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

This research was funded by the
Bureau of Indian Affairs
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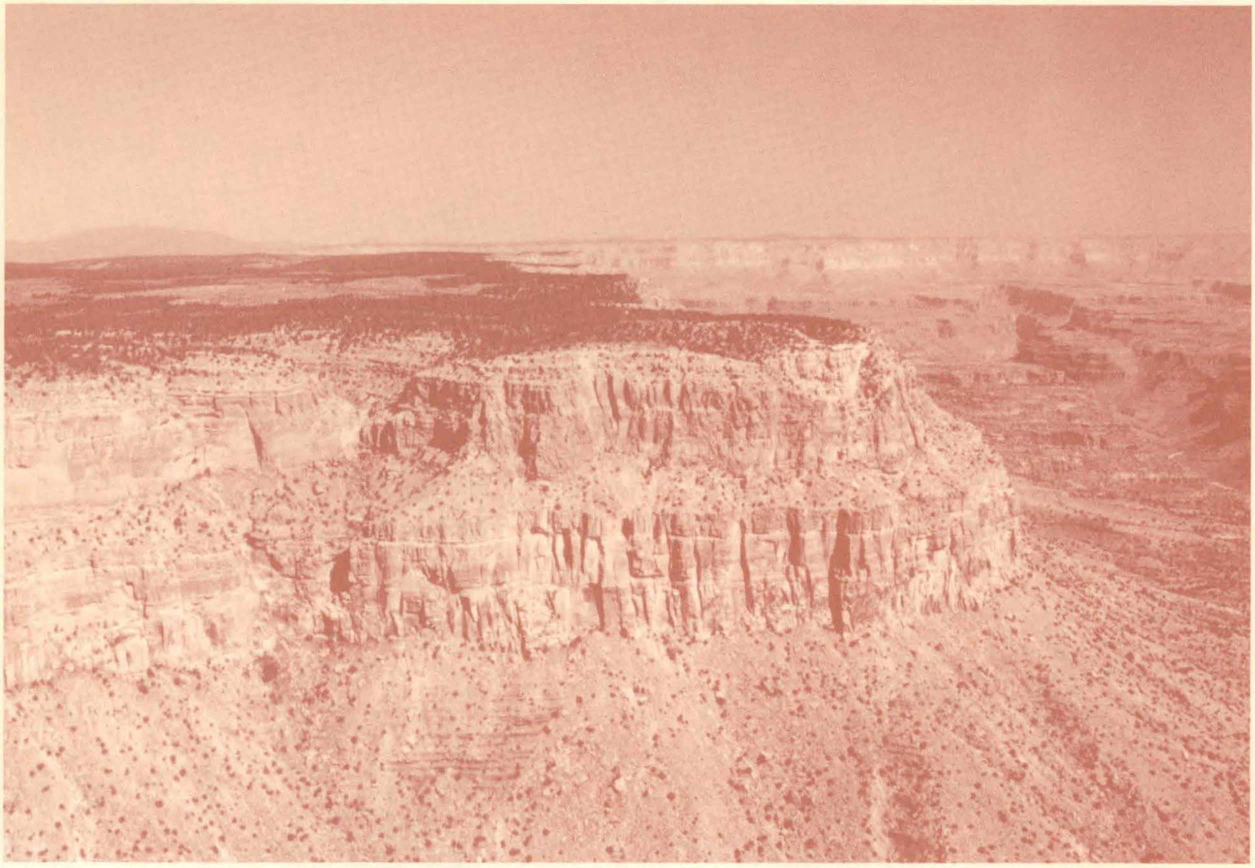

View looking north at the central half of the Mohawk Canyon Area. Mohawk Canyon extends along the eastern edge of the photograph; the Mohawk-Stairway fault has created the linear drainage along the bottom of this part of the canyon. The Mohawk Canyon pipe is exposed in the Kaibab Limestone visible in the foreground at the top eastern edge of the cliff (road on the plateau can be seen leading to the pipe). The pipe can be detected by the white bleached area that appears even lighter than the normal pale yellow to buff color of the Kaibab Limestone.

Chapter D

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

By KAREN J. WENRICH, GEORGE H. BILLINGSLEY, and BRADLEY S. VAN GOSEN

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BRECCIA PIPES IN NORTHERN ARIZONA

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

By Karen J. Wenrich, George H. Billingsley, *and* Bradley S. Van Gosen

Abstract

The Hualapai Indian Reservation is 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 Indian Reservation are in the Mohawk Canyon area. The Mohawk Canyon area has most of the various breccia-pipe morphologies on the Hualapai Indian Reservation; in addition, the area contains the greatest number 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 presently collared in one of three horizons: (1) the top of the Redwall Limestone (13 collapse features/breccia pipes), (2) the Esplanade erosion surface or along the cliffs formed by any Supai Group formation (14 collapse features/breccia pipes), or (3) the top of the Coconino Plateau capped by the Kaibab Limestone (19 collapse features/breccia pipes). The 13 structures that crop out within the Redwall Limestone are considered to have little or no economic potential. Two breccia pipes, 241 and 242, have significant mineralized rock exposed on the Esplanade erosion surface; unfortunately, their economic potential is questionable because of their inaccessibility at the bottom of Mohawk Canyon. In contrast, four features, 249, 493, 494, and 1102, on the Coconino Plateau have the greatest potential for being U-bearing breccia pipes and are accessible. All warrant further exploration: 249 exhibits excellent circular surface morphology; 493 also has similar circular morphology with concentric inward-dipping beds, but in addition, audio-magnetotelluric profiles show a vertical, strongly conductive zone (possibly a breccia core) beneath the collapse feature; 1102 contains the most radioactive surface exposure found anywhere on the reservation—18 times background; and 494 (the Mohawk Canyon pipe) was drilled by the U.S. Geological Survey in 1984 and proven to contain at least 1 foot of core containing 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 U 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 U ore, averaging as much as 0.74% U_3O_8 in the Canyon pipe (Casadevall, 1989), has made these deposits attractive, even at $15 per lb of U. Although the breccia pipes have also been mined in the past 100 years for Cu, Ag, Pb, V, and Zn, U 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 byproducts of U for several reasons: (1) the U mill, in Blanding, Utah, is more than 300 mi (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 V; and (3) the base-metal enrichments are sporadic;

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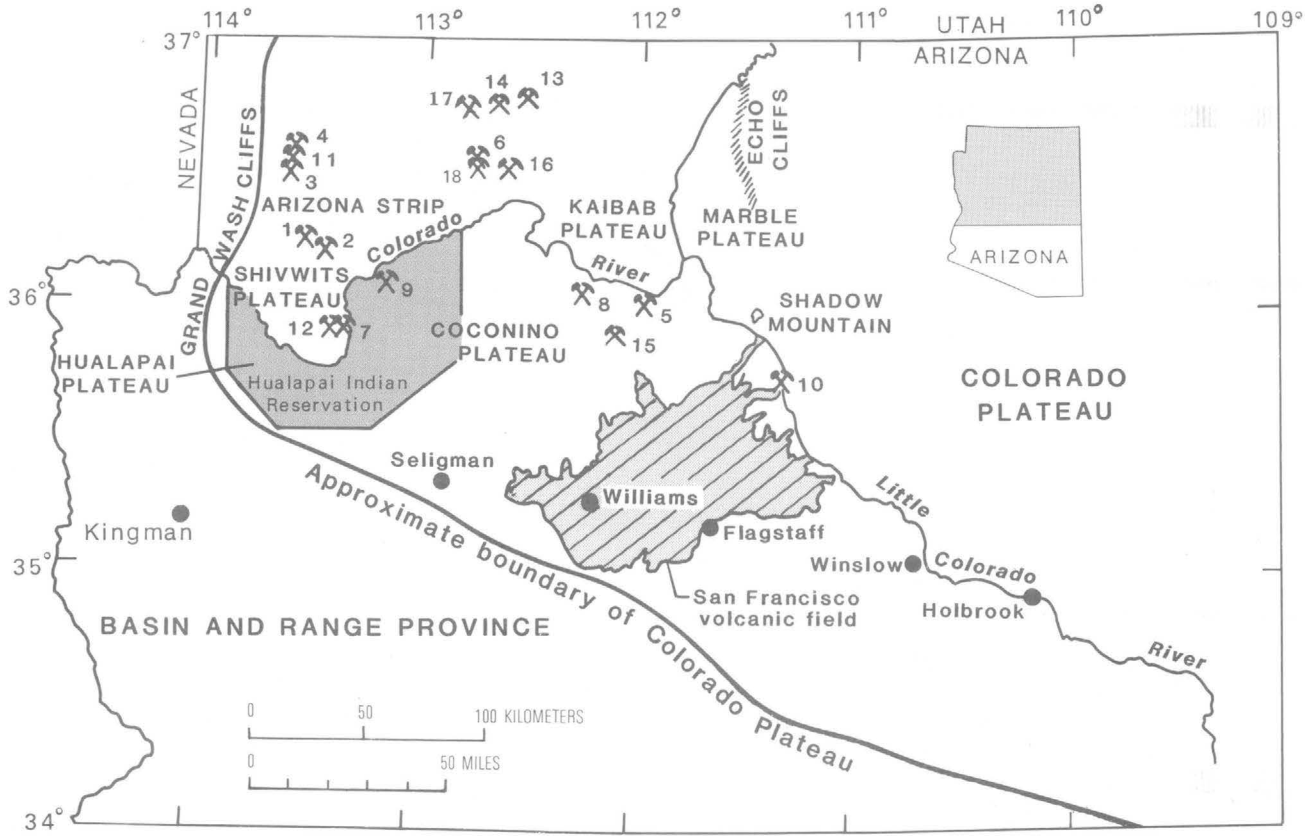


Figure 1. Index map of northern Arizona showing the locations of plateaus, Hualapai Indian Reservation, breccia pipes developed or being developed into mines, and the San Francisco volcanic field (patterned area) that buries terrane with high potential for breccia pipes. Numbers refer to the following 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. Savanic
12. Snyder
13. Pigeon
14. Kanab North
15. Canyon
16. Pinenut
17. Hermit
18. Arizona 1

for example, Ag is as high as 100 ppm (parts per million) in many samples but is more commonly below 20 ppm in unoxidized U 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 (fig. 1) that contain high concentrations of breccia pipes and have good potential for hosting U orebodies. The selection was based on the density of collapse features and the 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 four-wheel-drive vehicles. Mapping of such terrain, specifically the tens of miles of cliff exposure, can only be done by viewing aerial photographs, and by observations from a helicopter. (2) In the National Tank area (Wenrich, Billingsley, and Van Gosen, 1989), 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.

BRECCIA PIPES IN 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, the pipes 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-

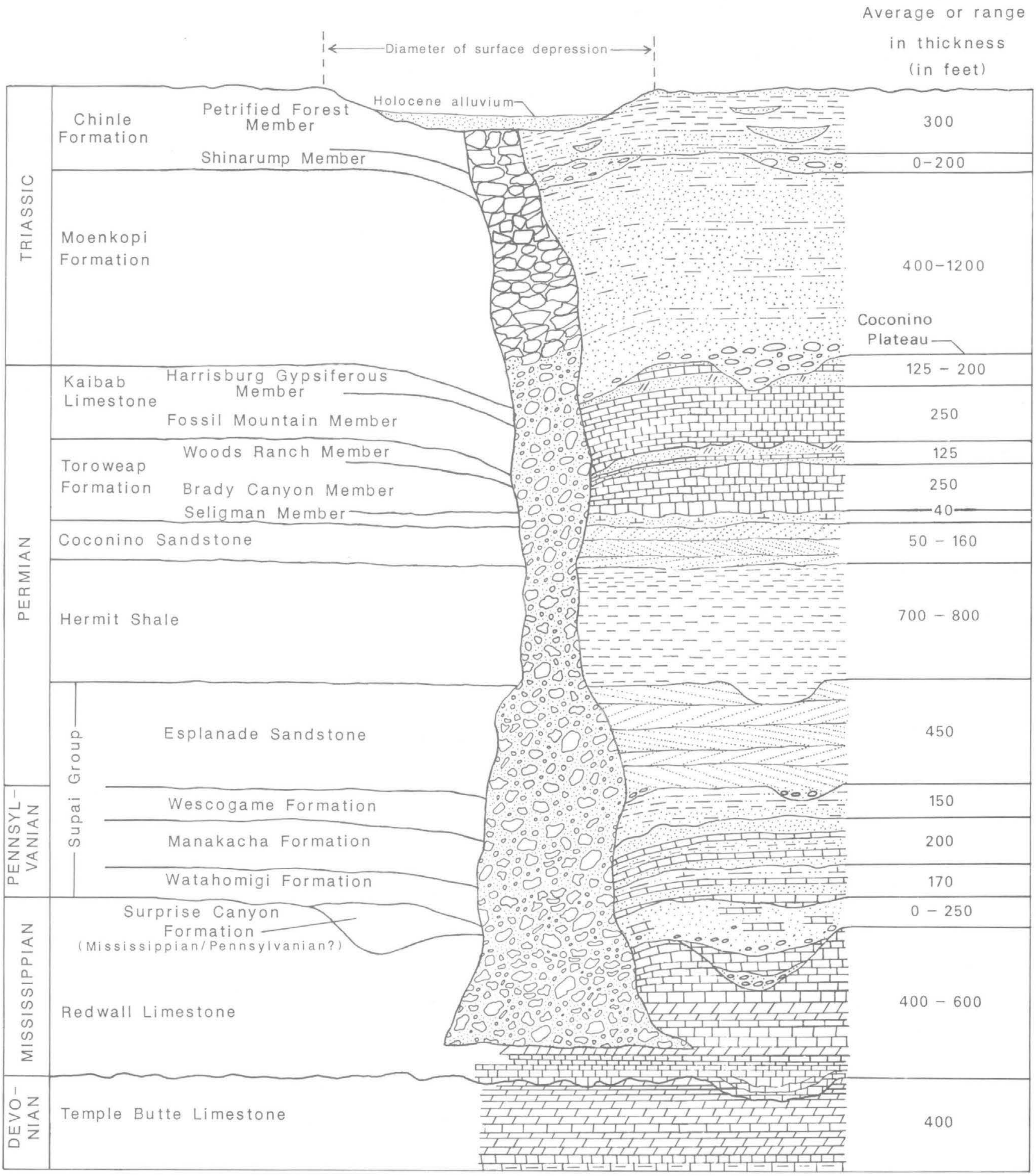


Figure 2. Schematic cross section of a breccia pipe (based on cliff exposures in the Grand Canyon of Arizona). The unit thicknesses shown for the Triassic Chinle and Moenkopi Formations (not present in the Mohawk Canyon area) represent their thickness ranges in the Grand Canyon area. The unit thicknesses for the Paleozoic strata correspond to thicknesses present in the Mohawk Canyon area (from Wenrich and others, 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. Modified from Van Gosen and Wenrich (1989).

filled, approximately 250-ft (feet) diameter pipelike 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 of about 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 (Wenrich, 1985, fig. 1b). This nearly vertical fracture is referred to throughout this report as the "ring fracture."

The breccia pipes of northern Arizona extend from the Utah state line 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 Indian Reservation (fig. 1). The pipes in the Mohawk Canyon area are typical of those in northwestern Arizona. They are exposed at various stratigraphic horizons from the Redwall Limestone to the Kaibab Limestone, which caps the Coconino Plateau. Many are 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, more than 17,275,000 pounds of U_3O_8 have been mined from northern Arizona breccia pipes, and 13,000,000 pounds have been mined since 1980 (Wenrich, Chenoweth, and others, 1989). The deposits are small and of high grade; the average diameter of the mined breccia pipes is about 250 ft, and ore mined between 1980 and 1986 averaged 0.65% U_3O_8. The breccia pipes mined as of 1990 have contained between 1 and 7 million pounds of U_3O_8 each (I.W. Mathisen, oral commun., 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 salinities are consistently more than 9 weight percent NaCl equivalent and generally more than 18 weight percent NaCl equivalent. A large set of U-Pb isotopic analyses from nine orebodies shows that the main U-mineralizing 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 are in Wenrich, Chenoweth, and others (1989); Van Gosen and Wenrich (1989); Wenrich and Sutphin (1989); Gornitz and others (1988); Krewedl and Carisey (1986); Wenrich (1985, 1986); and Gornitz and Kerr (1970).

BRECCIA PIPES IN THE HUALAPAI INDIAN RESERVATION

The Hualapai Indian Reservation is on the southwestern corner of the Colorado Plateau (fig. 1). The western half of the reservation, which is 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 of possible rock thickness is available to host an orebody, and little of the rock is sandstone. Most is limestone, which generally is an unfavorable host for U 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 mostly capped by the Harrisburg Gypsiferous Member of the Kaibab Limestone. This thick rock sequence, in excess of 2,500 ft, 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.

