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U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1299-A, B

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THOMAS A. STEVEN, Editor

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Main entry under title:

Igneous activity and related ore deposits in the western and southern Tushar Mountains, Marysvale Volcanic Field, west-central Utah.

(Geological Survey Professional Paper ; 1299)
Includes bibliographical references.
Supt. of Docs. no.: I 19.16:1299–A, B
1. Rocks, Igneous—Utah—Tushar Mountains. 2. Ore-deposits—Utah—Tushar Mountains.
I. Cunningham, Charles G. II. Series.
QE461.I426 1984 552'.1'0979246 83–600337

For sale by the Branch of Distribution
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304

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[Letters designate the chapters]

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IGNEOUS ACTIVITY AND RELATED ORE DEPOSITS IN THE WESTERN AND SOUTHERN TUSHAR MOUNTAINS, MARYSVALE VOLCANIC FIELD, WEST-CENTRAL UTAH

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1299–A

Unexposed alkali-rhyolite stocks and possible associated ore deposits can be located using field geology, geochemistry, geochronology, and geophysics

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MULTIPLE EPISODES OF IGNEOUS ACTIVITY, MINERALIZATION, AND ALTERATION IN THE WESTERN TUSHAR MOUNTAINS, UTAH

By CHARLES G. CUNNINGHAM, THOMAS A. STEVEN, DAVID L. CAMPBELL, CHARLES W. NAESER, JAMES A. PITKIN, and JOSEPH S. DUVAL

ABSTRACT

Igneous activity in the Marysvale volcanic field of western Utah can be separated into many episodes of extrusion, intrusion, and hydrothermal activity. The rocks of the western Tushar Mountains, near the western part of the volcanic field, include intermediate-composition, calc-alkalic volcanic rocks erupted from scattered volcanoes in Oligocene through earliest Miocene time and related monzonitic intrusions emplaced 24–23 m.y. ago. Beginning 22–21 m.y. ago and extending through much of the later Cenozoic, a bimodal basalt-rhyolite assemblage was erupted widely throughout the volcanic field. Only volcanic and intrusive rocks belonging to the rhyolitic end member of this bimodal assemblage are present in the western Tushar Mountains; most of these rocks either fill the Mount Belknap caldera (19 m.y. old) or are part of the rhyolite of Gillies Hill (9–8 m.y. old).

Episodic hydrothermal activity altered and mineralized rocks at many places in the western Tushar Mountains during Miocene time. The earliest activity took place in and adjacent to monzonitic calc-alkalic intrusions emplaced in the vicinity of Indian Creek and Cork Ridge. These rocks were widely propylitized, and gold-bearing quartz-pyrite-carbonate veins formed in local fractures. Hydrothermal activity associated with the Mount Belknap caldera mobilized and redeposited uranium contained in the caldera-fill rocks and formed primary concentrations of lithophile elements (including molybdenum and uranium) in the vicinity of intrusive bodies. Hydrothermal activity associated with the rhyolite of Gillies Hill altered and mineralized rocks at several places along the fault zone that marks the western margin of the Tushar Mountains; the zoned alunite and gold deposits at Sheep Rock, the gold deposit at the Sunday Mine, and an alunite deposit near Indian Creek were thus produced. Resetting of isotopic ages suggests that another center of hydrothermally altered rocks associated with a buried pluton about 16 m.y. old may exist near Indian Creek just west of the Mount Belknap caldera. Geophysical evidence confirms the probability of a buried pluton near Indian Creek, and also indicates that another buried pluton probably exists beneath the 9-m.y.-old mineralized area at Sheep Rock. The mineral potential of the different hydrothermal systems, and the types of minerals deposited probably vary considerably from one period of mineralization to another and from one depth environment to another within a given system.

INTRODUCTION

Volcanic rocks in the western Tushar Mountains of west-central Utah (fig. 1) show widespread evidence of hydrothermal activity and local mineralization. The area has been prospected off and on for about 100 years and small quantities of gold, silver, lead, zinc, uranium, and alunite have been produced from numerous deposits. Although all known deposits are small, the extent of hydrothermally altered rocks near the deposits is sufficiently large to suggest that more substantial undiscovered ore deposits may exist. The area has been subjected to recurrent episodes of igneous intrusion, hydrothermal alteration, and mineralization, and the mineral-resource potential of the different mineralized areas is directly related to local geologic history. The mineral commodities to be expected vary from one hydrothermal system to another, and from one depth to another within any given system. Uranium and molybdenum seem likely to have the greatest econonmic potential, although significant concentrations of gold may also exist.

The western Tushar Mountains lie in the western part of the Marysvale volcanic field near the east end of the Pioche-Marysvale mineral belt, which extends east-northeast from southeastern Nevada into west-central Utah. The western Tushar Mountains were first studied by Callaghan and Parker (1961), who began mapping in the late 1930's and completed the work in the early 1950's. Preliminary investigations of some of the uranium occurrences were reported by Wyant and Stugard (1951). Callaghan (1973) discussed the area as part of a general review of the mineral deposits of Piute

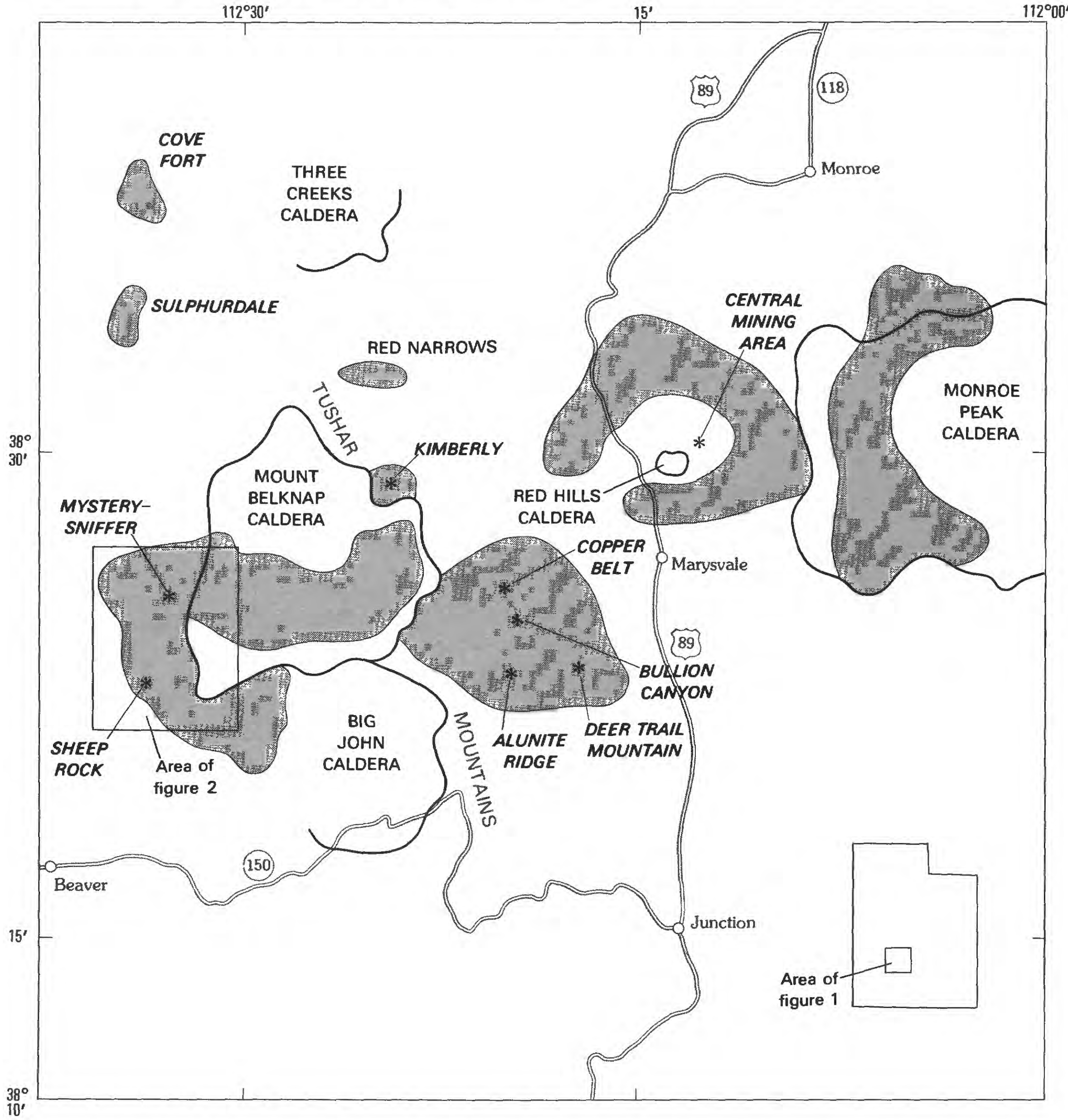


FIGURE 1.—Index map showing location of mapped area (fig. 2), calderas, major mining centers (starred), and principal altered and (or) mineralized areas (shaded) in and adjacent to Tushar Mountains.

County, Utah. More recently, the U.S. Geological Survey (Steven, Cunningham, Naeser, and others, 1978; Steven, Cunningham, and Rowley, 1978; Steven, Cunningham, and Anderson, 1979; Steven and others, 1981; Cunningham and others, 1978, 1980, 1981; Cunningham and Steven, 1979a, b, c, d, 1980; Rowley, Cunningham, and Kaplan, 1981; Rowley, Williams, and others, 1981; Rowley and others, 1984a, b; Anderson and others, 1980, 1981) remapped most of the Marysvale volcanic field at scales of 1:24,000 and 1:50,000, and pointed out many areas with potential for major undiscovered deposits of molybdenum, uranium, and base and precious metals. Tucker and others (1980, 1981) presented the results of a geochemical sampling program and considered its significance with respect to the occurrence of mineral deposits. The present report outlines the complex history of igneous activity and associated alteration and mineralization in the western Tushar Mountains, and points out implications for minerals exploration.

GEOLOGIC SETTING

Field relations and isotopic ages of rocks in the Marysvale volcanic field distinguish many episodes of extrusion, intrusion, and hydrothermal activity. Calc-alkalic volcanic rocks, in part called Bullion Canyon Volcanics (Callaghan, 1939; Steven, Cunningham, Naeser, and Mehnert, 1979), were erupted from scattered stratovolcanoes from Oligocene through earliest Miocene time; these gave way 22–21 m.y. ago to a bimodal assemblage of basaltic lava flows and rhyolitic lava flows and pyroclastic rocks. The basaltic rocks were erupted throughout the volcanic field in low volume until late Pleistocene time. The rhyolites, on the other hand, formed a succession of local, small to large accumulations that were erupted episodically from early Miocene to Pleistocene time.

Calderas (fig. 1) formed at different places in the volcanic field in response to episodic eruptions of silicic ash-flow tuff of both the calc-alkalic and bimodal suites. These tuffs accumulated as nearly flat sheets whose upper surfaces provide convenient, well-dated datum planes at different horizons within the volcanic field. The Three Creeks caldera formed 27 m.y. ago (Steven, 1982; Steven, Cunningham, Naeser, and Mehnert, 1979) in response to the eruption of the Three Creeks Tuff Member of the Bullion Canyon Volcanics. The Delano Peak Tuff Member of the Bullion Canyon Volcanics was erupted about 23 m.y. ago from the vicinity of the Big John caldera (Steven, Cunningham, and Anderson, 1979; and Chapter B of this Professional Paper); the Osiris Tuff, erupted shortly thereafter, had its source in the Monroe Peak caldera (Rowley, Cunningham, and Kaplan, 1981; Rowley, Williams, and others, 1981; Rowley and others, 1984a, b). The Mount Belknap and Red Hills calderas, which formed 19 m.y. ago, were the sources for the Joe Lott and Red Hills Tuff Members of the Mount Belknap Volcanics, respectively (Cunningham and Steven, 1979d).

The Bullion Canyon Volcanics in the western Tushar Mountains is a heterogeneous assemblage of intermediate-composition lava flows, volcanic breccia, and monzonitic to quartz monzonitic stocks that crops out between the Mount Belknap caldera and Beaver Valley (fig. 2). The Bullion Canyon rocks shown on figure 2 are younger than the Three Creeks Tuff Member (27 m.y.), and for the most part are only slightly older than the 23-m.y.-old Osiris Tuff, which crops out just north of the area of figure 2. Near Indian Creek, a monzonite pluton called the Indian Creek stock cuts lava flows of the Bullion Canyon Volcanics. Seven to twelve km north of the area of figure 2, monzonite stocks breached the surface, and fed lava flows lithologically similar to those flanking Indian Creek. Elsewhere in the Tushar Mountains, similar monzonite stocks that are about 23 m.y. old (Steven, Cunningham, Naeser, and Mehnert, 1979) were emplaced just prior to the petrologic changeover from calc-alkalic to bimodal igneous activity.

Rocks belonging to the bimodal basalt-rhyolite suite in the western Tushar Mountains are limited to the rhyolite end member. These rhyolites belong to two major assemblages, the Mount Belknap Volcanics and the younger rhyolite of Gillies Hill. Igneous activity during Mount Belknap time was much more long-lived in the eastern Tushar Mountains and adjacent Antelope Range north of Marysvale than in the western Tushar Mountains, and extended from slightly prior to 21 m.y. to about 14 m.y. (Cunningham and others, 1982). Most of the Mount Belknap Volcanics within the area of figure 2 were deposited within the Mount Belknap caldera after eruption of the Joe Lott Tuff Member about 19 m.y. ago (Cunningham and Steven, 1979d). Most of these volcanics are rhyolite lava flows and ash-flow tuff that filled the caldera and overflowed it.

Late during caldera evolution, this intracaldera fill was cut by silicic stocks intruded mostly along the southern ring fracture of the caldera. The U-Beva stock, along North Fork North Creek (fig. 2), cuts the lava flows and domes of the Mount Baldy Rhyolite Member of the Mount Belknap Volcanics. The stock is characterized by prominent flow-alined sanidine phenocrysts. A fission-track age on zircon from it is 19.8 ± 1.2 m.y. (table 1, M330), which is within the analytical uncertainty of the age of the caldera fill. Small rhyolite dikes of devitrified and altered glass located southwest of the caldera and trending parallel to the caldera wall appear to be cone-sheet intrusions. A sample from one of these dikes gives a fission-track age on zircon of 20.3 ± 0.9 m.y. (table 1, M336), also about the same age as the caldera fill. Apatite from the U-Beva stock (M330) gives an anomalously younger age of 13.4 ± 2.7 m.y., and apatite from one of the dikes has an age of 9.5 ± 1.9 m.y. (table 1, M335), which indicates that the ages of some minerals in these rocks have been reset. (See section on significance of reset isotopic ages.)

The rhyolite of Gillies Hill forms a series of nearly aphyric to crystal-rich rhyolite lava flows and domes that form low hills at the north end of Beaver Valley (Evans and Steven, 1982). The largest source area for the rhyolite (8 km northwest of the area of figure 2) is along the main fault separating the Mineral Mountains and Tushar Mountains structural blocks, where flows have been dated as about 9.1 m.y. old (Evans and Steven, 1982). Some flows belonging to the rhyolite of Gillies Hill occur in the western part of the area of figure 2, where a fission-track age of 8.4 ± 0.6 m.y.

