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CONTRIBUTIONS TO THE GEOLOGY OF URANIUM MINERALIZED BRECCIA PIPES IN NORTHERN ARIZONA

Dieter A. Krewedl*

Jean-Claude Carisey**

ABSTRACT

Exploration for high grade uranium bearing breccia pipes is centered on Mississippian to Triassic age rocks on the Colorado Plateau portion of Northern Arizona. Numerous pipes are exposed on the walls of the Grand Canyon and its tributaries, but their recognition on the undissected plateaus can be difficult.

Breccia pipes consist of two interrelated parts: the throat and the collapse cone. Originating in the Mississippian Redwall Limestone, the throat consists of the downward displaced and brecciated strata as young as the Triassic Chinle Formation.

The collapse cone surrounds the throat above the Coconino Sandstone level and was caused by dissolution within the Kaibab and Toroweap formations. Its area of influence is much wider than the throat and can be expressed on the plateau surfaces by concentric, inward dipping beds.

Uranium mineralization is found mostly within the throat in strata that range from the Seligman Member of the Toroweap Formation to the Supai Group. Associated metals include copper, arsenic, nickel, lead, zinc and silver.

The uranium was probably derived from the Chinle Formation and moved either down the pipe's throat directly or indirectly by lateral transport through an aquifer such as the Coconino Sandstone. Precipitation of the uranium occurred when the metal rich oxidizing solutions encountered the highly reduced breccia pipe environment. Reduction in the described EZ-2 breccia pipe was caused by hydrocarbons that probably migrated out of the Brady Canyon Member of the Toroweap Formation. The mineralization event occurred sometime between Late Triassic and Cretaceous time.

INTRODUCTION

Exploration and mining of various metals in Northern Arizona began in the late 19th Century. Small mines were developed throughout the area within rocks from the Mississippian Redwall Limestone to the Triassic Chinle Formation. Copper was the main metal produced as well as some silver, lead, and zinc.

Uranium mineralization was later discovered in association with some of these copper deposits that eventually became recognized as breccia pipes. The Orphan copper mine located on the South Rim of the Grand Canyon later became the first major uranium mine in the district (Figure 1). It produced 4.4 million pounds with an average grade of 0.42% U_3O_8. In addition to uranium, 6.7 million pounds of copper and 100,000 ounces of silver were mined (Baillieul & Zollinger, 1980).

Another noted copper mine located in Hack Canyon was also eventually recognized as a uranium bearing breccia pipe. The nearby Hack 2 breccia pipe currently being mined is reportedly of comparable size and grade to the Orphan mine.

Recent, intensive exploration has demonstrated these high grade uranium bearing breccia pipes to be more widespread than previously thought. The excellent exposures along canyon walls have aided in the discovery of mineralized breccia pipes such as Hack 2 and 3, Kanab North, Pigeon and Mohawk Canyon (Figure 1).

The wide aerial distribution of these breccia pipes is indicative of the enormous size of the prospective exploration area as well as the potential for more discoveries on the undissected plateaus. Recognition of breccia pipes on the flat, high plateaus is more difficult in that some show only subtle surface expressions. Discoveries have been made such as the Canyon and EZ-2 (Figure 1) suggesting more will be found as exploration continues.

The search for mineralized breccia pipes and understanding their origin are some of the most exciting challenges facing exploration geologists today. Thousands of circular features occur within Mississippian to Triassic formations in Northern Arizona. However, only a fraction of these are actual breccia pipes and even fewer may be significantly mineralized.

The purpose of this paper is to summarize some of our observations on the geology of the breccia pipes and present a model for their formation and mineralization. These observations are based both

* Pathfinder Mines Corporation
** Cogema, Inc.
1250 W. Sunset Blvd.,Suite A, St. George, Utah 84770

