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National Uranium Resource Evaluation

WILLIAMS QUADRANGLE ARIZONA

Bendix Field Engineering Corporation
Grand Junction Operations
Grand Junction, CO 81502

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A. J. O'Neill, R. J. Nystrom,
and D. S. Thiede

BENDIX FIELD ENGINEERING CORPORATION
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Grand Junction, Colorado 81502

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ABSTRACT

Geologic environments of the Williams Quadrangle, Arizona, were evaluated for uranium favorability by means of literature research, uranium-occurrence investigation and other surface studies, subsurface studies, aerial radiometric data, hydrogeochemical data, and rock-sample analytic data. Favorability criteria are those of the National Uranium Resource Evaluation program.

Three geologic environments are favorable for uranium: the Tertiary fluvial rocks of the Colorado Plateau where they unconformably overlie impermeable bed rock (for channel-controlled peneconcordant deposits); collapse breccia pipes in Paleozoic strata of the Colorado Plateau (for vein-type deposits in sedimentary rocks); and Precambrian crystalline rocks of the Hualapai, Peacock, and Aquarius Mountains, and Cottonwood and Grand Wash Cliffs (for magmatic-hydrothermal deposits). Unfavorable geologic environments are: Tertiary and Quaternary volcanic rocks, Tertiary and Quaternary sedimentary rocks of the Colorado Plateau, nearly all Paleozoic and Mesozoic sedimentary rocks, and the Precambrian-Cambrian unconformity of the Grand Wash Cliffs area. Tertiary rocks in Cenozoic basins and Precambrian crystalline rocks in the Grand Canyon region and in parts of the Aquarius Mountains and Cottonwood and Grand Wash Cliffs are unevaluated.

INTRODUCTION

PURPOSE AND SCOPE

The Williams Quadrangle, Arizona (Fig. 1), was evaluated to identify geologic environments and delineate areas that exhibit characteristics favorable for uranium deposits. Evaluations were based primarily on surface investigations; only limited subsurface data were available.

Selection of a favorable environment is based on the similarity of its geologic characteristics to the National Uranium Resource Evaluation (NURE) recognition criteria described in Mickle and Mathews (eds., 1978). A favorable environment contains, or is likely to contain, at least 100 tons U_3O_8 in rocks with an average grade not less than 100 ppm U_3O_8.

This study was conducted by Bendix Field Engineering Corporation (BFEC) for the NURE program, managed by the Grand Junction, Colorado, Office of the U.S. Department of Energy (DOE). The study began October 1, 1977, and ended July 7, 1979. About 2 man-years were spent in literature review, field investigations, data analysis and interpretation, and preparation of the final report.

ACKNOWLEDGMENTS

We thank Western Nuclear Corporation, Flagstaff, Arizona, for providing us with information developed during their exploratory drilling program on the Hualapai Indian Reservation. We also express our gratitude to the Hualapai Indian Tribal Council for permitting us to conduct studies within the reservation.

PROCEDURES

Surface geologic studies included examination, description, and classification of uranium occurrences previously reported in U.S. Atomic Energy Commission (AEC) Preliminary Reconnaissance Reports (PRR's); reconnaissance of all accessible geologic environments; regional rock sampling in Precambrian terrain to determine major rock types and radioactive-element contents and distribution; and detailed geologic and geochemical studies in specific geologic environments potentially favorable for uranium.

A depositional model for copper-uranium collapse breccia pipes (App. E) was developed by integrating published data. Included are possible physical and chemical parameters of breccia-pipe formation and subsequent copper and uranium mineralization.

A lineament map of the west part of the quadrangle (Pl. 14) was compiled from LANDSAT imagery and photo linears (1:250,000 scale), to identify Precambrian terrain having faults and other structures that enhance favorability.

Field data consist of geologic descriptions and reconnaissance geologic maps. Analytic data comprise chemical, gamma-ray spectroscopic, and petro-

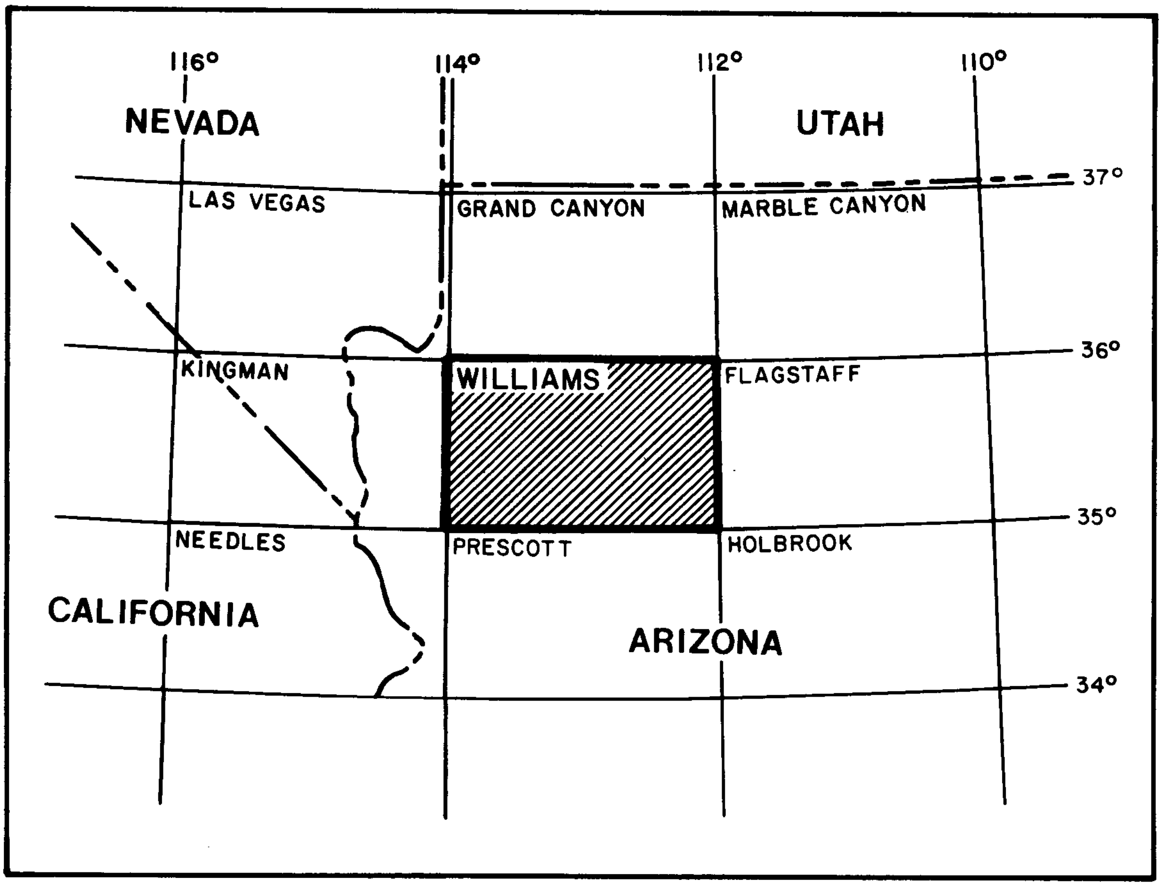

Figure 1. Location of Williams Quadrangle.

graphic analyses of rock, soil, and water samples, which were analyzed by Core Laboratories, Inc., Albuquerque, New Mexico, and Skyline Labs, Inc., Tucson, Arizona. Rock and soil samples were digested using hot hydrofluoric, perchloric, and nitric acids. Total-uranium (U_3O_8) contents were determined by fluorometric or, for samples exceeding about 400 ppm U_3O_8, colorimetric analyses. Additional element contents were determined by emission-spectrometric analysis (App. B). Gamma-ray spectroscopic, petrographic, and major-element oxide analyses were done by BFEC. In this report, equivalent-uranium and equivalent-thorium values were determined by gamma-ray spectroscopy.

The aerial radiometric survey (8800-line-km total) was conducted by Aero Service Division, Western Geophysical Company of America (1979). The data were received too late for ground checking of anomalies, but were interpreted by BFEC. Of the 25 anomalous areas outlined (Pl. 3) by BFEC, anomalies 9, 21, and 23 are associated with uranium occurrences. Other anomalies may be due to variation in surface-rock composition, especially where resistate minerals have been derived from Precambrian granitic and gneissic rocks (anomalies 3, 10, 11, 15, 16, and 22); lumping, for mapping purposes, of units with differing background radiometric responses (anomalies 1, 2, 5, 12, 13, 14, 17, 18, 19, 20, 24, and 25); errors in data standardization and/or flight-spacing changes (anomalies 6, 7, and 8); and high relief (anomalies 4 and, possibly, 5 and 9).

Approximately 1,450 stream-sediment and 135 water samples were collected during the hydrogeochemical and stream-sediment reconnaissance (HSSR), and analyzed (Wagoner, 1979) by Lawrence Livermore Laboratories, Livermore, California. Sediment samples were analyzed for uranium using delayed neutron counting, and for trace- and major-element contents using instrumental neutron activation. Water samples were analyzed using optical-emission spectrometry. Anomalies (Pl. 4) were not examined in the field because the data were not available in time. Dry-stream-sediment data were statistically analyzed by BFEC. Wet-stream-sediment and water samples were not used in statistical studies because of the low number and irregular distribution.

Two anomalous areas, both within Precambrian granitic-gneissic terrain and adjacent valley fill, are outlined on Plate 4. Anomaly 1, in the northern Aquarius Mountains, represents a cluster of stream-sediment samples with uranium values from 10 to 20 ppm U_3O_8; low thorium-to-uranium ratios (1:2) and a positive uranium residual coincide with anomalous uranium values. The anomaly closely coincides with an area shown, through analysis of rock samples, to be enriched (5 to 30 ppm chemical U_3O_8) in uranium. Anomaly 2, in the central Grand Wash Cliffs, is defined by high uranium values (2 to 10 ppm U_3O_8) in stream sediments and a high positive uranium residual; rock samples collected here, however, appear relatively depleted in uranium (1 to 5 ppm chemical U_3O_8) compared with Precambrian rocks elsewhere in the quadrangle.

Very little subsurface information is available for the quadrangle. The data are from drill-cutting samples and generalized drillers' logs of relatively shallow water wells in Cenozoic basins (available at the Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona, and the U.S. Geological Survey Water Resources Division, Flagstaff, Arizona). Information for two wells in the north part of Hualapai Valley (El Paso Natural Gas, Red

Lake 1, total depth about 1800 m; and a privately owned water well) was compiled to provide a general stratigraphic description of the sediments.

GEOLOGIC SETTING

The north and east parts of the Williams Quadrangle lie roughly within the Colorado Plateau; the south and west portions, in the Basin and Range Province. An intervening transition zone, which is structurally and topographically intermediate, lies between the two provinces and trends about northwest.

North-northwest-trending Cenozoic basins and Precambrian mountain ranges of the Basin and Range Province and transition zone lie within or are marginal to the North American Cordilleran Orogenic Belt (Drewes, 1978). The horst ranges and graben basins are the result of late Cenozoic basin and range faulting.

Cenozoic basins underlie the Hualapai, Big Sandy, Truxton, Aubrey, and Chino Valleys (Pl. 17). The Tertiary and Quaternary sediments are mostly fanglomerate and interior-basin deposits comprising unconsolidated to poorly consolidated conglomerate, sandstone, siltstone, claystone, and evaporites. The preponderance of granitic and gneissic detritus in the basin fill indicates that the sediments were largely derived from adjacent Precambrian terrain.

Precambrian rocks are widely exposed in the Hualapai, Aquarius, and Peacock Mountains, and the Cottonwood and Grand Wash Cliffs; isolated outcrops occur throughout the southwest portion of the quadrangle (Pl. 7). Older Precambrian (older than 1.8 b.y.) quartzofeldspathic gneiss, pelitic schist, and amphibolite, which have undergone amphibolite-grade regional metamorphism, have been extensively intruded by granitic to granodioritic plutons. Plutonic rocks in the northern Hualapai Mountains are (isotopic dating) from 1.3 to 1.8 b.y. in age (Kessler, 1976); some quartz monzonitic rocks, however, could be Laramide (Wilson and Moore, 1959).

In this report, the Precambrian rocks are collectively called the Precambrian crystalline complex. The rocks are part of a single basement complex, the Mohave Complex, found in adjacent parts of Arizona, California, Nevada, and Utah (Wasserburg and Lanphere, 1965). The complex is included in two metallographic provinces: the western United States tungsten province (Lamey, 1966) and the Arizona pegmatite belt (Jahns, 1952).

In the west part of the quadrangle, erosion has removed nearly all the Paleozoic strata; the Precambrian is in places directly overlain by Tertiary and Quaternary volcanic rocks. To the east, in the Grand Wash Cliffs that form the west boundary of the Colorado Plateau, the basal Cambrian Tapeats Sandstone unconformably overlies the Precambrian.

The lower Paleozoic stratigraphic section records several major marine transgressions-regressions, and major unconformities mark the system boundaries (Fig. 2). The lower Paleozoic comprises the Cambrian Tonto Group, consisting of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone; undivided Devonian limestones and dolomites; and the Mississippian Redwall

Limestone. These units are well exposed in the Grand Canyon region and are discontinuously exposed along the southwest border of the plateau.

The upper Paleozoic section also records major periods of marine advancement and retreat and minor continental deposition. This section is composed of the Callville Limestone, Supai Formation, Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone.

Mesozoic strata consist of the Triassic Moenkopi Formation and fluvial sandstones of the overlying Shinarump Member of the Chinle Formation; both units exist as erosional remnants on the plateau.

Erosion throughout northwest Arizona resulted from Laramide regional uplift in west-central Arizona. Tertiary fluvial, arkosic sandstone and conglomerate were deposited by a regionally north-flowing drainage system, which originated in largely Precambrian granitic and metamorphic terrain to the south (Fig. 3). This early or middle Tertiary erosional surface is overlain in places by Tertiary and Quaternary volcanic rocks; on the south Colorado Plateau, these rocks are mainly intermediate to mafic. Along the southwest boundary of the plateau and in the adjacent Basin and Range, the middle Miocene Peach Springs tuff of trachytic composition is widely distributed (Young and Brennan, 1974).

The regionally north-flowing drainage system was disrupted by a combination of escarpment developments along the Colorado Plateau-Basin and Range boundary (Peirce and others, 1979), widespread volcanism, and basin and range faulting. The Colorado River drainage system, established during the Pliocene, incorporated some interior and other poorly developed drainages (Lucchitta, 1975). Widespread Quaternary alluvium accumulated on the plateau surface and in major valleys.

ENVIRONMENTS FAVORABLE FOR URANIUM DEPOSITS

Geologic environments favorable for uranium deposits are the basal Tertiary fluvial rocks (Subclass 243, Austin and D'Andrea, 1978) of the Colorado Plateau where these rocks unconformably overlie impermeable bed rock (Areas A and B, Pl. 1a); collapse breccia pipes (Class 730, Mathews, 1978b) of the Grand Canyon area and Coconino Plateau (Area C, Pl. 1b); and Precambrian granitic rocks (Class 330, Mathews, 1978a) in the Hualapai, Peacock, and Aquarius Mountains, and Cottonwood and Grand Wash Cliffs (Areas D and E, Pl. 1a).

