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The 1987 Estimate of Undiscovered Uranium Endowment in Solution-Collapse Breccia Pipes in the Grand Canyon Region of Northern Arizona and Adjacent Utah

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The 1987 Estimate of Undiscovered Uranium Endowment in Solution-Collapse Breccia Pipes in the Grand Canyon Region of Northern Arizona and Adjacent Utah

By W.I. FINCH, H.B. SUTPHIN, C.T. PIERSON, R.B. McCAMMON, and K.J. WENRICH

Work done in cooperation with the Energy Information Administration, U.S. Department of Energy

U.S. GEOLOGICAL SURVEY CIRCULAR 1051

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1990

Free on application to the Books and Open-File Reports Section,
U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

The 1987 estimate of undiscovered uranium endowment in solution-collapse breccia pipes in the Grand Canyon region of northern Arizona and adjacent Utah / by W.I. Finch ... [et al.].

p. cm. — (U.S. Geological Survey circular ; 1051)
"Work done in cooperation with the Energy Information Administration, U.S. Dept. of Energy."
Includes bibliographical references (p.)
Supt. of Docs. no.: I 19.4/2:1051
1. Uranium ores—Arizona—Grand Canyon Region. 2. Uranium ores—Utah—Washington County. 3. Breccia—Arizona—Grand Canyon Region. 4. Breccia—Utah—Washington County. I. Finch, Warren Irvin, 1924- . II. United States Energy Information Administration.
TN490.U7A15 1990
553.4'932'097913—dc20 90-3340
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By W.I. Finch, H.B. Sutphin, C.T. Pierson, R.B. McCammon, *and* K.J. Wenrich

EXECUTIVE SUMMARY

In accordance with the Memorandum of Understanding (MOU) dated September 20, 1984, between the U.S. Geological Survey of the U.S. Department of the Interior and the Energy Information Administration of the U.S. Department of Energy, the Geological Survey is to provide estimates of uranium endowment for selected areas of the United States on a mutually planned and agreed-upon schedule. This report summarizes the estimates of undiscovered uranium endowment of solution-collapse breccia pipes in Pennsylvanian and Permian rocks of the Grand Canyon region in eight 1°×2° quadrangles located in Coconino, Mohave, Yavapai, and Navajo Counties, Ariz., and in Washington County, Utah. These new estimates for the eight quadrangles were made in 1987, and for six of the quadrangles they supersede the estimates of uranium endowment for this type of deposit given in the 1980 national resource assessment report (U.S. Department of Energy, 1980). The estimates were generated using the deposit-size-frequency (DSF, option C) method, a modified NURE (National Uranium Resource Evaluation) method, developed in accordance with the MOU (Finch and McCammon, 1987).

In order to assess the uranium endowment for the region, we established the Hack-Pinenut control area in one of the main mining areas. Data on production, reserves, and estimated additional resources were used to establish various deposit-size classes above the grade-cutoff of 0.01 percent U_3O_8 as well as to estimate the numbers of deposits in each size class. The mean uranium endowment in the control area was calculated to be 16,429 tons U_3O_8.

The areas assessed for uranium endowment are divided into two groups: (1) the principal favorable areas, where the host formations are either exposed or only thinly covered with sedimentary rocks, and (2) the basalt-covered favorable areas, where successful exploration for breccia pipes is virtually impossible with present-day technology. The principal favorable areas contain potentially economic resources; however, we conclude that the basalt-covered favorable areas should be considered in the same manner as areas deeper than 5,000 ft were treated in the NURE program, that is as uneconomic given present-day technology.

For the purpose of the assessment, the Grand Canyon region was divided into four areas of differing favorability, A, B, C, and D, and one unfavorable area, E. The areas overlain by either Tertiary sedimentary rocks or Quaternary sediments are shown as subdivisions of areas A and B (A_s, B_s), but are included for purposes of estimating the total endowment of the principal areas. Each favorable area was divided into subareas along 1°×2° quadrangle boundaries. The endowment was estimated in 17 separate principal areas that total 13,291 mi². These areas do not correspond everywhere with the favorable areas used in the 1980 NURE assessment report (U.S. Department of Energy, 1980). The probability distribution of the endowment for each principal favorable area is given in our report. The mean endowment as calculated from the probability distribution for each of the principal favorable areas is as follows:

Favorable area		Tons U_3O_8
Grand Canyon	A	482,148
	D	8,691
Cedar City	A	23,265
Williams	A	187,127
	A_s	22,590
	B	26,547
	B_s	4,053
	D	3,615
Marble Canyon	A	123,066
	D	694
Flagstaff	A	94,744
	B	58,769
	C	1,759
Holbrook	B	11,551
	C	25,308
St. Johns	C	583
Prescott	B	405

Manuscript approved for publication February 27, 1990

The total endowment for the principal areas of the Grand Canyon breccia-pipe region has a mean value of about 1,000,000 tons U_3O_8. Additional endowment in the nine basalt-covered areas that total 3,437 mi^2 has a mean value of about 240,000 tons U_3O_8. Thus, the total endowment in the Grand Canyon region of the 26 areas encompassing a land area of 16,728 mi^2 has a mean value of about 1,300,000 tons U_3O_8, about eight times the 158,000 tons estimated total endowment for breccia pipes in the 1980 NURE assessment.

The DSF method used here has resulted in an endowment increase over the NURE endowment estimate by about twice the amount expected from a previous DSF and NURE comparison (Finch and McCammon, 1987, p. 16). This larger endowment estimate is due primarily to three factors: (1) the DSF method allows for greater partitioning of the input data for calculating endowment and, thus, it tends to result in a less biased (generally larger) estimate (i.e., it evens out the inherent human tendency to underestimate parameters in order to be "on the safe side"); (2) our knowledge about the distribution of grade and tonnage of newly discovered and mined deposits is significantly greater than it was in 1980; and (3) our understanding of the geology of the region and of the deposits has improved greatly as a result of the past seven years of USGS study funded mainly by the Bureau of Indian Affairs of the U.S. Department of the Interior.

The large endowment estimated for the principal areas alone is significant because it is nearly as large as the 1980 NURE estimated endowment for the San Juan Basin, historically the most productive uranium-producing region in the United States. However, a reassessment of the San Juan Basin using the DSF method would probably yield an estimate much larger than the 1980 NURE estimate. Nevertheless, we conclude that the Grand Canyon region has the potential of becoming the second most important uranium-producing region in the United States. If exploration technology is developed to discover uraniferous pipes below the basalt cover, the Grand Canyon region could eventually become even more important.

INTRODUCTION

On September 20, 1984, a Memorandum of Understanding (MOU) between the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) and the U.S. Geological Survey (USGS) of the U.S. Department of the Interior (DOI) was signed. The MOU "describes the implementation of an agreement for assistance from the USGS in the assessment of U.S. potential uranium resources in support of EIA's work under Public Law 97–415 (January 4, 1983) to develop and provide information about the viability of the domestic uranium mining and milling industry" (Finch and McCammon, 1987). This MOU is a continuant to the MOU between DOE and DOI dated November 12, 1983, that called for a plan to conduct research on data collected under the National Uranium Resource Evaluation (NURE) program and to provide for continuing the assessment of the Nation's uranium resources. The Geological Survey is to provide estimates of unconditional uranium endowment for selected areas of the United States on a mutually planned and agreed schedule. Endowment[1] is used in this report to mean the inplace resource, some of which is discovered and the remainder of which is undiscovered. This report is concerned primarily with the undiscovered part.

In 1985, a modified NURE resource assessment method, called the deposit-size-frequency (DSF) method, was developed (Finch and McCammon, 1987). The first project to use this method was an assessment of surficial uranium deposits in Washington and Idaho (Finch and others, 1990). The assessment of the undiscovered uranium endowment for the Grand Canyon region described here also used the DSF method.

The chief purpose of this report is to convey the 1987 USGS assessment of the undiscovered uranium endowment in solution-collapse breccia pipes in the Grand Canyon region, which is in eight 1°×2° quadrangles located in Coconino, Mohave, Yavapai, and Navajo Counties, Arizona, and in Washington County, Utah (fig. 1). We discuss those aspects of the characteristics and geology of the uranium deposits that might be helpful to mining engineers, metallurgists, and mineral economists; explain the rationale for the determination of favorable areas; and review the method of estimating the endowment. Further information is available from the referenced material.