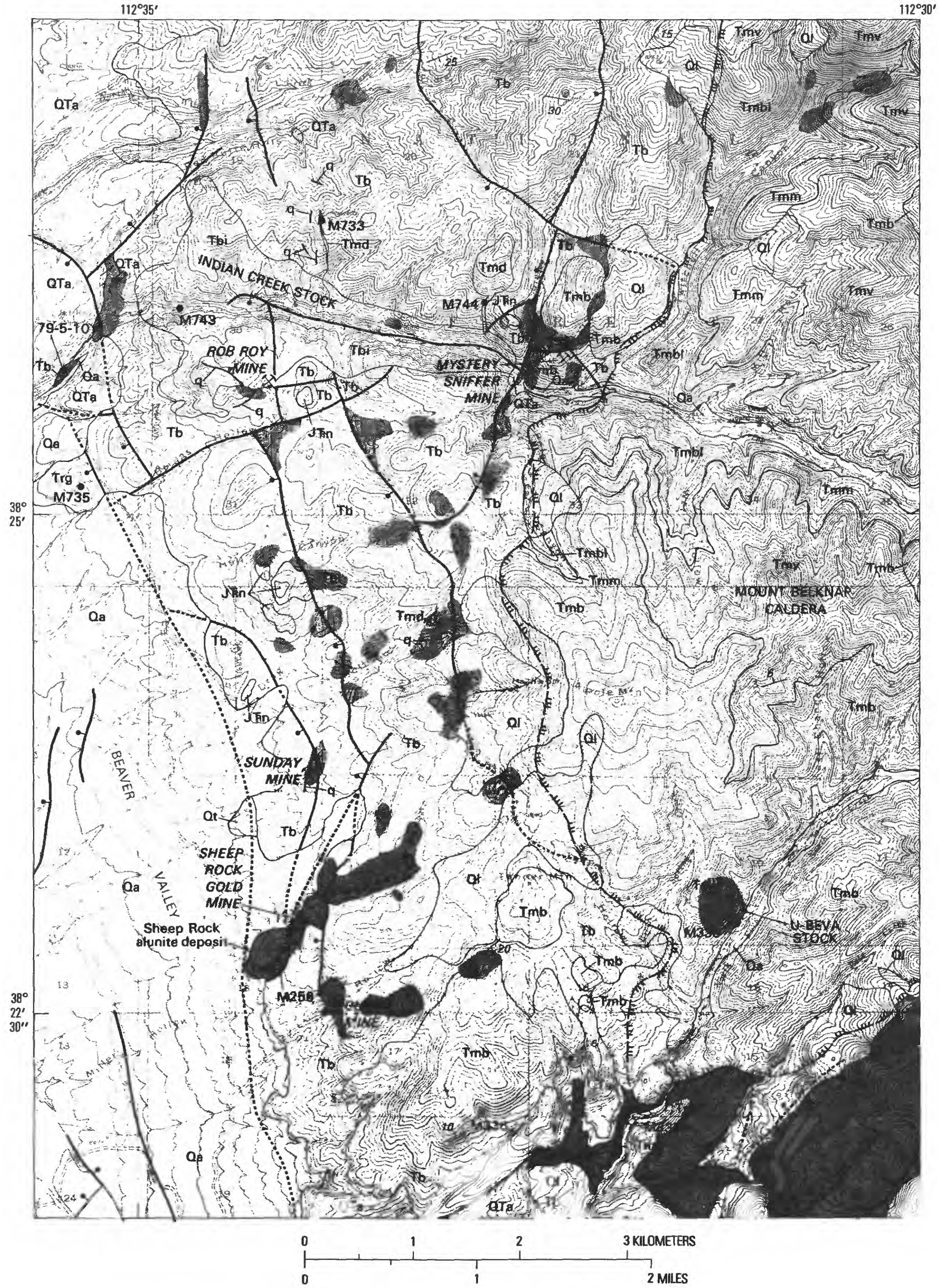
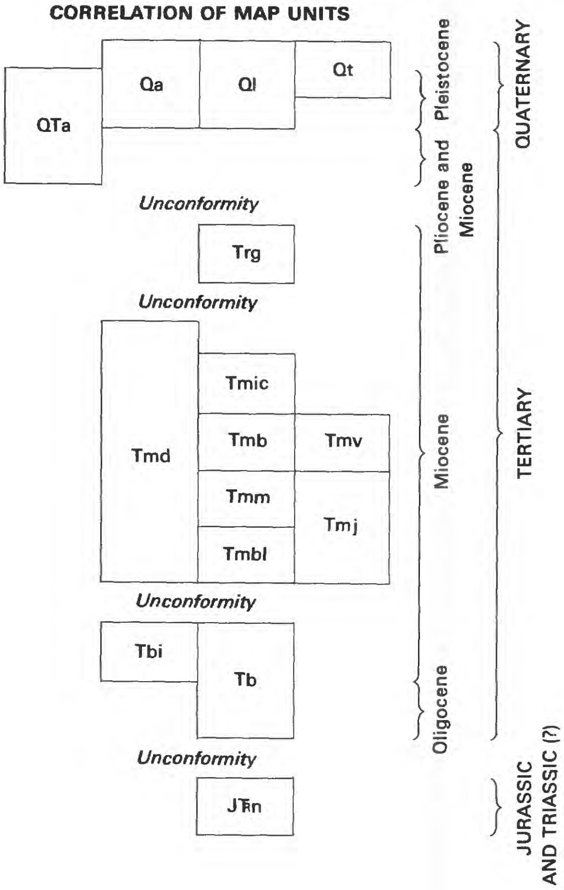


FIGURE 2.—Geologic map of western Tushar Mountains, Utah, showing areas of argillic and advanced argillic alteration, stocks, alunite deposit, and sample localities. Base from U.S. Geological Survey Beaver NE, SE unedited advance print. Geology mapped in 1979–1981.

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Qa — ALLUVIAL DEPOSITS (QUATERNARY)—Silt, sand, and gravel in alluvial fans, alluvial slope wash, and stream alluvium

Ql — LANDSLIDE DEBRIS (QUATERNARY)—Poorly sorted rock debris that moved downslope by gravity

Qt — TRAVERTINE (QUATERNARY)—Calcareous spring deposits

QTa — OLDER ALLUVIUM (PLEISTOCENE TO MIOCENE)—Poorly to moderately consolidated, fluviatile and lacustrine conglomerate, sandstone, and siltstone containing local interlayered airfall tuff beds. Includes fanglomerate and pediment gravel. Probably equivalent in part to Pliocene and Miocene Sevier River Formation

Trg — RHYOLITE OF GILLIES HILL (MIOCENE)—Light-gray to white, flow-layered rhyolite lava flows and volcanic domes containing phenocrysts of sanidine and partly resorbed quartz in a vuggy, devitrified groundmass

MOUNT BELKNAP VOLCANICS (MIOCENE)

INTRUSIVE ROCKS

Tmd — Dikes and small stocks—Several small, glassy to aphanitic, rhyolitic dikes, stocks, and lava flows

Tmic — Intracaldera intrusive rocks—Several small porphyritic quartz latitic to rhyolitic stocks within the Mount Belknap caldera. Contain sparse phenocrysts of quartz, plagioclase, and sanidine in a finely granular mosaic of alkali feldspar and quartz

INTRACALDERA FACIES VOLCANIC ROCKS (MOUNT BELKNAP CALDERA)

Tmb — Mount Baldy Rhyolite Member—Light-gray, crystal-poor, rhyolite lava flows and dikes consisting largely of a fine, granular mosaic of quartz and alkali feldspar, and minor plagioclase, biotite, and hematite. Contorted flow layers are common. Mostly intracaldera facies, but locally extends out across the margin of the Mount Belknap caldera

Tmv — Volcaniclastic rocks—Dominantly light-gray to white volcanic mudflow breccia derived from nearby lava flows of the Mount Baldy Rhyolite Member (Tmb). Some landslide debris and fluviatile sandstone and conglomerate are included in the unit

Tmj — Joe Lott Tuff Member—Partially welded, crystal-poor, light-gray or tan, alkali rhyolite ash-flow tuff containing 1–2 percent phenocrysts of quartz, sodic plagioclase, sanidine, and traces of biotite. Comprises most of the outflow facies derived from the Mount Belknap caldera source area (Cunningham and Steven, 1979). Stratigraphic position relative to radiometrically dated units indicates an age of about 19 m.y. (Steven and others, 1979)

Tmm — Middle tuff member—Partially welded, crystal-poor light-gray or tan, alkali rhyolite ash-flow tuff containing 1–2 percent phenocrysts of quartz, sodic plagioclase, sanidine, and traces of biotite

Tmbl — Blue Lake Rhyolite Member—Crystal-poor, rhyolite lava flows lithologically similar to those in the Mount Baldy Rhyolite Member (Tmb). Contorted flow layers are characteristic

BULLION CANYON VOLCANICS

Tbi — Intermediate-composition intrusive rock (Miocene)—Dark- to light-gray and brown, porphyritic to equigranular, medium-grained monzonite. Contains approximately equal proportions of plagioclase and orthoclase, 0–20 percent quartz, and subordinate augite, hornblende, and biotite. Accessory minerals are apatite, zircon, and Fe-Ti oxides

Tb — Heterogeneous lava flows and volcanic breccia (Miocene and Oligocene)—Porphyritic andesite, rhyodacite, and quartz latite. Contains phenocrysts of plagioclase, biotite, and clinopyroxene. In part consists of fine-grained dark lava flows and breccia of intermediate composition, containing small phenocrysts of plagioclase and clinopyroxene

JTRn — NAVAJO SANDSTONE (JURASSIC AND TRIASSIC?)—Fine-grained, buff, well-sorted, crossbedded sandstone. Occurs locally as large blocks in stocks and lava flows

CONTACT

FAULT—Dotted where concealed; bar and ball on downthrown side

10 — STRIKE AND DIP OF BEDDING

TOPOGRAPHIC WALL OF MOUNT BELKNAP CALDERA—Solid where it follows a contact; broken where concealed

AREAS AFFECTED BY ARGILLIC OR ADVANCED ARGILLIC ALTERATION

FIGURE 2.—Continued

(table 1, M735) on zircon was obtained from a lava flow just south of Indian Creek.

Extensional tectonism began 22–21 m.y. ago, about coincident with the change in chemistry of the igneous rocks from calc-alkalic to bimodal rhyolite-basalt. The Tushar Mountains block is a tilted horst, whereas Beaver Valley to the west is a graben formed by basin and range faulting related to this period of tectonism. The valley is filled with Miocene? to Pleistocene fluviatile and lacustrine sedimentary rocks.

TABLE 1.—*Data for fission-track ages of rocks*

Sample	Rock unit	Mineral	ρs[1]	No. tracks[2]	ρi[3]	No. tracks[4]	φ[5]	Age[6]	U (ppm)
M330 (DF–1745)	U-Beva stock.	Zircon	17.51	1,135	31.72	1,028	0.599	19.8±1.2	1,500
M330 (DF–1745)	U-Beva stock.	Apatite	0.122	254	0.589	1,227	1.08	13.4±2.7	16
M335 (DF–1747)	Rhyolite dike.	--do--	0.081	169	0.552	1,151	1.08	9.5±1.9	15
M336 (DF–1748)	Rhyolite dike.	Zircon	3.27	605	5.72	530	0.596	20.3±0.9	280
M733 (DF–2996)	Rhyolite dike.	--do--	3.86	536	14.75	1,024	1.00	15.6±1.1	420
M735 (DF–2997)	Lava flow.	--do--	1.84	315	12.84	1,100	0.985	8.4±0.6	380
M734 (DF–2998)	Tbi[7]	--do--	6.41	890	19.43	1,349	0.978	19.3±1.0	570
M743 (DF–3000)	Tbi[7]	Apatite	0.080	166	0.392	816	1.05	12.8±2.1	11
M744 (DF–2999)	Rhyolite dike.	Zircon	5.41	651	19.47	1,172	0.969	16.1±0.8	540

[1]Fossil-track density (tracks/cm^2)×10^6
[2]Number of fossil tracks counted
[3]Induced-track density (tracks/cm^2)×10^6
[4]Number of induced tracks counted
[5]Neutron dose (neutrons/cm^2)×10^{15}
[6]Age (m.y.) ±2σ λ_F=7.03×10^{-17}/yr
[7]Tbi is intrusive rock of Bullion Canyon Volcanics

SAMPLE LOCALITY DESCRIPTIONS

M330 U-Beva stock, along North Fork of North Creek; lat 38°22′57″ N., long 112°31′10″ W.
M335 Rhyolite dike cutting altered Bullion Canyon Volcanics along North Fork of North Creek; lat 38°21′25″ N., long 112°31′55″ W. (Anderson and others, 1981).
M336 Rhyolite dike cutting altered Bullion Canyon Volcanics near North Fork of North Creek; lat 38°21′17″ N., long 112°32′22″ W. (Anderson and others, 1981).
M733 Rhyolite dike on ridge between Wildcat and Indian Creeks; lat 38°26′30″ N., long 112°33′50″ W.
M735 Crystal-rich lava flow of rhyolite of Gillies Hill from southwest of entrance to Indian Creek Canyon; lat 38°25′15″ N., long 112°35′20″ W.
M743 Monzonite of Indian Creek stock; lat 38°26′10″ N., long 112°34′30″ W.
M744 Rhyolite dike feeding overlying lava flow and cutting Bullion Canyon Volcanics west of Mystery-Sniffer mine, along Indian Creek; lat 38°26′15″ N., long 112°33′00″ W.

MINERAL DEPOSITS

MINERALIZED AREAS ASSOCIATED WITH THE BULLION CANYON VOLCANICS

Mineral deposits and altered rocks genetically associated with the Bullion Canyon Volcanics in the Tushar Mountains are generally in or adjacent to 24- to 23-m.y.-old monzonite or quartz monzonite stocks. Precious metals commonly occur in veins that cut either the higher parts of the stocks or the adjacent volcanic wall rocks. The most productive deposits of this type in the Tushar Mountains are the epithermal gold-quartz-pyrite-carbonate veins at the old gold camp of Kimberly (fig. 1), which near the turn of the century yielded about $3.5 million worth of precious metals at $20.67 an ounce for gold (Callaghan, 1973). The ore occurs in veins that cut a 24.1±1.2-m.y.-old propylitized quartz monzonite stock (Steven, Cunningham, Naeser, and Mehnert, 1979). The veins are cut off on the north by a major basin and range fault and on the south by the topographic wall of the 19-m.y.-old Mount Belknap caldera. Primary ore includes native gold and sparse silver-bearing sulfides in manganese oxides (Lindgren, 1906).

Several other gold prospects related to the Bullion Canyon Volcanics occur in similar geologic settings on the east side of the Tushar Mountains. The top of a monzonitic stock exposed near the headwaters of Deer Creek (Cunningham and others, 1981) contains epithermal gold-quartz-pyrite veins that were explored at the Butler and Beck mine (Callaghan, 1973). In the Antelope Range north of Marysvale, gold-quartz-pyrite veins were explored at the Antelope mine (Callaghan, 1973); recent mapping (Cunningham and others, 1981) shows that these veins are also located in the carapace of a monzonite stock.

In the western Tushar Mountains, small- to medium-size, epithermal gold-quartz-pyrite veins, similar to those in the eastern Tushar Mountains, occur at the Rob Roy mine (fig. 2) near the west end of the Indian Creek quartz monzonite stock. The veins cut the stock and adjacent hornfelsed volcanic rocks. These veins, which appear to have formed late in the thermal history related to emplacement of the stock, are localized in fractures that appear related to doming, and probably were caused by forceful emplacement of the stock. One prominent fracture zone strikes east-west along the axis of the stock and localized the present course of Indian Creek. The selvages of the veins are argillically altered and contain disseminated pyrite, and the adjacent volcanic and intrusive rocks are propylitically altered. The main producing vein strikes north and dips westward. The Rob Roy mine produced at least $7,000 worth of gold in 1892 and 1893 (Butler and others, 1920).

The Cork Ridge area, near the southeast corner of the area of figure 2, is underlain by highly altered rocks that probably were altered by hydrothermal activity related to Bullion Canyon igneous activity. Another area of pervasive argillically altered rocks occurs near the head of Pine Creek, 1.5 km east of the southeast corner of the mapped area (Anderson and others, 1980; Cunningham and others, 1981). These rocks occur adjacent to a quartz monzonite stock and probably were altered during its emplacement. Although the alteration halo around the stock has not been dated directly, it is cut off by the topographic wall of the 19-m.y.-old Mount Belknap caldera (fig. 2), and thus is older than the caldera.