TERTIARY FLUVIAL ROCKS OF THE COLORADO PLATEAU

The Tertiary Music Mountain conglomerate and correlative (?) Blue Mountain gravels are widely distributed on the Hualapai and southern Coconino Plateaus. Outcrops and subsurface beds of the Music Mountain favorable for channel-controlled peneconcordant uranium deposits are in upper Milkweed and Peach Springs Canyons and in Truxton Valley. In these areas the conglomerate unconformably overlies the Tapeats Sandstone, Bright Angel Shale, or Precambrian granite (Area A, Pl. 1a), which may also be host rocks for uranium

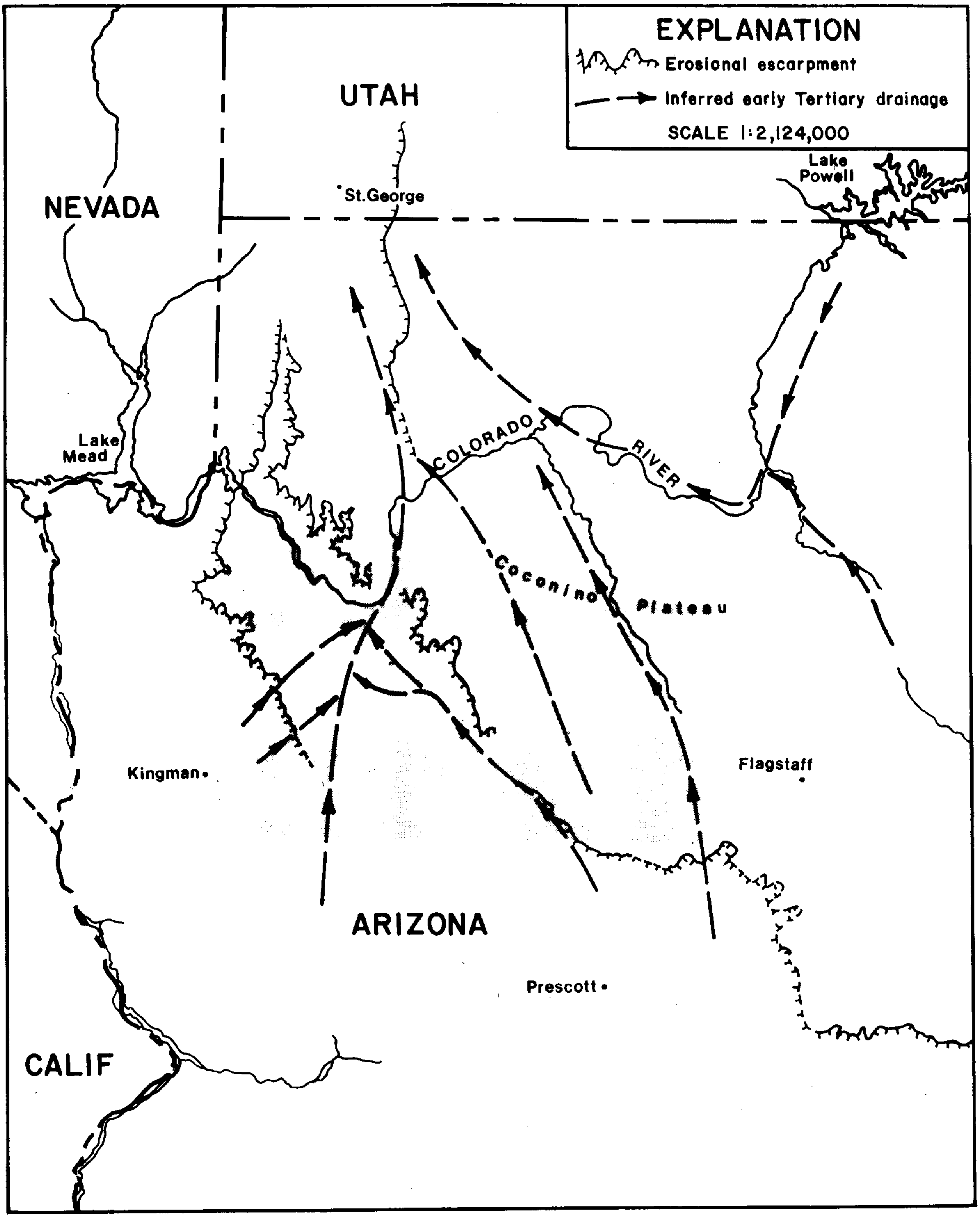

Figure 3. Regional early Tertiary paleodrainage and present topographic features.

that has been remobilized from the Music Mountain. Areas of Blue Mountain gravels favorable for channel-controlled peneconcordant uranium deposits (Area B, Pl. 1a) occur throughout the Blue Mountain-Rose Well-Long Point region where the gravels overlie the Supai Formation, Hermit Shale, or Moenkopi Formation. These relatively impermeable bedrock units may also contain uranium deposits associated with the Tertiary scour-channel deposits.

We emphasize that the Blue Mountain gravels are considered favorable due to their similarity to the Music Mountain conglomerate. There is little direct evidence (significant occurrences and/or radioactive anomalies) that concentration of uranium has occurred.

Music Mountain Conglomerate

The lower (?) Tertiary Music Mountain conglomerate (Young, 1966, 1979) is the basal Tertiary unit on the Hualapai Plateau. The Music Mountain is 150 m thick in Milkweed Canyon and 245 m thick in Peach Springs Canyon (Young, 1966); it consists mainly of gray to red arkosic sandstone with minor, thin interbeds of red and green siltstone and mudstone. The sandstones are commonly massive and fine to coarse grained. Pebble-cobble-boulder conglomerate lenses with well-rounded clasts occur throughout the unit; the lenses are thickest (as much as 12 m) and coarsest near the base. Clasts are mostly granite, gneiss, and schist, with minor quartzite, limestone, and volcanic rock (Young, 1966). The preponderance of igneous and metamorphic lithologies, the roundness of the clasts, and northerly paleotransport directions indicate that the Music Mountain sediments were derived mainly from Precambrian highlands to the south and southwest (Young, 1966). The Music Mountain is very poorly consolidated, forming extensive slope debris, and is weakly cemented by clay, calcite, and iron oxides. Some of the cement and silt-sized matrix may have been derived from the widespread in situ decomposition of the crystalline clasts. The unit is very porous and permeable and highly oxidized; hematite and limonite staining are common.

The Music Mountain is restricted to major paleochannels, some possibly fault controlled, that deeply downcut a lower (?) Tertiary regional erosional surface. The unit was probably deposited by aggrading streams, often under conditions of relatively high flow regime. Indistinctly stratified, the Music Mountain appears relatively flat lying, but dips comparatively steeply (25° to 35°) in lower Peach Springs Canyon in an area of suspected faulting.

In Peach Springs Canyon, uranium occurs at the surface in the basal Music Mountain, and, in the subsurface, it occurs both in the basal conglomerate and in the upper part of the underlying Cambrian Bright Angel Shale. A rock sample (MGC 170) from the most radioactive zone at the surface (occurrence 10, App. A and C) contained 0.13% chemical U_3O_8 (Table 1). The uraniferous rock consists of angular, silt-sized potassium feldspar (37%), quartz (9%), and lesser amounts of muscovite, plagioclase, and biotite. About 50% of the rock is matrix and cement, which consist mainly of iron oxides, manganese oxides, and clay. Pebbles and cobbles of decomposed granite, gneiss, schist, and some quartzite are also scattered throughout the sampled zone. The outcrop is oxidized, highly altered, and distinctively rose colored. Anomalous amounts of arsenic, beryllium, cobalt, iron, manganese, nickel, yttrium, and zinc are associated with the uranium (Table 1). Only traces of carbonaceous

TABLE 1. ANALYTIC RESULTS FOR ROCK SAMPLES OF LOWER (?) TERTIARY FLUVIAL DEPOSITS ON THE HUALAPAI PLATEAU

Geographic area	Formation	Sample no.	U_3O_8 (ppm)	eU (ppm)	eTh ppm)	Associated elements
Upper Peach Springs Canyon	Westwater Fm.	MGC 310	7	4	16	---
	Music Mountain Cgl.	MGC 311	3	3	17	---
Upper Milkweed Canyon	Music Mountain Cgl.	MGC 314	3	2	16	---
	Music Mountain Cgl.	MGC 315	1	1	9	---
	Music Mountain Cgl.	MGC 316	2	2	13	---
Blue Mountain	Blue Mtn. Gravels	MGC 318	2	2	15	---
	Blue Mtn. Gravels	MGC 319	2	2	15	---
H.E.C. Prospect	Music Mountain Cgl.	MGC 170	1,300	1,100	18	1,000(As), 70(Be), 70(Co), 70,000(Fe), >5,000(Mn), 100(Ni), 70(Y), 300(Zn)

material (0.02% organic carbon) are preserved, but silicified wood fragments and logs are abundant throughout the area. Fine, delicate structures are well preserved in the petrified wood, and the wood is believed indigenous to the Tertiary sediments, not reworked from Triassic strata once widespread in the area (Young, 1966). Results of recent drilling by Western Nuclear Corporation indicate that low-grade uranium concentration occurs discontinuously over a 3-km^2 area that includes occurrence 10. The radioactivity (uranium) is restricted to the lower 10 m of the Music Mountain conglomerate and the upper 10 to 30 m of the underlying mudstone and shale beds of the Cambrian Bright Angel Shale (Pl. 10). An analysis of subsurface data indicates considerable relief at the Tertiary-bedrock contact, due to deep channelling and scouring of the bed rock, or to offset related to faulting.

Music Mountain favorability is due in part to inferred scour-channel deposits, with included organic material, that cut deeply into relatively impermeable bed rock. Because the Tertiary sediments are very porous and permeable throughout and lack effective means of concentrating and preserving uranium, it may be locally preserved, under reducing conditions, in some deep scours and may have been remobilized into surrounding bed rock. Normally highly impervious bedrock units, the Precambrian granite, Cambrian Tapeats Sandstone, and Bright Angel Shale, may, near their contact with the overlying Tertiary sediments, have developed increased permeability related to deep weathering, thereby augmenting the infiltration of uranium-bearing fluids. Bedrock impermeability away from the unconformity would restrict downward flow of ground water thereby enhancing the preservation of uranium. Anomalous radioactivity was also encountered, on trend with the Music Mountain, in the basal Tertiary sediments and upper Precambrian granitic bed rock in a stratigraphic test hole drilled in Truxton Valley.

Possible uranium sources include the arkosic Music Mountain sediments, the overlying Peach Springs tuff, or both. The Peach Springs is a partly welded, silicic ash-flow tuff that was extruded about 17 m.y. B.P. from an area northwest of Kingman; its areal extent eastward probably exceeded 5000 km^2 (Young and Brennan, 1974). The thickest accumulations of the tuff (25 m) apparently developed along the early Tertiary drainage courses to which the Music Mountain conglomerate was restricted. Relatively high thorium-to-uranium ratios indicate that the tuff has probably been depleted of uranium (Table 2). The tuff, however, is separated from the Music Mountain conglomerate by 30 to 200 m of other sedimentary and volcanic rocks. Although there is no substantiating field evidence, the tuff may have directly overlain the basal Tertiary conglomerate in places.

Apart from the isolated surface occurrence (10) and the low-grade, discontinuous subsurface radioactivity in Peach Springs Canyon and Truxton Valley, very little evidence of uranium concentration was found in Tertiary fluvial and associated rocks throughout the Hualapai Plateau. Surface radiometric traverses and rock sampling in upper Milkweed and Peach Springs Canyons detected no anomalous radioactivity or uranium (Table 1). Aerial radiometric data indicate small uranium anomalies in Tertiary fluvial exposures in a tributary canyon of Peach Springs Canyon near occurrence 10 and in Hindu Canyon (Pl. 3). Dry-stream-sediment sample analyses (HSSR) did not indicate any anomalous uranium concentrations in areas of exposed Music Mountain conglomerate, but sample-site density is relatively low in those areas.

TABLE 2. SUMMARY OF CHEMICAL AND GAMMA-SPECTROSCOPIC RESULTS FOR PEACH SPRINGS TUFF AND OTHER SILICIC VOLCANIC UNITS

Geologic unit	Sample no.	U_3O_8 (ppm)	eU (ppm)	eTh (ppm)	eU/U_3O_8	eTh/eU
Peach Springs Tuff	MGC 020	<2	4	31	>2	7.8
	MGC 142	5	2	31	0.4	15.5
	MGC 246	5	2	34	0.4	17.0
	MGC 249	2	3	14	1.5	4.7
	MGC 301	3	6	26	2.0	4.3
	MGC 306	4	4	32	1.0	8.0
	MGC 308	4	---	---	---	---
	MGC 312	4	---	---	---	---
	MGC 320	5	5	30	1.0	6.0
Ft. Rock Creek Rhyodacite	MGC 250	3	4	16	1.3	4.0
Crater Pasture Fm.	MGC 251	8	10	48	1.3	4.8

The favorable environment, which includes the basal Music Mountain and upper parts of the Tapeats Bright Angel or Precambrian granite, has an average thickness of 30 m. It extends over an area of about 35 km^2. About 80% of Area A is within the Hualapai Indian Reservation; the remaining area, mainly Truxton Valley, is listed under U.S. Bureau of Land Management, State of Arizona, or private owners.

Blue Mountain Gravels

The Blue Mountain gravels (Koons, 1948) are fluvial and minor lacustrine rocks tentatively correlated with the Music Mountain conglomerate (Young, 1966). The gravels are widely distributed, but poorly exposed, on the eastern Hualapai and southern Coconino Plateaus. On the eastern Hualapai Plateau, the Blue Mountain gravels comprise mainly medium- to coarse-grained, gray to pinkish gray, arkosic sandstone; thin beds of red and green siltstone; and minor lenses of pebble-cobble-boulder conglomerate. Pebbles and cobbles are subrounded to rounded and consist primarily of Precambrian granite, gneiss, and schist, with abundant quartzite, chert, and volcanic rock (Koons, 1948; McKee and McKee, 1972). The unit is poorly consolidated and, like those of the Music Mountain conglomerate, the granitic and metamorphic clasts are deeply weathered. The gravels unconformably overlie red beds of the Pennsylvanian-Permian Supai Formation or Hermit Shale; the basal contact is obscured by slope debris. Near Blue Mountain the gravels are about 45 m thick (Koons, 1948). In the Rose Well and Long Point areas, the gravels consist of very fine- to medium-grained, white to pinkish gray, arkosic sandstone and of conglomeratic sandstone interbedded with siltstone, claystone, and fossiliferous limestone. In the Rose Well area the gravels overlie the Permian Kaibab Limestone; elsewhere throughout the southern Coconino Plateau they overlie the Triassic Moenkopi Formation. Near Long Point the unit is approximately 40 m thick (Squire and Abrams, 1975). About 45 m of feldspathic and lithic sandstone, thought to be Blue Mountain gravels, are in drill cuttings from a water well near Crookton. The sandstone here underlies basalts of the Mt. Floyd volcanic field, and may be widely distributed under the field (Pl. 7). Clast lithologies and the high degree of rounding suggest that the Blue Mountain sediments were deposited by streams that originated in Precambrian terrain to the south (Koons, 1948). Some pebbles may have been reworked from the Shinarump Member of the Chinle Formation, which formerly extended into this area (McKee and McKee, 1972). The Blue Mountain gravels, unlike the Music Mountain conglomerate, were not restricted to well-defined drainage courses; the limestone beds near Long Point indicate temporary lacustrine conditions. The age of the Blue Mountain gravels is not well established. Radiometric age dates of overlying basalt flows and an included volcanic clast (Peirce and others, 1979) indicate between Late Cretaceous and late Miocene.

The Blue Mountain gravels, like the Music Mountain conglomerate, consist mainly of highly oxidized, very porous and permeable sandstone and conglomerate; no carbonaceous material has been observed. The Blue Mountain sediments lack any effective means of concentrating uranium, but, like the Music Mountain, scour-channel deposits (with organic matter) in impermeable bed rock may have been important in localizing and preserving uranium. Associated bedrock units may host remobilized uranium. Uranium source rocks for the gravels include the arkosic host sediments themselves and possibly, in the westernmost part of the gravels extent, the Peach Springs tuff.

There is very little evidence of uranium in the Blue Mountain gravels. No anomalous radioactivity was detected during ground and aerial radiometric surveys, and chemical and gamma-ray spectroscopic analyses do not show any anomalous radioactive elements (Table 1). One ground-water anomaly (13 ppb U_3O_8) was detected in a well near Rose Well.

The favorable environment within the Blue Mountain gravels and underlying strata has an average thickness of 30 m and extends over an area of about 505 km^2. Most of Area B is private and state-administered land; a small portion of the westernmost area is within the Hualapai Indian Reservation.

COLLAPSE BRECCIA PIPES

The Williams Quadrangle was evaluated for vein-type uranium deposits in sedimentary rocks (Class 730) because of the nearby Grand Canyon area deposits, particularly the Orphan Lode Mine; lateral extension of the host rocks into the quadrangle; and the recent discovery of a weakly mineralized pipelike structure in the Diamond Creek area (App. A). An integrated model of ore deposition from which recognition criteria suitable for resource evaluation could be developed is presented in Appendix E and was the main objective of this evaluation.

It is proposed that formation and mineralization of the collapse breccia pipes were due to controlled vertical mixing of three compositionally different ground-water solutions. The breccia pipes were conduits for differing solutions; oxidizing, uranium-bearing ground water from the upper Supai Group (McKee, 1975) therein mixed with reducing ground water from the Redwall Limestone. The pipes then served as structural traps during the resulting uranium mineralization. (See App. E.)

The areal distribution of Orphan Lode Mine-type depositional factors and of known occurrences (Pl. 12) provides the information base from which Plate 13, a favorability map for Orphan-type deposits in the Williams Quadrangle, was derived. The Williams map is divided into six zones of decreasing occurrence probability, zone 1 having the most determining factors (recognition criteria) and being most favorable (see below).

Zone 1	All occurrences; edges of Esplanade; both faulting and uplift
Zone 2	Edges of Esplanade; either faulting or uplift
Zone 3	Central Esplanade; both faulting and uplift
Zone 4	Central Esplanade; either faulting or uplift
Zone 5	Esplanade; neither faulting nor uplift; Upper Pennsylvanian-Lower Permian sequence with either faulting or uplift
Zone 6	Supai (or equivalents) and Redwall together

Mineralization-control factors that were plotted include distribution and geometry of the Esplanade Sandstone (Lane, 1977) and distribution of the

Mississippian Redwall Limestone and the Pennsylvanian-Permian Supai Group and equivalents, patterns of post-Pennsylvanian to pre-Jurassic faulting (Peirce, 1976; Shoemaker and others, 1975), the area of the Grand Canyon Upwarp (Lane, 1977), and the southwest-to-northwest regional trend of Mesozoic ground-water movement. Orphan-type pipe locations plotted include seven occurrences, four with past U_3O_8 production (Orphan Lode, Hacks Canyon, Copper Mountain, and Ridenour; Nuclear Exchange Corporation, 1978), and the weakly mineralized pipelike structure in the Diamond Creek area of the Williams Quadrangle.

The mineralized breccia pipes occur near the facies boundaries of the Esplanade Sandstone, in the delineated fault zones, and in the area of the Grand Canyon Upwarp (Pl. 12). The correlation of occurrences with the east and west edges of the Esplanade Sandstone is interpreted as a function of uranium deposition, and could be explained by the major flow of uranium-bearing ground water being along Esplanade facies boundaries. Such flow could have been caused by a combination of facies-related permeability variations and a west-to-east increase in hydrostatic pressure in the Esplanade due to the Mesozoic structure. Rock exposure and intensive past exploration indicate that most, if not all, major Orphan-type occurrences in the main Grand Canyon area have been located. Because the six primary occurrences precisely outline the Esplanade Sandstone from east to west, the Grand Canyon excised area forms a representative east-west section that reveals the distribution of mineralized rock across the Esplanade.