The roles of the different authors in this assessment were as follows: H.B. Sutphin was the principal scientist. K.J. Wenrich provided geological expertise concerning the uranium deposits. The elicitation was carried out in the manner described in Finch and McCammon (1987) in two major sessions conducted by W.I. Finch, C.T. Pierson, and R.B. McCammon with the principal scientist. Pierson calculated the endowment distribution for each favorable area. McCammon calculated the total endowment for the region and checked all endowment calculations. Sutphin prepared figures 2 and 4.

We acknowledge the consultation of Luther Smith, EIA, on many aspects of the development of the assessment. We are particularly appreciative of Mr. I. W. Mathisen, Jr., Energy Fuels Nuclear, Inc., Denver, Colo., for providing exploration drill-hole logs and calculations

[1]Uranium endowment: the uranium that is estimated to occur in rock with a grade of at least 0.01 percent U_3O_8. Unconditional endowment is based on the assumption that one or more deposits exist in the favorable area.

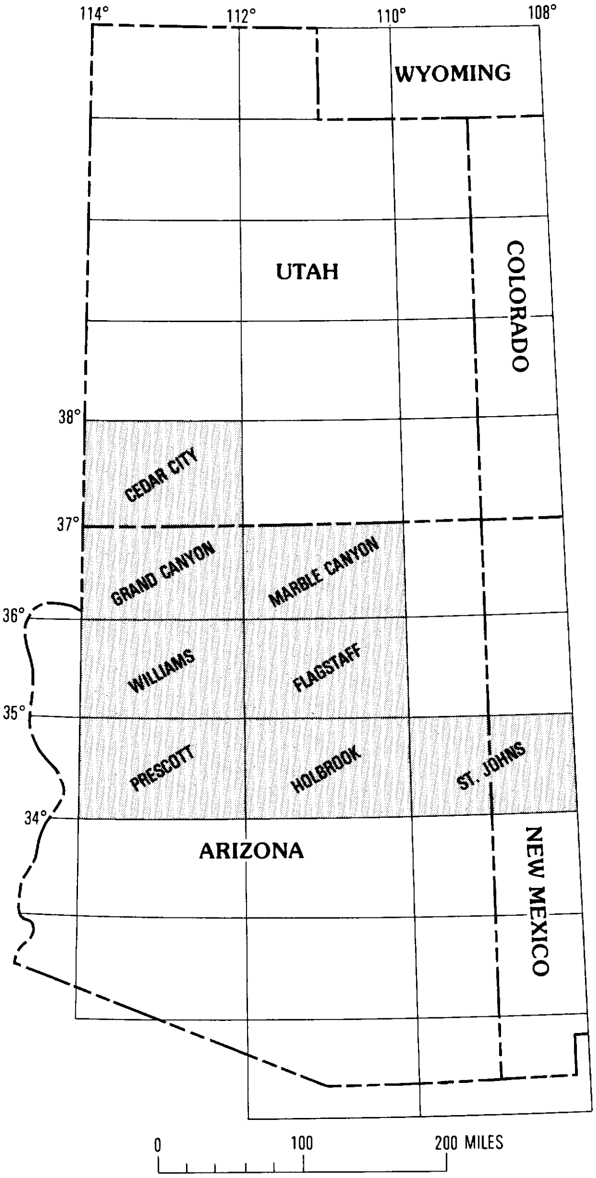


Figure 1. Index map showing the locations of the 1° × 2° quadrangles in Arizona and Utah assessed in this report.

of U_3O_8 reserve data at a 0.03 percent U_3O_8 cutoff grade for each mineralized hole for his company's entire exploration program. These data were essential for us to develop three useful candidates for control areas and to select the best one of the three.

The numerical results tabulated in this report are computer generated (McCammon and others, 1988) and are presented either as probability distributions or calculated means, and no attempt was made to round to significant figures. Tons used in this report are short tons.

POST-NURE ADVANCES IN THE KNOWLEDGE OF SOLUTION-COLLAPSE BRECCIA-PIPE URANIUM DEPOSITS

Since the completion of the NURE assessments of the Grand Canyon region in 1980 (U.S. Department of Energy, 1980), both exploration and mining have increased greatly, and significant advances have been made in our knowledge of the geology and distribution of uraniferous solution-collapse breccia pipes in northern Arizona.

The study of the breccia pipes in northern Arizona has been an ongoing project since 1976, when it was part of the USGS Uranium and Thorium Resource Program. Wenrich participated in the assessment of the Flagstaff quadrangle for the NURE program (Wenrich-Verbeek and others, 1982). From 1979 to 1981, Wenrich and Sutphin participated in the uranium assessment of the Navajo Reservation funded by the Bureau of Indian Affairs of the U.S. Department of the Interior by locating and mapping breccia pipes on the Marble Plateau (Sutphin and Wenrich, 1983, 1988; Sutphin, 1986). In 1982, the USGS undertook an intensive study of the uranium potential of the Hualapai Indian Reservation for the Bureau of Indian Affairs. This effort, in progress in 1987, included the following studies: (1) preparation of detailed breccia-pipe and geologic maps (scale 1:48,000) of the entire Reservation, divided into four maps—northeast (Wenrich, Billingsley, and Huntoon, 1986), southeast (Billingsley and others, 1986), northwest (Wenrich, Billingsley, and Huntoon, 1987), and southwest (in preparation) parts of the Reservation; (2) detailed studies of favorable breccia pipes on the Reservation (Wenrich, Billingsley, and Van Gosen, 1986, 1987, 1990), including geophysical (Senterfit and others, 1985; Flanigan and others, 1986), helium soil gas (Reimer, 1985), and magnetometer studies (Van Gosen and Wenrich, 1989); (3) drilling of the Mohawk Canyon pipe (Wenrich, Van Gosen, and others, 1987) and Blue Mountain breccia pipe (Van Gosen and others, 1989); and (4) general studies of the breccia pipes throughout northern Arizona (Wenrich, 1985, 1986a, 1986b; Gornitz and others, 1988; Van Gosen and Wenrich, 1987; and Wenrich and Sutphin, 1989).

These additional studies and maps, along with company confidential exploration and mining data, have increased our knowledge of breccia-pipe density and ore grade exponentially since 1980, when the previous assessment was completed. At that time, only one high-grade (average grade = 0.43 percent U_3O_8) breccia-pipe orebody, the Orphan mine, had been mined. In addition, the Hack Canyon mine had produced about 1,400 tons of ore at an average grade of 0.18 percent U_3O_8 (U.S. Atomic Energy Commission publicly released production records, 1972). Whether there were other mineralized pipes of high-grade ore similar to those at the Orphan mine was not public knowledge. Company confidential data on high-grade ore from the Hack No. 2 mine was available to DOE in 1979, but not to Wenrich when she assessed the Flagstaff quadrangle. Since 1980, five other mines, the Hack Nos. 1, 2, and 3, Pigeon, and Kanab North have gone into production (figs. 2, 4), at least ten more deposits have been delineated, and several mining projects are in various stages of lease application or development.

Exploration and mining in the breccia-pipe province have been intense since 1980. Between 1980 and the end of 1986, Energy Fuels Nuclear, Inc., has mined ore that yielded about 5,000 tons of U_3O_8 at an average grade of about 0.65 percent U_3O_8, and in 1987 it had six breccia-pipe mines in operation (Mathisen, 1987). Other companies have smaller but still successful exploration programs, yet none of them had operating mines in 1987. Because of the high grade of breccia-pipe ores, they were in 1987 one of the main sources of conventionally mined uranium in the United States.

GEOLOGY AND OTHER CHARACTERISTICS OF SOLUTION-COLLAPSE BRECCIA PIPES

Hundreds of solution-collapse breccia pipes are found in Paleozoic rocks of northern Arizona in the southwest part of the Colorado Plateau province (fig. 2; also see Sutphin and Wenrich, 1989). They formed as the result of solution collapse within the Mississippian Redwall Limestone and stoping of the overlying Pennsylvanian, Permian, and Triassic rocks (fig. 3). The pipes extend upward as far as the lower members of the Upper Triassic Chinle Formation. U/Pb isotope studies on ore from several pipes in the northern part of the region by Ludwig and others (1986) indicated a Late Triassic age of mineralization (similar to that of sandstone ores of the Chinle in eastern Utah), but more recent study on one pipe, the Canyon pipe (fig. 2*A*), in the southern part indicated an Early Permian age (Ludwig and Simmons, 1988). The main ore-bearing horizons in the pipes are adjacent to the upper part of the Supai Group, the Hermit Shale, and the Coconino Sandstone. Areas underlain by these formations are considered favorable for breccia pipes and for uranium deposits. However, pipes are sparse to absent where the Redwall is less than 50 ft thick.

