U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Breccia pipes in the Red Butte area of Kaibab National Forest, Arizona

By

Karen J. Wenrich[1]

Open File Report 92-219

[1]MS 939, Federal Center, Denver, CO 80225

BRECCIA PIPES IN THE RED BUTTE AREA OF KAIBAB NATIONAL FOREST

Karen J. Wenrich

INTRODUCTION

Thousands of solution-collapse breccia pipes occur within the southwestern corner of the Colorado Plateau in northern Arizona. Some of these breccia pipes are host to high-grade uranium deposits from which over 17 million pounds of U_3O_8 have been produced (Wenrich and others, 1989). Those deposits that have been mined range in size from 1 to 7 million pounds U_3O_8. Kaibab National Forest is located in the middle of this breccia pipe district and may include as many as several hundred breccia pipes. Nine confirmed breccia pipes located within Kaibab National Forest are known to be mineralized (contain ≥1 vertical core ft of 0.01% U_3O_8, Sutphin and Wenrich, 1988); all of these lie within the Tusayan Ranger District and include the Canyon, New Year, Black Box, Butte NE, Shale, Auto, Babbit, Otto 4, and Tap breccia pipes (see Sutphin and Wenrich, 1988 for locations). One of these, the Canyon pipe (fig. 1), contains a high-grade uranium orebody with associated Ag, Cu, Pb, V, and Zn. The mine permit for the Canyon pipe has been approved and the mine shaft headframe has been erected (fig. 2).

A four-quadrangle area, comprising approximately 40% of the Tusayan Ranger District, within Kaibab National Forest was selected as a control area to evaluate the potential of uranium-rich breccia pipes in Kaibab National Forest. Ideally the entire area should be mapped, but a small budget and a short time frame necessitated the need to select a representative area. An area of such size should be a reasonable pilot area--Finch and others, 1990, used a slightly smaller region as a control area to evaluate the uranium endowment of breccia pipes in the entire northwestern part of Arizona, an area 10 times the size of Kaibab National Forest. Their control area represented only 4% of the study area.

The Red Butte area (fig 1), including, but mostly south of, the town of Tusayan, was selected as the control area for this study because of (1) its accessibility, (2) reasonably good soil exposure throughout most of the area (tree density was high only in the northeastern part and no lavas bury the sedimentary strata as they do in the Williams and Chalendar Ranger Districts), and (3) its high potential for containing breccia pipes--5 uranium-mineralized breccia pipes have been drilled and identified by Energy Fuels Nuclear (Sutphin and Wenrich, 1989). The Red Butte area is comprised of the Tusayan East 7-1/2 minute quadrangle, where the Canyon Pipe is located, and the adjacent 7-1/2 minute quadrangles Tusayan West, Red Butte SW, and Red Butte; these 4 quadrangles have replaced the old Red Butte 15 minute quadrangle--hence, the name for the study area. This area was mapped for breccia pipes according to the methods and breccia pipe classification used by Wenrich and others (1986 and 1987) and Billingsley and others (1986 and 1990). The information in this report is based on four weeks of field work during May and June 1990, and prior experience by the author.

MINING OF BRECCIA PIPES IN AND ADJACENT TO KAIBAB NATIONAL FOREST

Mining activity in breccia pipes of the Grand Canyon region of northern Arizona began during the nineteenth century, although at that time production was primarily for Cu with minor production of Ag, Pb, and Zn. It was not until 1951 that uranium was first recognized in the Orphan breccia pipe (Chenoweth,

