UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Integrated Uranium Systems in the Marysvale Volcanic Field, West-Central Utah

By

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Open-File Report 80-524

1980

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INTEGRATED URANIUM SYSTEMS IN THE MARYSVALE VOLCANIC FIELD, WEST-CENTRAL UTAH

By T. A. Steven, C. G. Cunningham, and M. N. Machette

Abstract

Uranium in the Marysvale volcanic field is known to occur in several geologic environments, and is hypothesized to occur in others. Together the known and hypothetical occurrences range from a source in rhyolite magma, through porphyry-type deposits, hydrothermal vein deposits, dispersed hydrothermal deposits, and after transport in ground and surface water, to roll-front or sedimentary trap-deposits in basin-fill sediments. To date, only the hydrothermal vein environment has been productive, but billions of pounds of uranium were available in all other environments, and if proper circumstances occurred, significant concentrations probably exist there too. The intracaldera fill of the Mount Belknap caldera and sediment-filled basins adjoining the Tushar Mountains are especially favorable for the undiscovered uranium that may be expected.

Introduction

Uranium in the Marysvale volcanic field was derived ultimately from igneous sources, and was spread through a succession of geologic environments ranging from the source magma, through a variety of hydrothermal environments, to sedimentary fills in nearby structural basins. Economic and potentially economic concentrations of uranium occur in several of these environments; veins in the Central Mining Area 6 km north-northeast of Marysvale have provided most of the production to date, but some as yet unproductive environments may contain significant uranium deposits. This report examines the potential for uranium in this succession of environments and considers the processes that may have been involved in concentrating uranium in them.

Uranium in rhyolite magma is the starting point in what can be called the extended volcanogenic uranium system. This magmatic uranium has been studied in volcanic glasses (Carmony, 1977; Zielinski, 1978; Cunningham and others, 1980) and may exist in part in accessory minerals in epizonal plutons (Desborough and Sharp, 1978). Porphyry-type ore deposits, possibly containing accessory uranium, have been suggested to underlie the Deer Trail Mountain-Alunite Ridge area, 12 km southwest of Marysvale (Cunningham and others, 1978, Cunningham and Steven, 1979b) and the Central Mining Area (Cunningham and Steven, 1979a). The hydrothermal vein environment overlies the porphyry-type environment and is exposed in mines in the major uranium-producing Central Mining Area (Kerr and others, 1957; Cunningham and Steven, 1978, 1979a; Cunningham and others, 1979) and in the Mystery-Sniffer mine area on the west side of the Tushar Mountains (Wyant and Stugard, 1951). Pervasively altered rocks containing uranium deposits within the Mount Belknap caldera represent a dispersed hydrothermal environment within which epigenetic uranium deposits formed locally and uranium derived from host rocks was remobilized and in part redeposited. Paleovalleys filled with Sevier River Formation or equivalent sedimentary rocks once carried surface and ground water effluent from the uranium source areas, and nearby structural basins (Sevier River Valley, Beaver basin, etc.) provided sumps into which these channels drained. The Beaver basin and the Sevier River Valley (Cunningham and Steven, 1979c) and the Big John caldera (Steven and others, 1979a) have been suggested as possible sites of roll-front or sedimentary trap uranium deposits.

Current work by the U.S. Geological Survey in the Marysvale volcanic field began in 1975 as a restudy of the geology and ore deposits in the mineralized areas near Marysvale. The volcanic framework was greatly revised, and multiple ages and types of mineral deposits were recognized (Steven and

others, 1978a, b; 1979b; Cunningham and Steven, 1979d). In 1978, these local studies were extended into a broader multidisciplinary study of the geology and mineral resources of the entire Richfield $1^{\circ} \times 2^{\circ}$ quadrangle. Detailed studies of mineralized areas near Marysvale continued, and the current focus of these is on the evolution of the ore systems and on the potential for undiscovered deposits (Steven and others, 1978a, b; Cunningham and Steven, 1979b). More recently, a geochemical study has been begun of the mineral deposits (including uranium), using fluid-inclusion and isotope techniques and thermochemical calculations (Cunningham and others, 1979, 1980). Specialized studies of the structure and stratigraphy are being made in some of the structural basins where uranium may have accumulated.

Uranium in rhyolite magma

All known uranium occurrences in volcanic rocks of the Marysvale volcanic field seem associated in time and commonly in space with Miocene or younger rhyolites or related epizonal intrusives. Most of these rhyolites belong to the Mount Belknap Volcanics, which was erupted from two source areas in the central Tushar Mountains and the Antelope Range between 21 and 16 m.y. ago (fig. 1). Rhyolite eruptions also took place about 9 m.y. ago in the low hills marking the north end of the Beaver basin (S. H. Evans, University of Utah, written commun., 1980) and associated mineralization has been dated along the west flank of the Tushar Mountains (Steven and others, 1979b, p. 35).

Figure 1.--Near here

Elsewhere, rhyolitic volcanic rocks were emplaced about 8-5 m.y. ago (H. H. Mehnert, U.S. Geological Survey, written commun., 1978) in the Kingston

Canyon area and adjacent parts of the Sevier Plateau, 25-35 km south-southeast of Marysvale, and rhyolite domes and flows along the crest and western flank of the central Mineral Mountains have been dated (Lipman and others, 1978; Mehnert and others, 1978) as 0.8-0.5 m.y. old. Miller and others (1979) report anomalously high uranium contents in present-day spring waters in the Mineral Mountains, but no genetic association with either the 9 m.y. old or 0.8-0.5 m.y. old rhyolites has yet been established. All these rhyolites are interpreted to belong to the bimodal rhyolite-basalt assemblage (Christiansen and Lipman, 1972) erupted widely throughout western United States in late Cenozoic time concurrently with extensional tectonism.

