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# Uranium Deposits in Collapse Breccia Pipes in the Grand Canyon Region, Colorado Plateau, USA

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With 4 figures and 1 table in text
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## Introduction

The uranium district is located in the Arizona Strip area, to the north and south of the Grand Canyon, northwestern Arizona. Numerous solution collapse breccia pipes (not to be confused with diatreme pipes) crop out on the plateaus and in the canyons. Some contain economic Cu, Pb, Zn, Ag, and/or U mineralization.

Mining in breccia pipes started at the end of the last century, at the beginning primarily for copper (ore grades ‹15% Cu). Later, during the 1950's and 1960's, the Orphan Lode (headframe still visible a short distance to the west of Grand Canyon village on south rim of the Grand Canyon) was exploited for uranium with Cu and Ag as byproducts (production ca. 1900 t $U_3O_8$ at an ore grade of 0.43% $U_3O_8$, 3000 t Cu, 3400 kg Ag).

Revived exploration in the 1970's and 1980's resulted in new discoveries of uranium ore bearing pipes which are shown in Figure 1.

Mineable breccia pipes contain uranium reserves in a range from a few hundreds to about 2500 t $U_3O_8$. Total reserves discovered so far are in the order of about 14000 t $U_3O_8$ contained in about 15 pipes. Production grades are high averaging from 0.4 to 0.8% $U_3O_8$ and locally more. Ag, Cu and V are recoverable from some of the lodes.

The following presentation is a synopsis of a chapter in „Uranium Ore Deposits", DAHLKAMP 1990, Springer Verlag, and the reader is referred to this book for details of breccia pipe uranium deposits including extentive bibliography, and for other uranium deposits as well.

## Regional Geological Setting of Mineralized Breccia Pipes

The regional geological setting is the classical one of the Grand Canyon region with its well established stratigraphy and evolution. (BILLINGSLEY 1978, BREED & ROAT 1976, Four Corners Geol. Soc. 1969, KARLSTROM et al. 1974). The rock sequence ranges in age from Precambrian (›2 b. y.) to Permian (approx. 200 m. y.) and locally Triassic. These rocks are intruded and capped in places by Miocene to late Pleistocene volcanics. Figure 2 displays schematically the stratigraphy and lithology of the various formations in the Grand Canyon region.

