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Recognition of Breccia Pipes in Northern Arizona

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The southwestern corner of the Colorado Plateau in northern Arizona is host to thousands of solution-collapse breccia pipes. A breccia is a coarse-grained rock composed of large, angular, broken rock fragments that are cemented together in a finer grained matrix. A breccia pipe is a vertical pipelike column of broken rock (Figure 1). Because of the coarse-grained and initially porous nature of these breccia pipes, mineralizing fluids that passed through some pipes deposited a large suite of metallic minerals. Although thousands of pipes may exist, only a small fraction of these, probably less than 8 percent, were mineralized, and an even smaller percentage of these, perhaps less than 10 percent, contain economic concentrations of minerals. An example of mineralized breccia is shown in Figure 2.

U.S. Geological Survey (USGS) geologists have studied breccia pipes in northwestern Arizona since 1977, with the start of the National Uranium Resource Evaluation (NURE) program. After NURE quadrangle maps were completed in 1978, breccia-pipe research continued in conjunction with the Bureau of Indian Affairs as part of its mineral-resource assessment of the Navajo and Hualapai Indian Reservations. This article summarizes the location, description, origin, and mineralization of breccia pipes in Arizona, explains how they can be recognized at the surface, and outlines their mineral production and potential.

Location

Despite the depressed 1980's mineral market, exploration activity for breccia pipes has been steady during the past 8 years because some pipes contain high-grade uranium ore. Breccia pipes are located in flat-lying strata in areas where essentially the only deformation is folding and broad regional warping. They are abundant from the Grand Wash Cliffs (western margin of the Colorado Plateau) to the Echo Cliffs, and from the Mogollon Rim (southern margin of the Colorado Plateau) to the Utah border (Figure 3). A few have been recognized just north of the border in Utah. Although pipes have not been identified within the area of the Mt. Floyd and San Francisco volcanic fields, they are undoubtedly buried beneath the lavas; however, economic recovery of any minerals is doubtful. Pipes may also extend eastward, buried beneath sedimentary rocks. This is considered unlikely, however, because the Redwall Limestone, which contains the roots of the breccia pipes, pinches out to the east between Holbrook and the Four Corners area (McKee and Gutschick, 1969).

Description and Origin

Breccia pipes in northwestern Arizona are strictly collapse in origin and resulted from the dissolution of the Redwall Limestone, which formed caverns, followed by progressive stoping, or gravitative collapse, of the overlying strata. This collapse produced steep-walled, pipelike bodies (Figure 1) that were filled with angular to rounded fragments ranging from totally comminuted material to house-size blocks, bounded by a steeply dipping ring fracture. No pipes contain fragments from underlying formations; all material has been dropped downward into the pipe. This negates any theories of origin that invoke explosive activity from below.

Dissolution of the Redwall Limestone began during the Late Mississippian [approximately 330 million years (m.y.) ago], creating an extensive karst terrain characterized by closed depressions or sinkholes, caves, and underground drainage. Evidence for this can be seen throughout the Grand Canyon wherever Redwall caves, exposed in cross section along the canyon walls, are filled by channel deposits of the overlying Mississippian Surprise Canyon Formation. Dissolution of the Redwall and collapse of the overlying strata either continued throughout the late Paleozoic and early Mesozoic or ceased after the

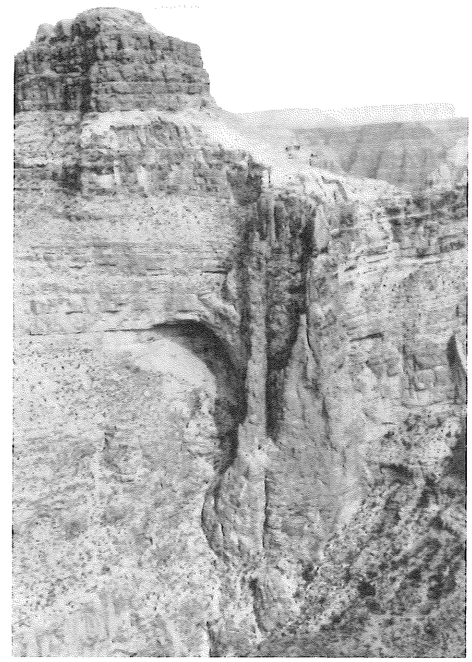

Figure 1. *The Bat Cave pipe forms a prominent 800-foot (250-meter) vertical column along the cliff face. This pipe is located just south of the Colorado River on the Hualapai Indian Reservation in the Lower Supai Group and upper part of the Redwall Limestone.*

