UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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

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INTRODUCTION

The Hualapai Indian Reservation, located on the southwestern corner of the Colorado Plateau, is host to hundreds of solution collapse breccia pipes (Wenrich, 1985), as is most of 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 minerals, most notably malachite, azurite, or brochantite, or gamma radiation in excess of 2.5 times background. Despite periods of depressed uranium prices, the breccia pipes have commanded considerable exploration activity because of their high grade uranium deposits. As of 1986, 10 breccia pipes have been, or will soon be, mined for uranium in northern Arizona, all with an average grade in excess of 0.4% U_3O_8. The Orphan Mine (fig. 1) was a major operation producing 495,107 tons of uranium ore (average grade of 0.4% uranium oxide), 6.68 million pounds of copper, 3,400 pounds of vanadium oxide, and 107,000 oz of Ag between 1956 and 1969 (Chenoweth, 1986). Because of its location in Grand Canyon National Park and the associated environmental restrictions, the unmined portions of the orebody will probably never be recovered. Small tonnages of U ore were removed from the Ridenour (located on the Hualapai Reservation - this map) and the Riverview Mines during the 1950's (fig. 1). The Hack 1, Hack 2, Hack 3, and Pigeon pipes were put into production during the early 1980's and the Kanab North, Canyon and Pinenut pipes (fig. 1) will probably go into production within a year or two.

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 mapped at a scale of 1:48,000, and has been divided into 4 separate maps: NE, SE, NW, 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. Outside of the reservation, pipes were not mapped in detail. Many of these pipes were taken from Huntoon and Billingsley (1981), and are shown as black dots whose boundaries were not mapped and are not shown to scale. Several collapse features outside of the reservation which were particularly well defined, were mapped as part of this study; they are shown with pipe numbers and have accurately mapped boundaries. With the exception of the Supai Group, all formations have been mapped as individual units. As can be observed from the maps, with the exception of several pipes in the Muav Limestone and an unnamed Cambrian unit in the area of Meriwhitica Canyon (NW map), all pipes are collared in the Mississippian Redwall Limestone or overlying strata. None of the Cambrian pipes have been observed to stope above their host formation; on the other hand, the overlying strata have been eroded off in the Meriwhitica Canyon area, the only place where these pipes have been recognized.

Each of the 4 maps of the Hualapai Reservation contains 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.

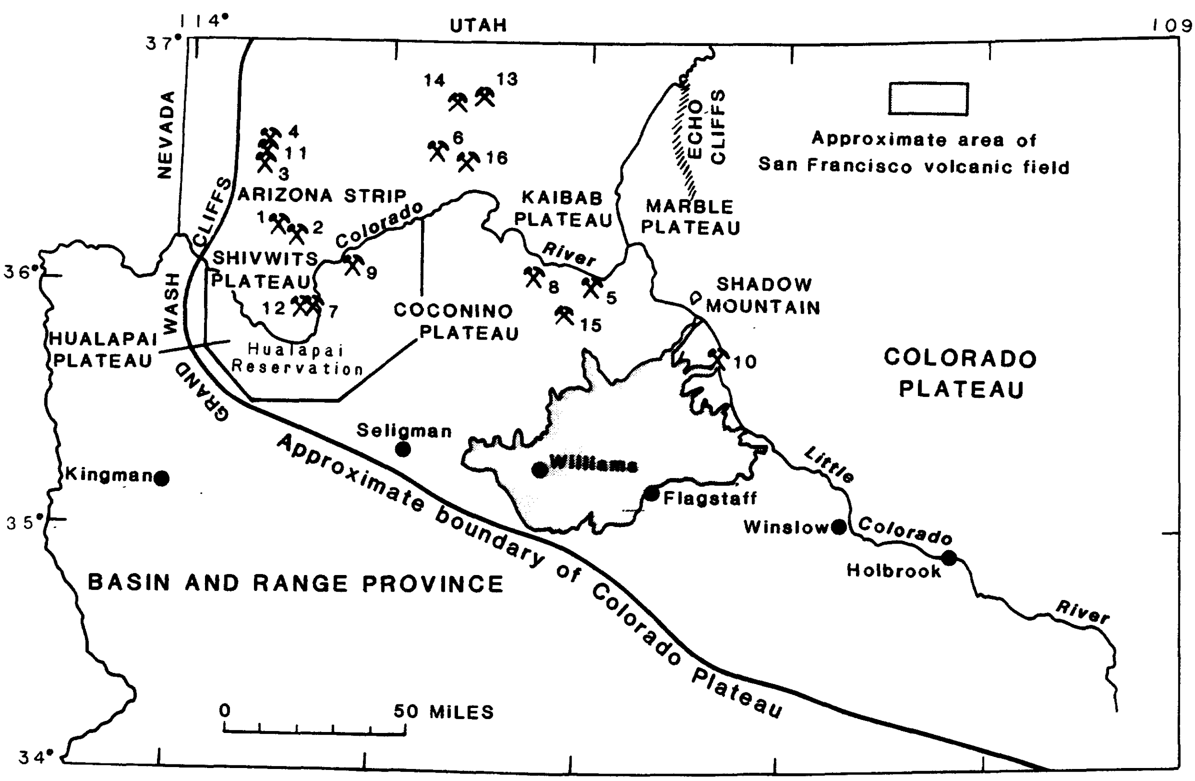

FIGURE 1. Index map of northern Arizona showing the location of plateaus, Hualapai Indian Reservation, breccia pipes developed into mines, and the San Francisco volcanic field which buries terrane with high potential for breccia pipes. Numbers refer tc the following mines: (1) Copper House, (2) Copper Mountain, (3) Cunningham, (4) Grand Gulch, (5) Grandview, (6) Hack Canyon, (7) Old Bonnie Tunnel, (8) Orphan, (9) Ridenour, (10) Riverview, (11) Savannic, (12) Snyder, (13) Pigeon, (14) Kanab North, (15) Canyon, and (16) Pinenut.

Geologic setting of the northeastern Hualapai Indian Reservation and vicinity, Arizona

The map area encompasses approximately 870 mi^2 (fig. 2) of the northeastern portion of the Hualapai Indian Reservation, Grand Canyon National Park (western and northern edge of map), NW corner of the Havasupai Reservation, private, and state lands bordering the eastern Reservation boundary (fig. 3). The map area occupies part of the southwestern Colorado Plateau geologic province that is dissected by the Colorado River forming the Grand Canyon. The boundary between Mohave and Coconino Counties is located down the middle of the Colorado River (fig. 3).

The Grand Canyon separates the Coconino Plateau (southeastern half of map) and the southern edge of the Uinkaret and Kanab Plateaus (northern edge of map). The Coconino Plateau is a broad irregular plateau of low relief that is broken by two major faults along the western edge that form prominant west-facing scarps. The canyons of the Colorado River occupy the west and northeastern sections of the map (fig. 3). Elevations range from 1400 ft at the Colorado River (southeast corner of map) to 7240 ft on the east side of Prospect Valley (southern edge of map). The Grand Canyon has a maximum depth of 5,765 ft at the southern edge of the map.

