Revised Stratigraphy and Radiometric Ages of Volcanic Rocks and Mineral Deposits in the Marysvale Area, West-Central Utah

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Mineralization took place many times during a complex history of volcanic activity in late Cenozoic time

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REVISED STRATIGRAPHY AND RADIOMETRIC AGES OF VOLCANIC ROCKS AND MINERAL DEPOSITS IN THE MARYSVALE AREA, WEST-CENTRAL UTAH

By T. A. STEVEN, C. G. CUNNINGHAM, C. W. NAESER, and H. H. MEHNERT

ABSTRACT

The Marysvale area, Utah, is near the northeast end of a broad belt of Tertiary igneous rocks that extends east-northeastward from southern Nevada to central Utah. In late Oligocene and early Miocene time (30–21 m.y. (million years) ago), a composite volcanic center consisting of numerous local volcanoes was active in the general Marysvale area. The volcanoes consisted of near-source lava flows, volcanic breccias, and minor pyroclastic deposits of generally intermediate composition flanked by coalescing aprons of volcaniclastic debris. Locally derived ash-flow tuffs form important marker beds within the assemblage. Concurrently with local volcanism, ash flows from distant sources in the Great Basin extended into the Marysvale area to interleave marginally with locally derived volcanic rocks.

Local volcanic activity in the Marysvale area probably began about 30 m.y. ago with eruption of mafic intermediate-composition lava flows and volcanic breccias. About 29 m.y. ago, a widespread sheet of crystal-rich ash-flow tuff (Oligocene Needles Range Formation) was spread across the region from distant, as yet unidentified centers to the west or southwest. The Needles Range Formation is exposed all around the Marysvale area, but may have been excluded in places within it by local volcanoes. Accumulation of intermediate-composition volcanic rocks from local centers continued after deposition of the Needles Range Formation, and by 21 m.y. ago, a major pile of volcanic rocks had been built in the Marysvale area. The name Bullion Canyon Volcanics is applied to this assemblage of Oligocene and Miocene volcanic rocks.

About 27 m.y. ago a sequence of distinctive crystal-rich ash flows was erupted from a center in the northern part of the Marysvale pile, and a small trapdoor type block subsided at the source. The resulting ash flow tuff sheet, here named Three Creeks Tuff Member of the Bullion Canyon Volcanics, made up a significant part of what was formerly considered part of the Dry Hollow Formation. The Dry Hollow previously was believed to be younger than the Bullion Canyon Volcanics. However, we have found the Three Creeks Tuff Member in Bullion Canyon, in the type locality of the Bullion Canyon Volcanics, thereby demonstrating the lateral equivalence of the Dry Hollow and part of the Bullion Canyon. We abandon the name Dry Hollow Formation.

Bullion Canyon rocks overlying the Three Creeks Tuff Member consist of a poorly understood assemblage that includes a basaltic andesite shield volcano, ash-flow tuffs of diverse lithologies and sources, and intermediate-composition lava flows and volcanic breccia. The Delano Peak Tuff Member (formerly the Delano Peak Latite Member) is one of the more distinctive of the ash-flow units in the upper part.

Between 21 and 18 m.y. ago, repeated rhyolitic eruptions from two source areas in the Marysvale area produced a heterogeneous assemblage of ash-flow tuffs, lava flows

and domes, and associated pyroclastic and mudflow breccias, and emplaced local rhyolite and granite intrusive bodies. Two cauldrons, the major Mount Belknap caldera and the minor Red Hills caldera, subsided in response to ash-flow eruptions. Intracaldera and near-source densely welded tuffs of the Mount Belknap Volcanics (formerly Mount Belknap Rhyolite) are generally equivalent to the less welded outflow facies of the Joe Lott Tuff Member (formerly formation rank), and the whole rhyolitic assemblage is here called the Miocene Mount Belknap Volcanics. The outflow is designated the Joe Lott Tuff Member of the Mount Belknap. The intracaldera and outflow facies from both source areas are divided into several new formal and informal members with complex interrelationships.

Basin-range faulting began after eruption of the Mount Belknap Volcanics, and continued through much of the remainder of Cenozoic time. The Sevier River Formation consists of fluviatile and minor lacustrine sediments deposited in basins that developed concurrently with faulting. Basalt flows were erupted widely but in low volume during the period of Sevier River sedimentation.

Alteration and mineralization in the Marysvale area took place at several times and at many different locations during middle and late Cenozoic time. Volcanic rocks adjacent to local monzonitic intrusions in the southern Antelope Range were widely altered about 22 m.y. ago during terminal stages of eruption of the Bullion Canyon Volcanics. Alunite of potential economic value was formed at many of the centers of alteration, and sparse copper is known at a few. The gold- and silver-bearing veins in the Kimberly area on the northern slope of the Tushar Mountains appear also to have formed at about this time.

The uranium-molybdenum-fluorine mineralization in the main uranium producing district of the Marysvale area (central mining area) took place later, after accumulation of the Mount Belknap Volcanics. This mineralization was most intense in the southern Antelope Range in the area that had previously been widely altered and mineralized during the latter part of Bullion Canyon volcanic activity. The major mineralized area in the eastern Tushar Mountains, characterized by zonally arranged alunite deposits and base-and-precious-metal veins and mantos, formed about 14 m.y. ago, after Mount Belknap volcanism. Widespread occurrences of uranium in the fill and in adjacent walls of the Mount Belknap caldera also formed after the Mount Belknap Volcanics had erupted.

A much younger, probably Pleistocene, period of mineralization is represented by native sulfur deposits along the northwest side of the Marysvale volcanic pile. These deposits probably are related genetically to geothermal systems generated by nearby basaltic volcanoes of Quaternary age.

INTRODUCTION

Restudy of the regional geology and mineral resources of the Marysvale area, Utah, begun in 1975, has resulted in significant revisions in the local volcanic stratigraphy. More such revisions will undoubtedly be required as the study progresses. Concurrently with the field studies, numerous radiometric age measurements of volcanic rocks and mineralized materials have been made. These, in conjunction with ages already published by earlier workers, establish a time frame for volcanic activity and mineralization in the area. The revised stratigraphy and age data have specific application to several mineralized districts near Marysvale, and are intended to aid in exploring for and in developing any mineral resources that may exist.

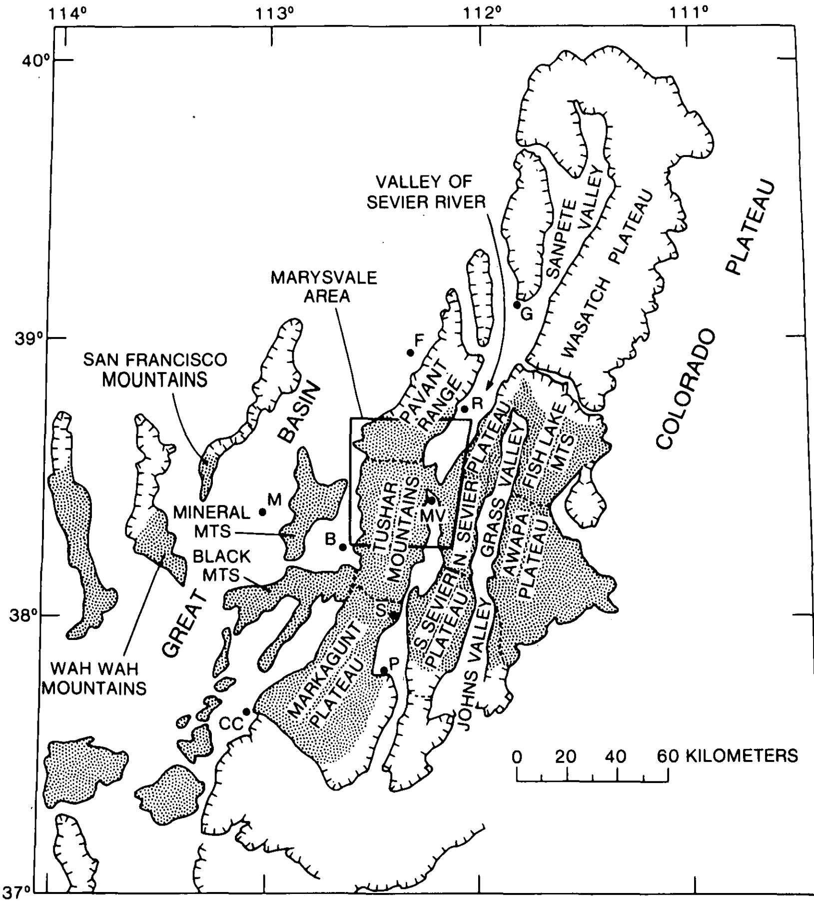

FIGURE 1.—High Plateaus and adjacent areas of southwestern Utah. Stippled areas are underlain largely by volcanic rocks. G, Gunnison; F, Fillmore, R, Richfield, Mv, Marysvale; B, Beaver; M, Milford; P, Panguitch; CC, Cedar City; S, Spry intrusion. Modified from Anderson and Rowley (1975, fig. 1).

GEOLOGIC SETTING

The Marysvale area (figs. 1 and 2) is near the northeastern end of a broad belt of Tertiary igneous rocks and associated mineral deposits as much as 100 km (kilometers) wide that extends for more than 350 km east-northeastward from southeastern Nevada into central Utah. The northeastern terminus is along the eastern margin of the Awapa Plateau and Fish Lake Mountains (Williams and Hackman, 1971) at the border between the High Plateaus subprovince and the Colorado Plateaus province proper (fig. 1). Marysvale is in the Sevier River valley about 65 km west-southwest of this terminus. The geologic relations described in this report are exposed largely in the Tushar Mountains and southern Pavant Mountains west and northwest of Marysvale.

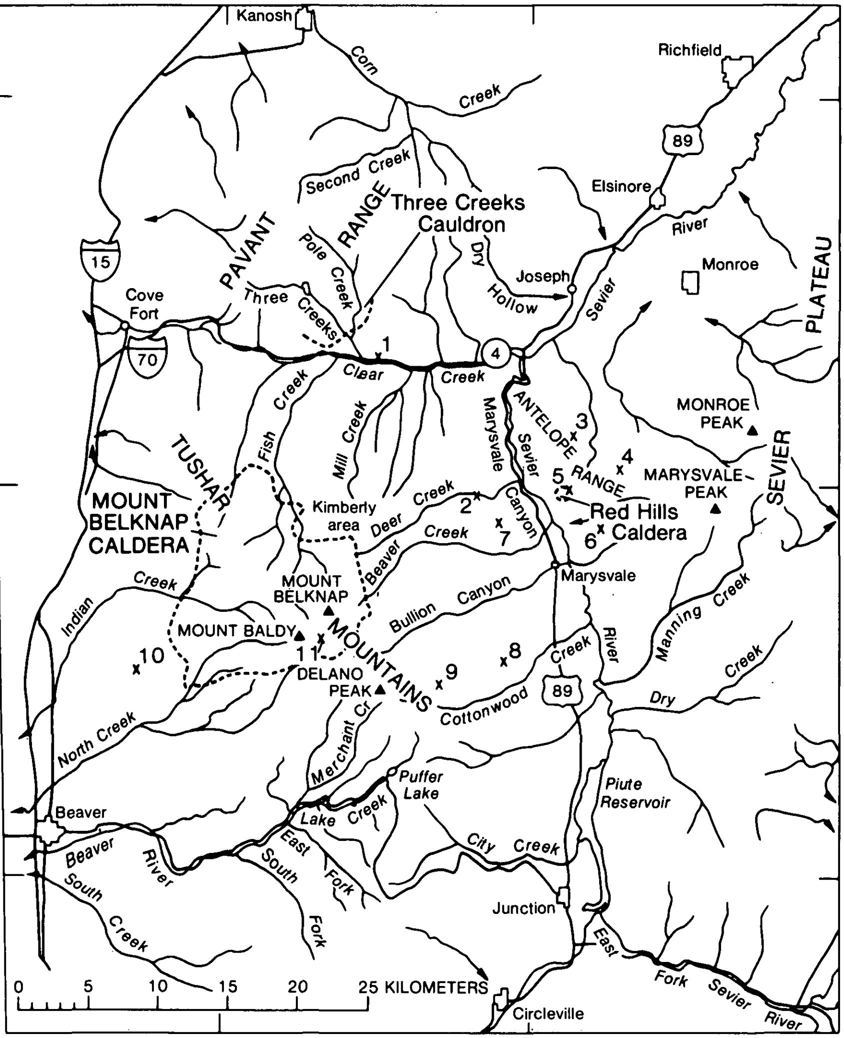

FIGURE 2.—Ash-flow-related cauldrons and points of reference in the Marysvale area, Utah. 1, The Narrows; 2, Winkleman alunite deposit; 3, Yellowjacket alunite deposit, 4, The Teacup, 5, Red Hills; 6, Whitehorse alunite deposit; 7, Gray Hills; 8, Deertrail mine; 9, Mineral Products mine; 10, Sheeprock mine; 11, Blue Lake.