The pipes are commonly 300 ft or less in diameter, but their expression at the ground surface above may be as shallow structural and topographic basins as large as a mile in diameter. Some pipes form prominent features at the surface, whereas others are difficult to discern from the surface and can be verified only by pattern drilling over a suspected area. All of the pipes positively identified at the time of the assessment are plotted on figure 2. Many pipes on the flat Esplanade Sandstone and Redwall Limestone surfaces have been exposed by erosion and are relatively easy to detect. As a result, the plateaus capped by these formations have a greater density of identified pipes than do the higher plateaus capped by Kaibab Limestone. Consequently, the density of pipes shown in figure 2 is not uniform.

The rocks on the Marble Plateau are very well exposed, and mapping of pipe locations there provides a good measure of pipe density. This density is 0.28 pipes per mi^2, which is considered to be typical for the region. In areas where bedrock exposures are poor due to alluvial veneer and forest cover, a similar distribution is assumed and was used as a basis to estimate pipe density in each favorable area. This assumption was especially useful in setting up the Hack-Pinenut control area.

Most of the breccia-pipe uranium deposits that have been mined are high grade by U.S. standards, averaging between 0.43 and 0.65 percent U_3O_8. Typical ore-bearing pipes contain 105,000–500,000 tons of ore, yielding 500–3,000 tons of U_3O_8. The boundaries of orebodies most commonly are sharp and in some cases correspond to the limits of brecciated rock. Low-grade rock (0.01–0.05 percent U_3O_8) is generally a small part of the entire deposit. The average grade of mineralized rock in breccia pipes is higher than that of most sandstone deposits (generally 0.10–0.25 percent U_3O_8) to the north and east in the Colorado Plateau province.

The unoxidized uranium ore consists of uraninite associated with abundant pyrite. Concentrations of silver, cobalt, copper, nickel, lead, and zinc are sufficiently high that these metals could become viable byproducts of mining some uranium ore. The ore is low in carbonate (average less than 5 percent). Copper has been produced from some pipes, particularly from those highly oxidized and exposed in and below the Esplanade Sandstone (Chenoweth, 1986).

METHOD OF ESTIMATING THE URANIUM ENDOWMENT

The uranium endowment was estimated using the deposit-size-frequency (DSF) method described in detail by Finch and McCammon (1987). Briefly, the DSF method is a modification of the NURE uranium endowment (U) estimation equation, $U=A \cdot F \cdot T \cdot G$, in which factors F and T (F = fraction of area, A, that is favorable for endowment; T = tons of endowed rock per unit area) are replaced by a single factor. This factor, shown in the equation below, is the summation of the estimates of the number of deposits in different deposit-size classes within the area being assessed, or, equivalently, the spatial density of deposits; hence, the name "deposit-size-frequency." The grade distribution

(G) of the endowment is the same in both methods. The DSF method requires that a deposit-size-frequency (a matrix of deposits in each size class) be established in a well-known to fairly well-known area, called the control area, and that the geologic factors that produced this frequency be determined. Using these requirements for a control area, the assessor estimates the size frequency of undiscovered deposits for the favorable area based on similarity to the control area. Three options, A, B, and C, are available for a given assessment (Finch and McCammon, 1987). The choice as to which option to use depends on the level of knowledge about the control area and the level of exploration of the region being assessed. Option C is used where the favorable area can be delineated in detail only in part so that the number and size of deposits within the control area, A_c, can be estimated. Option C is applicable to the Grand Canyon assessment, and the modified equation is:

$$U = A \left| \sum_{i=1}^{k} \left(\frac{n_{ic}}{A_c}\right) T_i \right| G \cdot L$$

where:

U = unconditional uranium endowment in tons of U_3O_8 above a cutoff of 0.01 percent U_3O_8,

A = favorable area in square miles,

k = number of deposit-size classes,

n_{ic}/A_c = spatial density (number of deposits/unit area) of deposits of size T_i (tons of endowed rock in the i^{th} deposit-size class) within a control area A_c,

A_c = control area from which estimates of n_{ic}/A_c are taken,

G = grade distribution of endowment, in decimal fraction form, and

L = optional scaling factor that expresses the relation between the endowment in the favorable area and that in either the control area or some designated subarea for which estimates of the number of deposits in different size classes have been made.

Option *C* requires that the principal scientist establish the size-frequency distribution of deposits in a well-known or control area, A_c, and the relations of the deposit-size-frequency distribution to measurable controlling geologic factors, such as breccia pipes. Using these relations, the principal scientist first establishes the number and range of the size classes, and then for each size class estimates the lower limit, most likely value, and upper limit for the number of deposits in the control area, A_c. The favorable area, A, is measured, and the grade distribution, G, is estimated. Finally, the lowest, most likely, and highest values for the scaling factor, L, which relates the endowment of the favorable area to that of the control area, are estimated. Using these estimates, obtained by elicitation, as input into the DSF equation and the TENDOWG program (McCammon and others, 1988), which is a modification of the program by Ford and McLaren (1980), one can calculate the probability distribution of undiscovered uranium endowment in a given area. The total endowment for any number of subareas, such as all those in a quadrangle, can be calculated using the same TENDOWG program.

For this study, the summation of estimates made for many subareas by a single investigator is assumed to be perfectly correlated. This is an extension of the basic premise in the DSF method for which a perfect correlation is assumed among the estimates of the number of deposits within each size class.

THE HACK-PINENUT CONTROL AREA

Production records and exploration data provided by Energy Fuels Nuclear, Inc., on three areas consisting of about four townships each—(1) Hack-Pinenut (T. 36–37 N., R. 4–5 W.), (2) Pigeon-Kanab North (T. 38–39 N., R. 2–3 W.), and (3) Orphan-Canyon (T. 28–29 N., R. 3 E.; E2/3 T. 28–29 N., R. 2 E.; E1/3 T. 30–31 N., R. 2 E.)—were considered in selecting a control area. The Hack-Pinenut area (fig. 4), which is controlled entirely by Energy Fuels Nuclear, Inc.[2], was selected as the control area because more information was available concerning pipe distribution, density of exploration, production, and ore reserves for it than for the other two areas. On the basis of these data, Sutphin established four size classes (table 1) and estimated the numbers of deposits in each class. The density of pipes estimated to occur in the Hack-Pinenut control area is 0.23 pipes per mi^2, which matches well the density of 0.28 per mi^2 determined for the well-exposed Marble Plateau area (fig. *2B*). In contrast to the control area of four townships used here, the 1980 DOE assessment used a single mine, the Hack No. 2 mine, as a grade-tonnage model for the control area.

The lower, most likely, and upper grade-distribution estimates used in this assessment are 0.06, 0.17, and 0.44 percent U_3O_8, respectively (table 1). These grade-distribution levels were estimated using all of the data currently available in 1987 for some of the most thoroughly explored areas, namely the three areas mentioned above as candidates for control area. The Orphan-Canyon area has the lowest average grade, 0.06 percent U_3O_8, which is used for the 5th percentile (lower) grade-distribution estimate. The average grade for all three areas combined (468 mi^2) is 0.17 percent U_3O_8, which is used as the 50th percentile, or most likely

[2]One Tabor Center, Suite 2500, 1200 17th Street, Denver, CO 80202.