Some of the many other altered areas between Indian Creek and the Cork Ridge area (fig. 2) also may have formed during the Bullion Canyon period of igneous activity, but these cannot be identified from available evidence.

Throughout the Tushar Mountains, stream-sediment samples derived from the Bullion Canyon Volcanics contain a distinctive suite of elements. Tucker and others (1981) found that heavy-mineral concentrates from these samples contain anomalously high concentrations of magnesium, calcium, copper, chromium, iron, strontium, and nickel. Many of these concentrations (Mg, Ca, Cr, Fe, Sr, and Ni) seem to reflect heavy accessory or phenocrystic minerals derived from unaltered volcanic rocks of mafic to intermediate composition, but at least some of the copper may have come from the many hydrothermally altered areas in the Bullion Canyon terrane, and thus may reflect significant metal concentrations.

The common occurrence in the Tushar Mountains, and elsewhere in the world, of gold-bearing quartz-pyrite-carbonate veins in both propylitized hypabyssal plutons and adjacent volcanic wall rocks implies a related origin. Circulating hot waters carrying CO_2 and H_2S will cause propylitic alteration, and the core plutons are a convenient heat source. The source of the gold and associated metals—whether scavenged from the altering wall rocks or supplied by the magma—cannot be determined from the data available for the western Tushar Mountains.

MINERALIZED AREAS ASSOCIATED WITH THE MOUNT BELKNAP VOLCANICS

Anomalous concentrations of lithophile elements genetically associated with the Mount Belknap Volcanics occur in several geologic settings within and adjacent to the Mount Belknap caldera. Uranium and molybdenum are the most important of the known concentrated elements, and potentially may form significant ore deposits. Tungsten and beryllium may be important locally. The anomalous concentrations appear to have formed from both primary (hypogene) processes and from secondary dispersal and redeposition.

The ash-flow tuffs and rhyolite lava flows filling the Mount Belknap caldera are widely bleached where they have been steamed and altered within the caldera, and they are locally silicified and argillized where affected by late hydrothermal solutions related to intrusion of stocks that are cogenetic with the caldera-filling rocks. The general steaming and alteration resulted in remobilizing of a significant amount of the uranium contained in the original rock. Delayed-neutron analyses of the uranium contents of volcanic glasses and their altered equivalents show that 3 ppm uranium was lost during devitrification, and as much as 6 ppm was lost when the rocks were subjected to more intense alteration (Steven and others, 1981). The quantity of uranium remobilized from Mount Belknap Volcanics source rocks is estimated at 2–4 billion pounds. Much of this uranium went into the hydrologic environment, possibly to be reconcentrated in adjacent basins if the necessary depositional conditions were met (Steven and others, 1981). Some of the uranium, on the other hand, appears to have migrated out of the caldera along fractures or other channelways. The mafic, reduced Bullion Canyon lava flows outside the caldera may have provided an environment for precipitation of some of this uranium. The analytical results for 122 water samples collected from within and adjacent to the Mount Belknap caldera (McHugh and others, 1980) indicate several areas of such uranium concentrations adjacent to the caldera wall. One area is near the headwaters of Pine Creek, 5 km north of the area of figure 2, and the other is along Pole Creek, near the southeast corner of the area of figure 2. The Twitchell Canyon area (fig. 2), near the topographic wall within the caldera, appears to contain secondary concentrations of uranium deposited in permeable intracaldera landslide breccia. On deductive grounds, it would seem likely that the process of mobilizing, transporting, and redepositing uranium originally found in the caldera-fill rocks should have isolated uranium from other members of the lithophile assemblage so that uranium alone should dominate in the secondarily concentrated deposits.

Other areas both within and adjacent to the caldera show anomalous concentrations of lithophile elements that seem to reflect primary deposition around local sources. Several areas near intrusions along the southern ring fracture zone, east of the area shown on figure 2, contain anomalous concentrations of uranium and molybdenum (Cunningham and Steven, 1979b; Steven and others, 1981). The U-Beva stock contains minor autunite and torbernite.

Several areas just outside the topographic wall of the caldera also warrant attention because of their anomalous concentrations of lithophile elements, including uranium. Tucker and others (1981) pointed out one area east of the Sheep Rock alunite deposit and another area south of the Mystery-Sniffer mine that are enriched in Be, Y, Mn, Pb, Mo, Sn, Ag, Ga, and Nb, and depleted in Mg, Ca, Ba, and Fe. Analytical results from water samples (McHugh and others, 1980) show that water in the area near the Mystery-Sniffer mine contains high concentrations of Li, Be, F, Mo, U, As, and Mn. If the presence of these assemblages is indicative of primary deposition, a local source at depth near the Mystery-Sniffer mine area may be indicated.

Other areas containing anomalous concentrations of lithophile elements that seem incompatible with the Bullion Canyon host rocks have been reported in the western Tushar Mountains. Tungsten is not a common element in the Bullion Canyon Volcanics, yet several occurrences have been noted near the southeast corner of the area of figure 2. Butler and others (1920) reported wolframite near the head of North Creek; this occurrence may be the reason for the name Tungsten Hollow for a small tributary 2 km east of the mapped area. Everett (1961) reportedly found huebnerite in quartz stringers nearby on Pole Creek.

The uranium deposits at the Mystery-Sniffer mine located along Indian Creek, just west of the Mount Belknap caldera, may have been formed both from remobilized uranium derived from the caldera fill and from primary uranium derived from a magmatic source at depth. The known areas of mineralized rock contain torbernite and autunite (Wyant and Stugard, 1951) concentrated along east-striking faults that cut argillically altered Bullion Canyon Volcanics. Records (Osterstock and Gilkey, 1956) indicate that 35 tons (70,000 pounds) of ore averaging 0.17 percent U_3O_8 were shipped from the mine in 1952. Pitchblende was tentatively reported from the mine by Callaghan and Parker (1961), but several samples of pitchblende collected from the dump almost certainly came from a completely different location in eastern Utah (Cunningham and Ludwig, 1980), and most of the mined ore contained only secondary uranium minerals. These minerals may have been deposited by solutions percolating outward from the altering core of the Mount Belknap caldera, although they also may have formed by oxidation of primary minerals deposited from a local source. On the other hand, some veinlets and irregular blebs of purple fluorite cut the altered host rocks, and Osterstock and Gilkey (1956, p. 6) reported that a ". . . rock unit exposed in the underground workings is a brecciated and intensely altered rhyolite dike(?) which has apparently been intruded along the east-striking Mystery fault zone." This evidence, along with the nearby areas reported by Tucker and others (1981) to contain anomalous concentrations of lithophile elements, suggests primary deposition.

Just west of the Mystery-Sniffer mine, a prominent fault (fig. 2) strikes generally north-south, parallel to the trace of the topographic wall of the Mount Belknap caldera, and dips west, opposite to the slope of the wall. Prospect pits show that the walls of the fault are irregularly altered and locally contain traces of autunite and torbernite (Callaghan, 1973). Nearby rhyolite dikes that cut Bullion Canyon Volcanics contain local trace amounts of fluorite and uranophane; these dikes, along with the dike reported by Osterstock and Gilkey (1956) in the Mystery-Sniffer mine, suggest that the local source for the anomalous concentrations of lithophile elements in this area may be an epizonal pluton hidden at depth. Such a pluton probably would not have been emplaced as part of the Mount Belknap caldera cycle, but must have been significantly younger inasmuch as two statistically identical fission-track ages on zircon of about 16 m.y. have been obtained from the dikes. (See section on significance of reset radiometric ages.)

LATE MIOCENE MINERALIZED AREAS

Hydrothermal activity associated with the period of volcanism that produced the rhyolite of Gillies Hill 9–8 m.y. ago also produced advanced argillic alteration and precious-metal mineralization in places along the western base of the Tushar Mountains. The Sheep Rock alunite deposit, first described by Loughlin (1915), is a 9-m.y.-old replacement alunite deposit located about 16 km northeast of Beaver (fig. 2). It forms a prominent, light-colored, rounded hill at the base of the mountains, and is in fault contact with the dark lava flows of the Bullion Canyon Volcanics. The alunite replaces 19-m.y.-old flow-layered rhyolite lava flows of the Mount Baldy Rhyolite Member of the Mount Belknap Volcanics that poured out over the lip of the Mount Belknap caldera. Erosional remnants of this outflow mass cap several hills near the Sheep Rock deposit. Here, the alunitic rock is pink to cream colored and consists of prominent bands of alunite and quartz that preserve the original flow structures of the rock. Alunite from this deposit has been dated by the potassium-argon method as 9.4±0.5 m.y. old (table 2, M256). Farther north along the same fault system, near the mouth of Indian Creek (fig. 2), alunite that replaces Bullion Canyon Volcanics lava flows has been dated as 9.18±0.33 m.y. old (table 2, M79-S-10).

The Sheep Rock gold mine is just north of the Sheep Rock alunite deposit (fig. 2). It was described by Butler and others (1920), who noted that gold and silver ore occurs in a quartz-calcite vein that strikes N. 20° E., dips 65°–75° E., and increases in width from 1.5 m at the surface to a maximum of 7.5 m at the bottom of a 100-m shaft. The rocks adjacent to the gold mine consist of propylitized Bullion Canyon Volcanics cut by numerous quartz veins that trend generally north-south parallel to the major faults in the area. The wall rock adjacent to the veins contains sericite and pyrite, and is locally highly silicified. Butler and others (1920) reported that calcite and fluorite are present at the bottom of the shaft. They also reported that the ore occurs in shoots containing manganese oxide, native gold, pyrite, and possibly argentite, cerargyrite, ruby silver, and tellurium.

The presence of 9- to 8-m.y.-old rhyolite lava flows, alunitically altered rocks, and precious-metal deposits along the fault zone marking the western margin of the Tushar Mountains indicates that basin and range faulting was active in that area at least as far back as late Miocene time. This same relation was reported by Evans and Steven (1982) in the Gillies Hill area northwest of the area of figure 2 where the source of the 9-m.y.-old lavas appears to have been localized along one of the faults.

The Sheep Rock alunite deposit appears to have formed by the near-surface oxidation of H_2S in hydrothermal solutions. The resulting sulfuric acid-dominated waters reacted with alkali rhyolite lava flows, in part converting them to alunite. The Sheep Rock gold mine and the precious metal deposits at the Sunday mine (fig. 2), located 1 km to the north, are along the same segment of the fault zone that localized the alunite deposit. The Sheep Rock gold deposit appears to be peripheral to the alunite deposit, and appears to have formed at the periphery of a hydrothermal system where the temperature was lower and the pH higher than toward the center of the system. The mineralized rock at the Sunday mine may have formed from the same hydrothermal system, or from a separate system localized along the same fault. Sulfur-isotope evidence (R. O. Rye, oral commun., 1981) indicates that the sulfur in the alunite had a probable magmatic source, which we postulate is represented by a local epizonal pluton beneath this area. The Sheep Rock alunite deposit thus may mark the former outlet of a paleo-hot spring located above the pluton. The associated zoned hydrothermal system potentially could have deposited economically important mineral concentrations at several depths, ranging from a porphyry environment at the top of the pluton, to a skarn or replacement environment adjacent to the pluton, and to vein environments now exposed at the surface.

SIGNIFICANCE OF RESET ISOTOPIC AGES

The multiple episodes of igneous and hydrothermal activity in the western Tushar Mountains are reflected in the isotopic ages that have been obtained by both the potassium-argon and fission-track methods. The dif-

TABLE 2.—*Data for potassium-argon ages of alunite*

[Constants: $^{40}K\ \lambda_\epsilon=0.581\times10^{-10}/yr$; $\lambda_\beta=4.962\times10^{-10}/yr$; $^{40}K/K=1.67\times10^{-4}$]

Sample	K_2O[1] (pct)	$^{*40}Ar$ (10^{-10} moles/gram)	$^{*40}Ar$ (pct)	Age[2]
M256	9.00, 9.11	1.234	49.2	9.4±0.5
M79–S–10 (DKA–3896)	7.88, 7.86	1.042	67.1	9.18±0.33

[1]Determined by atomic absorption
[2]Age (m.y.) ±2σ

SAMPLE DESCRIPTIONS

M256 Replacement alunite from Sheeprock Alunite Deposit, 13 km north-northeast of Beaver, Utah; lat 38°22′50″ N., long 112°34′05″ W. (From Steven, Cunningham, Naeser, and Mehnert, 1979, p. 19.)

M79–S–10 Replacement alunite from altered Bullion Canyon Volcanics near mouth of Indian Creek; lat 38°25′45″ N., long 112°35′30″ W. (From H. H. Mehnert, written commun., 1981.)

ferent susceptibilities of the various minerals to resetting, either by argon loss in the potassium-argon method or by annealing in the fission-track method, provide a powerful tool to sort out superimposed episodes of thermal activity (Naeser, 1979). For example, recent studies at Rico, Colo., using these techniques have identified the youngest mineralized rhyolite known in Colorado, and have located a paleothermal anomaly believed to be related to the rhyolite's unexposed source pluton (Naeser and others, 1980). In the western Tushar Mountains, the disparity in age between the zircon (~20 m.y.; sample M336) and apatite (~9 m.y.; sample M335) from two rhyolite dikes located about 0.5 km apart near North Fork North Creek apparently indicates that the rock from which sample M335 was collected was reheated enough during the Gillies Hill period of volcanism to completely reset the apatite (annealing threshold ~105°C), whereas the zircon (annealing threshold ~175–200°C) in the rock of sample M336 was not reset at all. Moreover, sample M330 from the U-Beva stock, located along North Fork North Creek at least 4 km farther from the fault zone separating the Tushar Mountains from Beaver Valley than the dikes at sample sites M335 and M336, contains apatite that was only partly reset to 13.4 m.y., whereas its zircon (19.8 m.y. in age) was not affected.

Geologic relationships combined with isotopic ages indicate that the Indian Creek stock has been subjected to three thermal events. The stock was initially emplaced late in the period of Bullion Canyon eruptions, probably 24–23 m.y. ago, on the basis of crosscutting relations and comparison with similar well-dated plutons elsewhere in the Tushar Mountains. A sample (table 1, M743) from within the stock shows that the heat associated with Mount Belknap magmatism and the formation of the nearby Mount Belknap caldera apparently completely reset the zircon to 19.3±1.0 m.y. A subsequent thermal event related to Gillies Hill magmatism and associated hydrothermal activity did not affect the zircon in the stock, but partly reset the apatite in the same sample to 12.8±2.1 m.y.

Fission-track ages on zircons from two rhyolite dikes north of Indian Creek and west of the Mystery-Sniffer mine indicate that yet another, until now unrecognized, episode of igneous and hydrothermal activity with potential economic overtones may have occurred (see later sections). Sample M733 is from a rhyolite dike cutting hornfelsed Bullion Canyon Volcanics on the ridge north of Indian Creek. The dike contains fluorite and secondary uranium minerals; zircons from the dike have a fission-track age of 15.6±1.1 m.y. About 1½ km east of that locality and less than ½ km west of the Mystery-Sniffer mine, another northerly trending rhyolite dike contains zircon with a fission-track age of 16.1±0.8 m.y. (table 1, M744). Both rhyolites have identical ages at the 95 percent confidence level; they do not appear to be related to the Mount Belknap caldera (19 m.y. old), nor are they partly reset by rhyolite of Gillies Hill (9 m.y. old). The rhyolite of Gillies Hill was sufficiently hot for a long enough time to partly reset the apatite, but not the zircon in the Indian Creek stock (M743) at a location closer to the known area of Gillies Hill magmatism and presumably toward the heat source. Thus, it would have been difficult for zircons from the two dikes to have been reset at all, let alone partially to exactly the same degree in late Miocene time. The fluorite and secondary uranium noted in association with the westernmost dike, in combination with the anomalous concentrations of lithophile elements near the Mystery-Sniffer mine discussed earlier, also point toward a local primary source of mineralizing solutions and heat. Emplacement of a hidden local intrusion, with attendant hydrothermal activity, in the area west of the Mystery-Sniffer mine about 16 m.y. ago seems a distinct possibility.