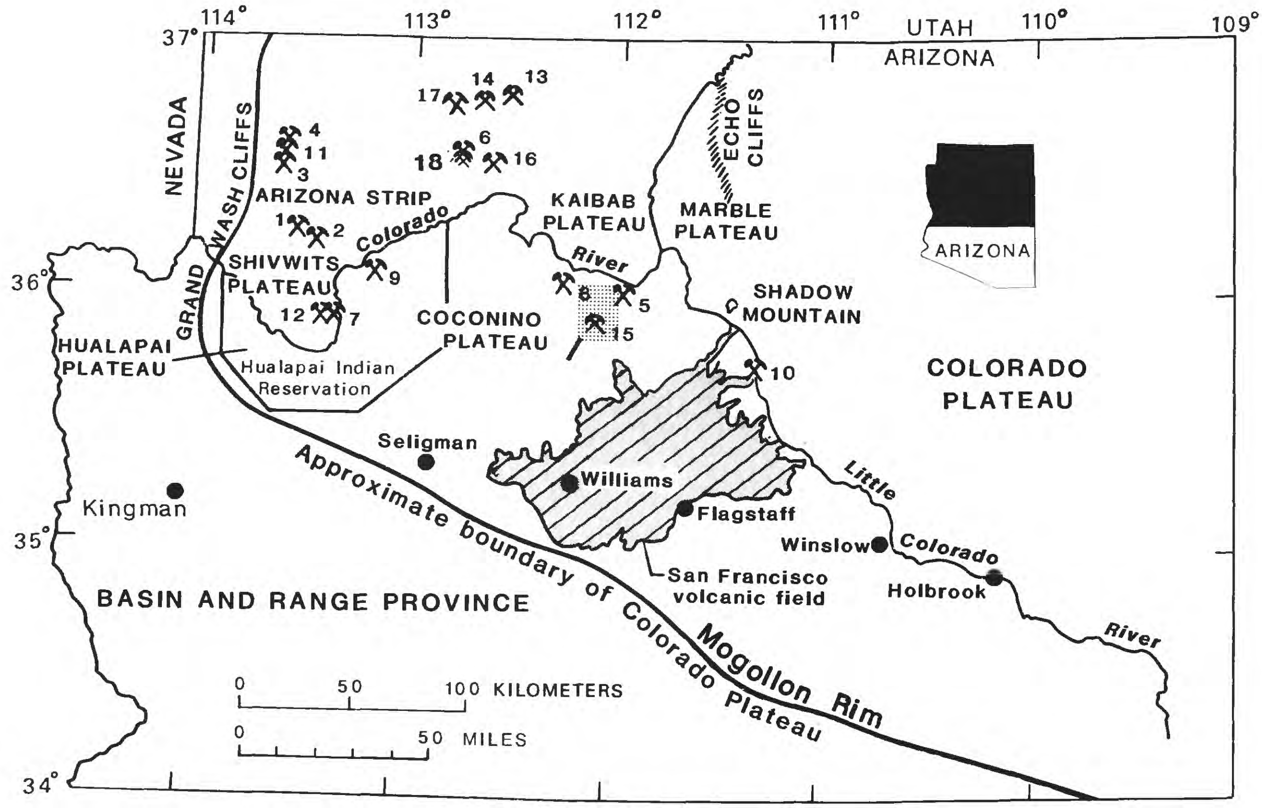

Figure 1.--Index map of northern Arizona showing the locations of plateaus, Hualapai Indian Reservation, breccia pipes developed into mines, and the San Francisco and Mt. Floyd volcanic fields (shown as hatched area) that bury terrane with high potential for mineralized breccia pipes. The Red Butte area is indicated by the stippled box immediately south of the Colorado River. Numbers refer to the following mines: (1) Copper House, (2) Copper Mountain, (3) Cunningham, (4) Grand Gulch, (5) Grandview, (6) Hack 1, 2, 3 and old Hack Canyon, (7) Old Bonnie Tunnel, (8) Orphan, (9) Ridenour, (10) Riverview, (11) Savannic, (12) Snyder, (13) Pigeon, (14) Kanab North, (15) Canyon, (16) Pinenut, (17) Hermit, and (18) Arizona 1.

(A)

(B)

Figure 2.--Canyon pipe. (A) Relatively undisturbed--photograph taken in 1986, and (B) Ready for mining operations--photograph taken in 1990.

1986; see fig. 1 for location). During the period 1956-1969, the Orphan mine yielded 4.26 million lbs of U_3O_8 with an average grade of 0.42%. In addition to uranium, 6.68 million lbs of copper, 107,000 oz of silver and 3400 lb of V_2O_5 were recovered from the ore (Chenoweth, 1986). The Orphan mine breccia pipe is located only 3.5 mi north of the Kaibab National Forest Boundary (Tusayan Ranger District) and 13 miles from the Canyon pipe.

The Hack 1, 2, and 3 and Pigeon pipes (fig. 1) were brought into production during the early 1980's, and the Kanab North mine during the mid 1980's. The Hack 1, 2, and 3 and Pigeon mines produced over 13 million lbs of U_3O_8 at an average grade of 0.65% U_3O_8 between January 1980 and August 1988 (Wenrich and others, 1989). Reid and Rasmussen (1990) report that the average grade of uranium ore mined in the Arizona Strip is 0.80%--this average probably includes the Kanab North mine, which was not included in the earlier 0.65% average.

LOCATION

Breccia pipes 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 (fig. 1). 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 under the lavas is doubtful, therefore, the possibility that accessible and economic breccia pipe orebodies exist in the Williams and Chalendar Ranger District is minimal. Moreover, the Redwall Limestone, which contains the roots of the breccia pipes, is thinner in these Districts (200 to 300 ft--McKee and Gutschick, 1969) than in the Tusayan District. Nevertheless, the absence of presently known pipes in the Williams and Chalendar districts is likely due to the fact that the area has not been as extensively explored as has been the Tusayan district. Pipes may extend to the east of the Echo Cliffs, buried beneath a thick pile of Mesozoic sedimentary rocks, but to date none are known. Southeast of Flagstaff, however, this is considered unlikely, because the Redwall Limestone thins toward the southeast (McKee and Gutschick, 1969) and pinches out between Holbrook and the Four Corners area.