The broad belt of igneous rocks, or various parts of it, has been called by many names, including the Wah Wah-Tushar belt (Hilpert and Roberts, 1969, p. 29–31), Pioche belt (Roberts, 1966; Shawe and Stewart, 1976, p. 226), Pioche-Beaver-Tushar belt (Callaghan, 1973) and informally the Pioche-Marysvale belt. Subsidiary trends within the belt have been called the Delamar-Iron Springs subbelt (Shawe and Stewart, 1976) and the Blue Ribbon lineament (Rowley and others, 1978). These refinements have little impact on this report other than to indicate existence of the complex belt, and the geographic position of the Marysvale area within it.

The Marysvale area has long been recognized as being a composite volcanic center that shed volcaniclastic debris and possibly pyroclastic deposits laterally in all directions to intertongue with volcanic units from other centers. The Marysvale accumulation consists of numerous local volcanoes made up of complex assemblages of near-source lava flows and volcanic breccias of generally intermediate composition (largely andesitic and rhyodacitic) that were erupted between 30 and 21 m.y. ago. The local vent facies rocks pass laterally into reworked deposits that coalesce into a widespread composite apron surrounding the clustered volcanoes. Local and regional ash-flow sheets are interleaved with the Marysvale volcanic assemblage, and provide much-needed stratigraphic markers.

During the same interval that the generally intermediate-composition volcanic rocks were erupted near Marysvale (30–21 m.y.. ago), widespread ash-flow tuff sheets were accumulating in adjacent parts of the Great Basin area from the Tushar Mountains westward into Nevada. This great ash-flow tuff field has been studied by many geologists, chiefly by J. H. Mackin (1960, 1963) and many of his students (Mackin and others, 1954; Nelson, 1950; Mackin and Nelson, 1950; Blank, 1959; Blank and Mackin, 1967; Threet, 1952, 1963a, 1963b; Cook, 1957, 1960, 1965; Williams, 1967; Anderson, 1965, 1971; Anderson and Rowley, 1975; Rowley, 1968). Other workers who have studied aspects of the volcanic geology of southwestern Utah are Armstrong (1970); Best and others (1973); Bushman (1973); Caskey and Shuey (1975); Earll (1957); Erickson (1973); Erickson and Dasch (1963); Gromme, McKee, and Blake (1972); Lemmon, Silberman, and Kistler (1973); Liese (1957); McGookey (1960); and Shuey, Caskey, and Best (1976). As a result, the complex stratigraphy of the ash-flow tuff field is fairly well known, and the distribution (although not the sources) of many of the individual sheets has been established. This well-known sequence in the Great Basin area, however, is only partly coordinated with coeval events in the Marysvale area, largely because many details of the volcanic sequence in the latter area have been poorly known.

Beginning about 21 m.y. ago, the volcanic materials erupted in the Marysvale area changed markedly to silicic alkali rhyolite flows, domes, and ash-flow tuffs. The largest volume of these silicic rocks was erupted between then and 18 m.y. ago, and a major caldera[1] in the central Tushar Mountains subsided 19 m.y. ago in response to catastrophic

[1]We use the terminology of Smith and Bailey (1968, p. 616) in which cauldron is the general term describing all volcanic subsidence structures regardless of size or shape, and caldera is limited to more or less circular depressions generally formed by volcanic subsidence.

eruption of many tens of km^3 of ash-flow tuffs. Similar rocks were erupted episodically throughout the remainder of Cenozoic time in west-central Utah, but only locally and in relatively small volume (Lipman and others, 1975; Mehnert and others, 1977; Erickson, 1973, p. 20–21; Earll, 1957, p. 60–62; Petersen, (1975). Scattered basalt flows were erupted from many centers during the same interval.

PREVIOUS STRATIGRAPHY

The basic stratigraphy of the Marysvale area as previously understood was largely established by Callaghan (1939). The bulk of intermediate-composition volcanic rocks was called Bullion Canyon Volcanics of Miocene(?) age. As described by Callaghan, the lower 2,500 feet[2] of the unit consist predominantly of latitic and andesitic tuffs and breccias with 10 percent or less flows. The Delano Peak Latite Member near the middle of the formation was considered to be a single thick lenticular lava flow over 800 feet thick. The upper part of the formation was described as a mixture of dark lava flows and volcanic breccias in which the flows constitute 50 percent or more of the assemblage; this part of the unit was believed to be 2,500 feet or more thick.

The sequence of rocks overlying the Bullion Canyon Volcanics of Callaghan (1939) was rearranged somewhat by Calwaghan and Parker (1961a, 1961b, 1962a, 1962b) and Willard and Callaghan (1962) to include the Roger Park Basaltic Breccia to the south, and a younger unit of thick widespread latite flows they called Dry Hollow Formation, both interpreted by them to be Pliocene(?) in age. Some tuffs and basaltic andesite lava flows were included in the Dry Hollow Formation. A major criterion Callaghan and associates used to distinguish the units was degree of alteration; the Bullion Canyon was described as widely altered, whereas the Roger Park and Dry Hollow are characteristically fresh. The age of the Roger Park was changed to Miocene by Anderson and Rowley (1975).

The young rhyolites of the Marysvale area were split into two presumably sequential units of Pliocene(?) age. Those in the central and eastern Tushar Mountains were called Mount Belknap Rhyolite, and were separated into the informal red Mount Belknap welded tuffs and the gray Mount Belknap lava flows. These were believed to be somewhat older than, although closely related to, the softer, gray, partly welded rhyolite tuffs of the Joe Lott Tuff that crop out in places all around the periphery of the high Tushar Mountains.

Fluviatile and minor lacustrine deposits of the Sevier River Formation filled structural basins that formed in late Cenozoic time, during widespread normal faulting that followed the major rhyolitic eruptions. Local basalt lava flows were erupted during the period of late faulting and Sevier River sedimentation.

This sequence established by Callaghan and associates has been used with only slight modification by most geologists who have worked in the Marysvale area in the last 25 years. A group from Columbia University,

[2]Thicknesses from Callaghan (1939) are given in the units used in the original report (1 foot=0.3 m.).

led by P. F. Kerr, studied the main uranium-producing district and some surrounding areas during the 1950's (summarized by Kerr and others, 1957). They used the basic framework with little change, but gave formal member names to numerous individual local lava flow and volcanic breccia units in the Bullion Canyon Volcanics of Callaghan (1939). Kennedy (1960, 1963a, 1963b) accepted without significant modification the main elements of the early stratigraphy, as did Callaghan (1973). The geology of the Marysvale area is depicted on the geologic map of Utah (Hintze, 1963) according to this same scheme.

The stratigraphic sequence used by Molloy and Kerr (1962) disagrees in important aspects with that used previously in the area, and does not fit with many of our own observations.

Geologists working into the Marysvale area from elsewhere, largely from the Great Basin to the west and southwest, have questioned aspects of the locally established sequence. Mackin (1963) believed that he recognized ash-flow units of his Needles Range Formation within the Dry Hollow Formation in the Clear Creek area between the Tushar Mountains and Pavant Range. The Needles Range Formation is a distinctive and exceptionally widespread ash-flow tuff unit at or near the base of the Tertiary volcanic succession throughout much of southwestern Utah and adjacent parts of Nevada, and is an excellent marker unit. Followup work by Caskey and Shuey (1975) demonstrated that the Needles Range Formation is indeed present in this area, but at a lower horizon near the base of the volcanic pile, and that the unit observed by Mackin was a lithologically similar but probably local ash-flow tuff higher in the volcanic succession. This younger tuff was named the Clear Creek Tuff Member of the Bullion Canyon Volcanics by Caskey and Shuey (1975), an appropriate name from local considerations, but one that has been preempted by prior use elsewhere and is thus unacceptable. Both Mackin (1963) and Caskey and Shuey (1975) recognized that the welded tuff along Clear Creek was equivalent in part to a local tuff member and in part to a latite lava flow member of the previously described Dry Hollow Formation.

A most important contribution in the volcanic stratigraphy of the High Plateaus area of Utah was made by Anderson and Rowley (1975), who mapped large areas in the southern Sevier Plateau, Markagunt Plateau, southern Tushar Mountains, and Black Mountains (fig. 1) south of the Marysvale area. These workers summarized all available data on the Cenozoic volcanic sequence to the south and southwest, and attempted to make preliminary correlations with the sequence described by Callaghan and associates in the Marysvale area. They noted certain discrepancies between the established Marysvale stratigraphy (largely within the Bullion Canyon Volcanics) and observations made by them. Being unable to coordinate the described sequences in the two areas, Anderson and Rowley (1975) named their assemblage of intermediate-composition lava flows and volcanic mudflow breccia the Mount Dutton Formation, and suggested that the term Bullion Canyon Volcanics might be a more appropriate term in the northern part of the Marysvale volcanic pile. This introduction of duplicate nomenclature for what is probably the same conceptual assemblage of rocks may have had advantages as a temporary palliative, but in the long term it cannot do other than confuse future stratigraphic discussions.

Anderson and Rowley (1975) clearly showed that the regional Needles Range Formation is at or near the base of the volcanic sequence along the southern margin of the Marysvale pile, that the overlying ash-flow sheets of the Great Basin sequence intertongue with peripheral deposits from the Marysvale centers along the southwestern side of the pile, and that other ash-flow tuff sheets of different provenance intertongue with similar marginal deposits to the south and southeast.

Williams and Hackman (1971) mapped the east end of the broad igneous belt in the northern Sevier and Awapa Plateaus and Fish Lake Mountains. Most of these deposits are marginal correlatives of the Bullion Canyon Volcanics or of the Mount Dutton Formation, but Williams and Hackman also distinguished at least one regional ash-flow tuff sheet (Osiris Tuff of Miocene age) also described by Anderson and Rowley (1975).

These peripheral studies thus have built a skeletal geologic framework nearly all the way around the local Marysvale pile. The framework of overlapping regional ash-flow tuff sheets provides a basis for deciphering the local complexities and placing them in a regional context.

PRESENT INVESTIGATIONS

Our own field investigations (by Steven and Cunningham) in the Marysvale area, made during the summers of 1975 and 1976, have indicated that major revisions are required in the previously used stratigraphy. Corroboratory evidence has come from radiometric dating of volcanic and mineralized rock samples (by Naeser and Mehnert). Rather than being sequential units, the formerly described Bullion Canyon Volcanics and Dry Hollow Formation are largely lateral equivalents. The Clear Creek Tuff Member of Caskey and Shuey (1975), herein renamed the Three Creeks Tuff Member of the Bullion Canyon, is a distinctive locally derived ashflow unit that has been recognized within both the Bullion Canyon and Dry Hollow; lithologic correlation is supported by radiometric ages. The Delano Peak Latite Member (Callaghan, 1939) is a thick simple cooling unit of densely welded ash-flow tuff of unknown source within the Bullion Canyon Volcanics in the central Tushar Mountains.

Ash-flow tuffs in the Mount Belknap Volcanics (the red member of the Mount Belknap) are densely welded near-source equivalents of the less welded peripheral Joe Lott Tuff; the two facies intergrade laterally and comprise a single outflow sheet derived from the Mount Belknap caldera source in the central Tushar Mountains. Rhyolite lava flows and domes of comparable composition (the gray member of the Mount Belknap) were erupted from a separate source area north of Marysvale over a span of 3–4 m.y., a span that also included the pyroclasttstic eruptions from the Mount Belknap caldera source. The caldera was filled by a complex mixture of rhyolite lava flows, volcanic breccias, and ash flow tuffs lithologically identical with comparable rock types in the Mount Belknap Volcanics outside the caldera.

Hydrothermal alteration and mineralization took place around local centers during both Bullion Canyon and Mount Belknap periods of eruption. In places the effects of different periods of hydrothermal activity are superimposed.

