UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Potential Breccia Pipes in the Mohawk Canyon Area, Hualapai Indian Reservation, Arizona

by

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ABSTRACT

The Hualapai Indian Reservation is located on the southwestern corner of the Colorado Plateau in northern Arizona. Hundreds of solution-collapse breccia pipes crop out in the canyons and on the plateaus of northern Arizona. The pipes originated in the Mississippian Redwall Limestone and stoped their way upward through the upper Paleozoic strata, locally extending into the Triassic Moenkopi and Chinle Formations. The occurrence of high-grade U ore, associated with potentially economic concentrations of Cu, Ag, Pb, Zn, V, Co, and Ni in some of these pipes, has stimulated mining activity in northern Arizona despite the depressed market for most of these metals.

Forty-six of the more than 900 confirmed and suspected breccia pipes that have been mapped on the Hualapai Reservation lie in the Mohawk Canyon area. The Mohawk Canyon area was selected for this report because examples of the most of the various breccia pipe geomorphologies on the Hualapai Reservation occur there; in addition, it contains the greatest concentration of mineralized pipes on the Reservation. Rocks in the area span the entire Paleozoic sequence of the Grand Canyon, from the Cambrian Tapeats Sandstone to the Permian Kaibab Limestone.

Identified collapse features (possible breccia pipes) and known breccia pipes in the Mohawk Canyon area are essentially all collared in one of three horizons: (1) the top of the Redwall Limestone (13 collapse features), (2) the Esplanade erosion surface or along the cliffs formed by any Supai Group formation (14 collapse features), or (3) the top of the Coconino Plateau capped by the Kaibab Limestone (19 collapse features). The 13 structures which lie at the top of the Redwall Limestone are considered to have little or no economic potential. Two breccia pipes, #241 and #242, which lie on the Esplanade erosion surface, have significant mineralized rock exposed; unfortunately, their economic potential is questionable because of their inaccessiblity at the bottom of Mohawk Canyon. In contrast, four features, #249, #493, #494, and #1102, lie on the Coconino Plateau and are accessible. All warrant further exploration: (1) #249 exhibits excellent surface morphology; (2) #493 also has excellent geomorphology, but in addition, audio-magnetotelluric profiles show a vertical, strongly conductive zone (possibly a breccia core) beneath the collapse feature; (3) #1102 contains the most radioactive surface exposure found anywhere on the Reservation--18 times background; and (4) #494 (the Mohawk Canyon pipe) was drilled by the USGS in 1984 and proven to contain at least some 0.52% U_3O_8.

INTRODUCTION

The Colorado Plateau of northern Arizona is host to thousands of solution-collapse breccia pipes. Many of these pipes were mineralized by Cu-, U-, Ag-, Pb-, Zn-, Co- and Ni-bearing fluids. Despite the depressed uranium market, the level of exploration activity for mineralized breccia pipes in north-central and northwestern Arizona remained high throughout the 1980's. The polymetallic, high-grade uranium ore, averaging up to 0.74% U_3O_8 in the Canyon pipe (Casadevall, 1989), has made these deposits attractive, even at $15 per pound uranium. Although the breccia pipes have also been mined in the past 100 years for Cu, Ag, Pb, V, and Zn, uranium has been the only commodity to turn a significant profit. During the 1980's mining cycle in the Grand Canyon none of these base metals were mined as by-products to uranium for several reasons: (1) the uranium mill, located in Blanding, Utah is over 300 miles from the mines, so transportion costs must be offset by high metal prices--none of these base metals commanded an impressive price during this period; (2) the mill does not have a circuit for any of these metals except vanadium; and (3) the base metal concentrations are inconsistent--for instance Ag is as high as 100 ppm in many samples, but is more commonly below 20 ppm in unoxidized uranium ore collected from North Rim mines.

The Hualapai Tribal Council requested in 1985 that the U.S. Geological Survey select and publish summary reports on two areas on the Hualapai Indian Reservation that contain high concentrations of breccia pipes and have good potential for hosting uranium orebodies (fig. 1). The selection was based on the density of collapse features and proximity to residential communities. The two areas selected represent two different exposures of breccia pipes: (1) In the Mohawk Canyon area (this report), mineralized rock is commonly exposed in cliff faces and along canyon bottoms within all formations from the Permian Kaibab Limestone to the Mississippian Redwall Limestone (fig. 2). Much of this area is not easily accessible and cannot be reached by 4-wheel drive vehicles. Mapping of such terrain, specifically the tens of miles of cliff exposure, can only be done through aerial photography, and from a helicopter. (2) In the National Tank area (Wenrich, Billingsley and Van Gosen, in press), mineralized rock is not exposed; in fact, little rock of any type is exposed, and most of the area is soil-covered. Consequently, mapping of breccia pipes is restricted to recognition of circular features on soil-capped plateaus. The Mohawk Canyon area is the focus of this report.

BRECCIA PIPES OF NORTHERN ARIZONA

The breccia pipes of northern Arizona differ from classic breccia pipes, those formed from volcanic or gaseous explosions, in that no volcanic rock is associated with the pipes in time or space, nor is there any evidence of upward movement of clasts. Instead, they result from solution collapse within the Redwall Limestone and stoping of overlying strata. Dissolution of the Redwall Limestone created caverns into which blocks of overlying strata collapsed, leading to gradual upward stoping of a rubble-filled, approximately 250 ft in diameter, pipe-like structure. The pipes and associated mineralized rock transgress formation boundaries from the Mississippian Redwall Limestone through the Triassic Chinle Formation (fig. 2)--a vertical distance on the order of 4,000 ft. The stoping produced extensive brecciation of the rock within the steep walls of the pipe. At no level in any pipe have breccia clasts been observed from deeper beds; all material has been dropped into the pipe from stratigraphically higher units. As a result of collapse, brecciated rock within each pipe abuts generally well-stratified, undeformed sedimentary rock; the plane demarking this contact is obviously one along which the breccia slid downward and is, therefore, a fracture (see fig. 1b, Wenrich, 1985). This nearly vertical fracture is referred to throughout this report as the "ring fracture".

The breccia pipes of northern Arizona extend to the Utah State line and south to the Mogollon Rim (the southern margin of the Colorado Plateau). They are abundant from the edge of the Grand Wash Cliffs (the western margin of the Colorado Plateau) across the Hualapai Indian Reservation and the remainder of the Coconino Plateau to the Marble Plateau of the Navajo Reservation (fig. 1). Those located in the Mohawk Canyon area are typical of northwestern Arizona. They are exposed at various stratigraphic horizons from the Redwall Limestone to the Kaibab Limestone, which caps the Coconino Plateau. Many are

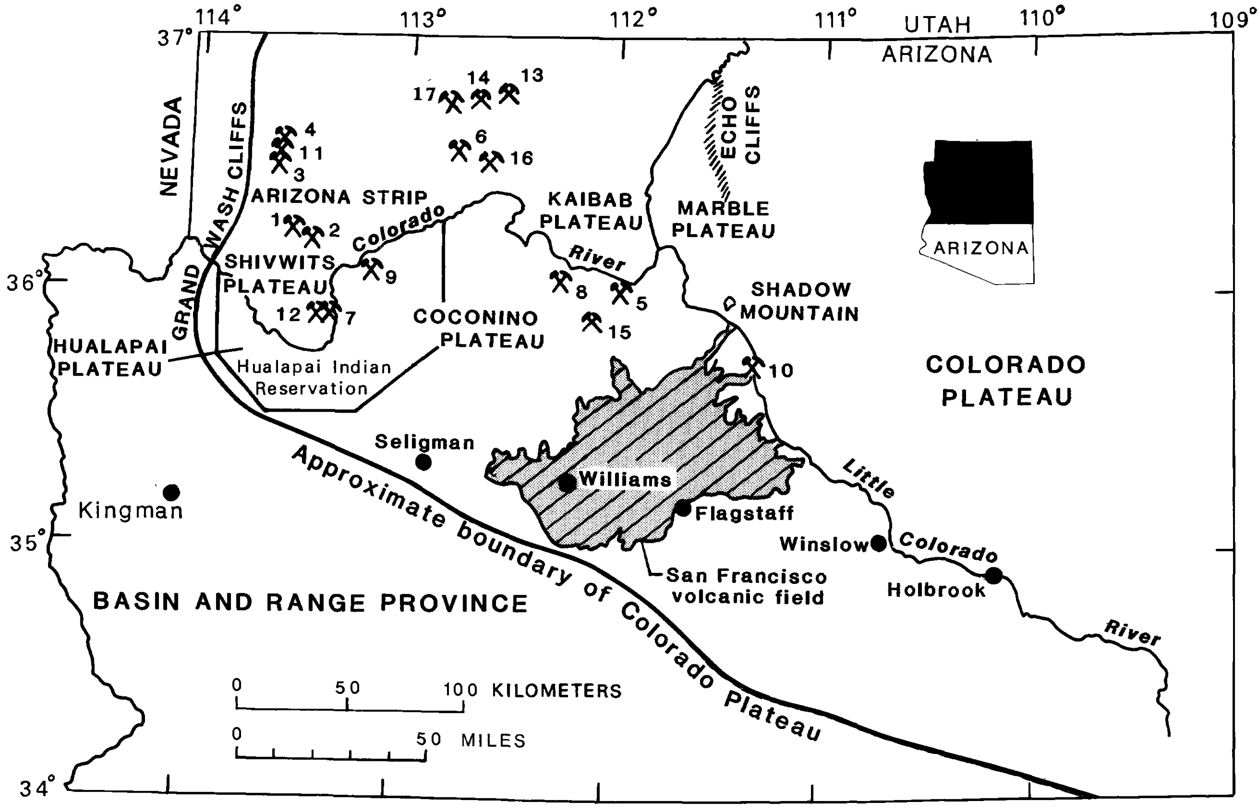


Figure 1.--Index map of northern Arizona showing the locations of plateaus, Hualapai Indian Reservation, breccia pipes developed into mines, and the San Francisco volcanic field that buries terrane with high potential for mineralized breccia pipes. Numbers refer to the following mines: (1) Copper House, (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, (16) Pinenut, and (17) Hermit.

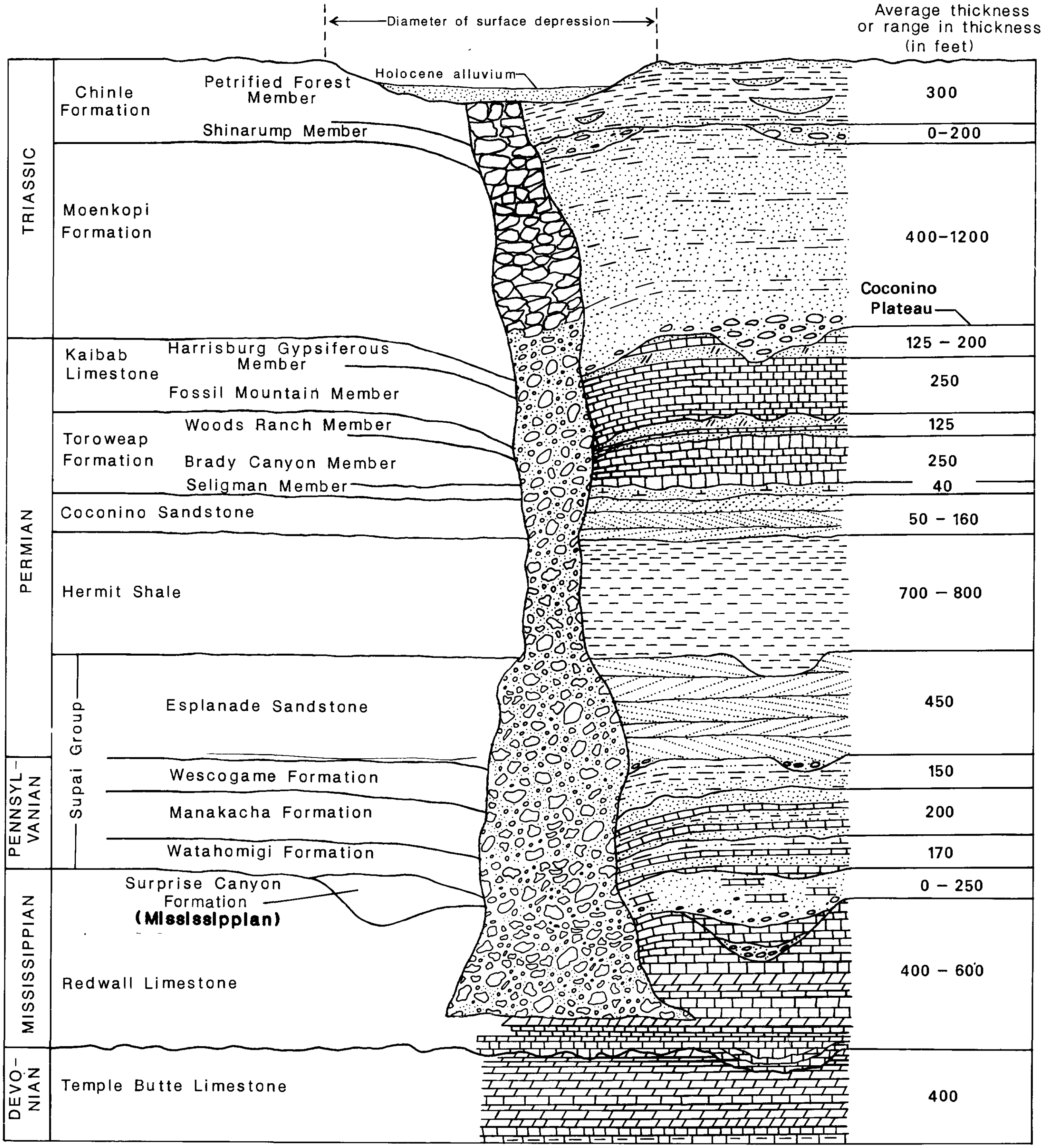


Figure 2.--Schematic cross section of a breccia pipe (based on cliff exposures in the Grand Canyon of Arizona). The unit thicknesses shown for the Triassic Chinle and Moenkopi Formations (not present in the Mohawk Canyon area) represent their thickness ranges in the Grand Canyon area. The unit thicknesses for the Paleozoic strata correspond to thicknesses that occur in the Mohawk Canyon area (from Wenrich, Billingsley, and Huntoon, 1986, which also provides unit descriptions). Some collapse features in the Mohawk Canyon area, such as collapse feature 493, have distinct reddish-orange soil developed in their center. This soil may be weathered from downdropped Moenkopi strata. Cross section is from Van Gosen and Wenrich (1989).

known to have been mineralized.

Mining activity in breccia pipes of the Grand Canyon region began during the 1860's, but prior to 1940 all of the production was for Cu, Pb, Zn, Ag, and minor Au. As of 1987 over 17,275,000 pounds of U_3O_8 have been mined from northern Arizona breccia pipes with 13,000,000 mined since 1980 (Wenrich, Chenoweth, Finch, and Scarborough, in press). The deposits are small and high grade; the average diameter of the breccia pipes is about 250 feet and ore mined between 1980 and 1986 averaged 0.65% U_3O_8. The breccia pipes mined to date have contained between 1 and 7 million pounds of U_3O_8 each (I.W. Mathiesen, personal communication, 1988). Uraninite is the ore mineral; pyrite, chalcopyrite, sphalerite, galena, and bravoite are other commonly associated metallic minerals. Less common metallic minerals are nickeline, rammelsbergite, millerite, gersdorffite, vaesite, siegenite, marcasite, arsenopyrite, tennantite, enargite, luzonite, lautite, bornite, chalcocite, djurleite, digenite, nukundamite, and covellite. Common gangue minerals are calcite, dolomite, and barite. Both the ore and gangue minerals occur primarily in the sandy matrix supporting the breccia clasts. Primary and secondary fluid inclusions in sphalerite, dolomite, and calcite yield filling temperatures that range from 80° to 173°C. Their corresponding salinites are consistently >9 wt. percent NaCl equivalent and generally >18 wt percent NaCl equivalent. A large set of U-Pb isotopic analyses from 9 orebodies shows that the main uranium-mineralizaing event occurred roughly 200 Ma ago; data from two of these pipes, however indicate at least one earlier period of mineralization roughly at 260 Ma (Ludwig and Simmons, 1988). Additional descriptions of breccia pipes and their mineralization can be found in Wenrich, Chenoweth, Finch, and Scarborough (in press); Van Gosen and Wenrich (1989); Wenrich and Sutphin (1989); Gornitz and others (1987); Krewedl and Carisey (1986); Wenrich (1985, 1986); and Gornitz and Kerr (1970).

BRECCIA PIPES IN THE HUALAPAI INDIAN RESERVATION

The Hualapai Indian Reservation is situated on the southwestern corner of the Colorado Plateau (fig. 1). The western half of the reservation, located on the Hualapai Plateau and bounded on the west by the Grand Wash Cliffs, is capped by the Redwall Limestone. No more than 500 ft (175 m) of possible rock thickness is available to host an orebody, and little of it is sandstone. Most is limestone, which generally is an unfavorable host for uranium mineralization; thus, the Hualapai Plateau is not considered favorable for economic breccia pipes, and has been eliminated for potential drilling targets. In contrast, the eastern part of the reservation occupies the western edge of the Coconino Plateau which is capped, for the most part, by the Harrisburg Gypsiferous Member of the Kaibab Limestone. This thick stratigraphic column of rock, in excess of 2,500 ft (800 m) provides ample host rock for potential mineral deposits. In addition, this plateau surface occupies the same stratigraphic horizon as does the plateau surface above most breccia pipes hosting orebodies in northern Arizona.

Over 900 confirmed and suspected breccia pipes have been mapped on the Hualapai Reservation (fig. 3). This density of collapse features is not unique to the Hualapai Reservation, the western edge of the pipe-rich region in Arizona, but extends eastward where a similar concentration has been mapped on the Marble Plateau (Sutphin and Wenrich, 1983). A map of breccia pipes across northwestern Arizona by Sutphin and Wenrich (1989) shows large areas with only a few pipes and some areas with no pipes--most of northwestern

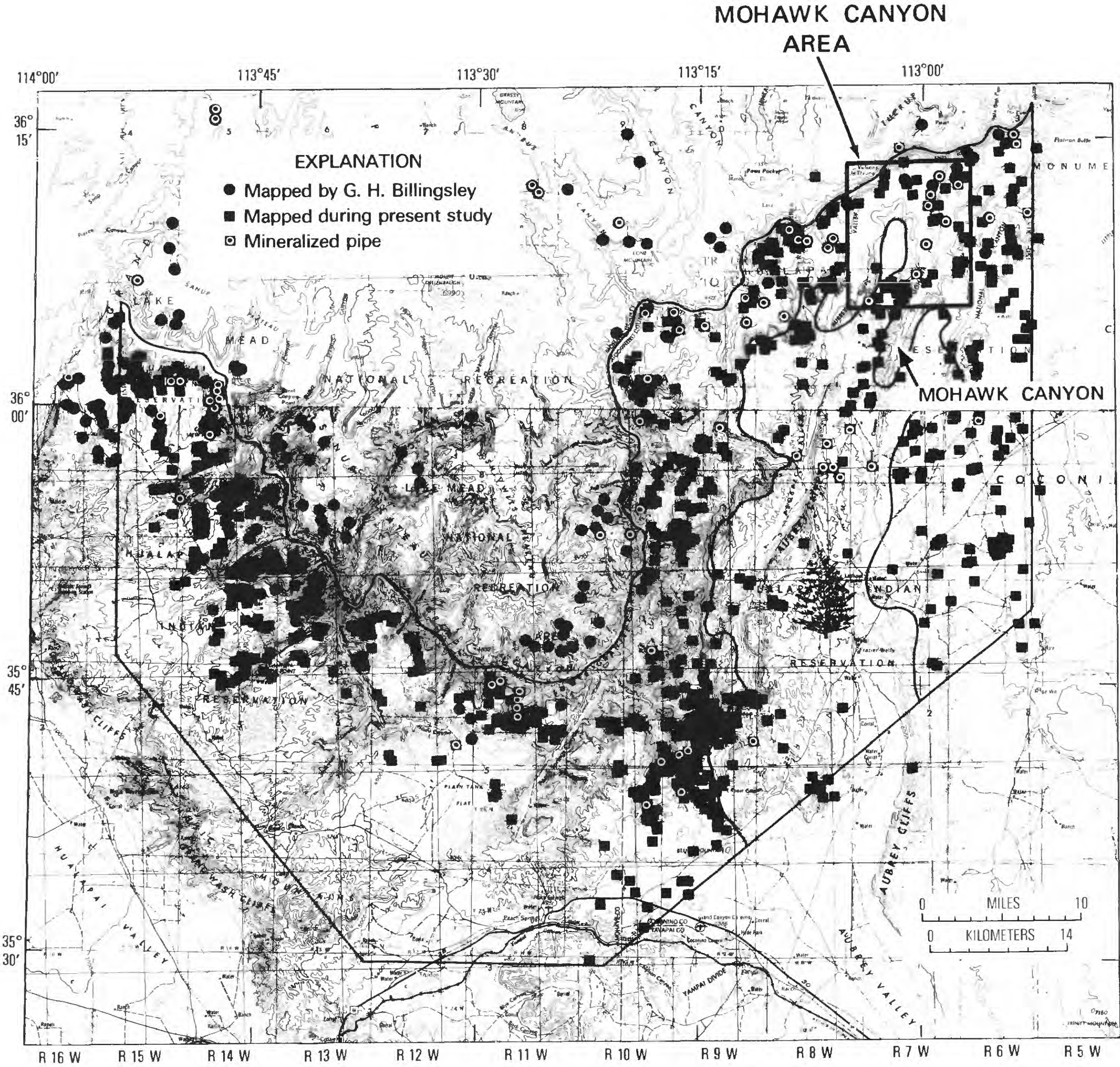


Figure 3.--This map of the Hualapai Indian Reservation illustrates the density of solution-collapse features existing in northern Arizona. Over 900 confirmed and suspected breccia pipes have been mapped within and adjacent to the Hualapai Reservation. Vegetation is sparse on the western side of the reservation, which is reflected in the greater density of identified collapses. Area outlined with black curvey line (shown with a tree symbol in the center) on the eastern side of map is densely tree covered, preventing recognition of most pipes. The Mohawk Canyon area is outlined with a rectangle at the northeastern corner of the reservation.

Arizona and especially these areas of low-pipe density have not been mapped in detail. The only data available for those areas containing few or no pipes is what was provided by the exploring mining companies.

Mapping collapse features as surface manifestations of breccia pipes on high plateaus (such as the Coconino, Kaibab, and Marble Plateaus) capped by the Kaibab Limestone or younger units is complicated both by karst development in the Kaibab and solution collapses formed where gypsum is dissolved from the underlying Toroweap Formation, or from the Harrisburg Gypsiferous Member of the Kaibab Limestone (fig. 4). Thus, throughout this paper the terms solution collapse, structure, or feature are defined as those areas that apparently collapsed due to dissolution of any underlying rock, whereas the term breccia pipe refers specifically to dissolution of the Redwall Limestone, which resulted in stoping and brecciation of the overlying rock. It is generally assumed that those collapse features resembling ordinary sink holes--with vertical walls, no tilted beds, and a bottom covered by uncemented rubble--are recent karst landforms. An example of this in the Mohawk Canyon area is the sinkhole (#591) shown on the geologic map (fig. 4). In contrast, collapse features with inward-tilted beds and alteration appear to be favorable indicators of concealed breccia pipes. Unfortunately, drilling results indicate that not all collapses possessing these favorable characteristics have breccia pipes beneath them, suggesting that geochemical and geophysical exploration techniques should be used before drilling (Wenrich, 1986; Flanigan and others, 1986).