DESCRIPTION AND ORIGIN

Breccia pipes in northwestern Arizona are strictly collapse in origin and resulted from dissolution and cavern formation within the Redwall Limestone, followed by progressive stoping, or gravitative collapse, of the overlying strata (fig. 3). Collapse produced steep-walled, pipelike bodies that were filled with angular to rounded fragments ranging from totally comminuted material to house-size blocks, bounded by a steeply dipping zone of ring fractures. No pipes contain fragments from underlying formations; all material has been dropped downward into the pipe. This presumably 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 ago), creating an extensive karst terrain characterized by closed depressions of 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 (fig. 4). Dissolution of the Redwall and collapse of the overlying strata either continued throughout the late Paleozoic and early Mesozoic or ceased after the Mississippian and was reactivated during the Late Triassic (approximately 210

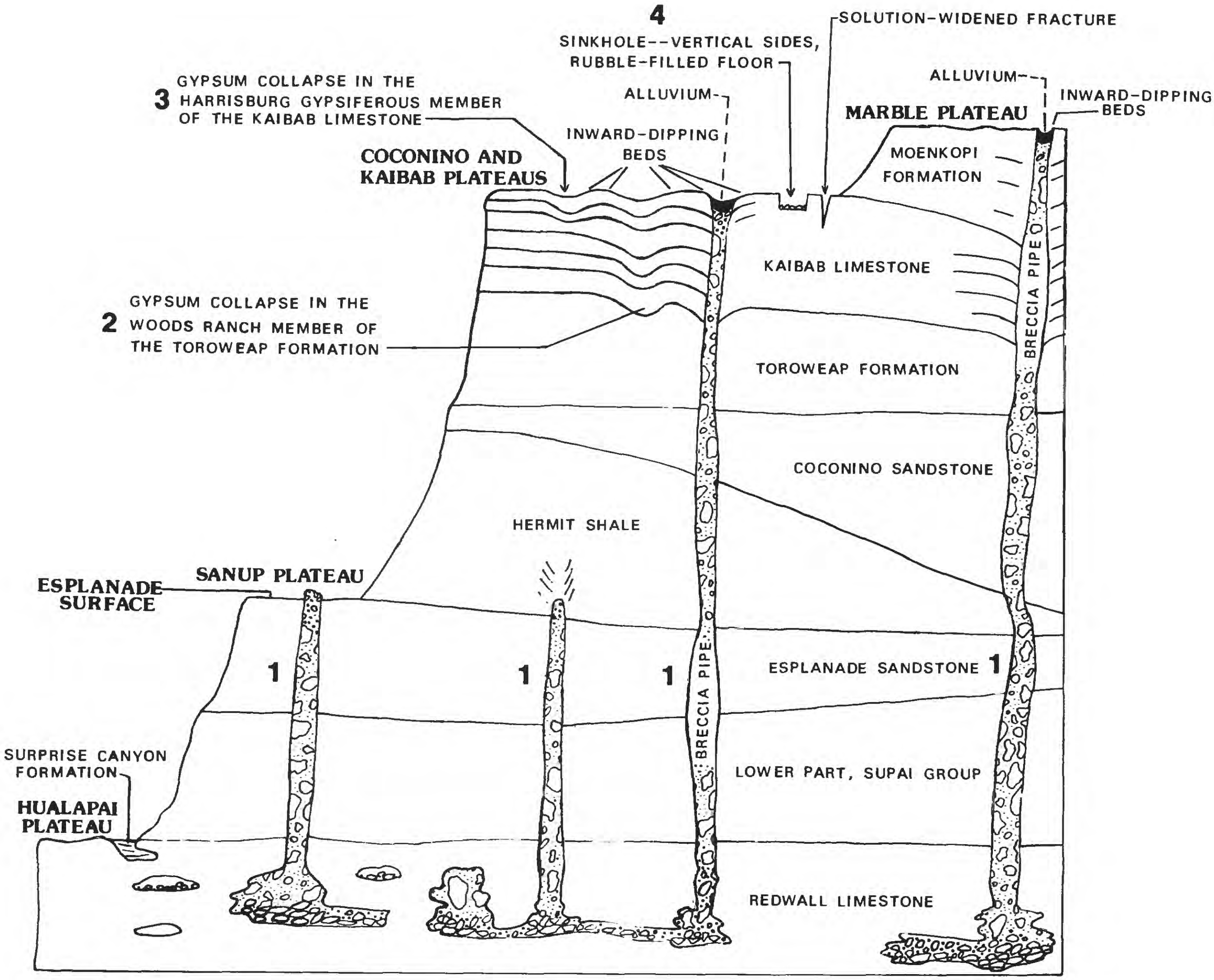

Figure 3.--Cartoon showing the various types of solution-collapse features found in northwestern Arizona: (1) Breccia pipes that bottom in the Redwall Limestone, (2) Collapse due to dissolution of gypsum beds in the Woods Ranch Member of the Toroweap Formation, (3) Collapse due to dissolution of gypsum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