Precambrian metamorphic granites, schists, and gneisses are exposed along the Colorado River at Granite Park, (southern edge of map) and one mile south of Whitmore Canyon (fig. 3). Paleozoic strata exposed in the walls of Grand Canyon and on adjacent plateaus were deposited from Middle and early Cambrian to early Permian time. Mesozoic deposits of the Moenkopi Formation (Lower and Middle Triassic) occur at two localities on the Coconino Plateau; (1) opposite points at the north end of Prospect Valley and (2) on top of an isolated mesa north of Granite Park (fig. 3). The Moenkopi occupies erosional channels cut into the Permian Kaibab Limestone. The Unikaret Plateau is largely covered by Quaternary basalt flows and cinders (Hamblin, 1970). Southern portions of the Coconino Plateau are partly covered by Cenozoic gravel deposits (Oligocene? Miocene, Pliocene?, and Holocene).

The Cenozoic gravels on the Coconino Plateau are divided into two distinct lithologies; gravels consisting of Precambrian clasts only (granites, schists, and quartzites) and gravels that consist of mixed Precambrian and upper Paleozoic clasts. The Precambrian clastic gravels are designated Frazier Wells Gravel as described by Koons (1964, p. 100) and adopted on this map. The mixed gravel deposits are inferred to be younger deposits of Tertiary? and Quaternary age eroded from Frazier Wells Gravels and the weathered surface of the Coconino Plateau, (i.e. Kaibab clasts). Cenozoic deposits within the Grand Canyon area consist of landslides, travertine, terrace gravels, basalt flows, and talus (Pliocene?, Pliestocene, and Holocene).

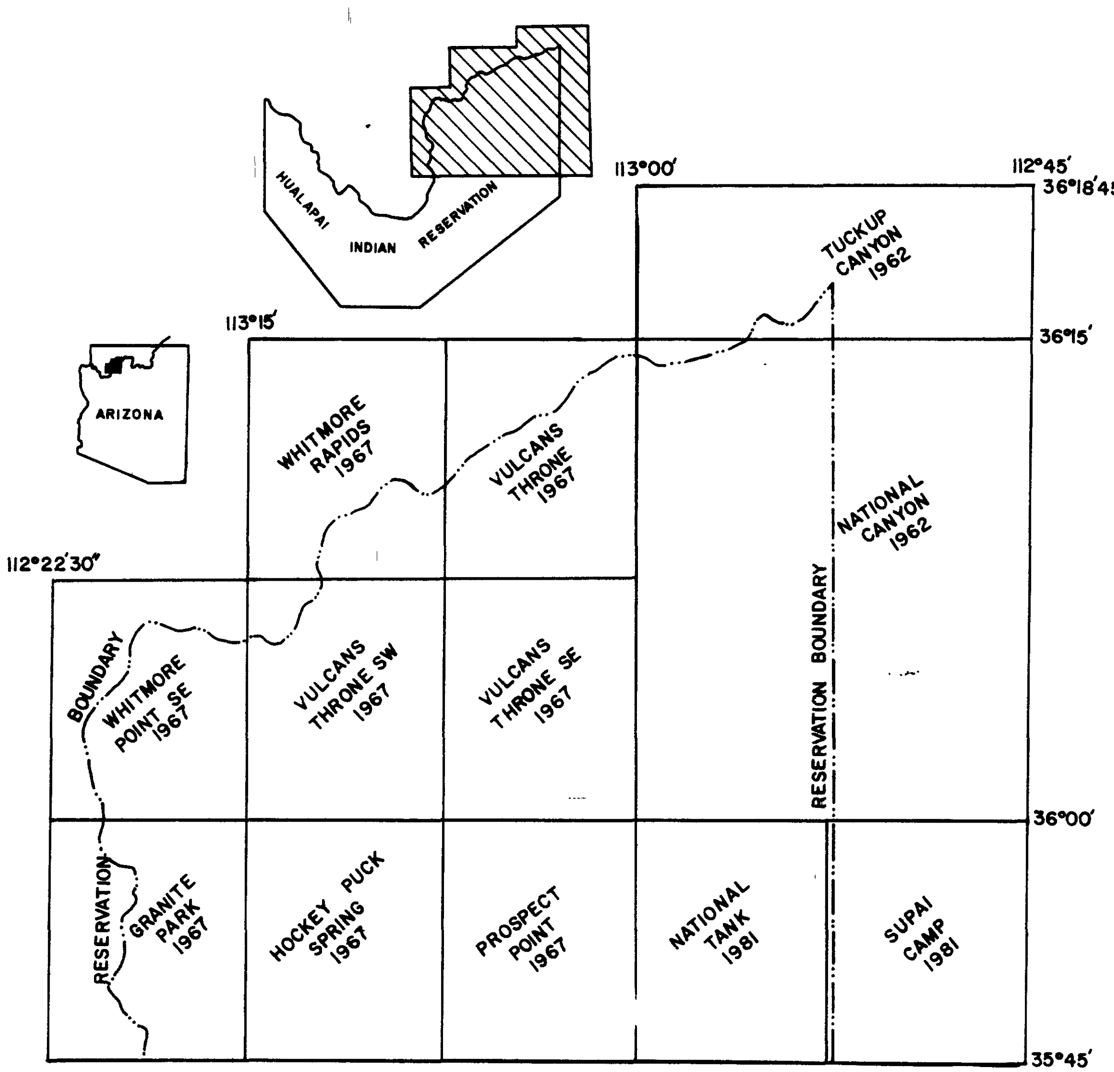

FIGURE 2. Location map of quadrangles mapped for the northeastern Hualapai Indian Reservation, Arizona (all quadrangles are 7 1/2 minute, scale 1:24,000 except the National Canyon and Tuckup Canyon quads which are 15 minute scale 1:62,500.