GEOPHYSICAL EVIDENCE

An airborne magnetic and gamma-ray spectrometric survey of Beaver Valley, including the area shown on figure 2, was made in 1980–1981 by High Life Helicopters, Inc.,[1] under contract to the U.S. Geological Survey. Data were gathered by helicopter flown east-west along the flight lines shown on figure 3 at a nominal 0.5-km line spacing and draped at a nominal 122 m above mean terrain.

Contours of total-field aeromagnetic field data are shown on figure 3. Combining the magnetic data (fig. 3) with the geologic data (fig. 2) and the geochronologic data of this report allows for the interpretation of geologic rock units and structural features at depth as shown on figure 4.

The high at the extreme northeast edge of the area of the magnetic map is the south end of a much larger high that lies to the north of the map area; this feature is shown prominently on the aeromagnetic map of Utah (Zietz and others, 1976). It apparently reflects a major intrusive body at depth that fed a cluster of magnetite-bearing, intermediate-composition, 24- to 23-m.y.-old stocks in the Pine Creek–Sulphurdale area. Farther south, but along the east side of the area of figure 3, is an area where the magnetic field is low. This is the area of the Mount Belknap caldera that contains rocks with low iron content that have been irregularly hydrothermally altered after emplacement. Some of the irregularity in the magnetic field may also reflect topographic relief within the caldera. Comparison of figures

[1]Any use of trade names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

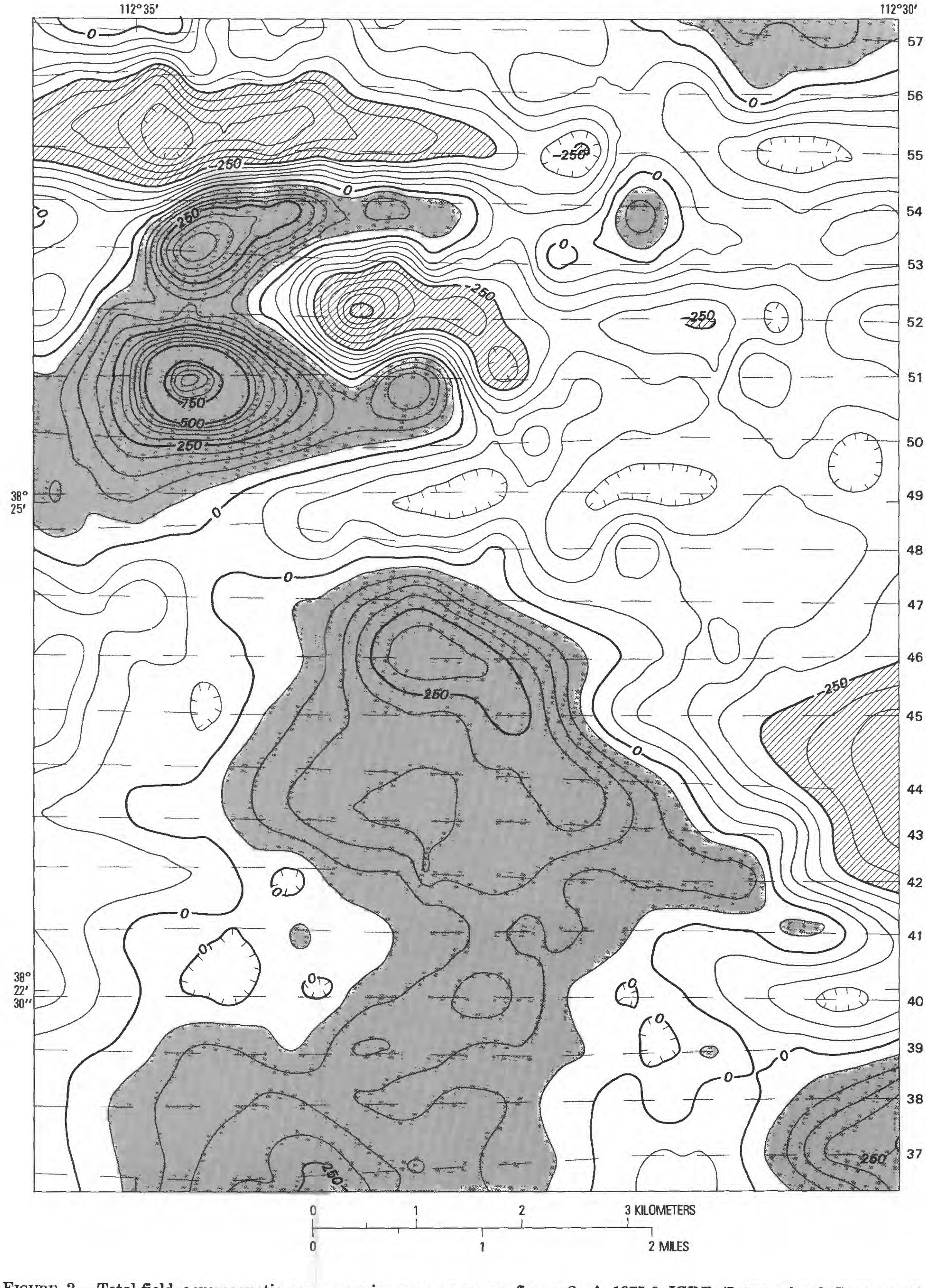


FIGURE 3.—Total-field aeromagnetic map covering same area as figure 2. A 1975.0 IGRF (International Geomagnetic Reference Field) has been removed. Contour interval 50 nT (1 nT=1 gamma). Hachures are on lower side of closed contour lines. Shaded areas have magnetic fields above 50 nT and lined areas have magnetic fields below –250 nT. Flight line number is given at far right end of each flight line.

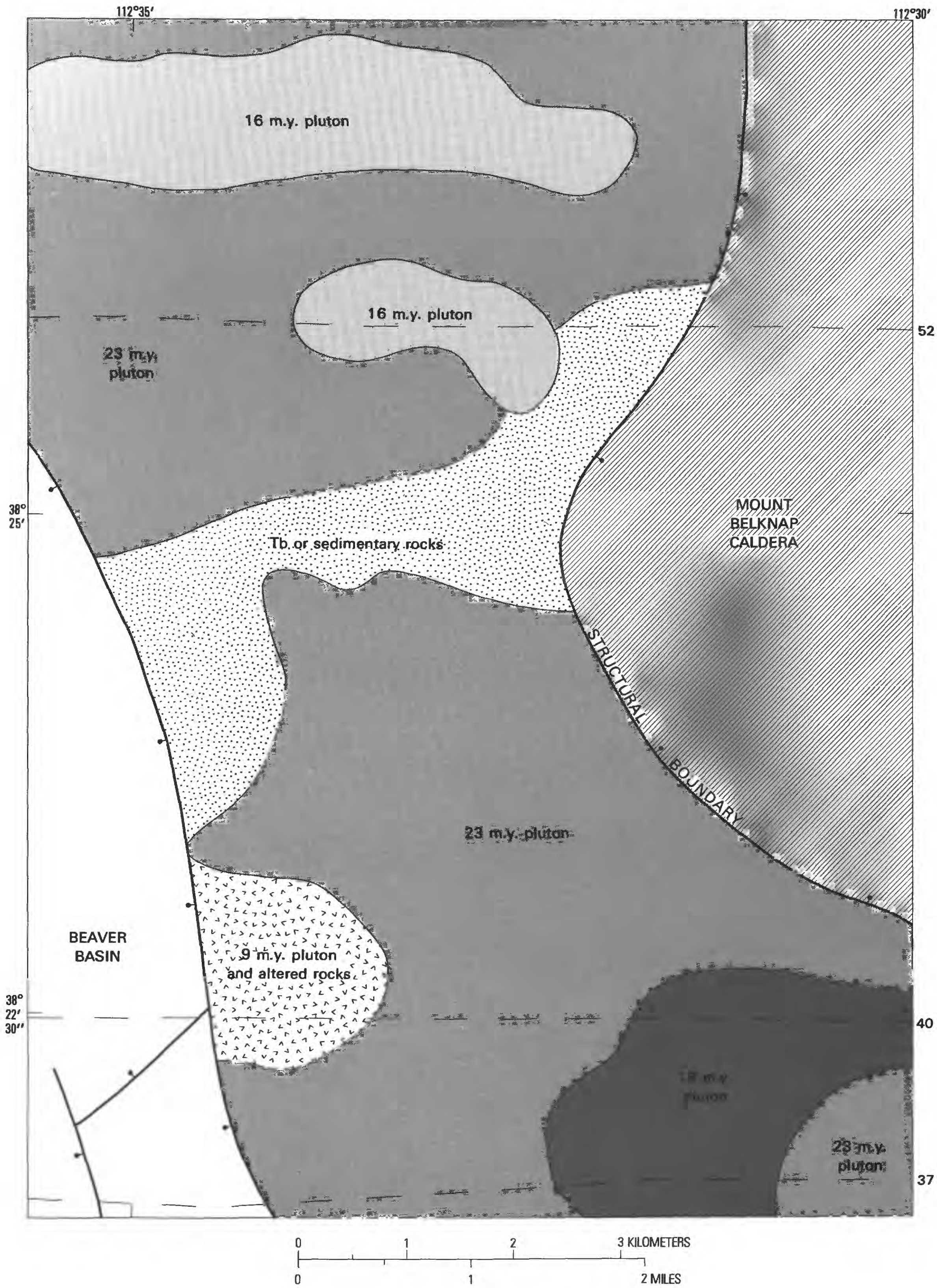


FIGURE 4.—Interpretive geologic map at lower volcanic or subvolcanic levels of same area as figure 2. Tb, heterogeneous lava flows of Bullion Canyon Volcanics. Heavy line, fault; bar and ball on downthrown side. Flight lines 37, 40, and 52 of figures 5, 6, and 7, respectively, are shown.

3 and 4 with figure 2 suggests that the structural boundary of the Mount Belknap caldera lies east of the mapped topographic wall of the caldera; although both features are subparallel in the northern section, they diverge to the south. The southwestern margin of the mapped topographic wall of the Mount Belknap caldera forms a salient along North Fork North Creek. The magnetic data suggest that this is a shallow feature where the wall dips gently and the structural boundary follows the steep magnetic gradient trending southeast between the prominent magnetic high and low, as shown on figure 4. This interpretation suggests that the U-Beva stock came up along the structural boundary, but intruded Mount Belknap Volcanics at shallow depths below the present surface.

A large magnetic high dominates the south-central part of the map area. This high connects with the high in the southeast corner of the map area by wrapping around the intervening low just south of the map area. Thus, most of the south half of the area is one magnetic province—an area of long-wavelength magnetic highs cut by reentrant lows. This province may reflect a regional batholith at depth, with cupolas that approach and locally reach the surface. Most outcrops in this province are of Bullion Canyon Volcanics that locally (such as at the southeast edge of the area) are substantially argillized. Samples of Bullion Canyon Volcanics have variable, but generally low magnetic susceptibilities (Mackie and Cunningham, 1982); those that are intensely altered have yet lower susceptibilities. If the observed magnetic patterns were caused by surface rocks, the lows in the magnetic field might correlate with altered zones, but this is not the case. In this magnetic province, short-wavelength anomalies are lacking and no close correlation exists with topography; thus, two lines of evidence suggest that the surface volcanics contribute relatively little to the observed field.

The reentrant low that extends southward from the area of the U-Beva stock to the southern margin of the area of figure 3, and seemingly separates the major high into two parts, coincides with an area of extensively altered surface rocks and with an area containing rhyolite dikes with partially reset radiometric ages (table 1, samples M335, M336). Magnetic modeling of flight line 37 (fig. 5) indicates a zone of relatively low-susceptibility material extending to depths of 2 km or greater below this site. The low could thus reflect destruction of magnetite by alteration in a zone extending to depth from the surface environment, or it could reflect an unexposed rhyolitic pluton with low magnetic susceptibility. The second interpretation is shown on figure 4.

Another prominent reentrant low with a pronounced squarish shape is located on the west side of the south-central magnetic high along flight lines 40, 41, and 42. This low contains the Sheep Rock alunite deposit and gold mine, but does not show any special influence by these features. More probably, the magnitude, extent, and shape are due to a 9-m.y.-old rhyolite stock postulated to underlie this area and to have served as a source for the heat and magmatic sulfur in this local hydrothermal cell. This feature is modeled on figure 6.

The northwest quarter of the area of figure 3 has a prominent C-shaped magnetic high that opens to the east and wraps around an equally prominent magnetic low. The magnetic high is due to the intermediate-composition, magnetite-bearing Indian Creek stock and its subsurface equivalents. The low is magnetically distinct; it is hard to explain as merely a polarization effect from the high, and it most likely represents either a reversely polarized magnetic body or an igneous body containing sparse magnetic minerals. Figure 7 shows attempts to model such a body along flight line 52. The west edge of the magnetic low approximately coincides with several 16-m.y.-old rhyolite dikes (fig. 2) (table 1, sample M733) and spatially associated quartz veins, and the middle part of the low corresponds with the location of another 16-m.y.-old rhyolite dike (table 1, sample M744). The east edge of the low is located over the Mystery-Sniffer mine. The close correlation between mapped geologic relationships of the rhyolite dikes, radiometric ages, anomalous metal concentrations and fluorite, and the magnetic low brings us independently to the same conclusion—that a 16-m.y.-old stock underlies the area and is responsible, at least in part, for the ore deposit at the Mystery-Sniffer mine and the mineralized rock accompanying the dikes farther to the west.

Further confirmation comes from examination of the radiometric data gathered along flight line 52 (fig. 8). These data were gathered using a multi-channel gamma-ray spectrometer with a scintillation detector consisting of 33.6 L (8 crystals, each 4.2 L), with no shielding (4π geometry), and 5.2 L (2 crystals, each 2.6 L), with bottom shielding (2π geometry) for detection of ^{222}Rn daughter products in the air. The effective ground area measured by the spectrometer is a strip along the flight line about 240 m wide. The spectrometric data reflect radioelement concentrations in the uppermost 0.5 m of rock and soil. The data were corrected for aircraft and cosmic background and normalized to the survey altitude, and processed to obtain surface concentrations of uranium (eU), thorium (eTh), and potassium (K). The "e" (for equivalent) prefix is used because of the potential for disequilibrium in the uranium- and thorium-decay series.