Although the dissolution of gypsum in the Toroweap Formation and of both limestone and gypsum in the Kaibab Limestone is a complicating factor, the process apparently enhances the surface expression of those features that are, indeed, breccia pipes. Most of the lower plateau surfaces, most notably the Esplanade surface (generally located near or at the top of the Esplanade Sandstone--fig. 2), do not have the density of features exposed that the Kaibab- Moenkopi-, and Chinle-capped plateaus have. Initially this greater density of features might appear to suggest that most features on these latter plateaus are merely sinkholes within the Kaibab and Toroweap. To the contrary, apparently the presence of a breccia pipes increases the movement of fluids not only within the pipe itself but also laterally in various formations adjacent to the pipe. The effects of enhanced circulation can be seen in the core from the Mohawk Canyon pipe (Wenrich and others, 1988); here the entire 100 feet of gypsiferous Woods Ranch Member of the Toroweap Formation has been almost entirely removed from the brecciated column. Dissolution of the upper soluble units in the vicinity of pipes accounts for the discrepancy in size between the pipes and the much larger collapse features that are commonly mapped above them. All known orebodies range from 100 to 500 ft (most commonly about 250 ft) in diameter, whereas many of the collapse features on plateau surfaces are as much as 1,300 ft across. One notable example, which contained an economic orebody that is now mined out, is the Pigeon pipe (fig. 1); the pipe diameter is about 250 ft yet its overlying collapse structure is approximately 0.5 mi in diameter. The largest known collapse--Shadow Mountain collapse on the Marble Plateau--is more than one mile in diamter, and is located about a mile NNE of Shadow Mountain, a Tertiary basaltic cinder cone. The actual Shadow Mountain breccia pipe may be no more than the average 250 ft in diameter--the Tertiary solutions associated with the nearby volcanism may have caused extensive recent dissolution of some of the formations underlying the collapse (such as large-scale dissolution of the Redwall or Muav Limestones, as there is no gypsiferous rock within the Toroweap and Kaibab on the Marble Plateau).

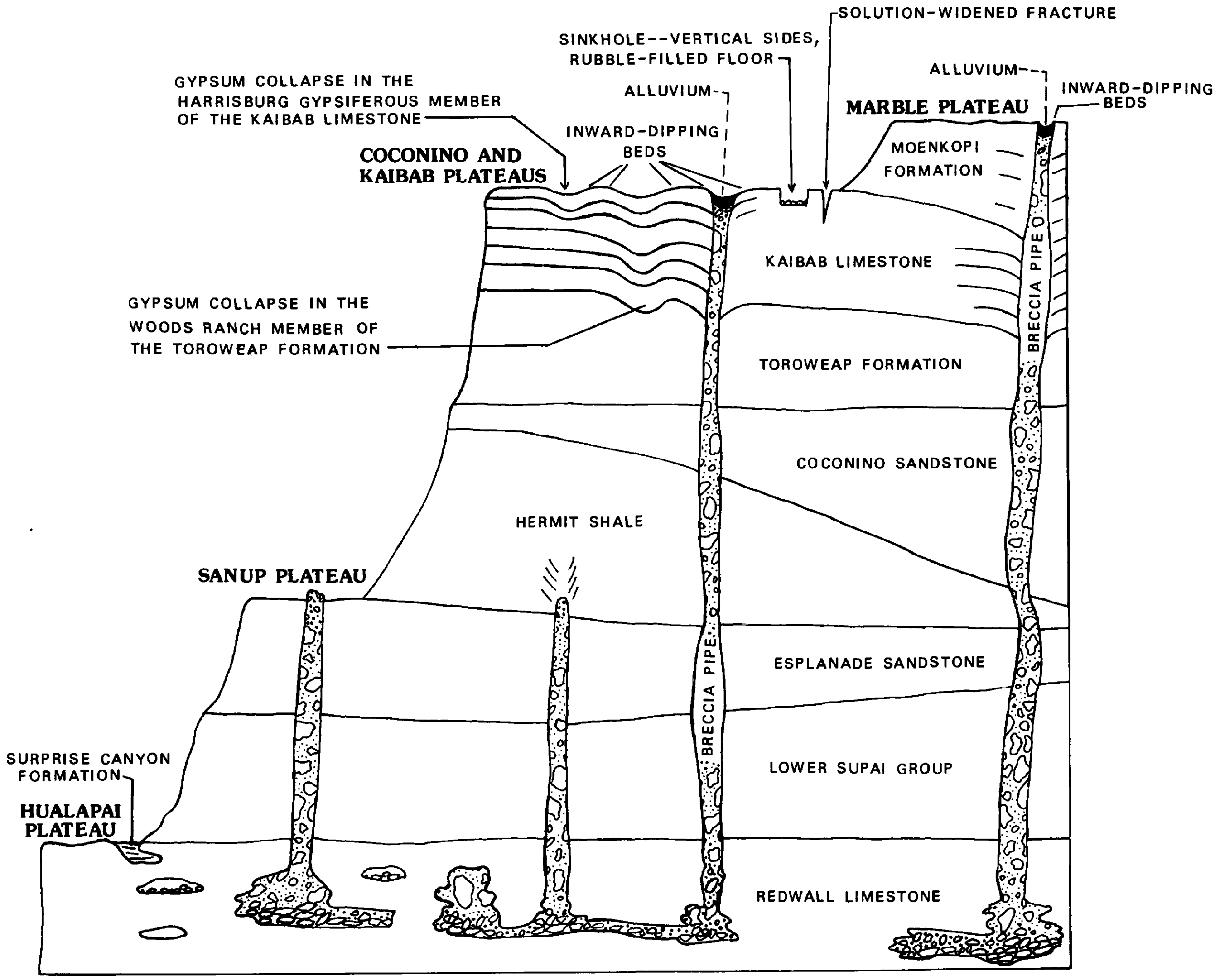


Figure 4--Cartoon showing the various types of solution-collapse features found in northwestern Arizona: (1) Breccia pipes that bottom in the Redwall Limestone, (2) Collapse due to dissolution of gypsum beds in the Woods Ranch Member of the Toroweap Formation, (3) Collapse due to dissolution of gypsum beds in the Harrisburg Gypsiferous Member of the Kaibab Limestone, and (4) Collapse (with vertical sides, as opposed to the gently-sloping sides of the other 3 collapse types) due to recent sinkholes in the limestone beds of the Kaibab Limestone.

Thus, locating the actual breccia pipe, and perhaps an orebody, will be more difficult in Shadow Mountain-sized collapses than in a small collapse, such as that which overlies the Mohawk Canyon pipe. Exploration for mineralized breccia pipes may be more successful on the upper plateaus where dissolution has enlarged the collapse within the upper Paleozoic units, in some places more than ten times the actual breccia pipe size, than on the lower plateaus which are capped mostly by insoluble rock such as the Esplanade Sandstone. This increase in solution collapse within the upper plateaus, which are capped by soluble Lower Permian and younger rocks, emphasizes the importance of mapping all solution features in these areas.

Many exploration criteria for detecting mineralized breccia pipes were developed during mapping of the Hualapai Reservation. Mapping began on 1:24,000 low-altitude color aerial photographs; pipes delineated on the photos were then field checked. Many pipes exposed along cliff faces are not recognizable in the deep shadows along the cliffs on aerial photographs, and are best identified from a helicopter.

The following exploration criteria are considered favorable indicators of mineralized breccia pipes:

1. Concentrically inward-dipping beds.
2. A circular topographic pattern. This pattern is commonly expressed as a topographically high rim around a central depression.
3. Anomalous radioactivity; 2.5 times background or higher was considered anomalous during the mapping.
4. Goethite pseudomorphs and molds of pyrite.
5. Colloform celadonite-stained chalcedony.
6. Copper mineralization expressed on surface exposure as the supergene minerals malachite, azurite, brochantite, and chrysocolla.
7. Breccia, other than intraformational breccias.
8. Anomalous concentrations in surface samples of such trace elements as Ag, As, Cd, Co, Cu, Mo, Ni, Pb, Se, V, and Zn.
9. A circular vegetation or color pattern.

To verify that a collapse feature mapped from the air is a breccia pipe, these criteria were checked in the field. Few pipes exhibit all these criteria on surface exposure, but the more that are present, the greater the certainty that the feature is a deep-seated breccia pipe as opposed to a shallower collapse structure.

Although breccia pipes are easily recognized within canyons where they are exposed in cross section, large expanses of northern Arizona are composed of undissected high plateaus. Recognition of pipes in these areas is particularly important because ease of access promotes mining that would be difficult or uneconomic in the canyons. In addition, pipes exposed in canyon walls have commonly lost much of their rock, including mineralized rock, to erosion and perhaps their metals to leaching. Shallow structural basins on the adjacent plateaus are probably surface expressions of the upper part of breccia pipes. This assumption is supported by the occasional exposure of a breccia pipe in a canyon wall directly beneath a shallow structural basin on the plateau surface (Wenrich, 1985, fig. 5). Because the ring fracture, which delineates the actual pipe, is well exposed in less than half the mapped collapse features, and in order to be consistent throughout the mapped area, the boundaries of the breccia pipes were mapped as the outermost extent of inward-dipping beds. It should be emphasized that this area mapped as a solution collapse can be as much as five time the size of the actual breccia pipe, due to dissolution of the Toroweap and Kaibab adjacent to the pipe.

THE MOHAWK CANYON AREA

The Mohawk Canyon area (rectangular area outlined in black in fig. 3) is located on part of the National Canyon 15', the Vulcans Throne 7 ½ ', and the Vulcans Throne SE 7 ½ ' quadrangles in the northeast corner of the Hualapai Indian Reservation. Rocks in the area span the entire Paleozoic sequence of the Grand Canyon, from the Cambrian Tapeats Sandstone to the Permian Kaibab Limestone (fig. 5). The area is dissected by Mohawk Canyon, and parts of the Colorado River and Prospect Valley. Both Mohawk Canyon and Prospect Valley are fault-controlled canyons. Several breccia pipes identified in this area contain mineralized rock with anomalous concentrations of U, Cu, Ag, As, Pb, and Zn.

Mapping of Collapse Features in the Mohawk Canyon Area

Most of the collapse structures identified within this area are exposed along cliffs, providing sufficient outcrop in 3-dimensions so that many of them have been positively identified as breccia pipes. Nineteen of the structures occur on plateaus capped by the Kaibab Limestone; outcrop is sufficiently sparse that circular erosion patterns and occasional dipping beds are all that are available to aid in their recognition as collapses. All of the mapped collapse structures essentially fall within three groups: (1) those that are exposed at the top of the Redwall Limestone surface along the inner gorge and side tributaries to the Colorado River (13 features), (2) those that are exposed on the Esplanade surface or along the cliffs in other formations of the Supai Group (14 features), and (3) those that crop out on the Coconino Plateau as circular features and shallow basins collared in the Kaibab Limestone (19 features).

The collapse features in the Mohawk Canyon area were initially mapped on 1:24,000 color aerial photographs. These were then field checked and 46 of them were either confirmed as breccia pipes (breccia was observed in outcrop) or considered to be, at least, collapse structures (possible breccia pipes). Table 1 lists all collapse features mapped in the Mohawk Canyon area. In addition, some comments describing each collapse are provided, as well as their respective collapse category that is based on the exploration criteria discussed in the previous section titled "Breccia pipes in the Hualapai Indian Reservation".

A photograph is provided in this report for 40 of the 46 mapped collapse features to allow each reader to make their own assessment of the potential for these collapse structures to be an actual breccia pipe. Even collapse features with poor exposure are included so that the exploration geologist can find the exact location of each collapse feature/pipe referred to in this report. Only those that are believed by the authors to have good potential are described in detail. Unfortunately, there was not always a photograph available to illustrate that which was observed in the field and considered to be important; nevertheless, a photograph of a collapse feature is commonly valuable to other geologists whose criterion might be different from those the authors used during this study.

Geochemical studies were completed on rock samples collected from those pipes that were categorized as mineralized. Fifty-five elements and "loss on ignition" were determined on each sample; analytical results are shown in table 2. These samples generally represent the "high-grade" from each pipe--collected because they contain gamma radiation exceeding 2.5 times background, malachite or azurite, goethite, or pyrite. The most accurate analytical method used for each element is listed unless it is not available for a

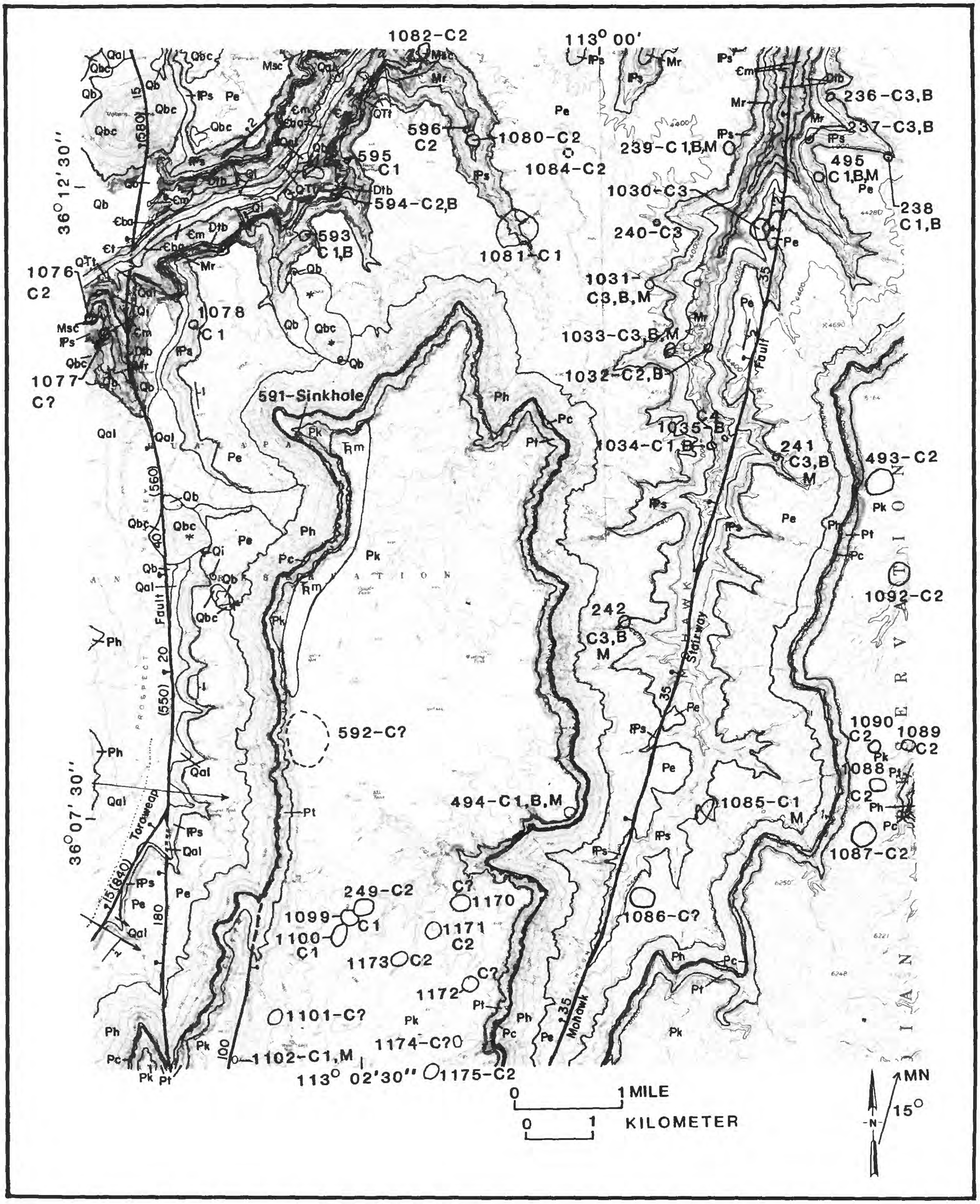


Figure 5a--Geologic map of the Mohawk Canyon area showing breccia pipes and collapse features.

DESCRIPTION OF MAP UNITS

SURFICIAL AND VOLCANIC DEPOSITS

Qal **ALLUVIUM (HOLOCENE)--**
Silt, sand, gravel and eolian deposits

Qbc **BASALTIC CINDERS AND ASH (PLEISTOCENE)**

Qb **BASALT FLOWS (PLEISTOCENE)**

Qi **INTRUSIVE VOLCANICS (PLEISTOCENE)--**
Includes dikes, plugs, and sills

QTt **TRAVERTINE (PLEISTOCENE AND PLIOCENE?)--**
Includes local calcareous cemented talus usually in and adjacent to travertine

SEDIMENTARY ROCKS

Ꞧm **MOENKOPI FORMATION (LOWER TRIASSIC)--**
Timpoweap Member; Light brown limestone and chert conglomerate with coarse-grained sandstone matrix; clasts are rounded to subrounded. Clasts are eroded and contain fossils from the Harrisburg Member of the Kaibab Limestone. Forms a cliff

Pk **KAIBAB LIMESTONE (LOWER PERMIAN)--**
Harrisburg Gypsiferous and Fossil Mountain Members undivided; the Harrisburg Gypsiferous Member consists of slope-forming gray and pale-red shales and gypsiferous siltstone interbedded with gray, ledge-forming limestone and dolomitic sandstone; the Fossil Mountain Member consists of cliff-forming yellowish-gray cherty fossiliferous limestone

Pt **TOROWEAP FORMATION (LOWER PERMIAN)--**
Top to bottom; includes the Woods Ranch, Brady Canyon, and Seligman Members undivided; the Woods Ranch is a pale-red and gray siltstone interbedded with gray to white gypsum and forms a slope; the Brady Canyon consists of gray fossiliferous cherty limestone that forms a cliff, gradational contacts with Woods Ranch and Seligman Members; Seligman consists of pale-red and yellow-white sandstone of Coconino Sandstone below, thin-bedded, medium- to fine- grained quartz, forms a recess beneath the Brady Canyon cliff

Pc **COCONINO SANDSTONE (LOWER PERMIAN)--**
Yellowish-white, fine-grained, cross-stratified. Forms prominent light colored cliff

Unconformity

Figure 5b--Explanation to the geologic map of the Mohawk Canyon area.

Ph **HERMIT SHALE (LOWER PERMIAN)--**

Red-brown, slope-forming, fine-grained siltstone and sandstone; fills local channels on Esplanade Sandstone

Unconformity

SUPAI GROUP
(PERMIAN AND PENNSYLVANIAN)

Pe **ESPLANADE SANDSTONE (LOWER PERMIAN)--**

Light red to red-brown, cliff forming, cross-stratified, medium- to fine-grained sandstone. Includes slope-forming red-brown siltstone above and below main sandstone cliff unit

Unconformity

IPs **WESCOGAME, MANAKACHA, AND WATAHOMIGI FORMATIONS UNDIVIDED (PENNSYLVANIAN)**

WESCOGAME FORMATION--

Red to pale-red siltstone and shale interbedded with thick beds of fine-grained, calcareous sandstone. Forms a cliff or series of ledges in lower part, slope with ledges in upper part

MANAKACHA FORMATION--

Reddish-brown, thick-bedded, fine-grained sandstone with some gray cross-bedded dolomitic sandstone. Also consists of a few beds of purple-red and gray shale. Forms a cliff in lower part, slope and ledges in upper part. Erosional unconformity between the Wescogame and the Watahomigi Formations

WATAHOMIGI FORMATION--

Interbedded gray-purple calcareous shale and siltstone with gray limestone. Limestone contains bands of red and white chert. Forms a slope with ledges in upper part

Unconformity

Msc **SURPRISE CANYON FORMATION (UPPER MISSISSIPPIAN)--**

Dark red-brown and orange-brown siltstone and sandstone interbedded with chert conglomerate and hematitic quartz sandstone in lower part. Also consists of thin-bedded, yellowish-gray crystalline limestone and gray conglomeratic limestone in upper part. Forms a slope with some ledges

Unconformity

Mr **REDWALL LIMESTONE (MISSISSIPPIAN)--**

Includes the Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members Undivided. Light gray cliff-forming, thick-bedded, fossiliferous limestone and dolomite. Contains a few beds of chert (white), especially in the Thunder Springs Member

Unconformity

Dtb **TEMPLE BUTTE LIMESTONE (DEVONIAN)--**
Interbedded light-gray to purple dolomite, dolomitic sandstone, sandy limestone, reddish-brown siltstone, and gray sandstone. Forms a series of ledges and cliffs

Unconformity

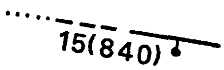
Єm **MUAV LIMESTONE (MIDDLE CAMBRIAN)--**
Mottled gray and purple dolomitic limestone; lower part contains tongues of Bright Angel Shale and a few beds of rusty-brown coarse-grained sandstone. Forms a series of alternating slopes and cliffs

Єba **BRIGHT ANGEL SHALE (MIDDLE CAMBRIAN)--**
Green and purple-red fissile siltstone interbedded with a few light-brown, coarse-grained, thin sandstone beds. Unit forms a slope with ledges of dolomite and sandstone. Gradational contacts with the Muav Limestone and the Tapeats Sandstone

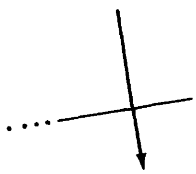
Єt **TAPEATS SANDSTONE (MIDDLE AND LOWER CAMBRIAN)--**
Brown medium- to coarse-grained sandstone and pebble conglomerate. Contains a few thin beds of green Bright Angel Shale, forms ledges

SYMBOLS


CONTACT BETWEEN MAP UNITS



FAULT--
Dashed where position uncertain; dotted where concealed; bar and ball on downthrown side; number in parentheses is estimated stratigraphic offset prior to Holocene deposits; numbers are approximate stratigraphic offset in feet


MONOCLINE--
Located approximately midway between top and bottom hinges of fold; length of arrows indicate distance between hinges; dotted where concealed

✳ **VOLCANIC CENTERS--**
Approximate location of vent

COLLAPSE FEATURES--
○ 494 Collapse feature number used in text to identify each collapse

COLLAPSE FEATURE CLASSIFICATION--

B	Brecciated rock observed in the field
M	Mineralized rock (either visible copper or surface radiation >2½ times background) present
C1	Concentric, inward-dipping beds and visible alteration (bleaching or limonite staining)
C2	Concentric, inward-dipping beds; no visible alteration
C3	Visible alteration; no visible dipping beds
C4	Distinctly circular feature, either due to vegetation or topography; no visible alteration or dipping beds
C?	Questionable. A circular feature appears to be present, but with no obvious dipping beds, alteration, vegetation change or topography delineation

Table 1.-- List of collspse features and breccia pipes mapped in the Mohawk Canyon area. "Formation" refers to the formation(s) in which the collapse crops out.

Pipe Number	Quadrangle	Section, Township, Range	Latitude, Longitude	Category	Formation(s)	Comments
236	National Canyon (15-minute)		36° 13′ 09" 112° 57′ 43"	C3, B	Esplanade, lower Supai Group	Beds down hillslope within pipe dip 28° N; conglomeratic breccia; bleached center and limonite alteration; massive calcite.
237	National Canyon (15-minute)		36° 12′ 47" 112° 57′ 52"	C3, B	lower Supai Group	Bleached; conglomeratic breccia.
238	National Canyon (15-minute)		36° 12′ 40" 112° 57′ 06"	C1, B	Esplansde, lower Supai Group	Good circular topographic shape; no dipping beds.
239	National Canyon (15-minute)		36° 12′ 43" 112° 13′ 32"	C1, B, M	Esplanade	Pink- and yellow-stained breccia.
240	National Canyon (15-minute)		36° 12′ 09" 112° 59′ 28"	C3	Esplanade	Sharp contact between bleached and unbleached rock; well-developed concentric jointing.
241	Nstional Canyon (15-minute)	Section 7, T 32N, R 6W	36° 10′ 15" 112° 58′ 12"	C3, B, M	lower Supai Group	Two tall pinnacles of breccia; surrounded at their base by breccia with more rounded clasts, downdropped in an amphi-theatre. Goethite nodules with malachite rims in breccia.
242	National Canyon (15-minute)	Section 23, T 32N, R 7W	36° 09′ 01" 112° 59′ 56"	C3, B, M	Esplanade, lower Supai Group	Brecciated sandstone with pyrite-bearing siderite concretions.
249	Vulcan's Throne SE (7 1/2-minute)	Section 33, T 32N, R 7W	36° 06′ 46" 113° 02′ 25"	C2	Kaibab	Concentric bands of outcropping Kaibsb Limestone; good circular topographic shape--concentric drainage around a circular hill; bleached; chert breccia (may be intraformational). Limonite pseudomorphs after pyrite.
493	National Canyon (15-minute)	Section 8, T 32N, R 6W	36° 10′ 04" 112° 57′ 18"	C2	Kaibab	Central hill with inward dipping (60°) beds of Moenkopi Formation(?); concentric depression around the hill surrounded by a concentric rim (breached on two sides); dissolution of Harrisburg Member and Woods Ranch Member gypsum in west slope and cliff below collapse.
494	Vulcan's Throne/ Vulcan's Throne SE (7 1/2-minute)	Section 26, T 32N, R 7W	36° 07′ 30" 113° 00′ 24"	C1, B, M	Kaibab	Drilled by USGS in 1984 (see Wenrich and others, 1988); U and Cu minerals present; 19th century copper prospect. Concentric ring fractures with semi-circular drainage eroded along one of the inner ring fractures. Limonite pseudomorphs and molds after pyrite. Concentric radially-inward dipping beds.
495	National Canyon (15-minute)		36° 12′ 30" 112° 57′ 57"	C1, B, M	lower Supai Group	Dipping beds; bleaching; limestone breccia clasts; limonite; hematite.
592	Vulcan's Throne (7 1/2-minute)	Section 29, T 32N, R 7W	36° 08′ 08" 113° 02′ 59"	C?	Kaibab	Dipping beds thst may be s collapse into the Toroweap Formstion gypsum; pale reddish-orange, crossbedded sandstone (Moenkopi Formation?). Largest collapse in the Mohawk Canyon area.