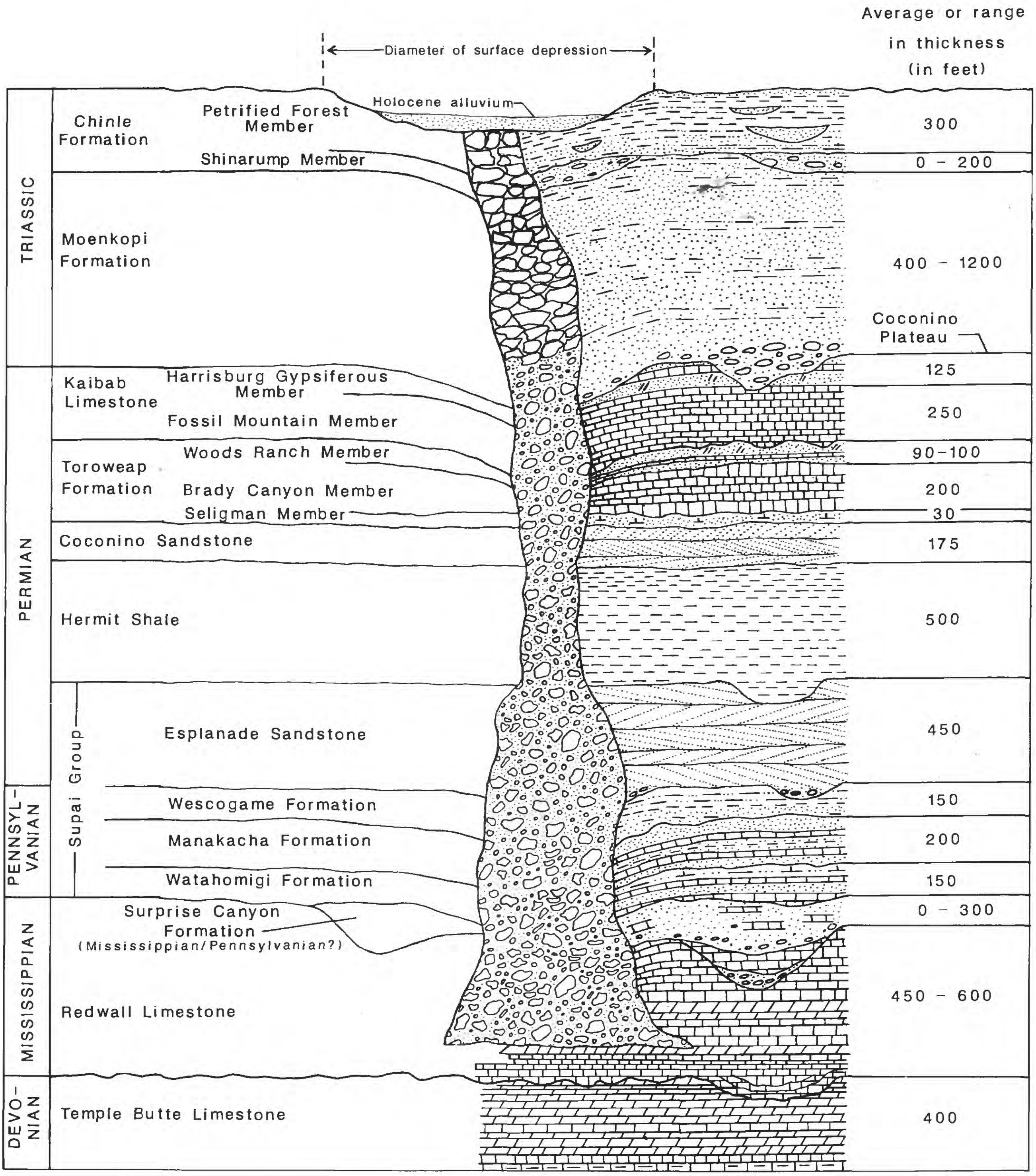

Figure 4.--Schematic cross section of a breccia pipe (based on cliff exposures in the Grand Canyon of Arizona). The unit thicknesses shown for the Triassic Chinle and Moenkopi Formations represent their thickness ranges in the Grand Canyon region. The unit thicknesses for the Paleozoic strata correspond to thicknesses that occur on the Coconino Plateau (from Wenrich, Billingsley, and Huntoon, 1986, which also provides unit descriptions). Cross section is from Van Gosen and Wenrich (1989).

m.y. ago) or earlier. No pipes have been observed in strata younger than Triassic. Such strata, however, have been removed by erosion across most of northwestern Arizona.

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

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 mi in diameter. 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 (fig. 3). These two formations create their own karst, which can easily be confused with that associated with the deeper-rooted breccia pipes (especially when tentatively identified on the basis of photogeologic interpretations that are not verified by field checking). This shallower karst is not known to contain any mineralized rock, and hence, should be distinguished from the circular features expressed on the Coconino and Kaibab Plateau surfaces that are surface manifestations of underlying, deeply-rooted breccia pipes.