Figure 8 shows that some of the data may reflect

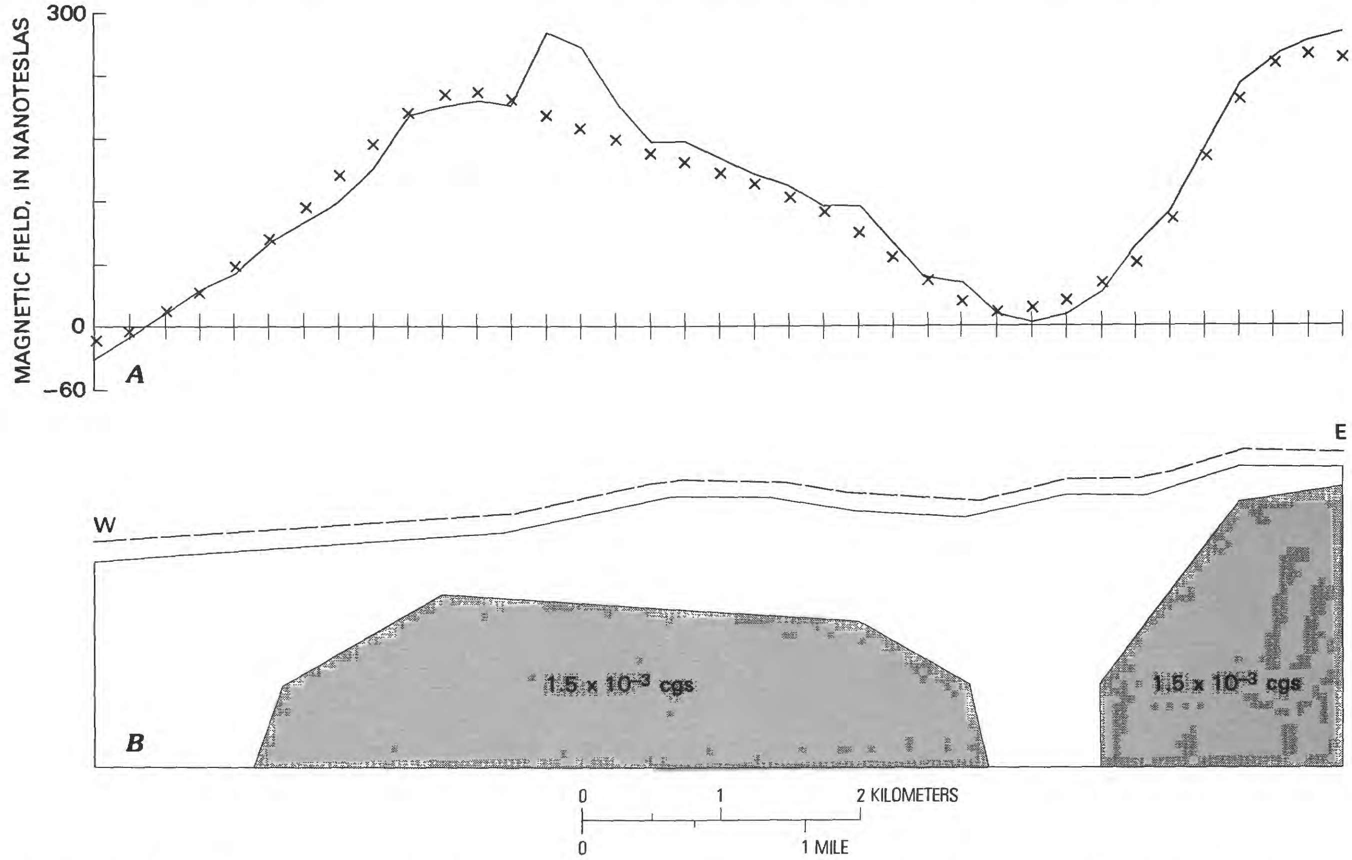


FIGURE 5.—Magnetic model along flight line 37. *A*, Solid curve shows observed magnetic field and X's show fields calculated for bodies shown in *B*. *B*, Section view of structure with two plutons ("23 m.y. pluton" of fig. 4). No vertical exaggeration. For the calculation, plutons have the magnetic susceptibility shown and extend unchanged for 5 km on either side of the section. Nonmagnetic zone between two plutons may represent a later intrusion ("19 m.y. pluton" of fig. 4). Magnetic fields were calculated on a datum (dashed line) that drapes topography at 122 m, the nominal altitude of survey helicopter. Regional field used for calculation had magnitude 53,500 nT, inclination 64.5°, and declination 14.5° east. Observed field curve shown on *A* has had a constant regional field of 40 nT added to values on contour map of figure 3.

topography, as indicated by the close correlation between data peaks and topographic highs indicated by the radar altimeter; these are most exaggerated in the areas of high topographic relief within the Mount Belknap caldera. The largest nontopographic eU, eTh, and K anomalies are in the center of the flight line and correspond to the location of the magnetic low, the 16-m.y.-old rhyolite dikes and flows, and the Mystery-Sniffer mine. The largest eU anomaly (fig. 8) is near the east end of the magnetic low, and the eTh/K and eU/eTh ratios indicate that the anomaly is the result of addition of uranium. The Mystery-Sniffer mine is just south of the flight line, but the mine dumps undoubtedly contribute to this radiometric anomaly. West of the mine, but still within the magnetic low, the data show substantive, and approximately equal, increases in eU, eTh, and K that correspond exactly with the lowest point on the residual magnetics curve. Because the radiometric high is localized within the otherwise uniform volcanic rocks, it is interpreted to reflect the addition of uranium, thorium, and potassium to the exposed volcanic rocks from the postulated buried alkali rhyolite stock.

Another prominent magnetic low occurs in the northwest corner of the area of figure 3. It is linear in an east-west direction, along the north edge of the Indian Creek stock, and its magnetic intensity is similar to the magnetic low to the south that encloses the rhyolite dikes and mine. It is unlikely to be a polarization effect of the Indian Creek stock. We interpret the low to indicate yet another buried rhyolite stock, but one that has no surface manifestation. It should be pointed out, however, that this anomaly largely reflects data gathered on a single flight line (flight line 55), and thus is not considered well established. Additional corroborative data are needed before this anomaly can be interpreted with confidence.

Radioelement spectral data, such as shown on figure 8, were acquired along all of the flight lines shown on figure 3 and composited to produce a radioelement

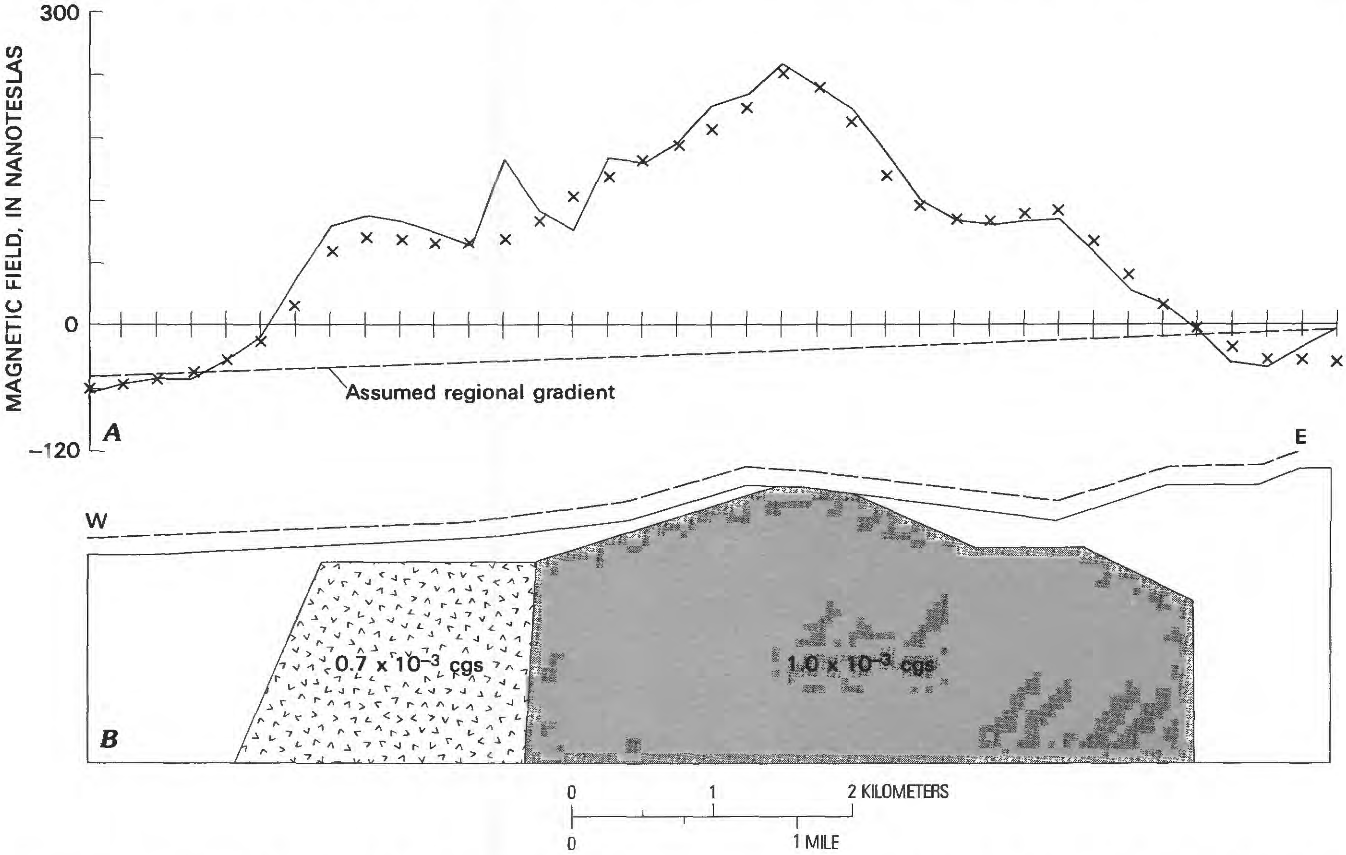


FIGURE 6.—Magnetic model along flight line 40. *A*, Solid curve shows observed magnetic field and X's show fields calculated for bodies shown in *B*. *B*, Section view of structure with two plutons. No vertical exaggeration. For the calculation, the plutons have the magnetic susceptibilities shown. Western pluton ("9 m.y. pluton" of fig. 4) extends unchanged for 1 km either side of section and eastern pluton ("23 m.y. pluton" of fig. 4) extends 5 km either side of section. Magnetic fields were calculated on a datum (dashed line) that drapes topography at 122 m, the nominal altitude of survey helicopter. Regional field used for calculation had magnitude 53,500 nT, inclination 64.5°, and declination 14.5° east. A constant regional field of 100 nT and a regional gradient as shown have been added to contoured values from figure 3 to give observed field (solid line) plotted in *A*.

spectral distribution map (fig. 9).[2] Areas that are white on figure 9 have high concentrations of eU, eTh, or K, areas that are black have low concentrations of the same elements, and areas that are gray have intermediate values. Contributing spectral components are distinguishable on the original color version of this map, but cannot be discriminated on this black and white rendition.

Comparison of figures 2, 3, and 4 with the radioelement spectral map shown on figure 9 shows that relatively localized highs in eU, eTh, and K occur within otherwise uniform lithologic units in areas where buried plutons and associated hydrothermally altered rocks have been postulated on other evidence. These local radiometric highs suggest that uranium, thorium, and potassium have been added to the surface rocks in these areas. The large white area (fig. 9) just to the lower left of center is located above the Sheep Rock alunite deposit and extends north over the Sheep Rock gold mine and Sunday mine. It is displaced slightly north of the magnetic low postulated to represent a buried 9-m.y.-old stock, and appears to reflect near-surface concentrations of eU, eTh, or K produced by hydrothermal leakage northward from the system, along the major fault system between the Beaver basin and Tushar Mountains.

The prominent northwest-southeast-trending white area in the upper-left part of figure 9 is located over the northern contact of the Indian Creek stock in the vicinity of the mapped rhyolite dikes where we have

[2]This map is a black and white representation of a composite color image of the radioelement data. The image was made using the procedure described by Duval (1983). Fully corrected data files for K, eU, and eTh were gridded with a standard gridding routine. A grid cell size of 268 m was used to obtain maximum resolution along flight lines; line spacing was 536 m. Following gridding, the data were converted to an image format in which the frequency distribution of each component was mapped to a uniform scale of 1:255. The image-format data were changed to a film base by means of an Optronics optical encoder. Each composite image consisted of three components (K, eU, eTh) that were assigned a specific color (red, green, or blue). The intensity of a color depends upon the numerical value of the component, and the density of data on film is linear as a function of input number. Although the colored image permits more subtle distinctions, the purposes of this report can be served by a black and white map (fig. 9) that was photographically produced from the color image.

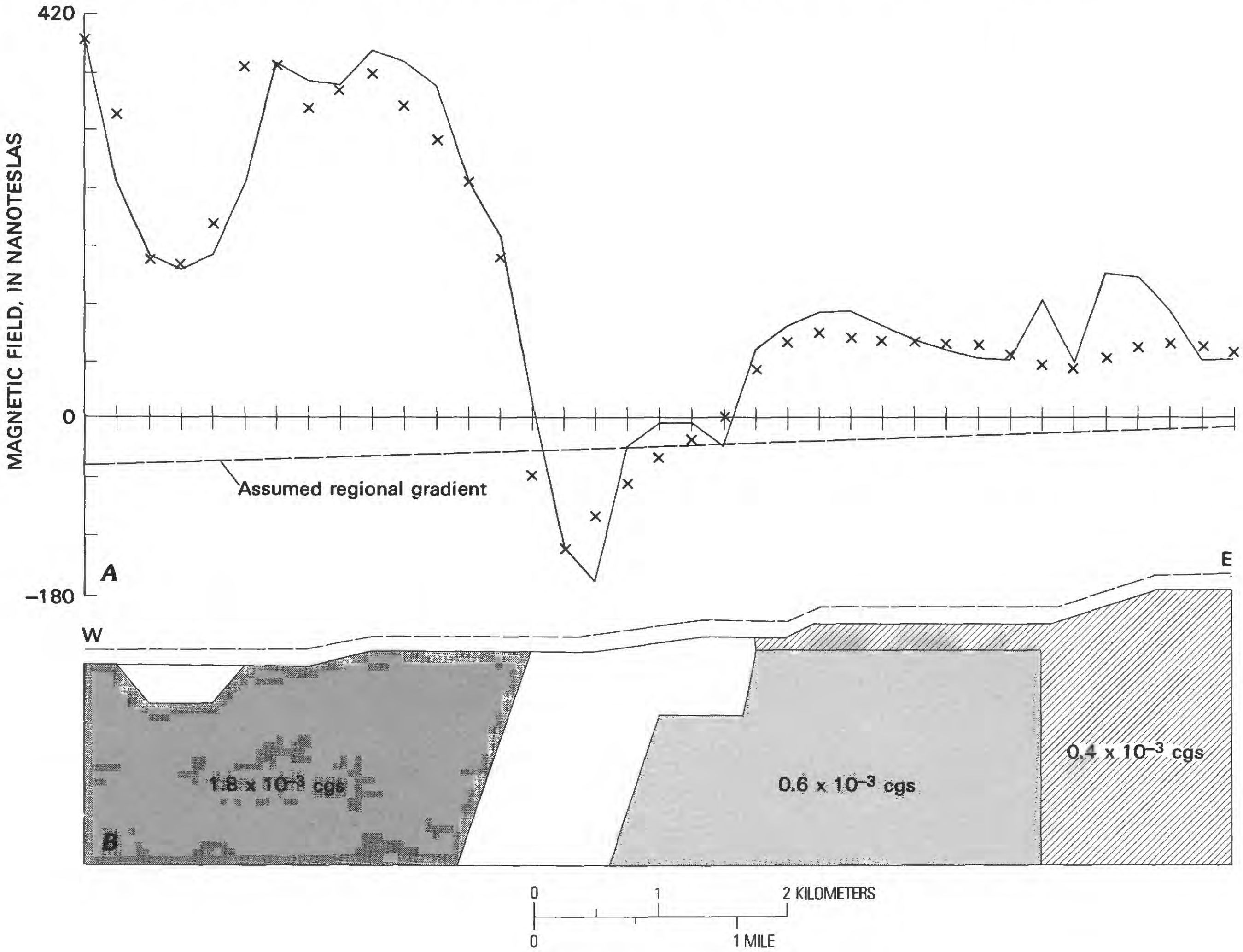


FIGURE 7.—Magnetic model along flight line 52. *A*, Solid curve shows observed magnetic field and X's show fields calculated for bodies shown in *B*. *B*, A possible configuration for Indian Creek stock ("23 m.y. pluton" of fig. 4), a deeper eastern pluton, and volcanics filling Mount Belknap caldera, from left to right. No vertical exaggeration. For the calculation, the plutons have the magnetic susceptibilities shown. Unshaded area between plutons has low susceptibility and may represent a later intrusion along east edge of Indian Creek stock ("23 m.y. pluton" of fig. 4). The Indian Creek stock and deep eastern pluton are assumed to extend 1 km, and Mount Belknap Volcanics 5 km, on either side of profile. Magnetic fields were calculated on a datum (dashed line) that drapes topography at 122 m, the nominal altitude of survey helicopter. Regional field used for calculation had magnitude 53,500 nT, inclination 64.5°, and declination 14.5° east. A constant 270 nT and a regional gradient as shown have been added to contoured values from figure 3 to give observed field (solid line) plotted in *A*.

predicted the location of a buried 16-m.y.-old stock. Mineralization at the Mystery-Sniffer mine is represented by the light-gray area just to the east of the white area.