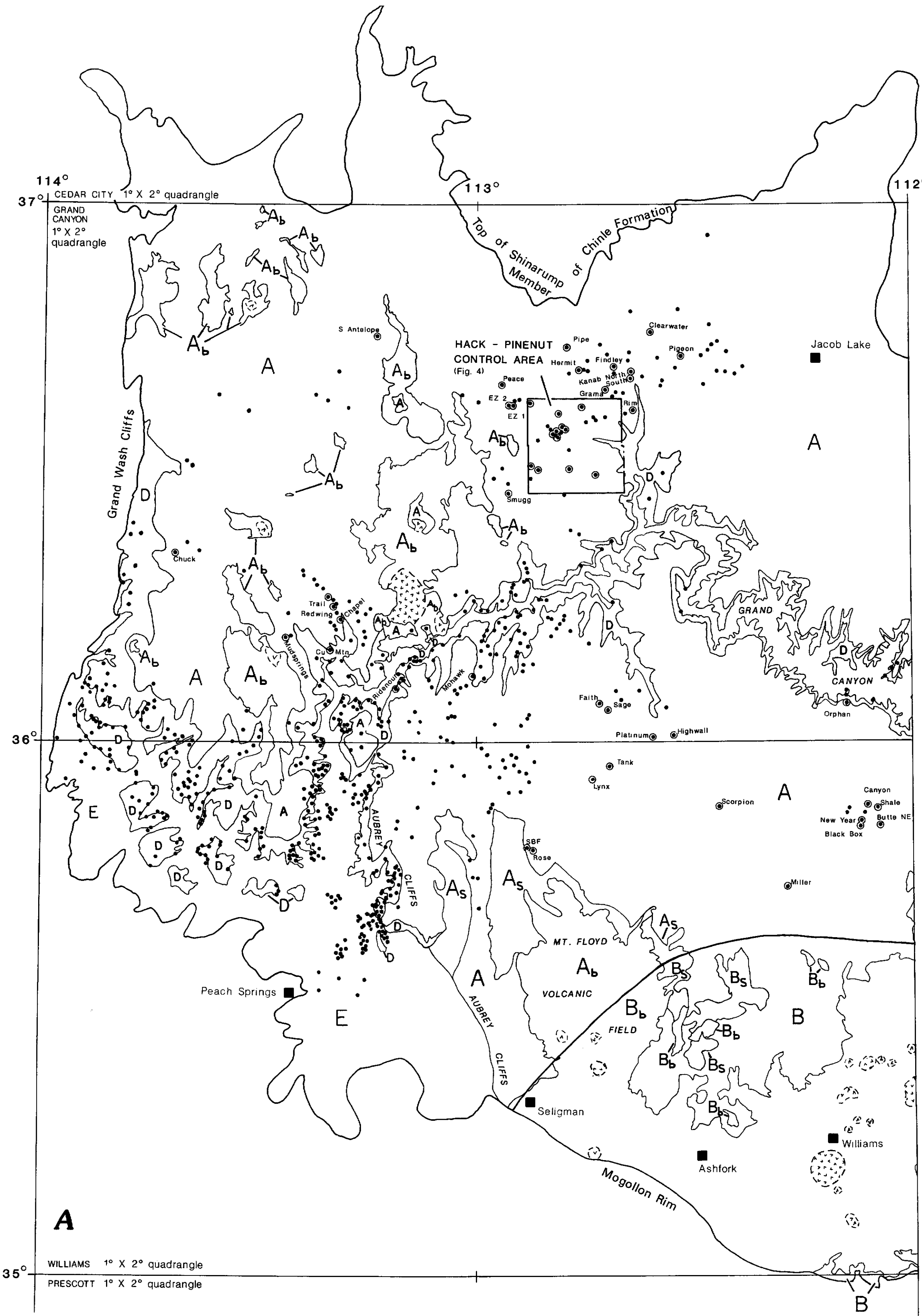
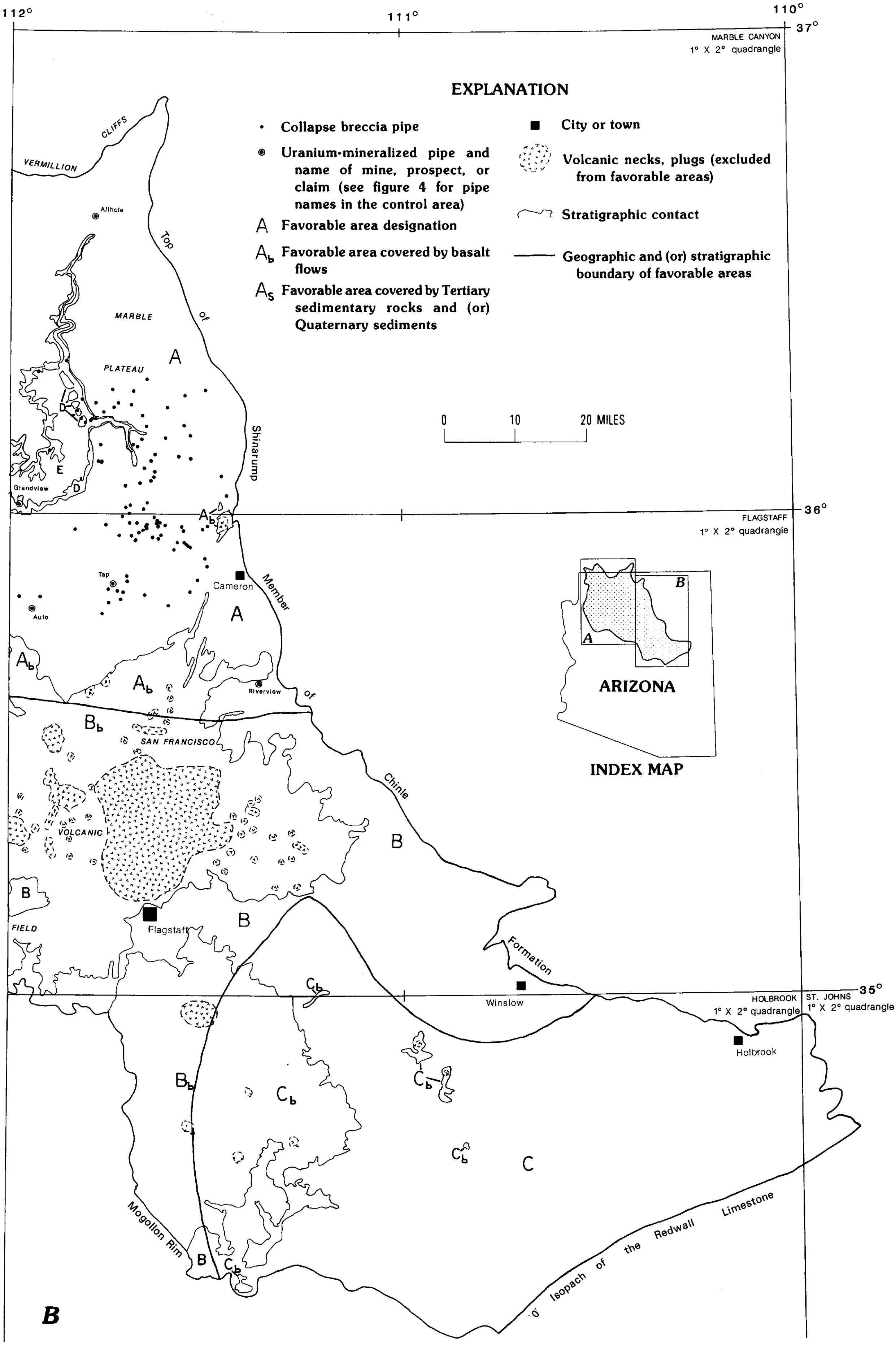


Figure 2 (above and facing page). Map showing locations of selected solution-collapse breccia pipes and areas favorable for uranium endowment in parts of eight 1° × 2° quadrangles in northern Arizona and adjacent Utah. *A*, Cedar City, Grand Canyon, Williams, and Prescott quadrangles; *B*, Marble Canyon, Flagstaff, Holbrook, and St. Johns quadrangles. The Hack-Pinenut control area is shown in greater detail in figure 4. See Sutphin and Wenrich (1989) for an update of breccia-pipe locations.



112°
111°
110°
37°
36°
35°
MARBLE CANYON
1° X 2° quadrangle
FLAGSTAFF
1° X 2° quadrangle
HOLBROOK
1° X 2° quadrangle
ST. JOHNS
1° X 2° quadrangle
EXPLANATION
Collapse breccia pipe
Uranium-mineralized pipe and name of mine, prospect, or claim (see figure 4 for pipe names in the control area)
A Favorable area designation
A_b Favorable area covered by basalt flows
A_s Favorable area covered by Tertiary sedimentary rocks and (or) Quaternary sediments
City or town
Volcanic necks, plugs (excluded from favorable areas)
Stratigraphic contact
Geographic and (or) stratigraphic boundary of favorable areas
0
10
20 MILES
ARIZONA
INDEX MAP
VERMILLION
CLIFFS
MARBLE
PLATEAU
Top of Shinarump Member of Chinle Formation
Allhole
Grandview
Tap
Auto
Cameron
Riverview
SAN FRANCISCO
VOLCANIC
FIELD
Flagstaff
Winslow
Holbrook
Mogollon Rim
'0' Isopach of the Redwall Limestone
B