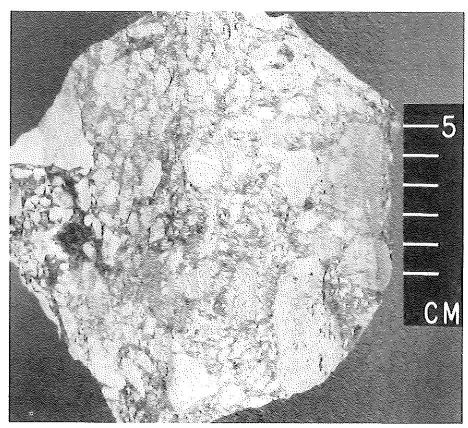

Figure 2. *This breccia is composed of fragments of angular, bleached Hermit Shale or Coconino Sandstone cemented by a finely pulverized matrix of quartz sand that includes minerals such as uraninite, pyrite, galena, sphalerite, and numerous other copper and nickel-cobalt-iron sulfides. These minerals are responsible for the dark-gray color of the matrix.*

Mississippian and was reactivated during the Late Triassic (approximately 210 m.y. ago) or earlier. No pipes have been observed in strata younger than Triassic, although such

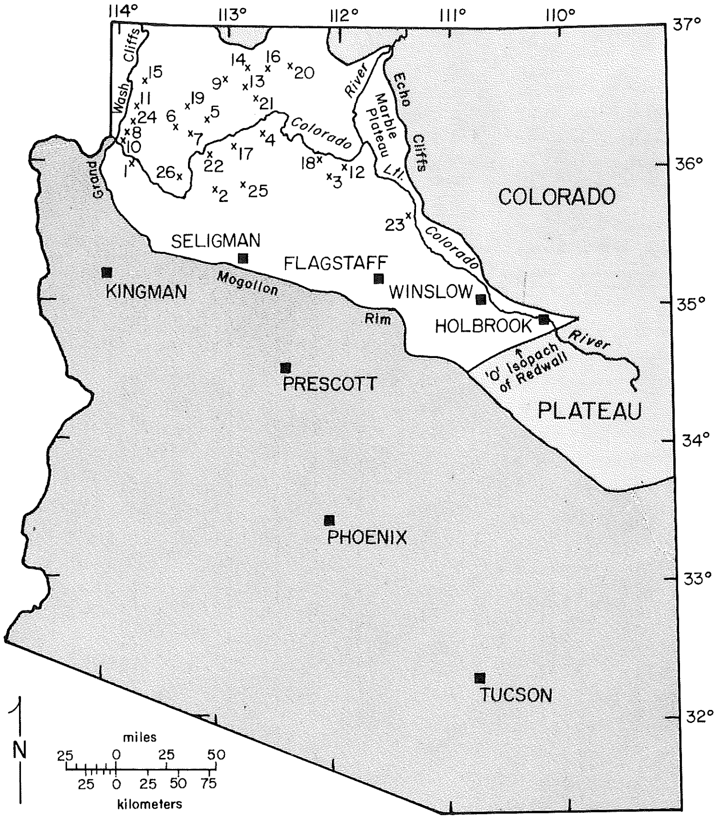

Figure 3. Location map of several solution-collapse breccia pipes in Arizona. Some of these, such as the Bat Cave and Carbonate Canyon pipes, do not contain economic minerals, whereas others contain orebodies of metallic minerals. The unshaded area is considered favorable for breccia pipes. Pipes are keyed by number; those shown with an asterisk have been or are being mined for uranium. (1) Bat Cave; (2) Blue Mountain; (3) Canyon; (4) Carbonate Canyon; (5) Chapel; (6) Copper House; (7) Copper Mountain; (8) Cunningham; (9) EZ-2; (10) Grand; (11) Grand Gulch; (12) Grandview; (13) Hack; (14) Hermit; (15) Hidden; (16) Kanab North*; (17) Mohawk Canyon; (18) Orphan*; (19) Parashant; (20) Pigeon*; (21) Pinenut; (22) Ridenour*; (23) Riverview*; (24) Savanic; (25) SBF; (26) Snyder.*

Table 1. Minerals found in Arizona breccia pipes listed by major metallic element. Those marked with an asterisk are primary-ore or gangue minerals; the remainder are slightly oxidized or supergene minerals.

