Geology and Structural Control of Ore Deposition in the Creede District San Juan Mountains Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 487

Prepared in cooperation with the Colorado State Metal Mining Fund Board

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By THOMAS A. STEVEN *and* JAMES C. RATTÉ

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GEOLOGY AND STRUCTURAL CONTROL OF ORE DEPOSITION IN THE CREEDE DISTRICT, SAN JUAN MOUNTAINS, COLORADO

By Thomas A. Steven and James C. Ratté

ABSTRACT

Sixty million dollars worth of silver, lead, zinc, and gold has been extracted from mines in the Creede district of Colorado. The principal source of this production has been from veins along faults that formed during long-continued subsidence concurrent with late Tertiary volcanic activity in the central San Juan Mountains. Most subsidence was in a large volcanic caldera, 10–12 miles in diameter, which we have called the Creede caldera. The known mineralization was confined largely to a complex graben that extends north-northwest from the caldera.

The rock units in the Creede area record a complex sequence of volcanic events, which can be divided with respect to recurrent subsidence. The oldest unit is the Outlet Tunnel Member of the La Garita Quartz Latite; the ash-flow eruptions responsible for this unit culminated in collapse along a series of faults roughly parallel to upper East Willow Creek, and along several northwest-trending normal faults.

The rhyolite of Miners Creek, the Bachelor Mountain Rhyolite, the Shallow Creek Quartz Latite, and the Phoenix Park Member of the La Garita Quartz Latite were erupted, at least in part, onto the irregular surface formed by the earlier collapse. The rhyolite of Miners Creek is a local steep-sided accumulation of rhyolite flow and pyroclastic rocks. This is overlapped by the Bachelor Mountain Rhyolite—a thick mass of pumiceous pyroclastic material that grades from a densely welded rock having a fluidal texture in the lower part (Willow Creek Member), through a compact rock that is obviously a welded tuff (Campbell Mountain Member), to a nonwelded to slightly welded tuff at the top (Windy Gulch Member). The upper two members intertongue to the west with quartz latitic lava flows and breccias of Shallow Creek Quartz Latite. To the east, the Bachelor Mountain rocks intertongue with and are overlain by crystal-rich welded tuffs of the Phoenix Park Member of the La Garita Quartz Latite.

Eruptions of the Bachelor Mountain Rhyolite culminated in collapse of the probable vent area and in displacement along a series of northwest-trending step faults. These step faults were the first to be active in the area of the present Creede graben.

Succeeding eruptions deposited first a local accumulation of pumiceous tuffs and welded tuffs that constitutes the Farmers Creek Rhyolite. This activity was followed in turn by deposition of thick units of welded tuff comprising the Mammoth Mountain Rhyolite and Wason Park Rhyolite. Concurrent eruptions of dacitic lava and pyroclastic rocks to the southwest deposited the Huerto Formation; tongues of these rocks extend into the Creede district where they underlie, are intertongued with, and overlie the Mammoth Mountain and Wason Park Rhyolites. Indirect evidence suggests that the Creede caldera may have subsided concurrently with at least some of these volcanic eruptions.

Crystal-rich quartz latitic ash was erupted later, during the time of caldera subsidence, to form the tuffs and welded tuffs of the Rat Creek Quartz Latite and the densely welded tuffs of the Nelson Mountain Quartz Latite. The last major eruptions during that time resulted in the accumulation of more than 6,000 feet of crystal-rich welded tuff in the core of the Creede caldera to form the Snowshoe Mountain Quartz Latite. The caldera sank concurrently with accumulation of the Snowshoe Mountain Quartz Latite, and talus and landslide debris from the exposed walls intertongue with and overlie the pyroclastic caldera fill.

Minor eruptions during caldera subsidence resulted in local volcanic necks and flows that cut and are intertongued with the more widespread units deposited then.

Caldera subsidence was followed by pronounced doming of the caldera core due, presumably, to magmatic pressure. Local flows, domes, and pyroclastic breccias of Fisher Quartz Latite were then erupted along the margin of the caldera or along fissure zones extending outward from the caldera. Concurrently, lake and stream deposits, volcanic ash, and travertine from many mineral springs were deposited in the structural moat around the margin of the caldera to form the Creede Formation.

The last major period of faulting followed deposition of the Creede Formation. Several of the faults in the Creede graben that formed during earlier periods of subsidence were active again at this time.

The known veins in the Creede district are localized along faults that were active during the last major period of movement. The Alpha-Corsair fault, the Amethyst fault and related hanging-wall fractures, and the Solomon–Holy Moses fault were widely mineralized and have provided most of the ore mined in the Creede district. Some disseminated ore in the Creede Formation has been mined in the Monon Hill area.

INTRODUCTION

Geologic studies in the Creede district and adjacent areas of Colorado have shown that the ore deposits there are largely localized along faults that formed during long-continued subsidence concurrent with Tertiary volcanic activity in the central San Juan Mountains. Currently known subsidence structures extend for more than 10 miles north of Creede and for at least 15 miles south of Creede, and the full extent in either direction has not been established. Major subsidence structures identified so far in this area include the La Garita, Bachelor Mountain, and San Luis Peak cauldrons and the Creede caldera.

In this report, the term "cauldron" will be used in the general sense suggested by Smith and Bailey (1962) for a structure formed by block subsidence as a consequence of volcanic eruption, without regard for the size or shape of the subsided block or resultant structure. The more specific term "caldera" will be used according to the restricted definition of Williams (1941, p. 246) for a roughly circular volcanic depression whose diameter is significantly greater than that of the related vent or vents.

The ore deposits in the Creede mining district are associated principally with faults of a complex graben that extends radially north-northwest from the Creede caldera. The main period of mineralization followed or was in part concurrent with the most recent period of faulting, but many of the mineralized faults formed much earlier and were reactivated one or more times during the succeeding subsidence.

The relations between volcanism and subsidence and between the rocks derived from different centers of eruption are complex, and at the time of writing (1958), all problems of the volcanic succession had not been solved. The main events in the structural evolution of the area could be distinguished, however, and the time and place of mineralization were determined. This information should help in the discovery and development of additional ore deposits in the Creede district, and it is the main subject of this report. Petrographic data are limited to those necessary to define and describe the different rock units, and the discussion of ore deposits focuses primarily on structural control. Geologic studies in the Creede area are continuing, and they will lead to further reports that will review other aspects of the geology more completely.

PREVIOUS INVESTIGATIONS

The Creede mining district is in Mineral County, southwestern Colorado, near the center of the great pile of volcanic rocks that constitutes most of the San Juan Mountains (fig. 1). Creede, the only incorporated town in the area (population 350, according to 1960 census), is on Willow Creek about 2 miles north of the confluence of the creek with the Rio Grande. Colorado Highway 149 connects Creede with U.S. Highway 160 to the southeast at South Fork, 21 miles distant, and in turn with Del Norte and Monte Vista in the San Luis Valley, 37 and 51 miles distant, respectively. Colorado Highway 149 extends generally northwest and north from the Creede area, connecting with Lake City, 52 miles distant, and U.S. Highway 50 along the Gunnison River, 98 miles distant. A branch line of the Denver and Rio Grande Western Railroad extends from Alamosa, in the San Luis Valley, along the Rio Grande to Creede.

Most of the mining and prospecting activity in the Creede district has been in the drainage basins of East and West Willow Creeks, Windy Gulch, and Rat and Miners Creeks, all tributaries to the Rio Grande. The main producing mines have been between 1½ and 3½ miles north and west of Creede (fig. 2).

Altitudes in the Creede district (pl. 1) range from about 8,500 feet along the Rio Grande east of Wason Ranch to 13,895 feet on La Garita Mountain. The terrain, although generally mountainous, has a distinct three-level aspect. Broad stream terraces and rolling hills flank the Rio Grande and lower courses of its main tributaries; steep slopes and precipitous cliffs characterize intermediate altitudes and flank the upper courses of all main tributaries; and many extensive high-level benches and summit areas are relatively flat or smoothly rounded. The upper courses of all main tributaries were intensely glaciated, and steep-walled, flat-bottomed valleys are characteristic.

The valleys along the Rio Grande and along lower courses of some of the main tributaries are easily accessible from Colorado Highway 149 and many local roads. The steep intermediate slopes, however, present a barrier that is traversed only by a few poor roads. The gorge of Willow and East Willow Creeks is followed by a good dirt road for about 5 miles from Creede to Phoenix Park; from here a narrow mine road winds over Campbell Mountain to West Willow Creek. The longest road providing access to the higher areas follows West Willow Creek past the main mining area in the district to the vicinity of the Equity mine, about 7 miles from Creede. Another dirt road extends west and then north from Creede through the old townsite of Bachelor, to join the road along West Willow Creek about 2½ miles south of the Equity mine. Elsewhere the intermediate slopes and higher mountains are accessible only on foot or by horse.

Except for fringes of alder and willow along stream margins and local patches of fir, pine, and spruce in a few protected gullies and on north-facing slopes, the stream terraces and lower slopes are generally open and grass covered. The intermediate slopes, where not too steep or rocky, generally are covered with timber. The lower parts of the timbered slopes and some of the higher, south-facing slopes support mixed fir, pine, and patchy spruce. Spruce predominates higher along the slopes and in local

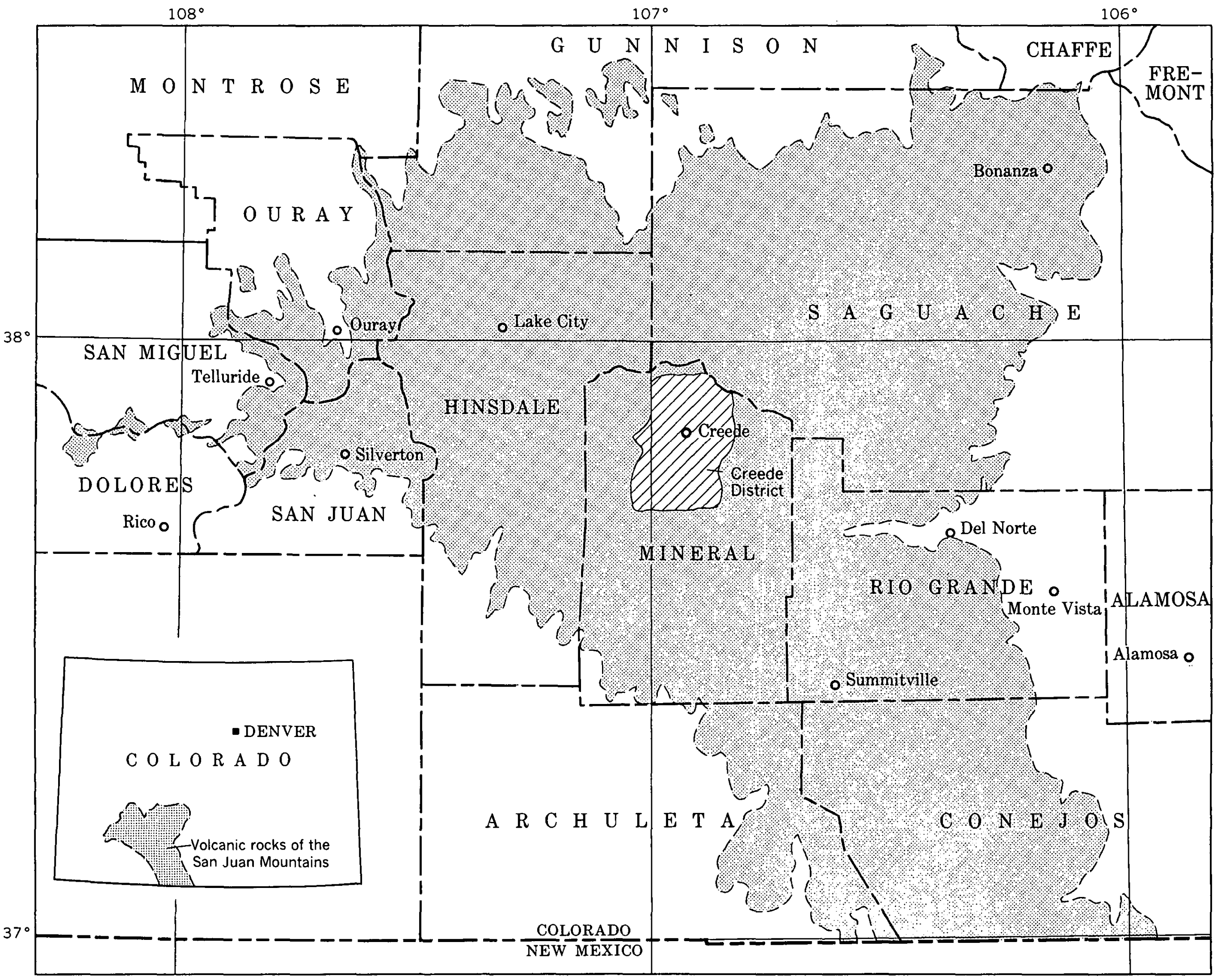

FIGURE 1.—Location of the Creede district with reference to the area of volcanic rocks of the San Juan Mountains, Colo.

tongues extending down north-facing slopes to lower altitudes. Aspen grows throughout the belt of timber but is more common at the intermediate or higher levels, particularly in areas that have been burned or logged off. Local open areas are present on south-facing slopes and in small valley bottoms throughout the timbered belt. Most trees are somewhat stunted above altitudes of 11,500 feet, and the upper timberline is generally between 11,700 and 12,000 feet. Grass, flowers, and low willow brush predominate above timberline.

Mining, tourism, ranching, and lumbering are the main industries and occupations in the Creede area. Of these, only mining and ranching are carried on all year, and mining provides the chief sustaining industry for the town of Creede. Most of the ranches scattered along the Rio Grande and its main tributaries rent cabins in the summer, and some are resorts that cater mainly to tourists and fishermen. Lumbering is strictly seasonal and is largely on National Forest land. Timber was not being harvested in the Creede district at the time of this investigation. Most of the better stands of timber here were cut during the early days of mining.

PREVIOUS INVESTIGATIONS

The valley of the Rio Grande provides the easiest natural ingress to the heart of the San Juan Mountains and was followed by most of the early explorers of this area. Although some brief early geographic descriptions were made of the general area, particularly of the hot springs near Wagon Wheel Gap 9

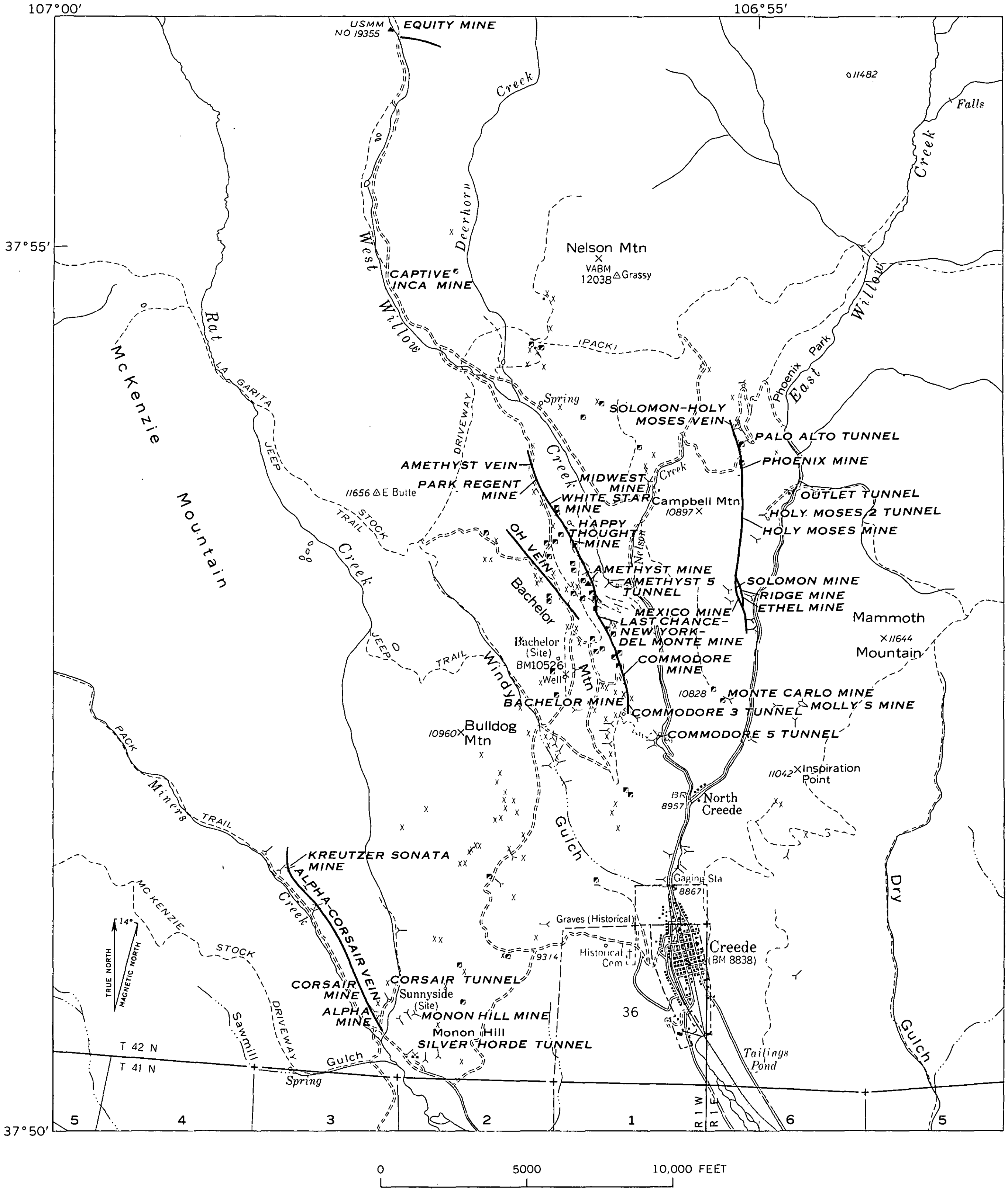

FIGURE 2.—Productive veins and principal mines in the Creede district, Colorado.

miles southeast of Creede, the first recorded geologic observations in the central San Juan Mountains were made in connection with the Hayden Survey (U.S. Geological and Geographic Surveys of the Territories) in the 1870's. Endlich's report (1877, p. 153–160) described the geography and incidental geologic features along the Rio Grande and particularly emphasized the area around Wagon Wheel Gap southeast of Creede, and Antelope Park southwest of Creede. On the geologic map of south-central Colorado compiled by the Hayden Survey (Hayden, 1877, pl. 16), the mountains around Creede are shown as "trachorheite eruptive rocks," and the Creede Formation along the Rio Grande is shown as Green River sediments filling a valley cut in Lower Carboniferous rocks.

Many brief articles and notes concerning the great mining boom at Creede, which began in 1891, were published in the different mining and scientific journals. Most of these are now of more historic than geologic interest, but they do give valuable and colorful accounts of the discovery and early history of the camp. Most significant of these early descriptions are those by MacMechen (1892), Kirby (1892), Rickard (1897, p. 845–846), and Lee (1903).

Production data for many of the early years of mining in the Creede district were recorded in successive volumes of the Mineral Resources of the United States by the U.S. Geological Survey. These and incidental notations concerning the active properties and the character of the ore mined help in reconstructing the progressive development of mining in the district.

Several articles describing the nearby Wagon Wheel Gap area, 8–10 miles southeast of Creede, were published during this same period; this area, however, is outside the scope of the present report, and references to these articles are omitted here.

The only comprehensive geologic study of the Creede district prior to the present investigation was made in 1911 and 1912 by Emmons and Larsen (1913; 1923). The areal geology of the district was mapped and described by Larsen, who had been working in the San Cristobal quadrangle to the west as part of a general study of the geology of the San Juan Mountains by Whitman Cross, E. S. Larsen, and associates. The units differentiated in the Creede district, therefore, were fitted into the general volcanic succession used in subsequent reports by these men on the geology, mineralogy, and petrology of the San Juan Mountains (Cross and Larsen, 1935; Larsen and others, 1936, 1937, and 1938a and b; Larsen and Cross, 1956). The ore deposits at Creede were studied by Emmons, and all the mines he could visit or obtain information about were described.

Silver ore in local beds in the Creede Formation, discovered on Bachelor Mountain in 1919, was described briefly by Lunt (1921, 1924) and by Hills (1924).

New mining developments in the Creede district made between 1913 and 1927 were reviewed by Larsen (1930), but, except for private reports by consulting geologists and a few theses by students, no further detailed geologic work was done in the district before the present investigation was begun in 1953.

PRESENT INVESTIGATION

The present report is based on a total of about 15 months' fieldwork by each of us during the summers of 1953 to 1957, inclusive. The investigations leading to the report were carried on as part of a cooperative program of the U.S. Geological Survey and the Colorado Metal Mining Fund Board.

In preliminary reports we discussed the development of the Creede caldera (Steven and Ratté, 1959) and the relations of ash flows associated with the caldera (Ratté and Steven, 1959). In another brief note (Steven and Ratté, 1960b) we considered the relation of mineralization to caldera subsidence. The Tertiary volcanic sequence in the central San Juan Mountains, including the Creede district, was revised in the light of new concepts that resulted from our work (Steven and Ratté, 1964). Changes in composition and mode of eruption of ash-flow sheets and lava flows related in origin to the Creede caldera were interpreted to indicate the course of magmatic differentiation in the source magma (Ratté and Steven, 1964).

ACKNOWLEDGMENTS

Our investigations of the geology and mineral deposits in the Creede district have been aided greatly by the wholehearted cooperation of many people engaged in mining at Creede. We are indebted to so many that only a partial list is practical.

Messrs. B. T. Poxson and T. B. Poxson of Emperius Mining Co. provided valuable information concerning their mining of the Amethyst and related veins, and they or members of their staff, particularly Messrs. Richard Lehman and Arthur Davis, assisted us in every way possible during our study of that vein zone.

Mr. W. I. Leary was an invaluable source of information on the history of mining in the Creede district and adjacent areas.

Our studies of the Solomon–Holy Moses vein zone benefited greatly from the cooperation of Messrs. Gavin Skinner, I. D. Crawford, Paul Schneider, and James Muir of the Outlet Mining Co. and Messrs. William Jackson, Jr., and John Jackson of the Jackson Mining Co.

Mr. Ivan Weaver of the Monon Leasing Co. provided much information on the history of mining in the Monon Hill area and on the Alpha-Corsair vein zone, and he and his associates assisted in many ways during our study of the Monon Hill mine.

HISTORY AND PRODUCTION

Creede is one of the younger of the major mining camps in Colorado, and its story of spectacular growth in the early 1890's was well chronicled in the newspapers and mining journals of the time. Discovery of rich ore in the Amethyst and Last Chance mines (fig. 2) in 1891 resulted in the rapid growth of the town to an estimated 8,000–10,000 people. In addition to the large numbers of legitimate mining men, numerous speculators, gamblers, and "floaters" from established mining camps were attracted by the prospect of easy money, and in its heyday Creede was as rough and rowdy as any other boomtown in the West.

Excellent summaries of the discovery and early development of ore at Creede were given by Rickard (1897, p. 845–846), Emmons and Larsen (1923, p. 3–5), and Henderson (1926, p. 55–56); and the subsequent development through 1928 was summarized by Larsen (1930). Only bare historical outlines for these periods will be presented in this report. The history of the district following reopening of the mines in 1934 has not been reported elsewhere and will be discussed in more detail than will be the earlier history. Throughout the discussion, emphasis will be given to the changes experienced by the local mining industry as the different ore bodies were progressively discovered, developed, and extracted. These changes are reflected by shifts in the quantity and value of the different metals produced (fig. 3), and the total value of all metals produced (table 1).

Although some mining claims had been filed on the later-named Alpha-Corsair vein (fig. 2) near Sunnyside and on the Amethyst vein on Bachelor Mountain in 1883 and 1884 (Emmons and Larsen, 1923, p. 3), mining development in the area really began with the discovery of the Solomon–Holy Moses vein in 1889 and received its greatest impetus in the fall of 1891 when high-grade ore was developed by workings of the Amethyst, Last Chance, and New York claims on the Amethyst vein (Emmons and Larsen, 1923, p. 3, 4). The first full year of production, 1892, ranks fifth in total value of minerals produced of all the years the district has been active; and the following year, 1893, was, by a margin of nearly $1.5 million, the most productive in the history of the camp (fig. 3). This spectacular beginning was followed by a long period of irregular but generally declining activity until 1930, when all the mines in the district were closed. From the reopening of the mines in 1934 until the end of 1956, annual production ranged from slightly more than a quarter of a million dollars to a little more than a million dollars (fig. 3).

In all this time, production from the Amethyst vein and related hanging-wall veins greatly exceeded the combined production from all other veins. The approximate total production, by vein or area, to the end of 1956 was:

Amethyst and related veins	$53,200,000
Solomon–Holy Moses vein	2,190,000
Monon Hill area	800,000
Alpha-Corsair vein	600,000
Equity vein	88,000
Mollie S vein	50,000

These estimates are adjusted figures from all sources available and, in total, exceed published production figures (table 1) by more than $200,000. Neither total is accurate within this limit, however, and the proportional production shown here is representative. Thus the main trends of production in the Creede district shown in figure 3 reflect largely the mining activity on the Amethyst and related veins; local peaks resulted from periodic activity in one or another of the other veins.

The bulk of production at the height of activity at Creede, from 1891 through 1899, came from the near-surface oxidized ores in the southern part of the Amethyst vein (fig. 2), largely from the Amethyst, Last Chance–New York–Del Monte, and Commodore mines. Silver accounted for 70–94 percent of the value of the ore produced (fig. 3). The low relative values of lead and gold that constitute the remainder reflect the dwarfing effect of the high silver content in the ores; to the extent we can determine, the grade of the lead in these early-mined ores did not differ greatly from that in ores produced subsequent to the boom period. The lower productivity during the period 1894–96 and the lower relative value of the silver produced (fig. 3) reflect the low price of silver during the so-called silver panic of the middle 1890's.

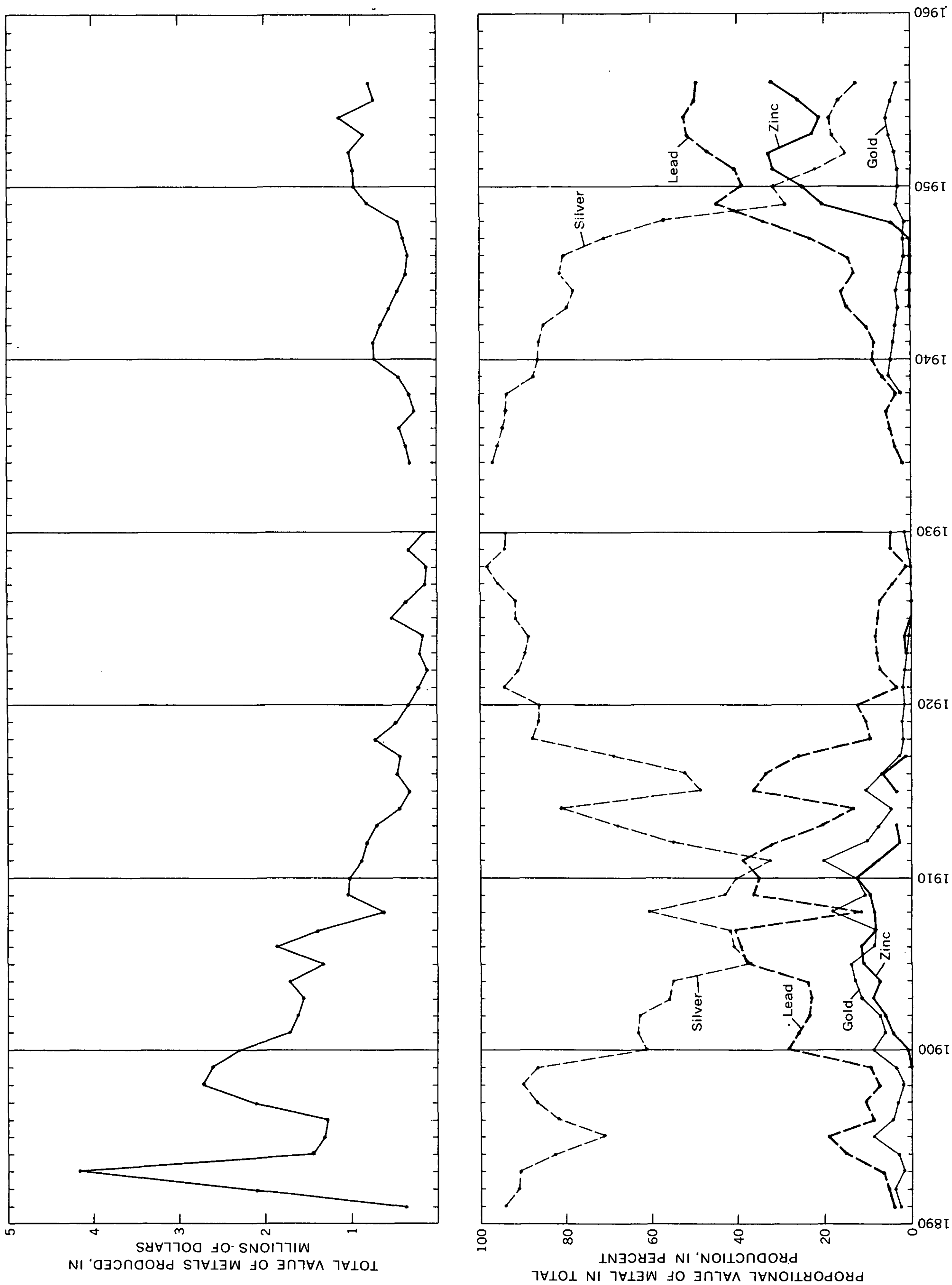

FIGURE 3.—Proportional value of metals produced in the Creede district, Colorado.

TABLE 1.—*Metal production from the Creede district (Sunnyside–King Solomon districts), Mineral County, Colo.*

Year	Ore sold or treated (short tons)	Gold		Silver		Lead		Copper		Zinc		Total value
		Fine ounces	Value	Fine ounces	Value	Pounds	Value	Pounds	Value	Pounds	Value	
1891 [1]		[2] 486	$10,055	378,899	$374,382	354,854	$15,259					$399,696
1892		[2] 4,219	87,219	2,391,514	2,080,617	3,000,000	120,000					2,287,836
1893		[2] 2,576	53,252	4,897,684	3,820,194	7,500,000	277,500					4,150,946
1894		[2] 1,950	40,336	1,866,927	1,176,164	6,500,000	214,500					1,431,000
1895		[2] 5,538	114,482	1,423,038	924,975	8,220,870	263,068					1,302,525
1896		[2] 2,527	52,238	1,560,865	1,061,388	6,021,109	180,633					1,294,259
1897		[2] 2,967	61,328	3,070,576	1,842,346	6,080,673	218,904	1,500	$180			2,122,758
1898		2,244	46,383	4,177,184	2,464,539	5,453,104	207,218	14,729	1,826	200,000	9,200	2,729,166
1899		4,435	91,671	3,796,899	2,278,139	5,677,162	255,472	20,223	3,458	100,000	5,800	2,634,540
1900		10,130	209,387	2,280,038	1,413,623	14,951,956	657,886	2,614	434	450,000	19,800	2,301,130
1901		4,974	102,813	1,816,023	1,089,614	10,519,895	452,355	1,007	168	1,800,000	73,800	1,718,750
1902		5,459	112,838	1,923,973	1,019,706	9,291,358	380,946			2,047,555	98,283	1,611,773
1903		8,568	178,961	1,608,788	868,746	8,600,646	361,227	133	18	2,634,000	142,236	1,551,188
1904 [3]	124,278	10,908	225,487	1,666,309	953,961	9,304,854	407,088			2,480,178	124,009	1,710,545
1905	91,338	8,813	182,162	814,189	491,770	10,526,146	497,079			2,513,457	148,294	1,319,305
1906	126,164	7,713	159,445	1,150,318	770,713	13,038,333	743,185			3,562,737	217,327	1,890,670
1907	104,977	5,706	117,946	870,456	574,501	10,656,962	564,819			1,838,136	108,450	1,365,716
1908	61,131	5,760	119,063	725,602	384,569	1,731,987	72,743			1,100,107	51,705	628,080
1909 [4]	64,941	5,264	108,825	891,185	463,416	9,036,816	388,583	17,401	2,262	1,817,296	98,134	1,061,220
1910	62,956	5,862	121,181	773,722	417,810	8,246,000	362,824	29,031	3,687	2,421,926	130,784	1,036,286
1911	65,932	8,669	179,196	545,319	289,019	7,674,556	345,355	33,384	4,173	1,258,561	71,738	889,481
1912	66,488	4,160	86,002	714,909	439,669	5,730,222	257,860	23,885	3,941	308,681	21,299	808,771
1913	56,763	2,432	50,282	805,343	486,427	3,398,364	149,528	31,647	4,905	454,875	25,473	716,615
1914	27,952	934	19,304	615,734	340,501	1,401,795	54,670	32,586	4,334			418,809
1915	28,071	1,598	33,039	291,807	147,946	2,382,128	111,960	8,943	1,565	85,984	10,662	305,172
1916	38,103	1,506	31,124	373,956	246,063	2,295,087	158,361	13,138	3,232	240,575	32,237	471,017
1917	32,755	489	10,101	361,517	297,890	1,305,744	112,294	19,297	5,268	54,971	5,607	431,160
1918	28,372	674	13,943	640,959	640,959	989,620	70,263	3,490	862			726,027
1919	16,718	439	9,083	369,575	413,924	934,113	49,508	355	66	96,274	7,028	479,609
1920	12,597	276	5,710	272,322	296,831	531,537	42,523	1,120	206			345,270
1921	7,076	185	3,816	192,468	192,468	156,778	7,055	1,899	245			203,584
1922	3,978	80	1,654	106,903	106,903	153,455	8,440	3,422	462			117,459
1923	6,462	116	2,394	228,867	187,671	237,557	16,629	1,088	160	41,000	2,788	209,642
1924	4,647	72	1,494	239,149	160,230	191,562	15,325			41,000	2,665	179,714
1925	8,047	43	885	738,735	512,682	501,000	43,587			8,000	608	557,762
1926	8,855	33	672	551,468	344,116	354,700	28,376					373,164
1927	3,592	12	246	214,850	121,820	75,286	4,743					126,809
1928	4,021	24	490	210,159	122,943	23,000	1,334					124,767
1929	5,436	122	2,517	612,497	326,461	271,000	17,073					346,051
1930	4,576	114	2,364	396,044	152,477	148,600	7,430					162,271
1931												
1932												
1933												
1934	5,907	55	1,922	479,890	310,232	176,900	6,545					318,699
1935	9,312	22	753	499,680	359,145	351,800	14,072					373,970
1936	10,738			422,071	326,894	370,800	17,057					343,951
1937	12,734	4	154	321,546	248,716	278,000	16,402					265,272
1938	35,656	187	6,552	457,595	295,819	241,006	11,086					313,457
1939	37,083	709	24,815	596,858	405,140	718,000	33,746	1,300	135			463,836
1940	41,113	893	31,255	866,402	616,108	1,299,000	64,950	10,200	1,153			713,466
1941	41,568	904	31,640	906,712	644,773	1,140,000	64,980	32,000	3,776			745,169
1942	39,243	644	22,540	805,202	572,588	1,051,600	70,457	77,600	9,390			674,975
1943	30,290	465	16,275	630,952	448,677	1,155,000	86,625	101,000	13,130	13,000	1,404	566,111
1944	27,883	444	15,540	518,161	368,470	957,000	76,560	75,000	10,125	15,000	1,710	472,405
1945	18,354	238	8,330	433,177	308,037	605,000	52,030	69,400	9,369	9,000	1,035	378,801
1946	16,032	175	6,125	355,110	286,929	492,000	53,628	61,000	9,882	6,000	732	357,296
1947	24,760	245	8,575	317,712	287,529	658,400	94,810	46,600	9,786	14,000	1,694	402,394
1948	28,614	247	8,645	297,926	269,638	902,000	161,458	36,000	7,812	176,000	23,408	470,961
1949	38,262	779	27,265	263,867	238,813	2,324,000	367,192	74,000	14,578	1,342,000	166,408	814,256
1950	47,072	803	28,105	345,247	312,466	2,844,000	383,940	68,000	14,144	1,746,000	247,932	986,587
1951	45,422	804	28,140	236,652	214,182	2,334,000	403,782	50,000	12,100	1,784,000	324,688	982,892
1952	41,685	1,122	39,270	174,219	157,677	3,026,000	487,186	48,000	11,616	2,048,000	339,968	1,035,717
1953	37,372	1,257	43,995	173,966	157,448	3,392,000	444,352	24,000	6,888	1,716,000	197,340	850,023
1954	45,399	1,964	68,740	238,685	216,022	4,356,000	596,772	50,000	14,750	2,222,000	239,976	1,136,260
1955	28,596	1,025	35,875	135,640	122,761	2,384,000	355,216	36,000	13,428	1,490,000	183,270	710,550
1956	29,432	802	28,070	111,731	101,122	2,531,100	397,383	47,200	20,060	1,853,400	253,916	800,551
Totals	1,758,753	141,865	3,131,969	56,155,771	37,567,359	217,056,435	12,403,832	1,168,192	223,574	39,989,713	3,391,408	56,718,142

[1] Production figures, 1891–1903, from Henderson (1926, p. 181). The same figures are given in Emmons and Larsen (1923, p. 9). These figures are based largely on smelter and mint receipts but are in part estimated.

[2] Calculated from value of production, with gold priced at $20.67 per ounce.

[3] Production figures, 1904–8, from U.S. Geol. Survey (1905–9). These figures differ from those given by Henderson (1926, p. 181) and Emmons and Larsen (1923, p. 9), who recorded an additional $1,559,054 total production during this period. The reason for this discrepancy is not known.

[4] Production figures, 1909–23, from U.S. Geol. Survey (1911–27); 1924–31, from U.S. Bur. Mines (1927–34); 1932–56, from U.S. Bur. Mines (1934–58).

The main mining activity during the 1890's, exclusive of that on the Amethyst vein zone, was on the Solomon–Holy Moses vein and the Alpha–Corsair vein (fig. 2). Early mining on the Solomon–Holy Moses vein exploited high-grade oxidized ore from near the surface on the southern part of the vein zone (Emmons and Larsen, 1923, p. 175), but by the late 1890's, lower grade sulfide ore below the strongly oxidized zone was being developed in both the Solomon and the Ridge mines. We estimate that approximately $800,000 worth of ore was produced from the Solomon–Holy Moses vein prior to 1904, the earliest date for which we have found individual records for the different operating mines. Some of the high-level oxidized ores are reported to have contained as much as 80 ounces or more of silver per ton, but the primary sulfide ores generally contained only a few ounces of silver per ton.

Approximately one-half million dollars worth of metal, predominantly silver, was produced from the

Alpha-Corsair vein zone prior to 1904. Most of this came from the Corsair mine, and most probably was produced during the 1890's.

By 1900 the Solomon and Ridge mines on the Solomon–Holy Moses vein zone and the Amethyst mine and the adjoining Happy Thought, White Star, and Park Regent mines to the north on the Amethyst vein (fig. 2) were producing sulfide ores in quantity. The Amethyst, Last Chance–New York–Del Monte, Commodore, and Bachelor mines on the south end of the Amethyst vein and the Alpha and Corsair mines near Sunnyside were still producing oxidized ores that had a high content of silver. The sulfide ores required beneficiation, and the Humphries, Amethyst, Solomon, and Ridge mills were constructed to treat ores from the different mines (Emmons and Larsen, 1923, p. 6–8).

The modifying effect of the lower grade sulfide ores on the relative production of the different metals is well shown in figure 3 for the period 1900–16. Silver provided a much lower percentage of the total value and at times was exceeded in value by the lead produced. Zinc was recorded in significant quantities only during the period when sulfide ores were being mined, and during the period 1905–10 it provided 8–12½ percent of the total value of metals produced. Gold also was produced in greater abundance during this period, but this reflected more the higher grade of gold in the ores from the Happy Thought mine, which was then at the peak of its production.

The erratic paths of the different curves (fig. 3) for the period 1900–16 reflects irregular variations in activity of mines producing predominantly oxidized ores and those producing predominantly sulfide ores. The chief producer of sulfide ores was the Creede United Mines Co., which operated the Happy Thought, White Star, and Park Regent mines on the northern part of the Amethyst vein; the Happy Thought provided most of this ore. All the ore mined by Creede United was beneficiated at the Humphries mill, near the junction of East and West Willow Creeks. The Amethyst mine produced large quantities of both oxidized silver-rich ore and sulfide milling ore; the sulfide ore was treated in the Amethyst mill on West Willow Creek below the mine. The Last Chance–New York–Del Monte mine had the greatest production of oxidized ores, followed in turn by the Commodore and Bachelor mines.

Production from the Amethyst vein from the beginning of detailed records in 1904 through 1910 ranged from about $1 million to $1.6 million per year, except in 1908 when production dropped to nearly $600,000. From 1911 through 1914, production ranged from $400,000 to $87,000 per year, and from 1915 through 1921, production ranged from $70,000 to $440,000 per year. This irregular diminishing of production reflected the progressive exhaustion of the better grade ores in the main Amethyst vein. Since the early 1920's the vein provided only a small percentage of the ore mined in the district.

The Solomon and Ridge mines were the most active mines on the Solomon–Holy Moses vein zone during the early part of the century. Their last big production was in 1907 when more than $150,000 worth of metal was produced; for the remainder of the period until the early 1920's, their annual production ranged from a few thousand to a few tens of thousands of dollars worth of metal, largely lead and zinc. The total value of production from the Solomon–Holy Moses vein zone from 1904 until 1923, when mining activity was halted for more than a decade, is estimated at slightly less than $1 million.

Production from the Alpha-Corsair vein zone from 1904 until 1922, when mining ceased until the middle 1930's, was slightly more than $100,000, most of which was accounted for by silver. The most productive single year was 1904, when about $18,500 worth of silver was produced; in most other years only a few thousands of dollars worth of silver was produced.

In 1917 the Creede Exploration Co., subsidiary of the American Smelting and Refining Co., consolidated several properties along the Amethyst vein, and between 1917 and 1920 this company cut back production and concentrated on deep-level exploration. According to Larsen (1930, p. 93), the results of this program were disappointing.

While production from the Amethyst vein zone generally diminished after 1914, the Monon Hill area temporarily became a major source of production in the district. Replacement ore along the contact between the Creede Formation and the underlying rhyolite was discovered in 1915 (Larsen, 1930, p. 103), and in the following years several good ore bodies were developed. Major mining activity began in 1918 and ended in 1922; Larsen (1930, p. 103) reported that 21 ounces of gold, 756,400 ounces of silver, and 345,000 pounds of lead were produced during that period. Estimates of the gross value of this ore range from $750,000 to more than $1 million. The intensive mining at Monon Hill resulted in a local peak in the curve of total production (fig. 3) in 1918 and resulted in a marked increase in the proportional value of silver relative to the other metals. A concurrent drop in production on the Amethyst vein in the years following 1918 masked the effect of the Monon Hill mine on the total production curve, but the continuing high proportional value of silver reflects the influence of the Monon Hill ores.

The year 1922 marked the beginning of intensive exploration and development of the hanging-wall block of the Amethyst vein, which has continued to the time this report was prepared. The first discoveries in this period were made in the Commodore mine (Larsen, 1930, p. 94–97), where several veins were developed. All the ore was oxidized and rich in silver. Larsen (1930, p. 96) reported that carload lots carried 40 to 200 ounces of silver per ton and 2½–3 percent lead. Production from these veins during the period 1924–30 ranged from $100,000 to $500,000 per year except in 1928, when it dropped to less than $70,000.

Other subsidiary hanging-wall veins were discovered in the late 1920's in the Last Chance and Amethyst mines (Larson, 1930, p. 97). Production from one of these veins in the Amethyst mine (Sloan lease) resulted in a significant peak in the total production for the year 1929 (fig. 3). The year 1929 also marked the discovery of some hanging-wall veins in the Last Chance mine that were to provide the bulk of the production from the Creede district in the middle and late 1930's (the P and E workings). Unfavorable economic conditions delayed development of these veins until 1934.

The character of ore mined in the 1920's from veins in the hanging wall of the Amethyst vein is reflected by the curves shown in figure 3. The high productivity of the Commodore mine in the years 1924–27 is marked by a pronounced local peak on the total production curve, and the development of the subsidiary veins in the Amethyst and Last Chance mines resulted in a smaller peak on the total-production curve for the year 1929. The high silver content of the ores is indicated by the proportional value curves, where the trends set by the silver-rich Monon Hill ores were continued.

The price of silver dropped sharply to 31 cents per ounce in 1930, and all mines in the district were forced to close. The price of silver remained low, generally between 25 and 40 cents per ounce, until December 1933, when it was "pegged" by Presidential proclamation at 65.65 cents per ounce. Mining activity was quickly resumed in the district in 1934 and continued without significant interruption until June 1958, when most mines were again inactive for a few months because of the low price of lead and zinc.

Mining during the middle and late 1930's was chiefly on hanging-wall veins in the Commodore, Last Chance–New York–Del Monte, and Amethyst mines, although some production was recorded from the northern part of the main Amethyst vein (Happy Thought, White Star, and Park Regent mines) and from the Monon Hill and Corsair mines near Sunnyside. The well-developed hanging-wall veins in the Commodore mine provided most of the production in 1934 and continued to supply ore until the early 1940's. In 1935, however, the Emperius Mining Co. (successor to Poxson and Emperius lease) brought the hanging-wall veins in the Last Chance–New York–Del Monte group, discovered in 1929, into large-scale production. Extraction from these veins progressively dominated mining in the Creede district, and by 1942 Emperius had gradually consolidated adjacent mining properties until it controlled most of the mines on the Amethyst and related veins and conducted all mining as an integrated operation.