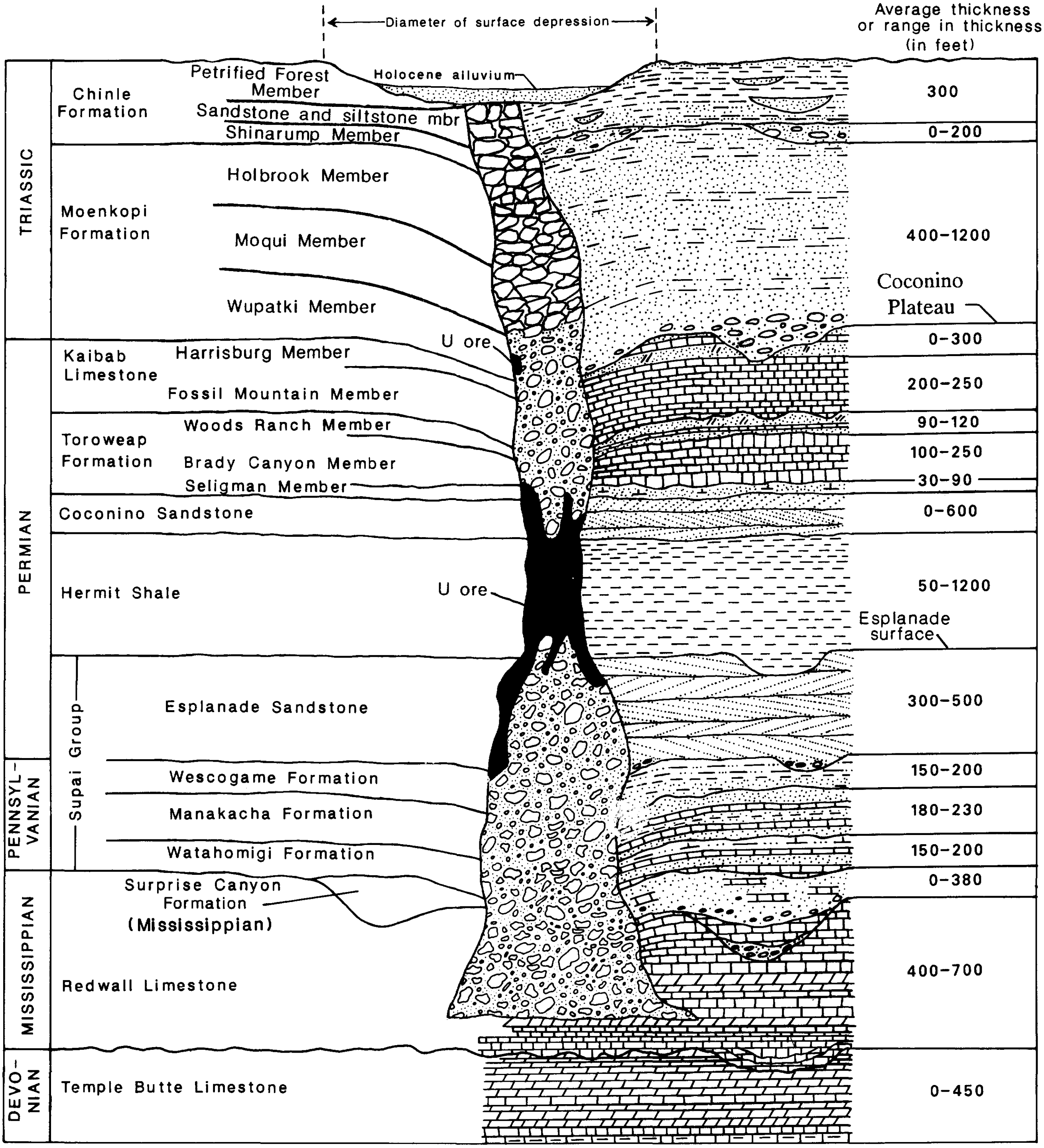


Figure 3. Schematic cross section of a typical solution-collapse breccia pipe and stratigraphic section in the Grand Canyon region (modified after Van Gosen and Wenrich, 1989).

estimate. The Hack-Pinenut area's average grade of 0.44 percent U_3O_8 is used as the 95th percentile (upper) grade-distribution estimate. This area is the most thoroughly explored and contains the greatest density of known ore-bearing pipes. The grade for the Pigeon-Kanab North area (0.61 percent U_3O_8) is higher than that of the Hack-Pinenut area but is based on data from only four pipes, two of which are active mines.

The estimated grade distribution used in this assessment has considerably greater values than were used in the NURE assessment for several reasons. The 1980 NURE assessment used 0.05, 0.16, and 0.20

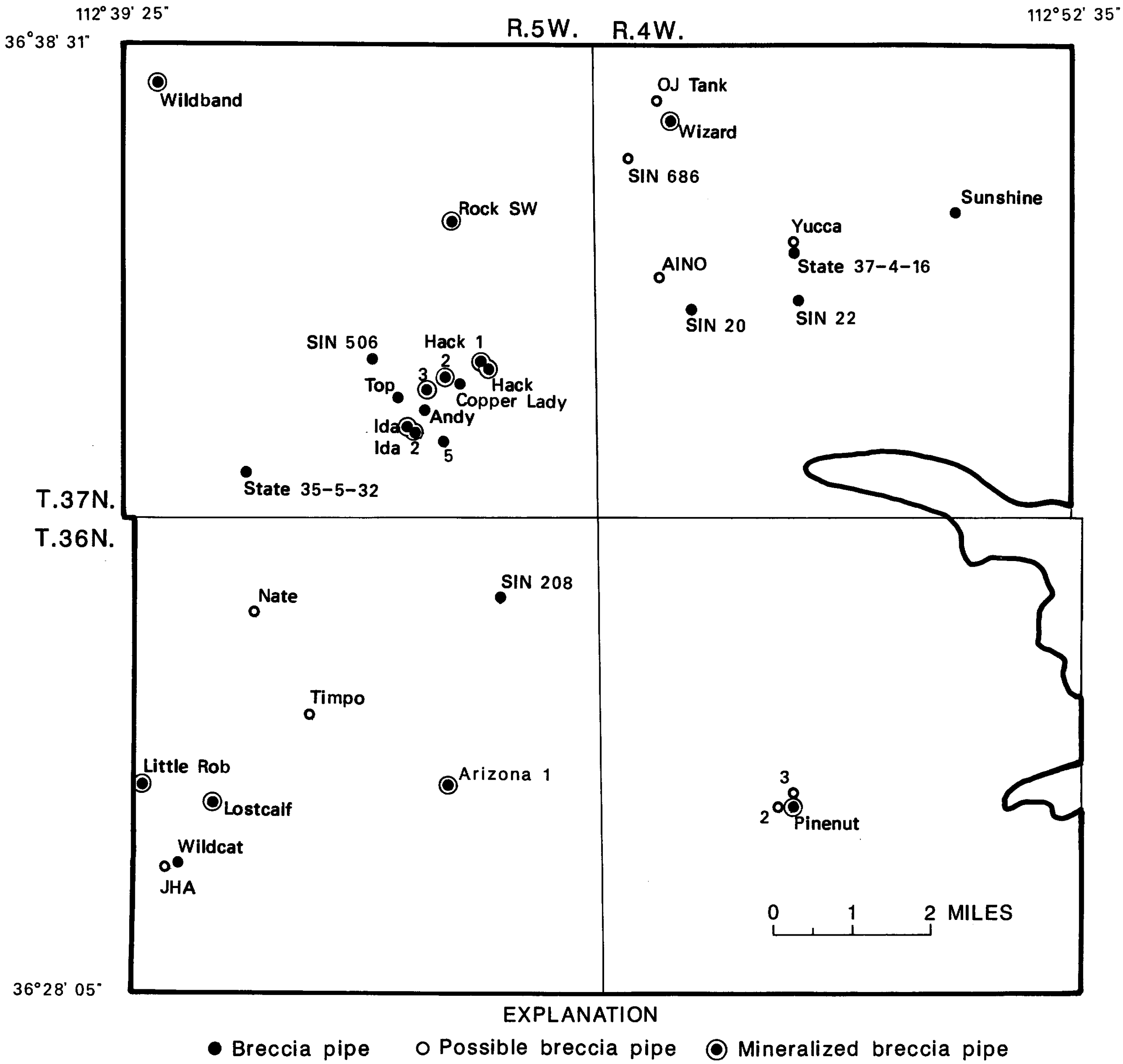


Figure 4. Map of the Hack-Pinenut control area for uranium-bearing collapse-breccia pipes in northern Arizona. See figure 2*A* for the location in the Grand Canyon 1°×2° quadrangle.

percent U_3O_8 as the lower, most likely, and upper values in the grade distribution. Study of considerable data from Energy Fuels Nuclear, Inc's., exploration drilling indicates that there probably are no large bodies of mineralized rock having average grades in the 0.01 to 0.09 percent U_3O_8 range within the stratigraphic interval under consideration in our assessment. However, drilling below the mined-ore horizon at the Orphan mine discovered a large body containing about 9,500,000 tons of rock with an average grade of 0.02 percent U_3O_8 (Chenoweth, 1986). The amount of low-grade (<0.10 U_3O_8) material in ore-grade deposits is small, as is shown by the unpublished 1979 DOE graph of the distribution of uranium inventory by grade for the Hack No. 2 deposit, where, at a 0.01 percent U_3O_8 cutoff, the inventory[3] is 20 percent of the total inventory and has an average grade of 0.21 percent U_3O_8. We judge that the low DOE grade-distribution estimate used in 1980 was tempered by experience with the lower grades of sandstone deposits on the Colorado Plateau. We believe that the grade distribution estimated in our report is reasonable and might even be conservative.

