GL01539

VOLCANIC SEQUENCE IN THE MARYSVALE REGION IN SOUTHWEST-CENTRAL UTAH

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Introduction

As a consequence of the detailed investigation of the alunite and other mineral deposits of the Marysvale Region in southwest-central Utah, opportunity was afforded to map and study the succession of volcanic rocks that underlie most of this area. The Marysvale Region is part of a large area of volcanic rocks, which occupies much of the High Plateaus of Utah (Fig. 1). It is believed that the Marysvale Region covers sufficient area to furnish an adequate sample of this volcanic area, and, though horizontal variations are known to occur, the study may serve as a guide as to what may be expected in other parts of the area. The chemical analyses are the most completely representative of any ever taken in this part of Utah, and they furnish a basis of comparison within the High Plateaus and with other areas in Utah.

The rocks in the Marysvale Region range from basalt to rhyolite, with latite and rhyolite as the dominant groups. Volcanic breccias and tuffs make up the greater volume of material. Three groups are distinguished: First, an earlier Tertiary group of latitic breccias, tuffs, and flows; second, a later Tertiary group of rhyolites, quartz latites, latites, and tuffs; and, third,

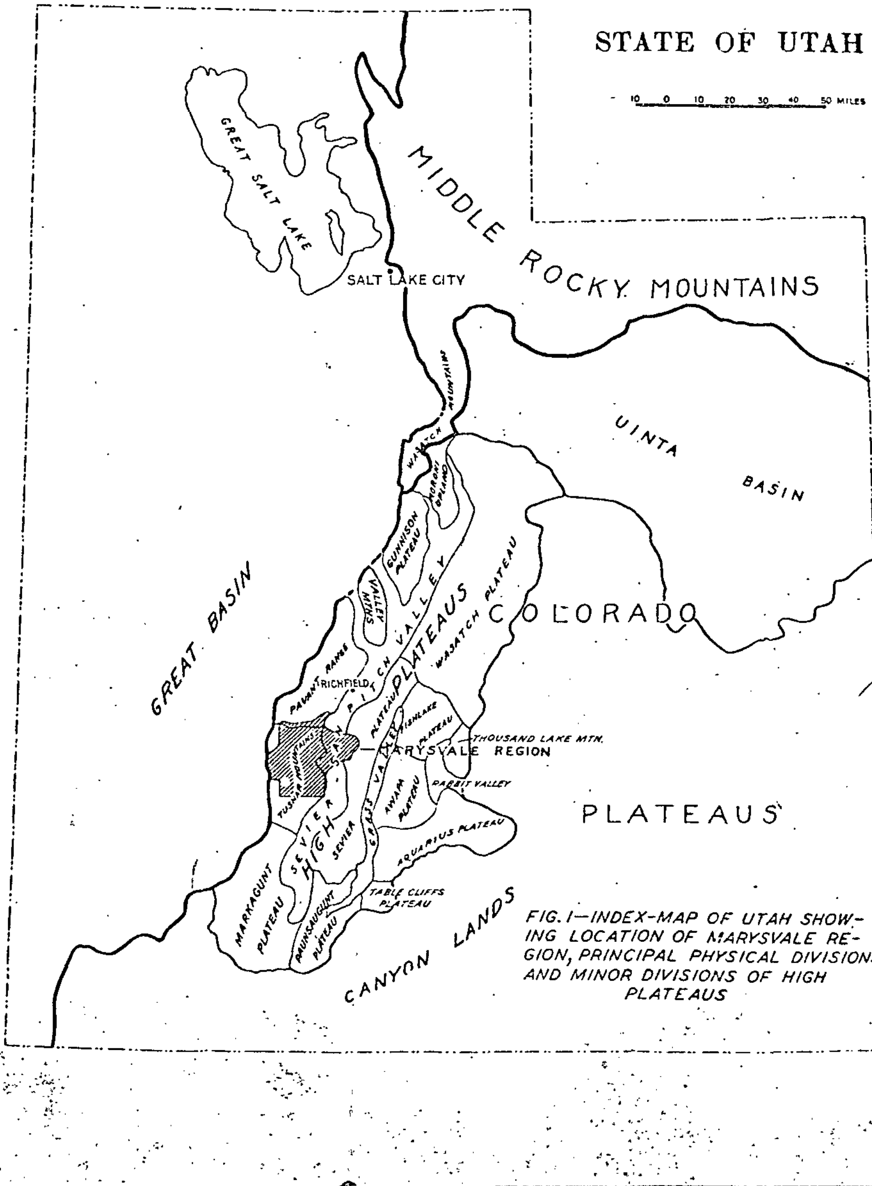

FIG. 1—INDEX-MAP OF UTAH SHOWING LOCATION OF MARYSVALE REGION, PRINCIPAL PHYSICAL DIVISIONS, AND MINOR DIVISIONS OF HIGH PLATEAUS

scattered thin basalt-flows, most of which are associated with the late Pliocene or early Pleistocene Sevier River formation. The position in the sequence of a group of basaltic breccias and flows in the southern part of the area is uncertain. It is the purpose of this paper to point out the stratigraphic relations of each of the units, to describe some of their general features, as well as some of the more pertinent petrographic features, particularly of the analyzed specimens. Suggested interpretations, based on the descriptions and the analyses, are made.

General geology

As shown in Figure 1, the Marysvale Region lies within the High Plateaus of Utah, a part of the Colorado Plateaus, but faces the Great Basin on the west. It is part of a region of long strips of upland and rugged mountains that break sharply into longitudinal valleys, a region long ago made known through Dutton's [see 1 under "References" at end of paper] classic descrip-

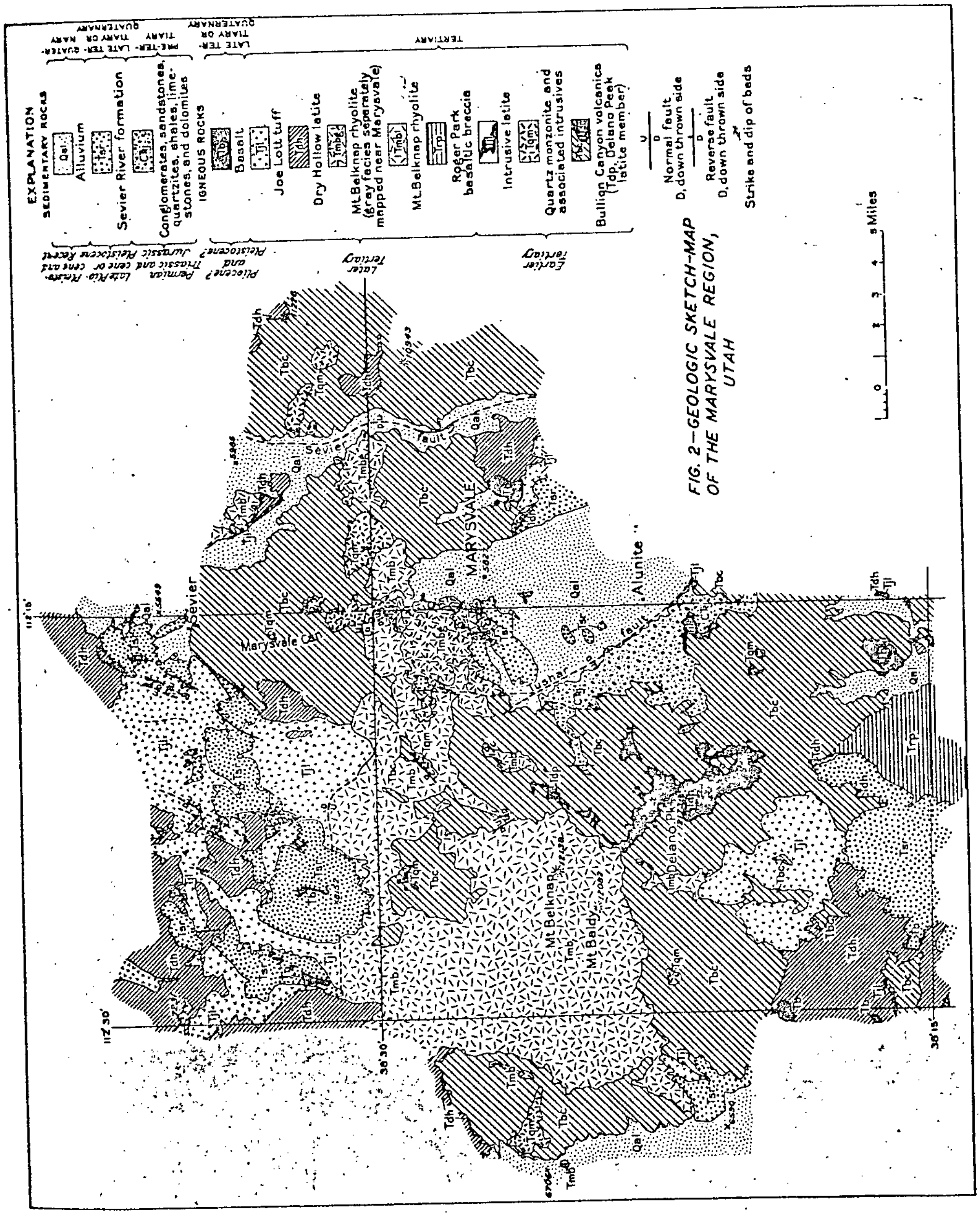

FIG. 2—GEOLOGIC SKETCH-MAP OF THE MARYSVALE REGION, UTAH

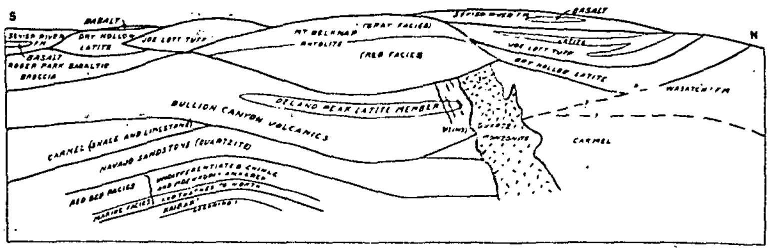

FIG. 3—DIAGRAMMATIC SECTION OF FORMATIONS IN THE MARYSVALE REGION

tion. The Marysvale Region embraces parts of four minor divisions of the High Plateaus, the Tushar Mountains, Pavant Range, Sevier-San Pitch Valley, and Sevier-Plateau. As shown in Figure 2, the Sevier-San Pitch Valley lies between the Tushar Fault and Marysvale Canyon on the west and

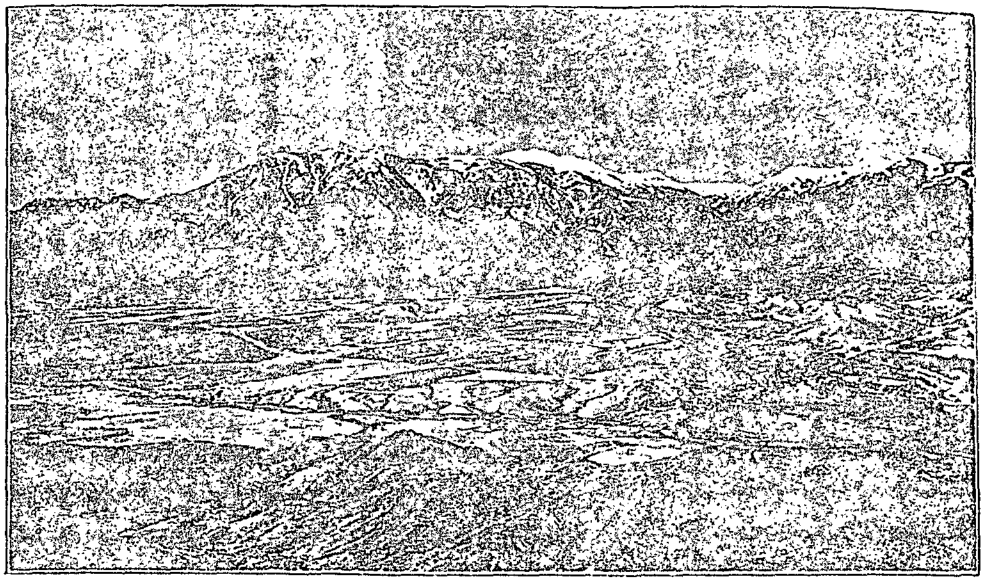

FIG. 4—VIEW OF EASTERN FRONT OF TUSHAR MOUNTAINS NEAR MARYSVALE (RIGHT MIDDLE GROUND)

FIG. 5—WESTERN FRONT OF SEVIER PLATEAU (DISTANCE IN BACKGROUND) AND MINOR MOUNTAIN BLOCKS WITHIN SEVIER-SAN PITCH VALLEY (LOOKING EAST FROM ALUNITE)

the Sevier Fault on the east. It thus includes several low mountain blocks, of which the Antelope Range, northeast of Marysvale, is the most prominent, as well as the alluvial valley-floor (middle ground, Fig. 4). Along the course of the Tushar Fault, the Tushar Mountains face the Sevier-San Pitch Valley in a very steep front (Fig. 4); the summits are 6000 feet above the valley-floor. The Sevier Plateau, which lies east of the Sevier Fault (Fig. 2), also has a steep scarp facing the valley to the west (Fig. 5). Summits in this plateau likewise rise nearly 6000 feet above the valley-floor. On the north the Tushar Mountains are separated from the Pavant Range, a dissected region of relatively less relief, by the downwarped area of the Clear Creek Basin, which lies west of Sevier (Fig. 2). Though not as steep as the eastern front, the western front of the Tushar Mountains breaks sharply into the Great Basin. All the elevated areas are deeply dissected, and the margins of the plateau-blocks are notched by profound canyons, such as are shown in Figures 2 and 4.

Various phases of the geology of the Marysvale Region have been described by Dutton [1], Butler and Gale [2], Loughlin [3], Butler [4], and Eardley and Beutner [5], and all previous work has been reviewed by Callaghan [6]. As shown in Figure 2, almost the entire region is underlain by volcanic rocks of Tertiary age. Pre-Tertiary sedimentary rocks--quartzites, dolomites, limestones, shales, sandstones, and minor conglomerates--are exposed in the steep eastern face of the Tushar Mountains (Figs. 2 and 4). Rocks of Permian, Triassic, and Jurassic age have been distinguished (Fig. 3). No Cretaceous rocks and no rocks assigned to the Wasatch formation, which are so prominent west of Richfield (Fig. 1), crop out in the Marysvale Region. Erosion remnants of the sedimentary Sevier River formation [6, pp. 100-101] overlie nearly all the volcanic rocks. This is a local formation derived from whatever rocks it happens to lie upon. It is believed to be of late Pliocene or early Pleistocene age. Alluvium of several ages occupies parts of the Sevier-San Pitch Valley and the Great Basin to the west.

The extrusive igneous rocks, whose stratigraphic relations are shown diagrammatically in Figure 3, are divided into three principal groups on the basis of profound breaks in the sequence. The earlier Tertiary group, called the Bullion Canyon volcanics, is perhaps the most wide-spread in the whole High Plateaus. Except in the Pavant Range, it occurs in all the local physical divisions. It has the greatest economic importance of all the groups in that the mineral deposits are confined to it. Largely made up of tuffs and volcanic breccias, it also contains a variety of latite-flows. Quartz monzonite and related intrusives are confined to it. An erosion interval separates the earlier Tertiary group from the later Tertiary group, for rhyolite of the later group rests directly on eroded quartz-monzonite. Rhyolite, latite, quartz latite, tuff, and possibly a group of basaltic breccias, whose complex stratigraphic relations are brought out in the following detailed descriptions and in Figure 3, compose the later Tertiary group. Thin basalt-flows, most of them closely associated with the Sevier River formation, make up the relatively minor third group.

The structure of the Region is relatively simple. The major blocks are outlined by normal faults and flexures as well as by erosion-forms. The rocks of the main mass of the Tushar Mountains dip gently to the west, but at the north end they dip into the downwarped Clear Creek Basin and to the northeast in the vicinity of Marysvale Canyon. The Antelope Range north of Marysvale is essentially an arm of the Tushar Mountains, which plunges eastward against the Sevier Fault. Later Tertiary rocks dip to the north and to the south from this eastward-trending axis, which is athwart the course of the Sevier-San Pitch Valley. The Sevier River has cut a deep trench, Marysvale Canyon, through this obstruction. The southward-dipping later Tertiary rocks are shown at the right-hand in the middle ground of Figure 5. Longitudinal blocks occupy the valley southeast of Marysvale. Most of the rocks in the Sevier Plateau dip eastward, and those in the Pavant Range within the mapped area dip to the south or southeast. Though there were doubtless earlier periods of deformation, the principal movement that has produced the present topography occurred after the deposition of the Sevier River formation; that is, after late Pliocene or early Pleistocene time. The last (Wisconsin?) glaciation has modified the summits of the Tushar Mountains, but little change has taken place in the land-surface since the last ice-age.

Earlier Tertiary igneous rocks

Bullion Canyon volcanics and associated intrusive rocks--As might be expected from the wide extent of the earlier Tertiary group of volcanic rocks, they vary greatly from place to place in proportion of flows to pyroclastics, in the type of rock, and in the degree of alteration. Nevertheless, a glance at the map (Fig. 2) shows that these rocks are widely distributed in the Tushar Mountains, in the Sevier Plateau, and in the lower mountains such as the Antelope Range and the longitudinal blocks east of Marysvale. With them are associated all the obviously granular intrusives and all the mineral deposits. No exact measurement is possible, but the total thickness in the Marysvale Region is at least 5000 feet.

Southwest of Marysvale in the eastern part of the Tushar Mountains, three distinct parts of the Bullion Canyon volcanics can be distinguished. The lower part, about 2500 feet thick six miles southwest of Marysvale, consists chiefly of latitic and andesitic tuffs and breccias with scarcely ten per cent of flows. At the base is a thin conglomerate, which rests unconformably upon the older sedimentary formations and consists of debris from the underlying rocks exclusively. Above the conglomerate is waterlaid tuffaceous sandstone, which contains some detrital material from the older rocks. Most of the lower part, however, consists of massively bedded tuffs, crystal tuffs, and minor coarse breccias with a few latite-flows, all well exposed in Bullion Canyon (Fig. 6).

The Delano Peak latite-member of the Bullion Canyon volcanics is a lenticular mass that forms conspicuous cliffs (Fig. 6), facing to the east at the highest part of the crest of the Tushar Mountains (Fig. 2). Faulted segments are preserved on some of the ridges, which branch to the east. Though the thickness is over 800 feet in the center of the lens, no separate flows could be distinguished. However, the upper part has more the appearance of a flow-breccia. The

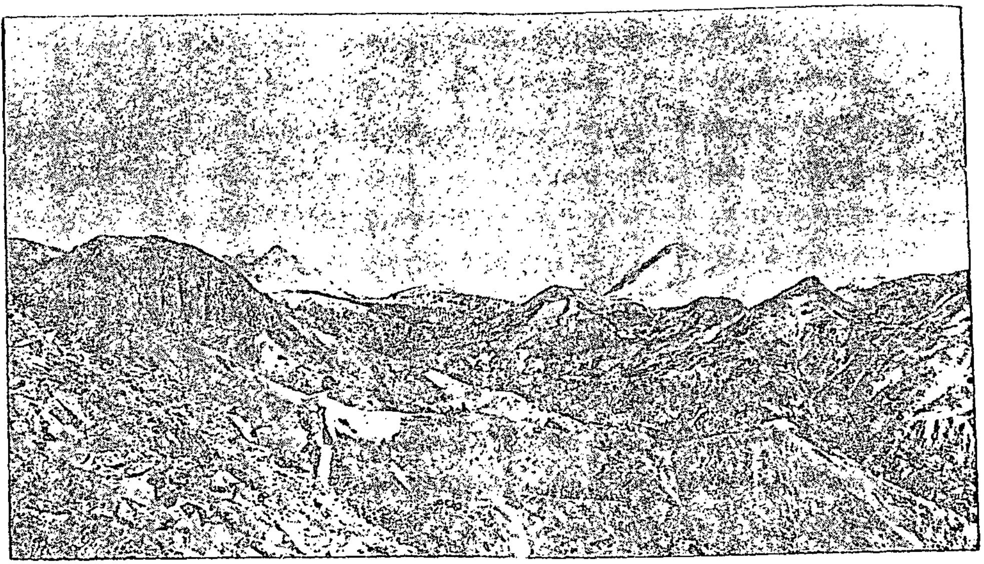

FIG. 6—GLACIATED AREA AT HEAD OF BULLION CANYON NINE MILES SOUTHWEST OF MARYSVALE, SHOWING VOLCANIC BRECCIAS AND FLOWS OF BULLION CANYON VOLCANICS (DELANO PEAK LATITE-MEMBER IN HIGH CLIFF AT LEFT AND RHYOLITE IN PEAKS IN DISTANCE)

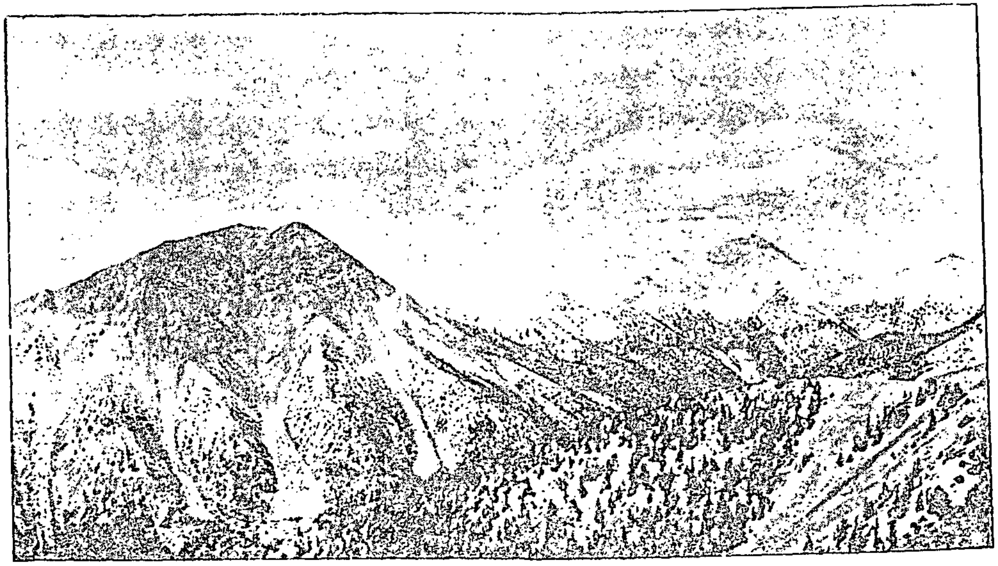

FIG. 7—MOUNT BELKNAP RHYOLITE IN MOUNT BALDY (LEFT) AND MOUNT BELKNAP

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Item	1
SiO_2	48.
Al_2O_3	10.
Fe_2O_3	7.
FeO	6.
MgO	5.
CaO	8
Na_2O	2
K_2O	3
H_2O+	1
H_2O-	0
TiO_2	4
P_2O_5	0
MnO	0
CO_2	
ZrO_2	
SO_3	
BaO	
Li_2O	
S	
Cr_2O_3	
	10
Q	
or	2
ab	2
an	
C	
th	
wo	1
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rocks in contact with it are not metamorphosed, and there is no evidence that it may be intrusive.

In the upper part of the Bullion Canyon volcanics west of Marysvale the proportion of flows to breccias is distinctly higher than in the lower part. This may exceed 50 per cent. They are mostly dark gray, some are nearly black, and most of them have a more calcic appearance than flows in the lower part. The total thickness is unknown, but is probably in excess of 2500 feet. These rocks crop out in the northern, western, and southern parts of the Tushar Mountains.

In the Sevier Plateau east of the Sevier Fault (Fig. 2), the earlier Tertiary rocks consist of a thick series of latitic breccias and thin flows at the base, a succession of latite-flows with almost no intervening volcanic breccia, and more calcic latite at the top. No exact correlation between the members in the Tushar Mountains and those in the Sevier Plateau is possible. Probably the lower breccias correspond to the lower part in the Tushar Mountains, and the remainder correspond to the upper part; the base is not exposed. The total thickness is over 5000 feet. Probably the calcic latite-flows and breccias in the Antelope Range east and north of Marysvale belong to the upper part of the Bullion Canyon volcanics.

The mineral and chemical composition of four rocks from the Bullion Canyon volcanics is given in Table 1. A fragment from a dark purplish-gray andesitic breccia (Column 4, Table 1) be-

Table 1--Analyses, norms, and modes of igneous rocks from the Marysvale Region, Utah

Item	Specimen number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
							Analyses						
SiO_2	48.65	54.71	57.62	57.83	57.96	59.16	59.57	62.25	67.18	70.17	75.83	76.15	76.16
Al_2O_3	10.40	11.59	14.54	13.34	15.71	16.08	16.92	15.61	12.00	11.83	12.36	12.56	12.64
Fe_2O_3	7.45	3.62	6.55	7.21	3.38	3.98	2.85	5.04	1.44	0.93	1.05	0.80	0.88
FeO	6.05	4.07	1.09	0.87	4.11	1.39	2.08	0.38	0.14	none	0.29	0.39	0.14
MgO	5.55	6.85	3.20	1.10	3.16	2.76	2.05	1.83	0.43	0.06	0.02	0.02	0.23
CaO	8.10	6.03	6.08	5.60	5.11	3.37	4.41	4.62	2.65	0.76	0.04	0.18	0.04
Na_2O	2.77	2.45	3.18	5.76	3.48	4.23	3.73	3.88	1.14	3.85	3.94	4.43	3.54
K_2O	3.40	2.89	3.12	1.08	4.08	4.16	4.98	2.81	3.71	3.74	5.08	5.13	4.75
H_2O+	1.09	2.88	1.18	0.95	1.26	1.98	1.36	1.34	7.06	8.72	0.42	0.40	0.54
H_2O-	0.62	0.47	1.18	0.24	0.11	0.61	0.24	1.16	3.69	-	0.24	0.09	0.50
TiO_2	4.75	2.28	0.81	0.96	1.05	0.55	1.34	0.58	0.20	0.17	0.24	0.18	0.15
P_2O_5	0.51	0.42		0.38			0.36		0.06		0.01	none	none
MnO	0.10	0.10	0.10	0.06	0.11	0.05	0.06	0.05	0.03		0.12	0.06	0.06
CO_2	0.86	1.88	0.86	4.73	trace	1.55		0.02	trace				
ZrO_2	0.01			0.01					0.03				
SO_3													0.11
BaO	0.12			0.10			0.16		0.01		0.01	0.01	0.02
Li_2O													0.003
S	0.07	0.06	0.04	0.07	0.07	0.04		0.05	0.08				
Cr_2O_3			0.03	none	0.02	0.02		0.02	0.01				
	100.40	100.30	99.58	100.29	99.61	99.93	100.11	99.64	99.86	100.23	99.65	100.40	99.76
							Norms						
Q	3.06	12.72	13.38	18.30	7.20	11.34	8.28	17.34	40.74	31.98	33.24	31.02	37.14
or	20.02	17.24	18.35	6.67	24.26	25.02	29.47	16.68	21.68	21.68	30.02	30.02	28.36
ab	23.45	20.96	27.25	48.73	29.34	35.63	31.44	33.01	9.43	32.49	33.54	36.68	29.34
an	5.84	11.95	15.85		15.01	6.95	14.73	16.68	12.23	3.89	0.28		0.28
C				2.55		2.04			1.73	0.10	0.31		1.63
th													0.14
wo	10.79	1.39	3.83		4.29		2.20	2.55				0.46	
en	13.90	17.10	8.00	2.80	7.90	6.90	5.10	4.60	1.10	0.20			0.60
fs		0.53			2.90								
ac												0.46	
mt	5.80	5.34	1.62		4.87	3.02	3.02				0.70	0.93	0.23
il	9.12	4.41	1.52	1.82	2.13	1.06	2.58	0.91	0.15		0.46	0.46	0.30
hm	3.52		5.44	7.20		1.92	0.80	5.12	1.44	0.93	0.64		0.80
ru								0.16	0.16	0.16			
ap	1.34	1.01		1.01			1.01		0.34				
pr	0.12	0.12		0.12	0.12				0.12				
cc	1.92	4.34	1.92	9.30		3.54							

Table 1--Concluded

Item	Specimen number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
					Modes								
Quartz		x	x	x	6	x	x	6	x		x	26	x
Orthoclase					29	x?			x		}x	}67	x
Oligoclase		x		x	33	35	x	39					
Andesine	x		22				x		x				
Hornblende		x	2	x?		8^1		12					
Biotite					14^2	6^1		5	x		x	5	x
Augite	x	x	9		11		x?						
Olivine	x												
Magnetite	x	x	6	x	7	7	x	4	x		x	2	x
Apatite		x	x		x	x	x	x					
Titanite					x								
Rutile												x	
Tourmaline					x								
Zircon											x		
Cristobalite	x?											x?	
Glass						44		34	x		x		x
Groundmass			61										
Carbonate	x	x	x	x		x	x						
Chlorite		x	x	x	x	x	x						
Iron oxide				x		x		x	x			x	
Sericite		x	x	x	x		x						
Epidote		x			x								
Iddingsite	x												

[1] As chlorite.

[2] Mainly as chlorite.

Analysts for specimens: 1 and 2, Charles Milton; 3, 4, 5, 7, 8, and 9, R. E. Stevens; 7, 11, and 12, J. G. Fairchild; 13, J. J. Fahey; 10, W. F. Hillebrand.

Descriptions of specimens

(1) Alkalic olivine basalt (III. 5.2.3.)--Vesicular flow surrounded by alluvium on U.S. Highway 89, 7 miles south-southwest of Alunite.

(2) Intrusive calcic latite (II. 4.3.3.)--Sill intrusive at base of volcanic sequence, center Sec. 24, T. 28 S., R. 4 W., 2 miles southwest of Alunite.

(3) Calcic latite (II. 4.3.3.)--Flow 500 feet south of summit of Delano Peak.

(4) Andesite breccia (II. 4.1.5.)--Coarse breccia 1200 feet west of Mineral Products Mine, Sec. 16, T. 28 S., R. 4 W., 4 miles west of Alunite.

(5) Quartz monzonite (II. 5.2.3.)--Intrusive stock on east side of Marysvale Canyon at mouth of Deer Creek, Sec. 29, T. 26 S., R. 4 W.

(6) Latite (II. 4.2.3.)--East slope of peak, west of L. and N. claims, Sec. 18, T. 28 S., R. 5 W., 5-1/2 miles west of Alunite.

(7) Latite (II. 5.2.3.)--Thick flow on north side of Beaver Creek west center, Sec. 25, T. 27 S., R. 5 W., 2-1/2 miles northeast of Mount Belknap.

(8) Quartz latite (II. 4.3.4.)--Thick flow in Narrows of Clear Creek Canyon, Sec. 32, T. 25 S., R. 4-1/2 W., 7 miles west of Sevier.

(9) Rhyolite tuff (I. 3.3.2.)--Joe Lott tuff, east side Mill Creek, southwest center Sec. 19, T. 26 S., R. 4-1/2 W., 8-1/2 miles southwest of Sevier.

(10) Rhyolite glass or pitchstone (I. 4.1.3.)--"Edge Gold Mountain Mining District 8 miles north of west of Marysvale." U.S.G.S. Bull. 168, p. 168, 1900. Probably in Deer Creek Canyon; no description.

(11) Banded gray rhyolite (I. 4.1.3.)--Flow near base of formation NW 1/4, Sec. 7, T. 27 S., R. 3 W., 2-1/2 miles north-northwest of Marysvale.

(12) Granular gray rhyolite (I. 4.1.3.)--Flow in upper part of Mount Belknap, Sec. 34, T. 27 S., R. 5 W.

(13) Tuffaceous red rhyolite (I. 3.1.3.)--Flow making high cliffs in Marysvale Canyon at mouth of Deer Creek, NE 1/4, Sec. 1, T. 27 S., R. 4 W., 3-1/2 miles north-northwest of Marysvale.

longing to the lower part of the Bullion Canyon volcanics was found under the microscope to be finely porphyritic, with partly altered oligoclase and chlorite aggregates indicating former hornblende or augite. The maximum size of the feldspars is about 2 mm; the groundmass crystals average about 0.03 mm. The rock is considerably altered, and contains much carbonate, chlorite, and quartz, with minor sericite. The striking feature brought out by the analysis is the relatively low content of potash. The breccias with smaller fragments, mostly less than one inch in diameter, are generally light-colored, and are probably less calcic than the analyzed specimen. The massive beds of crystal tuff closely resemble normal latite, and doubtless have a closely similar chemical composition.

The Delano Peak latite-member (Column 6, Table 1) is brownish red with abundant phenocrysts of oligoclase, hornblende, and biotite, and minor quartz and magnetite in a glassy base with fluidal structure. Many of the oligoclase phenocrysts, which may reach lengths of four mm, but average from one to two mm, are fragmented, and biotite plates are commonly bent. Much of the hornblende is surrounded by an envelope of minute grains of magnetite. The red color is due to films of red hematite, which cover or completely replace grains of magnetite. Nevertheless, there are gray streaks and splotches that are characteristic of much of the mass. The analyzed specimen is somewhat altered; hornblende and biotite are changed to chlorite, and carbonate and quartz have formed to some extent in the devitrified groundmass.