URANIUM	VANADIUM	COPPER	IRON
uraninite*	hewettite	chalcocite	pyrite*
tyuyamunite	vesignieite	djurleite	marcasite*
metatyuyamunite	volborthite	digenite	arsenopyrite*
zippeite	calciovolborthite	covellite	siderite*
zeunerite	roscoelite	enargite*	scorodite
metazeunerite		chalcopyrite*	melanterite
metatorbernite	NICKEL	lautite*	limonite
uranophane	nickeline*	bornite	hematite
bayleyite	rammelsbergite*	tennantite*	goethite
uranospinite	pararammelsbergite*	tetrahedrite*	siderotil
	gersdorffite*	cuprite	coquimbite
ZINC	bravoite*	tenorite	
adamite	siegenite*	chrysocolla	MISCELLANEOUS
sphalerite*	vaesite*	azurite	quartz*
smithsonite	millerite*	malachite	chalcedony*
aurichalcite		olivenite	pyrobitumen*
hemimorphite	COBALT	chalcanthite	jarosite
	skutterudite*	brochantite	celadonite
LEAD	Co-gersdorffite*	cyanotrichite	illite
galena*	erythrite	chalcoalumite	kaolinite*
anglesite	linnaeite*	langite	chlorite
cerussite	bieberite	antlerite	fluorite*
wulfenite		devilline	calcite*
	ANTIMONY	conichalcite	dolomite*
MANGANESE	stibnite*		ankerite*
rhodochrosite		SILVER	anhydrite*
	MOLYBDENUM	acanthite	gypsum
BARIUM	molybdenite*	naumannite	hexahydrite
barite*	ilsemannite	proustite	leonhardtite

strata have been removed by erosion across most of northwestern Arizona.

The pipes and associated mineralization (Table 1) transgress all formations from the Mississippian Redwall Limestone to the Late Triassic Chinle Formation. Unfortunately, nowhere in the Grand Canyon area does an exposure reveal one pipe cutting through 3,000 feet of sedimentary strata, as shown in Figure 4. This cross section is based on exposures of various pipes throughout northern Arizona that crop out in different stratigraphic horizons. Many pipes, however, do provide continuous profiles through more than 800 feet of the rock column (Figure 1).

The breccia pipes average about 300 feet in diameter; however, many collapse features found on the plateaus of northern Arizona and thought to be surface manifestations of underlying pipes are as large as 0.5 mile in diameter (Figure 5). The development of an enlarged cone above many breccia pipes is due to dissolution of the carbonate cement from many of the formations overlying the Redwall Limestone, and particularly the dissolution of gypsum and limestone in the upper Paleozoic Toroweap Formation and Kaibab Limestone.

Mineralization

Metallic minerals within the pipes were probably deposited by at least two separate mineralizing fluids. The main uranium-mineralizing event apparently occurred after deposition of the Triassic Chinle Formation. A large set of U-Pb isotopic analyses from the Hack 1, Hack 2, Kanab North, EZ-1, EZ-2, and Canyon pipe orebodies shows that the main uranium-mineralizing event occurred about 200 m.y. ago (Ludwig and others, 1986; Ludwig, personal commun., 1987). Petrographic studies suggest that uranium mineralization occurred after that of cobalt, copper, iron, lead, nickel, and zinc; hence, these other metals must have been deposited prior to 200 m.y. ago. During the last 5 m.y., dissection of the Grand Canyon exposed and oxidized the ore in many pipes. This produced the beautiful secondary copper minerals that attracted the attention of prospectors during the 1800's.

With such a large number of breccia pipes, an equally large number of accompanying minerals might be expected. The compiled list of minerals in Table 1 shows this to be the case. This list includes both primary ore and nonore (gangue) minerals, as well as secondary supergene minerals produced by oxidation from downward-moving ground water under near-surface conditions. Not all minerals are found in every mineralized pipe. Many are present in trace amounts; for example, cyanotrichite (Figure 6) has not been recognized in most pipes, yet the Grandview mine (pipe #12 shown in Figure 3) is its type locality.

