Ash Flows and Related Volcanic Rocks Associated With the Creede Caldera San Juan Mountains Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 524-H

Prepared in cooperation with the Colorado Mining Industrial Development Board

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Resurgent dome of the Creede caldera, viewed from McKenzie Mountain north of the caldera. (See photographic point, pl. 1). Rio Grande has cut its valley in soft lacustrine deposits that filled a structural moat bordering the caldera.

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

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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ASH FLOWS AND RELATED VOLCANIC ROCKS ASSOCIATED WITH THE CREEDE CALDERA, SAN JUAN MOUNTAINS, COLORADO

By James C. Ratté and Thomas A. Steven

ABSTRACT

A complex pile of Tertiary volcanic rocks in the central San Juan Mountains, Colo., consists of welded ash-flow tuffs, lava flows, and breccias from several sources. A more limited sequence within this assemblage originated in or bordering the Creede caldera and is the subject of this report.

The Creede caldera sequence consists of five major ash-flow formations, locally interlayered lava flows, a succeeding lava-flow formation, and the volcanic-clastic Creede Formation. The Bachelor Mountain Rhyolite, oldest formation of this sequence, consists of three members that form a composite ash-flow sheet with a thickness of at least 4,000 feet and a minimum volume of 5–10 cubic miles. Near its source in a cauldron largely obliterated by the younger Creede caldera, the Bachelor Mountain Rhyolite is a simple cooling unit with rare partings of any kind. Toward its margins, compound and multiple cooling units can be distinguished, and volcanic rocks from other areas intertongue with it. Simple cooling of the thick succession of ash flows near their source shows virtually continuous accumulation in the vent area, whereas the multiple cooling units and intertongued layers of other rocks are evidence of episodic deposition at the edges of the pile.

The three members of the Bachelor Mountain Rhyolite are distinguished mainly by different degrees of welding and compaction. The Willow Creek Member is densely welded, and fluidal rocks in the lower part are believed to represent an approach to complete reconstitution during welding. The overlying Campbell Mountain Member grades upward from a densely welded eutaxitic rock into a less welded vitroclastic rock, and the Windy Gulch Member at the top consists of poorly welded to nonwelded tuff. Near the source, contacts between the members are distinct although gradational, but near the margins of the deposit the members lose their identity through lateral gradations.

Eruption of the Bachelor Mountain Rhyolite caused the Bachelor Mountain cauldron to collapse. The extent and shape of this cauldron are not known, but it was in part coincident with the later Creede caldera. After cauldron collapse, the Bachelor Mountain Rhyolite was pervasively altered by potassic fluids that were guided in part by ring fractures and other subsidence structures.

After a period of quiescence, renewed eruptions formed the Farmers Creek Rhyolite, a heterogeneous assemblage of ash flows and poorly welded pumice breccia that is confined to the northeastern side of the Creede caldera. The source of the Farmers Creek evidently was in the caldera because the ash-flow units become less welded away from it. Differential tilting of these rocks indicates that some of the earliest deformation related to the Creede caldera was in response to the Farmers Creek eruptions.

The overlying Mammoth Mountain and Wason Park Rhyolites form extensive ash-flow sheets that nearly surround the present Creede caldera. These formations average 600–800 feet in thickness over wide areas, and each has a volume in excess of 25 cubic miles. Both formations range from simple cooling units near the caldera to compound cooling units away from the caldera, indicating a source within the subsided area. Detailed studies were made of the Mammoth Mountain and Wason Park Rhyolites to determine whether evidence of flow boundaries might exist in thick densely welded units that have no visible partings. Indications of such boundaries were found by measuring minor variations in density of the rocks and abundance and size-sorting of phenocrysts.

The Snowshoe Mountain Quartz Latite is the youngest ash-flow deposit in the Creede caldera sequence. It is confined to the core of the Creede caldera where, as a result of resurgent uplift, it forms a topographic dome. It is more than 6,000 feet thick and has a volume of at least 100 cubic miles. The ash flows are composed mainly of densely welded quartz latite tuff, but a partially welded zone is present at the top of the formation, and several discontinuous zones of partially welded tuff lie within the formation. Avalanche breccias derived from the caldera walls intertongue marginally with the ash flows, providing evidence for the composite nature of the ash-flow sheet. The Snowshoe Mountain Quartz Latite is similar petrographically, chemically, and stratigraphically to parts of the Rat Creek and Nelson Mountain Quartz Latites, but these two ash-flow sheets were derived from the San Luis Peak cauldron to the north and hence are not a part of the Creede caldera sequence.