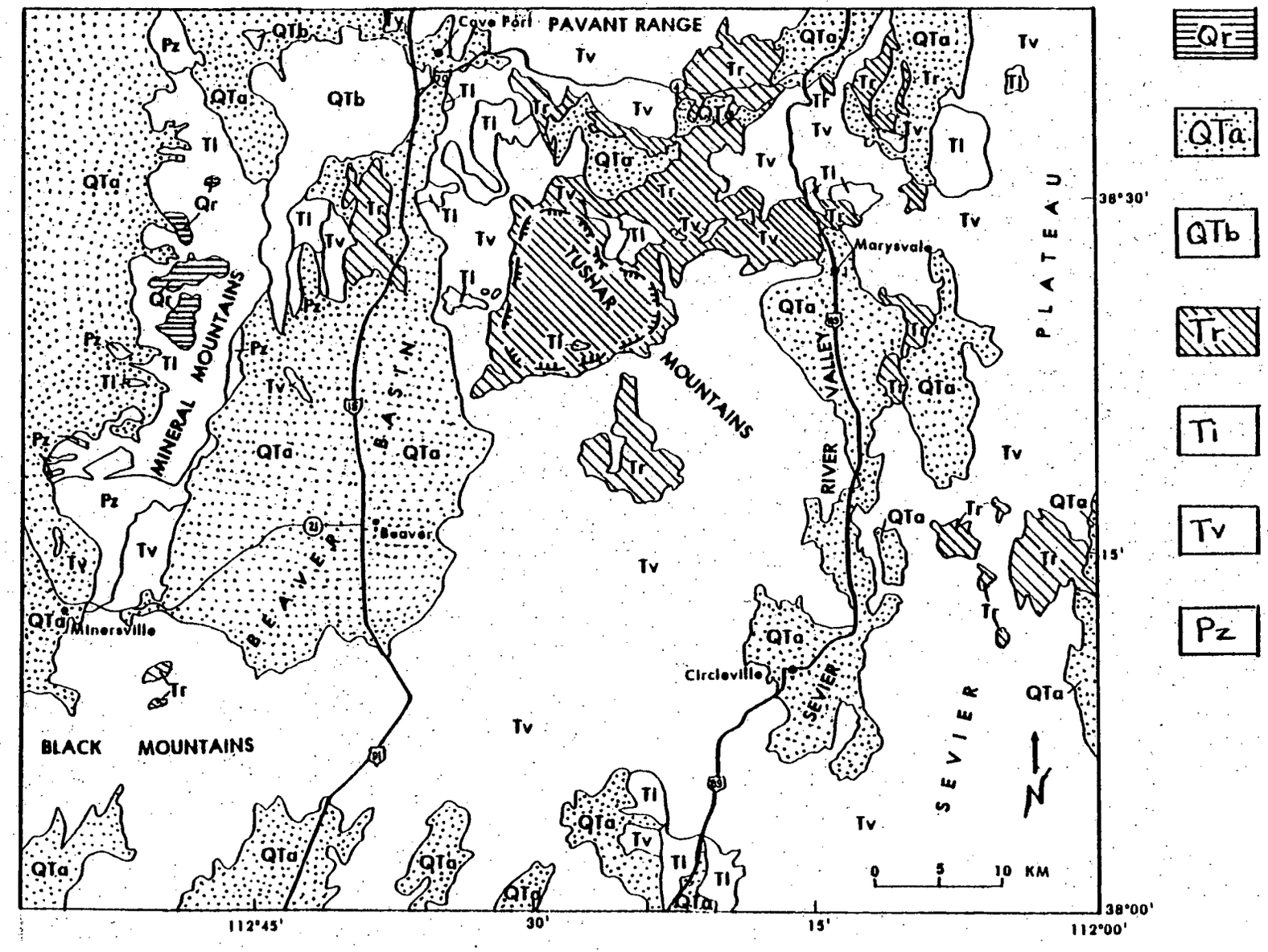

Figure 1.--Generalized geologic map of part of Marysvale volcanic field.

DESCRIPTION OF MAP UNITS

QTa	UNDIVIDED ALLUVIAL DEPOSITS (QUATERNARY AND TERTIARY)
Qa	RHYOLITE (QUATERNARY)--Rhyolite domes and flows along the crest and western side of the central Mineral Mountains
QTb	BASALT (QUATERNARY AND TERTIARY)--Includes only the young basalt volcanoes west and southwest of Cove Fort
Tr	RHYOLITE (TERTIARY)--Includes Mount Belknap Volcanics (21-16 m.y.) in the Tushar Mountains area, rhyolites of Foshea Mountain and Phonolite Hill (8-5 m.y.) in Sevier Plateau area, and rhyolite of Gillies Hill (9 m.y.) at north end of Beaver basin
Ti	UNDIVIDED INTRUSIVE ROCKS (TERTIARY)
Tv	UNDIVIDED VOLCANIC ROCKS (TERTIARY)
Pz	UNDIVIDED SEDIMENTARY ROCKS (PALEOZOIC)
ıllı ıllı	Outline of Mount Belknap caldera

The association in time and space of uranium occurrences and rhyolitic volcanic rocks implies a genetic relation, and the basic assumption of this paper is that all significant uranium occurring in the various geologic environments of the Marysvale volcanic field originated in the rhyolite magmas. This same conclusion was reached by Lindsey (1979, p. 96) in the Thomas and Dugway Ranges 150 km to the north in western Utah. To establish what the uranium content of these magmas was, volcanic glasses from a number of locations were collected and analyzed by the delayed neutron method for U and Th. The results are given in table 1:

Table 1.--Near Here

The uranium content of ten samples of volcanic glasses from the Mount Belknap Volcanics ranges from 9.7 to 15.2 ppm, and averages 12.9 ppm. All samples are of nonhydrated obsidians, and the values are believed to be very close to the original values in the magma at the time of eruption. Most samples are essentially aphyric and the uranium is dispersed through the glass. In those samples containing a few percent phenocrysts, uranium occurs in zircon as well as in glass.

Table 1:--Uranium and thorium contents of glassy and devitrified rhyolites from the Marysvale Volcanic Field.

[Determination by delayed neutron techniques. Analysts: H. T. Millard, Jr., R. B. Vaughn, S. W. Lasater, and B. A. Keaten. Data in parts per million. Leaders (---) indicate not determined]

Sample no.	Sample	Th	U	Th/U
Glass samples, Mount Belknap Volcanics				
M49B	Teacup dome	37.2	15.2	2.45
M119	Joe Lott Tuff Member	36.4	12.0	3.03
M408	Glassy dike, Freedom mine	42.6	13.8	3.08
M502	Red Hills Tuff Member	37.0	13.6	2.71
M672	Crystal-rich tuff member	25.9	9.69	2.67
M686A	Red Hills Tuff Member	42.0	13.9	3.03
M687A	Black Rock Stock	42.2	12.2	3.46
M689	Glassy dike, east of Jungfrau	45.4	11.5	3.94
78-S-16	Apache tears, Trinity mine	34.0	13.5	2.52
78-S-17	Black Rock stock	35.3	13.5	2.61
Devritified samples, Mount Belknap Volcanics				
M49A	Teacup dome	40.4	8.12	4.98
M680	Red Hills Tuff Member	45.7	9.18	4.98
M685	Joe Lott Tuff Member	42.8	10.4	4.13
M686B	Red Hills Tuff Member	44.7	15.5	2.88
M687B	Black Rock stock	33.4	7.57	4.42

