Uranium Resource Availability in Breccia Pipes in Northern Arizona

By James K. Otton and Bradley S. Van Gosen

Chapter A of
Hydrological, Geological, and Biological Site Characterization of Breccia Pipe Uranium Deposits in Northern Arizona
Edited by Andrea E. Alpine

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Conversion Factors

Inch/Pound to SI

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Chapter A
Uranium Resource Availability in Breccia Pipes in Northern Arizona

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Abstract

In 1990, the U.S. Geological Survey estimated that a mean undiscovered uranium endowment of 1.3 million tons (2.6 billion pounds) $U_3O_8$ is present in breccia pipe deposits in northern Arizona. This estimate exceeds the December 31, 2003, U.S. uranium reserves estimate of 445 thousand tons (890 million pounds) $U_3O_8$ for developed deposits elsewhere in the United States. This chapter examines what part of that undiscovered uranium endowment in northern Arizona is not available for exploration, development, or mining because of previous withdrawals of Federally owned land from mineral entry and the newly proposed withdrawals in the Grand Canyon area, announced July 21, 2009.

The estimated mean undiscovered uranium endowment for the areas in northern Arizona withdrawn from mineral entry prior to July 21, 2009—which include the national park, two national monuments, the game preserve on forest lands, and tribal lands—is 466,384 tons (about 933.6 million pounds) $U_3O_8$, or 35 percent of the 1990 estimate of 1,315,383 total estimated tons (about 2.63 billion pounds) $U_3O_8$ in all favorable areas in northern Arizona. The estimated mean undiscovered uranium endowment for the three segregation areas proposed for withdrawal in the July 21, 2009, announcement is 162,964 tons (about 326 million pounds) $U_3O_8$, or 12 percent of the total. Combined, the three segregation areas and previously withdrawn areas would contain about 48 percent of the total estimated undiscovered uranium endowment in all favorable areas for northern Arizona. However, these segregation areas and previously withdrawn areas are all within favorable area A, the most prospective area according to the 1990 estimate. The combined existing and proposed withdrawal lands would represent 69 percent of the 910,350 tons (1.82 billion pounds) $U_3O_8$ previously estimated to occur in favorable area A.

Introduction

On July 21, 2009, U.S. Department of the Interior Secretary Ken Salazar proposed the withdrawal of two parcels of Bureau of Land Management (BLM) land north of Grand Canyon National Park from further mineral entry for a period of two years. A few days later, U.S. Secretary of Agriculture Thomas Vilsack proposed the withdrawal of the Tusayan Ranger District of the Kaibab National Forest south of Grand Canyon National Park. Existing mining claims in the three areas with valid existing rights are not affected.

These three parcels of land (fig. 1) total 1,075,384 acres (R. Cox, U.S. Bureau of Land Management, oral commun., 2010). Underlying these parcels of land are numerous breccia pipes, a few of which contain uranium mineralization. Some of these breccias pipes contain sufficient uranium mineralization to have been mined from the early 1950s to about 1992. These uranium resources are the focus of this chapter.

Following BLM terminology, these parcels of land that have been proposed for withdrawal are referred to as the North, East, and South Segregation Areas (fig. 1). The North Segregation Area is mostly BLM land in the Kanab Creek drainage north of Grand Canyon National Park and west of North Kaibab National Forest. The East Segregation Area is also mostly BLM land in the House Rock Valley area east of North Kaibab National Forest, south of the Vermillion Cliffs National Monument, and northwest of the Colorado River. The South Segregation Area is U.S. Forest Service land, the Tusayan Ranger District of the Kaibab National Forest.

The Grand Canyon area has been the location of modest mining activity since the late 1800s. During the 1950s, five breccia pipe deposits were mined for uranium. From 1952 until 1969, the Orphan Mine produced a significant quantity of uranium, about 2,150 tons (4.3 million pounds) $U_3O_8$ (Chenoweth, 1986). In the 1970s, exploration for uranium in the Grand Canyon area became very active and thousands of mining claims were filed on Federal and other lands across the region. Much of this activity was focused on the Kanab Creek drainage area (North Segregation Area) because of the excellent exposures of several breccia pipes along canyon walls and other surface indications in aerial photos away from canyons. Figure 2 shows the distribution of mining claims in and near the three segregated areas; note the dense mining claim coverage in the North Segregation Area, the lesser amount of mining claims in the South Segregation Area, and the very few mining claims in the East Segregation Area. The mine claim coverage reflects the varied intensity of past exploration among these three land parcels.
Figure 1. Map showing northern Arizona and the three segregation areas, parcels of Federal land removed from further mineral entry for a two-year period beginning July 21, 2009, pending a longer withdrawal. Boundaries for other major land holdings are shown. From U.S. Bureau of Land Management, 2009. NRA, National Recreation Area.
Figure 2. Map showing mining claims in and near the North, East, and South Segregation Areas. Leases on State lands (blue areas) are not shown. Digital files for mining claims provided by Rody Cox, U.S. Bureau of Land Management, September 2009, and plotted by Laura Biewick, U.S. Geological Survey.
Evaluation of the availability of uranium resources defined by Finch and others (1990) through an estimate of the resource in lands withdrawn from mineral entry prior to July 21, 2009, and an estimate of the undiscovered uranium resource that may be present in the three segregation areas (currently proposed for withdrawal).