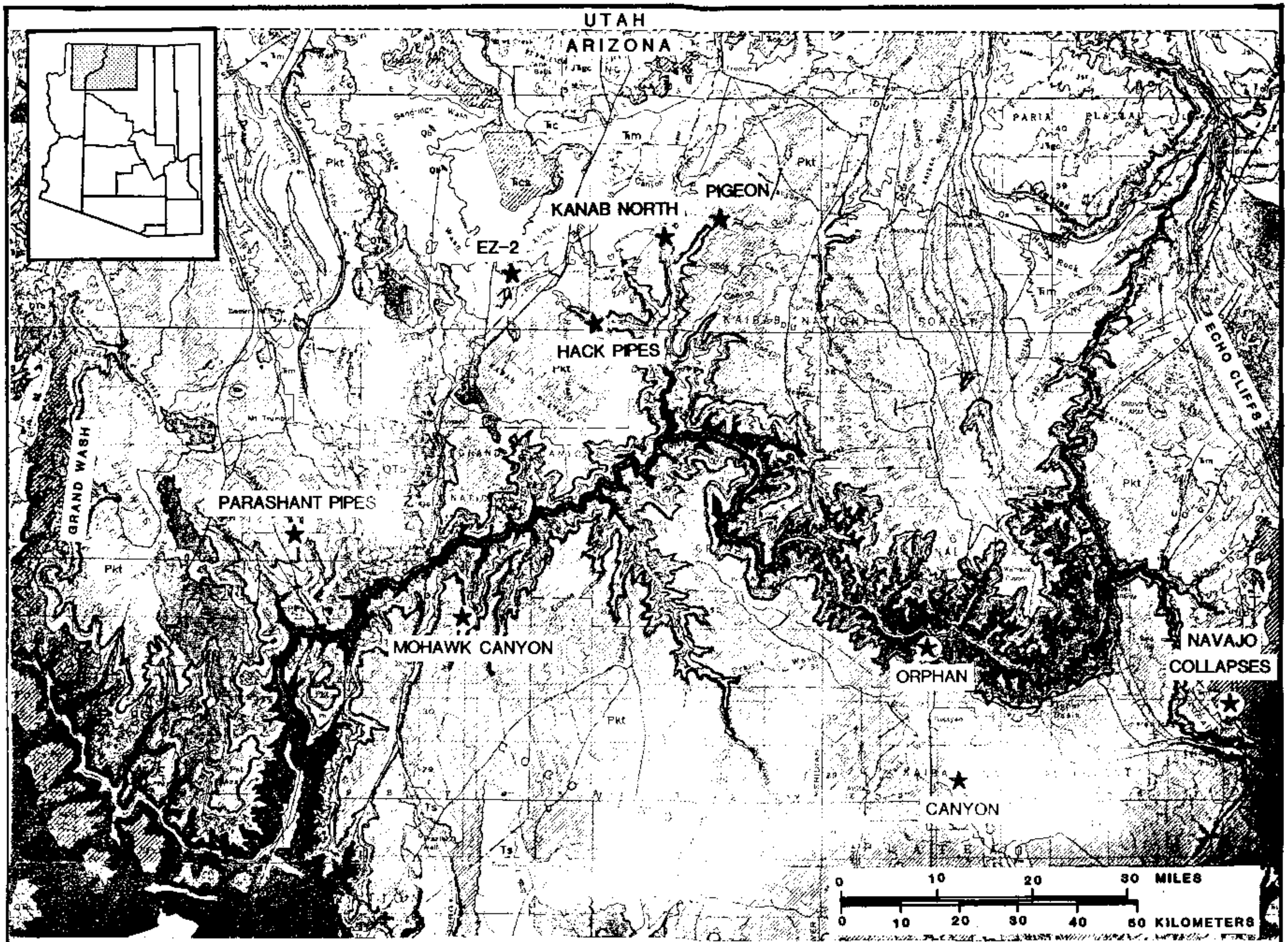

Figure 1. General geologic map of Northwestern Arizona showing location of selected breccia pipes.

on the exposed breccia pipes and drilling results, particularly from Pathfinder Mines Corporation's recent EZ-2 discovery.

GEOLOGIC SETTING

Exploration for breccia pipes is concentrated on the Colorado Plateau portion of Northern Arizona. Excellent exposures of the generally flat lying Paleozoic to Mesozoic strata are provided by the Grand Canyon and its tributaries (Figure 1). The broad, undissected plateaus between Grand Wash and Echo Cliffs are capped primarily by the Permian Kaibab Formation and to a lesser extent by the Triassic Moenkopi Formation. The only exposed igneous rocks are Tertiary basalt flows and dikes that locally cover the high plateaus.

Faults and broad folds traverse portions of Northern Arizona. These structures are considered to be Cretaceous to Tertiary in age.

VERTICAL AND LATERAL DISTRIBUTION OF BRECCIA PIPES

The development of karsts within the Mississippian Redwall Limestone accompanied by later upward stoping through the overlying Paleozoic and Triassic rocks resulted in the formation of breccia pipes (Figure 2). Downward displacement by block caving created an essentially vertical column affecting up to 3,000 ft. of strata.