Initial discovery and development of the hanging-wall veins in the Last Chance–New York–Del Monte group were on the Last Chance 2 level, high on the vein, where a complex of intersecting silver-rich veins was discovered. These veins, which provided most of the production from this group of mines until the early 1940's, were developed as the P and E workings. Mining was conducted through the Last Chance 2 tunnel until 1937, when deeper extraction made advantageous the reopening of the Amethyst 5 level. At greater depth the vein pattern became simpler and the grade of ore became lower as the complexly intersecting veins diminished in number. A major vein, the O H vein (fig. 2), extending northwestward from the complex of intersecting veins, was discovered in 1938 or 1939; most of the production from the Creede district in the 1940's and 1950's came from it.

In 1937, Creede Mills, Inc., built a custom flotation mill to treat the ores from the different mines. Most of the ore was supplied by the Emperius Mining Co. from the Amethyst and related veins and by the Monon Hill and Corsair mines near Sunnyside. As the operations of Emperius expanded, the company became the chief supplier of ore to the mill; Emperius took over operation of the mill on a lease basis in 1940 and completed purchase in 1945.

All the ore extracted from the P and E workings, as well as that from the hanging-wall veins in the Commodore and Amethyst mines, was oxidized and was rich in silver. The highest grade silver ore came from near the top of the P and E workings, where it undoubtedly was enriched by supergene processes; at greater depths the ratio of silver to lead diminished. These changes are shown (fig. 3) by the regular proportional decrease in the value of silver and increase in the value of lead from 1934 to 1938. The sharp break in the proportional-value curves between 1938 and 1939 reflects the shift in major production from the P and E workings to the O H vein.

Emperius Mining Co. began extracting ore from the south end of the O H vein in 1939, and in a few years most of the ore mined by this company was from this vein. Much of the ore was hoisted from the 7 and 9 levels to the Amethyst 5 level, and in 1943, Emperius began reconditioning the Commodore 5 level to provide deep access and haulage. By 1945 an access tunnel more than 2 miles long had been driven or reconditioned, and beginning in 1946 most haulage was through this tunnel. Through 1946, all the ore extracted from the O H vein was oxidized and was relatively high in the proportional value of silver (fig. 3). In 1947, stoping began on primary sulfide ores, and by 1949 most of the ore extracted was either all sulfide or partly oxidized sulfide ore. This major shift in type of ore mined is shown by the abrupt changes in the proportional-value curves (fig. 3) between 1946 and 1949. In this period the value of silver produced plummeted from 80 percent to about 30 percent of the total value of the ore produced, and the value of lead rose from 15 to 40 percent or more; zinc also became a significant mineral product for the first time since the end of major activity in the Happy Thought, White Star, and Park Regent mines in 1917. In the early 1950's the upper levels on the O H vein were driven northwestward into sulfide ore, and little oxidized ore has since been produced by Emperius.

Destruction by fire of the Emperius Mining Co. mill on August 15, 1955, resulted in a sharp cutback in overall production from the district. A new mill was built and in operation by May 1956.

The Ethel mine near the south end of the Solomon–Holy Moses vein was open briefly in 1934 in the general flurry of mining activity that followed "pegging" of the price of silver. No further activity is recorded until 1943 when the Ridge mine was opened; it remained active until 1949 and had an annual production of between $1,000 and $20,000. The Solomon and Ethel mines operated in 1950-52, and their total production was valued at about $20,000.

In 1951 the Outlet Mining Co. began mining an oxidized lead-silver ore body on the Phoenix and adjacent properties near the north end of the Solomon–Holy Moses vein zone (fig. 2). By 1956 an estimated $500,000 worth of metal, mostly lead and silver, had been produced. In contrast with the oxidized ores in the Amethyst and related veins, which were silver rich, the Phoenix ores were lead rich: generally lead in the Phoenix ores was worth three to six times the silver in them. The Outlet Mining Co. curtailed production in 1956 to concentrate on a deep-level exploration program.

The Monon Hill mine was active from 1935 to 1941. Most of the ore mined came from margins or extensions of ore bodies developed and largely extracted during the main period of mining there between 1918 and 1922. Approximately $50,000 worth of ore was mined during this later period, and most of this ore was beneficiated in the Creede Mills, Inc., custom mill. Exploration was in progress at the Monon Hill mine from 1952 through 1958, but no production was reported.

The Corsair mine on the Alpha-Corsair vein was reopened and was active in 1934–39. Value of ore produced ranged from a few thousand dollars to about $12,000 per year, and all but a small percentage of the value was accounted for by silver.

GEOLOGIC FORMATIONS

Nearly all rocks in the vicinity of the Creede district (pl. 1) are volcanic or were derived from reworked volcanic materials. Densely welded ash flows (welded tuff) or rhyolitic and quartz latitic composition predominate in a complex sequence that also includes lava flows, volcanic breccias, and air-fall pyroclastic rocks. One unit, the Creede Formation, consists largely of tuffs, volcanic debris deposited in lakes and streams, and travertine. No evidence was seen that indicated the depth to a prevolcanic basement.

Several centers of eruption generally were active during any given interval, and the type of eruption and composition of product commonly differed from one center to another. The topography on which many of the different units accumulated was rough, either because of irregular deposition of earlier units or recurrent subsidence and faulting or because of local erosion. As a result, the volcanic pile is a complex accumulation of irregularly distributed, locally intertonguing units that are separated here and there by unconformities and cut by faults of several ages (fig. 4).

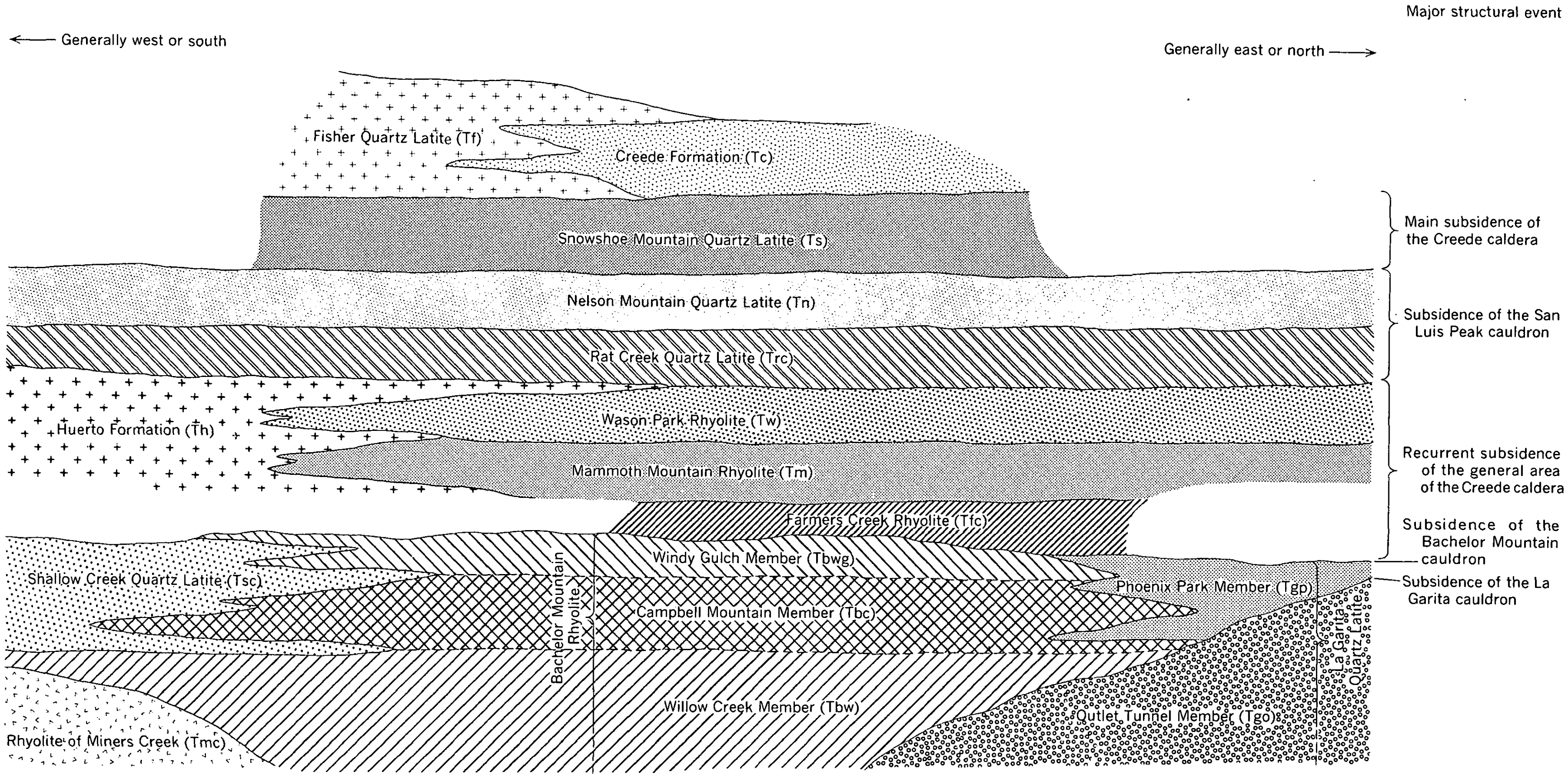

FIGURE 4.—General relations of major rock units in the Creede district, Colorado.

The volcanic sequence previously established in the central San Juan Mountains (Emmons and Larsen, 1923; Cross and Larsen, 1935; Larsen and Cross, 1956) is inadequate to explain the geology of the Creede area. In the works cited, the volcanic rocks were referred largely to the Potosi Volcanic Series, and mappable units were defined generally in sequential order within that series. Our mapping has shown that many of the previous units were miscorrelated, and we have been unable to apply the terminology of the Potosi Series as used by Larsen and Cross (1956) to the revised volcanic sequence that we determined (table 2). Therefore, the Potosi Volcanic Series nomenclature has been abandoned in the Creede area (Steven and Ratté, 1964). Luedke and Burbank (1963) redefined the Potosi at its original type locality to cover a specific assemblage of rocks.

In table 2 the rock units used in earlier reports are compared with those used in this report. Correlation key letters have been assigned to the different units described previously and are shown in parentheses following correlative units that we have determined. Some of the older formations or groups, such as the Alboroto and Piedra, consist of units that are so widely scattered among our different local sequences that they have been abandoned in the Creede area as well (Steven and Ratté, 1964).

Much of the volcanic activity near Creede was accompanied by recurrent subsidence, and the different rock units formed can be assigned relative ages corresponding to different stages of subsidence and accumulation. In a preliminary report (Steven and Ratté, 1960b), we assigned the units to three informal ages: precaldera, intracaldera, and postcaldera. Subsequent work that established earlier ages of subsidence than were known when that report was written has made the first of these age groups a misnomer. In consequence, we are retaining intracaldera as a descriptive term relating to the general period of recurrent volcanic eruptions and related subsidence, and postcaldera as a descriptive term relating to the period following the last major subsidence. This usage is believed sufficiently flexible to accommodate future modifications of the established geologic succession that will inevitably result from continuing work in the area.

The oldest unit exposed in the Creede district is the Outlet Tunnel Member of the La Garita Quartz Latite. Ash-flow eruptions responsible for this unit culminated in complex subsidence of a poorly defined area whose eastern margin generally follows East Willow Creek. The more strongly subsided blocks are bounded on the east by a series of generally north- to northwest-trending faults that are exposed only along upper East Willow Creek. A major southeast-trending normal fault of the same age extends along the south base of La Garita Mountain.

The rhyolite along Miners Creek and the Bachelor Mountain Rhyolite, Shallow Creek Quartz Latite, and Phoenix Park Member of the La Garita Quartz Latite were erupted, at least in part, onto the irregular surface formed by the earlier collapse. The rhyolite of Miners Creek is a local steep-sided accumulation of rhyolite flow and pyroclastic rocks. This unit is overlapped by the Bachelor Mountain Rhyolite, a thick mass of pumiceous pyroclastic material that grades upward from a densely welded rock having fluidal texture (Willow Creek Member) through a compact welded tuff (Campbell Mountain Member) to a nonwelded to slightly welded tuff at the top (Windy Gulch Member). The upper two members intertongue to the west with quartz latitic lava flows and breccias of Shallow Creek Quartz Latite. To the east, the Bachelor Mountain rocks intertongue with and are overlain by crystal-rich welded tuffs of the Phoenix Park Member of the La Garita Quartz Latite.

Eruptions of the Bachelor Mountain Rhyolite were followed by cauldron collapse of the probable vent area and formation of a series of northwestward-trending step faults in the area later to become the Creede graben.

After collapse of the Bachelor Mountain volcano and after a period of erosion, rhyolitic tuffs and welded tuffs were deposited locally east and southeast of Creede to form the Farmers Creek Rhyolite (pl. 1; fig. 4). This unit was succeeded in turn by widespread sheets of welded tuff that constitute the Mammoth Mountain and Wason Park Rhyolites. Dacitic and rhyodacitic lavas and breccias of the Huerto Formation were erupted from centers southwest of the Creede district during the same period, and the contrasting rock types intertongue west and southwest of Creede. One tongue of Huerto rocks overlying the Wason Park Rhyolite extends as far northeast as Bulldog Mountain near the center of the Creede district.

A rhyolite lava flow between Shallow and Miners Creeks in the Creede district and local quartz latitic lava flows in the Wagon Wheel Gap district southeast of Creede are interlayered with the Mammoth Mountain and Wason Park Rhyolites. A volcanic neck and related flows and breccias of quartz latite are exposed north of Nelson Mountain, but the age relations of these are not well known.

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TABLE 2.—*Comparison of rock units near Creede, Colo., used*

Epoch	Correlation key	Creede district [Modified from Emmons and Larsen (1923, insert facing p. 10)]	Correlation key		Correlation key	San Juan region [Larsen and Cross (1956, taken from table 18, p. 92-93); different designations in the text of their report, with page references, are shown in parentheses]
Miocene		Quartz latite porphyry dikes Fisher quartz latite. 0-100± ft				Fisher quartz latite and Los Pinos gravel
		Creede formation. 0-2,000± ft. Lake beds of tuff; some flows in upper part				Creede formation
		Potosi volcanic series: Piedra group:				Potosi volcanic series: Piedra rhyolite:
	p o	Nelson Mountain quartz latite. 0-350 ft Rat Creek quartz latite. 0-500 ft			I	1. Flows of hornblende-biotite-augite latitic rhyolites (The rhyolitic latite member, p. 155). Includes Nelson Mountain and Rat Creek quartz latites of the Creede district. 0-400 ft
	n	Quartz latite tuff. 0-500 ft			H	2. Tuff (The tuff member, p. 153). 0-400 ft
	m l	Andesite. 0-500 ft Intrusive andesite			G	3. Local lenses of dark quartz latite (local dark quartz latite at base of tuff, p. 153). 0-500+ ft
	k	Tridymite latite. 0-400 ft			F	4. Tridymite rhyolite (tridymite rhyolitic latite member, p. 152). 0-400+ ft
	i	Windy Gulch rhyolite breccia. 100-200 ft	j	Rhyolite tuff to east. 0-200 ft	E	5. Local dark quartz latite and rhyolite tuff (included in lower rhyolitic member, p. 147). Windy Gulch rhyolite breccia of the Creede district, and hornblende-quartz latite
	g	Hornblende quartz latite. 200 ft	h	Mammoth Mountain rhyolite. 0-1,000 ft	D	6. Rhyolite, mostly in thick flows with some tuff (lower rhyolite member, p. 146). 0-1,400 ft
		(Huerto absent)			C	Huerto quartz latite: Three local cones of dark pyroxene- and hornblende-quartz latites. Most of them in the San Cristobal quadrangle. 0-2,500 ft
		Alboroto group:				Alboroto rhyolite:
	f e	Equity quartz latite. 1-1,000 ft Phoenix Park quartz latite. 0-500 ft			B	1. Biotite-hornblende latitic rhyolite (upper rhyolitic latite member, p. 137). Makes up most of formation. Thick flows and tuff beds. Equity and Phoenix Park quartz latites. 0-3,000 ft
	d c b a	Intrusive rhyolite Campbell Mountain rhyolite. 0-1,000 ft Willow Creek rhyolite. 0-1,000 ft Outlet Tunnel quartz latite. 250-350+ ft			A	2. Tridymite rhyolite (lower rhyolite member, p. 135). Widespread thin flows and associated tuff beds. Found chiefly near the borders of mountains. Includes Campbell Mountain and Willow Creek rhyolites and probably Outlet Tunnel quartz latite of the Creede district. 0-500 ft

The Farmers Creek, Mammoth Mountain, and Wason Park Rhyolites are tilted differentially at places around the Creede caldera and are cut here and there by faults of different ages. These relations may reflect marginal deformation related to concurrent subsidence of the caldera core, but no direct supporting evidence was seen.

Continued pyroclastic eruptions resulted in the accumulation of great volumes of crystal-rich tuff and welded tuff to form the Rat Creek, Nelson Mountain, and Snowshoe Mountain Quartz Latites. The Rat Creek and Nelson Mountain Quartz Latites form widespread sheets in and adjacent to the northern part of the Creede district and probably were erupted through vents in the same general area. The Snowshoe Mountain Quartz Latite, on the other hand, is confined to the core of the Creede caldera, where more than 6,000 feet of crystal-rich welded tuff belonging to this formation accumulated.

The Creede caldera sank concurrently with the Snowshoe Mountain eruptions, and talus and landslide debris from the exposed walls intertongue with and overlie the pyroclastic caldera fill. After final subsidence, the core of the caldera was strongly domed, and the broken margin was marked by a deep topographic trough or moat.

Volcanic eruptions occurred at several places in the moat around the Creede caldera and along outward-extending broken zones; stream and lake sediments accumulated elsewhere in the lowlands. Numerous mineral springs were active around the caldera margin at this time and were responsible for widespread local accumulations of travertine and calcareous tufa. The lavas and related volcanic breccias have been called Fisher Quartz Latite, and the concurrently accumulated stream and lake sediments, tuffs, and travertine have been designated the Creede Formation (fig. 4).

in earlier reports with those used in this report

Creede district

Steven and Ratté, this report

[Comparison of units between this report and earlier reports in part shown by correlation key letters within parentheses]

GEOGRAPHIC DISTRIBUTION OF UNITS

← Generally west or south | Generally east or north →

Fisher Quartz Latite (0-800+ ft of flows and breccias)

Creede Formation (0-2,000+ ft of sedimentary rocks)

DOMING OF CREEDE CALDERA CORE

RECURRENT SUBSIDENCE OF CREEDE CALDERA (↕):

Snowshoe Mountain Quartz Latite (0-6,000+ ft of welded tuff) (B)

SUBSIDENCE AND RESURGENCE OF SAN LUIS PEAK CAULDRON (↕):

Nelson Mountain Quartz Latite (0-1,200+ ft of welded tuff) (f,p,B,I)

Rat Creek Quartz Latite (0-700+ ft of tuff and welded tuff) (n,o,H,I)

Huerto Formation (0-3,000+ ft of dacitic flows and breccias. In part called Conejos Quartz Latite by Larsen and Cross, 1956, p. 99) (l,m,C,G)

Rhyolite of Shallow Creek (0-500+ ft. Flow and neck. Neck called Fisher Quartz Latite by Larsen and Cross, 1956, p. 182)

Wason Park Rhyolite (0-650 ft of welded tuff) (k, F)

Mammoth Mountain Rhyolite (0-1,300+ ft of welded tuff and tuff) (h,j,D)

Farmers Creek Rhyolite (0-1,000+ ft of welded tuff and tuff) (D)

SUBSIDENCE OF BACHELOR MOUNTAIN CAULDRON

Shallow Creek Quartz Latite (0-1,000+ ft of flows and breccia) (g,E)

Bachelor Mountain Rhyolite:
- Windy Gulch Member (0-700+ ft of tuff) (i,E)
- Campbell Mountain Member (0-1,100+ ft of welded tuff) (c,A)
- Willow Creek Member (0-2,000+ ft of welded tuff) (b,A)

La Garita Quartz Latite:
- Phoenix Park Member (0-500 ft of welded tuff) (e,B)

Rhyolite of Miners Creek (0-1,000+ ft of flow and breccia)

SUBSIDENCE OF LA GARITA CAULDRON

Outlet Tunnel Member (0-2,000+ ft of welded tuff) (a,A)

The age of the volcanic rocks near Creede is uncertain. No diagnostic fossils have been reported from anywhere in the San Juan volcanic pile, so most ages suggested for these rocks heretofore seem to be poorly founded. The Telluride Conglomerate and Blanco Basin Formation that underlie volcanic rocks in the San Juan Mountains were tentatively referred to the Oligocene(?) by Larsen and Cross (1956, p. 61), but the reasoning of these men was admittedly tenuous. In our opinion the succeeding volcanic activity could have begun at any time in the middle Tertiary.

The Creede Formation near the center of the San Juan Mountains contains abundant well-preserved plant fossils, but none has proved diagnostic, and ages assigned from them have ranged widely. The most authoritative designations published recently were by Roland Brown (Larsen and Cross, 1956, p. 167), who considered the formation to be very late Miocene or very early Pliocene in age, and by MacGinitie (1953, p. 60–75), who stated that the formation cannot be older than Pliocene and that it probably is middle Pliocene in age. Pollen studies by Estella Leopold (written commun., 1961) suggest an age between late Miocene and middle Pliocene (p. 47). We know that the Creede Formation is one of the youngest units related to volcanic activity in the San Juan Mountains, and we also know that at least the main activity terminated some time in the late Tertiary, but we do not know precisely when.

LA GARITA QUARTZ LATITE

DEFINITION OF FORMATION

La Garita Quartz Latite was named (Steven and Ratté, 1964) for a great sequence of crystal-rich welded tuffs formerly included in the Outlet Tunnel and Phoenix Park Quartz Latites of Emmons and Larsen (1923, p. 18, 30, and table facing p. 10).

These rocks are exposed along the canyon of upper East Willow Creek, and they form the bulk of La Garita Mountain—the type area for the formation—farther northeast (pl. 1).

Emmons and Larsen (1923, p. 18) used the name Outlet Tunnel Quartz Latite for those rocks underlying the unit we have called the Willow Creek Member of the Bachelor Mountain Rhyolite (p. 21; table 2); Outlet Tunnel rocks are exposed in two small erosional windows along East Willow Creek and underground in the Outlet Tunnel and Holy Moses 2 Mines. The name Phoenix Park Quartz Latite, on the other hand, was used for identical rocks that intertongue with and overlie our Bachelor Mountain Rhyolite (Emmons and Larsen, 1923, p. 30). The great mass of quartz latitic welded tuff exposed farther north adjacent to upper East Willow Creek and on La Garita Mountain was erroneously believed by them to be part of their Phoenix Park Quartz Latite. The original Outlet Tunnel and Phoenix Park Quartz Latites were included in the former Alboroto Group (Emmons and Larsen, 1923), Alboroto Quartz Latite (Cross and Larsen, 1935), or Alboroto Rhyolite (Larsen and Cross, 1956).

In contrast, we found that the bulk of the La Garita Quartz Latite exposed along the canyon of upper East Willow Creek and on La Garita Mountain is equivalent to the rocks underlying the Bachelor Mountain Rhyolite, and it thus corresponds to the original Outlet Tunnel unit. Similar rocks intertongued with and overlying Bachelor Mountain rocks—the original Phoenix Park unit—comprise only a few local ash flows and pyroclastic breccias exposed along the flanks of East Willow Creek from the vicinity of Phoenix Park southward for several miles. Accumulation of the two main subdivisions of the La Garita Quartz Latite was interrupted by a period of major volcano-tectonic subsidence that depressed the area generally west of East Willow Creek. The thick pile of massive welded tuffs equivalent in age to the former Outlet Tunnel unit was broken along north- to northwest-trending faults, and a rough structural terrain was formed. Talus and reworked sedimentary breccias were deposited locally along south- and west-facing fault scarps that formed the northeast margin of the more strongly depressed area; these same scarps also formed barriers that limited the northeastward spread of succeeding volcanic rocks. Eruptions of pyroclastic material identical and probably comagmatic with the earlier La Garita Quartz Latite rocks covered the east margin of the strongly subsided block with local pyroclastic breccias and welded ash flow tuffs. These later rocks were erupted concurrently with voluminous rhyolite ash flows from the Bachelor Mountain center to the south or southwest, and the two rock types intertongue along the canyon of East Willow Creek south of Phoenix Park.

Those crystal-rich ash-flow deposits of the La Garita Quartz Latite that accumulated prior to subsidence are called the Outlet Tunnel Member; the talus and related sedimentary breccias locally deposited on the rough structural topography are informally called the breccia member; and the pyroclastic breccias and ash-flow deposits lithologically identical with rocks of the Outlet Tunnel Member that accumulated after subsidence are called the Phoenix Park Member.

DISTRIBUTION AND THICKNESS

The La Garita Quartz Latite in the Creede district (pl. 1) crops out along the canyon of East Willow Creek and forms most of La Garita Mountain to the northeast. The older Outlet Tunnel Member is the most widespread unit in the formation, and as currently known it extends from the canyon of East Willow Creek eastward along the crest of the La Garita Mountains at least as far as Wheeler Monument, 7 miles east of Phoenix Park, and northward beyond La Garita Mountain into the headwaters of Cochetopa and Sagauche Creeks. The western and southern parts of the Outlet Tunnel Member are covered by younger formations along the west side of East Willow Creek and under Wason Park (pl. 1). No similar rocks have been seen anywhere beneath the younger rocks in detailed or reconnaissance geologic studies farther south or west.

The full thickness of the Outlet Tunnel Member cannot be established in the Creede district, where the unit is broken into fault blocks in which neither the base nor the top of the unit is exposed. More than 1,700 feet of Outlet Tunnel rocks is exposed in one fault block on the west flank of La Garita Mountain east of upper East Willow Creek, and the total thickness will probably prove to be considerably greater than 2,000 feet after the whole unit is more completely mapped.

The breccia member of the La Garita Quartz Latite is irregularly distributed on the rough buried topography that resulted from collapse following the Outlet Tunnel eruptions, and present outcrops are so widely obscured by moraine, landslides, and surficial debris that the unit cannot be mapped separately from the underlying Outlet Tunnel Member. The largest exposures are within a radius of 1 mile north of the junction of Whited and East Willow Creeks, particularly on the nose of the ridge between the two creeks, and along cliffs east of East Willow Creek (pl. 1). Farther south the breccia member is exposed in Phoenix Park, where it forms part of the local hill capped by Mammoth Mountain Rhyolite, and in places along the subsidiary ridge extending from Wason Park on the east down to East Willow Creek at Phoenix Park. Talus breccias belonging to this member also crop out south of Phoenix Park in the southernmost of the two erosional windows along East Willow Creek that expose the Outlet Tunnel Member beneath Bachelor Mountain Rhyolite.

The breccia member forms such irregular local bodies that no satisfactory thickness can be established. Some breccia masses extend over vertical ranges of several hundred feet, but generally these masses appear to represent talus plastered against steep underlying slopes. Individual outcrops of rudely bedded breccias representing fanglomerate or mudflow deposits range from a few feet to as much as 40 feet in thickness, but in most exposures neither the top nor base of the reworked breccia is exposed. The breccia member is apparently absent over much of the more strongly subsided area.

The Phoenix Park Member of the La Garita Quartz Latite is exposed in Phoenix Park and along the slopes east of East Willow Creek from Phoenix Park south to near the top of Mammoth Mountain (pl. 1). The member, which varies widely in thickness from place to place, intertongues with Bachelor Mountain Rhyolite rocks to the west and overlaps rough topography on the breccia member and Outlet Tunnel Member to the east. For most of the distance south from Phoenix Park to the top of Mammoth Mountain, the aggregate thickness of the intertongued succession of Phoenix Park and Bachelor Mountain rocks appears to be between 350 and 500 feet.

GENERAL DESCRIPTION

The Outlet Tunnel Member of the La Garita Quartz Latite forms a thick sheet of massive crystal-rich welded tuff that exhibits compound cooling characteristics in the study area, and it probably constitutes a composite sheet in the sense defined by Smith (1960a, p. 812). As exposed in the west slope of La Garita Mountain, the rock appears virtually unbroken in sections several hundred to as much as 1,700 feet thick. Indistinct layers are apparent when exposures are viewed from a distance, but many of these cannot be discerned at close range. Less welded partings exist locally, but these generally cannot be traced far laterally. Reconnaissance indicates that partings in the Outlet Tunnel Member are more distinct northeast of La Garita Mountain, and the upper part of the member clearly becomes less welded eastward along the crest of the La Garita Mountains northeast of the Creede district. These relations indicate a source to the west or southwest, perhaps within the Creede district in the subsided area west of East Willow Creek now covered with younger rocks.

The massive welded tuffs in the Outlet Tunnel Member are broken into differentially tilted fault blocks along upper East Willow Creek (pl. 1). Many of the bounding faults are covered or obscured by younger formations or surficial deposits, but tectonic breccia associated with steep slopes and related talus breccia can be seen in many places, and some associated faults can be mapped locally. Tectonically broken massive welded tuff of the Outlet Tunnel Member is also exposed in the two erosional windows along East Willow Creek south of Phoenix Park. Most rocks of the Outlet Tunnel Member exposed underground in the Holy Moses 2 and Outlet Tunnel mines are widely and irregularly altered by hydrothermal activity, so that original detailed relations are obscured. Although much of the rock in the Outlet Tunnel appears massive, in a few places it contains vitrophyric zones, which probably represent local ash-flow boundaries.

The breccia member ranges from talus-rock fall breccia to rudely bedded fanglomerate or mudflow breccia. The talus breccia consists of discrete unsorted angular fragments ranging from fine debris to huge boulders 20 feet or more in diameter. This breccia is commonly plastered against steep underlying slopes, and in many places the underlying rocks and the larger individual fragments in the talus are pervasively sheared and shattered as though by tectonic activity. In a few places, well-defined faults can be mapped in the broken bedrock. Some larger masses of irregularly broken rock were seen in the talus breccia adjacent to upper East Willow Creek; the largest of these was at least 300 feet long and 100 feet wide. The enclosing talus breccia here is clearly associated with an old fault scarp, and we have interpreted the larger masses as individual rock falls from the then-recent scarp.

In a few places the talus breccia grade laterally into poorly bedded breccias. This gradation may indicate lateral transition into fanglomerate or similar reworked deposits. Some isolated exposures of rudely bedded sedimentary breccias not closely associated with talus may represent torrential or mudflow deposits farther from the source of debris. Exposures of the breccia member are so scattered that little could be reconstructed of the original extent or form of the deposits.

The Phoenix Park Member along the slopes east of East Willow Creek and south of Phoenix Park consists largely of three distinct welded ash flows. The lower two are each about 50 feet thick and consist of a basal vitrophyre that grades into phenocryst-rich devitrified welded tuff, which in turn grades into less welded pumiceous tuff at the top. The upper unit consists of several hundred feet of phenocryst-rich welded tuff identical with the devitrified tuff in the lower units. A tongue of Bachelor Mountain Rhyolite intervenes locally between the upper and middle ash-flow units in this area (p. 23).

Farther north, in Phoenix Park and on the subsidiary ridge extending from Wason Park on the east down to Phoenix Park, pyroclastic breccia is locally abundant in the Phoenix Park Member and is interlayered here and there with slightly to densely welded ash flows that resemble typical La Garita Quartz Latite. The pyroclastic breccias consist of unsorted angular fragments as much as 5 feet or more in diameter set in a fine, pink ash matrix. Fragments consist dominantly of typical densely welded La Garita Quartz Latite, but hypabyssal intrusive(?) and black andesitic lava fragments are abundant as well. The phenocrysts in the ash matrix are typical of the La Garita Quartz Latite; this fact and the evidence from the interlayered ash-flow deposits indicate that the whole assemblage belongs to the Phoenix Park Member. The pyroclastic breccias and interlayered ash flows overlap steep slopes of tectonically broken Outlet Tunnel Member or of talus-mudflow deposits of the breccia member in at least two places that could be mapped.

PETROGRAPHY

Typical La Garita Quartz Latite, whether seen as a breccia fragment or as part of a welded ash flow, is a reddish, crystal-rich rock containing many indistinctly bounded clots of irregular size containing larger and more euhedral phenocrysts. The reddish lithoidal matrix is microgranular and generally structureless in hand specimen. Fragments of foreign rock types are widespread and constitute 1–2 percent of most samples and as much as 5 percent of a few samples.

A common variant is a less thoroughly welded rock in which the irregular clots containing euhedral phenocrysts are sharply bounded and contrast strongly with the adjacent rock in color and hardness. The matrix in most of these rocks is brown to gray and ranges from structureless in the more densely welded rocks to eutaxitic in the less welded rocks. In contrast, the clots are commonly light gray, tan, or pink and tend to be more earthy. Some of the clots have a stringy texture indicative of collapsed pumice. The original fragmental character of many of these rocks is easily recognized in hand specimen.

Poorly welded to virtually nonwelded rocks in the La Garita Quartz Latite generally contain abundant pumice fragments in a pink to white tuffaceous matrix.

The vitrophyres marking the chilled base of some of the welded ash flows in the Phoenix Park Member are generally black glass speckled with light-colored phenocrysts. The darker phenocrysts as well as many of the foreign rock fragments are obscured by the dark matrix.

La Garita Quartz Latite commonly contains distinctive inclusions of dark-brick-red aphanitic volcanic rock, as well as various porphyritic flow rocks. In addition, the formation is unique among the different welded-tuff units in the Creede district in containing sparse but widespread fragments of nonvolcanic rocks. Metamorphic rocks, chiefly gneiss, are the most common types recognized; sedimentary(?) and granitic types are less surely identified. Fragments of all types locally attain dimensions of several inches but in most rocks are less than 1 inch in diameter.

The original fragmental condition of the La Garita welded tuffs is apparent in most thin sections. The matrices, although devitrified, have good maze textures and microeutaxitic structures in many of the more densely welded tuffs, and clear-cut vitroclastic textures can be seen in most of the less welded tuffs. Discrete fragments of pumice in various stages of compaction are widespread in the less welded rocks, and broken phenocrysts are characteristic of all La Garita welded tuffs.

The diffuse clots containing larger and more euhedral phenocrysts in the densely welded rocks and the collapsed pumice lapilli in the less welded rocks are similar in thin section and probably are similar in origin. Bodies of both types can be distinguished from the enclosing rock by the unbroken and euhedral form of their phenocrysts and the lack of evidence for fragmentation of their matrices. Intergrowths of phenocrysts are common.

An average of 17 modes of La Garita as seen in thin sections shows an abundance of major components as follows:

	Percent
Phenocrysts:	
Plagioclase (oligoclase-andesine)	30
Sanidine	6
Quartz	4
Biotite	4
Hornblende	4
Magnetite and accessory minerals	2
Total	50
Matrix	50

Most plagioclase in the La Garita Quartz Latite is calcic oligoclase or sodic andesine. Many of the crystals are unzoned, but others show irregular or oscillatory zoning. Most are broken crystal fragments; the more nearly euhedral grains commonly form intergrowths of several plagioclase crystals or of plagioclase and mafic crystals.

Sanidine generally forms irregular embayed grains that are rarely twinned. Most grains appear homogeneous in thin section, but some show the indistinct grid texture of cryptoperthite, and others are irregularly zoned.

The larger quartz phenocrysts, several millimeters in diameter, commonly are irregularly embayed and appear amoebic. Smaller crystals, although in part corroded, tend to show prismatic crystal form and many grains are doubly terminated.

Biotite and hornblende are the chief mafic minerals in the La Garita Quartz Latite. In this respect the formation contrasts with all other quartz latitic welded tuff units in the Creede district which have biotite and clinopyroxene as the major mafic constituents. The hornblende in the vitrophyres and less welded tuffs is green, but that in the more thoroughly welded tuffs is commonly oxidized brown and contains fine granules of iron oxide and pyroxene. Euhedral crystals of sphene as much as 1 mm long, although not abundant, are a common and distinctive constituent of this formation.

RHYOLITE OF MINERS CREEK

The oldest rock unit exposed in the western part of the Creede district is a steep-sided accumulation of rhyolite flows and pyroclastic rocks that underlies the Bachelor Mountain Rhyolite (fig. 4). This unit is represented by scattered outcrops that protrude through widespread talus and landslide debris in an oval area along Miners Creek (pl. 1). A formal name is not proposed for these rocks because there is little evidence of their areal extent or of their relation to rocks other than the Bachelor Mountain Rhyolite. Further mapping in adjacent areas is not expected to locate additional outcrop areas in which the rhyolite of Miners Creek is a significant unit.

Outcrops of this rhyolite along Miners Creek consist of breccia, flows, and probable pyroclastic rocks in rude layers dipping from 20° SE. to vertical. Much of this heterogeneous material is glassy and perlitic. To the north the heterogeneous rocks give way to an underlying pink to gray vesicular fluidal porphyry, which constitutes the major part of the unit. Flow structures parallel the lithologic layering of the deposit. The rhyolite of Miners Creek is overlapped on its southeast margin by the Bachelor Mountain Rhyolite, and the contact between the two formations rises sharply from an altitude of 9,200 feet at the level of Miners Creek to about 10,500 feet in a short distance both to the north and to the southwest. The attitude of the contact indicates that the main mass of the rhyolite of Miners Creek may be a bulbous volcanic dome or a steep-sided flow.

The pink to gray porphyry that constitutes most outcrops consists of about 20 percent phenocrysts and 80 percent lithoidal groundmass. Sanidine and plagioclase crystals constitute the bulk of the phenocrysts and range from tiny fragments to tabular crystals as much as 4 mm long. Small flakes and books of brown biotite are sparsely scattered through the rock.

Thin sections of the rhyolite show plagioclase (3–15 percent) to be somewhat more abundant than sanidine (2–10 percent). The average composition of the zoned plagioclase is andesine, and zones range from An_{30} to An_{50}. Rounded and embayed microphenocrysts of quartz are a rare constituent of the thin sections. The matrices of most specimens are microspherulitic, and flow layers generally consist of spherulites of contrasting size. Some sections show flow layers of alternating spherulitic and pilotaxitic structure.

SHALLOW CREEK QUARTZ LATITE

DEFINITION OF FORMATION

Shallow Creek Quartz Latite (Steven and Ratté, 1964) constitutes an accumulation of lava flows and volcanic breccias that crops out in the drainage basins of Shallow, Miners, and Rat Creeks in the western part of the Creede district. The flows and breccias are irregularly mixed, and the unit varies in lithology so greatly from place to place that no single section is representative; the largest known body is along the north flank of the Shallow Creek drainage.

The rocks here included in the Shallow Creek Quartz Latite were originally described by Emmons and Larsen (1923, p. 36–38) under the informal name "hornblende-quartz latite" (table 2). This unit marked the base of their Piedra Group in the western part of the Creede district, and they believed that it was separated from the underlying Alboroto rocks by an irregular erosional unconformity. Larsen and Cross (1956, p. 143) called the same rocks hornblende rhyolitic latites but considered their relations to be the same. In contrast, our mapping (pl. 1; fig. 4) has shown that the Shallow Creek Quartz Latite intertongues laterally with the upper members of a gradational sequence of rocks that we have named Bachelor Mountain Rhyolite (Steven and Ratté, 1964). The supposed unconformity between rocks included by Emmons and Larsen (1923) in their Alboroto and Piedra Groups is spanned by a gradational contact between our Campbell Mountain and Windy Gulch Members, and also by the Shallow Creek Quartz Latite.

DISTRIBUTION AND THICKNESS

Shallow Creek Quartz Latite is present only in the western part of the Creede district. The largest area of exposures is between Shallow and Miners Creeks, but scattered tongues, lenses, and small fault blocks of Shallow Creek Quartz Latite occur on McKenzie Mountain, east of lower Rat Creek, and in the complexly faulted area east of Sunnyside (pl. 1).

The Shallow Creek Quartz Latite varies greatly in thickness from scattered lenses and tongues a few tens to a few hundreds of feet thick in the Rat Creek drainage area to a possible maximum thickness of 600–700 feet between Miners and Shallow Creeks and on the west slope of McKenzie Mountain.

GENERAL DESCRIPTION

Shallow Creek Quartz Latite consists largely of volcanic breccias; lava flows are thin and are estimated to form less than 10 percent of the formation. Flow breccias appear to predominate, particularly in the western parts of the accumulation, although pyroclastic and possibly epiclastic breccias are widely intermixed. The flow breccias consist of completely unsorted angular to subangular fragments that range from fine chips to blocks as much as several feet in diameter. Bedding is crude or entirely absent. In many flow breccias the fragments are well indurated or are welded at their surfaces of contact. Some massive unsorted breccias are loose and rubbly and commonly contain a greater proportion of finer grained and tuffaceous material in the matrix. All the rocks are composed almost entirely of essential materials, with minor pumiceous fragments as the chief possible contaminants.

Crudely bedded and probably reworked materials are most abundant in the marginal tongues that are interlayed with volcanic rocks from other sources along Miners and Rat Creeks. Some tongues or lenses change laterally from coarse flow breccia or pyroclastic breccia to finer bedded reworked breccia.

Much of the breccia on the intermediate slopes north of Shallow Creek is irregularly bleached and silicified, and similarly altered breccia can be seen north of Miners Creek near the large vent of Fisher Quartz Latite (pl. 1).

It has not been feasible to split the Shallow Creek Quartz Latite into smaller mappable units. Lithology differs but little throughout the area in which the formation crops out, and poor exposures and converging rock types have discouraged attempts to trace individual units.

The source of the Shallow Creek Quartz Latite probably lies west of the present exposures in the Creede district. Evidences of this are the general thickening of the formation westward before it disappears beneath younger rocks and the fact that the formation intertongues eastward with Bachelor Mountain rocks.

PETROGRAPHY

Fresh specimens of Shallow Creek Quartz Latite are rare. The rocks commonly are either oxidized and burnt in appearance or irregularly altered to clay and crisscrossed with veinlets of quartz and carbonate. The rocks vary widely in color, depending largely on the type and degree of alteration: strongly oxidized rocks are red to brown; carbonate-bearing rocks are bluish gray or, in a few places, greenish gray; silicified or argillized rocks are generally light gray to white.

Shallow Creek Quartz Latite is invariably porphyritic; its small phenocrysts, rarely exceeding a few millimeters in maximum dimensions, are set in an aphanitic groundmass. Some breccia fragments are vesicular, in places pumiceous, but other fragments are compact. The rocks show little or no flow structures in the arrangement of phenocrysts or banding of the matrix.

Phenocrysts constitute 20–30 percent of most specimens of Shallow Creek Quartz Latite: 15 percent plagioclase (calcic andesine), 5 percent hornblende, and a few percent each of biotite and magnetite. Sanidine and clinopyroxene occur locally, and quartz grains were observed in the tuffaceous matrix of a pyroclastic breccia between Shallow and Miners Creeks. Plagioclase crystals are glassy where fresh, but most generally are partly to completely altered to chalky aggregates of white clay, carbonate, and quartz. Fresh plagioclase crystals are irregularly zoned; zones range in composition from sodic andesine to sodic labradorite. Sanidine phenocrysts are fresh and glassy wherever they are found.

Hornblende is either green or brown, and it generally contains granules of iron oxide along cleavages and at grain boundaries. In the more altered rocks, hornblende crystals are represented by "ghosts" of iron oxide or fine-grained skeletal pseudomorphs of dark earthy materials that include iron oxides, clays, carbonate, and quartz. Biotite is similarly altered in most of these rocks.

The matrix of the less altered specimens consists largely of plagioclase microlites in a cryptocrystalline aggregate having a low index of refraction. The microlitic matrix of bluish-gray rocks is patchily altered to granular quartz and calcite and is cut by veinlets of calcite; the oxidized breccias have matrices that are largely obscured by secondary ferritic material, mainly hematite.

BACHELOR MOUNTAIN RHYOLITE

DEFINITION OF FORMATION

The name Bachelor Mountain Rhyolite was given (Steven and Ratté, 1964) to all the intergradational rhyolitic ash flows and welded tuffs formerly included in the Willow Creek Rhyolite, Campbell Mountain Rhyolite, and Windy Gulch Rhyolite Breccia, as well as the rhyolite porphyry (intrusive) of Emmons and Larsen (1923). Emmons and Larsen (1923, p. 19–30) originally placed the Willow Creek and Campbell Mountain Rhyolites in their Alboroto Group and described the rocks as two sequences of rhyolitic lava flows and flow breccias separated by an irregular erosion surface. The name Windy Gulch Rhyolite Breccia, on the other hand, was assigned (Emmons and Larsen, 1923, p. 38–40) to their younger Piedra Group, and they believed that the Windy Gulch was separated from the Campbell Mountain Rhyolite by a major unconformity.

In contrast, we found the Willow Creek, Campbell Mountain, and Windy Gulch units to be members of an intergradational sequence of pumiceous pyroclastic rocks that warrants formation rank. These rocks grade upward from densely welded tuff closely resembling fluidal rhyolite flow rock (Willow Creek Member), through compact welded tuff in the middle (Campbell Mountain Member), to a porous moderately welded to nonwelded tuff at the top (Windy Gulch Member). Breaks in this sequence occur only where the Bachelor Mountain rocks intertongue with other volcanic rocks at the margins of the deposit.

As the distinctions between the members are based largely on degree of welding and compaction rather than on original depositional differences, the transitions between the members represent only approximate stratigraphic positions. We know, for example, that near the east and west margins the Willow Creek Member contains transitional layers that are typical Campbell Mountain rocks, and in the Miners Creek area the upper part of the Campbell Mountain Member becomes less welded northward and grades laterally into typical Windy Gulch rocks (pl. 1). Most of the known variations in vertical position of the transitions are toward the margins of the deposit. Similar changes might take place in the main mass of the formation owing to irregularities on the buried surface of deposition, which would control thickness and thus heat retention, degree of compaction, and welding (Smith, 1960b, p. 158). Present data are not sufficient to indicate how much the vertical position of the transitions does vary in the Creede district, but the variation probably is insufficient to invalidate the concept of members as here proposed.