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, Arizona 1, Pinenut, and Canyon pipe orebodies shows that the main uranium-mineralizing event occurred about 200 m.y. ago; data from Canyon and Pinenut pipes, however, indicate at least one earlier period of mineralization roughly at 260 Ma (Ludwig and Simmons, 1988). Petrographic studies suggest that uranium mineralization occurred after most of the Co, Cu, Fe, Mo, Ni, Pb, and Zn mineralization; hence, these other metals must have been deposited prior to 200 m.y. ago. Some Cu, Pb, and Zn minerals in both the Orphan mine and Canyon pipe appear to have formed after uraninite. 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.

MAPPING OF PIPES WITHIN KAIBAB NATIONAL FOREST

Surface Recognition

Breccia pipes are easily recognized within canyons where their vertical dimension is exposed. Most of Kaibab National Forest, however, is composed of undissected portions of the Kaibab and Coconino Plateaus. Recognition of pipes on these plateaus 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 (fig. 8 in Wenrich and Sutphin, 1988). Examples of such shallow structural basins can be seen south of Snake Gulch in the North Kaibab Ranger District of Kaibab National Forest--one good example lies on the west side of Table Rock Canyon (Billingsley, 1990).

Recognition of breccia pipes on Coconino and Kaibab Plateaus, which are capped by the Kaibab Limestone or Moenkopi Formation, 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. Such sinkholes are particularly conspicuous on the southern part of the Red Butte SW 7-1/2 minute quadrangle (Tusayan Ranger District) and along Fracas Canyon (North Kaibab Ranger District). In contrast, collapse features with tilted beds, brecciation, and alteration probably indicate the presence of breccia pipes that extend downward into the Redwall Limestone.

Mapping Techniques

The procedure for the mapping of breccia pipes as used successfully by Wenrich and others (1986 and 1987) and Billingsley and others (1986 and 1990) follows the following three steps:

1. Photogeologic interpretation using 1:24,000 color aerial photographs.
2. Low altitude (just above tree top) field checking using a helicopter.
3. Field checks on the ground to verify breccia, mineralized rock, surface formation, and/or inward-dipping beds.

Circular features are outlined on aerial photographs (step 1) to produce a template that should only be used as a preliminary guide for detailed field examination. Extreme caution was used during this study, as was done by Wenrich and others (1986 and 1987) and Billingsley and others (1986 and 1990), when mapping from the photographs, and under no circumstances were circular features not verified in the field transferred to a map with the implication that they are related to breccia pipes. Such a map is misleading and erroneous for the following reasons:

1. Circular features are also produced by geological and environmental phenomena other than breccia pipes, such as:
   a. Gypsum collapses into the Harrisburg Member of the Kaibab Limestone or Woods Ranch Member of the Toroweap Formation.
   b. Recent sink holes into the Kaibab Limestone.
   c. Sheep pens--those used by the Navajo Indians are circular and darker in the center (yes, due to organic enrichment of the soil).
   d. Man-made clearings and irrigation systems.
2. No significant correlation can be demonstrated between the number of circular features drawn on the photographs and the number of breccia pipes found on the ground. During mapping on the 1500 mi^2 Hualapai Reservation, for example, as many as 40% of the circular features identified by photogeologic analysis were verified on the ground to be pipes in some areas, whereas in other areas none could be verified as pipes (Wenrich and Billingsley, unpublished data). In addition, the number of aerial photo circular features observed in an area is strongly influenced by the vegetation density.
3. The number of circles drawn will be affected by the perceptual abilities and subjective state of the air-photo interpreter, and will

vary from day to day and from interpreter to interpreter as has been repeatedly demonstrated in lineament studies.

Any map of air-photo-generated circular features may lead to a signifcant overestimation of mineral resources, and create a false impression of a land pockmarked with uranium ore deposits. Any reliable map of possible breccia pipes must be a composite of field data including the scientific observations used to delineate terrane as a possible breccia pipe.

Field studies of less than one-quarter of the air-photo generated circular features in the original control area were completed due to a lack of funds--funds that were more limited than realized at the onset of the study. Because it is difficult to distinguish breccia pipes from the gypsum collapses even in the field, all circular features have been placed into categories dependent on such physical characteristics as: (1) the presence of concentrically inward-dipping beds, (2) altered rock (specifically, bleached and limonite-stained), (3) brecciated rock, (4) mineralized rock, and (5) circular vegetation or topographic anomalies--as done by Wenrich and others (1986). Figure 5 shows 4 areas where field mapping was completed; the physical characteristics that led to their classification as potential breccia pipes are discussed below. Other identified collapse features are not shown because mapping in these areas was not completed; presenting such features as isolated spots on the map would create a misleading collapse feature density. The density of collapse features within a control area is critical to an accurate mineral resource assessment.