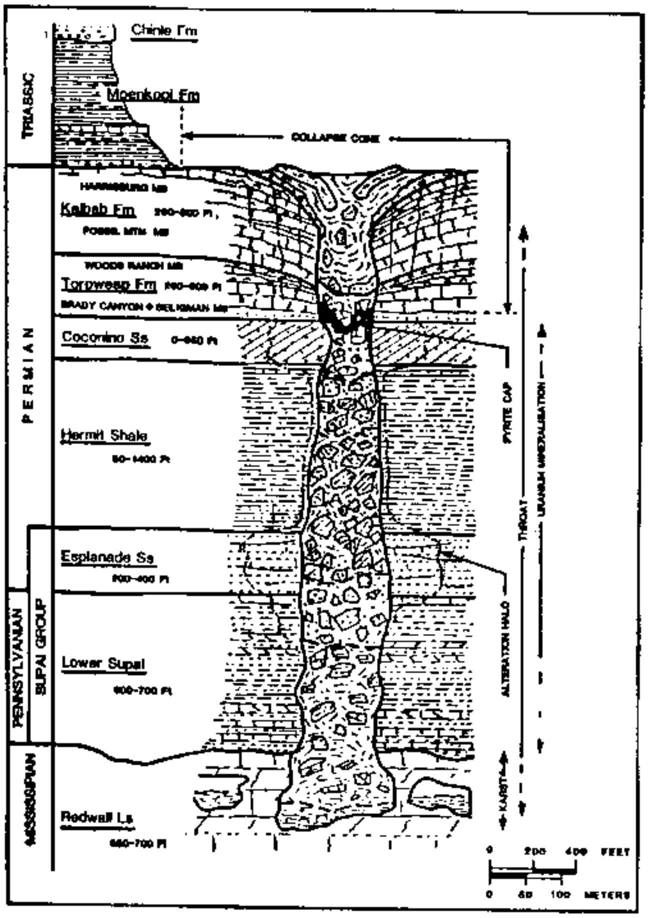

Figure 2. Stratigraphy and schematic cross section of a Northern Arizona breccia pipe.

Collapses, which are thought to be breccia pipes at depth, are exposed as high as in the Petrified Forest Member of the Chinle Formation on the Navajo Reservation to the east. Further to the west as in Parashant Canyon, breccia pipes outcrop in lower stratigraphic levels such as the Hermit Shale and Supai Group. Within the Grand Canyon itself, the base of the breccia pipes are exposed in the Redwall Limestone.

PIPE MORPHOLOGY

Analyses based on observations of exposures on canyon walls and drilling results demonstrate that breccia pipes consists of two interrelated parts: the throat and collapse cone. Some variations of the model presented in Figure 2 are to be expected depending on changes in facies or thickness of the strata.

THROAT

The throat of the breccia pipe is defined as that volume within which the rocks have been brecciated and displaced downward with respect to the surrounding strata. The lateral boundary of the throat can be envisioned as a cylindrical fault surrounding the "piston" of sediments, which have collapsed down the pipe.

The amount of displacement varies from pipe to pipe, but can be on the order of several hundreds of feet. For example, in the Kanab North pipe, the Moenkopi Formation was displaced downward approximately 700 ft. into the Toroweap Formation (Wenrich & Rasmussen, 1985).

The throat is generally circular in horizontal section, but may also be moderately elongated or irregular. The common diameter is on the order of 100 to 300 ft., which varies depending upon rock type and possibly on the size of the original Redwall Limestone cavity. The variations in diameter within one pipe are illustrated on the EZ-2 geologic map (Figure 3) where the projected throat at Toroweap Formation level is 175 ft. across and increases to about 300 ft. at Esplanade Sandstone level.

The axis of the throat is consistently within a few degrees of vertical but variations do occur. As an example the EZ-2 throat is essentially vertical through the upper part of the stratigraphic column (Figure 4). However, from the Coconino Sandstone down through the upper Hermit Shale, the throat's axis becomes less steeply inclined and plunges first to the south and then to the southwest. In the lower Hermit Shale and Esplanade Sandstone, the throat is again essentially vertical.

The intrapipe breccia consists of angular to rounded clasts ranging in size from less than an inch to tens of feet. The clasts and matrix themselves are of varying proportions and may originate from the same or different sedimentary units.

Coconino Sandstone and Hermit Shale derived breccia is compact and well indurated. On the other hand, breccia from the Kaibab and Toroweap formations show significant secondary porosity evidenced by the abundant fractures and vugs.

The heterogeneity of the clasts makes any lateral correlation within the throat very difficult. An unusual example [illegible] continuity