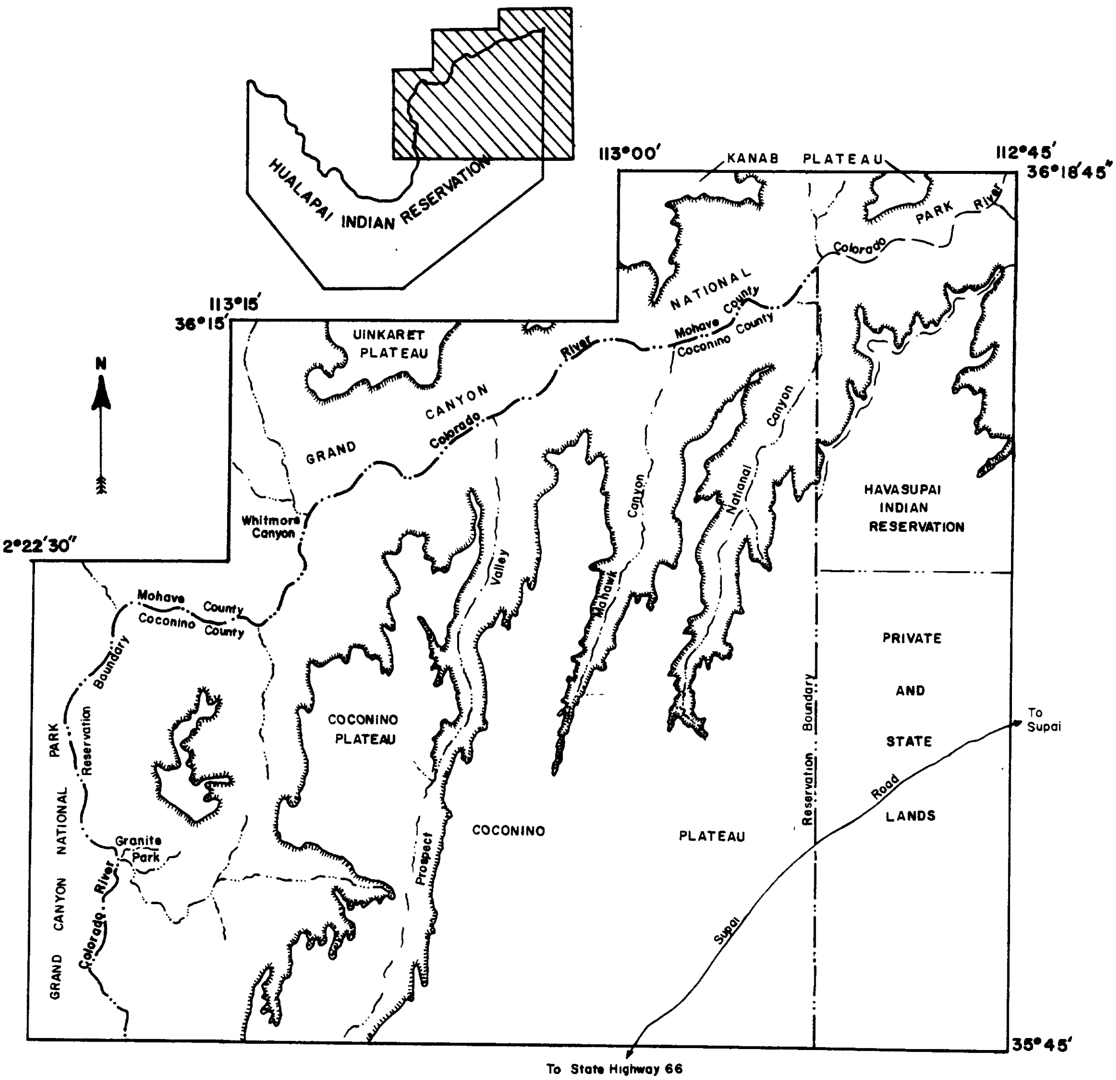

FIGURE 3. Geographic map of the northeastern Hualapai Indian Reservation, Arizona.

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 occupied a position that fluctuated within a few hundred feet of sea level. (3) The Laramide orogeny, herein used in a broad sense to embrace 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) a superimposed post-Laramide system of normal faults. The Laramide monoclines are crustal shortening features that generally overlie reactivated Precambrian normal faults, along which the sense of motion 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; one, located in the southwestern part of the Hualapai Reservation south of Supai Road, is topographically closed. 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 of the rocks in the region 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 this 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 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 Coconino Plateau and region to the south, and drainage was toward the northeast across what is now the 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 Plateau 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 east-northeast (Reches, 1978). The compression resulted in minor crustal shortening by a series of east-dipping monoclines having sinuous but generally northerly trends (Davis, 1978). The principal monoclines in the Hualapai Reservation include from east to west the Aubrey, Toroweap, Hurricane, and Meriwhitica monoclines. Laramide displacements across these folds were downward to the east with displacement as much as 1,500 feet. Individual monoclines developed over single, reactivated, west-dipping Precambrian faults. As reverse motion took place along the basement fault, the fault propagated variable distances upward into the section as the Paleozoic sediments simultaneously folded.

Typical monocline geometry is shown on Figure 4, 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.

The sinuosity of the monoclines results from selective reactivation of segments of Precambrian faults where the dip and strike of the 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.

Three prominent north-trending Laramide monoclines occur in the area encompassed by the northeast map: from west to east, the Lone Mountain, Hurricane, and Toroweap monoclines. Each displaces the Paleozoic strata down to the east. The Hurricane monocline splits into two segments in the southern part of the map area.

The maximum displacement associated with these monoclines is approximately 1,500 feet, east side down, along the Hurricane monocline south of the Colorado River. The maximum displacement along the Toroweap monocline is approximately 900 feet in the vicinity of Prospect Ridge. Displacements along each of the monoclines diminishes southward in the map area. The Lone Mountain monocline dies out completely to the south in Granite Park. The displacement along the Toroweap monocline also attenuates completely as it is traced northward throught the map area at a location 3 miles south of the Colorado River, leaving a gap in the fold between the segment shown on this map and an extensive segment that appears farther to the north.