DISTRIBUTION AND THICKNESS

Bachelor Mountain rocks crop out mainly in the central part of the Creede district from Farmers Creek on the east to Shallow Creek on the west. To the south, Bachelor Mountain Rhyolite is overlapped by sedimentary rocks of the Creede Formation in the Rio Grande valley, and to the north it is irregularly overlapped by younger volcanic units. In addition, the Willow Creek and Campbell Mountain Members are present in a large fault block near the head of West Willow Creek at the north edge of the district.

In areas outside the Creede district, rocks lithologically similar to Bachelor Mountain Rhyolite have been mapped near Wagon Wheel Gap along the east margin of the Creede caldera and observed in reconnaissance south of South River Peak in the southwestern part of the Spar City quadrangle, 20–25 miles south of Creede. Emmons and Larsen (1923, p. 19, 26) reported rocks resembling the Willow Creek and Campbell Mountain Rhyolites near the old mining camp of Bondholder on Spring Creek, 12 miles north of Creede.

Distribution of the Bachelor Mountain Rhyolite in the Creede district was partly controlled by the volcanic topography upon which the rocks were deposited, as well as by concurrent accumulation of volcanic materials from other sources. Thus the spread of Bachelor Mountain ash flows was restricted on the west by the rhyolite of Miners Creek and by the Shallow Creek Quartz Latite, and on the east by the La Garita Quartz Latite. North of Creede, 1,400 feet of Bachelor Mountain Rhyolite at the head of West Willow Creek indicates wider distribution in this direction. South of Creede, evidence for the original extent of these rocks is buried beneath younger deposits in the deeply subsided block in the center of the Creede caldera.

The Willow Creek and Campbell Mountain Members occur in all main areas of exposure of Bachelor Mountain Rhyolite in the Creede district. The Windy

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Gulch Member, however, is now exposed largely in downfaulted blocks in the central and western parts of the Creede district where it was protected in some degree during recurrent periods of erosion. No Windy Gulch was seen east of the Amethyst fault.

Intrusive plugs believed related to the Bachelor Mountain Rhyolite cut the Willow Creek and Campbell Mountain Members on the lower slopes of Bachelor Mountain north of Creede and on the east side of the canyon of Rat Creek west of Creede.

The maximum thickness of Bachelor Mountain Rhyolite cannot be measured in any one section in the Creede district, but the sum of maximum exposed thicknesses of individual members is between 3,500 and 4,000 feet. The greatest known thickness of the Willow Creek Member is in a nearly vertical section along the east flank of the canyon of lower East Willow Creek, where the member is more than 2,000 feet thick; this figure is minimal, however, as the base of the member is not exposed. The overlying Campbell Mountain Member is exposed over a vertical range of more than 1,000 feet on the ridge between Nelson and West Willow Creeks, and the top is marked by an unconformity. Underground we mapped Campbell Mountain rocks through a vertical range of more than 800 feet in mine workings in the hanging wall of the Amethyst fault, and neither the base nor the top of the member was seen. The thickest section of the Windy Gulch Member seen is in a fault block on the east flank of the canyon of Rat Creek, where about 900 feet of soft tuffaceous rock is present. The base of this section grades into the underlying Campbell Mountain Member, but the top is marked by an unconformity.

Two significant and related factors may cause serious errors in these measurements: irregularities on the underlying surface can cause abrupt thickening and thinning of the accumulation, and this in turn can affect the degree of welding and compaction of the rocks and thus possibly the vertical position of transitions between the members. The east and west margins of the accumulation were deposited on rough, mountainous terrain which clearly affected local thicknesses of the overlying rocks. Lateral facies changes are commonly obvious in these same areas, and thickness figures obtained here definitely cannot be compared confidently from place to place. However, no evidence was seen in deep canyons or lower mine workings for local buried hills beneath the Bachelor Mountain Rhyolite in the central area where the maximum thicknesses of the members were measured, so these measurements are still presented as minimum figures.

GENERAL DESCRIPTION

The densely welded tuffs in the lower two-thirds of the Bachelor Mountain Rhyolite are well exposed along all the major canyons north and west of Creede. The Willow Creek Member commonly forms cliffs or precipitous slopes which flatten upward to smooth talus-strewn slopes and rolling topography reflecting the surface cut on the overlying Campbell Mountain Member. The transition between the Campbell Mountain and Windy Gulch Members is commonly marked by another topographic break, and the surface on the overlying Windy Gulch Member is characterized by gentle soil-covered slopes.

Outcrops of the Willow Creek Member are commonly rough and jagged, and reflect conspicuous joints or a combination of joints and fluidal structures in the hard rhyolite. The jointing is blocky in most of these rocks, but adjacent to pervasively brecciated rocks along lower East and West Willow Creeks (pl. 1) it is manifested by innumerable closely spaced steeply dipping fractures (sheeting) that cut the rock into thin, flat slabs a fraction of an inch to a few inches thick. The jointed cliffs of the Willow Creek Member feed great banks of talus along the major creeks in the district. Less precipitous slopes may be veneered with flat stringy-surfaced fragments of fluidal rhyolite that resemble wood chips around a chopping block.

The Campbell Mountain Member is generally characterized by a rolling topography which contrasts markedly with the more rugged topography on the underlying Willow Creek Member. Although outcrops of Campbell Mountain rocks are numerous and widespread, they tend to be small and rarely stand much above the adjacent debris-covered slopes. Most weathered fragments of Campbell Mountain rocks are somewhat flattened, but they are more irregular and blocky than the "wood-chip" type of fragment common in Willow Creek debris, and they lack the stringy fluidal surface.

The soft tuffs that constitute the Windy Gulch Member are easily weathered and are rarely well exposed. Good exposures occur on both the west and east flanks of the canyon of Miners Creek and on the southwest slope of Bulldog Mountain, but even in these places the vertical continuity of outcrops is interrupted by slump and surficial debris.

The basal contact of the Bachelor Mountain Rhyolite (base of the Willow Creek Member) was observed in very small exposures in the canyon of East Willow Creek, where Bachelor Mountain rocks overlie the Outlet Tunnel Member of the La Garita Quartz Latite, and in the canyon of Miners Creek, where the formation overlies the rhyolite of Miners Creek. As exposed in the two erosional windows along East Willow Creek and underground in the Holy Moses 2 and Outlet Tunnel levels, the basal contact marks a very irregular surface of deposition whose local relief is at least several hundred feet. Steep to nearly vertical segments of the depositional surface, possibly representing old fault scarps, can be seen in several places. The lowest identifiable rock in the Willow Creek Member here is a mottled brown welded tuff closely similar in general aspect to tuff of the Campbell Mountain Member; this rock grades a few feet upward into typical fluidal-appearing Willow Creek rocks and apparently represents a chilled phase at the base of the unit.

Along Miners Creek the Bachelor Mountain Rhyolite overlaps the steep flank of the local rhyolite of Miners Creek (p. 19). A local black vitrophyre follows this basal contact for nearly 1,000 feet; this rock grades into the overlying Willow Creek rocks and appears to be a typical basal chilled phase. Relations are somewhat confusing, however, as the vitrophyre appears in part to intrude the underlying rhyolite of Miners Creek. Elsewhere in this same area the base of the Willow Creek Member is marked by a mottled welded tuff resembling that of the Campbell Mountain, which grades upward into typical rocks of the Willow Creek Member.

The Campbell Mountain and Windy Gulch Members of the Bachelor Mountain Rhyolite intertongue laterally with volcanic rocks from other sources (fig. 4). The intertonguing is particularly apparent along the west margin in the Shallow, Miners, and Rat Creeks drainage basins where the two members are complexly interlayered with flows and breccias of Shallow Creek Quartz Latite (pl. 1). Similar intertonguing is suggested on the east flank of East Willow Creek (pl. 1), where a lens of mottled brown welded tuff identical with rocks of the Campbell Mountain Member is interlayered with the Phoenix Park Member of the La Garita Quartz Latite between 150 and 200 feet above the top of the regular sequence of Willow Creek and Campbell Mountain rocks. Significantly, the positively identified Campbell Mountain rocks resting on the Willow Creek Member are abnormally thin here, and the Windy Gulch Member is not present; presumably the upper part of the Bachelor Mountain sequence was excluded from this area by concurrent accumulation of quartz latitic welded tuffs of the Phoenix Park Member.

Where not intertongued with concurrently erupted rocks, the top of the Bachelor Mountain Rhyolite is now marked by surfaces of erosion. At least two unconformities are represented: the older separates the Bachelor Mountain Rhyolite from the various younger ash-flow units which progressively overlapped the rough topography left by subsidence of the Bachelor Mountain volcano and succeeding erosion; the younger separates the Bachelor Mountain Rhyolite from the Creede Formation and represents the surface eroded on the steep outer wall of the Creede caldera after final subsidence.

Although the effects of compaction and welding vary continuously from the bottom to the top of the Bachelor Mountain Rhyolite, the most marked changes in the resulting rocks are across two fairly narrow transition zones which separate the members. These transitions correspond closely to the contacts shown by Emmons and Larsen (1923, pl. 2) and are the only significant changes in the entire sequence that can be mapped consistently. In many places, field mapping was facilitated by topographic changes that commonly accompany the transition from a harder lower member to a softer overlying member.

Ideally, the transition between the Willow Creek and Campbell Mountain Members is defined as the change from a rock whose matrix is best described as having a fluidal structure to a rock whose matrix is eutaxitic to vitroclastic. In the field we distinguished Campbell Mountain rocks by the mazelike texture of their matrix, for which we used the descriptive term "curlicue matrix." In the central part of the Creede district, the change in matrix textures is commonly accompanied by a color change and by a conspicuous change in the abundance of lithic fragments included in the rocks. Thus, the typical blues and grays of the Willow Creek Member change through purples to brown, red brown, and brick red in the overlying Campbell Mountain Member. Foreign lithic inclusions change in size and abundance from 1 or 2 percent of rounded inclusions generally smaller than 1 cm in diameter in the Willow Creek Member to 5 percent or more of rounded to angular inclusions as much as several centimeters long in the Campbell Mountain Member. In the thicker parts of the accumulation, the transition zone between the Willow Creek and Campbell Mountain Members ranges from a few feet to several tens of feet in thickness. Toward the margins of the deposit, the changes associated with the transition zone are all less pronounced. Near Farmers Creek and west of Miners Creek, the Willow Creek Member as now mapped contains intermixed Campbell Mountain rock types; in these two areas the contact is mapped so that the Campbell Mountain Member above does not include any rock typical of the Willow Creek.

The gradational contact between the Campbell Mountain and Windy Gulch Members is taken at the transition between relatively compacted and nearly noncompacted welded tuff. This transition was chosen in preference to the change from welded to nonwelded tuff for convenience in field mapping; the difference in compaction can be seen in many places and provided some basis for mapping, whereas the welded versus nonwelded contact is rarely exposed and would be nearly impossible to map. In most places where it could be seen, the change from welded to nonwelded tuff takes place wthin a few tens of feet above the contact we have chosen and is thus closely reflected by the map pattern. The transition mapped is comparable with the upward changes from densely to partially welded tuff mapped in several other units in the Creede district as well; in most of these the change from strongly compacted to poorly compacted rocks is the only internal difference available for mapping.

INTRUSIVE RHYOLITE

Several plugs of intrusive rhyolite cut Willow Creek and Campbell Mountain welded tuffs on the lower slopes between Willow and Rat Creeks (pl. 1).

Small plugs north of Creede show sharp crosscutting contacts against the enclosing Willow Creek and Campbell Mountain rocks. The contacts are tight and are marked by numerous tongues of intrusive penetrating the adjacent rocks; the border zone of the intrusive contains abundant fragments of the wallrocks. Flow layers in the intrusive rhyolite are mostly steep, although locally contorted. The intrusive bodies generally stand as resistant knobs above the surrounding welded tuff.

The larger intrusive bodies near Rat Creek contain a similar type of rock, but here the matrix of the rock is chalky and appears somewhat argillized. Because of its less resistant nature, the rock in these bodies does not form good outcrops, and the distribution of the intrusive rocks was mapped with the aid of many small prospect pits that dot the grassy slopes in this vicinity. The adjacent wall rocks of the Willow Creek and Campbell Mountain Members are likewise bleached and much brecciated near the intrusives. The brecciated rock appears to be in part included in the intrusive bodies and in part penetrated by tongues of the intrusive rock.

MODE OF DEPOSITION

Bachelor Mountain Rhyolite in the central part of the Creede district shows a virtually continuous gradation in compaction and welding features from the fluidal-eutaxitic Willow Creek Member, through the eutaxitic-vitroclastic Campbell Mountain Member, to nonwelded ash-flow tuff in the Windy Gulch Member. The absence of significant partings to indicate appreciable time lapse between ash-flow eruptions in this part of the deposit infers generally continual deposition of ash flows throughout this eruptive cycle. In contrast, toward the margins of the Bachelor Mountain Rhyolite outcrop area, significant partings such as alternating Willow Creek and Campbell Mountain rock types, a local vitrophyre between the Willow Creek and Campbell Mountain Members, and the lateral gradation from Campbell Mountain to Windy Gulch Members, as well as the intertonguing of Bachelor Mountain rocks with the other volcanic units, suggest episodic deposition of Bachelor Mountain ash flows. These aspects imply that the present marginal outcrop areas also represent original marginal areas of deposition, and that the thick mass of Bachelor Mountain Rhyolite in the central part of the Creede district is toward, if not near, the eruptive center of the deposit. The plugs of intrusive rhyolite support this contention. We interpret the eruption of ash flows in the vent area to have been virtually continuous, but in areas distant from the center distribution of ash flows was spasmodic and depended on the strength of individual paroxysms. In the terminology of Smith (1960a, p. 812), the Bachelor Mountain Rhyolite near the probable vent area is an example of a very thick simple cooling unit, consisting of a large number or individual ash flows, which laterally becomes a composite of simple and compound cooling units toward the edges of the mass.

PETROGRAPHY

The petrographic features of the Bachelor Mountain Rhyolite are consistent with the interpretation that the formation is a thick accumulation of once completely fragmental rhyolite pumice. Variations in texture are attributed mainly to progressive compaction and welding downward within the deposit. The fluidal texture in the lower part of the Willow Creek Member suggests flattening flow of formerly fragmental material that was largely reconstituted or homogenized by welding and compaction. Deuteric alteration and later hydrothermal alteration have caused recrystallization and changes in composition of much of the original rhyolite.

Ash flows of the Bachelor Mountain Rhyolite consist mainly of microcrystalline to cryptocrystalline matrix (75–95 percent), small phenocrysts (1–5 percent), and foreign lithic fragments (from less than

5 to as much as 20 percent). The texture of the deposit changes from a fragmental poorly welded ash-flow tuff at the top (Windy Gulch Member) through densely welded eutaxitic ash flows (Campbell Mountain Member) to extremely welded and compacted ash flows grading from eutaxitic to fluidal textures downward (Willow Creek Member).

In the upper members of the formation, relict cognate pumice fragments can be distinguished from the relicts of fine glass shards in the matrix, but in the lower part of the Willow Creek Member the original matrix constituents are rarely distinguishable. Pumice fragments in the Windy Gulch Member range from undeformed lapilli containing tubular vesicles to deformed bodies containing partly collapsed vesicles. The pumice fragments are enclosed in a mass of glass shards whose texture is vitroclastic. In the underlying Campbell Mountain Member, pumice lapilli are irregularly deformed into ragged-edged clots and lenticles, and vesicular structures are completely collapsed in many of them. Others retain a relict vesicular structure in which the vesicles are filled with quartz. Vitroclastic texture is obscure in the Campbell Mountain matrix and the closely appressed shards constitute a maze in which it is increasingly difficult to distinguish individual fragments. The closely compressed eutaxtic pumice fragments in the upper part of the Willow Creek Member commonly are easily recognized, but these become progressively more obscure downward, and in the fluidal rocks in the lower part of the member the pumice fragments are represented by discontinuous discoidal layers with planar dimensions many times their thickness. Unbroken feldspar phenocrysts and microphenocrysts can be seen in some of the relict pumice lapilli, and they contrast with the fragmented phenocrysts in the rest of the rock.

Fluidal rocks in the lower part of the Willow Creek Member consist of many very thin discontinuous laminae, which in places number 40–50 per millimeter. Laminae of cryptocrystalline material alternate with microcrystalline laminae. Thicker layers (1–2 mm) probably representing former pumice fragments consist of coarser crystals in micropegmatitic intergrowths; these layers also show frayed, irregular outer margins in contrast to the knife-edge limits of the thin laminae. Both the fine laminae and thicker layers bend around phenocrysts and foreign rock fragments in a manner comparable to flow layers in a true lava flow. Structureless crystal aggregates fill the pressure shadows on either side of many such fragments. Fine fragmental materials can be distinguished in the matrix of the Willow Creek only where the base of the deposit was chilled against the underlying rhyolite of Miners Creek.

All the Bachelor Mountain Rhyolite is devitrified except for a thin selvage of vitrophyre at the contact with the rhyolite of Miners Creek. The products of devitrification are so fine grained that the mineralogy of the matrix is poorly known. X-ray analyses of four Bachelor Mountain rocks show quartz to be the predominant constituent of the matrix with minor feldspar and traces of mica and clay. The thin discontinuous laminae of the fluidal rocks consist largely or entirely of quartz, but the thicker layers with relatively coarse crystallinity and micropegmatitic intergrowths consist mainly of quartz and alkali feldspar.

Phenocrysts make up only 1–2 percent of most Bachelor Mountain ash flows but they show an increase to about 5 percent in local phases of the Campbell Mountain Member. The phenocrysts consist largely of broken feldspar crystals whose maximum dimensions are 1–2 mm. Sanidine is more abundant than plagioclase. Some of the larger sanidine crystals are euhedral, but generally they are broken fragments exhibiting deeply embayed and corroded borders. The crystals are generally twinned and commonly zoned, and there is a progressive increase in soda content from center to border. Plagioclase phenocrysts have a composition of about An_{30} and are weakly zoned. Other phenocrysts and microphenocrysts include tiny flakes of biotite, scattered magnetite-ilmenite granules, and scarce crystals of hornblende, pyroxene, and quartz.

Inclusions of foreign rock fragments range from 2 percent or less in most of the Willow Creek Member to a maximum of 20 percent in some phases of the Campbell Mountain and Windy Gulch Members. Inclusions in the Willow Creek seldom exceed 2 cm in diameter, but blocks several inches across occur locally in the two upper members, and near the south end of McKenzie Mountain xenoliths as much as 3 feet across occur in an avalanche type of breccia in the Campbell Mountain Member. All the inclusions are of volcanic origin. Inclusions derived from other rock units in the Creede area include fragments of La Garita Quartz Latite and Shallow Creek Quartz Latite. Andesitic fragments are abundant in some parts of the Willow Creek Member along lower Shallow Creek and are conspicuous along with other rock types in Campbell Mountain and Windy Gulch rocks in all the area west of Windy Gulch.

Intrusive Bachelor Mountain Rhyolite closely resembles certain phases of the fluidal Willow Creek

Member except that it contains as much as 5 percent of euhedral sanidine tablets, commonly 5–10 mm long. The matrix is a cryptocrystalline to microcrystalline intergrowth of quartz and feldspar grains that rarely exceed a few hundredths of a millimeter in diameter. Some thin sections show a distinctive texture, best seen with crossed nicols, in which a sprinkling of single quartz grains in a uniform finer grained matrix stand out as stars in the sky. These may be vestiges of an original vesicular texture, in which the vesicles have been filled with quartz.

Alteration effects are widespread in the Bachelor Mountain Rhyolite and consist mainly of pervasive silicification and orthoclasization of the Willow Creek and Campbell Mountain Members. Plagioclase phenocrysts are represented by clay pseudomorphs throughout most of the deposit, and the relatively soft and porous Windy Gulch Member is highly weathered to clay minerals. The intrusive rhyolite is bleached and partly argillized over much of its outcrop area, and the smaller intrusive plugs are partly silicified.

FARMERS CREEK RHYOLITE

DEFINITION OF FORMATION

The name Farmers Creek Rhyolite was given (Steven and Ratté, 1964) to a heterogeneous assemblage of rhyolitic pyroclastic rocks and minor flow rocks that constitutes the first unit deposited in the Creede district after collapse of the Bachelor Mountain volcano. Larsen and Cross (1959, p. 146–147) referred the rocks here called Farmers Creek Rhyolite to the basal part of the lower rhyolite member of their Piedra Rhyolite.

The different rock types in the Farmers Creek Rhyolite and the complex relations between them, are well exposed in its type area along the intermediate slopes in the Farmers Creek drainage basin.

DISTRIBUTION AND THICKNESS

Although the present limited and discontinuous exposures do not indicate the original extent of the Farmers Creek Rhyolite, the abundance of coarse tuff breccia suggests a near-vent accumulation. In the Creede district the Farmers Creek Rhyolite is exposed in the Farmers Creek drainage basin and along the flanks of the canyon of West Bellows Creek in the contiguous area to the east. Additional exposures are known near Wagon Wheel Gap, a few miles to the east and southeast, where the formation crops out along the flanks of the Rio Grande, along the west side of lower Blue Creek, and in the hills east of lower Goose Creek.

Farmers Creek Rhyolite about 1,000 feet thick is exposed at several places in the Farmers Creek–West Bellows Creek area. At all these places this thickness is minimal, for in none of the places is the base of the formation exposed. In addition, the Farmers Creek Rhyolite probably varies significantly in thickness from place to place owing to irregularities on the underlying surface as well as to irregularities in deposition of the heterogeneous unit. The exposed beds of Farmers Creek pyroclastic rocks in the Farmers Creek–West Bellows Creek area are tilted generally northward and are overlapped by the more flat lying sheet of younger Mammoth Mountain Rhyolite, so the original top of the formation may not be anywhere exposed.

GENERAL DESCRIPTION

The Farmers Creek Rhyolite can be divided into three subequal parts in the Farmers Creek–West Bellows Creek area. The lower third consists largely of coarse pumice breccia that is generally soft and weak; it typically forms soil-covered and landslide slopes and few good outcrops. The middle third of the formation consists of a succession of layers of differentially welded tuffs whose harder units crop out in prominent ledges a few feet to a few tens of feet thick. These harder ledges stand out prominently on the intermediate slopes east of Farmers Creek where they form a sequence of steps between the slumped lower slopes and the capping rims of Mammoth Mountain and Wason Park Rhyolites. The upper third of the Farmers Creek Rhyolite is composed of crystal-rich welded tuffs and is exposed only along the canyon of West Bellows Creek; there, scattered outcrops protrude through the generally slumped and talus-mantled slopes.

Erosional windows cut through Farmers Creek Rhyolite west of Farmers Creek show an irregular underlying surface, and the whole unit pinches out laterally to the west against an older hill of Bachelor Mountain Rhyolite. The whole sequence of Farmers Creek Rhyolite dips 15°–30° N., and the north margin is covered by the more flat lying Mammoth Mountain Rhyolite, which overlaps the eroded edge of the tilted formation and rests progressively on the upper unit and then on the middle unit along the ridge between Farmers and West Bellows Creeks. Southward the upturned ledges of the tilted Farmers Creek Rhyolite are partly covered by postcaldera sedimentary rocks of the Creede Formation and lava flows of Fisher Quartz Latite that accumulated around the margin of the Creede caldera.

Most of the lower third of the exposed Farmers Creek Rhyolite is a soft cavernous-weathering pumiceous tuff breccia. The rock consists of massive unsorted layers of pyroclastic debris a few feet to a few tens of feet thick, which typically consist of fragments of pumice and foreign rocks ranging from small lapilli to boulder size, set in a finer ashy matrix. Some of the rocks are moderately welded, but most are only slightly welded or nonwelded. A few lenses of flow breccia(?) composed of red porphyritic lava occur in the lower part of the formation.

Several small dikes and irregular intrusive masses of black vitrophyre occur in the lower part of the Farmers Creek Rhyolite along the north side of Farmers Creek. One of the irregular masses is exposed over an area a thousand feet or more across. The vitrophyres are commonly devitrified irregularly to spherulites, which range from small nodules to irregularly rounded masses more than 1 foot in diameter.

The middle third of exposed Farmers Creek rocks is a heterogeneous assemblage of pyroclastic rocks and minor flow breccias. The conspicuous ledges consist of dark-brown densely welded tuffs that represent the more thoroughly welded central parts of ash flows that are generally 50–100 feet thick. The adjacent benches represent the softer tops and bottoms of these same units, as well as separate less welded ash-flow units. The different ash-flow units change markedly in appearance and degree of welding from place to place, particularly downdip from the ridge east of Farmers Creek toward West Bellows Creek. In the Farmers Creek basin, many of the harder rocks are subvitreous to lithoidal and lack megascopically obvious fragmental character. Laterally and downdip these same ledges change gradually to streaky eutaxitic welded tuffs whose obviously fragmental aspect is similar to that of the Campbell Mountain Member of the Bachelor Mountain Rhyolite. The softer pumice fragments in some of these less welded rocks weather out to give cavernous surfaces to some exposures.

Discontinuous lenses of an agglutinated breccia of homogeneous rock type, probably representing flow breccia, are interlayered here and there in the general ash-flow sequence.

The upper third of the exposed Farmers Creek rocks apparently consists largely of pink to gray, hard, lithoidal welded tuff. The surface is generally so covered by debris from overlying formations that relations between the different minor rock types are not known. Structures in the welded tuff are obscure; individual layers are internally massive and appear to be several tens of feet thick. The rock typically contains abundant fine-grained phenocrysts. A bed of coarse pumice breccia similar to that in the lower third of the formation separates the bulk of this part of the formation from the ledgy middle part of the formation.

The soft tuff breccia constituting the lower part of the Farmers Creek Rhyolite provides a very weak foundation beneath the hard overlying welded tuffs and lava flows in the general Farmers Creek and West Bellows Creek drainage areas. This has led not only to widespread recent slumping but also is believed largely responsible for the great topographic amphitheater than embays the outer caldera wall in this vicinity. For the most part, this amphitheater appears to have formed shortly after final caldera collapse, as remnants of the postcaldera Creede Formation and Fisher Quartz Latite (see pl. 1) still cover much of the floor. Avalanching from the caldera wall in this area in early postcaldera time spread mixed breccias widely over the floor of the calder (p. 42).

PETROGRAPHY

Porous, light-colored pumice breccia is the predominant rock type in the lower part of the Farmers Creek Rhyolite. Foreign rock fragments constitute 15–25 percent of the rock, and pumice blocks and lapilli and finer ash made up the remainder. The foreign rock fragments consist mainly of red to gray porphyritic lava of intermediate composition similar to that of many of the quartz latitic flows interlayered with the more abundant ash-flow units in and adjacent to the Creede district. Almost complete absence of distortion of the pumice fragments in most of the rock indicates that little compaction or welding has taken place. The original glass in the pumice and ash has been completely devitrified, and many of the pumice fragments have been converted to soft clay. Differential removal of these clayey masses by weathering gives many of the exposures a distinctly cavernous-appearing surface. Many of the foreign rock fragments have loosened and fallen out on weathered surfaces, where they add to the rough texture of the outcrops.

Massive dark-brown densely welded tuff is the most conspicuous rock type in the middle part of the Farmers Creek Rhyolite exposed in the Farmers Creek basin. It contains a few pumice fragments that can be recognized in hand specimens, but the matrix generally lacks conspicuous eutaxitic textures and megascopically appears nearly structureless. It contains 5–10 percent phenocrysts, which range from tiny chips to broken fragments as much as 2 mm across. The crystals are sanidine, plagioclase (oligoclase-andesine), biotite, and magnetite, and scarce pyroxene and amphibole. In thin section the matrix shows a tight, intricate maze texture formed by ash and pumice fragments that have molded and welded together into a dense rock. The original glass is completely devitrified, and axiolitic and spherulitic forms dominate. Tiny round to ovoid vesicles are widespread and commonly partly filled with tridymite.

Laterally this nearly structureless brown rock commonly passes into a lighter brown, obviously fragmental welded tuff exhibiting distinct eutaxitic textures. Flattened pumice fragments are easy to recognize in hand specimens, and the matrix shows the intricate maze texture typical of many moderately welded rhyolitic tuffs in the Creede district. With decreasing degree of compaction and welding, the rocks become more vesicular and show well-defined shards in thin sections; original tubular vesicles are readily recognized in the partly collapsed pumice fragments.

Foreign rock fragments constitute 5–10 percent of the middle part of the Farmers Creek Rhyolite and consist mainly of porphyritic lavas similar to those in the lower pumice breccia. Of special interest, however, are minor but widespread fragments of granitic texture that are thought to represent an intrusive phase of Farmers Creek Rhyolite.

The welded tuff in the upper part of the Farmers Creek Rhyolite is so rich in crystals that the pink to gray lithoidal matrix is obscured and appears structureless in hand specimen. Relict pumice fragments are apparent here and there in thin section, but in most rocks the matrix appears no more than sufficient to weld the aggregate of crystal fragments together. In order of decreasing abundance, the crystal fragments include plagioclase (oligoclase-andesine), sanidine, biotite, hornblende, pyroxene, sphene, quartz, and magnetite. The feldspars and biotite are predominant.

MAMMOTH MOUNTAIN RHYOLITE

DEFINITION OF FORMATION

The name Mammoth Mountain Rhyolite was originally applied by Emmons and Larsen (1923, p. 40) to what they believed was a single thick lava flow. An overlying unit consisting largely of softer tuffs was mapped separately. Larsen and Cross (1956, p. 147) later assigned all these rocks, as well as the underlying Farmers Creek Rhyolite, to the lower rhyolite member of their Piedra Rhyolite.

As redefined (Steven and Ratté, 1964), the Mammoth Mountain Rhyolite includes both units of Emmons and Larsen (1923) as well as all laterally equivalent rocks, which together form a great composite sheet of welded tuff and minor associated rocks.

DISTRIBUTION AND THICKNESS

Mammoth Mountain Rhyolite flanks most of the northern half of the Creede caldera from the high cliffs east of lower Goose Creek in the Wagon Wheel Gap district around to the Antelope Springs area south of Bristol Head. The only gap in this arc is across the central and western parts of the Creede district between Campbell Mountain and Shallow Creek, an area which apparently stood too high to be covered by the Mammoth Mountain ash flows. The formation wedges out northward against rough older topography along East Willow Creek and under Wason Park to the east and is nowhere present in the high mountains along the Continental Divide north of Creede. Any Mammoth Mountain Rhyolite that was deposited in the main caldera area has since subsided and been covered by younger rocks.

The full extent of the Mammoth Mountain Rhyolite east and west of the Creede district had not been traced at the time this report was prepared (1958). We know that it extends down the Rio Grande at least 10 miles from the east margin of the caldera and that it is present in the Clear Creek graben several miles southwest of Bristol Head, but these are in no way limiting figures.

The Mammoth Mountain Rhyolite filled the lower parts of an irregular, somewhat dissected fault-block topography in the East Willow Creek, Dry Gulch, and upper Farmers Creek areas and overlapped a local accumulation of lavas and breccias in the Huerto Formation southeast of Bristol Head (p. 33). The surface underlying the more widespread parts of the formation is too poorly exposed in the areas we mapped for its character to be ascertained in greater detail. The aggregate effect of the Mammoth Mountain ash-flow eruptions was to fill in many of the irregularities on the preexisting topography, and the widespread plain marking the upper surface of the formation provided a smooth base beneath the succeeding more tabular units.

In the Creede district the Mammoth Mountain Rhyolite is between 1,500 and 1,600 feet thick east of East Willow Creek where it fills a topographic trough, but the formation wedges out completely within half a mile northeast of the deepest exposed part of the trough. In the Farmers Creek–Bellows Creek area to the east, 400–500 feet of Mammoth Mountain Rhyolite is piled up on the local accumulation of Farmers Creek Rhyolite, and the Mammoth Mountain rocks appear to thicken northward down the dip of the underlying tilted layers of Farmers Creek Rhyolite. West of the caldera, Mammoth Mountain Rhyolite wedges out against older rocks north of Shallow Creek (pl. 1) and is only about 500 feet thick south of Bristol Head, where it overlies a local pile of Huerto rocks; however, it is more than 2,000 feet thick in the depression between these underlying accumulations. The more regular sheet of Mammoth Mountain Rhyolite in the Wagon Wheel Gap district east of the caldera seems to be 800–1,000 feet thick over wide areas.

GENERAL DESCRIPTION

The predominant highly welded tuff in the Mammoth Mountain Rhyolite is a resistant rock that typically forms massive outcrops or prominent cliffs. Subhorizontal joints accentuate the primary layered structures in most outcrops, and cliff exposures are divided into rude prismatic blocks by intersecting sets of steep joints.

Primary layering consists of compaction foliation derived by flattening of constituent pumice and shards and planar orientation of tabular phenocrysts in the crystal-rich rocks. The effect of underlying topography on compaction is illustrated in the canyon of West Bellows Creek, where the foliation in the lower cliffs of Mammoth Mountain Rhyolite appears to dip 20°–30° NE., parallel to the underlying layers of Farmers Creek Rhyolite. The dip decreases progressively upward in the Mammoth Mountain Rhyolite, and near the top of the formation, the foliation dips only 5°–10° NE., parallel to the primary layers in the overlying Wason Park Rhyolite.

Early phases of the Mammoth Mountain Rhyolite consist of crystal-poor ash flows, which are restricted largely to the East Willow Creek and Dry Gulch areas and to the area between Bristol Head and Shallow Creek. Some phases of the crystal-poor ash flows appear virtually identical with the hard, brown welded tuffs in the middle part of the Farmers Creek Rhyolite. Such rock is well exposed east of East Willow Creek, about opposite the Outlet Tunnel and Holy Moses mines, where about 1,200 feet of uniform hard welded tuff without obvious partings crops out. This rock grades upward into a layered section several hundred feet thick of less welded tuff with some harder layers (the rhyolite tuff unit of Emmons and Larsen, 1923, p. 44). Succeeding crystal-rich ash flows characterize the Mammoth Mountain Rhyolite in the Bellows Creek area on the northeast flank of the caldera and most of the rocks in the Bristol Head–Shallow Creek area.

The Mammoth Mountain Rhyolite is overlain in most places in the Creede district by the Wason Park Rhyolite, but local quartz latite lava flows intervene between these formations from Shallow Creek to Miners Creek and east of the Creede district in the palisades of intracaldera rhyolites. A thin discontinuous tongue of Huerto Formation separates the Mammoth Mountain and Wason Park Rhyolites near Bristol Head (p. 33).

PETROGRAPHY

The Mammoth Mountain Rhyolite ranges from crystal-poor welded ash flows containing 5–10 percent phenocrysts to crystal-rich welded ash flows containing 30–50 percent phenocrysts. The matrix of the densely welded tuff is typically lithoidal and reddish brown except for the black glass of the vitrophyre layer at the base of the formation. Relict pumice fragments are represented by varicolored streaks and dark hairline outlines in mottled crystal-poor rocks and by a very fine eutaxitic structure in the matrix of the crystal-rich rocks. The matrix of poorly welded phases of the Mammoth Mountain Rhyolite is light pinkish brown to white and may contain vesicular pumice fragments. Foreign lithic fragments rarely exceed 10 percent of this rhyolite, and they are generally smaller than 1 cm in diameter but have maximum dimensions of several centimeters. They are most abundant near the base of the formation, particularly in the basal vitrophyre, but they are also conspicuous in the less welded ash flows at the top of the Mammoth Mountain Rhyolite east of East Willow Creek. Fragments from the underlying La Garita Quartz Latite and Farmers Creek Rhyolite occur in the Mammoth Mountain along East Willow Creek, and the lower part of the formation in the Bristol Head–Shallow Creek area contains abundant fragments of dark lava, similar to the Huerto Formation, which intertongues with the Mammoth Mountain Rhyolite in that area.

Plagioclase phenocrysts predominate in the entire formation. Sanidine phenocrysts are common in the crystal-poor rocks but are absent in most of the crystal-rich phase. The plagioclase has an estimated average composition of sodic andesine, and zones range from An_{25} to about An_{50}. Most single crystals, however, show only small ranges in composition of about 5–10 percent anorthite. Some plagioclase phenocrysts in the crystal-rich rocks seem slightly more calcic in composition than phenocrysts of the crystal-poor rocks, but their average composition is probably still in the sodic andesine range. Sanidine phenocrysts are commonly twinned and may be rounded and embayed by the matrix. Some of the crystals are cryptoperthitic; others are conspicuously zoned and have rims more sodic than the cores. Biotite books are the prevalent mafic phenocrysts in all the Mammoth Mountain rocks, but green augitic clinopyroxene phenocrysts are characteristic of and restricted to the crystal-rich rocks.

The matrix of the Mammoth Mountain welded tuffs is completely devitrified above the basal vitrophyre. It consists mainly of cryptocrystalline spherulitic to granular aggregates assumed to consist largely of cristobalite and sanidine. Granophyric intergrowths occur in the interior of the larger relict pumice fragments, and tridymite is present in minor porous parts of the rock. Microtextures in the matrix range from a very tight maze texture in the densely welded tuffs to a vitroclastic texture in poorly welded tuffs. Much of the matrix in these rocks is obscured by a cloudy film of iron oxide, which gives the rock its reddish-brown color.

RHYOLITE NECK AND FLOW NEAR SHALLOW CREEK

Distinctive white to light-gray rhyolite forms a volcanic neck that is well exposed along the flanks of the canyon of Shallow Creek and a related lava flow that crops out discontinuously farther north along the steep east-facing slope between Shallow and Miners Creeks (fig. 2). This rock was erupted during the same general period as the widespread intracaldera rhyolite units; most of the exposed vertical extent of the neck cuts Mammoth Mountain Rhyolite, and the related flow is overlain by Wason Park Rhyolite.

The rock is a granular-appearing porphyry containing abundant glassy euhedral feldspar tablets as much as 5 mm long and scattered flakes of biotite set in a microcrystalline light-gray matrix. Thin-section study indicates that sanidine is the most abundant phenocrystic mineral and constitutes 15–25 percent of the rock; plagioclase (An_{30}) is nearly as abundant and constitutes 15–20 percent of the rock. Biotite phenocrysts are distinctly smaller and more sparse than the feldspar crystals and generally constitute only 3-5 percent of the rock. The remaining 60–70 percent of the rock consists of an aphanitic matrix with a pearly, subvitreous luster. In thin section the matrix appears as a finely cryptocrystalline aggregate containing irregularly formed spherulites.

The volcanic neck is exposed over a vertical range of about 1,400 feet. The lowest exposed rock near creek level has few vesicles, but higher in the neck the vesicles are progressively more abundant, and near the top of exposure some of the rock appears spongy under a hand lens. The related flow exposed farther north is irregularly vesicular, but it generally is not nearly as vesicular as some of the upper part of the neck.

Larsen and Cross (1956, pl. 1, p. 182) showed both the neck and the flow as a dike of Fisher Quartz Latite on their geologic map, but their text points out that the rock is similar to some of their Piedra Rhyolite and may belong to this unit.

WASON PARK RHYOLITE

DEFINITION OF FORMATION

The name Wason Park Rhyolite was given (Steven and Ratté, 1964) to a distinctive sheet of rhyolitic welded tuff that forms prominent cliffs on the north rim of the caldera for most of the distance from Wagon Wheel Gap southeast of Creede to the vicinity of Bristol Head southwest of Creede. It forms the floor of Wason Park, a high flat bench on the south flank of the La Garita Mountains northeast of Creede, which was designated the type area.

Wason Park Rhyolite is equivalent to the tridymite latite unit of Emmons and Larsen (1923, p. 45), and in its type locality and in most other places was included by Larsen and Cross (1956, p. 152–153) in the tridymite rhyolitic latite member of their Piedra Rhyolite. In places, however, particularly in the graben southwest of Bristol Head, exposures known by us to consist of Wason Park Rhyolite were included by Larsen and Cross (1956, p. 149) in the lower rhyolite member of the Piedra Rhyolite. This inconsistency resulted from an erroneous idea concerning the stratigraphic position of the Huerto Formation (p. 32), which Larsen and Cross (1956, p. 143) believed lay between their Alboroto and Piedra units but which we found to intertongue with both the upper part of their Alboroto and the lower part of their Piedra. The base of the Piedra thus varied in position from place to place, depending upon which tongue of Huerto was exposed locally.

DISTRIBUTION AND THICKNESS

Wason Park Rhyolite is largely coextensive with the Mammoth Mountain Rhyolite around the north margin of the Creede caldera, except that it appears to have once extended unbroken between Campbell Mountain and Shallow Creek, where the Mammoth Mountain is absent. Here, in the central part of the

Creede district, it covered low hills that projected slightly above the level of accumulation of the Mammoth Mountain Rhyolite. Farther north the Wason Park apparently wedges out and is absent under the western part of Nelson Mountain. The Wason Park Rhyolite overlaps the edge of Mammoth Mountain rocks and wedges out against older hills in the East Willow Creek and La Garita Mountains areas. A rim of Wason Park Rhyolite encloses at least the northern half of the Creede caldera, and we assume that the formation probably once extended across the caldera; any Wason Park rocks in the caldera, however, have subsided below present levels and have been covered by younger quartz latites.

Wason Park Rhyolite extends many miles east and west beyond the limits of the Creede district. We know that it extends as a continuous rim for at least 8 or 10 miles down the north flank of the canyon of the Rio Grande east of Wagon Wheel Gap, but we have no idea how far it spreads north or south of the canyon. We saw the formation here and there in reconnaissance traverses along the Rio Grande in the Clear Creek graben southwest of Bristol Head, in Sagauche Park, 20 miles northeast of Creede, and near the head of the West Fork of the San Juan River, 21 miles south of Creede.

Wason Park Rhyolite is generally 600–700 feet thick along the east-facing cliffs between Bristol Head and Miners Creek in the southwestern part of the Creede district; comparable thicknesses are present east of the Creede district in the Bellows Creek drainage area, and along the north flank of the canyon of the Rio Grande east of Wagon Wheel Gap. North and northwest of Creede the formation ranges in thickness from zero under Nelson Mountain to about 450 feet along Rat Creek, and to 250–300 feet on the west side of McKenzie Mountain.

GENERAL DESCRIPTION

Wason Park Rhyolite characteristically forms prominent cliffs at the edge of widespread high-level benches and tablelands. In part, this reflects the hardness and resistance of the formation, but it also reflects the contrasting relative softness of the immediately overlying rocks. Stripped, nearly flat surfaces on top of Wason Park Rhyolite, such as Wason Park and Blue Park east of the Creede district, are most extensive where the formation was once covered by soft tuffs of Rat Creek Quartz Latite. Cliffs of Wason Park are typically unbroken by soft zones or partings, but they are cut by intersecting steep joints that break the rock into rude, irregular columns.

A dense black vitrophyre 10–15 feet thick is generally present at the base of the Wason Park Rhyolite. This vitrophyre passes upward into a hard, red lithoidal welded tuff containing abundant phenocrysts and characterized by white to light-gray porous tridymitic streaks representing collapsed pumice fragments. The top of the formation locally retains a few feet to a few tens of feet of softer, less welded rock. This rock is poorly resistant and in most places has either been stripped from the top of the benches of Wason Park or is obscured by debris from overlying rocks.

The Wason Park Rhyolite was deposited on a nearly flat surface cut on the Mammoth Mountain Rhyolite throughout most of the Creede district. A variable thickness of poorly welded ash flows at the top of the Mammoth Mountain section and local associated fluvial deposits of reworked volcanic materials show that the underlying depositional surface is disconformable. A wedge-shaped tongue of quartz latite lava flows as much as 800 feet thick separates the Wason Park and Mammoth Mountain Rhyolites in the Wagon Wheel Gap district southeast of Creede, and a thin tongue of Huerto volcanic breccia 10 feet thick or less locally intervenes between the Wason Park and Mammoth Mountain Rhyolites along the ridge extending south from Bristol Head in the southwestern part of the Creede district (p. 33).

The Wason Park Rhyolite is almost unique in the Creede district in being a distinctive uniform rock. In contrast, converging rock types in many other formations constitute a major problem in fieldwork. Certain phases of Wason Park Rhyolite resemble typical crystal-rich Mammoth Mountain Rhyolite, and locally some of the upper rocks in the Mammoth Mountain contain white to gray collapsed pumice fragments similar to those that typify the Wason Park. These local complications generally can be resolved easily in the field and constitute problems only in complexly faulted areas or in areas of particularly poor exposure.

PETROGRAPHY

Typical Wason Park Rhyolite is a crystal-rich densely welded tuff containing 25–30 percent phenocrysts in a reddish-brown to brick-red lithoidal matrix. Streaked light-colored relict pumic fragments make up as much as 10 percent of the surface of some outcrops. Foreign lithic fragments are generally less than 1 cm in diameter and are concentrated toward the base of the formation; they may constitute 10 percent of the welded tuff in the vitrophyre and near the base of the devitrified zone, but they average less than 1 percent in the formation as a whole. Spherulites, several inches to a few feet in diameter, are conspicuous locally in the vitrophyre zone, and in one place the vitrophyre grades into devitrified welded tuff through a zone containing irregular lithophysae.

Most phenocrysts are plagioclase and sanidine; a few are biotite and magnetite; pyroxene and amphibole phenocrysts are scarce. The phenocrysts are uniformly distributed in the densely welded rocks and average about 25 percent of the Wason Park Rhyolite throughout the Creede area. Partially welded rocks at the top of this ash-flow sequence contain only about 15 percent phenocrysts.

The average composition of the plagioclase phenocrysts is estimated to be about An_{32} and ranges from An_{25} to An_{40}. The crystals are subhedral to euhedral, and the corners are generally broken. Smaller fragments and tiny chips are scattered through the matrix; but, on the whole, plagioclase crystals and other phenocrysts in the Wason Park Rhyolite are less fragmented than are those in many of the other welded tuffs in the Creede area.

Sanidine phenocrysts occur in Carlsbad twinned, slightly resorbed, homogeneous crystals in which evidence of compositional zoning or microperthitic structure is scarce. Sanidine from the basal vitrophyre about 10 miles west of Creede was analyzed by F. A. Gonyer (Larsen and others, 1938b, p. 418–421). It had a calculated composition of Or_{65}, Ab_{35}, An_3.