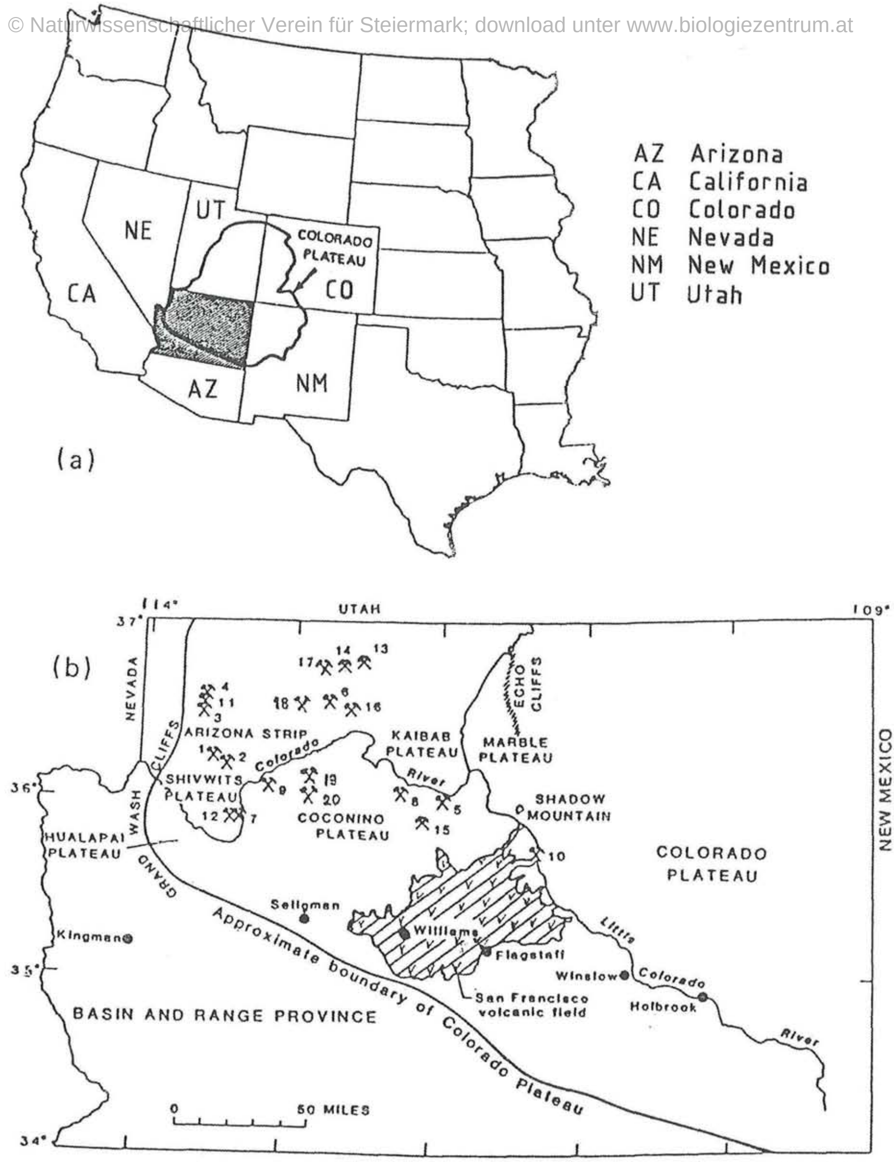


Figure 1: Location of breccia pipe mines and potential deposits of the Grand Canyon region/Arizona Strip area in the southwestern Colorado Plateau (b). Figure (a), index map of the western part of the USA, displays the location of Figure (b) (shaded area) and the approximate boundary of the Colorado Plateau. Numbers refer to the following mines and potential deposits (in brackets main product):
1 Copper House (Cu), 2 Copper Mountain (Cu), 3 Cunningham (Cu), 4 Grand Gulch (Cu), 5 Grandview (Cu), 6 Hack Canyon (U), 7 Old Bonnie (Cu), 8 Orphan Lode (U), 9 Ridenour (Cu), 10 Riverview (U), 11 Savannic (Cu), 12 Snyder (Cu), 13 Pigeon (U), 14 Kanab North (U), 15 Canyon (U), 16 Pinenut (U), 17 Hermit (U), 18 EZ-2 (U), 19 Sage (U), 20 SBR (U). Note that all breccia pipes producing primarily Cu and some of which only minor U are situaded in the western part of the region whereas all principal U producers occur in a belt in the central and southeastern segment (modified after WENRICH & SUTPHIN 1989).

The breccia pipe hosting Mississippian to lower Triassic stratigraphic units consist of almost horizontally bedded marine to marginal continental limestones, mudstones, and sandy to silty sediments (McGEE 1978).

Major tectonic features of the Arizona Strip area include blockfaulting with associated warping (e. g. Kaibab Uplift), N to NNE trending lineaments (e. g. Toroweap Fault), and NNW and NE striking fault systems.

## Collapse Breccia Pipes

Collapse structures called „collapse or solution breccia pipes" or simply „breccia pipes" are of combined solution and tectonic origin. They should not be confused with diatreme pipes generated by volcanic gaseous explosion. Collapse breccia pipes have been found in the Arizona Strip area in formations younger than the Mississippian. A pipe may crop out on surface or may be blind (Fig. 2).

Roof collapse of caverns (paleokarst) in the carbonate strata of the Mississippian Redwall Limestone initiated the formation of a pipe. The generally circular collapse transgressed chimney – like upwards into the overlying, essentially flatbedded sediments, from the Redwall Limestone as much as about 1200 m into the Permian Kaibab Limestone, and locally into the overlying Lower Triassic Moenkopi Formation or Upper Triassic Chinle Formation.