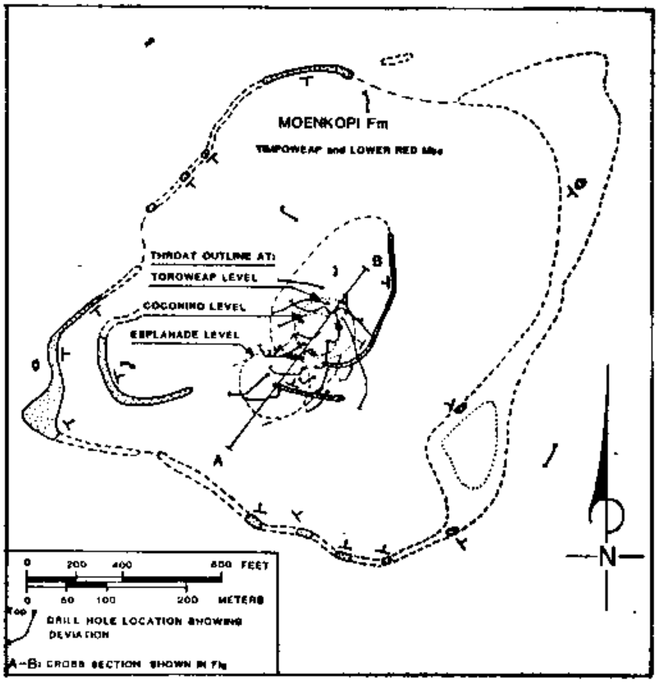

Figure 3. EZ-2 geologic map showing the outline of the throat at various stratigraphic levels.

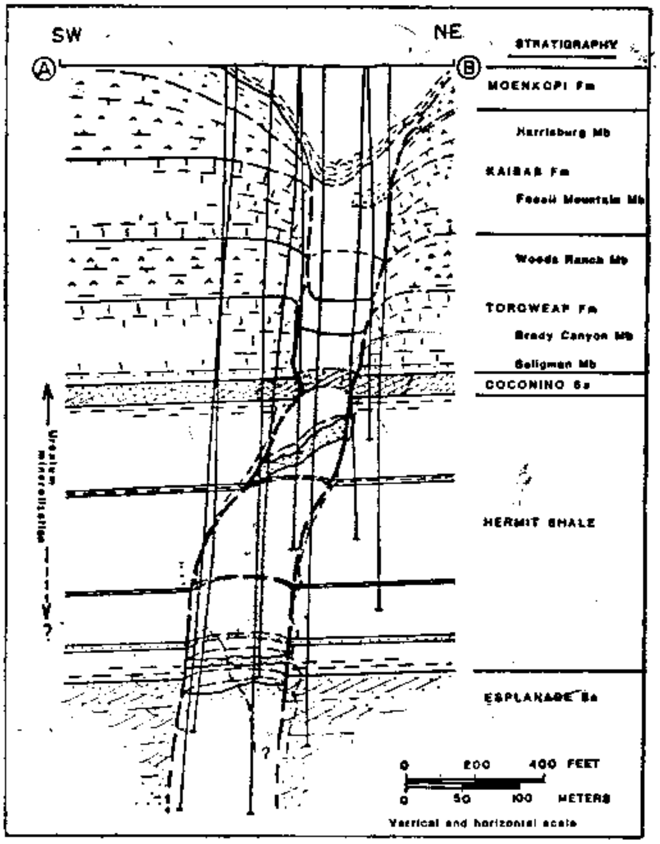

Figure 4. Cross section through the EZ-2 breccia pipe, Northern Arizona.

within the EZ-2 throat is shown in Figure 4. A 50 ft. thick sand unit apparently derived from the Coconino Sandstone has been redeposited 150-300 ft. below its normal position. In this case, the matrix and clasts are indistinguishable resulting in a massive, laterally continuous sandstone.

The strata immediately adjacent to the pipe's throat below the Coconino Sandstone show no deformation. However, surface mapping and drilling have shown that the strata overlying the Coconino Sandstone have been deformed over a substantially larger area surrounding the throat.

COLLAPSE CONE

The collapse cone is that volume of rock above the Coconino Sandstone and surrounding the throat, which has been structurally deformed (Figure 2). Surface and subsurface units form a series of inverted, nested cones. Dips are greatest near the center and gradually decrease outward. Additionally, the dip adjacent to the throat decreases with depth until at and below the Coconino Sandstone, no deformation is present.

The type of deformation within the collapse cone is essentially plastic in contrast to the brittle deformation characterizing the throat. Contacts can be recognized and lateral continuity is maintained. At the detailed level of examination, fracturing does occur in individual beds, but the large scale plastic character is revealed by their outcrop pattern (Figure 3) and their downwarp (Figure 4).

The cause of this deformation in the collapse cone is the systematic thinning of certain stratigraphic units towards the pipe throat. For example, over a horizontal distance of approximately 1,100 ft. on the EZ-2, a total of 300 ft. of limestones and evaporites from the Kaibab and Toroweap formations combined have been removed by dissolution. This allowed the remaining rocks to collapse downward forming the inward dipping collapse cone.

The resultant effect is to downdrop and preserve from erosion an ever increasing amount of Moenkopi Formation and younger sedimentary rocks towards the center of the structure (Figure 5). Drilling has shown that at least 365 ft. of Moenkopi Formation is preserved within the EZ-2 structure, but surface erosion has removed all except 20 ft. in the immediate area.