Zones 1 through 6 were evaluated for uranium deposits that could contain at least 100 tons U_3O_8 in rocks with an average grade not less than 100 ppm U_3O_8. There are no known breccia pipes within the Williams Quadrangle that meet these criteria. The models indicate, however, that the unexcised areas of zone 1 show 100% environmental correlation with the excised areas that contain the mineralized pipes. Therefore, the ratio of known occurrences to the area of exposed favorable section should extend, as a minimum, to the unexposed areas of zone 1. The same ratio of deposits to area should apply to the Williams zone 1.

The total area of zone 1 in northwest Arizona is 3760 km^2. Of this area, 679 km^2 of the Supai to Coconino section is exposed and contains a minimum of seven mineralized pipes. Five of these contain relatively small amounts of uranium, about 100 t or less U_3O_8; the others, the Orphan and the Hacks Canyon, contain substantial amounts of uranium. The Orphan Lode Mine has produced 509,000 tons of ore at 0.43% U_3O_8, containing 2190 t U_3O_8 (source H. Holen, DOE records). Peirce and others (1970) stated that several hundred thousand tons of ore with a grade greater than 0.3% U_3O_8 remain; past production plus future resources is about 3000 t U_3O_8 at the 0.01% NURE grade cutoff. Drilling underway at the Hacks Canyon Prospect has already delineated 500 t U_3O_8 (Nuclear Exchange Corporation, 1978). In this report, we assume that the U_3O_8 content of the Hacks Canyon Prospect is at least a half to a third that of the Orphan.

Because zone 1 in the Williams Quadrangle is 1400 km^2, it is estimated to contain a minimum of four Orphan-sized pipes and 10 smaller occurrences and is favorable. Further, several considerations indicate that zone 6, with the fewest favorable characteristics, is favorable, and with it zones 2 through 5. Primarily, it is probable that the Pennsylvanian-Permian section of zone 6 was within the regional ground-water flow system during Mesozoic time (Pl. 12, App. E), and both reductants and ore solutions were available. Although the model indicates that most migrating ore solutions were channeled into the Esplanade Sandstone, not present in zone 6, uranium-bearing ground waters were probably present in the rest of the Supai Group and its lateral equivalents. Another major control for uranium deposits was post-Mississippian to pre-Jurassic faulting; given the extent of time when faulting could have initiated pipe formation, and given tectonic activity of the region and the areal extent of zone 6, it seems reasonable that faulting occurred somewhere within zone 6. Moreover, just one mineralized pipe a thirtieth the size of the Orphan pipe would make zone 6 favorable. If zone 6 is favorable, all of Area C, including zones 2 through 5, is favorable.

The land status of Area C (Pl. 1a; zones 1 through 6) is mixed. Most consists of national forest, state, and private lands. There are small areas of Grand Canyon National Park, Lake Mead National Recreation Area, and the Hualapai Indian Reservation (Pl. 17) as well as small areas of lands administered by the U.S. Bureau of Land Management.

The Williams Quadrangle contains 10,850 km^2 of Area C, the environment is about 0.36 km thick, and the resultant volume is about 3900 km^3. The favorable environment is about 0 to 180 m from the surface; the projected surface dimension of an Orphan-sized orebody is a circular area about 150 m in diameter. Although substantial amounts of uranium are indicated, these figures show that locating deposits using current exploration techniques would be an expensive and time-consuming process.

PRECAMBRIAN CRYSTALLINE COMPLEX

Portions (Areas D and E, Pl. 1a) of the Precambrian crystalline complex in the northern Hualapai, Peacock, and northern Aquarius Mountains, and Cottonwood and southern Grand Wash Cliffs are favorable for magmatic-hydrothermal uranium deposits (Class 330). Favorable areas are characterized by quartz monzonite or granite plutonic rocks that contain an average, or slightly greater than average, amount of uranium; an abundance of fault, fracture, and shear zones, in part inferred from LANDSAT lineaments and photo linears; and evidence of regional or local uranium enrichment as indicated by uranium occurrences and (or) regional rock sampling, or aerial radiometric or HSSR studies.

Little has been known about the geologic history of the complex in general, and few data are available on the lithology, chemistry, or radioactive-element contents of the plutonic rocks. Our study objectives were to examine all felsic plutonic bodies (and adjacent metamorphic country rock) as potential uranium source and (or) host rocks; to compile a lineament map (based on LANDSAT and photo linears) to identify areas with potentially abundant faults, fractures, or shear zones; and to classify reported occurrences through detailed geologic and geochemical studies and to evaluate similar areas in the complex using the information gained.

Field reconnaissance studies revealed that intrusion of quartz monzonite and granite is more extensive than that portrayed on existing geologic maps (Wilson and Moore, 1959; Pl. 7). The plutonic bodies are mostly composite intrusives, complexly intermixed with the enclosing metamorphic rock; contact relationships are commonly gradational, often obscure. No mapping of the felsic intrusive rocks was done; however, petrographic and analytic studies were undertaken to classify and characterize these rocks. Quartz monzonite predominates, but granite also commonly occurs (App. D). The plutonic rocks are characteristically medium grained and anhedral-equigranular, but porphyritic phases are common. Microcline (perthitic and myrmekitic) and plagioclase (commonly unzoned) exist as discrete grains; biotite and muscovite are present, but muscovite is commonly secondary. Chemically the rocks are peraluminous, indicating that they are not highly differentiated and therefore less likely to have generated large amounts of uranium-rich volatile phases. However, high initial strontium-isotope ratios for many quartz monzonites in the northern Hualapai Mountains (Kessler, 1976) suggest they were derived from magma(s) having a significant crustal component. If this is the case, the parent magma(s) would have been enriched in lithophile elements, including uranium. Rocks similar in chemical composition, lithology, and texture to crustally derived (?) plutonic rocks of the Hualapai Mountains exist in the adjacent Precambrian ranges; crustally derived (?) plutons may be widespread throughout the Precambrian complex.

Field examination of selected areas revealed that major fault, fracture, and shear (brecciated) zones do transect both plutonic and metamorphic rocks. Because of the complex spatial rock relationships, confirmation of suspected fault and shear zones is commonly based on petrographic determination of cataclastic rocks. Evidence of hydrothermal activity is commonly found within, and closely associated with, major fault and shear zones. Evidence includes prominent, west-trending, silicified breccia in the northern Aquarius Mountains and Cottonwood Cliffs, and widespread base- and precious-metal concentration in northwest, north-south, and east-west fault and fracture zones in the Hualapai Mountains (Vuich, 1974) and along northwest-trending faults in the Peacock range. Anomalous concentrations of uranium are commonly associated with hydrothermally altered fault, fracture, and shear zones throughout the complex.

The aerial radiometric (Pl. 3) and HSSR (Wagoner, 1979) data show uranium enrichment in Areas D and E of Plate 1a. In addition, regional sampling indicates average or slightly greater amounts of uranium and thorium for quartz monzonite and granite as compared to worldwide averages (Taylor, 1964). Commonly, significantly anomalous amounts of uranium (>10 ppm chemical U_3O_8) and (or) thorium (>30 ppm eTh) are contained in these rocks, and are commonly associated with rare-earth elements, probably mainly in accessory minerals (Tables 3 and 4). The uranium in the felsic plutonic rocks is nearly in equilibrium as indicated by approximately equal values for equivalent uranium and chemical U_3O_8 (App. D), suggesting that uranium has not been significantly depleted. Equivalent thorium-to-equivalent uranium ratios for the quartz monzonitic rocks are from 8 to 13 (Table 3), suggesting that thorium and uranium may have been segregated during magmatic differentiation. Thorium-rich pegmatites (Heinrich, 1960; MGC 156) in the Precambrian complex may indicate that thorium remained in the pegmatitic silicate phase while uranium went into an aqueous hydrothermal phase. Although thorium-rich pegmatites seem unfavorable for uranium, their presence supports the hypothesis that uranium-enriched hydrothermal fluids were generated.

TABLE 3. AVERAGE CONTENTS OF URANIUM AND THORIUM AND AVERAGE THORIUM-TO-URANIUM RATIOS IN PRECAMBRIAN QUARTZ MONZONITIC ROCKS

Area	Number of samples	U_3O_8 (ppm)	eU (ppm)	eTh (ppm)	eTh/eU
Northern Hualapai Mountains	34	5	6	45	8
Aquarius Mountains-Cottonwood and southern Grand Wash Cliffs	51*	5	5	27	10
Peacock Mountains	13	4	6	73	13

*Only 50 samples for eU, eTh, and eTh/eU

TABLE 4. MODE OF OCCURRENCE OF URANIUM AND THORIUM IN QUARTZ MONZONITE AND GRANITE OF THE PRECAMBRIAN CRYSTALLINE COMPLEX

Area	Sample number	U_3O_8 (ppm)	eU (ppm)	eTh (ppm)	Elements detected by scanning electron microscope/X-ray energy dispersive system: Major	Minor	Trace	Possible mineral
Hualapai Mountains	103	5	10	46	P, Ce	Th	Ca	Monazite
					P, Th	Si, Ca, La	Pb	Cheralite(?)
					Ce, Si, P, Th			Cerphosphorhuttonite(?)
					P, Ce, Th	La, Si		Monazite
	119	10	14	88	Y, P		Dy, Al, Th, U, K, Ca, Ti, Fe	Xenotime
					Th, Si, P		Pb	Thorite
Peacock Mountains	197	3	4	58	Ti, Nb, Y Si	U, Th, Ca Fe	Ta(?)	Euxenite(?)
					La, Ce, Si, Ca, Al	Fe	Th	Allanite
					Ce, La, P		U, Th, Ca	Monazite
					Th, Si, P	V, Fe, Ca		Cheralite(?)
					Th, Si	P	Ca, Fe, V	Thorite
					Th, Si	P	Pb, Ca, V	Thorite
	199	2	6	171	Si, Fe, Ca, Ce, La, P	Th, U, Al		Allanite
					Si, Ca, Ce, La, P	Fe, Th, U, Al		Allanite
					Th, Si		Ca, Pb	Thorite
					Th, Si	P, Ca, U(?)	Pb	Thorite
					Th, Si	P, Ca, U	Pb	Thorite
					Ce, P	La	Th	Monazite
Aquarius Mountains	042	31	23	48	Zr, Si	Ca	Th	Zircon
					P, Th, Si	Ca	Fe	Cheralite(?)
	045	5	8	48	Ce	La, Ca, Si	U, Th	Cerianite(?) or Bastnaesite(?)
					Th, Si	P, Ca		Thorite
					Ce, Si La, Ca	Th, Fe, Al		Allanite
					Zr, Si		Th, U	Zircon
Cottonwood Cliffs	168	3	2	65	Si, Fe	Th, Ca,	Ti, Al, P, Pb	Allanite
					P, Th, Si	Ca, Fe		Cheralite(?)
					Si, P, Ce Th, Ca			Cerphosphorhuttonite(?)
	207	3	7	38	Th, P, Si	Ca	V	Cheralite(?)
					Th, Si		Al, Cu, Zn	Thorite

Northern Hualapai and Peacock Mountains

The northern Hualapai and adjacent Peacock ranges comprise Precambrian quartzofeldspathic gneiss, biotite and pelitic schist, and amphibolite that have been widely intruded by, and complexly intermixed with, granite to granodiorite rocks (App. D). In the northern Hualapai Mountains, five plutonic bodies about 1,800 m.y. to 1,300 m.y. in age have been distinguished using rubidium-strontium isotope and trace-element studies (Kessler, 1976). In addition, quartz monzonite stocks of undetermined age, possibly Laramide, have been mapped by Wilson and Moore (1959), and concordant and discordant pegmatites (some dated at about 1,100 m.y. by Kessler, 1976), aplites, and mafic dikes intrude both the plutonic and metamorphic rocks.

Strontium-isotope ratios for plutonic rocks in the northern Hualapai Mountains indicate parent magmas derived from both mixed mantle-and-crustal materials and crustal materials (Kessler, 1976). Three rock units, the Rattlesnake Hills granitic gneiss, the Holy Moses granite, and the medium-grained granite, have relatively high initial strontium-isotope ratios, and may have formed by partial melting of either old, crystalline-basement crustal rocks or miogeosynclinal rocks derived from such basement rocks. The Holy Moses granite (restricted to the northwest part of the Hualapai Mountains and within the adjacent Kingman Quadrangle) and the medium-grained granite are anomalously (2 to 4 times background) radioactive throughout most of their extent. Rocks of similar chemical composition, lithology, and texture, but of undetermined age and extent, exist in the Peacock range.

The Precambrian quartz monzonitic rocks (including quartz monzonite, granite, and cataclastic equivalents) in the northern Hualapai Mountains contain an average of 5 ppm chemical U_3O_8, 6 ppm equivalent uranium, and 45 ppm equivalent thorium; those in the Peacock range contain 4 ppm, 6 ppm, and 73 ppm, respectively (Fig. 4a; Table 3). In addition, anomalous concentrations of uranium are found in both the northern Hualapai and Peacock Mountains.

Uranium occurs in a gold- and silver-bearing quartz-sulfide vein at the Democrat Mine (occurrence 13X, Pl. 2) in the northern Hualapai Mountains. The vein, from 0.3 to 1 m thick, occupies a northwest-trending fault that transects Precambrian granodiorite gneiss and quartz monzonite. Vein samples contain from 0.02% to 0.11% chemical U_3O_8 (Hart and Hetland, 1953); no uranium minerals were observed, however. At the surface, the vein is deeply weathered and heavily iron stained; it is anomalously radioactive (2 to 3 times background) along a distance of about 30 m. Samples taken in this interval contain 3 ppm and 29 ppm chemical U_3O_8 and 26 ppm and 73 ppm equivalent uranium, respectively, suggesting that uranium has been effectively leached within the weathering zone.

Abundant arsenopyrite and pyrite and lesser amounts of quartz, chalcopyrite, and fluorite constitute the gangue. Both the hanging wall and footwall of the vein are intensely sericitized, chloritized, and argillized. Our petrographic studies of the country rock show evidence of similar, but less intense, alteration as much as 300 m from the vein.

The quartz monzonite host rock is gray to reddish brown, medium grained, and anhedral-equigranular, consisting of about 32% quartz, 30% plagioclase,

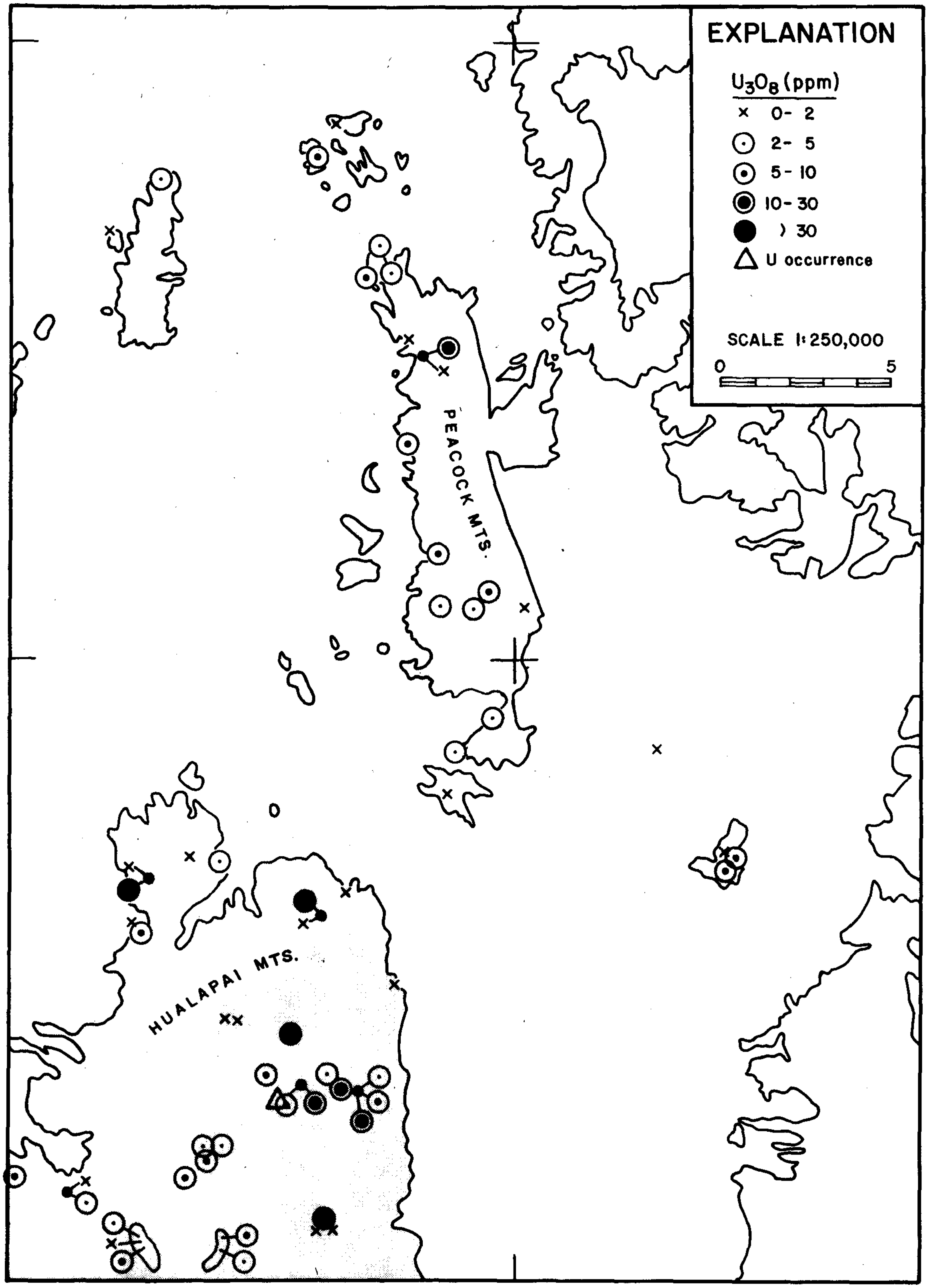

Figure 4a. Uranium contents of Precambrian rocks in the northern Hualapai and Peacock Mountains.