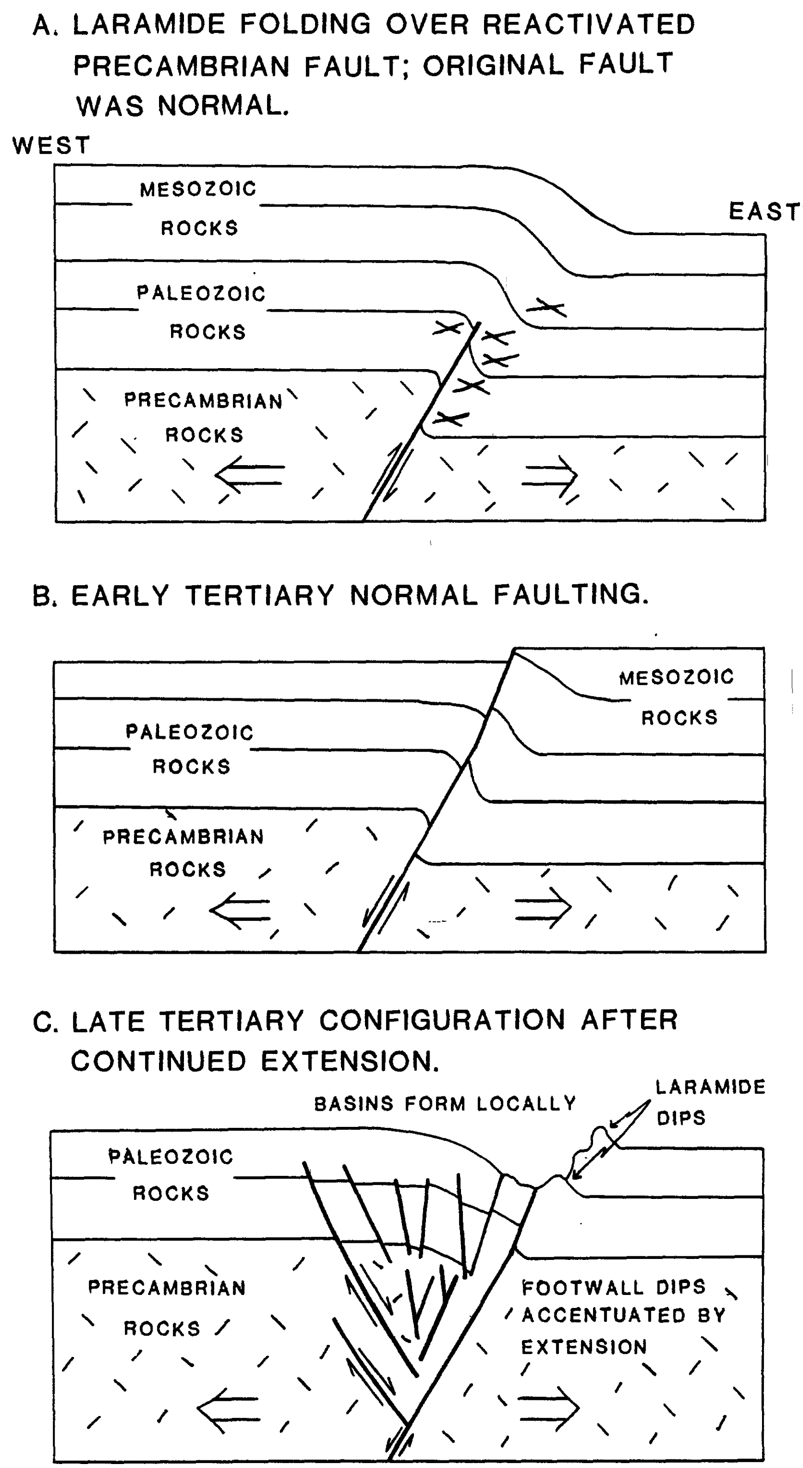

FIGURE 4. Structural cartoon of cross sections showing the stages in the development of the Hurricane fault zone in the western Grand Canyon, Arizona. Small crosses in figure 4A are low angle conjugate thrusts.

The monoclines are broad step-like folds at the level of the Permian rocks, characterized by dips less than 10 degrees and widths measured between the anticlinal and synclinal hinges that are as much as 1.5 miles. The lower Paleozoic units are folded to near vertical at deeper stratigraphic levels where the anticlinal and synclinal hinges of the monoclines converge downward on the underlying high-angle reverse faults that core the folds in the Precambrian basement. Excellent exposures of the folded lower Paleozoic rocks occur along both segments of Hurricane monocline where it is dissected by Three Springs Canyon. Exposures of the basement fault underlying the Lone Mountain monocline occur in Granite Park. The pre-history of Precambrian motion along the fault is indicated by the juxtaposition of dissimilar Precambrian rock types and foliation trends. The structure of the Toroweap monocline in the lower Paleozoic rocks is not exposed in the map area. All of the monoclines on this map are displaced by later normal faults with the west side down.

Stress indicators in the form of conjugate sets of low-angle thrust faults occur in the lower Paleozoic section. They reveal that the monoclines were formed under a compressive stress regime, wherein the maximum principal compresive stress was oriented horizontally and approximately perpendicular to the strikes of the folds. Excellent exposures of outcrop-scale low-angle thrust faults of this type occur in the southwest-facing Redwall Limestone northeast of Granite Park. These conjugate faults are shortening structures associated with the Lone Mountain monocline. Similar sets of minor thrust faults occur in Parashant Canyon where it dissects the Lone Mountain monocline.

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 Hurricane 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, displacement across the faults is greater than the opposite pre-existing displacement across the monocline, and the faults extend greater distances along strike. The result is downfaulting of the monoclines to such an extent that the parts of the western blocks that are immediately adjacent to the faults are successively stepped down 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 consist of a depression centered in the Parashant Canyon area (Huntoon, 1977), and a young basin developing east of the Toroweap Fault that is partially shown on the southeast quarter of this 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 exists along the Toroweap and Hurricane Faults. In fact, so continuous has been Miocene and later faulting that the number of discernable motions is limited only by the number of discrete Cenozoic units deposited across the fault planes. For example, successively older strata exposed along the Toroweap Fault exhibit progressively greater displacements near the Colorado River (Davis, 1903; McKee and Schenk, 1942). At this location, late Pleistocene alluvium (Anderson, 1979) on the adjacent plateaus is displaced as little as 20 feet while the underlying Paleozoic rocks are displaced 600 feet. Various Pleistocene and older lavas are displaced variable amounts between these extremes depending upon their relative ages. Vulcans Throne, a composite cone north of the river, is cut by the fault.

Recurrent Miocene and younger faulting is very obvious along the Hurricane Fault when observed amounts of displacement are compared between the alluvium, lavas, Tertiary sediments, and Paleozoic rocks. Scarps are particularly well preserved in the alluvium and volcanics north of the Colorado River. The amount of displacement of the older strata along the Hurricane Fault on the northeast map were exaggerated by contemporaneous infolding of the hanging wall strata that were lying to the west of the fault plane during extension (Hamblin, 1965). Consequently, both the dips of the strata to the west and the displacements are progressively greater for the older strata. Notice from Figure 4 that the effect of the infolding was to steepen the existing dips produced by the Laramide-age Hurricane monocline west of the fault.

So extensive is the recurrent faulting along the original Precambrian faults that chlorite has developed in the fault gouge in 193 Mile Canyon where the Pennsylvanian has been juxtaposed against the Devonian. In addition, significant movement of iron oxides along the fault zone has formed attractive liesegang bands.

Lineaments:

In addition to the obvious monocline and fault trends just discussed, lineaments occur on the northeast map. Two of these, the Sinyala lineament (NE) and the National Canyon trend (NNE) are prominent. The Sinyala trend is the southwestward extension of the Sinyala Fault zone (Huntoon and others, 1986). The trend passes through this map beginning at Yumtheska Point, and extends southwestward through a prominent reentrant on the west wall of National Canyon five miles south of the Colorado River. This lineament is defined to the east by a series of minor normal faults. The National Canyon trend is defined by the prominent trend of National Canyon. In both cases, the preferential erosion that has occurred along these lineaments is tentatively correlated with observed increases in joint density.

It appears that the lineaments represent upward propagation of fractures developed in underlying Precambrian fault zones, even though the magnitude of reactivation was insufficient to cause faulting of the Paleozoic section. This mechanism is plausible based on the parallel trends of the lineaments and nearby fault zones, and the obvious record for localization of later faults and folds over reactivated Precambrian faults in the immediate area.