Samples of the Kaibab and Toroweap formations from the collapse cone are highly porous and consist largely of the insoluble portions of the original rocks (Figure 6). For example, solution collapse breccia of the Kaibab Formation consists largely of siliceous remnants and chert fragments derived from what was originally a relatively massive, cherty limestone.

The size of collapse cones can vary greatly. The collapse structures on the Navajo Reservation in the Chinle Formation have affected a surface area over one mile in diameter. An example of the other extreme is the Hack 2 breccia pipe, which seems to have little or no surface expression on the Kaibab Formation surface. Some of the causes for the variations in size can include the amount of available leachable rock and the stratigraphic level of exposure.

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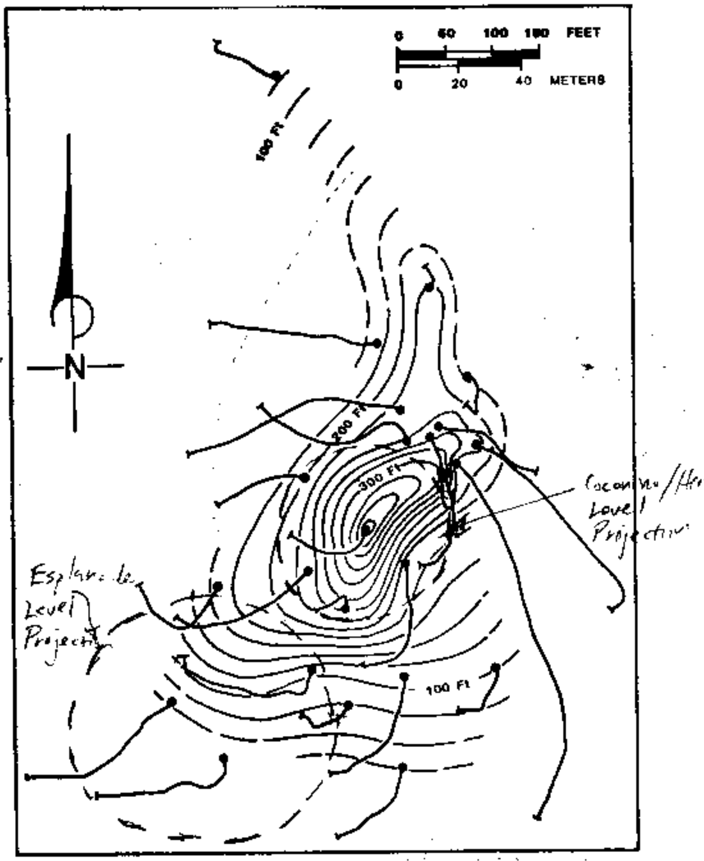

Figure 5. Isopach map of the Lower Red Member of the Moenkopi Formation in the EZ-2 breccia pipe.

The EZ-2 breccia pipe shows a typical series of inward dipping beds becoming progressively steeper and younger towards the center. The diameter of the area affected by the EZ-2 collapse cone is approximately 2,500 ft., or 10 times the diameter of the throat.

Recent solution cavities are fairly common in Northern Arizona where the Kaibab Formation outcrops. These shallow seated, flat bottom sinkholes are not to be confused with dissolution in a collapse cone. The latter is centered around the pipe's throat and is a much older feature, which developed beneath a relatively thick cover of Moenkopi Formation.

ALTERATION

The alteration associated with breccia pipes is of three general types: 1) reduction due to the introduction of hydrocarbons, 2) dissolution, and 3) oxidation.

REDUCTION

Hydrocarbons were introduced into the brecciated sediments of the pipe's throat. Potentially, the entire vertically displaced column could have been reduced in any given pipe. Particularly high concentrations of hydrocarbons are located at the lowermost Toroweap Formation and upper Coconino Sandstone levels. It is intimately associated with a mixed suite of sulfides, where pyrite is dominate. This heavy concentration of organics and sulfides is often referred to as a pyrite cap (Figure 2). Its thickness is highly variable being practically nonexistent in some pipes to almost 200 ft. in others.

Reduction has altered the normally tan colored Coconino Sandstone to a light gray unit. Selective quartz dissolution by the organics (Figure 7) is particularly noticeable. Reprecipitation of the silica occurs in the form of quartz overgrowths.

The pervasive reduction of the Hermit Shale breccia in the EZ-2 pipe seems to decrease with depth. The effect of reduction is easily discernible. The normally brick red sediments become light to greenish gray. Figure 6 shows the coarser grained matrix to be completely reduced while the finer grained, red Hermit Shale clasts show an alteration rim.

In the EZ-2 pipe, reduction is not restricted to the pipe's throat but extends at least 1,000 ft. from the center out into the Coconino Sandstone. The resultant lateral extent of the reduction halo is much wider in the Coconino Sandstone than in the adjacent units.