A specimen (Column 4, Table 1) from Delano Peak, believed to be typical of much of the dark flows in the upper part of the Bullion Canyon volcanics southwest of Marysvale, is medium dark gray and not conspicuously porphyritic, though andesine-phenocrysts are as much as three mm long and augite grains reach two mm in length. Phenocrysts of andesine, augite, hornblende, and magnetite are scattered through a groundmass of devitrification-products and a felted mass of plagioclase microlites. Slight alteration has produced quartz, carbonate, sericite, and chlorite. Another rock (Column 7, Table 1) from the upper part of the Bullion Canyon volcanics is purplish medium gray and conspicuously porphyritic, with some phenocrysts as much as ten mm in length. The average length of the phenocrysts is one-half to two mm, and the grain-size of the groundmass is from 0.03 to 0.05 mm. The andesine-phenocrysts are mottled and variably replaced by orthoclase. The former ferromagnesian mineral, probably augite, is now represented by chlorite and carbonate. The groundmass is a fine-grained aggregate with feldspar of low index of refraction, leucoxene (?), carbonate, minor sericite, and quartz. Magnetite and apatite are accessory.

In addition to those described, there are other varieties of flow-rocks and breccias. Though most of the breccias and tuffs are medium to light-gray, tuff and breccia near Sevier (Fig. 2) is yellowish white and resembles a part of the younger Joe Lott tuff. A nearly black flow-facies of latite at the west side of the Tushar Mountains contains large andesine phenocrysts, with inclusions of orthoclase, and chlorite pseudomorphs that strongly suggest former olivine. Carbonate has developed in the groundmass of minute plagioclase-laths as well as in the phenocrysts. A dark-gray rock at the summit of the Sevier Plateau superficially resembles basalt, but under the microscope is found to be a latite with large andesine and small augite phenocrysts in a groundmass consisting chiefly of minute (0.01-0.03 mm) feldspar of low index of refraction. Some chlorite pseudomorphs suggest former olivine. Magnetite and apatite are accessory. Much of the succession in the Sevier Plateau is composed of latite with large phenocrysts of andesine and conspicuous euhedral biotite. This rock is characteristically a medium to light purplish-gray. The groundmass, which is fine-grained, with minute crystals of orthoclase and interstitial quartz, is strikingly susceptible to recrystallization through contact metamorphism.

Intrusive bodies mostly occur along an axis trending earth-northeast just north of Marysvale (Fig. 2). They are chiefly small stocks; the largest is scarcely two miles wide. Some small dikes and plugs lie outside of this axial direction, but all are confined to the Bullion Canyon volcanics. The Mount Belknap rhyolite of the later Tertiary group overlies an eroded surface on the intrusive quartz-monzonite north of Marysvale, as is shown diagrammatically in Figure 3. Perhaps as a consequence of the small size of the intrusive bodies, the grain-size and appearance change abruptly from place to place within the same mass and between different bodies. However, under the microscope the mineralogy is found to be very similar throughout.

The medium-gray quartz-monzonite (Column 5, Table 1) from the intrusive at the south end of Marysvale Canyon (Fig. 2) is the most nearly equigranular and granitoid in appearance of all those investigated. The grain-size is mostly from one to four mm for the major minerals. The plagioclase tends to be in large elongate grains, but the abundant orthoclase and less plentiful augite and biotite are nearly equant. The rock consists of calcic oligoclase, orthoclase, quartz, augite, and biotite, accessory magnetite, apatite, and titanite, and later tourmaline, epidote, chlorite, and sericite. Dusty orthoclase tends to be interstitial to the plagioclase, but it also invades and replaces it. Myrmekitic intergrowths of quartz and orthoclase are common. Though some of the augite is completely changed to chlorite, much of it is unaltered. Some of the biotite seems to be a late mineral, which formed rims at the contacts of magnetite and

augite. Though the rock has less than ten per cent of quartz in either the norm or the mode, it is closer in composition to quartz-monzonite than to monzonite. A higher proportion of orthoclase to plagioclase appears in the mode than in the norm--probably some of the soda is included in the orthoclase.

In a small intrusive in a window of Bullion Canyon volcanics west of the intrusive in Marysvale Canyon, the rock is comparatively finer-grained and darker-colored than the analyzed material. Titanite and tourmaline are absent in this and all specimens other than the one analyzed. In the next group of very small intrusives to the west, one is black and not conspicuously porphyritic. It has very minor interstitial quartz, and has greater difference in size of phenocrysts and groundmass than the analyzed rock. Though it contains considerable plagioclase in the groundmass, there is replacement by orthoclase. The dark color is due chiefly to finely disseminated magnetite. This rock could doubtless be properly classified as monzonite. Minor intrusives are mostly fine-grained, but have the same mineral content as the coarser-grained bodies.

The contact-effects of the larger intrusive bodies, though variable, are characteristic. Latites in the contact-zone are mostly turned to a pink color, though in a few places they become black or green. They retain their plagioclase-phenocrysts, and in many places biotite phenocrysts are preserved, but the groundmass recrystallizes and becomes obviously granular, though very fine-grained. In the pink rock, orthoclase and minor quartz are introduced so that the groundmass becomes an aggregate of orthoclase and interstitial quartz. The degree of metamorphism is indicated by the size of grain. Though the plagioclase phenocrysts tend to persist, they are commonly partly replaced by orthoclase. Magnetite tends also to be introduced; in a number of places its abundance accounts for the black color. In one place north of Marysvale, sufficient magnetite was introduced to form an ore-body, which has been mined. Commonly a light-colored biotite has been introduced with the magnetite, so that the contact-aggregate is essentially orthoclase, magnetite, and light-brown biotite. In a few places epidote is sufficiently abundant to give a greenish cast to the rock. Chlorite is a minor constituent. In general, the outstanding feature of both the intrusive and contact-rocks is the introduction of orthoclase and replacement of earlier plagioclase.

An intrusive latite (Column 2, Table 1), which forms sills from a few feet to more than 100 feet thick southwest of Alunite (Fig. 2) deserves special mention. In intrudes the conglomerate at the base of the volcanic sequence, but was not recognized at any other horizon. The rock, which does not resemble the quartz-monzonite type of intrusive, is medium-dark gray, porphyritic, and contains small amygdules filled with quartz and carbonate. The phenocrysts, which are augite and hornblende rather than plagioclase, are mostly 0.3 to one mm long, though some are as much as five mm long. The grain-size of the groundmass is between 0.03 and 0.4 mm, but averages about 0.1 mm. Oligoclase and minor interstitial quartz compose most of the groundmass. Both phenocrysts and groundmass are, to a moderate extent, replaced by carbonate, epidote, chlorite, quartz, and a little sericite. Though superficially the rock has a diabasic appearance, the analysis shows that it belongs to the latite group. Its contact-effects on adjacent rocks are negligible.

Dikes of rhyolite porphyry, which has large phenocrysts of orthoclase, quartz, and minor plagioclase in a devitrified groundmass, intrude the Bullion Canyon volcanics, six miles southwest of Marysvale. As they are mineralized by quartz-veins older than the later Tertiary rocks, they must belong to the earlier Tertiary group rather than occurring as feeders for later Tertiary rhyolites.

The earlier Tertiary rocks are commonly much more altered than those in later groups, and this feature may be used with caution in distinguishing the two groups. The most wide-spread alteration has involved the formation of carbonate, chlorite, sericite, and minor quartz. These minerals are most abundant near some of the veins where they are often joined by disseminated pyrite. Nevertheless, the same minerals are observed in areas remote from veins.

Another type of alteration, apparently later and mutually exclusive to the type described above, is concerned with the formation of alunite and quartz, with or without associated pyrite, at the expense of pyrogenic minerals. This alteration is much more restricted in extent, though it covers small areas in the Tushar Mountains and large areas in the Antelope Range and small areas in the Sevier Plateau. Veins of alunite and some of the disseminated material were mined for potash during and immediately following the World War.

Later Tertiary volcanic rocks

Roger Park basaltic breccia--The position of the Roger Park basaltic breccia in the volcanic sequence of the Marysvale Region is not entirely clear. The formation was recognized in a small area in the southern part of the Region, where it enters as a wedge from the south. Though it is doubtless thicker and more extensive to the south, its maximum thickness within the mapped area may be as much as 2000 feet. The Roger Park basaltic breccia is overlain by latite, grouped with the Dry Hollow latite, and is underlain by latites and breccias of the Bullion Canyon volcanics. No sharp line could be drawn between the dark calcic latites of the underlying formation and the more basaltic-appearing rocks. Indeed, this formation may be a facies of the Bullion Canyon volcanics, but further investigation must precede any definite conclusion.

The flows near the top of the formation are dark gray, and have distinctly basaltic appearance. The breccias are various shades of gray or red, and the fragments are commonly vesicular. Thin sections from fragments showed that the rock is porphyritic with phenocrysts of labradorite and pyroxene (pigeonite) as much as five mm long in a groundmass of the same minerals, mostly between 0.02 and 0.1 mm long, interstitial brown glass, and abundant magnetite-grains. No trace of orthoclase could be detected, and olivine is conspicuously absent. Toward the base, the rocks more nearly resemble the dark calcic latites.

Mount Belknap rhyolite--In the area northwest of Marysvale two distinct facies of the Mount Belknap rhyolite are readily recognized, and were separately mapped. In the western part of the Tushar Mountains, the two facies also can be recognized, but, as their contact is much less distinct, the gray facies is not distinguished on the map. These rocks characteristically break up into thin plates and scales on exposed surfaces that cover gentle slopes or form long talus cones and sheets on steeper slopes, as shown in Figure 7. Nevertheless, these rocks compose the crest of the Tushar Mountains near the northern end as well as the picturesque yellowish-white peaks, Mount Baldy and Mount Belknap (Fig. 7). The entire mass of the rhyolite forms a lenticular body in the Tushar Mountains, and in conformity with the regional structure dips to the west on the west side, to the north on the north side, and to the east on the east side. Though its base is at an altitude of over 11,000 feet in the center of the mountains, it reaches the valley-floor on either side. Each facies now has a maximum thickness of about 2000 feet, but the total original thickness in the center of the lens was doubtless in excess of 4000 feet prior to erosion.

The two facies are not equally distributed; the gray facies extends farther to the west, to the south, and to the east than the red tuffaceous facies, but the red facies extends farther to the north, where it is directly overlain by latite-flows and the Joe Lott tuff. In some places the red facies rests directly on various older rocks, including the quartz-monzonite, but in most places there is intervening bedded tuff that may be 300 feet thick. Commonly the basal portion of the red facies is marked by a black to greenish black pitchstone (Column 10, Table 1). Lenticular masses of bedded tuffs and breccias are irregularly distributed through the red facies, and coarse breccias occur in the gray facies in the western part of the Tushar Mountains. North of Marysvale the two facies are separated by tuff. The gray facies commonly has a glassy base in which occur spherulites, several inches to more than a foot in diameter.

Though the various facies of the Mount Belknap rhyolite differ strikingly in appearance, their composition is remarkably similar. A photomicrograph of typical tuffaceous red rhyolite (Column 13, Table 1) is shown in Figure 8. The mass of the rock is reddish brown to salmon colored, and though not glassy, is obviously not granular." The fragments, commonly five to ten mm in diameter, are either light or dark gray, and clearly belong to the rhyolite; foreign fragments, except near the margins of the mass are rare. In the analyzed specimen both the fragments and the mass of the rock are devitrification-aggregates. Orthoclase phenocrysts, 0.2 to 0.8 mm long, and rare quartz phenocrysts stand out in a mass of minute feldspars with some biotite flakes (Fig. 8). Magnetite occurs in the fragments, but very little appears in the groundmass. The red color is due to minute flecks of hematite. Minute sperulites occur in groups, and crystallized streaks and lenses contain orthoclase. Some cavities are lines with orthoclase and quartz-grains. The tuffaceous character of the rock naturally suggested that this might be a welded tuff, but clear evidence is lacking. A few samples have a collapsed-bubble structure that suggests welded tuff, but the inference is that the bulk of the material is a flow-breccia. A very few flows of restricted extent are purplish porphyritic rhyolite with abundant quartz and orthoclase and minor plagioclase-phenocrysts in a glassy or only slightly devitrified groundmass.

The typical gray rhyolite (Column 11, Table 1) north of Marysvale is represented by Figure 9. The striking feature is the prominent contorted flow-banding; the darker bands include material that is only slightly devitrified, and the lighter bands are more obviously crystalline. Thin lenses parallel to the flowage-lamination are filled with small quartz and orthoclase crystals, and larger cavities are lined with visible quartz-crystals, some of them amethystine. As a whole the rock is light gray, has no phenocrysts, and has thin lenses and bands of obviously crystalline quartz and orthoclase alternating with devitrified material, which shows, under the

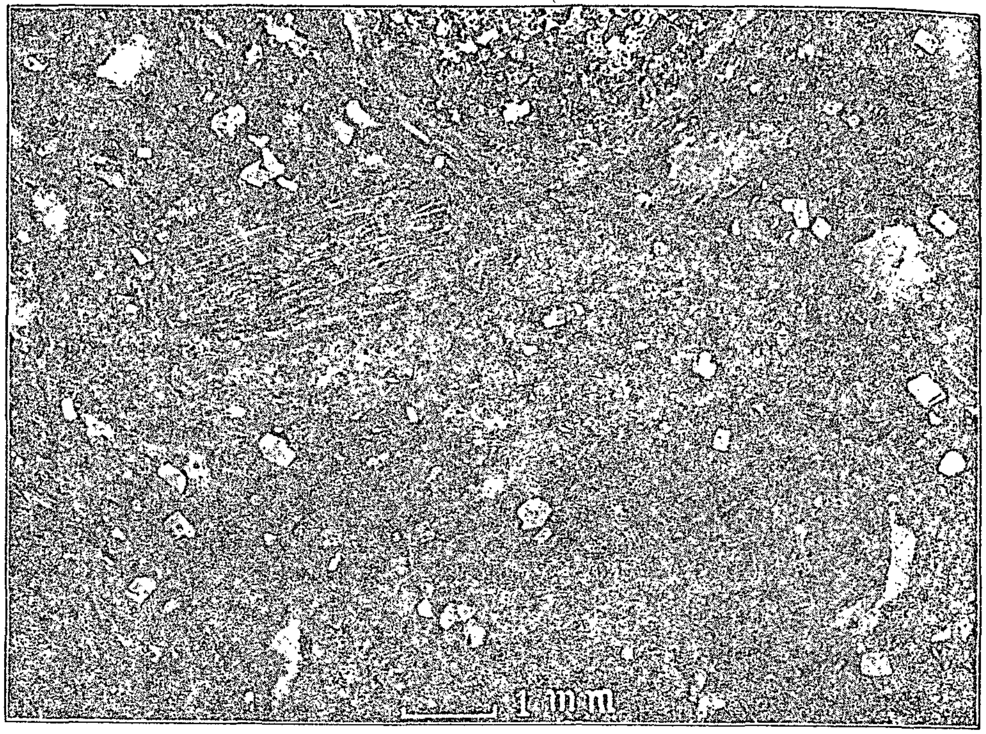

FIG. 8—PHOTOMICROGRAPH OF TUFFACEOUS RED FACIES OF MOUNT BELKNAP RHYOLITE, SHOWING FRAGMENTS AND PHENOCRYSTS

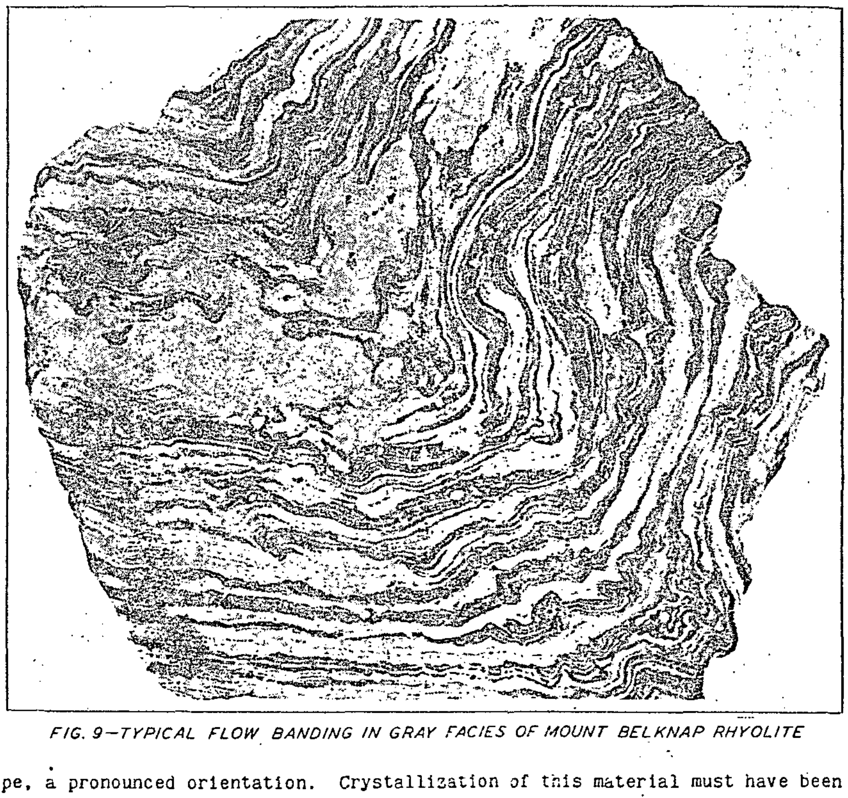

FIG. 9—TYPICAL FLOW BANDING IN GRAY FACIES OF MOUNT BELKNAP RHYOLITE

microscope, a pronounced orientation. Crystallization of this material must have been affected by pressure at the close of movement, whereas the unoriented quartz and orthoclase, most of which is between 0.01 and 0.07 mm long, formed after movement ceased. Minute pleochroic blebs are believed to be biotite, and one grain of zircon was seen..

Much of the banded or laminated gray rhyolite occurs on the western slope of the Tushar Mountains, but the most interesting variety, which is wide-spread and includes the upper part of Mount Belknap (Fig. 7), is a light gray to almost white rock, which resembles a very fine-grained quartzite. The rock (Column 12, Table 1) is essentially a holocrystalline, non-porphyritic, equigranular aggregate of quartz and feldspar, with very minor amounts of biotite, magnetite, red iron-oxide, and cristobalite (?). The grain-size of most of the quartz is 0.03 to 0.05 mm, and that of the feldspar is about 0.05 mm. The feldspar is all the same, a microcline microperthite. Under the microscope the feldspars show a herringbone unmixing structure, and under high magnification this structure is revealed as rows of plates of probable albite in orthoclase. No special conditions for the formation of this rock could be ascertained in the field. Though a very hazy broad flow-banding can be seen in some of the material, no data on the thickness or extent of individual flows were obtained.

Some outlying flows, one immediately west of the Sevier Fault northeast of Marysvale, and another at the west base of the Tushar Mountains (Fig. 2), differ in being distinctly porphyritic, with phenocrysts of quartz and feldspar in a devitrified base. As these flows have similar relations to the underlying rocks and doubtless differ little in composition, they are classed with the Mount Belknap rhyolite.

The Mount Belknap rhyolite contains no mineral deposits, nor is it intruded by granular rocks. However, a wide-spread alteration has bleached whole square miles of the red tuffaceous facies. This alteration has produced little change beyond the introduction of pyrite, decrease in soda, increase in potash, decrease in iron oxide, and formation of quartz and sericite. The increase in potash suggests that there has been a change in the orthoclase-content. In general, the alteration, which was probably of the hot-spring type, has only slightly modified the rhyolite in composition, though it has changed its appearance.

Dry Hollow latite--The later Tertiary latite and quartz-latite are widely distributed as erosion-remnants in all the physical divisions of the Marysvale Region (Fig. 2). Individual flows are more than 200 feet thick in many places, and the aggregate thickness is probably about 1000 feet. The latite rests upon the earlier Tertiary volcanic rocks and upon the Mount Belknap rhyolite. It is interbedded with the Joe Lott Tuff, and many flows are underlain by the tuff. It is overlain by younger rocks, including the Sevier River formation and basalt flows (Fig. 3).

A specimen (Column 8, Table 1) from a thick flow in the canyon of Clear Creek west of Sevier is brownish red and abundantly porphyritic. Dark-red spots contain few phenocrysts, and gray spots are made up almost entirely of phenocrysts. All the recognizable minerals, oligoclase, quartz, hornblende, biotite, magnetite, and apatite, occur as phenocrysts that reach a maximum length of about three mm. The groundmass contains minute grains, but is mostly fluidal light-brown glass. Coatings of red iron-oxide on the magnetite and disseminated minute red hematite-grains account for the red color. Quartz is embayed, and hornblende is partly changed to aggregates of magnetite at the margins of the crystals. The rock is unaltered, but resembles closely facies of the Delano Peak latite member of the Bullion Canyon volcanics.

Other flows of the Dry Hollow latite may differ in being gray instead of red, in having a lower proportion of phenocrysts, in having no visible quartz, or, as in the latite in the Sevier Plateau, in having large orthoclase phenocrysts. One flow has multitudes of small cavities partly or wholly filled with fibrous zeolite. Some flows closely resemble latite in the Bullion Canyon volcanics, but they are generally much less altered, and their associations serve to distinguish them from the older rocks.

Joe Lott tuff--Several discrete areas of conspicuous white to light-yellow or brownish tuff are grouped as the Joe Lott tuff, named for a creek in the northern part of the area. The largest exposures are in the basin of Clear Creek west of Sevier, and in the Beaver River Basin southwest of Delano Peak. Smaller outcrop areas occur in the Sevier-San Pitch Valley, both north and south of Marysvale. The thickness of the various outcrops of tuff is highly variable, but in the Clear Creek Basin the aggregate thickness is in excess of 1000 feet. The lower part of the tuff in Clear Creek Basin is in massive beds, in places between 50 and 100 feet thick, which along Clear Creek have columnar structure. These beds show no lamination, but thin pinkish interbeds are commonly laminated. The upper part, exposed in the northwestern part of the Region, is interbedded with abundantly porphyritic latite and quartz-latite flows of the Dry Hollow latite, and is largely composed of latite detritus. It has a pink or brownish cast, as compared with the white or light-gray cast of the lower rhyolite tuff.

Though the Joe Lott tuff rests on Bullion Canyon volcanics in a few places, and upon the Mount Belknap rhyolite, most of it rests on latite-flows belonging to the Dry Hollow latite, as

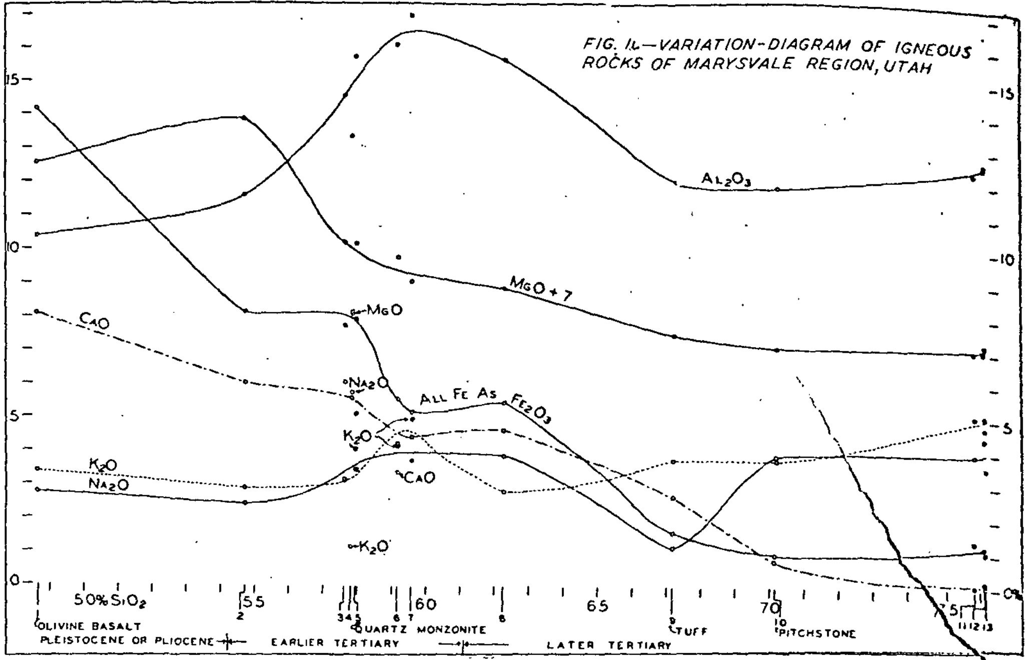
FIG. 10—VARIATION-DIAGRAM OF IGNEOUS ROCKS OF MARYSVALE REGION, UTAH

is shown in the diagrammatic section (Fig. 3). Thin tongues of the red facies of the Mount Belknap rhyolite occur in the tuff at the south side of Clear Creek Basin, but most of it is interbedded with flows of the Dry Hollow latite.

Rhyolite tuff (Column 9, Table 1) from the lower part of the Joe Lott tuff is white, ashy, and consists of white-ash fragments, mostly ten mm in diameter, and scattered fragments of dark porphyritic latite as much as 15 mm in diameter, which were doubtless derived from the Bullion Canyon volcanics, in an ashy matrix. Crystal fragments of orthoclase, biotite, and rare quartz are scattered through the glassy material. The analysis shows a higher proportion of potash to soda in the tuff than in the rhyolite. However, many fragments of the gray-banded rhyolite occur in the tuff near the rhyolite-contact.

Light-brownish crystal tuff from the upper portion is composed of the same material as the associated latite, so that even under the microscope it is scarcely distinguishable from the latite-flows.

Basalt--Flows of olivine basalt, most of them less than 50 feet thick, occur at a number of places throughout the Region. In the Clear Creek Basin southwest of Sevier and in the Beaver River Basin at the south end of the area, the basalt-flows are associated with the Sevier River formation. Elsewhere they lie upon the Bullion Canyon volcanics, the Dry Hollow latite, or the Joe Lott tuff.

A specimen (Column 1, Table 1) from an isolated outcrop in the Sevier-San Pitch Valley is an exceedingly fine-grained black vesicular rock with small phenocrysts of olivine, mostly 0.2 to 0.7 mm long, in a groundmass of andesine laths, blebs of augite, and granules of magnetite. Most of the grains in the groundmass are 0.01 to 0.04 mm long. The olivine crystals, both large and small, are stained red, and many are completely changed to iddingsite. Some isotropic grains in the groundmass are regarded as cristobalite. Other basalt-flows contain labradorite as well as olivine phenocrysts. There is little visible indication of the relatively high content of alkalies brought out in the analysis.

Interpretation

A study of the chemical analyses given in Table 1 and the variation-diagram (Fig. 10) together with the petrographic descriptions and field-relationships lead to certain generalizations concerning the igneous rocks of the Marysvale Region. First, in a chemical sense the entire group is saturated with respect to silica in the norm. No feldspathoid minerals were recognized, and though olivine occurs in the mode of the basalt, it is absent in the norm. Second, perhaps the most characteristic feature of these rocks is the essential equality of the alkalies throughout the group. This is especially well illustrated by the end-members of the group, the basalt and the rhyolite. In the basalt the total of alkalies is high, 6.17 per cent, and only three per cent less than the total alkalies in the rhyolites. This feature is significant in that it demonstrates the alkaline habit of this group of extrusive and intrusive rocks even more conclusively than do the intermediate rocks. Third, the rocks of the Marysvale Region are comparatively low in lime. Plagioclase is commonly of the soda-lime variety, even in the more mafic specimens. Augite starts to displace biotite at a point on the diagram (Fig. 10) between 59 and 60 per cent. The three rhyolites are particularly interesting in that though they are dissimilar in structure and apparent crystallinity, their composition is almost exactly the same. The quartz-monzonite resembles in its chemical habit the typical intrusives of the western half of Utah, though it is less siliceous than most of the analyzed intrusive rocks. The almost universal habit in the Region for the orthoclase to develop at the expense of plagioclase should be emphasized.

These features of the intrusive and extrusive rocks suggest a relationship or consanguinity of all of them, a strong indication that, though widely spaced in time, they are differentiates of a parent monzonitic magma. Gilluly [7, p. 67] has already suggested a like explanation of the monzonites and latites of the Stockton-Fairfield Area. An interesting corollary of this conclusion is that the basalt is a differentiate of the monzonitic magma, rather than a representative of the basaltic substratum. In chemical composition the basalt differs from Daly's [8, p. 17] average basalt or average plateau-basalt in the markedly high percentage of potash and low content of alumina. This compositional feature seems to tie the basalt to the monzonite-latite group of rocks.

The striking similarity of the intermediate group of intrusive and extrusive rocks throughout the western half of Utah has been brought out clearly by Gilluly. He [7, p. 68] concluded that "this wide-spread similarity in the chemistry of the igneous rocks of western Utah must reflect a regional magmatic character." The evidence of the Marysvale Region even more effectively supports this conclusion. Western Utah is evidently a distinct petrographic region, part, perhaps, of a larger "petrographic province." Any conclusion as to the cause of the distinction between this Region and contiguous regions involves the whole problem of regional magmatic activity and differentiation, a problem too large to be treated adequately here.

Nevertheless, it may be well to review the concept of petrographic provinces as applied to this Region, and to compare the western Utah area with areas to the west and east. Harker [9, pp. 88-109] reviewed the concept of petrographic provinces originally advocated by Judd [10] and the contribution that Iddings had made in pointing out the alkalic nature of the rocks along the east side of the Rocky Mountains and the sub-alkalic nature of the rocks of the Great Basin and the Pacific Coast. The eastern group is included in the "Atlantic branch" of Harker, and the western group is included in the "Pacific branch." Iddings [11, p. 480] pointed out the differences between the Sierra Nevada and Cascade rocks on the one hand and those to the east, and stated that the rocks of the Great Basin are more like those of Colorado than those of the Sierra Nevada. He suggested the existence of ill-defined zones that followed the major physiographic divisions, but called attention to the variations and complexities within these zones. Washington [12, p. 380] regarded this area as part of a complex comagmatic region "with rather high silica, soda, and lime, little potash and moderate iron and magnesia." Buddington and Callaghan [13, pp. 439-442] showed by means of a variation-diagram the marked difference between the intrusive rocks of the Cascade Mountains in Oregon and those of western Utah.

A glance at the geologic map of the United States will show that the volcanic region of southwest-central Utah is essentially continuous with that of southwestern Utah, which extends westward into Nevada. Few analyses are available for this large area. Analyses from the Iron Springs Region in southwestern Utah show a high proportion of potash, and F. G. Wells [personal communication] has found that basalt in southwestern Utah has equivalent alkalies. Out on what might be considered the outer margin of the volcanic region, in the Delamar District in Nevada, the rhyolite is of the usual high-potash, low-soda type, though the intrusive rock contains equivalent soda and potash in the unmodified facies. At Gold Hill, Utah, near the Nevada boundary, Nolan [14, pp. 49-53] found that the rhyolite was potassic, though the intermediate rocks were latites, and the basalt has equivalent soda and potash. Consequently, it may be assumed that somewhere within the Great Basin there is a transitional zone between the characteristic andesites and granodiorites of the Pacific branch or province and the typical quartz-monzonites and latites of the western part of Utah. East of the High Plateaus, the intrusives that penetrate the sedimentary rocks of the Colorado Plateau are distinctly different in that they are characterized by a preponderance of soda. In fact, feldspathoids are commonly found in these rocks.

Therefore, southeastern Utah represents another minor but contiguous petrographic region. In general, the rocks of the Marysvale Region are typical of a petrographic sub-province whose boundaries are as yet undetermined.

Conclusions

The igneous rocks of the Marysvale Region are believed to be representative of an area of volcanic rocks that occupies the central part of the High Plateaus of Utah. The aggregate thickness of the flows and pyroclastics is over 10,000 feet. They are divided into three groups on the basis of profound breaks in the sequence, and they rest upon pre-Tertiary rocks within the mapped area. Outside of the Marysvale Region, they rest upon what is regarded as an Eocene formation, and all but the last group, the basalts, are overlain by the late Pliocene or early Pleistocene Sevier River formation. The earlier Tertiary group consists of volcanic breccia, tuffs, and latite-flows, which tend to be less siliceous and more calcic than the latites, quartz-latites, rhyolites, and tuffs of the later Tertiary group. The intrusive quartz-monzonite and related rocks are confined to the earlier Tertiary group. The third and final group consists of alkalic olivine-basalt flows.

Chemical analyses bring out the most significant feature, the essential equivalence of the alkalies throughout the group from basalt to rhyolite. Petrographically, this chemical condition is suggested by the tendency of orthoclase to develop at the expense of plagioclase. The persistence of the equivalence of the alkalies suggests that the entire group is related, and that they have a common origin through differentiation from a parent monzonitic magma. The rocks of the Marysvale Region are regarded as typical of a petrographic region that includes most of western Utah.

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Washington, D. C.

NOLAN, PP 197-D

Regina

UNUSUAL CONCENTRATION OF ELEMENTS IN THE MONROE, UTAH, HOT SPRINGS APRONS[1]

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The Monroe hot springs 0.5 to 1 km east of Monroe flow from the Sevier normal fault, which extends northward along the western base of the Sevier Plateau. Tertiary andesitic to dacitic lava flows and breccias, rhyolitic tuffs, and monzonite plutons that form the Sevier Plateau east of the fault have been faulted up against Quaternary alluvium in the valley west of the fault, and Pleistocene landslide debris has been offset by the fault at the south end of Poverty Flat south of Monroe.

The large travertine mounds of Monroe hot springs were deposited from three groups of springs, the north, main or central, and south springs. The springs have been investigated in recent years as possible sources of geothermal energy, and at present the main springs supply warm water for the hot springs resort at Monroe.