Table 1--continued.

Pipe Number	Quadrangle	Section, Township, Range	Latitude, Longitude	Category	Formation	Comments
593	Vulcan's Throne (7 1/2-minute)		36° 12′ 06" 113° 02′ 54"	C1, B	lower Supai Group, Redwall	Amphitheater shaped; dipping beds; limonite-staining in medium-grained sandstone.
594	Vulcan's Throne (7 1/2-minute)		36° 12′ 25" 113° 02′ 39"	C2, B	Redwall	Steeply dipping beds; cave in limonite-stained Redwall directly below the pipe.
595	Vulcan's Throne (7 1/2-minute)		36° 12′ 42" 113° 02′ 30"	C1	lower Supai Group, Redwall	Dipping beds; oxidized and bleached; some very small limonite-stained spots in the Supai Group.
596	Vulcan's Throne (7 1/2-minute)		36° 12′ 55" 113° 01′ 18"	C2	lower Supai Group, Redwall	Dipping beds? Drainage opens up here.
1030	Nstional Canyon (7 1/2-minute)		36° 12′ 07" 112° 58′ 27"	C3	Esplanade, lower Supai Group, Surprise Canyon, Redwall	Amphitheater in the Redwall Limestone with Surprise Canyon Formation sediments and one limonite-rich patch exposed.
1031	National Canyon (15-minute)		36° 11′ 52" 112° 14′ 20"	C3, B, M	Esplanade, Watahomigi	Entirely covered with alluvium except for a small gully with limonite stained soil and breccia; breccia contains goethite and pyrite concretions. Anomalous gamma radioactivity all the way up the gully.
1032	National Canyon (15-minute)		36° 11′ 09" 112° 58′ 59"	C2, B	lower Supai Group, Redwall	Amphitheater with Horseshoe Mesa Member of the Redwall Limestone strata dropped down into the Mooney Falls Member of the Redwall Limestone. Small breccia outcrop in the center of the amphitheater; minor dip to beds.
1033	National Canyon (15-minute)		36° 11′ 08" 112° 59′ 19"	C3, B, M	lower Supai Group, Redwall	Limonite and hematite in the side of the gully; brecciated Horseshoe Mesa Member of the Redwall Limestone; Surprise Canyon Formation on top.
1034	National Canyon (15-minute)	Section 12, T 32N, R 7W	36° 10′ 23" 112° 58′ 56"	C1, B	lower Supai Group, Redwall	Very slightly dipping beds; limonite-stained breccia of the Horseshoe Mesa Member dropped into Mooney Falls Member.
1035	National Csnyon (15-minute)	Section 12, T 32N, R 7W	36° 10′ 28" 112° 58′ 50"	C4, B	Redwall	Amphitheater with breccia in Mooney Falls Member and 20 ft of Horseshoe Mesa Member on top.
1076	Vulcan's Throne (7 1/2-minute)		36° 11′ 27" 113° 05′ 02"	C2	lower Supai Group, Surprise Canyon, Redwall	Horseshoe Mesa Member barely dipping back into hillslope; Surprise Canyon Formation dipping inward.
1077	Vulcan's Throne (7 1/2-minute)		36° 11′ 19" 113° 04′ 55"	C?	lower Supai Group, Redwall	Altered and brecciated, but this may be related to lava located within the area.
1078	Vulcan's Throne (7 1/2-minute)		36° 11′ 24" 113° 04′02"	C1	lower Supai Group	One bleached bed of Wescogame Formation observed with a very slight dip.
1080	Vulcan's Throne (7 1/2-minute)		36° 12′ 50" 113° 01′ 16"	C2	lower Supai Group, Redwall	Dipping beds of Redwall Limestone; a lobe of travertine dipping into the gully.

Table 1--continued.

Pipe Number	Quadrangle	Section, Township, Range	Latitude, Longitude	Category	Formation	Comments
1081	Vulcan's Throne (7 1/2 -minute)		36° 12′ 07″ 113° 00′ 54″	C1	Esplanade, lower Supai Group	Very large collapse (second largest in Mohawk Canyon area); on plateau surface and spans the gully; very bleached dipping beds.
1082	Vulcan's Throne (7 1/2 -minute)		36° 13′ 34″ 113° 01′ 42″	C2	lower Supai Group, Surprise Canyon, Redwall	Beds of the Horseshoe Mesa Member of the Redwall Limestone and the Surprise Canyon Formation dip into an amphitheater.
1084	Vulcan's Throne (7 1/2 -minute)		36° 12′ 43″ 113° 00′ 18″	C2	Esplanade	Nicely dipping beds into a closed basin.
1085	National Canyon (15-minute)	Section 25, T 32N, R 7W	36° 07′ 30″ 112° 13′ 57″	C1, M	Esplanade, lower Supai Group	Bleaching and limonite staining; base of gully and exposed part of pipe is Wescogame Formation. Minor inward dip (toward amphitheater).
1086	National Canyon (15-minute)	Section 35, T 32N, R 7W	36° 06′ 49″ 112° 59′ 41″	C?	Esplanade	Circular drainage around a hill; some bleaching. No obvious dip to the beds.
1087	National Canyon (15-minute)	Section 31, T 32N, R 6W	36° 07′ 17″ 112° 57′ 30″	C2	Kaibab	Beds of Harrisburg Member dipping moderately to strongly into gully.
1088	National Canyon (15-minute)	Section 29, T 32N, R 6W	36° 07′ 41″ 112° 57′ 18″	C2	Kaibab	Dipping beds all the way around in the Harrisburg Member; Fe-stained chert.
1089	National Canyon (15-minute)	Section 29, T 32N, R 6W	36° 08′ 00″ 112° 57′ 01″	C2	Kaibab	Dipping beds in the Harrisburg Member.
1090	National Canyon (15-minute)	Section 29, T 32N, R 6W	36° 08′ 01″ 112° 57′ 24″	C2	Kaibab	Dipping beds in the Harrisburg Member; no outcrop on three sides.
1092	National Canyon (15-minute)	Section 17, T 32N, R 6W	36° 09′ 21″ 112° 57′ 08″	C2	Kaibab	A very slight bowl at top of Harrisburg Member; on the cliffs below collapse the Woods Ranch Member of the Toroweap Formation is largely dissolved away.
1099	Vulcan's Throne SE (7 1/2 -minute)	Section 33, T 32N, R 7W	36° 06′ 41″ 113° 02′ 35″	C1	Kaibab	In chert of the Harrisburg Member; dipping beds; abundant limonite and hematite staining on exposed outcrop and float.
1100	Vulcan's Throne SE (7 1/2 -minute)	Section 33, T 32N, R 7W	36° 06′ 33″ 113° 02′ 40″	C1	Kaibab	Dipping Harrisburg Member beds; limonite staining on chert.
1101	Vulcan's Throne SE (7 1/2 -minute)	Section 5, T 31N, R 7W	36° 05′ 54″ 113° 03′ 19″	C?	Kaibab	Dipping Harrisburg Member beds on one side of a circular hill.
1102	Vulcan's Throne SE (7 1/2 -minute)	Section 8, T 31N, R 7W	36° 05′ 35″ 113° 03′ 40″	C1, M	Kaibab	Nicely dipping beds around a gully; outcrops of dark orange Fe-rich gossan, 18 times background (550 cps); possibly a good drilling target in the Harrisburg Member.

Table 1.-- continued.

Pipe Number	Quadrangle	Section, Township, Range	Latitude, Longitude	Category	Formation(s)	Comments
1170	Vulcan's Throne SE ($7\frac{1}{2}$-minute)	Section 34, T 32N, R 7W	36° 06′ 47" 113° 01′ 29"	C?	Kaibab	Harrisburg Member beds dip into the stream meander on one side.
1171	Vulcan's Throne SE ($7\frac{1}{2}$-minute)	Section 33, T 32N, R 7W	36° 06′ 34" 113° 01′ 45"	C2	Kaibab	Concentric Harrisburg Member strata dip radially inward.
1172	Vulcan's Throne SE ($7\frac{1}{2}$-minute)	Section 3, T 31N, R 7W	36° 06′ 03" 113° 01′ 23"	C?	Kaibab	Harrisburg Member beds dip down the hillslope on one side.
1173	Vulcan's Throne SE ($7\frac{1}{2}$-minute)	Section 4, T 31N, R 7W	36° 06′ 14" 113° 02′ 05"	C2	Kaibab	Concentric Hsrrisburg Member strata dip radially inward. Goethite cubes pseudomorphed after pyrite.
1174	Vulcan's Throne SE ($7\frac{1}{2}$-minute)	Section 3, T 31N, R 7W	36° 05′ 42" 113° 01′ 31"	C?	Kaibab	Slightly inward-dipping beds of Harrisburg Member on two sides.
1175	Vulcan's Throne SE ($7\frac{1}{2}$-minute)	Section 9, T 31N, R 7W	36° 05′ 33" 113° 01′ 47"	C2	Kaibab	Harrisburg Member beds dipping inward and form a basin.

Table 2.-- Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area. (The first 3 or 4 digits of the sample number, preceeding the dash, are the pipe number shown in Table 1).

Sample number	Latitude	Longitude	Ag ppm ICP	Al_2O_3% XRF	As ppm AA	Au ppm HBR	Ba ppm ICP	Be ppm ICP	Total-C% CID	T-Org C%**
237-A-C82	36°12'47"	112°57'52"	<2	2.45	4700	+ <8	140	<1	0.08	0.03
238-A-C83	36°12'40"	112°57'06"	<2	4.13	99	+ <8	1100	<1	0.05	0.05
239-A-C83	36°12'44"	112°58'46"	<2	2.17	100	+ <8	200	<1	6.36	0.15
241-A-C82	36°10'15"	112°58'12"	170	1.4	5000	0.23	46	<1	0.06	0.04
241-B-C82	36°10'15"	112°58'12"	14	2.21	870	<0.05	47	<1	0.1	0.01
242-A-C82	36°09'01"	112°59'56"	11	3.23	6800	<0.05	19	<1	0.06	0.02
242-B-C82	36°09'01"	112°59'56"	3	3.88	2800	+ <8	7	<1	<0.01	<0.01
249-A-C83	36°06'46"	113°02'25"	<4	0.69	105	+<20	160	<2	0.23	0.07
493-A-C83	36°10'04"	112°57'18"	<2	0.56	4	+ <8	28	<1	12.2	<0.01
493-B-C83	36°10'04"	112°57'18"	<4	<0.1	6.8	+<20	150	<2	0.84	0.09
494-A-C83	36°07'30"	113°00'24"	<10	0.49	36	+<40	150	<5	0.17	0.05
494-B-C83	36°07'30"	113°00'24"	<2	14.4	72	+<40	350	<5	0.88	0.06
494-C-C83	36°07'30"	113°00'24"	100	2.24	400	<0.05	210	<5	1.58	0.57
495-A-C83	36°12'32"	113°57'50"	4	8.47	3300	+ <8	100	<1	0.07	0.05
593-A-C83	36°12'06"	113°02'54"	21	5.07	5800	<0.05	460	8	0.31	0.19
1031-A-C85	36°11'52"	112°59'05"	<2	0.69	+490	+ <8	54	<1	0.10	<0.01
1031-B-C85	36°11'52"	112°59'05"	<2	1.78	+830	+ <8	46	<1	0.04	0.04
1033-A-C85	36°11'08"	112°59'19"	<2	5.56	+1900	+ <8	23	<1	0.09	<0.01
1085-A-C85	36°07'27"	112°59'03"	<2	6.96	+<10	+ <8	270	1	4.29	0.19
1088-A-C85	36°07'41"	112°57'18"	<2	1.57	+190	+ <8	1700	<1	0.13	0.04
1102-A-C85	36°05'35"	113°03'40"	<2	1.00	+650	+ <8	76	<1	0.11	0.05
1102-B-C85	36°05'35"	113°03'40"	<2	0.55	+570	+ <8	120	<1	0.01	<0.01

+ ICP data
ICP= Inductively Coupled Argon Plasma Emission Spectroscopy
AA= Atomic Absorption
XRF= X-ray Fluorescence
HBR= Sample is digested in hydrobromic acid and bromine and analyzed using AA
CID= Combustion with Infrared Detection
** T-Org C% is calculated by (Total-C%) - ($T-CO_3$ C%)

Table 2.-- Continued.

Sample number	T-CO_3 C%	CaO%	Cd ppm	Ce ppm	Co ppm	Cr ppm	Cs ppm	Cu ppm	Dy ppm	Er ppm
	CT	XRF	ICP	ICP	ICP	ICP	AA	ICP	ICP	ICP
237-A-C82	0.05	0.44	<2	<4	<1	32	<1	140	<4	<4
238-A-C83	<0.01	<0.02	<2	23	3	26	<1	180	<4	<4
239-A-C83	6.21	15.6	<2	* 6.98	*12.9	15	* 0.63	190	<4	<4
241-A-C82	0.02	0.23	15	* 6	* 2.25	11	* 0.31	10000	* 1.6	<4
241-B-C82	0.09	0.43	20	<4	<1	76	<1	8800	<4	<4
242-A-C82	0.04	0.51	<2	*22	* 7.75	42	* 1.32	460	* 1.5	<4
242-B-C82	<0.01	0.79	<2	<4	<1	19	1	70	19	<4
249-A-C83	0.16	2.61	<4	<8	<2	62	<1	330	<8	<8
493-A-C83	12.2	30	<2	<4	13	20	<1	70	<4	<4
493-B-C83	0.75	32.3	<4	* 1.7	* 0.94	7	* 0.09	37	<8	<8
494-A-C83	0.12	0.63	<10	<20	<5	31	<1	40	<20	<20
494-B-C83	0.74	2.28	<10	*33.2	* 5.32	140	*11.4	20	<20	<20
494-C-C83	1.01	2.8	30	*26.5	*11.9	330	* 1.27	14000	<20	<20
495-A-C83	0.02	0.41	<2	56	9	140	1	20	8	<4
593-A-C83	0.12	0.91	<2	* 9.54	*38.6	81	* 2.18	380	39	4
1031-A-C85	0.11	1.71	5	* 1.8	* 7	21	* 0.99	120	-	-
1031-B-C85	<0.01	0.94	5	* 2.6	* 7.2	31	* 0.68	92	-	-
1033-A-C85	0.09	0.61	<2	*43	*31	53	* 1.1	120	-	-
1085-A-C85	4.1	19.8	<2	*40	* 4.5	35	* 7.8	4	-	-
1088-A-C85	0.09	0.72	10	* 5.1	* 2.5	16	* 0.25	26	-	-
1102-A-C85	0.06	1.69	<2	*11	* 110	59	* 0.57	49	-	-
1102-B-C85	0.03	1.31	<2	* 5.9	*11	43	* 0.29	25	-	-

* INAA data
INAA= Induced Neutron Activation Analysis
CT= Coulometric titration
ICP= Inductively Coupled Argon Emission Plasma Spectroscopy
AA= Atomic Absorption
XRF= X-ray Fluorescence

Table 2.-- Continued.

Sample number	Eu ppm	F%	T-Fe_2O_3%	Ga ppm	Gd ppm	Hf ppm	Hg ppm	K_2O%	LOI-900**	La ppm
	ICP	ISE	XRF	ICP	ICP	INAA	AA	XRF		ICP
237-A-C82	<2	0.01	11.9	<4	<10	-	0.11	0.34	2.8	4
238-A-C83	<2	0.02	0.49	5	<10	-	0.02	0.67	2.03	14
239-A-C83	* 0.55	0.02	0.61	<4	* 2.37	6.56	0.19	0.81	23.5	* 6.57
241-A-C82	* 0.34	0.01	11.9	<4	<10	4.66	0.06	0.44	4.58	* 5.1
241-B-C82	<2	<0.01	0.59	<4	<10	-	0.08	0.19	1.77	4
242-A-C82	* 0.28	0.02	56.5	<4	10	4.94	0.47	0.93	16.7	* 9.66
242-B-C82	<2	<0.01	35.5	<4	<10	-	0.49	0.59	20.9	8
249-A-C83	<4	0.14	1.58	<8	<20	-	0.02	0.07	1.4	15
493-A-C83	<2	0.03	1.05	<4	<10	-	0.01	0.15	44.4	<2
493-B-C83	* 0.03	<0.01	0.06	<8	<20	0.25	<0.01	0.05	-	* 0.81
494-A-C83	<10	0.01	2.68	<20	<50	-	0.05	0.07	1.25	<10
494-B-C83	* 0.51	0.33	15.2	<20	<50	7.46	0.20	4.6	11.5	*19.3
494-C-C83	* 0.67	0.16	18	<20	* 3.5	2.81	0.30	0.35	12.2	*27.4
495-A-C83	<2	0.02	9.82	16	<10	-	0.25	0.43	5.59	28
593-A-C83	* 0.32	0.05	63.5	19	<10	1.81	0.17	0.76	12.05	* 5.7
1031-A-C85	* 0.27	0.01	59.9	<4	-	0.91	0.04	0.17	14.4	* 4.2
1031-B-C85	* 0.11	0.04	63.7	5	-	3.4	<0.14	0.50	10.6	* 3.7
1033-A-C85	* 0.86	0.02	15	6	-	16	<0.14	0.34	5.91	*20
1085-A-C85	* 0.79	0.06	0.99	10	-	6.2	<0.02	2.65	17.5	*23
1088-A-C85	* 0.12	0.02	4.96	<4	-	0.69	<0.14	0.09	2.11	* 4.6
1102-A-C85	* 0.47	0.10	3.21	4	-	7.6	<0.14	0.16	1.93	*11
1102-B-C85	* 0.24	0.08	2.52	<4	-	3.1	<0.14	0.11	1.48	* 7.7

* INAA data
INAA= Induced Neutron Activstion Analysis
ICP= Inductively Coupled Argon Emission Plasma Spectroscopy
ISE= Ion Selective Electrode
AA= Atomic Absorption
XRF= X-ray Fluorescence
** LOI-900= Loss of ignition at 900° C

Table 2.-- Continued.

Sample number	Li ppm AA	Lu ppm INAA	MgO% XRF	Mn ppm ICP	Mo ppm ICP	Na% ICP	Nb ppm ICP	Nd ppm ICP	Ni ppm ICP	P% ICP
237-A-C82	+ 3	-	0.21	<4	39	<0.005	<4	<20	40	0.02
238-A-C83	23	-	0.45	9	2	0.08	<4	8	7	0.008
239-A-C83	5	-	10.1	240	34	0.09	<4	* 8.4	19	0.007
241-A-C82	+ 3	<0.085	0.26	5	270	0.05	<4	* 3.7	30	0.07
241-B-C82	+10	-	0.34	31	2000	0.10	<4	<20	15	0.11
242-A-C82	6	0.13	0.67	<4	140	0.12	7	* 14	39	0.02
242-B-C82	7	-	0.1	<4	8	0.01	5	<20	35	0.01
249-A-C83	14	-	0.24	82	14	0.06	<8	<8	16	0.63
493-A-C83	+ 4	-	19.3	720	5	0.06	<4	<4	16	0.03
493-B-C83	+<4	0.01	1.02	51	6	0.05	<8	<8	<4	<0.01
494-A-C83	7	-	0.23	40	<10	0.06	<20	<20	20	0.07
494-B-C83	99	0.51	3.94	60	<10	0.29	<20	*16.1	130	0.18
494-C-C83	10	0.18	2.34	70	140	0.41	<20	*13.7	70	0.62
495-A-C83	37	-	0.19	14	5	0.04	<4	21	30	0.04
593-A-C83	9	0.18	0.94	180	11	0.06	14	* 3.3	92	0.03
1031-A-C85	+ 8	-	0.50	100	65	0.06	-	* 3.3	87	<0.005
1031-B-C85	+ 6	0.077	0.55	<4	110	0.08	-	* 1.3	51	0.009
1033-A-C85	+22	0.41	0.57	23	4	0.24	-	*18	78	0.02
1085-A-C85	+17	0.29	1.09	100	<2	0.09	-	*19	30	0.02
1088-A-C85	+11	0.045	0.14	68	4	0.02	-	* 2.5	19	0.10
1102-A-C85	+11	0.15	0.14	51	760	0.02	-	* 7.2	420	0.49
1102-B-C85	+ 7	-	<0.10	31	450	0.02	-	* 5.7	73	0.41

+ ICP data
* INAA data
INAA= Induced Neutron Activation Analysis
ICP= Inductively Coupled Argon Emission Plasma Spectroscopy
AA= Atomic Absorption
XRF= X-ray Fluorescence

Table 2.-- Continued.

Sample number	Pb ppm	Rb ppm	Total-S%	Sb ppm	Sc ppm	Se ppm	SiO_2%	Sm ppm	Sr ppm	Ta ppm
	ICP	AA	CID	INAA	ICP	AA	XRF	ICP	ICP	ICP
237-A-C82	60	7	0.03	-	<2	20	79.7	<50	51	<40
238-A-C83	67	12	0.02	-	<2	0.6	91	<10	48	<40
239-A-C83	80	12	<0.01	23.2	* 2.59	0.2	46	* 2.28	44	* 0.21
241-A-C82	4000	<5	0.54	541	* 0.8	580	76.4	* 1.16	330	* 0.13
241-B-C82	6300	<5	0.19	-	<2	4.9	92.3	<50	45	<40
242-A-C82	130	17	15.3	37.7	* 2.17	89	21.3	* 1.57	62	* 0.36
242-B-C82	40	16	28.3	-	<2	15	37.8	<50	25	40
249-A-C83	<8	<10	<0.01	-	<4	0.1	90.4	<20	38	<80
493-A-C83	<4	<10	<0.01	-	<2	<0.1	3.76	<10	90	<40
493-B-C83	<8	* <2.5	17	0.54	* 0.13	<0.1	2.26	* 0.085	380	* 0.02
494-A-C83	50	<10	0.01	-	<10	1.5	92.3	<50	20	<200
494-B-C83	130	100	0.02	2.22	* 8.86	4.6	45.5	* 2.96	870	* 1.32
494-C-C83	12000	<10	0.22	106	* 2.4	350	53.7	* 3.62	1600	* 0.26
495-A-C83	6	<10	0.19	-	11	0.5	71.6	<10	160	<40
593-A-C83	9	<10	0.27	43.1	* 4.89	4.8	16.5	* 0.7	110	* 0.26
1031-A-C85	230	-	7.44	6.6	* 1.1	300	22	* 0.81	79	* 0.034
1031-B-C85	350	* 2.4	0.71	13	* 1.4	170	22.3	* 0.35	42	* 0.15
1033-A-C85	39	* 9.2	0.15	13	* 4.1	<10	70.9	* 3.9	150	* 0.57
1085-A-C85	12	-	0.02	0.42	* 7.4	0.2	50.4	* 4.1	150	* 0.59
1088-A-C85	51	* 4.8	0.09	1.1	* 0.62	1.9	89.5	* 0.54	57	* 0.062
1102-A-C85	130	-	<0.01	25	<2	1.4	90.3	* 2.2	63	* 0.20
1102-B-C85	94	-	0.05	7	<2	1.0	92.9	< 1.0	56	* 0.11

* INAA data
INAA= Induced Neutron Activation Analysis
ICP= Inductively Coupled Argon Emission Plasma Spectroscopy
CID= Combustion with Infrared Detection
AA= Atomic Absorption
XRF= X-ray Fluorescence

Table 2.-- Continued.