Lava flows are interlayered with the ash flows of the sequence above the Farmers Creek Rhyolite, becoming more abundant upward. Most of the lavas are quartz latite but rhyolite flows are interspersed irregularly. The Fisher Quartz Latite, most voluminous of the lava-flow units, was extruded during the final eruptions from the Creede caldera area. Vents for many of the lava flows have been identified near the caldera ring fracture zone.

The rocks of the Creede caldera sequence show a general change with time from crystal-poor rhyolite to crystal-rich quartz latite. The type of eruptive activity also changed from the early eruption of ash flows to final eruption of lava flows.

The rocks are believed to represent a genetic sequence derived from a common source magma in process of differentiation. Fractionation of volatile constituents and alkalies in the magma was interrupted repeatedly by eruption, and, with passing time, the magma available for eruption was progressively depleted in volatiles, contained more phenocrysts, and was more latitic or dacitic in composition.

INTRODUCTION

The San Juan Mountains in southwestern Colorado comprise several large overlapping volcanic accumulations of middle or late Tertiary age, which together form a composite volcanic pile 10,000 sq mi (square miles) in area and 1–2 miles thick. Each of the local volcanic accumulations contains several centers of eruption from which liquid lavas and incandescent ash flows poured forth in tremendous volumes. The ash flows were deposited very rapidly over large areas, and thus are particularly useful in unraveling the volcanic history. This exchange of large quantities of magma from within the crust to the earth's surface often led to collapse or subsidence in the vent areas, forming structural and topographic depressions known as cauldrons and calderas. The character and significance of the sequence of volcanic rocks related to one of these subsidence areas, the Creede caldera, are the subject of this report.

A major ash-flow field near Creede surrounds a cauldron complex at least 25 miles long and 5–15 miles wide that marks the general source area of the field. Four overlapping cauldrons, each related to one or more ash-flow eruptions, have been recognized so far within this complex. Two of the structures, the Bachelor Mountain cauldron and the Creede caldera, are at least partly coincident, and together or separately they underwent repeated subsidence during most of the time the central San Juan source area was active. The rock units associated with the Bachelor Mountain cauldron and the Creede caldera, called the Creede caldera sequence, show petrologic, stratigraphic, and structural relations that reflect changing conditions within the source magma chamber, as well as changes in the conditions of eruption, accumulation, and cooling.

This study is part of a comprehensive investigation of the geology and ore deposits of the central San Juan Mountains by the U.S. Geological Survey in cooperation with the Colorado Mining Industrial Development Board and predecessor agencies. Some of the results of this investigation have already been presented in preliminary form (Steven and Ratté, 1959, 1960, 1963, 1964; Steven, 1964; Ratté and Steven, 1959, 1964), and the detailed geology and structural control of ore deposits in the Creede mining district have been considered in a more comprehensive manner (Steven and Ratté, 1965). Fieldwork was begun in 1953 and is still in progress. Both authors participated in field investigations from 1953 to 1959, and Steven continued after 1959. An area of approximately 250 sq mi was mapped at scales ranging from 1:12,000 in the mining district to 1:40,000 in adjacent areas (pl. 1), and supplemental reconnaissance was done over a much wider area to determine the extent and changes in character of some of the ash-flow units.

Field conferences and numerous discussions with Robert L. Smith and Roy A. Bailey and other colleagues in the U.S. Geological Survey have been of great value in our studies. We also acknowledge the laboratory assistance of William Allen, William Thordarson, and Gary Curtin of the Geological Survey. Photographs of rock specimens and photomicrographs of thin sections were taken by Wendall Walker, Richard B. Taylor, and Ernest Krier, also of the Survey.

TERMINOLOGY

The terminology of ash-flow units used here follows the usage of Smith (1960a,b) and Smith and Bailey (1962). Some of the more frequently used terms are explained below.