Biotite is the only common mafic phenocrystic mineral in the Wason Park Rhyolite, and it is generally oxidized and partly resorbed. Pyroxene crystals are colorless in thin section and monoclinic. Amphibole is scarce; green crystals are found in the vitrophyre zone, but brown oxyhornblende occurs elsewhere. By comparison with the underlying Mammoth Mountain Rhyolite, the Wason Park rocks are consistently rich in sanidine and poor in pyroxene phenocrysts.

The matrix of the Wason Park Rhyolite is completely devitrified except for the basal vitrophyre. The devitrified matrix is largely cryptocrystalline, but from the bulk rhyolitic composition of the rock, it is assumed to consist mainly of cristobalite and sanidine. Tridymite is common in porous parts of the rock. The matrix texture ranges from vitroclastic in partially welded specimens from the upper part of the formation to tight eutaxitic or maze-type texture in the more densely welded and compacted rocks lower in the unit. In some thin sections of the basal vitrophyre, the matrix can be resolved clearly into fragmental aggregates, but in others the fragmental character is obscure. Much of the matrix is clouded by opacite.

The relicts of collapsed pumice fragments range from 1-mm streaks to tabular blocks several feet long and 3 or 4 inches thick. In three dimensions they are largely pancake shaped. Near the base of the devitrified zone they appear as thin streaks that may be compact or contain a medial lenticular gas cavity. The degree of compaction decreases progressively upward in the formation, but vesicular structures in the pumice can be recognized only in poorly welded ash flows near the top. In thin section, the relict pumice is more coarsely crystalline than the enclosing matrix and consists of granophyric intergrowths of sanidine and cristobalite or tridymite, or both. Tridymite is abundant in open cavities in the pumice and other microlitic cavities in the matrix. Phenocrysts enclosed in the relict pumice are less broken than phenocrysts in the matrix and seem to be slightly less abundant, though they are the same in composition.

HUERTO FORMATION

DEFINITION OF FORMATION

According to Larsen and Cross (1956, p. 143):

> The name Huerto formation was furnished by the authors to Patton (1917, p. 20) for that group of quartz latites (called andesitic rocks) belonging to the Potosi volcanic series, and lying between the Alboroto and the Piedra formations. The name was again quoted by Emmons and Larsen (1923, p. 12) and by Knowlton (1923, p. 184).
>
> Since these reports were written, the formation has been more completely studied and, as it has been found to be made up almost entirely of dark quartz latites, the name Huerto quartz latite is proposed in place of Huerto formation. The Huerto quartz latite is therefore defined as that body of dark quartz latites that lies between the Alboroto and the Piedra rhyolites.

Larsen and Cross (1956, p. 10) also stated that in classifying the rocks, the system of Johannsen was used. As we have previously noted (Steven and Ratté, 1960a, p. 10), Larsen and Cross (1956, p. 10) used the term "quartz latite" as the extrusive equivalent of granodiorite, whereas according to Johannsen (1932, p. 308–310, 356), rhyodacite is equivalent to granodiorite, and quartz latite to quartz monzonite. Accordingly, we have determined most of the Huerto rocks to be rhyodacites according to the Johannsen system.

Our local studies along the east fringe of the main Huerto mass have shown that similar-appearing lavas accumulated from several different local centers. Our limited data do not now permit separating this complex accumulation into different mappable units, so for expediency we have referred to the accumulation as a whole as the Huerto Formation, undivided (Steven and Ratté, 1964).

Larsen and Cross (1956, p. 143) believed that the Huerto rocks accumulated during a separate period of volcanic activity between eruption of their Alboroto and Piedra Rhyolites. In contrast, we have found that the Huerto intertongues with units previously included in both their Alboroto and Piedra Rhyolites (fig. 4). The dark lavas capping the Wason Park Rhyolite from Bristol Head to Bulldog Mountain (pl. 1), thought by Emmons and Larsen (1923, p. 51) and by Larsen and Cross (1956, p. 153) to be a separate unit in their Piedra Rhyolite, are continuous with the upper part of the thick section of bedded Huerto breccias on the west face of Bristol Head. A locally derived accumulation of dark lavas and breccias on the lower slopes southeast of Bristol Head was called Conejos Quartz Latite (Larsen and Cross, 1956, p. 99), but our mapping indicates that it is merely a lower segment of the compound Huerto accumulation.

DISTRIBUTION AND THICKNESS

The main mass of the Huerto Formation lies southwest of the Creede district in the San Cristobal quadrangle, where three main centers of accumulation were reported by Larsen and Cross (1956, p. 143). In the Creede district, marginal rocks of the Huerto Formation intertongue complexly with welded tuff units west and southwest of Creede. The local accumulation of dark lavas and breccias southeast of Bristol Head encloses a tongue of quartz latitic welded tuff of unknown affinities and is capped by Mammoth Mountain Rhyolite. A tongue of breccia no more than 10 feet thick intervenes locally between the Mammoth Mountain and Wason Park Rhyolites along the ridge extending south from Bristol Head; this tongue is too small and discontinuous to be mapped separately (pl. 1). The Mammoth Mountain and Wason Park Rhyolites pinch out westward in an inaccessible cliff exposure into the thick mass of rudely bedded Huerto breccias along the west face of Bristol Head, and the Huerto breccias above the Wason Park Rhyolite form a tongue that extends northeastward as far as Bulldog Mountain.

No Huerto lavas or breccias were seen east of the Amethyst fault, which extends north-northwestward across the main producing area of the Creede district. Higher topography on the northeast or footwall side of this fault seems to have limited the eastward spread of the Huerto rocks.

The Huerto Formation thickens and thins markedly from place to place, and the different flow and breccia accumulations may originally have varied greatly in thickness, particularly in marginal areas such as the Creede district. More than 2,000 feet of rudely bedded Huerto breccia is exposed on the west face of Bristol Head above the Santa Maria Reservoir and west of the area we have mapped in detail. This is a minimum figure as the base of the section is not exposed. The local accumulation of Huerto rocks southeast of Bristol Head seems to be at least 800 feet thick, and here too the base of the formation is not exposed. The maximum preserved thickness of Huerto rocks on Bulldog Mountain is nearly 450 feet; the top of this section very probably was eroded somewhat before the succeeding tuffs were deposited, and the original thickness may have been somewhat greater.

GENERAL DESCRIPTION

The local accumulation of Huerto rocks southeast of Bristol Head consists largely of complexly interlayered flows and breccias. Contacts are typically irregular, and abrupt lateral changes from flow to breccia are characteristic. Some of the better exposed flows appear to be tongues of lava that flowed down rubbly slopes. Fine-grained white tuff was seen here and there throughout the fragmental rocks but generally could not be traced laterally from the individual exposures.

The great cliffs of Huerto that form the west face of Bristol Head consist, for the most part, of rudely bedded breccias. These were examined only briefly along a few widely spaced reconnaissance traverses; in these places, most of the breccia consists of unsorted angular fragments of dark lava ranging from sand size to boulders 6 feet in diameter. Bedding is very poor and commonly can be recognized best from a distance of several hundred feet or more. Some well-bedded sandy layers were seen here and there along our traverses, but these constitute only a very minor part of the main pile. The bedding appears nearly flat in most places, although in general it may be inclined a few degrees to the north. Similar breccias elsewhere (Anderson, 1933; Curtis, 1954) have been interpreted as deposits of volcanic mudflows, or lahars.

The Huerto rocks in the vicinity of Bulldog Mountain in the center of the Creede district constitute another complex local assemblage of flows and breccias. Most of the fragmental rock appears to be either flow breccia or aa breccia on the margins of flows. Exposures are too poor to allow positive identification, but the limited lateral extent of some of the flow units suggests that they may be tonguelike rather than widespread. Bedded breccia on Bulldog Mountain locally appears to dip a few degrees northeast; similar low dips are indicated by the distribution of local flows. The predominance of flows and flow breccias suggests a nearby source, but other than for a few small dikes along Rat Creek, no Huerto vent was located.

PETROGRAPHY

Most of the Huerto rocks in the Creede area are dark fine-grained porphyritic lavas. Some of the lavas are markedly vesicular, particularly those in the vicinity of Bulldog Mountain, but more commonly they are massive or contain a few small and irregularly distributed gas holes. The vesicular lavas are generally lighter colored than the massive flows and range from light-gray to red hues in the oxidized rocks.

In thin sections, the matrix is weakly birefringent and has a general index of refraction below that of Canada Balsam. Abundant microlites in the matrix consist largely of minute laths of andesine with small pyroxene granules and an opaque dust of what is probably magnetite. The plagioclase microlites are commonly alined to form good flow structure.

Phenocrysts in Huerto rocks in the Creede area are generally small and inconspicuous in hand specimen but constitute 15–25 percent of the rock. They are mainly plagioclase with 1–5 percent pyroxene and hornblende and 1–3 percent magnetite. Hornblende phenocrysts are notably common in the local accumulation southeast of Bristol Head. The plagioclase crystals have maximum dimensions of 1–3 mm; they are complexly zoned, and their average composition is estimated to be calcic andesine. Euhedral monoclinic pyroxene phenocrysts and other mafic phenocrysts are generally less than 1 mm long.

Huerto rocks are locally oxidized and propylitized. Plagioclase phenocrysts are altered to clays and carbonate; pyroxene and hornblende are altered to clays, carbonate, and chlorite. Hornblende may be oxidized to brown oxyhornblende or replaced by opaque ferritic material. Altered mafic phenocrysts are particularly prevalent in the Huerto rocks southeast of Bristol Head where hornblende is more abundant than pyroxene.

QUARTZ LATITE NECK AND FLOWS NORTH OF NELSON MOUNTAIN

A local volcanic neck and the flows and flow breccias associated with it are exposed north of Nelson Mountain and south of the Equity fault (pl. 1). The neck stands as a prominent local hill; but the marginally associated flows are poorly exposed, and their relation to the adjacent Rat Creek Quartz Latite is obscure. The neck and flows may be older than the Rat Creek rocks and may represent a partly exhumed hill; this possibility is supported by the apparent overlap of Rat Creek welded tuffs onto the north flank of the neck. On the other hand, the neck and flows may intertongue and be coeval with Rat Creek rocks; this alternative is suggested by mixed relations of the local flows and Rat Creek rocks in the landslide mass east of the neck.

The quartz latite in the local neck and flows is dark-to light-gray porphyry containing conspicuous euhedral plagioclase phenocrysts as much as 1 cm across and lesser biotite and pyroxene phenocrysts set in a finely granular matrix. The dark-gray porphyry commonly appears dense and structureless in hand specimen, although some shows pink streaks and lenses that give the rock a layered fluidal structure. The lighter colored rocks commonly show conspicuous flow features such as alined phenocrysts, irregularly vesiculated layers, streaky color, and textural differences. Flow layers in the neck dip 35°–65° centripetally inward. Attitudes in the marginal flows are irregular, and exposures are so poor that no consistent pattern could be discerned.

All thin sections of rocks from this local center are closely similar, except for differences in vesicularity and degree of oxidation and alteration of mafic phenocrysts. The plagioclase phenocrysts (An_{37-40}) constitute 20–35 percent of the rock; oxidized and altered biotite crystals, 3–6 percent; colorless augitic pyroxene, about 2 percent; and granular to euhedral magnetite crystals, 2–3 percent. The matrix, which makes up 55–70 percent of most rocks, is microgranular and most commonly has a fluidal texture shown by alined plagioclase laths and pyroxene granules set in a formless crystalline aggregate having a low index of refraction. The matrix of some of the rocks is cryptocrystalline and appears structureless.

RAT CREEK QUARTZ LATITE

DEFINITION OF FORMATION

Rat Creek Quartz Latite as redefined by Steven and Ratté (1964) is a widespread sequence of welded and nonwelded ash-flow tuffs, with a local near-vent accumulation of lavas and pyroclastic rocks. Both the base and top of the formation are marked by surfaces that show evidence of erosion, but no break was recognized in the sequence. A cone complex along West Willow Creek intertongues laterally with the more widespread pyroclastic rocks.

As originally defined by Emmons and Larsen (1923, p. 57–58), the name Rat Creek Quartz Latite was applied only to the welded and nonwelded tuffs in the upper part of this pyroclastic sequence. These men believed that the sequence comprised interlayered lava flows and tuffs, but they recognized that the rocks were closely related to the underlying tuff and gave the rocks the informal name "quartz latite tuff" (Emmons and Larsen, 1923, p. 54–57).

Larsen and Cross (1956, p. 153–156) generally followed Emmons and Larsen (1923, p. 53–57) in separating the lower, soft (nonwelded) tuffs from the upper, mixed welded and nonwelded tuffs. The lower unit was called the tuff member of their Piedra Rhyolite, and the upper welded and nonwelded tuffs were grouped with the overlying Nelson Mountain Quartz Latite of Emmons and Larsen (1923, p. 59) as the rhyolitic latite member of their Piedra Rhyolite. In the Creede district, equivalents of these so-called members meet at a gradational contact between welded and nonwelded tuff in the closely related sequence of ash-flow deposits we call Rat Creek Quartz Latite, whereas Larsen and Cross' upper rhyolitic latite member is broken by an erosional surface representing a significant break in deposition of the pyroclastic rocks.

DISTRIBUTION AND THICKNESS

Rat Creek Quartz Latite is now restricted to the northern part of the Creede district, where it is exposed along many of the higher ridges between East Willow and Miners Creeks. The formation consists largely of soft pyroclastic rocks that typically form debris-covered slopes beneath the highest cliff-forming welded tuff unit in the area (Nelson Mountain Quartz Latite). Much of the area underlain by Rat Creek Quartz Latite is covered by great landslides; abundant debris of soft tuff clearly indicates the presence of the formation beneath the slides, but the contacts generally cannot be closely located.

Nonwelded to slightly welded ash-flow tuffs of Rat Creek Quartz Latite are excellently exposed in Wheeler Monument, 8 miles east of Creede, and similar rocks are exposed beneath the hard capping of Nelson Mountain Quartz Latite on Table Mountain—a high mesa north of Bristol Head and west of the Creede district. Rat Creek rocks once spread many miles farther both east and west of the Creede district.

Rat Creek Quartz Latite varies considerably in thickness from place to place in the Creede district. It is 625–675 feet thick on the south nose of the ridge between Whited and East Willow Creeks (pl. 1) but wedges out completely about 1 mile farther north against rough underlying topography. Under Nelson Mountain, equivalent rocks range in thickness from slightly more than 700 feet on the east face to about 560 feet at the southwest corner of the mountain. Lava flows and pyroclastic rocks in a local cone complex along West Willow Creek are exposed over a vertical range of more than 800 feet, and neither the original top nor the base is exposed. The formation is absent a short distance north of the cone complex, having been removed by erosion shortly after it accumulated. Rat Creek welded and nonwelded tuffs are only about 540 feet thick at the south end of exposure on the ridge between West Willow and Rat Creeks, where they overlie a wedging tongue of Huerto Formation. Similar rocks crop out here and there over a vertical range of more than 950 feet on the west-facing slope above Miners Creek at the northwest corner of the mapped area (pl. 1); the true thickness there cannot be determined because of widespread landslides.

GENERAL DESCRIPTION

The Rat Creek Quartz Latite in the Creede area consists largely of pyroclastic rocks or reworked pyroclastic deposits; porphyritic lava flows are abundant in the local complex along West Willow Creek. The pyroclastic deposits range from densely welded to poorly welded and nonwelded tuffs that probably were deposited largely as ash flows, for they consist mainly of poorly sorted unbedded layers of chunk pumice and ash. Excellent exposures of Rat Creek Quartz Latite at Wheeler Monument, northeast of the Creede area, show some thin-bedded air-fall ash between thick ash-flow layers; on the southwest slopes of Nelson Mountain, exposures of laminated to thinly bedded sandy to silty tuffs indicate local reworking of the pyroclastic materials.

In the Creede district, the widespread sheet of Rat Creek Quartz Latite can be divided into three main parts: a lower nonwelded to slightly welded tuff unit; a middle, welded tuff unit; and an upper nonwelded to slightly welded tuff unit. The lower tuff is the thickest unit in the formation, generally ranging from 400 to 500 feet in thickness from Nelson Mountain westward. Most rock exposed in the scattered outcrops or in landslide blocks is soft massive tuff; the pumice fragments are generally somewhat flattened by compaction; and the matrix appears to range from nonwelded to slightly welded.

A layer of pink welded tuff 50–100 feet thick forms a prominent ledge in the middle part of the Rat Creek Quartz Latite in the north-central and northwestern parts of the Creede district. This layer thickens northeastward; it is about 150 feet thick on the east face of Nelson Mountain and nearly 400 feet thick on the ridge between East Willow and Whited Creeks, where the whole upper part of the Rat Creek Quartz Latite consists of welded to partially welded tuff. A black vitrophyre layer about 10 feet thick constitutes the lower part of this welded layer everywhere the base is exposed.

The upper tuff unit of Rat Creek Quartz Latite is generally obscured by talus and landslide debris from the overlying hard Nelson Mountain Quartz Latite. The lower part of the unit is exposed in a few places and generally consists of massive pumiceous tuff-breccia similar to that in the lower tuff unit. Scattered float of bedded sandy or silty tuff from the upper unit can be seen in many places. The upper tuff unit appears to range from 50 to 200 feet in thickness through most of the north-central and northwestern parts of the Creede district, but it is absent in the northeastern part of the district where its place is taken by the underlying thicker section of welded tuff.

A local cone complex consisting of a central plug of vitrophyre surrounded by lava flows and heterogeneous pyroclastic rocks constitutes Rat Creek Quartz Latite in the West Willow-Deerhorn Creeks area. Lava flows are most abundant in the northwestern part of the cone, where they predominate almost to the exclusion of tuffaceous rocks. The landslide mass west of West Willow Creek and northwest of the central plug consists largely of great slices of these rocks that have slumped downhill as coherent blocks; the rock types are well displayed in these blocks, although the structural relations have been jumbled. Soft tuffs of the upper, widespread unit of Rat Creek Quartz Latite overlie these flows just beneath the rim of Nelson Mountain Quartz Latite that caps the ridge west of West Willow Creek, and the flows appear to pass laterally south into a mixture of flows and pyroclastic rocks west of the volcanic neck. Rocks bordering the central volcanic neck on the south, east, and northeast form a heterogeneous assemblage of tuffs, volcanic breccias, and lava flows. Pyroclastic rocks apparently predominate in these areas, and reworked and bedded tuff is particularly abundant in the scattered float.

The body of Rat Creek Quartz Latite north of Nelson Mountain (pl. 1) consists largely of tuff and welded tuff identical with that in the lower, middle, and upper units in the widespread sheet of Rat Creek. These rocks, however, could not be fitted into the informal stratigraphic sequence established farther south and southwest, and thus they are included in the undifferentiated rocks of the formation.

The similarity of many of the rocks in the cone complex with those in the adjacent pyroclastic units, and the laterally intertonguing relations, suggest that this cone may mark at least one of the vents—perhaps one of the main vents—from which the widespread sheet of Rat Creek pyroclastic rocks was erupted.

PETROGRAPHY

Our petrographic study of the Rat Creek Quartz Latite is sketchy, in part owing to the heterogeneity of lithologic types in this formation. The crystal-rich welded tuffs are the most easy to collect and to study in thin section, and our data are biased accordingly.

The welded tuffs generally contain 20–30 percent phenocrysts in a light-pinkish-brown to light- or dark-gray lithoidal matrix. Foreign lithic fragments are common only in the lower part of the unit and are concentrated in the vitrophyre zone. Some of the Rat Creek rocks are compact and dense, but in general they are welded tuffs that are not so densely welded as the Mammoth Mountain and Wason Park Rhyolites beneath or the Nelson Mountain Quartz Latite above. Much of the Rat Creek welded tuff is a porous partially welded rock.

Plagioclase crystals are the most abundant phenocrysts in the welded tuffs, ranging in size from broken crystals less than 3 mm long to euhedral crystals 5 mm long. The estimated average composition of the plagioclase is sodic andesine. Biotite books 3 mm or less in diameter constitutes 2–5 percent of the welded tuffs. Other minor phenocrysts include sanidine, quartz, monoclinic pyroxene, green to brown hornblende, and magnetite. Small grains of apatite and zircon and somewhat larger ones of sphene are minor accessory minerals.

Except for the vitrophyre, the matrix of the welded tuffs is completely devitrified. Vitroclastic to eutaxitic textures are characteristic and are indicative of the fragmental origin of these rocks.

The nonwelded tuffs in the Rat Creek Quartz Latite are light-colored pumiceous rocks in which phenocrysts are less conspicuous and appear to be smaller and less abundant than in the welded tuffs. Undeformed pumice fragments range in size from microscopic pieces to blocks several inches in diameter. Lithic fragments are more abundant and more uniformly distributed than they are in the welded tuffs. Their size range is similar to that of the pumice fragments. The lithic fragments consist entirely of volcanic rocks: some are similar to rocks in the cone complex along West Willow Creek, but most cannot be identified with known volcanic units of the Creede district. Inclusions of a distinctive dark-purple fluidal rhyolite are common in the lower tuffs of the formation from the Creede district to Wheeler Monument to the northeast.

The rocks in the cone complex of West Willow Creek consist of a wide variety of colorful pyroclastic tuffs and breccias, red and bluish-gray porphyritic lava flows, and perlitic vitrophyre in a central plug. The phenocrysts in the flows and glassy plug are similar in abundance and composition to phenocrysts in the welded tuffs.

NELSON MOUNTAIN QUARTZ LATITE

DEFINITION OF FORMATION

As redefined by Steven and Ratté (1964), Nelson Mountain Quartz Latite includes all rocks in the former Equity Quartz Latite (Alboroto Group) and Nelson Mountain Quartz Latite (Piedra Group) of Emmons and Larsen (1923, p. 32–34, 59–60). These former units intergrade and form a single genetic unit to which the name Nelson Mountain Quartz Latite was extended. The name Equity Quartz Latite has been abandoned. The redefined formation constitutes the youngest intracaldera quartz latite unit in the northern part of the Creede district. Typical rocks in the lower and upper parts of the redefined Nelson Mountain Quartz Latite, although similar, can locally be distinguished by appearance and physical characteristics; in the Creede district we have found the gradation between them a convenient marker to show structure. Farther north, however, the gradation varies widely in stratigraphic position and thus cannot be used to define formal members.

Larsen and Cross (1956) did not mention the former Equity unit specifically but showed the area underlain by it as Alboroto Rhyolite on their geologic map (pl. 1). The upper rocks, corresponding to the former Nelson Mountain Quartz Latite (Larsen and Cross, 1956, p. 155–156), were combined with the welded tuffs in the underlying Rat Creek Quartz Latite as the rhyolitic latite member of their Piedra Rhyolite.

DISTRIBUTION AND THICKNESS

Nelson Mountain Quartz Latite characteristically forms hard mesalike caps on high ridges. In the Creede district it forms the flat top of Nelson Mountain and adjacent ridges. A large block extends to creek level in the downfaulted Deerhorn-West Willow Creeks area northwest of Nelson Mountain. Reconnaissance north of the mapped area has shown that a great mass of Nelson Mountain Quartz Latite is exposed in the northwestern part of the Creede quadrangle. Similar welded and nonwelded tuffs cap the flat-topped ridge at Half Moon Pass to the east and rest on the soft Rat Creek tuffs at Wheeler Monument. The capping on Table Mountain north of Bristol Head and west of the Creede district also consists of hard Nelson Mountain welded tuffs resting on soft Rat Creek tuffs.

Nelson Mountain Quartz Latite varies widely in thickness in the Creede district, largely owing to irregularities at the base of the formation and to subsequent erosion of the top. It wedges toward the northeast where it was deposited against an older hill of La Garita Quartz Latite. The remnant capping the ridge between Whited and East Willow Creeks is now a little less than 200 feet thick, which probably is nearly the original thickness; there the formation has a vitrophyric base and an only slightly welded top.

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The hard cap of welded tuff on Nelson Mountain is now about 250 feet thick; a few small patches of partially welded tuff cap the higher parts of the mountain, so this may be nearly the original thickness of the formation in this area. Nelson Mountain Quartz Latite at least 1,200 feet thick is exposed on the steep hillside southeast of the Equity mine where the formation filled a local valley; this section, however, consists entirely of lower rocks of the Nelson Mountain and the original thickness may have been significantly greater. The Nelson Mountain Quartz Latite capping the ridge between West Willow and Rat Creeks now has a maximum thickness of about 400 feet, but this figure too is a minimum, as all the original less welded rock at the top has been eroded.

GENERAL DESCRIPTION

The Nelson Mountain Quartz Latite in the Creede district consists entirely of crystal-rich welded tuff. Everywhere that the base of the formation is exposed, it is marked by a black vitrophyre zone 10–20 feet thick. The vitrophyre grades upward into dense devitrified welded tuff, which makes up the bulk of the unit. On some of the ridge tops, as between Whited and East Willow Creeks, the dense welded tuff grades into 50 feet or more of partially welded tuff at the top of the formation. Elsewhere most of the softer rock has been eroded away.

Eutaxitic rocks in the Nelson Mountain Quartz Latite, which are generally equivalent to the Equity Quartz Latite of Emmons and Larsen (1923), occur only in the thicker parts of the formation, as in the Deerhorn–West Willow Creeks area where the formation filled a local deep valley. Farther north, beyond the limits of our geologic map (pl. 1), the Nelson Mountain Quartz Latite forms a thick mass that consists predominantly of eutaxitic rocks. The upper part of the thicker sections and the thinner and more widespread sheet in adjacent areas consist of more structureless lithoidal rocks that grade upward locally into porous partially welded rocks. These rocks are generally equivalent to the original Nelson Mountain Quartz Latite of Emmons and Larsen (1923).

The more eutaxitic rocks are generally tan to gray or bluish gray and have a dense finely eutaxitic matrix. Flattened pumice blocks can be distinguished in most of these rocks, and in places they are conspicuous. Talus fragments are typically discoidal. In contrast, the overlying rocks are only weakly eutaxtitic, and the red to gray lithoidal matrix appears nearly structurelessin hand specimen. Talus fragments of the lithoidal rocks are typically blocky. The partially welded rock that locally caps the Nelson Mountain Quartz Latite is a soft porous pink rock identical with the widespread partially welded rock in the underlying Rat Creek Quartz Latite.

The transitions between eutaxitic and lithoidal densely welded rocks and between densely welded and partially welded rocks are gradational everywhere we have seen them, and they appear to reflect changes in degree of flattening and welding more than stratigraphic position. This is particularly true of these rocks north of the Creede district (pl. 1), where the vertical position of the eutaxitic-lithoidal transition appears to vary widely. In the Deerhorn Creek area, on the other hand, the gradation between eutaxitic and lithoidal rocks is locally marked by a zone a few feet thick containing streaks of black glass, which probably represents a partly formed vitrophyre zone between successive ash-flow accumulations. In this local area the transition may fairly closely reflect a stratigraphic horizon, and we have found it a convenient marker to indicate structure.

PETROGRAPHY

The basal vitrophyre of the Nelson Mountain Quartz Latite ranges from a black megascopically structureless obsidian to a dull dark-brown pitchstone in which the original fragmental character is easily recognized. The vitrophyre grades upward through a narrow zone a few feet thick into devitrified rocks in which the matrix changes progressively from glassy to microgranular and is strongly streaked by lenses of dark obsidian in a lighter colored microgranular rock.

Typical rocks in the lower parts of thick sections of Nelson Mountain Quartz Latite have a dark-gray matrix whose eutaxitic texture is clearly apparent. This texture is shown by clots and streaks of lighter colored material, characteristically containing euhedral phenocrysts, that probably represent collapsed pumice lapilli, as well as by fine intricately contorted streaks and filaments that represent smaller pumice fragments that collapsed and molded together during welding. This fine eutaxitic texture can be recognized by the unaided eye in many of these rocks and is easily seen with a hand lens in others. Weathering commonly accentuates the eutaxitic texture by bringing out color differences.

The transition into the upper, more widespread lithoidal rocks in the Nelson Mountain Quartz Latite is marked by a reduction in visible eutaxitic character of the matrix and by a general change in color to reddish or purplish gray. Some larger streaks and clots representing collapsed pumice lapilli are still easily discernible in the lithoidal rocks, but the finer eutaxitic texture is generally obscure and in many rocks cannot be detected even with a hand lens. Some rocks show a rude alinement of tabular feldspar crystals, but others are virtually structureless. Weathering commonly brings out a faint or latent layered structure, which is most clearly apparent near the tops of many rims. The abrupt decrease in degree of welding noted locally near the top of the Nelson Mountain Quartz Latite is accompanied by a general decrease in size and abundance of phenocrysts.

Small fragments of fine-grained volcanic rocks are widespread in Nelsón Mountain Quartz Latite; most of these are of various unrelated rock types, but some may be related to Nelson Mountain rocks. Most fragments are less than 2 cm in diameter, and they generally constitute only a few percent or less of the rock.

Phenocrysts constitute 20–45 percent of the Nelson Mountain Quartz Latite and average a little more than 30 percent; the phenocrysts comprise predominant plagioclase, lesser biotite, and minor or accessory pyroxene, quartz, sanidine, hornblende, and magnetite. They range from small angular chips to well-formed euhedral crystals, but most are broken or deformed crystal fragments. The crystal fragments in the lower and middle parts of the formation show all gradations in size from minute chips to crystals 5 mm long, and the fragments are fairly evenly distributed throughout the size ranges. Toward the top of the formation, however, smaller sized fragments are distinctly more abundant than they are lower in the formation and predominate over the larger sized fragments.

The plagioclase phenocrysts are sodic andesine that has an average composition of An_{36}. Many of the larger plagioclase tablets are euhedral or nearly euhedral, particularly those in former pumice lapilli in the welded tuff, but most smaller grains are crystal fragments. Biotite is the most abundant mafic mineral in the Nelson Mountain Quartz Latite and generally averages about 4 percent of the rock. Most crystals are somewhat oxidized and burned appearing. Many grains are crowded with secondary ferritic granules, and some are strongly resorbed.

Subhedral to euhedral prisms of colorless augitic pyroxene are widely but irregularly distributed in the Nelson Mountain Quartz Latite, and many of these grains are partially altered to carbonate and clay, particularly in the lower, more eutaxitic rocks. Microscopic study of the rocks indicates that much of the apparently erratic distribution may have resulted from mechanical loss of partially altered pyroxene grains during preparation of the thin sections.

Hornblende is a trace phenocrystic constituent in many Nelson Mountain rocks and, where present, generally forms small prisms less than 1 mm long. Hornblende in the chilled basal vitrophyre is green, but in the overlying rocks it is brown oxyhornblende. Many hornblende crystals are so thoroughly altered that they are difficult to distinguish from highly oxidized biotite crystals.

Magnetite is present in all Nelson Mountain rocks and ranges from equant phenocrysts to fine dust in the matrix. Much of the secondary ferritic material in the oxidized biotite and hornblende may be magnetite.

Sparse grains of sanidine were found in nearly every thin section of Nelson Mountain Quartz Latite studied, and they constitute from 1 to 3 percent of about half the thin sections. One specimen contained nearly 7 percent sanidine. Sanidine crystals are generally among the largest phenocrysts present, and most of those seen are 1 mm or larger in diameter. Most sanidine grains are corroded and deeply embayed by the matrix.

Quartz grains were seen in about half the thin sections of Nelson Mountain Quartz Latite; some of these are stout doubly terminated crystals, but more are rounded or are irregularly embayed by the matrix.

The matrix of the Nelson Mountain Quartz Latite consists of welded fragments of pumice and ash that range in size from dust to lapilli and include some pumice blocks several inches in diameter. The relative proportions of the different-sized fragments change from the base of the formation upward, finer fragments being distinctly more abundant near the top. Except in the basal vitrophyre zone, the matrix of the Nelson Mountain welded tuff is completely devitrified to a cryptocrystalline to microcrystalline aggregate. Spherulites and axiolites are common in the finer parts of the matrix. In contrast, the larger relict pumice fragments have a relatively coarse devitrification texture, which serves to accentuate the microeutaxitic structures in thin sections of even the most massive Nelson Mountain rocks. Vitroclastic texture is common in thin sections of partially welded rocks at the top of the formation.

SNOWSHOE MOUNTAIN QUARTZ LATITE

DEFINITION OF FORMATION

Snowshoe Mountain Quartz Latite was the name given (Steven and Ratté, 1964) to the mass of quartz latite welded tuffs and minor tuffs that constitutes most of the core of the Creede caldera (fig. 4). Except for surficial deposits and minor talus and rock-fall breccias from the caldera walls, the exposed core consists entirely of rocks typical of this formation.

Larsen and Cross (1956, p. 132, 138) believed that the great mass of quartz latite under Snowshoe Mountain was a local accumulation, possibly a single large flow, in the upper rhyolitic latite member of their Alboroto Rhyolite. In contrast, we have found the Snowshoe Mountain Quartz Latite to be among the youngest of the intracaldera units and more equivalent to the upper part of the Piedra Rhyolite of Larsen and Cross (1956, p. 144–155).

RELATIVE AGE

Intertongued breccias containing fragments of Wason Park Rhyolite indicate that at least the upper 2,000 feet of Snowshoe Mountain Quartz Latite, and probably all Snowshoe Mountain rocks, are younger than the Wason Park. Thus, the Snowshoe Mountain Quartz Latite is possibly a time equivalent or a partial time equivalent of the Rat Creek and Nelson Mountain Quartz Latites in the northern part of the Creede district, although indirect evidence suggests that it probably is even younger. Although the rocks in each of these three quartz latitic formations are closely similar in general appearance, they differ in significant minor aspects and accumulated under different local conditions. The Rat Creek and Nelson Mountain Quartz Latites seem to have erupted from vents north of the caldera and spread widely in adjacent areas. No barrier is known that would have excluded these formations from the caldera area; yet equivalents have not been recognized in the core of the caldera, and, if present, they must be covered by the Snowshoe Mountain Quartz Latite. The tongues of avalanche breccia that project into the Snowshoe Mountain Quartz Latite along the west side of the caldera indicate that subsidence and accumulation progressed concurrently and that a caldera wall exposing rocks as old as the Wason Park Rhyolite existed at least now and again while the Snowshoe Mountain Quartz Latite was being erupted. Similar avalanche breccia caps the Snowshoe Mountain Quartz Latite (p. 42) and indicates that this formation was the last intracaldera unit to be erupted prior to doming of the caldera core and thus that it probably is the youngest intracaldera unit in the area.

DISTRIBUTION AND THICKNESS

So far as is known, the Snowshoe Mountain Quartz Latite is restricted to the core of the Creede caldera. The entire outer rim of the caldera has been mapped in detail, but neither this mapping nor widespread reconnaissance in adjacent areas has revealed equivalent rocks. The previously cited evidence (p. 39) that indicates concurrent subsidence and accumulation within the confines of the existing caldera walls suggests that the formation may never have extended beyond the limits of the caldera.

The core of the Creede caldera has been domed and faulted, so that considerable thicknesses of the Snowshoe Mountain Quartz Latite are exposed on the inner edges of the tilted fault blocks, but at no place was the base of the formation seen. Only a partial section can be measured at any given place, but total exposed thicknesses can be estimated by combining adjacent partial sections. At least 4,000 feet and possibly 6,000 feet of Snowshoe Mountain Quartz Latite unbroken by faults can be estimated in both the northeast and northwest flanks of the caldera core.

GENERAL DESCRIPTION

The Snowshoe Mountain Quartz Latite is a thick sequence of crystal-rich welded tuff. Most of the rock is densely welded, but an upper unit of partially welded tuff at the top of the formation has been traced around the north and east margins of the caldera core. Other slightly welded to nonwelded tuff partings, commonly containing foreign rock fragments, are present in the sequence, particularly toward the margins of the accumulation. These are all discontinuous, and all those traced died out into apparently unbroken welded tuff within distances of a few hundred feet to several miles. Toward the center of the caldera, sections as much as 3,000 feet thick, which are nearly total exposures, have no nonwelded or poorly welded partings.

Outcrops of Snowshoe Mountain Quartz Latite generally form ledges and give the formation a distinctly layered aspect as viewed from a distance. Some of the ledges represent less welded tuff partings, but commonly the rocks in successive ledges differ only slightly if at all, and much of the apparent layering is due to irregular joints that die out laterally.

Tongues of mixed breccias consisting of debris from the caldera walls project into Snowshoe Mountain welded tuffs along the west flank of the caldera core. These tongues wedge out, and their position is marked first by soft tuff partings which in turn pass into unbroken welded tuff toward the center of the caldera.

The most consistent difference in the Snowshoe Mountain Quartz Latite, and the difference most helpful in delineating structure and stratigraphic position, is the change from densely welded to partially welded tuff at the top of the sequence. The "upper soft," as it was termed in the field, has been mapped on the northwest flank and all around the east half of the caldera core, and similar and probably equivalent partially welded tuffs are at the top of the Snowshoe Mountain rocks in many fault blocks in the complex graben zone that extends south across the caldera core (pl. 1).

The rocks on the northwest flank of the caldera core have distinctly smaller crystal fragments than have equivalent rocks in the northeast flank of the core. The change is gradual over several miles, however, and the only differences that could be discerned in any given part of the transition were local alternating gradational layers showing contrasting grain size. Almost all rocks toward the center of the core, and deeper stratigraphically in the core, have the coarser phenocrysts typical of those in rocks of the northeast flank.

These general relations have been interpreted as indicating that many successive ash flows accumulated so rapidly that they welded together and cooled as a unit; locally, however, the tops of earlier ash flows were sufficiently cool to remain as discontinuous less welded partings in the sequence. The local differences in degree of welding or in abundance or size of crystals thus probably reflect minor differences between successive ash flows. The interleaved tongues of breccia derived from the caldera walls along the west margin of the caldera core also reflect concurrent subsidence and episodic eruption of ash flows in the caldera.

Evidence for the welding together of successive ash flows can be seen in a cliff south of Sevenmile Bridge, where discontinuous streaks of laminated tuff several inches thick, probably of air-fall origin, are exposed along two horizons 15 feet apart in densely welded Snowshoe Mountain Quartz Latite. The laminated tuff is just as completely welded as the adjacent material, and the levels on which it occurs are not marked by any physical breaks. This material appears to have been fused by the heat of the succeeding ash flows and welded with the adjacent rocks into the solid mass now exposed.

PETROGRAPHY

Snowshoe Mountain Quartz Latite is a drab, crystal-rich welded tuff that so closely resembles the upper lithoidal rocks of Nelson Mountain Quartz Latite that hand specimens from the two units cannot be distinguished with confidence. The same phenocrysts occur in both units, although in slightly different proportions, and the matrices commonly appear identical. The units differ mainly by abundance of phenocrysts; Snowshoe Mountain rocks consist, on an average, of nearly half phenocrysts, whereas lithoidal Nelson Mountain rocks average only about a third phenocrysts. As a result, Snowshoe Mountain rocks have a distinctly granular aspect, and the matrix, except for giving a general color to the rock, is commonly obscure.

The partially welded tuff at the top of Snowshoe Mountain Quartz Latite and along the local partings in the formation is a porous irregularly welded light-pink to gray rock that differs from the associated dense rocks only by degree of compaction and welding. It is virtually identical in appearance with the partially welded rocks at the top of the Nelson Mountain Quartz Latite or in the Rat Creek Quartz Latite.

Easily recognized pumice lapilli are common in the softer, less welded parts of Snowshoe Mountain Quartz Latite. As degree of compaction and welding increases, the pumice fragments are progressively flatter and the internal structures progressively more obscure. Irregular masses that probably represent former pumice lapilli can be recognized here and there throughout the hard Snowshoe Mountain welded tuff; these are closely similar in appearance to the adjacent parts of the rock, but they generally contain larger and more uniform euhedral phenocrysts in a less cluttered matrix. These masses appear now as indistinct clots whose borders are poorly defined.

Small angular chips and lapilli of foreign rock types, generally porphyritic fine-grained red volcanic rocks, are widespread in Snowshoe Mountain Quartz Latite but generally constitute only a small fraction of a percent of the rock.

For convenience in field mapping, the contact between densely welded and partially welded tuff in the Snowshoe Mountain Quartz (pl. 1) was assumed that place in the transition where the rock first changes from firm and compact to somewhat porous and punky. Thus, on the geologic map all rocks showing intermediate degrees of welding and compaction are shown with the softer phases of the formation.

Densely welded tuffs in the Snowshoe Mountain Quartz Latite, regardless of stratigraphic position, are even-textured rocks containing conspicuous feldspar and biotite phenocrysts and minor pyroxene, quartz, and hornblende phenocrysts set in a reddish-tan, purplish-gray, or dark-gray matrix. The phenocrysts vary in average size from place to place, but they are always abundant and are the characterizing feature of the rocks. The phenocrysts show all gradations in size from microscopic chips to euhedral crystals as much as 5 mm long.

Plagioclase phenocrysts on the average make up about 35 percent of Snowshoe Mountain rocks. The larger grains are generally euhedral or nearly euhedral, but most smaller grains are broken fragments which normally are sufficiently abundant to give the rock a gross fragmental aspect. Biotite flakes commonly are deformed or broken, and most are oxidized and altered in some degree. The grains commonly are oxidized red brown and are crowded with ferritic granules and colorless mica. Many grains are completely altered to opaque granular aggregates showing only the external form of the original mica.

Most hornblende is oxidized red brown and contains many secondary opaque granules along margins and cleavage planes. Some grains are clear and nearly unaltered, however, and range from green to light brown.

Light-green prisms of augitic pyroxene are widespread in the Snowshoe Mountain Quartz Latite; most of these are clear and fresh, but locally they are partially altered to carbonate or clay.

Hornblende and pyroxene show complex relations in Snowshoe Mountain rocks. Both minerals form euhedral crystals that probably represent primary crystallization from the magma. In addition, many hornblende grains have reaction rims of fine magnetite and pyroxene, and other formless granular aggregates of pyroxene and magnetite contain poikilitic remnants of hornblende. A few grains of pyroxene were seen that were overgrown with hornblende.

Quartz occurs in angular fragments and in deeply embayed grains commonly showing some crystal faces whose form indicates former short doubly terminated prisms. Sanidine is in angular fragments or in embayed grains that range from irregular formless masses to well-formed rectangular crystals.

The matrix of the Snowshoe Mountain Quartz Latite is completely devitrified; no glassy rocks were found in this formation. The matrix of all the densely welded tuffs shows at least some microeutaxitic texture, and in most of these rocks it is conspicuous. Collapsed former pumice lapilli are clearly defined. Devitrification has produced cryptocrystalline to microcrystalline aggregates and a fine cloud of opacitic granules. The pumice lapilli are somewhat coarser grained and less clouded. Microspherulites are common in some rocks, particularly in those that are partially welded, and the eutaxitic textures are largely destroyed.

MIXED BRECCIAS IN THE CALDERA CORE

Chaotic breccias, consisting of fragments from rock units exposed in the caldera walls, are intertongued with Snowshoe Mountain Quartz Latite along the west flank of the caldera core and form the tops of some fault blocks in the complex graben zone that cuts south across the middle of the core. Two facies of these breccias have been mapped (pl. 1); one consists largely of fragments derived from the Huerto Formation, and the other consists largely of fragments from the intracaldera rhyolite units. These breccias probably represent talus and avalanche debris that cascaded from the caldera walls during and after caldera subsidence. The intertongued breccias are evidence for postulating subsidence concurrent with accumulation of Snowshoe Mountain Quartz Latite, and the breccias capping the fault blocks indicate widespread distribution over the floor of the subsided block.

The intertongued breccias along the west flank of the caldera are unsorted, chaotic accumulations that are either structureless or form rude, indistinct ledges rather than good beds. Fragments range from boulders several feet in diameter down to dust in size and generally are angular or subangular. Typically the fragments consist of heterogeneous dark-drab flow rocks from the Huerto Formation, but there are also widely scattered fragments of rhyolite. Most rhyolitic fragments are of Wason Park Rhyolite, and in places these fragments predominate almost to the exclusion of all other rock types. Fragments of Mammoth Mountain Rhyolite, possible Willow Creek rhyolite, and other unrecognized rock types are widespread but minor in abundance. Fragments of the dark flow rocks and of the different rhyolites are common in the local tuff partings that separate some Snowshoe Mountain Quartz Latite ledges in the area just east of the intertongued mixed breccias.

Some local concentrations of Wason Park Rhyolite fragments form discrete bodies in the breccia tongues. In places these appear to grade into the adjacent breccias through zones of mixed fragments, but in other places the local bodies are sharply bounded. The largest mass of fragmented Wason Park seen, and the only one shown separately on the geologic map (pl. 1), extends diagonally across the southernmost tongue of mixed breccia mapped. This body consists almost entirely of shattered Wason Park Rhyolite and contains only a few scattered fragments of dark flow rocks; it is overlain locally by a thin, 1- or 2-foot bed of nonwelded tuff of Snowshoe Mountain Quartz Latite; adjacent breccias consist largely of Huerto rock types. We interpret this body as a mass that broke from the wall of the caldera and fell as a unit to its present position in the debris tongue. Although it was highly shattered in the process, it remained as a discrete body whose apparently discordant position represents conditions of accumulation in an avalanche-talus debris tongue.

The mixed breccias capping fault blocks in the central graben consist largely of Farmers Creek, Mammoth Mountain, and Wason Park Rhyolites and contain lesser quantities of Willow Creek rhyolite and a porphyritic quartz latite typical of lava flows interlayered with the intracaldera rhyolites in the Wagon Wheel Gap district east of Creede. Another distinctive minor constituent is a white rhyolite flow rock identical with that in the Point of Rocks volcano discussed later (p. 43). Farmers Creek Rhyolite, or a phase of Mammoth Mountain Rhyolite closely resembling the Farmers Creek Rhyolite, is by far the most abundant rock type in these mixed breccias.