More than 900 confirmed and suspected breccia pipes have been mapped on the Hualapai Indian Reservation (fig. 3). This density of collapse features/breccia pipes is not unique to the Hualapai Indian Reservation, which lies at the western edge of the pipe-rich region in Arizona. This region extends eastward where a similar concentration of collapse features/breccia pipes 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 Arizona and especially these areas of low pipe density have not been mapped in detail. The only data available for 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-collapse features formed where gypsum 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*

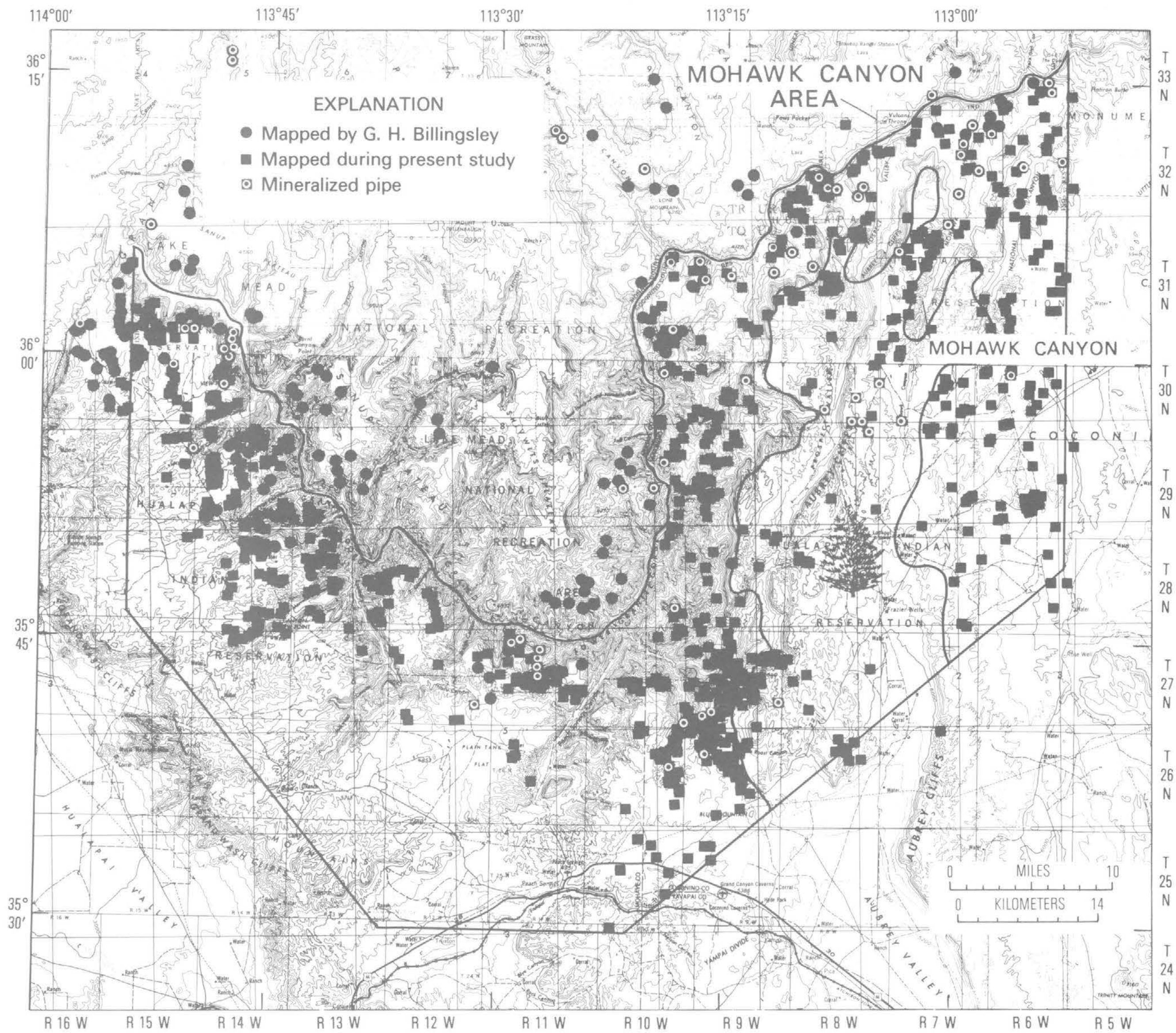


Figure 3. Map of the Hualapai Indian Reservation illustrating the density of solution-collapse features existing in northern Arizona made apparent when detailed geologic mapping is conducted. More than 900 confirmed and suspected breccia pipes have been mapped within and adjacent to the reservation. Vegetation is sparse on the western side of the reservation, which is reflected in the greater density of identified collapses. Outlined area with a tree symbol in the center on the eastern side of map area is densely tree covered, preventing recognition of most pipes. Solution-collapse features shown as black squares were mapped prior to the present study by G.H. Billingsley; solution-collapse features shown as black circles were mapped by the authors during the present study (1982 to 1988).

"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. Where the term "breccia pipe/collapse feature" is applied, either a collapse feature or a breccia pipe, or both, have been observed. 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 such a feature 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 altered rock 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).

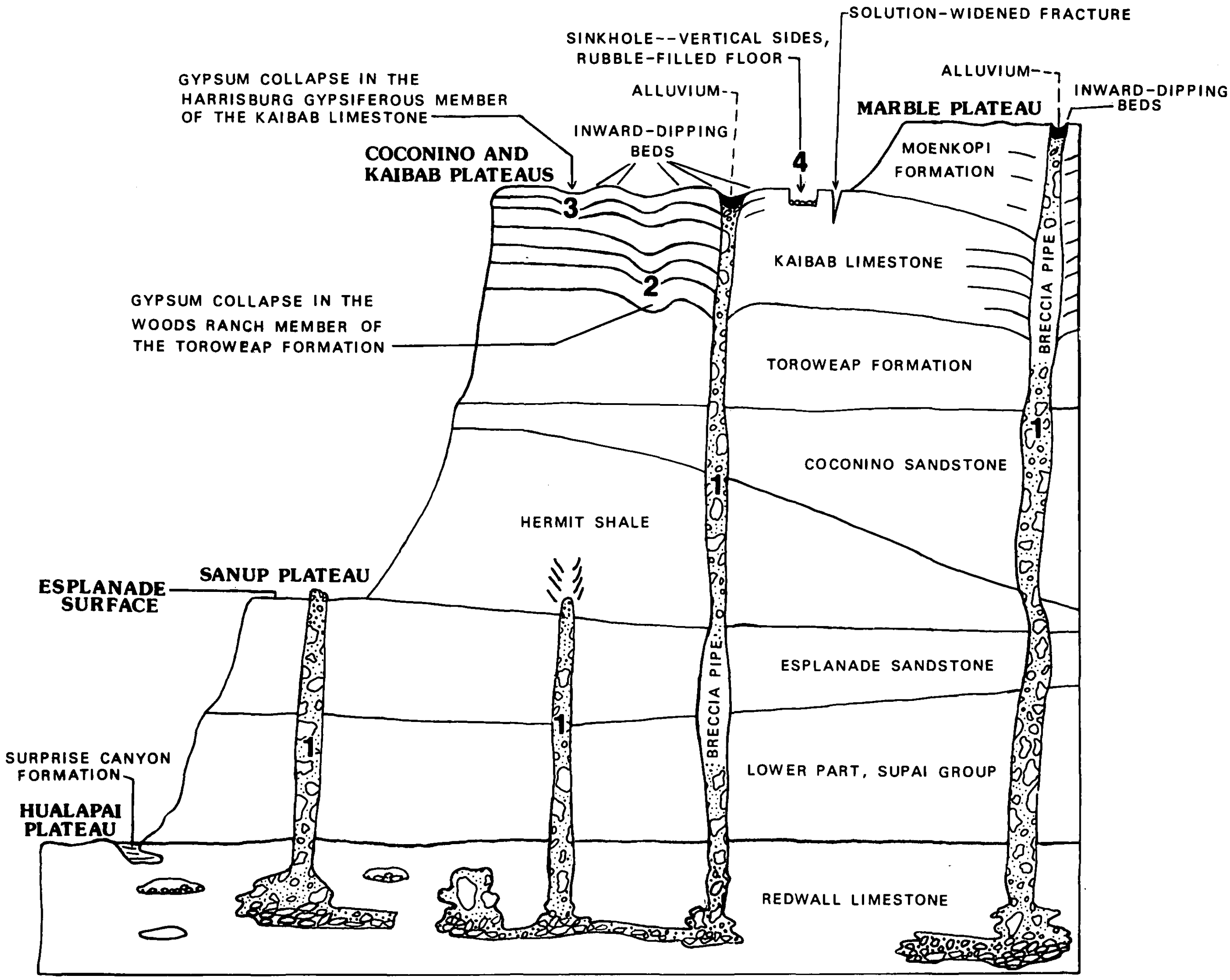


Figure 4. Types of solution-collapse features in northwestern Arizona. (1) breccia pipes that bottom in the Redwall Limestone; (2) collapse due to dissolution of gypsum beds in the Woods Ranch Member of the Toroweap Formation; (3) collapse due to dissolution of gypsum beds in the Harrisburg Gypsiferous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

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 pipe 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 (494, fig. 5) (Wenrich and others, 1988); here the entire 100 ft 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 (mine 13, 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 1 mi in diameter, and is about 1 mi north-northeast of Shadow Mountain (fig. 1), 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).

Thus, locating the actual breccia pipe, and perhaps an orebody, is more difficult in a Shadow Mountain-sized collapse 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 that 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 geologic mapping of the Hualapai Indian Reservation. Mapping began on 1:24,000-scale low-altitude color aerial photographs; pipes delineated on the photographs 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 actually 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 exposure in places 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 the area mapped as a solution collapse can be as much as five times 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 (fig. 3) is in the National Canyon 15-minute, the Vulcans Throne 7½-minute, and the Vulcans Throne SE 7½-minute quadrangles in the northeastern 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

Most of the collapse structures identified within this area are exposed along cliffs; this exposure provides sufficient outcrop in three dimensions so that many of these collapses 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 inward-dipping beds are the only guides to their recognition as collapses. All of the mapped collapse structures fall within three

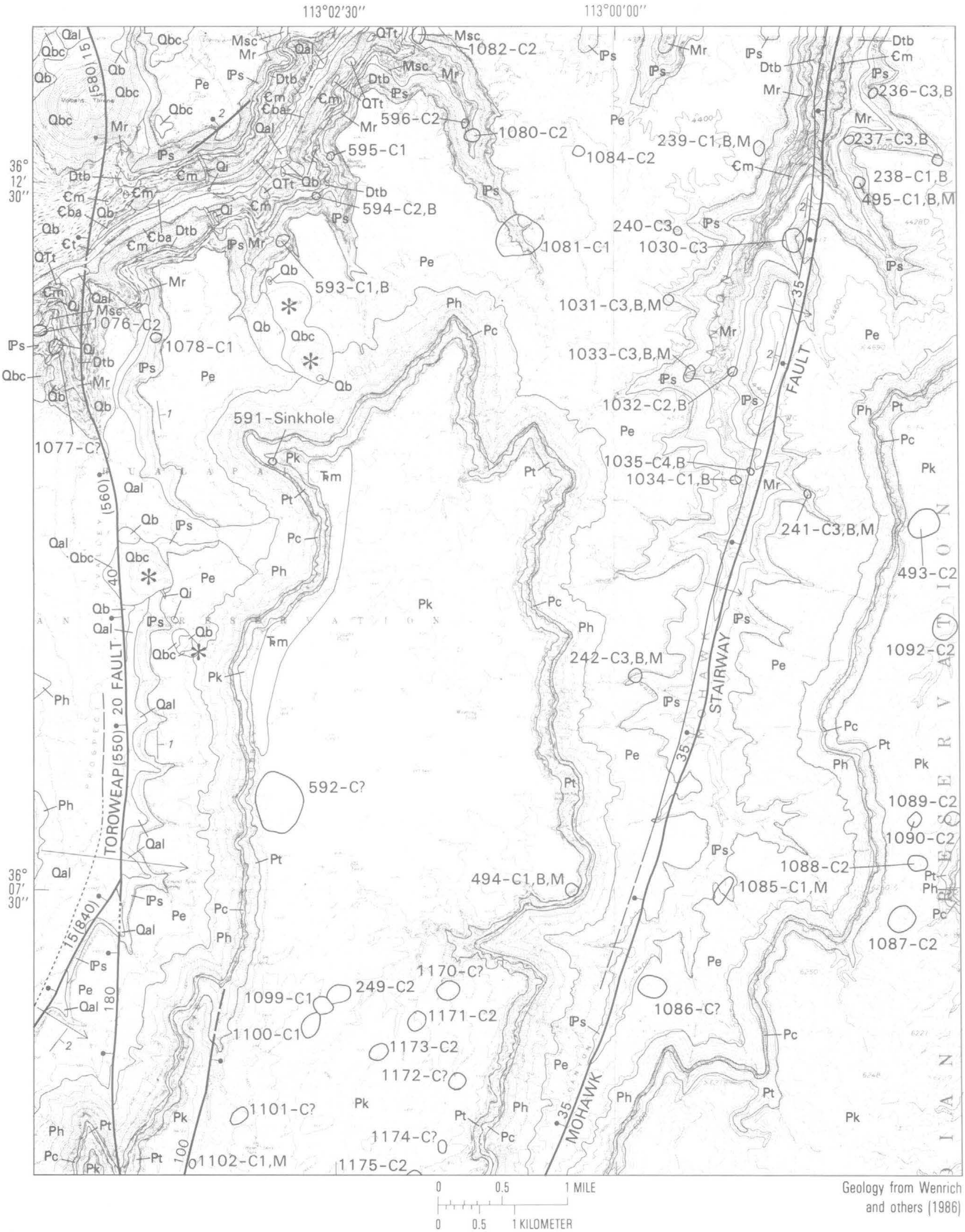


Figure 5 (above and two following pages). Geologic map of the Mohawk Canyon area, Hualapai Indian Reservation, showing breccia pipes and collapse features. This area is shown on the geologic and breccia pipe map of the northeastern Hualapai Indian Reservation by Wenrich and others (1986).

EXPLANATION

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 volcanic rocks (Pleistocene)**—Includes dikes, plugs, and sills

QTt — **Travertine (Pleistocene and Pliocene?)**—Includes local calcareous cemented talus commonly in and adjacent to travertine

SEDIMENTARY ROCKS

Ћm — **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; Harrisburg Gypsiferous Member consists of slope-forming gray and pale-red shale and gypsiferous siltstone interbedded with gray, ledge-forming limestone and dolomitic sandstone; Fossil Mountain Member consists of cliff-forming, yellowish-gray, cherty, fossiliferous limestone

Pt — **Toroweap Formation (Lower Permian)**—From top to bottom, includes Woods Ranch, Brady Canyon, and Seligman Members, undivided; Woods Ranch is pale-red and gray siltstone interbedded with gray to white gypsum, and forms a slope; 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 sand and forms a recess beneath the Brady Canyon cliff

Pc — **Coconino Sandstone (Lower Permian)**—Yellowish-white, fine-grained, cross-stratified sandstone. Forms prominent light-colored cliff

Unconformity

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 slope with ledges in upper part and a cliff or series of ledges in lower part. Unit unconformable with underlying Manakacha Formation. **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 cliff in lower part, slope and ledges in upper part. Unconformable with underlying Watahomigi Formation. **Watahomigi Formation:** Interbedded gray-purple calcareous shale and siltstone with gray limestone. Limestone contains bands of red and white chert. Forms 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 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 (Upper and Middle? Devonian)**—Interbedded light-gray to purple dolomite, dolomitic sandstone, sandy limestone, reddish-brown siltstone, and gray sandstone. Forms series of ledges and cliffs

Unconformity

Ꞓm — **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 series of alternating slopes and cliffs about 1,200 ft thick

Ꞓba — **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. Thickness about 400 ft

Ꞓt — **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, not fully exposed; estimated 200 ft thick

Contact

15(840) — **Fault**—Dashed where position uncertain; dotted where concealed; bar and ball on downthrown side; number shows approximate stratigraphic offset, in feet; number in parentheses shows estimated stratigraphic offset prior to Holocene deposits

Monocline—Line showing axis located approximately midway between top and bottom hinges of fold; dashed where position uncertain; dotted where concealed. Length of arrow indicates relative distance between hinges

*	**Volcanic vent**—Approximately located
595	**Outline of collapse feature**—Showing number used in text
2	**Strike and dip of beds**

Collapse-feature classification

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

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 on the Kaibab Limestone-capped plateau surface (19 features).

The collapse features in the Mohawk Canyon area were initially mapped on 1:24,000-scale color aerial photographs. These features were then field checked, and 46 of them were either confirmed as breccia pipes (breccia was observed in outcrop) or were considered to be at least collapse structures (possible breccia pipes) (table 1, fig. 5).

A photograph of each of 40 of the 46 mapped collapse features allows readers to make their own assessment of the potential for these collapse structures to be actual breccia pipes (figs. 6–26). Even poorly exposed collapse features are included so that readers can find the exact location of each collapse feature or breccia pipe described in this paper. Those features that are believed by the authors to have good potential to be breccia pipes are described in detail. Unfortunately, photographs were not available to illustrate all field observations that were considered important; nevertheless, a photograph of a collapse feature is commonly valuable to other geologists whose criteria might be different from those the authors used during this study.