	Mount Belknap caldera, intracaldera facies			
M209	Mount Baldy Rhyolite Member	48.6	18.3	2.66
M214	Blue Lake Rhyolite Member	31.2	12.7	2.45
M328	Mount Baldy Rhyolite Member	49.2	17.3	2.84
M329	Mount Baldy Rhyolite Member	48.4	21.3	2.28
M575	Blue Lake Rhyolite Member	28.0	11.5	2.44
M577	Middle tuff member	29.9	12.5	2.39
M578	Middle tuff member	32.6	13.7	2.38
M581	Mount Baldy Rhyolite Member	44.1	11.6	3.80
M582	Middle tuff member	46.2	18.1	2.55
M583	Blue Lake Rhyolite Member	42.0	15.5	2.71
M584	Mount Baldy Rhyolite Member	42.4	18.7	2.26
M585	Middle tuff member	47.6	10.5	4.55
M586	Middle tuff member	42.3	31.4	1.35
	Mount Belknap caldera, intracaldera stocks			
M330	U-Beva stock	45.4	12.3	3.68
M580A	Gold Mountain breccia pipe	19.3	7.94	2.44
M580B	Gold Mountain breccia pipe	20.1	9.11	2.20
M580C	Gold Mountain breccia pipe	34.4	13.4	2.56
M580D	Gold Mountain breccia pipe	29.4	11.3	2.61
M637B	North Fork North Creek stock	48.6	33.2	1.46
M638	do.	39.9	15.6	2.56
M639	do.	34.6	11.5	3.02
	Zeolitized samples			
M626	Joe Lott Tuff Member	36.2	5.46	6.64
M628	do.	39.1	8.31	4.71

Samples from west side of Tushar Mountains				
Glass				
79-S-8A	Rhyolite of Gillies Hill	18.0	2.08	8.64
79-S-9A	do.	24.1	6.67	3.61
Devitrified				
79-S-8B	Rhyolite of Gillies Hill	16.2	2.06	7.86
79-S-9B	do.	30.7	6.69	4.59
M335	Rhyolite dike	---	37.6	---
M336	do.	20.9	17.9	1.16
M733	do.	44.7	15.6	2.87
M735	Rhyolite of Gillies Hill	18.2	4.15	4.40
M737	Rhyolite dike	47.6	13.7	3.49
M744	do.	52.0	15.3	3.39

Table 1.--Continued

Sample Localities and Description--Detailed descriptions of most rock units are in Cunningham and Steven (1979d). All samples are from the Mount Belknap Volcanics except samples from the west side of the Tushar Mountains.

M49 Teacup dome in the lower heterogeneous member, lat. 38°30′41" N., long. 112°10′35" W.

M119 Joe Lott Tuff Member, basal vitrophyre, Deer Creek, lat. 38°30′ N., long. 112°16′ W.

M209 Intracaldera Mount Baldy Rhyolite Member, Indian Creek, lat. 38°25′ N., long. 112°29′ W.

M214 Intracaldera Blue Lake Rhyolite Member, Indian Creek, lat. 38°25′ N., long. 112°30′ W.

M328 Intracaldera Mount Baldy Rhyolite Member, near Little Shelly Baldy, lat. 38°27′ N., long. 112°29′ W.

M329 Intracaldera Mount Baldy Rhyolite Member, near Little Shelly Baldy, lat. 38°27′ N., long. 112°30′ W.

M330 U-Beva stock, North Fork North Creek, collected underground in adit, lat. 38°28′52" N., long. 112°31′10" W.

M335 Rhyolite dike, North Fork North Creek, lat. 38°21′57" N., long. 112°31′56" W.

M336 Rhyolite dike, North Fork North Creek, lat. 38°21′42" N., long. 112°32′19" W.

M408 Glassy dike, collected underground in Freedom mine, lat. 38°30′00" N., long. 112°12′48" W.

M502 Red Hills Tuff Member, basal vitrophyre, Royston Incline, lat. 38°29′03" N., long. 112°12′38".

M575 Intracaldera Blue Lake Rhyolite Member, Gold Mountain, lat. 38°26′ N., long. 112°24′ W.

M577 Intracaldera middle tuff member, Gold Mountain, lat. 38°26′ N., long. 112°29′ W.

M578 Intracaldera middle tuff member, Gold Mountain, lat. 38°27′ N., long. 112°24′ W.

M580A Gold Mountain breccia pipe, lat. 38°26′ N., long. 112°23′ W.

M580B do.

M580C do.

M580D do.

M581 Intracaldera Mount Baldy Rhyolite Member, Summit of Mount Belknap, lat. 38°25′ N., long. 112°25′ W.

M582 Intracaldera middle member, side of Mount Belknap, lat. 38°25′ N., long. 112°25′ W.

M583 Intracaldera Blue Lake Rhyolite Member, lat. 38°25′ N., long. 112°24′ W.

M584 Intracaldera Mount Baldy Rhyolite Member, lat. 35°24′ N., long. 112°24′ W.

M585 Intracaldera middle tuff member, lat. 38°24′ N., long. 112°24′ W.

M586 Intracaldera middle tuff member, lat. 38°24′ N., long. 112°24′ W.

M626 Joe Lott Tuff Member, near Three Creeks reservoir, lat. 38°17′ N., long. 112°24′ W.

M628 Joe Lott Tuff Member, near Three Creeks reservoir, lat. 38°18′ N., long. 112°25′ W.

M637 North Fork North Creek stock, lat. 38°24′ N., long. 112°28′ W.

M638 do.

M639 do.

M672 Crystal-rich tuff member, U.S. 89, lat. 38°28′36" N., long. 112°14′20" W.

M680 Red Hills Tuff Member above Royston Incline, lat. 38°29′07" long, 112°12′47" W.

M685 Joe Lott Tuff Member, near rest area, U.S. 89, lat. 38°30′05" N., long. 112°15′30" W.

M686 do.

M687 Black Rock stock, U.S. 89, lat. 38°28′42" N., long. 112°14′23" W.

M689 Rhyolite dike, Central Mining Area, east of Jungfrau, lat. 38°29′59" N, long. 112°12′27" W.

M733 Rhyolite dike, ridge between Wildcat and Indian Creeks, lat. 38°26′27" N., long. 112°33′49" W.