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[3]Uranium inventory is the preproduction tons U_3O_8 at and above minimum grade of 0.01 percent U_3O_8 contained in discovered mineralized material.

Table 1. Estimated grade distribution, *G*, and size-frequency distribution for the Hack-Pinenut control area, $A_o = 141$ mi^2 (fig 2*A*)

Grade Distribution (*G*)			Size-frequency distribution						
Percent U_3O_8 at 0.01% cutoff			Size class (*k*)	Size-class interval (tons of mineralized rock above cutoff of 0.01% U_3O_8)			Number of deposits[1]		
Lower (0.05)	Most likely value	Upper (0.95)		Lower (0.05)	Midpoint[2]	Upper (0.95)	Lower (0.05)	Most likely value	Upper (0.95)
0.06	0.17	0.44	1	1	1.4×10^2	2×10^4	5	14	16
			2	2×10^4	6.3×10^4	2×10^5	3	4	6
			3	2×10^5	6.3×10^5	2×10^6	2	3	4
			4	2×10^6	6.3×10^6	2×10^7	0	1	1
						TOTAL	10	22	27

[1]Odds are 9 to 1 that the true numbers lie within the lower and upper estimates.

[2]Midpoints of size-class intervals for size classes 1-4 are calculated and rounded as the geometric mean of the upper and lower limits.

ENDOWMENT IN THE HACK-PINENUT CONTROL AREA

On the basis of the data in table 1, the calculated results for the probability distribution and the mean unconditional uranium endowment are as follows:

Probability	Tons U_3O_8	Probability	Tons U_3O_8
0.05	4,337	0.55	15,990
.10	5,929	.60	17,229
.15	7,221	.65	18,561
.20	8,380	.70	20,043
.25	9,471	.75	21,696
.30	10,529	.80	23,636
.35	11,577	.85	25,994
.40	12,633	.90	29,129
.45	13,710	.95	34,063
.50	14,824		

Mean = 16,429 tons U_3O_8

DETERMINATION OF FAVORABLE AND UNFAVORABLE AREAS

The areas assessed in this report are divided into two groups: (1) the principal group, in which the host formations are either exposed or only thinly covered with sedimentary rocks, and (2) a secondary group, in which the host formations are covered by thick Tertiary and Quaternary basalt. Because of the extremely small size of the pipes (about 300 ft in diameter; uranium deposits within the pipes are even smaller in areal extent but large in vertical extent) and their low average density of occurrence (one in 3–4 mi^2), random drilling exploration in basalt-covered areas would be more expensive than drilling through only sedimentary rocks and also would have an extremely low success rate, perhaps only one discovery in 1,500 holes. Geophysical or geochemical techniques, not yet developed, could significantly increase this success ratio. We considered excluding basalt-covered areas as not being viable for assessment and treating them the same way areas deeper than 5,000 ft were treated in the 1980 NURE assessment. Nevertheless, we have estimated the uranium endowment for basalt-covered areas, except for volcanic vent areas that are entirely unfavorable. This will allow EIA to apply an economic model to the basalt-covered areas and will permit comparison with the 1980 NURE estimates, which included the basalt-covered areas. The amount of uranium in these areas (estimated mean undiscovered endowment = 240,000 tons U_3O_8) may be an incentive to develop geophysical or geochemical tools to locate pipes beneath basalt cover.

The favorable areas were determined on the basis of the distribution of uranium-bearing strata and breccia pipes within the strata and on other geologic factors. Solution-collapse breccia pipes penetrate strata from the Mississippian Redwall Limestone through the lower part of the Upper Triassic Chinle Formation (fig. 3). The uranium-ore horizon is generally adjacent to the upper part of the Supai Group, the Hermit Shale, and the Coconino Sandstone. The division of the breccia-pipe province into smaller areas of favorability is based on: (1) occurrence of known breccia pipes; (2) presence of favorable upper Paleozoic strata; and (3) thickness of the Redwall Limestone. Feeder vents to basalt flows, such as in the San Francisco volcanic field, are considered unfavorable.

Areas underlain by strata younger than the Wescogame Formation and strata south and west of the mapped surface contact between the Petrified Forest Member and the overlying Owl Rock Member of the Chinle Formation are considered in differing degrees favorable for uranium-bearing breccia pipes. The favorable area is divided into areas A, B, C, and D (fig. 2). Areas where favorable strata are overlain by Tertiary sedimentary rocks and by basalt flows are differentiated and labelled by subscript "s" or "b," respectively. The unfavorable area is labelled E on figure 2.

Small parts of favorable areas A and B are covered by Quaternary sediments and Tertiary sedimentary rocks. A thick wedge of Quaternary alluvial gravel, sand, and silt covers the down-faulted Kaibab Limestone west of the Aubrey Cliffs in favorable area A. Tertiary sedimentary rocks cover the Kaibab surface in the vicinity of the Mount Floyd volcanic field in favorable areas A and B. These rocks crop out beneath Miocene volcanic rocks and consist of as much as 165 ft of lacustrine limestone (Young, 1982). Locally the limestone contains interbedded sandstone and siltstone.

Favorable Area A

Area A is the most favorable area for the occurrence of uranium-bearing breccia pipes, although it excludes the Hack-Pinenut control area (fig. 2). Favorable area A contains many plateaus both north and south of the Grand Canyon. The plateaus are capped primarily by the Kaibab Limestone, although some are partially capped by younger rocks of the Moenkopi and Chinle Formations. The eastern and northern edges of area A are delineated by the top of the Petrified Forest Member of the Chinle Formation, because breccia pipes have not been observed in any of the younger, overlying strata. The western edge of area A is drawn at the base of the Hermit Shale, and thus the inner gorge of the Grand Canyon is excluded. The southern margin of area A is along a line approximately 10 mi south of the southernmost known pipes. In the Flagstaff 1° × 2° quadrangle this line also corresponds to the south edge of favorable area A, as shown in the NURE report (Wenrich-Verbeek and others, 1982).

Favorable Area B

Favorable area B contains the full section of favorable Paleozoic and Triassic formations, and thus contains rock favorable for the occurrence of uranium-bearing breccia pipes. It is considered less favorable than area A only because no pipes have been confirmed there. Within area B, the Redwall Limestone thins toward the southeast, and where the Redwall is thinner than a critical thickness (arbitrarily designated as 50 ft), dissolution may have been insufficient to have caused stoping and collapse of the overlying strata. This could explain why no pipes have been recognized in area B, but the lack of identified pipes could also be because this area has not been explored intensively. Alluvial and vegetative cover are thicker than in area A and may decrease the possibility of detecting any pipes that may exist. The south edge of area B (the boundary between B and C) is drawn along the 50-ft isopach of the Redwall Limestone (McKee and Gutschick, 1979).

Favorable Area C

Area C has very low favorability for the occurrence of uranium-bearing breccia pipes. The overlying Paleozoic section is present, but the Redwall thins from 50 to 0 ft in the area. This thickness of Redwall was probably inadequate for more than minor collapse, certainly not enough to produce the brecciation of 2,000 ft of overlying strata. The several solution-collapse features (not shown on fig. 2) that do occur in the eastern half of area C probably are the result of evaporite dissolution within the upper Paleozoic redbeds, specifically limestone and gypsiferous units of the Permian Schnebly Hill Formation (lateral equivalent of the Coconino Sandstone). These pipes are not considered favorable for uranium for two reasons: (1) they probably formed some time after the mineralizing event that produced the uranium-bearing

Redwall-related pipes, and (2) no northern Arizona uranium orebody or other significantly mineralized rock is known to occur in any solution-collapse feature except those rooted in the Redwall Limestone. Several circular depressions in the western part of area C have promising pipe-like surface expression, and they are located outside the evaporite facies mentioned above.