Sample number	Tb ppm	Th ppm	Ti%	Tm ppm	U ppm	V ppm	Y ppm	Yb ppm	Zn ppm	Zr ppm
	ICP	INAA	ICP	INAA	DN	ICP	ICP	ICP	AA	INAA
237-A-C82	<20	**<2.7	0.06	-	3.92	19	2	<1	29	-
238-A-C83	<20	**<2.3	0.10	-	2.36	17	3	<1	28	-
239-A-C83	* 0.35	2.68	0.05	0.19	114	51	8	* 1.16	15	185
241-A-C82	<20	2.7	0.04	-	303	35	3	* 0.88	950	<116
241-B-C82	<20	+ <4	0.06	-	33.9	47	7	<1	140	-
242-A-C82	* 0.28	3.63	0.12	0.14	34.2	30	<2	* 0.89	27	<56
242-B-C82	<20	** 4.1	0.14	-	1.58	14	<2	<1	17	-
249-A-C83	<40	**<2.7	0.01	-	5.44	14	21	<2	23	-
493-A-C83	<20	**<1.8	0.02	-	1.79	28	<2	<1	65	-
493-B-C83	* 0.02	0.13	<0.01	-	0.32	5	<4	* 0.06	39	12
494-A-C83	<100	**<3.1	<0.03	-	4.97	60	<10	<5	440	-
494-B-C83	* 0.37	18.8	0.26	0.46	16.7	90	20	* 3.37	2200	238
494-C-C83	* 0.45	3.03	0.09	0.22	49.5	290	20	* 1.29	16000	-
495-A-C83	<20	**16.5	0.52	-	4.15	130	11	2	6	-
593-A-C83	* 0.2	3.49	0.10	-	14.6	2400	6	* 1.15	110	208
1031-A-C85	* 0.64	0.64	0.02	-	29.6	170	4	* 0.54	* 130	-
1031-B-C85	* 1.9	1.9	0.05	-	41.8	58	<2	* 0.45	* 280	<190
1033-A-C85	* 0.6	5.1	0.15	-	12.3	240	16	* 2.5	* 72	-
1085-A-C85	* 0.54	5.8	0.16	-	3.81	36	13	* 2	* 120	-
1088-A-C85	* 0.088	0.59	0.01	-	1.83	52	3	*<0.34	* 2300	-
1102-A-C85	* 0.27	2.6	0.05	-	202	160	10	* 0.97	* 400	53
1102-B-C85	* 0.16	1.5	0.03	-	165	68	5	* 0.47	* 230	-

** DN data
+ ICP data
* INAA data
INAA= Induced Neutron Activation Analysis
ICP= Inductively Coupled Argon Emission Plasma Spectroscopy
AA= Atomic Absorption
DN= Delayed Neutron Activation Analysis

sample, in which case the results from the next best method are listed; for example, Au-HBR (hydrobromic acid digestion with atomic absorption) is only available for 5 samples, so ICP (inductively coupled argon plasma emission spectroscopy) results are listed for the other samples.

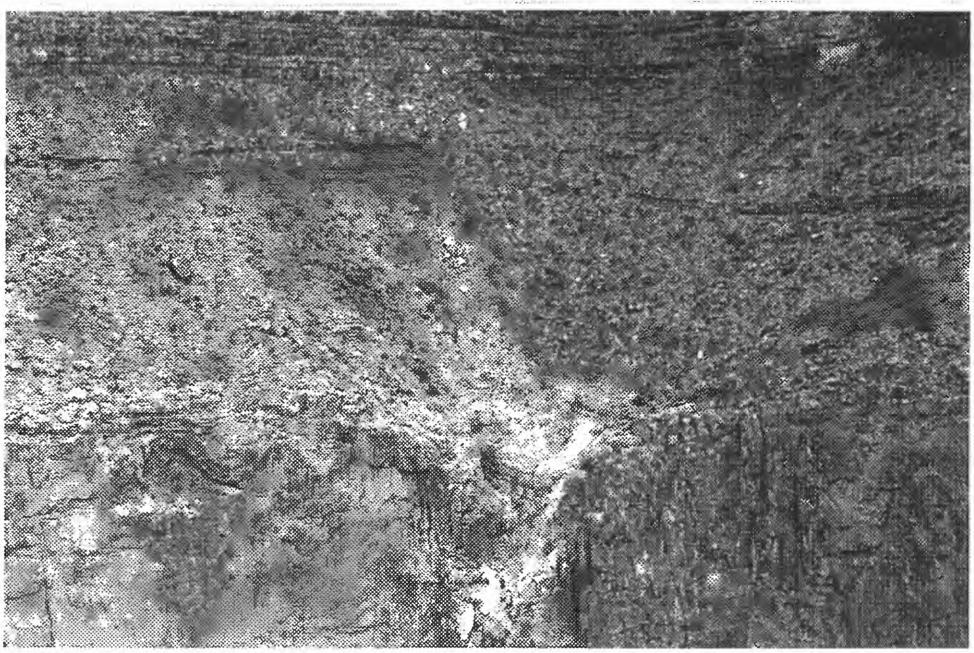
Collapse Features/Breccia Pipes Located at the top of the Redwall Limestone

This group consists of 13 collapse features and all are considered to have little or no economic potential, despite the mineralized rock observed at the surface in two of them. This judgement is based on the small possible thickness of potential host rock, which at most would not exceed 700 ft, and, more importantly, the Redwall is not known to contain uranium minerals. Uranium has not been mined from the Redwall in any of the pipes, although other metals have been (most notably copper from the Grandview mine). For those pipes in this group which contain some elevated gamma radiation, such anomalies are entirely restricted to downdropped sandstone blocks from the Surprise Canyon Formation or lower Supai Group.

Twelve of the 13 collapse features are readily recognized at the top of the Redwall Limestone cliff: Collapse structures 593, 594, 1030, 1032, 1034, 1035, 1076, 1077, 1080, and 1082 (figs. 6a-6j), and 595 and 596 (no photo available of either) are expressed as an amphitheater eroded back into the Redwall cliff and/or the overlying Watahomigi Formation. Five of these structures are confirmed to be breccia pipes. Many of these pipes have little outcrop and only after careful field work does it become apparent that any outcrop present does not contain flat lying beds but rather beds that tilt radially inward. Several of the 12 features have the basal Watahomigi Formation dipping radially inward toward the center of the amphitheater, and(or) down dropped into the Redwall Limestone. Because the basal Watahomigi Formation is composed of limestone in the Mohawk Canyon area, this unit is equally as unfavorable as the Redwall to host uranium mineralization. In contrast to these two limestones, the organic-rich stream channels of the Mississippian Surprise Canyon Formation were good hosts for uranium and copper mineralization, although only gamma radiation slightly in excess of 6 times background (150 cps) and minor malachite have been observed. Nevertheless, this is in sharp contrast to the Redwall Limestone, which has not been observed during any study by the authors to emit greater than 20 cps. Strata of the Surprise Canyon have collapsed downward into at least 3 of these 10 collapse features (shown in figs 6a-6j). It is interesting to note that throughout the Hualapai Indian Reservation common geographic association exists between the Surprise Canyon Formation and the breccia pipes (Wenrich and others, 1986, 1987; Billingsley and others, 1986). The Surprise Canyon was deposited within the Mississippian karst that developed on the Redwall Limestone surface. Evidence that post Surprise Canyon collapse occurred within the pipes is suggested by the tilting of Surprise Canyon strata into underlying brecciated Redwall. None of these 12 (of the 13 total) Redwall breccia pipes was categorized as "mineralized" ("M" in table 1), although a limonite-stained weathered sandstone from the lower Supai Group in pipe 593 (fig. 6a) did emit gamma radiation equal to two times background. A chemical analysis of this material (table 2) shows anomalous Ag (21 ppm), As (5800 ppm), Co (39 ppm), Cu (380 ppm), Fe (63%), Hg (0.17 ppm), Ni (92 ppm), U (15 ppm), V (2400 ppm), and Zn (110 ppm). These are all elements that are commonly anomalous within mineralized breccia pipes.

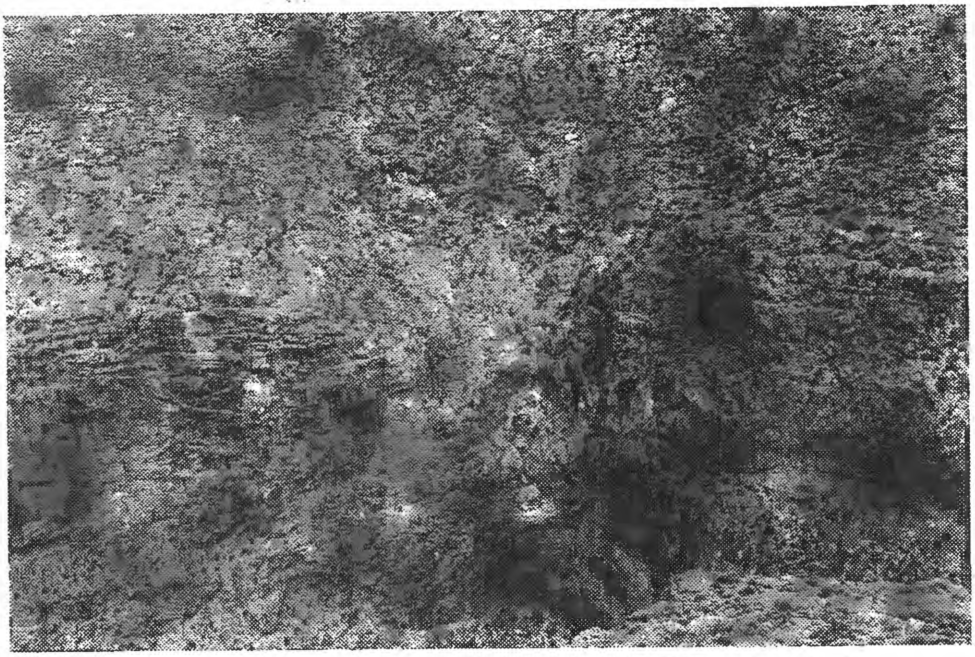
Within this group of 13 breccia pipes/collapses exposed in the Redwall Limestone, one pipe--1033--was mineralized by sufficient uranium to exceed 2.5 times background radioactivity on the surface. Pipe 1033 is mostly covered by

A. Breccia pipe 593. View as shown is about 600 ft wide.



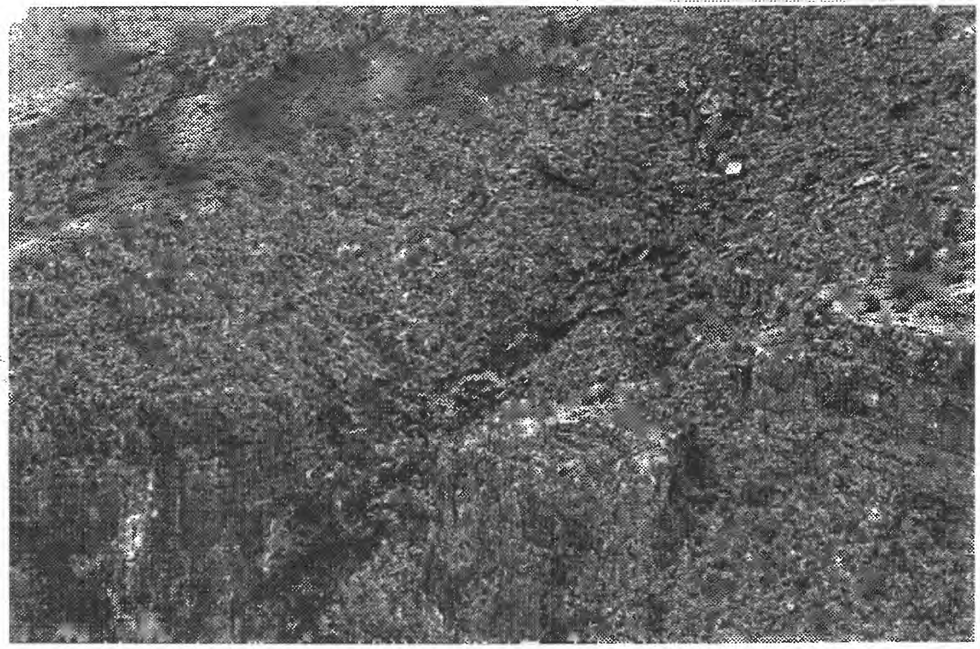
B. Breccia pipe 594. View as shown is about 700 ft wide.

Figure 6.--Photos illustrating the amphitheater style of erosion of breccia pipes/collapse features exposed along the top of the Redwall Limestone cliff.

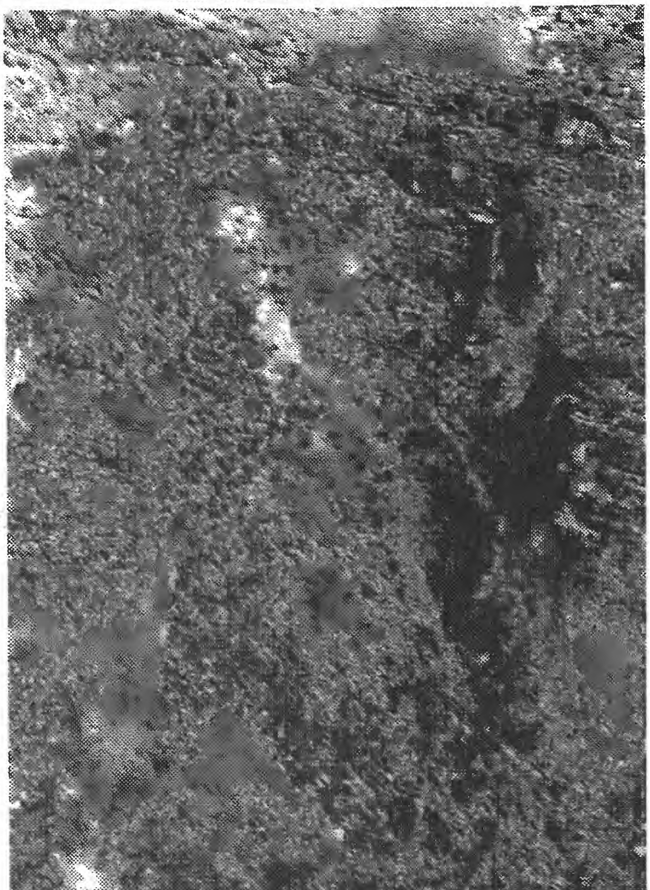


C. Collapse feature 1030. View as shown is about 700 ft wide.

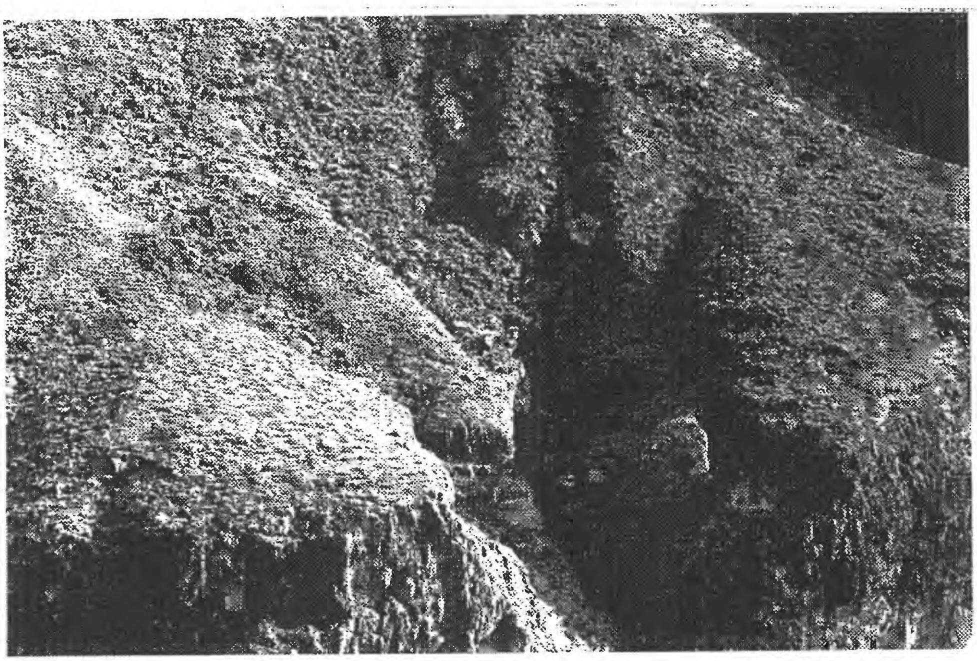
D. Breccia pipe 1032. View as shown is about 600 ft wide.



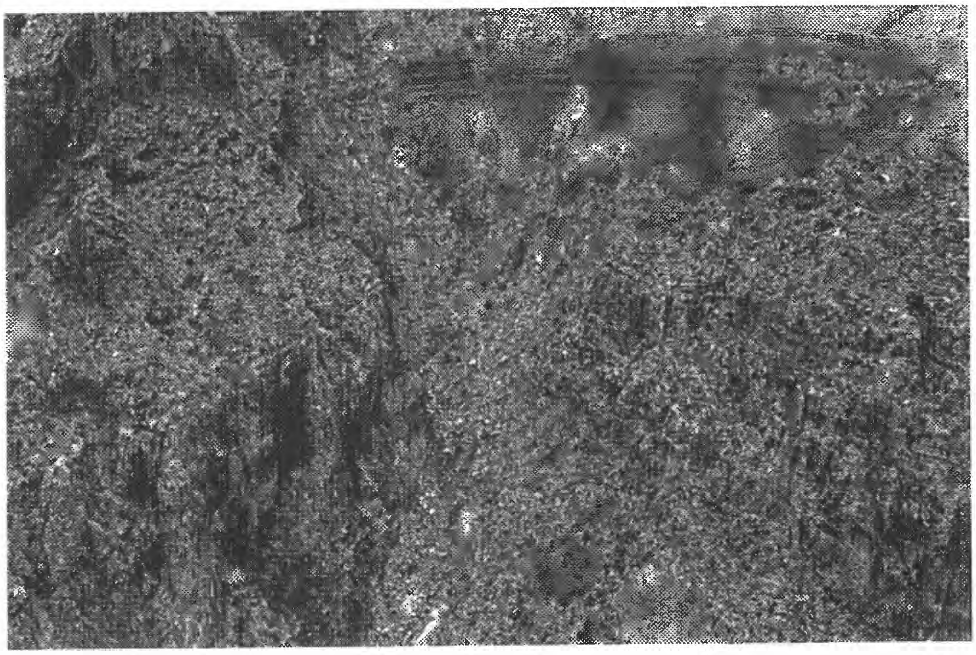
E. Breccia pipe 1034. View as shown is about 700 ft wide.



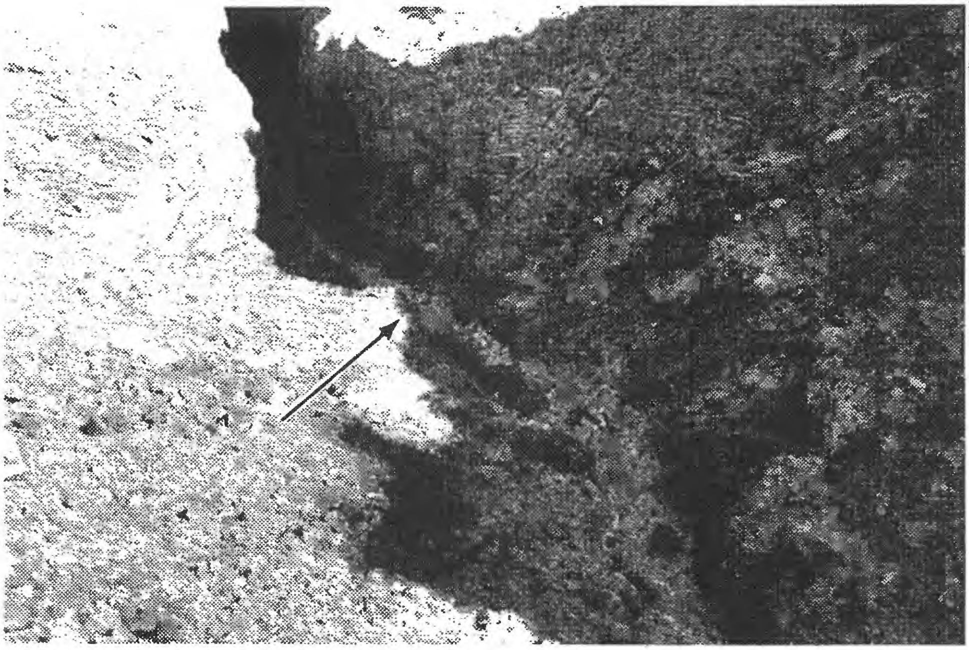
F. Breccia pipe 1035. View as shown is about 400 ft wide.



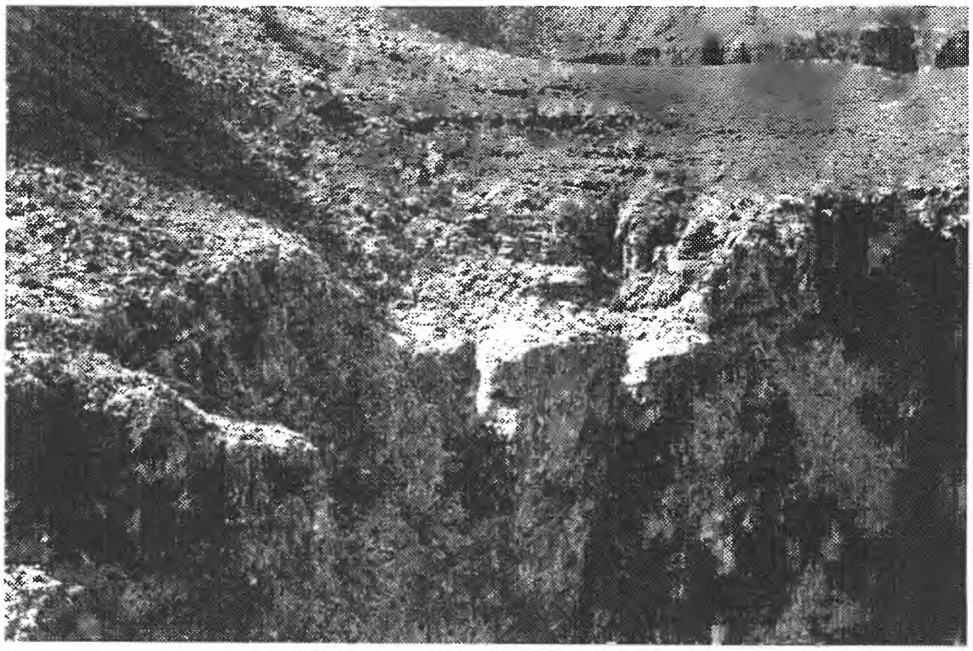
G. Collapse feature 1076. View as shown is about 600 ft wide.



H. Collapse feature 1077. View as shown is about 1000 ft wide.



I. Collapse feature 1080. View as shown is about 700 ft wide.



J. Collapse feature 1082. View as shown is about 900 ft wide.

alluvium in that the only exposure is a minor limonite-stained outcrop located in a gully (fig. 7a). Some Surprise Canyon Formation is associated with brecciated Horseshoe Mesa Member of the Redwall Limestone. A pinkish-yellow vuggy calcareous sandstone of the Surprise Canyon Formation emitted gamma radiation that was in excess of 4-times background; Liesegang bands are also prevalent in this same outcrop (fig. 7b). Geochemical analysis of this sandstone (Sample 1033-A-C85--table 2) shows anomalous As (1900 ppm), Co, Cu, Hf, Ni, V, and Zn.