Breccia pipes

Introduction:

The concentration of 347 solution collapse features within the northeastern part of the Hualapai Reservation is characteristic of their density throughout the Colorado Plateau of northwestern Arizona. This northeastern area contains 45 mineralized pipes, and consequently has probably over 90% of the potentially economic breccia pipes on the Hualapai Reservation. 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 into the limestone of the Kaibab (features #246, 255, 591, 609, 1134); these are readily discernable in the field from 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 very young, probably less than 2.4 m.a. (Wenrich and Billingsley, 1986). Because the age of the uranium mineralization is around 200 m.a. (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: (1) the presence of concentrically inward dipping beds, (2) altered rock (specifically, bleached and limonite-stained), (3) brecciated rock, (4) mineralized rock, and (5) circular vegetation 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 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 sand grains 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 not uncommon along the cliffs in the northeastern part of the Reservation, but it is rare on the high plateaus. Because the brecciated column of rock within each pipe abutes against generally well-stratified, relatively undeformed sedimentary rock, the plane demarking this contact is by definition a fracture. 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 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 inward dipping beds. It should be emphasized that this mapped area of solution collapse can be as much as 5 times the size of the actual breccia pipe, due to 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 those 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 Northeast Map:

No perfect correlation exists between the locations or alignments of breccia pipes and the principal faults and folds that deform the Paleozoic host rocks in the map area. However, populations of pipes tend to cluster in bands, or in some cases, trends of up to 7 pipes in straight lines that follow or parallel existing fault trends or prominent lineaments. For the most part, though, the alignments are not as numerous as, and several occur in directions not represented by, breccia pipes on the Marble Plateau (Sutphin and Wenrich, 1983). Nevertheless, a NW-trending alignment of pipes is apparent when the map is studied; each of 14 parallel lines, oriented between N20W and N28W, can be drawn through 3 to 6 pipes across the map. Although similar alignments can be drawn in other directions, this is the most pervasive trend. This trend is parallel to the Laramide normal faults that are particularly concentrated along the western border of the map. In additon, although somewhat sinuous, the Laguna Graben trends parallel to these alignments. One of these NW-trending alignments that contains 4 pipes extends across the Colorado River where 5 basaltic cinder cones fall in a straight line directly on the trend. Almost all cinder cones and dikes in this part of Arizona are aligned in NW trends. Many of the 14 parallel trends are equally spaced with the tightest spacing in the National Canyon/Mohawk Canyon areas; the groups of trends with equal spacing tend to have a wider spacing to the west.

The next most common trend includes pipes aligned almost N-S (N2W to N5W). The Toroweap Monocline extends N-S in the northern half of the map area. There are at least 7 alignments of pipes in a NE direction extending from N10E to N15E that run parallel to the Hurricane and the Mohawk Stairway Faults. The Hurricane Fault has been active since the Precambrian, and hence is a basement structure. These NE alignments are also parallel to the topography of National Canyon, Mohawk Canyon, and Prospect Valley.

Several alignments of 4 to 7 pipes occur in E-W trends that cannot be correlated with any structural or topographic features in the area. Nevertheless, the faults, monoclines and grabens are commonly sinuous and provide multiple orientations that may represent various basement structures. One interesting alignment extends through 4 mineralized pipes in a N45E direction that is parallel to, and only 2 miles south of, Lava Fault. These 4 pipes, #223, 243, 244, and 252, all have significant expressions of surface mineralized rock (malachite, azurite, pyrite, and various secondary uranium minerals) and include the Ridenour Mine (#223) as well as a prominent silicified plug of Coconino Sandstone breccia (#243) that was drilled by Western Nuclear, Inc. between 1975 and 1977 (drilling reports are stored in the Hualapai Tribal office files).

It might be noted that perhaps these trends may be a way of distinguishing questionable collapse features (category C?) that are real from those that are not. Those that lie along trends of known pipes are probably pipes or gypsum collapses in contrast to those that are probably figments of the imagination.

The greatest concentration of pipes on the northeast map occurs between Three Springs Canyon and Granite Park. It is interesting to note that similar to the Blue Mountain/Diamond Creek area (southeast map), this area does have several springs although their discharge is minor compared to the Diamond

Creek area. In addition, the greatest concentration of breccia pipes found anywhere in the Grand Canyon occurs across the Colorado River on the North Rim between the mouth of Diamond Creek and 209 Mile Canyon. The area between Three Springs Canyon and Granite Park lies within a heavily faulted area. It is interesting to note that although there are other areas that are also heavily faulted to the north, the Redwall Limestone has been, for the most part, eroded off from these areas and there is no way to determine whether they were also regions of breccia pipe concentrations. The Hurricane and Three Springs Faults trend NNE through this area. Here, 6 major NW-trending parallel faults terminate against the Hurricane Fault. This junction of structures lies at the center of the breccia pipe cluster. As on the southeast map in the Blue Mountain/Diamond Creek area, this is probably an area of intersecting basement blocks. Because faults such as the Hurricane have been documented to be active since the Precambrian, this heavily fractured area may well have been a region of major ground water discharge through much of geologic history, thus enhancing dissolution of the Redwall Limestone.

Most of the brecciation and mineralization of the pipes in this area predates the oldest of the folds and faults that deform the Paleozoic host rocks, specifically late Paleozoic/Triassic pipe events versus Laramide and younger tectonic events. Ludwig and others (1986) has shown that the age of the uranium mineralization was about 200 m.a. 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 lies in 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 allow 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 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 localizing those younger structures 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.

One of the major problems in uniform mapping of collapse features is contrasting vegetation density and types across the Reservation. In the southern part of the map, from the high plateau east of the Hurricane Fault, eastward across the Aubry cliffs, the vegetation is dense, particularly around Laguna Valley where tall Ponderosa Pines dominate the landscape. This region of the map contains no mapped collapse features, except for some old copper prospects, which may not be breccia pipes. This absence of breccia pipes does not preclude their presence, because their detection with such dense vegetation can probably only be made through geophysical methods. In the Aubrey Valley and vicinity, breccia pipes may be present, but covered by Cenozoic gravel deposits and alluvium. Further to the east the landscape becomes dominated by junipers and grasslands, but there still are few identified collapse features. On the other hand, there also are few major structural features mapped in this area; thus, the underlying structural control for the pipes may not occur here.