Geochemical studies were completed on rock samples collected from breccia pipes that were categorized as mineralized. The concentrations of 55 elements (plus loss on ignition) were determined on each sample (table 2). These samples generally represent the high-grade material 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 to determine each element is shown in table 2, unless the method was not used on a sample; then the results from the next-best method are shown. For example, Au-HBR (hydrobromic acid digestion with atomic absorption) was only available for five samples, so ICP (inductively coupled argon plasma emission spectroscopy) results are listed for the other samples.

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

The 13 collapse features/breccia pipes within the Redwall Limestone are considered to have little or no economic potential, even though mineralized rock was observed at the surface in two of them. This judgment is based on the small possible thickness of potential host rock, which at most would not exceed 700 ft, and, more important, the Redwall is not known to contain U minerals. Uranium has not been mined from the Redwall in any breccia pipe, although other metals have been (most notably copper from the Grandview mine, fig. 1). For those pipes in this group that contain elevated gamma radiation, the anomalies are entirely restricted to downdropped sandstone blocks from the Surprise Canyon Formation or the lower part of the 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 (fig. 6), and 595 and 596 (no photographs available) are expressed as amphitheaters eroded back into the Redwall cliff and (or) the overlying Watahomigi Formation. The thirteenth, 1033, is subtly exposed in a gully. Six of these 13 structures are confirmed to be breccia pipes. Many of the remaining 7 collapse structures/pipes have little outcrop, and only after careful field work does it become apparent that what outcrop is present contains beds that tilt radially inward. In several of the 13 features, the basal part of the Watahomigi Formation dips radially inward toward the center of the amphitheater, and (or) is dropped down into the Redwall Limestone. Because the basal part of the Watahomigi Formation is composed of limestone in the Mohawk Canyon area, this unit is as unfavorable as the Redwall as a host for U mineralization. In contrast to these two limestone units, the organic-rich stream-channel deposits of the Mississippian Surprise Canyon Formation (Billingsley and Beus, 1985) (fig. 2) were good host rocks for U and copper mineralization, although only gamma radiation slightly in excess of six times background (150 cps (counts per second)) and minor

Table 1. Collapse features/breccia pipes mapped in the Mohawk Canyon area, Hualapai Indian Reservation.

Feature/ Pipe No.	Quadrangle	Section, Township, Range	Latitude and Longitude	Category[1]	Unit(s)[2]	Comments
236	National Canyon (15-minute).	None...............	36° 13' 09" 112° 57' 43"	C3, B...	Esplanade, lower Supai.	Beds down hillslope within pipe dip 28° N.; conglomeratic breccia; bleached center and limonite alteration; massive calcite.
237	National Canyon (15-minute).	None...............	36° 12' 47" 112° 57' 52"	C3, B...	Lower Supai...	Bleached; conglomeratic breccia.
238	National Canyon (15-minute).	None...............	36° 12' 40" 112° 57' 06"	C1, B...	Esplanade, lower Supai.	Distinct circular topographic shape; no dipping beds.
239	National Canyon (15-minute).	None...............	36° 12' 43" 112° 13' 32"	C1, B, M	Esplanade.....	Pink- and yellow-stained breccia.
240	National Canyon (15-minute).	None...............	36° 12' 09" 112° 59' 28"	C3......	Esplanade.....	Sharp contact between bleached and unbleached rock; well-developed concentric jointing.
241	National Canyon (15-minute).	Section 7, T. 32 N., R. 6 W.	36° 10' 15" 112° 58' 12"	C3, B, M	Lower Supai...	Two tall pinnacles of breccia surrounded at their base by breccia with more rounded clasts, downdropped in an amphitheater. Goethite nodules with malachite rims in breccia.
242	National Canyon (15-minute).	Section 23, T. 32 N., R. 7 W.	36° 09' 01" 112° 59' 56"	C3, B, M	Esplanade, lower Supai.	Brecciated sandstone with pyrite-bearing siderite concretions.
249	Vulcans Throne SE (7 1/2 -minute).	Section 33, T. 32 N., R. 7 W.	36° 06' 46" 113° 02' 25"	C2......	Kaibab........	Concentric bands of outcropping Kaibab Limestone; distinct 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. 32 N., R. 6 W.	36° 10' 04" 112° 57' 18"	C2......	Kaibab........	Central hill with inward-dipping (60°) beds of Moenkopi Formation(?); concentric depression around 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	Vulcans Throne and Vulcans Throne SE (7 1/2 -minute).	Section 26, T. 32 N., R. 7 W.	36° 07' 30" 113° 00' 24"	C1, B, M	Kaibab........	Drilled by U.S. Geological Survey in 1984 (Wenrich and others, 1988); U and Cu minerals present; 19th-century Cu prospect. Concentric ring fractures with semicircular drainage eroded along one inner ring fracture. Limonite pseudomorphs and molds after pyrite. Concentric radially inward dipping beds.
495	National Canyon (15-minute).	None...............	36° 12' 30" 112° 57' 57"	C1, B, M	Lower Supai...	Dipping beds; bleached; limestone breccia clasts; limonite; hematite.
592	Vulcans Throne (7 1/2 -minute).	Section 29, T. 32 N., R. 7 W.	36° 08' 08" 113° 02' 59"	C?......	Kaibab........	Dipping beds that may be a collapse into the Toroweap Formation gypsum; pale-reddish-orange, crossbedded sandstone (Moenkopi Formation?). Largest collapse feature in the Mohawk Canyon area.

Table 1. Collapse features/breccia pipes mapped in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

Feature/ Pipe No.	Quadrangle	Section, Township, Range	Latitude and Longitude	Category[1]	Unit(s)[2]	Comments
593	Vulcans Throne (7 1/2 -minute).	None..............	36° 12' 06" 113° 02' 54"	C1, B...	Lower Supai, Redwall.	Amphitheater shaped; dipping beds; limonite stains in medium-grained sandstone.
594	Vulcans Throne (7 1/2 -minute).	None..............	36° 12' 25" 113° 02' 39"	C2, B...	Redwall......	Steeply dipping beds; cave in limonite-stained Redwall directly below pipe.
595	Vulcans Throne (7 1/2 -minute).	None..............	36° 12' 42" 113° 02' 30"	C1......	Lower Supai, Redwall.	Dipping beds; oxidized and bleached; some very small limonite-stained spots in the Supai Group.
596	Vulcans Throne (7 1/2 -minute).	None..............	36° 12' 55" 113° 01' 18"	C2......	Lower Supai, Redwall.	Dipping beds? Drainage widens here.
1030	National Canyon (7 1/2 -minute).	None..............	36° 12' 07" 112° 58' 27"	C3......	Esplanade, lower Supai, Surprise Canyon, Redwall.	Amphitheater in the Redwall Limestone with Surprise Canyon Formation sediments and one limonite-rich patch exposed.
1031	National Canyon (15-minute).	None..............	36° 11' 52" 112° 14' 20"	C3, B, M	Esplanade, Watahomigi.	Entirely covered with alluvium except for small gully with limonite-stained soil and breccia; breccia contains goethite and pyrite concretions. Entire gully has anomalous gamma radioactivity.
1032	National Canyon (15-minute).	None..............	36° 11' 09" 112° 58' 59"	C2, B...	Lower Supai, Redwall.	Amphitheater with Horseshoe Mesa Member of the Redwall Limestone strata dropped down into Mooney Falls Member of Redwall Limestone. Small breccia outcrop in center of amphitheater; minor dip to bedding.
1033	National Canyon (15-minute).	None..............	36° 11' 08" 112° 59' 19"	C3, B, M	Lower Supai, Redwall.	Limonite and hematite in side of gully; brecciated Horseshoe Mesa Member of Redwall Limestone; Surprise Canyon Formation on top.
1034	National Canyon (15-minute).	Section 12, T. 32 N., R. 7 W.	36° 10' 23" 112° 58' 56"	C1, B...	Lower Supai, Redwall.	Very slightly dipping beds; limonite-stained breccia of Horseshoe Mesa Member dropped into Mooney Falls Member.
1035	National Canyon (15-minute).	Section 12, T. 32 N., R. 7 W.	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	Vulcans Throne (7 1/2 -minute).	None..............	36° 11' 27" 113° 05' 02"	C2......	Lower Supai, Surprise Canyon, Redwall.	Horseshoe Mesa Member barely dipping back into hillslope; Surprise Canyon Formation dipping inward.
1077	Vulcans Throne (7 1/2 -minute).	None..............	36° 11' 19" 113° 04' 55"	C?......	Lower Supai, Redwall.	Altered and brecciated, possibly related to lava in the area.
1078	Vulcans Throne (7 1/2 -minute).	None..............	36° 11' 24" 113° 04'02"	C1......	Lower Supai..	One bleached bed of Wescogame Formation with a very slight dip observed.

Table 1. Collapse features/breccia pipes mapped in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

Feature/ Pipe No.	Quadrangle	Section, Township, Range	Latitude and Longitude	Category[1]	Unit(s)[2]	Comments
1080	Vulcans Throne (7 1/2-minute).	None..............	36° 12' 50" 113° 01' 16"	C2......	Lower Supai, Redwall.....	Dipping beds of Redwall Limestone; lobe of travertine dips into gully.
1081	Vulcans Throne (7 1/2-minute).	None..............	36° 12' 07" 113° 00' 54"	C1......	Esplanade, lower Supai.	Very large collapse feature (second largest in Mohawk Canyon area), on plateau surface and spanning gully; very bleached, dipping beds.
1082	Vulcans Throne (7 1/2-minute).	None..............	36° 13' 34" 113° 01' 42"	C2......	Lower Supai, Surprise Canyon, Redwall.....	Beds of Horseshoe Mesa Member of Redwall Limestone and Surprise Canyon Formation dip into an amphitheater.
1084	Vulcans Throne (7 1/2-minute).	None..............	36° 12' 43" 113° 00' 18"	C2......	Esplanade.....	Beds consistently dipping into a closed basin.
1085	National Canyon (15-minute).	Section 25, T. 32 N., R. 7 W.	36° 07' 30" 112° 13' 57"	C1, M...	Esplanade, lower Supai.	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. 32 N., R. 7 W.	36° 06' 49" 112° 59' 41"	C?......	Esplanade.....	Circular drainage around hill; some bleaching. No obvious dipping of beds.
1087	National Canyon (15-minute).	Section 31, T. 32 N., R. 6 W.	36° 07' 17" 112° 57' 30"	C2......	Kaibab........	Beds of Harrisburg Member dipping moderately to steeply into gully.
1088	National Canyon (15-minute).	Section 29, T. 32 N., R. 6 W.	36° 07' 41" 112° 57' 18"	C2......	Kaibab........	Dipping beds all around the feature in Harrisburg Member; Fe-stained chert.
1089	National Canyon (15-minute).	Section 29, T. 32 N., R. 6 W.	36° 08' 00" 112° 57' 01"	C2......	Kaibab........	Dipping beds in Harrisburg Member.
1090	National Canyon (15-minute).	Section 29, T. 32 N., R. 6 W.	36° 08' 01" 112° 57' 24"	C2......	Kaibab........	Dipping beds in Harrisburg Member; no outcrop on three sides.
1092	National Canyon (15-minute).	Section 17, T. 32 N., R. 6 W.	36° 09' 21" 112° 57' 08"	C2......	Kaibab........	Very slight bowl at top of Harrisburg Member; on cliffs below collapse, Woods Ranch Member of Toroweap Formation is largely dissolved away.
1099	Vulcans Throne SE (7 1/2-minute).	Section 33, T. 32 N., R. 7 W.	36° 06' 41" 113° 02' 35"	C1......	Kaibab........	In chert of Harrisburg Member; dipping beds; abundant limonite and hematite stains on exposed outcrop and float.
1100	Vulcans Throne SE (7 1/2-minute).	Section 33, T. 32 N., R. 7 W.	36° 06' 33" 113° 02' 40"	C1......	Kaibab........	Dipping Harrisburg Member beds; limonite stains on chert.
1101	Vulcans Throne SE (7 1/2-minute).	Section 5, T. 31 N., R. 7 W.	36° 05' 54" 113° 03' 19"	C?......	Kaibab........	Dipping Harrisburg Member beds on one side of circular hill.

Table 1. Collapse features/breccia pipes mapped in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

Feature/ Pipe No.	Quadrangle	Section, Township, Range	Latitude and Longitude	Category[1]	Unit(s)[2]	Comments
1102	Vulcans Throne SE (7 1/2-minute).	Section 8, T. 31 N., R. 7 W.	36° 05' 35" 113° 03' 40"	C1, M....	Kaibab........	Beds dipping consistently around a gully; outcrops of dark-orange Fe-rich gossan with radioactivity of 18 times background level (550 counts per second); a possible drilling target for U ore in the Harrisburg Member.
1170	Vulcans Throne SE (7 1/2-minute).	Section 34, T. 32 N., R. 7 W.	36° 06' 47" 113° 01' 29"	C?.......	Kaibab........	Harrisburg Member beds dip into stream meander on one side of pipe.
1171	Vulcans Throne SE (7 1/2-minute).	Section 33, T. 32 N., R. 7 W.	36° 06' 34" 113° 01' 45"	C2.......	Kaibab........	Concentric Harrisburg Member strata dip radially inward.
1172	Vulcans Throne SE (7 1/2-minute).	Section 3, T. 31 N., R. 7 W.	36° 06' 03" 113° 01' 23"	C?.......	Kaibab........	Harrisburg Member beds dip down hillslope on one side of pipe.
1173	Vulcans Throne SE (7 1/2-minute).	Section 4, T. 31 N., R. 7 W.	36° 06' 14" 113° 02' 05"	C2.......	Kaibab........	Concentric Harrisburg Member strata dip radially inward. Goethite cubes are pseudomorphous after pyrite.
1174	Vulcans Throne SE (7 1/2-minute).	Section 3, T. 31 N., R. 7 W.	36° 05' 42" 113° 01' 31"	C?.......	Kaibab........	Slightly inward dipping beds of Harrisburg Member on two sides of pipe.
1175	Vulcans Throne SE (7 1/2-minute).	Section 9, T. 31 N., R. 7 W.	36° 05' 33" 113° 01' 47"	C2.......	Kaibab........	Harrisburg Member beds dip inward, forming a basin.

[1] Refer to "COLLAPSE FEATURE CLASSIFICATION" in figure 5.
[2] Geologic unit or units in which collapse feature/breccia pipe crops out.

Table 2. Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area, Hualapai Indian Reservation.

[The first three or four digits of the sample number, preceding the dash, are the pipe number shown in table 1.]

Sample No.	Latitude	Longitude	Ag ppm ICP	Al_2O_3% XRF	As ppm AA	Au ppm HBR	Ba ppm ICP	Be ppm ICP	Total C% CID	Total organic 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

- Not determined
* ICP data
** Total organic C% calculated by (total C%)-(total C% as CO_3)
† INAA data
†† LOI-900= loss on ignition at 900°C
§ DN data
ICP = inductively coupled argon plasma emission spectroscopy
XRF = X-ray fluorescence
AA = atomic absorption
HBR = sample digested in hydrobromic acid and bromine and analyzed using AA
CID = combustion with infrared detection
CT = coulometric titration
INAA = induced neutron activation analysis
ISE = ion selective electrode
DN = delayed neutron activation analysis

Table 2. Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

[The first three or four digits of the sample number, preceding the dash, are the pipe number shown in table 1]

Sample No.	Total C% as CO_3 CT	CaO% XRF	Cd ppm ICP	Ce ppm ICP	Co ppm ICP	Cr ppm ICP	Cs ppm AA	Cu ppm ICP	Dy ppm ICP	Er ppm 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	-	-

Table 2. Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

[The first three or four digits of the sample number, preceding the dash, are the pipe number shown in table 1]

Sample No.	Eu ppm ICP	F% ISE	$T\text{-}Fe_2O_3$%[1] XRF	Ga ppm ICP	Gd ppm ICP	Hf ppm INAA	Hg ppm AA	K_2O% XRF	LOI-900††	La ppm 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

2 [1] $T\text{-}Fe_2O_3$ = Total iron reported as Fe_2O_3

Table 2. Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

[The first three or four digits of the sample number, preceding the dash, are the pipe number shown in table 1]

Sample No.	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

Table 2. Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

[The first three or four digits of the sample number, preceding the dash, are the pipe number shown in table 1]

Sample No.	Pb ppm ICP	Rb ppm AA	Total-S% CID	Sb ppm INAA	Sc ppm ICP	Se ppm AA	SiO_2% XRF	Sm ppm ICP	Sr ppm ICP	Ta ppm 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

Table 2. Chemical analyses of rock samples collected from collapse structures in the Mohawk Canyon area, Hualapai Indian Reservation—Continued.