**Previous Mineral Appraisals in the Grand Canyon Area**

During the 1980s, prior to the Finch and others (1990) study, several areas of northern Arizona had mineral resource appraisals completed that included areas with potential for breccia pipe deposits. None of these studies provided quantitative resource estimates. Areas covered in these studies include:

- Kanab Creek Roadless Area (Billingsley and Ellis, 1983; Billingsley and others, 1983; Hopkins and others, 1984).
- This roadless area is a narrow, 14-mi² tract that follows Snake Gulch, a major eastern tributary to Kanab Creek. It lies along the boundary between the section of the Kaibab National Forest north of the Grand Canyon and the North Segregation Area (fig. 1).

- Vermilion Cliffs–Paria Canyon area, now the Vermilion Cliffs National Monument (Bush and Lane 1982 a, b; Bush 1983). This area lies immediately north of the East Segregation Area (fig. 1).

- Mt. Trumbull Wilderness Study Area (McDonnell, 1984), now part of the Grand Canyon–Parashant National Monument (fig. 3).


Wenrich (1992) studied breccia pipe deposits in an area of four 7.5° quadrangles near Red Butte in the Tusayan Ranger District. The intent was to establish a control area for evaluating the uranium mineral potential of the remainder of Kaibab National Forest. During a joint USGS and U.S. Bureau of Mines study, Bliss and Pierson (1993) and Scott (1992) evaluated the mineral resources of the Kaibab National Forest. Bliss and Pierson (1993) provided quantitative resource estimates for uranium resources using the Finch and others (1990) methodology. The Kaibab National Forest districts evaluated include the North Kaibab Ranger District, a large, previously withdrawn forested area between the North and East Segregation Areas, and the Tusayan Ranger District (South Segregation Area).
Figure 3. Favorable (A–D) and unfavorable (E) areas for breccia pipe uranium deposits in northern Arizona. Boundaries for favorable areas digitized from Finch and others (1990, fig. 2). Previously withdrawn areas are shown where they occur within favorable area A only. The North, East, and South Segregation Areas are also shown.
Uranium Production and Inferred Resources from Pipes in and near the Three Segregation Areas

From 1951 to 1969, uranium production in the Grand Canyon region occurred at five breccia pipes: the Hacks (or Hack Canyon), Ridenour, Orphan Lode (or Orphan), Riverview, and Chapel Mines (Chenoweth, 1986, 1988). Except for the Orphan Mine, all production was modest. Only the Hack Canyon Mine lies within an area proposed for withdrawal, the North Segregation Area. The Hack Canyon Mine produced about 2.5 tons (5,000 pounds) U\textsubscript{3}O\textsubscript{8} from 1951 to 1954 and in 1961. The Orphan Mine produced about 2,150 tons (4.3 million pounds) U\textsubscript{3}O\textsubscript{8} from 1956 to 1969 from a breccia pipe located about 1 mi northwest of Grand Canyon Village (Chenoweth, 1986). The average grade was 0.43 percent U\textsubscript{3}O\textsubscript{8}. The Orphan Mine is within the Grand Canyon National Park, about 3.5 mi north of the South Segregation Area northern boundary. The Ridenour, Riverview, and Chapel Mines are within other lands previously withdrawn from mineral entry.

Exploration for breccia pipe uranium deposits occurred in the Grand Canyon region through much of the 1970s, but mining did not resume until 1980. Although the price of uranium dropped dramatically in the early 1980s, existing purchase contracts and the high grade of the breccia pipe ores allowed for profitable mining. During the 1980s and early 1990s, nine breccia pipe deposits were mined or developed: eight breccia pipes were in the North Segregation Area—Hack 1, Hack 2, Hack 3, Pigeon, Hermit, Kanab-North, Arizona 1, and Pinenut—and one breccia pipe was in the South Segregation Area—the Canyon Mine. Mining at the first five of these pipes has been completed and the sites have been reclaimed. Reclamation at the Hack 1, 2, and 3 Mines included the older Hack Canyon operations. The Kanab-North breccia pipe has been mined, but minor amounts of uranium ore remain in the workings and the mine has been on standby status since 1992. The Pinenut breccia pipe was also mined with an estimated 15 percent of the uranium ore removed; it has been on standby status since 1989. The Arizona 1 breccia pipe was developed by a shaft and nearly completed by 1992, but operations ceased without any uranium ore having been produced. Surface operations at the Canyon Mine breccia pipe were developed and a shaft collared to a depth of 50 ft (Pool and Ross, 2007). The Arizona 1 Mine and the Canyon Mine are also on standby status.

Production and inferred reserves reported for these nine mines are given in table 1. All data are from NI 43-101 independent technical reports for Denison Mines by Pool and Ross (2007) and Moreton and Ross (2009) and are herein considered the best information available. Energy Fuels Nuclear (EFN) developed and mined these nine breccia pipes in the North Segregation Area from 1980 through 1994, producing 9,550 tons (19.1 million pounds) U\textsubscript{3}O\textsubscript{8}.

Combined uranium production from the mines in the North Segregation Area plus production from the Orphan Mine near the South Segregation Area total 11,650 tons (23.3 million pounds). No production or reserves have been reported for the East Segregation Area.