These relations are only fragments of the total architecture of the Marysvale volcanic pile, but they do provide some limits within which other aspects of the geology must abide. They have direct bearing on mineral exploration now being conducted in the area, and this factor alone provides a major incentive to publish our partial conclusions now. The distribution of near-source (vent) facies rocks versus outflow volcaniclastic facies rocks within the Bullion Canyon Volcanics has not been determined yet, nor has the attempt been made to separate out mappable units within the Bullion Canyon other than a few selected ash-flow tuffs. Subtle variations have been observed within the Mount Belknap Volcanics, but the geologic significance of these remains to be established in more than a cursory manner. In only one very limited area has our work extended far enough out toward the margins of the local volcanic pile to include any of the regional ash-flow tuff sheets from distant sources in the Great Basin or elsewhere. These and other matters are for future study and discussion.

NEEDLES RANGE FORMATION AND OLDER VOLCANIC ROCKS

Inasmuch as most of our effort to date (1976) has been directed elsewhere, only the broad aspects of the lower part of the Bullion Canyon Volcanics of Callaghan (1939) can be discussed in this report. Work by others, corroborated by scattered observations by us, indicate that this part of the volcanic succession consists of locally derived intermediate-composition lava flows and volcanic breccias interleaved with ash-flow tuff sheets from various sources. The quantities of the different constituents vary widely from place to place, and little now can be said about relative distributions.

A major breakthrough (Mackin, 1960, 1963) in understanding the stratigraphy of the lower part of the volcanic succession has come from recognition of ash-flow tuffs of the Needles Range Formation near the base of the pile at many scattered localities around the periphery of the Marysvale accumulation. As the Needles Range rocks in this vicinity are commonly underlain by a few meters to as much as several hundred meters of locally derived lava flows and volcanic breccias, volcanism in this vicinity obviously started somewhat earlier. Fleck, Anderson, and Rowley (1975, p. 56–57; with additional details by Anderson and Rowley, 1975, p. 12–13) obtained an age of 31. 1±0.5 m.y. for a local ash-flow tuff below the Needles Range in the northern Markagunt Plateau, south of the Marysvale pile (fig. 1). The position of this tuff with respect to the pre-Needles Range volcanic rocks from centers near Marysvale is not known, but the age at least gives evidence for the beginning of volcanic activity in the general region. In the San Francisco and Wah Wah Mountains 90–115 km west of Marysvale (fig. 1), Lemmon, Silberman, and Kistler (1973) dated local pre-Needles Range volcanic rocks as 34–31 m.y. old; whereas these ages have regional significance on the beginning of middle Tertiary volcanism in southwestern Utah, they may have little bearing on the time that volcanism began near Marysvale. The relatively small volume of pre-Needles Range volcanic rocks known near Marysvale suggests that local volcanic activity here probably was not significant before about 30 m.y. ago, but additional data from radiometric dating are obviously needed.

Caskey and Shuey (1975, p. 18) described a local andesitic lava flow, which they called the Sulphur Peak Member of the Bullion Canyon Volcanics, several hundred meters thick, at the base of the volcanic succession along the southwestern margin of the Pavant Range northeast of Cove Fort (fig. 2). They did not specify the stratigraphic position of this lava flow with respect to the Needles Range Formation in their text discussion, but on their table 1 it is shown as older. At Site 200 of Caskey and Shuey (1975, fig. 3), 4.5 km north of Cove Fort on Highway 15, where they made magnetic measurements on the Needles Range Formation, we estimate that dark volcanic mudflow breccia 50–70 m thick underlies the Needles Range. When traced laterally southeastward for a kilometer or so, the Needles Range sheet overlies a thick porphyry lava flow of intermediate composition (possibly the Sulphur Peak Member of Caskey and Shuey, 1975) that must have been derived from a nearby source. Red and white sedimentary rocks of the lower Tertiary Claron Formation underlie the volcanic succession north of Site 200.

The base of the volcanic sequence was mapped in reconnaissance by us along Second Creek, 10 km southeast to south of Kanosh (fig. 2) to establish the local succession within our own area of concern. Here the Claron Formation is overlain by dark volcanic mudflow breccia a few tens of meters thick, which in turn is overlain by a succession several hundred meters thick of complexly intertonguing ash-flow tuffs of Needles Range Formation and local dark volcanic breccia and minor lava flows. Even the basal volcanic breccia just above the Claron Formation contains fragments of Needles Range ash-flow tuff. Clearly ash flows of distant derivation accumulated concurrently with locally derived intermediate-composition volcanic breccia and lava flows.

South and southeast of the Marysvale volcanic pile, Anderson and Rowley (1975, p. 14) described thin local deposits of ash-flow tuff, lava flows, volcanic mudflow breccia, and volcanic arenite that separate the sedimentary Claron Formation from the Needles Range Formation. A local laccolithic body called the Spry intrusion (Anderson and Rowley, 1975, p. 16) 45 km south of Marysvale (fig. 1) is believed to have been emplaced during the same interval; related volcanic eruptions spread autoclastic volcanic breccia and ash-flow tuffs widely over adjacent parts of the Markagunt Plateau and southern Tushar Mountains.

The Needles Range Formation is a distinctive crystal-rich ash-flow tuff that extends over an area of more than 50,000 km^2 in southwestern Utah and adjacent parts of Nevada. At least three separate ash-flow sheets, the Cottonwood Wash, Wah Wah Springs, and Lund Tuff Members, with different distributions and probably different local sources have been recognized (Shuey and others, 1976). All members contain abundant phenocrysts of plagioclase, quartz, biotite, and hornblende, in different proportions, set in a variably welded matrix. Numerous radiometric ages measured on samples of the three members from widely scattered areas, collected at different times by different geologists, and analyzed in different laboratories, indicate that the Needles Range eruptions took place in late Oligocene time about 29 m.y. ago; a "best estimate" age of 28.9 ± 1.2 m.y. has been given by Fleck, Anderson, and Rowley (1975, p. 58).

Rocks of the Needles Range Formation have been recognized as far east as the Fish Lake Mountains plateau northeast and east of the Marysvale area (fig. 1) (McGookey, 1960; Williams and Hackman, 1971), in the Sevier and Markagunt Plateaus southeast and south of Marysvale (Anderson and Rowley, 1975) and on the west side of the Pavant Range northwest of Marysvale (Caskey and Shuey, 1975). Magnetic measurements made by Caskey and Shuey (1975) and distribution maps published by Shuey, Caskey, and Best (1976) indicate that the Needles Range rocks near Marysvale belong to the Wah Wah Springs Tuff Member of the formation.

Whereas known exposures of Needles Range Formation virtually surround the Marysvale area, no evidence is known to indicate that the formation ever extended unbroken across the area. The base of the volcanic pile near Marysvale can be seen along the eastern face of the Tushar Mountains between Bullion Canyon and Cottonwood Creek (fig. 2), where an anticline of pre-Tertiary sedimentary rocks is exposed in cross section. Cursory examination of the lower part of the volcanic succession above the sedimentary rocks in local areas did not disclose any Needles Range ash-flow tuffs here; this may indicate that the sedimentary rocks are part of a prevolcanic hill that stood above the level of accumulation of the Needles Range Formation and earlier volcanic rocks. Elsewhere the Needles Range may have been excluded by local volcanoes built by earlier or concurrent eruptions, as for example the Spry intrusion (Anderson and Rowley, 1975), or by lower Tertiary upwarps that predate the volcanic rocks (Rowley, 1968).

BULLION CANYON VOLCANICS

The Oligocene and Miocene Bullion Canyon Volcanics is a complex assemblage of near source and outflow facies lava flows, volcanic breccias, and volcanic mudflow breccias that accumulated around a cluster of generally intermediate composition volcanoes centered in the Tushar Mountains, Antelope Range, and northern Sevier Plateau. Ash-flow tuffs of local and distant derivation interleave marginally with the heterogeneous volcanic rocks of the clustered volcanoes.

The resulting pile of volcanic rocks is obviously so complex that it will eventually have to be split into numerous units to be mapped separately. Our present state of knowledge is too rudimentary in many aspects to do this now in more than a preliminary manner. Certain ash-flow tuff units are distinctive and can be recognized as individual members, but the whole assemblage must now be treated as a single formational unit, which, following Callaghan (1939), we call the Bullion Canyon Volcanics.

LOWER PART

Bullion Canyon Volcanics overlying the Needles Range Formation have been accorded even less attention than those below the formation during these early stages of our investigation. In the type locality (Callaghan, 1939), along the southern slope of Bullion Canyon, the lower volcanic units of the Bullion Canyon seem largely to be mudflow breccias. This is the area where Callaghan (1939) described the lower 2,500 feet of the formation as consisting largely of volcanic tuffs and breccia, and less than 10 percent of lava flows. The thickness cited by Callaghan for the lower part probably includes an ash-flow tuff near the top to be described by us as part of the Three Creeks Tuff Member (new name).

We have studied the Bullion Canyon Volcanics overlying the Needles Range Formation in local detail only along the southwestern side of the Pavant Range north of Interstate Highway 70 (fig. 2), in an area mapped previously by Caskey and Shuey (1975). Thick local lava flows and associated volcanic breccia of intermediate composition are interlayered with ash-flow tuffs from unknown sources. Two of the tuffs form well-defined ledges that can be traced easily across the mountain front; these were named Wales Canyon Tuff Member by Caskey and Shuey (1975) for exposures in Wales Canyon north of Interstate Highway 70 and 8 km east of Cove Fort. Our observations in the type area of the Wales Canyon indicate that two ash-flow sheets of somewhat contrasting phenocryst mineralogy are included in this member; both contain 30–40 percent phenocrysts, largely plagioclase, but the lower sheet contains biotite and hornblende as the mafic crystals, whereas the upper sheet contains biotite and pyroxene. These ledges are broadly lenticular and wedge out laterally against topographic irregularities on the underlying lava flows. Caskey and Shuey (1975, p. 20) reported a maximum thickness of both units of about 200 meters in the type area. The Wales Canyon ledges are overlain in part by thick local lava flows, and in part by our Three Creeks Tuff Member. Present evidence is inadequate to indicate whether the known exposures of the Wales Canyon Member of Caskey and Shuey (1975) are parts of local sheets of limited distribution, or are parts of regional sheets.

Other ash-flow units, generally only partially welded and poorly exposed, are reported by Caskey and Shuey (1975, p. 18) from the post-Needles Range Formation volcanic section in this area, but at this time we have no idea of their distribution or lithology.

THREE CREEKS TUFF MEMBER

A thick crystal-rich ash-flow tuff forms the walls of the canyon of central Clear Creek for about 8 km (fig. 2), and is widespread in adjacent parts of the northern Tushar Mountains and Pavant Range where it overlies the intermediate-composition lava flows and interlayered ash-flow tuffs of the lower part of the Bullion Canyon Volcanics. The crystal-rich ash-flow tuff ranges from densely to slightly welded and shows striking compound cooling characteristics. The less welded parts were called the tuff of Dry Hollow Formation by Callaghan and Parker (1962b), whereas the more densely welded parts were generally included with adjacent lava flows into an informal latite flow member. Mackin (1963) correlated the entire ash-flow unit with his Needles Range Formation, which it closely resembles in gross aspect and phenocryst mineralogy. Caskey and Shuey (1975) recognized that the unit was distinct from the Needles Range Formation and probably was of local derivation. They named it the Clear Creek Tuff Member of the Dry Hollow Formation, and separated it into three informal divisions that differ in degree of welding and purportedly in phenocryst content. We follow Caskey and Shuey in recognizing this crystal-rich ash-flow tuff as a separate unit that can be divided into three parts. By recognizing it within both the Bullion Canyon Volcanics and the Dry Hollow Formation, we demonstrate the lateral equivalence of these two assemblages of rocks that heretofore have been considered to be sequential.

Whereas the name Clear Creek Tuff Member applied by Caskey and Shuey (1975) to this ash-flow unit is an excellent choice from local considerations, the name has been preempted by prior usage as a geologic name in other states. Thus there seems no alternative to renaming the unit, and for this purpose we have chosen the name Three Creeks Tuff Member; this name is taken from Three Creeks, a northern tributary of Clear Creek that traverses the main area of exposure of the unit in the southern Pavant Range (fig. 2). The type area of the Three Creeks is in the cliffs along Three Creeks just upstream from the mouth of Pole Creek where the upper two parts recognized both by Caskey and Shuey (1975) and by us are exposed within the trapdoor cauldron that formed in the source area of the Three Creeks. Inasmuch as the Three Creeks is distinct in distribution and source from all other volcanic units in the Marysvale pile, occurs within both the Bullion Canyon and Dry Hollow Formations, and provides a distinctive marker unit within the volcanic succession, we assign it member rank.