Most of the travertine deposits are rich in iron (as much as 20 percent) and are therefore brown, red-brown, yellow, and orange. The travertine mounds at all three springs are anomalous in many elements. For example, a representative sample of the travertine of the north spring deposit taken by Heyl in 1968 and analyzed by the laboratory of the Field Services Section of the U.S. Geological Survey in 1969 gave the following results, in percent: iron >20.0, magnesium 0.3, calcium 20.0, titanium 0.05, manganese .10, arsenic .15, boron 0.002, barium 0.0700, beryllium 0.0010, chromium 0.0010, molybdenum 0.0020, niobium 0.0010, antimony 0.0500, strontium 0.0700, vanadium 0.0020, tungsten 0.0500, yttrium 0.0030, zirconium 0.0030, mercury 0.000016, tellurium 0.000040, and traces of copper and nickel. The analyses were all semiquantitative spectrographic analyses by E. L. Moses, except for atomic absorption analyses for mercury by D. L. Murrey, and for tellurium by M. S. Rickard and C. L. Jacobsen.

The large hot springs travertine deposits of the main or central mounds were sampled in several places by Heyl, and analyzed by the same method and analysts. The results showed, in percent: iron 5->20, manganese 0.005-0.1, bismuth as much as .0015, cobalt 0.0015-0.0020, chromium 0.0010-0.0300, nickel 0.0005-0.0070, copper and lead as much as 0.0300 percent each, molybdenum as much as 0.0150, strontium 0.1000, vanadium 0.0300, zirconium 0.0700, mercury 0.000070, silver 0.0040, and tellurium 0.000060.

The temperatures of the springs at the surface range widely from about 70° C in one of the north springs to barely warm in some of the central and southern springs. Probably heated meteoric waters have been extracting elements from the country rocks and redepositing them in travertine mounds to form a low-grade mineral deposit of substantial volume. Water likely circulates deeply along the fault zone, is heated and takes up leached elements, and then rises to the surface. Leached country rocks are the Tertiary andesitic and rhyolitic volcanic rocks of the Sevier Plateau and possibly Jurassic carbonate rocks that underlie the volcanics. A small magmatic component, or metals derived from deeper and older mineral deposits, may be present as suggested by the small but measurable quantities of such elements as tungsten, bismuth, arsenic, molybdenum and antimony. The Monroe hot springs travertine mounds, a good example of a present day concentration of minerals formed from heated meteoric fluids, may be genetically similar to, but of much lower grade than, the manganese and iron oxide and calcium carbonate veins of the Escalante mine which also contains silver, lead, molybdenum, vanadium, and arsenic. Another genetically similar deposit is the tungsten enriched manganese oxide deposit at Golconda hot springs in the southern Osgood Mountains of north central Nevada described by Hewett and Fleischer (1960).

REFERENCE CITED

Hewett, D. F., and Fleischer, Michael, 1960, Deposits of the manganese oxides: Econ. Geology, v. 55, p. 1-55.

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[1] Publication authorized by the Director, U.S. Geological Survey.

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Petrology of Oligocene and early Miocene calc-alkalic volcanism in the Marysvale area, Utah

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INTRODUCTION

The Marysvale region, located in the High Plateaus of south-central Utah (Fig. 1), was the site of extensive and prolonged volcanism from middle to late Cenozoic time. The area contains flows, breccias, and pyroclastics some 3,000 m thick covering approximately 1,000 km^2. The volcanics range in composition from basalt to rhyolite and in age from 30 m.y. to at least 7 m.y. old.

The general geology and volcanic stratigraphy of the Marysvale area has been studied by Callaghan and co-workers (Callaghan, 1939; Callaghan and Parker, 1961a, 1961b, 1962a, 1962b; Willard and Callaghan, 1962) and more recently by Steven and Cunningham (Steven and others, 1977; Cunningham and Steven, 1977). The volcanic stratigraphy of the surrounding southern High Plateaus has been described by Rowley and Anderson (Rowley, 1968; Anderson and Rowley, 1975; Rowley and others, 1975), but correlations of volcanic sequences of rocks between the High Plateaus and the Marysvale area remain problematic. The reader is referred to Steven and others (1977) for a comprehensive discussion of the Marysvale stratigraphy.

The area has received attention because of its mineral resources (Kerr, 1963; Kerr and others, 1957; Callaghan, 1973). Principal mineral deposits include base metal replacement bodies in the Permian Toroweap Formation, gold-silver veins in the older volcanic rocks, and uranium veins and disseminations associated with quartz monzonite intrusive bodies as well as with younger silicic volcanics.

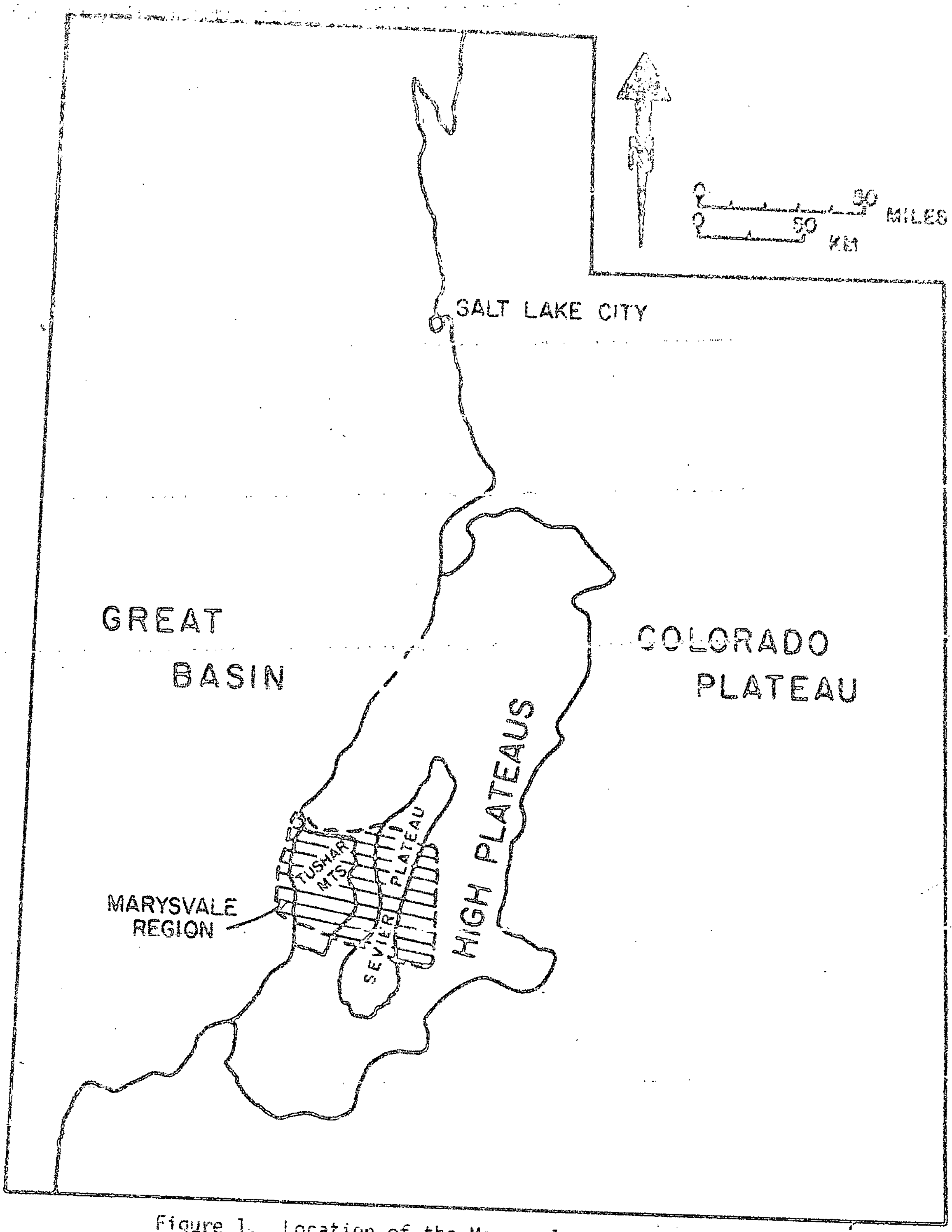

Figure 1. Location of the Marysvale region, Utah.

However, in these earlier studies, no detailed petrologic investigation had been done; in this paper, we describe the petrological evolution of the pre silicic calc-alkaline suite of volcanic rocks.

IGNEOUS HISTORY

The buildup of the Marysvale volcanic sequence began approximately 30 m.y. ago with the extrusion of voluminous andesitic flows and breccias from local clusters of volcanoes. Ash flow tuffs from local and regional sources interleaf with this assemblage constituting the series known as the Bullion Canyon Volcanics. Monzonite stocks intruded the Bullion Canyon Volcanics approximately 23 m.y. ago (Steven and others, 1977) to mark the end of this period of volcanism characterized by mafic to intermediate composition extrusives. Following a brief quiescence, volcanism in the area evolved to a more silicic and explosive nature, culminating in the formation of the Mount Belknap and Red Hills calderas at 18 to 19 m.y. ago (Cunningham and Steven, 1977). The silicic volcanic rocks of this episode have been termed the "Mount Belknap Volcanics" by Steven and others (1977). Fluvial and lacustrine sedimentation followed closely with the onset of Basin and Range faulting, thought to have begun about 17 m.y. ago in this area, and continued until Pleistocene time. This sedimentation now constitutes the Sevier River Formation. Minor basalt flows, probably related to extensional tectonism, were erupted during this time and are intercalated with the Sevier River sediments.

The volcanic rocks of the Mount Belknap and Red Hills calderas (Cunningham and Steven, 1977) are high silica, alkalic rhyolites characteristic of a number of late Cenozoic rhyolite centers in the western United States such as Yellowstone National Park, Wyoming; Long Valley and the Coso Mountains, California; Jemez Mountains, New Mexico; and the Mineral Mountains in Utah. These rhyolites are not characteristically associated with voluminous calc-alkalic volcanism. Our study is directed toward the calc-alkaline volcanic products, and although we include one sample from the silicic suite, there is no overwhelming evidence that the two groups are necessarily genetically related.

Figure 2 shows sample locations, and

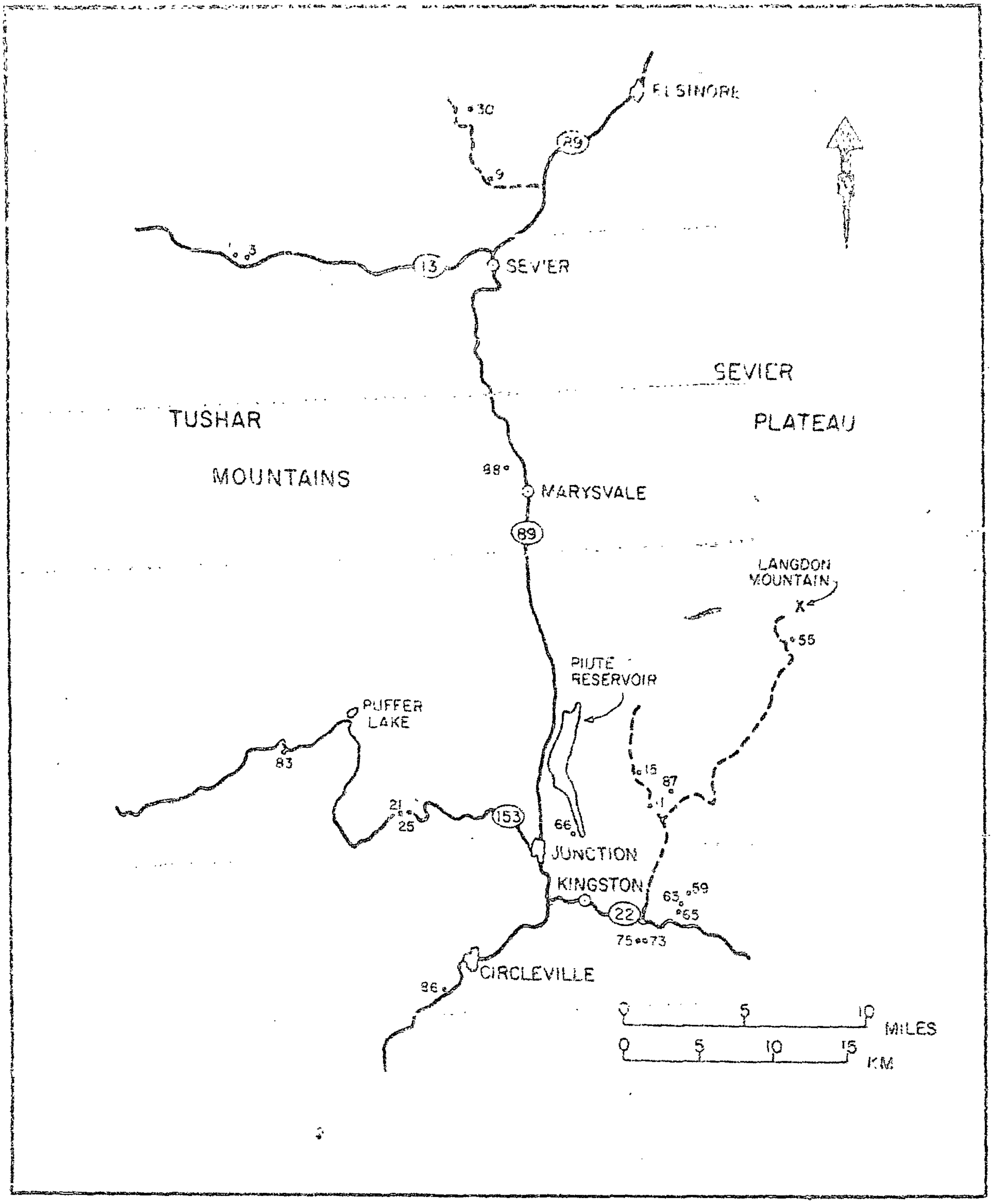

Figure 2. Index map for analyzed samples.

Figure 3 contains a stratigraphic correlation chart as well as an index for the analyzed samples. The exact age relationships of the three mafic lavas described in this paper are not clear. Sample 66 is an absarokite flow from the west side of Paiute Reservoir that was mapped as younger basalt by both Rowley (1968) and Willard and Callaghan (1962). However, its unusual composition is not characteristic of young basalts along the eastern margin of the Basin and Range Province, and an age of 21.1 ± 0.2 m.y. has been obtained on this flow (M. G. Best, 1978, personal commun.). It does not overlie the Sevier River Formation, which is the usual criterion employed for recognizing young basalts in the area. Sample 15, collected 4 km east of Paiute Reservoir, overlies the Sevier River Formation and is presumably Pliocene to Pleistocene in age. Sample 87 is from a unit mapped as older basalt by Rowley (1968), and is not mapped by Willard and Callaghan (1962). However, the outcrop is adjacent to basalt flows mapped by all investigations as young basalt. It is chemically similar to sample 15, and may or may not be a young basalt. Sample 80 is an obsidian from the Gray Hills Rhyolite Member of the Mount Belknap Volcanics (Cunningham and Steven, 1977)

ANALYTICAL METHOD

The particular rocks studied have been selected on the basis of degree of freshness and stratigraphic location; due to pervasive hydrothermal alteration, a number of volcanic units are not well represented. Mineral analyses were determined with an ARL/EMX-SM electron microprobe, bulk-rock analyses were made by wet chemical methods described by Carmichael and others (1968), and trace elements were determined with a Phillips X-ray fluorescence spectrometer using U.S. Geological Survey whole-rock standards.

PETROGRAPHY

Mafic Volcanic Rocks

Basalts in the Marysvale region are transitional between alkaline and tholeiitic types. Silica contents are moderately high (between 51% and 52%) as are alkali contents, and all contain a single monoclinic pyroxene which is characteristically non-titaniferous. Modal analyses of the rocks studied are given in Table 1. Four

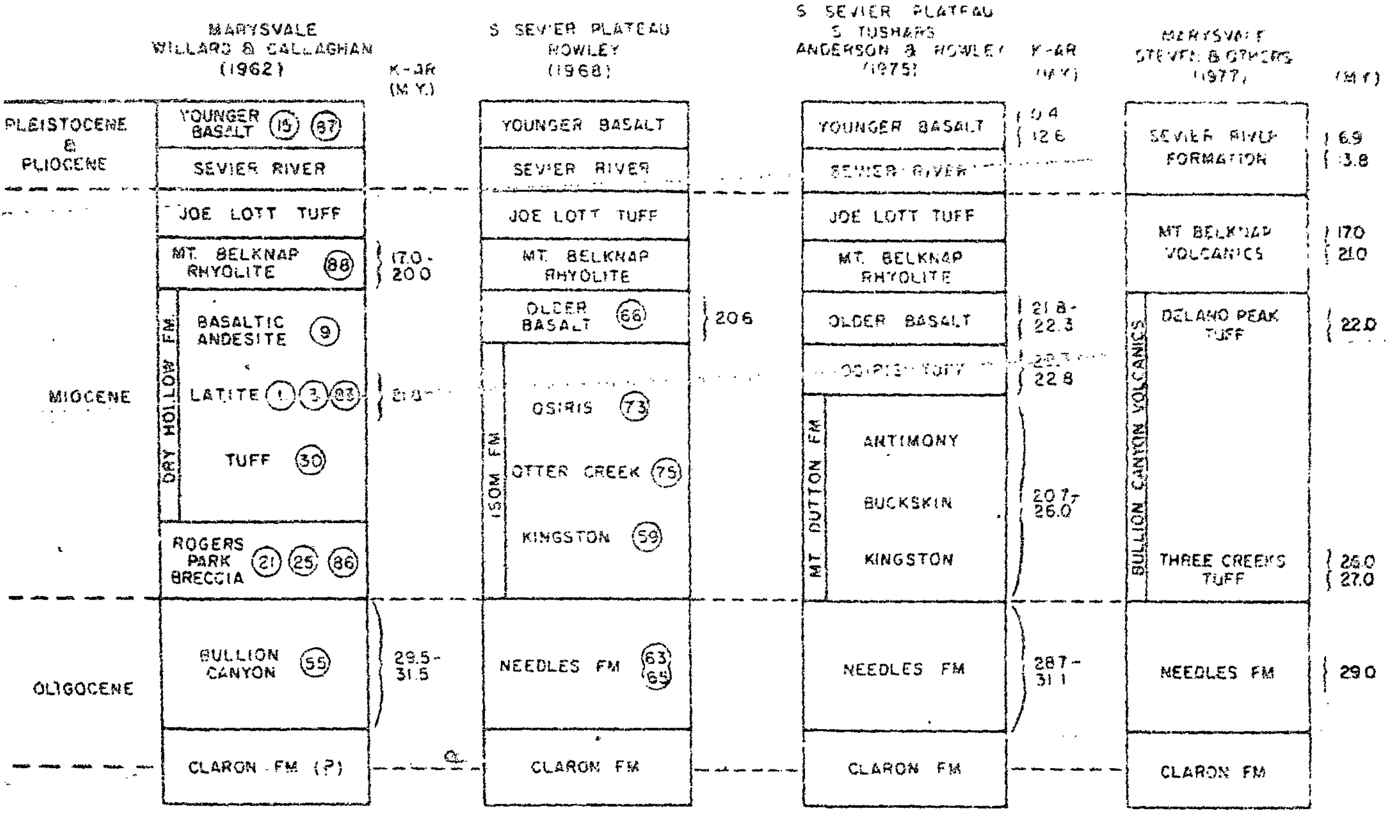

Figure 3 Stratigraphy of the Tushar Mountains and southern Sevier Plateau. Circled numbers are samples discussed in the text. Ages of volcanic units are from Bassett _et al._ (1963), Fleck _et al._ (1975), and Steven _et al._ (1977).

Table 1. Marysvale modal analysis (volume %)

Sample No.	15	66	87	9	21	86	3	25	73	55
Phenocrysts										
Plagioclase	14.8	-	11.7	21.8	13.9	40.8	18.1	20.2	21.3	16.4
Olivine	2.6	4.0	6.1	2.5	0.5	-	-	-	-	-
Clinopyroxene	7.4	0.3	7.4	9.9	2.4	5.3	4.0	-	0.4	-
Orthopyroxene	-	-	-	0.4	1.4	1.8	-	-	0.1	-
Amphibole	-	-	-	-	-	TR.	-	11.9	-	16.6
Biotite	-	-	-	-	-	-	-	-	2.1	-
Fe-Ti Oxides	0.2	1.1	0.5	2.0	0.7	2.5	4.0	1.5	0.7	0.7
Alkali Felds.	-	-	-	-	-	-	-	-	1.2	-
Apatite	-	1.1	-	-	-	-	-	-	TR.	-
Lithic Frag.	-	-	-	-	-	-	-	-	TR.	-
Groundmass										
Undifferentiated	75.0	93.5	74.3	63.4	81.1	49.6	73.9	66.4	-	66.3
Glass	-	-	-	-	-	-	-	-	74.1	-

Sample No.	59	83	75	11	88	1	30	63	65
Plagioclase	6.6	18.8	10.2	19.6	-	35.1	31.4	30.2	30.9
Olivine	-	-	-	-	-	-	-	-	-
Clinopyroxene	0.6	6.4	0.8	-	-	-	-	-	-
Orthopyroxene	0.2	-	1.0	-	-	-	-	-	-
Amphibole	0.1	-	0.2	7.9	-	7.6	6.0	10.4	12.6
Biotite	0.5	4.2	-	1.9	-	4.5	1.5	3.0	1.9
Fe-Ti Oxides	0.8	1.7	1.2	1.4	-	2.3	2.9	2.0	2.4
Alkali Felds.	-	-	1.6		-	-	TR.	TR.	TR.
Apatite	TR.	-	-	-	-	-	-	-	-
Lithic Frag.	11.6	-	2.7	-	-	-	-	-	-
Groundmass									
Undifferentiated	-	68.9	-	69.2	-	50.5	58.2	54.4	52.2
Glass	79.6	-	82.3	-	100	-	-	-	-

varieties of basalt can be recognized from petrographic criteria. These data, combined with differences in bulk rock chemistry and mineral composition, indicate a diversity among lava flows which have been collectively mapped as "younger basalts" by Willard and Callaghan (1962) in the Marysvale quadrangle.

One distinctive type of mafic lava (sample 66), an absarokite, contains euhedral to subhedral olivine and minor clinopyroxene phenocrysts set in a sub-ophitic groundmass of labradorite, alkali feldspar, pyroxene, and olivine. It contains approximately 1% modal apatite as microphenocrysts, often intimately associated with olivine. This lava is compositionally similar to absarokite from Yellowstone National Park described by Iddings (1895) and Nicholls and Carmichael (1969); the most notable differences are high magnesium and lower iron in the Yellowstone absarokite. Hogg (1972) has described mid-Tertiary absarokite lavas from west-central Utah which are chemically and petrographically similar to the Marysvale sample.

A second type of mafic lava has all of the petrographic characteristics of the first except that it lacks apatite microphenocrysts. A third type (sample 15) contains phenocrysts of labradorite, olivine, and clinopyroxene, the last in much greater abundance than the first two types (Table 1). The phenocrysts are set in a sub-ophitic groundmass of more sodic plagioclase, pyroxene, and olivine. A fourth basalt type (sample 87) has phenocrysts of olivine, clinopyroxene, and labradorite set in a groundmass of plagioclase, olivine, and pyroxene. Abundant olivine is characteristically corroded and embayed, whereas clinopyroxene and plagioclase occur as large euhedral grains.

Intermediate Volcanic Rocks

Intermediate volcanics dominate the Marysvale sequence. They include andesites, latites, and dacites; they occur as flows, pyroclastics, and breccias. The andesites studied at Marysvale are porphyritic with phenocrysts of calcic plagioclase, olivine, clinopyroxene, and orthopyroxene; amphibole occurs in one sample (86). Two varieties of andesite can be distinguished by phenocryst mineralogy. The first variety (samples 21 and 86) contains highly calcic plagioclase phenocrysts which have strong normal zoning from An_{85} to An_{50} and commonly show a glomeroporphyritic texture. Olivine may occur as microphenocrysts, but it is not abundant. The second variety (sample 9) has phenocrysts of moderately zoned laboradorite, with clinopyroxene and olivine constituting a significant proportion of the phenocrysts. Both varieties contain orthopyroxene as phenocrysts and alkali feldspar in the groundmass. The plagioclase phenocrysts of each variety display a prominent potted or "sieve" texture. The andesites contain 56% to 58% SiO_2 and are enriched in alkalies ($Na_2O + K_2O$ averaging more than 6%); they are the most aluminous rocks at Marysvale.

The remaining intermediate volcanics are dacites and latites that display a wide mineralogical variety (Table 1). Two latite vitrophyres (samples 73 and 75) contain phenocrysts of orthopyroxene, clinopyroxene, and andesine, with or without sanidine, biotite, and amphibole. Dacitic varieties contain phenocrysts of andesine, amphibole, clinopyroxene, and biotite in various proportions, with alkali feldspar and/or quartz occurring as a sparse phase in the groundmass. Samples 73, 75, and 83 have silica contents between 62% and 64% with a pronounced high K_2O/Na_2O ratio; because they all contain modal pyroxene, the term "pyroxene latite" is appropriate.

Silicic Volcanic Rocks

The Marysvale volcanic sequence contains more than 2,000 m of silicic flows and tuffs of the Mount Belknap Volcanics. These have been erupted from two source areas, one in the central Tushar Mountains and the other in the southern Antelope Range (Cunningham and Steven, 1977). These source areas were the sites of subsidence following voluminous ash flow tuff eruptions forming the Mount Belknap and smaller Red Hills calderas, respectively. The single sample analyzed from this suite (no. 88) is a phenocryst-poor obsidian.

MINERALOGY

Feldspar

Feldspar is present, either in the groundmass or as phenocrysts, in all rocks studied at Marysvale. Electron probe analyses of feldspars are graphically depicted in Figure 4.[1] Plagioclase phenocrysts vary from bytownite to sodic andesine; these correspond to compositional extremes of An_{78} (sample 21) to An_{32} (sample 65). Zoning, with few exceptions, is normal and strongest at the margins. Sanidine phenocrysts range from Or_{77} (sample 30) to Or_{55} (sample 75). Zoning of the sanidine phenocrysts is subtle, but there is usually a slight increase in the albite component toward the margins.

Groundmass plagioclase ranges from labradorite to oligoclase in composition. It is more sodic than coexisting plagioclase phenocrysts, with the exception of sample 3 in which groundmass plagioclase is more calcic than phenocrysts. Samples 59 and 75 contain small lithic fragments with plagioclase feldspar as calcic as An_{82} (Fig. 4), which may be from units such as samples 86, 25, or 21, the only other lavas sampled which contain plagioclase as calcic as this.

Alkali feldspar occurs in the groundmass of most samples and displays a wide compositional range. The common mode of occurrence is as small interstitial grains between plagioclase laths. Several are rich in barium and iron; for example, phenocrysts from the lower unit of the Needles Range Formation contain 2.4% BaO.

Olivine

Olivine phenocrysts from basalts range in composition from Fo_{85} to Fo_{65}, whereas olivine phenocrysts in andesites are more iron-rich and have a compositional range of Fo_{75} to Fo_{55} (Fig. 5).

Orthopyroxene

Orthopyroxenes have a limited compositional range from En_{80} to En_{70} (Fig. 5). Zoning is minimal, with the most highly zoned showing a total range of about 8 mole percent $FeSiO_3$.

SiO_2 contents do not vary by much more than 1 percent, and TiO_2 is consistent throughout. Al_2O_3 contents of andesitic orthopyroxenes (samples 9, 21, and 86) are somewhat higher as a whole than orthopyroxenes in dacitic rocks. The MnO content of three of the analyzed pyroxenes is substantial (more than 1%), and as expected,

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[1] Tabulated analyses of feldspar, olivine, and pyroxene are available from the authors.

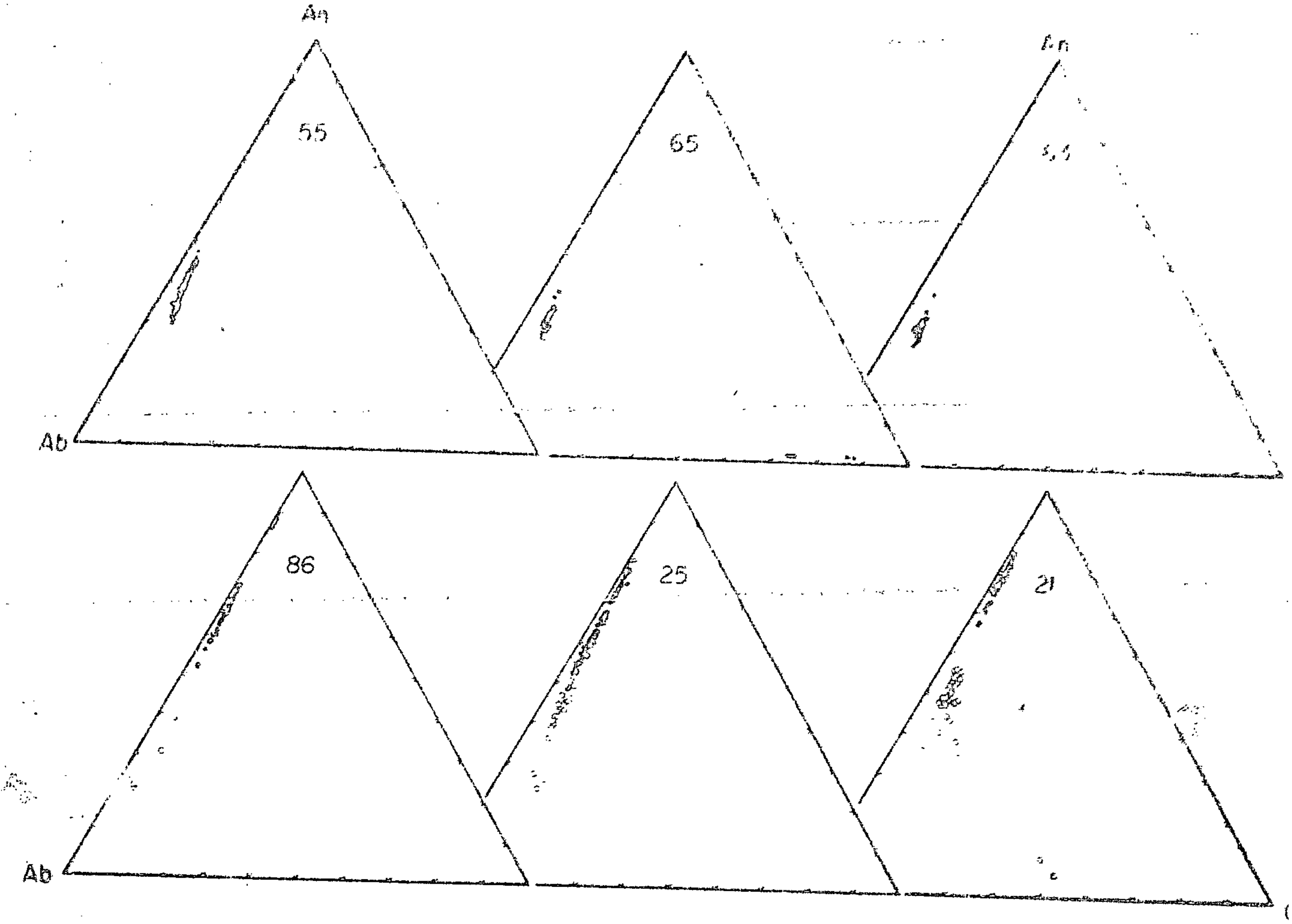


Figure 4 Microprobe analyses of feldspar in terms of weight percent anorthite (An), albite (Ab), and orthoclase (Or). Phenocrysts are shown as solid circles, groundmass grains as open circles. Crosses in samples 59 and 75 are feldspar from lithic fragments. The samples are arranged in a general age sequence from oldest (upper left) to youngest (lower right). (See Fig. 3). Fig. 4 is continued on the next two frames.