The supergene copper minerals, uranium-bearing minerals, vanadium-bearing minerals, and the more common minerals such as pyrite, galena, barite, and sphalerite are usually megascopic in size. The obvious presence of these minerals at the surface or in drill core, or an alteration product of them, is indicative of an underlying mineralized pipe (Figure 7). All of the rarer primary metallic minerals, particularly the nickel-cobalt-iron sulfides such as siegenite, vaesite, and gersdorffite, are microscopic and distinguishable only in thin section. Analysis of samples under the microscope reveals many of the complex zoning and textural relationships of this large suite of minerals.

In some instances, the presence of supergene copper minerals may not indicate an orebody. This is particularly true along the Grand Wash Cliffs and within the Grand Canyon and its tributaries, where many pipes have been dissected and entirely oxidized. In these areas, the primary ore minerals have been removed and uranium production is probably not economically feasible.

Surface Recognition

Breccia pipes are easily recognized within canyons where their vertical dimension is exposed (Figure 1). Large expanses of northern Arizona, however, are composed of undissected plateaus. Recognition of pipes in these areas is particularly important because mining access to the plateaus is far better than to the canyons. Hundreds of shallow structural basins on the plateaus are thought to be surface expressions of breccia pipes, an assumption supported by the occasional exposure in a canyon wall of a pipe that continues upward to a shallow structural basin on the plateau surface. Pipe #226 (Figure 8), located on the Hualapai Plateau on the northwest side of Horse Flat Canyon south of the Colorado River, crops out from the Watahomigi Formation upward to an erosional surface of Manakacha Formation, where it forms a shallow structural basin with inward-dipping beds. The Grand Pipe (Figure 5) is a larger example of such a structural basin with concentrically inward-dipping beds of Esplanade Sandstone and Hermit Shale.

Recognition of breccia pipes on the high plateaus of northern Arizona, such as the Coconino, Kaibab, and Marble Plateaus, which are capped by the Kaibab Limestone or younger units, is complicated by the development of karst depressions in the Kaibab Limestone and collapse features in the gypsum of the underlying Toroweap Formation. Collapse features that resemble ordinary sinkholes (with vertical walls, no tilted beds, and a flat-bottomed depression containing uncemented rubble) are probably from recent karst development and are shallow seated, bottoming in the Kaibab or Toroweap. In contrast, collapse features with tilted beds, brecciation, and alteration probably indicate the presence of breccia pipes that extend downward into the Redwall Limestone.

Breccia pipes can commonly be recognized on low-altitude, 1:24,000-scale, color aerial photographs by the presence of the following features:

(1) *Concentrically inward-dipping beds that generally surround a basin.* This type of structure is more diagnostic of breccia pipes than of shallower collapses, especially when the basin contains rocks from a formation that overlies the normal plateau cap rock. A good example of such a closed basin can be seen at the EZ-1 breccia pipe (Figure 9), located near EZ-2 on Figure 3.

(2) *Amphitheater-style erosion.* Semicircular depressions or canyons along a cliff face result from preferential erosion along the ring fracture of a breccia pipe (Figure 10).

(3) *Concentric drainage, soil, and vegetation patterns.* Where rock outcrops are few, such as in the ponderosa pine forests and denser vegetation of the high plateaus, identification of these circular features on aerial photographs may be the only way to locate breccia pipes. A circular gully around a central hill (Figure 11) and a circular patch of grass surrounded by desert vegetation (Figure 12) strongly suggest the presence of underlying breccia pipes.

(4) *Breccia.* Though rarely exposed on plateau surfaces, breccia can usually be seen in cliff faces. Breccia columns, such as those that form the Bat Cave pipe