The breccias in the central graben consist of unsorted, highly broken angular fragments as much as several feet in diameter set in a more finely broken matrix of similar material. The breccias commonly are shattered coherent aggregates resembling tectonic breccia rather than accumulations of individual fragments characteristic of reworked or mudflow breccia. In some places, fragments from several different formations are highly mixed, but more commonly one or another rock type predominates at any given location. The major constituents change from place to place both vertically and laterally in a body of breccia, and the change generally appears fairly abrupt, as though the breccia consists of many local concentrations of contrasting composition.

Although the concentrations of different rock types appear randomly mixed in most places, one remnant of breccia consists of a lower unit 20–30 feet thick of shattered Farmers Creek or Mammoth Mountain Rhyolite, a middle unit of 20–30 feet thick of shattered Wason Park Rhyolite, and an upper unit of 10–15 feet thick of broken quartz latite flow rock identical with that in a flow that now caps Wason Park Rhyolite east of West Bellows Creek. The rocks in this remnant are in proper stratigraphic succession, although the units represented are greatly thinned.

The mixed breccias near the center of the caldera core were probably derived largely from a source to the northeast, as the proper assemblage of major rock units is found only in the Farmers-Bellows Creeks area. In addition to having the required source rocks, the lower part of the Farmers Creek Rhyolite contains weak tuffaceous rocks underlying hard welded tuffs in the overlying Farmers Creek, Mammoth Mountain, and Wason Park Rhyolites. These rocks constitute a weak structural assemblage that is particularly susceptible to avalanching and landsliding. These mixed breccias on the floor of the caldera at least 5 miles from the nearest probable source can be explained as resulting from catastrophic rockfalls similar to those described from Elm, Switzerland (Heim, 1882); Frank, Alberta (McConnell and Brock, 1904) (both summarized in Sharpe, 1938, p. 77–80); Saidmarreh, Iran (Harrison and Falcon, 1937); and Madison Canyon, Mont. (Hadley, 1960). However, structural-topographic conditions, including a newly exposed and presumably steep caldera wall consisting of hard rocks above a weak base, would favor such rock falls. Earthquakes that probably accompanied final caldera subsidence and attendant graben faulting may have been major contributing factors.

POINT OF ROCKS VOLCANO

Remnants of a small rhyolite volcano crop out along the northwest flank of the caldera core, just southeast of Sevenmile Bridge. The lower part of this accumulation, including part of the underlying vent, is well exposed on steep slopes and cliffs flanking a prominent knob above the Rio Grande known locally as the Point of Rocks.

Present remnants of the volcano consist of massive rhyolite breccia, probably part of a domal protrusion, that is continuous into the upper part of the neck through which it was extruded. The material is pervasively broken; angular fragments ranging in size from dust to blocks several feet in diameter are stuck together into a coherent unsorted aggregate that shows all degrees of fragmentation. Exposed contacts of the neck and adjacent parts of the pile are grooved and striated. These markings indicate that movement took place after the lava had chilled enough to break. Extrusion of nearly solid lava probably accounts for much of the pervasive brecciation.

A younger dike of coarsely porphyritic rock, probably of Fisher Quartz Latite, is exposed along part of the south margin of the neck.

The Point of Rocks volcano consists of light-gray to white irregularly altered rhyolite containing conspicuous feldspar and sparse biotite phenocrysts set in a somewhat fluidal-textured microgranular matrix. Fresh glassy-appearing sanidine tablets are the most abundant phenocrysts, but they generally constitute less than 10 percent of the rock. Most former plagioclase phenocrysts are now represented by clayey pseudomorphs, and the biotite is generally highly oxidized and crowded with ferritic granules. Some rocks contain 1 or 2 percent disseminated pyrite, and others are somewhat argillized and appear earthy on fresh breaks. Many fractures are partly healed with quartz.

Larsen and Cross (1956, pl. 1) included the Point of Rocks volcano in the Fisher Quartz Latite. Our work, however, has shown that it is older than the Creede Formation and was probably active late in the period of caldera subsidence or shortly following subsidence. The rhyolite breccia rests unconformably on soft, nonwelded to slightly welded tuff at the top of the Snowshoe Mountain sequence. This relation indicates that the breccia is younger than the main caldera fill. On the other hand, because fragments of identical white rhyolite occur in the mixed breccias now found at the tops of local fault blocks in the domed core of the caldera, the eruption apparently preceded doming.

Pebbles of the white rhyolite are abundant in the reworked conglomerates that characterize the marginal parts of the Creede formation all along the west flank of the caldera core. This probably indicates that rhyolite from the Point of Rocks volcano was once widespread over at least the western parts of the caldera floor and that the present remnants represent only a small near-vent part of the original accumulation.

FISHER QUARTZ LATITE

DEFINITION OF FORMATION

Prior to our work in the Creede district, the name Fisher Quartz Latite (or latite-andesite) was applied by Larsen and Cross (1956, p. 172) to a sequence of local accumulations of coarsely porphyritic flows and breccias in the San Juan Mountains which they believed to be younger than the Potosi Volcanic Series and the Creede Formation and older than the Hinsdale Formation. Bodies of rock assigned to this formation occur through the central San Juan Mountains from the Lake City area 24 miles west-northwest of Creede, through the vicinity of Creede to the Summitville area 35 miles southeast of Creede (Steven and Ratté, 1960a). Larsen and Cross (1956, p. 172) stated that these rocks have certain textural and mineralogical characteristics that distinguish them from rocks of the Potosi Volcanic Series and that at different places they rest unconformably on the Silverton Volcanic Series, the Potosi Volcanic Series, and the Creede Formation.

Our work in the Creede district and adjacent areas has shown that this earlier concept of the relations of Fisher Quartz Latite must be revised in significant aspects (Steven and Ratté, 1964). The rocks in the type area of the formation on Fisher Mountain were erupted after the last main subsidence of the Creede caldera and are definitely younger than the rocks that Larsen and Cross called the Potosi Volcanic Series. All those rocks in the Creede district and adjacent areas that we have included in the Fisher Quartz Latite have comparable relations. In the Wagon Wheel Gap area and south along the flanks of Goose Creek, southeast of Creede, flows of Fisher Quartz Latite are intertongued throughout the Creede Formation; these were erupted concurrently with Creede sedimentation after the last caldera subsidence and following doming of the caldera core. Although the evidence is not so clear cut, the Fisher flows on the west flank of the caldera core also appear to be older than remnants of the Creede Formation exposed nearby. Some dikes of probable Fisher Quartz Latite appear to cut Creede beds between Shallow and Miners Creeks, but here again the evidence is not conclusive. The evidence for the Fisher being equivalent in age to the Creede Formation directly contradicts Larsen and Cross' (1956, p. 168, 172) belief that the Fisher lavas flowed down deep valleys cut into the Creede.

Many Fisher rocks in the Wagon Wheel Gap area appear identical with coarsely porphyritic flows interlayered with adjacent intracaldera welded tuffs (Piedra Rhyolite of earlier terminology), and Larsen and Cross (1956, pl. 1) included several of these older flows in their Fisher Quartz Latite. The only clear distinction between these different flows is in age relative to caldera subsidence. Thus the contention of Larsen and Cross (1956, p. 172) that Fisher Quartz Latite is distinct from all rocks in the Potosi Volcanic Series in time and petrographic character does not appear tenable in the Creede area, and in our opinion the Fisher Quartz Latite eruptions here represent merely a continuation of a related sequence of volcanic events.

If correct, this conclusion raises questions concerning the correlation of other isolated bodies of coarsely porphyritic lava that have been called Fisher Quartz Latite. For example, the mass of so-called Fisher near Summitville rests unconformably on older units in the Potosi Volcanic Series of Larsen and Cross (1956), chiefly the Conejos Formation (Steven and Ratté, 1960a, pl. 1), and no way is now known for determining its age with respect to the local sequence near Creede. Conceivably it might be the same age as the postcaldera flows and thus would truly correspond to the Fisher Quartz Latite at its type locality, or it might be equivalent to similar earlier flows interlayered with the intracaldera welded tuffs near Wagon Wheel Gap or be completely independent in time and genesis.

DISTRIBUTION AND THICKNESS

Most Fisher Quartz Latite near Creede was erupted near the margin of the caldera or along the graben extending outward from the caldera. The largest body underlies the Fisher Mountain area south of the caldera (Larsen and Cross, 1956, p. 173 and pl. 1); another substantial body accumulated in the Wagon Wheel Gap area 5–8 miles southeast of Creede. The largest body of Fisher Quartz Latite in the Creede district (pl. 1) caps upper McKenzie Mountain between Rat and Miners Creeks; most of this body consists of one large flow that can be traced continuously into the volcanic neck through which it was erupted. A series of related dikes extends south-southeast from the vicinity of the neck to the caldera margin. A smaller body of Fisher Quartz Latite, consisting of at least two flows and possibly, a volcanic neck, is exposed along the west flank of the caldera core 7 miles southwest of Creede. Sparse small dikes, probably of Fisher Quartz Latite, are scattered through the western and southwestern parts of the Creede district, but most would not be apparent at the scale of our geologic map (pl. 1).

Fisher Quartz Latite flows are of viscous lava that was erupted on irregular topography, and the resulting local accumulations vary in thicknesses and form. The flow capping the ridge between Rat and Miners Creeks is nearly 1,000 feet thick just east of its vent, but it wedges out within 1 mile to the northeast against an ancient valley wall. The Fisher flows on the west flank of the caldera core accumulated on a hillside and are thickest near the base, where they are estimated to aggregate more than 500 feet and possibly more than 700 feet. Larsen and Cross (1956, p. 172) reported that Fisher Quartz Latite in the main accumulation in the Fisher Mountain area is more than 2,500 feet thick.

GENERAL DESCRIPTION

The Fisher Quartz Latite capping the ridge between Rat and Miners Creeks was erupted into a flat-floored, steep-walled valley that apparently drained southward toward the caldera. The valley was cut through the hard Nelson Mountain Quartz Latite and the soft tuffs of the Rat Creek Quartz Latite, and the floor was a stripped surface on harder underlying rocks in the Huerto Formation and Wason Park Rhyolite. The main vent was near the bottom of this valley and formed along a line of north-northwest-trending fissures now marked by a series of dikes of Fisher Quartz Latite.

The first eruptions were largely pyroclastic, and white tuff and tuff breccia as well as local thin lava flows accumulated in the bottom of the valley to a maximum observed thickness of about 75 feet. These were succeeded by a single thick flow of coarsely porphyritic quartz latite that filled the valley to depths of more than 1,000 feet near the vent. The remnant of this flow left by subsequent erosion extends about 2 miles north of the vent and 1 mile east of the vent; in both of these directions the flow abuts Rat Creek tuff in the valley walls. The present top of this flow remnant is fairly flat and, although considerably eroded, probably represents the approximate configuration of the original surface of the flow.

Erosion has exposed the feeding neck of this thick quartz latite flow over a vertical range of more than 900 feet. The upper part of the neck grades upward and laterally into the adjacent flow. The rock in the lower part of the neck is massive, but it becomes irregularly vesicular near the top, where it is identical with the bulk of the rock in the flow. Pervasively brecciated inclusions as much as 50 feet across of tuff, gravel, Wason Park Rhyolite, and other rock types occur both in the neck and in the nearby flow. Flow layers in the neck generally dip steeply; they are contorted and irregular in the transition from neck to flow, and they are arched upward in the flow above the neck.

The dikes that extend south-southeast from the large neck east of Miners Creek were injected into a zone of echelon fissures that roughly parallels the west margin of the Creede graben. None of the fissures intruded by the dikes show significant displacement, however, and several of the dikes were cut by later faulting; so the main graben faulting in this vicinity appears to be younger. The largest dike is about half a mile long and as much as 100–150 feet wide. Many of the smaller dikes, particularly near the large neck, are less than 200 feet long and 50 feet wide and have rounded ends. Some of these are markedly more resistant to erosion than are the surrounding rocks and stand as elongated, oval-shaped walls. Many dikes of similar rock, which would not be apparent at the scale of the geologic map (pl. 1), were seen along the flanks of lower Miners Creek and in the lower part of McKenzie Mountain.

The body of Fisher Quartz Latite on the west flank of the caldera core is opposite a bend in strike of the underlying ledges of Snowshoe Mountain Quartz Latite. The oldest unit in this body consists of a dense gray to purple porphyritic flow or flows exposed locally along the south side of the mass. This rock is cut by a vitrophyric neck that passes laterally east into a glassy gray porphyry flow, whose base is a pumiceous flow breccia. Similar gray porphyry, also underlain by pumiceous flow breccia, is exposed at the base of the Fisher along the north side of the body. The earlier flows are capped by a distinctive vesicular pink porphyritic flow, which extends eastward across the edges of the lower flows to where it rests directly on soft Snowshoe Mountain Quartz Latite.

All these flows were erupted on an outward-dipping slope on the domed core of the caldera and seem to have accumulated on slopes of 20° or more. The pronounced cuestalike form of this body of Fisher Quartz Latite depends largely on the upper flow of pink porphyry; the west slope appears to reflect an eroded constructional dip slope, and the generally northeast- and southeast-facing rims reflect the eroded upper edges of the flow. Sedimentary breccia belonging to the Creede Formation has been preserved along the east margin of this body of Fisher Quartz Latite, where it appears to have been deposited on the eroded edges of the flows. Identification of fragments of the older, glassy gray porphyry flows of the Fisher in the sedimentary breccias indicates that the Fisher lavas are the older.

A volcanic dome of coarsely porphyritic Fisher Quartz Latite protrudes through the Creede Formation between Farmers and West Bellows Creeks along the east margin of the Creede district. This body rests directly on Farmers Creek Rhyolite along its north margin and is partly covered by the Creede Formation along its south and west flanks. It appears to be an exhumed and only slightly modified dome that once probably was completely covered by the Creede Formation. It is an outlier of a more widespread local field of Fisher Quartz Latite in the Wagon Wheel Gap area immediately adjacent to the east and will not be considered in detail in this report.

The south ends of two bodies of coarsely porphyritic lava capping high ridges between upper West Willow and Miners Creeks extend into the northwest corner of the Creede district (pl. 1). Neither flow has been studied in sufficient detail to be considered further in this discussion of the Fisher Quartz Latite.

PETROGRAPHY

The Fisher Quartz Latite in the Creede district consists largely of coarsely porphyritic quartz latitic lavas that differ little from earlier lavas that are interlayered here and there with intracaldera ash flows around the Creede caldera. The phenocryst content of Fisher Quartz Latite also is closely similar to that of the intracaldera quartz latite ash-flow formations that preceded it. The close association in space and time and the petrographic similarities between postcaldera Fisher Quartz Latite and the earlier intracaldera quartz latitic rocks have led us to the conclusion that all these formations are probably comagmatic and can be separated only with respect to stages in the development of the Creede caldera.

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All Fisher Quartz Latite lavas are porphyritic and generally contain 30–35 percent phenocrysts. The phenocrysts are conspicuous, and tabular feldspar crystals are commonly as much as 1 cm long. Plagioclase (average about An_{40}) is the most abundant phenocrystic mineral and constitutes 25 percent or more of most flows—biotite averages between 5 and 10 percent; augitic pyroxene, between 1 and 5 percent; and magnetite, between 1 and 3 percent. Hornblende, sanidine, and quartz are minor phenocrystic constituents in some flows but are virtually absent in others. The matrix of Fisher lava flows ranges from glassy to microgranular and shows wide variation in vesicularity. Many lavas are distinctly flow layered.

Hypabyssal intrusive rocks of Fisher Quartz Latite, mostly in dikes, are widespread in parts of the Creede district. Most of these rocks are dull light- to medium-gray massive porphyry containing the same phenocrystic minerals as do the flows. The matrix is generally microgranular and structureless and commonly has a somewhat greasy luster. Although nondescript, the rock is easily recognized in the Creede district, and many dikes have been found by tracing float fragments.

The large flow capping the ridge between Rat and Miners Creeks consists largely of coarsely porphyritic vesicular pink lava. Rectangular white glassy plagioclase tablets constitute nearly a third of the rock; biotite, pyroxene, and magnetite are minor phenocrystic minerals. The matrix is glassy along the base and toward the margins of the flow, but in the bulk of the rock it is lithoidal. Flow layers are conspicuous locally but are faint in much of the rock. The rock is irregularly vesicular, ranging from frothy pumice at places along the margins to nearly massive rock toward the center of the flow. The feeding neck is irregularly vesicular near the top but is dense and massive in exposed lower parts.

The rock in the series of dikes extending south-southeast along the canyon of Miners Creek is closely similar to that in the large flow farther north. The same phenocrysts are present in about the same proportions, except that almost all pyroxene and some plagioclase have been altered to a carbonate mineral. The matrix is more coarsely crystalline, although still microgranular. Small feldspar laths are scattered through an anhedral aggregate of colorless grains, and the whole matrix is crowded with fine dark grains which give the rock a very dirty appearance in thin section. The matrix in some rocks is irregularly altered and replaced by a carbonate mineral.

The glassy gray porphyry in the older flow and related neck in the Fisher Quartz Latite mass on the west flank of the caldera core contains abundant large plagioclase tablets as much as 1 cm across and less abundant crystals of biotite, hornblende, and pyroxene set in a dark-gray obsidian matrix. The lower part of the flow consists of a frothy, vesicular rock that contrasts with the overlying dense, glassy flow. The vesicular base is commonly highly broken and rubbly.

The younger flow of Fisher Quartz Latite on the west flank of the caldera core closely resembles the thick flow between Rat and Miners Creeks. It is irregularly vesicular, in places almost frothy and contains conspicuous phenocrysts of plagioclase and smaller ones of brown oxidized biotite and hornblende set in a cellular flesh-pink to gray matrix. In contrast with the other main Fisher flows in the Creede district, however, this flow contains only sparse and irregularly distributed pyroxene. Quartz and sanidine are minor phenocrysts but are distinctly more abundant in this flow than in the other Fisher flows studied. The rock ranges from massive to markedly flow layered. Some of the flow layers are open and rubbly, and in places the entire rock is pervasively broken as though by continued movement during cooling.

CREEDE FORMATION

DEFINITION AND AGE OF FORMATION

The Creede Formation was originally named and described by Emmons and Larsen (1923, p. 61–70), who subdivided it into a lower member consisting largely of fine-grained well-bedded deposits containing interbedded travertine and an upper member consisting of coarser material, largely stream deposits, and a few thin lava flows. Larsen and Cross (1956, p. 167–172) closely followed the earlier description. We have included the same assemblage of rocks in the Creede Formation that was included by Emmons and Larsen (1923) (Steven and Ratté, 1964), but we have found that the subdivisions recognized earlier are in a large part laterally equivalent facies, which we have not differentiated in our mapping.

The age of the Creede Formation is not known with certainty. On the basis of fossil plants, F. H. Knowlton (Emmons and Larsen, 1923, p. 70) compared the Creede with the Florissant Lake Beds in the southern Front Range, Colo., and assigned a Miocene age to both. MacGinitie (1953, p. 60–75) showed that the Florissant Lake Beds are Oligocene in age and, after reexamining Knowlton's collection, gave the opinion (MacGinitie, 1953, p. 73) that the Creede Formation cannot be older than Pliocene and probably is middle Pliocene in age. Larsen and Cross (1956, p. 167) interpreted the age of the Creede Formation as probably very late Miocene or very early Pliocene on the basis of a study of fossil plants by R. W. Brown.

Fossil pollen from the Creede Formation was examined by Estella Leopold of the U.S. Geological Survey (written commun., 1961), who reported that the pollen evidence and R. W. Brown's leaf identifications yielded the following list of identified plant genera:

Pteridophytes:
- *Polytrichium* (leaves)
- *Chamaebatiana* (leaves)
- *Selaginella* (spores)

Gymnosperms:
- *Picea* (pollen)
- *Pinus* (leaves and pollen)
- *Ephedra* (pollen)
- *Abies* (pollen)
- *Juniperus* (leaves and pollen)

Dicots:
- *Salix* (pollen)
- *Populus* (leaves and pollen)
- *Alnus* (leaves)
- *Carya* (pollen)
- *Quercus* (pollen)
- *Acer* (pollen and leaves ?)
- *Sarcobatus* (pollen)
- *Planera* (leaves)
- *Edwinia* (leaves)
- *Cercocarpus* (leaves)
- *Crategus* (leaves)
- *Shepherdia* (pollen)
- *Berberis* (= Mahonia) (leaves)
- *Artemisia* (pollen)

Miss Leopold noted that of the 22 plant genera identified, only 2 (*Carya* and *Planera*) are now exotic to the region, and that with 91 percent of the genera now native, this flora compares with Wyoming floras of late Miocene through middle Pliocene age.

Thus, the more recent opinions based on paleobotanical evidence favor a late Tertiary age for the Creede Formation.

DISTRIBUTION AND THICKNESS

The Creede Formation consists largely of stream and lake deposits and travertine from mineral springs, all of which accumulated in a structural trough around the margin of the Creede caldera. These deposits follow the moatlike valley from the vicinity of Spar City on the south margin of the caldera, northwest along Lime Creek to its junction with the Rio Grande, around the great arc of the Rio Grande to the mouth of Goose Creek near Wagon Wheel Gap, and south up Goose Creek for about 3 miles. In all, the Creede Formation follows the subcircular caldera margin for nearly 270° of arc.

The largest areas underlain by the Creede Formation in the Creede district (pl. 1) are on the outer wall of the caldera, where remnants of sedimentary rocks extend up subsidiary ridge crests or fill old valleys in the caldera wall. The longest tongue, which fills an old stream canyon, extends north across Bachelor Mountain to the Amethyst fault near the center of the district. Isolated remnants of Creede Formation crop out here and there along the margin of the caldera core, south and southeast of the Rio Grande; these are so small and scattered that only fragmentary data could be collected on the formation in this area.

The original thickness of the Creede Formation is not known, but as now preserved in the Creede district, the formation extends over a vertical range of at least 2,400 feet. The Creede Formation was deposited in a closed basin of volcano-tectonic origin, and the surface data available are not sufficient to allow determination of the location or present altitude of the deepest part. Travertine and sedimentary rocks typical of the formation are exposed at river level in many places, and their presence in water wells drilled at ranches along the Rio Grande valley indicates that the formation extends at least 100 feet or more below this level. The lowest exposures in the Creede district are along the Rio Grande near the mouth of Farmers Creek, at an altitude of about 8,480 feet.

An unknown thickness of rocks has been eroded from all remnants of the Creede Formation that have been studied. The highest typical lake deposits found are at an altitude of about 9,800 feet, which may be near the original top of the lacustrine facies of the Creede Formation. Stream deposits and coarse sedimentary breccia of local derivation intertongue marginally with the lake deposits and apparently once formed alluvial-fan deposits out over the lake deposits. These coarse clastics are now exposed at altitudes of about 10,800 feet on Bachelor Mountain and on the south-facing slope of Mammoth Mountain east of Creede, but at both these places an unknown amount has been eroded from the surface of the formation.

GENERAL DESCRIPTION

The Creede Formation consists of several distinct facies, each of which shows many local variations. Thin-bedded tuffaceous lake deposits, largely shale and sandstone with some tuff beds, constitute the predominant facies. These rocks intertongue marginally with fluviatile sandstone and conglomerate beds in the vicinity of old tributary valleys, and with fanglomerate and coarse sedimentary breccias of local derivation elsewhere along the margins. The edge of the formation against buried rough topography is commonly marked by accumulations of talus, landslide debris, slope wash, and similar deposits, and much of this older surficial material has been reworked into the

Creede Formation. Travertine and calcareous tufa in bodies ranging from irregular masses to well-defined beds are found throughout the Creede Formation; these bodies represent material supplied by many mineral springs that were active concurrent with sedimentation. Many exposures of volcanic breccia, probably reworked pyroclastic breccia, were seen in the Farmers Creek basin, and a few thin layers of welded tuff were found in the Creede Formation along Windy Gulch.

The lacustrine facies of the Creede Formation consists typically of yellow thin-bedded tuffaceous silty shale and sandstone. The shale ranges from fine, paper-thin laminations to beds 1 or 2 inches thick. Many shales are soft and clayey, but in places they are impregnated or partly replaced by calcite or silica and are hard and platy. Carbonized plant remains are abundant along shaly partings, and good plant-fossil collections can be made at many places. Volcanic ash is a major constituent of the shale, and reworked tuff clearly constitutes the beds in places. Soil formed on the lake deposits is typically bentonitic and is very sticky when wet and loose and fluffy when dry. Massive white tuff beds, some largely altered to bentonite, occur here and there throughout the lacustrine facies and range from a few inches to as much as 10–15 feet in thickness. Bentonite has been produced commercially from one of the altered tuff beds (Larsen, 1930, p. 108–109).

Sandstone is common in the lake deposits and consists of intergrading lacustrine and fluviatile types. Uniform-textured silty sandstone beds that are laterally extensive and relatively thin probably were deposited in a lake; these rocks occur in beds a fraction of an inch to as much as 10 feet thick and are complexly interlayered with the shales. All gradations exist between silty sandstones and silty shales on the one hand and pebbly sandstones of probable fluviatile origin on the other.

The lake deposits show many features indicating deposition in shallow water or even under playa conditions. Mud cracks and ripple marks are widely distributed throughout the facies. Cliff exposures show many local cut-and-fill relations, and local unconformities of several hundred feet lateral extent are common. Even the thin-bedded lacustrine-type sandstones are broadly lenticular and crossbedded. Abundant tongues of fluviatile sandstone and intergrading fluviatile and lacustrine types of sandstone all indicate shallow-water deposition.

Local slump features, formed contemporaneously with deposition, and sandstone dikes extending from thicker sandy beds across adjacent thin-bedded sandstones and shales were seen at several places along cliffs flanking the Rio Grande and in roadcuts.

Fluviatile sandstones and conglomerates are most common in the Creede Formation in the vicinity of buried tributary valleys, and they constitute almost all the tongue of Creede Formation that fills the old valley extending north across Bachelor Mountain to the Amethyst fault. Lenticular tongues of these rocks are particularly abundant in the lake deposits opposite the mouth of the old valley, and these apparently pinch out toward the center of the basin of deposition.

In the old stream valley across Bachelor Mountain, the fluviatile deposits range from coarse unsorted, torrential-type conglomerates to evenly bedded sandstone and locally to fine siltstone. The deposits represent deposition under widely varying conditions. Most of the rocks are poorly sorted and conglomeratic and therefore must have been deposited by swiftly flowing water. Some beds as much as 30–40 feet thick consist of completely unsorted subangular to rounded fragments whose sizes range from boulders 6 feet in diameter to fine silt. These beds appear to have been laid down as units, probably as mudflows. Other beds consist of rounded but poorly sorted gravel containing boulders as much as 6–18 inches across; these indicate deposition by torrential streams. Interlayered even-grained sandstone and local thin-bedded yellow siltstone represent deposition by more slowly flowing or stagnant water. Fragments of wood occur here and there through the fluviatile beds, and some gravel beds are black owing to the presence of carboneous matter.

Most of the fluviatile deposits in the Creede Formation forming the top of Bachelor Mountain are silicified, some to dense quartzite, and many of the beds are impregnated with barite and black manganese oxides. A few beds contain valuable quantities of silver (p. 85.) The rocks are in general most intensely and uniformly silicified toward the Amethyst vein, but silicified and mineralized rock is also abundant along the north flank of Windy Gulch. The rocks south of Windy Gulch are spottily silicified and mineralized.

Coarse poorly sorted conglomerates and sedimentary breccias are common elsewhere along the margin of the Creede Formation in the Creede district, particularly in the Dry Gulch area and the Farmers Creek basin, where they intertongue with finer lake deposits. Good stream gravels are not common in these areas, however, and many of the rocks are poorly bedded and unsorted aggregates that represent torrential wash or mudflow type of deposition. Many of the marginal sedimentary breccias consist of rock types exposed on adjacent bedrock slopes and are probably fanglomerates of local derivation. Some of the so-called sedimentary breccias in the Farmers Creek basin closely resemble nearby breccias of probable pyroclastic origin in the Creede Formation and may represent slightly reworked volcanic debris.

The marginal stream-gravel–fanglomerate facies along the west side of the caldera core has been mapped separately (pl. 1), as it is of particular significance in determining the structural history of the caldera. Most of the coarse debris north of the outcrop of Fisher Quartz Latite consists of angular to subrounded rhyolite fragments in irregular beds 1–5 feet thick and some finer sandy beds a few inches to 1 foot thick. Lenses of travertine and some lake deposits are interlayed locally. The conglomeratic beds vary considerably in degree of sorting and character of matrix: some are hard and have a firm siliceous or ferruginous matrix, and others are loose aggregates having little or no matrix. Most of the fragments near Point of Rocks volcano (p. 43) are clearly from this source. In addition, their angular to subangular shapes reflect the local origin. Farther south the rhyolite fragments are more diverse and show the same variety found in the local patches of mixed avalanche breccias in the core of the caldera. Some beds of coarse sedimentary breccia consisting largely of blocks of Snowshoe Mountain Quartz Latite as much as 4 feet across are interlayered with the predominant rhyolitic conglomerates and breccias.

South of the outcrop of Fisher Quartz Latite on the west flank of the caldera, the marginal facies of the Creede Formation consists largely of rhyolitic stream gravels below an altitude of about 10,000 feet; above this level, coarse fanglomerate consisting largely of soft, slightly to moderately welded blocks of Snowshoe Mountain Quartz Latite predominates. This fanglomerate is a rudely bedded aggregate containing angular boulders as much as 5 feet in diameter set in a heterogeneous matrix of smaller fragments. All these beds are nearly flat lying and abut the more steeply dipping underlying ledges of Snowshoe Mountain Quartz Latite. They represent, in inverse order, the material stripped from the domed core of the caldera and deposited along the margin of the adjacent basin.

Travertine and calcareous tufa form many bodies of diverse shape and relations in the Creede Formation. A common type consists of an irregular mass, commonly crosscutting, that accumulated around a mineral spring. Such a mass commonly has leaflike sheets that extend outward and intertongue with adjacent sedimentary strata. Accretionary growth features are common in the irregular masses, and cylindrical spring orifices surrounded by successive encrustations have been seen in many places. Some probable relict travertine-terrace features have been recognized. The crustified layers generally are contorted and irregular, and they commonly pass laterally into massive, fragmental, or irregularly porous rock. Intermixed local layers or irregular pockets of yellow shale or sandstone are abundant in many travertine masses, and quartz, chalcedony, or opal commonly line cavities or form irregular masses. Much of the travertine, particularly the more massive type, is dark brownish gray on fresh breaks and has a distinct fetid odor.

The sheets of travertine extending outward from the irregular masses into the surrounding sedimentary beds range from nearly pure calcium carbonate to shaly or sandy beds impregnated or partly replaced by carbonate. Except for being in bedded deposits, much of this rock is identical with that in the adjacent irregular mass.

Beds of limestone and limy shale or sandstone apparently not connected with any large near-source mass of travertine occur in many places in the Creede Formation. Some beds of nearly pure calcium carbonate are thinly laminated and appear to have been deposited as successive layers, possibly by evaporation of shallow ponds of carbonate-rich water derived from the mineral springs. These beds grade into normal, calcite-impregnated lake deposits through progressive increase in content of clastic material.

The margin of the Creede Formation is marked in many places by inclined tabular masses of travertine a few feet to several tens of feet thick that parallel the underlying surface of deposition. The lower parts of these bodies typically consist of fragments of the underlying rocks, probably slope wash or talus, that have been cemented by travertine. The upper parts of the bodies are generally of typical crustified to irregularly massive travertine containing admixed clastic material. These bodies probably represent sheets of travertine deposited downslope from mineral springs that issued above the general level of concurrent sedimentation.

SURFICIAL DEPOSITS

Surficial deposits cover much of the Creede district and have been mapped in various categories in most places where they obscure the bedrock geology. Thus, the geologic map (pl. 1) shows large areas covered by landslides and glacial moraine. Terrace gravels, fanglomerate, and alluvium—but not talus banks—have also been mapped separately. The surficial deposits themselves have been accorded scant attention except where they provide clues to the bedrock distribution and major events in the geologic history of the district.

The headwaters of all the main tributaries to the Rio Grande were intensely glaciated during the Pleistocene, and morainal debris flanks the upper courses of East and West Willow Creeks and Rat Creek in the Creede district (pl. 1). In addition, ground moraine from an icecap covers much of the higher ground in the caldera core, and lateral moraines flank the upper parts of the stream drainages extending outward from this higher ground. The terminal moraine of the great glacier that extended down the Rio Grande barely projects into the southwestern part of the Creede district (pl. 1).

Outwash gravels from valley glaciers flank the Rio Grande and the lower courses of its main tributaries. The greatest accumulation fills the valley of the Rio Grande from the terminal moraine southwest of Creede around to the Wagon Wheel Gap area southeast of Creede. In the upper half of this extent, original depositional features such as gravel bars and braided channels are clearly apparent on aerial photographs, but in the lower half the terraces are smoother and appear to represent erosional surfaces cut across earlier deposited outwash gravels.

Landslides are widespread throughout the mountain areas of the Creede district. They are particularly abundant in the areas where nonwelded to slightly welded tuff units are interlayered with the more common densely welded tuffs, but they are not limited to these areas. The landslides are of varied appearance; some are great masses of debris that obviously fell in one piece; some are jumbled aggregates that cover square miles of area; others are smaller, indefinitely bounded areas of hummocky terrain where loose debris has slumped and crept irregularly downhill. In places the lower parts of talus banks have formed pressure ridges and bulbous protrusions typical of rock glaciers.

Alluvial fans are common along the base of many slopes where minor gullies and stream canyons emerge from mountainous areas onto flatter topography near the main streams. The fans are most abundant along the outer margins of the areas underlain by terrace gravels, where the mountain slopes terminate against the nearly flat depositional surface on outwash gravels.

Alluvium related to present stream levels is sparse along the Rio Grande, which is generally confined to a narrow channel entrenched in outwash gravels. Alluvium is more abundant along the main tributaries north of the Rio Grande. Those streams have been entrenched for only short distances above their junctions with the main river.

STRUCTURE

Structural features in the Creede district formed largely as the result of recurrent subsidence related to voluminous ash-flow eruptions or of postsubsidence doming and faulting. In tracing the geologic history of the Creede district, it has been possible to establish the different periods of movement on many of the faults and to interpret probable periods of movement on most others. Some faults were active during several different periods, whereas others were active only once and either cut or are cut by faults of different ages. The faults active during the several periods of movement are distinguished on the tectonic map (pl. 2), along with successive assemblages of rock units that accumulated between periods of major subsidence. Many age designations for faults shown on this map are interpretive and based on analogy with or extrapolation from known features. The degree to which the relations of the different features are known or interpreted is discussed in the following sections.

LA GARITA CAULDRON

The earliest major subsidence recognized in the central San Juan Mountains resulted from the voluminous ash-flow eruptions that deposited the Outlet Tunnel Member of the La Garita Quartz Latite. Only part of the east margin of the subsided area is now exposed in the Creede district (pl. 1); the remainder is covered by younger formations to the south and west. Structural features known to have formed during this period of subsidence belong to two general groups: an assemblage of jumbled fault blocks and pervasively broken rock along East Willow Creek, and at least one and perhaps several normal faults that extend southeastward from the jumbled and broken East Willow Creek area.

Almost all the more strongly subsided rocks of the Outlet Tunnel Member are densely welded, and, except for a few local less welded partings, they constitute a simple cooling unit at least 2,000 feet thick. The same rocks show compound cooling characteristics east and north of the Creede district. This leads to the conclusion that in the exposed area of Outlet Tunnel rocks, the subsided block is toward the eruptive source.

The time of subsidence has been interpreted as following eruption of the Outlet Tunnel Member and preceding eruption of the Phoenix Park Member of the La Garita Quartz Latite and the Bachelor Mountain Rhyolite. Talus and related breccias accumulated along steep slopes underlain by tectonically broken rocks of the Outlet Tunnel Member. In places these steep slopes are scarps associated with faults, and, by analogy, most of the other steep slopes and rough topography that can be established on top of the Outlet Tunnel Member along East Willow Creek were probably tectonically derived. Owing to the lack of distinctive markers in the massive, densely welded Outlet Tunnel rocks, many of the faults that we believe to exist could not be located or mapped, and details of the structure of the subsided area are largely unknown.

Specific evidence for the age of subsidence is given by the local accumulations of talus-rockfall-mudflow breccias of the breccia member. These are older than, or concurrent in age with, the ash-flow deposits of the Phoenix Park Member of the La Garita Quartz Latite and the Bachelor Mountain Rhyolite, and in places both the shattered Outlet Tunnel bedrock and the local breccias are overlapped by unbroken tuffs or welded tuffs of typical Phoenix Park or Bachelor Mountain aspect. The Outlet Tunnel rocks are propylitically altered as well as tectonically broken in the Outlet Tunnel mine and in the nearby erosional windows along East Willow Creek, whereas the overlying Bachelor Mountain rocks are neither broken nor altered. Local interlayering of both Bachelor Mountain and Phoenix Park rocks with talus-rockfall-mudflow breccias indicates some concurrent accumulation of local breccias with more widespread ash-flow deposits. Elsewhere, intertonguing of Phoenix Park and Bachelor Mountain rocks indicates that these too accumulated concurrently.

OUTLET TUNNEL AND HOLY MOSES MINES AREA

Individual structural features related to the La Garita cauldron are obscure in the vicinity of the Outlet Tunnel and Holy Moses mines, but certain relations in this area seemingly require it to have been extensively broken during subsidence of the La Garita cauldron. Steep to nearly vertical contacts between the Outlet Tunnel Member and the overlying Bachelor Mountain Rhyolite are exposed at several places and at widely varying altitudes in the Outlet Tunnel and Holy Moses mines and in nearby surface exposures. The attitude of these contacts indicates that the Bachelor Mountain Rhyolite covered a very rough topography whose local relief was at least 500 feet. The steep slopes face both east and west, and in places, particularly in the surface exposures along East Willow Creek, they are partly covered with chaotic talus-type breccia. The Outlet Tunnel rocks are commonly shattered as though by tectonic movement and are propylitically altered in many places. The overlying Bachelor Mountain rocks are neither altered nor tectonically broken. In the southernmost erosional window through the Bachelor Mountain Rhyolite along East Willow Creek, talus adjacent to a nearby steep scarp of tectonically broken Outlet Tunnel rocks is clearly interlayered with unbroken welded tuff belonging to the Willow Creek Member of the Bachelor Mountain Rhyolite. In some other places the talus fragments are irregularly enclosed in an ash matrix that appears to have sifted down into the more open parts of the talus breccia.

PHOENIX PARK AREA

Although too widely covered by moraine and landslide debris for individual structures to be mapped well, the Phoenix Park area contains local areas of outcrop that illustrate significant aspects of the La Garita cauldron subsidence. The isolated small hill capped by Mammoth Mountain Rhyolite near the north end of Phoenix Park is particularly instructive even though many of the detailed relations are obscured by surficial debris. Near the south end of this hill, the lowest rock is tectonically broken Outlet Tunnel Member. A steep buried slope separates this rock from overlying talus breccia of the breccia member that contains locally interlayered and intermixed pumiceous crystal-poor pink tuff probably related to the Bachelor Mountain Rhyolite. This talus-tuff aggregate in turn is overlain by a hard, densely welded ash flow of the Phoenix Park Member of the La Garita Quartz Latite.

A northwest-trending fault younger than the Phoenix Park rocks but older than the capping Mammoth Mountain Rhyolite forms the northern limit of the sequence just described and places the hard Phoenix Park welded tuff to the south adjacent to talus-mudflow breccias to the north. Although the mapped fault is younger than the Phoenix Park Member and probably is related to subsidence of the Bachelor Mountain cauldron (p. 56), it is nearly coincident with an older steep slope of tectonically broken Outlet Tunnel rocks and associated talus breccias. This relation suggests reactivation of an older fault.

Near the north end of the local hill, isolated exposures of massive Outlet Tunnel welded tuffs on both sides of East Willow Creek are at altitudes comparable to those of talus-mudflow breccias farther south on the isolated hill. Perhaps this indicates that yet another northwest-trending fault extends through this area.

These faults are identical in trend with younger northwest-striking faults in the Whited Creek area and in the Farmers Creek area, and the younger faults may represent reactivated movement along a fracture zone formed at least as early as subsidence of the La Garita cauldron.

To the east along a subsidiary ridge extending west from Wason Park to East Willow Creek at Phoenix Park, a series of isolated exposures indicate overlap of interlayered pyroclastic breccias and welded tuffs of the Phoenix Park Member over a steep slope on talus-mudflow breccias of the informal breccia member of the La Garita Quartz Latite. These exposures are 1,000–1,500 feet higher topographically than the isolated hill at Phoenix Park, but it is not known how much of this difference in altitude reflects rough topography in the subsided area of the La Garita cauldron and how much resulted from later dislocations related to subsidence of the Bachelor Mountain cauldron.

UPPER EAST WILLOW CREEK AREA

Complex structural features resulting from subsidence of the La Garita cauldron are much better exposed in the upper East Willow Creek area than elsewhere, although the age of subsidence cannot be established as firmly here as it has been farther south. Rocks of the Outlet Tunnel Member are cut into slices by a series of north- to northwest-trending faults along the west flank of La Garita Mountain. The easternmost of these faults is a northwestern segment of a normal fault zone whose reactivated extension has been mapped in detail through the Wheeler Monument area and in reconnaissance for a distance of more than 10 miles beyond the eastern limits of the Creede district (pl. 1). Massive rocks of the Outlet Tunnel Member constitute both walls of this segment, and compaction foliation is nearly flat on both sides. The fault was mapped largely on the basis of locally exposed broken rock along a series of topographic saddles, in addition to a clearly defined lineament apparent on aerial photographs; one local wedge of less welded rocks was displaced deeply down between walls of densely welded rocks. Displacement across this fault could not be estimated owing to a lack of marker horizons.

Two small faults identified by minor zones of broken rock and by lineaments conspicuous on aerial photographs extend north from a west-trending cross fault in the hanging wall of the eastern bounding fault. One of these faults dips east and the other is nearly vertical, and both appear to be minor antithetic fracture zones.

Another major west-dipping normal fault extends along the lower slopes of La Garita Mountain generally parallel to and 1,000–2,000 feet east of upper East Willow Creek. This fault dips 65°–75° W. and separates massive nearly flat lying rocks of the Outlet Tunnel Member on the east from west-dipping tectonically shattered rocks of the same member on the west. Extension of talus breccia belonging to the informal breccia member of the La Garita Quartz Latite across the trend of the fault at the south indicates that a topographic scarp existed in this vicinity. This talus breccia, representing deposition on rough topography in the subsided block, is 3,000–3,500 feet below massive Outlet Tunnel bedrock at the top of La Garita Mountain. This relation provides a measure of minimum offset across the faulted belt in this vicinity.

The compaction foliation in the Outlet Tunnel rocks forming the tectonically brecciated hanging wall of the fault parallel to upper East Willow Creek dips generally 40°–70° W. in the area shown on plate 1; farther north the fault appears to have had much less displacement, and the dips range from 15°–30° W. near the fault to nearly flat a thousand feet or so from the fault.

Other faults probably exist in the same area. For example, talus breccia of Outlet Tunnel fragments is widely exposed on the south nose of the ridge between Whited and East Willow Creeks, at altitudes comparable with those of tectonically broken Outlet Tunnel rocks farther north. No structural features were mapped that would account for the presumed scarp between these outcrops, but some fault or combination of faults must exist to account for the rough buried topography on the tectonically broken bedrock.

WASON PARK-LA GARITA MOUNTAIN AREA

A fault zone forms the boundary between the high flat bench of Wason Park and the surmounting La Garita Mountain to the north. The most apparent displacement along this zone is younger than the Nelson Mountain Quartz Latite and perhaps concurrent with final subsidence of the Creede caldera to the south. Relations in two areas, however, indicate that movement on the fault zone between Wason Park and La Garita Mountain started much earlier and probably was concurrent with subsidence of the La Garita cauldron.

At the northwest end of Wason Park, the easternmost fault of the series parallel to upper East Willow Creek projects toward the southeast-trending fault zone but is covered by unbroken Wason Park Rhyolite in an area where the younger rhyolite pinches out northward against a rough south-facing topographic scarp of Outlet Tunnel rocks. In the same area, but about 2,000 feet farther south, minor displacement on a younger fault probably has been no more than 50 feet. These relations indicate that most of the topographic disparity between the Wason Park area and La Garita Mountain is relatively old and that the younger ash-flow units wedged out against a mountain front higher and more abrupt than the one now existing. The relations described in the preceding sections indicate that the La Garita ridge originated as a result of subsidence of the La Garita cauldron.

East of the Creede district (pl. 1) in the vicinity of Wheeler Monument, the Rat Creek Quartz Latite and the lower part of the Nelson Mountain Quartz Latite wedge out abruptly to the north against a steep scarp on rocks of the Outlet Tunnel Member along the line of the fault that cuts Nelson Mountain Quartz Latite. The Outlet Tunnel rocks at this locality form the east end of the great La Garita Mountain mass, and the overlapped scarp is part of the same old mountain front that limited the northward spread of the Wason Park Rhyolite at the northwest end of Wason Park. The later fault movement appears to have closely followed the old scarp and, presumably, the old fault.

BACHELOR MOUNTAIN CAULDRON

Eruption of the great volume of pumice and ash that constitutes the Bachelor Mountain Rhyolite culminated in complex subsidence near the location of the town of Creede. The exposed structural features known to have formed at this time are east, north, and northwest of Creede (pl. 2) and consist of a pervasively brecciated mass of rock that has been downdropped along overlapping curved faults, and a series of normal faults that extend north to northwest out from the brecciated mass along the trends of the later Bulldog Mountain, Amethyst, and Solomon–Holy Moses faults. In the Phoenix Park area, at least one of the older northwest-trending faults related to the La Garita cauldron (pl. 2) was reactivated at this time. From the vicinity of Creede southward, all related faults are covered by younger rocks, and the form or extent of the Bachelor Mountain cauldron cannot be determined in this direction.

