees. Likewise, it is possible that those circular features with increased vegetation growth (specifically trees) may merely represent sink holes, or unmineralized collapse features, which 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 2 breccia pipes. Collapse feature #1104 forms a circular reddish soil patch, which may represent alteration at the surface, or downdropping of redder Harrisburg Member into cream- to white-colored units. Feature #1117 is located off of the reservation and is a curiosity. It represents an area of dipping beds that appear to be inwardly dipping. Breccia containing abundant pyrolusites also present. No other breccia pipes are known to contain significant Mn anomalies.

There are very few favorable features on the SE map that 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. It too is off of the reservation, but only by one-half mile. It represents a circular grassy patch surrounded by inward dipping beds of the Toroweap Formation and by trees.

Conglomerate Cave:

One interesting feature with little economic potential is a sink hole, feature #1103, in the Robbers Roost Gravels, known locally as Conglomerate Cave. A funnel-shaped hole descends vertically through 220 feet of Robbers Roost conglomerate cemented by calcite. These gravels lie on the Esplanade Sandstone, so a hole of this magnitude could only have been dissolved within the underlying Redwall Limestone. The vertical, open nature of the hole suggests that at least some of the collapse must have been recent, although the walls are covered with well-cemented conglomerate that must have been there prior to collapse. The Robbers Roost Gravels are Cenozoic and probably older than 14.6 m.a. as mentioned earlier.

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 that are mapped into the C4 category. Most pipes within the cluster on the western side are collared in the Redwall Limestone or Supai Formation and hence have little overlying host rock for a uranium ore body. The Blue Mountain Pipe, located to the 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 breccia plug (see the northeast map description of the silicified plugs for an explanation).

The Mississippian Surprise Canyon Formation (Billingsley and Beus, 1985) appears to be more important to breccia pipe exploration than realized in the past. More than 40% of the breccia pipes exposed in the Redwall Limestone have either beds of the Surprise Canyon Formation dipping into the pipe, or contain breccia derived from the Surprise Canyon. The Surprise Canyon channel-fill sediments obviously followed the Mississippian drainages. This was also the area of greatest spring discharge (where the hydrostatic heads converged), and hence greatest dissolution of the Redwall Limestone. Thus, the map of Surprise Canyon channels (in preparation by Billingsley) across NW Arizona will provide the exploration geologist with the Mississippian paleogradient, and hence probably zones of greatest breccia pipe density.

DESCRIPTION OF MAP UNITS

SURFICIAL AND VOLCANIC DEPOSITS

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

Qd Dune sand (Holocene and Pleistocene?)--Coarse to very fine sand, stabilized by moderately dense vegetation. Includes combinations of parabolic dunes, complex linear dunes, and sand sheet deposits

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

Qtg Terrace deposits (Holocene? and Pleistocene)--Fluvial deposits interbedded with basalt flows and talus deposits several tens of feet above the Colorado River; contains abundant angular to rounded boulders, gravel, sand, and silt; poorly sorted and partially consolidated

Qbc Basaltic cinder deposits (Holocene? and Pleistocene)--Basaltic cinder fragments with olivine phenocrysts in most deposits; glassy, black or red (oxidized) in color

Qb Basalt flows (Holocene? and Pleistocene)--Olivine basalt, exhibits radial and columnar cooling joints along the Colorado River

QTt 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 Older)--Unsorted and unconsolidated material; consists mainly of Paleozoic sedimentary rock that has rotated and presently dips toward the base of the parent wall

QTg Younger gravels (Miocene? and Younger)--Reworked conglomerates (lag gravels), sand, gravel and silt from older gravel deposits consisting of locally derived Paleozoic clasts mixed and reworked with some Precambrian quartzite clasts. Commonly covered by thin colluvium

Tb Basalt (Pleistocene? and Older)--Basaltic lava flows of the Blue Mountain and Nelson areas. The Blue Mountain volcanics, 14.6 million years old (Damon, 1968) overlie fanglomerates and other gravel deposits

Tmf Mount Floyd-Round Mountain Volcanics (Pliocene and Miocene?)--Alkali olivine basalt flows (Koons, 1964, p. 111)

Ti Intrusive volcanics (Pliocene and Miocene?)--Alkali olivine basalt

Unconformity

Trr Robbers Roost Gravel (Paleocene? and Eocene?)--Consists of consolidated, rounded to subrounded (fluvial) and angular pebbles and boulders, up to 2 ft. in diameter, of Coconino Sandstone, Toroweap Formation, and Kaibab Limestone lithologies (Koons, 1948, p. 58). Clasts are matrix supported with calcium carbonate cement. Forms resistant rounded hills in a valley on the plateau east of Diamond Creek. Maximum thickness is 200 ft

Tfw Frazier Wells Gravel (Paleocene? and Eocene)--Originally called Blue Mountain Gravel by Koons (1948, p. 58). Unit was renamed Frazier Wells Gravel by Koons (1964, p. 100). Consists of unconsolidated pebbles and boulders of well-rounded granite, gneiss, schist, and red and white quartzite, up to 20 in. in diameter; matrix supported, consisting of uncemented, coarsely textured, arkosic sandstone and siltstone; forms gently rounded hills and slopes. In the vicinity of Rose Well, gravel, sandy siltstone, and silty limestone similar to Frazier Wells Gravel are exposed under basalt lava flows of the Mount Floyd-Round Mountain Volcanics (Koons, 1964, p. 111). Dated as Middle Eocene or older by correlation to similar gravel and limestone section 30 km east of map area at Long Point (Young, 1985). Variable thickness up to 120 ft