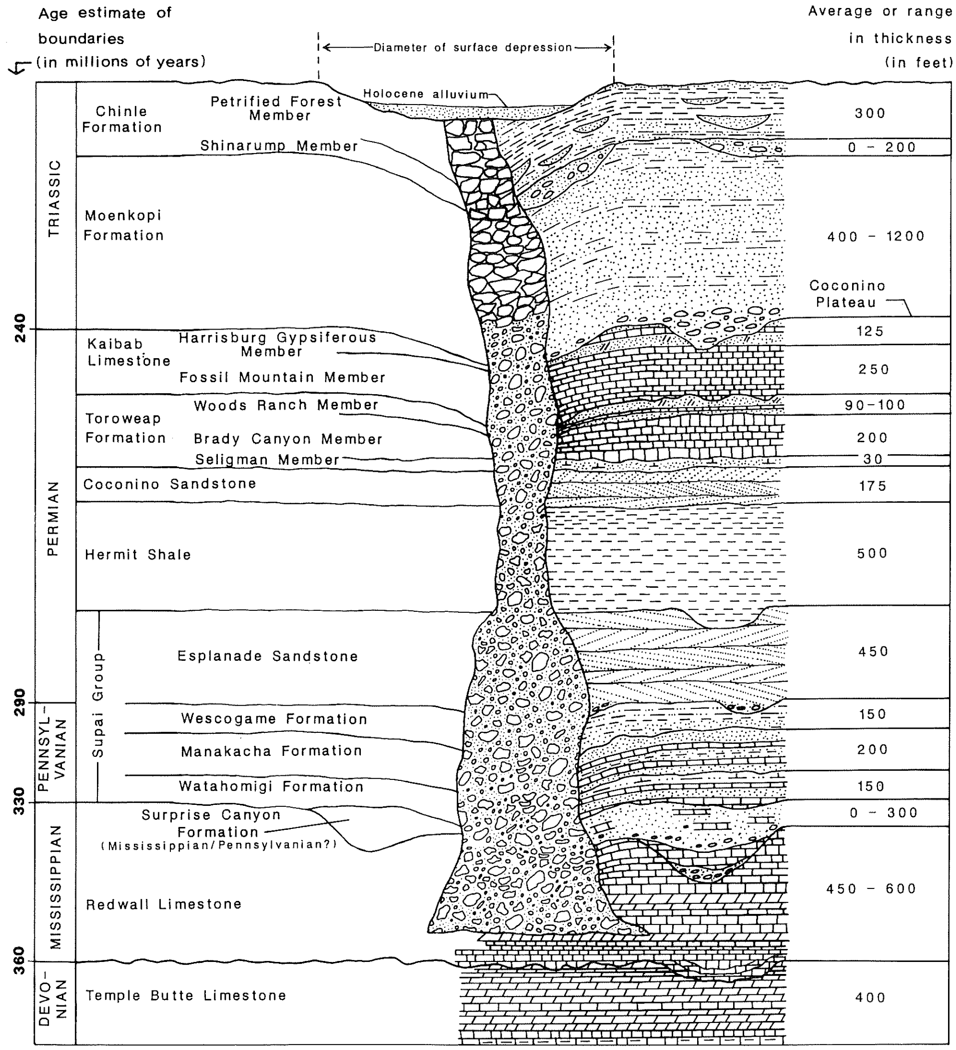

Figure 4. Schematic cross section of a breccia pipe. The unit thicknesses shown for the Triassic Chinle and Moenkopi Formations represent their thickness range throughout the Grand Canyon region. Thicknesses for the upper Paleozoic strata correspond to the average unit thickness within the Coconino Plateau of the eastern Hualapai Indian Reservation. From Van Gosen and Wenrich, 1988.

Figure 5. The Grand pipe, located just north of the Colorado River near the Grand Wash Cliffs (Figure 3), is one of many shallow structural basins exposed on a plateau surface and believed to be the surface expression of an underlying breccia pipe. The Grand pipe (#288) is described in Wenrich and others (1987).

(Figure 3), are recognizable on aerial photographs, as are silicified hills of breccia (Figure 11).

(5) *Altered and mineralized rock.* These are distinctive indicators of a nearby breccia pipe. Bleaching of normally red rock, caused by reduction of iron, is the most common type of alteration, although limonite (Figure 11) and hematite staining is also common. Bleaching of the normally reddish-orange Esplanade Sandstone is distinctive in the area of the Ridenour mine (Figure 13). Although mineralized rock can rarely be seen on aerial photographs, it is a good indicator in the field of an underlying breccia pipe. Supergene copper minerals such as malachite and azurite are commonly present, formed by migrating ground water along the ring fracture. Although unoxidized minerals from the ore zone, such as pyrite, marcasite, chalcopyrite, galena, sphalerite, and uraninite, are rarely preserved on the surface, secondary-alteration products of them, such as goethite altered from pyrite, are occasionally speckled throughout a pipe (Figure 7).