[The first three or four digits of the sample number, preceding the dash, are the pipe number shown in table 1]

Sample No.	Tb ppm ICP	Th ppm INAA	Ti% ICP	Tm ppm INAA	U ppm DN	V ppm ICP	Y ppm ICP	Yb ppm ICP	Zn ppm AA	Zr ppm 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	-

malachite have been observed. Nevertheless, this radioactivity level is in sharp contrast to that of the Redwall Limestone, which has not been observed during any study by the authors to be greater than 20 cps. Strata of the Surprise Canyon Formation have collapsed into at least 3 of these 13 collapse features (fig. 6). It is interesting to note that throughout the Hualapai Indian Reservation a 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. Only one of the 13 Redwall breccia pipes was categorized as "mineralized" ("M" in table 1), although a limonite-stained, weathered sandstone from the lower part of the Supai Group in pipe 593 (fig. 6A) did emit gamma radiation equal to two times background. A chemical analysis of this material (sample 593–A–C83, table 2) shows anomalous concentrations of Ag (21 ppm), As (5,800 ppm), Co (39 ppm), Cu (380 ppm), Fe_2O_3 (64%), Hg (0.17 ppm), Ni (92 ppm), U (15 ppm), V (2,400 ppm), and Zn (110 ppm). These are all elements that are commonly anomalous within mineralized breccia pipes.

Within this group of 13 collapse features/breccia pipes exposed in the Redwall Limestone, one breccia pipe—1033—was mineralized by sufficient U to show radioactivity of more than 2.5 times background on the surface. Pipe 1033 is mostly covered by alluvium, in that the only rock exposure is a minor limonite-stained outcrop located in a gully (fig. 7*A*). 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 exceeded four-times background level; Liesegang bands are also prevalent in this outcrop (fig. 7*B*). Geochemical analysis of this sandstone (sample 1033-A-C85, table 2) shows anomalous amounts of As (1,900 ppm), Co, Cu, Hg, Ni, V, and Zn.

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

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

Mineralized rock exposed at the surface, as in 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 Cu minerals have oxidized, and Cu presently occurs in malachite, azurite, and brochantite. The pyrite has oxidized to goethite, which commonly occurs as 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/breccia pipes are discussed below in order of increasing U potential.

1078, 1086.—These features (fig. 9) have few of the recognition criteria for collapse-feature identification, and hence have low potential as mineralized breccia pipes. They have bleached sandstone, and feature 1078 has some minor inward dip to the beds.

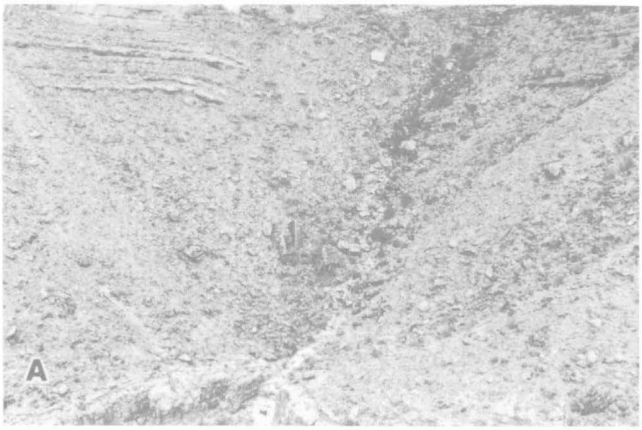
1084.—Although this collapse structure (fig. 10) in the uppermost Esplanade Sandstone has no exposed breccia, or altered or mineralized rock, it forms a completely closed basin with concentrically inward-dipping beds. Surface radioactivity was slightly elevated (1.5 times background).

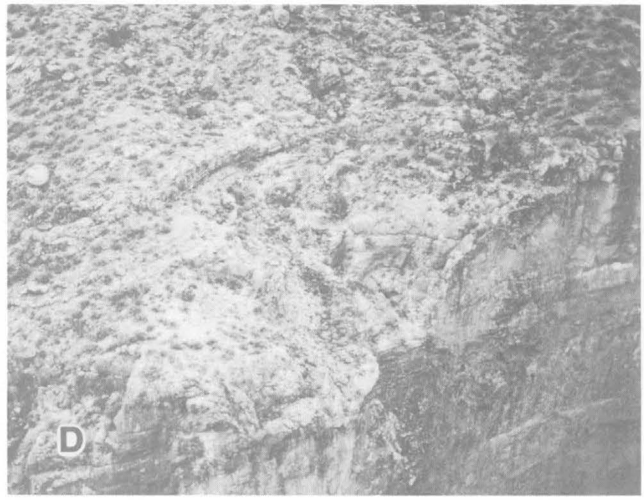
1081.—This collapse is relatively large with extensive bleaching of the Esplanade Sandstone (fig. 11). The beds dip inward toward the canyon from all sides; there is no breccia, anomalous radioactivity, or any evidence of mineralized rock.

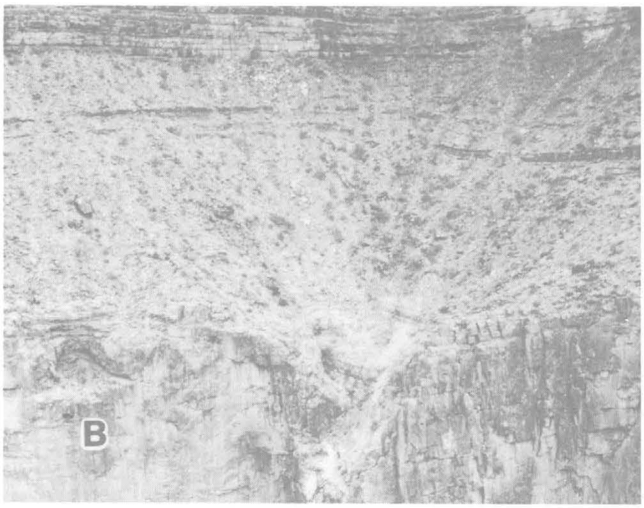
240.—Only the bleaching of the Esplanade Sandstone and concentric fractures delineate this collapse (fig. 12). There is a sharp contact between the bleached and unbleached sandstone, but the most striking feature of this collapse is the concentric jointing, which bounds the collapse on the northeast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

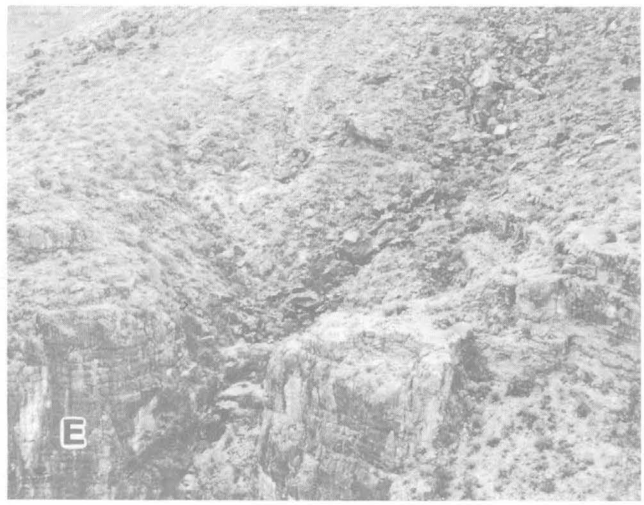
1085.—This collapse is a large structure (fig. 13) located within the exposed top and base of the Wescogame Formation. The Esplanade Sandstone is bleached, and some pale-yellow limonite staining occurs in a Wescogame limestone bed. This unit emitted a maximum gamma radiation of three times background. Geochemical analysis of a sample from this anomalous area (sample 1085–A–C85, table 2) shows essentially no enrichment of any of the metals commonly found in breccia pipes, except for minor enrichment in Zn (120 ppm).

239.—This breccia pipe (fig. 14) can be identified along the slopes of the Supai Group formations through its bleached rock with minor tilting of beds, and the small mass of breccia exposed a short distance above the Redwall cliff. The breccia is stained pink and yellow by hematite and limonite alteration. Geochemical analysis of a sample









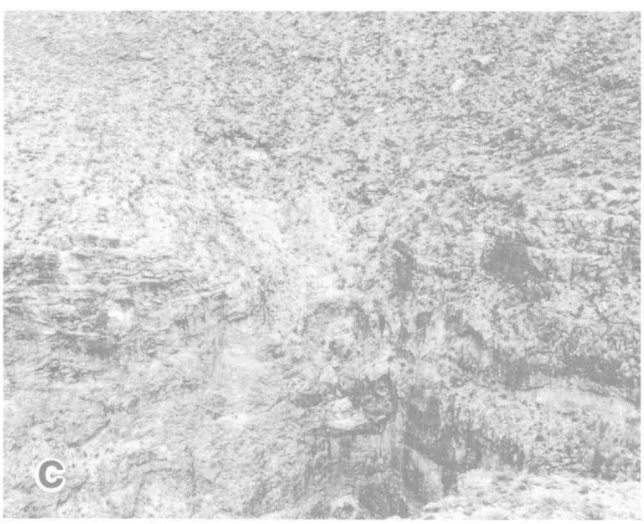
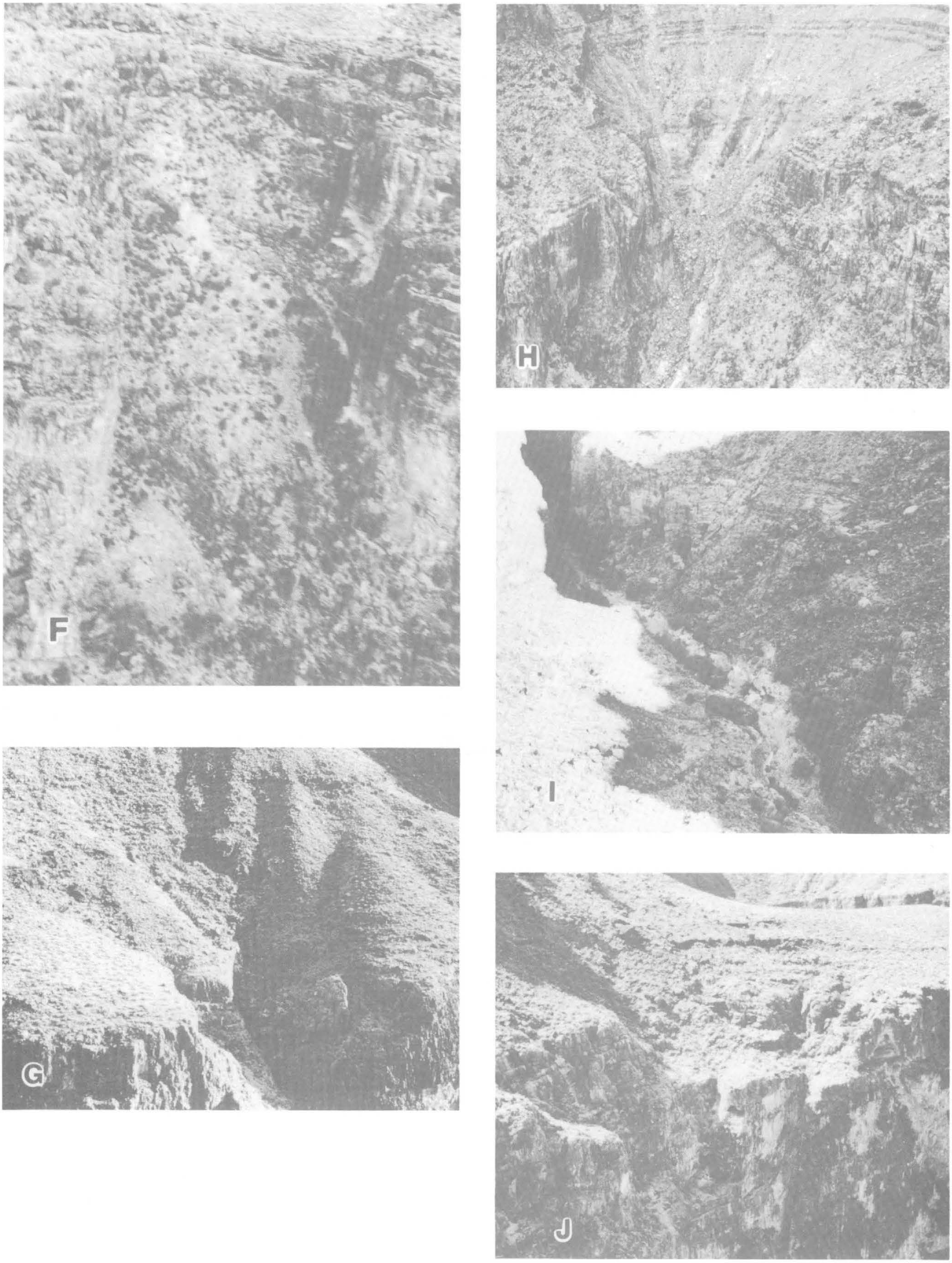


Figure 6 (above and following page). The amphitheater style of erosion of breccia pipes/collapse features exposed along the top of the Redwall Limestone cliff, Hualapai Indian Reservation. Pipe and feature localities are shown in figure 5. A, Breccia pipe 593; view is about 600 ft wide. B, Breccia pipe 594; view is about 700 ft wide. C, Collapse feature 1030; view is about 700 ft wide. D, Breccia pipe 1032; view is about 600 ft wide. E, Breccia pipe 1034; view is about 700 ft wide. F, Breccia pipe 1035; view is about 400 ft wide. G, Collapse feature 1076; view is about 600 ft wide. H, Collapse feature 1077; view is about 1,000 ft wide. I, Collapse feature 1080; view is about 700 ft wide. J, Collapse feature 1082; view is about 900 ft wide.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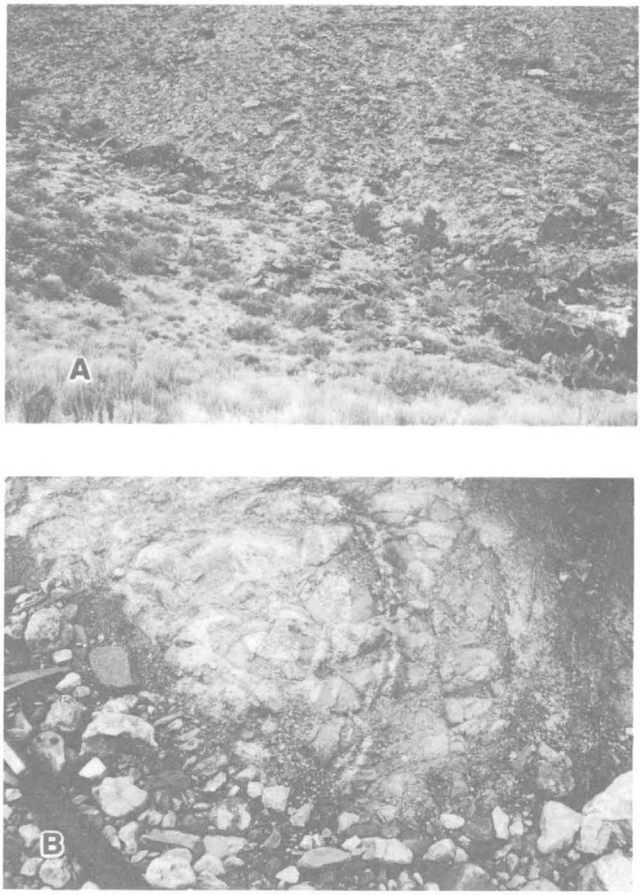


Figure 7. A, Breccia pipe 1033 can be recognized as a pipe only by limonite-stained, brecciated outcrops in a gully of Surprise Canyon Formation and Horseshoe Mesa Member of the Redwall Limestone, Hualapai Indian Reservation. View is about 500 ft wide. B, Liesegang-banded and brecciated outcrop of Surprise Canyon Formation in breccia pipe 1033.

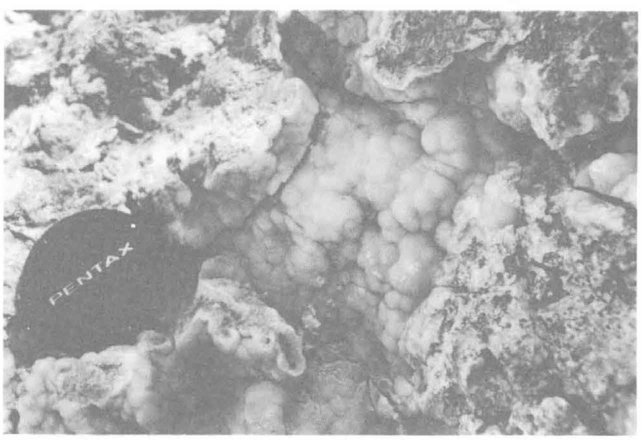


Figure 8. Hemimorphite, such as this botryoidal mass, commonly forms from surface weathering of primary sphalerite when a breccia-pipe orebody is exposed to oxidation by canyon erosion, Hualapai Indian Reservation.