M735	Rhyolite of Gillies Hill, near Indian Creek, lat. 38°25′10" N., long. 112°35′25" W.
M737	Rhyolite dike, Indian Creek, lat. 38°26′03" N., long 112°37′49" W.
M744	Rhyolite dike, west of Mystery Sniffer mine, lat. 38°26′10" N., long. 112°32′50" W.
78-S-16	Apache tears, near Trinity mine, lat. 38°32′ N., long. 112°15′ W.
78-S-17	Black Rock stock, U.S. 89, lat. 38°28′42" N., long. 112°14′23" W.
79-S-8	Rhyolite of Gillies Hill, Gillies Hill, lat. 38°28′50" N., long. 112°39′00" W.
79-S-9	Rhyolite of Gillies Hill, Cedar Knoll, lat. 38°27′30" N., long. 112°37′15" W.

No appreciable difference was noted between the average uranium concentration of ash-flow vitrophyres and glassy margins of small stocks. One anomalously low uranium concentration is in the crystal-rich tuff member of the Mount Belknap Volcanics, which also contains the greatest volume of crystals. It is also one of the last rock types to be erupted from the Mount Belknap caldera following eruption of large volumes of the crystal-poor Joe Lott Tuff Member. This may signify that the pre-eruptive magma chamber was zoned with respect to uranium as well as phenocrysts, with volatiles and uranium concentrated in the upper part and phenocrysts below.

Thorium contents of the same Mount Belknap glasses range from 25.9 to 45.4 ppm and average 37.8 ppm.

Zielinski (1978) found that the uranium content of 11 samples of upper Tertiary obsidian from the western United States varies from 5 to 46 ppm, compared to a range of 2 to 10 ppm for most granites and rhyolites (Rogers and Adams, 1969). Most of Zielinski's analyzed obsidians had uranium contents of less than 10 ppm, but two notable exceptions were the Gold Flat Member, Thirsty Canyon Tuff, Nevada, with about 46 ppm uranium (Noble and others, 1964), and the rhyolite of Nellie Creek, Colorado, with as much as 40-42 ppm uranium (Steven and others, 1977). Rytuba and others (1979) have reported uranium contents from the basal vitrophyres of ash-flow tuffs from the McDermitt caldera, Nevada-Oregon, that range from about 6 to 9 ppm, with the higher values associated with peralkaline rocks.

Uranium in the porphyry-type hydrothermal environment

Porphyry-type deposits have been predicted near the top of the hidden intrusives under the Deer Trail Mountain-Alunite Ridge area (Cunningham and others, 1978; Cunningham and Steven, 1979b), 12 km southwest of Marysvale, and the Central Mining Area (Cunningham and Steven, 1978; 1979a), 5.7 km north of

Marysvale. Exploration programs by industry to test these suggestions are either underway (Deer Trail Mountain-Alunite Ridge), or contemplated (Central Mining Area), but by spring 1980, no results had been reported. Thus, discussions of this environment must be highly tentative and depend largely on analogy with other better known areas.

The hydrothermal system in the Central Mining Area is probably about 18 m.y. old according to fission track ages on associated rhyolite dikes, and a uranium-lead isochron based on samples of the uranium-bearing veins (K. R. Ludwig, U.S. Geological Survey, oral commun., 1980). At the levels exposed, the primary veins consist largely of the gangue minerals fluorite, quartz, and minor pyrite, the uranium minerals uraninite and coffinite, and the molybdenum minerals jordisite, molybdenite, and umohoite. The age is within the span of eruptions of the Mount Belknap Volcanics, and the mineralized area is located within the eastern source area of that unit. The postulated underlying intrusion is probably very silicic in composition, like the coeval lava flows and welded tuffs nearby, and any associated porphyry-type mineral deposit probably contains molybdenum as the dominant metal, with byproduct uranium and other lithophile elements. By analogy with similar ore deposits at the Climax and Henderson mines in Colorado, the byproduct elements probably are largely in oxide minor accessory minerals (Desborough and Sharp, 1978).

Several glassy rhyolite dikes are exposed in underground workings and at the surface in the Central Mining Area. They are located in the same area as that predicted to be underlain by the porphyry system, and the dikes contain anomalous molybdenum and uranium. A breccia pipe exposed in the mine workings contains 78 ppm uranium.

Mineralization in the Deer Trail Mountain-Alunite Ridge area took place

about 14 m.y. ago (Steven and others, 1979b), about 2 m.y. after the youngest Mount Belknap eruptions yet determined. No coeval volcanic rocks exist in the area, and the composition of the intrusion postulated to underlie the area is conjectural. The mineralized center is a highly faulted dome cut by fracture-filling veins of nearly pure alunite, and is surrounded by a halo of gold- and silver-bearing quartz carbonate veins in propylitically altered volcanic rocks and base- and precious-metal mantos in sedimentary rocks. Fluid-inclusion data from the alunite veins suggest that these formed in a highly acid, wet-steam geothermal system (Cunningham and others, 1978); the near-absence of metal concentrations in the same area suggests that these elements were largely flushed from the system by the strongly oxidized, low pH fluids. The predominant metals in the surrounding veins and mantos are lead, zinc, copper, silver, and gold. Anomalous molybdenum, uranium, mercury, and selenium values have been detected. Molybdenum contents of the Deer Trail Mine manto deposits are as high as to 1,000 ppm.

The composition of the postulated intrusion beneath the faulted dome at Alunite Ridge is critical in anticipating what metals may exist in any associated porphyry-type ore deposit. The time of intrusion (14 m.y.) is well within the span of bimodal igneous activity, so a highly silicic composition for the intrusive body and a molybdenum-rich ore deposit might be expected. On the other hand, the common presence of copper as a major constituent in the associated manto deposits, compared to minor molybdenum and uranium, suggests a more intermediate composition intrusive with associated copper-molybdenum porphyry-type ore. In either circumstance, any uranium in the predicted porphyry ore environment is likely to be a minor constitutent and of economic interest largely for its byproduct value.

Other potential porphyry-type ore environments exist around the largely

buried structural margin of the Mount Belknap caldera (Cunningham and Steven, 1979c). Several minor intrusions along this belt are exposed, and at least one center of mineralization contains as much as 5,000 ppm molybdenum in veins. Other hidden intrusions probably exist, particularly along the eastern and southern part of the ring-fracture zone. All associated volcanic rocks are highly silicic, and the hidden intrusions are probably of the same general composition. Anomalous concentrations of molybdenum and uranium are present in the nearby caldera fill, and any porphyry-type deposit that may exist along the structural margin of the caldera probably would have molybdenum as its major ore constituent.

Uranium in the hydrothermal vein environment

Most of the uranium that has been produced from the Marysvale volcanic field has come from fracture-filling veins deposited in shallow hydrothermal environments. The Central Mining Area has produced about 1 million pounds of U_3O_8 from an oval area about 500 m by 1,300 m across. Small quantities of uranium have been produced from other vein systems, chiefly at the Mystery-Sniffer mine on the west flank of the Tushar Mountains west of the Mount Belknap caldera.