The Bachelor Mountain cauldron clearly subsided before the Mammoth Mountain and Farmers Creek Rhyolites were erupted. The evidence for this is that curving faults and associated brecciated rock of the cauldron are overlapped to the east by unbroken Mammoth Mountain and Farmers Creek Rhyolites (pls. 1 and 2). In addition, a tilted block of intertongued Bachelor Mountain Rhyolite and Phoenix Park Member of the La Garita Quartz Latite exposed along East Willow Creek is overlapped on the east by nearly flat-lying Mammoth Mountain Rhyolite.

ARCUATE FAULTS AND BRECCIATED ROCK

The pervasively brecciated rock and associated arcuate faults north and east of Creede are well exposed in many places. The largest of these faults are at least partly arcuate in plan and extend east and southeast from the south end of Bachelor Mountain into the south-facing slopes of Mammoth Mountain. These faults have stepped the contact between the Willow Creek and Campbell Mountain Members down an aggregate vertical distance of nearly 1,500 feet and are largely responsible for the low position of the contact in the subsided blocks just north of Creede. Minor faults of diverse trend and direction of displacement cut the main downdropped blocks. These faults are generally obscure, and in all probability similar faults exist which do not offset contacts in present exposures, and thus were not recognized during fieldwork.

Brecciated Bachelor Mountain rocks are exposed in the steep canyon walls adjacent to Willow Creek and its main forks for 1–1½ miles north of Creede. The rocks are highly shattered and consist of fragments a fraction of an inch to several inches across; although individual fragments are commonly disoriented, the breccia in many outcrops is massive and appears to lack internal sheared structures. In most places the gradational contact between the Campbell Mountain and Willow Creek Members can be traced consistently through the broken rock, and offsets of the contact are generally obvious. The bulk of the rock, therefore, appears to be more shattered than sheared, and most differential movement has been confined to surfaces or narrow zones that mark the faults.

Most of the breccia is thoroughly silicified, so that the rock in outcrop is as hard and resistant as normal, unbroken Bachelor Mountain rocks in adjacent areas. Many of the faults are likewise healed, and in places fault surfaces are so obscured as to be unrecognizable in cliff exposures below obviously offset contacts between the Willow Creek and Campbell Mountain Members.

An exception to the generally massive character of the breccia can be seen in the low slopes just north

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of Creede. The rock here is thoroughly sheared and is cut by many intersecting zones and surfaces showing fine breccia and slickensides. Many of the sheared zones are more thoroughly silicified than the adjacent rock and tend to stand as low ragged walls in the present topography. These are most obvious on the east side of Willow Creek, where they are easily discernible from a distance.

The pervasively brecciated rock along East and West Willow Creeks is bounded on the north by strongly sheeted rock, in which the sheeting fractures are either vertical or dip steeply north or south. The sheeting is closely spaced near the brecciated rock and cuts the rock into innumerable thin slabs a fraction of an inch to several inches thick (fig. 5). Farther north the sheeting becomes less well defined and the slabs thicken, and the rock passes irregularly into jointed rocks typical of normal Bachelor Mountain Rhyolite. The more closely sheeted rock is commonly cut by narrow crushed zones that generally dip approximately 45° S. toward the downdropped area. In these zones, the sheeted rhyolite ranges from completely brecciated (fig. 5, left photo.) to distorted sigmoidal form (fig. 5, right photo.). The crushed zones are south-dipping shear surfaces that reflect minor insliding toward the more strongly subsided area to the south.

A body of pervasively broken rock 1,000–2,000 feet wide and entirely in the Willow Creek Member extends southeast from the Willow Creek area to the ridge between Dry Gulch and Farmers Creek, where it is overlapped by unbroken younger rocks. The direction of relative movement along much of its length could not be determined. However, the body extends southeast from a clearly defined fault that is downthrown to the south, and the same sense of displacement probably continued along it.

Another south-dipping fault on Mammoth Mountain north of this breccia displaces the contact between the Willow Creek and Campbell Mountain Members downward about 500 feet to the south. This fault is outside the area of pervasively brecciated rock, but it has the same trend and sense of displacement as the faults associated with the breccia and also is overlapped to the east by unbroken rocks of Mammoth Mountain Rhyolite.

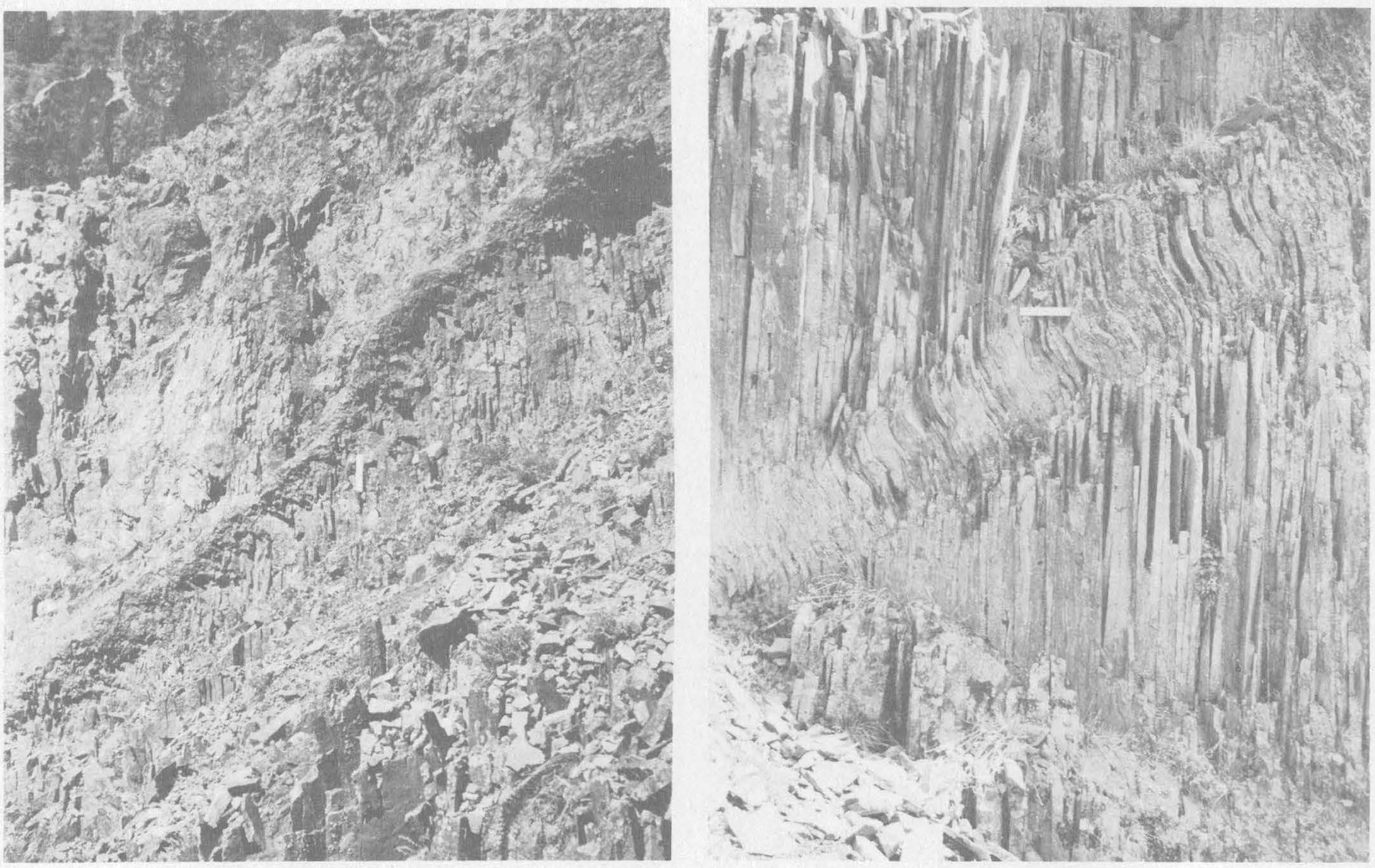

FIGURE 5.—Sheeted rock in the Willow Creek Member of the Bachelor Mountain Rhyolite. Note 6-inch rule near center of photographs. Left, sheeted rock cut by a highly brecciated zone. Right, sheeted rock distorted into sigmoidal form along a broken zone.

Offset relations of Bachelor Mountain Rhyolite beneath Bachelor Mountain and the east side of Bulldog Mountain apparently indicate at least two faults, possibly related to the Bachelor Mountain cauldron, that are now largely covered by younger formations. The larger of these extends southwest from a fault along West Willow Creek at least to the trend of the Bulldog Mountain fault zone and drops the rocks to the northwest downward with respect to the brecciated rocks north of Creede. The other fault extends west from an arcuate fault along West Willow Creek. This fault has been mapped on the surface near West Willow Creek and for short distances underground on the Commodore 5 and Commodore 3 levels (p. 70).

ANCESTRAL BULLDOG MOUNTAIN FAULT

Existence of a fault probably related to subsidence of the Bachelor Mountain cauldron is indicated beneath Bulldog Mountain by discordant thicknesses of Windy Gulch tuff exposed beneath the capping Wason Park Rhyolite on either side of the mountain. As nearly as can be determined, only 150 feet of soft Windy Gulch tuff intervenes between the Campbell Mountain Member and the Wason Park Rhyolite on the east side of the Bulldog Mountain fault zone (section A–A′, pl. 1). In contrast, nearly 800 feet of Windy Gulch tuff is exposed between the Campbell Mountain and Wason Park units on the west side of Bulldog Mountain. The fault responsible for this abrupt thickening is nowhere exposed, and its precise location, trend, and attitude are not known. Poorly defined exposures on the south side of Bulldog Mountain apparently indicate that the old fault here is near the west branch of the later Bulldog Mountain fault zone, but the trend to the north is uncontrolled. In drawing the tectonic map (pl. 2) we have assumed that the later faults probably formed nearly parallel to the trend of the earlier fault, even though the displacement is in the opposite direction.

The Wason Park Rhyolite under Bulldog Mountain shows no discordance comparable to that shown by the underlying Windy Gulch Member. This lack of discordance indicates that the postulated old fault was active before the Wason Park was erupted, and, by analogy with other faults having similar relations, this old fault probably was active during subsidence of the Bachelor Mountain cauldron. The ancestral Bulldog Mountain fault is the westernmost structural feature of this age that has been recognized in the Creede district.

The actual position of the ancestral fault has an important bearing on the possible economic potential of the Bulldog Mountain fault zone. If the old fault is near or west of the position shown on the geologic section (pl. 1), the younger faults will be mostly in walls of the hard rhyolitic rocks that have proved favorable hosts along productive veins in the district. If the position is farther east, on the other hand, relatively unfavorable soft tuffs of the Windy Gulch Member will constitute significant segments of the walls of the younger faults.

ANCESTRAL AMETHYST FAULT

Several lines of evidence indicate that the Amethyst fault was active during subsidence of the Bachelor Mountain cauldron. Most directly, healed silicified breccia marking the old fault extends outward from and is closely similar to the silicified breccia related to the Bachelor Mountain cauldron that is exposed along Willow Creek and its branches north of Creede. In addition, the area east of the Amethyst fault was deeply eroded prior to eruption of the succeeding intracaldera units, a rough surface was cut across it, and many of the rocks were removed here that still persist on the west side of the fault. In particular, no Windy Gulch tuff is known east of the Amethyst fault, where Mammoth Mountain and Wason Park Rhyolites rest directly on a hilly surface cut into and locally through the underlying Campbell Mountain Member. Soft tuff of the Windy Gulch Member still persists on the western, downthrown side of the fault. Thus the upthrown block was more deeply eroded than was the more protected, downthrown block.

Although there is generally a marked change in formations across the Amethyst fault zone as a whole, the surfaces of the faults active during the more recent periods of movement do not everywhere form the major separation between adjacent formations. At the surface, the mapped Amethyst fault (pl. 1) has rocks of the Willow Creek Member on both the hanging wall and the footwall for at least 2,000 feet north of the intersection of the Amethyst fault zone with the curved faults and pervasive breccia of the Bachelor Mountain cauldron on the east side of Bachelor Mountain. A geologic map of the mine workings on the Commodore 3 level (pl. 3) that underlie this area shows the same relation; here Willow Creek rocks are on both walls of the main fault, as marked by the Amethyst vein, and the change from Willow Creek to Campbell Mountain rocks that marks the ancestral fault occurs 350–400 feet out into the hanging wall near the portal and about 300 feet out into the hanging wall 1,000 feet in from the portal. The change in rock types takes place across a zone of silicified breccia about 50 feet thick that is so completely healed that no physical break marking the ancestral fault now exists; the footwall side of the breccia consists of Willow Creek fragments—Willow Creek and Campbell Mountain fragments are complexly mixed across a narrow zone somewhere in the breccia—and the hanging-wall side consists of Campbell Mountain fragments. The breccia zone is followed in part by a younger mineralized fracture, but this is but one of many similar mineralized fractures that cut the hanging-wall block of the main Amethyst fault in this vicinity and is clearly younger than the healed breccia.

A similar healed-breccia zone separating rocks of the Willow Creek and Campbell Mountain Members was mapped here and there along the hanging wall of the main Amethyst fault (Amethyst vein) on the lowest active mine workings, the Commodore 5 level (pl. 4), for at least the southernmost 6,000 feet exposed along the fault zone. The divergence between the ancestral fault and the younger mineralized fault is greatest near the south end of the level, where the main change in rock type and the younger fault zone are commonly 80–100 feet apart. Farther north the change in rock units ranges from coincident with the younger fault to about 50 feet into the hanging wall. As in the upper levels, where not broken by demonstrably later fissures, the breccia is so completely healed that it is fully as hard and homogeneous appearing as the adjacent unbroken rhyolite.

Silicified breccia marking the ancestral Amethyst fault forms the walls of the later fault at many places along the Amethyst 5 level (pl. 3; fig. 2). The ancestral fault diverges from the later fault near the south end of accessible workings on this level and appears to be 10–15 feet out into the hanging wall.

Total displacement on the Amethyst fault zone has been greater than that on any other fault on the east side of the Creede graben (section A–A′, pl. 1). Although total displacement of all periods of movement cannot be determined from present exposures, it must have been at least 1,200 feet. Late movements seem to have accounted for 600–700 feet of this total displacement, as is indicated by the apparent displacement of the Wason Park Rhyolite; pre-Wason Park movements account for the remaining 500 feet or more of displacement. In view of the subjective character of the projections shown on the geologic section, these figures are obviously not precise, but they probably represent the approximate order of magnitude of the different displacements.

ANCESTRAL SOLOMON-HOLY MOSES FAULT

Although the evidence is far from convincing, a zone of fracturing along the trend of the Solomon–Holy Moses fault zone appears to have been active during subsidence of the Bachelor Mountain cauldron. Rocks of the Willow Creek and Campbell Mountain Members of the Bachelor Mountain Rhyolite and of several layers of welded tuff in the Phoenix Park Member of the La Garita Quartz Latite east of this fault zone are inclined 15°–20° NE., in contrast with the much more gentle inclination of 2°–3° E. for the Willow Creek-Campbell Mountain contact west of the fault (section A–A′, pl. 1). This change in inclination must have taken place before the Mammoth Mountain Rhyolite was erupted, for nearly flat-lying rocks of this formation rest on the more steeply inclined older rocks.

On the south the Solomon–Holy Moses fault zone projects toward an outward bulge of the pervasive breccia related to the Bachelor Mountain cauldron and toward a complex series of north-trending faults of similar age exposed in the high cliffs near the Mollie S. mine (pl. 2). Many discontinuous shear zones cut the Willow Creek Member where it is exposed along the steep east flank of the canyon of East Willow Creek, but the age relations of these shear zones were not determined.

Some silicified and healed breccia that is older than the latest period of faulting and the associated mineralization was noted underground in the Outlet mine. This breccia is similar to that noted along the ancestral Amethyst fault, but the age relations are not nearly so well defined.

The offset contact between the Willow Creek and Campbell Mountain Members near the center of the Solomon–Holy Moses fault zone indicates that aggregate displacement along the zone has been no more than 300–400 feet. Contacts between younger formations that can be compared across the fault zone are lacking; therefore, we cannot even estimate what proportion of this aggregate displacement may have taken place during subsidence of the Bachelor Mountain cauldron.

FAULTS IN PHOENIX PARK

As discussed in detail with respect to the La Garita cauldron (p. 51), certain relations evident from exposures in the small hill capped by Mammoth Mountain Rhyolite near the north end of Phoenix Park indicate recurrent movement along a northwest-trending fault zone. Early offset related to subsidence of the La Garita cauldron is indicated by a steep scarp overlapped by interlayered talus breccia and tuffs of the

Bachelor Mountain Rhyolite and by a sheet of densely welded tuff of the Phoenix Park Member of the La Garita Quartz Latite. Movement on reactivated faults is indicated by offset relations of the Phoenix Park welded tuff and the talus breccias. Unbroken Mammoth Mountain Rhyolite caps the faults and indicates that they were reactivated by Bachelor Mountain cauldron subsidence.

The indicated faults in the Phoenix Park area are about on trend with the east margin of the tilted block of pre-Mammoth Mountain Rhyolite age east of the Solomon–Holy Moses fault zone. (See preceding section.) The older scarp related to subsidence of the La Garita cauldron seems to have limited the eastward spread of the Phoenix Park Member and the Bachelor Mountain Rhyolite; movement on reactivated faults during subsidence of the Bachelor Mountain cauldron tilted the block of rocks between this zone and the Solomon–Holy Moses fault zone, whereas the adjacent blocks remained relatively flat lying.

Later movements on reactivated faults along this same trend have been recognized in the Whited Creek area to the northwest (next col.) and in the Farmers Creek area to the southeast (p. 61).

SAN LUIS PEAK CAULDRON

Geologic mapping in the area north of the Creede district subsequent to our detailed study of the district has disclosed that the San Luis Peak area forms the core of a complex cauldron related in time to eruption of the Rat Creek and Nelson Mountain Quartz Latites. Few details are known of the form or geologic evolution of the San Luis Peak cauldron, except that many of the seemingly discordant structural relations along the north margin of the Creede district (pl. 1) are related to subsidence and later resurgence of this structure.

The geologic framework of the San Luis Peak cauldron consists of an older assemblage of densely welded tuffs identical with but older than the Nelson Mountain Quartz Latite in the Creede district, which overlapped southward against a preexisting steep slope along the Continental Divide at the head of East Willow Creek. These rocks were deformed and uplifted by resurgence of the cauldron core, and a series of coarsely porphyritic lavas and breccias accumulated in a structural moat along at least the south and east margins. Renewed ash-flow eruptions during and following accumulation of the local lava flows and breccias deposited densely welded tuffs that are continuous southward in outcrop into the typical densely welded Nelson Mountain Quartz Latite in the northern part of the Creede district. The younger welded tuffs in turn were differentially faulted and deformed by renewed resurgence of the complex San Luis Peak cauldron area. Related structural features in the northern part of the Creede district appear, for the most part, to be marginal features formed during the later periods of deformation.

DEPRESSED AREA OF NELSON MOUNTAIN

The nearly flat layers of Wason Park Rhyolite, Rat Creek Quartz Latite, and Nelson Mountain Quartz Latite under Nelson Mountain are about 200 feet lower than comparable layers on the ridge east of Whited Creek and about 400 feet lower than the base of the Wason Park Rhyolite under Wason Park. The layers east of Whited Creek are inclined west at a low angle, and a local increase in the dip to form a monoclinal flexure along the trend of Whited Creek may have accounted for the dislocation here. However, we have been unable to find positive evidence that such a flexure existed and have thus postulated a minor fault along this trend (pls. 1, 2). Whether by fault or flexure, the dislocation across Whited Creek appears to have been one of several similar dislocations that have taken place along the trend of a zone of recurrent faulting that extends southeast into the Farmers Creek basin and beyond (pls. 1, 2).

The downward displacement of about 400 feet across East Willow Creek from Wason Park to Nelson Mountain may involve either faults, or folds, or both. Two small northeast-trending faults cut across the slopes between Wason Park and East Willow Creek. Maximum displacement on the eastern fault appears to have been no more than 80–100 feet. There has been even less displacement on the south end of the western fault, but displacement on the northern part of this fault may have been greater; this possibility cannot be ascertained owing to poor exposures and the lack of distinctive units.

THE EQUITY FAULT

The Equity fault is a steep north-dipping fault that extends west across the northern part of the Creede district, transverse to the later normal faults of the Creede graben. North-trending faults cut the Equity fault, and the different blocks comprising the north and south walls of the Equity fault vary widely in relative direction and amount of displacement. The complexities of these relations seem best explained if the Equity fault is assumed to have formed as a result of magmatic intrusion at depth, which caused resurgence of the San Luis Peak cauldron to the north. Some segments of the hanging-wall block were uplifted much more than were adjacent segments. Later normal movement on faults of the Creede graben (see following sections) reactivated some of the earlier faults, reversing the direction of displacement on some and increasing the relative displacement on others.

The Equity fault terminates to the east against a nearly vertical north-trending fault that cuts diagonally across the ridge east of Whited Creek (pls. 1, 2). Near the terminating fault, the Equity fault is a steep north-dipping reverse fault having an apparent displacement of 600–650 feet; this amount of displacement is indicated by the nearest exposures of the welded-tuff–tuff contact in the Rat Creek Quartz Latite on opposing sides of the Equity fault.

The Equity fault is closely bracketed near the ridge crest west of Whited Creek (pl. 1). In contrast with other segments along the fault, Rat Creek Quartz Latite south of the fault appears to be structurally higher than the younger Nelson Mountain Quartz Latite north of the fault. Relations may be complicated somewhat in this vicinity by an irregular and generally north-inclined erosion surface between the Rat Creek and Nelson Mountain Quartz Latites. For this reason, the relative fault displacement may be less than is indicated by the difference in altitude between the highest rocks of the Rat Creek south of the fault and the lowest rocks of the Nelson Mountain north of the fault. However, at least several hundred feet of normal-fault movement along the Equity fault in this vicinity seems indicated.

The direction and amount of displacement along the Equity fault change abruptly and markedly across the north-trending fault that extends along the west side of Nelson Mountain into upper Deerhorn Creek Valley (pls. 1, 2). The hanging wall of the Equity fault west of this fault is structurally much higher than all adjacent blocks, and the Equity is a clear-cut reverse fault having about 1,300 feet of throw. North of the Equity fault, aggregate displacement on the north-trending fault has been more than 500 feet, and the rocks on the east side have been dropped down. South of the Equity fault, the displacement is reversed and the rocks on the west side are down; the actual displacement cannot be estimated because of the irregular surface between the Rat Creek and Nelson Mountain Quartz Latites, but it appears to be at least several hundred feet. The resulting structural pattern in this vicinity shows that the blocks northwest and southeast of the fault intersection are structurally high, whereas the blocks northeast and southwest of the intersection are structurally low. The following two-stage sequence of events is suggested to explain this complex situation:

1. Differential movement along the Equity fault began in response to magmatic intrusion at depth. The hanging-wall block west of the fault along upper Deerhorn Creek was strongly uplifted, and the adjacent block to the east was depressed somewhat.
2. Later subsidence of the Creede graben (see following sections) created a west-dipping normal fault that was coincident in its northern parts with the earlier fault separating differentially displaced blocks in the hanging wall of the Equity fault. A fault such as the younger one would have reversed the direction of movement along the fault north of the Equity fault, but it would not have done so sufficiently to erase the earlier displacement.

The west margin of the structurally high block on the hanging wall of the Equity fault between upper Deerhorn and West Willow Creeks is marked by the northern extension of the Amethyst fault. Aggregate displacement on the Amethyst fault north of the Equity fault is in excess of 1,400 feet, measured from exposures of Nelson Mountain Quartz Latite along the creek bottom west of the fault and from the exposed base of Nelson Mountain Quartz Latite on top of the high ridge east of the fault. South of the Equity fault, however, displacement on the Amethyst fault appears to be much less and may be no more than a few hundred feet. These relations also suggest that the segment of the Amethyst fault north of the Equity fault was active when the hanging-wall block between Deerhorn and West Willow Creeks was so strongly uplifted, presumably by magmatic pressures, and that it was reactivated by later movements when the Creede graben last subsided. (See following sections.) Movement on the reactivated fault here, however, was in the same direction as the original movement and increased the amount of throw.

Displacement on the Equity fault between West Willow and Rat Creeks does not appear to have been great and perhaps was no more than a few hundred feet. On this segment of the fault the north side was uplifted.

CREEDE CALDERA

The Creede caldera is a nearly circular subsided block 10–12 miles in diameter, whose north edge is occupied by the Rio Grande south of Creede. The core of the caldera has been strongly domed, and the margin on all but its south side is clearly marked in the present topography by valleys along the Rio Grande or its tributaries—Lime and Goose Creeks. Subsidence of at least some parts of the caldera area seems to have been recurrent during eruption of the Farmers Creek Rhyolite and succeeding intracaldera formations; details of the earlier periods of sinking are incomplete, however, as the older units in the core have subsided below current levels of exposure and been covered by younger rocks. The last subsidence accompanied and followed eruption of the Snowshoe Mountain Quartz Latite and involved all the caldera core as we now know it. The highly faulted zone marking the caldera margin is exposed only locally, and the pattern of faulting in these small areas is too complex for broad generalizations to be made.

Several faults in the Creede graben extending north to northwest out from the caldera are known to have been active during subsidence of the Creede caldera, and undetected movement may have taken place on other faults.

Two major northwest-trending faults extend into the eastern part of the Creede district (pl. 1) in the Wason Park and Farmers Creek areas. These and related faults are the northwest end of a belt of faults nearly 10 miles wide that extends southeast from the Creede caldera area to South Fork, 20–25 miles southeast of Creede, and possibly farther.

SUBSIDENCE IN THE CALDERA CORE

The beginning of subsidence of the Creede caldera cannot be dated closely in the Creede district because the older intracaldera units are nowhere exposed in the core of the caldera and the only exposures of caldera-margin faults are in an area where many of these units are thin or absent in the adjacent caldera walls. Evidence elsewhere, however, suggests that subsidence may have started at least as early as the eruptions of Farmers Creek Rhyolite.

The Farmers Creek Rhyolite in the drainage basins of Farmers and West Bellows Creeks consists in part of coarse pumice breccias, probably reflecting a nearby source, as well as numerous welded tuff layers representing many successive ash-flow eruptions. Similar Farmers Creek pyroclastic rocks underlie Mammoth Mountain Rhyolite in the complexly faulted caldera margin near the Wagon Wheel Gap fluorspar mine along the east side of the caldera, 9 miles southeast of Creede; these rocks are cut by a series of intrusive plugs, some of which are clearly older than the Mammoth Mountain Rhyolite. A few of the intrusive plugs near the Wagon Wheel Gap fluorspar mine were emplaced along caldera-margin faults. This suggests that at least some of the caldera-margin faults were active before eruption of Mammoth Mountain Rhyolite.

Pyroclastic beds in the Farmers Creek Rhyolite of the Farmers–West Bellows Creeks area, including the welded tuffs which commonly accumulate as nearly flat lying sheets, dip 20°–30° NE. in the lower part of the pile but only 10°–20° NE. in the upper part of the pile, and compaction foliation near the base of the overlying Mammoth Mountain Rhyolite appears to dip even more gently. These relations can be explained by progressive tilting during the period of recurrent eruptions, possibly concurrent with caldera subsidence to the south.

Except for the local absence of Mammoth Mountain Rhyolite in the area northwest of Creede, the widespread Mammoth Mountain and Wason Park Rhyolites have been mapped from the ridge south of Bristol Head all around the north flank of the caldera to the Leopard Creek area southeast of the Creede district, and the southern limit of the formations was not reached on either side. These sheets probably once extended across the site of the caldera that they now so nearly surround. However, these rocks are not exposed in the core of the caldera, and evidence for or against possible subsidence of the caldera at these times is buried.

The Rat Creek and Nelson Mountain Quartz Latites cap many of the high ridges north of the caldera, but no clearly recognized remnants have been found in or adjacent to the caldera. No barrier is known that would have barred these widespread sheets from spreading south, and in all likelihood they once covered part or all of the caldera area. Any remnants in the caldera are now buried below levels of observation, and relations with possible subsidence are unknown.

The main subsidence of the Creede caldera that can be established was concurrent with and followed eruption of Snowshoe Mountain Quartz Latite, presumably the youngest of the major intracaldera units in the area (p. 39). During this time, more than 6,000 feet of welded tuff accumulated in the core of the caldera, yet no remnants of this formation have been recognized outside the caldera. Tongues of talus and avalanche debris in the upper 2,000 feet of Snowshoe Mountain Quartz Latite along the west flank of the caldera indicate that the caldera wall as low or lower than the Wason Park Rhyolite was exposed, at least periodically, during subsidence and accumulation. Virtual parallelism between sparse interflow partings and compaction foliation between the successive ledges of Snowshoe Mountain welded tuff indicates that the core of the caldera sank as a cylinder concurrent with accumulation.

Final subsidence after eruptions of Snowshoe Mountain Quartz Latite ceased left a flat-floored caldera whose surface was near or below the present relative level of the Rio Grande. Only a surface this low would have exposed known source rocks on the caldera walls for avalanche débris (p. 42) and would have provided sufficient fall for these materials to spread widely. The caldera floor must have been nearly flat to account for distribution of the avalanche breccia at least 5 miles from the nearest source area.

CALDERA-BORDER FAULTS

Most of the faulted margin of the Creede caldera is covered by the Creede Formation or by more recent surficial deposits, and the character of the faulting is largely unknown. A complexly faulted segment along the outer edge of this margin is exposed from Shallow Creek to the area adjacent to lower Rat Creek (pl. 1), and similar complexly faulted segments are exposed in the Wagon Wheel Gap district on the east side of the caldera, but in neither of these areas is the full width of the caldera-border zone shown. The faults in the Shallow Creek–lower Rat Creek area form a complex mosaic outside the main line of the caldera border as reflected by the valley of the Rio Grande, and these faults may represent a nontypical extension of fracturing outward toward the concurrently active Creede graben. (See next section.)

Between Shallow and Miners Creeks, the exposed belt of caldera-border faults is bounded on its outer edge by a southeast-dipping normal fault that displaces the hanging-wall block about 300 feet downward toward the caldera (pl. 1). This fault is joined by the later, Alpha-Corsair fault near the Kreutzer Sonata mine east of Miners Creek; the Alpha-Corsair fault bends sharply north at the junction and appears to have been deflected by the trend of the older fault. The hanging wall of the bounding fault is cut into a jumbled series of fault blocks in which little system can be discerned. Many of the blocks are downdropped with respect to all adjacent blocks, and the mosaic appears to form a fractured mass that is in part lower structurally than the rocks either to the east or west.

A similar complexly fractured mass is exposed in the Monon Hill area, where jumbled blocks of younger rocks are infaulted between marginal blocks of Willow Creek and Campbell Mountain Members of the Bachelor Mountain Rhyolite (pl. 1). Two wedges of Wason Park Rhyolite are particularly deeply infaulted between walls of older rocks, and their positions seemingly cannot be accounted for by simple recurrent subsidence of the main caldera to the south. These narrow discordant blocks probably worked their way downward along with the other blocks during recurrent periods of tension. Such periods could have resulted from a tendency for the walls adjacent to the caldera to pull apart during major subsidence, but they might also reflect distention resulting from upward bulging of the volcanic edifice prior to major eruptions such as has been noted in many volcanoes, particularly those in Hawaii and Japan (Waesche, 1942; Powers, 1946; Minakami, 1950a, 1950b; Minakami and Mogi, 1959).

FAULTING IN THE CREEDE GRABEN

The Creede graben is defined as the complexly broken area extending north to northwest outward from the Creede caldera, generally between Miners Creek on the west and East Willow Creek on the east. Two faults in the graben were active in the Rat Creek–McKenzie Mountain area after the Wason Park Rhyolite and Huerto Formation were deposited, but before Fisher Quartz Latite was erupted, possibly concurrently with subsidence of the Creede caldera to the south (pl. 2). These faults can be mapped, although with some difficulty, along the soil-covered and generally grassy slopes east of lower Rat Creek, but to the northwest they pass beneath great landslides and their positions cannot be determined closely. Wason Park Rhyolite and the Huerto Formation are exposed here and there beneath the cliff-forming cap of Fisher Quartz Latite on upper McKenzie Mountain (pl. 1), and the general location of the faults can be bracketed by discordant structural positions of these formations in adjacent windows.

The southwestern fault is coincident at its south end with one of the faults in the caldera-border zone in the Monon Hill area. To the north along the slopes above lower Rat Creek, it displaces welded tuffs and intrusive rocks of the Bachelor Mountain Rhyolite 100–200 feet down to the west; offset relations beneath landslide material farther north are obscure. The southwestern fault appears to merge for a distance with another fault of similar trend but opposite displacement (pls. 1, 2) but diverges again northwestward under McKenzie Mountain. The Fisher Quartz Latite flow capping McKenzie Mountain rests on Wason Park Rhyolite at an altitude of about 11,250 feet east of the southwestern fault but rests on a 50- to 60-foot-thick layer of the Huerto Formation at altitudes of 10,800–10,950 feet on the point of the McKenzie Mountain ridge west of the fault. The layer of Huerto rests in turn on Wason Park Rhyolite, and the contact appears to dip north. These relations indicate that the present difference in altitude between highest known Wason Park Rhyolite on either side of the fault, between 600 and 800 feet, probably represents minimum offset in this vicinity. Along the projection of this same fault on the west side of McKenzie Mountain, the Huerto Formation west of the fault is at an altitude comparable to that of Wason Park Rhyolite east of the fault, but a reference horizon for estimating displacement is lacking.

The more easterly fault of comparable age in the Rat Creek–McKenzie Mountain area is closely controlled on the slopes east of lower Rat Creek, where soft Windy Gulch tuffs on the eastern hanging-wall block contrast strongly in color and topographic expression with harder intrusive rhyolite and Campbell Mountain welded tuff on the footwall. The fault passes beneath landslide debris and the Creede Formation to the southeast, and its relations to the zone of caldera-border faults and to the later Bulldog Mountain fault zone are largely conjectural (pls. 1, 2). Near Rat Creek, this fault appears to merge beneath a landslide with the fault just discussed, only to diverge again toward the top of McKenzie Mountain where the Huerto Formation on the eastern, downthrown block is at altitudes comparable to and lower than those of Wason Park Rhyolite on the western block. Minimum offset on the east side of the mountain is at least 400 feet across this fault. Northwestward on the west side of McKenzie Mountain, Rat Creek tuffs and welded tuffs to the east of this same fault are at altitudes comparable to those of Wason Park Rhyolite across the fault, but exposures on the downthrown side are too far from the probable trace of the fault to provide close control on the position or minimum offset.

Isolated exposures of Wason Park Rhyolite, Huerto Formation, and Rat Creek Quartz Latite on the west side of upper McKenzie Mountain and others east of Rat Creek indicate that these formations are displaced downward to the northwest across a northeast-trending zone that probably represents a fault or combination of faults. Unbroken Fisher Quartz Latite covers this zone; the dislocation must therefore be similar in age to that of subsidence of the Creede caldera, but no evidence is known to indicate the relation of possible faulting along this zone to movement along the northwest-trending faults in the Rat Creek–McKenzie Mountain area.

The Amethyst fault zone may have been active concurrent with subsidence of the Creede caldera; we have been unable to separate possible displacements of this age from increments of displacement during the later known period of activity.

The westernmost fault related to the Solomon–Holy Moses fault zone (pl. 2) is the only one of this set that clearly was active during intracaldera time. Mammoth Mountain Rhyolite on the east side of the fault is downfaulted against rocks of the Campbell Mountain Member, and the trend of the fault is overlapped to the north by apparently unbroken Rat Creek Quartz Latite. Movement of similar age may have taken place on other faults of the same general zone, but we have been unable to detect it.

NORTHWEST-TRENDING FAULTS IN THE FARMERS CREEK-WASON PARK AREAS

A major northwest-trending normal fault extends into the West Bellows–Farmers Creeks area in the eastern part of the Creede district and dies out northwestward in the upper Farmers Creek drainage basin. From reconnaissance, we know that this fault extends at least 8 miles southeast from West Bellows Creek. The rock units are downdropped 400–700 feet to the southwest in the Bellows Creek basin and eastern part of the Farmers Creek basin, but the displacement diminishes markedly in the northwestern part of the Farmers Creek basin, and the fault has not been detected near the junction of Mammoth Mountain and Wason Park.

The constituent ledges in the Farmers Creek Rhyolite are differentially tilted against this fault; the lower layers dip 20°–30° NE., and the higher layers dip only 10°–20° NE. Younger rocks in the Mammoth Mountain and Wason Park Rhyolites dip less than 10° NE. These relations are interpreted to indicate recurrent movement along this fault zone throughout an extended period of intracaldera time.

A series of minor west-trending faults cuts the hanging-wall block of the main northwest-trending fault along the ridge between West Bellows and Farmers Creeks. The northernmost and southernmost of these minor faults form the boundaries of a transverse graben in which the several individual blocks are lower structurally than adjacent parts of the main hanging-wall block.

The fault is about on trend with the faults in the Phoenix Park area that were active during subsidence of the La Garita and Bachelor Mountain cauldrons (p. 52, 56) and with the younger fault or monoclinal flexure along Whited Creek (p. 57), and all may mark recurrent movement along the same zone of weakness.

Another northwest-trending normal fault separates the high bench of Wason Park from the main mass of La Garita Mountain to the north. This fault also follows the trend of an earlier fault probably active during subsidence of the La Garita cauldron (p. 52), but the last displacement clearly followed deposition of the Nelson Mountain Quartz Latite. The later period of movement on this fault was probably analogous to movement on other nearly parallel faults to the south and thus was related to subsidence of the Creede caldera to the south. Late movement near the west edge of Wason Park appears to have been minor, perhaps no more than 50 feet. In the Wheeler Monument area just east of the Creede district, however, a hard densely welded tuff layer in the Nelson Mountain Quartz Latite is displaced down about 300 feet to the south across the fault. A fault active during this last period of movement has been traced in detail and in reconnaissance for more than 10 miles southeast from the edge of the Creede district (pl. 1).

DOMING OF THE CALDERA CORE

Following final subsidence of the Creede caldera and after rockfalls and avalanches from the caldera walls had spread debris widely over the depressed floor, the core of the caldera was domed so that the highest parts near the center stood about 4,000 feet above the moatlike margin. A complex graben was deeply infaulted to form a broken keystone across the center of the domed core, and the northwest flank was cut by a prominent north-trending step fault.

FORM OF DOME

The core of the Creede caldera consists of an eastern part having a simple half-dome form and a western part consisting of tilted and warped blocks whose aggregate form is half dome but which show many complexities when viewed in detail. In the eastern part, the constituent ledges of Snowshoe Mountain Quartz Latite dip radially 25°–45° outward from a central high point adjacent to a crestal graben (pl. 1). Although somewhat modified by erosion, the present topography of the eastern part of the core reflects original structural topography. Snowshoe Mountain, the highest part of the core, is near the original high point, and the outer slopes are dissected dip slopes. The original upper, partially welded rocks in the core are exposed near the outer base of the slopes all around the eastern half of the core.

The outer slopes of the western half of the core closely reflect dip slopes along the northwestern part; but, farther south, broken edges of the rudely layered Snowshoe Mountain Quartz Latite form inclined steps that expose progressively deeper rocks in the core and the topography is more irregular. The rocks between the crestal graben and the step fault along Gardnier Gulch form a simple tilted block that strikes northeast and dips generally 20°–30° NW. The outer slopes still retain patches of the partially welded rocks that originally formed the upper part of the caldera core. The same general structure and stratigraphic succession are repeated west of the step fault south to the vicinity of the Marshall Park Campground. The rocks and structure are excellently exposed in prominent cliffs that mark the fault scarp along Gardnier Gulch and in the broken outer margin of the caldera south of the campground. Farther south the topography reflects stripped segments of Snowshoe Mountain Quartz Latite ledges, followed by abrupt slopes or cliffs where the surface breaks sharply across the ledges. The talus and landslide breccia from the caldera walls that intertongue with Snowshoe Mountain Quartz Latite (p. 42, 59) are generally best exposed in or near the sharp steps downward across the layered caldera fill.

CRESTAL GRABEN ZONE

A complex graben along the crest of the domed core separates the eastern and western halves of the dome. The zone as a whole clearly forms a fractured keystone that is much lower structurally than the adjacent blocks. Many individual blocks in the graben zone still have remnants of the softer, partially welded rocks that formed the upper part of the caldera fill, and in places these partially welded rocks are capped by mixed breccias derived by avalanching from the caldera walls after final subsidence (p. 42). Structural details in the crestal graben would have been nearly undecipherable without these marker units, and the position of the partially welded rocks and mixed breccias in relation to the partially welded upper rocks along the outer slopes of the domed core provide a measure of the depth of infaulting.

At the northern end of the crestal graben, a mosaic of fault blocks along the north-plunging crest of the dome ends in irregular cuspate masses of tectonic breccia that do not extend to the outer margin of the caldera. The breccia is generally massive, and only a few local shear planes cut it. The rock ranges from finely granulated to irregularly shattered and contains angular fragments from a fraction of an inch to several feet across. Unbroken masses as much as several hundred feet in diameter are common. Edges of the brecciated masses are very irregular, and tongues of breccia into the adjacent rock commonly end abruptly. The general impression is that the rock represents pervasive shattering without much differential movement. Larger tongues of breccia extending south outward from the masses generally pass into the distinct faults that separate blocks in the adjacent fault mosaic. The change in strike from northwest to northeast on the north flank of the domed core is fairly sharp in the mosaic; north of the breccia masses the change is more regular, and the unbroken arch is more open.

The deepest part of the crestal graben near the north margin of the core is west of the axis of the arch and is marked by a topographic bench along the east side of Deep Creek where the partially welded to nonwelded upper part of the Snowshoe Mountain Quartz Latite extends down to an altitude as low as 9,200 feet in a narrow subsidiary graben. The graben is overlapped on the north by a reentrant of the Creede Formation and appears to have formed a trough that extended considerably farther north, perhaps to the margin of the caldera.

The west margin of the crestal graben is marked by a single well-defined fault that extends from the north margin of the caldera southward near the top of the steep slopes west of lower Deep Creek. The fault in this area is separated from the highly broken rocks east of Deep Creek by a relatively unbroken block ranging in width from 1,500 to more than 3,000 feet.

Faults extending south from the tectonic breccia and the local deeply infaulted graben form a pattern of longitudinal graben faults joined irregularly by cross faults which break the graben into a complex mosaic (pl. 1).

Remnants of the partially welded upper part of Snowshoe Mountain Quartz Latite cap fault blocks at altitudes ranging from 10,000 to 10,890 feet near the center of the caldera. Densely welded tuffs of the same formation form the top of Snowshoe Mountain at an altitude of 12,006 feet adjacent to this area on the east; thus, altitudes of outcrops indicate that minimum displacement of the crestal graben here is in excess of 2,000 feet. If comparable soft Snowshoe Mountain Quartz Latite exposed near the eastern base of Snowshoe Mountain is projected over the top of the mountain, a displacement of more than 4,000 feet is indicated.

CAUSAL FORCE

Doming of the core of the Creede caldera seems most reasonably ascribed to magmatic pressure, although no direct supporting evidence can be cited. We know that magma existed at depth, for doming was followed by eruptions of quartz latitic lava along the west, south, and northeast sides of the caldera. Deformation was restricted to the core of the caldera and appears to have resulted from vertically directed forces, for the various segments of the core were uplifted differentially, half acting as part of a dome and half acting more as a series of tilted blocks. The higher parts of the core were raised 4,000 feet or more, while the margins remained low to form a peripheral moat. Doming resulted in marked distention of the caldera core, as indicated by the deeply infaulted crestal graben.

The analogy between the strongly domed cores of the Creede caldera and the Valles caldera in New Mexico is impressive. According to Smith and others (1960), subsidence at the Valles caldera was followed by "* * * (1) rise of an elongate central structural dome transected by longitudinal and radial grabens followed by (2) extrusion of a peripheral ring of volcanic domes." They concluded that extrusion of lava contemporaneous with faulting suggests that the Valles caldera core was domed by intrusions of a central stock or laccolith.

LATE FAULTING IN THE CREEDE GRABEN

The last period of fault movement in the Creede district took place after the Creede Formation and Fisher Quartz Latite formed and thus followed caldera subsidence and attendant doming or uplift due to magmatic intrusion. All known movement took place in the Creede graben (pl. 2), and most of the major faults trend north-northwest from the margin of the Creede caldera to the northern limit of the area mapped in detail (pls. 1, 2).

The faults active at this time were in part coincident with earlier faults, in part near the trends of earlier faults, and in part seemingly independent of earlier faults. Virtually all the movement on the Alpha-Corsair and nearby faults along the west margin of the graben took place at this time, and these faults transect older ones that were active during subsidence of the Creede caldera. The Bulldog Mountain fault zone formed in part along the probable trend of a fault formed during subsidence of the Bachelor Mountain cauldron, but the direction of displacement and probably the direction of dip were reversed (p. 55). The southern part of the Amethyst fault zone clearly followed an older fault (p. 55), and the northern segments of the Amethyst fault and a related branch fault have been interpreted (see previous section) as following reactivated faults in the hanging wall of the Equity fault. The Solomon–Holy Moses fault zone follows what was probably a zone of minor dislocation during subsidence of the Bachelor Mountain cauldron (p. 56).

As shown by the geologic section (pl. 1), downward displacement along the Alpha-Corsair fault zone dominated movement in the southern part of the Creede graben during the late period of faulting, and the lowest structural part of the graben is along the hanging wall of this fault zone under McKenzie Mountain. The main part of the graben in this area forms a west-tilted block between the Alpha-Corsair and Amethyst fault zones; the block is broken near the middle by the Bulldog Mountain fault zone, but movement on this zone was definitely subordinate to that on the Alpha-Corsair and Amethyst zones. Movement on the Solomon–Holy Moses fault zone on the east margin of the graben was minor relative to that on the other late graben faults.