The scattered white and gray areas along the east edge of the map area reflect variously altered uranium-bearing rocks within the Mount Belknap caldera. The northernmost of these white areas on figure 6 indicates altered rocks (fig. 2) containing anomalous quantities of secondary uranium minerals. The white area, about a third of the way north along the eastern border of the area of figure 9, straddles North Fork North Creek and includes the area of the U-Beva stock.

The white area in the southeast corner of the area of figure 9 is located over Cork Ridge. This area contains abundant altered rocks and is in the same area as a prominent magnetic high (fig. 3). This area is contiguous with a larger area to the southeast that contains scattered concentrations of ore minerals; it is not well understood at the present time and deserves additional study.

SUMMARY

The geologic history of the western Tushar Mountains, supported by numerous isotopic ages, indicates that hydrothermal activity took place: (1) in association

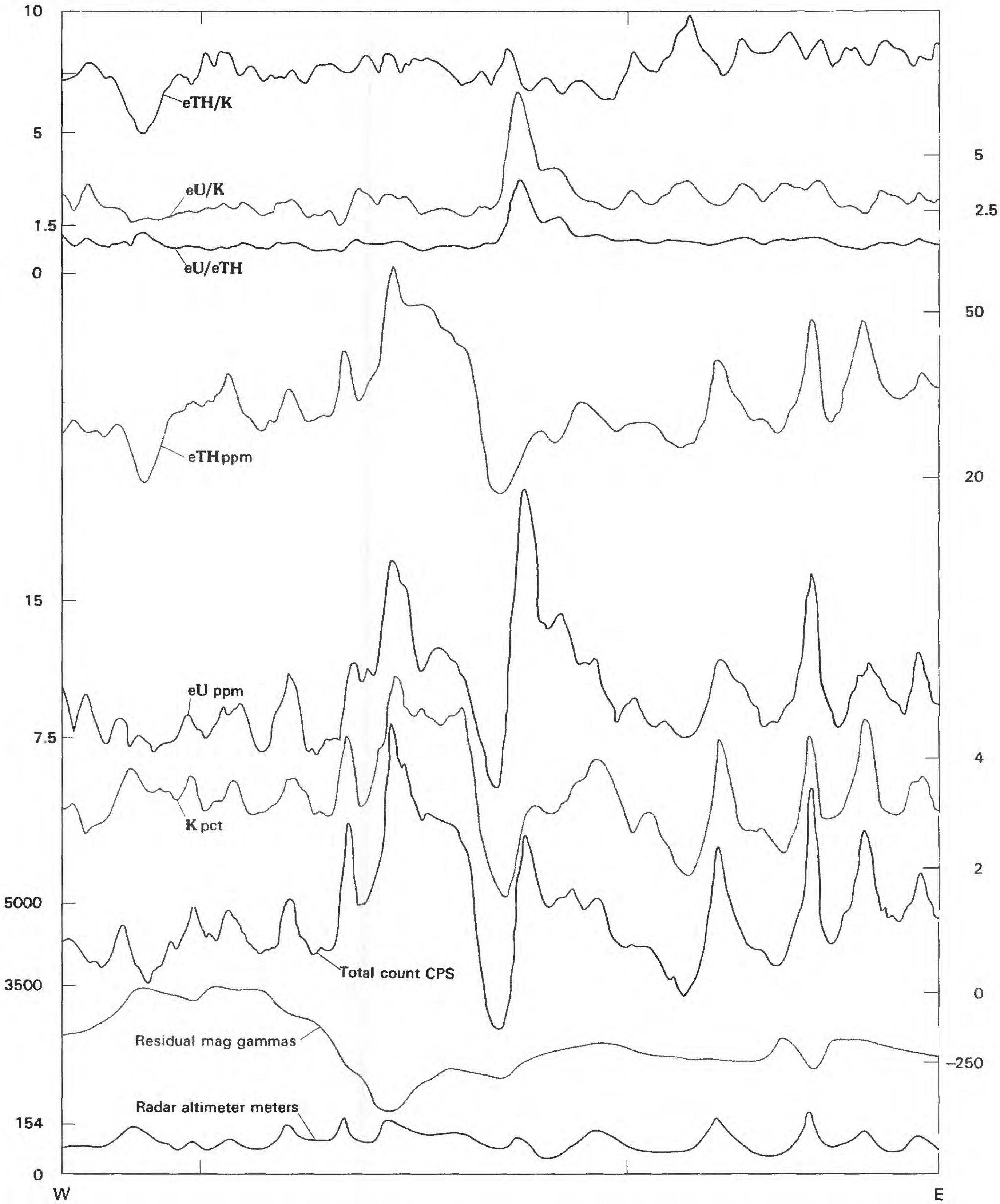


FIGURE 8.—Geophysical data gathered along flight line 52 and ratios of data. A 1975.0 IGRF (International Geomagnetic Reference Field) has been removed from the aeromagnetic data.

FIGURE 9.—Radioelement spectral distribution map of same area as figure 2.

with emplacement of monzonitic stocks related to the Bullion Canyon Volcanics 24–23 m.y. ago, (2) during the Mount Belknap caldera cycle about 19 m.y. ago, (3) possibly in association with emplacement of a younger Mount Belknap pluton about 16 m.y. ago, and (4) locally along the fault marking the western margin of the Tushar Mountains 9–8 m.y. ago. Some of the resulting mineralized areas are distinct and easily recognizable, but others are partly to completely superimposed; the effects of the different mineralization episodes are difficult to separate. The products of the different periods of mineralization should be identified as precisely as possible, inasmuch as potential exploration targets and the mineral resources sought will vary considerably from one period of mineralization to another and from one depth environment to another.

The known gold-bearing quartz-pyrite veins associated with the Bullion Canyon period of igneous activity are small and appear to be low in grade. Propylitically altered rocks of this association are known in the vicinity of the Indian Creek stock and in the Cork Ridge area (fig. 2), and some of the many areas of altered rocks between these two areas may have formed at about the same time. No zoning pattern was discerned within the altered areas known to be associated with the Bullion Canyon period of igneous activity that would indicate the presence of more favorable environments for mineral concentrations at depth.

Small concentrations of secondary uranium minerals have been noted in more permeable parts of the Mount Belknap caldera fill, and anomalous uranium not accompanied by other lithophile elements has been noted in Bullion Canyon rocks adjacent to the caldera. These concentrations are believed to have formed by redeposition of uranium mobilized by devitrification and hydrothermal alteration of the silicic fill in the Mount Belknap caldera. Known deposits are small, but large quantities of mobilized uranium appear to have been available and more significant deposits may occur where reducing chemical conditions coincided with permeable solution channelways.

Epizonal plutons emplaced during the Mount Belknap Volcanics period of igneous activity are known to occur in the caldera fill along the southern ring fracture zone of the Mount Belknap caldera, and are postulated on indirect evidence to exist in the belt of Bullion Canyon Volcanics between the caldera and Beaver Valley. These plutons were emplaced in part during the caldera cycle about 19 m.y. ago, and in part about 16 m.y. ago. One of these postulated plutons along Indian Creek is strongly indicated by geophysical evidence. Anomalous concentrations of lithophile elements, which are believed related to these known or postulated plutons, have been outlined by geochemical data both in and adjacent to the caldera. Geophysical evidence suggests addition of uranium, thorium, and potassium to roof rocks above the postulated Indian Creek pluton. The metals with the best potential for economic mineral concentrations associated with such plutons seem to be molybdenum in the porphyry environment near the top of the plutons, and uranium in overlying veins. Several areas with significant anomalous concentrations of lithophile elements have been outlined, and all these deserve careful study to see if exploration targets can be outlined. The Indian Creek area seems especially attractive.

Hydrothermal activity related to the late Miocene igneous activity responsible for erupting the 9-m.y.-old rhyolite of Gillies Hill was restricted to the basin and range fault zone marking the western margin of the Tushar Mountains. The Sheep Rock alunite deposit, Sheep Rock gold mine, and possibly the Sunday gold mine seem to have formed as parts of a single zoned hydrothermal system characterized by sulfur with a magmatic-isotopic affinity. This area is marked by a well-defined magnetic low believed to reflect an underlying hidden pluton that supplied heat, sulfur, and perhaps other constituents to the hydrothermal system. Another alunite deposit near the mouth of Indian Creek canyon marks the core of another hydrothermal system. Significant quantities of uranium, thorium, and potassium have been added to the surface rocks in the Sheep Rock area. The zoned Sheep Rock system, with its probable magmatic core, deserves special consideration as a potential exploration target.

Further study in other areas containing favorable combinations of geologic, geochemical, and geophysical factors could elevate some of these areas to higher priority in exploration interest.

Geologic, geochemical, geophysical, and geochronologic data in the western Tushar Mountains area have meshed especially well in supporting unified interpretations of many local areas. The fact that several areas of seemingly high economic potential have been outlined is particularly gratifying. Additional data are probably needed in most of these areas to locate exploration targets more precisely; a multiple approach would seem advantageous in this more detailed work as well. The final member of such an exploration team effort, of course, is the drill.

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Geologic History and Uranium Potential of the Big John Caldera, Southern Tushar Mountains, Utah

By THOMAS A. STEVEN, CHARLES G. CUNNINGHAM,
and JOHN J. ANDERSON

IGNEOUS ACTIVITY AND RELATED ORE DEPOSITS IN THE WESTERN AND SOUTHERN TUSHAR MOUNTAINS, MARYSVALE VOLCANIC FIELD, WEST-CENTRAL UTAH

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1299–B

Uranium leached from younger ash-flow tuffs may be present in gravels covering the caldera floor or in the drainage outlet

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GEOLOGIC HISTORY AND URANIUM POTENTIAL OF THE BIG JOHN CALDERA, SOUTHERN TUSHAR MOUNTAINS, UTAH

By THOMAS A. STEVEN, CHARLES G. CUNNINGHAM, and JOHN J. ANDERSON

ABSTRACT

The Big John caldera, on the western flank of the Tushar Mountains in the Marysvale volcanic field in west-central Utah, formed 23–22 m.y. ago in response to ash-flow eruptions of the Delano Peak Tuff Member of the Bullion Canyon Volcanics. These eruptions were near the end of the period of Oligocene-early Miocene calc-alkalic igneous activity that built a broad volcanic plateau in this part of Utah. About 22 m.y. ago, the composition of rocks erupted changed to a bimodal assemblage of mafic and silicic volcanics that was erupted episodically through the remainder of Cenozoic time. The alkali rhyolites are uranium rich in part, and are associated with all the known uranium deposits in the Marysvale volcanic field.

The Big John caldera was a broad drained basin whose floor was covered by a layer of stream gravels when ash flows from the western source area of the Mount Belknap Volcanics filled the caldera with the Joe Lott Tuff Member about 19 m.y. ago. Devitrified and zeolitized rocks in the caldera fill have lost one-quarter to one-half of the uranium contained in the original magma. This mobilized uranium probably moved into the hydrologic regime, and some may have been redeposited in stream gravels underlying the Joe Lott within the caldera, or in gravels filling the original drainage channel that extended south from the caldera.

INTRODUCTION AND PREVIOUS WORK

The Big John caldera is an obscure subsidence structure on the western flank of the Tushar Mountains, within the Marysvale volcanic field of west-central Utah (fig. 10). The caldera subsided about 23 m.y. ago in response to ash-flow eruptions that deposited the Delano Peak Tuff Member of the Bullion Canyon Volcanics. During caldera development and subsequent filling and erosion, several geologic environments were formed that were favorable for the concentration of uranium; these environments form the focus of this report.

The Big John caldera is within the Delano Peak quadrangle, which was mapped initially by Eugene Callaghan in the 1930's and later published by Callaghan and Parker (1962). Callaghan (1939) interpreted a thick, hard unit within the Bullion Canyon Volcanics to be a single lava flow, which he called the Delano Peak Latite Member. Steven, Cunningham, Naeser, and Mehnert (1979) recognized the unit as a largely propylitized, simple cooling unit of densely welded, crystal-rich ash-flow tuff and named it the Delano Peak Tuff Member of the Bullion Canyon Volcanics. Steven, Cunningham, and Anderson (1979) recognized the source of the Delano Peak Tuff Member as the Big John caldera and made a preliminary assessment of the economic potential of the caldera.

This report is one of a series describing the major geologic features and main mining areas of the Marysvale volcanic field. As described by Steven, Rowley, and Cunningham (1978), the volcanic rocks can be divided into two main assemblages: an assemblage of largely intermediate-composition calc-alkalic rocks erupted during Oligocene and early Miocene time, and a subsequent bimodal assemblage of mafic lavas and high-silica alkali rhyolites erupted episodically through the rest of Cenozoic time. The changeover from calc-alkalic to bimodal assemblages in the Marysvale volcanic field took place about 22 m.y. ago, about coincident with the beginning of extensional tectonism in this part of the Basin and Range province of the Western United States. Calderas formed in response to voluminous ash-flow eruptions during accumulation of both assemblages of volcanic rocks. The 27-m.y.-old Three Creeks (Steven, 1982), 23-m.y.-old Big John (Steven, Cunningham, and Anderson, 1979), and 23-m.y.-old Monroe Peak (Rowley, Cunningham, and Kaplan, 1981; Rowley, Williams, and others, 1981; Rowley and others, 1984a, b) calderas formed during calc-alkalic eruptions, and the 19-m.y.-old Mount Belknap and Red Hills calderas (Cunningham and Steven, 1979a) formed during bimodal eruptions. Major mineralized and altered areas described include the Central Mining Area, the Mount Belknap caldera, the Deer Trail Mountain–Alunite Ridge area, the Cove Fort-Sulphurdale area, and the Mystery–Sniffer–Sheep Rock area (Steven, Cunningham, and Rowley, 1978; Cunningham and Steven, 1979b, 1979c, 1979d; Steven and Morris, 1981; Cunningham, Steven, and Naeser, 1982). Most of the area of figure 10 is also included in published geologic maps and alteration maps at a scale of 1:50,000 (Cunningham and others, 1983, 1984).