The veins in the Central Mining Area follow steeply dipping and flat-lying fractures in granitic and volcanic rocks that overlie a postulated shallow intrusion (Cunningham and Steven, 1978). Sparse glassy rhyolite dikes follow some of the steeper fractures and are believed to have been derived from the same magma that formed the intrusion. The mineralized area is within the eastern source area of the Mount Belknap Volcanics (Cunningham and Steven, 1979d), and the postulated hidden intrusion is believed to be one of the younger of a succession of cupolas that developed above a larger magma chamber that underlay the whole source area. The mineralized fractures are

interpreted to have formed by local distention above the intrusion which was emplaced during regional late Cenozoic basin-range extensional tectonism. The mineralized fractures are especially abundant and have diverse trends, as compared to the more regional basin-range fault pattern that developed concurrently, and the mineralized area appears to have been uplifted somewhat relative to adjacent ground.

Fluid-inclusion data indicate that the hydrothermal fluids that invaded the broken ground shortly after fracturing were dilute brines at about 150°C. Mineral assemblage and paragenesis indicate that the solutions were rich in fluorine, carried some H_2S, and were acid and reducing. Uranium, probably carried in uranous fluoride complexes, was deposited as the acid solutions rose along the fractures, cooled, and became progressively neutralized by reaction with wall rocks. Uranium combined with oxygen and silica to form uraninite and coffinite, and fluorine combined with calcium to form fluorite. H_2S combined with iron to form pyrite, which is widely but sparsely distributed. The generally low pyrite content is believed to indicate relatively low concentrations of sulfur in the hydrothermal system.

A question especially pertinent to discussions later in this paper relates to how complete the reactions were that caused precipitation of the uranium. Was virtually all uranium deposited when the uranous fluoride complexes broke down, or did a significant proportion continue upward with the mineralizing fluids to escape into surface or ground-water regimes? Zoning patterns within the veins indicate that the primary solutions became progressively more oxidized upward within the range now exposed in developed mine openings. Total molybdenum decreases upward, and as it diminishes, the molybdate umohoite becomes progressively more abundant relative to the sulfide molybdenite. Inasmuch as oxidized uranium species are especially soluble, it

would seem that the progressive changes in chemistry across the zone of precipitation favored loss of at least some of the uranium, and perhaps a significant proportion of it. Scattered uranium prospects containing oxidized uranium minerals form a halo several kilometers wide around the Central Mining Area; these may reflect primary dispersion of uranium outward from the main center of mineralization or later secondary dispersion by supergene processes.

Uranium in a dispersed hydrothermal environment

The Mount Belknap caldera in the central Tushar Mountains formed about 19 m.y. ago in response to rapid eruption of voluminous alkali rhyolite ash flows that deposited the Joe Lott Tuff Member of the Mount Belknap Volcanics (Cunningham and Steven, 1979d). As the caldera subsided, the unsupported walls caved back to form a flaring depression whose topographic margin slopes inward at 45 degrees or less. This depression was in part filled with welded ash-flow tuff equivalent to the Joe Lott Member, and in part with thick domal rhyolite lava flows of the same highly silicic composition. Wedges of talus and mudflow breccia flank some of the thick lava flows and extend inward from the marginal walls. The tuffs and flows are complexly interlayered, but in general, can be divided into lower, middle, and upper tuff units separated by wedge-like accumulations of lava flows--the lower Blue Lake Rhyolite Member and the upper Mount Baldy Rhyolite Member. Some late intrusions were emplaced into the lower part of the caldera fill along at least the southern and eastern parts of the buried structural margin of the caldera.

The caldera fill was extensively bleached and recrystallized shortly after accumulation. Alteration was largely confined to the rhyolites within the caldera; the darker intermediate-composition volcanic rocks of the caldera walls show only minor modification. No detailed studies of the altered rocks have been made, but the pervasive bleaching of the rocks indicates that the

rocks in the cauldron pot were pervasively steamed and altered with only minor evidence for local centers of hydrothermal activity. Whether this general alteration resulted from meteoric water heated by contact with still-hot rocks in the caldera fill, from convectively circulated waters driven by heat from the underlying magma chamber, or from both, cannot be told from available information.

The pervasively altered rocks range from mildly bleached white to yellow rocks that still retain most of the original rock textures, to nearly structureless granular masses of silicified rock whose faint layering is all that remains of the original fabric. Small areas of argillically altered rocks containing pyrite were noted at places, generally near intrusive bodies, and these are interpreted to mark local centers of hydrothermal activity superimposed on the more pervasively altered rocks.

The behavior of uranium during the pervasive bleaching and recrystallization of the caldera fill is of significance with respect to the uranium budget of the Marysvale volcanic field. Rough estimates place the volume of the fill as somewhat more than 150 km^3; on the general assumption that the volume of a caldera is about equal to the volume of ash erupted therefrom, the volume of the outflow Joe Lott Tuff Member also can be considered to have had an original volume of about 150 km^3. The magma that supplied all this rock may have had about the same uranium content as that measured for the volcanic glasses of the Mount Belknap Volcanics (table 1), or about 13 ppm uranium.

Samples of the pervasively altered caldera fill were analyzed for uranium and thorium for comparison. The results (table 1) show that the average uranium content of caldera-filling rocks is 16.4 ppm, and the average thorium content is 41 ppm. The average uranium content is somewhat higher than that

in Mount Belknap Volcanics glasses elsewhere, whereas the thorium contents are not significantly different. Both uranium and thorium exhibit a greater range in concentrations within the caldera than in outflow rocks. These observations may be explained by: (1) the original contents of uranium and thorium in the caldera-filling rocks may have been different than those in the outflow rocks; (2) differential mobilization and redeposition of uranium and thorium took place during pervasive hydrothermal alteration of the caldera fill; and (3) significant quantities of epigenetic uranium were introduced into the caldera fill.

The first explanation probably had minor influence. Some of the intracaldera welded tuffs in the middle parts of the caldera fill are continuous over the caldera edge into the outflow sheet; these tuffs overlie some of the cogenetic lava flows in the lower part of the fill, and no reason can be envisaged to suggest any differences in uranium and thorium contents in the source magma.