27% potassium feldspar (perthite), 5% biotite, and 3% zircon, apatite, allanite, and iron oxides. The quartz monzonite (medium-grained granite of Kessler, 1976), dated by the rubidium-strontium method, is about 1.3 b.y. old.

Anomalous uranium is also in areas adjacent to the Democrat vein and elsewhere in the northern Hualapai Mountains. A sample of mine-dump rock near the Democrat vein contains 73 ppm chemical U_3O_8 (MGC 116, Table 5), and another sample (MGC 028, App. B) collected near a prospect about 3 km northeast of the Democrat vein contains 600 ppm chemical U_3O_8. Surface radiometric reconnaissance of several gold-silver mines in the northern Hualapai Mountains showed radioactivity 1.5 to 5 times background. Rock samples from three mines contain 47, 61, and 8 ppm chemical U_3O_8 (MGC 012, 013, and 100, respectively). Because pressure-temperature conditions for the formation of gold-bearing sulfide veins (Krauskopf, 1967a, b) are in the range for uranium-bearing quartz-sulfide veins (Rich and others, 1977), some of the gold-silver deposits in both the northern Hualapai and Peacock Mountains may be uranium enriched.

There are no known uranium occurrences in the Peacock Mountains; however, surface radiometric traverses and rock sampling detected several anomalous areas of very limited areal extent. Thorium, rather than uranium, accounts for much of the anomalous radioactivity; greater amounts of equivalent uranium relative to chemical U_3O_8 suggest that uranium has been, in part, leached from surface outcrop samples.

Areas favorable for magmatic-hydrothermal uranium deposits in the northern Hualapai and Peacock Mountains were delineated using the locations of granitic to quartz monzonitic plutons; of numerous inferred fault, fracture, or shear zones in the plutons and adjacent country rock; and of uranium concentrations in gold and silver quartz-sulfide veins and regional uranium enrichment.

The favorable portion of the Precambrian in the Hualapai and Peacock Mountains is 317 km^2; the subsurface extent is not known. Most of the land is administered by the U.S. Bureau of Land Management or the State of Arizona, or is private land.

Northern Aquarius Mountains and Cottonwood and Southern Grand Wash Cliffs

The northern Aquarius Mountains and Cottonwood and southern Grand Wash Cliffs form a continuous belt of Precambrian quartz monzonite, granodiorite, amphibolite, pelitic schist, and quartzofeldspathic gneiss; commonly the plutonic rocks show varying degrees of cataclastic deformation. A Precambrian chronology has not been documented for the Aquarius Mountains and adjoining cliffs, but it is presumably similar to that for the northern Hualapai Mountains.

The Precambrian felsic plutonic rocks of the Aquarius Mountains and Cottonwood and Grand Wash Cliffs contain, on the average, 5 ppm chemical U_3O_8, 5 ppm equivalent uranium, and 27 ppm equivalent thorium (Fig. 4b; Table 3). Anomalous amounts of uranium, as indicated by regional rock sampling and aerial radiometric and HSSR data, often are within areas transected by dense, commonly west-trending linears. Two uranium occurrences, the Big

TABLE 5. SELECTED CHEMICAL AND GAMMA-SPECTROSCOPIC RESULTS FOR SELECT SAMPLES FROM URANIUM OCCURRENCES IN THE PRECAMBRIAN CRYSTALLINE COMPLEX

Occurrence name and no.	Sample no.	Rock description	U_3O_8 (ppm)	eU (ppm)	eTh (ppm)	Significant associated elements (ppm)
Big Ledge 11	MGC 175	Siliceous breccia (highest radioactivity)	2,000	1,500	8	90(F), 7(Ag), 300(As), 150(Cu), 100(Pb)
	MGC 051	Limonite-quartz vein rock	9	22	5	170(F), 200(La), 200(Zn)
	MGC 031	Quartz monzonite mylonite gneiss (wall rock)	3	6	29	100(F)
	MGC 033	Highly chloritized granite(?) (hydrothermally altered shear)	24	26	32	1,100(F), 50(B), 300(Mn), 200(Nb), 70(Sn)
	MGC 042	Quartz monzonite	31	23	48	---
Uranium Basin 12	MGC 077	Silicified, chloritized granite (?)	49	72	1,300	200(La), 500(Mn), 100(Pb), >1,000(Zr)
	MGC 015	Silicified, chloritized granite (?)	100	120	2,100	---
Democrat 13X	F 8199*	Select sample of U-bearing vein	1,100	2,640	---	---
	MGC 117	Highly weathered surface sample of vein	29	73	23	590(F), 70(Ag), 7,000(As), 3,000(PB)
	MGC 113	Mine dump on vein 100 m west of Democrat vein	73	110	55	100(Pb), 100(Y)
	MGC 116	NE-trending offshoot(?) of Democrat vein	27	27	9	70(Ag), 10,000(As), 2,000(Pb), 200(Zn)
	MGC 109	Vein NE of Democrat vein	8	8	70	---
	MGC 119	Granite wall rock	10	14	88	5(Ag), 100(Pb), 160(F)
	MGC 120	Granodiorite gneiss wall rock	8	5	10	200(As), 450(F)
	MGC 108	Quartz monzonite representative country rock	4	5	70	200(La), 70(Pb)

*From Hart and Hetland, 1953

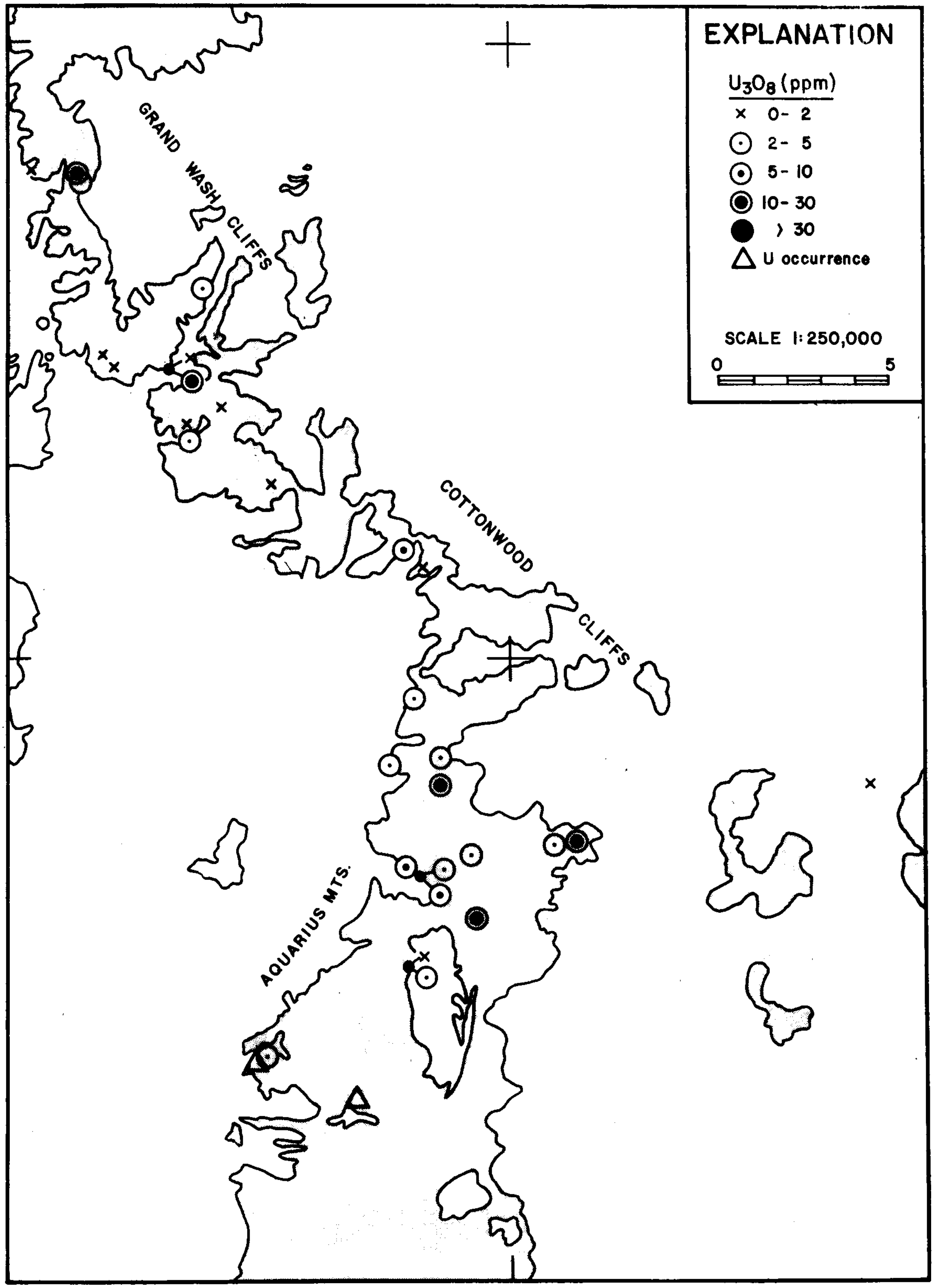

Figure 4b. Uranium contents of Precambrian rocks in the northern Aquarius Mountains and Cottonwood and southern Grand Wash Cliffs.

Ledge and Uranium Basin, are in a part of the northern Aquarius Mountains that is enriched in uranium and characterized by abundant faults and shear zones. Mode of uranium occurrence and local controls for uranium concentration were used in selecting other belt areas favorable for magmatic-hydrothermal uranium deposits.

At Big Ledge (occurrence 11, Pl. 2), uranium occurs in a prominent ridge of siliceous breccia (20 m wide and 1400 m long) that occupies a west-trending, almost vertically dipping shear zone. Anomalous radioactivity occurs discontinuously along the ridge and in the adjacent, veined quartz monzonite host rock and in associated, nonsilicified shear zones. The uraniferous breccia occurs within a much larger, west-trending shear or fault system inferred (Fuis, 1974) from studies conducted by Shoemaker and others (1975) of a broad (15 km), linear (75 km) magnetic discontinuity shown on the aeromagnetic map of Arizona (Sauck and Sumner, 1971).

The breccia at Big Ledge consists of fine- to coarse-grained, angular fragments of microcryptocrystalline to medium-grained silica in a matrix of limonite and microgranular silica; a few angular granitic fragments are present. Exceedingly fine-grained uraninite is disseminated in the limonitic portion of the matrix (MGC 175, Table 5). No secondary uranium-bearing minerals were observed.

The host rock for the breccia is a medium-grained, anhedral-equigranular quartz monzonite consisting of approximately 25% quartz, 31% plagioclase, 36% potassium feldspar, 3% biotite, 4% muscovite, and 1% apatite, zircon, and allanite. The quartz monzonite has been cataclastically deformed in places, and rocks varying from blastomylonite to mylonite gneiss are present.

Hydrothermal alteration is present in a zone extending as much as 300 m from the main breccia. Silicification, minor argillization, slight to intense sericitization, and slight but widespread chloritization are also present. Locally, intense chloritization is associated with intensely sheared granite. Petrographic and vein-mineral paragenetic studies indicate that there was repeated brecciation and silicification of rocks within the shear zone. Fracturing of highly indurated (silicified) rocks may have developed channel ways for mineralizing solutions and favorable sites for precipitation of uraninite.

One such highly fractured site may exist where a subsidiary siliceous breccia intersects the main breccia (occurrence 11, App. C). A highly radioactive sample collected from this site has 0.2% chemical U_3O_8 (MGC 175). Uranium values from other anomalously radioactive parts of the main breccia are from 9 to 350 ppm chemical U_3O_8 (samples MGC 015, 056, 058; Table 5). Uranium is enriched in the adjacent, veined quartz monzonite (12 ppm chemical U_3O_8) (App. B). In addition, ground-water samples containing from 9 to 608 ppb U_3O_8 (MGC 065, 070, 076; App. B) were found along the projected eastward trend of the Big Ledge breccia (where it may occur under alluvial and Tertiary volcanic cover) and in areas adjacent to the projected breccia.

At Uranium Basin (occurrence 12, Pl. 2), uranium is in a chloritized and silicified granite bounded to the south by a west-trending pegmatite and to the north by a heavily chloritized shear zone. Radioactivity is 10 times background in the granite, 3 times background in the shear zone, and 1.5 times background in the pegmatite. Reconnaissance within the area did not reveal anomalous radioactivity along the projected strike of the pegmatite-granite-shear-zone complex. Most radioactivity is from thorium (2,100 ppm eTh), but as much as 100 ppm chemical U_3O_8 is present (MGC 015, Table 5). Silicification at Uranium Basin is not as intense or as widespread as that at Big Ledge, and thorium, not uranium, is the major radioactive element.

Other parts of the northern Aquarius Mountains and Cottonwood and Grand Wash Cliffs have siliceous breccias, similar to those at Big Ledge, that transect quartz monzonitic plutons; these breccias commonly coincide with west-trending, field-checked shear zones or linears shown on the lineament map (Pl. 14). Samples collected from two of these breccias contain 10 to 13 ppm chemical U_3O_8 (MGC 182 and 235); five other breccias do not show anomalous amounts of uranium or radioactivity.

Regional rock samples and HSSR and aerial radiometric data indicate that areas of relatively high uranium and thorium contents correspond in part to areas with abundant west-trending linears likely to represent faults or shear zones. These structures may have served as conduits for uranium-bearing, hydrothermal solutions and, in addition, may have acted as sites for uranium precipitation.

Favorable Area C (Pl. 1a) is 261 km^2. Most of the land is administered by the U.S. Bureau of Land Management or State of Arizona, or is private land.

ENVIRONMENTS UNFAVORABLE FOR URANIUM DEPOSITS

Geologic environments unfavorable for uranium deposits are the Precambrian-Cambrian unconformity of the Grand Wash Cliffs; lower Paleozoic strata; most upper Paleozoic strata, including most of the Pennsylvanian-Permian Supai Formation and the Permian Kaibab Limestone; Mesozoic formations; most of the Tertiary and all Quaternary sedimentary rocks of the Colorado Plateau; and Tertiary and Quaternary volcanic rocks.

PRECAMBRIAN-CAMBRIAN UNCONFORMITY OF THE GRAND WASH CLIFFS

The Grand Wash Cliffs comprise the lower cliffs of Precambrian rocks, and the upper cliffs of lower Paleozoic strata that unconformably overlie them. Other than the Precambrian-Cambrian unconformity itself, no characteristics of Australian or Canadian vein-type deposits, as summarized by Kalliokoski and others (1978), were observed. The potential Precambrian host rock, which consists of quartzofeldspathic gneiss, biotite schist, granodiorite, and quartz monzonite, has no effective reductants. The overlying Cambrian Tapeats Sandstone is neither a good source for uranium nor an effective aquifer for uranium-bearing solutions. Scintillometer traverses and rock sampling across the unconformity showed no significant radioactivity or anomalous uranium values (Table 6).

TABLE 6. ANALYTIC AND PETROGRAPHIC DATA FOR SAMPLES COLLECTED AT THE PRECAMBRIAN-CAMBRIAN UNCONFORMITY

Area	Rock unit	Sample no.	U_3O_8 (ppm)	eU (ppm)	eTh (ppm)
Grand Wash Cliffs	Tapeats Sandstone	159	1	1	9
	Quartz monzonite	160	3	3	52
	Quartz monzonite	161	8	8	18
Grand Wash Cliffs	Tapeats Sandstone	163	1	1	6
	Quartz monzonite	162	3	---	---
	Granite	164	3	10	70
Grand Wash Cliffs	Tapeats Sandstone	165	1	2	4
	Granite	166	2	2	5
	Quartz monzonite	167	2	3	16
Peach Springs Canyon	Tapeats Sandstone	174	2	2	9
	Quartz monzonite	172	4	4	21

LOWER PALEOZOIC STRATA

The Cambrian Tonto Group consists, in ascending order, of the Tapeats Sandstone, the Bright Angel Shale, and the Muav Limestone, units that record a major marine transgression. The Tapeats is a shelf deposit consisting mainly of medium- to coarse-grained sandstone; no fluvial facies are present (Hereford, 1977). The Bright Angel Shale consists of mudstones, siltstones, and fine-grained sandstones deposited in deepening waters of the transgressing sea. The Muav Limestone is composed of limestone and dolomite deposited under relatively deep marine conditions.

The Devonian Chino Valley Formation is restricted to a portion of Chino Valley in the southeast part of the quadrangle (Hereford, 1977). The 15-m-thick unit consists of lithic sandstone and pebble-boulder conglomerate. It unconformably overlies the Tonto Group and probably consists largely of material reworked from the underlying units.