Red Butte Area

The Red Butte area was selected for detailed study as an example of breccia pipe distribution within Kaibab National Forest because five uranium-mineralized breccia pipes are already known to be present. In addition to the Canyon pipe, the Shale, New Year, Black Box, and Butte NE pipes were drilled and all contain ≥ 1 vertical ft of 0.01% U_3O_8 (Sutphin and Wenrich, 1989). These five pipes lie within a 10 mi^2 area.

The Canyon, New Year, and Black Box pipes are expressed on the Coconino Plateau as large (about 1/3 mi across) circular patches of soil with spotty sage and grass in a subtle depression surrounded by Ponderosa Pines. The New Year pipe forms a closed depression. In contrast, the Butte NE pipe has good rock exposure, which forms a horseshoe-shaped ridge around a circular depression. Thin beds of red Moenkopi Sandstone dip inward toward the central depression of red soil. Beds of the Harrisburg Member of the Kaibab Limestone surround the Moenkopi Sandstone beds. Malachite chips were observed in drill cuttings spread about on the surface. The distinctive red color of the Shale pipe produces a marked contrast with the surrounding landscape; this contrast is presumably a result of downdropped Moenkopi within the pipe, surrounded by Kaibab Limestone.

The selection of targets for examination began with the mapping of suspiciously circular features or alteration halos visible on 1:12,000- and 1:24,000-scale color aerial photographs; the large number of targets identified within the four-quadrangle area reaffirmed its selection as an important area for evaluating breccia pipes within Kaibab National Forest. As many targets as possible (within the limitations of available funding) were examined from a helicopter and on the ground.

Several circular features were mapped during this study that exhibit surface characteristics similar to the above 5 known mineralized breccia pipes.

1. In T. 28N., R. 3E., Sec. 14 a large circular anomaly is visible from aerial photographs. On the ground the north, east, and south portions