The second explanation is favored by the wide range in uranium contents in the different samples of bleached and altered rocks, and by the fact that some uranium clearly was mobilized and redeposited as local concentrations of ore grade in favorable places in the caldera fill. We have not made exhaustive searches for these local concentrations, but have observed a number that have been exposed by prospect pits or by drilling. Most of these local concentrations have been in more permeable horizons, either talus-mudflow aprons adjacent to thick lava flows, or in talus-landslide tongues that extend from the caldera wall into adjacent parts of the caldera fill. Other loci of redeposition could easily exist, and further careful study is needed. Uranium was probably more mobile than thorium, which shows no significant difference in concentration between the caldera fill rocks and outflow rocks. This

conforms to the findings of Steven and others (1977) in the western San Juan Mountains of Colorado, where uranium was significantly more mobile than thorium in shallow volcanic environments.

An additional quantity of uranium may have been supplied by the intrusive bodies emplaced in the caldera fill above the buried ring-fracture zone (explanation 3). The average uranium contents of these bodies is 14.3 ppm (table 1). Some epigenetic uranium minerals are associated with a small plug at the U-Beva prospect along the North Fork of North Creek, above the southern part of the buried ring-fracture zone. Stream-sediment samples farther east show anomalous contents of uranium that are clearly related to a larger intrusive body exposed along the North Fork farther upstream. The anomalous uranium in the stream sediments is largely in the heavier minerals (panned concentrates) and seems to be coming from relatively unaltered parts of the intrusive body; these relations suggest that the uranium is an original constituent of this intrusive and is concentrated in heavy minor accessory minerals. In either case, the possibility clearly existed for some uranium to have leaked from the crystallizing intrusives into the surrounding caldera fill to become inextricably mixed with the mobile rock uranium being freed by pervasive alteration.

These incomplete data would seem to indicate that uranium moved around somewhat during pervasive bleaching and alteration within the dispersed hydrothermal environment of the caldera fill, but that much was redeposited within the fill. In fact, the total content of uranium appears to have been increased in the caldera fill rocks now exposed. If major quantities of epigenetic uranium were involved, hydrothermal alteration of the caldera fill may have been accompanied by loss of large quantities of uranium to ground and surface waters draining the Tushar Mountains area but this cannot be proven by

available information. In addition, a significant quantity of uranium probably was derived from the caldera fill by later erosion and ground-water leaching.

No major ore bodies have yet been found in the fill in the Mount Belknap caldera, but with the large quantity of mobilized uranium available, there is a good possibility that such exist.

Uranium mobilized by devitrification, zeolitization, or ground water leaching

Pervasive devitrification and zeolitization of glassy rocks are significant processes that lead to mobilization of uranium. Uranium may be mobilized directly by the processes, or it may redistribute into sites which are more susceptible to leaching by ground water. The net result is to make a vast quantity of uranium available for dissolution and movement into the hydrologic regime.

Zielinski (1978) has compared equivalent glassy and devitrified rhyolites, and has shown that devitrification results in uranium being concentrated into specific mineral phases, such as zircon, sphene, apatite and Fe-Mn oxide minerals, where it is available for secondary leaching. Uranium depletion in devitrified rocks (felsites) compared to coexisting glass suggests that this leaching is time- and composition-dependent, with older or more peralkaline felsites being more depleted in uranium than younger or less alkaline felsites. Paired samples of glassy and devitrified Mount Belknap Volcanics were analyzed to quantify the uranium loss from these rocks (table 1). The average uranium content of the glassy member of each pair is 13.3 ppm, and the average uranium content of the devitrified equivalent is 10.2 ppm. This shows an average loss of 3 ppm uranium from devitrified rhyolite flows and welded tuffs of the Mount Belknap Volcanics since they were

erupted in early Miocene time.

Zeolitization of glassy ash-flow tuffs is also a possible means of releasing uranium. Steven and Cunningham (1979) reported that the Joe Lott Tuff Member in the southern part of the Big John caldera had been converted to clinoptilolite. Samples collected of this zeolitized tuff (table 1) contain an average of 6.9 ppm uranium, indicating that these particular rocks lost about half the original uranium (about 6 ppm). Data elsewhere (Zielinski and others, 1980) indicate that zeolitization is not everywhere effective in mobilizing uranium, and care must be used in extrapolating the values obtained for the Joe Lott (table 1). However, zeolitized rocks constitute only a very small percentage of the Joe Lott Tuff Member, and have little significance with respect to the magnitude of the crude estimates being made here.

If the estimate of about 150 km^3 for the original volume of the outflow Joe Lott Tuff Member has any validity, then the average loss of about 3 ppm uranium from devitrified rocks, and perhaps even more from zeolitized rocks, relative to the equivalent glassy rocks indicates that more than 2 billion pounds of uranium has been lost to ground and surface water over the last 19 m.y. Whether the loss of uranium was uniformly distributed over this time span, or was irregular depending on changing local environments, cannot be told from present data. Experimental data (Zielinski, 1980) suggest that the rate of uranium loss during glass dissolution (diagenesis) or leaching of crystalline rocks is greatest during periods of elevated solution temperatures, i.e., and shortly after emplacement (Zielinski, 1980). Uranium removal rates and pathways of migration were probably further modified by changing patterns of erosion and sedimentation during basin-range tectonism in later Cenozoic time. Overall, however, an enormous quantity of uranium has been leached from source rocks in the Marysvale volcanic field and transported into adjacent basins.

Uranium in transit

Lacking knowledge of the changing drainage patterns in the Marysvale volcanic field for the past 20 m.y., few specifics can be given about the outward transport of uranium in ground and surface waters. This time span, however, was broadly concurrent with basin-range extensional tectonism in western United States which caused widespread block faulting with attendant erosion (and leaching) of upthrown blocks and deposition of stream and lake sediments in the downthrown blocks. In the Tushar Mountains and Sevier Plateau, remnants of fluviatile and lacustrine sediments of the Miocene and early Pliocene Sevier River Formation are preserved on both uplands and valleys, and were deposited in broad basins before the present mountainous terrain was developed. The most intense faulting, which formed the present mountains and valleys, appears to have taken place largely during Pliocene time, although related faulting still continues in the area. This relatively young intense faulting undoubtedly disrupted earlier patterns of flow of uranium-bearing ground and surface waters. The early history of structural development in the Great Basin to the west is not well known, and could well have differed significantly. Much careful work is needed to determine the structural-geomorphic history of the Marysvale volcanic field to determine which areas were basins and when, relative to available water-borne uranium.

Some uranium leached from anomalously radioactive rhyolitic rocks has probably been present in the hydrologic regime in the Marysvale volcanic field since early Miocene time. Surges in uranium contents may have coincided with pervasive alteration of the caldera fill about 19 m.y. ago, with inputs from localized hydrothermal systems in the Central Mining Area 18 m.y. ago and Deer Trail Mountains-Alulnite Ridge area 14 m.y. ago, possibly with emplacement of the rhyolite field and related hydrothermal systems along the west flank of

the Tushar Mountains 9 m.y. ago, with the rhyolitic eruptions and hydrothermal activity in the Kingston Canyon area 8-5 m.y. ago, and possibly with eruption of the Pleistocene rhyolite domes and flows in the central Mineral Mountains 1.0-0.5 m.y. ago. The anomalously radioactive modern springs in the Mineral Mountains area reported by Miller and others (1979) indicate that local spot sources of uranium in ground water are still active.