Nearly half of the Three Creeks Tuff Member consists of phenocrysts in a matrix of devitrified glass shards and collapsed pumice fragments. The phenocrysts are about 30 percent andesine, 12 percent amphibole, and 2 percent quartz with beta morphology, together with less than one percent each of biotite, Fe-Ti oxides, sanidine, apatite, sphene, zircon, and scattered grains of calcium-rich monocline pyroxene. The amphibole is kaersutite and is commonly oxidized to an assemblage of Fe-Ti oxides. The amphibole:biotite ratio is variable, but exceeds 5:1 in all samples examined.

The Three Creeks Tuff Member is a multiple ash flow compound cooling unit over much of its extent. To the northeast, near its distal margin in the eastern Pavant Range, volcanic materials from other sources intertongue between some of the individual ash flows, demonstrating that the Three Creeks is indeed a composite sheet in the sense defined by Smith (1960a, p. 801; 1960b, p. 158). The lower part of our Three Creeks Member is generally hard and densely welded, although the multiple ash flow compound cooling characteristics can still be recognized in the ledgy outcrops that display minor variations in degree of welding and local partings. The lower part is best displayed in the reference section of the Three Creeks in the Narrows area (fig. 2) of Clear Creek Canyon, where it forms vertical cliffs of densely welded tuff 100 m high. These cliffs break back into a stepped area of benches and cliffs reflecting compound cooling as the transition toward the softer middle part of the Three Creeks is approached. The total thickness of the lower part exposed along Clear Creek is about 200 m, and the base of the member is not exposed.

The lower part of the Three Creeks Member is also widely exposed in the headwaters area of Clear Creek, Three Creeks, and Pole Creek, where it rests on intermediate-composition lava flows and welded ash-flow tuffs in the lower part of the Bullion Canyon Volcanics. The densely welded ledges of the lower part of the Three Creeks in these areas form broad, slightly inclined surfaces where erosion has stripped off the overlying softer tuffs. The joint pattern in the densely welded tuffs exposed on these surfaces has been etched out by weathering and erosion to give a rough texture to the topography that appears on aerial photographs as a distinctive reticulate pattern. An arbitrary contact between the lower and middle parts was taken at the highest horizon on which this pattern can be recognized. This subjective position can be used only where the lower layers are widely stripped, as in the headwaters of Pole and Three Creeks. To the south along the canyon of Clear Creek, a local parting marked by a meter or so of bedded volcaniclastic sediments was used to separate the members. This parting is well exposed along the southern side of the ridge between Clear Creek and Three Creeks about 400 m west of their confluence, where it separates soft, partially welded tuffs about 10 m above the highest densely welded tuff of the lower member. This parting marks the first clear break above the lowest rocks of the Three Creeks Tuff Member exposed along Clear Creek. Although the parting appears to be at about the same place in the transition from generally hard lower part to soft middle part of the member as the arbitrary position used to separate the parts farther north, we have no assurance that the positions in the transition we have used in different places correspond more closely than within a few tens of meters of each other.

The lower part grades up into the middle part of the Three Creeks Member by a general decrease in degree of welding. Most of the middle part consists of soft, partially welded tuff containing some ledges of harder, more densely welded tuffs. The middle part crops out as prominent ledgy cliffs and benches along Clear Creek and along the middle courses of Three Creeks and Pole Creek. Most of the middle part is white to light-gray, variably welded tuff identical in mineralogy with the lower part. Depending on the local hardness, its topographic expression ranges from smooth slopes or rounded outcrops with local areas of badland topography, to strongly ledgy slopes, where numerous more densely welded layers are interspersed in the softer tuffs. The middle part is 200–250 m thick along Clear Creek, where it is part of the outflow sheet; within the cauldron source area as exposed along Pole Creek, the middle part is more than 500 m thick, and the base is not exposed. This relationship is interpreted to indicate subsidence of the cauldron while the middle part was accumulating. The middle part is generally softer in the outflow facies, and more ledgy in the intracaldera facies.

The upper part of the Three Creeks Tuff Member is restricted to a moat area along the southern margin of the source cauldron, and to the outflow sheet north of the cauldron. It is as hard and densely welded as the lower part, and it typically forms hard caps on hills whose lower slopes are of soft tuffs of the middle part. The phenocryst mineralogy is closely similar to that of the lower and middle parts, and it differs from them only in stratigraphic position and degree of welding.

The base of the upper part was nowhere seen in the outflow area in the headwaters of Three Creeks and Pole Creek because talus from the capping hard upper part covers the smooth slopes on the softer underlying middle part. Along the southern margin of the source cauldron, however, the contact is a clear unconformity; the densely welded upper part abuts and wedges out against the topographic wall of the cauldron. This relation is exceptionally well shown on the west side of Pole Creek canyon, but is also apparent on both sides of Three Creeks canyon to the west. A tongue of the hard upper part filling a canyon tributary to the cauldron extends southwest across Clear Creek about 2.5 km west of the mouth of Three Creeks.

The belt of hard upper part of Three Creeks Tuff Member along the southern side of the source cauldron is an erosional remnant left in the moat of the cauldron after resurgence had uplifted the core and erosion had removed that part of the sheet that once connected these exposures with those capping the hills in the outflow area to the north.

The strongly propylitized succession of volcanic rocks flanking Bullion Canyon in the central Tushar Mountains southwest of Marysvale (fig. 2), and forming the type locality of the Bullion Canyon Volcanics (Callaghan, 1939), contains within it crystal-rich welded ash-flow tuffs, about 100 m thick, that appear once to have been identical to the Three Creeks Tuff Member in its type area. Alteration has modified the original matrix and phenocryst compositions so that only pseudomorphs of the original plagioclase (now albite), biotite, and hornblende (both now chlorite and (or) clay) have survived; the quartz phenocrysts are unchanged. The phenocryst types and abundances are the same as those in the type Three Creeks Tuff Member, however, and the relic texture is identical. The stratigraphic position of this tuff within a section of generally intermediate composition lava flows and volcanic breccia also is comparable.

Caskey and Shuey (1975) reported a K-Ar age of 27.5±0.4 m.y. for the biotite in the lower part of the Three Creeks Tuff Member from the upper Clear Creek drainage area. Our samples (table 1, no. 15) from the same part of the section but from the Narrows along Clear Creek gave

K-Ar ages of 26.9±2.2 m.y. and 28.9±1.3 m.y. for plagioclase, and 30.6±1.3 m.y. and 32.1±1.4 m.y. for biotite. A fission-track age of 27.4±1.3m.y. (table 1, no. 15) for zircon was obtained from the same sample. No reason is known for the discordance between the cluster of ages at 26.9–27.5 m.y. and the cluster at 28.9–32 m.y. However, the average age of the older cluster (30.5 m.y.) is older than the stratigraphically underlying Needles Range Formation (28.9 m.y.) and is thus geologically unreasonable. A fission-track age on zircon from a sample (table 1, no. 14) of the propylitized welded tuff from the southern side of Bullion Canyon is 27.0±1.2 m.y. This age is in close agreement with the younger and more geologically reasonable ages on the Oligocene Three Creeks from the Clear Creek area, and to the degree that any of the ages can be trusted it supports the correlation made above.

Recognition of the Three Creeks Tuff Member within the type locality of the Bullion Canyon Volcanics establishes the partial equivalence of the Dry Hollow Formation (Callaghan, 1939; Callaghan and Parker, 1961a, 1961b) and the Bullion Canyon Volcanics of Callaghan (1939). This indicates that degree of alteration, which was a major criterion used by Callaghan and associates to distinguish the relatively fresh Dry Hollow from the commonly altered Bullion Canyon, has little stratigraphic significance. This conclusion is supported by radiometric ages on sericite (12–14 m.y., Bassett and others, 1963) and alunite (14 m.y., this report, table 1, nos. 16 and 17) from the altered and mineralized area south of Bullion Canyon, to be discussed later. Evidently the alteration and mineralization were much later than emplacement of the host rocks.

THE DRY HOLLOW FORMATION PROBLEM

The rocks immediately overlying the Three Creeks Tuff, constituting much of the Dry Hollow Formation of Callaghan and Parker (1961a, 1961b; 1962a, 1962b), comprise a mixture of intermediate-composition lava flows and volcanic breccia with interlayered welded ash-flow tuffs; this mixture varies widely from place to place, and at present our knowledge of the assemblage is incomplete. In the Clear Creek area (fig. 2), Caskey and Shuey (1975) distinguished three ash-flow tuff units and one intermediate-composition lava flow unit in the Dry Hollow above the rocks we have called Three Creeks Tuff Member. Our reconnaissance suggests that elsewhere lava flows are locally much more abundant than the tuffs.

Along the eastern side of the Pavant Range the assemblage of lava flows and tuffs typical of the Clear Creek area intertongue laterally with a sequence of mafic lava flows that Callaghan and Parker (1961a; 1962b) called the basaltic andesite flows of the Dry Hollow Formation. Callaghan and Parker (1961a; 1962b) noted that these mafic flows thicken

TABLE 1.—*Fission-track and K-Ar analytical data and sample descriptions, Marysvale area, Utah*

[For ρs and ρi, ( ) indicates number of tracks counted. Constants: $\lambda_F = 7.03\times10^{-17}yr^{-1}$; $^{40}K\lambda_\varepsilon = 0.581\times10^{-10}yr^{-1}$; $\lambda_\beta = 4.962\times10^{-10}yr^{-1}$; atomic abundance, $^{40}K = 1.167\times10^{-4}$]

Fission-track analytical data

Sample No.; mineral analyzed[1]	[2]ρs	[3]ρi	[4]$\phi\times10^{15}$	[5]T	U (ppm)
1. M153 (DF-1336); Z	0.972 (144)	10.45 (774)	1.28	7.1±0.7	260
2. M152 (DF-1335); Z	2.57 (369)	13.89 (999)	1.29	14.2±0.9	350
3. M89 (DF-1093); Z	4.29 (755)	15.22 (1338)	1.07	18.0±0.8	460
4. M75 (DF-1083); Z	4.44 (534)	14.51 (873)	.835	15.3±0.8	560
5. M74 (DF-1080); Z	4.72 (918)	14.80 (1439)	.846	16.1±0.7	560
M74 (DF-1352); Z	3.90 (632)	16.91 (1370)	1.24	17.1±0.8	440
6. M92 (DF-973); Z	4.09 (927)	18.20 (2064)	1.46	19.6±0.8	400
M92 (DF-972); A	.129 (537)	5.93 (2469)	1.45	18.8±1.7	13
7. M28 (DF-1106); Z	8.19 (1137)	26.84 (1864)	1.07	19.5±0.7	810
M28 (DF-1106); Z	8.22 (1484)	9.65 (871)	.418	21.3±0.9	740
8. M29B (DF-1092); Z	6.44 (865)	20.38 (1368)	1.08	20.4±0.9	610
9. M50 (DF-1078); Z	5.17 (957)	13.00 (1204)	.851	20.2±0.9	490
10. M49B (DF-1122); Z	3.54 (607)	11.05 (946)	1.09	20.9±1.1	330
M49B (DF-1124); A	.136 (283)	.271 (565)	.930	27.8±3.9	9.4
11. M83 (DF-1114); Z	4.03 (840)	12.72 (1325)	1.15	21.8±1.0	350
M83 (DF-1115); A	.114 (237)	.259 (540)	.904	23.7±3.6	9.2
12. M27A (DF-1130); A	.206 (429)	.468 (976)	.888	23.3±2.6	17
M27A (DF-1129(; Z	8.32 (1464)	10.95 (963)	.418	19.0±0.8	840
13. M98 (DF-1334); Z	5.34 (668)	17.12 (1070)	1.29	24.1±1.2	430
14. 75-S-20 (DF-1123); Z	5.74 (903)	14.47 (1139)	1.14	27.0±1.2	410
15. M90 (DF-1107); Z	4.11 (762)	9.49 (879)	1.06	27.4±1.3	290

TABLE 1.—*Fission-track and K-Ar analytical data and sample descriptions, Marysvale area, Utah*—Continued

K-Ar analytical data				
Sample No.; mineral analyzed[6]	K_2O (percent)	$^{*40}Ar$ (10^{-10} moles/gram)	$^{*40}Ar$ (percent)	[5]T
16. M51A; Al	6.73, 6.73	1.349	66.2	13.8±0.6
17. M51; Al	9.10, 9.17	1.893	62.1	14.3±0.6
18. M48; N	4.79, 4.84	1.155	59.0	16.6±0.8
5. M74; S	5.62, 5.67	1.581	81.1	19.4±0.8
4. M75; S	7.38, 7.32	1.977	75.6	18.5±0.8
7. M28; B	[7]5.81	1.806	77.0	21.4±0.9
8. M29; B	[7]8.53, 8.58	2.678	59.6	21.6±0.9
19. M53; Al	7.65, 7.66	2.424	13.4	21.8±4.3
20. M47B; Al	8.18, 7.99	2.639	63.0	22.5±1.0
21. M30; Al	6.94, 6.93	2.284	52.0	22.7±1.1
10. M49B; S	6.33, 6.35	1.967	83.2	21.4±1.0
M49B; S	9.70, 9.55	3.053	89.9	21.6±0.9
M49B; B	8.94, 8.95	2.805	61.5	21.6±1.1
11. M83; B	8.04, 8.11	3.385	67.6	28.9±1.4
15. M90; P	.74, .75	.292	39.3	26.9±2.2
M90B; P	.82, .75	.329	77.4	28.9±1.5
M90; B	5.47, 5.45	2.542	83.0	32.1±1.4
M90B; B	7.38, 7.19	3.242	86.0	30.6±1.3
22. M256; Al	9.00, 9.11	1.234	49.2	9.4±0.5

[1]Z, zircon; A, apatite.