ASH-FLOW UNIT: The fundamental unit of deposition that results from a single eruption of ash-flow materials. The term "ash flow" is used both for the eruptive unit and the depositional unit, comparable to the use of the term "lava flow."

COOLING UNIT: All the ash-flow units (one or many) that have shared virtually the same cooling history, that is, have cooled effectively as a single deposit. The cooling of a single ash flow results in the formation of a definite pattern of zones of welding and crystallization and consititutes a SIMPLE COOLING UNIT. Where several ash flows have shared a common cooling history, and the zonal pattern is superimposed on the whole, they also form a simple cooling unit.

COMPOUND COOLING UNIT: A group of ash flows that have had much the same cooling history except that minor interruptions in cooling can be recognized in deviation from the zonal pattern of a simple cooling unit.

COMPOSITE SHEET: A group of ash flows that pass laterally from simple or compound cooling units into separate cooling units.

PARTING: A gap or hiatus between ash flows in simple or compound cooling units. Partings include such features as concentrations of lump pumice, lapilli, or blocks; bedded airfall ash; bedded reworked ash; and minor erosional unconformities (Smith, 1960b, p. 149, 157). In densely welded zones, partings may be manifested by variations in the abundance and size of phenocrysts and rock fragments, and in the density and porosity of the rocks.

CAULDRON: A subsidence structure of volcanic origin, of unspecified size and form.

CALDERA: A cauldron having a nearly circular outline.

RESURGENT CALDERA: A caldera that has the structural form of a dome as a result of postsubsidence uplift of its core (frontispiece).

Not all simple and compound cooling units can be readily distinguished. Some sheets of densely welded tuff in the Creede area were classed as simple cooling units in the field but laboratory studies indicate that they are compound. As a practical matter, however, field appearance is generally the basis for classification.

More comprehensive discussions of ash-flow units, cooling units, and the zones of welding and crystallization are given by Smith (1960a, b) and by Ross and Smith (1961).

GEOLOGIC SETTING

The major ash-flow field that surrounds the cauldron complex of the central San Juan Mountains has an areal extent of at least 1,000 sq mi and a volume of at least 1,000 cu mi, or approximately 4,000 cu km (cubic kilometers). The ash-flow eruptions caused formation of four subsidence units, the older La Garita and Bachelor Mountain cauldrons, and the younger San Luis Peak and Creede calderas. The Bachelor Mountain and Creede calderas are evidently nested. The rock units associated with them form a geographically and genetically related assemblage within the larger field. The area of recurrent subsidence marked by the Bachelor Mountain cauldron and Creede caldera is referred to in this report as the Creede subsidence area, and the rock units associated with it as the Creede caldera sequence. The position of this sequence in the revised volcanic stratigraphy of the central San Juan Mountains (Steven and Ratté, 1964), which include most of the units in the larger ash-flow field, is shown in figure 1.

The oldest known formation in the Creede caldera sequence is the Bachelor Mountain Rhyolite, a voluminous pile of rhyolite pumice and ash that was deposited on a rough terrain underlain by the rhyolite of Miners Creek west of Creede and the Outlet Tunnel Member of the La Garita Quartz Latite north of Creede (pl. 1). The rhyolite of Miners Creek apparently formed a local lava dome in the Creede area and may belong to the Creede caldera sequence, but so little of it is exposed that it is given only an informal name and will not be considered further. The Outlet Tunnel Member of the La Garita Quartz Latite forms a large pile of ash flows related to the La Garita cauldron northeast of Creede. The Bachelor Mountain Rhyolite intertongues to the west with lava flows and breccias of the Shallow Creek Quartz Latite; these flows and breccias also may belong to the Creede caldera sequence, but available evidence is too sketchy to permit discussion.