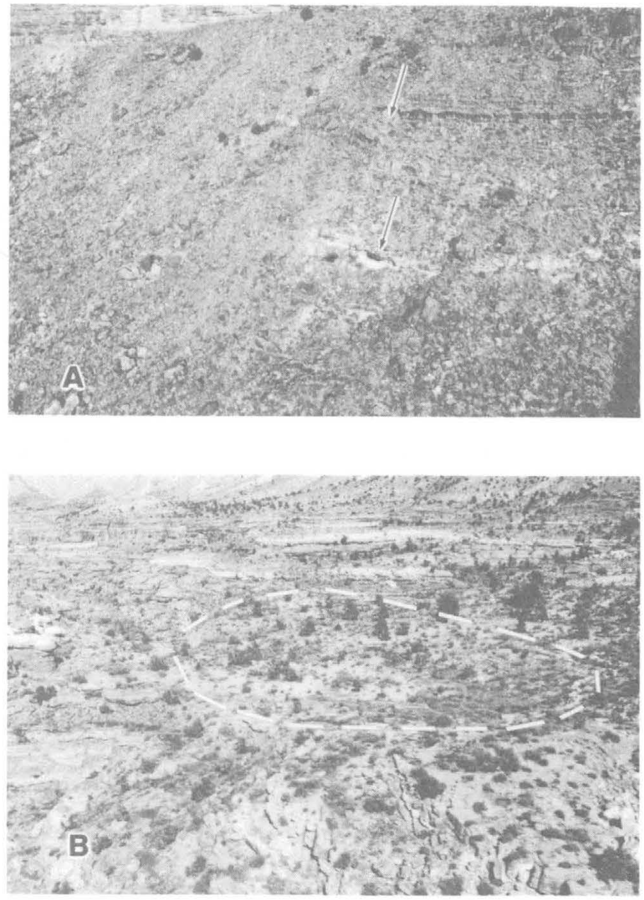


Figure 9. A, Collapse feature 1078 contains some bleached rocks and minor inward dip (arrows) of several beds of Wescogame Formation, Hualapai Indian Reservation. View is about 800 ft wide. B, Collapse feature 1086 (dashed line) lies in the Esplanade Sandstone. The only evidence of a possible collapse is the bleached Esplanade and a circular gully around a hill. Collapse as outlined is about 700 ft long.

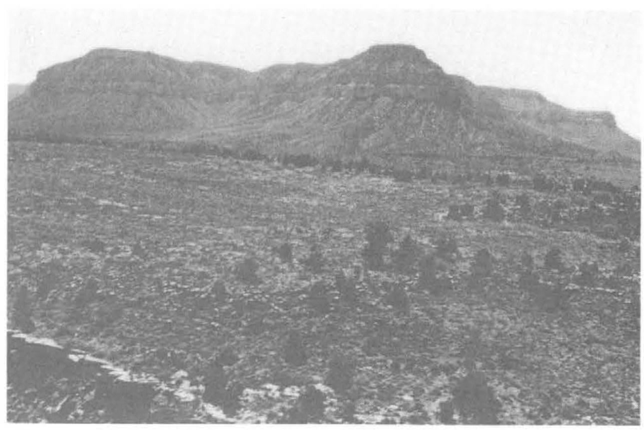


Figure 10. Collapse feature 1084 forms essentially a closed basin with concentrically inward-dipping beds of Esplanade Sandstone. Collapse occupies most of the foreground in this photograph. View is about 400 ft wide.

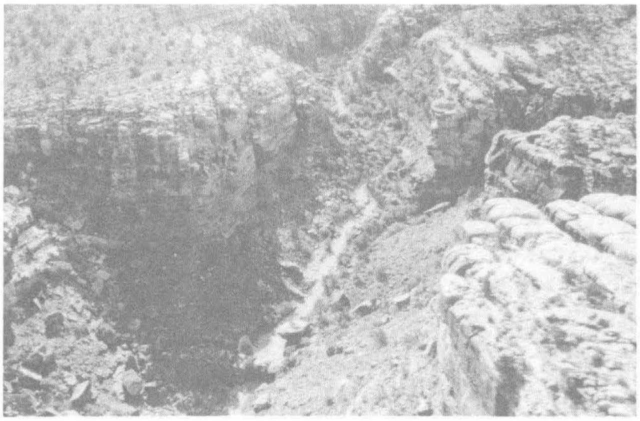


Figure 11. Collapse feature 1081, Hualapai Indian Reservation, is relatively large with extensive bleaching of the Esplanade Sandstone (note the bleached Esplanade on all sides of the widened gully; collapse occupies the entire field of view). View is about 700 ft wide.

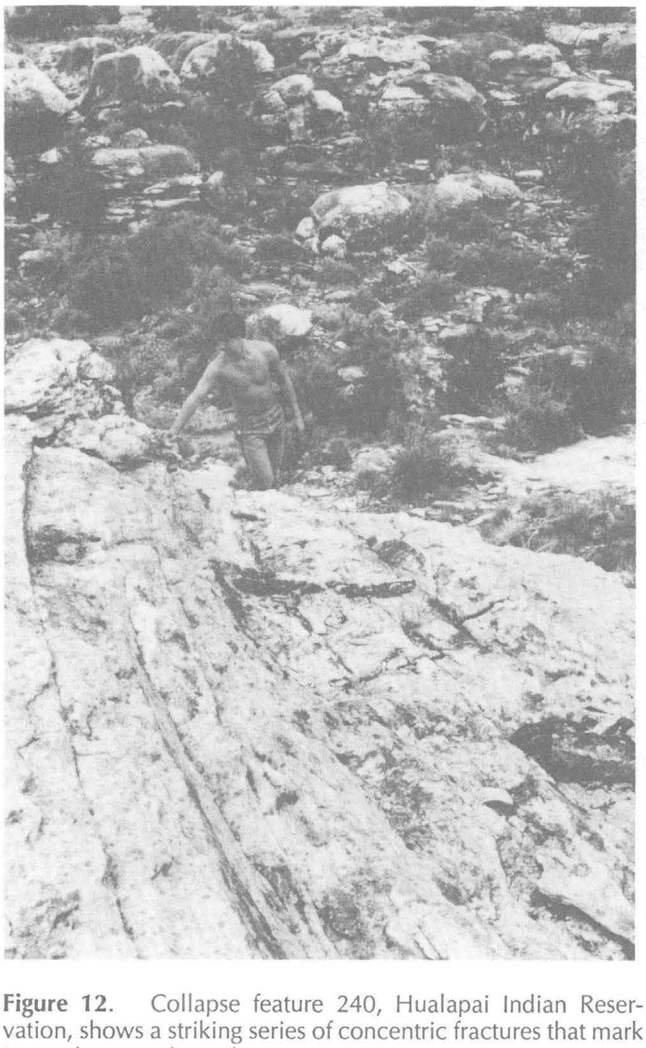


Figure 12. Collapse feature 240, Hualapai Indian Reservation, shows a striking series of concentric fractures that mark its northeastern boundary.

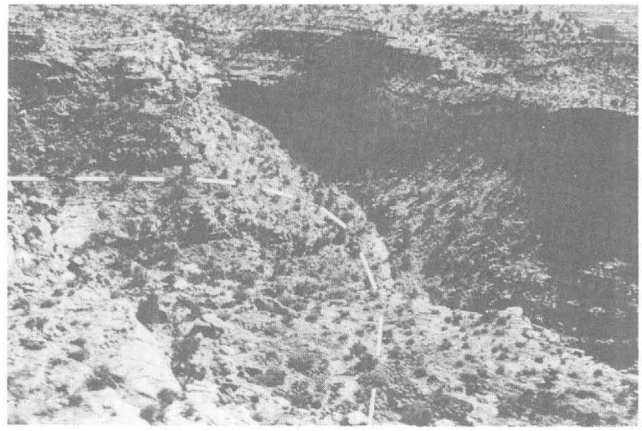


Figure 13. Collapse feature 1085 (dashed line), Hualapai Indian Reservation, was identified by bleached Esplanade Sandstone and limonite staining in the Wescogame Formation. View is about 700 ft wide.

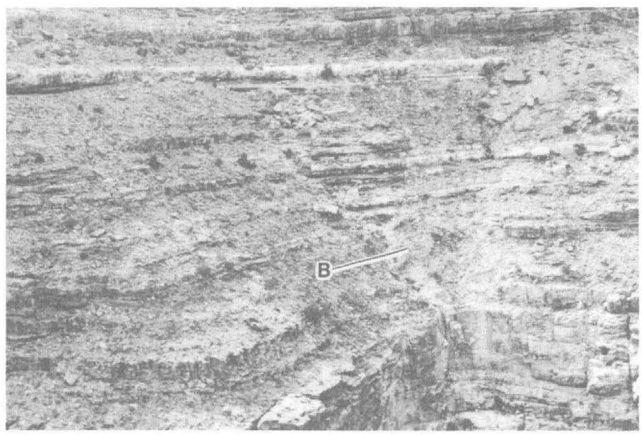


Figure 14. Breccia pipe 239, Hualapai Indian Reservation, has a small mass of breccia (B). View is about 1,000 ft wide.

(239–A–C83, table 2) of fine- to medium-grained sandstone emitting gamma radiation of five 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 Redwall collapse feature 593 (sample 593-A-C83, table 2).

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. Geochemical analysis of a sample (495–A–C83, table 2) that was three times background in surface radioactivity shows significantly anomalous concentrations of As (3,300 ppm), Cr (140 ppm), Hg

Figure 15. Breccia pipe 495, Hualapai Indian Reservation, is expressed on the surface as bleached rock in a slight recess of the hillslope (initial stages of formation of an amphitheater along the pipe ring-fracture zone). Pipe as outlined is about 500 ft long.

(0.25 ppm), and V (130 ppm). Despite the anomalous surface radioactivity, the U concentration in this sample was only 4 ppm.

236.—This breccia pipe (fig. 16) is easily located by its well-defined surface expression; the breccia pipe sits within an eroded amphitheater of Esplanade Sandstone. The center of the pipe is bleached and in places stained yellow by limonite. Massive calcite is abundant throughout the breccia that appears conglomeratic (pipe 241 (fig. 21) has similar breccia). No anomalous radioactivity or mineralized rock was observed.

237.—This breccia pipe (fig. 17) is essentially identical to pipe 236 in morphology, stratigraphic horizon, alteration, and breccia. Although no anomalous radioactivity was detected, geochemical analysis of a limonite- and hematite-stained sandstone (sample 237–A–C82, table 2) shows anomalous amounts of As (4,700 ppm), Cu (140 ppm), Fe_2O_3 (12%), Pb (60 ppm), and Se (20 ppm).

1031.—Alluvium extensively covers this breccia pipe (fig. 18) 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 eight times background and contains goethite concretions with unaltered pyrite cores. In places, despite the intense

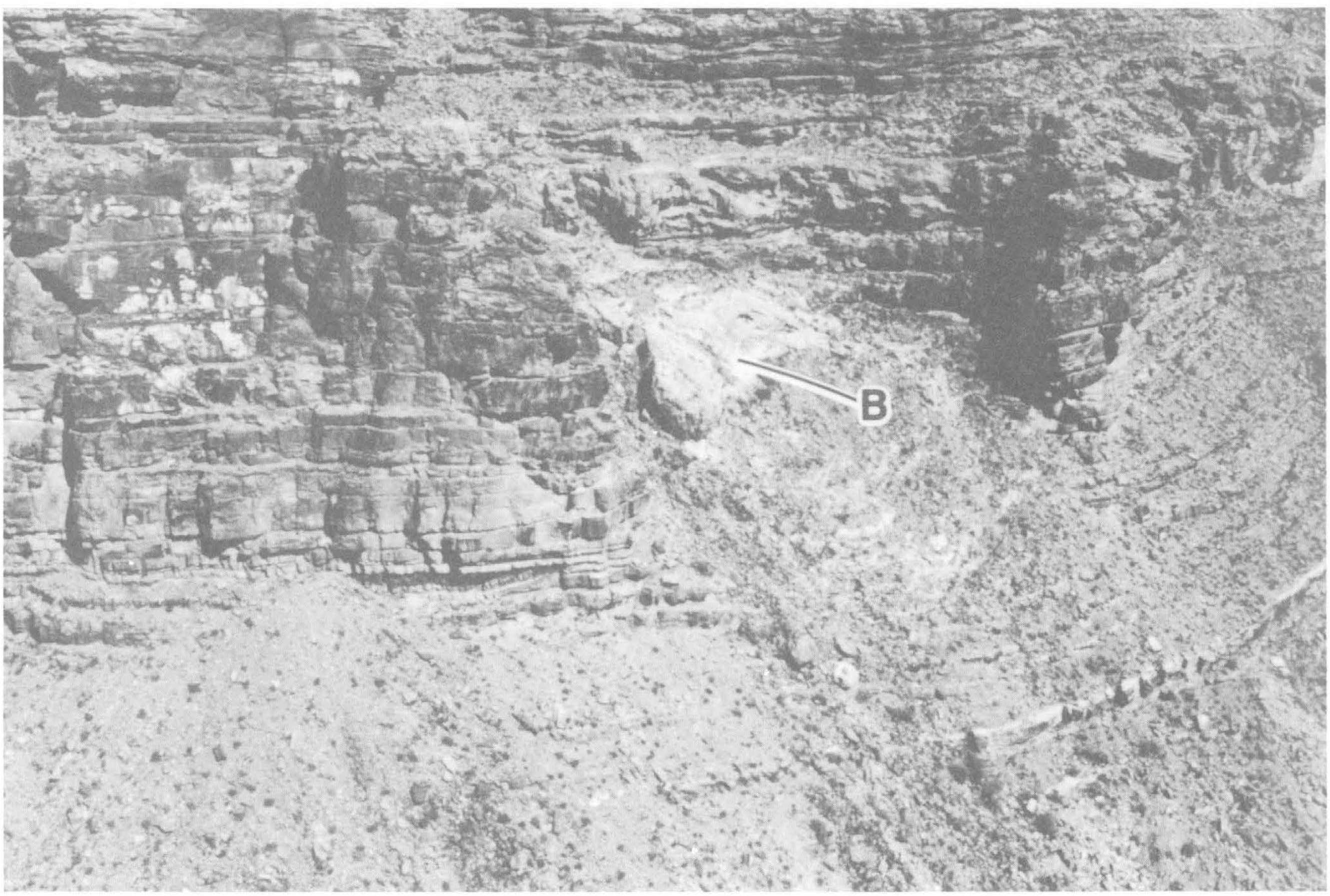


Figure 16. Breccia pipe 236, Hualapai Indian Reservation, has the ideal pipe morphology: a plug of breccia (B) within an amphitheater that has eroded along the ring fracture of the breccia pipe. The plug of breccia is about 200 ft wide.

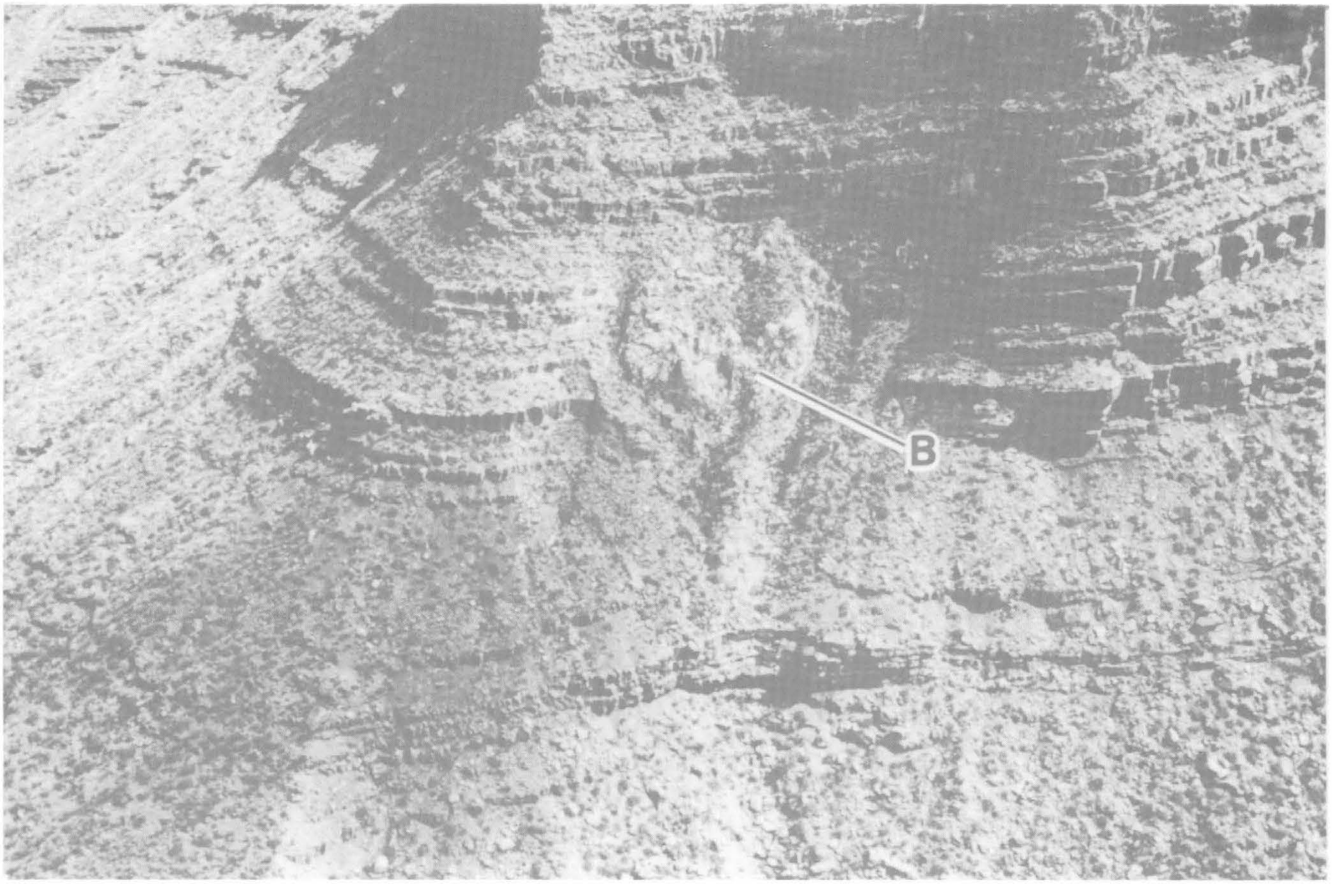


Figure 17. Breccia pipe 237, Hualapai Indian Reservation, is similar to 236 in morphology, stratigraphy, alteration, and breccia (B). Also, it lies directly across from pipe 236 on the opposite side of a tributary canyon to Mohawk Canyon. The mass of breccia is about 250 ft wide.

weathering of the pipe, pyrite was exposed on the surface of the outcrop. Two samples containing goethite and pyrite, and emitting anomalous gamma counts, were geochemically analyzed (samples 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 (fig. 19) is expressed on the surface as a bleached amphitheater of Esplanade Sandstone. The bleached-unbleached rock contact is sharp. Concentric joints encircle the amphitheater, marking the pipe boundary where they die out. Brecciated rock (fig. 19B) lies on 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 anomalous amounts of few elements except for Ba (1,100 ppm), Cu (180 ppm), and Pb (67 ppm).