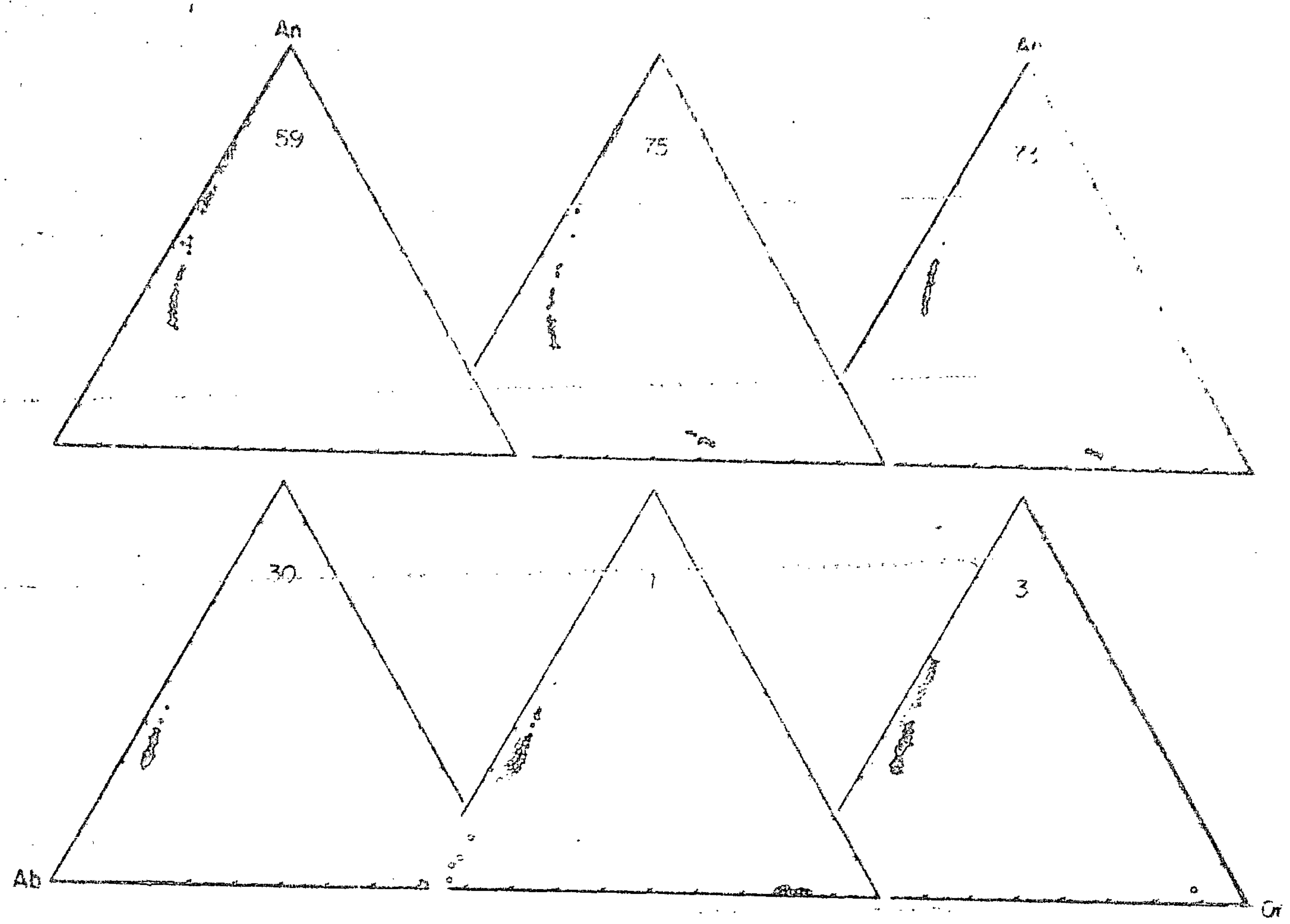
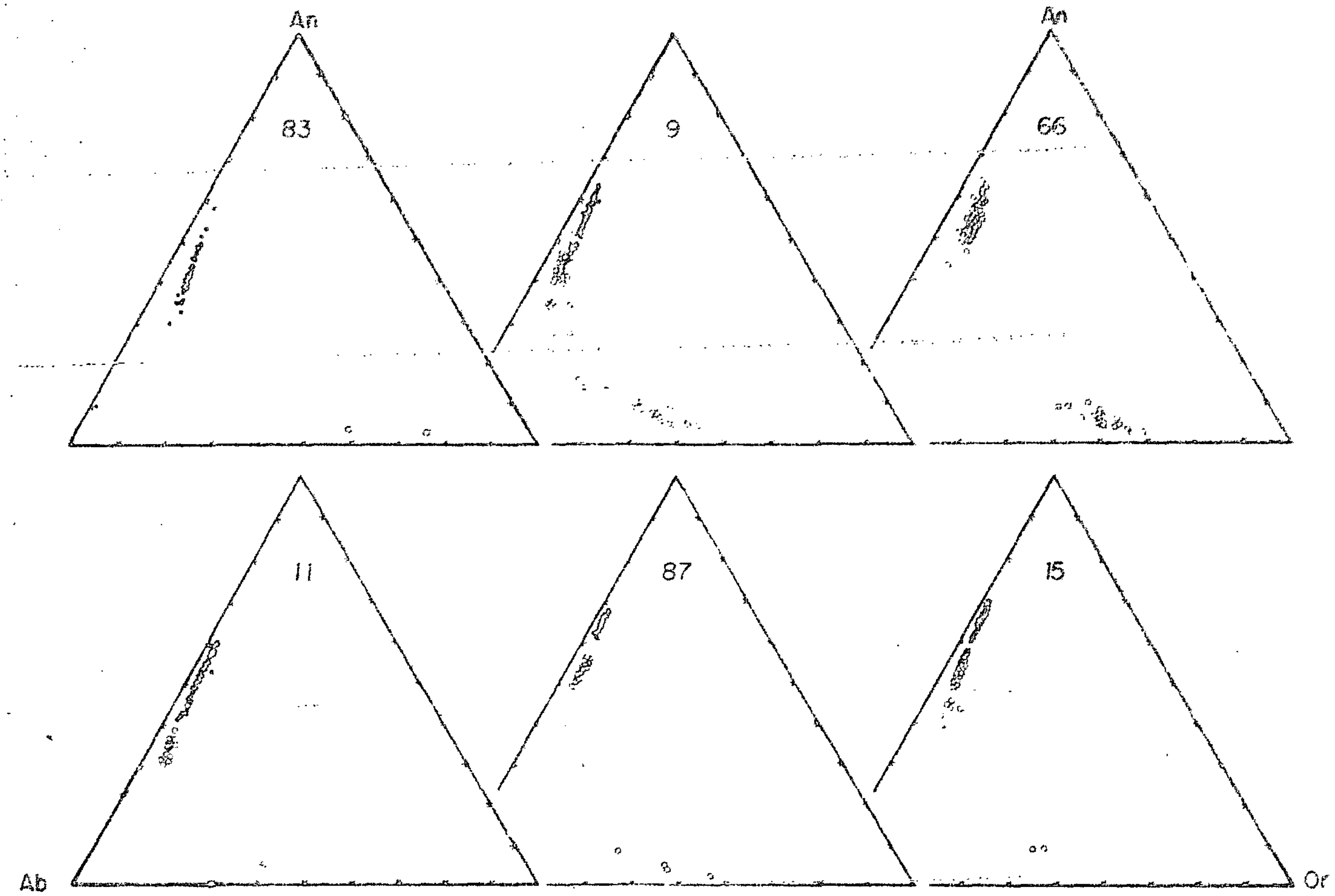


Figure 4 continued



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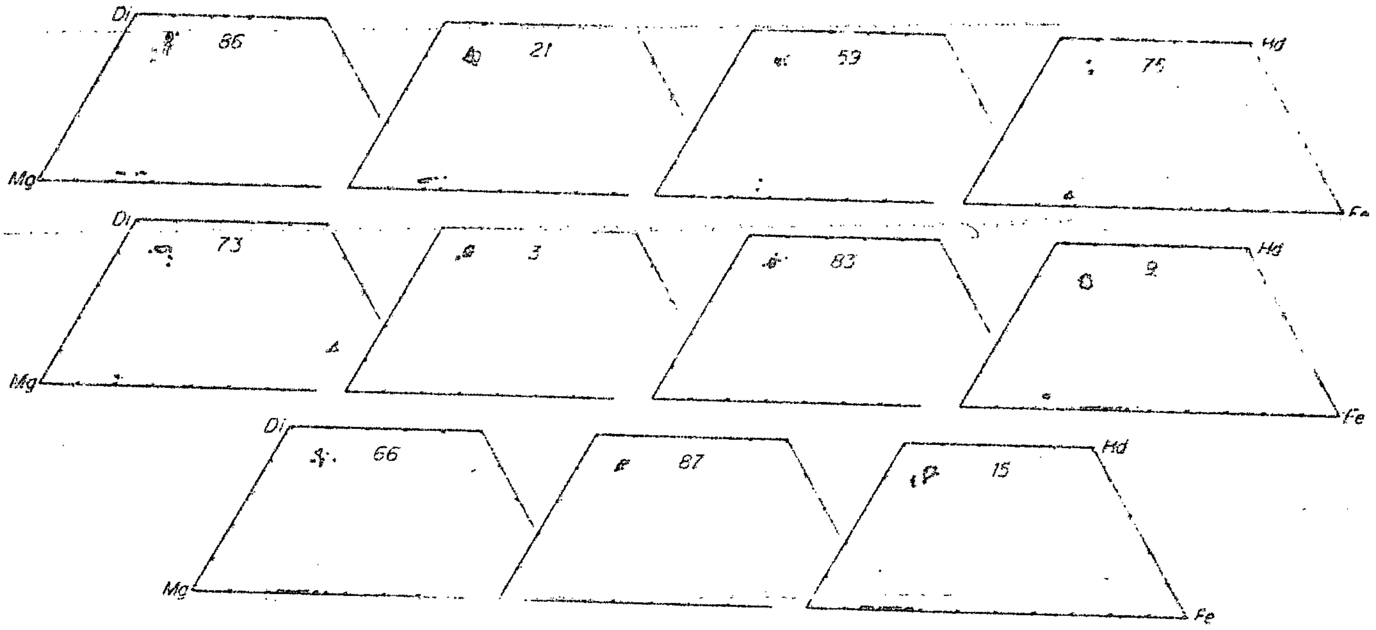

Figure 5 Microprobe analyses of pyroxene (circles) and olivine (triangles) in terms of atom percent Ca, Mg and Fe. Phenocryst and groundmass grains are represented by solid and open symbols, respectively. As in the feldspar diagram, sample ages decrease from left to right, with the oldest samples in the upper left.

increases with total iron content.

Clinopyroxene

Clinopyroxene analyses (Fig. 5) cluster around diopsidic augite in composition. Although there is a slight tendency toward iron enrichment in some, the pattern is one of generally uniform composition. In late Cenozoic rocks from southwestern Utah, Lowder (1973) also found a random scattering of points around an augitic composition which he attributes to the relatively low Al_2O_3 content of the pyroxenes (about 4.5%). Marysvale augites have even lower Al_2O_3 contents and, as Lowder (1973) also found, the only augites that show any tendency to zone toward the diopside-hedenbergite join are those with highest Al_2O_3 contents (samples 15 and 87).

Titanium is not abundant in augite, a characteristic of calc-alkaline volcanic rocks. Sample 66, an older basalt, contains augite with 1.5 weight percent TiO_2, the highest value observed. Augites from younger basalts average 1.2% TiO_2, with the remaining analyzed pyroxenes containing less than 1%. The most titaniferous varieties are those containing the most aluminum.

The SiO_2 content systematically increases in clinopyroxene with increasing silica concentration of the host magma (Fig. 6). The sodium content of Marysvale augites is low (less than 0.5%) and this, combined with low aluminum, suggests crystallization at shallow depths (Green and Ringwood, 1968).

Amphibole

Hornblende phenocrysts are common in the dacitic rocks at Marysvale, and a few grains of amphibole were found in one andesite (sample 86). Microprobe analyses show that hornblendes fall into two distinct groups based on Al_2O_3 content (Table 2) which is independent of rock type. One group has Al_2O_3 values falling between 7 and 8 weight percent, whereas the other has Al_2O_3 values between 10 and 11 weight percent (with the exception of the andesitic hornblende, which has an even higher aluminum content). TiO_2 contents lie between 1.4 to 1.6 weight percent for the low alumina group and 1.9 to 2.4 percent for the high aluminum group. The sodium content is consistently higher in the aluminous varieties, with manganese behaving in the opposite manner. All of the amphiboles contain measurable

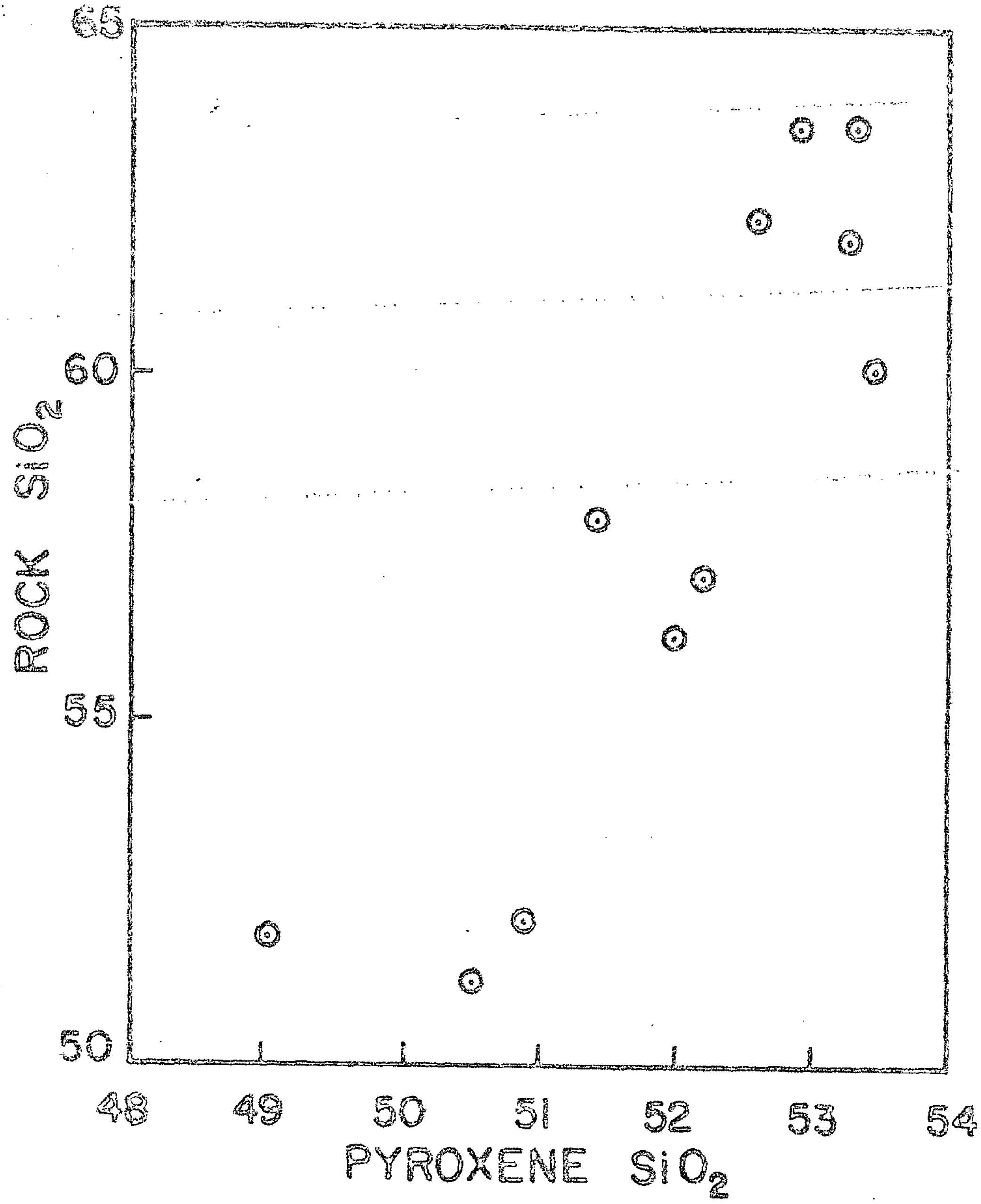

Figure 6 SiO_2 contents of clinopyroxene and host rocks.

Table 2. Average microprobe analyses and structural formulas of Marysvale amphiboles

Sample no.	1	11	25	30	55
SiO_2	47.1	45.0	44.2	47.8	43.6
TiO_2	1.39	2.05	2.38	1.43	1.88
Al_2O_3	7.71	10.2	10.9	7.27	10.9
FeO*	14.8	12.2	11.9	15.1	14.5
MnO	0.41	0.26	0.18	0.41	0.33
MgO	13.6	15.1	14.9	13.3	12.9
CaO	12.0	11.5	11.8	12.0	11.4
Na_2O	1.37	1.97	2.11	1.35	2.07
K_2O	0.85	0.61	0.76	0.84	0.89
F	0.26	0.41	0.30	0.25	0.27
Cl	0.10	0.03	0.02	0.10	0.04
Sum	99.59	99.33	99.45	99.85	98.78
-O - F, Cl	0.13	0.18	0.13	0.13	0.12
TOTAL	99.5	99.2	99.3	99.7	98.7

Number of ions on the basis of 23 oxygens

	1		11		25		30		55	
Si	6.872	8.00	6.521	8.00	6.406	8.00	6.952	8.00	6.444	8.00
Al	1.128		1.479		1.594		1.048		1.556	
Al	0.197	5.16	0.271	5.26	0.274	5.21	0.200	5.13	0.342	5.22
Ti	0.152		0.223		0.259		0.157		0.209	
Fe	1.801		1.475		1.439		1.840		1.789	
Mn	0.051		0.032		0.022		0.051		0.042	
Mg	2.961		3.261		3.216		2.883		2.834	
Ca	1.881	2.43	1.787	2.45	1.825	2.56	1.870	2.41	1.803	2.56
Na	0.387		0.553		0.592		0.381		0.593	
K	0.158		0.113		0.141		0.156		0.167	

* All iron computed as FeO

Table 2 - continued

Sample No.	59	63	65	75	86
SiO_2	46.8	47.7	48.0	45.0	42.5
TiO_2	1.56	1.37	1.38	2.15	2.18
Al_2O_3	7.71	7.61	7.43	10.7	12.3
FeO*	13.7	14.7	14.5	12.9	12.9
MnO	0.43	0.41	0.41	0.33	0.18
MgO	14.5	13.9	13.9	13.8	13.9
CaO	11.8	12.0	12.0	11.4	11.7
Na_2O	1.58	1.26	1.29	2.08	2.34
K_2O	0.79	0.78	0.85	0.64	0.59
F	0.30	0.25	0.26	0.23	0.15
Cl	0.10	0.12	0.11	0.02	0.01
Sum	99.24	100.10	100.13	99.25	98.75
-O - F, Cl	0.15	0.14	0.13	0.10	0.06
TOTAL	99.1	99.9	100.0	99.2	98.7

Number of ions on the basis of 23 oxygens

	59		63		65		75		86	
Si	6.829	8.00	6.911	8.00	6.943	8.00	6.533	8.00	6.228	8.00
Al	1.171		1.089		1.057		1.467		1.772	
Al	0.155	5.20	0.211	5.18	0.211	5.16	0.366	5.19	0.361	5.24
Ti	0.171		0.149		0.159		0.235		0.240	
Fe	1.668		1.777		1.754		1.567		1.586	
Mn	0.053		0.050		0.050		0.041		0.022	
Mg	3.151		2.989		2.992		2.981		3.034	
Ca	1.842	2.44	1.865	2.36	1.857	2.38	1.775	2.48	1.835	2.61
Na	0.447		0.353		0.362		0.585		0.666	
K	0.147		0.144		0.156		0.119		0.111	

* All iron computed as FeO

Table 3. Average microprobe analyses and structural formulas of biotites.

Sample no.	1	11	30	59
SiO_2	37.3	36.7	36.9	36.6
TiO_2	4.66	4.13	4.70	7.58
Al_2O_3	13.2	13.6	13.3	13.4
FeO*	16.1	12.7	18.0	12.7
MnO	0.20	0.13	0.22	0.17
MgO	14.1	17.5	13.1	15.3
CaO	0.07	0.14	0.07	0.09
Na_2O	0.56	1.08	0.53	0.89
K_2O	9.14	8.18	9.23	8.58
BaO	0.41	0.99	0.37	0.95
F	0.53	0.76	0.72	0.63
Cl	0.16	0.05	0.17	0.04
Sum	96.43	95.96	97.31	97.02
-O≡F, Cl	0.26	0.33	0.34	0.28
TOTAL	96.2	95.6	97.0	96.7

Number of ions on the basis of 22 oxygens

	1		11		30		59	
Si	5.613	8.00	5.484	8.00	5.568	8.00	5.412	8.00
Al	2.337		2.391		2.361		2.336	
Ti	0.050		0.125		0.071		0.252	
Ti	0.477	5.70	0.339	5.84	0.462	5.72	0.591	5.56
Fe	2.029		0.592		2.274		1.576	
Mn	0.025		0.016		0.028		0.021	
Mg	3.170		3.894		2.954		3.375	
Ca	0.011	1.95	0.022	1.95	0.011	1.97	0.012	1.96
Na	0.163		0.313		0.156		0.256	
K	1.754		1.559		1.778		1.629	
Ba	0.024		0.058		0.022		0.055	

* All iron computed as FeO

Table 3 continued

Sample no.	63	65	73	83
SiO_2	36.9	37.1	36.8	36.7
TiO_2	4.81	4.80	7.72	6.15
Al_2O_3	13.3	13.3	13.3	13.2
FeO*	16.5	16.4	11.6	12.8
MnO	0.20	0.20	0.13	0.15
MgO	14.1	14.1	16.6	16.2
CaO	0.09	0.08	0.07	0.05
Na_2O	0.57	0.56	0.75	0.74
K_2O	9.28	9.28	9.03	9.14
BaO	0.49	0.42	1.01	0.82
F	0.64	0.58	1.37	1.10
Cl	0.17	0.16	0.03	0.06
Sum	97.05	97.00	98.41	97.11
-O≡F, Cl	0.31	0.28	0.59	0.47
TOTAL	96.7	96.7	97.8	96.6

Number of ions on the basis of 22 oxygens

	63		65		73		83	
Si	5.555	8.00	5.572	8.00	5.393	8.00	5.460	8.00
Al	2.353		2.348		2.291		2.317	
Ti	0.092		0.080		0.316		0.223	
Ti	0.452	5.71	0.462	5.71	0.534	5.59	0.465	5.67
Fe	2.070		2.058		1.416		1.594	
Mn	0.025		0.025		0.016		0.019	
Mg	3.162		3.160		3.627		3.590	
Ca	0.014	1.99	0.013	1.98	0.011	1.97	0.008	2.00
Na	0.166		0.162		0.213		0.213	
K	1.780		1.778		1.688		1.733	
Ba	0.029		0.024		0.058		0.047	

* All iron computed as FeO

fluorine and chlorine. Chlorine seems to be more abundant in amphiboles of the low alumina group, whereas fluorine does not vary. In general, hornblendes are similar in composition to those of calc-alkaline volcanic rocks from island arcs and continental margins (Jakes and White, 1972).

Oxides

Iron-titanium oxides occur as microphenocrysts and/or in the groundmass of all of the volcanic rocks studied at Marysvale. In addition, small euhedral chromite grains are poikilitically enclosed in olivine phenocrysts of some basaltic rocks. Titanomagnetite is common in all rocks, but ilmenite is absent in some basalts, all andesites, and is a sporadic phase in dacites. When found, it was usually homogenous in composition. Microprobe analyses of Fe-Ti oxides are given in Table 3, recalculated in the manner of Carmichael (1967).

Oxygen fugacities and equilibration temperatures (Table 4) have been determined from rocks containing coexisting Fe-Ti oxides (Buddington and Lindsley, 1964) and show a temperature range from 865 to 950 °C. The logarithm of the fugacity of oxygen varies from -16.1 to -13.8. The two mafic lavas (samples 66 and 87) fall just below the FMQ buffer, as is to be expected for lavas containing titanomagnetite and olivine. Samples 73 and 75 (both latites) coexist with orthopyroxene and lie above the FMQ buffer, ~~and sample 11,~~ containing both amphibole and biotite, falls even farther above the FMQ buffer. These results seem to bear out the relationship between magmatic oxygen-fugacity and the buffering effect of condensed phases initially described by Carmichael (1967).

CHEMISTRY

Major Elements

Basalts are olivine normative, whereas all the andesites are quartz normative (Table 5). SiO_2 contents cover a broad range and can be divided conveniently into four groups: basaltic (51% to 52%), andesitic (56% to 58%), dacitic-latitic (60% to 65%), and a single rhyolite (73%). Although the silica breaks are distinct, a silica gap as noted in southern Utah by Lowder (1973) and Hausel and Nash (1977) is not present at Marysvale. Callaghan (1939) reports analyses of three rocks from

Table 4. Microprobe analyses of Iron-titanium Oxides

Sample No.	11	66	73	75	87
			Spinel Phase		
SiO_2	-	-	-	-	
TiO_2	7.14	22.1	13.1	16.7	19.2
Al_2O_3	2.10	2.60	2.30	2.17	1.75
V_2O_3	0.36	0.75	0.42	0.39	0.84
Cr_2O_3	0.11	1.01	0.08	0.05	0.89
FeO	84.0	68.6	76.6	73.7	71.0
MnO	0.69	0.54	0.88	1.08	0.55
MgO	1.39	2.76	2.79	2.58	2.19
CaO	0.04	0.05	0.03	0.02	0.19
ZnO	0.20	0.13	0.20	0.19	0.14
Sum	96.0	98.6	96.4	96.9	96.8
Fe_2O_3	53.9	23.6	42.5	35.4	29.0
FeO	35.4	47.4	38.4	41.9	44.9
Total	101.4	101.0	100.7	100.5	99.7
			Rhombohedral Phase		
SiO_2	0.04	-	-	-	0.02
TiO_2	39.1	50.6	44.4	49.3	50.2
Al_2O_3	0.35	0.20	0.35	0.27	0.18
V_2O_3	0.48	0.60	0.47	0.47	0.54
Cr_2O_3	0.02	0.02	0.03	-	0.03
FeO	56.6	44.6	49.0	44.9	44.7
MnO	0.51	0.53	0.80	1.19	0.64
MgO	1.65	2.69	3.92	4.07	1.80
CaO	0.06	0.14	0.11	0.02	0.27
ZnO	0.05	-	0.08	0.02	
Sum	98.8	99.4	99.2	100.2	98.4
Fe_2O_3	27.8	5.41	19.0	10.3	4.3
FeO	31.5	39.8	31.9	35.7	40.8
Total	101.6	100.0	101.1	101.2	98.8
Mole % ulvospinel	19.9	59.9	35.9	46.0	53.4
Mole % R_2O_3	27.0	5.9	18.5	10.2	5.0
T^oC	925	930	950	910	865
$-\log fO_2$	10.1	12.4	10.5	12.0	13.8

Table 5. Chemical Analyses and CIPW Norms of 15 Lavas and 2 Residual Glasses from the Marysvale Area

Sample no.	16	66	87	9	21	86	3	25	73
SiO_2	51.23	51.92	52.05	56.18	57.11	57.89	60.08	61.34	62.00
TiO_2	0.64	1.25	0.58	0.56	0.54	0.71	0.44	0.35	0.36
Al_2O_3	15.54	14.59	15.65	15.96	17.53	17.45	15.73	15.53	17.05
Fe_2O_3	3.89	3.62	4.30	3.62	0.53	3.63	4.90	3.26	1.13
FeO	5.90	7.44	5.34	5.61	6.87	3.58	2.16	2.61	1.69
MnO	0.08	0.07	0.05	0.08	0.07	0.08	0.04	0.05	0.03
MgO	6.43	4.76	7.37	4.27	2.89	2.51	2.42	3.06	1.17
CaO	9.38	7.08	8.26	6.85	6.55	6.96	6.04	5.16	2.91
Na_2O	3.52	2.97	3.64	3.56	3.58	3.43	3.85	3.43	4.12
K_2O	1.59	4.13	2.00	3.02	3.04	2.38	3.17	3.42	5.00
P_2O_5	0.28	0.82	0.23	0.21	0.26	0.32	0.18	0.17	0.06
H_2O+	0.11	0.19	0.01	0.09	0.31	0.63	0.16	0.96	3.02
H_2O-	0.18	0.12	0.06	0.09	0.24	0.19	0.33	0.29	0.83
CO_2	1.18	0.54	-	-	-	-	-	-	-
Total	99.95	99.50	99.54	100.10	99.52	99.76	99.50	99.63	99.37
CIPW Norms									
Q	-	-	-	3.50	3.57	11.48	12.21	14.07	10.51
C	-	-	-	-	-	-	-	-	-
or	9.40	24.41	11.82	17.85	17.96	14.06	18.73	20.21	29.55
ab	29.79	25.13	30.80	30.12	30.29	29.02	32.58	29.02	34.86
an	21.91	14.28	20.45	18.65	22.79	25.19	16.28	16.88	13.26
di-wo	6.40	5.04	7.94	5.83	3.34	3.03	5.22	3.18	0.33
di-en	4.20	2.79	5.61	3.43	1.31	2.00	4.51	2.36	0.20
di-fs	1.76	2.06	1.65	2.11	2.08	0.81	-	0.50	0.11
hy-en	9.92	6.89	4.11	7.20	5.89	4.26	1.51	5.26	2.72
hy-fs	4.16	5.08	1.21	4.43	9.34	1.74	-	1.11	1.52
fo	1.33	1.52	6.05	-	-	-	-	-	-
fa	0.61	1.24	1.96	-	-	-	-	-	-
mt	5.64	5.25	6.23	5.25	0.77	5.26	5.82	4.73	1.64

Table 5. (cont.)

Sample no.	15	66	87	9	21	86	3	25	73
Il	1.22	2.37	1.10	1.06	1.03	1.35	0.84	0.66	0.58
Ap	0.66	1.94	0.54	0.50	0.62	0.76	0.43	0.46	0.14
Hm	-	-	-	-	-	-	0.89	-	-
Cc	2.68	1.23	-	-	-	-	-	-	-
Rest	0.29	0.31	.07	0.18	0.55	0.82	0.49	1.25	3.85
Total	99.97	99.54	99.55	100.11	99.53	99.78	99.51	99.64	99.37
Trace elements in ppm									
Nb	20	28	25	10	19	22	12	18	41
Zr	176	309	196	180	260	203	201	244	420
Y	34	30	33	27	25	35	22	24	40
Sr	1020	1351	904	801	902	798	979	1015	547
Rb	30	106	30	75	69	32	84	72	258
K/Rb	440	324	553	335	365	619	313	394	163
Differentiation index	39.2	49.5	42.1	51.5	51.8	54.6	63.5	63.3	74.9

Table 5. (cont.)

Sample no.	55	59	83	75	11	88	73_G	75,
SiO_2	62.16	62.24	63.59	63.62	65.47	73.01	64.02	64.09
TiO_2	0.34	0.37	0.32	0.35	0.27	0.07	0.69	0.66
Al_2O_3	14.50	15.43	15.17	15.73	15.26	12.24	14.81	15.00
Fe_2O_3	3.77	1.33	4.40	1.36	2.26	0.41	-	-
FeO	2.28	2.44	0.85	1.70	1.92	0.68	2.26	2.56
MnO	0.06	0.04	0.03	0.05	0.03	0.08	0.08	0.09
MgO	3.17	1.25	1.93	1.07	1.26	0.21	0.45	0.44
CaO	3.76	3.78	3.48	1.78	3.90	0.41	1.34	1.18
Na_2O	3.52	4.31	3.52	4.02	3.99	3.46	3.89	3.59
K_2O	3.70	1.77	5.40	5.84	3.20	5.59	6.12	6.15
P_2O_5	0.18	0.06	0.19	0.05	0.12	0.01	-	-
H_2O+	1.79	4.80	0.34	3.63	1.37	3.20	-	-
H_2O-	0.20	1.60	0.30	0.49	0.21	0.37	-	-
CO_2	-	-	-	-	-	-	-	-
Total	99.43	99.42	99.52	99.69	99.37	99.74	93.66	93.76
CIPW Norms								
Q	15.97	19.48	14.03	12.12	20.61	30.03	14.46	16.09
C	-	-	-	-	-	-	-	0.25
or	21.86	10.46	31.91	34.51	18.91	33.03	36.16	36.34
ab	29.79	36.47	29.79	34.02	33.76	29.28	32.92	30.38
an	12.84	17.53	9.65	7.63	14.28	1.36	4.88	5.98
di-wo	1.94	0.35	2.66	0.36	1.50	0.25	0.77	-
di-en	1.58	0.18	2.30	0.22	0.99	0.09	0.44	-
di-fs	0.12	0.16	-	0.13	0.40	0.17	0.29	-
hy-en	6.32	2.94	2.51	2.44	2.15	0.43	0.68	1.10
hy-fs	0.50	2.68	-	1.39	0.87	0.78	0.45	0.74
fo	-	-	-	-	-	-	-	-
fa	-	-	-	-	-	-	-	-
mt	5.47	1.93	1.91	1.97	3.28	0.59	1.32	1.65

Table 5. (cont.)

Sample no.	55	59	83	75	11	88	73_G	75_G
il	0.65	0.70	0.61	0.66	0.51	0.13	1.31	1.25
ap	0.43	0.14	0.45	0.12	0.28	0.02	-	-
hm	-	-	3.08	-	-	-	-	-
cc	-	-	-	-	0.25	-	-	-
rest	1.99	6.40	0.64	4.12	1.58	3.57	-	-
Total	99.46	99.42	99.54	99.69	99.37	99.74	93.68	93.78
Trace elements in ppm								
Nb	23	39	25	22	33	87		
Zr	254	410	274	318	264	251		
Y	35	33	37	40	40	26		
Sr	1008	784	582	310	838	67		
Rb	92	221	238	226	98	397		
K/Rb	334	67	188	215	271	117		
Differentiation index	67.6	66.4	75.7	80.7	73.3	92.3		

[illegible] Marysvale which would fill in these gaps at 56%, 59.5%, and 67% SiO_2. Titanium contents are low, as is typical of most calc-alkaline rocks. The highest Ti content is 1.25% in absarokite (sample 66); its genetic relationship to the calc-alkaline volcanic sequence is not clear. Marysvale volcanic rocks show little or no relative iron enrichment (Fig. 7), consistent with the trend of typical calc-alkaline lavas. Most of the samples fall slightly above the average Cascade differentiation trend, but still show the typical dominant alkali enrichment with increasing silica content. The trend closely resembles that of Tertiary calc-alkaline volcanics of the Basin and Range Province in southwestern Utah (Hausel and Nash, 1977).

The group, as a whole, is characterized by high alkali content; several samples are particularly rich in potassium. Six of the lavas and two residual glasses have K_2O/Na_2O ratios greater than one. When total alkalies are plotted against silica (Fig. 8), this "potassic group" has a trend distinct from that of the more sodic group. This suggests the presence of at least two magma types in the Marysvale region.