At Hermit Shale level reduction is restricted to less than 50 ft. outside the pipe's throat. However, the lateral extent of reduction in the top of the Hermit Shale parallels the alteration in the Coconino Sandstone. A thin, reduced zone at the top of the Hermit Shale can extend outward from the throat for hundreds of feet.

DISSOLUTION

Dissolution is most obvious in the evaporite rich Harrisburg and Woods Ranch members of the Kaibab and Toroweap formations. As an example, in the EZ-2 pipe the Woods Ranch Member of the Toroweap Formation decreases from its normal 200 ft. thickness to approximately 100 ft. adjacent to the pipe's throat. This dramatic thinning is mostly accomplished by the selective removal of anhydrite and gypsum.

Furthermore, dissolution effects on the massive limestone members in the Kaibab and Toroweap formations consist of the progressive removal of all carbonates. The remnant product is a tan, vuggy solution breccia comprised of siliceous, insoluble residues.

OXIDATION

Oxidation of the pyrite within the throat and the adjacent country rock resulted in the presence of limonite, goethite and box work textures. It is primarily noticeable in the Kaibab and Toroweap section which in combination with dissolution formed a vuggy, porous breccia.

Destruction of the previously deposited uranium mineralization within the throat is possible by oxidizing ground water. In the EZ-2 pipe, oxidation occurs down to the pyrite cap in the lower Toroweap Formation.

MINERALIZATION

Uranium mineralization is found in reduced rocks ranging from the Seligman Member of the Toroweap Formation to the Lower Supai Group. It occurs either in vertical, discontinuous pods inside