McMurray Geological Consulting (2003) has independently evaluated the uranium reserve potential of the Grand Canyon area by studying exploration and development drilling information from several companies for the pipes discussed here as well as for other breccia pipe deposits drilled but not developed. The report concludes that “proven, probable, and potential reserves” of 24 million pounds U\textsubscript{3}O\textsubscript{8} are present in 11 breccia pipes in the area north and south of the Grand Canyon (in the North and South Segregation Areas) and in State and private lands west of the South Segregation Area, which includes the 6 pipes listed above (McMurray Geological Consulting, 2003, table 3, p. 13). The report further states that, in the breccia pipes mined in the North Segregation Area, inferred reserves based on surface drilling can be expanded

<table>
<thead>
<tr>
<th>Table 1. Production and inferred reserve amounts of U\textsubscript{3}O\textsubscript{8} reported for nine mines in the North and South Segregation Areas.</th>
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<td>EZ2</td>
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\(^1\)Six properties only; Pool and Ross, 2007; Moreton and Ross, 2009.
\(^2\)“e” refers to reliance on gamma logging of deep drill holes for the reserve measurement.
\(^3\)Reported as proven, probable, and potential mineral reserves by EFN, February 1988. Pathfinder Mines Corp. reported indicated mineral reserves at 1.4 million pounds U at 0.66% eU\textsubscript{3}O\textsubscript{8} in 2004.
\(^4\)Reported as proven, probable, and potential mineral reserves by EFN, February 1988. Pathfinder Mines Corp. reported indicated mineral reserves at 1.9 million pounds U at 0.44% eU\textsubscript{3}O\textsubscript{8} in 2004.
significantly when the company in question completes a shaft
and drifts and conducts more detailed development drilling
underground. The individual orebodies in these pipes are typi-
cally very narrow, vertically oriented, and difficult to intercept
during surface drilling. Using data reported for the 6 mined
pipes (McMurray Geological Consulting, 2003, table 4),
the report concludes that the ratio of actual measured reserves
to surface-indicated reserves is 3.65:1. Based on his analysis,
which found increases in uranium reserves based on the past
underground development of pipes, McMurray (2003, table 5,
p. 17) concluded that, in his terms, “adjusted reserves” of
87.5 million pounds UO₃ exist in breccia pipes drilled at the
time of the analysis. This value, combined with known pro-
duction cited above, exceeds 100 million pounds UO₃.

Companies known to have recently conducted explora-
tion in and near the three segregation areas include Denison
Mines, Quaterra Resources Inc., VANE Minerals Group,
Tournigan Energy Ltd. (Tournigan USA Inc.), Liberty Star
Uranium & Metals Corp., Energy Fuels Resources Corp.,
DIR Exploration, Inc., and Uranium One Exploration,
U.S.A. (R. Cox, U.S. Bureau of Land Management, written
commun., 2009).

**Characteristics of Breccia Pipes, Related Circular Features,
and Resultant Uncertainties in Resource Estimation**

The principal question in resource estimation is how
many deposits of what size are present in a particular area. For
the Grand Canyon region, the question is not only how many
breccia pipes are present, but also how many of them are min-
eralized with uranium. A description of the breccia pipes and
their geologic setting helps geologists understand the difficul-
ties in exploring for them.

Breccia pipes in the Grand Canyon region typically
extend vertically from the Mississippian Redwall Limestone
as much as a few thousand feet, locally reaching the Petrified
Forest Member of the Triassic Chinle Formation (fig. 4). The
breccia pipes are roughly circular in shape, about 200–400 ft
in diameter, and have a solution-collapse origin. The breccia
pipes are often characterized by inward-dipping beds along the
margins and internal ring-shaped fracture zones. The width of
the collapsed zone in the overlying beds can be many times
larger than the largest diameter of the pipe itself. The solution
collapse has generated abundant breccia derived from over-
lying strata. The breccias may have abundant voids or open-
ings or may be tightly cemented by a variety of minerals,
including uranium minerals.

Where it occurs, uranium mineralization is usually located in
the pipe adjacent to the upper part of the Supai Group, the Hermit
Formation, or the Coconino Sandstone, but can also extend much
higher or lower stratigraphically. Weak uranium mineralization
may extend several hundred feet to over 1,000 feet within a pipe.
A sulfide cap may be present in the upper part of the mineralized
portion of a pipe. A wide variety of other trace elements accom-
pany the uranium; copper and silver are present in many breccia
pipes in sufficient quantities to have been mined in years past.
Bleaching of nearby wallrock, weakly uranium-rich iron-cemented
zones in permeable wallrock, and a weak geochemical signature
in soils, springs, and stream sediments may be present. The
breccia pipe deposits formed 200–260 million years ago (Wenrich
and Sutphin, 1989).

Several plateaus formed in the areas north and south of
the Grand Canyon, mostly during erosion that predates the
canyon. Each of the plateaus is capped by resistant rocks, from
varying formations in the stratigraphic section. Examples of
plateau-capping units include the Redwall Limestone in the
western part of the Grand Canyon area and the lower Permian
Kaibab Formation in the east. The level of erosion controls
the degree of preservation of uranium deposits in the Grand
Canyon area. Where the Redwall Limestone caps a plateau,
many breccia pipes are exposed, but there is little remnant
oxidized mineralization preserved in the pipes because the
mineralization primarily occurs adjacent to formations well
above the Redwall Limestone. Where the Kaibab Formation
forms the plateau surface, the pipes are only occasionally
exposed in deeper canyons. In the Vermilion Cliffs area,
formations that postdate the Chinle Formation cap the plateau
and there is no known exposure of breccia pipes, although
they may be present beneath the plateau.