Favorable Area D

Area D has a lower favorability for the occurrence of uranium-bearing breccia pipes than does area B in that it does not contain the total section of strata favorable for mineralization, but it is adjacent to area A, so the rocks should have been subjected to the same dissolution and mineralization events as those in area A. Area D is defined by the outcrop of the Esplanade Sandstone and contains other rocks of the Supai Group, but all overlying strata have been stripped off by erosion. The lower parts of the Orphan, Pigeon, and Kanab North orebodies extend down into Esplanade Sandstone, so area D may contain significant uranium-mineralized rock, but the total mineralized body remaining in any one pipe would be smaller than in one formed in a full section of strata.

Unfavorable Area E

Area E is underlain by pipe-bearing Paleozoic strata consisting solely of the Redwall Limestone. Even though numerous pipes are present, these pipes have been eroded far below the main uranium-ore-bearing horizon. The Grandview copper mine (fig. 2B), mined at the turn of the century, is in a breccia pipe in the Redwall Limestone on the boundary between areas E and D. Uranium does occur in this pipe, but the uranium-bearing rock appears to be in finely comminuted sandstone of the Supai that has dropped down into the Redwall. Area E is unfavorable for uranium, except for small, insignificant secondary concentrations, primarily in sandstone blocks of the Supai downdropped during erosion. Area E is restricted to the Grand Wash Cliffs region and to the inner part of the Grand Canyon and its tributary canyons (fig. 2).

Basalt-Covered Areas

The volcanic rock of the San Francisco and Mount Floyd volcanic fields covers much of favorable area B and laps into favorable areas A and C. The age of the Mount Floyd volcanic field is 9.8 (Arney and others, 1985) to 2.6 Ma (L.D. Nealey, oral commun., 1989), whereas that of the San Francisco volcanic field is somewhat younger, ranging from 6 Ma (Damon and others, 1974) for Anderson Mesa to 1250 A.D. for the eruption of the red cinders at the summit of Sunset Crater (E.M. Shoemaker and D.E. Champion, written commun., 1978). The San Francisco volcanic field is dominated by San Francisco Mountain, a stratovolcano composed of andesite, dacite, rhyodacite, and rhyolite flows and pyroclastic deposits. It is surrounded by more than 600 basaltic cinder cones and associated flows and by scattered silicic domes and dome complexes. The large cones and vents are shown on figure 2 as unfavorable areas because any breccia pipes that may have once existed beneath them probably were obliterated by volcanic explosions and magma movement associated with the volcanic eruptions. In addition, the high heat flow associated with such volcanic activity probably would have altered, remobilized, or removed the uranium deposits.

The favorable basalt-covered areas labelled A_b, B_b, and C_b on figure 2 are underlain by host rocks similar to these in the adjacent uncovered areas. Thus, they have the same favorability as adjacent areas for the occurrence of uranium endowment. The thickness of the basalt in areas A_b, B_b, and C_b ranges from about 5 ft along margins of flows to more than 300 ft near vents, on the basis of descriptions in Moore and Wolfe (1976). The basalt-covered areas are considered an essentially nonviable resource under present conditions because of the difficulty of exploring beneath the basalt cover for the small targets of pipes and their contained uranium deposits. Present-day geophysical techniques are inadequate to locate hidden pipes. The basalt-covered areas are assessed as having a uranium endowment in addition to the principal favorable areas.

ELICITATION

Elicitation for the assessment was carried out with the principal scientist, H.B. Sutphin, in two sessions, April 13 and 20, 1987. Several follow-up discussions were held, and the final essential input for calculations was received on June 11, 1987. The elicitations were made by W.I. Finch, C.T. Pierson, and R.B. McCammon. The sessions were attended by K.J. Wenrich. The results of the elicitations are given in tables 1 and 2.

The total area favorable for uranium endowment is 16,728 mi^2, which is nearly 16 percent less than the total area of 19,879 mi^2 designated as favorable in the 1980 NURE assessment. This difference is due to designating volcanic vents as unfavorable and removing them from basalt-covered areas (fig. 2) and to refinements in identifying favorable areas. A large area deleted from the favorable category as defined in the NURE assessment is area E on figure 2.

Table 2. Land areas and estimated *L* factors of favorable areas

Favorable area		Land area (mi^2)	*L* factor Lower (0.05)	Most likely	Upper (0.95)
Grand Canyon	A	4,290*	0.90	0.99	1.00
	A_b	399	.90	.99	1.00
	D	589	.10	.13	.15
Cedar City	A	207	.90	.99	1.00
Williams	A	1,665	.90	.99	1.00
	A_s	201	.90	.99	1.00
	A_b	232	.90	.99	1.00
	B	393	.45	.55	.75
	B_s	60	.45	.55	.75
	B_b	748	.45	.55	.75
	D	245	.10	.13	.15
Marble Canyon	A	1,095	.90	.99	1.00
	A_b	1	.90	.99	1.00
	D	47	.10	.13	.15
Flagstaff	A	843	.90	.99	1.00
	A_b	173	.90	.99	1.00
	B	870	.45	.55	.75
	B_b	1,085	.45	.55	.75
	C	166	.01	.10	.15
	C_b	17	.01	.10	.15
Holbrook	B	171	.45	.55	.75
	B_b	311	.45	.55	.75
	C	2,388	.01	.10	.15
	C_b	471	.01	.10	.15
St. Johns	C	55	.01	.10	.15
Prescott	B	6	.45	.55	.75
Total area		16,728			

*Excludes Hack-Pinenut control area.

Table 3. Undiscovered uranium endowment in the principal areas

[Values are in tons U_3O_8. For each favorable area in a quadrangle, the odds are 9 to 1 that the true unconditional endowment in tons of U_3O_8 is between the values given for the 5 percent and 95 percent probabilities]

	Grand Canyon		Cedar City	Williams					Marble Canyon	
Favorable area . . .	A	D	A	A	A_S	B	B_S	D	A	D
Probability										
0.05	126,950	2,238	6,126	49,272	5,948	6,758	1,032	931	32,404	179
.10	173,610	3,066	8,377	67,380	8,134	9,287	1,418	1,275	44,313	245
.15	211,470	3,741	10,204	82,073	9,908	11,339	1,731	1,556	53,976	298
.20	245,450	4,349	11,844	95,264	11,500	13,185	2,013	1,809	62,651	347
.25	277,460	4,923	13,388	107,690	13,000	14,928	2,279	2,048	70,821	393
.30	308,510	5,481	14,886	119,740	14,455	16,623	2,538	2,280	78,746	437
.35	339,280	6,037	16,371	131,680	15,896	18,309	2,795	2,511	86,599	482
.40	370,270	6,597	17,866	143,710	17,348	20,014	3,056	2,744	94,510	526
.45	401,910	7,171	19,393	155,990	18,831	21,761	3,322	2,983	102,580	572
.50	434,630	7,766	20,972	168,690	20,364	23,575	3,599	3,230	110,940	620
.55	468,920	8,392	22,626	181,990	21,970	25,485	3,891	3,491	119,690	670
.60	505,320	9,058	24,383	196,120	23,676	27,527	4,203	3,768	128,980	723
.65	544,480	9,778	26,272	211,320	25,511	29,744	4,541	4,067	138,980	780
.70	588,090	10,576	28,376	228,240	27,554	32,188	4,914	4,399	150,110	844
.75	636,770	11,482	30,725	247,140	29,835	34,986	5,341	4,776	162,530	916
.80	693,870	12,538	33,480	269,300	32,510	38,243	5,839	5,215	177,110	1,000
.85	763,370	13,837	36,834	296,270	35,766	42,290	6,456	5,755	194,850	1,104
.90	855,750	15,566	41,291	332,130	40,095	47,762	7,292	6,475	218,430	1,242
.95	1,001,400	18,337	48,321	388,670	46,920	56,558	8,635	7,628	255,610	1,463
Mean	482,148	8,691	23,265	187,127	22,590	26,547	4,053	3,615	123,066	694