A breccia pipe consists of a throat ranging in diameter from about 15 m to 100 m and more. Pipes stoped upward to surface exhibit a surface expression in form of a collapse cone that may have a diameter of up to 750 m. The cone results from dissolution of gypsum and other leachable material of the Kaibab and Toroweap Formations causing a gradual thinning of the affected strata towards the pipe throat. In contrast, a pipe which does not outcrop has no solution cone.

A breccia pipe is filled with clasts of highly variable size up to several meters in diameter which are embedded in matrix. Fragments and matrix are made up of downward displaced material of the stoped sediments.

## Principal Host Rock Alteration

A variety of alterations affected either both or separately the pipe infill and the strata peripheral to the pipe. Principal alterations include pyritization, dolomitization, calcitization, silicification, desilicification, Mg-depletion (dedolomitization), gypsum/anhydrite formation and bleaching. It is not established, however, which of these processes were related to mineralization and which developed during the pipe formation itself. Most alteration processes tend to have been very mild although some produced striking colour changes. Figure 3 displays the distribution of the various alteration features within and outside a pipe.

## Principal Characteristics of Mineralization

The ore mineralogy of the collapse breccia pipes is quite heterogenous. The most common uranium mineral is pitchblende, locally coffinite. A series of associated minerals but not necessarily paragenetic ones are present in variable amounts (Table 1, Fig. 4). They include sulfides, arsenides, sulfoarsenides, locally oxides, carbonates and sulfates of Fe, Cu, Ni, Co, Mo, Pb, Zn and Ag. Traces of Au, Cd, Mo, Sb, Se and V are also present. Gangue minerals which may or may not be related to mineralization are calcite, dolomite, siderite, baryte, collophane, chalcedony, quartz, anhydrite and gypsum. A black glassy bitumen is locally abundant but only in some pipes.