The ease of investigating breccia pipes exposed on can-
yon walls throughout the region led to the mining of copper
and silver in the late 1800s and more recently for the mining
of uranium. However, detection of the presence of unexposed
breccia pipes on plateaus is more difficult. On plateau surface
areas, features that suggest a breccia pipe may be present
include roughly circular grassy outlines in vegetation, inward
dipping beds, zones of alteration in the center, oval to circular
depressions with radial drainage, and depressions with sur-
rounding raised ridges (Wenrich and Sutphin, 1988; Wenrich
and others, 1990). However, many of these features can have
other origins, including:

- sinkholes derived from the dissolution of limestone in
  the Kaibab Formation;
- collapse features caused by dissolution of gypsum beds
  in the Harrisburg Gypsiferous Member of the Kaibab
  Formation and Woods Ranch Member of the Toroweap
  Formation; and
- zones of stratabound, oxidized copper-mineralized
  breccias in the Kaibab Formation.
Figure 4. Simplified geologic cross section of a typical breccia pipe showing maximum known vertical stratigraphic extension (about 3,000 feet) and location of ore. Internal structure of the pipe is not shown. The width across a pipe is typically 200–400 feet and is often narrowest in the “throat” where it passes through the Hermit Formation.
Once a feature is evaluated for geologic, geochemical, and geophysical characteristics, further exploration would involve drilling. Pool and Ross (2007, p. 11-1) report:

Shallow drilling was often conducted to locate the centre of the collapse feature as a guide to the throat of the underlying breccia pipe. The basic tool for exploring breccia pipes in northern Arizona is deep rotary drilling supplemented by core drilling, to a depth of 2,000 ft. and more from surface. Prospective pipes were usually first tested with three drill holes. If no showing of mineralization was present, the effort was abandoned.

Drilling of breccia pipes is a difficult process. Substantial depths, approximately 2,000 ft., small targets, approximately 200 ft. in diameter, and non-homogeneous rock formations combine to limit the accuracy of the drilling process. The presence of cavernous and brecciated sediments near the present land surface can result in loss of circulation of drilling fluid; as a result, much drilling is conducted “blind.” Periodic “spot cores” are taken to determine whether or not holes are within the target structure or have drifted away from the pipe. Indeed, most pipes cannot be completely drilled out from the surface due to deviation from desired targets. All drill holes are surveyed for deviation and logged with gamma logging equipment.

If surface drilling provides sufficient encouragement that a mine can be developed on that basis, a vertical shaft is sunk or drilled to its ultimate depth and underground drill stations are established at various levels to provide platforms for further exploration and delineation drilling. Drilling from underground stations typically utilized large-bore percussion drills. The resulting drill holes, out to as much as approximately 200 ft., were then gamma logged and surveyed as a supplement to surface drilling.

As previously discussed, many breccia pipes may have little or no surface expression and are thus hidden. The Hack 2 pipe was recognized only by some surface bleaching in an outcrop of Hermit Shale along a canyon wall. The presence of the breccia pipe was confirmed by subsequent drilling (G. Billingsley, oral commun., 2009). Without the canyon incision, the breccia pipe would not have had any surface expression. Quaterra Resources Inc. has used airborne variable time-domain electromagnetic (VTEM) geophysical surveys to identify possible hidden breccia pipes (Spiering, 2009). The company announced a significant drilling intercept of 57 ft averaging 0.33 percent U on their A-1 VTEM anomaly. Upward stipping by solution collapse at the A-1 pipe had stopped about 400 ft below the present land surface. The company reports that another hidden pipe, A-20, has been confirmed as having significant uranium intercepts. In their surface holdings of 85 mi² within and near the North Segregation Area, Quaterra reports over 200 geophysical anomalies, only a few of which have been drilled.

These factors make it difficult to use estimates of numbers of pipes or density of pipes per square mile, percentage of mineralized pipes, and the average size of orebodies to estimate undiscovered uranium resources. This is especially true for gently rolling plateau surfaces with very limited dissection, which do not provide three-dimensional exposure necessary to recognize breccia pipes. The East and South Segregation Areas occupy such topography, whereas the North Segregation Area has substantial dissection along Kanab Creek and its tributaries. Work by Scott (1992) on the South Segregation Area illustrates the difficulty. Using simple drainage, topography, color, and vegetation criteria developed by Wenrich and Sutphin (1988) and from analyses of aerial photos, Scott lists 495 “circular features” (Scott, 1992, table 4, p. 121–126). Of these, 104 circular features were field checked for evidence of concentric, inward-dipping beds and visible alteration. Only 9 of the 104 features had both of these criteria (Scott, 1992, table 5) and are thus more likely to be breccia pipes. Even with these two criteria at a site, only drilling can determine with certainty whether a breccia pipe is present and if it contains uranium mineralization. Wenrich (1992) reports nine documented mineralized breccia pipes in the Tusayan Ranger District.

The 1990 Finch and Others Estimate

In 1987, Finch and others (1990) prepared a quantitative estimate of the undiscovered uranium “endowment” in breccia pipes in the Grand Canyon region of northern Arizona. This estimate did not consider whether the deposits are economically recoverable. The estimate was based on studies that established the criteria that appear to control the presence of breccia pipes, regional geologic mapping, detailed investigation of a well-characterized area, and the deposit-size-frequency (DSF) method (Finch and McCammon, 1987). The DSF method is a modified version of the DOE’s National Uranium Resource Evaluation method used to assess undiscovered uranium resources for the entire United States. Based on geologic criteria related to formation and preservation of the deposits, the northern Arizona region was divided into four favorable areas (A–D) and one unfavorable area (E) (fig. 3). Unfavorable area E is underlain by the Redwall Limestone, but none of the pipes in the Redwall Limestone contain significant uranium mineralization in that area. The method evaluates the undiscovered uranium endowment of the various favorable areas by comparing the favorable areas to a reasonably well-exposed and explored “control area.”
The formula used to assess undiscovered uranium endowment (Finch and McCammon, 1987; Finch and others, 1990, p. 5) is as follows:

\[
U = A \left( \sum_{i=1}^{k} \left( \frac{n_{ik}}{A_i} \right) T_i \right) G \times L
\]

(1)

where

- \( U \) is the unconditional uranium endowment in tons of \( U_3O_8 \) above a cutoff of 0.01 percent \( U_3O_8 \),
- \( A \) is the favorable area in square miles,
- \( k \) is the number of deposit-size classes (four for the Grand Canyon area),
- \( n_{ik}/A_i \) is the spatial density (number of deposits/unit area) of deposits of size \( T_i \) within a control area \( A_i \),
- \( T_i \) is the tons of endowed rock in the \( i \)th deposit-size class,
- \( A_c \) is the control area from which estimates of \( n_{ik}/A_i \) are taken,
- \( G \) is the grade distribution of endowment, in decimal fraction form,
- \( L \) is the optional scaling factor that expresses the relation between the endowment in the favorable area to either the control area or some designated subarea for which estimates of the number of deposits in different size classes have been made.