The nearly flat capping of Nelson Mountain Quartz Latite on the ridge between Rat and West Willow Creeks (pl. 1) indicates that the core of the northern part of the Creede graben was not significantly tilted during late faulting. The downward displacement of Nelson Mountain and Rat Creek Quartz Latites in the northern part of the graben appears significantly less than that shown in the geologic section for older units farther south.

ALPHA-CORSAIR FAULT ZONE

All major movement on the Alpha-Corsair fault zone appears to have taken place after eruption of the Fisher Quartz Latite flow that caps McKenzie Mountain, as the fault zone displaces this flow virtually the same amount as it does the earlier rock units. Although equivalent rocks cannot be compared directly across the fault zone, the nearest exposures of the basal contact of the Fisher Quartz Latite, the top and bottom contacts of the Wason Park Rhyolite, and the contact between the Windy Gulch and Campbell Mountain Members of the Bachelor Mountain Rhyolite are all about 1,000–1,200 feet higher on the footwall side of the fault zone than they are on the hanging-wall side. In addition, the southern segment of the Alpha-Corsair fault zone cuts several echelon dikes of Fisher Quartz Latite along lower McKenzie Mountain; although these dikes are nearly parallel to the later fault zone, they are part of a broader zone of similar dikes that filled discontinuous fissures on either side of Miners Creek. These dikes show no indication that an integrated fissure zone was in existence when they were injected.

The Alpha-Corsair fault zone is exposed in many mine workings and prospect pits along lower McKenzie Mountain. In the Alpha and Corsair mines near the south end (fig. 2), the fault zone ranges from a few feet to as much as 50 feet in width and consists of brecciated to granulated rock that is commonly bleached and variably silicified or argillized. The fault zone dips 55° NE., and most slickensides and grooves point almost downdip. Farther north near the Kreutzer Sonata mine, the fault is less well exposed but appears to consist of similar altered fault breccia along a more regular 2- to 6-foot-wide zone. The dip appears to be 50°–60° NE., although no reliable measurements were obtained. Emmons and Larsen (1923, p. 190) reported that a parallel fissure in the hanging wall of the Alpha-Corsair fault zone at the Reno shaft, 2,000 feet south of the Kreutzer Sonata mine, strikes northwest and dips 60° NE.

The hanging-wall block between the Alpha and Kreutzer Sonata mines is highly broken and is cut by many zones of brecciated and irregularly altered and mineralized rock. Only those faults that caused detectable offset of geologic contacts could be mapped and are shown on plate 1. Other faults and sheared zones are clearly apparent in local outcrops but could not be followed across adjacent areas of poor exposure. Those subsidiary hanging-wall faults that show the greatest displacement are generally at right angles or nearly so to the main fault zone. The three largest ones cut the hanging wall of the Alpha-Corsair fault on lower McKenzie Mountain into blocks that have subsided differentially. The lowest rocks in the hanging wall of the Alpha-Corsair fault zone are in the block just south of the Kreutzer Sonata mine. Other faults and shear zones trend either about parallel or at low angles to the trend of the Alpha-Corsair fault. Two branching faults have sufficient displacement to be mapped, but other sheared zones, although numerous, seem to be minor.

The trend of the Alpha-Corsair fault zone is deflected from northwest to nearly north at the Kreutzer Sonata mine, where the zone intersects a northwest-trending fault that probably was active during subsidence of the Creede caldera (p. 60; pl. 2). The fault zone is largely covered northward from this deflection, but it can be located fairly closely in several places and its general relations seem clear. The fault zone splits into two main branches about 4,000 feet north of the Kreutzer Sonata mine; the eastern branch extends along the east slope of McKenzie Mountain, and the western branch cuts across the top of McKenzie Mountain. Both branches extend into the upper Rat Creek drainage basin, where they appear to converge somewhat. The northern limit of the branches has not been determined, and both may extend beyond the positions shown on the geologic and tectonic maps (pls. 1, 2). The only dip measurement that could be made was along the western branch near the top of McKenzie Mountain, where the fault dips 80° E. Whether this steep dip is a local feature or widespread is not known.

A small fault 1,000–3,000 feet to the west follows the general trend of the Alpha-Corsair fault zone from the vicinity of the Kreutzer Sonata mine to the top of McKenzie Mountain. Displacement on this fault, although much less than that on the Alpha-Corsair fault zone, is in the same direction, and together the two faults define the west margin of the main Creede graben.

AMETHYST FAULT ZONE

The Amethyst fault zone was clearly active during the last major period of faulting in the Creede graben, as the north end of the tongue of Creede Formation that extends across Bachelor Mountain is cut off by the fault. A dike, probably of Fisher Quartz Latite, is cut by the Amethyst fault on the Commodore 5 level between the Berkshire and Park Regent shafts (pl. 4). The Creede Formation is not present now on the footwall side of the Amethyst fault zone; therefore, the full amount of late movement could not be measured. The minimum displacement must be more than 300 feet, as the base of the Creede Formation on the hanging wall is that far below rocks of the Willow Creek Member on the adjacent footwall. As previously indicated (p. 56), the Wason Park Rhyolite has been displaced as much as 600–700 feet along the Amethyst fault zone. There seems to be no way to determine how much of this aggregate displacement took place during the last period of movement and how much during earlier periods concurrent with subsidence of the Creede caldera.

The surface trace of the Amethyst fault zone in the area along Bachelor Mountain west of West Willow Creek is sinuous, and some of the bends can be related to control of late movement by preexisting faults. At the south end of the Amethyst fault zone, late movement was deflected southeast along crescentic faults that originated during subsidence of the Bachelor Mountain cauldron, and the movement appears to have dissipated and died out somewhere near the forks of Willow Creek north of Creede. North of these earlier crescentic faults, the Amethyst zone consists of several nearly parallel strands that trend north-northwest for about 3,500 feet from the Bachelor mine through the Commodore mine to the Last Chance mine (pl. 1; fig. 2). This segment is largely in the footwall block of the ancestral Amethyst fault that formed during subsidence of the Bachelor Mountain cauldron, and rocks of the Willow Creek Member or the Creede Formation constitute the walls at the surface for most of the distance. The old and young faults merge and the whole trend is sharply deflected north through the Last Chance mine and back to north-northwest in the adjacent Amethyst mine. Subsidiary mineralized fractures are abundant in the hanging-wall block adjacent to this bend and will be discussed in detail later in this section.

The Amethyst fault zone appears to swing slightly more to the north in the Park Regent mine (pls. 1, 4), and what little can be learned from sparse surface exposures suggests that it extends without further marked change in trend to the northern limit of the area mapped in detail in the vicinity of the Equity mine.

Several branch faults apparently split off the main Amethyst fault zone beneath the moraine that covers the trend of the fault in the vicinity of West Willow Creek. The presence of a northwest-trending fault along the general course of West Willow Creek is suggested by the relations exposed in a local area of outcrop south of the Rat Creek Quartz Latite eruptive center. In that area, Rat Creek lavas are apparently displaced relatively downward to a position adjacent to dark Huerto rocks. The exposed rocks are irregularly bleached and altered and several prospect shafts have been sunk, but none of these exposes the fault. This fault probably extends from the Amethyst to the Bulldog Mountain fault zones, but no evidence was seen at the surface to indicate the position of the probable intersections.

A west-dipping normal fault cuts across the west end of Nelson Mountain and projects south beneath a great landslide mass toward the Amethyst fault zone. Exposures of Rat Creek and Campbell Mountain rocks limit the possible position of this projected fault on the east, but no similar control exists to establish a western limit. The trend shown on the geologic map (pl. 1) was determined by assuming that the fault does not deviate much from the trend mapped farther north.

From Deerhorn Creek to upper West Willow Creek, the Amethyst fault zone traverses a talus-flanked ridge that consists largely of the Nelson Mountain Quartz Latite. Exposures are poor, but the general trend of the fault is indicated by discontinuously altered rock, fault-breccia float, and a soil-covered saddle across the ridge crest.

An east-dipping normal fault branches from the Amethyst fault zone near upper West Willow Creek and extends south along the ridge between West Willow and Deerhorn Creeks at least to the vicinity of the Captive Inca mine. The south end of this fault clearly displaces rocks of the Nelson Mountain Quartz

Latite down against the local cone complex of Rat Creek Quartz Latite. Adjacent rocks are irregularly altered along at least the southern part of this fault, and at the Captive Inca mine the dump of the caved shaft consists largely of soft argillized rock.

The dip of the Amethyst fault zone was measured at many places in the mine workings along the east side of Bachelor Mountain; most measurements were 50°–70° SW., although some were as low as 40° SW. and others were nearly 80° SW. More reliable figures on the general dip of the fault zone were obtained from the relative positions of the fault zone on different mine levels. As measured between the Commodore 3, Amethyst 5, and Commodore 5 levels (pls. 3, 4), the dip averages 55°–60° SW. north of the pronounced bend in surface trace of the fault at the Last Chance mine, 65°–70° SW. for at least 2,000 feet south of the bend, and 60°–65° SW. toward the south end of the major mine workings. These changes in dip result from a fault that is sinuous near the surface but nearly straight at the level of the lower mine workings.

The hanging wall of the Amethyst fault is highly broken for several hundred feet west of the main fault near its south end in the Bachelor and Commodore mines. The fractures form a persistent zone of late cracks that dip generally west but are steeper than the main fault. Veins occupy many of these fractures and have been developed in extensive mine workings on the Commodore 3 and Commodore 5 levels (pls. 3, 4). The veins are stoped on some of the higher levels of the mines. In the Commodore mine, minor antithetic faults that are either nearly vertical or dip steeply northeast are abundant, particularly in the upper levels of the mine; many of these were filled with metalliferous veins that have since been mined out. None of the subparallel to antithetic hanging-wall faults near the south end of the Amethyst vein sufficiently offset contacts to be detected by surface geologic mapping.

The pattern of fractures in the hanging wall of the Amethyst fault farther north opposite the Last Chance and Amethyst mine segments is markedly different. Near the main fault, many subparallel hanging-wall fractures form a highly sheared zone as much as 100 feet wide or more adjacent to the main fault. Farther out in the hanging wall, the subsidiary faults form intersecting nearly vertical conjugate fractures. In the upper levels of the mine, these fractures are very abundant and form a complex pattern; they become progressively fewer and simpler in pattern downward. The highly sheared hanging wall and the focus of the conjugate fractures are both opposite the pronounced bend in the main Amethyst fault at the Last Chance mine. Maps of currently inaccessible mine workings on the Last Chance 2 and adjacent levels in the upper parts of the mine show that a maze of intersecting veins has been mined out in this area. Several hundred feet lower, on the Amethyst 5 level (pl. 3), we mapped many intersecting mineralized fractures on both trends of the conjugate system; at this level the pattern is much simpler than that indicated by maps of the higher workings. On the lowest accessible mine workings on the Commodore 5 level (pl. 4), the conjugate system is represented by only one main fracture zone on each trend.

As the subsidiary fractures are nearly vertical, the focus of most abundant conjugate fracturing is progressively closer to the main Amethyst fault in successively deeper mine levels. On the Amethyst 5 level, the most abundant conjugate fractures are about 300 feet out into the hanging wall, whereas 700 feet lower, on the Commodore 5 level, they are concentrated only 100–150 feet out into the hanging wall. Both the pronounced bend in the main Amethyst fault and the nearby focus of conjugate fracturing in the hanging wall rake north, and on the lower, Commodore 5 level they are 200–400 feet north of comparable positions on the Amethyst 5 level.

Outside the general focus area, fractures following the two generally conjugate directions are dissimilar; those that trend south to southwest generally are indistinct and discontinuous, and those that trend northwest are much more persistent. The northwest-trending O H vein marks a conspicuous zone of integrated fractures that extends at least 4,500 feet northwest from the focus area (pls. 3, 4); this zone was abundantly mineralized and has provided most of the ore produced in the Creede district in recent years. Two minor zones of fractures have been followed south to southwest 500–1,000 feet from the focus area on different levels. The zone exposed on the Amethyst 5 level (pl. 3) is indistinct and discontinuous, whereas the zone exposed on the Commodore 5 level (pl. 4) is more persistent, although still not a zone of intense fracturing.

Movement on the O H fracture zone appears to have been minor and largely strike slip; the northeast side moved relatively southeast. Little or no finely granulated rock or gouge was noted along the zone, and the appearance of the abundant fractures and open spaces suggests that the movement was no more than enough to form them and spread them to their present position. For the length of the zone exposed, a right-lateral sense of displacement is indicated consistently by the fact that deflections to the right remained open and were abundantly mineralized, whereas deflections to the left were tight and sparsely mineralized. Diagonal tension fractures in the vein or fracture zone trend more to the north than does the main fracture zone; this also indicates a right-lateral sense of displacement.

The abundant conjugate fractures focused in the hanging wall of the Amethyst fault opposite the Last Chance mine probably resulted from stresses generated by the relative downward displacement of a highly curved segment of the main Amethyst fault, represented by the present surface trace, to a position adjacent to the nearly straight segment of the fault exposed on the Commodore 5 level. The resulting deformation is thus analogous to the collapse of a steeply inclined arch under the influence of the vertically acting force of gravity. Compression at right angles to the axis of the collapsing arch and at right angles to the direction of maximum tension on the main fault would thus account for the conjugate system of fractures; movement of the wedge of rock between the O H and Amethyst faults toward the collapsing arch would account for the indicated minor right-lateral displacement along the O H fault.

BULLDOG MOUNTAIN FAULT ZONE

The younger faults along the Bulldog fault zone can be mapped closely for only about 1½ miles along the top of Bulldog Mountain; to the north and south they pass under great landslide masses and their relations are obscure. Two well-defined faults of this zone cut Wason Park Rhyolite and Huerto Formation from the south face of Bulldog Mountain to the head of Windy Gulch. Both faults have curving trends—the western fault convex to the west, and the eastern fault convex to the east—and they enclose a lens-shaped block of rock 1,500 feet wide in the middle that pinches out in both directions. Measured dips are 60°–70° E. on the western fault and 65° E. on the eastern fault. Rock units are offset downward about 240 feet on the western branch and about 120 feet on the eastern branch; thus, the aggregate displacement across the zone is about 360 feet.

The Bulldog Mountain fault zone extends south beneath a large landslide mass on the south face of Bulldog Mountain. Poorly defined erosional windows through the landslide expose the Creede Formation and different members of the Bachelor Mountain Rhyolite in positions that suggest offset of the Creede Formation by the fault zone and, thus, late movement on the zone. Relations to the earlier faults in this same area are even more obscure, and the interpretations shown on the geologic and tectonic maps (pls. 1, 2) are strictly hypothetical.

From the junction of the two main branch faults at the head of Windy Gulch northward nearly to the latitude of the Equity mine, the Bulldog Mountain fault zone is covered by a great landslide mass and its position cannot be located closely. It can be bracketed in a zone 1,500 feet wide adjacent to the local Rat Creek Quartz Latite eruptive center along West Willow Creek, but the heterogeneous character of the adjacent rocks precludes estimation of the offset in this area.

Near the north edge of the geologic map (pl. 1), an east-dipping normal fault, probably the north extension of the Bulldog Mountain fault zone, displaces Nelson Mountain Quartz Latite down to the east against Rat Creek Quartz Latite lavas and tuffs. The base of Nelson Mountain Quartz Latite is at least 500 feet lower on the east side of the fault than it is under the ridge crest west of the fault, but the actual displacement on the fault may be considerably less than this, as Nelson Mountain rocks buried an east-sloping valley wall in this vicinity.

As can be seen from the geologic section (pl. 1), the Bulldog Mountain fault zone near Bulldog Mountain is a relatively minor fault zone in the main subsided block in the Creede graben. However, it probably intersects the Amethyst fault zone at depth, and it may have an economic potential that greatly exceeds its structural significance. (See "Suggestions for prospecting.")

SOLOMON-HOLY MOSES FAULT ZONE

The Solomon–Holy Moses fault zone is a minor zone of dislocation that marks the east margin of the Creede graben. The fault zone was active during subsidence of the Bachelor Mountain cauldron and was reactivated some time after deposition of the Mammoth Mountain Rhyolite and Rat Creek Quartz Latite. None of the younger rock units crop out near the fault zone, and the more recent period of movement cannot be dated with assurance more closely than relatively late in the sequence of volcanic and tectonic events in the Creede area. Unoxidized or partially oxidized vein material similar to that along the Amethyst vein zone was seen in a few places in mine workings along the Solomon–Holy Moses fault zone; in these places evidence of several ages of brecciation was seen. Mineralized fractures cut silicified breccia that antedates ore deposition and is similar to that formed during early subsidence along the Amethyst fault zone; the ore itself shows evidence of fracturing and rehealing during mineralization, and late shears cut the veins and mineralized breccia. Similar relations were noted along the main Amethyst fault zone, which is known to have been active during the latest period of faulting.

As previously noted (p. 56), aggregate displacement across the middle segment of the Solomon-Holy Moses fault zone, measured by the offset contact between the Willow Creek and Campbell Mountain Members, is no more than 300–400 feet. No evidence was seen that would enable assignment of the increments of displacement to the different periods of movement on the fault zone. Slickensides, noted most commonly along late shears, are generally steep and indicate predominant downdip movement. The fault zone consists of many complexly branching fractures, and individual dips measured in the different mine workings range from 50° to 80° W. An average dip obtained from the general position of the fault zone on different mine levels is about 60° W.

In gross aspect, the Solomon–Holy Moses fault zone appears to reflect a subsidiary sag adjacent to the main Creede graben. It forms a fairly well defined zone only in the middle segments, where displacement was 300–400 feet. To the north and south, the zone splits into many branches, which dissipated movement over wider areas, and the zone appears to die out in both directions. At the south end, the north-trending Solomon–Holy Moses fault zone is intersected and deflected by a broad zone of discontinuous north-northwest-trending fractures that parallel adjacent segments of the Amethyst fault zone and are about on trend with a minor fault zone farther northwest in the vicinity of the Midwest mine. Some of these fractures may extend south under the great banks of talus that flank the canyon of East Willow Creek, but we were not able to trace them. Toward the north, the Solomon–Holy Moses fault zone curves from north to northwest, and branches split out both north and south from the main trend. None of these faults cuts the high rims of welded tuff that cap Nelson Mountain to the north; this fact clearly indicates that the fault zone dies out in this direction.

ORE DEPOSITS

Our studies of the ore deposits were limited to those mines that were open when underground mapping was being done. Many of the older mines were closed and partly or entirely inaccessible, and our coverage was incomplete. Even along the Amethyst fault zone where mines were active throughout the period of our field studies, many of the older workings on the main Amethyst vein were inaccessible. We decided, therefore, to concentrate on determining the structural control of the ore deposits and not on investigating in detail the mineralogy, paragenesis, wallrock alteration, or distribution of ore values along the veins. Much of this information is contained in the earlier study of the Creede district by Emmons and Larsen (1923, p. 98–193), and for most of the vein zones it seemed unlikely that their data could be matched, let alone extended.

The only ore deposit that was sufficiently accessible to be studied in detail was the O H vein in the hanging wall of the main Amethyst vein. This ore body seemed deserving of intensive study for the following reasons: It was well exposed; its mineralogy and paragenesis were sufficiently varied yet regular; and its environment was readily susceptible to interpretation. With the helpful cooperation of the Emperius Mining Co. and at our invitation, Edwin Roedder, Paul Barton, Philip Bethke, and Marc Bodine of the U.S. Geological Survey undertook a detailed study of the mineralogy and geochemistry of the vein (Bethke and others, 1960; Roedder, 1960), and we restricted our own studies to the more general aspects, particularly structural control.

AGE OF MINERALIZATION

Mineralization in the Creede district was related in time to the late period of faulting in the Creede graben and thus followed deposition of the Creede Formation and eruption of Fisher Quartz Latite. The mineralized Alpha-Corsair fault is clearly younger than Fisher Quartz Latite dikes and the Creede Formation; the ore minerals in the Monon Hill area impregnate the basal part of the Creede Formation; and the Creede Formation is mineralized along the Amethyst fault zone. The Creede Formation is highly silicified on Bachelor Mountain; barite and manganese oxides impregnate the silicified Creek Formation here and there, and in places silver is present in sufficient quantity to be of economic interest.

Mineralization along the Solomon–Holy Moses fault zone and other minor fault zones in the eastern part of the district cannot be dated so closely, but it was similar in kinds of ore and gangue minerals deposited to that along the Amethyst fault zone and probably was virtually contemporaneous.

Detailed relations observed chiefly along the Amethyst fault zone suggest that mineralization took place toward the end of the late period of faulting. Displacement on the main Amethyst fault zone before mineralization was sufficient to form an extensive system of hanging-wall fractures, but the main Amethyst vein shows evidence of repeated brecciation and rehealing during vein deposition, and the vein is cut by fractures that formed after ore deposition and are characterized by slickensides and granulated rock and ore. The late movement was not of sufficient magnitude to affect the hanging-wall fractures nearly as thoroughly as it did the main vein, and most of the smaller veins along these fractures show no evidence of movement after ore deposition. The ore along the larger, O H vein shows evidence of only minor breaking and rehealing during ore deposition.

Nonoxidized or only partially oxidized ore was seen in only a few places along the Solomon–Holy Moses fault zone, and the relations in these places are much like those along the Amethyst fault zone. The vein shows evidence of breaking and rehealing during ore deposition, and slickensided fractures formed after ore deposition cut the veins in many places. The only basis for judging the relative amounts of movement before and after ore deposition is the degree of brecciation, and this suggests that movement before deposition was greater.

All the ore we saw in the Alpha-Corsair fault zone was oxidized, and the relations between fault movement and ore deposition were obscure.

ORE DEPOSITS ALONG THE AMETHYST FAULT ZONE

Most of our detailed studies of ore deposits in the Creede district have concentrated on the Amethyst fault zone, but even here our coverage has been uneven. We mapped the geology of accessible mine workings on only three levels: the Commodore 5 level (portal alt about 9,220 ft), which constitutes the lower main haulage level; the Amethyst 5 level (portal alt about 9,900 ft); and the Commodore 3 level (portal alt about 10,080 ft). Of these, only the workings along the Commodore 5 level exposed both the hanging-wall veins and the main Amethyst vein for most of their lateral extent (pl. 4). The Amethyst 5 level (pl. 3) provided excellent exposures of the hanging-wall veins, but only limited segments of the main Amethyst vein were accessible. Open workings on the Commodore 3 level (pl. 3) were limited to the southern part of the vein zone, where only about 1,500 feet along the main Amethyst vein and related hanging-wall veins was available for study. We briefly traversed intermediate levels along the O H vein but did not see the main Amethyst vein underground between the Commodore 5 and Amethyst 5 levels.

AMETHYST VEIN

VEIN MATERIAL

The main Amethyst vein as seen on the Commodore 5 and Amethyst 5 levels is largely mineralized fault breccia, which in an unoxidized state consists of fragments of silicified country rock set in a variable matrix of clay, chlorite, amethystine quartz, white quartz, and sulfide minerals. The different matrix components vary widely in relative abundance, and at any given place one or another may dominate almost to the exclusion of all others. Late fault movement formed postmineralization sheared zones that range from narrow granulated zones along the margins or through the center of the vein to broad shattered zones that encompass the entire width of the vein and parts of the adjacent walls as well.

Mineralized rubble breccia is exposed for nearly 9,000 feet along the Amethyst vein on the Commodore 5 level (pl. 4). In the southern two-thirds of this extent, the matrix around the wallrock fragments consists of chlorite and abundant vuggy amethystine and white quartz in crusts around the rock fragments and in veinlets and irregular masses through the soft chlorite. Galena, sphalerite, and pyrite are irregularly dispersed through the chlorite and to a much lesser extent are associated with the quartz. Much of the amethystine and white quartz appears barren or virtually barren of sulfide minerals. In a few places, amethystine quartz predominates and forms a complexly layered vein of ribbon quartz. Some of the layers are clearly successive crusts that formed along the margins of open spaces, but others are complexly crosscutting and formed through alternating fracturing and vein deposition. Small quantities of fluorite and rhodochrosite were noted in a few places. Along the northern third of the vein exposed along the Commodore 5 level, quartz is a very minor constituent of the vein, and the matrix consists largely of soft, greasy-appearing green chlorite in which galena, sphalerite, and pyrite are irregularly disseminated.

Barren segments occur here and there along the vein throughout the length exposed on the Commodore 5 level; these grade laterally into adjacent mineralized segments, which they appear to underlie. The barren zones range from muddy breccias containing angular wallrock fragments set in dirty-brown to yellow clay to open breccias in which the angular fragments form loose aggregates without finer matrix material. The loose aggregates commonly have a

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washed appearance and probably represent watercourses along the vein structure. The barren zones grade into mineralized vein material; the interstitial clay first assumes a faint green cast and then becomes progressively more chloritic until the entire matrix is altered to and replaced by chlorite or by associated quartz and sulfides.

Only short segments of the Amethyst vein are exposed in the Amethyst 5 level; in most of these, amethystine quartz is much more conspicuous than along the lower Commodore 5 level. The pillar around the Amethyst shaft (pl. 3) consists largely of quartz. A central zone of layered ribbon quartz separates hanging-wall and footwall zones of white quartz. The ribbon quartz shows many stages of shearing and rehealing and apparently grew by accretion of successive layers of quartz along fractures formed during recurrent movement along the fault.

In the upper levels of the mine, in part on the Amethyst 5 level but generally above it, the walls of the Amethyst vein commonly are intensely argillized and consist of soft light-colored clay. These clayey wallrocks, called porphyry by the local miners, generally signal the upper limit of economic mining; the veins are commonly the highest in grade near the base of the argillized rock but reportedly become leaner and noneconomic farther up between the altered walls. We have seen little of the argillized rock, as the soft walls cave easily and mine workings generally become inaccessible within a short time after they are abandoned.

DETAILED DESCRIPTION

Mineralization along the main Amethyst vein was confined largely to fractures and fault breccia along the Amethyst fault and to nearby fractures in the hanging wall. Detailed control on the distribution of ore in this fractured zone is not everywhere clear on the levels we studied, as only the Commodore 5 level exposed significant lateral segments of the vein. The following discussion, therefore, is based to a considerable extent on data given by Emmons and Larsen (1923) and by Larsen (1930), supplemented by information obtained from many Creede area people who have long been associated with the mining industry there.

For convenience in discussion, we shall consider the vein in three parts: a southern segment developed by the Bachelor and Commodore mines and southern part of the Last Chance–New York–Del Monte mine (from coordinate −1600 N. southward, pls. 3, 4); a middle segment developed mostly by the Last Chance–New York–Del Monte and Amethyst mines (between coordinates −1600 N. and +800 N.); and a northern segment developed by the northern parts of the Amethyst, Happy Thought, White Star, and Park Regent mines (from coordinate +800 N. northward).

SOUTHERN SEGMENT

As we mapped it on the Commodore 3 and Commodore 5 levels (pls. 3, 4), the southern part of the main Amethyst vein consists of a mineralized breccia zone, a few feet to as much as 30 feet wide, which follows that part of the Amethyst fault zone most active during the latest period of faulting. The oxidized ore on the Commodore 3 level appears to be higher grade and more uniformly distributed along the vein than that along the Commodore 5 level, where lean or nearly barren appearing segments of the vein intervene between segments containing abundant limonite, manganese oxides, and barite.

The footwall of the Amethyst vein is well exposed in the long crosscut that extends from the portal of the Commodore 5 level to the Amethyst vein in the Bachelor mine (pl. 4). The rock exposed along the crosscut belongs entirely to the Willow Creek Member, and, although highly jointed and locally sheeted, it is not cut by any significant mineralized shear zones. The hanging wall, on the other hand, is cut by many mineralized shear and breccia zones between the main Amethyst fault and the ancestral Amethyst fault 100 feet or so farther west. Late fractures are particularly abundant along the trend of the ancestral fault; as exposed along the McClure drift on the Commodore 5 level, many of these fractures contain veins of vuggy amethystine and white quartz as well as limonite, manganese oxides, and barite.

The McClure and Overholt crosscuts extend into the hanging wall for 500 feet or more west of the ancestral Amethyst fault in the Bachelor mine and expose many minor steeply dipping mineralized seams and cracks. An arcuate generally west-trending south-dipping vein was intersected by the McClure crosscut and was followed for 300 feet west by the Teller drift (pl. 4). This vein appears to follow the trend of a curving fault formed during subsidence of the Bachelor Mountain cauldron (p. 55) that was later rebroken and mineralized. It appears to be the downdip extension of a similar arcuate vein, the Copper vein, exposed on the Commodore 3 level (pl. 3) and at the surface (pl. 1). The Copper vein clearly follows a reactivated arcuate fault formed during subsidence of the Bachelor Mountain cauldron. The late movement preceding mineralization, however, was not sufficient to displace the base of the Creede

Formation, which overlaps the trend of the fault without offset (pl. 1). Mineralization clearly followed deposition of the Creede Formation.

On the Commodore 3 level (pl. 3), the haulage tunnel follows the vein north along one strand of the main Amethyst fault through the Bachelor mine to the Commodore mine, where it is blocked by caved ground. Hanging-wall fractures formed during the latest period of fault movement are most abundant near the trend of the ancestral Amethyst fault, 200–400 feet west of the main fault and vein; these are locally referred to as the Dean fault. The Dean fault consists of two mineralized fracture zones, 15–80 feet apart, that locally were sufficiently wide and rich to be stoped. Late movement along the ancestral fault trend, however, was insufficient to produce offset of the overlying Creede Formation detectable in field mapping. The block intervening between the ancestral and main Amethyst faults, as exposed along the Dean 2 crosscut, is cut by many minor mineralized seams.

Surface mapping above the Commodore 3 level indicates that the main Amethyst fault consists of two principal strands 75–100 feet apart. Only the western strand is exposed along the Commodore 3 level, and to our knowledge the eastern strand has not been prospected underground.

Emmons and Larsen (1923, p. 143–147) were aware that the main mineralized vein did not follow the main change in rock formations across the fault zone in the Bachelor mine area, but they apparently did not realize that at least two separate periods of fault movement were involved. The vein along the fracture that had the predominant movement during the last period of faulting was called the Bachelor vein, and they referred to the somewhat broken trend of the ancestral Amethyst fault as "the Amethyst fault." The fractures along the ancestral Amethyst fault on the Commodore 3 level were later called the Dean fault (Larsen, 1930, p. 94); these fractures probably form a continuous zone with those concentrated along the trend of the ancestral Amethyst fault on the Commodore 5 level as shown along the McClure drift (pl. 4).

The dip of the Amethyst vein in the Bachelor mine (north boundary near coordinate −3200 N.) is about 60° W. The late hanging-wall fractures, particularly those near the trend of the ancestral Amethyst fault, generally dip somewhat more steeply and appear to intersect the main vein at depth. Many of the subsidiary fractures are antithetic and dip steeply east toward the main fault and vein.

Our information on the Commodore and southern part of the Last Chance–New York–Del Monte mines (between coordinates −3200 N. and −1600 N.) is not as complete as that on the Bachelor mine to the south because the only workings we could study in detail were on the Commodore 5 level. Some data on higher levels were presented in the reports of Emmons and Larsen (1923, p. 148–152) and Larsen (1930, p. 95–96). From the information available, no relation was recognized between grade of ore, width of fault breccia, or dip or strike of the vein.

The ancestral Amethyst fault is about 40 feet west of the main Amethyst vein at the Archimedes raise (pl. 4), about 20 feet west of the vein 200 feet south of the Commodore shaft, and virtually coincident with the vein at the Commodore shaft. A short crosscut 200 feet south of the Commodore shaft extends 140 feet west into the hanging wall of the Amethyst vein. This crosscut exposes many mineralized seams but no significant veins.

The hanging wall of the Amethyst vein and major Amethyst fault is highly broken on the upper levels of the Commodore mine, particularly from the Commodore 3 level to the surface (Emmons and Larsen, 1923, p. 150–151; Larsen, 1930, p. 95), by antithetic faults, most of which are vertical or dip east toward the Amethyst vein. A cross section by Emmons and Larsen (1923, p. 151) shows a series of mineralized east-dipping antithetic faults joining the main Amethyst vein. Subsequent mine developments disclosed similar mineralized faults that join the Amethyst vein farther downdip from those illustrated (Larsen, 1930, p. 95). The westernmost of the larger hanging-wall fissures is 50–70 feet west of the main Amethyst vein on the Commodore 3 level and presumably joins the main vein a short distance below that level.

As reported by Emmons and Larsen (1923, p. 151) and Larsen (1930, p. 95), the main Amethyst vein and adjacent hanging-wall veins were extensively stoped between the Commodore 1 and Commodore 3 levels throughout the Commodore mine. Little ore was taken out within 200 feet of the surface, but much ore was stoped in places below the Commodore 3 level.

MIDDLE SEGMENT

The central and commonly most productive part of the Amethyst vein (generally between coordinates −1600 N. and +800 N.) is developed by the Last Chance–New York–Del Monte mine and by the Amethyst mine. This segment of the vein is characterized by an abrupt bend in surface trace and intense fracturing of the hanging wall adjacent to the bend. The main Amethyst vein in these mines was more continuously mineralized than along any other comparable segment, and the vertical range of the ore also was greater. Good ore cropped out at the surface near the collars of the Last Chance and Amethyst shafts, and the vein is reported to have been largely stoped in the upper levels, where oxidized ore secondarily enriched in silver was extracted. Continuous stopes extended along the better ore shoots to the main lower haulage tunnel. As reported by Larsen (1930, p. 93), the only significant ore discovered in a program of deep exploration by the Creede Exploration Co. between 1917 and 1920 was in the Amethyst mine, where a drift 120 feet below the Nelson tunnel (portal about 45 ft below the Commodore 5 tunnel portal) exposed a vein 3–4 feet wide that contained 12–15 percent lead and zinc combined and a little silver.

As previously described (p. 65), the trend of the Amethyst fault and vein is deflected from northwest to north and then northwest again in the vicinity of the Last Chance shaft (pl. 1). The segment just south of the first bend is continuous in trend with the vein in the Commodore mine to the south, but the dip is somewhat steeper (generally 70° SW.). At the bend, the strike swings north and the dip lessens to 55°–60° W. Farther north, in the southern part of the Amethyst mine, the strike bends back to northwest, but the dip remains about 55° SW. Changes in dip and strike on the Amethyst 5 level (pl. 3) are nearly comparable with those at the surface, but they are much more subdued on the Commodore 5 level (pl. 4), 700 feet below. The double deflection in the fault surface rakes steeply north and crosses the Commodore 5 level at least 200 feet farther north than it does the Amethyst 5 level.

The many antithetic hanging-wall fractures and veins in the upper part of the Commodore mine persist northward, and in the Last Chance–New York–Del Monte mine they combine with many west-dipping fractures just south of the bend in the main fault to form a complex assemblage of closely spaced hanging-wall veins. Although more numerous than farther south, the hanging-wall veins near the more southerly bend in the fault are closely grouped adjacent to the more steeply dipping main vein, and in one place the whole assemblage was mined as a unit to form the "Big Cave" (Emmons and Larsen, 1923, p. 155). These many mineralized hanging-wall fissures are well exposed in the mine workings on the Amethyst 5 level (pl. 3) and, according to Emmons and Larsen (1923, p. 154–155), were apparently even more abundant in higher levels.

On the Commodore 5 level (pl. 4), hanging-wall fractures are more abundant near the bend in the fault than farther south but are not nearly as abundant nor as well mineralized as in the upper parts of the mine. North of the bend, roughly halfway between the Amethyst and Berkshire shafts, subsidiary workings extending as much as 100 feet into the hanging wall expose several interlacing vein zones (pl. 4).

Many conjugate fractures formed farther out in the hanging wall adjacent to the pronounced bend in the Amethyst fault, and these were thoroughly mineralized to form the O H and related veins. These veins are discussed in greater detail in subsequent sections.

The intense fracturing of the hanging wall adjacent to the bend in the fault appears to have resulted largely from downdip movement of the hanging wall across a north-raking bend in the fault surface that diminished in amplitude with depth. The many antithetic tensional fractures in the upper mine levels just north and south of the bend appear to have formed through increased tension in those areas where the walls of the main fault tended to be wedged apart by movement down and across the strongly curved near-surface part of the raking bend.

NORTHERN SEGMENT

In the northern segment of the Amethyst vein (generally north of coordinate +800 N.), both the hanging wall and footwall are well explored by crosscuts and drifts on the Commodore 5 level 180–800 feet north of the Berkshire shaft (pl. 4). The southernmost crosscut extends northeast from the O H vein across the Amethyst vein and about 120 feet into its footwall. The footwall consists of firm but slightly chloritized and argillized Willow Creek rocks for 80 feet from the Amethyst vein and then of hard, unaltered Willow Creek. Few late fractures cut these rocks, but the slightly altered rocks consist of pervasively broken fault breccia of the type commonly associated with the ancestral Amethyst fault. The hanging wall, on the other hand, is cut by many subsidiary mineralized fractures within 120 feet of the Amethyst vein; these fractures dip steeply west and generally parallel the main vein. One integrated minor vein zone in the fractured hanging wall was followed northwest by a drift for about 270 feet, at which point the drift was turned north to northeast back to the main Amethyst vein. The subsidiary vein zone fills a system of interlacing late fractures that follows the approximate west margin of pervasively broken and silicified fault breccia related to the ancestral Amethyst fault. In its last exposure, this vein zone is indistinct; only a minor mineralized seam appears on trend in a crosscut 300 feet farther northwest.

The North Drift crosscut, about 650 feet north of the Berkshire shaft, extends west from the Amethyst vein to the O H vein (pl. 4). Hanging-wall fractures are abundant a short distance west of the intersection of the crosscut with the Amethyst fault but are not conspicuous at the intersection. The Amethyst vein near the intersection is much narrower than farther south and consists of sheared chloritic breccia containing sulfide minerals and ranging from a few inches to a few feet in width. A crosscut extending about 200 feet into the adjacent footwall exposes widely spaced mineralized fractures.

The trend of the ancestral Amethyst fault deviates somewhat from the trend of the main mineralized Amethyst fault in the vicinity of the North Drift crosscut. On the crosscut itself, the change from brecciated Willow Creek to brecciated Campbell Mountain rocks occurs about 45 feet west of the main vein; the ancestral and main Amethyst faults converge both north and south, however, and appear to coincide for a distance of 150 feet along the vein in both directions from the crosscut.

North of the North Drift crosscut, in the Happy Thought, White Star, and Park Regent mines, our firsthand data are limited to the Commodore 5 tunnel level, and even here exposed segments of the vein account for only about two-thirds of the length of the vein developed by mine workings. The upper levels of these mines were inaccessible in 1911 and 1912, when Emmons and Larsen (1923) did their fieldwork; so even previously published firsthand data concern only the lower parts of the mines.

According to Emmons and Larsen (1923, p. 164, 168), most of the ore extracted from the Happy Thought mine and at least the southern part of the White Star mine came from between 600 and 1,200 feet below the surface; our own underground studies showed that large stopes bottomed on or near the lower tunnel level that we mapped. In the Park Regent mine, a shaft collared at the surface extends to the lower tunnel level, and several raises extend up from this level along the vein. We have no idea how extensive the mine workings are above the tunnel level, but apparently the vein has not been stoped significantly.

The Amethyst vein is poorly exposed on the Commodore 5 level for nearly 1,700 feet north of the intersection with the North Drift crosscut. The tunnel was driven in the footwall for much of the distance, and intersections with the vein were commonly marked by caved stopes or were lagged so tightly that only parts of the veins could be seen.

The haulage tunnel intersects the Amethyst vein 120 feet north of the North Drift crosscut, where the vein is only 1–2 feet wide. From this point, the tunnel cuts unaltered and virtually unsheared Willow Creek rocks for 460 feet in the footwall of this vein. A short crosscut extending west from the tunnel 400 feet north of the North Drift crosscut exposes nearly 15 feet of somewhat chloritic rubble breccia containing sulfide minerals, but the full width of the vein zone was not exposed and we were able to establish only the local strike and dip of the footwall of the vein.

The tunnel again intersects the Amethyst vein 460 feet north of the North Drift crosscut and follows it for nearly 150 feet. The back of the tunnel was lagged tight, however, and we were able to observe only thin skins of the vein along the walls. The vein appears to be 5–15 feet wide and to consist largely of chloritic rubble breccia containing disseminated sulfide minerals. The dip in this segment is generally 60° W. An altered porphyry dike is exposed along the footwall 670–950 feet north of the North Drift crosscut, and in this area a conspicuous series of footwall splits from the Amethyst vein was mapped. Workings along the main vein are caved, and the haulage tunnel follows the subsidiary veins into the footwall, bypassing the caved area. The footwall veins follow curved fractures that rejoin the main vein to the north and enclose lens-shaped masses of wallrocks (pl. 4).

The haulage tunnel intersects the Amethyst vein again about 1,000 feet south of the Park Regent shaft and follows its trend for 220 feet farther north. Where first intersected, the vein is only 2–6 inches wide; but 40–50 feet farther north, footwall splits join the vein from the south, and the whole zone widens to 5–10 feet of chloritic rubble breccia containing irregularly distributed sulfide minerals. A conspicuous footwall split joins the main vein near the north end of this local area of exposure, and the vein zone widens to nearly 20 feet. The dip of the hanging wall in this segment is about 60° W. Granulated and sheared vein material resulting from postmineralization movement along the fault is common.

About 800 feet south of the Park Regent shaft the haulage tunnel again turns into the footwall, first through about 30 feet of intrusive porphyry and then into unaltered Willow Creek rocks. It follows about parallel to the Amethyst vein to a point about 500 feet from the Park Regent shaft where it again intersects the main vein. Adjacent to this unexposed segment, however, the strike of the Amethyst vein changes from about N. 30° W. to about N. 10° W. The trend of N. 10° W. persists northward to at least 250 feet north of the Park Regent shaft. It is unfortunate that the area including this bend in strike is not exposed, because farther south along the Amethyst vein such areas are commonly marked by associated hanging-wall fractures. A branch may split out from the main vein in this vicinity.

From the Park Regent shaft to a point 500 feet south, the Amethyst vein is generally only a few inches to 1 foot wide, but a few local pods are as much as 4 feet wide. The vein consists largely of chlorite and hematite and disseminated sulfide minerals. Some segments are largely yellow clay and appear virtually barren. The dip is generally 60° W., and the strike of the vein is regular.

From the Park Regent shaft the Amethyst vein widens progressively to a point about 120 feet farther north, where it occupies the full width of the tunnel and consists of chloritic rubble breccia containing sulfide minerals. Still farther north, 250–300 feet beyond the shaft, the trend of the vein again swings more to the north; and from here to the end of the accessible workings, 700 feet north of the shaft, the vein strikes about N. 5° W. The vein ranges from 2 to 5 feet in width through most of the segment north of this bend and consists for the most part of chloritic rubble breccia containing sulfide minerals. When the northern part of the tunnel was visited, the air in it contained little oxygen, and that part of the tunnel was mapped so hurriedly that only the general relations were observed.

O H VEIN

VEIN MATERIAL

The O H vein and related hanging-wall veins are grossly similar in mineralogy and general paragenesis to the Amethyst vein, although some notable textural and structural differences exist. As reported by Bethke and others (1960, p. 1826), the mineral assemblage in the O H vein includes galena, sphalerite, chalcopyrite, pyrite, quartz, hematite, and chlorite, and minor amounts of fluorite, barite, and ankerite.

On the lower, Commodore 5 level, the O H vein consists largely of galena, sphalerite, and pyrite disseminated through a soft, green chlorite gangue. Coarse chalcopyrite is a vein constituent near the north end of the same level. Quartz is a common but generally minor constituent. Hematite occurs both as a primary mineral and as an apparently hypogene alteration product of chlorite. As on the Amethyst vein, the different vein materials vary widely in abundance. Green chlorite or a hematitic alteration product of chlorite is present nearly everywhere and generally contains variable amounts of sulfide minerals. The sulfides range from sparse, highly dispersed small grains to massive or vuggy layered aggregates containing only minor chlorite in the interstices. Quartz ranges from nearly absent in some segments to abundant in a few places where it is the predominant gangue mineral. Stringers of early white quartz commonly cement wallrock fragments or form early coatings along the margin of the veins; in other places quartz forms late vuggy veinlets or irregular masses in the chloritic vein itself. Some of the later quartz near the south end is amethystine and generally appears barren of sulfide minerals.

The upper parts of the O H vein, as typified on the Amethyst 5 level, are appreciably higher grade, particularly in silver, than are the lower parts. Chlorite was widely deposited, but generally as a minor constituent, and in part was later altered to hematite. Quartz is relatively more abundant in the higher parts of the vein, commonly forming late drusy coatings lining cavities in the vuggy sulfide ore as well as forming early seams and veinlets in the silicified walls. Galena and sphalerite are the predominant vein minerals and commonly form porous aggregates or layers of crystals lining or filling open spaces. Many of these aggregates consist of well-formed euhedral crystals from a fraction of an inch to several inches across. Minor chalcopyrite is associated with the other sulfide minerals in the veins and is also evident in disseminated grains in the adjacent wallrocks. Irregular masses as well as columnar veinlets and cavity linings of late botryoidal pyrite follow late fractures through the vein.

The O H vein formed by deposition in open spaces along an irregular fracture zone, and the wider parts of the vein are generally crustified and vuggy where deposition was incomplete. Many slabs or fragments of wallrock occur in the vein, and in places the vein is merely a zone of stringers through highly broken wallrock. Evidence for fracturing concurrent with vein deposition can be recognized, but nowhere was the late fracturing comparable in its effects with that on the main Amethyst vein.