[2]ρs, tracks/cm² fossil, x10⁶.

[3]ρi, tracks/cm² induced, x10⁶.

[4]ϕ, neutrons/cm².

[5]T, age in m.y. ±2σ.

[6]Al, alunite; B, biotite, N, natroalunite; P, plagioclase; S, sanidine.

[7]By isotope dilution.

SAMPLE DESCRIPTIONS

1. Glassy welded ash from the upper part of the Sevier River Formation. Located 49 m S. 35° E. from the intersection of U.S. highways 89 and 4; lat 38°35'20" N., long 112°15'21" W.
2. Glassy welded ash from the lower part of the Sevier River Formation. Collected 50 m above the Joe Lott Tuff Member upper contact, in the Castle Creek campground on Mill Creek; lat 38°32'55" N., long 112°21'26" W.
3. Upper gray tuff member of Mount Belknap Volcanics. Collected 4.99 km west of the junction of Beaver Creek and the Sevier River; lat 38°28'37", long 112°17'16"
4. Crystal-rich tuff member of Mount Belknap Volcanics. Collected 1.45 km west of the junction of Beaver Creek and the Sevier River; lat 38°28'37", long 112°14'57".
5. Crystal-rich tuff member of Mount Belknap Volcanics. Collected on Grizzly Ridge, 2.4 km west of Puffer Lake; lat 38°18'53", long 112°22'35".
6. Crystal-rich welded tuff in the lower heterogeneous member of Mount Belknap Volcanics. Collected 2.09 km west-northwest of the junction of Deer Creek and the Sevier River; lat 38°30'00", long 112°16'46".
7. Fine-grained granite dike cutting quartz monzonite in the central uranium area. Located 61 m west of the Freedom No. 2 mine; lat 38°29'58", long 112°12'53".
8. Altered quartz monzonite (M29B) cut by fine-grained granite dike (M28), in the central uranium area. Samples picked from the dump of the V.C.A. mine; lat 38°29'55", long 112°12'48".
9. Freshest sample obtainable of the fine-grained granite in the central uranium area. Located at the portal of the Blue Eagle mine; lat 38°30'24", long 112°13'10".
10. Teacup dome in the lower heterogeneous member of Mount Belknap Volcanics; collected from the glassy margin on the south side of Teacup dome; lat 38°30'41", long 112°10'35".
11. Delano Peak Tuff Member of Bullion Canyon Volcanics. Located near the southeast margin of the Mount Belknap caldera, 1.04 km northeast of Mud Lake; lat 38°22'22", long 112°23'52".

TABLE 1.—Sample Descriptions—Continued

12. Quartz monzonite from the central uranium area. Fresh sample from the dump of the Prospector 1 mine; lat 38°29'45", long 112°12'47".
13. Quartz monzonite from the Gold Mountain mining district. Collected on Tip Top, near the Sevier mine; lat. 38°29'20", long 112°24'31".
14. Propylitized Three Creeks Tuff Member of Bullion Canyon Volcanics; collected on the south side of Bullion Canyon, 1.84 km northeast of Mount Brigham; lat 38°23'23", long 112°20'00".
15. Three Creeks Tuff Member of Bullion Canyon Volcanics; collected along Clear Creek at the Narrows; lat 38°34'23", long 112° 22'44".
16. Vein alunite from Mineral Products mine on Alunite Ridge, lat 38°22'25", long 112°19'20".
17. Vein alunite from Mineral Products mine on Alunite Ridge, lat 38°22'25", long 112°19'20".
18. Vein natroalunite from Al Kee Mee mine, northeast of the central uranium area, lat 38°31'39", long 112°10'12".
19. Replacement alunite from the Winkleman alunite deposit in Deer Creek; lat 38°29'38", long 112°17'32".
20. Replacement alunite from the Yellow Jacket mine, north of the central uranium area; lat 38°32'04", long 112°12'30".
21. Replacement alunite from the Whitehorse alunite mine, southeast of the central uranium area; lat 38°28'25", long 112°11'27".
22. Replacement alunite from the Sheeprock mine, 13 km north-northeast of Beaver, Utah; lat 38°22'50", long 112°34'05".

eastward and are as much as 600 m thick in places in the northern Sevier Plateau (fig. 1). Our own observations suggest that this assemblage of flows probably constituted a broad shield volcano that extended eastward into and perhaps across the area of the present northern Sevier Plateau.

In the eastern part of the northern Sevier Plateau just east of the area shown in figure 2, and adjoining the area mapped by Callaghan and Parker (1961a), Williams and Hackman (1971) showed the basaltic andesite flows equivalent to the Dry Hollow to underlie the Osiris Tuff, a regional sheet of densely welded ash-flow tuff that extends throughout wide areas east and south of the Marysvale volcanic pile (Anderson and Rowley, 1975, p. 31–32). Rowley and Anderson (1975, p. 30) reported Osiris Tuff on the eastern flank of the Pavant Range west of Elsinor (fig. 2) but the stratigraphic position of this occurrence is not known. The age of the Osiris Tuff was determined by Fleck, Anderson, and Rowley (1975) to be 22–23 m.y., on the basis of four concordant K-Ar determinations on biotite.

In the southern part of the Marysvale volcanic pile, thick quartz latitic lava flows flanking the Beaver river west of the mouth of Merchant Creek (fig. 2) were mapped by Callaghan and Parker (1962a) as Dry Hollow Formation. Anderson and Rowley (1975) redefined the Dry Hollow Formation as limited to these flows and equivalents, and noted that in the southern Tushar Mountains their redefined Dry Hollow is younger than the Osiris Tuff. Fleck, Anderson, and Rowley (1975) obtained closely concordant K-Ar ages of 21.7±0.4 and 21.8±0.4 m.y. from two of these flows, in conformity with their stratigraphic position above the 22–23-m.y.-old Osiris Tuff.

Thus we find that similarity in lithologic descriptions (only partly matched by similarity in actual rock appearance) between some phenocryst-rich rocks in the northern part of the Marysvale volcanic pile and some thick local quartz latite lava flows in the southern part of the field has led to erroneous correlations. The rocks called Dry Hollow by Callaghan and Parker (1962b) in the Clear Creek area, where descriptions most closely fit those of the flows near Beaver River, are actually densely welded ash-flow tuffs that we now include in the Three Creeks Tuff Member.

The confusion arising from a succession of erroneously interpreted relations has nearly eliminated any utility the name Dry Hollow Formation might have had. Recognizing the Three Creeks Tuff Member as a separate unit within the Bullion Canyon Volcanics, and recognizing the lateral equivalence of the remainder of the type Dry Hollow with parts of the Bullion Canyon Volcanics, takes care of the nomenclature requirements of the assemblage of rocks originally defined as Dry Hollow Formation. The post-Osiris quartz latitic lava flows adjacent to Beaver River appear distinct enough to warrant separate designation. For reasons herein detailed, however, the name Dry Hollow for these flows seems totally inappropriate, and we recommend that they be treated as an informal unit until more is known about their stratigraphic relations. We therefore abandon the name Dry Hollow Formation.

DELANO PEAK TUFF MEMBER

Our observations to date (1976) on those units of the Bullion Canyon Volcanics above the Three Creeks Tuff Member in the central Tushar Mountains have centered on a thick lens of ash-flow tuff that Callaghan (1939) called the Delano Peak Latite Member and that he interpreted to be a single thick lava flow in the middle of the formation. We identify the Delano Peak as a largely propylitized simple cooling unit of densely welded crystal-rich ash-flow tuff and not a latite flow. The rock contains 46 percent phenocrysts including 32 percent andesine, 9 percent amphibole converted to Fe-Ti oxides and calcite, 4 percent Fe-Ti oxides, and less than 1 percent each of quartz, biotite, and apatite in a groundmass of devitrified, altered glass and pumice. The Delano Peak is as much as 250 m thick near the center of the lens. It forms a series of prominent cliffs along the east side of the crest of the Tushar Mountains from the head of Bullion Canyon southeastward for nearly 9 km, and irregularly caps some of the ridges that extend northeastward down from the crest of the range. We have determined three radiometric ages on a sample (table 1, no. 11) of the unit: a K-Ar age on biotite is 28.9$\pm$1.4 m.y., and fission-track ages on apatite and zircon are 23.7 $\pm$3.6 m.y. and 21.8 $\pm$1.0 m.y. respectively. The biotite age is obviously too old, inasmuch as the Delano Peak unit is stratigraphically younger than the 27-m.y.-old Three Creeks unit. The more nearly concordant apatite and zircon ages are geologically reasonable, and suggest that the unit was emplaced about 22 m.y. ago or in Miocene time.

The Delano Peak unit is distinctive in rock type, origin, and topographic expression, and forms a much-needed stratigraphic marker within the Marysvale volcanic pile. We herein call it the Delano Peak Tuff Member of the Bullion Canyon Volcanics. The type locality is at Delano Peak—the same locality used by Callaghan (1939) when he originally defined the unit.

We have mapped none of the rocks either directly below or above the Delano Peak. The section of rocks between the Three Creeks and Delano Peak is within the informal lower sequence of the Bullion Canyon that Callaghan (1939) described as being predominantly volcanic tuff and breccia. We have identified intermediate-composition lava flows at places in this section, and volcanic mudflow breccia elsewhere, but have no idea of their relative abundances or distributions. Callaghan and Parker (1962a) described the rocks overlying the Delano Peak Tuff Member as consisting mostly of dark calcic latite lava flows.

VOLCANIC CENTERS AND INTRUSIVE ROCKS OF THE MARYSVALE CANYON-ANTELOPE RANGE AREA

Near-source lava flows and volcanic breccia (vent-facies of Parsons, 1969) of the Bullion Canyon Volcanics are excellently exposed for the length of Marysvale Canyon (fig. 2), from 4 km north of Marysvale to the confluence of Sevier River and Clear Creek, and make up most of the Antelope Range to the east. Our own observations in this area have been limited to preliminary reconnaissance traverses and to observations along Highwaay 89, which follows the bottom of Marysvale Canyon. Kerr and others (1957, pl. 12) mapped the southern two-thirds of Marysvale Canyon and Antelope Range at a scale of 1:12,000, and separated out numerous individual lava flow and volcanic breccia units within the Bullion Canyon Volcanics. Several monzonitic to quartz monzonitic intrusive bodies cut the vent-facies volcanic rocks (Kerr and others, 1957, pl. 12; Callaghan and Parker, 1961a; Willard and Callaghan, 1962); the largest of these are in the southern Antelope Range, where two plutons, 1–3 and 3–4 km across, are widely exposed. Smaller bodies of fine-grained granite cut the larger of the quartz monzonitic plutons (referred to locally as the "central intrusive") in the vicinity of the main uranium-producing area (central mining area of Kerr and others, 1957). The central mining area is located just east of reference point 5, fig. 2, and the central intrusive body occupies the western two-thirds of the area between points 4 and 5.