Undivided Devonian limestones and dolomites, which include the Temple Butte Limestone in the Grand Canyon area and Martin Limestone in the south part of the quadrangle, unconformably overlie Cambrian units. The limestone and dolomite were deposited in shallow marine and possibly sabkha environments (McKee, 1975).

The Mississippian Redwall Limestone is composed of varied limestone and dolomite and bedded chert (McKee and Gutschick, 1969). Lithologic and faunal evidence record three marine transgressive-regressive cycles during the Mississippian (McKee, 1975). The unit is quite susceptible to solution and is characterized by caverns and karst structures.

Sedimentary rocks deposited in open-marine and nearshore environments commonly do not exhibit characteristics favorable for uranium concentration; most of these lower Paleozoic rocks are unfavorable. Data collected through surface and aerial radiometric reconnaissance and HSSR indicate commonly low uranium and other radioactive-element contents for the lower Paleozoic rock exposures. Two important exceptions are: where impermeable Tapeats Sandstone and Bright Angel Shale are unconformably overlain by the Music Mountain conglomerate and Blue Mountain gravels, and where solution collapse within the Redwall Limestone-Supai Formation interval has formed uranium-bearing breccia pipes.

UPPER PALEOZOIC STRATA OTHER THAN THE SUPAI FORMATION AND KAIBAB LIMESTONE

The Pennsylvanian-Permian Callville Limestone consists mainly of gray limestone and red-brown shale. The unit is restricted to the west Grand Canyon area; it pinches out to the east in the nearshore deposits of the Supai. The Coconino Sandstone is well sorted and quartzitic; large-scale wedge-planer cross-bedding and ripple marks indicate that it is an eolian deposit.

The Permian Toroweap Formation consists of red calcareous sandstone, dolomite, sandy dolomite, and gypsum. Recent stratigraphic studies of the Toroweap indicate widespread sabkha environments (Rawson and Turner, 1974), where sedimentary and geochemical processes favor stratiform copper deposits (Renfro, 1974) and certain uranium deposits (Rawson, 1975).

Neither the Callville Limestone nor the Coconino Sandstone have favorable lithologic characteristics, sedimentary structures, potential reductants, or potential uranium sources. Despite potentially favorable sabkha facies in the Toroweap, the overall uranium potential is low; no carbonaceous reductants and no potential uranium source exist. Aerial radiometric and HSSR dry-stream-sediment data do not indicate regional uranium enrichment in upper Paleozoic exposures.

SUPAI FORMATION

In the Williams Quadrangle, the Pennsylvanian-Permian Supai Formation includes shallow-water marine, tidal-flat, and tidal-channel sequences that were deposited on an unstable shelf in a miogeosyncline (Lane, 1977). No fluvial facies are recognized. Dominant lithologies are red-bed mudstone, siltstone, sandstone, and conglomerate and limestone. Surface and limited subsurface data indicate that the unit is widely oxidized; no reduced beds have been observed. The Supai within the Williams Quadrangle contains no appreciable organic material; only 0.02% to 0.08% organic carbon was detected using chemical analyses of selected outcrop samples (Table 7).

No sandstone-type uranium occurrences are known in the Supai in the quadrangle. Surface scintillometer traverses revealed very low total-gamma radiation, and neither the aerial radiometric survey nor the HSSR sampling indicated any radioactive-element or uranium enrichment. Results of fluorometric uranium analyses (1 to 4 ppm chemical U_3O_8) of selected outcrop samples are within the normal average range for a suite of sandstone, shale, and limestone.

KAIBAB LIMESTONE

The Kaibab Limestone extends over nearly the entire Coconino Plateau (Pl. 7), but is poorly exposed south of the Grand Canyon. The Kaibab is a transgressive-regressive sedimentary sequence (McKee, 1938) consisting of open-marine and nearshore facies of limestone, sandy limestone, red-bed siltstones and sandstones, and, locally, gypsum beds. The Kaibab is divided into two members, a lower Fossil Mountain member (present in the quadrangle) and an upper Harrisburg member (Cheevers and Rawson, 1978).

Five uranium occurrences in the Kaibab were examined during this study (App. A and C; Pl. 2). Anomalous radioactivity is confined to small (0.5 m by 0.5 m) pods in a sandy limestone facies and is associated with secondary copper mineralization, although not all copper-bearing rocks in the Kaibab are radioactive. Radioactive-pod samples contain 10 to 640 ppm chemical U_3O_8 (Table 8); no uranium minerals were found, however. No carbonaceous material was observed in outcrop, and very little organic carbon was detected using chemical analysis (Table 8). Small fractures and associated solution features in breccia zones seem to have acted as loci for uranium concentration. The five occurrences are aligned within the northeast-trending

TABLE 7. ANALYTIC AND PETROGRAPHIC RESULTS FOR SAMPLES FROM AREAS OF SUPAI FORMATION SURFACE EXPOSURES

Area	Sample no.	U_3O_8 (ppm)	eU (ppm)	Lithology	Organic carbon analysis (%)
Black Mesa	MGC 089	3	4	Composite	0.02
Aubrey Cliffs (Chino Point)	MGC 009	1	---	Limestone pebble conglomerate	---
Aubrey Cliffs (Chino Point)	MGC 093	1	1	Composite	0.02
Aubrey Cliffs (Chino Point)	MGC 094	2	1	Dolomitic quartz arenite	0.08
Black Mesa	MGC 095	2	2	Calcareous siltstone	---

TABLE 8. ANALYTIC AND PETROGRAPHIC RESULTS FOR SELECTED SAMPLES FROM URANIUM OCCURRENCES IN THE KAIBAB LIMESTONE

Occurrence no.	Sample no.	U_3O_8 (ppm)	eU (ppm)	Lithology	Organic carbon analysis (%)	Uranium mineral ident.
1	MGC 092	10	10	Quartz arenite	---	---
2	MGC 085	59	49	Limestone	---	---
3	MGC 090	4	3	Limestone	---	---
4	MGC 082	270	210	Limestone	---	---
5	MGC 078	120	91	Limestone	0.06	Uraninite (?) Uranyl carbonate (?)
6X	MGC 007	640	---	Calcareous sandstone	---	---

Vishnu fault system (see Shoemaker and others, 1975); however, no genetic association with the faults, except possibly with related brecciation, is evident.

Uranium mineralization in the Kaibab Limestone is apparently superficial and areally restricted. Gamma-ray logs of drill holes (30- to 365-m depths) at several occurrences show no anomalous radioactivity at depth, nor were anomalously radioactive areas, other than the reported occurrences, detected during surface scintillometer traverses. Furthermore, no anomalously radioactive areas were detected during the aerial radiometric and HSSR surveys.

MESOZOIC FORMATIONS

Outliers of the Lower Triassic Moenkopi Formation are widely distributed throughout the Coconino Plateau (Squires and Abrams, 1975). The unit consists primarily of red-brown siltstone, green and red-brown claystone, fine-grained sandstone, and, locally, a basal conglomerate, and does not have the requisite characteristics to be favorable for sandstone-type uranium deposits. Elsewhere in Arizona and parts of Utah, the upper Moenkopi contains uranium from the overlying channel-fill sandstones of the Shinarump Conglomerate in the Chinle Formation. An erosional remnant (too small to be favorable) of the Shinarump is reported in the northeast corner of the Williams Quadrangle (Moore and others, 1960).

TERTIARY AND QUATERNARY SEDIMENTARY ROCKS OF THE COLORADO PLATEAU

Music Mountain Conglomerate and Blue Mountain Gravels

The Music Mountain conglomerate and Blue Mountain gravels are highly porous and permeable and appear widely oxidized. No appreciable amounts of carbonaceous material have been found. Having only minor interbeds of siltstone and claystone, the basal Tertiary units have a low differential permeability. Except where the Music Mountain conglomerate and Blue Mountain gravels have scour-channel deposits in impermeable bed rock, they are unfavorable for significant uranium deposits.

Younger Tertiary and Quaternary Units

A thick sequence of siltstone, sandstone, conglomerate, and, locally, limestone overlies the Music Mountain conglomerate throughout a large area of the Hualapai Plateau (Pl. 9). These units are, in ascending order, the Westwater formation, the Buck and Doe conglomerate (with lower Milkweed and upper Peach Springs members), and the Willow Springs formation (Young, 1966). None of these units exhibit characteristics considered important in the formation of sandstone-type uranium deposits. No appreciable carbonaceous material has been found in any of the units. The predominantly siltstone and limestone Westwater and the well-cemented, predominantly limestone-pebble conglomerate Milkweed member of the Buck and Doe are highly impermeable. The Peach Springs member, although arkosic, was derived mainly from the Grand Wash Cliffs, Precambrian terrain regionally impoverished in uranium. The Peach Springs is also very permeable and widely oxidized. The Willow Springs consists of limestone and volcanic-pebble conglomerate and playa-lacustrine deposits. Although the interfingering of transmissive fluvial facies and less-permeable lacustrine facies provides a potentially good stratigraphic locus for uranium concentration, no potential reductant, such as carbonaceous material, has been observed.

No uranium occurrences are known within any of the formations. Further, both the aerial radiometric survey and HSSR sampling indicate regionally low radioactive-element contents for these units. Regional rock sampling revealed isolated, insignificant, anomalous amounts of uranium in the red claystone facies of the Westwater formation in Peach Springs Canyon (MGC 310; 7 ppm chemical U_3O_8) and in a caliche layer within the Willow Springs formation in Truxton Valley (MGC 151; 15 ppm chemical U_3O_8).

TERTIARY AND QUATERNARY VOLCANIC ROCKS

Intermediate to mafic Tertiary and Quaternary volcanic rocks are unfavorable for volcanogenic uranium deposits because silica-deficient magmas are not likely to generate or concentrate appreciable amounts of lithophile elements, including uranium. Two relatively silicic units, the Peach Springs tuff and Ft. Rock Creek rhyodacite, are also unfavorable as hosts for significant uranium deposits because they are widely oxidized and deeply weathered. The tuff may be a uranium source rock for associated Tertiary sediments, however.

Abundant volcanic rocks, from about 14 m.y. to 1 m.y. in age (Luedke and Smith, 1978), occur along the southwest margin of the Colorado Plateau. These volcanics consist largely of basalt flows and associated pyroclastic-surge and ash-flow materials. Scattered throughout this otherwise basaltic terrain are small domes of dacite and rhyolite, which occur at the centers of Mt. Floyd, Trinity and Round Mountains, Picacho Butte, and Bill Williams and Sitgreaves Mountains (Gilman, 1965; Pugmire, 1977; Neeley, U.S. Geological Survey, pers. comm., 1979).

To the west, in the Aquarius Mountains, is a large Tertiary volcanic field, consisting mostly of intermediate to mafic rocks. In addition, olivine basalt and basaltic andesite overlie Precambrian rocks in the northern Hualapai and Peacock Mountains and Cottonwood Cliffs.

Although reconnaissance scintillometer surveys and stream-sediment sampling commonly revealed very low gamma radiation and uranium contents throughout the volcanic terrain, the more felsic Peach Springs tuff and Ft. Rock Creek rhyodacite were found to be relatively slightly more radioactive and uraniferous. Furthermore, several apparent radiometric anomalies identified for the volcanic terrain may represent the relatively higher potassium, uranium, and thorium contents in these more felsic units.

UNEVALUATED ENVIRONMENTS

TERTIARY SEDIMENTARY ROCKS

Tertiary sedimentary rocks in the Hualapai, Big Sandy, Truxton, Aubrey, and Chino Valleys (Pl. 17) were not evaluated because of widespread alluvial cover and inadequate subsurface data. However, reconstruction of the early

Tertiary paleodrainage in northwest Arizona (Fig. 3) indicates that rocks in the subsurface may correlate with the uranium-bearing Music Mountain conglomerate. The basal Tertiary rocks of Truxton Valley, in particular, are believed to be part of the Music Mountain fluvial deposit exposed to the northeast in Peach Springs Canyon; rocks within this channel trend are favorable. Data from a stratigraphic test well recently drilled in Truxton Valley by DOE and BFEC show that a thick (about 200 m) section of arkosic conglomerate and sandstone in fact exists along this trend. Anomalous radioactivity (2 to 4 times background) was encountered in the basal rocks and the upper part of the underlying Precambrian granite bed rock. The distribution and extent of similar fluvial rocks in the basin are not known, however. Also, limited exposures of rangeward-dipping, fluviolacustrine (?) strata in the Big Sandy Valley indicate that the basins may contain rocks of age, depositional environment, and lithology similar to those of uraniferous rocks elsewhere in Arizona.

In northern Hualapai Valley, the aerial radiometric anomaly within unconsolidated Cenozoic sediments (Pl. 3) may be due to greater uranium content in the locally derived detritus than in alluvial material with fewer granitic and gneissic constituents. Aerial radiometric data indicate a broad zone of anomalous uranium and thorium along the west margin of Big Sandy Valley (occurrence 22, Pl. 3) in poorly exposed Tertiary sediments and Quaternary alluvium. The anomalies may reflect high uranium and thorium contents of the granitic detritus derived from the Hualapai Mountains (Pl. 3, 4, and 9).

Ground-water samples from Big Sandy Valley contain 5 to 67 ppb uranium. However, numerous ground-water anomalies exist in Precambrian rocks and in alluvium within the Hualapai and Aquarius ranges flanking the valley.

PRECAMBRIAN ROCKS

Precambrian rocks in the Grand Canyon region were not evaluated because access was prohibited--the land is in the Lake Mead National Recreation Area. Aerial radiometric anomalies in the Grand Canyon near the Cambrian-Precambrian unconformity (Pl. 3) are questionable because of inherent inaccuracies introduced by high relief; their significance is unknown, although the gamma-ray signature indicates uranium.

A Tertiary volcanic field covers a large portion of the Precambrian crystalline complex in the east portions of the northern Aquarius Mountains, Cottonwood Cliffs, and southern Grand Wash Cliffs; lack of exposure precluded evaluation.

The central and northern parts of the Grand Wash Cliffs as shown on Plate 7 are Precambrian gneiss except for a portion of the Garnet Mountain plutonic complex. However, field investigations revealed that abundant quartz monzonite and granite are associated with quartzofeldspathic gneiss, biotite schist, and various intermediate plutonic rocks (App. D). Although time limitations and lack of adequate geologic maps precluded evaluation of this portion of the Grand Wash Cliffs, our reconnaissance studies revealed that quartz monzonite and other plutonic rocks are common in the western part of the area, whereas foliated rocks predominate to the east; that many quartz monzonitic rocks have well-developed cataclastic textures; that samples of Precambrian rock from the northern and central Grand Wash Cliffs (Fig. 4c) commonly contain less uranium than do others from the quadrangle; and that relatively fewer lineaments are in the cliffs than in adjacent Precambrian terrain (Pl. 14). Also, aerial radiometric and HSSR data do not indicate any regional pattern of uranium enrichment in the cliffs although one isolated area of high uranium values (10 to 20 ppm chemical U_3O_8) and high uranium residuals exists (Area 2, Pl. 4).

RECOMMENDATIONS TO IMPROVE EVALUATION

To evaluate major Cenozoic basins, stratigraphic test-hole drilling is recommended for the Hualapai, Big Sandy, Truxton, Aubrey, and Chino Valleys. Drilling should be concentrated on projected paleochannel trends and along basin margins for rangeward-dipping fault blocks; suggested drill-site locations are shown in Table 9. Detailed ground-water sampling (water wells) and a closely spaced aerial radiometric survey (0.4-km spacing) are recommended for the western Big Sandy Valley; aerial reconnaissance surveys delineated high uranium and thorium response that coincides with a uranium ground-water anomaly.

We recommend that large-scale (1:62,500) mapping be undertaken within the Precambrian crystalline complex to delineate accurately the felsic plutonic rocks not shown on reconnaissance-scale maps. Wherever possible, determine ages by the rubidium-strontium method.

Because breccia and fault zones within the Precambrian crystalline complex may provide dominant controls for magmatic-hydrothermal uranium deposits, regional (1:125,000) and detailed (1:62,500) structural analyses of the northern Hualapai, Aquarius, and Peacock Mountains, and Cottonwood Cliffs should be made. Fault-fracture maps could be made from black-and-white aerial photos (1:60,000; 1:24,000), and closely spaced (0.4 km) aerial radiometric surveys should then be conducted in structurally favorable areas.

To improve evaluation of Orphan-type collapse breccia pipes, studies to locate undiscovered occurrences and to improve the model for favorable areas should be undertaken. A detailed study of trace-element distribution in a mineralized collapse breccia pipe and the surrounding rocks would yield trace-element-dispersion data for possibly locating buried pipes by trace-element anomalies. The Hacks Canyon pipe is recommended for such a study. If buried pipes do produce surficial trace-element anomalies, a detailed soil-sampling program for favorable areas is suggested. An experimental and theoretical geophysical study of all pipes and the surrounding stratigraphy would determine the feasibility of using geophysical techniques such as ground gravimeter or refraction seismic surveys to locate breccia pipes. If feasible, a limited geophysical field survey is recommended as a test case. Comparing mineralized and unmineralized breccia pipes would be useful, primarily to check the proposed formation age and stratigraphic initiation-point differences. This information may help determine if surficial topographic expressions of unmineralized pipes are consistently different from those of mineralized pipes.