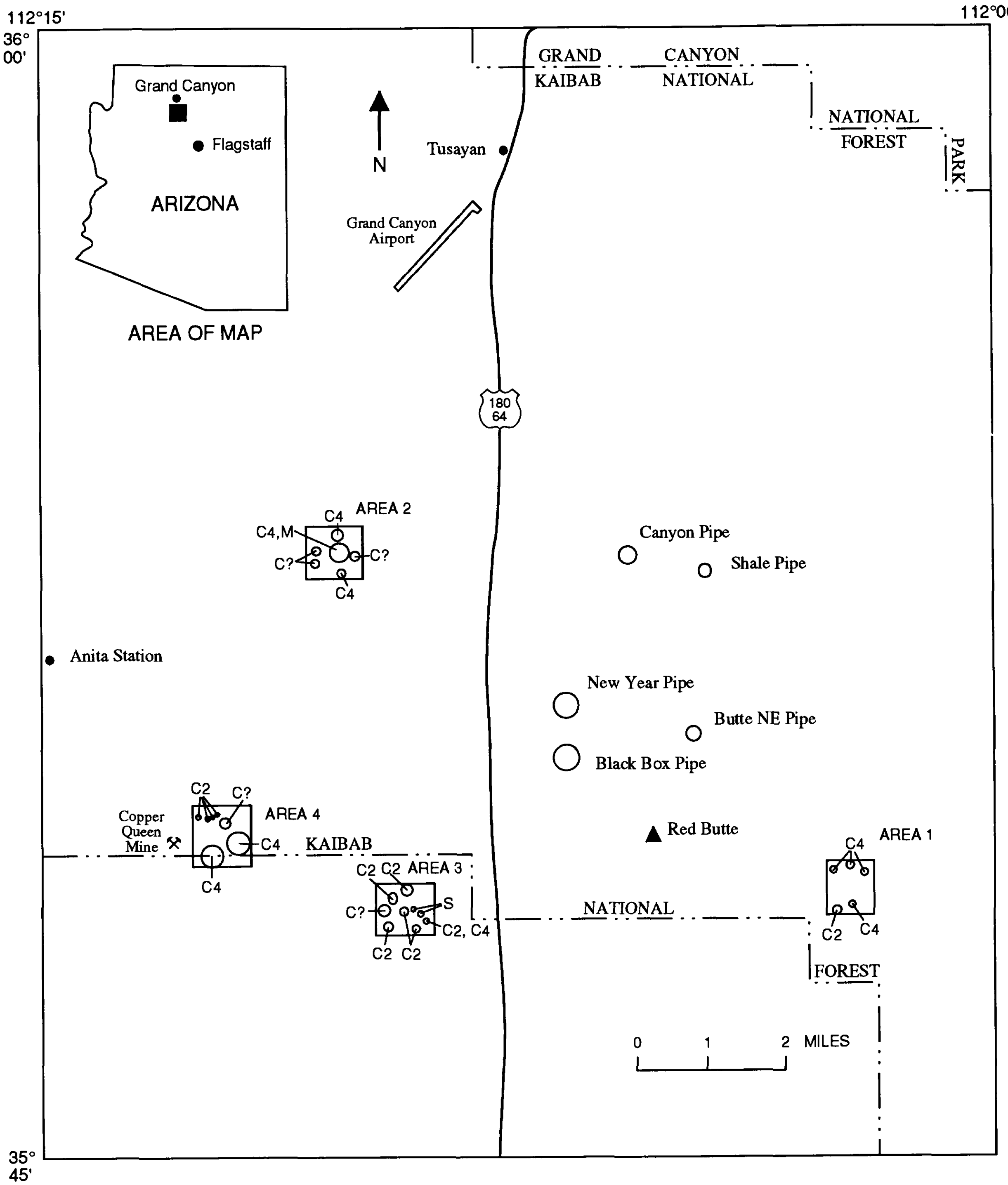

Figure 5.--Map showing the location of four areas where mapping of collapse features is complete within the Red Butte 15' quadrangle. These features were classified into 7 categories, based on the following physical properties observed in the field (category code shown in parenthesis): (C1) Altered rock and inward-dipping beds, (C2) Inward-dipping beds, (C3) Altered rock--specifically bleached and limonite-stained, (C4) Circular vegetation, soil, or topographic anomalies, (C?) Questionable vegetation or topographic anomalies, or inward-dipping beds, (S) Sinkhole, (M) Mineralized rock, and (B) Breccia.

of the perimeter of this feature are delineated with 5 smaller (about 500 ft in diameter) circular features. Several of these contain red Moenkopi Sandstone beds, providing a red color similar to that of the Shale or Butte pipes. The Moenkopi Sandstone beds within the southernmost of these features dip concentrically inward at 5-7°.

2. A distinctive circular feature with a central low hill and five centripetal drainages lies within T. 29N., R. 2E., Sec. 21 and 22. A 5-ft-deep prospect pit that was dug on the northern perimeter of the circular feature exposes hematitic breccia with goethite clasts, and emits gamma radiation of 2 times background. Due north of this collapse is a less conspicuous circular feature delineated by a drainage. Another prospect pit with gossan development, located within this feature, emitted gamma radiation of 10 times background. A sample of gossan from the pit (USBM sample no. 62) contains anomalous concentrations of several metals that are characteristic of breccia pipe deposits (7760 ppm As, 760 ppm Co, 222 ppm Mo, 2350 ppm Ni, 94 ppm U, and 3700 ppm Zn--sample submitted for analysis by the U.S. Bureau of Mines, Carl Almquist, written communication, 1990).
3. Facies changes within the Harrisburg Member of the Kaibab Limestone and the Toroweap Formation resulted in a thick sequence of gypsum along the western part of the area (in all parts of the Red Butte SW quadrangle except for the northeast). Dissolution of this exposed and near-surface gypsum has created a localized modern karst surface. Sinkholes with diameters ranging from 10-400 ft and depths of 1-30 ft form clusters throughout the area. In T. 28N., R. 2E. at the corner of sections 14, 15, 22, and 23, six circular features (one a sinkhole) lie along the perimeter of a larger circular feature. Three distinct sinkholes (shown on the 7-1/2 minute quadrangle with depression contours) occur within the center of the larger feature. Another significant cluster of sinkholes occurs in area 4 to the northeast in the area of the Copper Queen Mine.

This study revealed 71 field-verified, circular feature sites scattered about in the Red Butte area with physical characteristics established by Wenrich and Sutphin (1988) (discussed above under "Recognition Criteria") as favorable criteria for breccia pipe recognition. Several of these sites physically resemble one or the other of the 5 known mineralized breccia pipes in the area. Nevertheless, under no circumstances should the 71 sites be assumed to be a final reliable number of circular features for the control area as the study is less than half complete.

CONCLUSION

Only a small fraction of the breccia pipes present within Kaibab National Forest have been mapped. Any map of air-photo-generated circular features will produce overestimated mineral resources of at least an order of magnitude, and may create an image in the public mind of a land pockmarked with uranium ore deposits. Any map of possible breccia pipes must be a composite of field data, which includes the scientific criteria used to identify the breccia pipes. It was determined from this study and from studies by Billingsley and others (1986 and 1990) and Wenrich and others (1986 and 1987) that aerial photograph circular feature maps can not be used to make reliable resource estimations (or land management decisions) as a substitute for the more time-consuming and costly field-generated maps that show careful delineation of breccia pipe ring fracture zones. As a consequence, this report merely shows examples of four areas to illustrate the possible density of potential breccia pipes. Although 71 collapse features have been identified on the ground in the Red Butte area, the identification has been random. Only those four areas shown in figure 5 have been completely mapped to the extent that the author feels confident that no obvious breccia pipes have been omitted from within each area. Maps of scattered collapse features within incompletely mapped areas fail to provide an accurate breccia pipe density or show the common clustering of breccia pipes, and hence, result in inaccurate mineral resource estimates. Probably not all of the 71 collapse features mapped to date in the Red Butte area are the deeply-rooted breccia pipes--some are merely near-surface unmineralized gypsum collapses. Confirmation of the collapse features as breccia pipes can only be done in areas where the third dimension of the feature is exposed along cliffs, or on the plateaus through drilling or Audio-Magnetotelluric profiles.