Mining History

Mining is no stranger to the Grand Canyon. Mining activity in breccia pipes of the Grand Canyon region began during the 1870's. At that time, production was primarily for copper and minor amounts of silver, lead, and zinc. The finely tuned eyes of prospectors roaming the canyons in search of wealth missed few surface exposures of malachite or azurite within the cliffs and tributaries of the Colorado River. Old copper mines included the Chapel, Copper House, Copper Mountain, Cunningham, Grand Gulch, Grandview, Hack, Orphan, Ridenour, Savanic, and Snyder (Figure 3).

It was not until 1951 that uranium was first recognized in the Orphan breccia pipe (Chenoweth, 1986). During the period 1956-69, the Orphan mine yielded 4.26 million pounds of the uranium oxide U_3O_8 with an average grade of 0.42 percent U_3O_8. In addition to uranium, 6.68 million pounds of copper, 107,000 ounces of silver, and 3,400 pounds of the vanadium oxide V_2O_5 were recovered from the ore (Chenoweth, 1986). The Hack 1, Hack 2, Hack 3, Pigeon, and Kanab North pipes were brought into production during the 1980's. All of these pipes have been or are being mined solely for uranium.

Mineral Potential

Because erosion has stripped off much of the Mesozoic and uppermost Paleozoic rock along the western margin of the Colorado Plateau (Grand Wash Cliffs), the potential volume of uranium-mineralized rock in this region is minimal. In addition, many pipes along the Grand Wash Cliffs or in the depths of the Grand Canyon have been so thoroughly oxidized during the past 5 m.y. of canyon dissection that any uranium ore that may have been present has been oxidized and removed from the pipe.

Breccia pipes extend across most of the Colorado Plateau in northwestern Arizona and into the Basin and Range Province wherever the Redwall Limestone and overlying strata have been preserved. The potential for additional economic uranium-mineralized breccia pipes is enormous and is greatest beneath the flat plateaus where erosion and oxidation of the ore have been minimized. It is only on the Colorado Plateau, with its history of tectonic stability, that the uraninite has been preserved. Along the edges of the plateau and in the canyons, the ore-bearing minerals are usually oxidized to colorful secondary minerals.

The Basin and Range Province may also contain breccia pipes; however, they are probably entirely oxidized, such as at the Apex mine outside of St. George, Utah. Although the oxidized ore at this mine contains no significant amounts of uranium, it has yielded the new economic commodities, gallium and germanium. Even oxidized pipes, therefore, have economic potential.

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(continued on page 11)

Figure 6 (above). *Cyanotrichite [$Cu_4Al_2(SO_4)(OH)_{12} \cdot 2H_2O$] from the Grandview mine. Specimen photographed from the collection of the Denver Museum of Natural History.*

Figure 7 (right). *Goethite nodules, oxidized from pyrite, are exposed in an eroded surface of Esplanade Sandstone within a breccia pipe. The cores of some of the larger nodules contain unaltered pyrite.*

Figure 8. *Pipes exposed from the canyon wall upward to the overlying plateau are rare. Here at pipe #226 (location shown in Wenrich and others, 1987), the pipe exposure in the canyon wall is overlain by a shallow structural basin with concentrically inward-dipping beds.*

Figure 9. *Many pipes are expressed at the surface as a concentric series of gently dipping beds that form a closed, or nearly closed, basin. Such circular features are particularly evident on the Marble, Kaibab, and Coconino Plateaus where pipes are exposed in the Mesozoic or uppermost Permian rocks. Here in the EZ-1 pipe, beds of the Triassic Moenkopi Formation form a rim around the basin. An old copper prospect pit lies along the rim in the far side of the photograph.*