The rhyolite contains 75.9% SiO_2 on an anhydrous basis and contains more than 9% total alkalies, a characteristic of many late Cenozoic rhyolites in the western United States. Rhyolites in calc-alkaline associations commonly contain less silica and alkalies.

Trace Elements

X-ray fluorescence analyses (Table 5 and Fig. 9) show uniformly low yttrium concentrations (<40 ppm) and similarly low Nb values, except for the highly evolved rhyolite (87 ppm). Zr concentrations are highest in two vitrophyres (samples 59 and 73), and the absarokite has a relatively high Zr content for a basic rock (309 ppm). The Kingston tuff vitrophyre (sample 59) is distinct from the other rock types in its trace element chemistry. This is particularly evident in a plot of Rb versus K/Rb (Fig. 10) which shows a general logarithm relation between Rb and K/Rb, with the Mount Belknap rhyolite lying at the end of this typical trend. The Kingston tuff vitrophyre contains significant Rb considering its low K content (1.45%). It contains

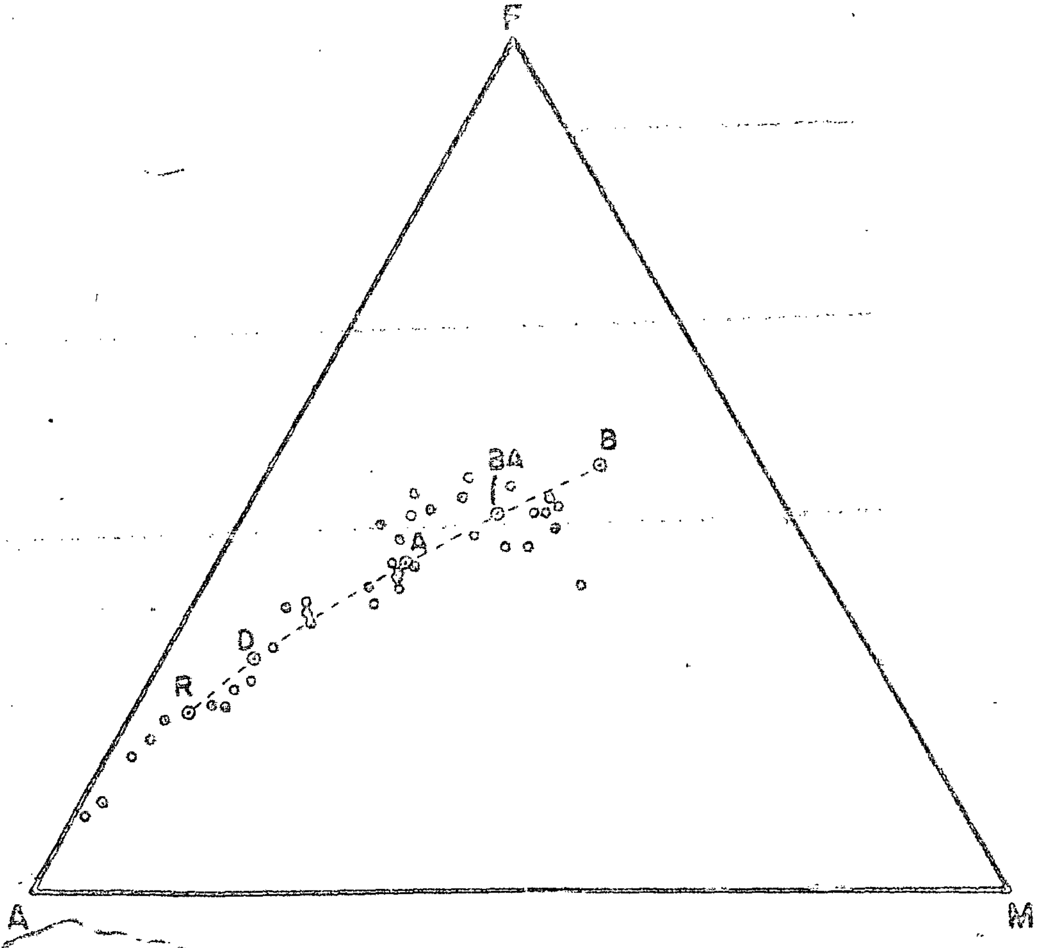

Figure 7 A ($Na_2O + K_2O$) - F ($FeO + Fe_2O_3$) - M (MgO) diagram for the Marysvale volcanics. Rocks from the Marysvale province are represented by solid circles. Open circles are mid and late Cenozoic volcanics from the Basin and Range in southwestern Utah (Hausel and Nash, 1977). The dashed line is the average Cascade trend for basalt, (B), basaltic-andesite (Ba), andesite (A), dacite (D), and rhyolite (R) (Carmichael et al., 1974).

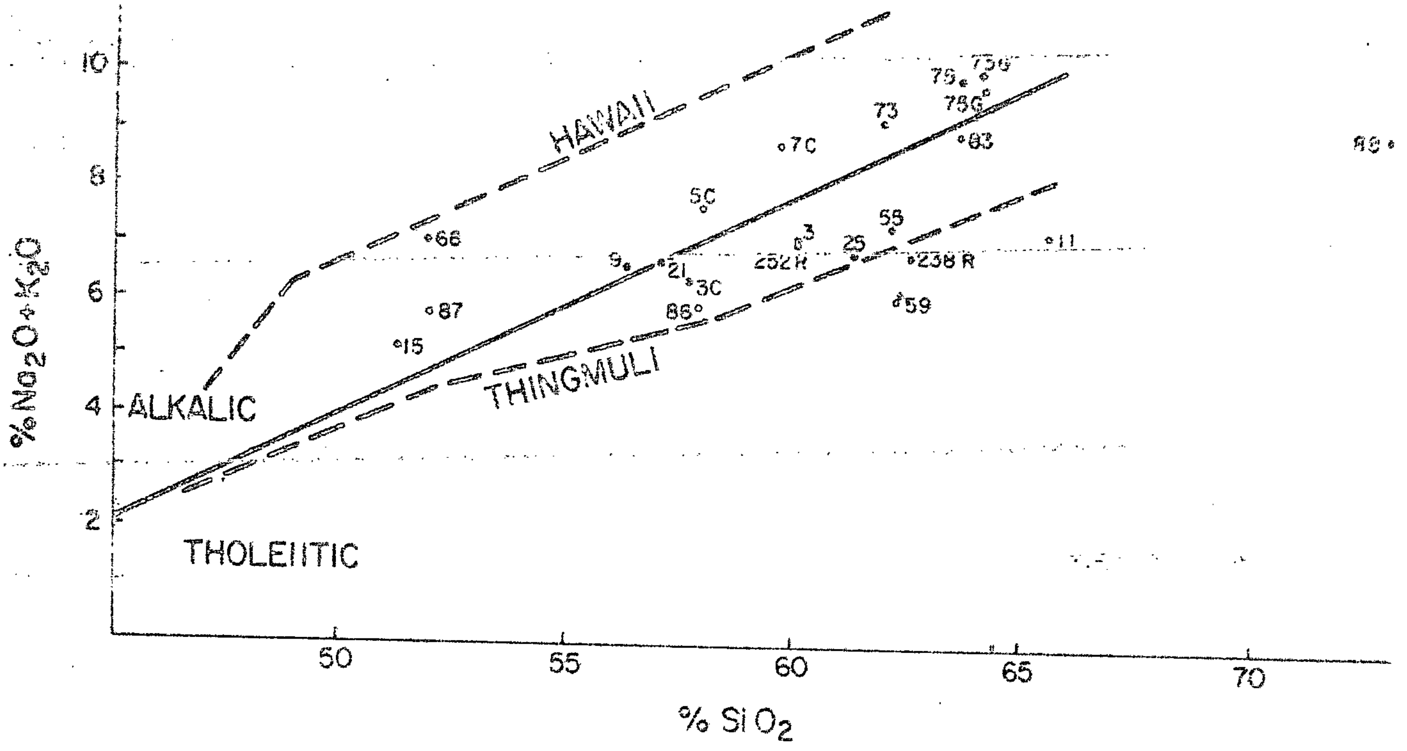

Figure. 8 Alkali-silica diagram. The solid line represents the division between Hawaiian alkaline and tholeiitic lavas. The dashed lines represent average trends of Hawaiian alkaline lavas (Macdonald and Katsura, 1964) and Thingmuli, Iceland, tholeiitic lavas (Carmichael, 1964). Subscripts G, C and R refer to, respectively, microprobe analyses of residual glasses, Callaghan's (1939) published analyses for samples from the Bullion Canyon unit (3C and 7C) and quartz monzonite (5C) and Rowley's (1968) analyses for the upper (252R) and lower (238R) units of the Needles Range Formation.

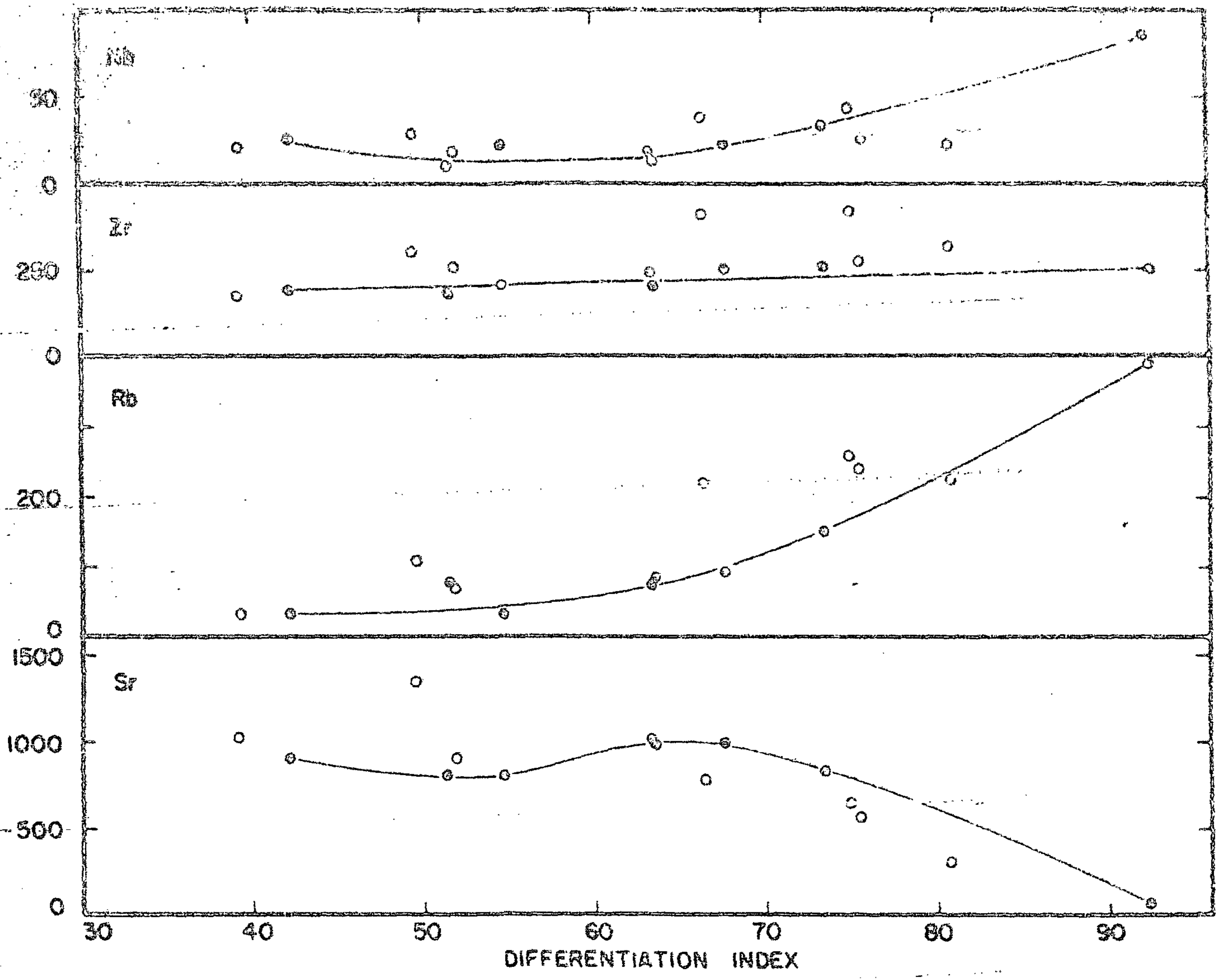

Figure 9 Trace element concentrations in parts per million plotted as a function of Differentiation Index (Thornton and Tuttle, 1960). Samples shown by solid circles are from the low alkali trend observed in Fig. 8.

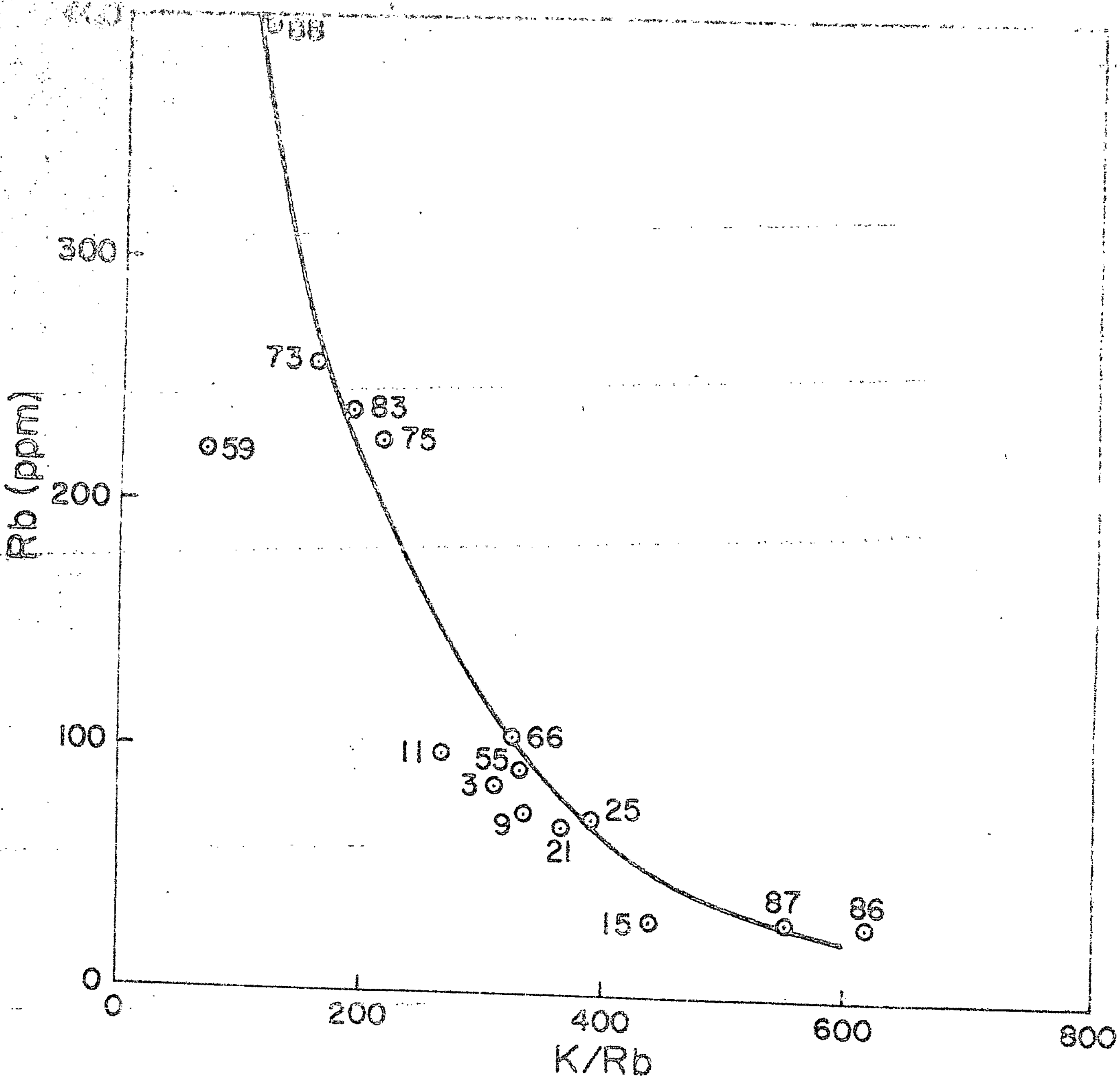

Figure 10 Rb versus K/Rb for Marysvale volcanic rocks.

lithic fragments which mineralogically appear to be derived from samples 21 or 25 (see feldspar discussion). Mixing of these samples which have normal K/Rb ratios could not account for the anomalous values in sample 59. Thus, although the composition of sample 59 does not represent an original liquid composition due to the presence of inclusions, we are unable to account for its behaviour in terms of the other rocks present. The low K/Rb ratio may be due to preferential loss of potassium upon hydration of this glassy rock which now contains 5.4% water.

Figure 10 supports our general observation that many of the volcanic rocks of the Marysvale area may be comagmatic and related in part by crystal fractionation. Figure 9 illustrates that selected samples (that is, those from the low alkali region of Fig. 7) fall on smooth curves in the trace-element variation diagrams. A quantitative fractionation model based on these data is described in a following section.

PETROLOGY

Geothermometry

Recent advances in geothermometry make it possible to calculate temperatures of equilibration for a variety of mineral assemblages. Table 6 is a compilation of temperatures obtained based on five such methods. The thermometer of Buddington and Lindsley (1964) yields solutions that are reasonable for equilibrium groundmass temperatures at 1 bar pressure. Temperatures obtained using the two-feldspar thermometer of Stormer (1975) at 1 bar are 1010 °C and 1060 °C for sample 75 and 73 (both vitrophyres), respectively, approximately 100 °C higher than their respective Fe-Ti oxide equilibration temperatures.

Temperatures obtained from a thermometer based on the distribution of F between apatite and phlogopite (Stormer and Carmichael, 1971) are anomalously low, (100 to 400 °C) and are probably the result of subsolidus exchange of OH^- for F in biotite in an aqueous fluid (Epstein and Taylor, 1967; Nash, 1976).

Two pyroxene temperatures (Wood and Banno, 1973) are significantly higher than iron-titanium oxide temperatures. If these pyroxene equilibration temperatures are correct, they probably do not reflect

Table 6. Comparative thermometry (T^oC)

Sample	Fe-Ti	Two Feldspar	Pyroxene	Apatite-Phlogopite	Plagioclase 0kb	Plagioclase 1kb	Revised Plagioclase 0kb
15					1259	1172	1217
66	930				1201	1114	1166
87	865				1245	1157	1205
9			1190		1194	1106	1160
21			1194		1354	1258	1299
86			1158		1376	1279	1318
3					1079	995	1062
25					1266	1170	1220
73	950	1060	1218	100	1176	1083	1142
55					1069	978	1052
59			1175	400	1115	1023	1091
83					1142	1048	1113
75	910	1010	1157		1219	1120	1178
11	925				1149	1055	1119
65		788					
30		690					

eruptive temperatures, but rather crystallization temperatures for pyroxene phenocrysts at depth. A comparison of Fe-Ti oxide equilibration temperatures with the pyroxene equilibration temperatures in two samples (73 and 75) show the latter to be about 250 °C higher; this may represent the crystallization interval between these phases.

Temperatures obtained from the Kudo-Weill geothermometer (Mathez, 1973) are also high. This is expected, however, because the core compositions (most calcic) of plagioclase were used together with bulk rock compositions in the temperature determinations. In several cases, the temperatures are comparable to those of the two pyroxene determinations, and again reflect pre-eruptive temperatures.

Water Fugacity

An estimation of the water fugacity can be determined based on the following reaction (Wones and Eugster, 1965):

$$\underset{\text{annite}}{KFe_3AlSi_3O_{10}(OH)_2} + \underset{\text{gas}}{1/2\ O_2} =$$

$$\underset{\text{sanidine}}{KAlSi_3O_8} + \underset{\text{magnetite}}{Fe_3O_4} + \underset{\text{gas}}{H_2O}$$

when rearranged:

$$\log f_{H_2O} = \frac{7409}{T} + 4.25 + 1/2 \log f_{O_2} + \log X^{\text{biotite}}_{Fe^{2+}} + 2 \log X_{OH} - \log a_{san} - \log a_{mt}.$$

Where the 2 log X_{OH} term takes into account the effect of ideal mixing of F in the OH^- site in biotite.

Sample 73, a basal vitrophyre of an ignimbrite, contains the appropriate mineral assemblage, as well as a groundmass temperature and oxygen fugacity determined from coexisting Fe-Ti oxides, to allow such a calculation. The calculated water fugacity is 2,745 bars which corresponds to a P_{H_2O} of about 3,000 bars. Based upon a re-evaluation of the original experimental data over the temperature range of 680 to 800 °C, Hildreth (1977) recommended a revised estimate for the free energy change for the previous reaction. Utilization of this free energy value yields a water fugacity approximately 1/3 of the above value, or a P_{H_2O} of about 1,000 b. This value is similar to the estimate for the younger Belknap rhyolite by Cunningham and Steven (1977) of 800 ± 200 b based upon plotting whole-rock normative constituents in the system $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-H_2O. This latter estimate is subject to some error, because these rocks contain two feldspars and 1.4% to 2.9% normative anorthite, and should properly be considered in a quinary system with anorthite as an additional component.

Pressure and Temperature Solutions

Nicholls and Carmichael (1972) have demonstrated that the pressure and temperature of equilibration of a magma with mantle peridotite can be calculated if the activities of silica and alumina in the magma and mantle source region are known. An absarokite (66) and a basalt (87) have the mineral assemblages necessary for this calculation as outlined by Carmichael and others (1975). The equilibration of absarokite with spinel peridotite of the mineralogical composition (mole fraction) 0.90 forsterite, 0.85 enstatite, 0.75 spinel, yields an equilibration pressure and temperature of 18 kb and 1235 °C. This places it in the spinel peridotite pressure-temperature regime of Wyllie (1971). The basalt yields a pressure and temperature solution of 35 kb and 1553 °C when equilibrated with an idealized garnet peridotite (0.90 forsterite, 0.85 enstatite, 0.65 pyrote). These pressures are equivalent to depths of approximately 60 and 115 km, respectively.

Crystal Fractionation

By using the bulk rock and mineral chemical data, it is possible to test quantitatively whether or not low pressure fractional crystallization could be responsible for the chemical diversity of the intermediate to silicic lavas. The method is based upon a linear least-squares solution of an overdetermined set of mass balance equations such as described by Bryan and others (1969) and Stormer and Nicholls (1978).

A proposed parent magma for a suite of rocks related by fractional crystallization should have the following characteristics: it should be of a relatively mafic nature, occur early in the stratigraphic sequence, and be abundant (as evidenced, for example, by areal outcrop extent). At Marysvale the andesites of the lower part of the Bullion Canyon Volcanics meet these requirements.

Figure 11 illustrates a possible fractionation scheme for the derivation of sample 3 from sample 86. In the same manner, either sample 86 or sample 3 could theoretically give rise to sample 88 (Mount Belknap Volcanics). Additionally, the latitic rocks (samples 73, 75, and 83) could be derived from a magma with the chemical and mineralogical characteristics of sample 21 (a more alkalic andesite from the Bullion Canyon Formation). These lavas, however, do not yield a favorable solution when an attempt is made to derive them from a parent represented by sample 86, the other proposed magma. In addition, it is not possible to derive samples 3 and 88 from a parent magma with a composition of sample 21 by removal of the phenocryst phases. These results lend support to the possible existence of two magmatic types in the Marysvale region, as noted in Figure 8. The two possible parental magma type differ very little in bulk chemistry except that sample 21 is more potassic than 86. The potassic enrichment of the latitic suite is apparently produced by the fractionation of proportionally lesser amounts of plagioclase than in the dacite-rhyolite series.

Fractionation schemes constructed in this manner are only permissive in nature and are not conclusive evidence that the chemical variety observed arises from such a process. A further petrologic constraint can be placed on the method, and that is that the amounts of the phases removed in the calculation correspond, within reason, to the amounts present as phenocrysts in the proposed parent lavas. Figure 12 is a comparison of the percentage (by mass) of the phenocrysts present in the selected parental lavas with the masses of each phase removed in the fractionation calculations. The values correspond reasonably well with the exception of the derivation of 3 from 86, and 88 from 3. In both of these instances, the mass of the iron-titanium oxides removed in the calculations is less than the amount observed in the selected parental lavas, whereas the amount of plagioclase removed exceeds the observed fraction. By simple Stokes law relations, we would expect the oxides to be fractionated most effectively despite their somewhat

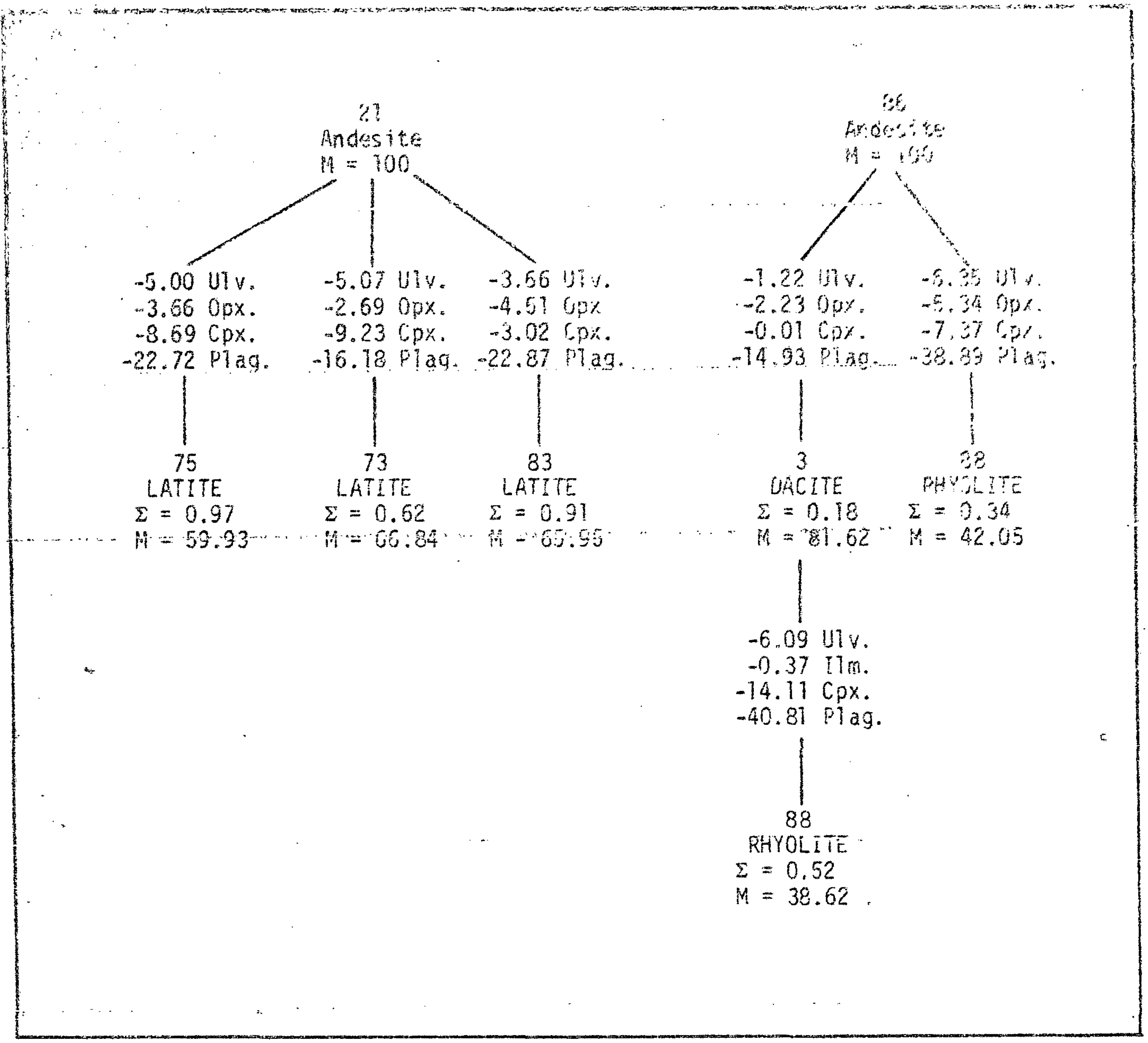

Figure 11 Fractionation model for Marysvale volcanic rocks discussed in text. M is the mass of the new magma relative to 100 units of the parent magma. Σ is the sum of the squares of the residuals. Ulv. = ulvospinel; Opx = orthopyroxene; Cpx = clinopyroxene; Plag. = plagioclase; Ilm = ilmenite. The negative values indicate removal of that phase from the parent in the amount shown.

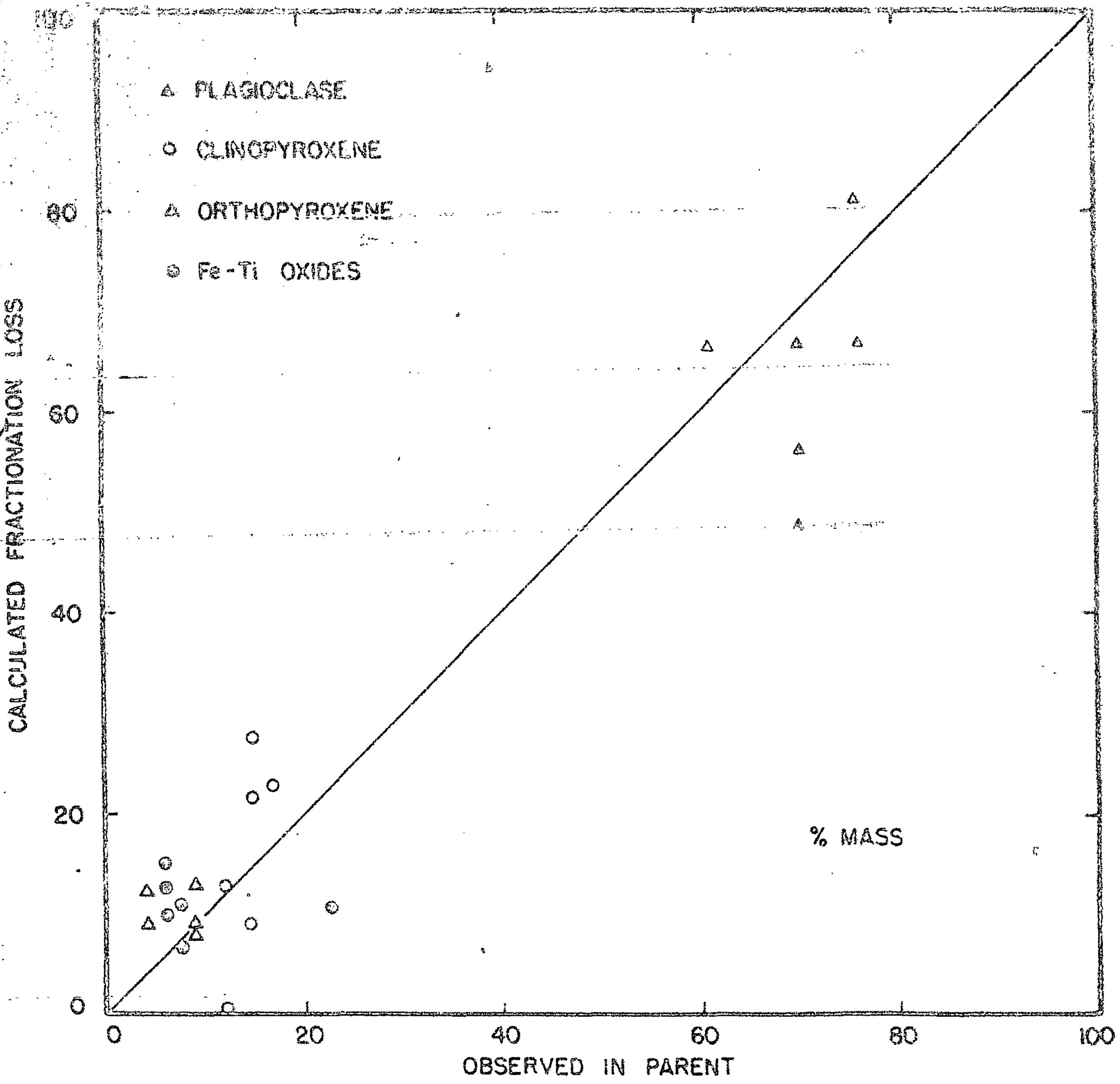

Figure 12 A plot of the calculated fractionated mass for each phase versus the mass of the phases present as phenocrysts in postulated parental liquids. The diagonal line indicates a 1:1 ratio.

smaller size. For this reason, we prefer to discount the 86-3-88 fractionation scheme; the other aspects of the model remain reasonable. Additionally, it should be born in mind that the silicic volcanism may not be genetically related to the earlier calc-alkaline sequence by a liquid line of descent. The silicic event may result from an independent generation of magma as a result of continued thermal input into the crust.

SUMMARY

The generation of calc-alkaline volcanic rocks above subduction zones is a widely recognized relationship. The parental magmas of the calc-alkaline volcanics at Marysvale probably were derived by partial melting of subducted lithospheric material postulated to have been present in early to middle Cenozoic time in the western United States (Atwater, 1970). In the Marysvale region, volcanism began approximately 30 m.y. ago and continued to about 17 m.y. ago, with one period of minor quiescence about 22 m.y. ago, which separated earlier mafic to intermediate calc-alkaline volcanism from a period of more silicic and explosive extrusive activity. Near-surface fractionation has played an important role in the calc-alkaline evolution at Marysvale, and two andesitic magma types may have given rise to the more intermediate to silicic varieties. These types are represented by sample 86, which could have been parental to the dacitic and possibly rhyolitic members of the suite, and the more alkalic sample 21 which could have given rise to the latitic members of the group.