This assemblage of near-source volcanic rocks and associated intrusive bodies represents part of a cluster of Bullion Canyon central vent volcanoes. The stratigraphic position of these volcanic rocks with respect to Bullion Canyon Volcanics elsewhere in the Marysvale area, particularly those places where the Bullion Canyon is segmented by recognizable ash-flow tuffs, is still problematic. The walls of Marysvale Canyon expose vent-facies rocks over a vertical range of nearly 900 m, yet neither the Needles Range Formation nor Three Creeks Tuff Member have yet been recognized in this area. On the basis of abundant inclusions of quartzite within some of the smaller quartz monzonitic intrusions, Kerr and others (1957, p. 42) postulated that the base of the volcanics lies at shallow depths beneath present exposures in this area. This interpretation is supported by the presence of an uplifted wedge of contact-metamorphosed sedimentary rocks along the northern margin of one of the larger intrusions (Kerr and others, 1957, pl. 12). This admittedly tenuous suggestion needs more definitive supporting evidence, but if it is true, the thick assemblage of vent-facies volcanic rocks exposed in the Marysvale Canyon-Antelope Range area could be time equivalent to much of the Bullion Canyon sequence and included ash-flow tuffs exposed elsewhere in the region. Under this interpretation, local volcanoes in this area stood high and excluded the ash-flow sheets that periodically flooded lower lying surrounding terrain. This suggestion will obviously be the target of future investigations.

An upper limit to the age of the Bullion Canyon Volcanics in the southern Antelope Range is give by radiometric age determinations on the large quartz monzonitic intrusion (the "central intrusive") in that area. Bassett and others (1963) analyzed seven biotite concentrates from three rock samples; four analyses ranged between 21.3 and 25.3 m.y., whereas three were between 25.1 and 27.2 m.y. Two of the more discordant determination (25.1 and 27 m.y.) were of altered biotite from sample KA 11, and can be disregarded. The third discordant determination (27.2 m.y.) was one of three determinations on biotite from sample KA 2; the other two determinations were more closely concordant at 21.3 and 22.3 m.y. An average of the four most nearly concordant determinations reported by Bassett and others (1963) is 23 m.y. McDowell (1971, p. 15) determined a K-Ar age of 21.8±0.7 m.y. on biotite from the same pluton. We have obtained a fission-track age of 23.3±2.6 m.y. (table 1, no. 12) on apatite from the same quartz monzonitic intrusion; this corresponds closely to the average of most concordant ages obtained by Bassett and others and to the age by McDowell, leading us to conclude that this intrusive body was emplaced about 23 m.y. ago. This age is older than the youngest Bullion Canyon rocks in the central Tushar Mountains, which overlie the 22-m.y.-old Delano Peak Tuff Member.

The fine-grained granite bodies that cut the 23-m.y.-old "central intrusive" were interpreted by Kerr and others (1957) to be closely related to the enclosing quartz monzonite and to be derivatives of the same magma. Our radiometric age determinations on the fine-grained granite, to be discussed more fully in later sections, indicate that this granite was emplaced significantly later, about 20 m.y., during the period of rhyolitic eruptions responsible for depositing the Mount Belknap Volcanics. Different genesis and petrologic association are indicated.

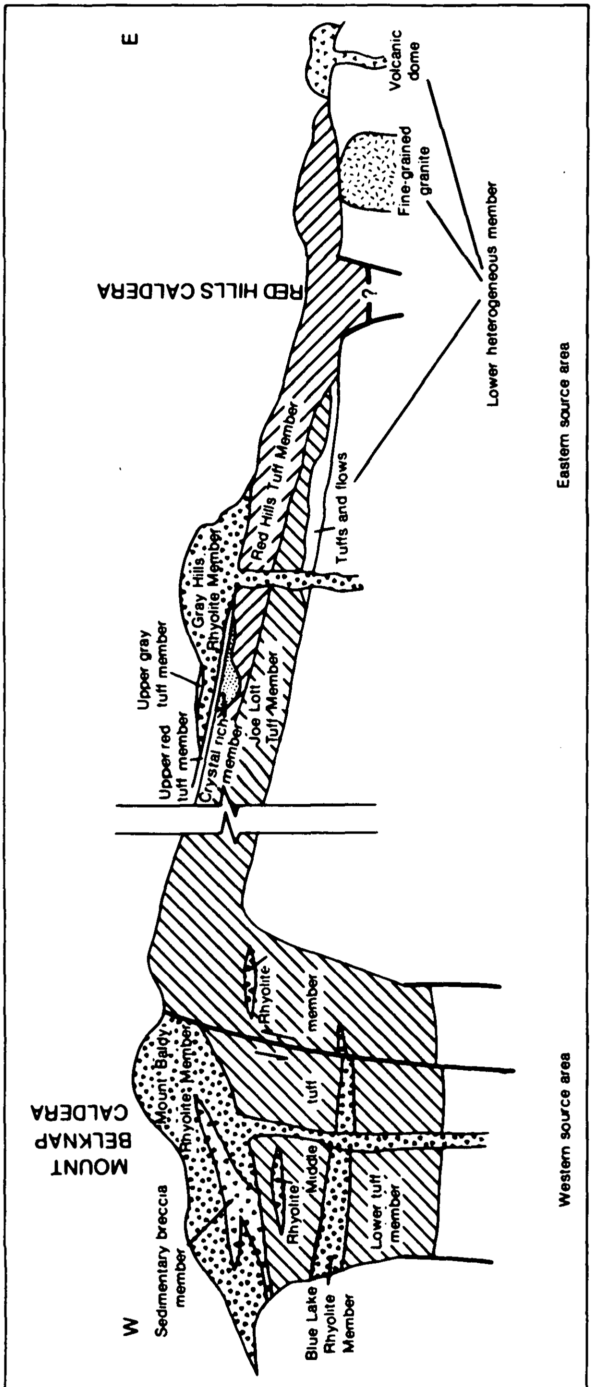

FIGURE 3.—Diagrammatic cross section showing stratigraphic relations of the Mount Belknap Volcanics. Heavy lines, faults; arrows show direction of movement. Not to scale.

MOUNT BELKNAP VOLCANICS

Between 21 and 18 m.y. ago in Miocene time, two source areas, one in the central Tushar Mountains and the other in and adjacent to the southern Antelope Range, were the sites of repeated rhyolitic eruptions that produced a heterogeneous assemblage of ash-flow tuffs, lava flows and domes, and associated volcanic breccias, and also emplaced local rhyolitic to granitic intrusive bodies (fig. 3). Two calderas, the major Mount Belknap caldera and the minor Red Hills caldera (fig. 2) subsided in response to the ash-flow eruptions. With minor exceptions, the assemblage consists of highly silicic, phenocryst-poor alkali rhyolite. The heterogeneous rocks that accumulated near their source in the central Tushar Mountains and Antelope Range were called Mount Belknap Rhyolite by Callaghan (1939), Callaghan and Parker (1961a; 1961b; 1962a, 1962b), and Willard and Callaghan (1962), and the "Mount Belknap volcanic series" by Kerr and others (1957, p. 24). Generally less welded outflow tuffs belonging to the same assemblage were interpreted to be younger than the Mount Belknap and were called Joe Lott Tuff by these workers.

We have demonstrated the general equivalency of part of the Mount Belknap with the Joe Lott rocks and call the whole assemblage the Mount Belknap Volcanics, a formational name comparable in rank and lithologic ending to the underlying Bullion Canyon Volcanics (Callaghan, 1939). The Mount Belknap Volcanics is divided into a complex outflow facies (that includes the Joe Lott) comprising many individual units of lava flows and ash-flow tuffs from both source areas; an intracaldera facies of ash-flow tuffs, lava flows, and volcanic mudflow breccia filling the Mount Belknap caldera; and associated intrusive rocks that cut both facies. The Joe Lott is reduced in stratigraphic rank to a member of the Mount Belknap.

The exposures of rhyolite lava flows and densely welded tuffs on the steep slopes of Mount Belknap constitute the type locality of the Mount Belknap Volcanics. However, these exposures are limited to the lower part of the caldera fill, and most of the heterogeneous intracaldera and outflow facies members are not represented. Each formal member will be accorded a type area as it is described below.

A detailed account of the Mount Belknap Volcanics and of the evolution of the associated calderas is given in another report (Cunningham and Steven, 1979).

OUTFLOW FACIES

Mount Belknap eruptions began in the southern Antelope Range 21–20 m.y. ago with the extrusion of a number of viscous rhyolite flows and domes. Teacup rhyolite dome (table 1, no. 10) in the southeastern Antelope Range (fig. 2) which yielded a fission-track age of 20.9±1.1 m.y. on zircon and K-Ar ages of 21.6±1.1 m.y. on biotite and 21.4±1.0 and 21.6±0.9 m.y. on sanidine, is typical of these; but numerous other domes formed nearby. The rock contains about 45 percent phenocrysts in a matrix that is black glass near the margin of the dome and devitrified elsewhere. The phenocrysts include about equal proportions of sanidine and oligoclase, with lesser amounts of brown biotite, green hornblende, apatite, sphene, and zircon. Heterogeneous minor lava flows and tuffs at the base of the Mount Belknap Volcanics are exposed in lower Deer Creek canyon just west of southern Marysvale Canyon (fig. 2); fission-track age determinations (table 1, no. 6) on zircon (19.6±0.8 m.y.) and apatite (18.8±1.7 m.y.) from a local ash-flow tuff at the top of this local accumulation indicate that these eruptions continued at least until 19 m.y. ago. All these early rocks are here included in an informal lower tuff member of the Mount Belknap Volcanics.

About 19 m.y. ago the Mount Belknap caldera source area became active, and major pyroclastic eruptions spread rhyolitic ash flows outward in all directions. The resulting tuffs are densely welded near their source, but they become progressively less welded toward the periphery, where they have been called the Joe Lott Tuff. All but the most densely welded phases of this sheet show obvious multiple-ash-flow compound cooling characteristics. The tuff contains 1.4 percent phenocrysts including quartz, plagioclase, alkali feldspar, and traces of biotite and accessory minerals in a groundmass of shards and pumice. The Mount Belknap caldera subsided in response to these ash-flow eruptions. The outflow sheet deposited by these major pyroclastic eruptions is here reduced in stratigraphic rank from formation to the Joe Lott Tuff Member of the Mount Belknap Volcanics. The type locality of the Joe Lott (Callaghan, 1939), along Joe Lott Creek 2.5–4.0 km south of Clear Creek, has excellent exposures of the outflow member. The member is about 460 m thick at this locality and shows a wide range in degree of welding as well as numerous partial to complete cooling breaks, representing individual ash-flow boundaries.

Pyroclastic eruptions in the eastern source area in the southern Antelope Range followed those from the Mount Belknap caldera source in rapid succession, and a local, densely welded ash-flow tuff as much as 300 m thick accumulated on both sides of the southern Marysvale Canyon, in the vicinity of the source. The rock contains 7.6 percent phenocrysts of alkali-feldspar, quartz, plagioclase, Fe-Ti oxides, and traces of apatite and zircon. The vent area was in the Red Hills-Dome Hill area (Kerr and others, 1957, pl. 12) 3–5 km north of Marysvale; subsidence accompanied eruption, and the still soft welded tuffs were drawn back downward by the subsiding block of a small caldera about a kilometer across. Small rhyolite lava flows are interleaved with the ash-flow tuffs near their source. The rocks derived from the Red Hills caldera are here called the Red Hills Tuff Member of the Mount Belknap Volcanics. The type area is in the Red Hills about 4.8 km N. 10° E. of the center of Marysvale (fig. 2, loc. 5).

The Red Hills area was recognized as an eruptive source for the "red rhyolite" by Kerr and others (1957) and Gilbert (1957). Molloy and Kerr (1962) described the erupted material as a mixture of rhyolite flows and tuffs from a single magma chamber. John Carmony (oral commun., 1976) suggested to us that the source was in fact a caldera, and we have accepted and enlarged upon his suggestion.