Copper Prospects Located on the Northeast Map:

There are 8 Cu prospects, primarily concentrated south of Laguna Graben, on the northeast map. They are shown on the geologic map as mineralized "circular" features with a "Cu" beside them; they are features #220, 221, 222, 472, 473, 1125, 1130, and 1177. These prospects were mined intermittently between the early 1900's to the 1950's. A claim paper was found in an old tobacco can at feature #1125 which stated that the claim was filed in Coconino County in March, 1929 by E.A. Shray. These Cu prospects are similar in appearance to the Jacob Lake prospect on the North Rim and the Anita Claims further to the east. They consist of malachite- and azurite-impregnated chert breccias. The breccias are apparently not tectonic breccias, but intraformational breccias within the Harrisburg Member of the Kaibab Limestone. Features #220, 222, and 473 were drilled during 1975 by Western Nuclear, Inc.; these features were apparently believed to be channels by geologists working for Western Nuclear, according to cross sections provided by Western Nuclear to the Hualapai Tribe. Recent mapping from this project indicates that these are not channels, but intraformational breccias formed during deposition of the Kaibab Limestone. These breccias may be related to movement along the Toroweap and Aubrey Faults during deposition of the Kaibab, as the breccias appear to be thickest adjacent to the faults.

Five holes were drilled into feature #220 by Western Nuclear. All gamma logs show radiation <40 counts per second (cps) except for hole 4 where 100 cps were encountered between a depth of 20 and 30 feet (drilling reports are stored in the Hualapai Tribal office files). Sparse Cu was found in some of the holes and some limonite and hematite alteration occur through much of the core. Four of the holes were <200 feet deep and hole 2 went to 297 feet. Three holes were drilled into feature #222 with all gamma radiation <40 cps; some minor Cu was encountered at depths <55 feet, and some limonite and hematite alteration were noted through the core. The holes were all <300 feet in depth. Feature #473 had 15 holes drilled into it, all with depths <115 feet. All radiation was <40 cps; minor Cu was found in some holes at depths of <30 feet and again limonite and hematite alteration occurs sporadically throughout the core.

Although the disrupted copper-rich areas of these prospects are roughly circular in outline, there is no evidence of concentrically inward dipping beds. Thus, they are believed to be merely strataform copper deposits within the Kaibab Limestone. Nevertheless, they may have been deposited by the pipe mineralizing fluids as their trace element signature is identical to that found in the pipes. These Cu prospects have anomalous concentrations of Ag, As, Co, Cu, Mo, Ni, Pb, Se, U, and Zn. These are not simply minor anomalies, because many of them exhibit element concentrations as high as samples taken from ore-bearing pipes, for example: Co concentrations of 100 ppm, Ni of 300 ppm, Pb of 410 ppm, and Zn of 4200 ppm. The highest U concentration observed was 41 ppm. Soil surveys taken over these prospects show circular anomalies, as would be expected over pipes rather than over strataform deposits. Thus, there still remains the possibility that these are epigenetic Cu deposits, located over breccia pipe orebodies. As such, they formed where the host rock was exceptionally favorable for ore deposition, in an intraformational breccia.

Drilled Breccia Pipes Located on the Northeast Map:

The only known production of uranium on the Hualapai Reservation came from the Ridenour Mine (pipe #223). The initial discovery of the Cu deposit reportedly took place some time during the 1870's (Miller, 1954). The property was worked intermittently for Cu prior to and during World War I (Miller, 1954). Clyde Hutchinson of Flagstaff leased the Ridenour Mine from the Hualapai Tribe on May 21, 1960 (William L. Chenoweth, personal communication, 1986). In January of 1961 he made a 14 ton ore shipment to the Kerr-McGee Mill in Shiprock, N.M. containing 42 lbs of uranium with a grade of 0.15% U_3O_8 and 667 lb of vanadium with a grade of 2.36% V_2O_5 (William L. Chenoweth, personal communication, 1986). Most of the ore removed from the Ridenour Mine came from the inner ring fracture zone; the core of the pipe, above the base of the Esplanade sandstone, has been eroded away and all that remains is a semi-circular cliff face along the ring fracture. Three drill holes were placed into the Ridenour pipe during 1976 by Western Nuclear, Inc. to depths of 440 ft., 324 feet, and 990 feet (data from the Hualapai Tribal office files). The two shallower holes were placed along the road following the western side of the ring fracture, and the hole to 990 feet was placed outside the ring fracture to the west. None of the holes had any gamma radiation >40 cps and apparently none of the rock was reduced. The only signs of any mineralized rock were apparently located between a depth of 715 ft and 990 ft where traces of pyrite were observed. The lease was dropped in 1978 because the property was believed to have little potential and had difficult access. If the property were to be drilled in the future, holes should be place toward the center of the pipe, either near the bottom of the drainage, or along the road as angle holes inward to the core of the pipe. All previous holes were vertical and apparently did not go into the center of the pipe. The Ridenour Mine contains the highest vanadium concentrations of any of the pipes studied in northern Arizona; it is not uncommon to find samples with 2 to 4% V. Similar to most of the mineralized breccia pipes, the Ridenour contains anomalous As (3000 ppm is not uncommon), Co (200 ppm), Cu (8000 ppm), Hg (6 ppm), Mo (260 ppm), Ni (500 ppm), Pb (1%), U (3000 ppm), and Zn (150 ppm). In addition, some Ga concentrations are high, 80-110 ppm, which has not been observed in most of the breccia pipes, although ore grade concentrations of Ga are present in the Apex Mine to the northwest near St. George, Utah.

Pipe #253, near the Ridenour pipe, was drilled by Western Nuclear in 1977 and 1978. Three holes to depths of 240 ft., 320 ft., and 600 ft. were collared in the Hermit Shale. The results from the two more northern holes were more favorable than those from the Ridenour Mine (data from the Hualapai Tribal office files). Hole 3 was the most favorable and contained several intervals of reduced rock that contained pyrite. The Western Nuclear lithology logs are somewhat confusing in that the top of the hole is labeled as Supai, whereas in the field the collar to the hole can clearly be seen to be near the top of the Hermit Shale. There are several intervals in this hole, located between 90 and 260 ft. that exhibit gamma radiation between 100 and 180 cps. Surface samples of the small silicified brecciated plug, which is similar, but smaller than the plug at Blue Mountain, contain anomalous Ag, As, Cu, Mo, Pb, Se, U (120 ppm), and Zn. This pipe, which is a smaller version of pipe #243 drilled by Western Nuclear, appears to have some potential and more holes should probably be drilled into the center of the pipe. The silicified plug is probably located along the ring fracture as opposed to the center of the pipe; this is based on observations of the West Collapse on the Marble Plateau where a series of silicifed, brecciated plugs appear to lie along the western side of the West Collapse ring fracture. If this is the case, perhaps none of the pipes (253, 243, or Blue Mountain) on the reservation with silicified brecciated plugs have been drilled in their centers. Thus, any future holes drilled into 253 should probably angle eastward into the hillside from hole 3.