Collapse Features/Pipes Exposed Along Supai Slopes and the Esplanade Erosion Surface

Pipes/collapse features exposed within Supai Group rocks are commonly recognized by the bleaching of the otherwise red Supai rock. Four of the 14 features have significant mineralization exposed at the surface; 8 of the 14 have exposed breccia, and thus, are confirmed breccia pipes. Although sufficient volume of rock necessary to host an orebody is present beneath these features, most of them are exceptionally inaccessible, lying at the bottom of Mohawk Canyon; this limits the economic potential of these pipes.

Mineralized rock exposed at the surface, as it is at pipes 239, 241, 242, and 1031 (fig. 5), is weathered and the primary ore zone minerals, such as uraninite, pyrite, chalcopyrite, sphalerite, or galena have been oxidized. The primary copper phases have oxidized to malachite, azurite, and brochantite. The pyrite has oxidized to goethite, which commonly occurs as goethite concretions or cubic pseudomorphs after the original pyrite; in places where the oxidation is incomplete, the centers of the concretions contain remnant pyrite. Sphalerite has oxidized and the Zn presently occurs in surface outcrop as hemimorphite (fig. 8) or smithsonite. The Supai Group collapse structures/pipes are discussed below in order of increasing uranium potential:

1078, 1086: Both of these features (figs. 9a and 9b) have few of the recognition criteria for collapse feature identification, and hence have low potential as mineralized breccia pipes. They have bleached sandstone, and only 1078 has some minor inward dip to the beds.

1084: Although this collapse structure (fig. 10) in the uppermost Esplanade Sandstone has no exposed alteration, breccia, or mineralized rock, it forms a completely closed basin with concentrically inward dipping beds. Surface radioactivity was slightly elevated to 1.5 times background.

1081: This collapse is relatively large with extensive bleaching of the Esplanade Sandstone (fig. 11). The beds dip inward toward the canyon from all sides; there is no breccia, anomalous radioactivity, or any evidence of mineralized rock.

240: Only the bleaching of the Esplanade Sandstone and concentric fractures delineate this collapse (fig. 12). There is a sharp contact between the bleached and unbleached sandstone, but the most striking feature of this collapse is the concentric jointing (fig. 12), which bounds the collapse on the NE side. This is suggestive of the concentric ring fractures observed at the Mohawk Canyon pipe (Wenrich and others, 1988).

1085: This collapse is a large structure (indicated by dashed line in fig. 13) located within the exposed top and base in the Wescogame Formation. The Esplanade Sandstone is bleached and some pale yellow, limonite staining occurs in a Wescogame limestone bed. This unit emitted a maximum gamma radiation of three times background. Geochemistry of a

Figure 7a.--Breccia pipe 1033 can be recognized as a pipe only by limonite-stained, brecciated outcrops in a gully of Surprise Canyon Formation and Horseshoe Mesa Member of the Redwall Limestone. View as shown is about 500 ft wide.

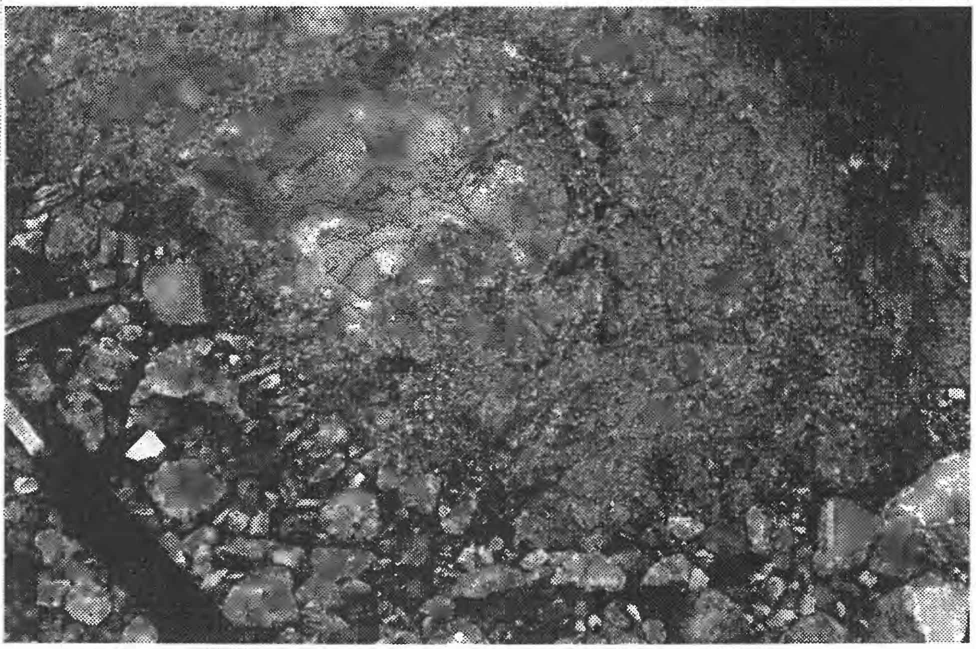


Figure 7b.--Liesegang-banded and brecciated outcrop of Surprise Canyon Formation in pipe 1033.

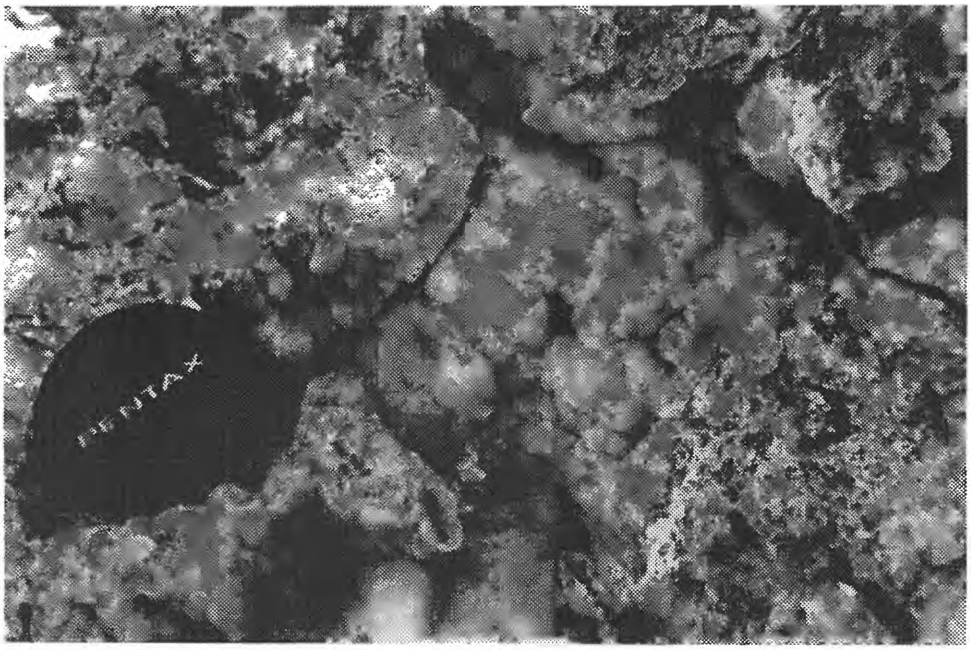


Figure 8.--Hemimorphite, such as this botryoidal mass, commonly forms from surface weathering of primary sphalerite when the orebody is exposed to oxidation by canyon dissection.

Figure 9a.--Collapse feature 1078 contains some bleaching and minor inward dip (indicated by arrows) of several beds of Wescogame Formation. View as shown is about 800 ft wide.

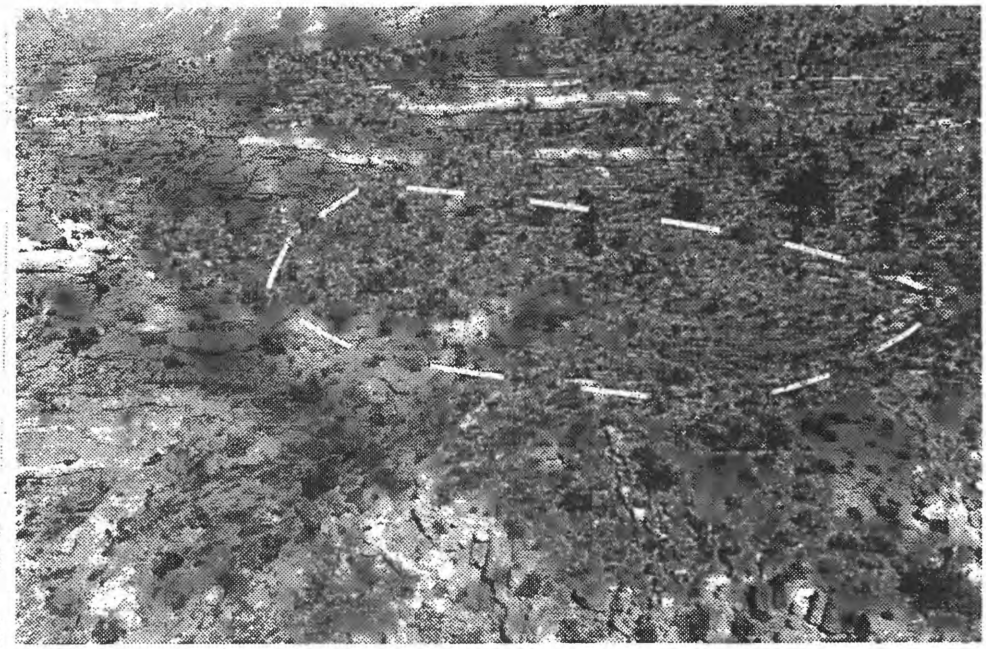


Figure 9b.--Collapse feature 1086 (indicated by dashed line) lies in the Esplanade Sandstone. The only evidence of a possible structure is the bleached Esplanade and the circular gully around a hill. Collapse as outlined is about 700 ft long.

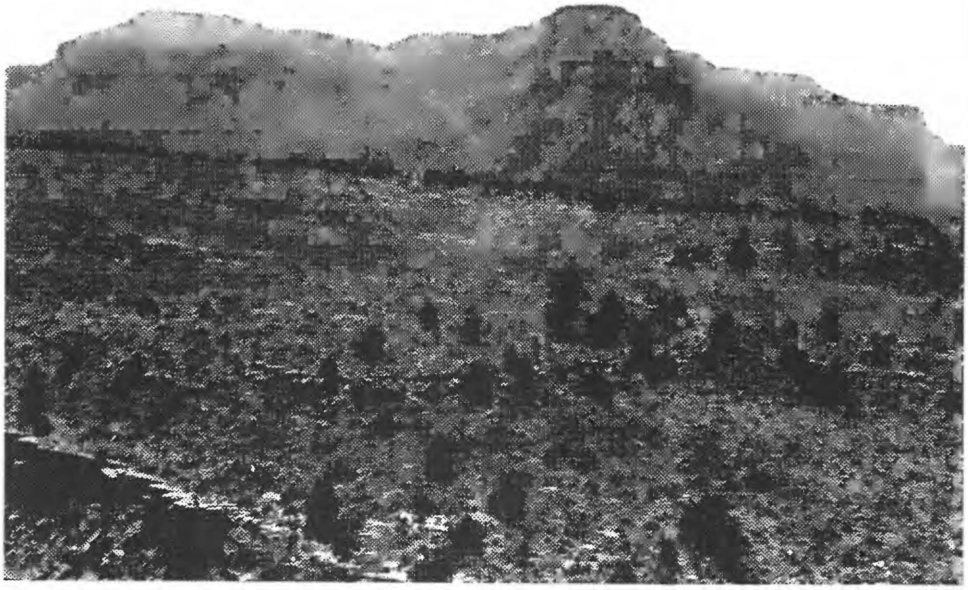


Figure 10.--Collapse feature 1084 forms essentially a closed basin with concentrically inward-dipping beds of Esplanade Sandstone. Collapse occupies most of the foreground in this photo. View as shown is about 400 ft wide.

Figure 11.--Collapse feature 1081 is relatively large with extensive bleaching of the Esplanade Sandstone (note the bleached Esplanade on all sides of the widened gully--collapse occupies the entire field of view). View as shown is about 700 ft wide.

Figure 12.--Collapse feature 240 exhibits a striking series of concentric fractures which mark its NE boundary.

sample from this anomalous area (1085-A-C85--table 2) shows essentially no enrichment of any of the breccia pipe metals, with the exception of minor enrichment in Zn (120 ppm).

239: This breccia pipe can be identified along the slopes of the Supai Group formations through its bleached rock with minor tilt, and the small mass of breccia (fig. 14) exposed a short distance above the Redwall cliff. The breccia is stained pink and yellow by hematite and limonite alteration. Chemical analyses (table 2) of a sample of fine to medium grained sandstone emitting gamma radiation of 5 times background (85 cps) reveals anomalous values for: As (100 ppm), Cu (190 ppm), Hg (0.19 ppm), Pb (80 ppm), Sb (23 ppm), U (114 ppm), and V (51 ppm); these values are not as anomalous as those in a Surprise Canyon sample from the Redwall collapse 593.

495: This breccia pipe (fig. 15) contains highly fractured, highly oxidized bleached sandstone. The breccia is composed of limestone and chert fragments with hematite squeezed between the clasts. Chemical analyses (table 2) of a sample that was three times background in surface radioactivity shows significantly anomalous concentrations of As (3300 ppm), Cr (140 ppm), Hg (0.25 ppm), and V (130 ppm). Despite the anomalous surface radioactivity, the uranium concentration in this sample was only 4 ppm.

236: This breccia pipe is easily located with its well-defined surface expression--the breccia pipe sits within an eroded amphitheater of Esplanade Sandstone (fig. 16). The center of the pipe is bleached and in places stained yellow by limonite. Massive calcite is abundant throughout the conglomeratic appearing breccia (see pipe 241 for a similar breccia). No anomalous radioactivity or mineralization was observed.

237: This breccia pipe is essentially identical to 236 in morphology (fig. 17), stratigraphic horizon, alteration, and breccia. Although no anomalous radioactivity was detected, chemical analyses of a limonite- and hematite-stained sandstone (sample 237-A-C82--table 2) show anomalous As (4700 ppm), Cu (140 ppm), Fe (12%), Pb (60 ppm), and Se (20 ppm).

1031: Alluvium extensively covers this pipe on the slope above the Redwall Limestone cliff; the only significant outcrop is a small area of limonite-stained sandstone in the upper part of the Watahomigi Formation. This sandstone emitted gamma radiation in excess of 8-times background and contained goethite concretions with unaltered pyrite cores. In places, despite the intense weathering of the pipe, pyrite was exposed on the surface of the outcrop (fig. 18). Two samples containing goethite and pyrite, and emitting anomalous gamma counts, were geochemically analyzed (1031-A-C85 and 1031-B-C85--table 2). Results showed the Fe_2O_3 content of the two samples to be around 60%; As, Cu, Mo, Ni, Pb, Se, U, V, and Zn were also present in anomalous concentrations.

238: The breccia pipe is expressed on the surface as a bleached amphitheater (fig. 19a) of Esplanade Sandstone. The bleached/unbleached contact is sharp. Concentric joints encircle the amphitheater marking the pipe boundary where they die out. Brecciated rock (fig. 19b) lies along the floor of the amphitheater. No anomalous gamma radioactivity was detected in the pipe. Chemical analyses of a fine-grained sandstone (sample 238-A-C83--table 2) from the pipe show few anomalous elements except for Ba (1100 ppm), Cu (180 ppm), and Pb (67 ppm).

242: This breccia pipe is one of the two most interesting found in the Esplanade Sandstone in the Mohawk Canyon area. The breccia column is

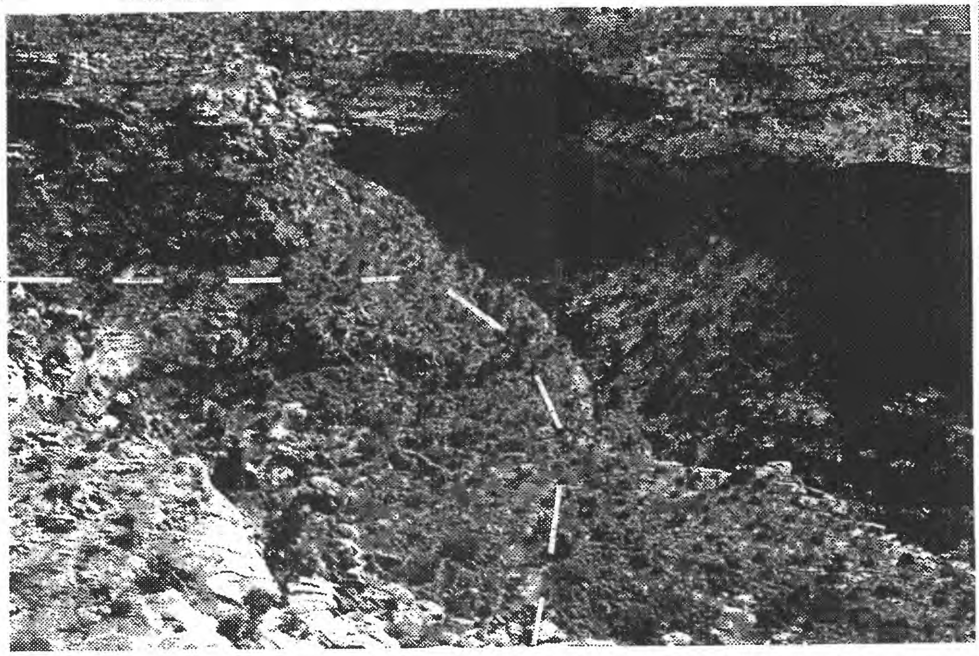


Figure 13..--Collapse feature 1085 (indicated by dashed line) was identified by its bleaching in the Esplanade Sandstone, and limonite staining in the Wescogame Formation. View as shown is about 700 ft wide.

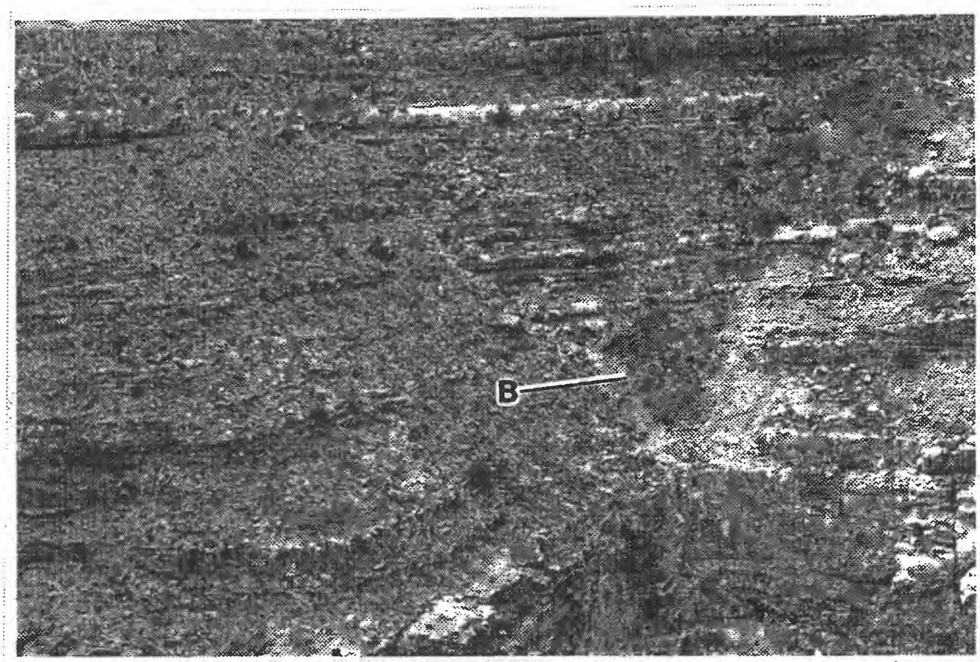


Figure 14.--Breccia pipe 239 has a small mass of breccia (indicated by a "B") exposed just above the sandstone cliff to the right of center. View as shown is about 1000 ft wide.

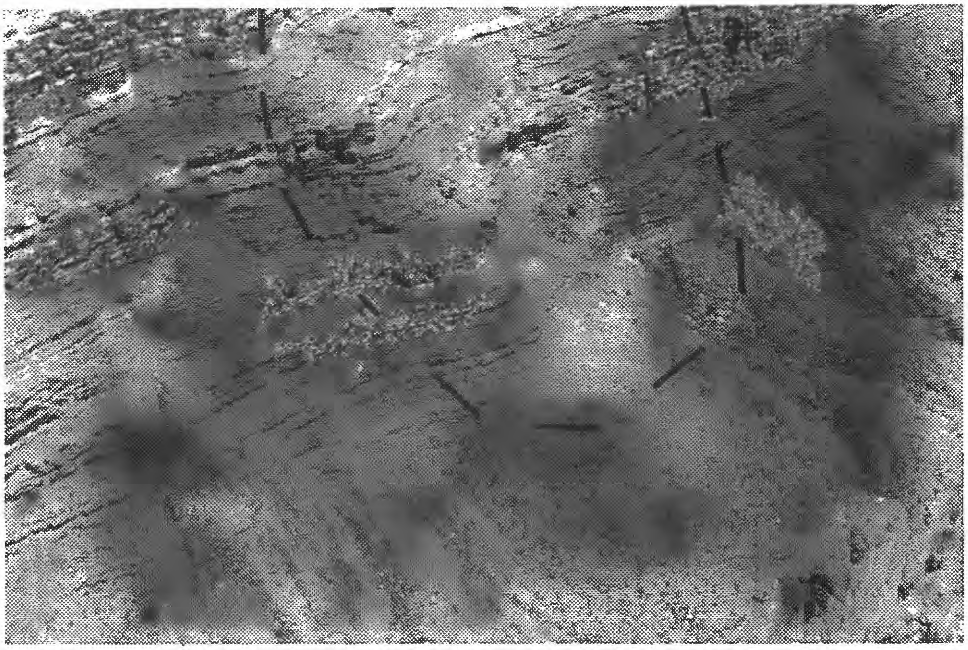


Figure 15.--Breccia pipe 495 is expressed on the surface as bleached rock in a slight recess of the hill slope (initial stages of erosion of an amphitheater forming along the pipe ring fracture zone). Pipe as outlined is about 500 ft long.

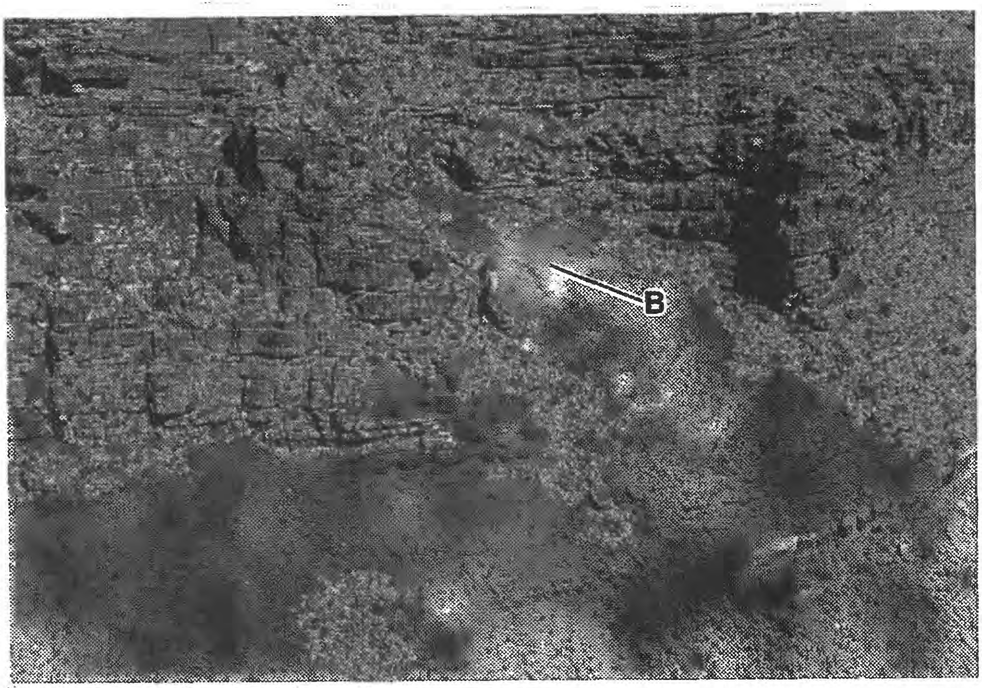


Figure 16.--Breccia pipe 236 has the ideal pipe morphology: a plug of breccia (B) sitting within an amphitheater that has eroded out along the ring fracture of the breccia pipe. The plug of brecca is about 200 ft wide.