Note that the factor within the parentheses when multiplied by \( G \) has the unit of tons \( U_3O_8 \) per square mile and therefore can be considered as an endowment density.

Grade distributions, size-frequency distributions, L-factors, and associated probabilities of occurrence were established by elicitation from the principal scientist, H.B. Sutphin, on April 19 and 20, 1987. The surface areas of all favorable area subdivisions were calculated. The Finch and others (1990) study also subdivided favorable areas by the presence of volcanic rocks or younger age sedimentary formations. The eight National Topographic Mapping System (NTMS) \( 1^\circ \times 2^\circ \) quadrangles that cover the region were also used to subdivide the region. The TENDOWG software developed by DOE and modified by the USGS (McCammon and others, 1988) was used to calculate the undiscovered uranium endowment in 17 favorable subareas. The calculated undiscovered uranium endowments for each subarea were ranked according to probability of occurrence from 0.05 to 0.95 and a mean probability value was calculated. The sum of the mean probabilities for the entire Grand Canyon region is the most likely endowment value for undiscovered uranium according to the method.

The North Segregation Area includes the Hack-Pinenut control area used in the Finch and others (1990) resource estimate, a 141-mi\(^2\) area within favorable area A covering almost all of four townships centered on the Hack and Pinenut Mines (fig. 5). Characterization of the Hack-Pinenut control area by Finch and others (1990) was based on a USGS review of exploration and development drillhole logs and calculations of \( U_3O_8 \) reserves provided by EFN for its entire drilling program. EFN was the primary mining claim owner and the only producer of uranium in the area during the 1980s.

Finch and others (1990) show that most of the undiscovered uranium endowment (910,350 tons [1.82 billion pounds] of \( U_3O_8 \) out of a total 1.315 million tons [2.6 billion pounds] of \( U_3O_8 \) lies within the highest ranked favorable area A. As mentioned earlier, all three segregation areas fall within favorable area A (fig. 3). Favorable area A is limited on the west by outcrops of the base of the Hermit Formation where it is exposed in cliffs along the western margin of the Colorado Plateau and in the canyon of the Colorado River. On the north and east, it is bounded by outcrops of the top of the Petrified Forest Member of the Chinle Formation. Breccia pipes have not been observed in rocks younger than this member. The southermost limit is a line drawn arbitrarily about 10 mi south of the southermost known breccia pipes. Favorable area A includes many areas underlain by volcanic and young sedimentary rocks of varying thickness that would make it very difficult to explore for and develop deposits. The endowment of those areas was calculated but considered separately as a secondary group in Finch and others (1990). Volcanic and young sedimentary rocks do not occur in any of the three segregation areas.

The calculated results for the mean endowment of the Hack-Pinenut control area is 16,429 tons \( U_3O_8 \) (Finch and others, 1990) or 32.8 million pounds \( U_3O_8 \) in the 141-mi\(^2\) area. The range of values (probability 0.05–0.95) was from 4,337 to 34,063 tons (8.7 to 68 million pounds) \( U_3O_8 \). The mean endowment figure yields an average density of 116.5 tons \( U_3O_8/\text{mi}^2 \). To date, known production (Hack 1, 2, 3, Pinenut) and inferred reserves (Pinenut, Arizona 1) in the Hack-Pinenut control area total 5,950 tons \( U_3O_8 \) (11.9 million pounds \( U_3O_8 \)). Several additional mineralized breccia pipes (10), known breccia pipes (12), and possible breccia pipes (9) (fig. 5) are in the Hack-Pinenut control area and hidden pipes may be present (Finch and others, 1990, map on p. 9; McMurray Geological Consulting, 2003; Spiering, 2009). These pipes would contain the balance of the uranium resource estimate.
Figure 5. Map of the Hack-Pinenut control area for uranium-bearing solution-collapse breccia pipes. From Finch and others (1990). East side shows boundary between favorable area A and favorable area D.
Differences in the Surface Area Calculation between the 1990 Finch and Others Report and the Present Study

During GIS analysis of surface areas for the areas withdrawn before July 21, 2009, the authors noted that calculated surface areas for the present report were higher than those cited by Finch and others (1990). The surface area for favorable area A derived from Finch and others (1990) is shown in table 2. Note that not all of the surface area of certain Federal units (Grand Canyon National Park, Grand Canyon–Parashant National Monument), tribal land (the Hualapai and Havasupai Reservations), and other entities are in favorable area A. The surface areas of those land units are split between favorable area A away from the Colorado River and favorable area D and unfavorable area E along the river where erosion has removed the most favorable rock units. The surface of the Hack-Pinenut control area is included in the total because Finch and others (1990) excluded it from their resource appraisal and the endowment was calculated separately.