Pipe #243 is similar to #253 except that it is larger and more striking. The silicified pinnacle of brecciated Coconino Sandstone is approximately as high as the Blue Mountain Plug. The vuggy breccia with large angular equant clasts is characteristic of a collapse breccia, as compared to ones that form along a faults with smaller elongate clasts. Concentrically inward-dipping joints, filled with goethite and pyrite, penetrate the adjacent country rock of Hermit Shale on both exposed sides of the pipe. Samples taken from the ring fracture where the gamma radiation exceeded 3 times background are anomalous in Ag, As, Cu, Mo, Ni, Pb, Se, and Zn. This pipe was drilled by Western Nuclear in 1975 and 1977. Data for the hole drill in 1975 was not available, but the two drilled in 1977 went 605 and 600 feet, entirely through oxidized material with no gamma radiation >40 cps (data from Hualapai Tribal office files). As with pipe #253, the silicified pinnacle may lie on the ring fracture, and any future drilling should be in toward the ridge where the center of the pipe is probably located. Either this is a fairly large pipe or there is a second pipe within the ridge, as the bleached Hermit Shale extends through to the other side of the ridge that lies on the west side of Prospect Valley.

The Mohawk Canyon Pipe (#494) is believed to be one of the pipes on the Hualapai reservation with the greatest potential as an economic orebody. It was discovered in June 1983 during this mapping program, and was drilled during July-October 1984 by the U.S. Geological Survey in cooperation with the Bureau of Indian Affairs and the Hualapai Tribe (Wenrich and others, 1985). The upper exposed, concentrically inward-dipping beds of Harrisburg Member of the Kaibab Limestone contain secondary Cu minerals, malachite, azurite, brochantite, and chrysocolla, as well as goethite pseudomorphs and molds of pyrite along the inner ring fracture. The Cu minerals are primarily exposed in two old adits dug around the turn of the century; no written record or past knowledge of these old adits has been found. Samples from along the ring fracture contain anomalous concentrations of Ag (110 ppm), As (400 ppm), Cu (1.4%), Fe (18%), Hg (0.3 ppm), Mo (140 ppm), Ni (70 ppm), Pb (1.2%), Sb (106 ppm), Se (350 ppm), U (50 ppm), V (190 ppm), and Zn (1.2%). Five holes were drilled into the Mohawk Canyon Pipe (Wenrich and others, 1985). One hole, penetrating to a depth of 1335 feet, showed a 1-foot interval of 0.52% eU_3O_8 at a depth of 1191 feet, and a 20-foot zone averaging 0.04% eU_3O_8; This is approximately the same stratigraphic horizon as the top of the orebodies in active mines located on similar plateaus capped with the Harrisburg Member of the Kaibab Limestone on the North Rim. Drilling problems such as lost circulation, lost casing into a 30-foot-high cavern within the breccia, and great water consumption limited the drilling results. Core recovered from holes in the center of the pipe shows breccia to the total depth of 1,010 feet, abundant pyrite, and minor galena, sphalerite, arsenopyrite, and bravoite. Sufficient mineralization, specifically the presence of Pb, Zn, and Ni minerals common to breccia pipes hosting economic mineralization, was verified in the Mohawk Canyon pipe that further drilling is warranted to assess its economic potential.

Other Collapse Features with Economic Potential on the Northeastern Map:

Two features that have not been drilled but appear to have significant economic potential are #493 and 1102. Feature #493 is one of the larger collapse features on the Hualapai Reservation, about one-third of a mile in diameter. This structure is a classic example of a small hill almost totally encircled by a moat and surrounded by higher hills (Wenrich and others 1986, figs. 24a and b) of Gypsiferous Harrisburg Member of the Kaibab Limestone. The central hill has an outer, perfectly circular ring of steeply, inward-dipping beds around a center of reddish soil. Along the Mohawk Canyon cliff, running along the extreme western edge of the collapse, the gypsiferous Woods Ranch Member pinches to zero thickness just beneath the collapse. In addition, a cave located just beneath the collapse in the Fossil Mountain Member of the Kaibab Limestone attests to increased dissolution directly beneath this structure. Chemical analyses of samples taken from the central ring of inward-dipping beds and from gypsum-bearing altered beds on the western edge of the collapse, show essentially no anomalous elements; the most anomalous element was Cu at 70 ppm. Similarly, soil geochemical surveys completed over the collapse show no distinct anomaly over the pipe as compared to the background terrain. In contrast, the audio-magneto telluric (AMT) surveys show a very sharp (resembling the Washington Monument) resistivity anomaly over the center of the collapse (Flanigan, 1986, personal communication). These data, along with the collapse morphology, suggest that further exploration is warranted over this collapse.

Feature #1102 is barely noticeable from a helicopter (see fig. 23a, Wenrich and others, 1986) and was not originally recognized on the 1:24,000 color aerial photography. The Gypsiferous Harrisburg Member beds are dipping inward toward the central drainage. There are small outcrops and float of an orangish-brown, Fe-rich gossen scattered about the center of this feature where the gamma radioactivity reached 550 cps (18 times background). Soil geochemical surveys provided favorable results as did the AMT surveys. Additional studies over this feature should be made.

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 raised, slightly bleached rims of Gypsiferous 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 #534 and #570 appear similar (photos of these features are shown in Wenrich and others, 1986). Although both 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. Other similar features in the C4 category that are also located on the northeast map, but are not quite as morphologically striking are: #531, 546, 557, 571, and 577. Results from a soil survey completed over collapse feature #571 show very significant anomalies of metals, such as Co, Cu, Mo, Ni, Pb, and Zn, rich in ore-bearing breccia pipes, over the center of the collapse.

Along the eastern edge of the Hualapai Reservation, east of the headwaters to National Canyon lies an interesting series of circular features, which have been collectively labeled as collapse feature #232. They consist of a series of areas (8 are mapped, but more are present), which are noticeably circular from the air. They are difficult, and in fact almost impossible, to recognize on the ground. What makes them circular in appearance are the rings of Kaibab Limestone beds. The beds are fractured and broken sufficiently that it is difficult to determine whether the beds are inward dipping. In one of them, several juniper trees occur within the circular area; this is striking because there are no other trees within a half-mile of this feature. These small, generally <150 feet, circular features are concentrically arranged along the top of a large, about one-half mile, circular depression. It is possible that these small circular features are indeed sink holes into the Kaibab or Toroweap that formed around the ring fracture of a breccia pipe, which is represented by the larger circular depression.

Several other features in the C4 category are worthy of note. Feature #1144 are represented by a circular patch of trees. This is in contrast to many features, such as #478 which are circular grass or shrub patches in contrast to 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 orebody to prevent the growth of trees. On the other hand, 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 #1144 may not be of further interest. Features #476, 480, 1115, 1116, 1119, 1122, and 1140 are other circular grassy patchs surrounded by trees, although many of them are not as circular and not all of them represent a depression, as does the Canyon Pipe.