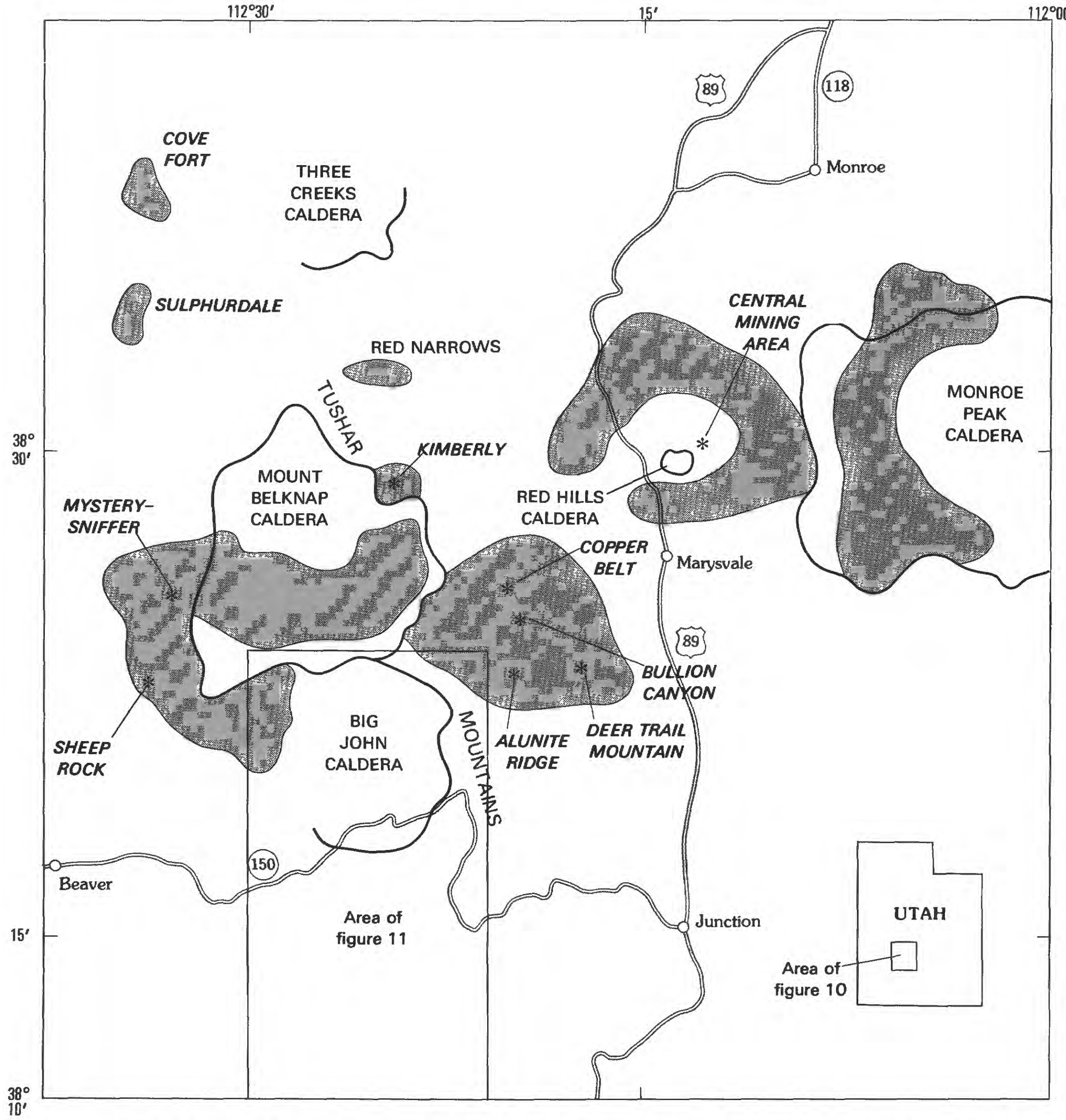


FIGURE 10.—Index map showing location of mapped area(fig. 11), calderas, major mining centers (starred), and principal altered and (or) mineralized areas (shaded) in and adjacent to Tushar Mountains.

PRECALDERA GEOLOGY

The Marysvale volcanic field (Steven, Rowley, and Cunningham, 1978; Steven, Cunningham, Naeser, and Mehnert, 1979; Rowley and others, 1979) consists of products from many local volcanic centers coalesced into a broad volcanic plateau that was surmounted by the crests of large volcanoes. Some time before 30 m.y. ago, the earliest volcanic activity in the northern Tushar Mountains built a large composite volcano consisting of generally intermediate-composition porphyritic lava flows and breccia. Subsequently, flank eruptions formed smaller volcanoes around the margins of the composite volcano, and ash-flow tuff sheets from local and distant sources lapped onto the flanks of the older volcano and intertongued marginally with it. Most of the locally derived rocks in the northern part of the Marysvale volcanic field are included in the Bullion Canyon Volcanics, shown on the northern part of figure 11. The 30- to 29-m.y.-old[1] (Fleck and others, 1975) Wah Wah Springs Tuff Member of the Needles Range

[1]All potassium-argon ages given in this report have been recalculated using the data of Dalrymple (1979).

Formation, which was erupted from a source in the southern Needle (Mountain Home) Range more than 100 km west of the Tushar Mountains, is a key stratigraphic marker that rests directly on prevolcanic sedimentary rocks over a broad area of western Utah, but overlaps and wedges out against the flanks of Bullion Canyon volcanoes in the northern Tushar Mountains (Steven, Cunningham, Naeser, and Mehnert, 1979).

After the Wah Wah Springs Tuff Member was emplaced, a series of volcanoes began to form in the southern part of the Marysvale volcanic field. These volcanoes consist largely of dacitic and andesitic lava flows, and volcanic breccia that have been called the Mount Dutton Formation (Anderson and Rowley, 1975). Mount Dutton volcanoes are scattered across a wide area, from the Sevier Plateau on the east, across the northern Markagunt Plateau and southern Tushar Mountains, to the Black Mountains on the west. Products from these volcanoes overlap northward, and in part intertongue with concurrently erupted rocks of the Bullion Canyon Volcanics in the northern Tushar Mountains. Local ash-flow tuff units are interlayered with both the Bullion Canyon and Mount Dutton assemblages.

At the time the Big John caldera formed, about 23 m.y. ago, the Marysvale volcanic field was extremely active; some of the Bullion Canyon volcanoes were still erupting, but in diminished volumes, and many of the Mount Dutton volcanoes to the south were vigorously active.

BIG JOHN CALDERA

At the time the Big John caldera formed, the lower part of the volcanic plateau between the major eruptive centers of the Bullion Canyon Volcanics and Mount Dutton Formation was the site of violent ash-flow eruptions that emplaced the crystal-rich quartz latitic Delano Peak Tuff Member of the Bullion Canyon Volcanics. The tuff was largely confined to the valleys, where it puddled to thicknesses of 300 m (fig. 11), and lapped out against older volcanoes to the north, east, and south. The western extent of the tuff is not known, but it could have spread many kilometers in this direction. This sheet appears to have had a moderate volume measured in terms of tens of cubic kilometers; it definitely was not a major regional sheet with a volume of hundreds of cubic kilometers.

The Delano Peak ash-flow eruptions led to the collapse of the source area, and the formation of the Big John caldera. The subsided area measures about 10 km across north-south and 6 km across east-west. Subsidence is clearly defined along the eastern margin, where offsets of the Delano Peak Member in excess of 300 m mark the structural margin. The western margin of the subsided block is poorly exposed and its character is difficult to ascertain. No sharp structural boundary has been found here, and it seems likely that on the west side of the caldera the subsided rocks merely bend down across a hinge zone like a trapdoor.

The topographic wall along the eastern margin of the Big John caldera is well exposed locally near the crest of the Tushar Mountains in the north half of the area shown on figure 11. The high divide marking the crest consists largely of the densely welded, flat-lying Delano Peak Tuff Member (fig. 11) which is as much as 220 m thick. West of the divide, these flat-lying rocks are cut off abruptly by a westward-sloping wall that was covered by lava flows and local welded tuffs of the upper member of the Bullion Canyon Volcanics (fig. 11). The oldest exposed unit in the upper member is a thin, rhyolitic, welded ash-flow tuff that was deposited here and there on the wall northwest of Delano Peak, and became strongly lineated by secondary flow down the wall while it was welding. This unit is overlain by dark, crystal-poor andesitic lava flows that were erupted from sources to the east and that flowed westward down the scarp to accumulate as a thick sequence of steeply dipping flows. Similar lava flows exposed in erosional windows near the center of the caldera indicate that the floor of the caldera also was widely covered during the same period of eruption.

The southeastern wall of the caldera consists of a mixed assemblage of lava flows and volcanic breccia of the Bullion Canyon Volcanics and Mount Dutton Formation, and is so widely covered by younger units and obscured by surficial deposits and timber that only general relations could be established.

Farther west, the southern margin of the Big John caldera is covered by several younger volcanic accumulations now well exposed in the canyon of Beaver River. The Delano Peak Tuff Member is exposed in a small window along Beaver River 7 km southwest of the area of figure 11, where it has been dated as about 23 m.y. old (table 3). The Delano Peak in the window is overlain by dark, andesitic lava flows, volcanic breccias, and local intercalated ash-flow tuffs. These overlying rocks are parts of two small, relatively young volcanoes of the Mount Dutton assemblage, and these in turn are overlain by thick, coarsely porphyritic, quartz latite lava flows and domes that Sigmund (1979) has called the formation of Lousy Jim (fig. 11).

Three potassium-argon ages from Lousy Jim rocks (formerly called Dry Hollow Formation, a name abandoned) cluster near 22 m.y. old (Fleck and others, 1975), within a million years of the time the Big John caldera formed. However, another ash-flow sheet, the tuff of Lion Flat, intervenes between Delano Peak and Lousy

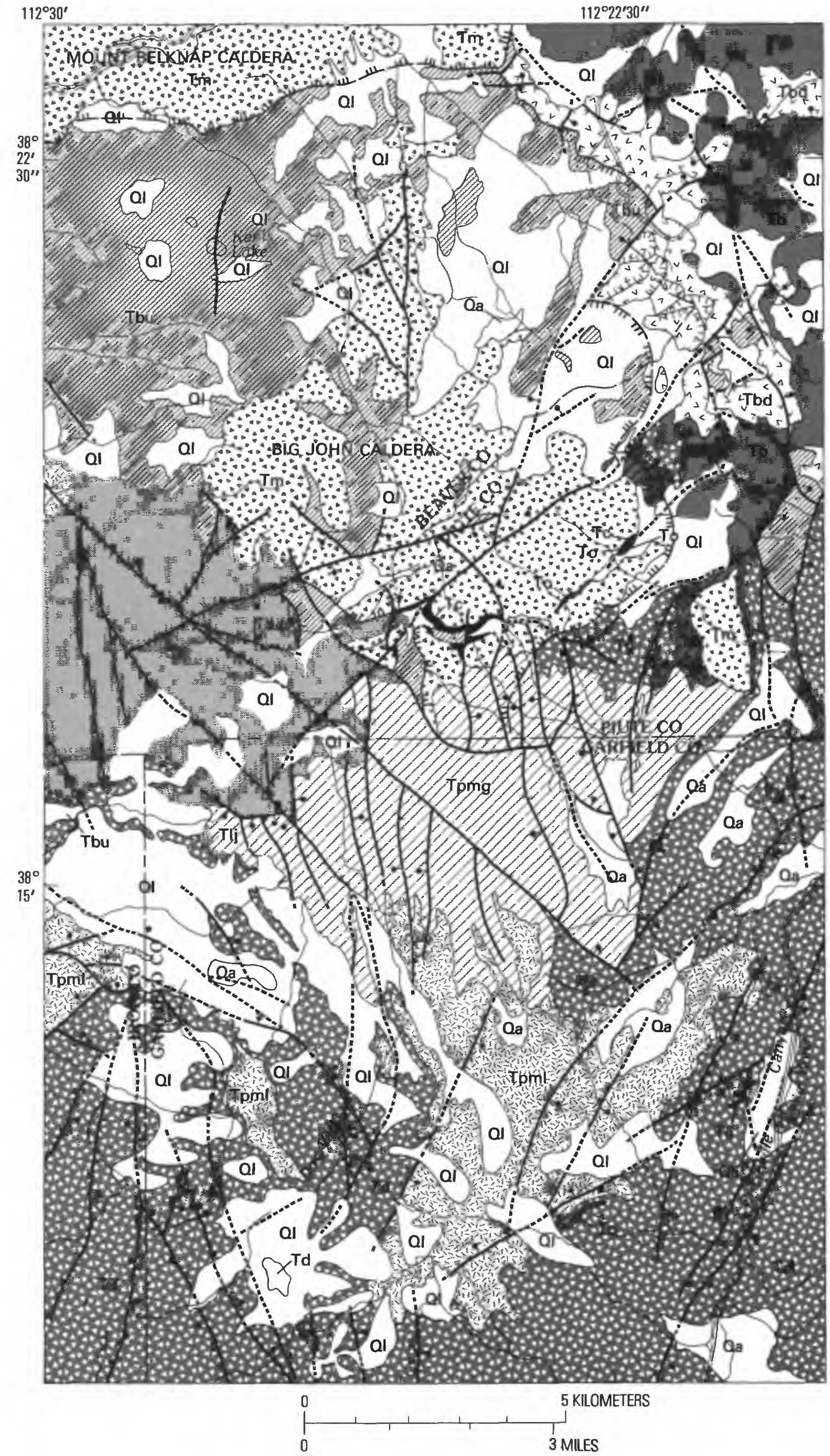
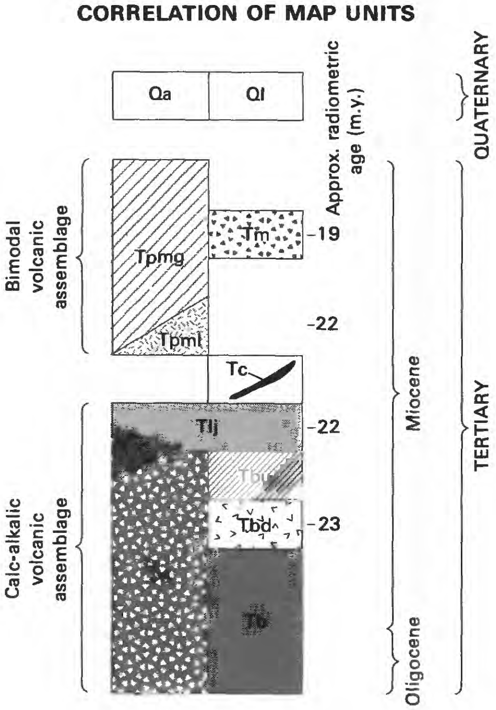


FIGURE 11.—Geologic map of the Big John caldera and surrounding area.

EXPLANATION

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Qa — ALLUVIAL DEPOSITS (QUATERNARY)—Silt, sand, and gravel mostly in alluvial fans, alluvial slope wash, and stream alluvium

Ql — LANDSLIDE DEBRIS (QUATERNARY)—Poorly sorted rock debris that moved downslope by gravity. Locally contains significant glacial drift, rock glaciers, talus, and alluvial deposits

Tm — MOUNT BELKNAP VOLCANICS, UNDIVIDED (MIOCENE)—Within the Mount Belknap caldera, the rocks consist of alternating thick rhyolite units of densely welded ash-flow tuff and lava flows. Outside the caldera, most rocks are poorly and irregularly welded ash-flow tuffs, most of which belong to the Joe Lott Tuff Member

Tc — CONGLOMERATE (MIOCENE)—Brown and locally red, fluviatile conglomerate and sandstone containing rounded clasts of Bullion Canyon Volcanics. Accumulated in the lower parts of the eroded basin of the Big John caldera

Tpmg — GRAVELS OF POTASSIUM-RICH MAFIC VOLCANIC ROCKS (MIOCENE)—Poorly consolidated fanglomerate and conglomerate composed largely of fragments of potassium-rich mafic lava flows

Tpml — POTASSIUM-RICH MAFIC LAVA FLOWS (MIOCENE)—Black to dark-gray, vesicular to dense lava flows containing phenocrysts of olivine, pyroxene, plagioclase, and Fe-Ti oxides. Includes amygdaloidal flows and scoria. Flows capping Circleville Mountain contain pyroxene phenocrysts as much as 1 cm across. Potassium-argon age is about 22 m.y. (Fleck and others, 1975; Best and others, 1980)

Tlj — FORMATION OF LOUSY JIM (MIOCENE)—Light- to dark-gray, coarsely porphyritic, quartz latitic lava flows and volcanic breccia containing about 25 percent phenocrysts of plagioclase, amphibole, clinopyroxene, magnetite, biotite, and quartz in a glassy groundmass

MOUNT DUTTON FORMATION (MIOCENE and OLIGOCENE)—Dense, resistant, light- to dark-gray and brownish-gray lava flows, flow breccia, sparse mudflow breccia, local ash-flow tuff, and fluviatile conglomerate and sandstone. Lava flows are dacitic to andesitic and contain textures ranging from aphanitic to porphyritic. Phenocrysts are generally sparse and consist of plagioclase, hornblende, and (or) pyroxene, and minor Fe-Ti oxides

OSIRIS TUFF (MIOCENE)—Gray and reddish-brown, densely welded, crystal-rich ash-flow tuff. Phenocrysts consist of andesine and subordinate sanidine and pyroxene, and minor biotite and Fe-Ti oxides. Potassium-argon age is about 23 m.y. (Fleck and others, 1975)

BULLION CANYON VOLCANICS

Tbu — Upper member (Miocene)—Mostly dark-gray to black, fine-grained rhyodacitic to andesitic lava flows and local densely welded ash-flow tuff, some of which show prominent lineate texture due to secondary flowage

Tbd — Delano Peak Tuff Member (Miocene)—Reddish-brown, densely welded, crystal-rich quartz latitic ash-flow tuff. Phenocrysts make up 50 percent of the rock and consist of andesine (30 percent), hornblende (12 percent), biotite (2 percent), sanidine (1 percent), Fe-Ti oxides (4 percent), and traces of quartz, zircon, and apatite. Most hornblende is altered to Fe-Ti oxides and calcite

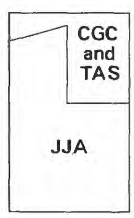
Tb — Midle and lower members, undivided (Miocene and Oligocene)—Largely porphyritic intermediate-composition lava flows and mud-flow breccia. Includes the 27-m.y.-old crystal-rich Three Creeks Tuff Member of the Bullion Canyon Volcanics

CONTACT

BREAKAWAY LANDSLIDE SCARP

TOPOGRAPHIC WALL OF CALDERA—Dashed where concealed

FAULT—Dotted where concealed. Bar and ball on downthrown side



Area mapping responsibility by author

FIGURE 11.—Continued

Jim rocks, so it is unlikely that the Lousy Jim is related to the Big John caldera cycle. So many volcanic eruptions were taking place within such a brief span of time 23–22 m.y. ago that it is difficult to distinguish those that are genetically related.