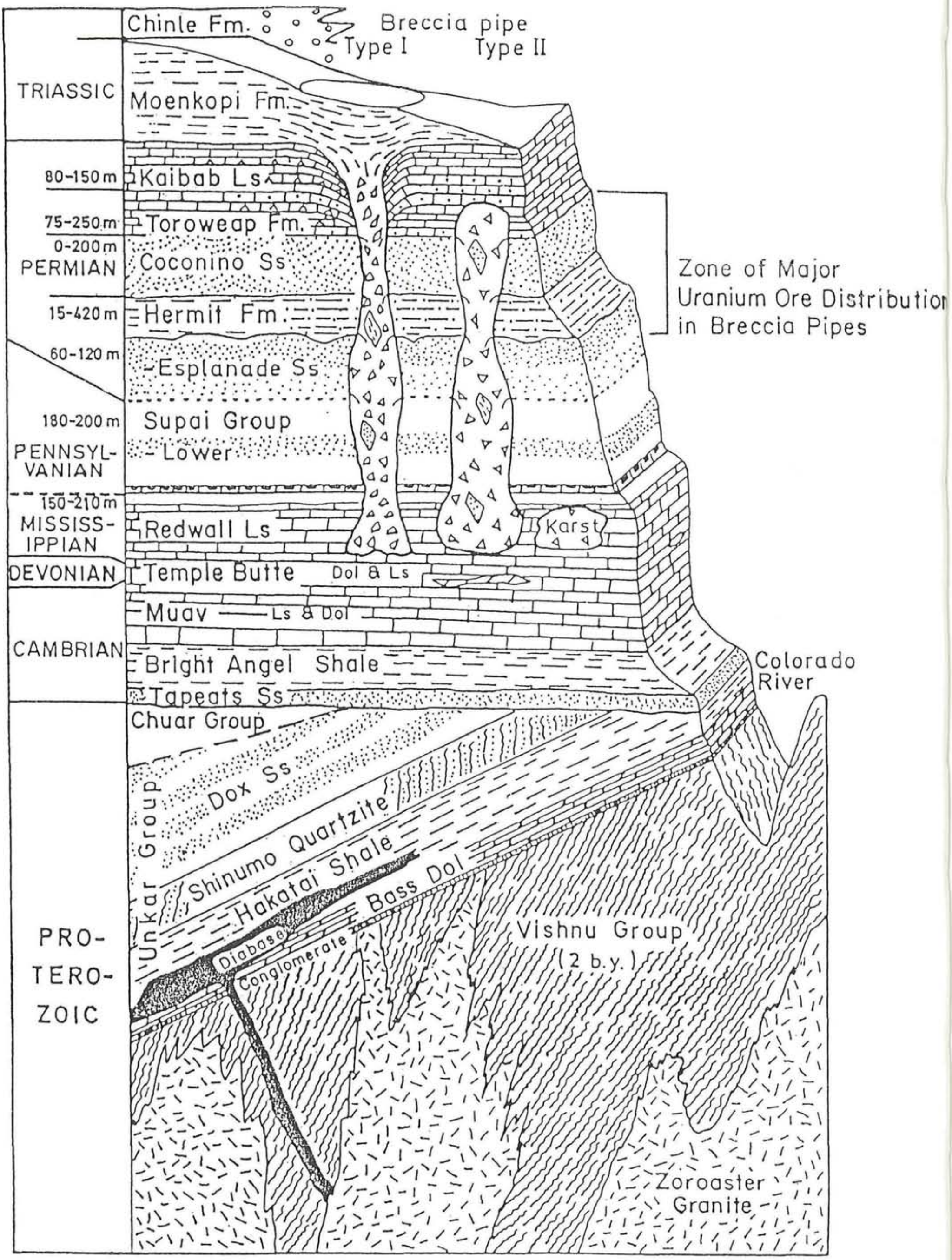


Figure 2: Schematic stratigraphic section of the Grand Canyon region showing position and mode of collapse breccia pipes (type I outcropping, type II blind).
(Modified after drawing by HOLLAND, R. F., unpubl.; stratigraphy based on BREED & ROAT 1976.)

The mineral assemblages vary from pipe to pipe. The Orphan Lode and Hack pipes for example (Table 1), display a large variety of metallic minerals whereas the Pigeon pipe has a more simple mineralogy (RASMUSSEN, J. D., and GAUTIER, A., pers. commun.). WENRICH & SUTPHIN (1989) distinguish three principal paragenetic stages of mineralization succeeded by a fourth, supergene stage as documented in Figure 4.

Uranium forms irregular ore bodies distributed intermittently over a vertical pipe interval of as much as 200 m from the Coconino stratigraphic level downward. Ore grade mineralization is generally concentrated in sections filled with not or partially cemented sand and silt. These particular lithologic sections are located, within the pipe, just below the Coconino – Hermit contact in the stratigraphic "wall rock" pile, or immediately below the Hermit – Supai boundary (Fig. 3).

The pitchblende occurs within these intervals (a) as veinlets and stringers in fractures, both within the pipe and in an annular ring closely surrounding the pipe, (b) as pseudo-stratiform mineralization in permeable sandstone blocks, and predominantly (c) distributed in irregular masses, disseminated in mainly sandy – silty matrix within the reduced, intensely brecciated interior of the pipe.

Sulfides occur disseminated in variable amounts within the whole pipe. Particular concentrations of sulfide containing up to 80% pyrite and marcasite form a 3 to 15 m thick sulfide cap above the uranium ore, at an elevation corresponding to the stratigraphic Toroweap-Coconino contact (Fig. 3).

## U – Pb Systematics/Geochronology of Mineralization

Uranium – lead isotope dating of pitchblende from various pipes yield four groups of apparent ages:
- ca. 260 m. y. (LUDWIG, K., pers. commun.)
- ca. 220 to 200 m. y. (LUDWIG et al. 1986)
- ca. 184 to 165 m. y. (KREWEDL & CARISEY 1986)
- ca. 141 m. y. (minimum age, MILLER & KULP 1963)

The significance of these ages within a frame of metallogenetic modelling will be discussed in the subsequent section.