Tg Unnamed fanglomerate and other undifferentiated gravels, undivided (Paleocene?, through Miocene)--Includes gravels consisting entirely of Precambrian lithologies, Paleozoic lithologies, or combinations of both types but does not contain clasts typical of the type section of Robbers Roost Gravel or Frazier Wells Gravel. In places these deposits underlie gravels produced by the reworking of Robbers Roost and Frazier Wells Gravel and thus are commonly covered by a thin deposit of alluvium, lag gravel, or caliche. The lag gravels create problems in distinguishing the correct stratigraphic sequence in areas of low relief. The largest deposit of well-cemented fanglomerate fills a valley in upper Diamond Creek and Blue Mountain Canyon less than 120 ft thick

STRATIGRAPHIC UNITS

Unconformity

Pk Kaibab Limestone (Lower Permian)--Harrisburg Gypsiferous Member and Fossil Mountain Member 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; forms alternating cliffs and slopes along canyon rims and a nearly flat surface on the Coconino Plateau; averages 125 feet thick. The underlying Fossil Mountain Member consists of a light-gray, cherty limestone and sandy limestone that forms a cliff. A silicified, intraformational, fossiliferous chert breccia is present along the Aubrey and Toroweap Faults. The Fossil Mountain member averages 250 feet in thickness

Unconformity

Pt Toroweap Formation (Lower Permian)-Woods Ranch, Brady Canyon, and Seligman Members undivided - Top to bottom: the Woods Ranch consists of a 90-100 foot interval of slope-forming, gypsiferous, pale-red and gray siltstone and sandstone with some thin-bedded dark-gray limestone; locally absent along canyon walls where dissolution has occurred. The Brady Canyon Member is a cliff-forming, medium-bedded, dark- to light-gray fossiliferous limestone averaging 200 feet in thickness. The Seligman Member is a 30 foot thick, thin-bedded, yellowish-white to pale-red sandstone, and 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 cliff along canyon walls and a resistant slope along the margins of Aubrey Valley. Thickness averages nearly 175 feet

Ph Hermit Shale (Lower Permian)--Slope-forming, red-brown, fine-grained, thin-bedded siltstone and sandstone; mostly covered by colluvium. Average thickness is 500 feet

Unconformity

Supai Group (Permian and Pennsylvanian)

Pe Esplanade Sandstone (Lower Permian)--Pale-red to reddish-orange cross-stratified, medium- to fine-grained, medium-bedded sandstone. Interbedded with thick beds of slope-forming sandy siltstone in upper and lower most parts of a generally cliff-forming unit; also contains within the middle and upper sandstone beds gray, thin-bedded limestone tongues of the Pakoon Limestone that pinch out eastward. Thickness averages nearly 450 feet

Unconformity

Ps Wescogame, Manakacha, and Watahomigi Formations undivided (Pennsylvanian)--

Wescogame Formation--Red to pale-red siltstone and shale interbedded with grayish-red calcareous sandstone; forms a slope in upper part, cliff in lower part. Average thickness is 150 feet

Unconformity

Manakacha Formation--Reddish-brown, thick-bedded, fine-grained sandstone and crossbedded sandstone; interbedded with thin-bedded gray limestone and dolomite, and red-brown shale. Forms a sequence of slopes and ledges about 200 feet thick

Unconformity

Watahomigi Formation--Gray calcareous siltstone and fine-grained sandstone interbedded with gray, thin- to medium-bedded limestone that forms a series of ledges in a slope. A purple siltstone with a few conglomerate and thin-bedded limestone beds occur near the base. Limestone beds commonly contain red and white chert lenses or bands. Average thickness is 150 feet

Unconformity

Msc Surprise Canyon Formation (Upper Mississippian)--Consists of a basal ledge of chert pebble conglomerate, clasts supported with a dark red-brown to black iron-stained saniy matrix; a middle cliff-forming, yellowish-gray, coarsely crystalline silty, crumbly, thin-bedded, fossiliferous limestone; an upper dark red-brown, thin-bedded, fine-grained siltstone and sandstone and laminated thin beds of silty limestone forming slopes and ledges; depositional within caves and stream-eroded valleys on the underlying Redwall Limestone. Thickness ranges from a few feet to 300 feet

Unconformity

Mr Redwall Limestone (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 consist 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 400 feet to as much as 650 feet

Unconformity

Dtb Temple Butte Limestone (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 400 feet in thickness

Unconformity

Tonto Group (Cambrian)

Ꞓm 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 Peach Springs Member of Muav Limestone (McKee and Resser, 1945). Averages 800 to 900 feet in thickness

€ba 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 (Red-Brown Sandstone Member of McKee and Resser, 1945), forms a cliff at about the middle of the unit. Lower contact with the Tapeats Sandstone is arbitrarily placed at or near top of Tapeats Sandstone cliff. Lower part contains abundant thin beds of light-brown, sandstone of Tapeats lithology. Forms a slope nearly 380 feet thick

€t 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 cross-bedding and thin green-shale partings between beds in upper part; forms cliff that ranges in thickness from 100 to 200 feet

Unconformity

Vishnu Group (Older Precambrian)

P€gr Non-foliated Granitic Plutons (Precambrian)--Brown to light-red holocrystalline, quartz-bearing granite pluton

P€vs Mica Schist (Precambrian)--Mica and quartz, schistose foliation, mainly muscovite and biotite

P€va Mafic Schist and Amphibolite (Precambrian)--Very fine grained, schistose-foliated; dark-colored minerals, also amphibole and plagioclase with little or no quartz

P€vm Paragneiss (Precambrian)--Granular feldspar and quartz alternating with lenticular micaceous layers and fine-grained amphibole minerals

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