Another recommended study includes a detailed structural analysis in northwest Arizona that would more accurately delineate post-Mississippian to

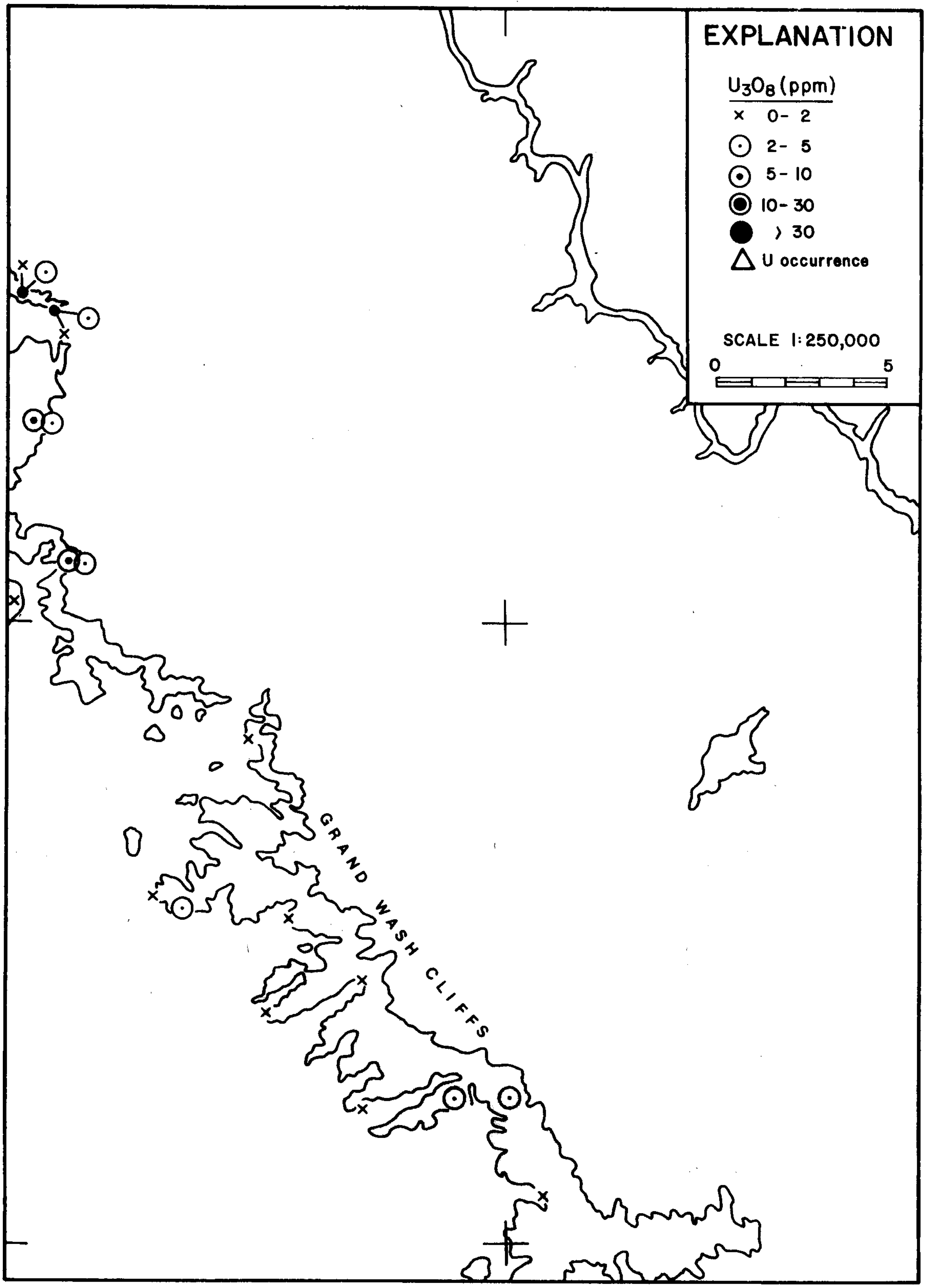

Figure 4c. Uranium contents of Precambrian rocks in the Grand Wash Cliffs.

TABLE 9. PROPOSED DRILLING-SITE LOCATIONS, WILLIAMS QUADRANGLE

Test hole no. and locality	Location	Map (7-1/2' topo.)	Ground elev. (m)	Approx. total depth (m)	Geologic unit at total depth	Land status
1 Hualapai Valley	N1/2 S12 T25N R16W Mohave Co.	Music Mountians SW Arizona	880	1,100	Precambrian	Bureau of Land Management
2 Hualapai Valley	N1/2 S34 T25N R15W Mohave Co.	Music Mountains SW Arizona	920	900	Precambrian	Bureau of Land Management
3 Big Sandy Valley	S1/2 S24 T21N R14W Mohave Co.	Tin Mountain NW Arizona	1,170	600	Precambrian	Private
4 Big Sandy Valley	S1/2 S6 T19N R13W Mohave Co.	Bottleneck Wash Arizona	1,040	600	Precambrian	Bureau of Land Management
5 Truxton Valley	E1/2 S8 T24N R12W Mohave Co.	Truxton Arizona	1,320	150	Cambrian Tapeats Sandstone	State Surface Trust Land
6 Aubrey Valley	S24 T25N R8W Coconino Co.	Blue Mountain SE Arizona	1,600	750	Cambrian Tonto Group (?)	State Surface Trust Land
7 Chino Valley	E1/2 S30 T20N R4W Yavapai Co.	South Butte Arizona	1,400	600	Cambrian Tonto Group	State Surface Trust Land

pre-Jurassic faulting. A permeability study of the Upper Pennsylvanian-Lower Permian red-bed sequence of northwest Arizona, especially the Esplanade Sandstone, would more accurately determine favorable trends for ore solution transport and subsequent mineralization. A detailed examination of stratigraphy, alteration, mineralogy, and mineral and chemical zonation of at least one Orphan-type pipe in the Grand Canyon area is needed to increase the data base of the model.

SELECTED BIBLIOGRAPHY

Aero Service Division, Western Geophysical Company of America, 1979, Airborne gamma-ray spectrometer and magnetometer survey, Las Vegas Quadrangle (Arizona, California, Nevada), Williams Quadrangle (Arizona), Prescott Quadrangle (Arizona), and Kingman Quadrangle (Arizona, California, Nevada), and Airborne gamma-ray spectrometer and magnetometer survey, Williams Quadrangle (Arizona): U.S. Department of Energy Open-File Report GJBX-59(79), v. I and II, p. 1-69, App. A-J.

Arizona Bureau of Mines, 1958, Geologic map of Yavapai County, Arizona: scale 1:375,000.

Austin, S. R., and D'Andrea, R. F., Jr., 1978, Sandstone-type uranium deposits, in Mickle, D. G., and Mathews, G. W., eds., Geologic characteristics of environments favorable for uranium deposits: U.S. Department of Energy Open-File Report GJBX-67(78), p. 87-120.

Barrington, Jonathan, and Kerr, P. F., 1963, Collapse features and silica plugs near Cameron, Arizona: Geological Society of America Bulletin, v. 74, p. 1237-1258.

Berner, R. A., 1971, Principles of chemical sedimentology: New York, McGraw-Hill, 240 p.

Blakey, R. C., 1978, Pennsylvanian and Lower Permian paleogeography and paleotectonism of the southern Colorado Plateau [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 96.

Blissenbach, Erich, 1952, Geology of the Aubrey Valley, south of the Hualapai Indian Reservation, northwest Arizona: Plateau, v. 24, no. 4, p. 119-127.

Bogli, A., 1964, Corrosion par melange des eaux: International Journal of Speleology, v. 1, pt. 1-2, p. 61-70.

Bowles, C. G., 1965, Uranium-bearing pipe formed by solution and collapse of limestone: U.S. Geological Survey Professional Paper 525-A, p. A12.

-----1977, Economic implications of a new hypothesis of origin of uranium-copper-bearing breccia pipes, Grand Canyon, Arizona, in Campbell, J. H., ed., Short papers of the U.S. Geological Survey Uranium-Thorium Symposium, 1977: U.S. Geological Survey Circular 753, p. 25-27.

Cheevers, C. W., and Rawson, R. R., 1978, Facies analysis of the Kaibab Limestone in northern Arizona, southern Utah, and southern Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 99.

Chenoweth, W. L., and Malan, R. C., 1969, Significant geologic types of uranium deposits-United States and Canada: Remarks at U.S. Atomic Energy Commission Uranium Workshop, Grand Junction, Colorado, Paper 5, 50 p.

Davidson, E. S., 1973, Water-resources appraisal of the Big Sandy area, Mohave County, Arizona: Arizona Water Commission Bulletin 6, 40 p.

Drewes, Harald, 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, p. 641-657.

Finch, W. I., 1967, Geology of epigenetic uranium deposits in sandstone in the United States: U.S. Geological Survey Professional Paper 538, 121 p.

Fuis, G. C., 1974, The geology and mechanics of formation of the Fort Rock Dome, Yavapai County, Arizona: Pasadena, California Institute of Technology, Ph.D. dissertation, 278 p.

Gabelman, J. W., 1957, The origin of collapsed plug pipes: Mines Magazine, v. 47, p. 67-72, 79-80.

Gabelman, J. W., and Boyer, W. H., 1958, Relation of uranium deposits to feeder structures, associated alteration and mineral zones, _in_ Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy: Geneva, September 1-13, 1958, v. 2, p. 338-350.

Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: New York, Harper and Row, 450 p.

Gillespie, J. B., and Bentley, C. B., 1971, Geohydrology of Hualapai and Sacramento Valleys, Mohave County, Arizona: U.S. Geological Survey Water-Supply Paper 1899-H, 37 p.

Gilman, C. R., 1965, Geology and geohydrology of the Sitgreaves Mountain area, Coconino County, Arizona: Tucson, University of Arizona, M.S. thesis, 87 p.

Goff, F. E., 1979, "Wet" geothermal potential of the Kingman-Williams region, Arizona: Los Alamos Scientific Laboratory Informal Report LA-7757-MS, 25 p.

Goff, F. E., Eddy, A. C., and Arney, B. H., 1979, Reconnaissance geologic strip map from Kingman to south of Bill Williams Mountain, Arizona: Los Alamos Scientific Laboratory LAMS Map (in press).

Gornitz, V. M., 1969, Mineralization, alteration, and mechanism of emplacement, Orphan ore deposit, Grand Canyon, Arizona: New York, Columbia University, Ph.D. dissertation, 186 p.

Gornitz, V. M., and Kerr, P. F., 1970, Uranium mineralization and alteration, Orphan Mine, Grand Canyon, Arizona: Economic Geology, v. 65, p. 751-768.

Granger, H. C., and Raup, R. B., 1962, Reconnaissance study of uranium deposits in Arizona: U.S. Geological Survey Bulletin 1147-A, 54 p.

Hart, O. M., and Hetland, D. L., 1953, Preliminary report on uranium-bearing deposits in Mohave County: U.S. Atomic Energy Commission RME-4026, 48 p., issued by U.S. Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee.

Hem, J. D., and Cropper, W. H., 1959, Survey of ferrous-ferric chemical equilibria and redox potentials: U.S. Geological Survey Water-Supply Paper 1459-A, p. 1-31.

Hereford, Richard, 1977, Deposition of the Tapeats Sandstone (Cambrian) in central Arizona: Geological Society of America Bulletin, v. 88, p. 199-211.

Heinrich, E. W., 1960, Some rare-earth mineral deposits in Mohave Co., Arizona: Arizona Bureau of Mines Bulletin 167, 22 p.

Huff, L. C., Santos, Elmer, and Raabe, R. G., 1966, Mineral resources of Sycamore Canyon Primitive Area, Arizona: U.S. Geological Survey Bulletin 1230-F, 19 p.

Jahns, R. H., 1952, Pegmatite deposits of the White Picacho district, Maricopa and Yavapai Counties, Arizona: Arizona Bureau of Mines Bulletin 162, 105 p.

Kalliokoski, Jorma, Langford, F. F., and Ojakangas, R. W., 1978, Criteria for uranium occurrences in Saskatchewan and Australia as guides to favorability for similar deposits in the United States: U.S. Department of Energy Open-File Report GJBX-114(78), 480 p.

Kessler, E. J., 1976, Rubidium-strontium geochronology and trace element geochemistry of Precambrian rocks in the northern Hualapai Mountains, Mohave County, Arizona: Tucson, University of Arizona, M.S. thesis, 73 p.

Kofford, M. E., 1969, The Orphan Mine, in Geology and natural history of the Grand Canyon region: Four Corners Geological Society Guidebook, 5th Annual Field Conference, Powell Centennial River Expedition, p. 190-194.

Koons, Donaldson, 1948, Geology of the eastern Hualapai Reservation: Plateau, v. 20, no. 4, p. 53-60.

Krauskopf, K. B., 1967a, Introduction to geochemistry: New York, McGraw-Hill, 721 p.

-----1967b, Source rocks for metal-bearing fluids, in Barnes, H. L., ed., Geochemistry of hydrothermal deposits: New York, Holt, Rinehart, and Winston, p. 1-33.

Krieger, M. H., 1967a, Reconnaissance geologic map of the Ash Fork Quadrangle, Yavapai and Coconino Counties, Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-499, scale 1:62,500.

-----1967b, Reconnaissance geologic map of the Picacho Butte Quadrangle, Yavapai and Coconino Counties, Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-500, scale 1:62,500.

-----1967c, Reconnaissance geologic map of the Turkey Canyon Quadrangle, Yavapai County, Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-501, scale 1:62,500.

Lamey, C. A., 1966, Metallic and industrial mineral deposits: New York, McGraw-Hill, 567 p.

Lane, C. L., 1977, Pennsylvanian-Permian stratigraphy of west-central Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 115 p.

Lucas, J. R., and Adler, Lawrence, eds., 1973, Roof and ground control, in Cummins, A. B., and Given, I. A., eds., SME mining engineering handbook: American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 1, p. 13-2 to 13-196.

Lucchitta, Ivo, 1966, Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona: State College, Pennsylvania State University, Ph.D. dissertation, 218 p.

-----1975, Application of ERTS images and image processing to regional geologic problems and geologic mapping in northern Arizona--Part IVB, The Shivwits Plateau: National Aeronautics and Space Administration Technical Report 32-1597, p. 41-72.

Luedke, R. G., and Smith, R. L., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1091-A, 2 sheets.

Magleby, D. N., 1961, Orphan Lode uranium mine, Grand Canyon, Arizona: U.S. Atomic Energy Commission Technical Memorandum TM-134, 8 p.

Malan, R. C., 1972, Summary report--Distribution of uranium and thorium in the Precambrian of the western United States: U.S. Atomic Energy Commission Open-File Report RD-12, 59 p.

Mathews, G. W., 1978a, Uranium occurrences in and related to plutonic igneous rocks, in Mickle, D. G., and Mathews, G. W., eds., Geologic characteristics of environments favorable for uranium deposits: U.S. Department of Energy Open-File Report GJBX-67(78), p. 121-180.

-----1978b, Uranium occurrences of uncertain genesis, in Mickle, D. G., and Mathews, G. W., eds., Geologic characteristics of environments favorable for uranium deposits: U.S. Department of Energy Open-File Report GJBX-67(78), p. 221-248.

McKee, E. D., 1938, The environment and history of the Toroweap and Kaibab Formations of northern Arizona and southern Utah: Carnegie Institution of Washington Publication 492, 268 p.

-----1958, The Redwall Limestone, in Anderson, R. Y., and Harshbarger, J. W., eds., Black Mesa Basin, northeastern Arizona: New Mexico Geological Society Guidebook, 9th Annual Field Conference, p. 74-77.

-----1960, Lithologic subdivisions of the Redwall Limestone in northern Arizona--Their paleogeographic and economic significance: U.S. Geological Survey Professional Paper 400-B, p. 243B-245B.

-----1975, The Supai Group--Subdivision and nomenclature: U.S. Geological Survey Bulletin 1395-J, p. J1-J11.

-----1976, Paleozoic rocks of the Grand Canyon, in Breed, W. J., and Roat, Evelyn, eds., Geology of the Grand Canyon (2nd ed.): Flagstaff, Museum of Northern Arizona and Grand Canyon Natural History Association, Northland Press, p. 42-64.

McKee, E. D., and McKee, E. H., 1972, Pliocene uplift of the Grand Canyon region: Time of drainage adjustment: Geological Society of America Bulletin, v. 83, no. 7, p. 1923-1932.

McKee, E. D., and Gutschick, R. C., 1969, History of the Redwall Limestone of northern Arizona: Geological Society of America Memoir 114, 726 p.

Mickle, D. G., and Mathews, G. W., eds., 1978, Geologic characteristics of environments favorable for uranium deposits: U.S. Department of Energy Open-File Report GJBX-67(78), 250 p.

Miller, R. D., 1954, Reconnaissance for uranium in the Hualapai Indian Reservation area, Mohave and Coconino Counties, Arizona: U.S. Atomic Energy Commission RME-2007, p. 1-18, issued by U.S. Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee.

Moore, R. T., 1958, Geology of northwestern Arizona, Mohave County, Arizona: Tucson, University of Arizona, M.S. thesis, 81 p.

Moore, R. T., Wilson, E. D., and O'Haire, R. T., 1960, Geologic map of Coconino County, Arizona: Arizona Bureau of Mines, scale 1:375,000.

Nuclear Exchange Corporation, 1978, Uranium occurrences in breccia pipes: NUEXCO Publication 123, p. 22-23.

Oborn, E. T., and Hem, J. D., 1961, Microbiologic factors in the solution and transport of iron: U.S. Geological Survey Water-Supply Paper 1459-H, p. 213-235.