The surface area calculated by the present study for favorable area A, 10,750 mi$^2$, is 16.3 percent larger than that calculated by Finch and others (1990). The Finch and others map (1990, fig. 2) included longitude and latitude lines that permitted georeferencing and facilitated a recalculation of the area for this study. As the exact surface area affects the endowment density calculation, the surface areas calculated for this study for two Forest Service units of land and two reservations were also compared to those reported from official sources (table 3). The comparisons show that the surface areas determined in the present study for tribal, park, monument, and forest entities are reasonably accurate representations. Differences may reflect differences in delineation of boundaries, exclusion or inclusion of inholdings and water bodies, and the type of projection used to calculate surface areas. If the higher values for surface areas are accepted, then the endowment densities determined during the Finch and others (1990) study need to be adjusted downward from 112.4 tons U$_3$O$_8$/mi$^2$ to 96.6 tons U$_3$O$_8$/mi$^2$ (from 224,800 pounds to 193,200 pounds). Note that the lower, corrected undiscovered uranium endowment density (96.6 tons U$_3$O$_8$/mi$^2$) is compensated for by the increased surface area for all favorable areas; therefore, the Finch and others (1990) endowment numbers are the same.

Estimated Resources Associated with Pre-2009 Mineral Withdrawal Lands in Northern Arizona

Prior to July 2009, several tracts of land in favorable area A were withdrawn from mineral entry in the Grand Canyon area. An estimate of the surface areas of these withdrawn lands within favorable area A was made using a digitized version of the Finch and others map (1990, fig. 2), boundary files for the withdrawn lands, and GIS techniques for calculating surface areas of intersecting polygons using the Albers equal area projection. The calculated surface areas of specific lands is given in table 4.

Using the corrected average of the endowment density for favorable area A of 96.6 tons (193,200 pounds) U$_3$O$_8$/mi$^2$, the endowment for the areas withdrawn before July 2009 can be calculated as in table 5.

Bliss and Pierson (1993, p. 33) also evaluated the undiscovered uranium endowment of the Kaibab National Forest (KNF), based on the Finch and others (1990) assessment:

The total mean unconditional endowment of 233,000 short tons (st) (211,000 metric tons (mt)) U$_3$O$_8$ for the KNF is 18 percent of the total mean endowment of 1,320,000 st (1,200,000 mt) estimated for solution-collapse breccia pipes in the Grand Canyon Region of Northern Arizona and adjacent Utah (Finch and others, 1990). Most of the undiscovered U$_3$O$_8$ endowment in this region for this deposit type is expected to be found

Table 2. Surface areas reported for favorable area A by Finch and others (1990, table 2).

Table 3. Comparison of surface areas calculated during this study compared to other sources.

<table>
<thead>
<tr>
<th>Name of withdrawn area</th>
<th>Surface area of unit calculated during this study (mi$^2$)</th>
<th>Published surface area from official sources (mi$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tusayan Ranger District</td>
<td>520</td>
<td>518$^1$</td>
</tr>
<tr>
<td>Havasupai Reservation</td>
<td>269</td>
<td>294$^4$</td>
</tr>
<tr>
<td>Hualapai Reservation</td>
<td>1,590</td>
<td>1,551$^1$</td>
</tr>
<tr>
<td>North Kaibab Ranger District</td>
<td>1,022</td>
<td>1,010$^4$</td>
</tr>
</tbody>
</table>

$^1$U.S. Forest Service, 2009a; M. Porter, Kaibab National Forest, written commun., October 2009.

$^2$Center for American Indian Economic Development, 2009a.

$^3$Center for American Indian Economic Development, 2009b.

in areas outside of the KNF. Of the three units evaluated (North Kaibab District, Tusayan District, and the combined Chalendar-Williams districts), the North Kaibab district is expected to contain approximately half of the undiscovered uranium endowment (mean of 112,000 st (102,000 mt) \(U_3O_8\)) predicted in the KNF. The remaining undiscovered uranium endowment is almost equally divided between the other two units—57,800 st (52,400 mt) in the Tusayan District and 63,400 st (57,500 mt) in the combined Chalendar-Williams districts. [A short ton, “st” in Bliss and Pierson (1993), is equivalent to a ton.]

Pierson was one of the authors of the Finch and others (1990) report; in their report, Bliss and Pierson (1993) appear to have used the 112.4 tons (224,800 pounds) \(U_3O_8/\text{mi}^2\) endowment density and a surface area very similar to that determined here for the North Kaibab Ranger District to calculate the reported 112,000 tons (224 million pounds) \(U_3O_8\), as that number is identical to the number calculated here using the uncorrected endowment density.

### Estimates of the Uranium Resources in the Three Segregation Areas

The three proposed withdrawal areas are the North Segregation Area (BLM lands mostly in the Kanab Creek watershed), the East Segregation Area (BLM lands in the House Rock Valley area), and the South Segregation Area (Forest Service lands in the Tusayan Ranger District). Table 6 gives the surface area of these lands based on digital boundary files provided by Rody Cox (BLM, written commun., 2009).

Again using the corrected endowment density for favorable area A of 96.6 tons (193,200 pounds) \(U_3O_8/\text{mi}^2\), the endowment for the three proposed withdrawal areas can be calculated as in table 7.

The undiscovered uranium endowment estimate calculated for the South Segregation Area is less than the estimate calculated by Bliss and Pierson (1993), apparently because they used the higher, uncorrected endowment density and an accurate surface area. If the original endowment density is used, then the calculated values would be about 1 percent greater than Bliss and Pierson’s calculation.

In testimony to The Subcommittee on National Parks, Forests, and Public Lands of the Committee on Natural Resources on July 21, 2009, Madan Singh of the Arizona Department of Mines and Mineral Resources stated that 375 million pounds (187,500 tons) \(U_3O_8\) occur within the three segregation areas (Singh, 2009). This estimate is also based on the Finch and others (1990) resource analysis and used the surface areas of the three proposed withdrawal areas as originally found in the bill by Representative Grijalva and the uncorrected endowment density at 112.4 tons (224,800 pounds) \(U_3O_8/\text{mi}^2\) (M. Singh, written commun., 2009).