In the late Cenozoic time, the Basin and Range Province underwent crustal extension with synchronous basaltic and rhyolitic volcanism. Shuey and others (1973), relying primarily on aeromagnetic data, place the geophysical boundary of the Basin and Range Province and Colorado Plateau at least 50 km east of the physiographic boundary. This would place Marysvale, as well as most of the High Plateaus, in the current Basin and Range tectonic regime; late Cenozoic volcanism centered near Marysvale may be closely related to Basin and Range tectonics. These features suggest that Basin and Range tectonism is currently extending eastward at the expense of the Colorado Plateau, with the Basin and Range upper mantle regime extending considerably east of the physiographic boundary of the Basin and Range Province.

ACKNOWLEDGMENTS

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GEOLOGIC OBSERVATIONS IN THE UPPER SEVIER RIVER VALLEY, UTAH.*

HERBERT E. GREGORY.

CONTENTS.

ABSTRACT. The East Fork and South Fork valleys of the Sevier River roughly coincide with the trend of the Sevier and Paunsaugunt faults that outline the Sevier Plateau, and mark borders of the Markagunt and Aquarius Plateaus. Along the faults, in the slopes and escarpments produced by uplifts of 600 to 2,000 feet, the Tertiary rocks characteristic of southern Utah are exposed: the pink limestones of the Wasatch formation (Eocene); the white tuffs and gray igneous conglomerates of the newly recognized Brian Head formation (Miocene ?); the widely spread andesitic lavas; and, in places, the gravels of the Sevier River formation (Pliocene ?). In Antimony Canyon erosion has revealed Jurassic and Cretaceous strata. From south to north the Wasatch limestones and the overlying stratified pyroclastics of the Brian Head formation decrease in thickness and the igneous conglomerates increase to thicknesses of exceeding 1,000 feet.

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Black Canyon, then in turn the meadow lands about the village of Antimony, the deep rock-walled Kingston Gorge, and finally an alluvial flat. The average gradient of the South Fork below the mouth of Red Canyon is about 24 feet to the mile; of the East Fork below Widtsoe, 31 feet to the mile, but in their steepest stretches the gradients are as much as 120 feet to the mile.

Because of topographic control the form and gradient of the tributary streamways is unlike those of the master channels. The western tributaries of the Sevier have gentle gradients; most of them flow in shallow trenches on bare rock. On the other hand, the eastern tributaries occupy short, steep, narrow canyons that head abruptly at the plateau rims. Throughout their courses in the canyons Casto, Limekiln, Sanford, and Smith Creeks, tributary to the South Fork, and Birch, Cleaves, Center, and Antimony Creeks, tributary to the East Fork, have gradients of 400 to 800 feet a mile. The South Fork of the Sevier is through-flowing. Its eastern tributaries are permanent in their upper courses and at times of floods carry water across their alluvial fans; but, except for Panguitch Creek, which drains a large part of the well-watered Markagunt Plateau, its western tributaries are ephemeral. The East Fork, through Emery Valley and parts of Johns Valley, is intermittent; the combined flow of a score of tributaries from the back slope of the Sevier Plateau and the front of the Aquarius Plateau is insufficient to maintain a continuous stream. At the head of Black Canyon the East Fork receives contributions from the spring-fed Deer Creek, and more from springs farther down the canyon. But the chief contributor to its waters is Antimony Creek, which occupies the longest, deepest, crookedest, and most intricately branched of the canyons that dissect the western flank of the Aquarius Plateau. Formerly the creek entered a lake where its waters, together with those of the East Fork of the Sevier, were ponded while farther north in Kingston Gorge a stream was sinking its channel through the resistant volcanics of the Sevier Plateau to a depth sufficient to provide a continuous outlet.

As agents of erosion both forks of the Sevier River are relatively inefficient; they are chiefly engaged in widening their runways in unconsolidated sand and gravels. In contrast, the streams that flow down the precipitous fronts of the Sevier and Aquarius plateaus are vigorously scouring bed rock, transporting talus, and removing from their channels the alluvial débris deposited during a previous physiographic cycle. Their work is facilitated by the flash floods and seasonal floods that characterize the stream runoff in the High Plateaus of Utah.

The plant life in the upper valleys of the Sevier River is that characteristic of the rugged plateau lands of central Utah. The types of vegetation are related to altitude and the consequent range in temperature and amount of precipitation, but the normal zonal arrangement is much modified by the conditions of insolation imposed by the height and position of canyon walls, the erratic distribution of perennial streams and springs, and the wide range in altitude of areas of bare rock and fertile soil. The complex vertical and horizontal arrangement of gorges, stream flats, slopes, cliffs, and plateau tops naturally provides local habitats with little regard to contour lines. At altitudes above 8,000 feet the most common trees are yellow pine, replaced at the highest levels by spruce and fir. Beautiful groves of aspen and scattered clumps of manzanita, mountain mahogany, and shrub oak are common. Interspersed with the pines and extending to altitudes below them, widely spaced junipers and piñons stand in fields of vigorously growing sage brush. In the lower valleys sage brush, rabbit brush, and introduced weeds are dominant, and immediately along water courses box elder, birch, willow, cottonwood, clematis, grape, and "bullberry." In distribution the vegetation is "patchy." Expanses of matted grasses, of sod, and of closely spaced trees mingled with dense underbrush are small and rare. On the broad glaciated summit of the Aquarius Plateau treeless glades, hundreds of acres in area, are features of the forest lands. Most of the canyon walls and many steep slopes are substantially bare of vegetation (see Pls. 1, 2, 4, 6).

The region that includes the upper valleys of the Sevier River is primarily "stock country." During the summer months the cattle and sheep find palatable brush, grasses, and weeds on the highlands and the natural meadow lands along streams. When snow covers the ground the livestock either return to the home ranches where hay is provided, or migrate to the warmer lowlands along the Colorado River. To conserve forage, most of the Sevier, Aquarius, Paunsaugunt, and Markagunt plateaus is included in the Powell National Forest. For general agriculture the conditions are unfavorable. The growing season is short, the precipitation small and erratically distributed in time and place, and the surface runoff, chiefly from melting snows, supplies few streams with water sufficient for profitable irrigation. At Panguitch the average period without killing frost is but 80 days (June 15-September 8); the mean annual rainfall is 9.69 inches. At Antimony the growing season is 72 days, the annual rainfall 8.13 inches—in some years less than 5 inches.

Irrigation farming is profitable at Panguitch, where 3,850 acres are watered by 3 canals leading from Panguitch Creek and the South Fork of the Sevier River; also at Antimony, where the run-off from Antimony Creek and East Fork of the Sevier makes possible the irrigation of 2,557 acres, given over chiefly to the cultivation of potatoes and forage crops. At ranch homes along the base of the Aquarius Plateau, along Sanford, Sweetwater, Horse, Birch, Branch, and Center creeks, a few acres are "under ditch" but irrigated lands at the mouths of Casto, Limekiln, Sand, and Smith Canyons, and in Emery Valley and Johns Valley have been abandoned, and attempts to develop dry farming at Henderson resulted in costly failure.

The only mineral of economic importance is stibnite, which has been mined intermittently since 1880 without substantial profit.

STRATIGRAPHY.

General Relations.

Most of the consolidated sedimentary rocks in the upper valleys of the Sevier River are representatives of well known Mesozoic and Cenozoic formations that characterize the plateau province: Shinarump conglomerate and Chinle (?) formation of Upper Triassic age; Navajo sandstone of Jurassic (?) age, Carmel formation, Entrada sandstone, Curtis (?) formation, and Winsor (?) formation of Jurassic age; Dakota (?) sandstone and Tropic formation of Upper Cretaceous age; and Wasatch formation of Tertiary age. In addition to these widely exposed stratigraphic units measured sections include tuffs, igneous agglomerates, breccias, and flows that mark the southern border of the large Tertiary volcanic field of central Utah. These interbedded lavas and proclastics conform in regional attitude with the ordinary sedimentary strata and thus in the development of the topography have exercised no peculiar control. The partly consolidated sediments include the Sevier River formation of the late Pliocene or early

Pleistocene age, Pleistocene drift and lacustrine marls, and Recent stratified sands deposited along streams, and the jumbled débris of alluvial fans piled at the west bases of the Sevier and the Aquarium plateaus.

MESOZOIC DEPOSITS.

Distribution.

Along the upper branches of the Sevier River, sediments of Triassic, Jurassic, and Cretaceous age are exposed only at the northwestern edge of the Aquarius Plateau where in an area of about 6 square miles they form the walls of Antimony Canyon and its many branch gorges. The rocks in this small area are peculiarly isolated; the nearest of corresponding age lie northeast of the Aquarius, south of the Paunsaugunt, and west of the Markagunt plateau at distances of 35 to 70 miles (see Pl. 3).

The geologic features of Antimony Canyon have been described in general terms by Dutton[2] and more recently with particular reference to mineral resources by Richardson,[3] Butler,[4] and Duncan.[5]

Dutton states:

> The northwestern angle of the Aquarius is laid open by an immense gorge.[6] A mass of lavas and conglomerates more than 2,000 feet thick is revealed, and beneath them the Tertiary. Near the opening of this gorge the Grass Valley fault [northern extension of the Paunsaugunt fault] cuts across it, throwing down the platform to the west.

In agreement with Dutton, Richardson assigned the sediments in Antimony Canyon to the Tertiary—a conclusion adopted also by Butler and his associates. In his pioneer report on the ore deposits, Richardson writes:

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[2] Dutton, C. E.: 1880, Report on the geology of the High Plateaus of Utah; U. S. Geog. Geol. Survey Rocky Mt. region, pp. 299, 295.

[3] Richardson, G. B.: 1908, Antimony in southern Utah; U. S. Geol. Survey Bull. 340, pp. 253-256.

[4] Butler, B. S., and others: 1920, The ore deposits of Utah; U. S. Geol. Survey Prof. Paper 111, pp. 561-563.

[5] Duncan, D. C.: Antimony deposits in Antimony Canyon, Garfield County, Utah; U. S. Geol. Survey; manuscript on file.

[6] This gorge is shown on Dutton's maps as Mesa Canyon. To the pioneer settlers it was known as Coyote Canyon and the town site near its mouth, Coyote. In recognition of the mining interests, the postoffice at Coyote was renamed Antimony (1921) and this term is now generally applied also to the canyon.

At the base of the section there is 150 feet of gray conglomerate composed of rounded pebbles of quartz and quartzite up to 6 inches in diameter, in a sandy matrix. The conglomerate is overlain by a great mass of fine-textured buff and reddish sandstone, with subordinate drab and red sandy and clayey shale and thin-bedded limestone, amounting in all to several hundred feet in thickness. No fossils have been found in these rocks, but because of their lithologic resemblance to Eocene strata elsewhere in the plateau region they are provisionally referred to that period.

The report by Duncan, though chiefly an exhaustive treatment of the occurrence, quality, and potential economic exploitation of the stibnite ores, includes a measured section of the exposed rock units in which appears 1,500 + feet of Jurassic sediments, not previously recognized. In addition to a basal series of massive sandstones and thin-bedded vari-colored shales and limestones classed as undifferentiated Jurassic, the section includes arenaceous and calcareous strata that extend upward to sheets of lava. Regarding these upper beds Duncan remarks

> The Jurassic beds are unconformably overlain by a sequence of red, buff, and gray sandstones and shales, gray boulder conglomerate and light-gray limestone, which totals about 1,500 feet thick. These beds were considered to be of Eocene age by Richardson and are probably equivalents of the Wasatch (?) formation as recognized in nearby areas. The known antimony deposits in the area are confined to a sandstone and shale zone about 200 feet thick near the middle of the formation. Middle (?) Tertiary volcanic rocks mostly dense acidic flows, with some agglomerate and scoria, overlie the Wasatch (?) formation. The volcanic flows are estimated to be about 1,000 feet thick.

Thus Duncan, accepting the conclusion of Dutton and Richardson, records thick Tertiary but no Cretaceous strata. However, beds of Cretaceous age—possibly also of Triassic age—are present, and Tertiary rocks other than volcanics are believed to be absent. In brief, the Mesozoic formations in the walls of Antimony Canyon are characterized as follows:

Upper Triassic Strata.

The conglomerate exposed in the walls of Little Forest Creek (a southern tributary to Antimony Creek) closely resembles the rock elsewhere recognized as the Shinarump conglomerate,

Plate 1. View looking across the upper East Fork Valley in the vicinity of Widtsoe. Flat land developed by the deposition of alluvium on maturely eroded surface of Wasatch formation Altitude 7,000 feet. Vegetation chiefly sage, annual compositae, and (near the stream channel) yellow pine. Photograph by U. S. Forest Service.

Plate 2. A park in the Powell National Forest, Aquarius Plateau, near the head of Antimony Canyon, altitude 10,000 feet. The surface has been scoured by glaciers.

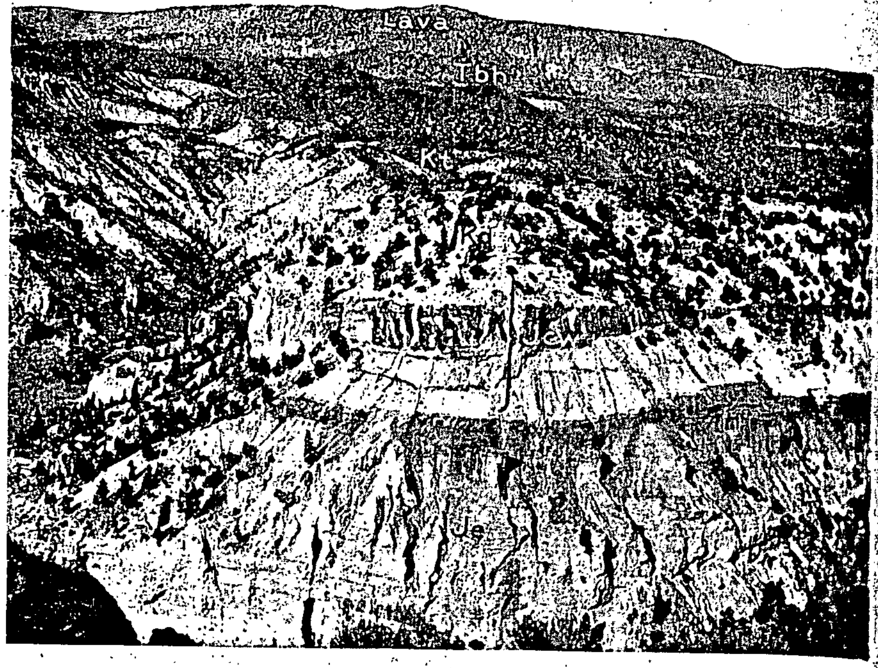

Plate 3. View of formations exposed on the northwest face of Aquarius Plateau near the mouth of Antimony Canyon. Je, Entrada sandstone; Jcw, Curtis and Winsor formations; Kd, Dakota (?) sandstone; Kt, Tropic formation; Tbh, Brian Head formation. Lavas, Tertiary andesites that form the top of Aquarius Plateau. Photograph by D. C. Duncan.

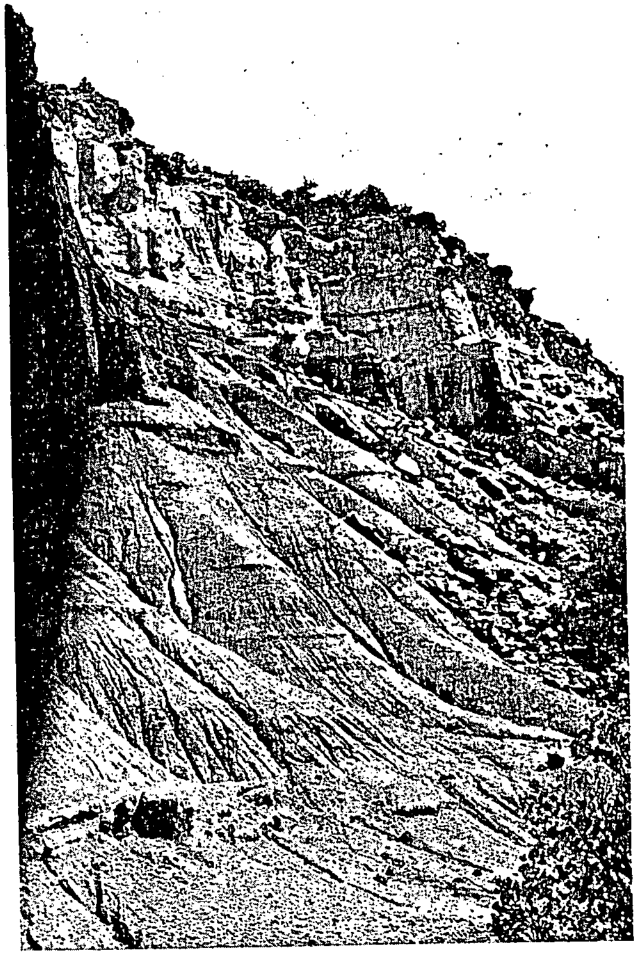

Plate 4. Entrada sandstone and overlying Curtis (?) formation in the north wall of Antimony Canyon.

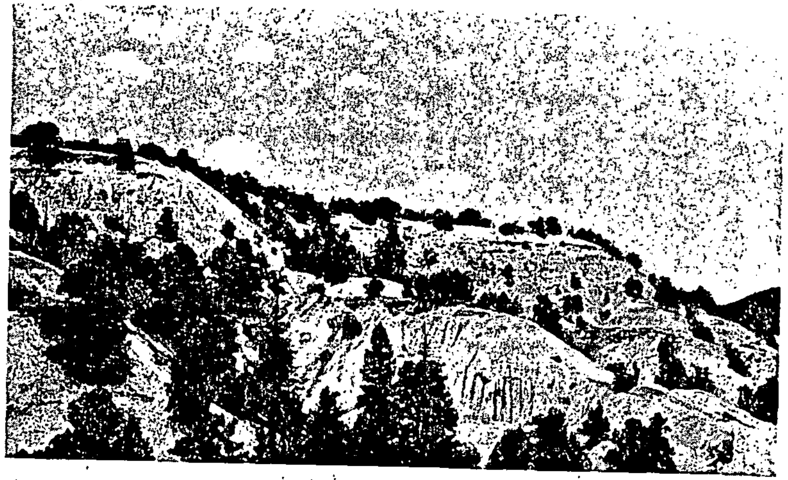

Plate 5. Typical view of the Tropic formation near the southwest rim of Antimony Canyon.

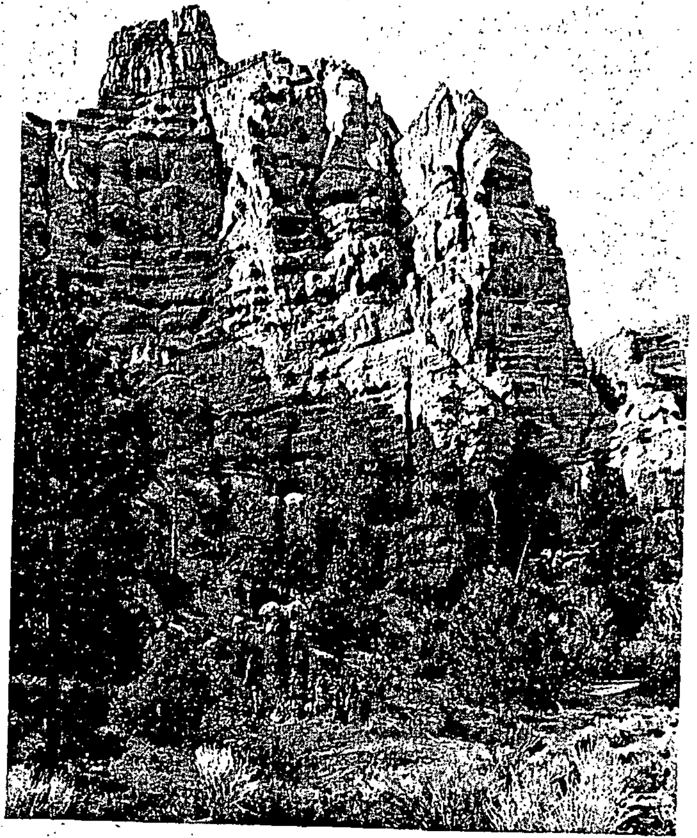

Plate 6. Strata exposed in the wall of Casto Canyon. Bedding and style of erosion is characteristic of the pink limestones in the Wasatch formation.

and in texture and composition it is unlike the other coarse-grained rocks in the Antimony region. Its coarser parts consist almost wholly of smoothly rounded quartzite and quartz pebbles 1 to 5 inches in diameter embedded in quartz sand and gravel; its finer parts of short lenses of stratified sandstone. Fossil wood seems to be absent. The conglomerate lies within a zone traversed by a series of roughly parallel fractures and its contacts with beds below and above, both concealed, are probably fault planes.

On both sides of Antimony Creek near the mouth of its canyon, strata, possibly Upper Triassic in age, are pressed tightly against a lofty ridge of sandstone. In a gully north of the creek the outcrop is a sequence of varicolored shales and sandstones that dips westward at angles of 30° to 50° and constitutes a block between faults; on the east it is in contact with massive red sandstone and on the west with sheeted lava. Roughly the exposed rocks are divisible into three groups of beds; brown and tan, thin bedded sandstones (at the base); red arenaceous shales; and greenish argillaceous shales. But within these groups color, composition, texture, and style of bedding are not persistent. In places the brighter colors appear as blotches and streaks; some beds otherwise uniform in texture include flakes and concretions of clay and aggregates of gypsum crystals. The beds at this small isolated exposure lack features clearly recognizable as diagnostic of any formation known elsewhere, and in the absence of fossils and of formations in normal stratigraphic sequence above and below their age is uncertain. Their component shales and sandstones would not be out of place in the lower part of the Chinle formation, which in Utah is highly variable in content, and as they lie in a zone of cross faulted strata they possibly may be fragments of Chinle oriented in some undetermined fashion. However, the structural relations indicate an age younger than the Triassic. The beds are on the downthrow side of a fault, in contact with the upthrown Middle Jurassic (?) Navajo sandstone and may therefore be downfaulted fragments of Upper Jurassic formations, which, like the Chinle, includes rocks widely diverse in composition and origin.

Middle Jurassic (?) Strata.

The deposits classified by Duncan[7] as undifferentiated Juras-

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[7] Duncan, D. C.: op. cit.

sic in Antimony Canyon include "white, gray, and tan quartzitic sandstone . . . . 950 to 1,200 feet thick"—a stratigraphic unit identifiable as the Navajo sandstone. Its physical features substantially duplicate those displayed by the Navajo elsewhere in the Colorado plateau province and described in many geologic reports. It is a massive, thick-bedded, in large part cross-bedded, stratum, composed essentially of cleanly washed, small, spherical quartz grains, uniform in size and weakly cemented by calcium carbonate and iron oxide. It includes a few thin lenses of calcareous silt and scatterd fragments of magnetite and metamorphic minerals. Unlike its usual attitude—a flat-lying bed terminated by cliffs—the Navajo sandstone in Antimony Canyon stands nearly vertical, forming a high, narrow ridge through which Antimony Creek has cut a deep gorge—a conspicuous scenic feature of the local topography. From its crest the ridge descends precipitously 600 feet to the flat lands along lower Antimony Creek. Eastward it slopes steeply downward 500 feet to Black Jack Creek, along which the relatively soft Upper Jurassic rocks have been worn into gullies, rounded ridges, and low rock terraces. The sandstone mass is bordered by faults of large displacement and crossed and recrossed by minor fractures so close-spaced and unsystematically orientated that much of the rock seems shattered.

Upper Jurassic Formations.

In Antimony Canyon rocks of Upper Jurassic age include the Carmel formation, the Entrada sandstone, and an undifferentiated unit that probably represents the Curtis and the Winsor formations. At its western edge the Carmel stands in vertical position in fault contact with the Navajo sandstone and elsewhere dips steeply eastward. Likewise the other Upper Jurassic formations are upturned along their western edges at angles of 5° to 30° but generally conform with the regional northeast dip of 2° to 5°.

The Carmel formation, in addition to its characteristic compact, gray-blue marine limestone and interbedded hard calcareous shales, includes more than the usual amount of thin red sandstones and green, gray, and maroon shales.

The Entrada sandstone, though meagerly exposed, is a very conspicuous stratigraphic unit: its edges are displayed as vertical cliffs decorated by grooves and columns, and its color—deep red streaked with yellow—strongly contrasts with the gray of the formations above and below. The sandstone is arranged in thin, somewhat irregular beds, more evenly foliated near the base, and consists dominantly of fine quartz grains weakly cemented by lime and iron. Irregularly interbedded are lenses of gray white and greenish calcareous, slightly gypsiferous sandstone which on weathered slopes project as shelves (see Pl. 4). Thus parts of the Entrada in Antimony Canyon resemble the generally massive cliff-making sandstone of like age in the Waterpocket fold and along Glen Canyon and other parts the strata in the Parunuweap and Virgin Valleys, which are remarkably uniform in composition and bedding and contain much gypsum.

The Jurassic sediments above the Entrada sandstone are thought to represent the Curtis and the Winsor formations, though in general appearance they are unlike either of these formations as expressed elsewhere and no persistent features serve to mark a division plane between them. The lower part of the undifferentiated unit contains the roughly bedded sandstones, thin hard limestones, and lenticular conglomerates commonly present in the Curtis, but lacks the thick beds of gypsum which generally in Utah constitute the bulk of the formation. In the middle part lenses of fine conglomerate, calcareous nodules, and other minor features of the typical Winsor are recognizable but no duplicates of the remarkable color banding, the uniformity of bedding, and the peculiar basal conglomerates that characterize the formation at its typical exposures. In the upper part the style of bedding, the texture, and the composition resemble rare features of the Winsor formation in the Zion Park region.

Fossils in the Upper Jurassic beds in Antimony Canyon are representative of the Carmel and the Curtis (?) faunas. In collections from arenaceous limestone beds near their contact with the Navajo sandstone, John B. Reeside, Jr. found a Carmel fauna: "*Ostrea strigilecula* White, *Pleuromya* sp., *Trigonia* cf. *T. americana* Meek, *Dosinia jurassica* (Whitefield)?, and *Camptonectes stygius* White" and recognized broken shells in lenticular gray limestone above the Entrada sandstone as "fragments of *Camptonectes* sp., *Ostrea* sp., *Pinna* sp., and other fossils of Jurassic age."

Cretaceous Formations.

The Cretaceous strata in Antimony Canyon are prominently exposed. Along Antimony Creek and 10 or more tributaries they combine in forming cliffs and steep slopes little encumbered by talus and dense vegetation and because of their light color they are readily distinguishable from the nearly black igneous rocks that mark their upper limit and the dark red Entrada sandstone near their base. In distant view the upper half of the Cretaceous slopes appears to be wholly shale and the lower half shale irregularly interbedded with thick sandstones and throughout the exposure the bedding indicated by slightly projecting benches or faintly outlined by color seems to be regular. However, closer examination shows that shale, thin sandstones, and thick, massive sandstones are unsystematically interbedded, that in all classes of sediments few beds retain their individuality for as much as 1,000 feet and that in addition to quartzose, argillaceous, and calcareous sandstone, the unit includes arenaceous, gypsiferous, calcareous, and rarely carbonaceous shale, limestone, bentonite, and conglomerate, all commonly in lenticular beds. Thus in general appearance the Cretaceous rocks in Antimony Canyon are unusual, but in variety of sediments and style of bedding they closely resemble the Dakota (?) sandstone and the Tropic formation which make up the lower part of Cretaceous sections in adjoining parts of Utah. Outstanding differences are the color tones and the scarcity of carbonaceous material. In Antimony Canyon the Cretaceous rocks are green-gray, yellow, and light tan, in contrast with drab, brown, and dark gray common elsewhere; a few carbonaceous sandy shales that contain partly carbonized plant fragments, and a reported "layer of muddy coal" are the meager representatives of the many coal beds in corresponding positions at other Cretaceous outcrops. Another noteworthy feature is the absence above the Tropic formation of thick strata like the Wahweap and Straight Cliffs sandstones, and the Mesa Verde and Kaiparowits formations—a group of units that 40 miles distant in Paria Valley make up the topmost 2,000-3,000 feet of the Cretaceous deposits. These absent strata are believed to have been worn away during a long period of denudation that removed also the overlying Tertiary limestone of the Wasatch formation (see Pls. 3, 5).

In contrast with their abundance in the Jurassic strata,

fossils in the beds of Cretaceous age of Antimony Canyon are extremely rare. They were found only in a few lenses of calcareous, speckled black and gray sandstone 10 to 30 feet above the conglomeratic Dakota (?) sandstone and include no complete forms. In the collection submitted for determination Reeside noted,

> "a number of fragmentary specimens of a gastropod that suggest *Pachymelania chryssaloides* White, of the early Upper Cretaceous Bear River formation of southwestern Wyoming [the equivalent of the Dakota (?) and the lower Tropic formation in Utah]. I have compared the specimens with the various Coniobasis of the Eocene. It does not match any of them."

TERTIARY FORMATIONS.

Composition and Relations. Except for the Triassic (?), Jurassic, and Cretaceous rocks in Antimony Canyon, the consolidated sediments along the upper branches of the Sevier River belong to the Tertiary and Quaternary systems. In ascending order they comprise the Eocene Wasatch formation; the Miocene (?) Brian Head formation and overlying sheets of igneous rock; the late Pliocene or early Pleistocene Sevier River formation; Pleistocene silts and marls; and Recent alluvial stream terraces and fans. Of these stratigraphic units the Wasatch, the Brian Head, and the lavas extend without interruption into the regions outside of the Sevier valleys, the younger formations are restricted to areas where topographic control has been favorable.

WASATCH FORMATION. (*Eocene*).

Along tributaries to the upper Sevier River the Wasatch formation consists essentially of thick bedded, fresh-water, pink limestone which generally at its base and sporadically above includes lenticular conglomerates of well-worn quartzite, chert, and igneous pebbles. In general appearance, in composition, texture, color, and manner of erosion the bulk of the formation differs little from rocks of this age in adjoining regions. Its exposures in Casto, Limekiln, Sweetwater, and Horse Canyons substantially duplicate those in Red Canyon and in the Pink Cliffs of the Paunsaugunt and Markagunt plateaus which have been mapped and described in detail.[8] Differences concern

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[8] Gregory, H. E.: The Paunsaugunt region, Utah; U. S. Geol. Survey Prof. Paper [in preparation].

chiefly its extent, its relation to superjacent formations, and the origin and composition of its upper part—the so-called white Wasatch. Northward from the latitude of Widtsoe on the East Fork and from Casto Canyon on the South Fork, the pink limestone of the Wasatch rather rapidly decreases in thickness; the white limestone beds become more and more siliceous and even tuffaceous until they are indistinguishable from the dominantly pyroclastic Brian Head formation. Regionally the upper part, known as the white Wasatch, and the equally white lower part of the Brian Head formation occupy the same stratigraphic position. Characteristic features of the Wasatch formation are shown in Pl. 6.

Along the Paunsaugunt fault which marks the western edge of the uplifted Aquarius Plateau the thick-bedded pink limestone of the Wasatch in Sweetwater Canyon is about 1,100 feet thick: above it lies about 400 feet of white almost pure limestone in thin uneven beds. Northward in Horse and Birch Canyons the exposed pink limestone of the Wasatch is 520 feet thick and the so-called white Wasatch, here highly siliceous and rich in chalcedony, 120 feet thick. At Cleaves Gulch the corresponding units are respectively 70 + feet and 130 feet. Farther north along the edge of the Aquarius Plateau the Wasatch, if present beneath the alluvial fans, doubtless continues to decrease in thickness, for in Antimony Canyon both the pink limestone and the overlying siliceous white rock are absent; igneous conglomerate and lava immediately overlie Cretaceous shales. Likewise west of the Paunsaugunt fault the thickness of the Wasatch decreases northward from 1,800 at Bryce Canyon to about 300 feet in Prospect Canyon. Still farther north none is exposed in the canyons that trench the eastern slope of the Sevier Plateau and in Kingston Gorge, where the East Fork of the Sevier has cut a trench over 1,000 feet deep, only igneous rocks are in sight. These stratigraphic relations of the Wasatch along the East Fork of the Sevier River are duplicated along the South Fork in the upthrown block of the Sevier fault. In the walls and upper slopes of Casto Canyon the pink limestones of the Wasatch and the white siliceous shales above them attain a combined thickness of about 1,600 feet, then thin rapidly northward across Petersen, Limekiln, and Sand canyons and are not represented in Sanford, Smith, or Bulrush canyons, nor farther north in the deep

Circleville or Lost Creek canyons, which are walled in by pyroclastics and lavas. Callaghan[9] states that "no rocks assigned to the Wasatch formation crop out in the Marysvale region." This decrease northward in exposed thickness of the Wasatch is in part due to its northward dip, which is greater than the inclination of the bordering valleys, and in part to shearing by faults, but in greater part it is probably the record of erosion.

It thus appears that within the area occupied by the northwestern Aquarius, the northern Sevier Plateau, and the adjoining Awapa plateaus and the Tushar Mountains, the Eocene Wasatch sediments if ever present had been erased by erosion before the middle Tertiary igneous conglomerates and lavas were laid down. It seems worthy of note that the plane—in places an unconformity—that separates the calcareous sediments and the volcanics dips northward and northwestward while the lavas and accompanying beds of igneous conglomerates lie nearly flat. As if to maintain a uniform combined thickness, the volcanics progressively thicken to compensate for the thinning and final disappearance of the limestone. Their regional distribution suggests that the older volcanics in Central Utah spread southward from a source in the northwestern Sevier Plateau and the adjoining Tushar Mountains—areas in which Tertiary non-volcanic sediments are largely lacking and latite and related lavas, tuff, ash, volcanic breccia, and igneous agglomerates are piled to depths exceeding 3,000 feet.