Shallow paleochannels were cut into the tops of both the Joe Lott and Red Hills Tuff Members, and were in turn filled with a distinctive ash-flow tuff containing about 30 percent phenocrysts of quartz, sanidine, plagioclase, and biotite. Remnants of this tuff have been found south, east, and north of the Mount Belknap caldera and are believed to have been derived from that source. K-Ar age determinations are 18.5±0.8 m.y. (table 1, no. 4) on sanidine from this unit near the southern end of Marysvale Canyon 12 km east of the caldera (fig. 2) and 19.4±0.9 m.y. (table 1, no. 5) on sanidine from an outcrop near the mouth of Merchant Creek 10.5 km south of the caldera (fig. 2). Fission-track ages (table 1) on zircon from these same samples were respectively 15.3±0.8 m.y. and 17.1±0.8 m.y.; not only do these numbers disagree with the K-Ar ages, but they also contradict evidence from other radiometric ages that Mount Belknap volcanism was largely over by 18 m.y. ago. This distinctive ash-flow tuff is here informally called the crystal-rich member of the Mount Belknap Volcanics.

A thin, lower, densely welded ash-flow tuff about 5 m thick has been mapped between lower Beaver Creek and lower Deer Creek, where in places it overlies the upper crystal-rich member and in places overlies the Red Hills Tuff Member. It appears to have been deposited by a single ash flow from an unknown source. This unit is a distinctive crystal-poor rock characterized by black, partly collapsed pumice lapilli (fiamme) as much as 3 cm long, enclosed in red devitrified matrix. A basal vitrophyre is exposed locally. It is sufficiently distinctive to serve as a local marker horizon in the area where it occurs. We informally call this unit the upper red tuff member of the Mount Belknap Volcanics.

Locally derived small-volume porphyritic latite lava flows containing phenocrysts of plagioclase, clinopyroxene, and hornblende underlie parts of Beaver Hill (Kerr and others, 1957, pl. 12), 1.6 km northwest of Marysvale and south of Beaver Creek (fig. 2). Kerr and others (1957, p. 32) called these flows "purple porphyry." Whereas these particular lava flows occupy a stratigraphic position between the upper red tuff member and the Gray Hills Rhyolite Member (to be described next), they probably are only one of many local flow units that exist at one place or another within the Mount Belknap Volcanics.The flows contain phenocrysts as much as one cm across of andesine and pale-green diopsidic augite, as well as sparse oxidized crystals of hornblende in a felted groundmass of microcline and hematite. They are noteworthy mostly because their intermediate composition and porphyritic texture contrast with the more common crystal-poor rhyolite that constitutes most of the formation.

The Gray Hills (Kerr and others, 1957, pl. 12) north of lower Beaver Creek (fig. 2, loc. 7) are made up largely of thick rhyolite lava flows with prominent contorted flow layers. Total thickness of the unit is 700 m or more. Phenocrysts are typically sparse, and the flows are characterized by devitrification spherulites and by thin lenticular gas cavities lined with euhedral vapor-phase crystals of quartz and sanidine. The thick local flows, containing contorted flow-folds overturned generally outward from the highest parts of the Gray Hills, argue for accumulation of viscous lava above local vents. These rocks constitute most of the "gray facies" of the Mount Belknap Rhyolite of Callaghan (1939), and were called the Gray Hills Rhyolite by Molloy and Kerr (1962). We call these rocks the Gray Hills Rhyolite Member of the Mount Belknap Volcanics. The area of distribution and the type area (the Gray Hills) of the member are virtually coextensive.

The youngest unit in the composite outflow facies of the Mount Belknap Volcanics that we have identified to date (1976) is a local layer of massive, light-gray, pumice-rich, welded ash-flow tuff that caps the Gray Hills Rhyolite Member near Indian Hollow, 1.8 km north of lower Beaver Creek on the west side of the Gray Hills. It contains a few scattered phenocrysts of quartz and sanidine in a devitrified welded ash matrix. A fission-track age on zircon from this youngest Mount Belknap unit (table 1, no. 3) is 18.0 ± 0.8 m.y. We informally call this unit the upper gray tuff member of the Mount Belknap Volcanics.

INTRACALDERA FACIES

Rocks filling the Mount Belknap caldera are a mixture of densely welded crystal-poor ash-flow tuffs identical with near-source parts of the Joe Lott Tuff Member, thick crystal-poor rhyolite lava flows containing contorted flow layers, and volcanic mud flow breccia and associated finer grained volcanic sediments. The lower part of the caldera fill, exposed best in the eastern and northern parts of the caldera, consists largely of massive densely welded ash-flow tuff that forms layers as much as 500 m thick and is petrographically similar to the outflow Joe Lott Tuff Member. A wedge of rhyolite flow rock splits the welded tuffs into two parts. Only the top of the lower part is exposed in the deeper canyons, and we have no idea how thick this tuff is in the lower, buried parts of the caldera; we informally call this lower unit the lower tuff member of the intracaldera facies of the Mount Belknap Volcanics.

The overlying wedge of lava flows is here called the Blue Lake Rhyolite Member of the intracaldera Mount Belknap Volcanics. The cliff exposures of this member on the flanks of the glaciated valley adjacent to

Blue Lake comprise the type area; it is about 260 m thick in this vicinity. The Blue Lake Member is exposed locally along the west side of the caldera, and prominently just east of Mount Belknap and Mount Baldy in the eastern third of the caldera, and it thins northward and eastward. It is absent near the eastern margin of the caldera. Its stratigraphic position is everywhere covered in the northern part of the caldera, but the great thickness of the overlying welded ash-flow tuff in this area suggests that it may wedge out in this direction as well. The rock contains less than one percent phenocrysts, most of which are sanidine and quartz.

The ash-flow tuffs above the Blue Lake lava flows are identical with those in the lower member; these thin southward against the underlying lava flows and are locally absent along the south and perhaps southwest sides of the caldera. To the north and northeast, however, they thicken to as much as 500 m, and contain local small rhyolite lava flows. These tuffs are called informally the middle tuff member of the intracaldera Mount Belknap Volcanics.

The upper part of the Mount Belknap caldera fill, now exposed largely in the western and southern parts of the caldera, consists of thick, crystal-poor rhyolite lava flows, domes, and marginal talus and mudflow breccias, with local lenses of densely welded tuff. These flows consist of a granular mosaic of quartz, alkali feldspar, minor plagioclase, biotite, and hematite. Some of the flows and domes are as much as 500–700 m thick and 1–2 km across; they commonly thin abruptly toward their margins and are flanked by wedging masses of rudely layered volcanic mudflow breccia and minor finer sediments deposited in low areas between flows. Small lenses of ash-flow tuff also accumulated in the low areas.

The lava flows in the upper part of the caldera are herein called the Mount Baldy Rhyolite Member of the intracaldera Mount Belknap Volcanics. The excellent exposures on the precipitous cliffs forming the upper slopes of Mount Baldy (fig. 2) are designated as the type area, where the member is about 300 m thick. The associated volcaniclastic rocks are called informally the sedimentary breccia member of the intracaldera Mount Belknap Volcanics.

Much of the intracaldera facies has been altered to dense white siliceous rock, probably by hydrothermal activity associated with the many vents that fed the intracaldera flows. The more permeable lava flow margins and flanking breccias were particularly susceptible to alteration. These altered rocks are widely distributed, and their striking white color makes them seem even more abundant than they actually are; this is one natural cauldron that obviously was used for cooking.

To date it has not been possible to establish precise chronology between intracaldera and outflow facies of the Mount Belknap Volcanics. By analogy with calderas in the San Juan Mountains of Colorado

(Steven and Lipman, 1976), in southern Nevada (Byers and others, 1976), and elsewhere, the thick layers of densely welded tuff (lower and middle tuff members) in the lower part of the caldera fill may be generally correlative with the outflow Joe Lott Tuff Member. Caldera subsidence commonly results from voluminous ash-flow eruptions that deposit the outflow sheet; the thick intracaldera tuffs then accumulate in the subsided or concurrently subsiding basin. The flows and domes in the upper part of the fill (Mount Baldy Member) abut the topographic wall around much of the western and southern parts of the caldera margin, but locally on the northwest side of the caldera some of the youngest flows extend out over the edge of the caldera and lie on top of outflow Joe Lott Tuff Member. At one place a lens of distinctive crystal-rich ash flow tuff 5–10 m thick is interleaved with these young lava flows above the Joe Lott; this lens is believed to be correlative with the informal crystal-rich member of the outflow Mount Belknap Volcanics described above. If this correlation is correct, a younger age limit is placed on most of the intracaldera facies. All outflow facies units younger than the crystal-rich member so far identified are of small volume and areal extent, and the intracaldera facies seems largely to have been deposited either concurrently with or shortly after accumulation of the outflow Joe Lott Tuff Member.

INTRUSIVE ROCKS

Rhyolite or granitic intrusive bodies were emplaced locally in the two main source areas during eruption of the Mount Belknap Volcanics. Some of those bodies now exposed were probably feeders for overlying volcanic rocks, and many more of these would undoubtedly be exposed were the level of erosion somewhat deeper beneath areas that currently expose numerous rhyolite flows and domes. We mapped several such pluglike intrusions within the Mount Belknap caldera, and Kerr and others (1957, pl. 12) mapped others in the southern Antelope Range near The Teacup and adjacent volcanic domes. A few rhyolite dikes were mapped by Kerr and associates in the southern Antelope Range and were described by them as being exposed underground in some of the uranium mines in the central mining district.

The largest intrusive body emplaced during the Mount Belknap period of igneous activity is the small stock of fine-grained granite that cuts the older (23 m.y. old) quartz monzonitic central intrusive in the southern Antelope Range, described previously. Kerr and others (1957) believed this granite to be comagmatic with the enclosing quartz monzonite. However, concordant fission-track ages on zircon (19.5±0.7, 21.3±0.9, and 20.2±0.9 m.y.) from two samples (table 1, nos. 7 and 9) are supported by K-Ar ages (table 1) on biotite (21.4±0.9 m.y., no. 7, and 21.6±0.9, no. 8) from the same area. A fission-track age of 20.4±0.9 m.y. on zircon from a sample (table 1, no. 8) of altered quartz monzonite from the same area apparently was reset during emplacement of the nearby fine-grained granite. An overall average of all these generally concordant ages is 20.7 m.y. The fine-grained granite thus appears to be a more coarsely crystalline representative of the same magma that erupted the nearby rhyolite ash-flow tuffs, domes, and flows from the eastern source areas of the Mount Belknap Volcanics.

The complex relations that exist between the fine-grained granite (21–20 m.y. old), the adjacent Red Hills caldera and associated ash-flow tuffs (19 m.y. old), the glassy rhyolite dikes described by Kerr and others (1957), and the uranium-bearing veins that cut all these rocks in the central mining district are an obvious target for future detailed investigation.

SEVIER RIVER FORMATION

The Sevier River formation (Callaghan, 1938, p. 100–101) consists of predominantly fluviatile and minor lacustrine sediments deposited in the developing basins of the High Plateaus in late Cenozoic (Miocene to early Pleistocene) time. Sedimentation was generally concurrent with the widespread basin-range faulting that disrupted the area and led to the present mountainous terrain. Many local ash-fall tuffs within the Sevier River Formation represent episodic volcanic activity in the region during the same period. Basalt flows are locally interleaved with the Sevier River sediments, also indicating episodic volcanism. As each local basin of deposition had its own unique history of structural development and sedimentation, it is difficult to establish any widespread chronology within the Sevier River Formation. Furthermore the formation is generally soft and easily eroded, and outcrops are commonly sparse. Locally, however, it forms badland topography with virtually total exposure.

Our mapping to date (1976) has touched only slightly on the Sevier River Formation and associated basalt flows, and we can add little to descriptions already published. We collected a sample of volcanic ash from a tuff bed about 50 m above the base of the Sevier River Formation along Joe Lott Creek 2.4 km south of the confluence of Clear Creek and Mill Creek, where the formation was deposited on the Joe Lott Tuff Member of the Mount Belknap Volcanics. The two formations appear conformable and no sign of channeling was noted. Zircons separated from this sample (table 1, no. 2) yielded a fission-track age of 14.2±0.9 m.y. We have no explanation yet for the seeming lack of erosion during the several millions of years between emplacement of the Joe Lott and deposition of the Sevier River, as deformation related to basin-range faulting has been documented elsewhere in the region during this same interval.

Another sample of volcanic ash was collected from a tuff bed near the eroded top of the Sevier River Formation, at the type locality near the confluence of Clear Creek and the Sevier River (fig. 2). Zircons from this sample (table 1, no. 1) yielded a fission-track age of 7.1±0.7 m.y. This age certainly does not represent the end of Sevier River sedimentation; it merely indicates that this sedimentation continued well into the late Cenozoic, and that in the depositional basin now drained by Clear Creek, it spanned more than 7 m.y.