Several collapse features form circular reddish soil patches, which may represent alteration at the surface, or downdropping of the redder Harrisburg Member into somewhat more white units. Others form circular depressions where water ponds or greener grass grows. Many of these may merely be sink holes, but they are worthy of note: #525, 545, 573, 1113, and 1114. Features #244 and 1134 are what has been classified as sink holes in this study: vertical walls of Kaibab Limestone surrounding a rubble-filled floor. Both of these features are probably young (similar to the Citadel sink - <2.4 m.a.; Wenrich and Billingsley, 1986).

There are tens of collapse features on the northeast map that have concentrically inward-dipping beds. Several of the more favorable ones, in terms of geology as well as accessibility, are #249, 474, 491, 492, 550, 985, 1024, 1029, 1081, 1089, 1107, 1152, 1171, and 1173.

There are over 50 breccia pipes on this northeast map that have been eroded to the level of the Redwall Limestone. Over 40% of these contain some exposure of Surprise Canyon Formation.

Many 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.

Conclusions:

The northeastern part of the Hualapai Reservation contains most of the breccia pipes on the reservation with economic potential for uranium deposits. Several breccia pipes that have been drilled in the past still merit additional drilling. In addition, features such as #493, 1102, and several in the C4 category, such as #570, 534, and 571 appear to be worthy of further study. There are several mineralized breccia pipes exposed in the Esplanade Sandstone in Mohawk and National Canyons, but their inaccessibility reduces their potential as an economic orebody.

The Mississippian Surprise Canyon Formation 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 Surprise Canyon beds dipping into the pipe, or contain breccia of 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, a map of Surprise Canyon channels across NW Arizona would provide the exploration geologist with the Mississippian paleogradient, and hence possibly provide the 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 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.

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, red, or black in color.

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

QB Landslides (Holocene? and Pleistocene).

QTt Travertine Deposits (Holocene, Pleistocene, and Older)--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 now dips towards the base of the parent wall.

QTg Younger Gravels undivided (Holocene and Pleistocene?)--Well-rounded gravel, sand, and silt from older gravel deposits of Precambrian clastic material mixed with angular chert and limestone clasts derived from the Kaibab Limestone. Clasts are matrix supported and are cemented with calcium carbonate.

QTi Intrusive volcanics (Pleistocene? Pliocene? and Older)--Alkali-olivine basalt dikes and plugs; includes one small basalt flow on hill about 1 mi west of Whitmore Canyon.

Unconformity

Tfw Frazier Wells Gravel (Oligocene? Miocene)--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. diameter; matrix supported, consisting of uncemented, coarsely textured, sandstone and siltstone; forms gentle rounded hills and slopes.

Unconformity

Tm Moenkopi Formation (Middle? and Lower Triassic)--Timpoweap Member - Light gray and pale reddish-gray conglomerate; consists of reddish-gray siltstone and sandstone matrix with light gray, rounded, fossilifereous 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.

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. The underlying Fossil Mountain Member consists of a light-gray, cherty, fossiliferous limestone and sandy limestone that forms a cliff. Silicified intraformational chert breccia is present within a half-mile of either side of the Toroweap Fault.

Unconformity

Pt Toroweap Formation (Lower Permian)--Woods Ranch, Brady Canyon and Seligman Members Undivided - Top to bottom, the Woods Ranch consists of a slope-forming, gypsiferous, pale-red and gray siltstone and sandstone and some thin-bedded dark-gray limestone; locally absent along canyon walls where dissolution has occurred. The underlying Brady Canyon Member is a cliff-forming, medium-bedded, dark- to light-gray fossiliferous limestone that has a fetid smell. At the base of the formation, the Seligman Member is a yellowish-white to pale-red sandstone; thin-bedded; forms a slope or recess in cliff.

Pc Coconino Sandstone (Lower Permian)--Light-brown to yellowish-red, fine-grained, cross-stratified sandstone; forms a cliff.

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

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 very lower portions of generally cliff-forming unit; also contains within the middle sandstone cliff gray, thin-bedded limestone tongues of Pakoon Limestone that pinch out eastward; outcrops in the northwest portion of map.

Unconformity

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

Wesagame Formation--Red to pale-red siltstones and shales interbedded with grayish-red calcareous sandstone; forms a slope in upper part, cliff in lower part; unconformable contact with underlying Manakacha Formation.

Manakacha Formation--Reddish-brown, thick-bedded, fine-grained sandstone and crossbedded sandstone; interbedded fine-grained sandstone and crossbedded dolomite; thin-bedded gray limestone and dolomite; and thin, red-brown shales; forms a sequence of slopes and ledges.

Watahomigi Formation--Gray, calcareous siltstone and fine-grained sandstone interbedded with gray, thin- to medium-bedded limestone that forms a sequence of ledges and slopes. Lower part is mainly a purple siltstone with some conglomerate and thin-bedded limestones. Limestone beds commonly contain red and white chert lenses or bands; unconformable contact with overlying Manakacha Formation.

Unconformity

Msc Surprise Canyon Formation (Upper Mississippian)--The thicker deposits (Granite Park and National Canyon area) consists of a basal ledge of chert-pebble conglomerate; clasts supported with a dark red-brown to black, iron-stained sandy matrix, overlain by a pale-yellow, medium-grained, crossbedded sandstone in some areas; overlain by 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 ripple-laminated, thin beds of silty limestone form slopes and ledges; deposited within caves and stream-eroded paleovalleys eroded into underlying Redwall Limestone.

Unconformity

Mr Redwall Limestone (Mississippian)--Undivided members, top to bottom are the Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members. All members form a continuous shear cliff. The Horseshoe Mesa Member forms a slight recess at the contact with underlying Mooney Falls Member; a light-gray, thick-bedded, aphanitic limestone and dolomite; contains marine fossils throughout. White chert bands are common in the Thunder Springs Member.

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 and cliffs.

Unconformity

Tonto Group (Cambrian)

€m Muav Limestone (Middle Cambrian)--Mottled gray and purple dolomitic thin-bedded limestone that weathers rusty gray. Limestone units are separated by thin beds of green shale; forms ledges or small cliffs separated by tongues of slope-forming green shale that is 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).

€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 Sandstone lithology and rusty-brown dolomitic tongues of the Muav Limestone. A very coarse-grained, purple-red sandstone (Red-Brown Member of McKee and Resser, 1945) forms a cliff/ledge about the middle of the unit. Lower contact is gradational with the Tapeats Sandstone and arbitrarily placed at or near top of Tapeats Sandstone cliff. Lower part contains increasing abundance of thin beds of light-brown, sandstone of Tapeats lithology; forms a slope.

€t Tapeats Sandstone (Middle and Lower Cambrian)--Light-gray to light-brown, medium- to coarse-grained, thin-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.

Unconformity

Vishnu Group (Older Precambrian)

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

P€gp Layered mafic complex (Precambrian)--Very fine-grained schistose-foliated, dark-colored minerals with intrusive holocrystalline quartz and feldspar pegmatites.

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

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