Osterwald, F. W., 1965, Structure control of uranium-bearing vein deposits and districts in the conterminous United States: U.S. Geological Survey Professional Paper 455-G, p. 121-146.

Otton, J. K., 1977, Geology of uraniferous Tertiary rocks in the Artillery Peak-Date Creek Basin, west-central Arizona, in Campbell, J. H., ed., Short papers of the U.S. Geological Survey Uranium-Thorium Symposium, 1977: U.S. Geological Survey Circular 753, p. 35-36.

-----1978, Tertiary geologic history of the Date Creek Basin, west-central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 140-141.

Pasteels, Paul, and Silver, L. T., 1966, Geochronologic investigations in the crystalline rocks of the Grand Canyon, Arizona [abs.], in Abstracts for 1965: Geological Society of America Special Paper 87, p. 124.

Peirce, H. W., 1972, Red Lake salt mass, in Fieldnotes: Arizona Bureau of Mines, v. 2, no. 1, p. 45.

-----1973, Evaporite developments, thickest anhydrite in the world? in Fieldnotes: Arizona Bureau of Mines, v. 3, no. 2, p. 1-2.

-----1976, Elements of Paleozoic tectonics in Arizona, in Tectonic Digest: Arizona Geological Society Digest, v. X, p. 37-57.

Peirce, H. W., Keith, S. B., and Wilt, J. C., 1970, Coal, oil, natural gas and uranium in Arizona: Arizona Bureau of Mines Bulletin 182, 289 p.

Peirce, H. W., Jones, Nile, and Rogers, Ralph, 1977, A survey of uranium favorability of Paleozoic rocks in the Mogollon Rim and Slope region--East central Arizona: Arizona Bureau of Geology and Mineral Technology Circular 19, 60 p., App. A.

Peirce, H. W., Damon, P. E., and Shafiqullah, M., 1979, An Oligocene (?) Colorado Plateau edge in Arizona: Tectonophysics, v. 61, p. 1-24.

Perry, V. D., 1961, The significance of mineralized breccia pipes: Mining Engineering, v. 13, p. 367-376.

Pugmire, R. U., 1977, The geology of Bill Williams Mountain, Coconino County, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 97 p.

Puttuck, H. E., 1954, Examination of copper-uranium occurrences in the Willaha area, Coconino County, Arizona: U.S. Atomic Energy Commission RME-2018, 15 p., issued by U.S. Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee.

Rawson, R. R., 1975, The sabkha environment: A new frontier for uranium exploration [abs.]: Geological Society of America Abstracts with Programs, v. 7, p. 1238-1239.

Rawson, R. R., and Turner, C. E., 1974, The Toroweap Formation: A new look, in Geology of northern Arizona, Pt. 1, regional studies: Flagstaff, Arizona, Geological Society of America, Rocky Mountain Section Meeting, p. 155-192.

Renfro, A. R., 1974, Genesis of evaporite-associated stratiform metalliferous deposits--A sabkha process: Economic Geology, v. 69, p. 33-45.

Rich, R. A., Holland, H. D., and Peterson, Ulrich, 1977, Developments in economic geology, 6, in Hydrothermal uranium deposits: New York, Elsevier, 264 p.

Rieke, H. H., and Chilingarian, G. V., 1974, Compaction of argillaceous sediments, in Developments in sedimentology: New York, Elsevier, v. 16, 424 p.

Sauck, W. A., and Sumner, J. S., 1971, Residual aeromagnetic map of Arizona: Tucson, University of Arizona, Department of Geosciences, scale 1:1,000,000.

Scarborough, R. B., and Peirce, H. W., 1978, Late Cenozoic basins of Arizona, in Land of Cochise, southeastern Arizona: New Mexico Geological Society Guidebook, 29th Annual Field Conference, p. 253-259.

Shoemaker, E. M., Squires, R. L., and Abrams, M. H., 1975, Application of ERTS images and image processing to regional geologic problems and geologic mapping in northern Arizona--Part IVA, The Bright Angel, Mesa Butte, and related fault systems of northern Arizona: National Aeronautics and Space Administration Technical Report 32-1597, p. 23-41.

Sorauf, J. E., 1962, Structural geology and stratigraphy of Whitmore Wash area, Mohave County, Arizona: Lawrence, University of Kansas, Ph.D. dissertation, 361 p.

Squires, R. L., and Abrams, M. H., 1975, Application of ERTS images and image processing to regional geologic problems and geologic mapping in northern Arizona--Part IVC, The Coconino Plateau: National Aeronautics and Space Administration Technical Report 32-1597, p. 73-81.

Stensrud, H. L., and More, Syrer, 1979, Precambrian geology and massive sulfide environments of the west-central Hualapai Mountains, Mohave County, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 129.

Taylor, S. R., 1964, Abundance of chemical elements in the continental crust: A new table: Geochimica et Cosmochimica Acta, v. 28, p. 1273-1284.

Thrailkill, John, 1968, Chemical and hydrologic factors in the excavation of limestone caves: Geological Society of America Bulletin, v. 79, p. 19-45.

Turner, G. L., 1962, The Deming Axis, southeastern Arizona, New Mexico and Trans-Pecos Texas, in Mogollon River region: New Mexico Geological Society Guidebook, 13th Annual Field Conference, p. 59-71.

Twenter, F. R., 1962, Geology and promising areas for ground water development in the Hualapai Indian Reservation, Arizona: U.S. Geological Survey Water-Supply Paper 1576-A, p. 1-37.

Vuich, J. S., 1974, A geologic reconnaissance and mineral evaluation, Wheeler Wash area, Hualapai Mountains, Mohave County, Arizona: Tucson, University of Arizona, M.S. thesis, 77 p.

Waesche, H. H., 1933, The Anita copper mine, in Grand Canyon nature notes: Grand Canyon Natural History Association, v. 7, no. 2, p. 108-112.

Wagoner, J. L., 1979, Hydrogeochemical and stream sediment reconnaissance basic data report for Williams NTMS Quadrangle, Arizona: U.S. Department of Energy Open-File Report GJBX-71(79), 17 p.

Wasserburg, G. J., and Lanphere, M. A., 1965, Age determination in the Precambrian of Arizona and Nevada: Geological Society of America Bulletin, v. 76, p. 735-758.

Wilson, E. D., and Moore, R. T., with additional data from maps by Ransome, F. L., Longwell, C., Lasky, S. G., Webber, B. N., Dings, M. G., and Sims, P. K., 1959, Geologic map of Mohave County, Arizona: Arizona Bureau of Mines, scale 1:375,000.

Young, R. A., 1966, Cenozoic geology along the edge of the Colorado Plateau in northwestern Arizona: St. Louis, Washington University, Ph.D. dissertation, 167 p.

-----1978, Nature of Cenozoic tectonism, volcanism and erosion along the southwestern edge of the Colorado Plateau in Arizona [abs.], in Papers presented to the Conference on Plateau Uplift: Mode and mechanism: Lunar and Planetary Institute Topical Conference, Flagstaff, Arizona, p. 56-58.

-----1979, Laramide deformation, erosion, and plutonism along the southwestern margin of the Colorado Plateau: Tectonophysics, v. 61, p. 25-47.

-----unpublished, Geologic maps of Fort Rock NW and Fort Rock SW Quadrangles: scale 1:24,000.

Young, R. A., and Brennan, W. J., 1974, Peach Springs Tuff: Its bearing on structural evolution of the Colorado Plateau and development of Cenozoic drainage in Mohave County, Arizona: Geological Society of America Bulletin, v. 85, p. 83-90.

Young, R. A., and McKee, E. H., 1978, Early and middle Cenozoic drainage and erosion in west-central Arizona: Geological Society of America Bulletin, v. 89, p. 1745-1750.

APPENDIX E

PRELIMINARY DEPOSITIONAL MODEL FOR COPPER-URANIUM COLLAPSE BRECCIA PIPES IN NORTHWEST ARIZONA

INTRODUCTION

A depositional model for copper-uranium collapse breccia pipes was begun by constructing a single-pipe model that defined the physical and chemical parameters of breccia-pipe formation, ore transport, and ore deposition as determined from published data and theoretical evaluations. The Orphan Lode Mine (Pl. 11 and 12) was chosen as the single-pipe type occurrence because it is a type example (Class 730) in Mathews (1978b), is less than 8 km outside the Williams Quadrangle, has produced large tonnages of ore, and has the most extensive literature of any Grand Canyon breccia pipe. Using the Orphan Lode Mine model, data on Mesozoic paleogeography, sedimentology, structure, facies distribution, and hydrogeology were combined to produce a regional map showing ore solution source, transport, deposition, and favorable trends for breccia-pipe formation.

PREVIOUS WORK

Formation of the Orphan breccia pipe was attributed by early workers to volcanic action. Kofford (1969) proposed a diatreme theory, with brecciation caused by explosive drilling of a volcanic vent by gases unmixed from a late Pliocene-Quaternary magma. Perry (1961) suggested collapse caused by withdrawal of magma. Gabelman (1957) and Gabelman and Boyer (1968) proposed a cryptovolcanic origin. However, the evidence opposed to any volcanic or magma-associated origin for the Orphan pipe is substantial. The age of uranium mineralization and of sediments involved in pipe formation is roughly between Late Permian and Late Jurassic (Gornitz and Kerr, 1970), whereas volcanism in the Grand Canyon region is restricted to the Tertiary or later. Furthermore, the Orphan pipe is not silicified; breccia pipes associated with volcanic vents are commonly silicified (see for example Barrington and Kerr, 1963). Gornitz and Kerr (1970) reported that pipe breccia fragments are universally down-dropped relative to wall rocks, which supports a collapse mechanism rather than an explosive venting mechanism for brecciation.

Bowles (1965 and 1977) and Gornitz and Kerr (1970) favored the cavern-collapse hypothesis for the Orphan breccia pipe. In this hypothesis, overlying rocks collapse into a cavern or sinkhole formed by migrating aqueous solutions in the Redwall Limestone, and a vertical pipe of down-dropped breccia results. Continued movement of aqueous solutions into the developing pipe dissolves additional carbonate rocks and cement, resulting in additional open space and continued collapse. For the Orphan Lode Mine, the textures, composition, and position of the breccia fragments (Gornitz and Kerr, 1970) support cavern collapse. Also, sinkholes at the top of, and caverns within, the Redwall Limestone (McKee and Gutschick, 1969) show the Redwall was amenable to carbonate dissolution. Further, breccia pipes in the Grand Canyon area never extend below the Redwall, indicating an initiation point within, or higher than, the Redwall.

Gornitz and Kerr (1970) proposed that the aqueous solutions that dissolved carbonates in the Redwall and initiated breccia-pipe formation were ascending reactive hydrothermal fluids at temperatures higher than those of ambient ground water. The proposed hydrothermal solutions would also have had undetermined UO_2^{+2} complexes and copper, lead, and zinc in solution. Biogenetic H_2S, as indicated by sulfur-isotope data for the Orphan Lode Mine, acted as a reducing agent and caused ore deposition. The evidence for heated hydrothermal fluids is inconclusive. Fluid-inclusion geothermometry by Gornitz and Kerr (1970) suggests that the ore-solution temperature may have been less than 100°C; during ore deposition in the Grand Canyon region, the sedimentary sequence was thick enough that a normal geothermal gradient would have sufficiently heated local ground waters.

Bowles (1965 and 1977) proposed that low-temperature hypogene solutions consisting mostly or entirely of artesian ground water initiated breccia-pipe formation and caused primary mineralization. Collapse-breccia-pipe formation was initiated in the lower Redwall during the Mesozoic when mixing of compositionally different ground waters caused disequilibrium and solution of the surrounding carbonates. Oxidizing solutions containing uranium and other metals entered the pipe when it penetrated the sandstone aquifers of the Supai Group. The reductants were dissolved sulfide species transported by the Redwall ground waters. Mineralized pipes exposed by late Miocene-early Pliocene Grand Canyon erosion underwent supergene or mesogene enrichment.

DESCRIPTION OF TYPE OCCURRENCE

Uranium ore in the Orphan Lode Mine occurs in a nearly circular collapse-breccia-pipe structure with a vertical extent between 460 m (Gornitz, 1969) and 610 m (Kofford, 1969). The diameter ranges from approximately 45 to 150 m.

The lower limit of the pipe is near the base of the Mississippian Redwall Limestone (Kofford, 1969). The pipe extends upward through the Redwall, the Pennsylvanian-Permian Supai Group, and the Permian Hermit Shale, and crops out in the Permian Coconino Sandstone (Pl. 11). Due to erosion, the original uppermost stratigraphic limit of pipe penetration is not known.

Both hypogene and supergene suites of minerals are present in the pipe (Gornitz and Kerr, 1970). Uranium is present as hypogene uraninite and subsidiary supergene minerals. Kofford (1969) reported minor coffinite, but other investigators, including Gornitz (1969) and Gornitz and Kerr (1970), do not. Iron, copper, lead, zinc, copper-iron, and copper-arsenic-antimony sulfides and minor cobalt and nickel arsenides are present. Gangue minerals include calcite, dolomite, siderite, and barite.

Minerals within the pipe display both vertical and horizontal zonation (Gornitz and Kerr, 1970). Uranium is concentrated at the pipe margins and in large irregular masses within the pipe. Iron sulfides and uraninite at the core of the pipe grade outward into a complex mineral assemblage at the pipe margins. The pipe also displays a rough upward zonation of copper to uranium (Pl. 11).

The primary alteration is bleaching of normally red sediments and carbonatization of the breccia material (Kofford, 1969; Gornitz and Kerr, 1970). The pipe fill material is bleached light whitish gray by the removal of hematite. Bleaching of unfractured rocks surrounding the pipe extends to a maximum of 30 m and shows permeability control. The vertical and horizontal extent of alteration greatly exceeds that of metallization.

A general paragenetic sequence (Kofford, 1969; Gornitz and Kerr, 1970) begins with alteration of breccia, which includes bleaching. Bleaching is followed by dolomitization and then pyritization. After pyrite formation, the complex sulfide minerals and uraninite are deposited. An episode of calcification is followed in turn by the deposition of further uraninite and the simple sulfides. The final stage is supergene enrichment.

Sulfur-32-to-sulfur-34 ratios are from 22.28 to 22.84. Filling temperatures of calcite fluid inclusions are from 45° to 124°C, but cluster in the range of 60° to 100°C. Uranium-to-lead age dating indicates minimally 141 m.y. for the uranium mineralization (Gornitz and Kerr, 1970).

DEPOSITIONAL MODEL

As Bowles (1965 and 1977) first suggested, and the following model elucidates, formation and mineralization of Orphan-type copper-uranium breccia pipes in northwest Arizona resulted from controlled vertical mixing of three compositionally different ground-water solutions (Pl. 11). The breccia pipes acted first as conduits that enabled oxidizing uranium-bearing ground waters and reducing ground waters from different stratigraphic intervals to mix, and then acted as structural traps during the resulting mineralization.

Mechanism of Breccia-Pipe Formation

Collapse brecciation of overlying sediments into caverns or voids in the Redwall Limestone (Bowles, 1965, 1977; Gornitz, 1969; Gornitz and Kerr, 1970) is the general mechanism for pipe formation proposed here.

Bowles (1977) suggested that mixing of ground-water solutions in the Redwall could initiate cavern formation but did not propose a mechanism. The bedded chert at the top of the Thunder Springs member (Pl. 11) would have been impermeable, until tectonically fractured, and would have separated the Redwall into two aquifers. The bedded chert has a lateral distribution of hundreds of miles in the Grand Canyon region with no appreciable change in character (McKee, 1958). The ground waters in the dolomitic Whitmore Wash and Thunder Springs members (Pl. 11) below the chert were saturated with respect to Ca^{+2}, Mg^{+2}, and HCO_3^- and had a partial pressure of CO_2 equal to x. Above the chert, ground waters in the calcitic Mooney Falls and Horseshoe Mesa members of the Redwall were saturated with respect to Ca^{+2} and HCO_3^- and had a partial pressure of CO_2 less than x. Mixing of the two solutions would have caused disequilibrium, undersaturation with respect to $CaCO_3$, calcite dissolution, and, consequently, cavern formation (Bogli, 1964; Thrailkill, 1968).

Even though the ground water below the chert barrier had a higher artesian pressure than did the ground water above the chert, mixing was very improbable without some breach in the chert zone. A logical breaching mechanism would be late Paleozoic and early Mesozoic faulting, but any tectonic activity that fractured or displaced the chert zone, such as folding or fracturing associated with regional uplift, would also serve. Many writers, including Miller (1954), Osterwald (1965), and Finch (1967), have noted a spatial relationship between Grand Canyon breccia pipes and fault zones. They attributed the relationship to the faults acting as conduits for hydrothermal ore solutions. However, it seems more probable that the relationship is simply due to late Paleozoic to early Mesozoic fault zones being favorable areas for the initiation of breccia-pipe development.

Plate 12 shows the regional extent of two systems, the Grand Canyon Upwarp and the major fault systems, that may have provided the requisite faulting. The Grand Canyon Upwarp was a local feature that operated intermittently throughout the Pennsylvanian to the Early Permian (Lane, 1977), and was active in the post-Redwall but premineralization period. As the chert beds in the Redwall are much more brittle than the surrounding carbonates, stress resulting from gentle flexing of the Redwall could have fractured the chert beds and not appreciably affected the carbonates.