ALTERATION AND MINERALIZATION

Altered and mineralized rocks are widespread in the Marysvale area, and geographically they can be separated into many local mining districts and mineralized areas. These have been cataloged in detail by Callaghan (1973), who gave excellent descriptions of the main mines and prospects in each district or area. For our purposes, a broader classification based on geologic occurrence is more convenient. We will discuss age relationships of mineralization in several of the larger areas of occurrence, and some economic implications of these relationships.

The monzonitic intrusive rocks in the southern Antelope Range and adjacent parts of the eastern Tushar Mountains are surrounded by a belt as much as 4 km wide that contains numerous local areas of intensely altered and mineralized rocks. These areas include many of the well-known alunite deposits of the Marysvale area, and some of the altered rocks contain local occurrences of copper minerals. Altered and mineralized rock is exposed within this belt for at least 24 km around the western, northern, eastern, and southeastern periphery of the intrusive center, and may be present under the remainder of the periphery beneath a cover of younger volcanic rock and alluvium. Whereas some of the altered rocks are along the margins of the exposed intrusive bodies, more commonly they are well out into the surrounding volcanic rocks, where they tend to form clusters of altered areas marking centers of hydrothermal activity. These more isolated centers may be localized above hidden satellitic intrusions, as is further suggested by the presence of small plugs of quartz monzonite within some of the outlying altered areas (Kerr and others, 1957, pl. 12; Willard and Callaghan, 1962).

Except for small low-grade occurrences of copper at the Copper Butte-Winkleman mine area (fig. 2, loc. 2) and the Trinity mine (just east of the Sevier River and north of the mouth of Deer Creek) on the west and northwest sides of the intrusive center, published descriptions of the alunitic altered areas (summarized in Kerr and others, 1957; and Callaghan, 1973) do not indicate significant associated base-metal or precious-metal contents. The Trinity deposit is in a wedge of contact-metamorphosed sedimentary rock uplifted along the northern flank of one of the larger monzonitic bodies. Sparse chalcopyrite in this wedge may indicate a potential for contact-metamorphic copper ores in the buried sedimentary rocks beneath other altered areas. Small quantities of uranium were noted by Kerr and others (1957) in many altered areas, but, as will be discussed later, the uranium is demonstrably younger than the alunite and probably was introduced during a later, unrelated mineralizing episode.

Geologic evidence in many places indicates that most alunitic alteration in the southern Antelope Range predated eruption of the Mount Belknap Volcanics. The larger areas of intensely altered rocks are limited to vent-facies Bullion Canyon Volcanics peripheral to a cluster of monzonitic plutons (one of which was dated as 23 m.y. old). In many places unaltered Mount Belknap Volcanics rest unconformably on intensely altered Bullion Canyon Volcanics. This geologic evidence is strongly supported by K-Ar ages on alunite from the Winkleman mine (fig. 2; table 1, no. 19) west of the intrusive center (21.8±4.3 m.y.), from the Yellow Jacket mine (table 1, no. 20) north of the intrusive center (22.5±1.0 m.y.), and from the White Horse mine (table 1, no. 21) south of the center (22.7±1.1 m.y.). Apparently emplacement of the monzonite intrusive rocks was followed shortly by intense hydrothermal alteration of the adjacent volcanic rocks. Future investigations will focus on whether any metallic mineralization took place at lower levels during this period of hydrothermal activity.

Renewed igneous activity during the Mount Belknap period of volcanism erupted rhyolitic lavas and ash flows, and it also emplaced rhyolite and fine-grained granite intrusions in the same general area occupied by the 23-m.y.-old monzonitic intrusions and associated altered rocks in the southern Antelope Range and adjacent areas (the eastern source area of the Mount Belknap Volcanics). Associated hydrothermal activity altered local bodies of rock (largely to clay and silica) and deposited veins containing significant quantities of uranium, molybdenum, and fluorine. In places this newly mineralized material is located separately from the older altered and mineralized rock, but in other places mineralized material of both ages are superimposed. In areas where the hydrothermal episodes were superimposed, paragenetic relations are complex.

The young veins and altered zones cut the fine-grained 21–20-m.y.-old granite of the central mining district, as well as the 19-m.y.-old Red Hills Tuff Member of the Mount Belknap Volcanics. Glassy rhyolite dikes associated with uranium-bearing veins have been reported by Kerr and others (1957); a general association in time between the uranium mineralization and Mount Belknap volcanic eruptions thus is indicated.

Radiometric age determinations (lead/uranium) on pitchblende from the central mining district have ranged widely. J. L. Kulp and associates (in Kerr and others, 1957, p. 61) determined the age of sooty pitchblende to be 9.8±1.2 m.y. from the $^{206}Pb/^{238}U$ ratio. This age was corrected by B. J. Giletti (in Kerr and others, 1957, p. 61) to 10.5±1.2 m.y. Kulp and associates (reported by Walker, 1963, p. 31) also obtained a $^{207}Pb/^{235}U$ age of 24.0±10 m.y. from the same pitchblende—a geologically unreasonable age for material deposited after intrusion of the pre-mineralization fine-grained granite about 21–20 m.y. ago. Kerr (1968, p. 1030) reported a lead/uranium age of about 13 m.y. from uraninite from the same area, analyzed by D. S. Miller. The wide spread in lead/uranium ages that have been obtained from pitchblende (uraninite) from the central mining district casts doubt on the accuracy of any of them. This doubt seems justified as well by the fact that sooty pitchblende seems to have been the material most commonly analyzed. We have attempted to obtain better material for analysis, but so far without success. All that can be said at this time is that the uranium-molybdenum-fluorine veins are younger than the Mount Belknap host rocks, and possibly are several millions of years or more younger.

Vein natroalunite from the Al Kee Mee prospect, 1.6 km north of the Teacup (fig. 2, no. 4), has a K-Ar age of 16.6±0.8 m.y. (table 1, no. 18), indicating that alunitic alteration in the southern Antelope Range also took place during two widely separated episodes. The Al Kee Mee natroalunite and the uranium-molybdenum-fluorine deposits of the central mining district could possibly have been formed during the same general period of mineralization.

Another important mineralized area containing zonally arranged altered rocks and mineral deposits is in the eastern Tushar Mountains in the drainage basins of Bullion Canyon and Cottonwood Creek (fig. 2). Vein deposits of alunite in the Alunite Ridge area on the north side of Cottonwood Creek canyon are flanked on the north by base- and precious-metal deposits in veins in volcanic and sedimentary rocks on both sides of Bullion Canyon and in vein and manto deposits in sedimentary rocks on the eastern front of the Tushar Mountains between Bullion Canyon and Cottonwood Creek. The volcanic rocks in this mineralized area were pervasively propylitized, probably as a result of the same period of hydrothermal activity that formed the veins and mantos. Radon is present in many of the old mine workings, indicating the nearby presence of uranium.

Whereas it was tacitly assumed by most earlier workers that the alunite deposits in the eastern Tushar Mountains and Antelope Range were formed at approximately the same time, evidence now indicates that they formed during different and probably unrelated periods of hydrothermal activity. The deposits in the eastern Tushar Mountains are in largely volcaniclastic facies of the Bullion Canyon Volcanics, and do not appear to be associated with any local volcanic center of that age. The ash-flow sheet of Three Creeks Tuff Member extended across the area, indicating that no local volcanic edifice existed at that time. Bassett and others (1963) reported a K-Ar age of 14–13 m.y. for sericite associated with the base- and precious-metal manto deposit in sedimentary rocks at the Deertrail mine (fig. 2) at the eastern front of the Tushar Mountains, and we have obtained K-Ar ages of 13.8±0.6 and 14.3±0.6 m.y. from two samples (table 1, nos. 16 and 17) of alunite from the Mineral Products mine (fig. 2) on Alunite Ridge. Thus the altered and mineralized rocks in the eastern Tushar Mountains appear to have formed 7–8 m.y. after development of the main alunite deposits in the southern Antelope Range, and are more nearly coeval with the younger natroalunite of the Al Kee Mee prospect and the uranium-molybdenum-fluorine mineralization of the central mining area.

Another relatively young alunite deposit in the Marysvale area is at the Sheeprock mine at the western base of the Tushar Mountains 13 km north-northeast of Beaver, Utah (fig. 2). As described by Callaghan (1973, p. 117–119), the alunite here formed in flow-banded rhyolite typical of the Mount Belknap Volcanics. A K-Ar age (table 1, no. 22) on alunite from the Sheeprock mine is 9.4±0.5 m.y., marking a third episode of alunitic alteration in the greater Marysvale area.

Ore deposits in the Kimberly mineralized area (Gold Mountain district) on the northern flank of the Tushar Mountains (fig. 2) consist of gold- and silver-bearing quartz-carbonate veins cutting Bullion Canyon Volcanics. The volcanic rocks are cut by small monzonitic intrusions and are widely propylitized; on casual inspection the Bullion Canyon rocks seem to consist of near-source volcanics typical of those that accumulate around volcanic centers. Zircon from one of the small monzonitic intrusions (table 1, no. 13) at the Sevier mine yielded a fission track age of 24.1±1.2 m.y., well within the period of Bullion Canyon eruptions.

The altered and mineralized rocks of the Kimberly area form the north wall of the Mount Belknap caldera, and mineralization appears to have predated eruption of the Mount Belknap Volcanics that fill the caldera. The northern margin of the mineralized area is a northwest-trending normal fault that drops unaltered Joe Lott Tuff Member of the Mount Belknap Volcanics down against the altered and mineralized Bullion Canyon Volcanics. The fault is one of many basin-range faults that fragmented the High Plateaus in late Cenozoic time, and thus does not provide a close bracket on the age of mineralization. The lack of evidence for hydrothermal activity in welded tuffs of the Joe Lott in the hanging wall, however, suggests that mineralization at the Kimberly area took place before the Mount Belknap Volcanics were erupted. Several kilometers north of this major fault, two clay pits along Mill Creek exploit kaolinite deposits that formed by intense alteration of Joe Lott Tuff Member adjacent to a minor east-northeast trending fault (Callaghan, 1973, p. 119–120). Evidently two periods of hydrothermal activity affected rocks on the north side of the Tushar Mountains, and the possibility of superimposed mineralization in the Kimberly area cannot be discounted.

Scattered uranium occurrences are known throughout the Mount Belknap caldera fill as well as in the immediately adjacent wall rocks. Some of these seem to be secondary concentrations related to the widespread but patchy alteration that affected the more permeable parts of the caldera fill. In other places, particularly in the precaldera rocks forming the west wall of the caldera, as well as locally within the caldera fill, the uranium occurs in veins and seems to have been introduced (Callaghan, 1973, p. 51–52). Both types of occurrences, however, are either in or associated with rocks or structures related to the Mount Belknap caldera, and are of that age or younger; thus they are broadly comparable in age and geologic association with the major uranium deposits of the central mining district in the southern Antelope Range to the east.

Some of the vein-type uranium deposits west of the caldera are in or near a quartz monzonite intrusion that cuts Bullion Canyon Volcanics on either side of Indian Creek 1.5–4.8 km west of the caldera. The volcanics adjacent to the pluton are locally altered and are cut by gold-bearing quartz veins (Callaghan, 1973, p. 30). Assuming that this intrusive body and associated altered and mineralized rocks are related to Bullion Canyon igneous activity, there seems a strong probability that here, too, at least two episodes of mineralization are superimposed.

An even younger mineralizing event in the Marysvale area is represented by the native sulfur deposits at Sulphurdale and Sulphur Peak near Cove Fort (fig. 2) (Callaghan, 1973, p. 121). The sulfur occurs in siliceous sinter in alluvium of the present surface, and probably is Pleistocene in age. It may be due to hydrothermal activity caused by the same period of volcanism that formed the nearby Quaternary basaltic volcanoes west of Cove Fort.

The mineralized areas we have discussed represent only selected parts of the total assemblage of mineralized occurrences in the Marysvale area. For a comprehheeensive discussion of all known occurrences, the reader is referred to Callaghan's (1973) excellent review. The areas discussed here were chosen to illustrate the multiple ages of mineralization, extending from early Miocene time to Pleistocene, which can now be demonstrated or reasonably inferred. Not only did mineralization take place during widely separated periods of hydrothermal activity, but in many places products of the different periods of activity are superimposed. Some mineral commodities were deposited during more than one mineralizing episode, but others apparently only during one.Proper appraisal of the economic potential of any given mineralized area thus involves consideration not only of "what," "where," and "how much," but also of "when," and "in association with which."

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