242.—This breccia pipe (fig. 20) is one of the two most interesting found in the Esplanade Sandstone in the Mohawk Canyon area. The breccia column is 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 (11 and 3 ppm), As (6,800 and 2,800 ppm), Cu (460 and 70 ppm), Fe_2O_3 (57 and 36%), Hg (0.47 and 0.49 ppm), Mo (140 ppm), Pb (130 and 40 ppm), Se (89 and 15 ppm), and U (34 ppm).

241.—This breccia pipe (fig. 21) is the most interesting of the Mohawk Canyon area collapse features 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 Indian Reservation and previously drilled by Western Nuclear in the 1970's. Except for the Orphan mine, none of the other U-producing breccia pipes have had exposures of silicified breccia. Such exposures subject the pipes to oxidation and removal of much of the orebody. The brecciated column of pipe 241 abuts against undeformed

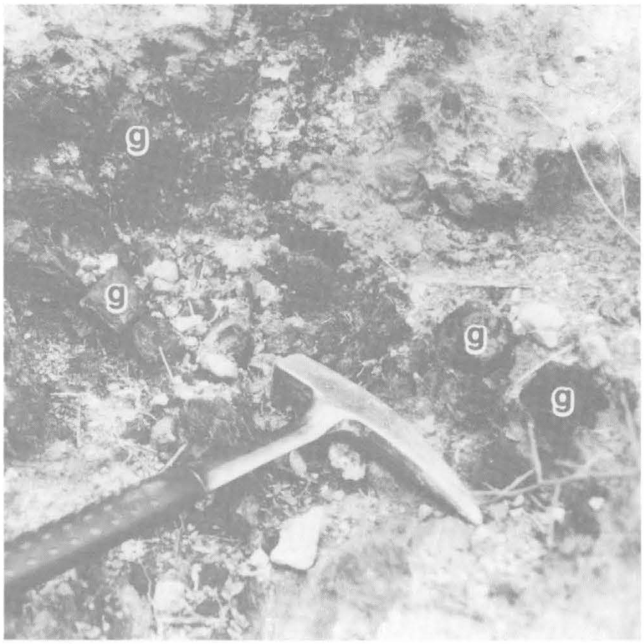
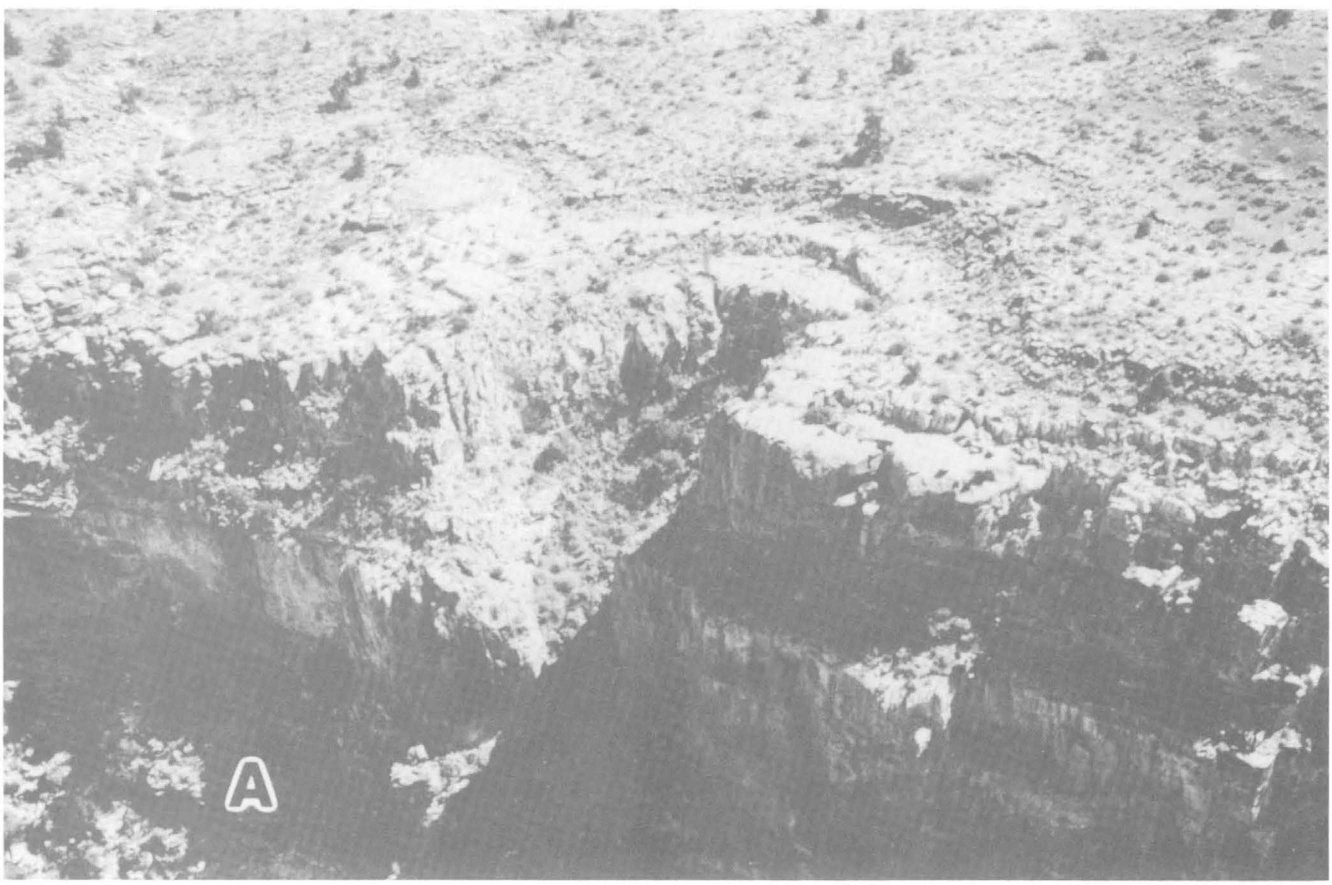


Figure 18. Breccia pipe 1031, Hualapai Indian Reservation, is almost totally covered by alluvium except for this small outcrop containing goethite (g) and pyrite nodules that emitted gamma radiation exceeding eight times background level.

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) speckled with green malachite show anomalous concentrations of most elements commonly enriched in breccia-pipe orebodies: Ag (170 and 14 ppm), As (5,000 and 870 ppm), Cu (1 and 0.9%), Mo (2,000 and 270 ppm), Pb (6,300 and 4,000 ppm), Sb (541 ppm), U (303 and 34 ppm), and Zn (950 and 140 ppm).

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

No collapse structures have been observed to date (1990) in the Mohawk Canyon area between the Esplanade surface and the Kaibab Limestone. This absence of features 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, which is commonly covered by alluvium; and (3) the vertical cliffs of Coconino Sandstone and Toroweap Formation expose little rock 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



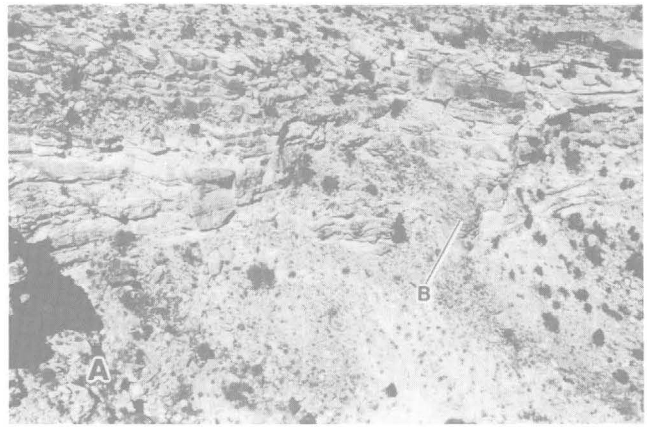
Sandstone and Brady Canyon Member of the Toroweap Formation could be easily overlooked. Even though fewer pipes stoped all the way to the Kaibab Limestone, dissolution of gypsum in the underlying Toroweap and gypsum and limestone in the Kaibab accentuate and enlarge any surface expression of pipes that did reach the Coconino Plateau surface. This surface consists of at least as much exposed rock in the Mohawk Canyon area as does the Esplanade erosion surface, yet it contains 19 collapse features in contrast to the 14 exposed along the Esplanade surface. Of course, some of the 19 Kaibab collapse features probably extend no deeper than the Harrisburg Gypsiferous Member of the Kaibab Limestone or the Woods Ranch Member of the Toroweap Formation (fig. 4). These shallow-seated collapses are most likely the "Kaibab" collapses listed under "Category" in table 1 as "C?."

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 redbeds composing the top 200 ft of Harrisburg have been stripped from this part of Arizona, leaving the white 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 Limestone surface (Coconino Plateau), are considered to be the pipes with the most potential for U ore in the Mohawk Canyon area. Compared to other features in the area, they are by far

Figure 19 (above and facing page). Breccia pipe 238, Hualapai Indian Reservation. A, The pipe is expressed on the surface as a bleached amphitheater with the breccia column exposed on the amphitheater floor. View is about 600 ft wide. B, Brecciated rock from the breccia column in pipe 238. Note the minor vugs throughout the breccia.



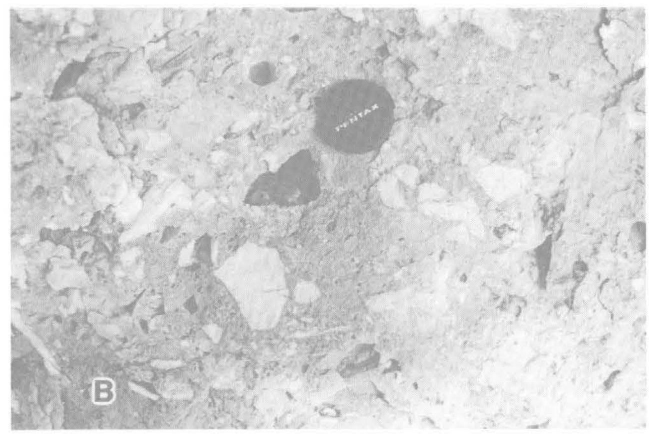
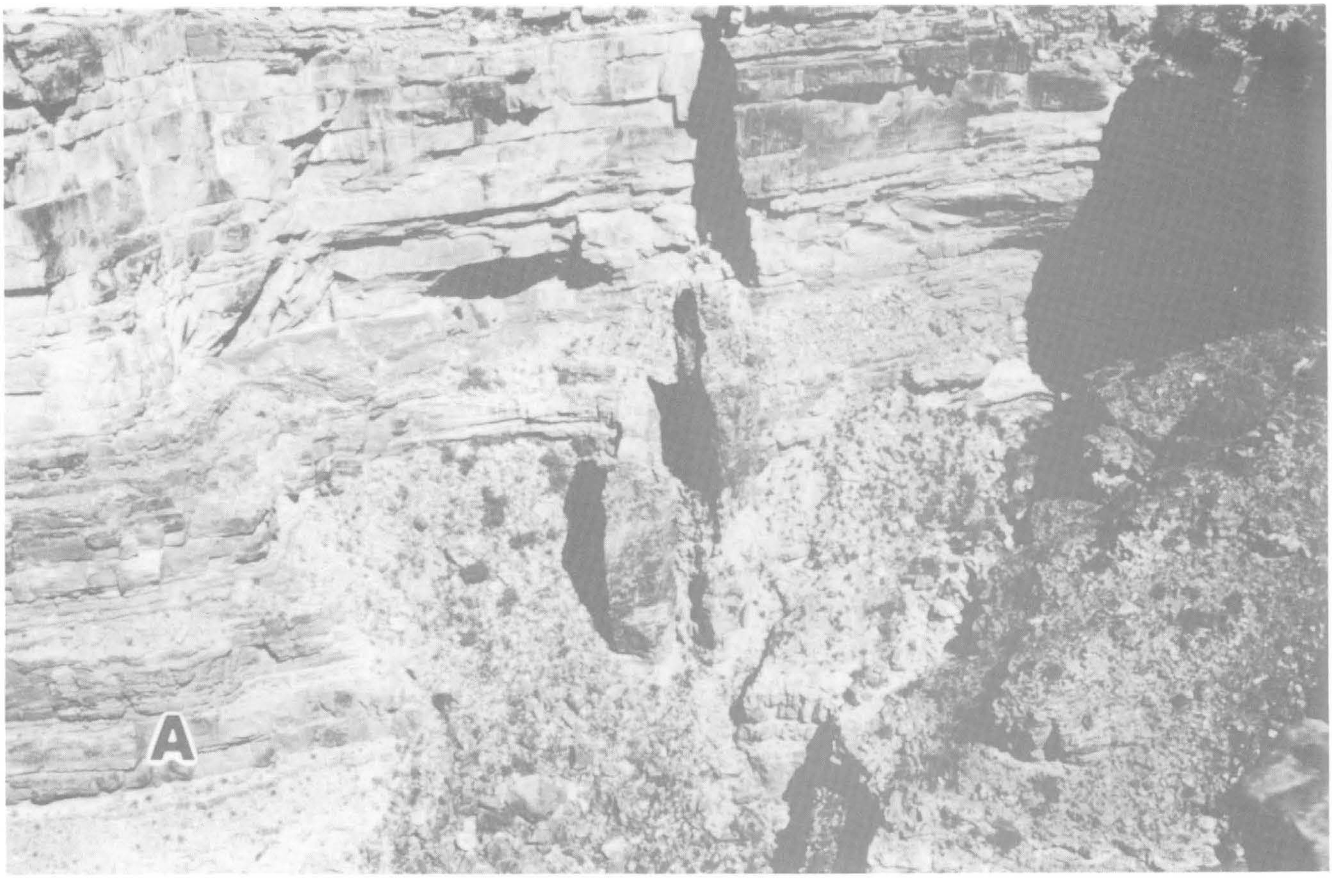


Figure 20. Breccia pipe 242, Hualapai Indian Reservation. A, Breccia (B) is clearly visible in the cliff of Esplanade Sandstone. View is about 700 ft wide. B, The breccia is composed of angular fragments of sandstone within a vuggy, well-cemented matrix. C, Large goethite nodules (g), with remnant pyrite cores and anomalous gamma radioactivity, altered from pyrite concretions.



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 features have no anomalous radioactivity, altered or mineralized rock, or breccia. Other than the four Kaibab collapses that contain altered, radioactive, or brecciated rock, geophysical, geochemical, or drilling surveys would be needed to determine whether the other features 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 of the pipe. In the cliffs adjacent to some of these 15 "C2" or "C?" (fig. 5) collapses, the Woods Ranch Member can be seen to thin to only a few feet. Whether the draping of the overlying beds and dissolution of this member is due to weathering along the canyon face, causing localized collapse, or is due to fluids moving through a breccia pipe and dissolving these units, cannot be determined without drilling or AMT (audio-magnetotelluric) geophysical surveys. Beds of Harrisburg Gypsiferous Member dip inward at collapse structures 592, 1101, 1170, 1172, 1174, 1087, 1088, 1090, 1189, 1175, 1092, 1099, 1100, 1171, and 1173 (listed in increasing order of potential as breccia pipes). All of these collapse structures except 1170, 1172, 1174, and 1175 are shown in figure 22.

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-scale aerial photographs, and have minor inward dip of some of the strata.

1087, 1088, 1089, 1090, 1092, 1099, 1100, 1171, and 1173.—All nine of these collapse features have beds with a significant inward dip and appear more circular on the aerial photographs than the five features listed above. Also, features 1088 and 1100 have some iron-stained chert, and 1099 has abundant limonite-stained rock within the pipe. Soil geochemical surveys were completed over features 1171 and 1174; the results will be released in a separate report. Geochemical analysis of an iron-stained sample (1088–A–C85, table 2) from collapse feature 1088 shows minor enrichment of As (190 ppm), Ba (1,700 ppm), Cd (10 ppm), and Pb (51 ppm), and a significant enrichment of Zn (2,300).