### Table 4. Calculated surface areas of previously withdrawn lands that lie within favorable area A (see fig. 3).

<table>
<thead>
<tr>
<th>Withdrawn land designation</th>
<th>Surface area (mi²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Canyon National Park</td>
<td>762</td>
</tr>
<tr>
<td>Grand Canyon–Parashant National Monument</td>
<td>976</td>
</tr>
<tr>
<td>Havasupai Reservation</td>
<td>234</td>
</tr>
<tr>
<td>Hualapai Reservation</td>
<td>557</td>
</tr>
<tr>
<td>North Kaibab National Forest</td>
<td>997</td>
</tr>
<tr>
<td>Navajo Reservation</td>
<td>1,194</td>
</tr>
<tr>
<td>Kaibab Paiute Reservation</td>
<td>90</td>
</tr>
<tr>
<td>Vermilion Cliffs National Monument</td>
<td>18</td>
</tr>
<tr>
<td><strong>Total for withdrawn areas</strong></td>
<td><strong>4,828</strong></td>
</tr>
</tbody>
</table>

### Table 5. Estimated undiscovered uranium endowment for previously withdrawn lands within favorable area A.

<table>
<thead>
<tr>
<th>Withdrawn land designation</th>
<th>Endowment in tons (U_3O_8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Canyon National Park</td>
<td>73,609</td>
</tr>
<tr>
<td>Grand Canyon–Parashant National Monument</td>
<td>94,282</td>
</tr>
<tr>
<td>Havasupai Reservation</td>
<td>22,604</td>
</tr>
<tr>
<td>Hualapai Reservation</td>
<td>53,806</td>
</tr>
<tr>
<td>North Kaibab National Forest</td>
<td>96,310</td>
</tr>
<tr>
<td>Navajo Reservation</td>
<td>115,340</td>
</tr>
<tr>
<td>Kaibab Paiute Reservation</td>
<td>8,694</td>
</tr>
<tr>
<td>Vermilion Cliffs National Monument</td>
<td>1,739</td>
</tr>
<tr>
<td><strong>Total for withdrawn areas</strong></td>
<td><strong>466,384</strong></td>
</tr>
</tbody>
</table>

### Table 6. Surface area of the July 2009 segregation areas.

<table>
<thead>
<tr>
<th>Segregation area</th>
<th>Surface area (mi²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>952</td>
</tr>
<tr>
<td>East</td>
<td>226</td>
</tr>
<tr>
<td>South</td>
<td>509</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,687</strong></td>
</tr>
</tbody>
</table>

### Table 7. Estimated undiscovered uranium endowment in the July 2009 segregation areas.

<table>
<thead>
<tr>
<th>Segregation area</th>
<th>Endowment in tons (U_3O_8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>91,963</td>
</tr>
<tr>
<td>East</td>
<td>21,832</td>
</tr>
<tr>
<td>South</td>
<td>49,169</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>162,964</strong></td>
</tr>
</tbody>
</table>
Pre-Existing Mining Claims and Estimated Undiscovered Uranium Endowment

Under the withdrawal proposal, mining claims filed before the proposal date will not be withdrawn from further development, but the validity of existing rights will need to be established during the segregation period. These pre-existing mining claims occupy varying percentages of each of the proposed withdrawal areas (fig. 2): for the North Segregation Area, 474 mi², or 49.8 percent of the area; for the East Segregation Area, 4.4 mi², or 1.9 percent of the area; and for the South Segregation Area, 149 mi², or 29 percent of the area.

Although it seems probable that pre-existing mining claims were filed in areas with a higher potential for finding breccia pipes with significant uranium resources, an analysis of this effect on resource availability was not possible for this study. Table 8, based on the corrected endowment density and the surface area of pre-existing mining claims and areas outside of pre-existing mining claims, gives the uranium endowment within each segregation area that underlies existing mining claims and the endowment that does not.

Table 8. Estimated undiscovered uranium endowment in the July 2009 segregation areas under pre-existing mining claim and not under pre-existing mining claim (in tons U₃O₈). Differences between the total endowment in this table (163,380 tons U₃O₈) and that in table 7 (162,964 tons U₃O₈) are due to rounding errors.

<table>
<thead>
<tr>
<th>Segregation area</th>
<th>Endowment—existing claims</th>
<th>Endowment—not in existing claims</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>45,808</td>
<td>46,136</td>
</tr>
<tr>
<td>East</td>
<td>425</td>
<td>21,832</td>
</tr>
<tr>
<td>South</td>
<td>14,403</td>
<td>34,776</td>
</tr>
<tr>
<td>Total</td>
<td>60,636</td>
<td>102,744</td>
</tr>
</tbody>
</table>

Conclusions

The Finch and others (1990) uranium resource estimate compares the well-exposed, reasonably well-explored and developed Hack-Pinenut control area to other areas where there is much less exposure and much less exploratory and development drilling. For favorable area A, the assumption was that the endowment in all favorable area A closely resembles that of the Hack-Pinenut control area. The L-factors (see equation 1) used for all the favorable area A sectors throughout northern Arizona were 0.90 (lower), 0.99 (most likely), and 1.00 (upper), suggesting close resemblance to the Hack-Pinenut control area (Finch and others, 1990, table 2). L-factors for the other favorable areas are lower. Most likely L-factors for favorable areas B, C, and D were 0.55, 0.10, and 0.13, respectively. The estimate does not rely on counts of circular features, assumptions about the number of breccia pipes and mineralized breccia pipes represented by those circular features, or the tons of uranium in an average uranium mineralized breccia pipe. The key uncertainty is how well the Hack-Pinenut control area represents the remainder of favorable area A where most of the endowment occurs. This cannot be known with a greater degree of certainty without further exploration and development drilling in other areas, including further exploration for hidden breccia pipes suggested by geological techniques. The possibility of hidden breccia pipes was not considered explicitly in the Finch and others (1990) assessment. Further development of genetic models for the formation of the breccia pipe uranium ore deposits could aid a new assessment by allowing additional favorable and unfavorable factors to be developed and applied.