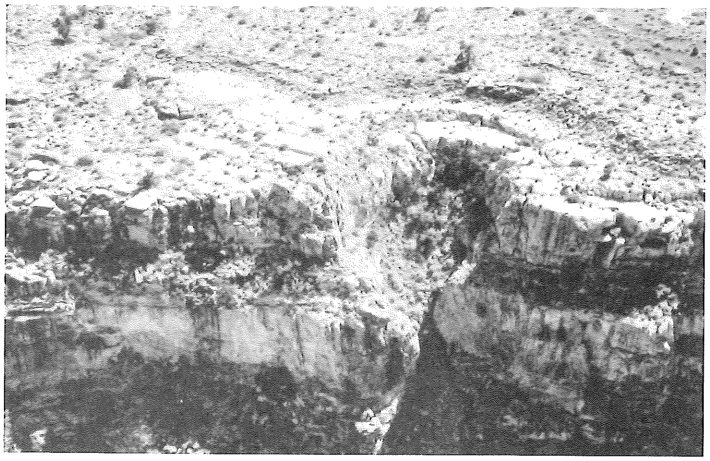

Figure 10. *Some pipes, such as #238 exposed in the Esplanade Sandstone on the Hualapai Indian Reservation (Wenrich and others, 1986), are expressed as semicircular steep-sided depressions open along the cliff face. This pipe is also bleached along its upper rim both within and outside the pipe. Toward the bottom of the depression, brecciated Esplanade Sandstone outcrops inside the ring fracture.*

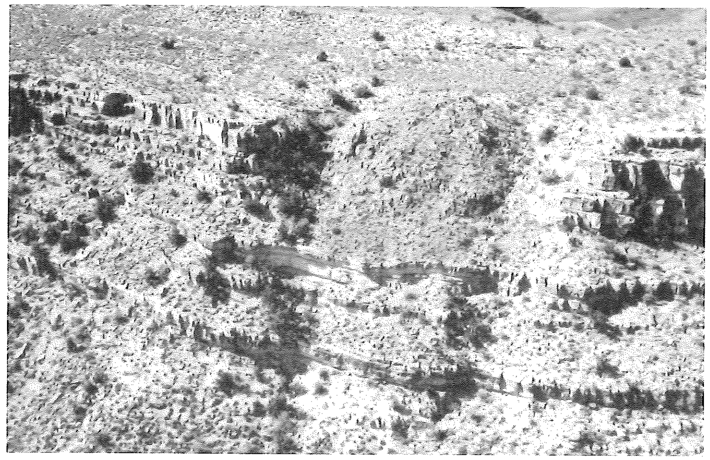

Figure 11. *Pipes are often preferentially eroded around the ring fracture, and occasionally the core of the pipe is preserved as a central hill. At pipe #267, located on the Hualapai Indian Reservation, the core of the hill is composed of a limonite-stained, silicified breccia, which rendered it more resistant to erosion than the surrounding country rock or ring fracture.*

Figure 12. *Circular patches of different vegetation types may suggest the presence of an underlying breccia pipe, as at pipe #321. This circular feature is produced by a grass-covered red soil developed on Surprise Canyon Formation downdropped into the cactus-bearing Redwall Limestone.*

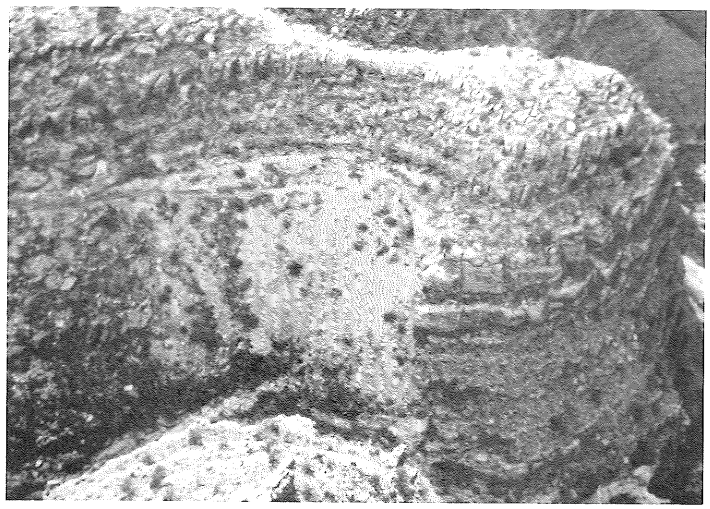

Figure 13. *The Ridenour mine, located on the Hualapai Reservation, has been mined intermittently for copper since the 1870's. All that remains of this pipe at the level of the Esplanade Sandstone is one-third of the ring-fracture zone. The pipe can easily be recognized on aerial photographs by the amphitheater and bleaching of the reddish-orange sandstone along the canyon wall. Samples with uranium concentrations of 3,000 parts per million and vanadium concentrations of 4 percent are present on the outcrop surface where the bleached Esplanade Sandstone has been dissected by the canyon.*