249.—This feature is a classic example of a small hill of flat-lying strata completely encircled by concentrically

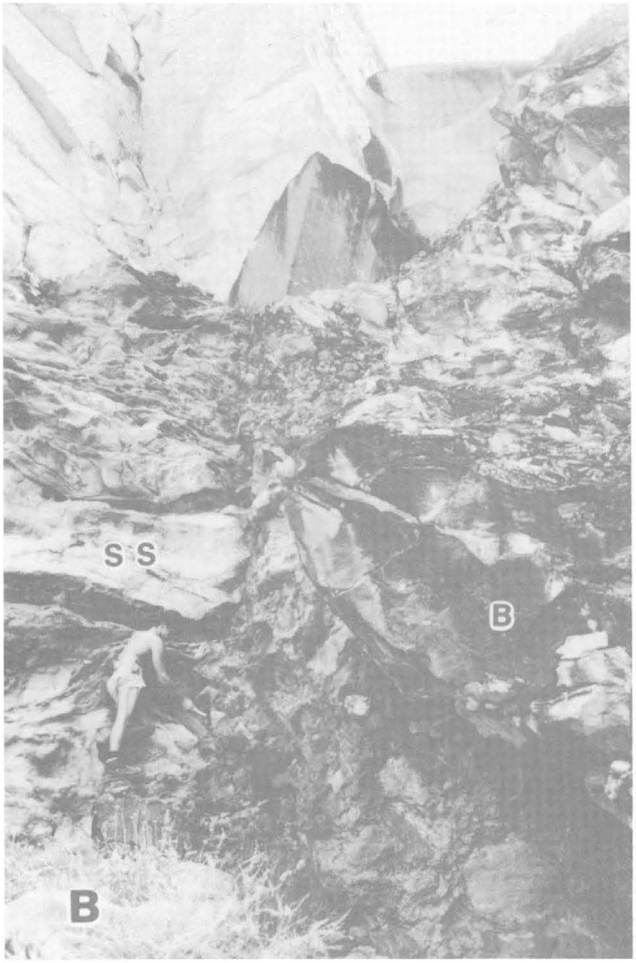


Figure 21(above and facing page). Breccia pipe 241, Hualapai Indian Reservation. A, The pipe is expressed on the surface as two silicified pinnacles of breccia on the floor of an amphitheater eroded out of the Esplanade Sandstone. View is about 700 ft wide. B, The breccia column (B) abuts against untilted sandstone (SS). C, The breccia has the appearance of a conglomerate. Photograph is of the area in figure 21B that the man is pointing to.

inward-dipping beds; a moat lies between the hill and the dipping beds (fig. 23). 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 mineralized rock is apparent. A sample of hematite-stained chert breccia (90% SiO_2) was submitted for geochemical analysis (sample 249–A–C83, table 2). Although not visibly mineralized, it did contain elevated As (105 ppm) and Cu (330 ppm) concentrations. A soil geochemical survey was completed over this feature, but the data will be presented in a separate report. The geochemical results (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), make this feature a favorable target for further exploration.

1102.—At this collapse feature, the beds of Harrisburg Gypsiferous Member dip inward toward a central drainage (fig. 24A). The morphology is not distinctly circular as it is at feature 249 (described 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 measured gamma radioactivity reached 550 cps (18 times background) over the gossan. Except for the Blue Mountain pipe (pipe 287, Billingsley and others, 1986; Van Gosen and others, 1989), this feature has the highest surface radioactivity found anywhere on the Hualapai Indian Reservation; such levels of gamma radiation are particularly rare on the Kaibab erosion surface. Two samples from the gossan (1102–A–C85 and 1102–B–C85, table 2) were geochemically analyzed and indicate a striking enrichment of elements commonly associated with breccia-pipe 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 report. An AMT geophysical survey was completed by Flanigan and others (1986). The two (east-west and north-south) AMT cross sections indicate three vertical conductive zones that extend from about 300 ft to 2,400 ft below the collapse surface exposure. Flanigan believed that the central conductive zone represented the pipe core, and the outer two zones 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 suggest that collapse 1102 holds excellent economic potential as a U-mineralized breccia pipe.

493.—This is one of the larger collapse features in the Mohawk Canyon area, about one-third mile in diameter. Like feature 249, this structure is a classic example of a small hill almost totally encircled by a moat that is surrounded by higher hills (fig. 25) of Harrisburg Gypsiferous Member. The central hill contains concentric sets of

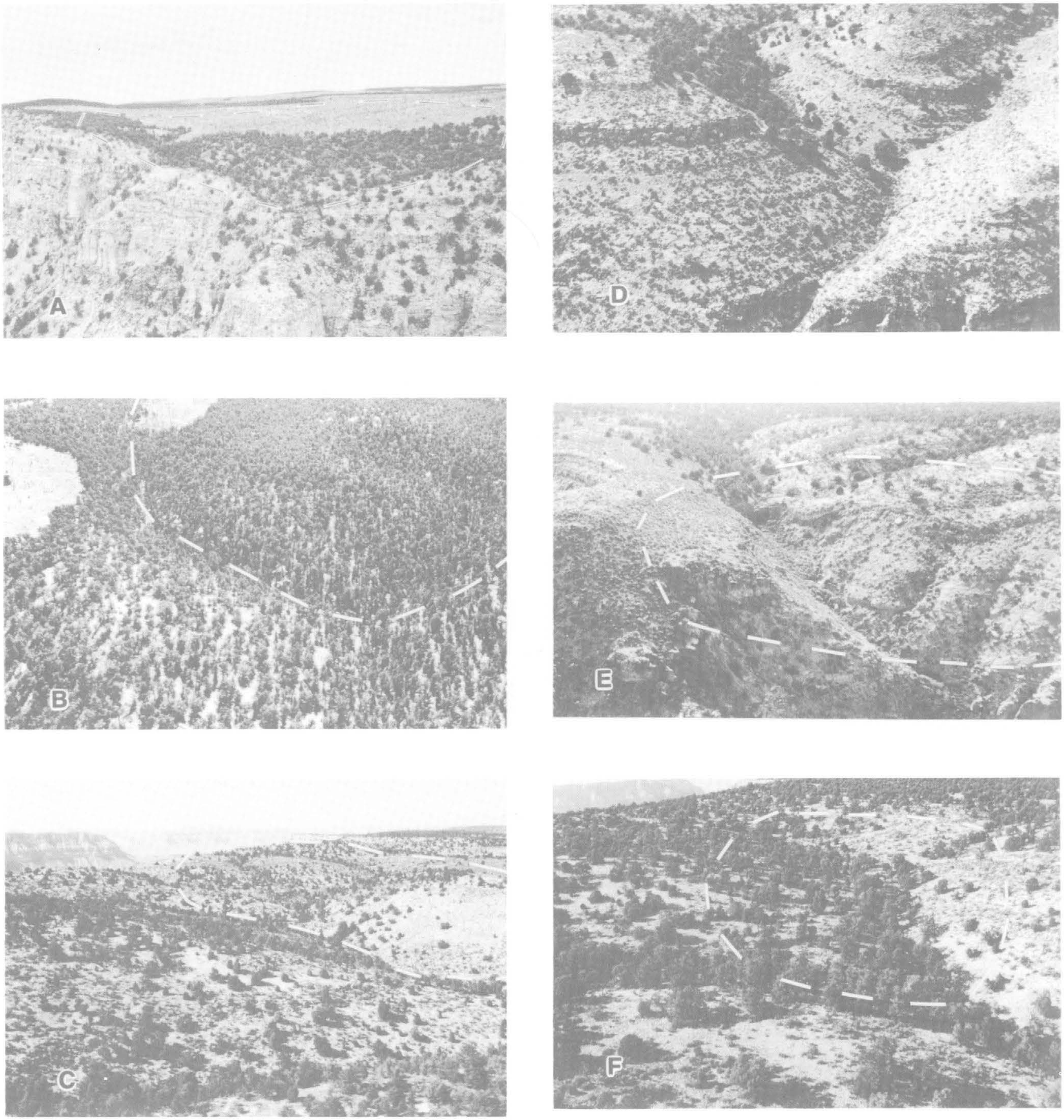
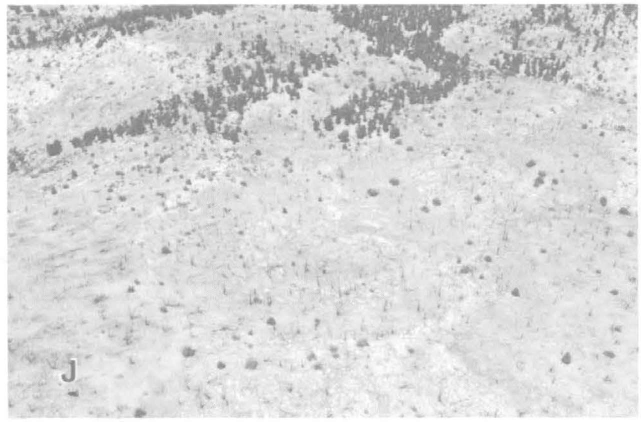
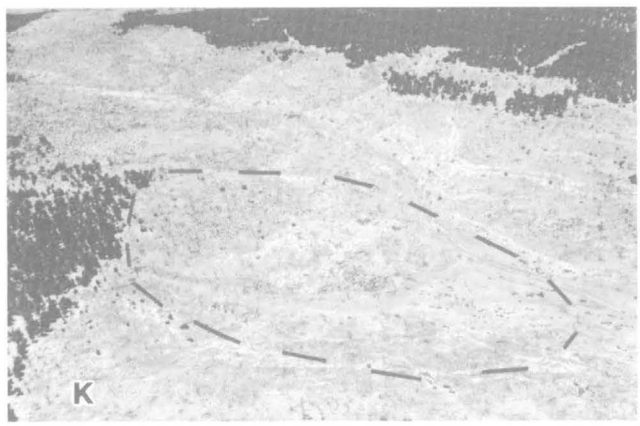


Figure 22 (above and facing page). Collapse features in the Mohawk Canyon area, Hualapai Indian Reservation, on the Kaibab Limestone-capped plateau that are expressed solely as inward-dipping beds, with no evidence of surface alteration, brecciation, or mineralization. Photographs taken from a helicopter. A, Collapse feature 592; dashed line shows feature. Collapse as outlined is about 2,500 ft wide. B, Collapse feature 1101; dashed line shows feature. View is about 900 ft wide. C, Collapse feature 1087; dashed line shows feature. View is about 1,000 ft wide. D, Collapse feature 1088. The entire field of view is within the collapse; the junction of the gullies is the center of the collapse. View is about 700 ft wide. E, Collapse feature 1089; dashed line shows feature. View is about 600 ft wide. F, Collapse feature 1090; dashed line shows feature. View is about 500 ft wide. G, Collapse feature 1092; dashed line shows feature. View is about 1,000 ft wide. H, Collapse feature 1099; dashed line shows feature. View is about 800 ft wide. I, Collapse feature 1100; the entire foreground is within the collapsed area. View is about 1,000 ft wide. J, Collapse feature 1171; note the concentric inward-dipping beds in the center of the photograph. 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.

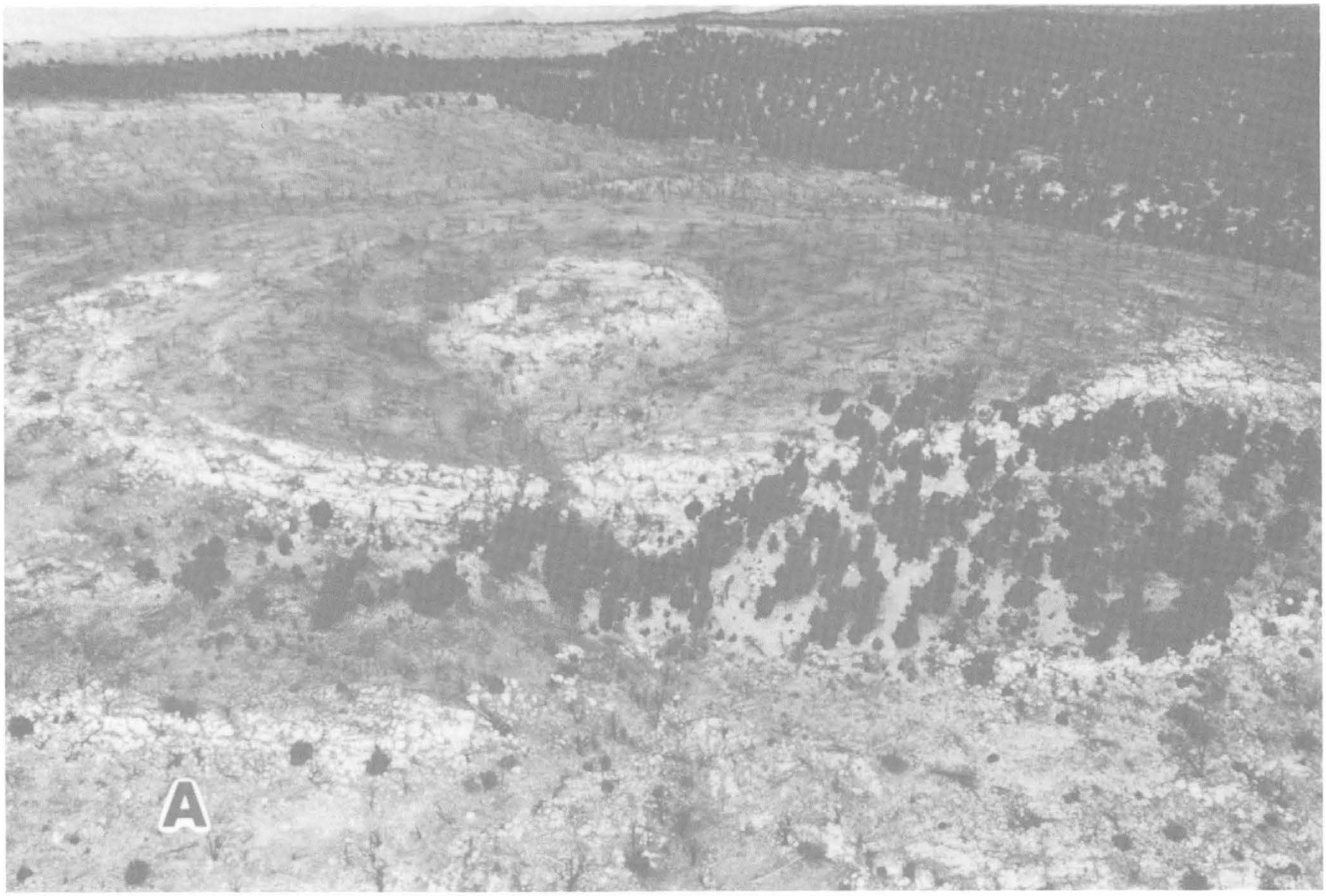




perfectly circular rings of unusually steep (nearly vertical toward the center), inward-dipping beds around a center of red soil. This red soil could be downdropped Triassic Moenkopi Formation strata; if so, there has been more than 200 ft of downdrop at the present Harrisburg erosion level because the 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 basal 100 ft of white Harrisburg remains, capping 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 sedimentary rocks, such as the redbeds of the Harrisburg or the Moenkopi Formation, that are more magnetic 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 thins to about 30 ft in thickness just beneath the collapse (fig. 25C). Also, a cave, just beneath the collapse in the Fossil Mountain Member of the Kaibab Limestone (fig. 25C), attests to increased dissolution directly beneath this structure. Geochemical 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). Such low concentrations of ore-bearing metals are discouraging in contrast to samples from some other pipes in the Mohawk Canyon area (table 2). A soil geochemical survey was also completed over this collapse; the results will be published in a separate report.



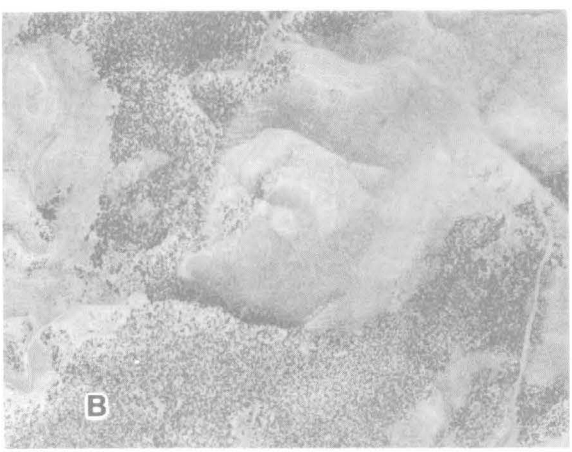


Figure 23 (above and facing column). Collapse feature 249, Hualapai Indian Reservation. A, The small hill is completely encircled by concentrically inward-dipping beds. Between the hill and the concentric beds is a moat that perhaps represents the more easily eroded ring-fracture zone surrounding a downdropped plug overlying a breccia core. Photograph taken from a helicopter. The diameter of the outline made by the concentric beds is about 1,000 ft. B, View of collapse feature 249 on a 1:24,000-scale aerial photograph (center of figure).