Uranium in the basin fills

The deductions and analytical data presented in earlier sections indicate that billions of pounds of uranium have been mobilized from rock or magmatic sources into the hydrologic regime in the Marysvale volcanic field in the last 20 m.y. Inasmuch as this mobilization into and lateral transport by surface and ground waters was generally concurrent with the tectonic break-up of the Basin and Range province, it is likely that most of the uranium-bearing waters were caught in the developing basins. Did this water-borne uranium remain dispersed through the sediments being deposited in the basins? Or was some significant part reconcentrated in local reducing environments to form roll-front or sedimentary-trap uranium ore deposits?

The ultimate sumps for waters derived from the Marysvale volcanic field were probably the major tectonic basins of western Utah, as exemplified by the interconnecting Escalante Desert area west of the Mineral Mountains and the Sevier Desert area to the north and northwest. Minor or interim sumps were in the smaller structural basins within or adjacent to the volcanic field. Discussions here will deal primarily with several of the smaller basins where we have some knowledge of the geologic relations, although the reasoning used has general application to the major basins as well.

Big John caldera

An early basin formed during active volcanism was the Big John caldera,

which subsided about 22 m.y. ago with eruption of the Delano Peak Tuff Member of the Bullion Canyon Volcanics (Steven and others, 1979a). At 19 m.y. ago, when the adjacent Mount Belknap caldera formed, the area of the Big John caldera was a broad basin drained by a southward-flowing stream. A blanket of stream gravels and sands 30 m or more thick covered the lower parts of the depression near the outlet. Ash flows from the Mount Belknap caldera source filled the earlier depression to overflowing with the Joe Lott Tuff Member of the Mount Belknap Volcanics. Subsequent erosion, volcanic activity, and tectonism comprise a complex history in which the ground-water drainage pattern probably has been disrupted many times.

The stream gravel underlying devitrified and locally zeolitized tuffs of the Joe Lott within the Big John caldera would seem to be a potential host for secondarily deposited uranium (Steven and others, 1979a). The stream gravels exposed farthest upstream (east) from the paleo-outlet have been secondarily oxidized to a hematite-bearing assemblage, and the same gravels near the outlet are relatively unoxidized. The area between the exposures is covered by zeolitized and devitrified tuffs of the Joe Lott. No direct evidence for the presence of uranium deposits in the sedimentary unit was discerned in the field, however, and a reconnaissance helium survey (Reimer, 1979) failed to detect anomalous concentrations of this pathfinder gas nearby. No physical exploration had been done by spring 1980, and a possibility still exists that such a deposit may occur in the more deeply buried part of the sedimentary unit.

Sevier River valley

Thick remnants of Sevier River Formation are exposed in many places within the complex graben followed by the Sevier River between the Sevier Plateau on the east and the Tushar Mountains and Pavant Range on the west.

Many of these remnants are near-rhyolitic rocks of the Mount Belknap Volcanics, the uranium-bearing hydrothermal systems in the Central Mining Area and the Deer Trail Mountain-Alunite Ridge area, and the rhyolite centers and associated altered rocks in Kingston Canyon. These potential source areas range in age from 21 m.y. for the oldest rocks in the Mount Belknap Volcanics in the southern Antelope Range, to 5 m.y. for the rhyolites in Kingston Canyon (H. H. Mehnert, U.S. Geological Survey, written commun., 1978).

In the Clear Creek Canyon area between the Tushar Mountains and Pavant Range, Steven and others (1979b), have dated the Sevier River Formation as being largely 15-7 m.y. in age. The rocks were deposited in broad basins that only in part reflect the present distribution of mountains and valleys. Major faulting which led to the present topographic configuration of the area definitely took place after deposition of the dated Sevier River rocks. These same relations appear to apply in the Marysvale area to the south where deformed Sevier River Formation with dated (Miocene) basalt flows interlayered (Rowley and others, 1979) are now exposed in the deeper parts of the graben.

Thus the configuration of the basins during sedimentation, and the flow patterns of uranium-bearing surface and ground waters for at least parts of later Cenozoic time probably were different than those now in existence. By the same token, the locations of potential uranium-precipitating environments would have had little to do with present patterns of ground- and surface-water flow, or with the present distribution of remnants of the Sevier River Formation.

Reconnaissance radiometric surveys have shown that the different areas of exposed Sevier River Formation have different radiometric signatures, and that even within individual areas of exposure the level of radioactivity changes from place to place. Whether this is due to different contents of anomalously

radioactive rhyolite clasts in the sediments, or to different contents of secondarily deposited uranium is not known from the present limited data.

As uranium was certainly available in the ground waters during the period of Sevier River sedimentation, it would seem reasonable to assume that secondary precipitation would probably have taken place in favorable reducing environments within the original depositional basins. Little detailed work to check this possibility had been done by spring 1980, to the best of our knowledge.

Beaver basin

Beaver basin is a sharply defined structural and topographic basin that has been the site of extensive sedimentation and potential uranium deposition since at least late Miocene time. The basin is 25 km long north-south and 16-22 km wide east-west. It is bordered on the east by volcanic rocks of the Tushar Mountains, and on the west by the granite-cored Mineral Mountains. Low hills at the north end consist of 9 m.y. old rhyolite domes and flows (rhyolite of Gillies Hill) resting on a platform of older volcanic rocks equivalent to those in the Tushar Mountains. The south end of the basin ends against volcanic rocks of the Black Mountains. The eastern and western margins of the basin are abrupt and linear, reflecting recurrently active border faults.

The early history of development of Beaver basin is obscure because only the youngest basin-fill deposits are exposed. A few tens of kilometers north of Beaver a basin of some sort existed in middle Miocene time. There poorly exposed gravelly silts and sands underlie the 9 m.y. old rhyolite of Gillies Hill, but exposures of these deposits are sparse and small and provide no evidence on the thickness of the strata or configuration of the depositional basin. No barrier is known to have existed between these scattered exposures

of early basin-fill deposits and Beaver basin where equivalent rocks could well exist at depth. At the southwestern corner of Beaver basin, pumice-bearing conglomerates and a 7.6 m.y. old basalt flow (Best and others, 1980) fill a narrow west-flowing channel that drained at least part of the Beaver basin area. The contained pumice fragments may indicate that the conglomerates accumulated during the 9 m.y. old episode of rhyolitic volcanism that has been documented elsewhere in the area. Whether or not a significant basin existed upstream from the conglomerate-filled channel is not known. This channel was later closed by basin-range faulting along the east flank of the Mineral Mountains.