One can probably expect to find a distribution of breccia pipes similar to that in the Red Butte area in any part of Kaibab National Forest, outside of the San Francisco and Mt. Floyd volcanic field cinder cones, silicic centers, and stratovolcanoes, which undoubtedly destroyed any underlying solution-collapse breccia pipes during their intrusion. Bearing in mind that the breccia pipes tend to be clustered, the regional distribution of breccia pipes across Kaibab National Forest should be roughly similar. That is, several pipes may be clustered within a one square mile area (such as the 4 Hack Canyon pipes on the North Rim), while surrounding square miles may have none. It is recommended that a study of the Red Butte, Red Butte SW, Tusayan East, and Tusayan West quadrangles be completed so that this Red Butte area might be used as a control area for uranium resource assessment of the remainder of Kaibab National Forest.

ACKNOWLEDGEMENTS

The author wishes to express her appreciation to Carl Almquist for his assistance in the field. His cheerful contributions and continual enthusiasm for breccia pipe mapping made the field work particularly fruitful. The patient assistance of Regina Aumente-Modreski in assembling the manuscript is also appreciated. Thanks goes to William Bagby, Branch Chief Western Mineral Resources, who provided much logistical help, scientific input, and funds for some illustrations used in this manuscript. His interest in seeing the scientific integrity of breccia pipe research preserved was a delight to witness.

REFERENCES CITED

Billingsley, G.H., 1990, Geologic map of the Jumpup Canyon and Big Springs Quadrangles, Mohave and Coconino Counties, Arizona: Geological Survey Open-File Report 90-258, 15 p., 1 plate, scale 1:62,500 (I-map 2290).

Billingsley, G.H., Wenrich, K.J., and Huntoon, P.W., 1986, Breccia pipe and geologic map of the southeastern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458-B, 26 p., 2 plates, scale 1:48,000.

Billingsley, G.H., Wenrich, K.J., Huntoon, P.W., and Young, R.A., 1990, Breccia pipe and geologic map of the southwestern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458D, 33 p., 2 plates, scale 1:48,000.

Chenoweth, W.L., 1986, The Orphan Lode mine, Grand Canyon, Arizona, a case history of a mineralized, collapse-breccia pipe: U.S. Geological Survey Open-File Report 86-510, 126 p.

Ludwig, K.R., and Simmons, K.R., 1988, Progress in U/Pb isotope studies of collapse-breccia pipes in the Grand Canyon region, northern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A139.

Finch, W.I., Sutphin, H.B., Pierson, C.T., McCammon, R.B., and Wenrich, K.J., 1990, The 1987 estimate of undiscovered uranium endowment in solution-collapse breccia pipes in the Grand Canyon region of northern Arizona and adjacent Utah: U.S. Geological Survey Circular 1051, 19 p.

McKee, E.D., and Gutschick, R.C., 1969, History of the Redwall Limestone of northern Arizona: Geological Society of America Memoir 114, 692 p.

Reid, A.R., and Rasmussen, J.D., 1990, The use of soil-gas CO_2 in the exploration for sulfide-bearing breccia pipes in northern Arizona: Journal of Geochemical Exploration, v. 38, nos. 1/2, p. 87-101.

Sutphin, H.B., and Wenrich, K.J., 1989, Map locations of collapse-breccia pipes in the Grand Canyon of Arizona: U.S. Geological Survey Open-File Report 89-550, 1 plate, scale 1:250,000.

Van Gosen, B.S., and Wenrich, K.J., 1989, Ground magnetometer surveys over known and suspected breccia pipes on the Coconino Plateau, northwestern Arizona: U.S. Geological Survey Bulletin 1683-C, 31 p.

Wenrich, K.J., Billingsley, G.H., and Huntoon, P.W., 1986, Breccia pipe and geologic map of the northeastern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458-A, 29 p., 2 plates, scale 1:48,000 (to be later released in the I-map series).

______1987, Breccia pipe and geologic map of the northwestern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458-C, 32 p., 2 plates, scale 1:48,000 (to be later released in the I-map series).

Wenrich, K.J., Chenoweth, W.L., Finch, W.I., and Scarborough, R.B., 1989, Uranium in Arizona, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 759-794.

Wenrich, K.J. and Sutphin, H.B., 1988, Recognition of breccia pipes in northern Arizona: Field Notes, v. 18, No. 1, p. 1-5, 11.