Although many faults are mapped for northwest Arizona, only those faults active in the post-Mississippian to pre-Jurassic would have initiated Orphan-type breccia-pipe formation. The exact delineation of post-Mississippian to pre-Jurassic faults is beyond the scope of this study. However, Peirce (1976) has stated that there appears to be spatial linkage between pre- and post-Paleozoic tectonism. Furthermore, work by Shoemaker and others (1975) gives strong evidence that major faults in northwest Arizona reflect deep-seated zones of weakness along which repeated faulting occurred from the Precambrian to post-Laramide. Probably most, if not all, post-Mississippian to pre-Jurassic faulting in northwest Arizona occurred in fault trends as delineated by Shoemaker and others and shown on Plate 12.

Lucas and Adler (eds., 1973) summarized empirical and theoretical data on roof and ground control in subsurface mining. Two concepts involving the collapse of bedded rocks into a subsurface void are the laminated-beam and pressure-arch theories. Empirically, these two concepts involve, as determining factors for collapse, the horizontal dimension of the subsurface cavity and the thickness of the overburden. Above any subsurface cavity, a pressure arch forms, outlining a roughly elliptical zone of fractured rock, the major axis roughly four times the minor axis, above the opening. In general, the width, W, of the pressure arch depends only upon thickness of the overburden, that is, depth, d, and $W = 0.15d + 60$ (in feet). If the horizontal dimension of the cavity is less than the calculated pressure-arch width, collapse will not occur.

At the time of Orphan pipe formation and mineralization, there were roughly 1100 m of sediments above the present Kaibab surface (Gornitz and Kerr, 1970). According to pressure-arch theory, collapse should not have occurred, as the pipe diameter was less than the calculated pressure-arch width. However, pressure-arch theory takes no account of the pipe fluids that entered the fractured rock in the pressure-arch zone and enlarged the fractures through carbonate dissolution so that the rock eventually collapsed. A new pressure-arch zone then formed and the pipe enlarged upward. The pipe continued to enlarge until either the pipe solutions no longer dissolved the fractured rock in the pressure arch due to chemical changes, or the solutions no longer reached the pressure arch due to hydrogeologic changes.

Underlying the Toroweap Formation is the Coconino Sandstone, a well-sorted eolian sandstone with excellent aquifer characteristics. Ascending fluids in the pipe may have recharged the Coconino on a massive scale. The small amount of fluid reaching the overlying carbonates may not have been enough to continue the solution-collapse-pressure arch cycle. If so, during middle to late Mesozoic, breccia-pipe development would have terminated at the top of the Coconino or in the lower Toroweap Formation, with a pressure arch extending roughly two times pipe diameter into the Kaibab.

By the late Tertiary, erosion would have reduced the post-Coconino stratigraphic sequence from 1100 m to almost the present 175 m. With this reduction of overburden, the pressure arch in the Kaibab would not be stable and collapse brecciation would resume. Near-surface collapse results in surface subsidence (Lucas and Adler, eds., 1973), creating a shallow dishlike depression centered over the breccia pipe. The diameter of the surface depression is several times the diameter of the breccia pipe; for an Orphan-sized pipe (Pl. 11) the diameter would be about 260 m with a vertical displacement between 3 and 15 m.

Source and Transport of Reductants

Bowles (1977) suggested that the reductants were probably dissolved sulfide species and organic carbon released from dissolved carbonates transported to the pipe by the Redwall ground waters. Using cores and well cuttings, McKee (1960) and Peirce and others (1970) found traces of petroleum in the Redwall Limestone. McKee (1960) reported traces of oil in only the Whitmore Wash and Thunder Springs members of the Redwall. The presence of biogenetic H_2S in petroliferous carbonates is well documented, and ground waters would easily transport the H_2S as dissolved H_2S and HS^-. The Redwall ground waters flowed into and up the developing breccia pipes, so the pipes would have had a continuing supply of reductants not limited to a fixed in situ supply.

Early Mesozoic uplift of the Deming Axis (Turner, 1962) across south-central Arizona, and the northeast tilting of the Colorado Plateau (Bowles, 1977) exposed the Paleozoic strata of southwest Arizona to erosion. Also, the northeast-dipping Paleozoic strata were exposed to recharge by surface waters in a northwest-trending belt across central Arizona (Pl. 12). Reductants in the Redwall were transported by ground waters moving downdip and northeast, away from the zone of recharge.

Chemically, ground-water solutions with biogenetic sulfur from the carbonates of the Redwall would have had a low sulfur and high carbonate content. The absence of reported native sulfur in the pipe (Gornitz, 1969; Kofford, 1969; Gornitz and Kerr, 1970) and calculated Eh-pH diagrams of the Fe-S-CO_3 and S systems indicate that the reducing solutions had a total dissolved concentration of less than 10^{-3} $\underline{m}$ (molal) sulfur and close to 10^{-1} $\underline{m}$ carbonate.

Source and Transport of Ore Solutions

The data available enable placing fairly restrictive limits on the chemical composition of the ore solutions as well as the P-T conditions of the breccia pipe during ore deposition. Fluid-inclusion geothermometry by Gornitz (1969) indicates a pipe temperature during deposition between 50° and 100°C. Gornitz and Kerr (1970) calculated a lithostatic pressure of 340 atm. However, in a breccia-pipe environment recharged by ground water, it is suggested that a hydrostatic pressure of approximately 150 atm is more appropriate. Limits on the pH were imposed by the buffering action of the large amounts of carbonate in the system.

The above limits and Eh-pH relationships indicate that uranium and copper were transported in oxidizing solutions as carbonate complexes, uranium as $UO_2(CO_3)_2 \cdot 2H_2O^{-2}$ and $UO_2(CO_3)_3^{-4}$, and copper as $CuCO_3$. They also indicate that the trace metals were transported in the ore solution as simple ions and oxide complexes. Bowles (1977) suggested large amounts of iron were brought to the pipe in the ore solution; such iron transport is both unnecessary and unlikely. $CaCO_3$ and $FeCO_3$ coexist in the pipe (Gornitz and Kerr, 1970); Berner (1971) stated that for siderite to be stable, the concentration of Fe^{+2} must be at least 5% that of Ca^{+2}. At the Eh and pH conditions of the ore solution, it is very unlikely that the necessary amounts of iron could be transported (Hem and Cropper, 1959; Oborn and Hem, 1961). It is more likely that iron was supplied by in situ reduction and dissolution of hematite. Large amounts of hematite were available from the Supai and Hermit red beds, both as breccia in the pipe and as the immediately adjacent rocks (Gornitz and Kerr, 1970).

Combining available stratigraphic and mineral zonation data of the Orphan Lode Mine (Gornitz and Kerr, 1970) with calculated Eh-pH mineral stability data, the stratigraphic level at which ore solutions enter the breccia pipe and the major flow direction of the ore solutions can be determined.

Several writers, including Chenoweth and Malan (1969) and Gornitz and Kerr (1970), have noted the apparent correlation of pipe ore grade with external pipe stratigraphy. Mineralized rock first appears in the upper half of the Supai Group, and the highest-grade ore correlates with the Esplanade Sandstone of the Supai Group (Pl. 11).

Patterns of mineral zonation within the pipe also indicate that the ore solutions entered the pipe at the Supai stratigraphic level. Ore solutions moving up the pipe from depth and intersecting reductants at the Supai level are ruled out by reduced iron below the ore zone in the pipe (Gornitz, 1969). Ore solutions descending the pipe from the surface and intersecting reductants at the Supai level are ruled out by the vertical zonation of uraninite and chalcocite in the breccia pipes (Pl. 11) in conjunction with mineral stability relationships. These relationships were calculated using thermodynamic data (Garrels and Christ, 1965) and ion concentrations suitable for the pipe depositional environment. They show clearly that if copper and uranium were transported downward from the surface in an oxidizing solution and then encountered a reducing environment, depositional order would be copper then uranium, the reverse of what is actually present (Pl. 11).

Bowles (1977) proposed that, as water pressure in the pipe dropped during pipe formation, the ore solutions first entered the pipe from the lower sandstone aquifers of the upper Supai. As the breccia pipe stoped upward and pipe water pressure continued to fall, ore solutions entered the pipe from successively higher and more sand-rich Supai sandstone aquifers. It is concluded that the ore solutions were oxidizing ground waters transported in the Esplanade and perhaps the upper Wescogame formation (Pl. 11) with the bulk entering the pipe from the massive sandstones of the Esplanade Sandstone.

Determination of flow direction of the ore solutions in the Supai is hampered by insufficient detailed geochemical and mineral-distribution data. As a first approximation, ground-water flow through an aquifer being anisotropic, a larger volume of oxidizing Supai ore solutions would have entered the pipe from the "upstream" direction. The "upstream" side of the pipe or the solution flow direction is indicated by the following data: the highest grade ore is in an arc along the northeast rim of the pipe (Gabelman and Boyer, 1958), and bedded ore is in the upper Supai adjacent to the peripheral shear zone of the pipe, especially on the northeast side (Chenoweth and Malan, 1969; Gornitz and Kerr, 1970). Because of redox gradients set up by an anisotropic flow of oxidizing ore solutions into the pipe and the Eh-pH limits of uraninite stability, major ore concentrations should occur on the "downstream" side of the pipe. It is concluded that the ore solutions in the upper Supai regionally moved south to north, or southwest to northeast.

The source of the Supai ore solutions remains to be determined. In brief, it is proposed that the ore solutions originated during the Mesozoic when the Paleozoic sedimentary rock sequence of north Arizona was recharged by north-moving ground waters. The oxidizing ground waters obtained uranium and other metals from the Lower Pennsylvanian to Lower Permian red-bed sediments. The solutions were channeled by facies-related permeability boundaries into the north-trending Esplanade Sandstone.

The Lower Pennsylvanian-Lower Permian red-bed sequence is primarily the Supai Formation, centered in the Pedregosa Basin area (Pl. 12) south and southwest of the Zuni-Defiance Uplift (Peirce and others, 1977), and the Supai Group described by McKee (1975) in the Grand Canyon region. Correlation between the two areas is provided by Lane (1977).

A number of factors make the Lower Pennsylvanian-Lower Permian red-bed sequence a source of ore solutions. One such is the sediment sources (Lane, 1977) of the red beds. Primary sources are detritus shed by the exposed Precambrian granites of the Zuni-Defiance Uplift (Pl. 12) and the Uncompahgre Uplift in south Utah and Colorado. The secondary source is the occasional reworking of the red beds in the Grand Canyon Upwarp area (Pl. 12). Lane (1977) stated that the dominant sediment source for the Esplanade Sandstone in the Grand Canyon area was the Uncompahgre.

Peirce and others (1977) stated that diagenesis of the Zuni-Defiance sediments released uranium for the deposits in the Supai Formation in the Pedregosa Basin area. Therefore, it seems reasonable to expect diagenesis would have liberated uranium in other areas where the sediments are present--the lower three formations of the Supai Group of the Grand Canyon region.

The restriction of known uranium occurrences in the red beds (excluding breccia pipes) to the Supai Formation in the Pedregosa Basin is felt by this writer to be due to the concentration of the carbonaceous trash shed by the Zuni-Defiance to the Pedregosa Basin area (Peirce and others, 1977). The carbonaceous-trash content of Supai Group red beds appears very low. However, Kofford (1969) has reported traces of carbonaceous material in the Supai Group as far north as the Orphan Lode Mine area.

In areas other than the carbonaceous-trash-rich Pedregosa Basin, it is proposed, first, that the diagenesis-released uranium in the U^{+6} state may have been adsorbed on clay minerals, and was probably also reduced and deposited by dispersed carbonaceous material and scattered reducing zones within the red beds. Eh-pH mineral stability relationships show that a red bed can contain stable hematite and still be reducing enough for uranium to be precipitated. Because of the shortage of carbonaceous material, uranium fixed in the sediments in the ways just suggested would have been extremely vulnerable to dissolution and mobilization by oxidizing ground waters.

The second proposed path of diagenesis-released uranium was to remain in solution. Due to the presumably low levels of reductants in the Supai red beds, an unknown but probably significant fraction remained in the U^{+6} state in the interstitial solutions of the sediments. A large percentage of the solutions were expelled due to compaction and authigenic clay formation, but a significant fraction remained in the sediments as residual pore solutions. Upon compaction, these solutions would migrate to sand-rich, more permeable members of the sequence such as the Esplanade Sandstone (Rieke and Chilingarian, 1974).

These post-compaction residual pore solutions would have remained within the sediments until actively flushed out by ground-water movement. In northwest Arizona, the first opportunity for pore-solution migration in the Supai Group was during the Mesozoic recharge by surficial waters. Simple mass-balance calculations show that 50,000 to 100,000 tons U_3O_8 could have been in residual pore solutions of the Supai Group.

During the early Mesozoic, in the same regional tilting (Turner, 1962) and erosional bevelling of the Paleozoic rocks that allowed surficial waters to enter the Redwall Limestone, the Lower Pennsylvanian-Lower Permian red-bed sequence was recharged by oxidizing ground water (Bowles, 1977). It is proposed that this ground water became uranium-bearing in the following manner.

First, the introduced surficial waters would have expelled the U^{+6}-bearing residual pore solutions along a broad solution front oriented normal to the direction of solution flow. Second, the ground water would have oxidized the scattered organic material and the reduced, zoned depositional remanent. This oxidation would have mobilized the diagenetic, reduced uranium and would have effectively destroyed almost all traces of carbonaceous material and reduced sediments. Such a process would have resulted in north-moving uranium-bearing ground water leaving behind the present Supai Group, an almost completely oxidized red-bed sequence with a low residual uranium content.

One additional possible source of uranium for the ground-water solutions is those sections of the red-bed sequence where the dominant sediment source is the Uncompahgre or reworked red beds. These sediments undoubtedly had a lower uranium content than did the red beds derived from the Zuni-Defiance, and have a much lower labile and feldspathic fraction (Lane, 1977). However, in the proposed hydrogeologic system where very large amounts of solution move through very large volumes of sediments, the most important factors in ore deposition are a good source of reductants and the plumbing necessary to transport the uranium-bearing solutions to the depositional site, not the uranium content of the sediments.

Sediments that act as uranium sources for aqueous solutions are not necessarily favorable environments for uranium deposition. The red beds of the Supai Group in the Williams Quadrangle may have been a uranium source, but are an unfavorable environment for peneconcordant sandstone uranium deposits.

Whatever the uranium sources, permeability-related facies transitions and formational boundaries (McKee, 1975; Lane, 1977) in the red-bed sequence would have channelled the north-moving ground waters into the north-trending massive sandstones of the Esplanade.

Ore Deposition

The copper-uranium collapse-breccia-pipe ore of northwest Arizona was formed in two stages: Late Permian to late Mesozoic hypogene mineralization, and supergene ore enrichment beginning in the middle Tertiary.

Pipe development began when Late Permian to early Mesozoic tectonic activity ruptured the bedded chert zone at the top of the Thunder Springs member of the Redwall Limestone (Pl. 11). Artesian pressure forced ground-water solutions upward through fractures in the bedded chert where mixing occurred with ground waters in the Mooney Falls member of the Redwall. Disequilibrium between the two solutions initiated dissolution and cavern development. The breccia pipe stoped its way upward with a cyclical progression of open-space development, pressure-arch development, solution of fracture rock in the pressure arch, collapse, and development of a new pressure arch. The ground-water solutions moving upward in the pipe under artesian pressure contained reductants derived from the Redwall.

As the pipe stoped upward, it penetrated the impermeable shales of the lower Supai (Pl. 11) that separated the reducing Redwall ground waters from the oxidizing, ore-transporting solutions of the upper Supai. As the reducing solutions from the Redwall encountered the hematite-rich rocks of the Supai, iron reduction commenced. Hematite was first dissolved, resulting in bleaching of the breccia and surrounding rocks. Further reduction caused pyrite to form.

Sandstone aquifers in the Supai were recharged by pipe solutions with consequent lowering of pipe water pressure (Bowles, 1977). At some point, the pressure was low enough for copper-uranium-bearing oxidizing ground-water solutions in the upper Supai Group to enter the pipe. Mixing of the solutions caused reduction of the metals transported by the ore solutions. Ore deposition in and immediately adjacent to the pipe occurred upwards from the point where ore solutions entered the pipe. Ore and metal zonation developed according to the redox potentials of the minerals deposited, resulting in the mineral distribution and paragenetic sequence reported by Gornitz (1969), Kofford (1969), and Gornitz and Kerr (1970).

Pipe development and mineralization probably continued to the top of the Coconino where pipe solutions were diverted into the massive Coconino aquifer. The first stage of pipe development ended with the breccia pipe terminating in the lower Toroweap. Capping the pipe was a pressure arch of fractured rock, extending several hundred feet into the Kaibab Limestone. The period of mineralization during this stage of pipe development was from Late Jurassic to Middle Cretaceous.

The second stage of pipe development began as early as mid-Tertiary when erosion had reduced the stratigraphic section above the pipe to almost the present level. The removal of overburden made the pressure arch over the breccia pipe unstable, with renewal of collapse and surface subsidence, but not of hypogene mineralization.

Where late Pliocene development of the Grand Canyon exposed breccia pipes, supergene enrichment occurred (Kofford, 1969; Gornitz and Kerr, 1970), compressing the mineralized column in the breccia pipe downwards into a rich ore zone at the level of the upper Supai and lower Hermit Shale Formations.

CONCLUSION

The model presented postulates a post-Mississippian to pre-Cretaceous ground-water origin for both the breccia pipes and the Orphan-type mineralization. The model does not exclude hydrothermal contribution to the ore solutions transported by the upper Supai Group, but a ground-water origin alone is consistent with available data.