On the two levels we mapped, wallrock alteration was limited chiefly to silicification. It was widespread near the south end of the O H vein on the Commodore 5 level but was much less apparent farther north. On the upper Amethyst 5 level, however, the walls generally are highly silicified and contain widely disseminated grains of sulfide minerals. These grains consist largely of pyrite and lesser quantities of chalcopyrite and, close to the vein, galena. Many of these wall rocks contain sufficient silver to constitute good ore. Above the Amethyst 5 level, the O H vein is surrounded by soft, highly argillized wallrocks, and the vein reportedly diminishes in size upward in these walls. The base of the argillized rock is not at a uniform level and from reports appears to vary in vertical position as much as several hundred feet from one part of the vein to another. In general, it appears to be progressively lower toward the north. We have seen this soft capping rock in only a few places; a raise on the O H vein near the Brown crosscut penetrated the altered rock slightly more than 100 feet above the Amethyst 5 level, and the wallrocks adjacent to the O H vein at the north end of the Amethyst 5 level are largely soft and argillized.

DETAILED DESCRIPTION

Conjugate fractures in the hanging wall of the Amethyst vein are most concentrated and have their apparent focus opposite the pronounced bend in the Amethyst fault near the Last Chance mine. As indicated in the discussions of structure (p. 67), these fractures apparently are due to the collapse of this segment of the hanging wall toward the main Amethyst fault after the displacement of a highly curved fault surface downward to an area where the adjacent fault surface was more nearly straight.

Fractures of both conjugate trends occur together only in the focus area; the northwest-trending set, including the O H vein, becomes dominant northward, and the south- to southwest-trending set becomes dominant southward. Minor structures along the O H vein indicate that the wedge-shaped block between the O H and Amethyst veins apparently moved south and somewhat downward, and the same sense of displacement is indicated along the Winchester vein in this block where the east side moved relatively south (pl. 3). Similar evidence in the West drift on the Commodore 5 level (pl. 4) suggests that the wedge of rock between the southwest-trending conjugate vein and the Amethyst vein moved relatively north, also toward the collapsing arch, but on the upper levels this direction of movement may have been reversed. Apparent directions of relative movement in the general focus area are confusing; on lower levels there was a general collapse toward the Amethyst vein, but no clear-cut pattern could be discerned on the upper levels.

The pattern of fracturing in the focus area is increasingly complex from the lower to the higher levels of the mine. On the lower, Commodore 5 level (pl. 4), only one fracture exists for each trend in the conjugate pair; the O H vein extends more than 4,000 feet northwest from the focus area, and a somewhat smaller vein extends more than 800 feet southwest along the West Drift. These two vein zones are joined in the focus area through a series of overlapping curved mineralized fractures that link from one trend to the other (pl. 4). Although minor fractures may connect with the nearby Amethyst vein, the main plexus of fracturing in the hanging wall is over 100 feet west of the main fault, and neither the O H nor its complementary conjugate vein actually joins the Amethyst vein on this level. Apparently the focus area merely gaped open toward the Amethyst fault but was the site of little other relative movement.

The O H vein on the Commodore 5 level (pl. 4) shows evidence of right-lateral strike-slip movement. The most open parts of the fracture zone, now represented by the widest parts of the enclosed vein, are closely associated with deflections to the right in the strike of the fault zone where right-lateral movement pulled the walls apart. Such segments are particularly apparent on plate 4 between coordinates 00 N. and +400 N., adjacent to +1200 N., and just north of +1600 N. Deflections to the left, on the other hand, are generally accompanied by a narrow vein along a tight fracture. Most of the mineralized tension joints and gash fractures strike north diagonally to the vein, a factor that also indicates right-lateral strike-slip movement. These fractures are common along the length of the vein but are particularly abundant near the open deflections to the right.

Actual movement along the O H vein on the Commodore 5 level appears to have been minor and barely more than enough to form the existing fractures. Little if any gouge or granulated rock was formed, and grooves or slickensides are virtually absent. In places, such as near coordinates +1200 N. and +2000 N., the linking fractures along the zone are actually discontinuous or nearly so.

The lesser vein zone extending southwest out from the focus area along the West Drift on the Commodore 5 level (pl. 4) shows no clearcut relation between width of vein and trend of fissure. The wider parts generally occur in those areas where the vein breaks into several strands along braided fractures, and the open spaces filled by the vein appear to have formed largely by wedging action of the blocks between the fractures. Tension joints and gash fractures, however, generally strike more nearly north than the associated vein and join it from both sides; these would suggest that relative movement along the fracture zone had a left-lateral component of movement and that the wedge of rock between this zone and the Amethyst fault tended to move relatively north toward the focus area.

The conjugate fractures on the Amethyst 5 level, some 700 feet above the Commodore 5 level, are much more numerous than below, and the focus is larger and consists of several local concentrations of intersecting mineralized fractures (pl. 3). The southwest-trending vein that was mapped along the West Drift on the Commodore 5 level was not recognized on the Amethyst 5 level, and none of the south- to southwest-trending representatives of the conjugate pair extends far from the focus area. The O H vein, on the other hand, is generally wider and more broken than on the lower levels, and it extends fully as far to the north.

Two main centers of intersecting fractures—one centered along coordinate −800 N., and the other centered along the Albion crosscut—are apparent in the focus area on the Amethyst 5 level (pl. 3). The southernmost one is more important economically, as it forms the root of an even more complex system of intersecting veins that was extensively mined in the inaccessible P. and E. workings higher in the mine, and the highly productive O H vein extends northwest from this center. The details of the intersecting veins in this center are incompletely known, as many veins are stoped out above the Amethyst 5 level, and continuous stopes extend through the level on some of the veins. As seen along unstoped segments or in the backs of stopes that did not extend far above the Amethyst 5 level, the many intersecting veins range from thin branching partly discontinuous seams to persistent veins a few inches to a few feet wide. The pattern of fracturing did not indicate any consistent direction of relative movement, and in part the discontinuous nature of the fractures suggests that little actual movement took place. One minor vein zone was followed south from the center of intersecting fractures for more than 460 feet; individual fractures in this zone are generally curving, discontinuous, and overlapping as though the zone merely broke open. What movement there was has a right-lateral sense of displacement, as deflections to the right of the curving fractures generally contain pods of ore as much as 2 feet wide, whereas deflections to the left are tight seams that tend to pinch out. Northeast-trending gash fractures intersect this vein zone and provide additional evidence of right-lateral sense of displacement.

Little can be seen along the O H vein for 900 feet northwest of the center of intersecting veins that marks its southeast end on the Amethyst 5 level. No mine workings expose the actual junction of the O H vein with the intersecting set, and except for a few small pillars, the vein has been stoped completely through the level from 200 feet south to 400 feet north of the Albion crosscut. In a pillar where the Albion crosscut crosses the stopes, the O H vein consists of several minor veins 1–3 inches wide occupying widely spaced fractures in a zone 5–10 feet wide.

The fissures are irregular branching cracks that show little evidence of movement. Approximately parallel veins exposed in mine workings both east and west of the O H vein in this locality appear fully as rich, but none has proved as persistent along the strike, and certainly none has been as extensively stoped.

From the north end of the Albion stopes near coordinate 00 N. (pl. 3), and extending for 800-900 feet farther north, the O H vein expands from a few mineralized fissures several inches wide into a broad irregular zone of highly fractured and mineralized rock. The vein is extremely variable along strike, however, and in one place or another a pod of breccia passes abruptly into a series of braided fractures, or into a few subparallel fractures, and these in turn may pass abruptly into breccia again. The thicker segments of the vein are related in part to deflections in the strike of the vein to the right, but more commonly they appear to have resulted from a wedging action of blocks in a zone of fractures. Even though the vein is better formed in this area than near the Albion crosscut, the actual movement along the fault appears to have been minor, as the vein is actually discontinuous about 70 feet south of coordinate +400 N. (pl. 3).

The O H vein is offset en echelon about 80 feet to the east near the intersection by the Brown crosscut (between coordinates +400 N. and +800 N., pl. 3). The vein south of the offset links across to the main trend north of the offset through a series of curved seams and fractures; possibly comparable linkages westward from the south end of the eastern trend are not exposed in present mine workings. The two echelon segments join at depth 150–200 feet below the Amethyst 5 level, where a stope begun on the trend of the eastern segment flattened markedly to the west to follow the main mineralized zone over to the trend of the western segment. Superposed mine workings on the different levels of the mine clearly show that the O H vein follows the easternmost trend at depth.

In the concentration of intersecting conjugate veins centered about on the Albion crosscut midway between the Amethyst and O H veins (pl. 3), the workings north of the Albion crosscut were caved and inaccessible, but the position of the mineralized fractures is indicated by the mine workings that followed them. South of the Albion crosscut, the main vein in this intersecting group has been stoped both above and below the Amethyst 5 level, but many of the minor fractures can be seen in nearby drifts and crosscuts. As in the other center of intersecting conjugate fractures, the individual veins range from minor discontinuous seams to persistent veins 1 inch to several feet wide, and no consistent pattern of relative displacement was established.

The whole area between the two main centers of intersecting fractures in the hanging wall and the adjacent curved segment of the main Amethyst fault is highly broken, and fractures belonging to the conjugate system become inextricably confused with the antithetic and parallel fractures associated with the main vein.

North of the Brown crosscut, the O H vein on the Amethyst 5 level (pl. 3) follows a conspicuous zone of once open fractures that have been filled or partly filled with high-grade ore. As in segments to the south, the character of fracturing changes abruptly from place to place, and the width and grade of the vein vary widely. In part, generally between coordinates +1200 N. and +1600 N. (pl. 3), the O H vein consists of two nearly parallel zones of mineralized fractures 20–30 feet apart. The western zone is richer, but both zones contain good ore, and the septa of wallrock between them is sufficiently mineralized to be ore grade in part. Wedging action between the many slivers of rock in the highly fractured zone appears to have been more significant than changes in strike in localizing the wider and higher grade parts of the vein.

Although north-trending diagonal gash fractures are common all along the O H vein on the Amethyst 5 level, a right-lateral sense of displacement is most clearly shown near the north end of the exposed vein. Adjacent to the intersection with coordinate −4800 E. (pl. 3), the vein is a torn zone 100 feet long consisting of main eastern and western segments bounding a lens-shaped horse that is cut into ribbons by diagonal, north-trending tensional fractures. North of this torn zone the vein is less conspicuous than it is to the south, and where last exposed it has degenerated to a few weak seams.

OXIDATION

The south ends and higher parts of both the main Amethyst vein and related hanging-wall veins are highly oxidized, and the primary sulfide minerals and gangue have been converted to a soft muddy aggregate containing associated limonite, manganese oxides, coarsely crystalline barite, and dense jaspery silica. The original amethystine and white quartz generally persisted through oxidation without obvious change. All veins seen on the Commodore 3 level (pl. 3) were oxidized, and most of the veins on the Amethyst 5 level south of the Brown crosscut (pl. 3) are oxidized or partially oxidized. On the lower, Commodore 5 level (pl. 4), the veins are oxidized or partially oxidized for the southern 1,200–1,500 feet of the vein zone exposed underground.

The ores are currently undergoing oxidation and leaching by supergene processes. Workings on the lower levels only a few years old are commonly coated with a thick fur of goslarite fibers, and broken ore left in stopes commonly is recemented by secondary metallic minerals.

From information supplied by local miners, as well as from the descriptions given by Emmons and Larsen (1923, p. 126–134), the veins near the surface were commonly leached and low grade. The richest parts of the veins underlay the leached segments and reached the surface only in the Last Chance and Amethyst mines. Zinc was largely absent from the oxidized segments of the vein, and lead generally ranged from 1 to 7 percent and appeared to be residual from the original lead in the vein. The high silver content in the upper parts of the oxidized ores was clearly the result of secondary enrichment, and Emmons and Larsen (1923, p. 130–132) cited evidence indicating that gold also was secondarily enriched in some of the oxidized ores.

We are able to add little to the description of oxidized and enriched ores given by Emmons and Larsen, and readers interested in a more complete account are referred to their report (Emmons and Larsen, 1923).

ALPHA-CORSAIR VEIN ZONE

Our first-hand information on the ore deposits along the Alpha-Corsair vein zone is fragmentary and adds little to the data already given by Emmons and Larsen (1923, p. 187–192). The Alpha and Corsair mines were inaccessible when our underground studies were being done, and although the Corsair mine has been reopened since then, our observations have been limited to a few brief visits.

The vein zone follows the main late fault on the west side of the Creede graben. Virtually all displacement on this fault occurred during the last main period of faulting (p. 64), and at one place or another the fault offsets the Creede Formation, Fisher dikes and lava flows, as well as many older formations. At the levels developed by present mine workings, the ore deposits form local ore shoots that have been mined in the Alpha and Corsair mines and prospected farther northwest, by various smaller pits and mine workings (Emmons and Larsen, 1923, p. 188–192). Much of the fault zone at these levels apparently is barren or was too low grade to mine. Wallrocks are commonly bleached and altered, and in some places we observed strongly argillized rock similar to that found adjacent to the higher parts of the Amethyst vein zone (p. 70). Most of the reported production has been in silver, and virtually all has been from oxidized ores. Assays quoted range from a few ounces to more than a thousand ounces of silver per ton of ore. The descriptions given of the ore produced from the Corsair mine (Emmons and Larsen, 1923, p. 189) indicate that it is similar in many respects to the ore found in the higher, southern parts of the Amethyst vein. Some sulfide ores are reported from the Kreutzer Sonata mine and from a winze in the Corsair mine, but the descriptions given do not permit comparison with the ores found on other vein zones in the district.

Of probable significance is the fact that high-grade silver ore has been reported from many places along the southern part of McKenzie Mountain (Emmons and Larsen, 1923, p. 193), where the hanging wall of the Alpha-Corsair fault zone is highly broken by subsidiary fissures. Many prospect pits have been dug in this area, and some old caved tunnels extending into the ridge from the Rat Creek side—for instance, the Cowboy Johnson tunnel—are reported to have cut stringers of rich silver ore. These occurrences are likewise reminiscent of the high-grade silver ores found in the highly fractured hanging wall of the Amethyst vein.

ORE DEPOSITS IN THE CREEDE FORMATION

The Creede Formation is irregularly silicified and mineralized near the south end of the Creede graben, where the Monon Hill mine penetrates the sedimentary cover above an area of caldera-border faults, opposite the south end of the Alpha-Corsair fault. Mineralizing solutions evidently came up through the fractured volcanic rocks to the base of the Creede Formation and were then channeled up along this contact, impregnating and mineralizing the more permeable abutting beds. Highly silicified rocks also occur in the basal part of the Creede Formation near the south end of the Bulldog Mountain fault zone. Soil cover and slumped ground obscure detailed relations, but the general situation appears similar to that at the Monon Hill mine.

On Bachelor Mountain, the Creede Formation fills an old stream channel cut into the underlying rhyolites. The Creede rocks are altered and mineralized throughout this channel but are most thoroughly silicified where they abut the Amethyst fault. They apparently were altered and mineralized by solutions that rose along the Amethyst fault and leaked into the permeable sedimentary strata.

MONON HILL MINE

The Monon Hill mine exploits disseminated ore in the lower part of the Creede Formation. The ore is localized along the overlapping contact between the Creede Formation and a buried hill of older rhyolites and is particularly abundant in the coarser and originally more permeable beds where they pinch out against the steep west slope of this hill.

The known mineralized zone is probed by six tunnels over a vertical range of about 400 feet (pl. 5). Three main stopes as well as several smaller stopes of ore have been extracted, and a few minor sublevels have been dug. Many of the workings are inaccessible or cannot be entered safely, and our geologic work was limited to the lower, Silver Horde level, and the intermediate, Magnusson level 149 feet higher. A few observations were made along the walls of some of the safer stopes. The general geologic relations have been outlined, but detailed delineation of the stratigraphy, including distinguishing individual favorable host beds, has not been possible.

That part of the buried hill exposed underground in the Monon Hill mine consists entirely of the Campbell Mountain Member of the Bachelor Mountain Rhyolite; but, as exposed in an erosional window at the surface, the top of the hill consists of a faulted mosaic which includes the Campbell Mountain and

Windy Gulch Members of the Bachelor Mountain Rhyolite, Wason Park Rhyolite, and Shallow Creek Quartz Latite (pl. 1). The west flank of the hill is steep and irregular and is nearly vertical in places. It is overlapped by the Creede Formation, which consists of complexly and irregularly intertonguing fanglomerate, thin-bedded shale, siltstone, and sandstone, and travertine. The fanglomerate is locally derived and appears to form tonguelike bodies that pinch out between the finer, thin-bedded fluviatile and lacustrine rocks away from the buried hill. The travertine ranges from thin-bedded layers of limestone and calcareous shale to irregular masses of fanglomerate or fluviatile and lacustrine beds thoroughly impregnated and in part replaced by calcium carbonate. The beds dip more steeply near the basal contact with the buried hill than farther west (pl. 5); this has probably resulted largely from differential compaction of the sedimentary rocks.

Most of the mineralized rock we saw was in the tongues of fanglomerate, and even in these rocks certain layers were mineralized in preference to others. The ore shoot followed by the Collins and Wheeler stope is localized in a bed in fanglomerate within the Creede Formation on the Magnusson level (pl. 5). The stope was unsafe and could not be studied in detail; however, the bed containing the ore appeared to converge upward with the abutting basal contact of the Creede Formation, and the ore body probably pinched out downdip in the Creede Formation. The Yellow stope, on this same level, clearly developed a lower bed in the sedimentary sequence (pl. 5). This bed abuts the buried hill a short distance above the Magnusson level and projects into the thicker Creede section to the west. Another stope followed the contact of the Creede Formation and the buried hill on the Silver Horde level below the Yellow stope (pl. 5). Relations are clearcut in this stope, where thoroughly mineralized rock is restricted to an even lower tongue of fanglomerate, and the overlying spottily mineralized thin-bedded standstone overlaps the fanglomerate updip onto the buried hill. The Wabash stope farther south on the Silver Horde level in part developed this same fanglomerate unit and in part developed the overlying finer grained rocks, which include some travertine.

The general picture of the structural and stratigraphic environment that is believed to have controlled mineralization in the Monon Hill mine is illustrated in figure 6. The fundamental control appears to have been the steep slope on the buried hill, as all known ore bodies are localized in the adjacent

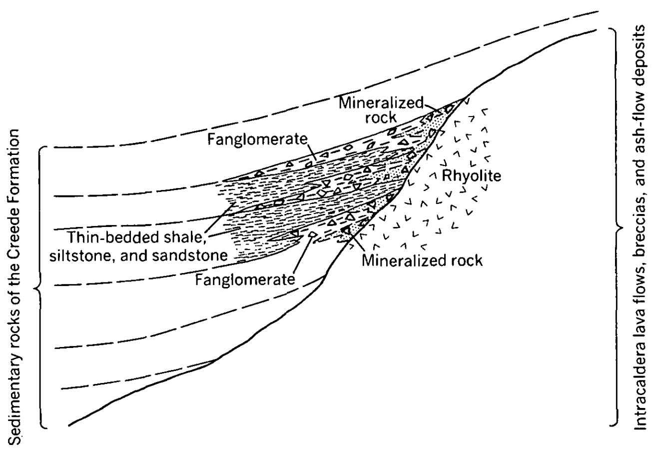


FIGURE 6.—Cross section showing typical structural and stratigraphic control of mineralized rock in the Monon Hill mine. 1 inch = 170 feet (approx.).

Creede Formation near the overlapping contact. In the Creede Formation the mineralized rock is most abundant in the coarser, presumably more permeable fanglomerate units, and the ore bodies extend outward from the contact much farther on some beds than on others.

Mineralized rock in the Monon Hill mine is generally silicified and porous and is distinctly harder than the adjacent unmineralized or slightly mineralized rock. Ore minerals impregnate the silicified rock and in part appear as drusy coatings of euhedral crystals in the more porous rocks. Pyrite is the most abundant sulfide mineral, but sphalerite, galena, and chalcopyrite are widespread and locally abundant. Barite also has been identified in many ore specimens. The degree of silicification and abundance of ore minerals vary widely and erratically from one place to another in the generally mineralized rock.

SOLOMON–HOLY MOSES VEIN ZONE

Ore has been produced from three general parts of the Solomon–Holy Moses vein zone; exploration elsewhere has exposed large segments of the zone without disclosing comparable mineralized rock. The first discoveries were made in the Holy Moses mine, where a small tonnage of high-grade silver ore was extracted from near the surface during the early days of mining in the Creede district (Emmons and Larsen, 1923, p. 175). Subsequent exploration developed ore at the south end of the vein zone in the Mexico, Solomon, Ethel, and Ridge mines (fig. 2), which produced most of the ore extracted from the Solomon–Holy Moses vein zone prior to World War II. In the early 1950's, an ore body was discovered on the Palo Alto level of the Phoenix mine, north of the

Holy Moses mine. This ore body was being extracted when fieldwork for this report was being done and has accounted for most of the recent production from the Solomon–Holy Moses vein zone.

We mapped three mine levels: the Palo Alto and Outlet Tunnel levels in the Phoenix mine and the Holy Moses 2 level in the Holy Moses mine (pl. 6). Mine workings along the southern part of the vein zone and in the upper levels of the Holy Moses and Phoenix mines were largely inaccessible and were not studied. For information on these workings, we have had to depend on earlier published and unpublished reports and maps that were available to us.

Mineralized rock on the Palo Alto level is largely oxidized, although nodules of sulfides, largely galena, were seen in a few places. The ore in place consists of sticky, soft, yellow to orange mud that fills fractures and surrounds rubbly breccia fragments along the vein zone. Some jaspery vein material is present but is generally subordinate to the soft mud. Some local harder nodules and veinlets of cerussite or anglesite occur in the zone, particularly along and above the Palo Alto level, but individual ore minerals could not be recognized megascopically in most of the ore. Lead generally ranges from a few percent to 20–30 percent of the mud, and silver generally averages less than 10 ounces per ton of ore.

Most of the wallrocks along the Palo Alto level are hard and silicified, although locally they are soft and argillized or chloritized. A hundred feet or so above the Palo Alto level, the vein zone commonly is enclosed between soft, highly argillized walls (called "porphyry" by the local miners), and workings are difficult to drive and to maintain. Slickensides are common on the sheared zones that cut the hard wallrocks on the Palo Alto level, but the ore is so thoroughly oxidized that the age sequence of mineralization and fault movement cannot be determined. In the upper levels, however, the soft argillized rock is highly sheared and slickensided; therefore, at least some of the fault movement followed hydrothermal alteration.

The vein zone on the Holy Moses 2 level is significantly mineralized only in the more highly broken segments near conspicuous splits or bends along the zone (pl. 6). Most of the mineralized material is highly oxidized and consists of a clayey matrix surrounding breccia fragments or filling anastomosing fractures along the braided vein zone. Some unoxidized nodules of galena were noted in the larger pod of vein material mapped near the southern limit of accessible workings (pl. 6). A winze sunk about 70 feet on this pod of mineralized rock exposes what appears to be the top of a galena-sphalerite ore body 15–20 feet wide. Although the lateral extent of the ore is not known, the bottom of the winze is not far above or north of mine workings extending north from the Solomon mine (pl. 7) from which Emmons and Larsen (1923, p. 179) reported sulfide ore.

The vein walls along the Holy Moses 2 level commonly are grooved and slickensided, although, as in the Palo Alto level, oxidation of the ore has obscured the age relations of mineralization and fault movement.

Mineralized rock along the Outlet Tunnel level ranges from oxidized limonitic mud to unoxidized vein material consisting largely of fine-grained pyrite or marcasite in a clayey or locally chloritic matrix. Galena was seen locally. The best exposure of base-metal sulfides seen was in a shallow winze about 130 feet north of the haulage tunnel, where a 6- to 12-inch vein of solid granular galena followed the hanging wall of the vein zone.

Evidence of many ages of brecciation and fault movement was apparent along some of the unoxidized segments of the vein zone on the Outlet Tunnel level. Early silicified and healed breccia was in places rebroken, and the new fractures were filled with pyritic vein material. Fault movement after ore deposition formed extensive shear planes and granulated rock along and across the sulfide-bearing veins; it left widespread slickensided surfaces. A conspicuous fault postdating ore deposition cuts off the vein zone near the south end of the Outlet Tunnel level.

We have not seen any of the ore from the southern part of the vein zone in place. Emmons and Larsen (1923, p. 177–179), however, reported that the veins in the Mexico, Solomon, Ethel, and Ridge mines (pl. 7) consist largely of galena, sphalerite, pyrite, and a little chalcopyrite in a gangue of green chlorite, talc, and quartz. A small amount of gold is present, but the silver content is very low. Fault movement postdating ore deposition is clearly apparent, and "indeed, both the Solomon and Ethel veins at most places are zones of green chloritic clay with abundant crystals of galena and zinc blende mixed with considerable crushed country rock. At some places the sulphides are powdered and mixed with green mud resembling putty." (Emmons and Larsen, 1923, p. 179.) The ore near the surface is oxidized or partially oxidized and consists of cerussite, limonite, manganese dioxide, a little galena and sphalerite, and considerable pyrite.

Although the mineralized rock, and particularly the better grade mineralized rock, is clearly localized in highly fractured ground along the vein zone, all the highly fractured ground is by no means well mineralized, and some thoroughly shattered segments are virtually barren. Nor is the ore-grade material located at any consistent level or position in the vein zone. Apparently, only the most open and permeable parts of the vein zone were significantly mineralized, and in these parts ore deposition was localized by some local combination of factors that may have differed for each area. Plate 6 shows that the wider pods of mineralized rock are closely associated with abrupt bends in the vein zone, with conspicuous splits or branches along the vein zone, or with both. The ore body exposed along the Palo Alto level is just south of an area where the vein zone at the surface splits into three main branches (pl. 1). Some of these branches probably join on the Palo Alto level a short distance north of the haulage tunnel where the drift northward appears to have followed out along a footwall split. A similar split may take place on the Outlet Tunnel level below, between 200 and 280 feet north of the main haulage tunnel, where several strong mineralized fractures extend out into the west wall of the drift. The drift north of this area clearly follows a footwall split, as a raise driven upward on this fracture toward the Palo Alto level had to be crosscut west 40–50 feet midway between the levels to pick up the strand of the vein zone that had been mined above.

The highest grade pod of mineralized rock exposed on the Holy Moses 2 level (pl. 6) is near the south end of the workings that were accessible when the geologic map was made. This pod is near another conspicuous split along the vein zone, and a winze sunk on this pod shows ore-grade material at a depth of about 70 feet. The pod of mineralized rock just north of the haulage tunnel is localized at a bend in the vein zone and just south of a local split.

A similar association of mineralized rock with branching segments of the vein zone occurs in the southern part of the Solomon–Holy Moses vein zone, where our surface mapping (pl. 1) indicates that the fault zone splits complexly into several branches. The Mexico and Solomon mines and the Ethel and Ridge mines developed, respectively, the western and eastern branches of the fault zone, which enclose an elongate, lens-shaped mass of rhyolite. The general position of the two branch veins is indicated on the composite mine workings map of this area (pl. 7). Some stopes of ore have been extracted from the Mexico vein segment of the western branch, but the chief production has come from below the Solomon adit level in the Solomon vein segment in the area where workings are shown as incomplete (pl. 7). On the eastern branch vein, some stopes are reported along the Ethel vein segment, but most production has come from the Ridge vein segment, which has been extensively developed below the Ridge tunnel level. The branches are reported to join to the north and apparently constitute a single vein in the northern part of the workings shown on plate 7. Emmons and Larsen (1923, p. 179) reported good ore values from workings along this northern segment, and some of the old maps and sections we have seen of this area also indicate the presence of ore-grade material.

The known ore along the Solomon–Holy Moses vein zone does not occur consistently within any particular vertical range. Stopes in the Solomon and Ridge mines are between altitudes of 8,900 and 9,500 feet; the ore body extracted from the Phoenix mine was largely between altitudes of 10,000 and 10,300 feet; and the small pockets of high-grade silver ore in the Holy Moses mine apparently were near altitudes of 10,200 and 10,300 feet. These figures suggest that each ore body, or the ore bodies in each given local area, were deposited in response to local environmental conditions. The controlling factors in these local conditions have not been established, and no means is known whereby the vertical position of possible ore bodies in other parts of the vein zone can be predicted.

EQUITY VEIN

At least two and perhaps three periods of hydrothermal activity are apparent in the vicinity of the Equity mine. The oldest period definitely preceded eruption of the Nelson Mountain Quartz Latite and resulted in pervasive bleaching and alteration of Bachelor Mountain Rhyolite exposed on the hanging-wall block of the Equity fault between West Willow and Deerhorn Creeks (pl. 1). Most of the altered rock is bleached and softer than normal Bachelor Mountain rocks and contains widely disseminated grains of pyrite; rusty knobs representing silicified and more thoroughly pyritized rock protrude through loose talus and surface debris at several places on the steep slopes above West Willow Creek. Unaltered Nelson Mountain Quartz Latite rests unconformably on top of this block of altered Bachelor Mountain Rhyolite and is in fault contact with it in many places along the Equity fault.

The second known period of hydrothermal activity affected rocks chiefly in the vicinity of the Equity fault. In the cursory examinations made during field mapping, the results of this period of alteration were apparent largely in the Nelson Mountain rocks adjacent to the fault, which were locally and irregularly argillized or chloritized. Disseminated pyrite is common in these altered rocks. The limited distribution and irregular character of the altered rocks formed during this period of alteration contrast markedly with the pervasively altered Bachelor Mountain rocks affected by the earlier period of alteration. Underground in the Equity mine, this period of alteration is represented by argillized and silicified rock along the Equity fault.

The possibility of a third period of hydrothermal activity is suggested by late mineralized fractures that cut the argillized and silicified rocks exposed underground. It is not known whether the origin of these late veins is related to the period of hydrothermal activity responsible for altering the enclosing rock or whether the veins are much later and are unrelated.

To correlate the geology mapped underground at the Equity mine (fig. 7) with that exposed on the hillside high above, we had to reorient our base map. As originally drawn, the main haulage tunnel extended into the hill on a trend of about N. 80° E. A compass bearing near the portal, however, indicated that this trend is more nearly S. 80° E. and that the original map is probably in error. Independent support for reorienting the map is given by the geology; surface and underground geology correspond to the haulage tunnel trending S. 80° E., whereas they do not correspond to the tunnel trending N. 80° E.

The portal of the Equity tunnel is in rocks of the Willow Creek Member north of the Equity fault. The fault, now marked by a zone of highly argillized rock between the Willow Creek and Campbell Mountain Members, is about 520 feet in from the portal (fig. 7) and strikes about east, parallel to the strike on land surface. A crosscut from the end of the haulage tunnel, about 750 feet from the portal, extends south from the fault for nearly 340 feet into rocks of the Campbell Mountain Member in the footwall block without exposing any other kind of rock or intersecting another fault or sheared zone. A short crosscut north from the end of the tunnel intersects a zone of highly silicified fault breccia as much as 40 feet wide along the Equity fault. Workings along the Equity fault exposed similar silicified breccia over a length of about 420 feet. A crosscut driven about 280 feet north into the hanging wall exposes bleached and somewhat altered rocks of the Willow Creek Member, cut by a few minor widely spaced mineralized fractures.

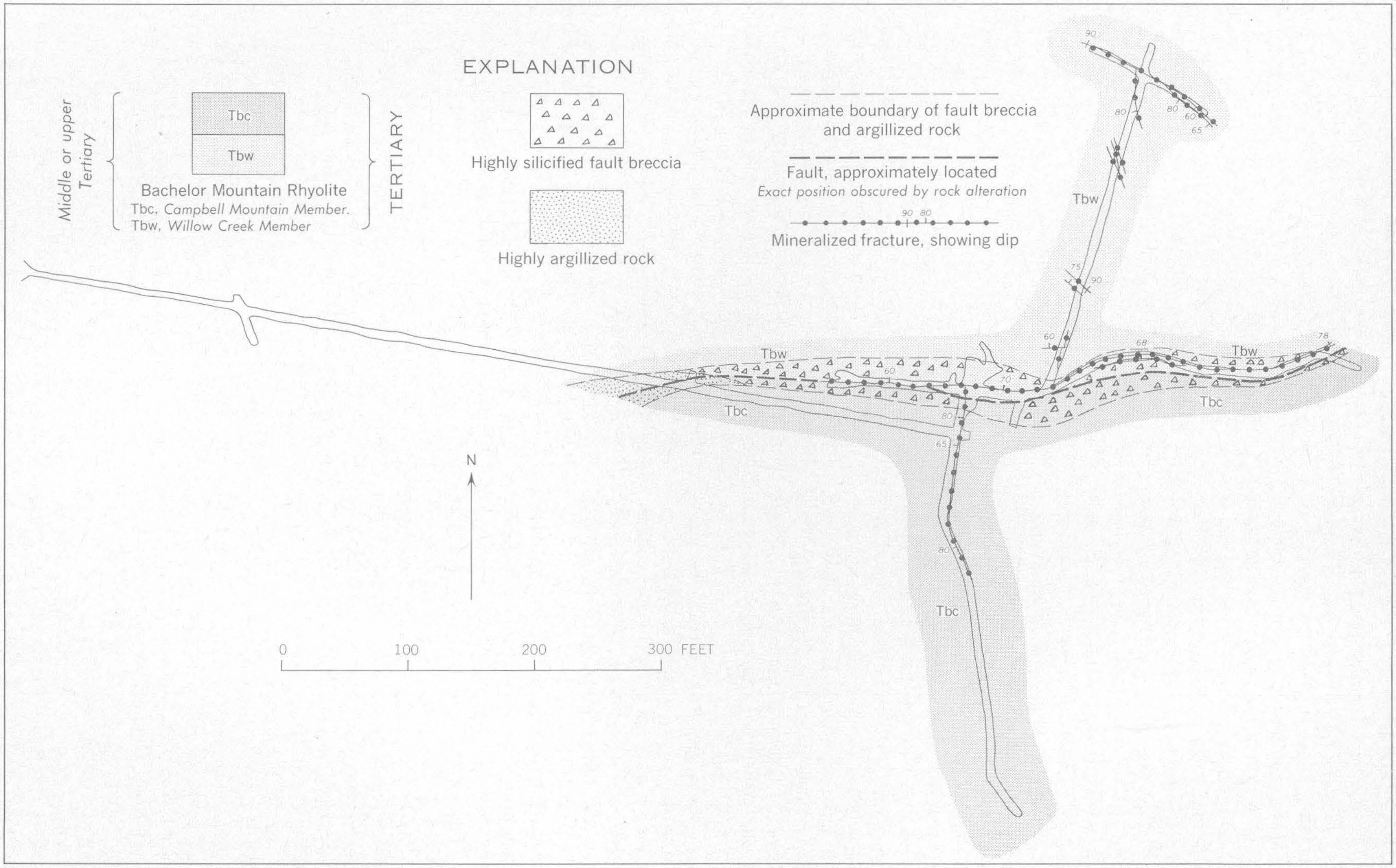
The pod of silicified and highly argillized rock that follows the Equity fault throughout the length exposed in the mine healed the fault breccia so thoroughly that the location of the actual change in formations in the broken zone is difficult to find. This alteration clearly followed major fault movement, and the resulting altered rocks probably are related to the spottily altered Bachelor Mountain and Nelson Mountain rocks that occur along the surface trace of the Equity fault and formed during the second period of hydrothermal activity in this vicinity. This period of alteration may have closely followed the main period of fault movement on the Equity fault (p. 57), or it may have been later.

The late sheared zones representing the possible third period of hydrothermal activity cut the argillized and silicified rocks that heal the Equity fault. These sheared zones are marked at different places by open breccia, fault gouge, argillized rock, and by sulfide minerals, chiefly pyrite. It is not known whether the late veins of these sheared zones are related in origin to the period of hydrothermal activity responsible for altering the enclosing rock or whether they are much later and are unrelated.

Larsen (1930, p. 101–102) reported that ore valued at $91,000 had been extracted from the mine; assays across the stoped ore ranged from 6.3 to 154.3 ounces of silver and 0.06 to 1.61 ounces of gold per ton, and small quantities of lead, zinc, and copper were also reported.

SUGGESTIONS FOR PROSPECTING

Major production in the Creede district has come from only one of the several fault zones that constitute the complex Creede graben. Through 1956 the Amethyst vein and associated hanging-wall veins supplied about 93 percent of the value of the ore produced from the district (p. 6), and from that year until 1960 the percentage was even greater. Several other fault zones are known to contain mineralized rock, but only one, the Solomon-Holy Moses, has been extensively prospected through significant lateral and vertical segments. Additional ore bodies might well exist on other faults in the graben, and some areas appear particularly promising. In addition, the Creede Formation is known to be mineralized on Bachelor Mountain and beneath Monon Hill, although production has been limited to one very small area. The following discussions of areas that we consider most favorable for prospecting should be read in conjunction with appropriate preceding sections on individual vein zones, where most of the specific geologic details have been enumerated.



Base modified from an old company map

Geology by T. A. Steven and J. C. Ratté, August, 1955

FIGURE 7.—Geologic map of the Equity mine.

AMETHYST AND RELATED VEINS

We have made no specific review of the intensively developed parts of the Amethyst vein to determine whether unstoped blocks remain that are worthy of prospecting. A careful comparison of assay records and stope and level maps might well disclose such blocks, and this comparison would probably be a profitable undertaking. Deep exploration by the Creede Exploration Co. between 1917 and 1920 (Larsen, 1930, p. 93) exposed good ore in the Amethyst mine 120 feet below the Nelson tunnel level, but elsewhere the results were disappointing. We do not know how far laterally the ore extends along the vein beneath the Amethyst mine, but some stoping ground may exist in this vicinity.

The northernmost mine workings on the Amethyst vein in the Park Regent mine on the Commodore 5 level (pl. 4) expose good widths of vein material for at least 700 feet north of the Park Regent shaft, and to our knowledge the north end of the mineralized ground was not reached. Several higher levels have been driven north from the Park Regent shaft and some interconnecting raises exist, but apparently little ore has been stoped. Continued exploration of this northern part of the Amethyst vein seems a logical program.

With regard to the hanging-wall veins, we again have not reviewed in detail the possibility that blocks of stoping ground may still exist in the more intensively developed parts of the mines. Careful study of existing records and maps might prove profitable in these areas as well.

More important to future exploration is the possibility that hanging-wall veins may branch off from the more northerly parts of the Amethyst vein. As noted earlier (p. 74), the strike of the Amethyst vein on the Commodore 5 level changes abruptly 500–600 feet south of the Park Regent shaft, and it changes again, in lesser degree, about 250 feet north of the shaft. The southernmost bend was not exposed in accessible mine workings, so firsthand information is lacking. From experience farther south on the Amethyst vein, however, the hanging-wall block adjacent to such a bend is a likely place to seek subsidiary fractures; if such exist here, they most probably would be mineralized to some degree. Surface mapping west of the Amethyst vein and north of West Willow Creek disclosed relations that seemingly indicate a northwest-trending fault (p. 65), and bleached and altered rocks near the fault indicate at least some hydrothermal activity. Such a fault might well intersect the Amethyst fault to the southeast somewhere in the vicinity of the Park Regent shaft (pls. 1, 2). An intersection thus located would definitely be of interest as a possible ore-bearing structure. The surface is largely covered with glacial debris, so tracing the fault or determining its possible economic potential must depend either on physical exploration or on some geophysical technique.

Little can be said concerning the economic potential of various branches of the Amethyst fault north of West Willow Creek. Local bleaching and alteration of adjacent wallrocks indicates at least some hydrothermal activity. Were we able to date the deposition of ore at the Equity mine relative to that along the productive parts of the Amethyst vein, we might be able to assess the prospecting possibilities along these north-trending faults more fairly. Geochemical prospecting might indicate whether further exploration would be warranted.

BULLDOG MOUNTAIN FAULT ZONE

In a preliminary report on the Creede district (Steven and Ratté, 1960b), we suggested that the Bulldog Mountain fault zone appeared to be a favorable structure to prospect. These faults constitute an antithetic zone within the main subsided block of the Creede graben and probably intersect the Amethyst fault zone at depth (p. 67; fig. 5). As the Amethyst fault zone was abundantly mineralized, it seems logical that mineralizing solutions also had access to the Bulldog Mountain fault zone. Emmons and Larsen (1923, p. 186) reported assays of from a few ounces to 87 ounces of silver per ton from scattered shafts and pits along the surface trace of the eastern branch fault.

The prospected near-surface formations are underlain by at least 100–200 feet of soft Windy Gulch tuff, which may have inhibited upward passage of mineralizing solutions. The underlying hard rhyolites of the Campbell Mountain and Willow Creek Members of the Bachelor Mountain Rhyolite would be much more favorable hosts, as they enclose the known ore bodies on the other main fault zones in the district.

An exploration program to test the Bulldog Mountain fault zone, based on the recommendations made in our preliminary report (Steven and Ratté, 1960b), was underway in 1964.

DISSEMINATED DEPOSITS IN THE CREEDE FORMATION

Nearly $1 million worth of ore has been extracted from basal beds in the Creede Formation in the Monon Hill mine, and silicified and mineralized rocks in the Creede Formation have been widely recognized on the south face of Bulldog Mountain and on Bachelor Mountain. Some of the beds on Bachelor Mountain contain sufficient silver to be of definite economic interest, as for example the Creede flat vein (Lunt, 1921 and 1924; Hills, 1924), but no successful mines have yet been established. In all these areas, the most thoroughly silicified or mineralized rocks are adjacent to the overlapping contact of the Creede Formation onto the rough underlying surface on volcanic rocks. The best ore values in the Monon Hill and Bachelor Mountain areas are found in particularly favorable beds within the Creede Formation. In general, the more permeable tongues of fanglomerate contain ore in the Monon Hill mine, and similarly permeable rocks would seem to offer the best locale for discovery of additional ore deposits. Geochemical sampling throughout this area might be the best way to determine what parts of the Creede Formation warrant further exploration.

Except for the small group of ore bodies intensively developed by the Monon Hill mine, this potential source of ore has not been systematically prospected. That ore of this type should be restricted to the one place that has been carefully explored seems highly unlikely. The lower part of the Creede Formation in the whole area opposite the south end of the Creede graben, from Willow Creek on the east to Miners Creek on the west, should be considered as potentially ore bearing. Large parts of this area may be barren, and few detailed guides to prospecting can be offered at this time. Exploration would probably be most successful adjacent to known ore-bearing structural features in the underlying volcanic rocks, and experience gained here could provide guides for additional exploration.

In the Monon Hill area, there is no reason known why commercial-grade ore should bottom at the Silver Horde level, and deeper abutting beds of fanglomerate may be similarly mineralized. Other nearby segments of the contact between the Creede Formation and the buried hill also might well be mineralized. The Monon Hill mine is adjacent to a promontory or nose on the buried hill, and other such noses might be more favorable than valley areas.

Most prospecting for disseminated ore on Bachelor Mountain has been on lenses of sandstone on the south side of the mountain, high in the Creede Formation and relatively remote from the probable sources of mineralizing solutions along the Amethyst or Bulldog Mountain faults. The intensely silicified rocks near the basal contact might be relatively unfavorable, but more permeable beds near these might be more highly mineralized.

ALPHA-CORSAIR FAULT ZONE

Although detailed firsthand information on the ore deposits along the Alpha-Corsair fault zone is lacking, general considerations suggest that this fault zone warrants prospecting. It is the largest fault on the west side of the Creede graben, and, indeed, displacement on it has been greater than on any other fault in the graben. Virtually all this displacement took place during the late period of faulting, which preceded and in part accompanied mineralization. The exposed parts of the Alpha-Corsair vein along lower McKenzie Mountain resemble the upper parts of the Amethyst and related veins in that they contain high silver values in the ores and are enclosed in part by highly altered wallrocks. In addition, high-grade silver assays have been reported from some minor veins in the hanging-wall block of the main vein zone. These factors all suggest that exploration at depth might well disclose significant mineralized rock.

Careful study of the reopened Corsair mine might disclose more detailed geologic control on localization of the ore bodies and thus provide guides for any such deep exploration.

Little evidence was seen for hydrothermal activity along the northern parts of the Alpha-Corsair fault zone. So much of this part of the zone is covered with talus, landslide, and moraine, however, that little can be said concerning the economic potential. We suggest that the known mineralized segment along the southern part of McKenzie Mountain might logically be explored first and the findings there used to guide future prospecting farther north.

SOLOMON–HOLY MOSES FAULT ZONE

The Solomon–Holy Moses fault zone has been explored over a vertical range of more than 800 feet in the combined Phoenix and Holy Moses mines and nearly as great a range in the Mexico–Solomon and Ethel-Ridge mines to the south. Except for the Phoenix ore body, the only block of ground in these explored areas reported to contain significant mineralized rock is in the northern part of the Solomon mine and in the adjacent parts of the Holy Moses mine, and this area appears to be the most favorable for developing additional ore. We have seen mineralized rock in this block only in the bottom of a 70-foot winze sunk from the Holy Moses 2 level where the apparent top of a galena-sphalerite ore body was exposed (p. 80). Emmons and Larsen (1923, p. 179) reported good ore in adjacent blocks to the south in the northern part of the Solomon mine and southern part of the Holy Moses mine, and some old longitudinal sections of the mines that we have seen indicate ore in this same area.

The fault zone north of the Phoenix mine is generally obscured by surface debris, and its economic potential is difficult to assess. In a few places, however, adjacent rocks are altered to some degree, a factor that indicates at least local hydrothermal activity.

MINOR FAULTS

Although emphasis has been given in preceding sections to the larger faults in the Creede graben and to the disseminated deposits in the Creede Formation, many minor faults may be mineralized and warrant investigation. The main period of activity of the faults extending northwest across Rat Creek was probably concurrent with subsidence of the Creede caldera (p. 60), but some evidence exists for movement toward the southeast after Creede deposition; there the faults intersect the zone of caldera-border faults north of Monon Hill. Although probably not as favorable as faults that were more active during the late period of faulting, these seem worthy of some attention at least. Geochemical prospecting techniques might well indicate whether or not they warrant further exploration.

The Midwest mine developed a minor vein zone that extends northwest across the ridge between Nelson and West Willow Creeks. The vein seen in the Midwest mine contained chiefly pyrite and was enclosed by highly argillized walls. Some pockets of galena were observed, however, and by analogy with other more thoroughly developed veins in the district, the vein here might be more persistent and higher in grade at depth below the zone of argillized wallrocks.

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