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, 3,000 ft. Such results strongly suggest that not only is feature 493 a breccia pipe, but it is also entirely vertical, without the bending shape that plagues many pipes (such as pipe EZ–2, AMT profile shown by Flanigan and others, 1986), making orebody delineation very difficult. Hence, the vertical, highly conductive zone beneath the collapse (AMT results), the collapse morphology, and the dissolution of the underlying Toroweap (see the section on "Woods Ranch dissolution in Mohawk Canyon pipe," Wenrich and others, 1988) suggest that feature 493 has good potential as a U-mineralized breccia pipe, and it certainly warrants exploratory drilling.

494 (Mohawk Canyon pipe).—This breccia pipe (fig. 26) is considered to have the greatest potential for an orebody of any pipe on the Hualapai Indian Reservation. It was originally identified as a collapse by the senior author

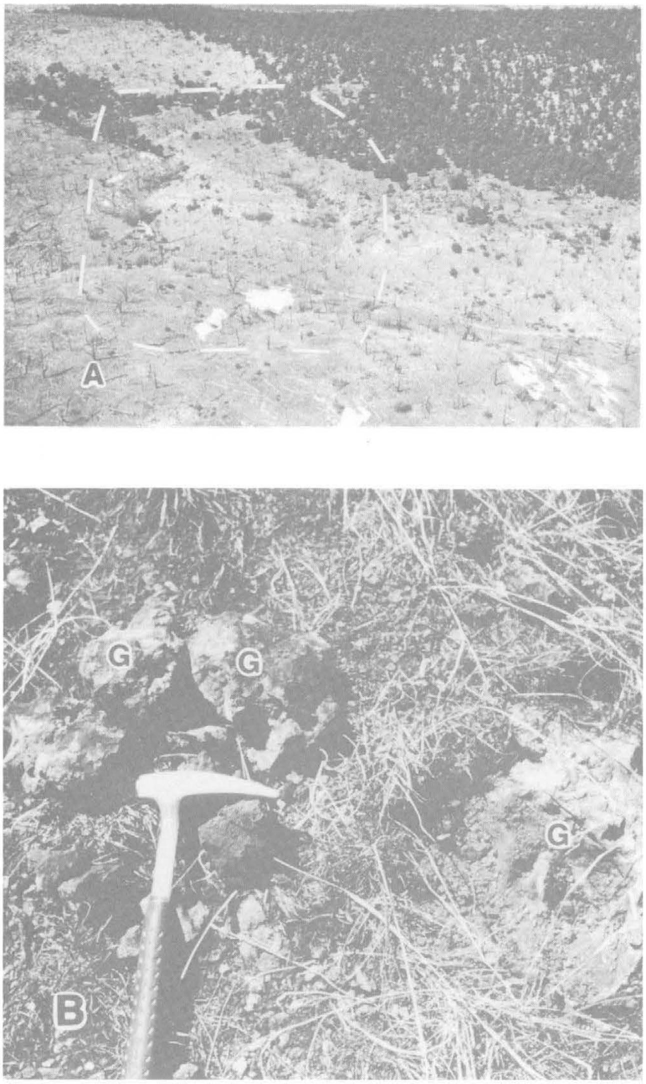


Figure 24. Collapse feature 1102, Hualapai Indian Reservation. A, Strata of Harrisburg Gypsiferous Member dip slightly inward toward a central drainage (center of photograph). Collapse as outlined is about 300 ft long. B, Small outcrops and float of orange-brown, Fe-rich gossan (G) emitted gamma radioactivity exceeding 18 times background level.

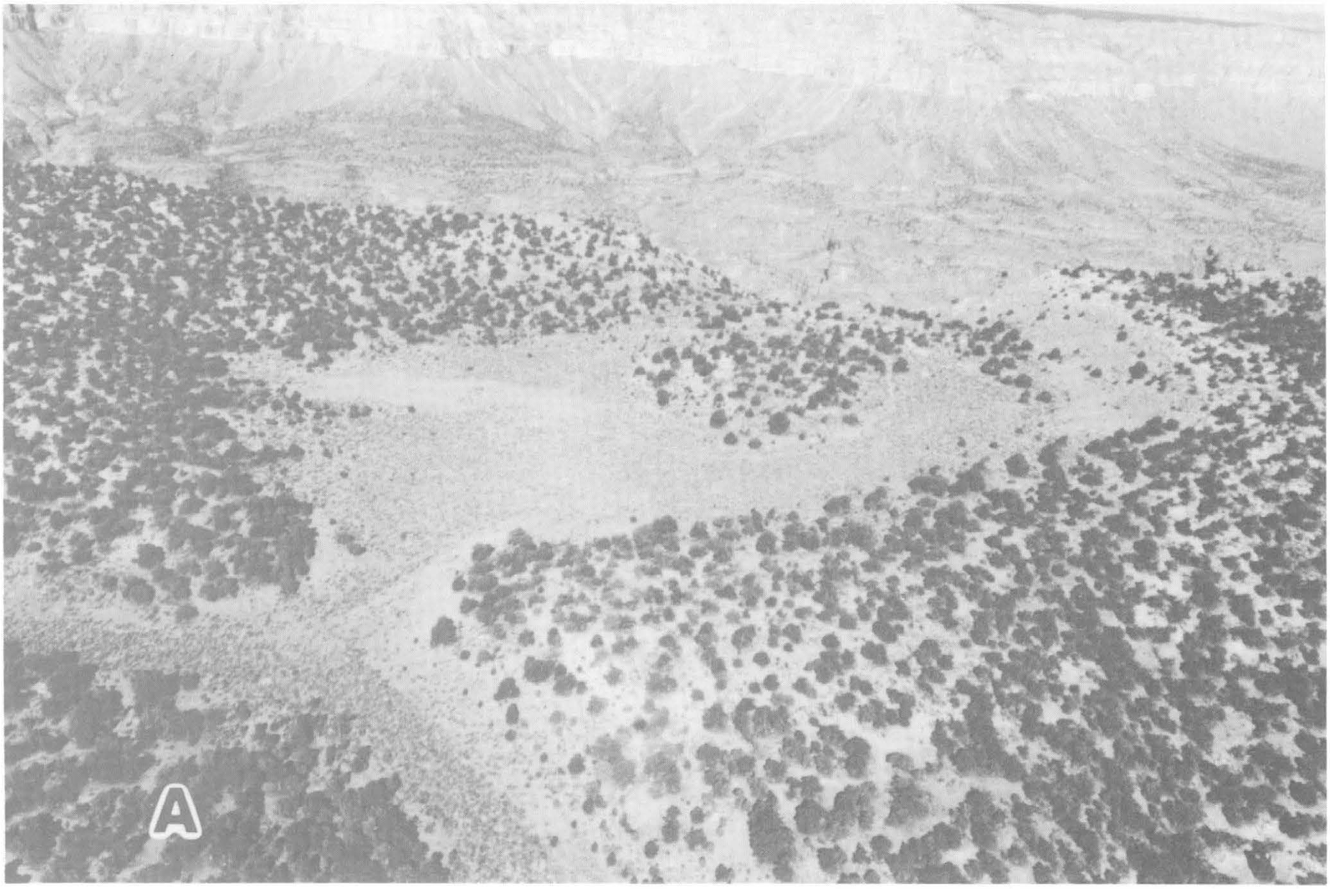
in June 1983 while mapping collapse structures in the Mohawk Canyon area. Although the turn-of-the century Grand Canyon miners probably did not recognize this area as a breccia pipe, they obviously discovered its Cu minerals (malachite, azurite, and chrysocolla) during the 19th century—this timing is suggested by the square nails in the timbers that are lying about on the ground near two adits driven into the west side of Mohawk Canyon, at the cliff edge. The adits lie 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 revealed a dipole anomaly (Van Gosen and Wenrich, 1989). The dipole high is over the core of the pipe, suggesting that the downdropped core may contain some of the redbeds (presently bleached) of the Harrisburg Gypsiferous Member, which have been stripped from the surrounding areas. In fact, lithologic logs from 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—as much as 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 (330 ppm), Cu (1.4%), Fe_2O_3 (18%), Hg (0.3 ppm), Mo (140 ppm), Ni (70 ppm), P (0.62%), Pb (1.2%), Sb (106 ppm), Se (350 ppm), Sr (1,600 ppm), U (50 ppm), V (290 ppm), and Zn (1.6%).

Five holes were drilled. The gamma log from one hole, penetrating to a depth of 1,335 ft, shows a 1-ft interval of 0.52% eU_3O_8 at a depth of 1,191 ft and a 20-ft zone averaging 0.04% U_3O_8 from 1,191 to 1,211 ft of depth (Wenrich and others, 1988); this depth is the same stratigraphic horizon as the top of orebodies in active breccia-pipe 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 U is hardly an orebody, the grade of 0.52% eU_3O_8 is near the average grade mined from those northern Arizona breccia pipes that 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.



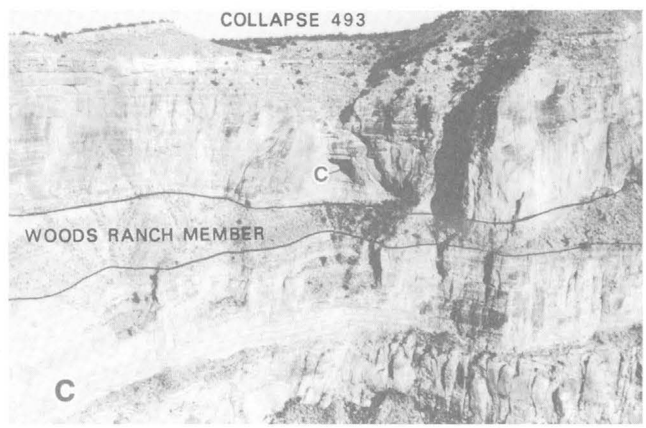


Figure 25 (above and facing column). Collapse feature 493, Hualapai Indian Reservation. A, A small hill of concentrically inward dipping beds is almost totally encircled by a moat that is surrounded by higher hills. Rim to rim, the feature is about 1,600 ft wide. B, photograph of 493 taken from low-altitude aerial photography (1:24,000 scale); dashed line shows feature. Note the outer concentric ring of beds on the central hill. C, The Woods Ranch Member of the Toroweap Formation thins to about 30 ft in thickness near collapse feature 493 (arrow). Also notice the cave (C) in the Fossil Mountain Member of the Kaibab Limestone just below the collapse feature. The western edge of the collapse can be recognized by the amphitheater beginning to develop at the top of the cliff.

CONCLUSIONS

The Mohawk Canyon area has a greater concentration of surface-mineralized collapse features than anywhere else on the Hualapai Indian Reservation. Those collapse features exposed in the Redwall Limestone and overlying lower part of the Supai Group are not considered to have any potential for U orebodies. Of the 46 collapse features mapped in the area, 6 should undergo additional exploration surveys, including the Mohawk Canyon pipe (494) that was drilled and discovered to contain U concentrations as high as 0.52 percent eU_3O_8. Three of the six features, 241, 242, and 494, 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 Indian 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 have been U mineralized, they have two negative economic considerations: (1) They are inaccessible by vehicle and difficult to reach even on foot; and (2) the top 1,500 ft of rock, that rock which hosts most of the ore in all of the past or presently active breccia-pipe U mines, has been eroded away. The other four favorable features crop out on the Coconino Plateau and are reasonably accessible; 493 and 494 have roads to them. Classic breccia-pipe morphologies are developed over 249, 493, and 494.

The morphology of collapse feature 249 strongly suggests the presence of an underlying breccia pipe. Such morphology, of concentric inward-dipping beds of the Harrisburg Gypsiferous Member of the Kaibab Limestone enclosing a moat that surrounds a central hill of flat-lying strata, probably results from a ring-fracture zone (less resistant to erosion) underlying the "moat". This ring-fracture zone bounds an underlying breccia pipe. Although 249 is not considered as favorable a feature as 1102, 493, and 494 for hosting a U orebody, it should certainly be explored further.

The dissolution of the Woods Ranch Member of the Toroweap Formation, adjacent to and under feature 493 (similar to what was observed while drilling feature 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 redbeds 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 gamma radioactivity of 18 times background suggests that, at least for the surface exposure, the U gamma radioactivity and U content are approximately in chemical equilibrium. That is, the background U concentration in this rock is about 4–8 ppm. The high conductivity zones delineated underneath 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 U orebody on the Hualapai Indian Reservation because it has been proven through drilling to be both U mineralized and a breccia pipe. A 1-ft interval of 0.52 percent eU_3O_8 (which as shown at feature 1102 is in approximate chemical equilibrium) was found in drilling, along with 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 northeast-trending zone (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 northeast alignment of the Ridenour mine and three 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) exploration surveys such as those for *Bacillus cereus* or helium soil gas, plus magnetometer surveys over features 249, 493, and 1102, and an AMT survey over 249; and (3) exploratory drilling of 493 and 1102.

ACKNOWLEDGMENTS

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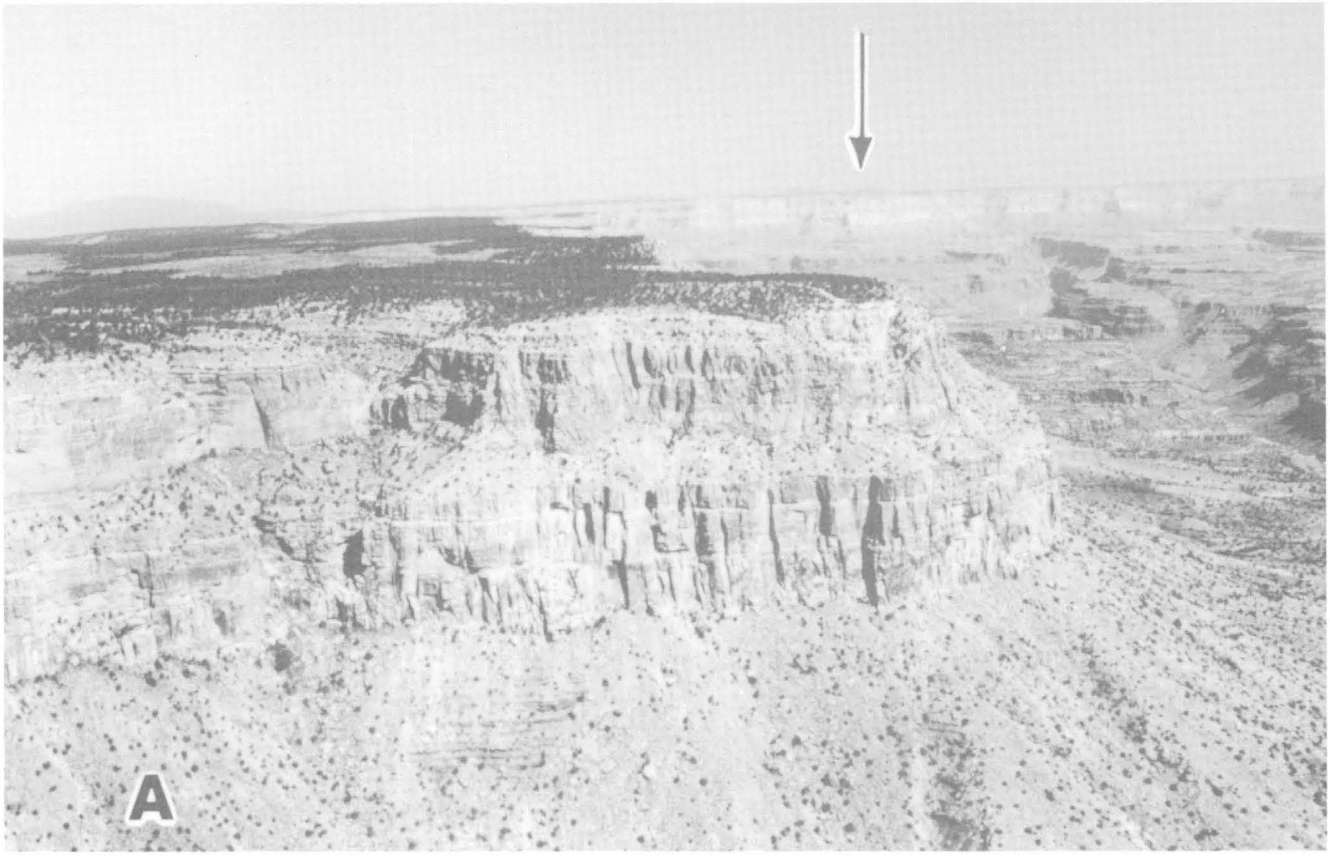

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Figure 26 (above and facing page). Breccia pipe 494 (Mohawk Canyon pipe), Hualapai Indian Reservation. A, The pipe shows up as a small bleached point on the Kaibab Limestone cliff (arrow). Fault-controlled Mohawk Canyon can be seen to the right heading north towards the Colorado River. This photograph was taken during drilling of the Mohawk Canyon pipe in 1984. B, Concentric beds of Harrisburg Gypsiferous Member of the Kaibab Limestone dip 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.

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