Table 3. Undiscovered uranium endowment in the principal areas—Continued

	Flagstaff			Holbrook		St. Johns	Prescott	Total endowment for principal areas
Favorable area . . .	A	B	C	B	C	C	B	
Probability								
0.05	24,947	14,961	263	2,941	3,782	87	103	277,790
.10	34,115	20,558	417	4,041	5,994	138	142	382,080
.15	41,554	25,101	551	4,934	7,929	183	173	466,680
.20	48,233	29,188	678	5,737	9,753	225	201	542,630
.25	54,523	33,046	802	6,495	11,536	266	228	614,180
.30	60,623	36,799	926	7,233	13,322	307	254	683,600
.35	66,669	40,532	1,053	7,967	15,142	349	280	752,430
.40	72,760	44,307	1,182	8,708	17,010	392	306	821,820
.45	78,976	48,173	1,317	9,468	18,951	436	332	892,680
.50	85,407	52,189	1,460	10,258	21,002	484	360	966,040
.55	92,144	56,418	1,613	11,089	23,205	534	389	1,043,000
.60	99,297	60,938	1,779	11,977	25,586	589	420	1,124,700
.65	106,990	65,844	1,960	12,942	28,196	649	454	1,212,900
.70	115,560	71,256	2,164	14,006	31,135	717	491	1,310,700
.75	125,130	77,449	2,400	15,223	34,529	795	534	1,420,800
.80	136,350	84,660	2,678	16,640	38,521	887	584	1,549,400
.85	150,010	93,619	3,027	18,401	43,544	1,003	646	1,706,800
.90	168,160	105,730	3,502	20,782	50,378	1,160	729	1,915,900
.95	196,780	125,200	4,284	24,609	61,631	1,419	863	2,248,200
Mean	94,744	58,769	1,759	11,551	25,308	583	405	1,074,910

UNDISCOVERED URANIUM ENDOWMENT IN THE PRINCIPAL AREAS

The probability distribution of the undiscovered unconditional uranium endowment for each favorable area in the eight 1°×2° quadrangles is given in table 3.

ADDITIONAL UNDISCOVERED URANIUM ENDOWMENT IN THE BASALT-COVERED AREAS

The probability distribution of the undiscovered unconditional uranium endowment for each of five 1°×2° quadrangles having basalt cover is given in table 4.

TOTAL ENDOWMENT IN THE GRAND CANYON BRECCIA-PIPE PROVINCE

From the previously given individual estimates, the probability distribution of the undiscovered unconditional uranium endowment for the entire northern Arizona breccia-pipe province, including both the principal and basalt- covered areas, was calculated using the computer program TENDOWG (McCammon and others, 1988), which assumes that estimates in the subareas are perfectly correlated. The computer-generated probability distribution of the unconditional uranium endowment for the entire province is as follows:

Probability	Tons U_3O_8	Probability	Tons U_3O_8
0.05	338,740	0.55	1,274,900
.10	466,410	.60	1,375,100
.15	569,870	.65	1,483,200
.20	662,730	.70	1,602,900
.25	750,230	.75	1,738,300
.30	835,120	.80	1,896,100
.35	919,320	.85	2,089,600
.40	1,004,200	.90	2,347,000
.45	1,090,900	.95	2,757,200
.50	1,180,700		

The odds are 9 to 1 that the true endowment is between 338,740 and 2,757,200 tons U_3O_8 in the region. The mean or expected value for the unconditional endowment is 1,315,390 tons U_3O_8. A small part of this endowment has been discovered.

The mean endowment of the Hack-Pinenut control area, which is in addition to the above total, is 16,429 tons U_3O_8 distributed in an area of 141 mi^2. Part of this endowment has been discovered.

The depths to the endowed strata range from 500 ft to more than 2,000 ft in most areas. Only in favorable area D are the depths less than 500 ft. The depths generally are greater in basalt-covered areas than in adjacent areas.

The mean total endowment of the 17 principal favorable areas in the Grand Canyon region is 1,074,910 tons U_3O_8 distributed in an area of 13,291 mi^2. Additional endowment in the nine basalt-covered areas has a mean value of 240,473 tons U_3O_8 distributed in an area of 3,437 mi^2. The basalt-covered areas probably contain no economically viable resources. Nevertheless, the mean total endowment for the 26 favorable areas is 1,315,390 tons U_3O_8 distributed in an area of 16,879 mi^2. The 1980 NURE mean total endowment in a comparable area, but measuring 19,728 mi^2, is 158,000 tons U_3O_8. Thus, the new estimate is eight times larger than the NURE estimate. In the test case reported by Finch and McCammon (1987), the DSF method was compared to the NURE method using the same principal investigator, and the result of the DSF method was 4.4 times more than that calculated using the NURE method. This difference can probably be attributed to the DSF method allowing for greater partitioning of the input data into many estimates of grade and size of deposits, rather than a single F factor as in the NURE method for calculating endowment. This tends to result in a less biased (generally larger) estimate (i.e., it evens out the inherent human tendency to underestimate in order to be "on the safe side").

In addition to the partitioning character of the DSF method, the eight-fold increase may be explained by several other factors. Since 1980, knowledge of the distribution of grade and tonnage of newly discovered and mined deposits has increased significantly. Furthermore, knowledge of the geology of the Grand Canyon region and the deposits has increased several fold. For this assessment, the entire region was assessed by a single principal investigator with much greater knowledge of the uranium deposits and their geology (increased consistency promoted a more perfect correlation). For the NURE assessments, six investigators participated; of these only one had much experience with the geology and the breccia-pipe deposits, and the others probably had a "sandstone-deposit bias" that probably lowered input values.

The large endowment reported here for the principal areas alone is significant because it is nearly as large as the 1,281,000 tons U_3O_8 reported in the 1980 NURE estimate for the entire San Juan Basin (McCammon and others, 1986, p. 351). However, a reassessment of the San Juan Basin using the DSF method would probably yield an estimate much larger than the 1980 NURE estimate. Nevertheless, we conclude that the principal areas have the potential of becoming the second most important uranium-producing region in the United States. If exploration technology is developed to explore the basalt-covered areas, the Grand Canyon region could become an even more important uranium province in the United States.

Table 4. Undiscovered uranium endowment in the basalt-covered areas

[Values are in tons of U_3O_8. For each favorable area in a quadrangle, the odds are 9 to 1 that the true unconditional endowment in tons of U_3O_8 is between the values given for the 5 percent and 95 percent probabilities]

	Grand Canyon	Williams		Marble Canyon	Flagstaff			Holbrook		Total endowment for basalt-covered areas
Favorable area . . .	A_b	A_b	B_b	A_b	A_b	B_b	C_b	B_b	C_b	
Probability										
0.05	11,807	6,865	12,863	30	5,119	18,658	27	5,348	746	61,158
.10	16,147	9,389	17,675	40	7,001	25,639	43	7,349	1,182	84,358
.15	19,668	11,436	21,581	49	8,528	31,304	56	8,973	1,564	103,160
.20	22,829	13,274	25,095	57	9,898	36,401	69	10,434	1,924	120,040
.25	25,806	15,005	28,412	65	11,189	41,212	82	11,813	2,275	135,960
.30	28,694	16,684	31,638	72	12,441	45,892	95	13,154	2,628	151,430
.35	31,555	18,348	34,848	79	13,682	50,548	108	14,489	2,986	166,780
.40	34,438	20,024	38,093	86	14,932	55,256	121	15,838	3,355	182,290
.45	37,380	21,735	41,418	94	16,207	60,078	135	17,221	3,738	198,150
.50	40,424	23,505	44,870	101	17,527	65,086	150	18,656	4,142	214,590
.55	43,613	25,359	48,506	109	18,910	70,360	165	20,168	4,577	231,890
.60	46,998	27,327	52,392	118	20,378	75,997	182	21,784	5,046	250,330
.65	50,640	29,445	56,611	127	21,957	82,116	201	23,537	5,561	270,290
.70	54,696	31,803	61,264	137	23,715	88,866	222	25,472	6,141	292,230
.75	59,224	34,436	66,588	148	25,679	96,589	246	27,686	6,810	317,460
.80	64,535	37,524	72,788	162	27,981	105,580	274	30,264	7,598	346,680
.85	70,999	41,283	80,491	178	30,784	116,750	310	33,466	8,588	382,850
.90	79,591	46,278	90,905	199	34,509	131,860	359	37,796	9,936	431,110
.95	93,140	54,157	107,650	233	40,384	156,150	439	44,757	12,156	509,020
Mean	44,843	26,074	50,528	112	19,443	73,292	180	21,008	4,992	240,473

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☆U.S. GOVERNMENT PRINTING OFFICE: 1990-773-047/06054

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