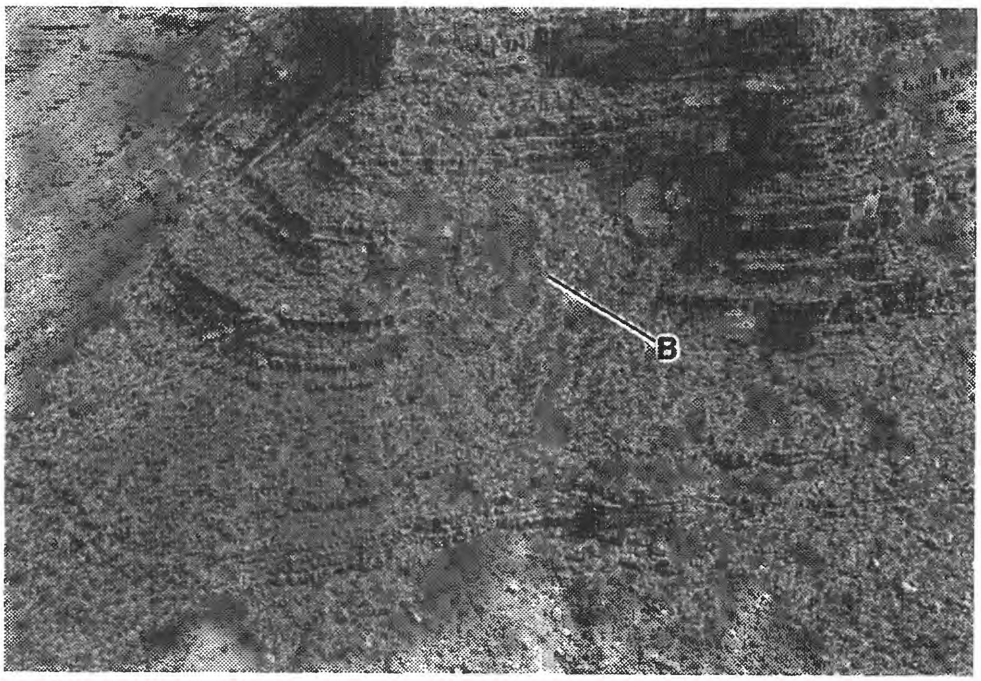


Figure 17.--Breccia pipe 237 is similar to 236 in morphology, stratigraphy, alteration, and breccia (B). In addition, it lies symmetrically across from 236 on the opposite side of a tributary canyon to Mohawk Canyon. The mass of breccia is about 250 ft wide.

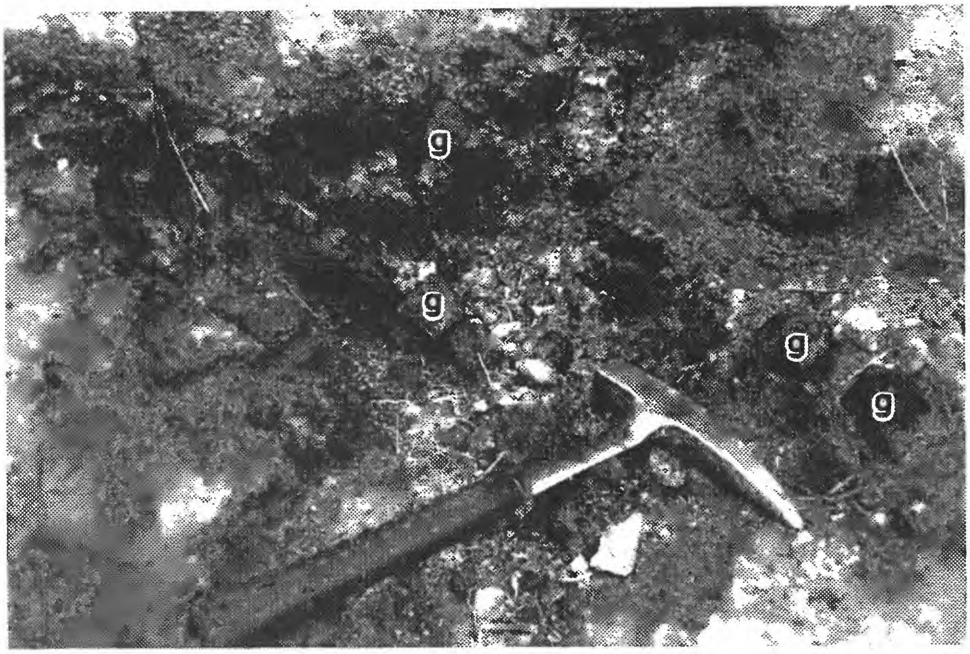


Figure 18.--Breccia pipe 1031 is almost totally covered by alluvium except for this small outcrop of goethite (g) and pyrite that emitted gamma radiation in excess of 8-times background.

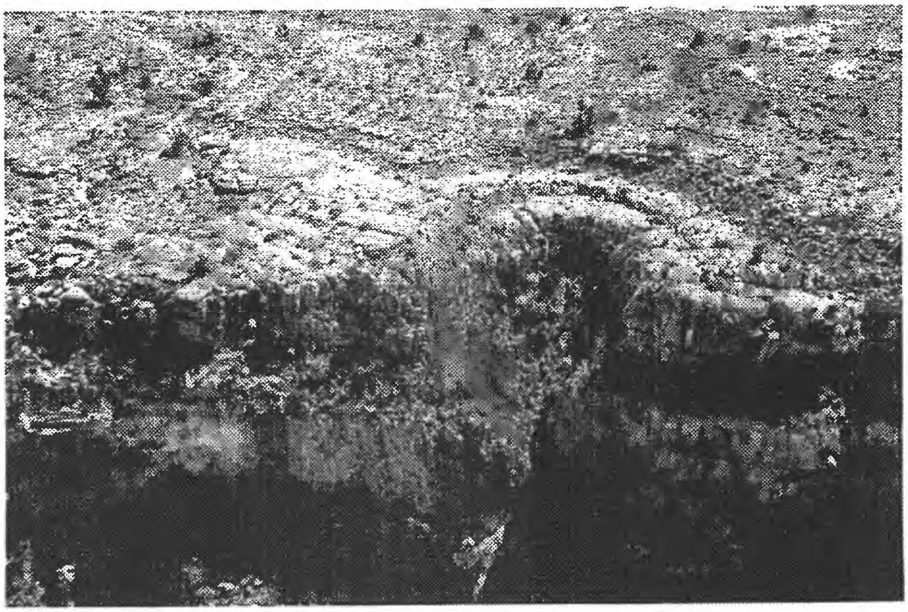


Figure 19a.--Breccia pipe 238 is expressed on the surface as a bleached amphitheater with the breccia column exposed on the amphitheater floor. View as shown is about 600 ft wide.

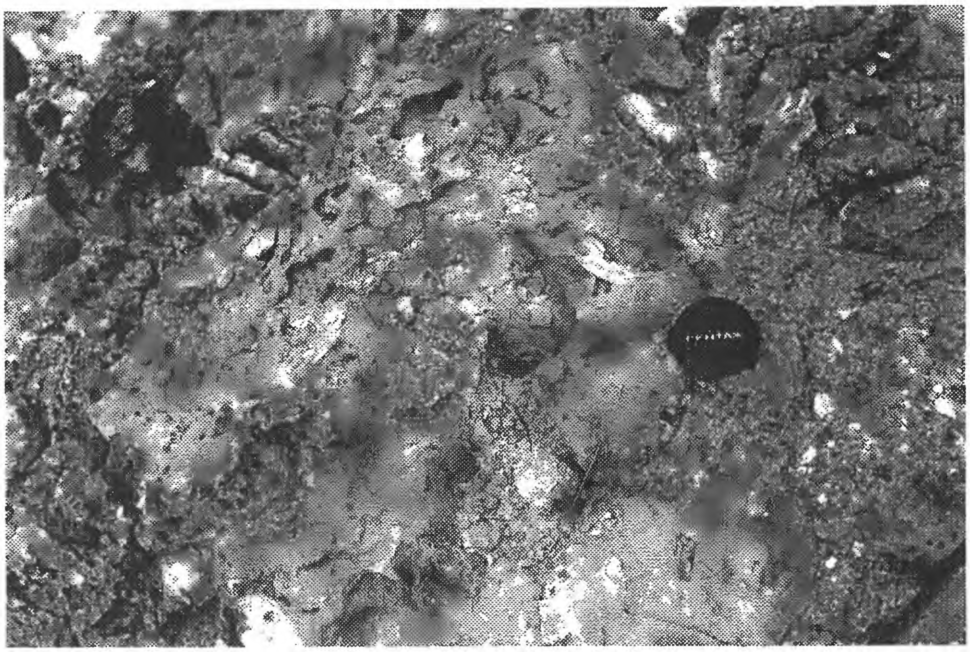


Figure 19b.--Brecciated rock from the breccia column in pipe 238. Note the minor vugs spotted through the breccia.

clearly visible in the cliff of Esplanade Sandstone (fig. 20a). The breccia is composed of angular fragments of sandstone in a well-cemented matrix (fig. 20b). Large goethite nodules (fig. 20c), 1 to 3 in. in diameter, are common; these concretions have pyrite in their cores and gamma radioactivity in excess of 2.5 times background. Chemical analyses of pyrite concretions (samples 242-A-C82 and 242-B-C82--table 2) show anomalous values of Ag (3 and 11 ppm), As (2800 and 6800 ppm), Cu (70 and 460 ppm), Fe (36 and 57%), Hg (0.47 and 0.49 ppm), Mo (140 ppm), Pb (40 and 130 ppm), Se (15 and 89 ppm), and U (34 ppm).

241: This breccia pipe is the most interesting of the Mohawk Canyon area features found exposed below the Kaibab Limestone surface, in part, because of the two silicified pinnacles (fig. 21a), and, in part, because surface samples are mineralized. This is the only pipe in the Mohawk Canyon area with silicified spires similar to the Blue Mountain pipe (pipe #287 in Billingsley and others, 1986; Van Gosen and others, 1989) and pipe #237 (Wenrich and others, 1986) located to the south and west on the Hualapai Reservation, and previously drilled by Western Nuclear in the 1970's. It is interesting to note that, with the exception of the Orphan mine, none of the other uranium producing breccia pipes have had exposures of silicified breccia. Such exposure subjects the pipes to oxidation and removal of much of the orebody. The brecciated column abuts against undeformed sandstone (fig. 21b). The breccia itself has a conglomeratic appearance of rounded cobbles in a well-cemented matrix (fig. 21c). The chemical analyses of breccia samples (241-A-C82 and 241-B-C82--table 2) spotted with green malachite, show anomalous concentrations of most elements enriched in breccia pipe orebodies: Ag (14 and 170 ppm), As (870 and 5000 ppm), Cu (0.9 and 1%), Mo (270 and 2000 ppm), Pb (4000 and 6300 ppm), Sb (541 ppm), U (34 and 303 ppm), and Zn (140 and 950 ppm).

Collapse Features/Breccia Pipes Exposed in the Hermit Shale, Coconino Sandstone, and Toroweap Formation

Essentially no collapse structures have been observed in the Mohawk Canyon area between the Esplanade surface and the Kaibab Limestone. This is probably because: (1) many of the pipes top out by the time they reach the Esplanade Sandstone; (2) there is little exposure of the red slope-forming Hermit Shale that is commonly covered by alluvium; and (3) the vertical cliffs of Coconino Sandstone and Toroweap Formation yield little exposure of these units relative to the total exposure of Esplanade along its flat erosion surface--in addition, any bleaching in the already white cliff-forming Coconino Sandstone and Brady Canyon Member of the Toroweap Formation could be easily overlooked. Even though fewer pipes stoped all the way to the Kaibab Limestone, dissolution of gypsum in the underying Toroweap and gypsum and limestone in the Kaibab accentuate and enlarge any surface expression of pipes that did reach the Coconino Plateau surface. This surface occupies at least as much of the exposed rock in the Mohawk Canyon area as does the Esplanade erosion surface, yet it contains 19 features in contrast to the 14 exposed along the Esplanade surface. Of course, some of the 19 "Kaibab" collapse features probably go no deeper than the Harrisburg Gypsiferous Member of the Kaibab Limestone or the Woods Ranch Member of the Toroweap (see cartoon of various types of collapse features in the area--fig. 4). Those that fall into this group of shallow-seated collapses are most likely the "Kaibab" collapses listed under "Category" in table 1 as "C?".

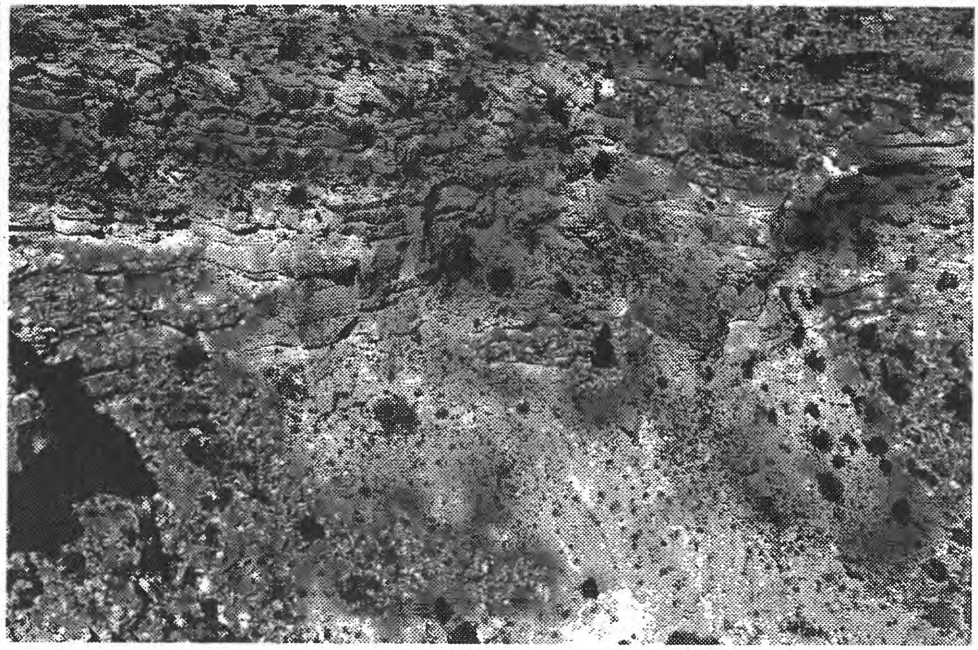


Figure 20a.--Breccia pipe 242 (breccia indicated by "B") is clearly visible in the cliff of Esplanade Sandstone. View as shown is about 700 ft wide.

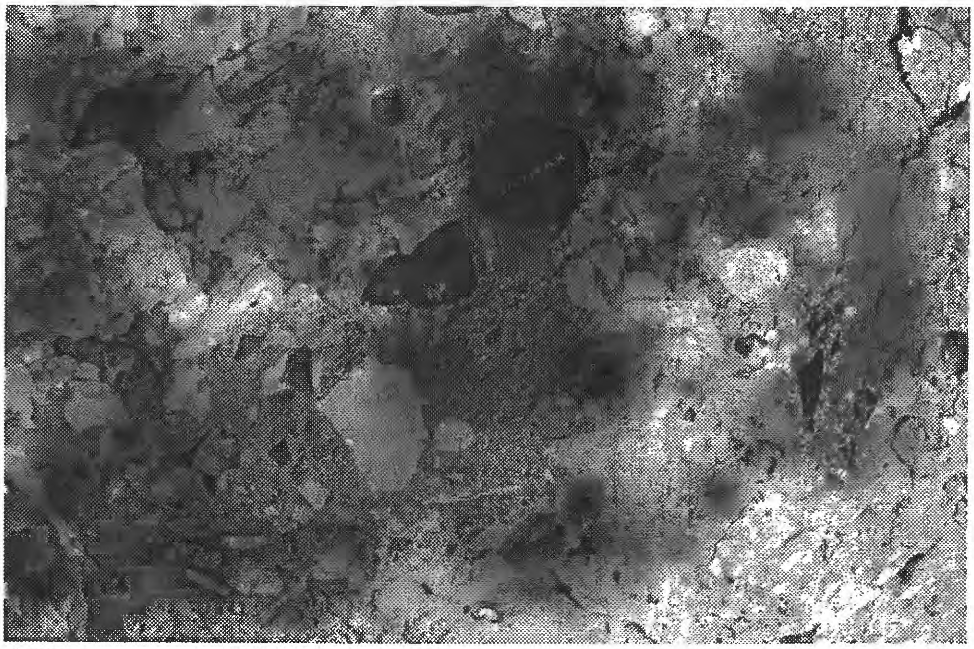


Figure 20b.--The breccia from pipe 242 is composed of angular fragments of sandstone within a vuggy well-cemented matrix.

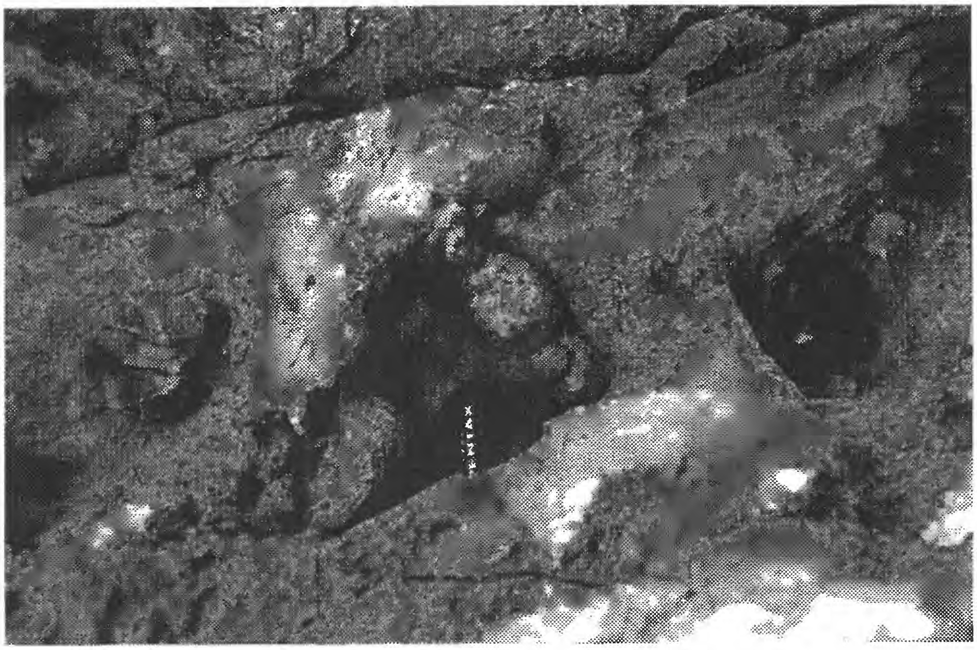


Figure 20c.--Large goethite nodules, with remnant pyrite cores and anomalous gamma radiocativity of 2.5 times background, altered from pyrite concretions.

Figure 21a.--Breccia pipe 241 is expressed on the surface as two silicified pinnacles of breccia sitting on the floor of an amphitheater eroded out of the Esplanade Sandstone. View as shown is about 700 ft wide.

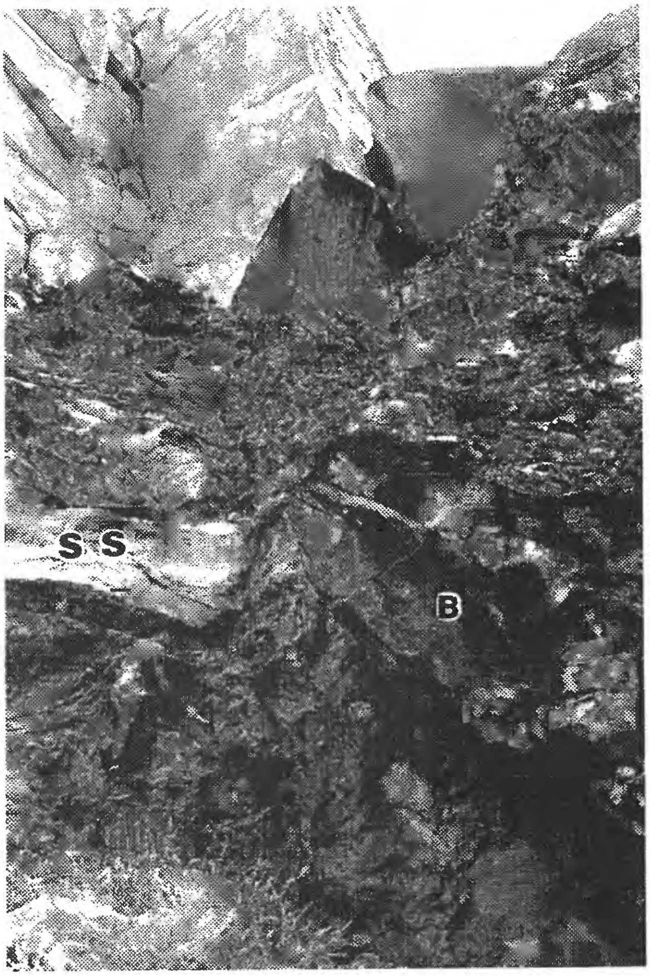


Figure 21b.--The breccia column of pipe 241 (B) abuts against untilted sandstone (SS).

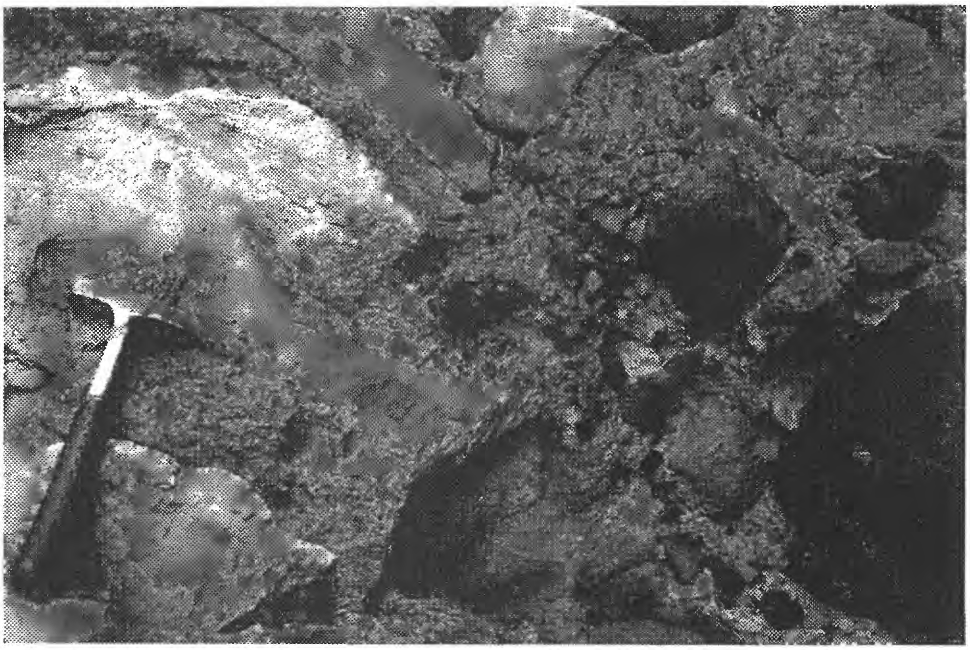


Figure 21c.--The breccia from pipe 241 has the appearance of a conglomerate. Photograph is of the area in figure 21b that the man is pointing to.

Collapse Features/Breccia Pipes Exposed on the Kaibab Limestone-Capped Plateaus

Within the Mohawk Canyon area, on this part of the Coconino Plateau, the highest plateau surfaces are capped by the Harrisburg Gypsiferous Member of the Kaibab Limestone. The top 200 ft of Harrisburg are redbeds that have been stripped from this part of Arizona, leaving the white-colored bottom 100 ft of Harrisburg to cap the Coconino Plateau.