Also dated by the potassium-argon method as about 23 m.y. old (Fleck and others, 1975; Best and others, 1980; and table 3) is a local shield volcano or lava plateau consisting of potassium-rich mafic lava flows (fig. 11) that now forms the crest of Circleville Mountain in the southern part of the area of figure 11. This pile of mafic lava flows was derived from local sources and filled a broad valley cut in the older Mount Dutton volcanoes.

TABLE 3.—*Fission-track and potassium-argon age determinations*

[Fission-track data from Charles W. Naeser (written commun., 1979); potassium-argon data from Harald H. Mehnert (written commun., 1980). Constants: $^{40}K\lambda_{\epsilon}=0.581\times10^{-10}$/yr; $\lambda_{\beta}=4.962\times10^{-10}$/yr; $^{40}K/K=1.167\times10^{-4}$]

Fission-track determinations

Sample No.	Rock unit	Mineral	ρs[1]	No. tracks[2]	ρi[3]	No. tracks[4]	φ[5]	Age[6] (m.y.)	U (ppm)
M508 (DF-2262)	Tbd[7]	Zircon	3.06	764	7.74	968	0.957	22.6±1.0	230

Potassium-argon determinations

Sample No.	Rock unit	Sample	K_2O[8] (pct)	*^{40}Ar (10^{-10} moles/gram)	*^{40}Ar (pct)	Age[9]
M657 (DKA3842)	Tpml[10]	Whole rock.	3.80, 3.78	1.254	91.2	22.8±0.65

[1]Fossil-track density (tracks/cm^2)×10^6
[2]Number of fossil tracks counted
[3]Induced-track density (tracks/cm^2)×10^6
[4]Number of induced tracks counted
[5]Neutron dose (neutrons/cm^2)×10^{-15}
[6]Age (m.y.)±=2σ $\lambda_F=7.03\times10^{-17}$/yr
[7]Tbd is Delano Peak Tuff Member of the Bullion Canyon Volcanics
[8]Determined by atomic absorption
[9]Age (m.y.)±2σ
[10]Tpml is potassium-rich mafic lava flows

SAMPLE DESCRIPTIONS

M508 Delano Peak Tuff Member of the Bullion Canyon Volcanics collected alongside Utah Highway 153, east of Beaver, Utah; lat 38°15'20" N., long 112°31'37" W.
M657 Potassium-rich mafic lava flows collected about 1 km southwest of Big Flat; lat 38°16'16"N., long 112°22'04" W.

POSTCALDERA GEOLOGY

By 19 m.y. ago, the area of the Big John caldera was a broad basin that was drained through a south-trending canyon that had been cut across older volcanic rocks south of the caldera (fig. 12). The outlet canyon extended southward from the south wall of the caldera toward the present position of Circleville Mountain, but its south end is not exposed. No details of the erosional history that led to cutting of this canyon have been established, because most of the evidence has been removed by erosion or covered by younger volcanic units. The lower part of the eroded caldera basin, and at least the upper part of the outlet canyon, were filled to an unknown thickness by stream-deposited conglomerate and subordinate sandstone (fig. 11).

The drained and eroded topographic basin of the Big John caldera was just south of the western source area of the Mount Belknap Volcanics (Cunningham and Steven, 1979a), which was the site of voluminous eruptions of rhyolitic ash and lava flows as well as subsidence of the Mount Belknap caldera about 19 m.y. ago. Ash flows from this source area filled the Big John basin with irregularly welded ash-flow tuffs of the Joe Lott Tuff Member (figs. 11 and 12). The degree of welding in the Joe Lott changed markedly outward from the source; near the southern outlet of the basin, much of the ash was virtually nonwelded. This soft vitric material was largely altered by ground water to the zeolite mineral clinoptilolite; the quality and quantity of the zeolite suggest a potential economic resource of clinoptilolite (Steven and Cunningham, 1979).

Several minor ash-flow units, also derived from the western source area of the Mount Belknap Volcanics, overlie the Joe Lott Tuff Member in the southern part of the Big John caldera (Anderson and others, 1980). These too are largely nonwelded and also were diagenetically altered to clinoptilolite and clay (Steven and Cunningham, 1979).

The Joe Lott and associated units of the Mount Belknap Volcanics now extend only 2–3 km down the outlet canyon (fig. 12), although they probably were originally deposited much farther southward. Most of the soft Joe Lott filling the canyon was removed when later erosion reexcavated the canyon. Not only were the soft Mount Belknap tuff units in the canyon eroded, but any older stream sediments that underlay the Mount Belknap also were stripped during this period of erosion.

Southward flow of the stream draining the Big John caldera was disrupted by accumulation of a shield volcano of potassium-rich mafic lavas (fig. 11) near the present site of Circleville Mountain. This volcano shed a volcaniclastic apron of gravels (fig. 11) onto adjacent areas. The basal part of the volcaniclastic apron was contemporaneous with the mafic lava flows in the shield

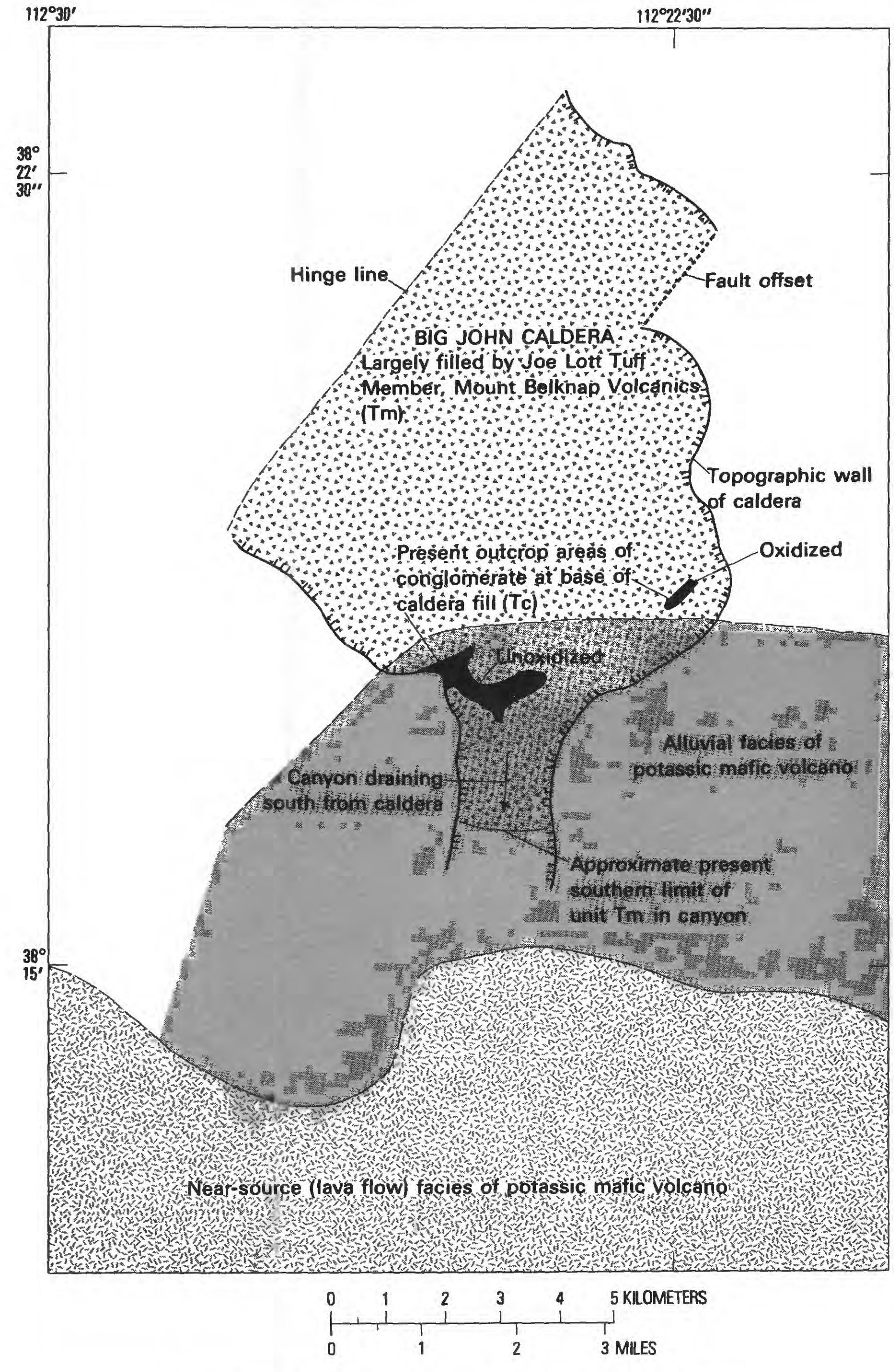


FIGURE 12.—Geologic environment of potential uranium deposits.

volcano, but the upper part continued to accumulate after eruption of the lava flows had ceased. Southeast of the caldera, the gravel unit extends beneath the 19-m.y.-old Joe Lott Tuff Member of the Mount Belknap Volcanics, but farther west it overlaps the Joe Lott. Near the south edge of the Big John caldera, the canyon that had been filled by tuffs of the Joe Lott Member had been partially reexcavated by this time. The gravel apron backfilled the canyon as far north as the edge of the Mount Belknap rocks that still filled the Big John caldera. A conglomerate and the overlying Joe Lott Tuff Member form most of the fill in the Big John caldera; the contact between these units and the gravels of potassium-rich mafic volcanic rocks now occupying most of the outlet canyon is irregular and close to the topographic wall of the Big John caldera (figs. 11 and 12). The coincidence, within a small area, of several rock units meeting along steep erosional contacts with opposite inclinations has made a relatively simple sequence of events quite difficult to decipher.

The accumulation of the shield volcano that consists of potassium-rich mafic rocks and related gravels and the widespread basin and range faulting and deformation in later Cenozoic times totally disrupted the earlier drainage system of the Big John caldera. Modern Beaver River and its tributaries now drain westward, consequent on the westward-tilted mountain range. The deep canyons cut by this new drainage system are athwart the earlier trends and give cross-sectional exposures that permit reconstruction of the earlier events.

ENVIRONMENTS FAVORABLE FOR URANIUM ACCUMULATION

Uranium deposits and occurrences are widespread in the Marysvale volcanic field. These typically are associated with Miocene or younger rhyolites that form the silicic end member of the bimodal basalt-rhyolite assemblage that was erupted concurrent with regional basin and range tectonism. This bimodal assemblage is younger than the Oligocene to lower Miocene calc-alkalic volcanic rocks of the Marysvale volcanic field. The oldest and most voluminous rhyolite unit in the Tushar Mountain area is the Mount Belknap Volcanics. In part, the uranium is in epigenetic veins, as in the Central Mining Area (Cunningham and Steven, 1979b), and in part, the uranium occurs dispersed through rhyolitic rocks, or has been leached from these rocks and either redeposited elsewhere or moved in solution into the hydrologic regime (Steven and others, 1981). No epigenetic uranium occurrences were noted in the Big John caldera, but two environments have been recognized in which remobilized uranium leached from the rhyolites may have been deposited.

The stream gravels and sands that accumulated in the lower part of the Big John caldera before eruption of the Mount Belknap Volcanics (fig. 12) would seem to represent an excellent potential host rock for sandstone-type uranium deposits. The sediments were originally relatively permeable; although now somewhat indurated, they still are more permeable than most of the surrounding volcanic rocks. They were covered by uranium-rich ash-flow tuffs of the Mount Belknap Volcanics, the chief rock unit associated with known uranium deposits in the Marysvale volcanic field. Some of these tuffs within the Big John caldera have been diagenetically altered to zeolite and clay, and their contained uranium has been partly released from the original glassy ash. Delayed-neutron-activation analyses of glassy and devitrified rocks of the Joe Lott Tuff Member (Steven and others, 1981) indicate that original uranium contents were in the range of 12–18 ppm. Samples of zeolitized rocks of the Joe Lott Tuff Member within the Big John caldera contain only 5–8 ppm uranium, suggesting that about one-half of the original uranium has been lost to the hydrologic regime. In addition, the more welded rocks of the Joe Lott are completely devitrified, making the uranium susceptible to ground-water leaching as noted by Zielinski (1978).

The conglomerate in the base of the Big John caldera basin is exposed in two general areas (fig. 11 and fig. 12): (1) just southwest of Puffer Lake, where stream sediments at least 15 m thick underlie the Joe Lott Tuff Member in stream cuts along Lake Stream and along nearby State Highway 153; and (2) near Three Creek Reservoir, 4 km farther southwest, where stream sediments of comparable thickness underlie the Joe Lott along the same stream and highway. In neither locality is the base of the conglomerate unit exposed. The area between these two occurrences is completely covered by rocks of the Joe Lott Tuff Member, as are all adjacent areas within the southern part of the Big John caldera. Of especial interest, the sandstones and conglomerates near Puffer Lake are thoroughly oxidized and typically are stained bright red by hematite. In contrast, where these rocks occur near Three Creek Reservoir, which is downstream in the original drainage system near the outlet of the Big John basin, they are dull brown in color and show little evidence of alteration. Therefore, an oxidation-reduction front could exist in the covered area between these occurrences, and, in a uranium-rich province such as this, could have uranium deposits associated with it. Preliminary helium and thermoluminescence studies (Reimer, 1979; C. S. Spirakis, U.S. Geological Survey, oral commun., 1979) have been undertaken in this area, but thus far results have been inconclusive.

The outlet canyon that led southward from the Big John caldera provides another potential environment for precipitating uranium from ground water (fig. 12). Except for the first few kilometers outside the Big John caldera, the early postcaldera stream sediments, as well as the overlying ash-flow tuffs of the Mount Belknap Volcanics, were largely stripped from this channel before the younger potassium-rich mafic gravels were deposited. Two circumstances bearing on the potential for uranium occurrences can be envisaged. (1) Ground water from the caldera area could have drained southward through the gravel fill in the channel until the surface and subsurface water-flow pattern was disrupted by basin and range tectonism in later Cenozoic time. The mafic gravels that back-filled the channel thus may have served as a semiconfined aquifer in which oxidation/reduction reactions could have taken place, perhaps with attendant precipitation of uranium. (2) On the other hand, if these younger gravels were derived from a block-faulted terrain to the south caused by concurrent basin and range deformation and basaltic volcanism, ground-water drainage could have been highly disrupted, and ground-water flow might as well have been toward, rather than away from, the uranium-bearing source area to the north. In this case, the potential for uranium deposits in the filled channel would be low. More field studies should be conducted to determine which of these alternatives is the more likely.

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☆U.S. GOVERNMENT PRINTING OFFICE:1984—776-041/4037