BRIAN HEAD FORMATION [*Miocene (?)*].

General Features and Relations.

Generally along the upper branches of the Sevier River wherever all the Tertiary formations are exposed, the conspicuous pink limestones of the Wasatch are overlain by an equally conspicuous series of white, calcareous, and siliceous shale-like beds and in turn by gray, igneous agglomerates which in places form the surface of the plateaus and in other places extend upward to capping sheets of black lava. On the Paunsaugunt and the southern Aquarius plateaus the white strata immediately below the conglomerates are essentially lime-

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[9] Callaghan, Eugene: 1936, Volcanic sequence in the Marysvale region, Utah: Am. Geophysical Union Trans. for 1939, pt. 3, p. 441.

stones; some of them wholly calcareous, others more or less siliceous. On the Sevier, the northern Aquarius, and the central Markagunt plateaus equivalent strata consist chiefly of volcanic ash, tuff, and highly siliceous limestones and contain much chalcedony. Naturally these conspicuous tuffaceous beds—in places brightly colored and beautifully carved—attracted the attention of Dutton,[10] who treated those exposed in "Sanford Canyon" (Limekiln Gulch ?), and Kingston Gorge as records of volcanic activity and the beds elsewhere in the Sevier valleys in the same stratigraphic position and more or less similar in composition as "lacustrine limestones"—the "upper white limestones and calcareous marls" . . . "the summit of the Bitter Creek Group" (Wasatch formation in part). Dutton[11] writes,

> [At Sanford Canyon] the strictly eruptive part of the [Sevier] Plateau ends, and the continuation of it southward is composed of Tertiary beds of the Bitter Creek group, overlaid by an enormous mass of volcanic conglomerate. Between the two are thin layers of those fine-grained marls and sandstones which have been derived from the decay of ancient lavas, and which were evidently deposited in water. Of the age of these intermediate beds it is possible to say but little. They are apparenly conformable to the Bitter Creek below, but the conformity is no proof of continuity of deposition. They contain no fossils. . . . . Veins of chalcedony and agate often cut the beds, and the fragments strew the soils and badland at the foot of the cliffs.

In more recent reports on the southern High Plateaus the white strata that generally overlie the pink limestones and include pure calcareous silts, siliceous limestones, calcareous sandstones, and volcanic ash have been treated as a phase of Wasatch deposition. In the present paper these stratified beds are classed as the lower part, and the coarse igneous conglomerates above them as the upper part, of the Brian Head formation, tentatively considered Miocene in age. The name is derived from Brian Head, a prominent projection of the Markagunt Plateau near the Cedar Breaks National Monument.[12]

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[10] Dutton, C. E.: 1880, Report on the geology of the High Plateau of Utah: U. S. Geog. Geol. Survey Rocky Mt. region, pp. 73-74, 158-159, 199, 237-238.

[11] Dutton, C. E.: op. cit., pp. 237-238, 73-74.

[12] Gregory, H. E.: Geology of eastern Iron County, Utah; U. S. Geol. Survey Prof. paper (in preparation).

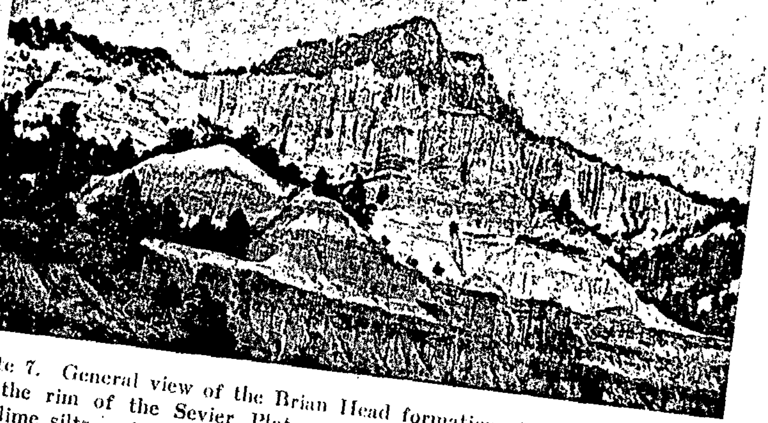

Plate 7. General view of the Brian Head formation at Hancock Bluff on the rim of the Sevier Plateau. Brightly colored stratified siliceous lime silts and pyroclastics are overlain by igneous conglomerates.

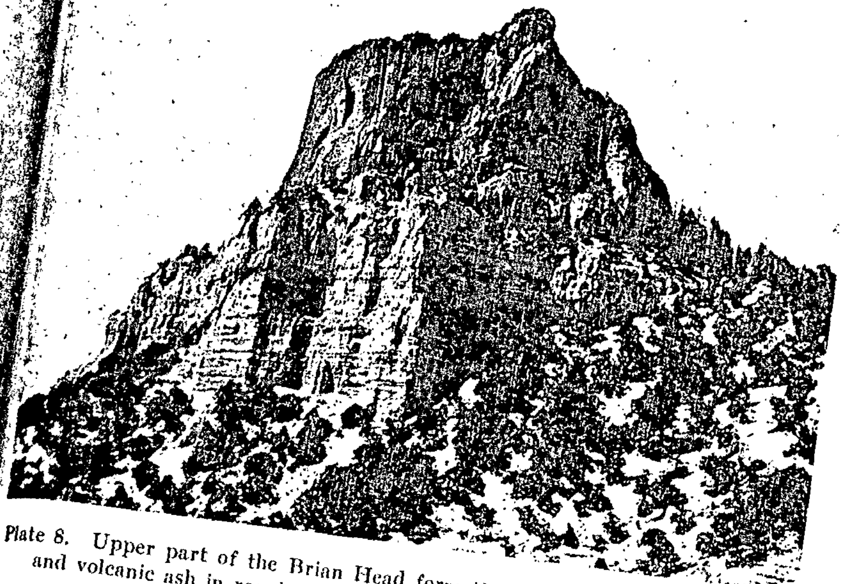

Plate 8. Upper part of the Brian Head formation at Casto Bluff. White tuff and volcanic ash in regular beds are overlain by andesitic breccia and lava.

Plate 9. Detailed view of the upper part of the Brian Head formation in Black Canyon along the East Fork of the Sevier River.

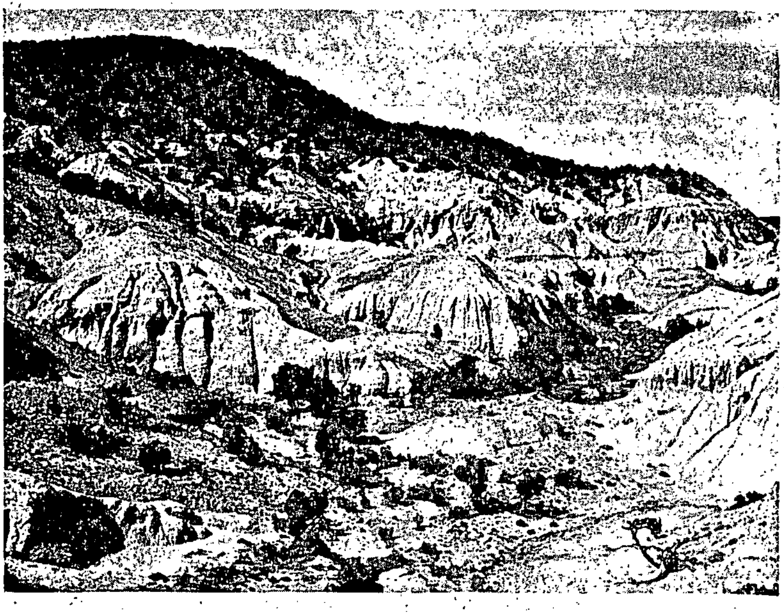

Plate 10. Detailed view of the lower part of the Brian Head formation in Limekiln Gulch. The thin-bedded, white, gray, and green pyroclastics and lenses of chalcedony are intricately eroded.

view of the upper part of the Brian Head formation along the East Fork of the Sevier River.

view of the lower part of the Brian Head formation
ulch. The thin-bedded, white, gray, and green pyro-
ses of chalcedony are intricately eroded.

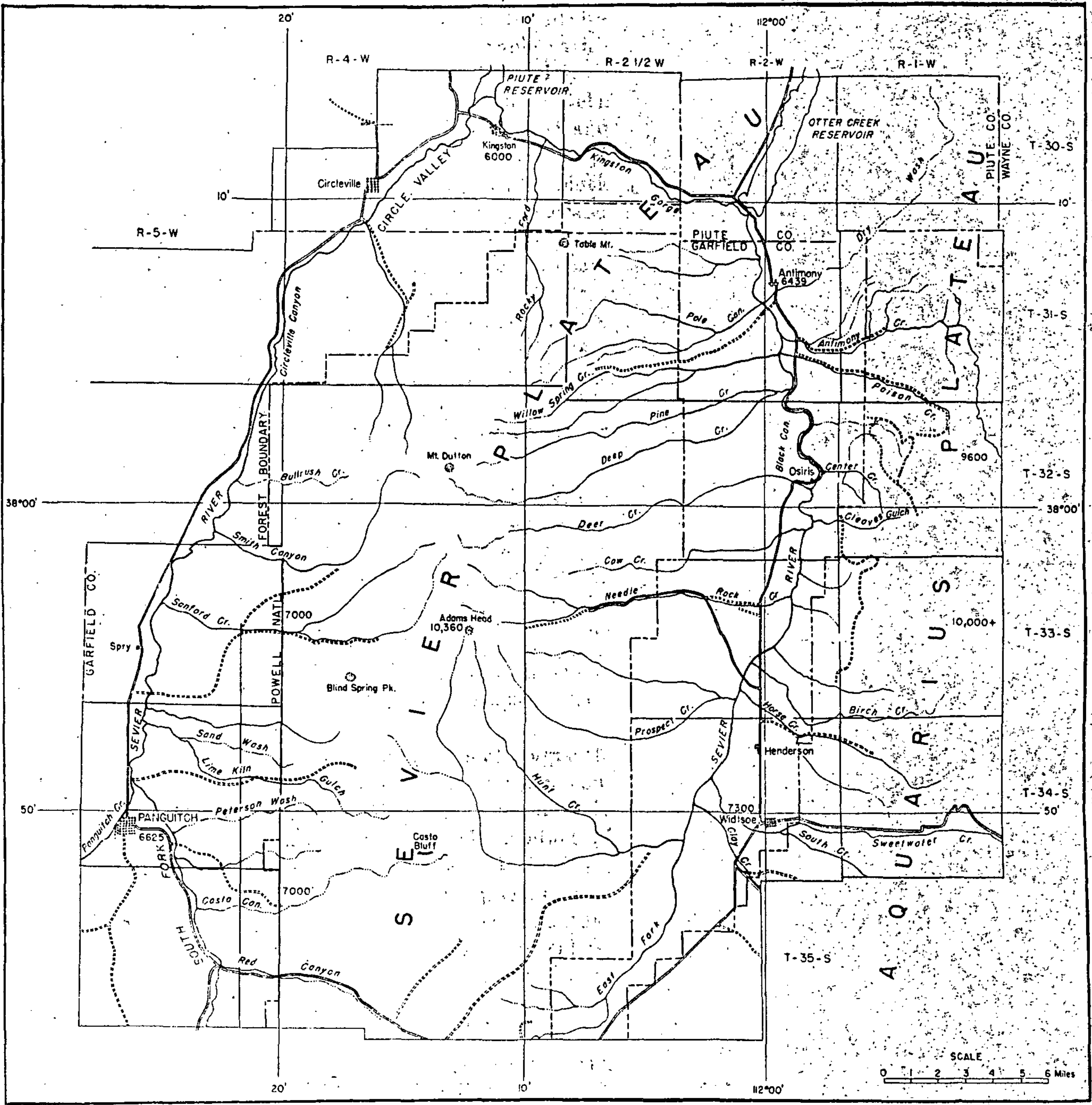

Fig. 1. **Map of west central Garfield County, Utah, showing the relations of the South Fork and East Fork of the Sevier River to the Sevier and Aquarius Plateaus.**

Examination of the Brian Head formation within the drainage basin of the upper Sevier River shows considerable variation in composition and arrangement of beds (see Pls. 4-10).

Along the southern rim of the Sevier Plateau and the western rim as far north as Sand Wash both the bedded lower part and the conglomeratic upper part of the formation are continuously exposed in the upthrown and in places the downthrown block of the Sevier fault. North of Sand Wash only conglomeratic rock is exposed, but in such thickness (500 to 1,000 + feet) and such intermingling of fine-grained, bedded, and massive rock as to give the impression that the two classes of sediments inter-grade and that finally the ash and tuffaceous deposits disappear. At Casto Bluff[18] and nearby headlands the lower part of the Brian Head formation is displayed as brightly colored slopes that weather in badlands fashion—mounds, grooved hillocks, rounded ridges, spires, and columns. As described by Norman C. Williams, Field Assistant,

> "it consists of four dominant types of water-marked sediments: (1) fine ash, (2) a mixture of sand, ash and products of disintegration of moderately crystalline volcanics, (3) pumice conglomerates, composed of well rounded pumice fragments ranging up to 4 inches in diameter embedded in a matrix of sand and ash, (4) stream and channel deposits consisting of conglomerates composed of well rounded quartzite, chert, and "rotten" rhyolite, granite and andesite pebbles; pure homogeneous sand, some of it crossbedded; exceedingly pure, thin clay lenses; and mudball conglomerates."

The black and white banded beds include lenses of magnetite and other heavy minerals, partly decomposed feldspar, conspicuous as white chunks. Some of the pink clays minutely interbedded with white ash resemble varves. The contact of the soft variegated Brian Head with the dense pink limestone characteristic of the Wasatch, though abrupt, appears to be gradational. A few feet below the contact the limestone includes thin lenses of green shale in which the dominant calcite is mingled with subangular quartz grains (10± per cent), feldspar, biotite, and limonite.

At the head of Petersen Canyon and in Limekiln Gulch the

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[18] Casto Bluff and Casto Canyon were named for a pioneer settler, Abel N. Casto. On some maps ths word is misspelled "Castro."

Brian Head consists chiefly of white, gray, and green, well-stratified, coarse "marls" but includes gray sandstone; lenses of well-worn quartz and quartzite pebbles; and thinly foliated beds sufficiently calcareous to justify quarrying for plaster. Chalcedony is abundant in strings, lumps, and beds as much as 4 feet thick and on weathering coats several acres with gray, blue, red translucent shards. The gray sandy beds contain bones and impressions of horny skin, probably of soft shell turtles. The green rock in Limekiln Gulch is described by Clarence S. Ross as

> composed dominantly of volcanic-rock minerals, among which plagioclase is dominant. This is associated with small amounts of hornblende, biotite, and magnetite. Detrital quartz in well-rounded grains, and fragments of limestone represent nonvolcanic materials which form around one-third of the rock. There is an almost total absence of potassic feldspars, and the plagioclase is calcic, some of it being sodic labradorite. The character of the feldspars indicates that these were derived from andesitic rocks, and this is confirmed by the presence of andesitic rock grains.
>
> A green, secondary material forms films around the mineral grains. Chemical tests show that this is a potassium mineral and this together with a moderately high birefringence, indicates that it is essentially similar to celadonite in composition.

In Sanford Canyon the oldest beds exposed are white siliceous shales (ash ?) that include long and short lenses 1 to 20 feet thick of the peculiar green rock displayed in Limekiln Gulch. Above this material lies several hundred feet of volcanic conglomerate and breccia, overlain in places by andesitic lavas. In the walls of Smith Canyon the dominant rock is a conglomerate of angular igneous boulders, many of them as much as 4 feet in diameter. Within the conglomerate are slabs and lenses of stratified ash and below it irregular beds of green white ash and tuffaceous material. The rocks in the canyon walls are arranged as blocks tilted in various directions along local (?) faults of undetermined trend and displacement. In Lost Creek Canyon south of Circleville the walls and adjoining areas consist wholly of conglomerate dominantly of angular, andesitic fragments, most of them 2 to 6 inches in diameter. Near the mouth of the canyon the conglomerate is finer-grained, some of it evenly bedded, and includes a few green pebbles.

Immediately along the East Fork of the Sevier the lower part

of the Brian Head formation is absent. Black Canyon is walled in by volcanic breccia that normally constitutes the upper part of the formation, and for about 4 miles below the mouth of Deer Creek this material is covered by lava flows. Farther north the overlying lava has been largely removed and the conglomerate forms the bench lands along the river and presumably lies beneath the alluvium about Antimony. In the walls of Black Canyon where 60 to 100 feet is exposed, the conglomerate is roughly bedded but very poorly sorted. It consists chiefly of wedge-shaped and slab-like fragments of igneous rock, 2 to 4 inches in diameter but contains some slabs as much as 4 feet long and considerable gravel-like material in which the larger fragments are embedded. The components of the igneous conglomerates are sharply angular and essentially unweathered; they resemble fragments freshly broken from dense massive lavas. This conglomeratic mass includes rare lenses of thin-bedded, medium-grained sandstone, but amygdaloidal and scoriaceous fragments, lapilli, and bombs appear to be absent. In thickness and in size and abundance of fragments the conglomerate in East Fork Valley seems to increase progressively westward and northward and thus suggests a source high on the northern Sevier Plateau, where, near the head of Sanford Canyon Dutton[14] noted "a brief exposure of what seems to have been an ancient trachytic vent and which is composed chiefly of cinders."

The Brian Head formation includes the oldest volcanics in the southern High Plateaus and though thick and widely extensive its source is unknown. No cinder cones or sheets of lava from which comparable material might have been derived are exposed along branches of the upper Sevier, and in adjacent regions the dikes in the Tertiary sediments pass entirely through the formation. Likewise, in the absence of diagnostic fossils or other conclusive evidence the age of the Brian Head formation is uncertain. Because it lies above the typical limestones of the Wasatch of late (?) Eocene age and, disregarding the lava flows below strata believed to represent the late Pliocene or early Pleistocene Sevier River formation, it seems reasonable tentatively to assign the Brian Head to the Miocene. The formation pre-dates the movements along the Paunsaugunt and Sevier faults in late Tertiary and early Quaternary times.

[14] Dutton, C. E.: op. cit., p. 77.

Petrography.

Selected rock specimens from the Brian Head formation were studied by Prof. Bronson Stringham, University of Utah, whose report is summarized as follows.

Rocks from the Western edge of the Sevier Plateau:

Mouth of Red Canyon. Limestone. Calcite 98 per cent; quartz fragments 2 per cent.

Losee Ridge. Acidic tuff. Clastic fragments of quartz, feldspar, hornblende, and glass.

Limekiln Gulch. Calcareous grit (tuff ?). Fragments in order of abundance: chalcedony, carbonate, quartz, feldspar, hornblende. Grains 1 mm. to 0.1 mm. in diameter, very irregularly shaped and angular. Cement of coarse calcite grains make up about 25 per cent of the rock.

Limekiln Gulch. Green sands. Clastic fragments in order of abundance: quartz, feldspar (andesine and labradorite), calcite and dolomite, quartz and feldspar aggregates, glass, lithic fragments of basalt and andesite, hornblende, magnetite, and kaolin. Fragments round to subround, 2 mm. to 0.05 mm. in diameter cemented by a green flaky to fibrous mineral identified as chlorite, var. clinoclore; chemical and optical tests distinguish it from vivianito, glauconite, celadonite, chamosite, and greenalite.

Sanford Canyon. Igneous conglomerate. Fragments of andesite and basalt of usual composition.

Smith Canyon. Igneous conglomerate. Lithic andesite and basalt fragments and porphyritic crystals. Grains in groundmass 1-3 mm. in diameter.

Smith Canyon. Vitric crystal tuff. The 7 specimens from lenses in igneous conglomerate are dark to light green in color and contain quartz, feldspar, hornblende, biotite, acidic glass with shards, and other minerals characteristic of igneous rocks. Green color due to numerous shreds of chlorite, which constitutes the cement. Closely similar to "green sands" in Limekiln Gulch.

Rocks from the Western edge of the Aquarius Plateau:

Sweetwater Canyon. Limestone. Calcite 98 per cent;

quartz fragments of various sizes and a little colloform chalcedony.

Birch Creek. Limestone. Chiefly calcite (90 + per cent), and angular fragments of quartz. [This rock closely resembles the calcareous silt in nearby Horse Canyon, analyzed in Section 2.]

Cleaves Gulch. Consolidated ash. Contains quartz, orthoclase, plagioclase, biotite, glass, and chalcedony. Glass in shreds, rods, and shard-shaped bodies.

Black Canyon. Igneous conglomerate. Chiefly coarse and fine-grained andesite and basalt boulders; includes hornblende crystals and black vitrophyre.

The laboratory study of thin sections of rock considered typical of the Brian Head formation supports the field observations that on the Paunsaugunt and the southern Aquarius plateaus the lower part of the Brian Head formation consists almost wholly of calcite and that northward the relative amount of clear quartz and of chalcedony increases and the pyroclastics become more and more prominent. However, the change from dominant limestone to dominant tuff is not regularly progessive. In places the pyroclastics include calcareous silts and in other places chunks of chalcedony and rotted andesite appear in outcrops composed essentially of thin-bedded limestone.

SEVIER RIVER FORMATION *(Pliocene or Pleistocene).*

Rocks doubtfully correlated with the Sevier River formation outcrop in small areas on the Aquarius Plateau and along the South Fork of the Sevier River and its tributaries. Characteristically they are partly consolidated gray boulder conglomerates lenticularly interbedded with gray, tan, and black sandstones. As exposed along Highway 89, south of Panguitch they include basaltic and andesitic conglomerates containing boulders as much as 2 feet in diameter, fine-grained volcanic débris, clay, silt, and scattered pebbles of chert and chalcedony. The material obviously was deposited by streams flowing in poorly defined channels and subject to wide fluctuation. The outcrops show the texture, the style of bedding, and the vertical and lateral unconformities that characterize fanglomerates of local origin, accumulated in local basins (see Pl. 11).

PLEISTOCENE AND RECENT SEDIMENTS.

On the Aquarius Plateau glacial till, in some valleys kames, rest on the lavas and ice-borne débris borders several lakes. Near the mouths of Casto and Red Creeks stratified drift that contains Pleistocene fossils is exposed beneath alluvium and talus. In the banks of Casto Creek 60 + feet of glacial sediments are sufficiently consolidated to permit erosion by spalling. The predominant material is dark-gray, compact sandy clay in roughly shaped beds 1 to 3 feet thick; subordinate materials are marls and coarse gravel. The marl, in places chalklike and interbedded with ash, siliceous silts, and ash (?), forms white layers 6 to 20 inches thick and continues for at least 200 feet. The gravel, which consists chiefly of irregularly shaped little worn igneous fragments ⅛ to ½ inch in diameter, is distributed as lenses—thicker, more numerous, and coarser toward the top of the deposit.

In consequence of erosion during Recent times most of the streams are cutting deeply into the valley fill laid down during a previous cycle of aggradation.

In late Pliocene and Recent times the rock-floored canyons were partly filled with alluvial and, locally, lacustrine deposits, which, in consequence of a change in stream habit from aggradation to degradation, is now in process of removal. Generally along the Sevier River and its tributaries the once continuous flat expanses of stratified sand and gravel have been cut into terraces. During the past half century the intricate dissection of the fill has caused the relocation of roads and the abandonment of much farm land (see Pl. 12).

STRATIGRAPHIC SECTIONS.

1. Section in Antimony Canyon.

Composite of 4 sections measured within an area of about a square mile.

	Feet
16. Alluvial sand and gravels in terraces bordering streams; talus and landslide debris on slopes	0–100
Unconformity	
15. Basalt, thin sheet, covering small areas on the Aquarius Plateau.	
Unconformity	
14. Sevier River (?) formation. [Recorded by D. C. Duncan]. Gray boulder conglomerate interbedded with salmon pink sandstone. Conglomerate consists of volcanic boulders in angular sand matrix. Unit poorly consolidated, weathers in low banded cliffs and steep slopes, estimated	600
Unconformity	
13. Andesite (?), dense and porphyritic, in overlapping flows 2 to 6 feet thick; includes irregular masses of igneous agglomerate and of massive, amygdaloidal and scoriaceous lava. Stands as a wall about the headwater branches of Antimony Canyon and southward forms the surface of Aquarius Plateau. At the mouth of the canyon, on the downthrown block of the Paunsaugunt fault, remnant masses weather into knolls. Maximum thickness, estimated	1000
Unconformity	
Brian Head formation	
12. Volcanic conglomerate: chiefly angular fragments of acidic lava: contains some blocks of sandstone and scattered quartzite pebbles	0–80 +
Unconformity	
Tropic formation	
11. Shale and sandstone, lower part faintly banded gray brown, buff, and drab; upper half dominantly gray green and tan; arenaceous and argillaceous, rare gypsiferous and carbonaceous shales in groups 2 to 100 feet thick overlap or replace along strike massive, thick bedded, and thin bedded sandstone 1 to 40+ feet thick; includes lenticular masses of limestone, concretionary nodules of iron, lenses and veinlets of stibnite, and near the top a thin bed of bentonite; the calcareous sandstones contain fragmentary fossils; weather as steep slopes broken by narrow projecting ledges of limestone of concretionary iron	860–1180
Dakota (?) sandstone	
10. Conglomerate and sandstone, gray and tan; commonly roughly bedded, coarse sandstone with scattering pebbles; locally a mass of well worn quartzite and limestone pebbles, ¼ to 2 inches in diameter and angular slabs of sandstone embedded in a calcareous and siliceous matrix; grades into No. 11	10–180
Dakota (?) sandstone	
Unconformity	
Curtis and Winsor formations, undifferentiated	
9. Sandstone, gray, highly calcareous; irregular, lumpy beds 1 inch to 1 foot thick. fragmentary fossils; relatively resistant, forms cliff and bench above, varies much in thickness and along strike, in places is absent	6–35
8. Shales, yellow gray, sandy, slightly gypsiferous; irregularly alternating and lenticular, even bedded. Forms steep slope	42
7. Shales and subordinate thin sandstones; roughly banded, yellow gray, green gray, white, and light red; includes gypsum in thin irregular seams and disseminated grains; includes near the middle hard thin bedded limestone as much as 10 feet thick and at the top subangular pebbles of varicolored quartzite, white quartz, hard limestone, and clay balls, 1/16 to 1 inch in diameter, embedded in a dark gray calcareous sand	88
Total Curtis and Winsor formations	165 ±

Unconformity (?)

Entrada sandstone

6. Sandstone, deep red, streaked with white, even bedded, in places shaly; well rounded, fine grains of quartz cemented by lime and iron; slightly gypsiferous; generally at the base and locally higher up includes yellow-white bands and lenses of well worn pebbles of quartzite, quartz, and limestone. Weathers as steep slopes and cliffs marked by grooves, pilasters, columns, and detached towers; generally top beds hardened to form shelves and projecting ledges 180–220

Unconformity ?

Carmel formation

5. Limestone, gray, blue gray on fresh fractures; very thin bedded, even bedded; dense, brittle, in places friable; weathers into hard, angular chips. At the base and top, brown and greenish, sandy, calcareous shales; surface of some beds show ripple marks, worn trails, and lumpy aggregates (algae ?); marine fossils. Stands nearly vertical against Navajo sandstone; weathers into dikelike ridges and grooves 460

Unconformity

Navajo sandstone

4. Sandstone, light gray, in places tan, generally massive except for units outlined by widely spaced indistinct bedding planes, in part cross bedded; composed of very fine spherical glistening grains of quartz; intricately fractured and faulted on a small scale both along and across strike; stands nearly vertical. Average thickness estimated 1100

Unconformity: fault plane

Chinle (?) formation: Curtis (?) and Winsor (?) formations

3. Shale, green, ash gray, rarely pink or white; argillaceous, arenaceous, and gypsiferous; very friable; dips westward; separated from No. 4 by a fault. Nos. 2 and 3 are generally concealed by coarse gravel 50

2. Shale and thin irregularly bedded sandstone, deep red, in places tan; includes tiny flakes and lenses of drab, gypsiferous, compact clay; dips steeply west to a fault contact with acidic lavas 180

Unconformity ? fault plane ?

Shinarump (?) conglomerate

1. Conglomerate, gray, lenticularly stratified and cross bedded; pebbles chiefly quartzite, quartz, and rare hard, black limestone, well rounded, some polished, the largest pebbles as much as 5 inches in diameter; includes lenses of sandstone; matrix of siliceous sand and gravel in which are tiny fragments of metamorphic and igneous (?) rock 20–60

Total thickness 4586–5329

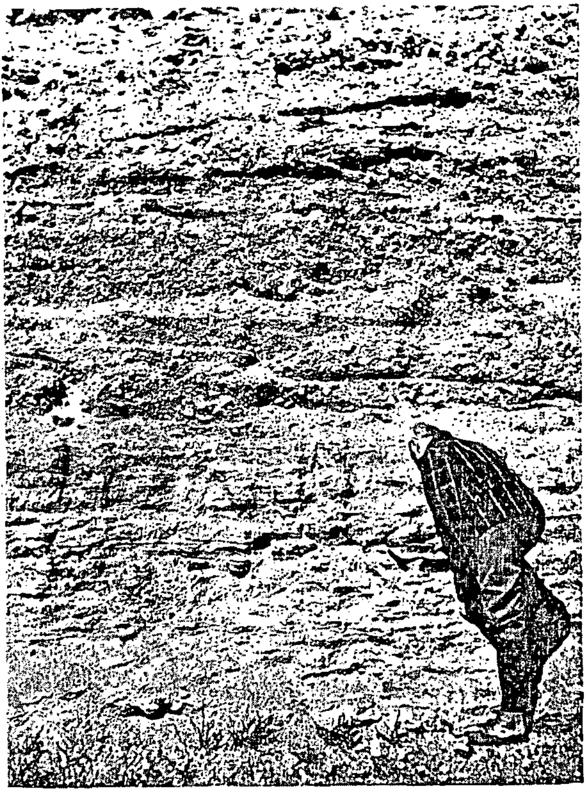

Plate 11. Characteristic exposure of the Sevier River (?) formation along Federal highway 89 south of Panguitch.

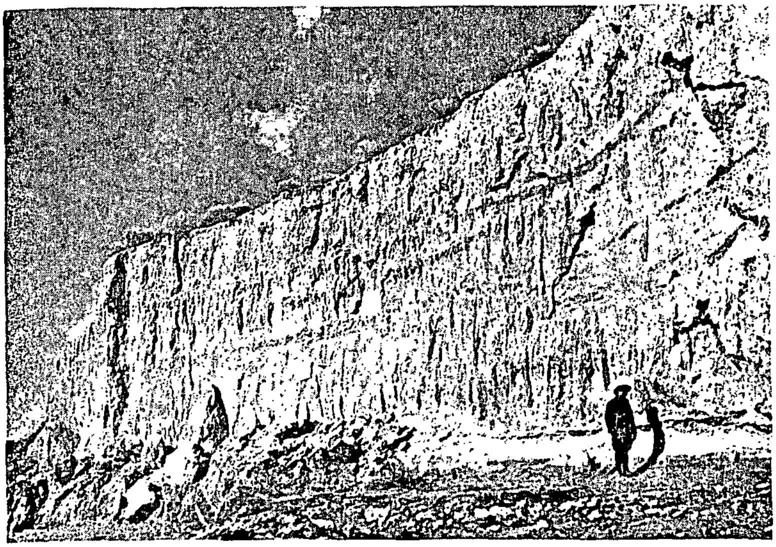

Plate 12. Bank of Red Creek below the mouth of Red Canyon. Wall of Recent alluvium rests unconformably on fossiliferous marls of Pleistocene age.