Despite the exposure of mineralized rock in some of the "Esplanade" collapses, such as 241 and 242, collapse structures 249, 1102, 493, and 494 (listed in increasing order of favorability), exposed on the Kaibab surface (Coconino Plateau), are considered to be the most favorable for uranium potential in the Mohawk Canyon area. Compared to other features in the area they are by far the most accessible, and if an orebody is present the total tonnage of U_3O_8 is believed to be greater than that which might remain in the dissected pipes exposed along the Esplanade cliffs and Esplanade erosion surface.

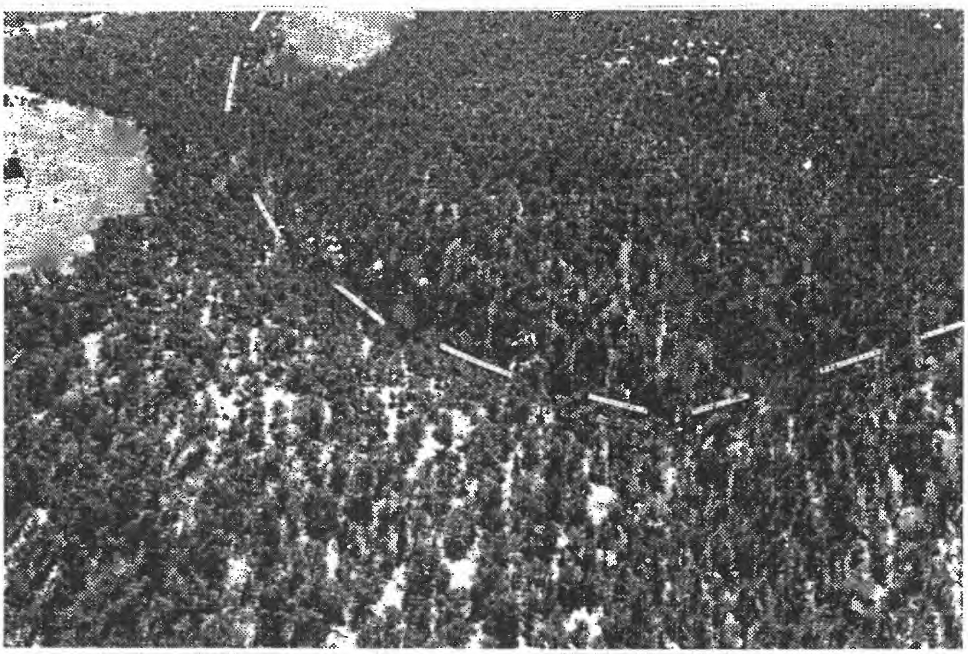
Fourteen of the 19 collapse features found on the Kaibab Limestone-capped plateau have inward-dipping beds; 10 of these have no alteration, anomalous radioactivity, mineralized rock, or breccia. Other than the 4 "Kaibab" collapses that contain altered, radioactive, or brecciated rock, it is difficult to determine without geophysical, geochemical, or drilling surveys, whether the other collapses formed due to an underlying breccia pipe or merely from dissolution of the Kaibab Limestone or Toroweap Formation. It is known from drilling at pipe 494 that the Woods Ranch (gypsum bearing) Member of the Toroweap Formation has been almost totally removed (Wenrich and others, 1988) within the pipe, despite its presence in the cliff exposure on either side adjacent to the pipe. In the cliffs adjacent to some of these 15 "C2" or "C?" collapses, the Woods Ranch Member can be seen to thin to only a few feet. Whether the drapping of the overlying beds and this dissolution is due to weathering along the canyon face, causing localized collapse, or from fluids moving through a breccia pipe and dissolving these units, can not be determined without drilling. The inward-dipping beds of Harrisburg Gypsiferous Member of the Kaibab Limestone can be seen in figures 22a-k for collapse structures 592, 1101, 1170 (no figure), 1172 (no figure), 1174 (no figure), 1087, 1088, 1090, 1189, 1175 (no figure), 1092, 1099, 1100, 1171, and 1173 (listed in increasing order of potential as breccia pipes).

592, 1101, 1170, 1172, and 1174: All five of these features are considered very questionable as breccia pipes. They are all exposed in the Harrisburg Gypsiferous Member of the Kaibab, are vaguely circular on the 1:24,000 aerial photographs, and have minor inward dip to some of the strata.

1087, 1088, 1090, 1089, 1092, 1099, 1100, 1171, and 1173: All 9 of these collapse features have significant inward-dipping beds and appeared more circular on the aerial photographs than did the 4 features listed above. In addition, both features 1088 and 1100 have some iron-stained chert and 1099 has abundant limonite staining on rock within the pipe. Soil geochemical surveys were completed over collapse features 1171 and 1174; the results will be released in a separate report. Chemical analysis of an iron-stained sample from collapse feature 1088 (1088-A-C85--table 2) shows some minor enrichments of elements such as As (190 ppm), Ba (1700 ppm), Cd (10 ppm), and Pb (51 ppm), and a significant enrichment of Zn (2300).

249: This collapse feature is a classic example of a small hill of flat-lying strata completely encircled by concentrically inward-dipping

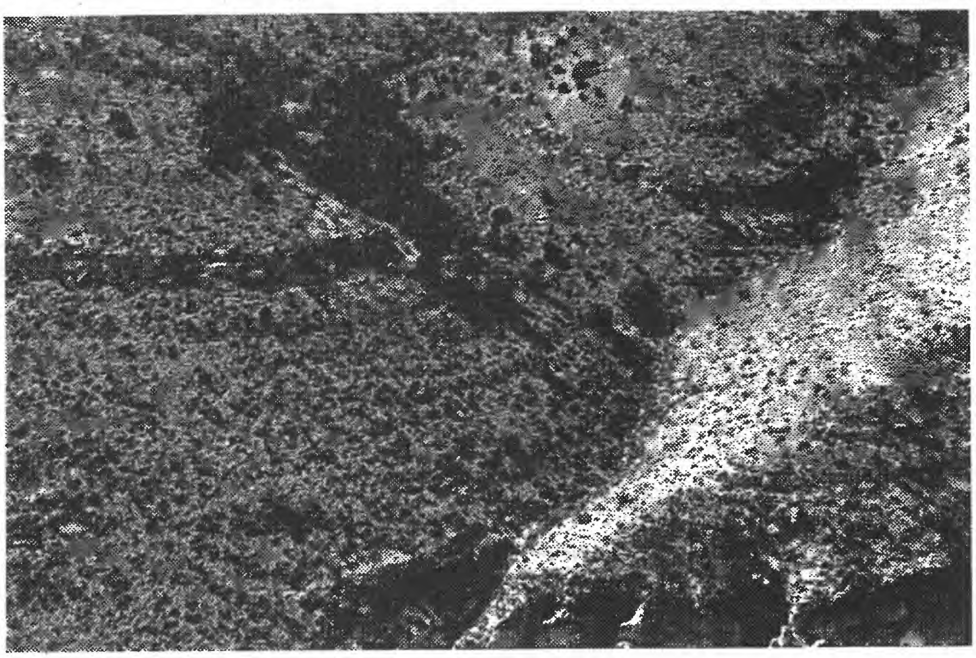
a. Collapse feature 592. Collapse as outlined is about 2500 ft wide.



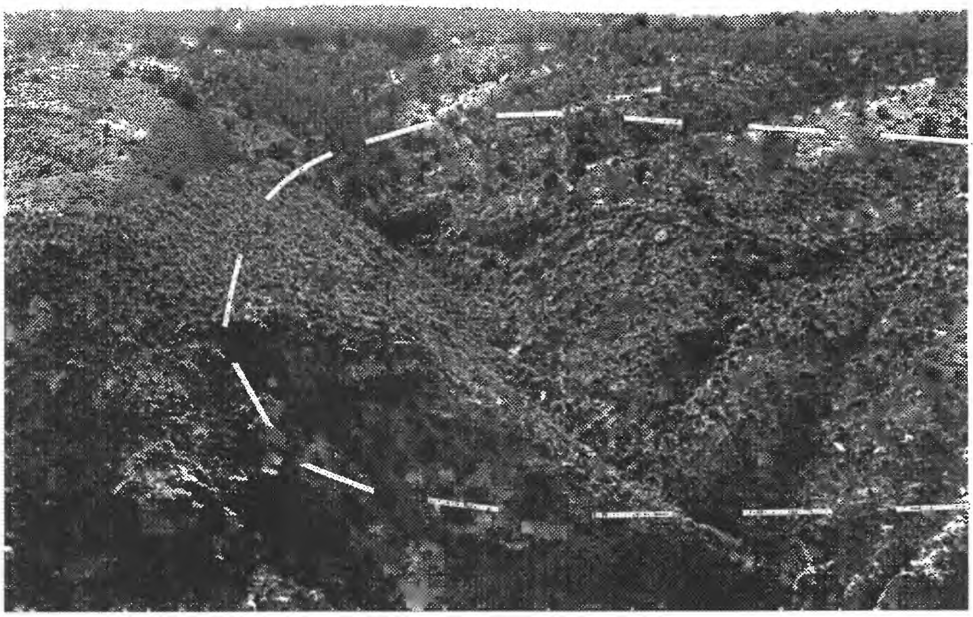
b. Collapse feature 1101. View as shown is about 900 ft wide.

Figure 22.--Photos a-k show collapse features in the Mohawk Canyon area on the Kaibab Limestone-capped plateau that are expressed solely as inward-dipping beds, with no surface alteration, brecciation, or mineralization, making it difficult to tell a solution collapse in the Permian from a deep-rooted (Mississippian) breccia pipe. Photos taken from a helicopter.

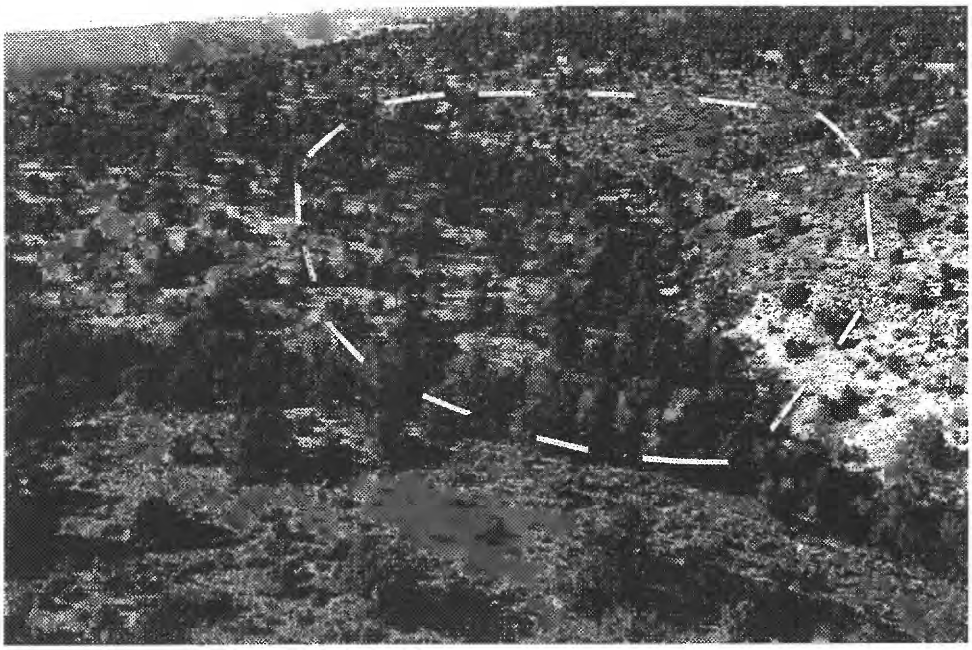
c. Collapse feature 1087. View as shown is about 1000 ft wide.



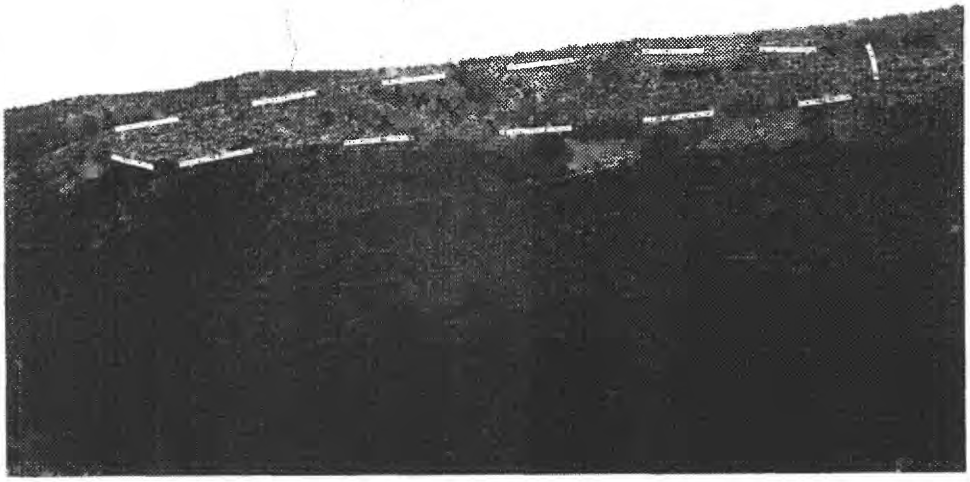
d. Collapse feature 1088. The entire field of view is within the collapse--the junction of the gullys is the center of the collapse. View as shown is about 700 ft wide.



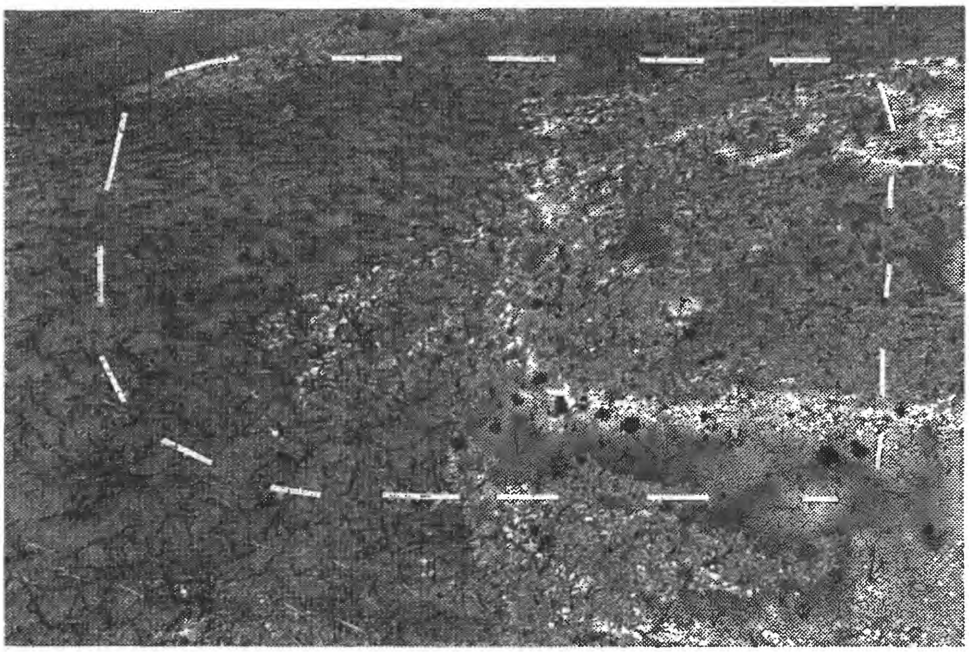
e. Collapse feature 1089. View as shown is about 600 ft wide.



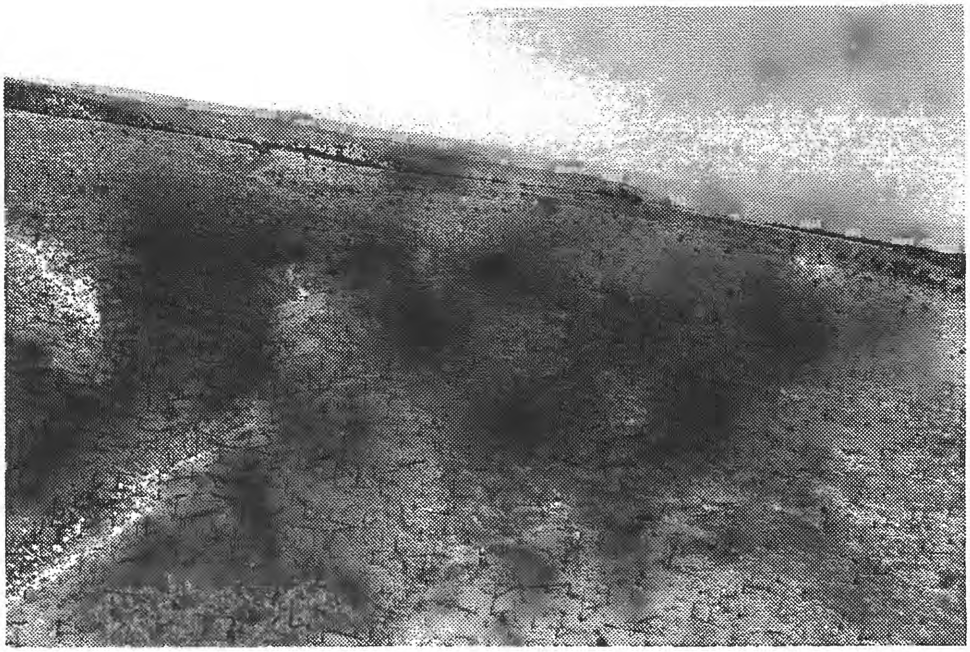
f. Collapse feature 1090. Collapse as outlined is about 500 ft long.



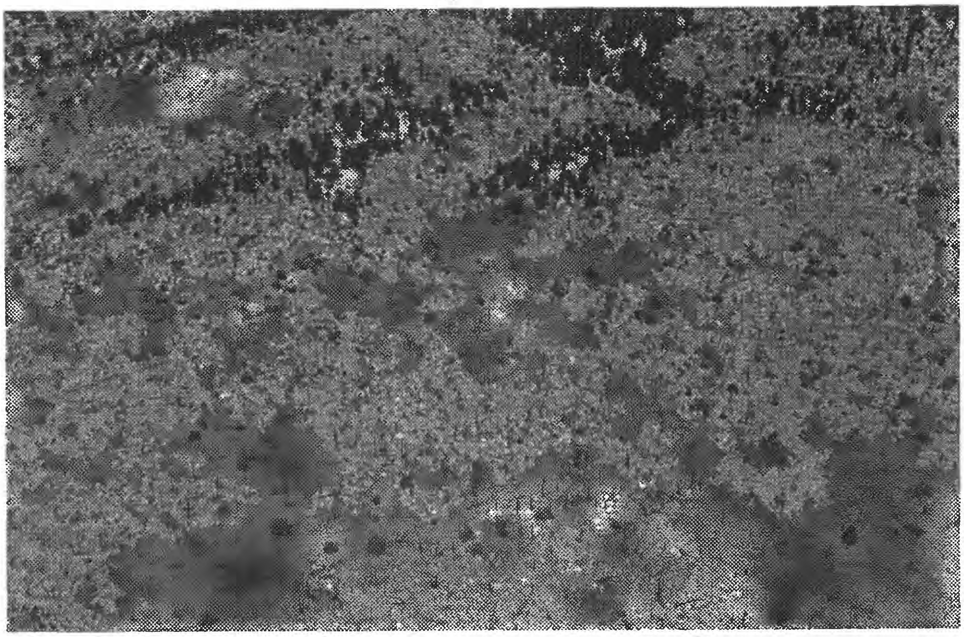
g. Collapse feature 1092. Collapse as outlined is about 1000 ft long.



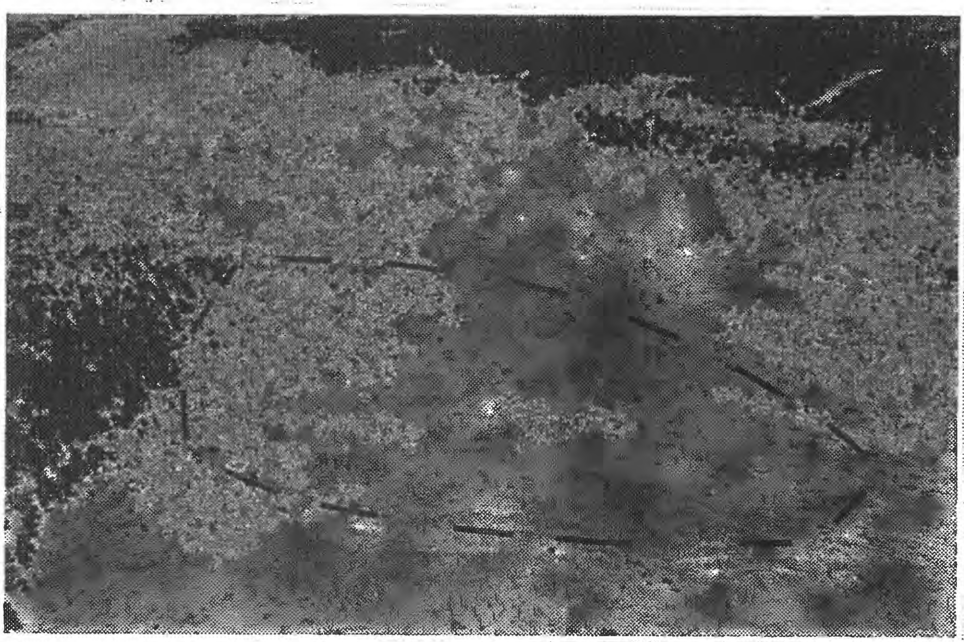
h. Collapse feature 1099. Collapse as outlined is about 800 ft long.



i. Collapse feature 1100--the entire foreground is within the collapse. View as shown is about 1000 ft wide.



j. Collapse feature 1171. Note the concentric inward-dipping beds in the center of the photo. Diameter of the collapse as viewed is about 800 ft.



k. Collapse feature 1173. Dashed line marks the area of collapse and inward-dipping beds. Length of the collapse as outlined is about 700 ft.

beds; a "moat" lies between the hill and dipping beds (figs. 23a and 23b). This exposure of Harrisburg Gypsiferous Member appears bleached, although such alteration is difficult to identify in a rock that is normally "white" (such as this part of the Kaibab Limestone). Chert breccia is present, although it is possibly an interformational breccia of the Harrisburg, and unrelated to pipe brecciation. No anomalous radioactivity or other mineralized rock is apparent. A sample of hematite-stained chert breccia (90% SiO_2) was submitted for chemical analysis (sample 249-A-C83--table 2). Although not visibly mineralized, it did contain high As (105 ppm) and Cu (330 ppm). A soil geochemical survey was completed over this feature, but the data will be presented in a separate paper. The rock geochemistry (table 2) along with the collapse morphology, specifically the "moat" (which may represent the more easily dissected ring fracture zone of a deep-rooted breccia pipe), makes this structure a favorable target for further exploration.

1102: The beds of Harrisburg Gypsiferous Member are dipping inward toward the central drainage (fig. 24a), although the morphology is not distinctly circular as it is at collapse feature #249 (above). Small outcrops and float of gold to orangish-brown Fe-rich silicified gossan are scattered about the center of this feature (fig. 24b). The gamma-radioactivity reached 550 cps (18 times background) over the gossan. With the exception of the Blue Mountain pipe (pipe #287--Billingsley and others, 1986; Van Gosen and others, 1989), this is the highest surface radioactivity encountered anywhere on the Hualapai Reservation, and such levels of gamma radiation are particularly rare on the Kaibab erosion surface. Two samples from the gossan were geochemically analyzed (1102-A-C85 and 1102-B-C85--table 2) and indicate a striking enrichment of elements commonly associated with breccia pipes orebodies: As (650 and 570 ppm), Co (110 and 11 ppm), Mo (760 and 450 ppm), Ni (420 and 73 ppm), Pb (130 and 94 ppm), Sb (25 and 7 ppm), U (202 and 165 ppm), V (160 and 68 ppm), and Zn (400 and 230 ppm). Soil geochemical samples were collected over this feature, but the results will be discussed in a separate paper. An audio-magnetotelluric (AMT) geophysical survey was completed by Flanigan and others (1986). The two (east-west and north-south) AMT crossections indicate three vertical conductive zones that extend from about 300 ft to 2400 ft below the collapse surface exposure. Flanigan believed that the central conductive zone was due to the pipe core and the outer two were a result of the ring fractures. Hence, Flanigan and others (1986) concluded that feature 1102 was a deep-seated breccia pipe. These AMT results and the anomalous surface geochemistry certainly suggests that 1102 holds excellent economic potential as a uranium-mineralized breccia pipe.