## Metallogenetic Considerations

A collapse breccia pipe containing economic uranium ore bodies is a unique feature characterized by the coincidence of multiple geologic and metallotectic criteria and derived by complex processes, in particular
- a thick sequence of flat-lying sediments which include interbedded arenaceous units,
- presence of a basal limestone which underwent extensive karst development to form large caverns,
- collapse of the caverns associated with discriminative stoping through the superjacent sediments to create a chimney – like breccia pipe. Certain structural systems such as sets of joints or shears are very probably required for the karst and pipe development,
- arenaceous lithologies providing a porous and transmissive pipe infill, in volume and physico-chemical properties adeqate to host ore bodies,
- presence of chemical constituents in the system to supply the essential elements for the creation of a reducing environment, like $H_2S$, $SO_2$, $Fe^{2+}$, hydrocarbons a. o.,
- transmissive systems to permit mineralizing and other chemical fluids needed for ore formation to migrate to a pipe, and within a pipe to optimum sites for ore emplacement,
- a uranium source capable to supply the quantities required for economic ore grades and reserves,

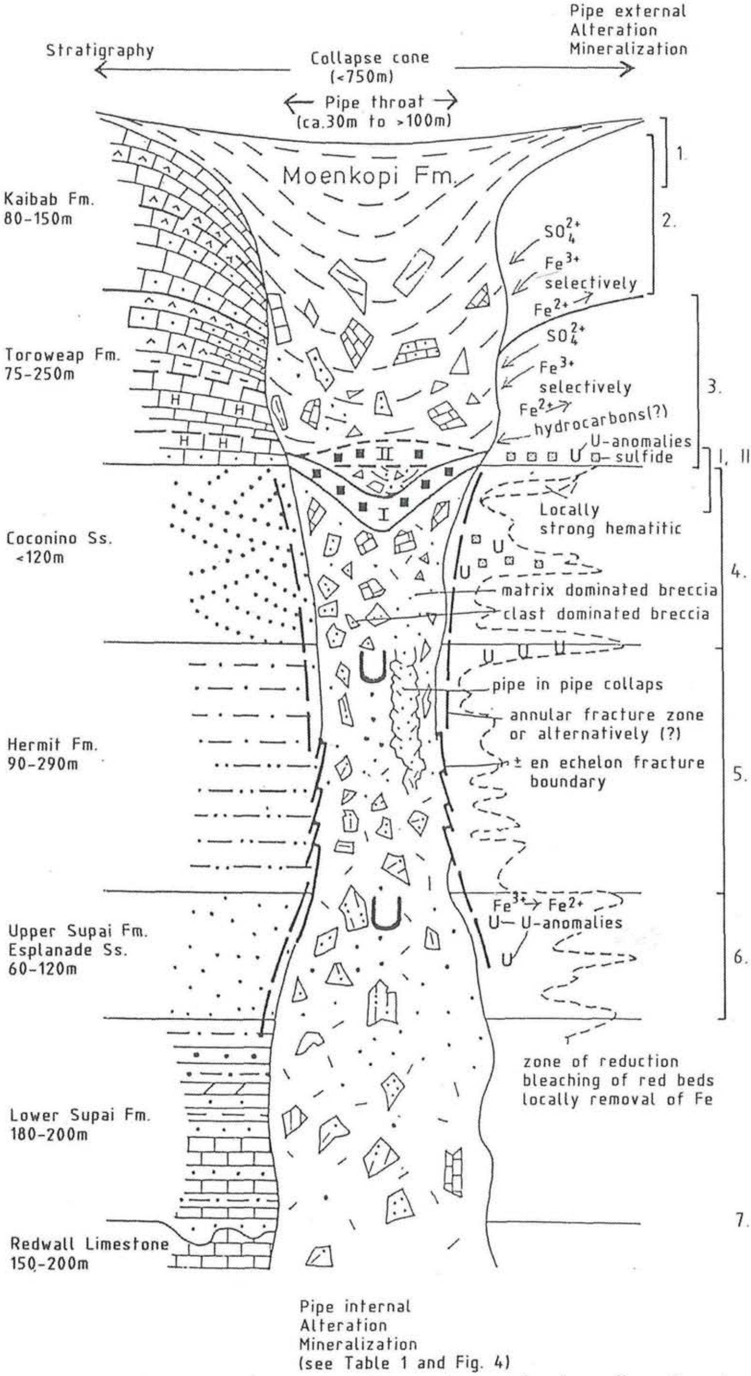


Figure 3: Diagrammatic section of an outcropping uranium ore bearing collapse breccia pipe with types of alteration and mineralization. The various features of alteration and mineralization are not necessarily associated with all mineralized pipes.

Legend to Figure 3, Pipe external, Alteration and Mineralization

1. **Collapse cone/surface expression**
concentric collapse, breccia, arcuate, fractures, anomalous limonite pseudomorphic after pyrite.

2. **Kaibab Fm.**
- dissolution of evaporites, carbonate
- removal of $SO_4$, Fe
- thinning
- deformation
- strata-selective reduction/sulfidization with gradational increase toward pipe.

3. **Toroweap Fm.**
- as in Kaibab Fm.
- removal of hydrocarbons (?)
- dissem. sulfidiz. in basal Toroweap
- kaolinitization

in pipe: ± massive sulfide cap I in outcropping pipe, II in blind pipe (?)

4. **Coconino Ss.**
- disaggregation with thinning
- reduction particularly in upper and lower portions
- locally sulfidization
- locally U, or Pb, Zn, As anomalies
- locally strong hematitic near upper contact
- kaolinitization

5. **Hermit Fm.**
- bleaching