Eruption of the Bachelor Mountain Rhyolite led to the first known collapse in the Creede subsidence area; this collapse formed the Bachelor Mountain cauldron. The extent and shape of the Bachelor Mountain

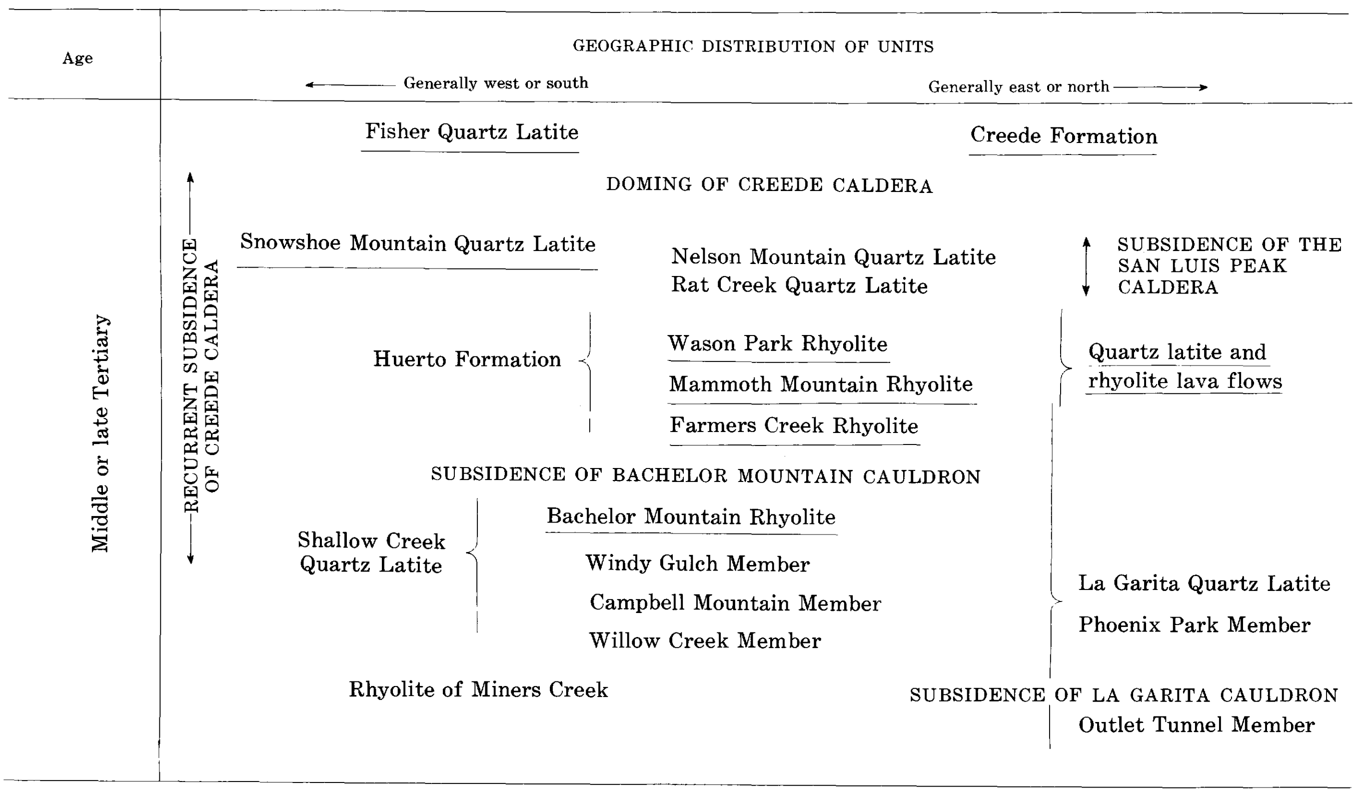


FIGURE 1.—Volcanic stratigraphy of the central San Juan Mountains, Colo. Formations underlined belong to the Creede caldera sequence.

cauldron are not known, but remnants of the northern part of the ring fracture zone that bounded it are exposed north of Creede. The remnants are parallel to and just outside the margin of the later Creede caldera, suggesting that the two structures were at least partly coincident.

After collapse of the Bachelor Mountain cauldron, ash-flow eruptions related to the Creede caldera proper began with the Farmers Creek Rhyolite, followed in succession by the Mammoth Mountain Rhyolite, Wason Park Rhyolite, and the Snowshoe Mountain Quartz Latite. Local lava flows were erupted between the periods of major ash-flow activity, and extensive lava eruption after the last of the ash flows formed widespread flows and domes of Fisher Quartz Latite, the youngest volcanic unit in the Creede caldera sequence.