493: This is one of the larger collapse features in the Mohawk Canyon area, about one-third mile in diameter. Like 249, this structure is a classic example of a small hill almost totally encircled by a "moat" that is surrounded by higher hills (figs. 25a and 25b) consisting of Harrisburg Gypsiferous Member. The central hill contains concentric sets of perfectly circular rings of unusually steep (near vertical toward the center), inward-dipping beds around a center of reddish soil. This reddish soil could be downdropped Triassic Moenkopi Formation strata, but if so there has been over 200 ft of downdrop at the present Harrisburg erosion level because the upper 200 ft of red Harrisburg (the stratigraphic distance between the present plateau surface and the Moenkopi Formation) has been stripped from the Plateau surface. Only the

Figure 23a.--Collapse feature 249. Note the small hill completely encircled by concentrically inward-dipping beds. Between the hill and the concentric beds is a "moat" that perhaps represents the more easily eroded ring fracture zone surrounding a downdropped plug overlying a breccia core. Photograph taken from a helicopter. The diameter of the outline made by the concentric beds is about 1000 ft.

Figure 23b.--View of collapse feature 249 from a 1:24,000 aerial photograph.

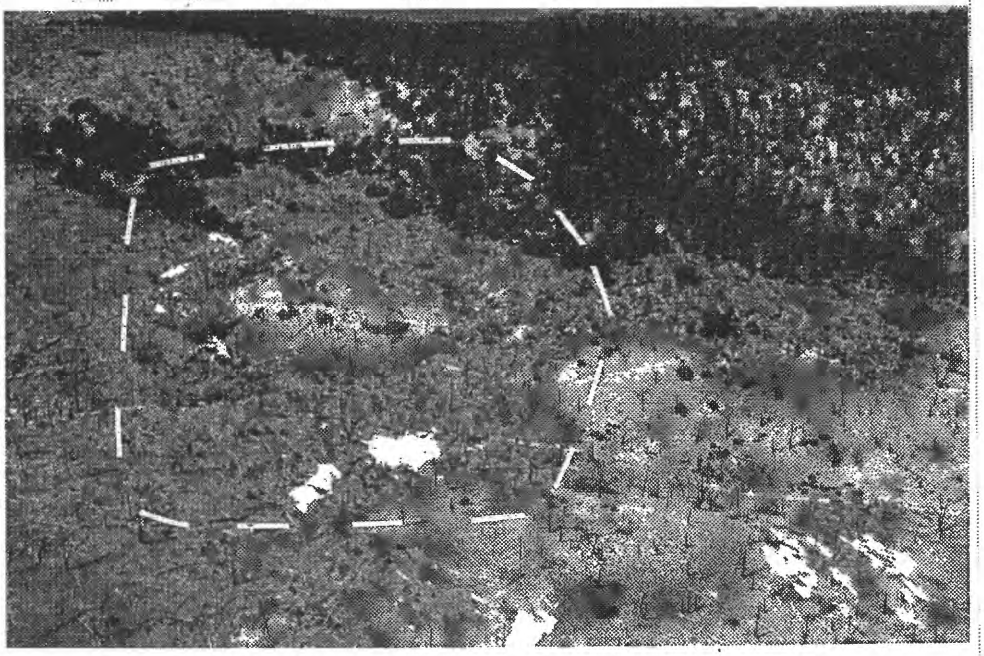


Figure 24a.--The geomorphology of collapse feature 1102 is not as distinctly circular as is that of feature 249 (fig. 23a), but it does have strata of Harrisburg Gypsiferous Member dipping slightly radially inward toward a central drainage (center of photo). Collapse as outlined is about 300 ft long.

Figure 24b.--Small outcrops and float of orangish-brown, Fe-rich gossan (G) emitted gamma radioactivity in excess of 18 times background at #1102.

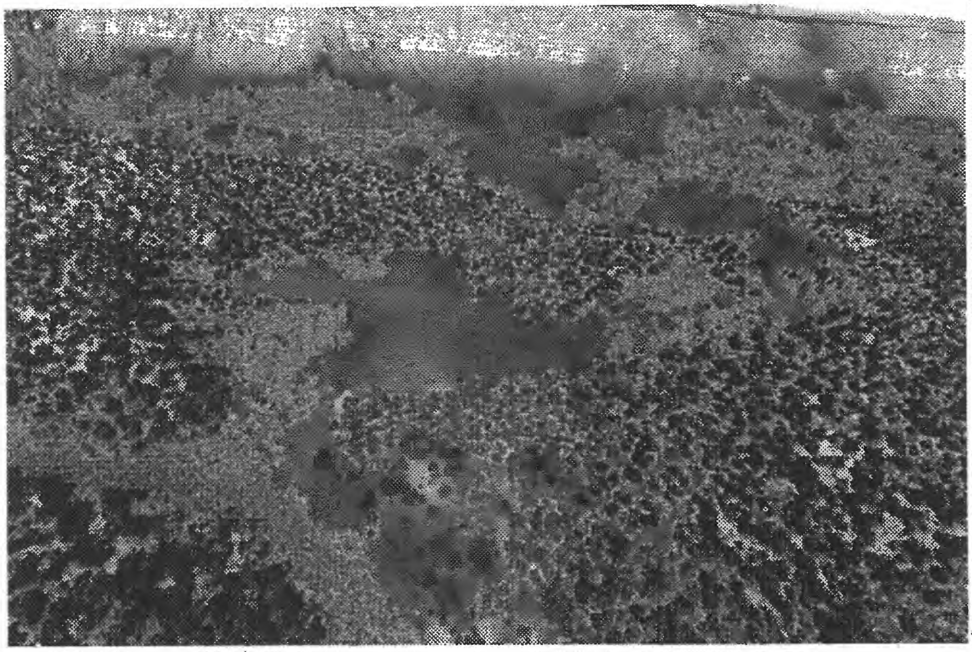


Figure 25a.--Collapse feature 493 has a classic breccia pipe surface morphology: a small hill of concentrically inward-dipping beds almost totally encircled by a moat that is surrounded by higher hills. Rim to rim the feature is about 1600 ft wide.

Figure 25b.--Photo of collapse feature 493 taken from low-altitude aerial photography (1:24,000 scale). Note the outer concentric ring of beds on the central hill.

basal 100 ft of white-colored Harrisburg remains to cap the plateau surfaces in the Mohawk Canyon area.

A ground magnetometer survey over this feature yielded an anomalous magnetic high over the middle of the central hill, adjacent to an area of an anomalous magnetic low, just outside the eastern rim of the central hill (Van Gosen and Wenrich, 1989); these data suggest that the central hill contains a significant thickness of more magnetic sediments, such as the red beds of the Harrisburg or the Moenkopi Formation, than the rock of the surrounding hillsides.

Along the Mohawk Canyon cliff on the extreme western edge of the collapse, the gypsiferous Woods Ranch Member pinches to zero thickness just beneath the collapse (fig. 25c). In addition, a cave, located just beneath the collapse in the Fossil Mountain Member of the Kaibab Limestone (fig. 25c), attests to increased dissolution directly beneath this structure. Chemical analyses of samples (493-A-C83 and 493-B-C83--table 2), taken respectively 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); these concentrations are discouraging in contrast to samples taken from other pipes in the Mohawk Canyon area (see table 2). A soil geochemical survey was also completed over this collapse; the results will be published in a separate report.

Fourteen AMT soundings by Flanigan and others (1986) were completed over collapse 493. The north-south cross section illustrates a striking, perfectly vertical zone of very high conductivity from about 100 ft below the surface of the collapse down to the base of the survey, 3000 ft. This strongly suggests that not only is 493 a breccia pipe, but is a vertical pipe without the bends that plague many pipes (such as pipe EZ-2--AMT profile shown by Flanigan and others, 1986), making orebody delineation very difficult. Hence, the high vertical conductive zone benearth the collapse (AMT results), the collapse morphology, and dissolution of the underlying Toroweap (see section on Woods Ranch dissolution in Mohawk Canyon pipe, Wenrich and others, 1988) suggest that 493 has good potential as a uranium-mineralized breccia pipe, and certainly warrants exploratory drilling.

494 (Mohawk Canyon pipe): This breccia pipe (fig. 26a) is considered to have the greatest potential to contain an orebody of any pipe on the Hualapai Reservation. It was originally identified as a collapse by the senior author in June 1983 while mapping collapse structures in the Mohawk Canyon area. Although the "turn-of-the century" Grand Canyon miners probably did not recognize this area as a breccia pipe, they obviously discovered its copper minerals (malachite, azurite, and chrysocolla) during the 19th century--this timing is suggested by the square nails in the timbers that are lying about on the ground by two adits driven into the west side of Mohawk Canyon, at the cliff edge. The adits are located on the outermost ring fracture of the pipe.

An AMT survey could not be made over this pipe because of its proximity to the cliff. A soil survey was completed; the results will be released in a separate report. A ground magnetometer survey over this pipe revealed a dipole anomaly (Van Gosen and Wenrich, 1989). The dipole high is over the core of the pipe, suggestive that the downdropped core may contain some of the redbeds (presently bleached) of the Harrisburg Gypsiferous Member, which have been stripped from the surrounding

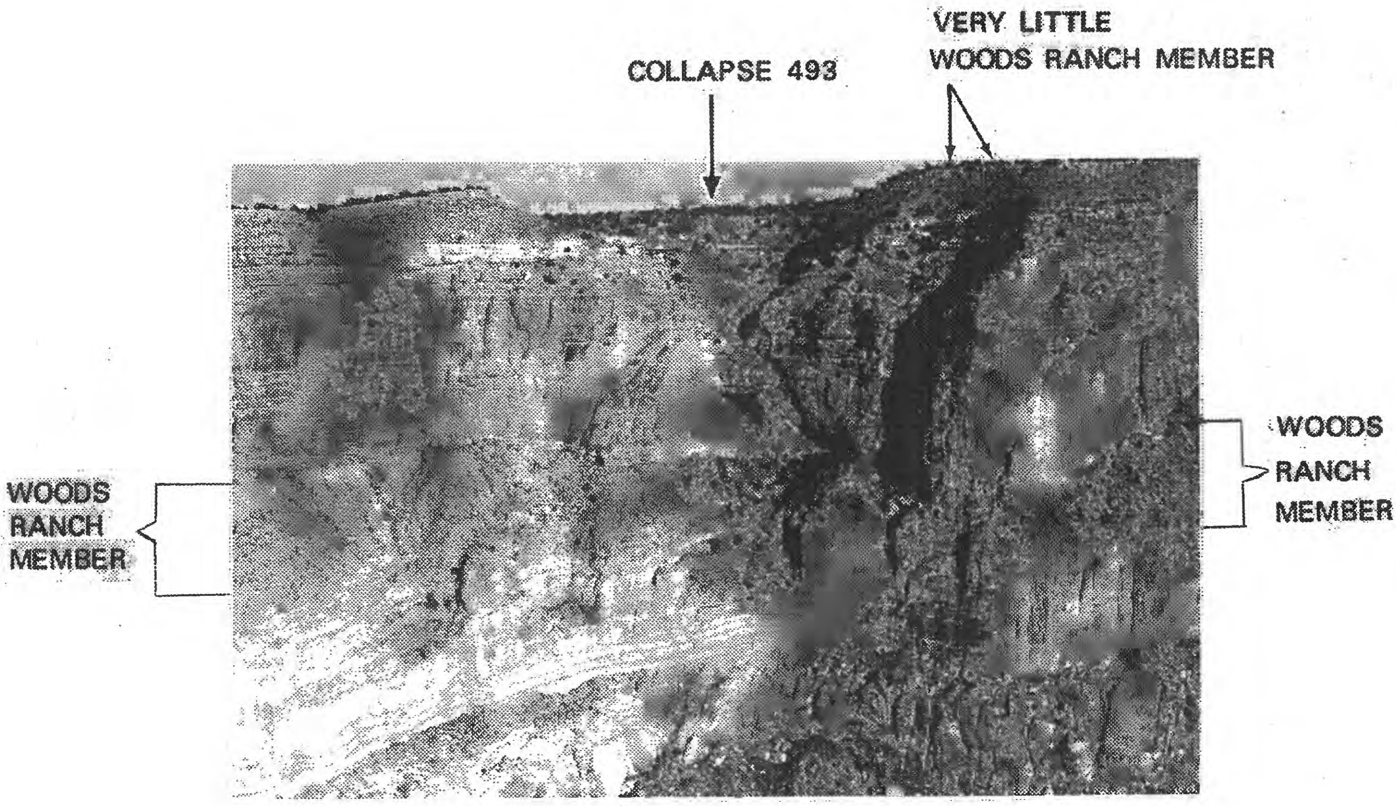


Figure 25c.--The Woods Ranch Member of the Toroweap Formation thins to zero thickness near the collapse feature (arrow). Also notice the cave in the Fossil Mountain Member of the Kaibab Limestone just below the collapse. The western edge of the collapse can be recognized by the amphitheater beginning to develop at the top of the cliff.

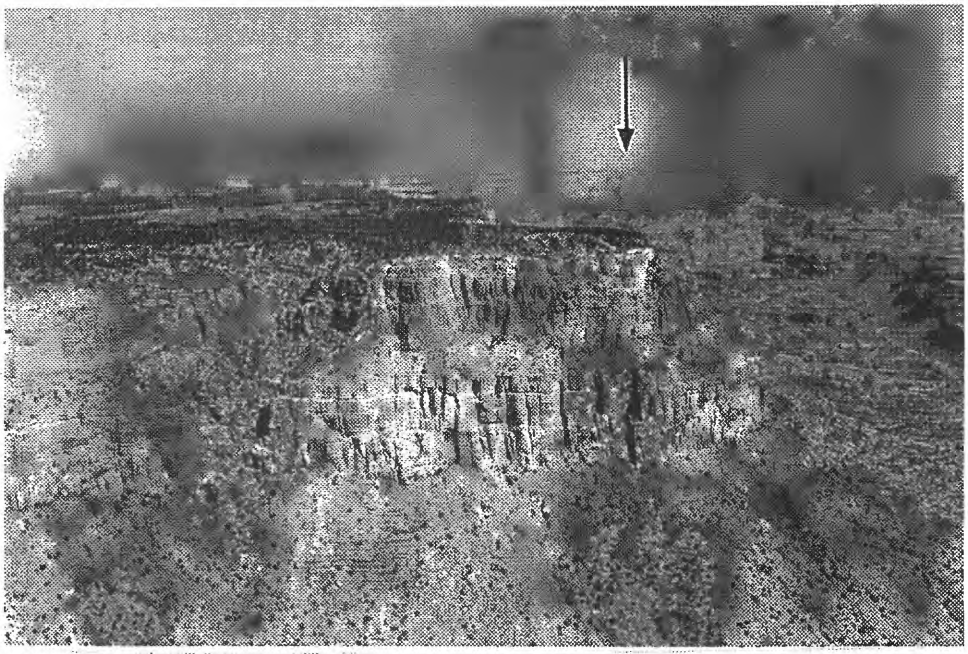


Figure 26a.--The Mohawk Canyon pipe shows up as a small bleached point on the Kaibab Limestone cliff (arrow). Fault-controlled Mohawk Canyon can be seen to the right heading north towards the Colorado River. This photograph was taken during drilling of the Mohawk Canyon pipe in 1984.

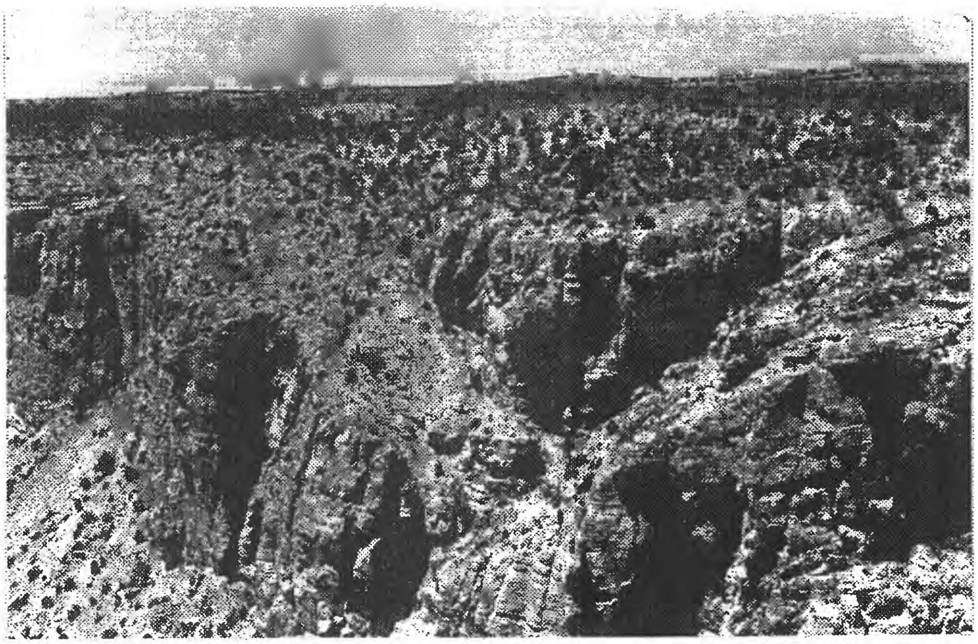


Figure 26b.--This close-up photo of area pointed to by arrow in figure 26a shows concentric beds of Harrisburg Gypsiferous Member of the Kaibab Limestone dipping radially into the ring fracture zone (eroded to form the drainage). This photograph was taken prior to drilling. The distance between the drainages in this view is about 650 ft.

areas. In fact, the lithologic logs from the drilling indicate 210 to 255 ft of Harrisburg in the core (Wenrich and others, 1988)--only the basal 100 ft are the normally white, less magnetic, Harrisburg. The pipe was selected for exploratory drilling during July-November 1984 because it exhibited the following exploration criteria:

1. Concentrically inward-dipping beds of Kaibab Limestone (fig. 26b).
2. A circular drainage pattern.
3. Anomalous surface radioactivity--up to five times background.
4. Goethite pseudomorphs and molds of pyrite.
5. Colloform celadonite-stained chalcedony.
6. Supergene Cu minerals, such as malachite, azurite, brochantite, and chrysocolla.
7. Breccia.
8. Anomalous concentrations in surface exposure of several elements (Cu ore sample--494-C-C83--table 2), such as Ag (100 ppm), As (400 ppm), Cr (244 ppm), Cu (1.4%), Fe (18%), Hg (0.3 ppm), Mo (140 ppm), Ni (70 ppm), P_2O_5 (1.5%), Pb (1.2%), Sb (106 ppm), Se (350 ppm), Sr (1600 ppm), U (50 ppm), V (290 ppm), and Zn (1.2%).

Five holes were drilled. One hole, penetrating to a depth of 1335 ft, shows a 1-ft interval of 0.52% eU_3O_8 at a depth of 1191 ft, and a 20-ft zone averaging 0.04% U_3O_8 (Wenrich and others, 1988); this is the same stratigraphic horizon as the top of orebodies in active mines, located on similar plateaus capped with the Harrisburg Gypsiferous Member of the Kaibab Limestone. Zones of sulfide mineralization in the drill core include crystals of galena, 1-3% pyrite, and minor bravoite. A detailed discussion of the drilling results, including lithologic and geophysical logs, can be found in Wenrich and others (1988). Although the 1-ft-thick zone of high-grade uranium is hardly an orebody; the grade of 0.52% eU_3O_8 is the average grade mined from those northern Arizona breccia pipes which host orebodies (Mathisen, 1987). Sufficient mineralized rock was verified in the Mohawk Canyon pipe that additional drilling is warranted to determine whether an orebody is present.

CONCLUSIONS

The Mohawk Canyon area has a greater concentration of surface-mineralized collapse structures than anywhere else on the Hualapai Reservation. Those collapse features exposed in the Redwall Limestone and overlying lower Supai Group are not considered to have any potential for uranium orebodies. Of the 46 collapse features mapped in the area, 6 of them, including the Mohawk Canyon pipe (#494) that was drilled and discovered to contain U concentrations as high as 0.52% eU_3O_8, should undergo additional exploration surveys. Three of the six structures, 494, 242, and 241, are confirmed breccia pipes that have been mineralized. The other three, 249, 493, and 1102, have not been dissected by canyons, so no brecciated rock is exposed, although 1102 has an Fe-rich gossan developed on its surface that is more radioactive than any other examined rock exposed on the Hualapai Reservation (except at the Blue Mountain pipe).

Breccia pipes 241 and 242 lie on the Esplanade erosion surface at the bottom of Mohawk Canyon, and although they are known to be uranium mineralized, there are two negative economic considerations: (1) They are inaccessible by vehicle and difficult to reach even on foot; (2) The top 1500 ft of rock, that rock which hosts most of the ore in all of the past or presently active breccia pipe uranium mines, has been eroded away. The other four favorable pipes crop out on the Coconino Plateau and are reasonably accessible; 493 and 494 have roads to them. Classic breccia pipe geomorphologies are developed over 249, 493, and 494.

The geomorphology of collapse feature 249 strongly suggests that there is an underlying breccia pipe. The concentric inward-dipping beds of Harrisburg Gypsiferous Member of the Kaibab Limestone enclosing a "moat" that surrounds a central hill of flat-lying strata strongly suggests that this "moat" may overlie a ring fracture zone (less resistant to erosion) that bounds an underlying breccia pipe. Although 249 is not considered as favorable as 1102, 493, and 494 to host a uranium orebody, it should certainly be explored further.

The dissolution of the Woods Ranch Member of the Toroweap Formation, adjacent to and under 493 (similar to what was observed while drilling 494), makes this structure a favorable target, as do (1) the AMT results that show a vertical, pipe-shaped, zone of high conductivity lying beneath the surface collapse structure, and (2) the nearly vertical, inward-dipping beds that enclose red soil at the center of the collapse. The red soil is either weathered Harrisburg Gypsiferous Member (upper 200 ft of red beds in the Kaibab Limestone) or Moenkopi Formation, suggesting that (1) a minimum of 40 ft of downdrop occurred if the soil is weathered Harrisburg strata (the red soil is about 40 ft below the top of the enclosing basal 100 ft of white Harrisburg), or (2) 200 ft of downdrop occurred if it is weathered Moenkopi Formation.

The anomalous gamma radioactivity of 18 times background at the surface of feature 1102, as well as the exceptionally elevated concentrations of As, Co, Mo, Ni, Pb, Sb, U, V, and Zn in the Fe-rich gossan make this feature an excellent exploration target for an orebody. The geochemical results of 165 ppm U for the sample that emitted 18 times background gamma radioactivity suggests that, at least for the surface exposure, the uranium gamma radioactivity and uranium content are approximately in chemical equilibrium. That is, the background values for uranium contents in this rock are about 4-8 ppm. The high conductivity zones delineated underneath of this feature by an AMT survey also strongly suggest that this is a breccia pipe (Flanigan and others, 1986) rather than a near-surface, unmineralized gypsum or limestone collapse.

Collapse feature 494 is considered to have the greatest potential for a uranium orebody on the Hualapai Reservation because it has been proven through drilling to be both uranium mineralized and a breccia pipe. One foot of 0.52% eU_3O_8 (which as shown at feature 1102 is in approximate chemical equillibrium) has been encountered along with the presence of minerals such as bravoite, galena, and pyrite that are always associated with the uraninite ore in northern Arizona breccia pipes.

It is interesting to note that these six favorable structures lie in a NE-trending zone (see their location on fig. 5), similar to breccia pipe alignments on the Marble Plateau shown by Sutphin and Wenrich (1983) and Sutphin (1986). Wenrich and others (1986) pointed out a similar NE alignment of the Ridenour mine and 3 other mineralized pipes just to the west of the Mohawk Canyon area.

Finally, any additional exploration in this area should concentrate on (1) additional drilling of pipe 494 (see Wenrich and others, 1988, for recommended sites); (2) geochemical surveys such as Bacillus cereus or helium soil gas, plus magnetometer surveys over 249, 493, and 1102, and an audio-magnetotelluric (AMT) survey over 249; and (3) exploratory drilling of 493 and 1102.

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