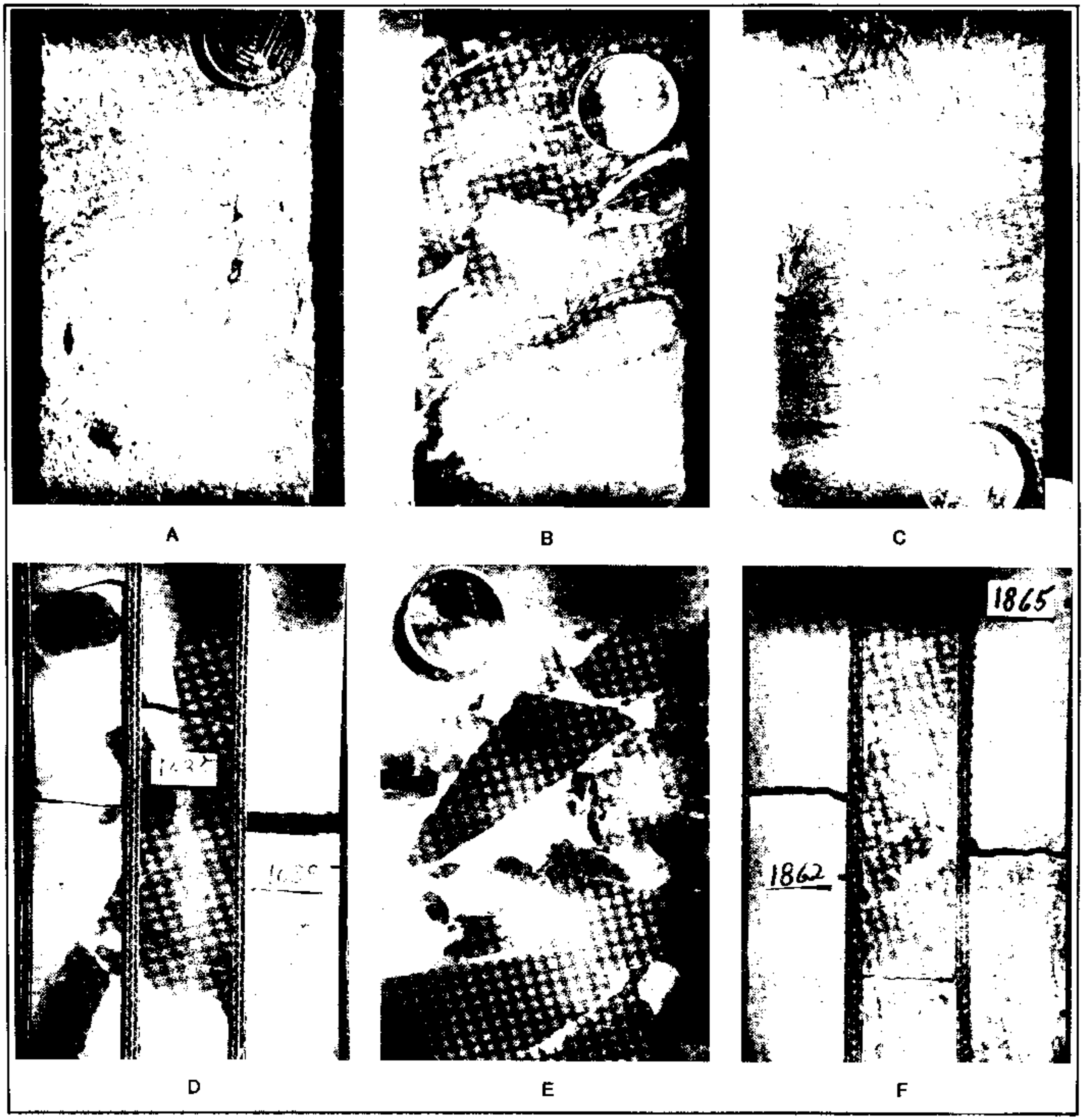

Figure 6. Core samples taken from various stratigraphic levels in the EZ-2 breccia pipe.
6A. Limestone breccia from the Kaibab Fossil Mountain Member.
6B. Anhydrite breccia with gypsum veinlets from the Toroweap Woods Ranch Member.
6C. Organic facies from the Toroweap Brady Canyon Member with bitumen (black) and pyrite (white).
6D. Hermit breccia showing reduction in the matrix (white) and along the contact with unaltered clasts (black).
6E. Unaltered Hermit breccia.
6F. Hydrocarbons impregnating Esplanade Sandstone.

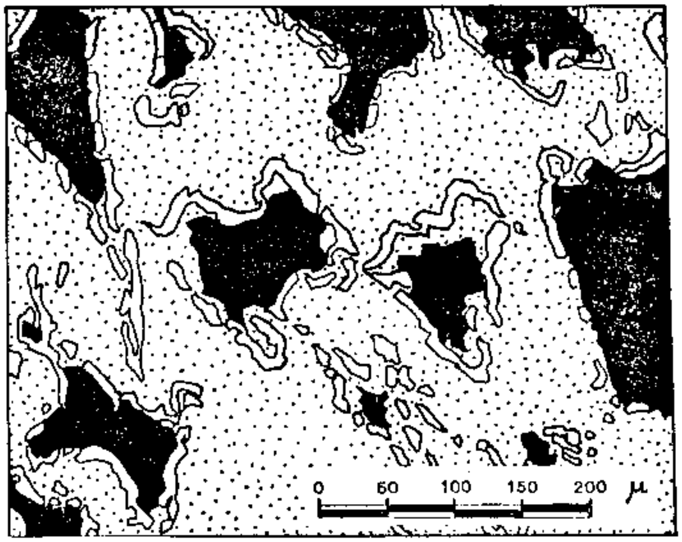

Figure 7. Sketch of a thin section from the Coconino Sandstone showing partly dissolved quartz grains (black), bitumen stiped and contorted pitchblende halos (white).

the pipe or in annular rings at the outside edge of the pipe. Mineralization over a 600 ft. vertical interval in any one pipe is not uncommon.

The primary uranium mineral is pitchblende. Mineralization occurs in the matrix and to a lesser degree the clasts in the breccia where it coats individual grains. It occurs in fractures and can also impregnate primary sedimentary features outside the throat.

Numerous anomalous trace elements have been found in the breccia pipe directly associated with uranium. Most significant are copper, arsenic, nickel and lead, and to a lesser extent zinc and silver. No obvious metal zonation is recognizable at present.

SOURCE OF REDUCTANTS

Introduced hydrocarbons are responsible for the reduction both within breccia and in portions of the unbrecciated wall rocks surrounding mineralized breccia pipes. The source rocks and migration pathways for these hydrocarbons are, therefore, of great significance.

The marine limestones present in the Mississippian to Permian strata each contain variable amounts of hydrocarbons. One or more of these limestones could be the source rock for the migrated hydrocarbons in any given breccia pipe.

Certain characteristics of the oil found in the EZ-2 breccia pipe suggests that the source rock is the Brady Canyon Member of the Toroweap Formation. Before any definite conclusions can be made, further studies must be undertaken on the oil bearing carbonate units in the Supai Group or Redwall Limestone.

The migration of reductants within porous zones of the breccia is directly illustrated by the alteration pattern within partially reduced breccia. Similarly, relative porosity controls the lateral limits of reduction in wall rock beds surrounding the throat.

The vertical direction of reductant migration is not as clearly indicated. Reduction has been observed as high in the stratigraphic column as the Moenkopi Formation and as deep in the section as the Redwall Limestone.

No clear criteria demonstrate that oil flowed upward or downward through the pipes, which basically depends on the position of the source rock. Volumetrically in the EZ-2 pipe, degraded oil is abundant in vuggy carbonate breccia of the Toroweap Formation. Additionally, some evidence exists that the amount of reduction within the throat decreases and eventually ceases at depth in some pipes.