The estimated mean undiscovered uranium endowment for the areas withdrawn from mineral entry prior to July 21, 2009, is 466,384 tons (about 933.6 million pounds) U₃O₈ or 35 percent of the 1,315,383 total estimated tons (about 2.6 billion pounds) U₃O₈ in all favorable areas in northern Arizona (Finch and others, 1990, tables 3 and 4). The estimated mean undiscovered uranium endowment for the three segregation areas proposed in the July 21, 2009, announcement is 162,964 tons (326 million pounds) U₃O₈ or 12 percent. Combined, the three segregation areas and previously withdrawn areas would contain about 48 percent of the total estimated undiscovered uranium endowment in all favorable areas for northern Arizona (Finch and others, 1990, fig. 2). However, all three areas under consideration are within favorable area A, the most prospective area. The combined withdrawal would represent 69 percent of the 910,350 tons (1.82 billion pounds) U₃O₈ estimated to occur in favorable area A.

If the endowment under pre-existing mining claims is excluded from withdrawal in each of the three segregation areas, the estimated mean uranium endowment for the three segregation areas proposed in the July 21, 2009, announcement is 102,744 tons (205 million pounds) U₃O₈ or 7.8 percent of the endowment in all favorable areas. Combined, the three segregation areas and previously withdrawn areas would contain about 43 percent of the total estimated uranium endowment in all favorable areas for northern Arizona. As noted above, all three segregation areas are within favorable area A, the most prospective area. Thus the combined withdrawal would represent 62.5 percent of the 910,350 tons (1.82 billion pounds) U₃O₈ estimated to occur in favorable area A.

Because of the difficulties in exploring for breccia pipes, assessing them, and proving that a breccia pipe uranium ore deposit can be mined economically, it seems likely that development of the resource would occur slowly. Nine breccia pipes were mined (Pigeon, Hermit, Hack 1, 2, 3), partly mined (Kanab North, Pinenut), or partially developed without mining (Arizona 1, Canyon) over a period of 12 to 14 years. The rate of development is sensitive to the price received for the produced uranium, a factor that has varied substantially in the past ten years; higher prices would encourage development.
Acknowledgments

We thank Laura Biewick (USGS) for creating maps from GIS databases to display location information and for extracting surface area data from GIS files provided by Rody Cox (BLM) for the various features described in this report. Rody Cox, Madan Singh (Arizona Department of Mines and Mineral Resources), Cindy Woodward (Denison Mines), and David Scott (USGS) provided useful discussion and copies of documents related to uranium resources in breccia pipes in northern Arizona. Thomas M. Roesch (Newmont Mining Corporation) granted permission to use the McMurray Geological Consulting, Inc. report. We thank Warren Finch (USGS, emeritus) and David Scott (USGS) for reviewing an early version of this paper.

References Cited


Glossary

**E**

**Endowment**  The physical aggregate of mineral occurrences in a region above some lower cutoff (U.S. Bureau of Mines, 1996). As used in this report, “uranium endowment” is the uranium that is estimated to occur in rock with a grade of at least 0.01 percent $U_3O_8$ (Finch and others, 1990).

**M**

**Mineral entry**  The filing of a claim for public land to obtain the right to any minerals it may contain (U.S. Bureau of Mines, 1996).

**Mineralization**  The process or processes by which a mineral or minerals are introduced into a rock, resulting in a valuable or potentially valuable deposit (U.S. Bureau of Mines, 1996).

**O**

**Ore**  The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably (U.S. Bureau of Mines, 1996).

**Orebody**  A continuous, well-defined mass of material of sufficient ore content to make extraction economically feasible (U.S. Bureau of Mines, 1996).

**Ore deposit**  A mineral deposit that has been tested and is known to be of sufficient size, grade, and accessibility to be producible to yield a profit (U.S. Bureau of Mines, 1996).

**R**

**Reserves**  “Reserves” as used by U.S. Energy Information Administration (2004, p. 1) refers to “the sums of quantities estimated to occur in known deposits on properties where data about the ore grade, configuration, and depth indicate that the quantities estimated could be recovered at or less than the stated costs given current mining and milling technology and regulations.” The “stated costs” are forward cost estimates at $30 per pound and $50 per pound. The term “reserves” is qualified by various authors cited in this report by words such as proven, indicated, probable, potential, and adjusted. The reader is referred to these cited reports for further information.

**Resource**  “Resource” or “uranium resource” as used in this report closely follows the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) definition:

A Mineral Resource is a concentration or occurrence of…natural solid inorganic material…in or on the Earth’s crust in such form and quantity and of such a grade or quality that it has reasonable prospects for economic extraction. The location, quantity, grade, geological characteristics and continuity of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge (CIM Standing Committee on Reserve Definitions, 2005).

**U**

**Undiscovered uranium resource**  As used in this report refers to a uranium resource not presently known to exist but which can be inferred to exist by using geologic information and resource estimation methods.