2. Section in Horse Creek Canyon.

	Feet
4. Andesite (?) in sheets and lumpy masses of igneous conglomerate; forms a bench between faults (?) on the west flank of Aquarius Plateau; thickness estimated	600
Brian Head formation	
3. Igneous agglomerate. Bouders of dense and scoriaceous lavas; largely concealed by talus from No. 4. Thickness estimated	400
2. Shales, white, calcareous and siliceous, mainly amorphous consolidated silt; regularly stratified in beds 2 to 4 inches thick; resistant beds form projecting ledge near the top and little shelves and mesas on an otherwise nearly vertical cliff; slopes coated with glistening white powder which are small fragments of chalcedony	120
Total Brian Head formation	520
Wasatch formation	
1. Limestone, pink and light red; generally in thick, massive, poorly defined beds; fairly well stratified near the top; includes thin, hard, porous layers concentrically overlapping as in travertine; near the base lenses of gray conglomerate—small rounded pebbles of quartzite and quartz embedded in calcareous material; forms nearly vertical cliff carved into pinnacles; part exposed	520
Total thickness measured	1640

3. Section in Cleaves Gulch near "Burro Flat," 4+Miles South of Center Creek.

	Feet
4. Andesite porphyry?, megascopic crystals of orthoclase in a groundmass of feldspar and quartz; basal 6 feet red and black sheets, 2 to 5 inches thick, extremely dense, some of it glassy. Forms top of fault block on the lower west flank of Aquarius Plateau; largely destroyed by erosion	260
Unconformity	
Brian Head formation	
3. Conglomerate, unstratified, composed of angular igneous pebbles, the largest as much as 4 feet in diameter; groundmass of igneous gravel and sand. Forms nearly vertical cliff	86
Unconformity	
2. Limestone, siliceous, dark gray near base, white above; fairly regular beds 3 inches to 3 feet thick; includes chalcedony in thin sheets and lenses. Forms steep uneven slope	130
Total Brian Head formation	216
Unconformity	
Wasatch formation	
1. Limestone, pink, massive, sandy, includes lenses of calcareous	

clay shales stratified like lacustrian silts; largely concealed by debris from landslides and dissected alluvial fans; part exposed	70
Total thickness measured	546

4. Section in North Branch of Limekiln Gulch.

	Feet
Brian Head formation	
7. Volcanic breccia; part exposed estimated	200+
6. Calcareous and siliceous shale, volcanic ash, travertine, and fine-grained sandstone, indistinctly banded pink, white, and yellow; regular beds; much chalcedony in thin slabs 1 to 4 feet in diameter; weathers as hard surfaced, steep slope	84
5. Sandstone, green, coarse grained; in 5 fairly regular groups of beds 1 to 5 feet thick, hard enough to form cliffs that weather into knobs and columns; contains small pebbles of quartz, quartzite, and igneous rock, isolated and in strings; at base irregular lenses 1 to 5 inches thick, 10 to 50 feet long of gray hard, siliceous limestones; in the green sand the microscope reveals hornblende, magnetite, kaolin, glass, andesane, labradorite, calcite, dolomite, and subrounded fragments of basalt and andesite .05 to 2 mm. in diameter cemented by a fibrous green mineral—chlorite (?), celadonite (?)	26
4. Shale, along strike and in sequence various shades of green, yellow, brown, and gray; essentially sandy clay and ash; fine grained regular beds; very friable except for tightly cemented lozenges and discs that weather as knobs and caps of pinnacles. At 22 feet above the base thin band of rusty pink limestone and at 42 feet a thin black band composed chiefly of magnetite grains. An intricately dissected slope	180
3. Shale, green, sandy, interbedded with impure limestones; includes lenses of conglomerate and sandstone, much chalcedony including near the base a lenticular mass 2 to 2¾ feet thick and 100+ feet long; forms a steep slope dissected into mounds and gullies	286
2. Limestone, white, siliceous, thin bedded, includes much conglomerate with calcareous matrix composed of subangular pebbles of black and white quartz, variegated quartzite, black limestone, and dense igneous rock fragments, some as much as 2 inches in diameter	92
1. Red conglomerate	67
Total Brian Head formation	968
Wasatch formation; compact pink limestone	

In this section units 1-3 were measured by J. C. Anderson on the upthrown side of the Sevier fault at the base of Blind Spring Peak, about 2 miles northeast of Nos. 4-7; probably duplicates in part unit 4, incompletely exposed in the downthrown block.

EXTRUSIVE IGNEOUS ROCKS.

Within the drainage basin of the upper Sevier River andesites and closely related lavas are displayed as extensive, more or less continuous sheets on the top of the Aquarius Plateau, and on the Sevier Plateau they are irregularly distributed over the volcanic breccia which forms the general surface. The field relations suggest that these rocks represent lavas that were extruded during one general period of volcanic activity and not long after the volcanic breccia in the Brian Head formation was laid down. Basalts of younger age occupy small areas in various topographic positions and came from local vents. All the lava sheets are older than the major faults. The composition of the lavas is shown by the following descriptions of specimens thought to represent the most common varieties within the region under review. Farther north casual traverses reveal a greater variety of rock type and much more complex interrelations.

1. Mouth of Red Canyon. Olivine basalt. Well shaped phenocrysts of olivine and labradorite in lattice-like groundmass of labradorite. Crowded between the laths are grains of augite and magnetite. In part vesicular.

2. Mouth of Red Canyon. Hornblende basalt. Minerals in order of abundance: labradorite in small crystals and phenocrysts, augite, hornblende, glass, and magnetite. Shows small-scale vesicular structure.

3. Losee Ridge. Basalt. Microscopic crystals of labradorite, augite, magnetite, and subordinate glass. In one thin section the structure is vesicular, in another compact.

4. Outlier of Sevier Plateau; North branch of Casto Canyon. Andesite. Contains andesine, augite, and magnetite crystals, many of them surrounded by glass. Andesine crystals, submicroscopic to 2 mm. in diameter constitute the bulk of the rock. Probably represents in general the lava cap of parts of the Sevier Plateau.

5. South branch of Peterson Wash. Andesite porphyry. Large and small crystals of andesine, prominently zoned and variously oriented; unaltered augite (or diopside), and phenocrysts of light, broad, beautiful pleocroic hornblende. Groundmass contains much magnetite, some isotropic material (glass?) and patches of green chlorite that may represent biotite.

6. Black Canyon near Osiris. Andesite porphyry. In hand

specimens a very dense, light-purple rock criss-crossed with short white laths. Microscope reveals phenocrysts of andesine in a ground mass of crystals of submicroscopic size.

7. Aquarius Plateau near head of Antimony Creek. Basalt. Minerals content: olivine phenocrysts, about 10 per cent, augite 5 per cent, magnetite 2 per cent, and basic turbid glass. The labradorites, which constitute 90 per cent of the feldspar crystals, range in size from phenocrysts 3 mm. in length to microscopic fragments and are more or less tabular in form. Their molecular composition is $Ab_{45}An_{55}$. The larger crystals are zoned and material of the outer rim is close to albite in composition. A little opal is present in vugs. This rock, collected as representative of the extensive lava sheets on the Aquarius Plateau, may be part of local extrusion. Dutton states that the rocks on the Aquarius are "chiefly hornblendic trachytes commingled with very extensive masses of augitic andesites."

STRUCTURE.

The major structural features of the upper Sevier valleys are the Paunsaugunt fault, which marks the west base of the Aquarius Plateau, and the Sevier fault, which lies along the west base of the Sevier Plateau. The main Paunsaugunt fault lies in a zone of faulting that extends southward across Utah and into Arizona and northward along the base of the Awapa Plateau—the Grass Valley fault of Dutton. The Sevier fault, which also extends far southward and northward, is in most places represented by a single escarpment and a narrow belt of displaced rock.

The position and the effect of the Paunsaugunt fault zone is revealed in the topography and the attitude of the lavas and underlying sediments. Toward the fault the lavas and the underlying igneous conglomerates that cap the Sevier Plateau dip eastward to their termination in the East Fork Valley, where remnants stand as inclined blocks. East of the fault the corresponding lavas and pyroclastics form the surface of the Aquarius Plateau, at altitudes of 10,000 to 11,000+ feet. Thus the height of the Aquarius Plateau—about 3,500 feet above its westward bordering lowlands—measures the movements within a zone of fracture which here consists of three or more roughly parallel faults that give to the west flank of the plateau the appearance of a series of giant steps. The westernmost of these faults forms the eastern wall of Black Canyon between Osiris and the mouth of Deer Creek and for a few miles south is marked by tilted and fractured blocks through which the East Fork of the Sevier finds its way. North of Osiris the fault continues across Center and Poison creeks where, in the upthrown block, cliffs of pyroclastics and lava are about 2,000 feet high. At Antimony Creek the major displacement is estimated to be 1,800 feet; it has raised the Jurassic strata to the level of the Tertiary volcanic conglomerate. A second long fault marks the base of the escarpment at the heads of Birch, Ranch and Center creeks, and a third is assumed to mark the position of the high cliff-bound tables near the plateau top (see Fig. 2). In addition to these major displacements, expressed in the regional topography, faults with throws of 130, 250, and 400 feet cut the walls of Antimony Canyon; movements of similar amounts doubtless have occurred elsewhere along the western edge of the Aquarius Plateau. Faults with throws of 2 to 10 feet, slickensided fractures, and belts of crushed rock, are fairly common, especially along lines of closely spaced jointing.

The Sevier fault is marked by discordance of strata associated with abrupt termination of color bands and, in distant views, by rock terraces which outline the upthrown and downthrown blocks. Its position and its salient features are plainly revealed in the great canyons that score the west face of the Sevier Plateau. Crossing the mouths of Red and Casto Canyons the fault-line scarp developed in Wasatch formation is a vertical wall 100 to 500 feet high. Farther north in Petersen Wash and Limekiln Gulch the pink limestone of the Wasatch abuts against the white tuffaceous material and the conglomerates of the Brian Head formation—in places against lavas—and in association with the major fault, minor parallel and oblique faults cut the sediments into blocks variously orientated; some dip east against the main fault plane, some southeast or southwest. The Sevier fault, as pointed out by Gilbert,[15] lies within a very narrow zone of disturbance; in places it is a single fracture. Disregarding the effect of the slight eastward dip of adjacent strata, the stratigraphic displacement effected by the fault east of Panguitch is estimated to be 1,000 feet;

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[15] Gilbert, G. K.: 1875, Geog. Geol. Expl. and Surveys W. 100th Mer., vol. 3, p. 49.

the severed parts of once continuous masses of igneous rock remain at altitudes of approximately 7,000 and 8,000 feet.

For about 100 miles north of the Grand Canyon of the Colorado the Paunsaugunt and Sevier fauts are roughly parallel, nearly vertical, and essentially single displacements, but in the vicinity of Widtsoe and Panguitch these simple structures lose their identity. Especially in the downthrown blocks numerous faults replace single features, and north of Circleville Canyon the fault patterns become remarkably complex. It is interesting to note that this radical change in the character and distribution of fractures within the Sevier fault zone —more characteristic of the Great Basin Province than of the Colorado plateaus—is substantially duplicated at Kanarraville and Cedar City, where the Hurricane fault fans out into many faults of various displacements and alinement, among which the master fault is difficult to place.

In the absence of established time markers, the date of faulting in the upper Sevier Valley can be fixed only approximately. The Paunsaugunt and the Sevier faults have broken all the Tertiary sediments, pyroclastics, and lavas, and most of the smaller faults traverse several formations, but the pressure that produced them may have been exerted at any time or at several times since regional uplift created the present High Plateaus. The great erosion that has remodeled the upthrown blocks and covered the downthrown blocks with alluvium, in places fully 800 feet thick, is evidence of long lapses of time. On the other hand, some of the movements have been so recent as to leave fault scarp almost intact.

The structural, stratigraphic, and physiographic evidence seems sufficient to prove that the movements within the major and some of the minor fault zones in the Upper Sevier Valley were recurrent rather than contemporaneous; and that the forces that uplifted the Sevier and Paunsaugunt Plateaus to their present great height operated intermittently. Satisfactory interpretation of the geologic history of the Upper Sevier valleys involves the assumption that structural disturbances began in late (?) Tertiary time and are still in progress.

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NOTES ON THE CRETACEOUS SPECIES DESCRIBED BY KARRER.

JOSEPH A. CUSHMAN.

ABSTRACT. The new species described by Karrer in 1870 from the Cretaceous of Austria were studied in Vienna. The actual specimens were redrawn and notes made as to the validity of the species.

IN 1870 Karrer described a foraminiferal fauna from the Cretaceous of Austria: "Ueber ein neues Vorkommen von oberer Kreideformation in Leitzersdorf bei Stockerau, und deren Foraminiferenfauna" (Jahrbuche der k. k. geologischen Reichsanstalt, vol. 20, 1870, pp. 157-184, pls. 10, 11). Many of the species are referred to those described earlier by d'Orbigny, Reuss, and others, but thirty species are described as new. As some of our American Cretaceous species resembled the figures given by Karrer, I made a study of the type specimens in Vienna in the summer of 1932. Although the type specimens were not in all cases segregated, it was possible to determine which were the figured ones. It was at once apparent that, as in many other papers, the illustrations were more or less conventionalized and in some cases were misleading. For future reference notes were made on these types and nearly all of them were redrawn from the original types. As some of the species names have been used in connection with our American Cretaceous forms and others are closely allied to them it seems worthwhile to present these notes and drawings that they may be available to American workers on the foraminifera.

Gaudryina cretacea (Karrer) (Pl. 1, fig. 1).

Verneuilina cretacea Karrer, Jahrb. k. k. geol. Reichsanst., vol. 20, 1870, p. 164, pl. 10, fig. 1.

Gaudryina rugosa Karrer (not d'Orbigny), l. c., p. 166.—Egger, Abhandl. kön. bay. Akad. Wiss. München, Cl. II, vol. 21, 1899, p. 37, pl. 4, figs. 14, 15.

Gaudryina cretacea Cushman, Special Publ. No. 7, Cushman Lab. Foram. Res., 1937, p. 40, pl. 6, figs. 3-9.

The type, here refigured, is the young triserial stage. The Karrer collection shows adults also that he referred to *G. rugosa* d'Orbigny but they are not the same as d'Orbigny's species. The species is common and widely distributed in the

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CONTENTS

Cover: East flank of San Rafael Swell, Emery County, Utah; looking north. Photo

Geology of the Marysvale Volcanic Field, West Central Utah

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ABSTRACT.—The Cenozoic geologic history of the Marysvale area of west central Utah is largely a chronicle of volcanic events that took place during a succession of tectonic regimes. Volcanism began in late Oligocene time, about 30 m.y. ago, during a period of tectonic quiet. In the succeeding 10 m.y., a complex cluster of intermediate-composition volcanoes, surrounded by coalescing volcaniclastic aprons, and local ash-flow tuffs from caldera sources formed in an area 80–100 km across, in the southwestern High Plateaus; concurrently a widespread field of ash-flow tuffs developed in adjacent parts of the Great Basin to the west. Structural differentiation of the High Plateaus and the Great Basin probably began during this 10-m.y. span, but no extensive basin-range faulting took place until after it was over.

About 21–20 m.y. ago, composition of erupted rocks shifted abruptly from a predominantly intermediate constitution to highly silicic alkalic rhyolites. The largest volumes of rhyolites were erupted 21–17 m.y. ago from sources in the Tushar Mountains and the Antelope Range near Marysvale, where ash-flow tuffs and lava flows of the Mount Belknap Volcanics accumulated, and the major Mount Belknap and minor Red Hills calderas formed (Steven et al. 1977, Cunningham and Steven 1977).

Basin-range faulting began shortly after the Mount Belknap eruptions and continued through the remainder of Cenozoic time. Fluviatile and lacustrine sediments of the Miocene to Pleistocene Sevier River Formation (Callaghan 1938) were deposited in the developing structural basins; widespread but generally sparse basalt lava flows were interbedded in these sediments. Silicic alkalic rhyolite flows and domes were erupted elsewhere in western Utah during this same period, and together with the basalts define a bimodal compositional suite that is part of a regional assemblage of similar rocks erupted throughout western U.S. concurrently with late Cenozoic basin-range extensional faulting (Christiansen and Lipman 1972).

Mineralization took place episodically at one place or another in the Marysvale area from early Miocene (22 m.y. ago) until Pleistocene time (Kerr et al. 1957, Kerr 1968, Bassett et al. 1963, Callaghan 1973, Steven et al. 1977).

PREVOLCANIC ROCKS

The Marysvale volcanic field (fig. 1) extends across a major structural boundary that separates folded and faulted Paleozoic and Mesozoic sedimentary rocks of the late Mesozoic Sevier orogenic belt (Armstrong 1968) on the west from flat-lying strata of comparable age in the Colorado Plateaus province to the east. This transition zone was highly broken during later basin-range block faulting when the High Plateaus were developed, but the position of the Marysvale field above the earlier tectonic boundary is clear cut. Deep erosion took place after the Sevier orogeny, and the continental Claron Formation of Eocene and Oligocene age was deposited widely across the beveled edges of earlier deformed strata. The top of the Claron Formation provided a widespread surface of low relief across which the first Tertiary volcanic rocks accumulated (Mackin 1960).

A few hills of older sedimentary rocks protruded through the cover of Claron sedimentary rocks and formed local barriers that affected the distribution of the early volcanic units. One of these hills is now represented by an anticline of Paleozoic and Mesozoic rocks exposed in cross section on the face of Deer Trail Mountain on the east side of the Tushar Mountains 5–10 km south of Marysvale.

INTERMEDIATE-COMPOSITION VOLCANIC ROCKS OF LATE OLIGOCENE–EARLY MIOCENE AGE

Volcanism began in the Marysvale volcanic field about 30 m.y. ago when a few widely scattered andesitic to rhyodacitic volcanoes began to form. The best documented of these early volcanoes are in the Pavant Range in the northern part of the field where Caskey and Shuey (1975) and Steven et al. (1977) have described local accumulations of dark lavas and breccias. Anderson and Rowley (1975, p. 14) noted thin local deposits of ash-flow tuff, lava flows, volcanic breccia, and volcanic arenite of late Oligocene age at the base of their volcanic section along the southern margin of the field in the Black Mountains and northern Markagunt Plateau. A laccolithic(?) intrusion marking a volcanic center of this age was emplaced near the abandoned small community of Spry, 25 km north of Panguitch (Anderson and Rowley 1975, p. 16). An east-northeasterly line of volcanoes extending from the west side of the Tushar Mountains, through the Marysvale Canyon area, to the northern Sevier Plateau east of Monroe may have begun to form at this time.

These early accumulations in the Marysvale field were largely overwhelmed by tremendous outpourings of crystal-rich ash flows of the Needles Range Formation (Mackin 1960, Shuey et al. 1976) about 29 m.y. ago. The Needles Range Formation consists of at least three members of closely similar lithology derived from sources somewhere in the southeastern Great Basin to the west; these members covered more than 50,000 km^2. Over most of their extent in southwestern Utah and eastern Nevada, the Needles Range ash flows spread across a surface of low relief on older sedimentary rocks. In the Marysvale area, however, the Needles Range ash flows overlapped and locally abutted and wedged out against preexisting hills of sedimentary rocks (Deer Trail Mountain) or of somewhat older middle Tertiary volcanoes (Pavant Range, Spry area, Marysvale Canyon?). Along the northwest side of the Pavant Range, the Needles Range ash flows were contemporaneous with eruptions at local intermediate-composition volcanoes, and here the regional Needles Range ash-flow tuffs are complexly interlayered with locally derived lava flows and volcanic breccia. Where the local barriers did not exist, however, the Needles Range ash flows extended unbroken across the site of the later Marysvale volcanic field and, together with the underlying sedimentary Claron Formation, demonstrate that no topographic barrier existed along the trend of the transition zone between the present Great Basin and Colorado Plateaus provinces.

The local volcanic activity in the Marysvale volcanic field, which began before and continued during accumulation of the Needles Range Formation, became more widespread thereafter and formed a composite volcanic edifice consisting of stratovolcanoes with coalescing volcaniclastic aprons, shield volcanoes, and plateaus of flat-lying lava flows and welded ash-flow tuffs. An east-northeast-trending line of stratovolcanoes extended across the north central part of the field north of Marysvale from the west side of the Tushar Mountains, 15 km north of Beaver, through the Kimberly area, Deer Creek Canyon, Marysvale Canyon, Antelope Range, to the northern Sevier Plateau east of Monroe. Farther south, Anderson and Rowley (1975) reported scattered vent-facies volcanic rocks (mostly lava flows and flow breccia) extending along an east-trending lineament (Rowley, Lipman et al. 1978) from the northern Black Mountains across the southern Tushar Mountains and northern Markagunt Plateau. These stratovolcanoes were flanked in part by thick aprons of volcaniclastic debris (mostly volcanic mudflow breccia) that are especially prominent along the south side of the east-northeast-alined volcanoes north of Marysvale and around the scattered volcanic centers farther south. Volcaniclastic debris is curiously nearly absent along the north flank of the stratovolcanoes north of Marysvale, as will be discussed later.

A major shield volcano of basaltic andesite formed along the north flank of the east-northeast-trending volcanoes from the eastern flank of the Pavant Range eastward across the northern Sevier Plateau. This shield is at least 700 m thick near its center (Callaghan and Parker 1961a, 1962b), and it intertongues westward into a volcanic plateau consisting of flat-lying flows and low domes of rhyodacite and quartz latite lava and a thick accumulation of crystal-rich ash-flow tuff of the Oligocene Three Creeks Tuff Member of the Bullion Canyon Volcanics. The source of the Three Creeks Tuff Member is in the Clear Creek drainage area of the southern Pavant Range, where it is marked by an obscure trapdoor-type subsided block, or cauldron (Steven et al. 1977).

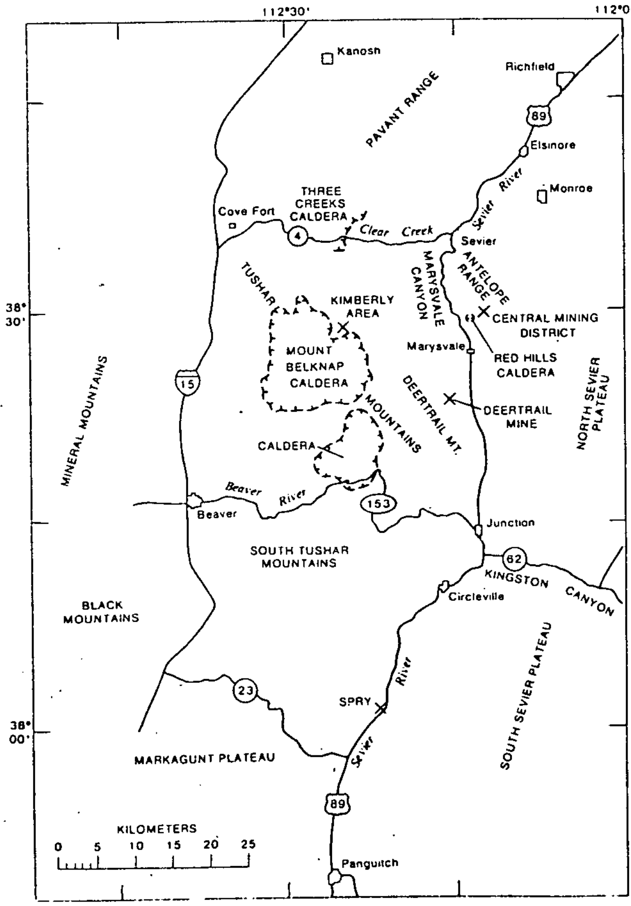

FIGURE 1.—Index map to geographic features in the Marysvale area, west central Utah.

The shield volcano and volcanic plateau along the north side of the east-northeast-trending line of volcanoes were partly responsible for excluding volcaniclastic deposits from this flank of the volcanic field, but other factors also may have been involved. In the eastern Pavant Range west of Elsinore and near the present edge of the volcanic rocks, the Needles Range Formation near the base of the volcanic section is separated by only 15–20 m of dark lava flows from a higher welded ash-flow-tuff unit possibly correlative with the Osiris Tuff. Farther south in the Marysvale Canyon area, neither the base of the volcanic section nor the Needles Range Formation is exposed, but overlying vent-facies volcanic rocks at least 400–500 m thick are exposed beneath the possible Osiris equivalent. This southward increase in volume and thickness of vent-facies rocks seems to require southward tilting of this part of the volcanic field concurrent with eruptions and prior to emplacement of the Osiris(?) Tuff; and such tilting could also have inhibited accumulation of volcaniclastic debris along the northern side of the alined stratovolcanoes.

In the northern Sevier Plateau south of the east-northeast-trending volcanoes, the volcanic edifice is largely a plateau consisting of flat-lying intermediate-composition lava flows with some interlayered volcanic mudflow breccia and welded ash-flow tuff sheets. The Needles Range Formation is exposed locally at the base of the cliffs along the west side of the plateau, so nearly the full section of remaining volcanic rocks, about 1 km thick, is exposed. Farther south toward Kingston Canyon, alluvial-facies rocks become increasingly abundant. They predominate in the southern Sevier Plateau south of Kingston Canyon, where only sparse local lava flows and two distinctive ash-flow tuff units, the Oligocene and Miocene Kingston Canyon and Miocene Antimony Tuff members of the Mount Dutton Formation, are present (Rowley and Anderson 1975).

Volcanic mudflow breccia predominates in the central to southern Tushar Mountains south of the east-northeast-trending line of volcanoes, but vent-facies volcanics are locally prominent near former volcanic centers. Two major ash-flow tuff sheets are well exposed in the central Tushar Mountains; the lower is the Three Creeks Tuff Member already mentioned, and the other is the Delano Peak Tuff Member (Miocene) of the Bullion Canyon Volcanics, which came from a cauldron source 7 km across that occupies much of the central Tushar Mountains north of Beaver River.

South of the Beaver River, in the southernmost Tushar Mountains and northernmost Markagunt Plateau, the volcanic pile consists largely of local vent-facies accumulations at volcanic centers formed along an east-trending lineament (Rowley, Lipman et al. 1978). Some locally distinct units of Miocene age have been recognized and mapped (Anderson and Rowley 1975) in the northern Markagunt Plateau. Chief among these are the autoclastic and mudflow breccia of the Buckskin Breccia derived from the Spry igneous center; the cross-bedded dune sand of the Bear Valley Formation caught against the Spry volcanic pile and filling grabens; and plugs, lava flows, and volcanic mudflow breccia of the Horse Valley Formation in the Black Mountains. The Osiris Tuff is a distinctive sheet of ash-flow tuff that is distributed widely throughout the eastern part of the Marysvale volcanic field. It is near the top of the volcanic succession in most places and provides a convenient marker bed. The source of the Osiris Tuff is probably in the northern Sevier Plateau east of Marysvale (P. L. Williams pers. commun. 1970).

The detailed stratigraphy of many parts of the complex pile of generally intermediate-composition volcanic rocks of late Oligocene–early Miocene age has been worked out only in part, and many important relations remain to be established. The whole succession in the northern part of the field was included at one place or another in the Bullion Canyon Volcanics by Callaghan (1938, 1939), Callaghan and Parker (1961a, 1961b, 1962a, 1962b), and Willard and Callaghan (1962); but in other places the succession was broken up into several units of which the Bullion Canyon was only one. Most rocks on the southern flank of the volcanic field belong to the Mount Dutton Formation of Anderson and Rowley (1975). Presently available data are insufficient to make meaningful lateral correlations between units within these two broadly equivalent assemblages of rocks.

Marginally to the south and southwest, the locally derived intermediate-composition rocks of the Marysvale volcanic field intertongue with regional ash-flow tuffs in the southeastern Great Basin (Mackin 1960; Williams 1960, 1967; Anderson and Rowley 1975). The densely welded and fluidal-textured silicic ash-flow tuff and lava flows of the Isom Formation (26–25 m.y.) underlie alluvial facies of the Mount Dutton Formation, but the position of the Isom relative to older intermediate-composition rocks in the northern part of the field is not known. Younger ash-flow tuff formations of the Quichapa Group (24–20 m.y.) are interlayered marginally at higher levels and also are not present in the northern part of the field. Interestingly, none of these welded tuff sheets of Great Basin provenance extends significantly east of the line of the present-day Hurricane Cliffs, which now mark the boundary between the Great Basin and the High Plateaus. The ash-flow tuffs may have been excluded in part by the contemporaneous volcanic rocks in the Marysvale field or by structural disturbances along this line which may have marked the beginning of differentiation between what are now distinctly different geologic provinces.

MOUNT BELKNAP VOLCANICS

About 21 m.y. ago the compositions of volcanic rocks erupted in the Marysvale volcanic field changed drastically and abruptly from predominantly intermediate compositions to silicic alkalic rhyolite. This change broadly coincided with the beginning of extensional basin-range tectonics in adjacent parts of the Great Basin, and the rocks are interpreted to belong to the bimodal basalt-rhyolite assemblage that was erupted widely throughout the Basin-Range province of western U.S. in later Cenozoic time (Christiansen and Lipman 1972).

The most voluminous rhyolites in the Marysvale field were erupted shortly after the compositional changeover, during the period 21–17 m.y. ago, and they constitute a composite unit that has been redefined (Steven et al. 1977) as the Mount Belknap Volcanics. The Mount Belknap Volcanics were erupted from two contemporaneously active source areas, and the products from the two sources intermix complexly (Cunningham and Steven 1977). The eastern source area is largely in the southern part of the Antelope Range, but it extends into the lower foothills of the Tushar Mountains to the west. Eruptions began 21–20 m.y. ago in the eastern part of the source area, where a series of volcanic domes was erupted in an area about 5 km across. Volcanic activity progressed west-southwestward with the emplacement of a stock of fine-grained granite on the western flank of the Antelope Range about 19 m.y. ago, the nearby eruption of ash-flow tuffs of the Red Hills Member of the Mount Belknap Volcanics, and related subsidence of the small Red Hills caldera (1 km diameter) about 18 m.y. ago. Final eruptions took place 18–17 m.y. ago in the Gray Hills (name of Kerr et al. 1957, pl. 12) in the southwestern part of the eastern source area, where many viscous rhyolite lava flows and volcanic domes accumulated above their source vents.

The western source area is marked by the major Mount Belknap caldera, 11 km across, which was the source of voluminous rhyolite ash flows and local lava flows 19–18 m.y. ago. Outflow ash-flow tuffs formed the Joe Lott Tuff Member of the Mount Belknap Volcanics; eruption of this member resulted in subsidence of the Mount Belknap caldera, which in turn was filled with an alternating sequence of ash-flow tuffs similar to those in the Joe Lott and by rhyolite lava flows of identical chemistry. The outflow Joe Lott tuffs intertongue with varied products from the eastern source area along the lower slopes of the Tushar Mountains between the two source areas.

The source areas of the Mount Belknap Volcanics were in the eroded near-source lavas and breccia of earlier intermediate-composition stratovolcanoes. The outflow rocks accumulated in valleys extending radially out from the elevated cores of these older volcanoes and in low areas on the marginal volcaniclastic aprons and volcanic plateaus. To the south, the Joe Lott Tuff Member filled the older caldera source of the Delano Peak Tuff Member of the Bullion Canyon Volcanics.

The evolution of the Red Hills and Mount Belknap calderas has been interpreted in relation to the eruptive history of the Mount Belknap Volcanics by Cunningham and Steven (1977). They believed that the source areas developed above cupolas extending upward from a common magma chamber, and that the differences in eruptive behavior at the two sources reflected differences in size, shape, and depth of the two cupolas.

SEVIER RIVER FORMATION AND BIMODAL BASALT RHYOLITE VOLCANISM

Basin-range faulting became active in the High Plateaus area in middle Miocene time and was particularly intense during later Miocene and Pliocene time. Recent low scarps cutting Quaternary alluvial deposits have been recognized widely, particularly in the Cove Fort, Beaver, and Marysvale areas, and attest to continued activity, but possibly at a reduced rate, to the present.

Fluviatile and lacustrine sediments of the Sevier River Formation were deposited in the developing structural basins during Miocene through early Pleistocene time (Callaghan 1938). The character of the sediment ranges widely from basin to basin, depending on local source rocks, configuration of the basin, and many other factors. Exposures range from loose deposits of sand and gravel to well-bedded, tan-to-salmon-colored, compacted, ashy siltstones and sandstones. White ash beds are common, particularly in more evenly bedded local sequences. An ash bed near the base of the Sevier River Formation on the north side of the Tushar Mountains yielded a zircon fission-track age of about 14 m.y., whereas another ash bed near the top of the succession at Sevier yielded a zircon fission track age of about 7 m.y. (Steven et al. 1977). The ages are not of the oldest or the youngest strata in the Sevier River Formation, but they do give some idea of the general span of sedimentation. Modern alluvial valley fills locally lie unconformably on deformed Sevier River Formation strata.

Mafic volcanic eruptions took place widely during Sevier River sedimentation, and basalt flows are interlayered with the fluviatile sedimentary rocks of the formation at many places. These flows range in age from middle Miocene to Pleistocene or even Holocene, and near Cove Fort and the southern Markagunt Plateau some basalt shields and cinder cones are virtually unmodified by erosion.

Alkalic rhyolite was erupted from scattered centers during the same late Cenozoic interval (Mehnert et al. 1978), but generally in quite small volume. Rhyolite centers erupted 20–7 m.y. ago are sparsely distributed along an east-west zone of igneous centers and structural disturbances that Rowley, Lipman et al. (1978) have called the Blue Ribbon lineament. Several small rhyolite flows and plugs at and near Phonolite Mountain in Kingston Canyon are examples. Small rhyolite domes, flows, and ash-flow tuffs were erupted in the Mineral Range as recently as 0.8–0.5 m.y. (Lipman et al. 1975); they are in close proximity to potential geothermal steam fields.

MINERALIZATION

Mineralization took place at many times in the Marysvale volcanic field, beginning about 22 m.y. ago and extending into the Pleistocene(?) or Holocene (Steven et al. 1977). The oldest mineralization was associated with emplacement of 23-m.y.-old quartz monzonitic intrusions into the cores of older intermediate composition volcanoes. The gold-silver deposits in the Kimberly area and the alunite-kaolinite deposits in the southern Antelope Range are examples. Uranium was deposited widely in the core of the Mount Belknap caldera some time after it was filled by ash-flow tuffs and lava flows about 18 m.y. ago. A mineralized area in the eastern Tushar Mountains is zoned around an intensely altered core on Alunite Ridge. It has base- and precious-metal deposits in veins and mantos on its northern and eastern periphery. K/Ar ages in sericite and alunite from this mineralized area indicate that mineralization took place 14–13 m.y. ago. The productive uranium deposits in the Central Mining district in the southern Antelope Range perhaps formed between 13 and 9 m.y. ago. Alunite deposits on the west side of the Tushar Mountains 13 km north of Beaver have been dated (K/Ar on alunite) as 9 m.y. old. Native sulfur deposits at Sulphurdale and Sulphur Peak near Cove Fort are in alluvial fan deposits near Holocene fault scarps. Mineralization seems to have been related to nearby basaltic volcanoes of Pleistocene or Holocene age.

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