SOURCE OF URANIUM

The source of the uranium and other metals present in breccia pipes has not been firmly established.

An abundant source for uranium which became available at approximately the correct time is the silicic volcanoclastic sediments and tuffs deposited within the Chinle Formation. Ore deposits within the Chinle Formation commonly occur within stream channels indicating significant mobilization and groundwater transport of uranium and other metals.

At least some breccia pipes are known to penetrate Chinle Formation rocks. Any hydrologic connection could have transported this uranium to the pipes, whether directly through the upper part of the throat or via connecting aquifers such as the Coconino Sandstone. Possible ingress of metal rich ground water could have occurred in areas such as the Black Mesa Basin towards the east where the Chinle Formation directly overlies the Coconino Sandstone.

PIPE FORMATION AND MINERALIZATION - TIME AND TEMPERATURE CONSTRAINTS

The broadest time constraints on the formation of breccia pipes are provided by stratigraphic evidence and age dating of the mineralization.
Timing for the most recent proven movement is constrained by the fact that breccia of Triassic Chinle Formation rocks occurs in some pipes thus far explored. Furthermore, given the fact that the breccia pipes probably had to be formed under the water table, the stoping process is thought to have occurred prior to the Laramide Orogeny and the eventual dewatering of the Grand Canyon area.

Uranium age dates are also useful since mineralization post dates the formation of breccia pipes. Published age dates vary from 101 m.y. to 200 m.y.. Mineralization at the Orphan Mine has been dated at 141 million years (Gornitz & Kerr, 1970) and Hack ore indicates age dates of roughly 200 million years (Wenrich, 1985). Recently determined U-Pb dates on two uranium samples from the EZ-2 pipe indicate ages of 165 and 184 m.y.

Homogenization temperatures of fluid inclusions were determined from gypsum, anhydrite, calcite, sphalerite and barite samples from various pipes (Landais, unpub. data). Results range from 54°C to 125°C with the average being about 90°C. Under normal geothermal gradients, these temperatures are consistent with depths of burial to be expected during Mesozoic time.

CONCLUSIONS

It is generally accepted that the formation of breccia pipes was the result of overlying strata collapsing into Mississippian Redwall Limestone caves. Their locations were probably influenced by fracture systems along which the caves developed in the Redwall Limestone.

When the stoping began is uncertain, but in some of the pipes it was at least active later than Triassic Chinle time. The stoping process may have occurred under the water table while about 6,000 ft. of Jurassic and Cretaceous sedimentary rocks covered the area.

The sources of the reductants and the mineralizing solutions are controversial. As mentioned above, hydrocarbons could have migrated into the porous throat and moved either up and/or down the breccia pipe.

The origin of the uranium is uncertain since no source rocks, except the Chinle Formation, occur adjacent to the breccia pipes. Uranium had to be transported some distance either laterally and/or vertically before being deposited in the breccia pipe.

The model preferred by the authors begins with the breccia pipe stoping upwards until it cuts through the Coconino Sandstone and the Brady Canyon Member of the Toroweap Formation. In the EZ-2 pipe, hydrocarbons, which probably originated from the Brady Canyon Member, were then expelled and flowed down into the throat following the most permeable pathway.

The most likely source for the uranium is the Triassic Chinle Formation. Uranium could have moved into the pipe either directly from above or laterally through the Coconino Sandstone aquifer. Uranium bearing oxidizing water could have been moved into the aquifer in those areas such as Black Mesa Basin, where the Chinle Formation unconformably overlies the Coconino Sandstone.

Under burial pressure, uranium bearing ground water could move into the Coconino Sandstone aquifer until it encountered a strongly reducing pipe environment. Solutions would enter and flow down the breccia pipe precipitating uranium and associated elements as deep as the reducing conditions were available.

The direction of flow was most likely to have been downwards because the lack of an overlying aquifer prevented any upward flow. Furthermore, the Redwall Limestone karst system was interconnected with the base of the breccia pipe, which would allow the confined ground water to flow down and out.

Mineralization probably occurred sometime between Late Triassic and Cretaceous time and shortly after the throat breached through the Brady Canyon Member of the Toroweap Formation. Evidence to substantiate this includes age dates of the mineralization, paleotemperatures established from fluid inclusion studies and projected depth of burial compatible with the formation of hydrocarbons.

The collapse cone developed with further upward stoping of the pipe and wall rock dissolution in the Kaibab and Toroweap limestones and evaporites. Eventually, the Triassic mudstones within the Moenkopi and Chinle formations may have plugged the pipe due to brecciation and deformation. The mineralizing process was terminated by the dewatering of the Coconino Sandstone aquifer as a result of Laramide uplift.

Erosion dominated during Tertiary time resulting in the partial or total destruction of the breccia pipes. Related surface oxidation could also have removed any or all of the mineralization.

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