- local. Fe-removal
- local. anomal. U at top

6. **Supai Fm./Esplanade Ss.**
- bleaching
- local. Fe and $CO_3$ removal
- local. anomal. U

7. **Redwall Ls.**
- karst development
- local. Pb, Zn mineralization

- distinct epeirogenic, geohydrologic and climate related conditions to generate the necessary processes for leaching, transport and concentration of the elements involved in ore formation,
- a long lasting cratonic stability that continued until the present and prevented the deposits from destruction.

Ore formation was apparently not a single event but the result of several pulses of mineralization as indicated by the paragenetic interrelationship of ore and gangue minerals. The time frame for the metallogenesis is given by the following criteria.

The time of formation of the breccia pipes in the Arizona Strip area started in late Mississippian time (BILLINGSLEY et al. 1986) and continued intermittently into late Triassic Chinle time.

Time constraints on the episode of mineralization are provided by the stratigraphic sequence involved in the collapse, and the rediometric pitchblende ages. The stratigraphically bracketed period of ore formation is comprised within the late Permian and the Triassic and that of initial uranium introduction by the oldest host rock, viz. the Esplanade Sandstone. Consequently, the first uranium introduction cannot be older than the Esplanade what appears to be consistent with the 260 m. y. U – Pb pitchblende age, and almost certainly not younger than Triassic. Furtheron, initial ore introduction into the pipes must have occurred prior to the final cementation of the ore hosting sands.

Mineralogical, isotope and fluid inclusion data provide certain evidence on the processes involved in ore formation. The presence of calcite suggests that uranium was probably transported as a uranyl-carbonate complex. Deposition of pitchblende and other minerals as well may have occurred when the mineralizing fluids entered the more open spaces in a solution pipe. Pressure release in breccia zones, fissures (annular ring structures etc.) and porous sands are considered a significant factor in the break-up of uranyl compounds. Invading hydrocarbons or $H_2S$ derived from the pipe surrounding sediments

Table 1: Ore minerals of selected breccia pipes.
(Ref. Orphan Lode: GORNITZ & KERR 1970, KOFFORD 1969; Hack, Pigeon, Canyon: RASMUSSEN, J. D., and GAUTIER, A. M., pers. commun.)