Rhyolite domes and flows forming Gillies Hill and adjacent areas at the north end of the Beaver basin have been dated as about 9 m.y. old (S. H. Evans, Univ. Utah, written commun., 1980). The eastern border fault of Beaver basin was active at about the same time these rhyolites were erupted as alunite from altered and mineralized rock at the Sheeprock mine, located along this fault 27 km northeast of Beaver, has also been dated as about 9 m.y. old (Steven and others, 1979b).

The basin-fill deposits exposed in Beaver basin south of the rhyolite of Gillies Hill consist of three informal units. The oldest and most poorly exposed consists of moderately oxidized slightly gypsiferous, fine-grained bolson deposits of unknown thickness; these rocks crop out only locally and their relation to the rhyolite of Gillies Hill is not known. This oldest exposed unit is overlain by coarse-grained sands, gravels, and conglomerates informally termed the conglomerate of Maple Flats, which overlies the rhyolite of Gillies Hill and may be late Miocene or early Pliocene in age. Boulders in the conglomerate are as much as 2 m in diameter and reflect vigorous upheaval along the bordering faults of Beaver basin. Inasmuch as no marker beds are

present, it is not possible to determine the thickness of the unit, although at least 250 m is exposed on Maple Flats and 500 m or more may be present in the subsurface to the south.

The youngest and areally largest component of the basin fill now exposed is a complex assemblage of lacustrine, piedmont slope, fluvial, and alluvial fan deposits. These facies represent lateral components of fill in a large permanent lake basin which persisted for most of Pliocene and half of Pleistocene time. Into this basin fell a variety of Pliocene-Pleistocene volcanic ashes (tephra), some locally derived and some from sources thousands of kilometers away. The most persistent and thickest is the Pearlette type "B" (G. A. Izett, U.S. Geological Survey, written commun. 1980), the airfall component of a 1.9 m.y. old rhyolitic eruption at Yellowstone Park, Wyoming. Water-laid Pearlette "B" ash is found in the western half and southern two-thirds of the basin, indicating the minimum extent of the early Pleistocene lake that then existed. The youngest dated unit in the fill is a basalt flow that was erupted in the west-central part of the basin about 1.1 m.y. ago (the basalt of Black Mountain, Best and others, 1980).

The first indication of basin-breaching and drainage into Escalante Desert via Minersville Canyon was recorded by the deposition of a rhyolitic obsidian lapilli and pumice deposit, the tepra of Ranch Canyon (Lipman and others, 1978). This unit was erupted from rhyolite domes in the central Mineral Mountains about 0.5 m.y. ago (G. A. Izett, written commun, 1980), and was deposited in alluvial channels cut into the basin-fill deposits. Since 0.5 m.y. ago the history of the basin has been one of periodic downcutting and minor sedimentation related to climatic and tectonic controls, as recorded by widespread gravel-capped pediments and terraces.

A north-trending horst involving the conglomerate of Maple Flat, older

basin-fill deposits, and volcanic rocks is exposed in the north-central part of the basin, and probably extends southward under younger basin fill. These younger sedimentary rocks are deformed by a pervasively faulted antiform on trend with the horst; this antiform is cut by closely spaced antithetic normal faults trending N to N. 20° E., and by more subtle but clearly contemporaneous north-northeast normal faults displaced down to the northwest. All these faults show progressively larger displacement downward in the basin fill, reflecting recurrent displacement during sedimentation and growth of the antiform. Very young faults cut latest Pleistocene deposits between the antiform and the Tushar Mountains to the east.

Evidence for uranium in the thick, largely closed-basin fill in the Beaver basin is circumstantial. A preliminary radiometric reconnaissance of the basin was made by M. G. Nelson of the U.S. Geological Survey in 1978, who found that surface radioactivity was abnormally high relative to that in adjacent basins. To a degree, the abnormal radioactivity seems to reflect modern and ancestral alluvial fans deposited by streams draining the Tushar Mountains, and may reflect a high content of relatively radioactive rhyolite clasts from the Mount Belknap Volcanics. However, geologic deduction indicated that Beaver basin had long been a structural sump for waters draining important uranium source areas, and a possibility for secondarily deposited uranium in the valley fill seemed good (Cunningham and Steven, 1979c). A geochemical survey by the U.S. Geological Survey disclosed important ground water sources for uranium in the Mineral Mountains to the west (Miller and others, 1979), and in addition found geochemical anomalies in well waters in the basin itself that strongly suggest the presence of uranium deposits (Miller and others, 1980). A reconnaissance helium survey, also by the U.S. Geological Survey (Reimer, 1979), indicated highly anomalous values

in the south-central part of the basin where ground waters may have their outlet to the surface. These helium anomalies may well reflect buried uranium concentrations toward the source of the ground waters.

An independent radon and geochemical reconnaissance by industry carried on concurrently with U.S. Geological Survey studies (Spenst M. Hansen, written commun. 1980) also indicated highly anomalous values at several places in the Beaver basin. These results led to further testing and to land acquisition. The independent studies by industry and by the U.S. Geological Survey together sparked the present intense exploration interest in the Beaver basin. Although no results had been reported by spring 1980, several drilling programs were either under way or contemplated.

Several stratigraphic, structural, and geomorphic factors are important in considering the potential for uranium concentrations in the Beaver basin: (1) The basin contains a thick sequence of bolson and lacustrine deposits that may date back into the Miocene, and buried parts of this section may contain significant carbonaceous material. (2) Rapid lateral facies changes may provide both chemical and lithological discontinuities favorable for uranium precipitation. (3) The faulted antiform near the center of the basin undoubtedly influenced flow of ground water, and the recurrent nature of the faulting may have caused the flow pattern to change numerous times. (4) The basin had a high ground-water table and the possibility for reducing environments at depth until an outlet was established shortly before 0.5 m.y. ago. Since then, downcutting has progressively lowered the ground-water table, but the valley followed by present-day Beaver River still has a high ground-water table with abundant surface seeps.

Present surface exposures within the main part of the Beaver basin are largely limited to Pliocene and younger strata, and do not provide sufficient

data to establish how these factors apply in the subsurface where the best possibilities for uranium concentrations exist. Geophysical and geochemical studies might help in defining exploration targets somewhat more closely, but the ultimate test of economic potential will require physical exploration. The drill is still the ultimate tool.

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