| MINERAL | HACK | PIGEON | ORPHAN | CANYON |
|---|---|---|---|---|
| Arsenopyrite | × | | ? | |
| Bornite | | × | × | × |
| Bravoite | × | × | × | × |
| Chalcocite | × | | × | × |
| Chalcopyrite | × | × | × | |
| Cinnabar | | | × | |
| Clausthalite | × | | × | |
| Cobaltite | | | × | |
| Coffinite | | | × | |
| Covellite | × | × | × | |
| Digenite | | | × | × |
| Enargite (Luzonite) | × | × | | |
| Galena | × | × | × | × |
| Gersdorffite | × | × | × | |
| Hematite | × | | × | |
| Ilsemanite | × | | | |
| Jordisite | × | | | |
| Marcasite | × | × | × | |
| Millerite | × | | | |
| Pitchblende | × | × | × | × |
| Proustite | | | × | |
| Pyrite | × | × | × | × |
| Rammelsbergite | | | × | |
| Siegenite | × | | × | |
| Skutterudite | | | × | |
| Sphalerite | × | × | × | |
| Stibnite | | | × | |
| Violarite | | × | | |
| Tennantite-tetrahedrite | × | × | × | |

may have been the agent for the required reduction of the $U^{6+}$ ions but dissolution of early sulfides such as pyrite may have likewise created a reducing environment. A coeval oxidation of some pyrite to hematite associated with the pitchblende deposition could possibly explain the local coexistence of these minerals and may support the latter hypothesis.

Fluid inclusion studies suggest that the ore forming solutions, at least those which deposited calcite, dolomite and sphalerite but not necessarily pitchblende had temperatures ranging from about 80° to 170° C and salinities of always ›9 and commonly ›19 wt. % eq. NaCl (WENRICH & SUTPHIN 1989).

Sulfur isotope studies yield $\delta^{34}S$ values of – 3 to – 20 (ADAMEK, P., pers. commun.) a spread similar to common sandstone – type uranium deposits on the Colorado Plateau but in contrast to the narrow range of isotopic rations in magmatic hydrothermal deposits.

Non-radioactive lead isotope systematics of galenas give Pb 206/Pb 204 ratios of ›19 and Pb 208/Pb 204 ratios of ›38 comparable to Mississippi Valley type mineralization (LUDWIG, K. R., pers. commun.)

In summary, fluid inclusion and stable isotope data compare to some extent with


Figure 4: Generalized paragenetic sequence for ore and gangue minerals in collapse breccia pipes (from WENRICH & SUTPHIN 1989).

those of Mississippi Valley type mineralization hence they support a metallogenetic synthesis involving brines derived from connate or supergene waters in ore formation but reject a magmatic origin of the mineralizing fluids. A not magmatic origin is also consistent with the geological evolution of the Grand Canyon region because there are no igneous instrusions contemporaneous with the presumed time of ore formation.

Conduits for the uranium mineralizing fluids are speculated to be either sandy horizons or structures. A conduit horizon favoured by many geologists is the Coconino Sandstone. But any metallogenetic model involving this lithologically fairly uniform horizon of eolean clastics faces the problem to explain the discriminative ore formation in different pipes that occur adjacent to each other in the same area and in the same facies of strata instead of a mutual ore emplacement in all these pipes. A more selective pathway for the solutions could more easily explain this phenomenon. For example, more localized conduits such as faults or cataclastic zones through which fluids could migrate from uranium mineralized Chinle sandstone channels into the Coconino horizon and then downdip along the unit into a breccia pipe if not directly. Other potential conduits include channel – hosted arenaceous sediments as found in the Esplanade Sanstone or perhaps silty – sandy channels in the Toroweap Formation.

The source of the uranuim is still enigmatic. Considering the different age determinations for pitchblende a speculated source can include uraniferous sandstones of Permian, Triassic, and even Jurassic age which elsewhere on the Colorado Plateau gave rise to extensive uranium mining. These formations are now largely eroded in the Grand Canyon region but remnants testify the former presence at least for the Triassic Chinle Formation. Last but not least the Proterozoic basement may be considered a potential source either in the Mogollon Highland exposed to the S and SE, or immediately underlying the Arizona Strip area.

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