Dacitic lavas and breccias of the Huerto Formation, derived from another source area to the southwest, intertongue with parts of the Creede caldera sequence west of the caldera, and the Rat Creek and Nelson Mountain Quartz Latites, erupted from the San Luis Peak caldera area north of Creede, accumulated late in the period of major ash-flow activity, perhaps during the same general time interval as the Snowshoe Mountain Quartz Latite.

The Creede caldera (frontispiece) subsided recurrently during the period of ash-flow eruptions. Early collapse is indicated by differential tilting of the Farmers Creek and Mammoth Mountain Rhyolites in fault blocks along the northeast side of the caldera and by ring faults along the east margin of the caldera which show evidence of several periods of movement. The final collapse of the caldera accompanied eruption of the Snowshoe Mountain Quartz Latite; many of the details of this collapse are recorded in the rocks now exposed in the core of the caldera. After collapse, the core of the Creede caldera was domed. The moat left between the domed core and the margin of the caldera was then filled with lacustrine and fluvial volcanic sediments, and with calcareous tufa and travertine of the Creede Formation which was deposited while the Fisher Quartz Latite was being erupted.

BACHELOR MOUNTAIN RHYOLITE

The Bachelor Mountain Rhyolite is a composite ash-flow sheet formed by the eruption, accumulation, and welding of rhyolitic pumice and ash that contained small percentages of phenocrysts and foreign rock fragments. The formation consists of the Willow Creek, Campbell Mountain, and Windy Gulch Members, which are distinguished principally by differences in the degree of their welding and compaction. The members intergrade, and near the margins of the Bachelor Mountain they lose their identity through lateral gradations in welding and compaction.

In an earlier report on the geology of the Creede area (Emmons and Larsen, 1923) the three units now classed as members of the Bachelor Mountain Rhyolite were treated as formations. The Willow Creek was reported to consist of several flows of banded to felsitic rhyolite; the Campbell Mountain was described as mottled flow breccia, and the Windy Gulch as flow breccia and tuff. Later, Larsen (in Cross and Larsen, 1935; Larsen and Cross, 1956) described these rocks as being largely lava flows. The rocks are now recognized as welded ash-flow tuffs, and are classed as members rather than as formations because they intergrade and constitute a simple cooling unit in the source area (Steven and Ratté, 1964).

DISTRIBUTION AND THICKNESS

Bachelor Mountain Rhyolite dominates the rock exposures north of the Creede caldera in a broad arcuate belt that extends from Shallow Creek to Farmers Creek, passing through the north end of Creede (pl. 1). Relations with older rocks show that this ash-flow sheet accumulated upon a rough volcanic topography and that the distribution of the ash flows was restricted both west and northeast of Creede by older and concurrently erupted volcanic rocks. Bachelor Mountain Rhyolite exposed along upper West Willow Creek probably is continuous beneath a cover of younger rocks with the thick section of Bachelor Mountain north of Creede. The Willow Creek and Campbell Mountain Members of the formation are largely coextensive in present outcrops, but the Windy Gulch Member which overlies them is preserved mainly in down-faulted blocks between Miners Creek and Willow Creek.

Rocks similar to Bachelor Mountain Rhyolite have been reported by Larsen and Cross (1956, p. 135–136) in the Spring Creek drainage north of the area shown on plate 1, and we have seen rocks of this type near the head of the Piedra and San Juan Rivers south of the Creede area. More work is needed before the relations between these widely separated exposures and the main body of the Bachelor Mountain Rhyolite in the Creede area can be established, and thus the original extent of the Bachelor Mountain ash-flow sheet is still conjectural.

Intrusive rhyolite in several small bodies ranging from less than 1 to about 10 acres just northwest of Creede and in two larger bodies of about 50 acres each on the south slopes of Bulldog Mountain are included in the Bachelor Mountain. The intrusive masses are somewhat irregular; they cut both the Willow Creek Member and the Campbell Mountain Member, but were not observed in contact with the Windy Gulch Member except along a fault.

A complete section of Bachelor Mountain rocks cannot be measured at any one locality because of recurrent faulting and erosion and a widespread cover of surficial deposits. A thickness of at least 4,000 feet is indicated by adding the maximum thicknesses of the individual members as they are exposed in the central part of the Creede area. The Willow Creek Member is more than 2,000 feet thick in East Willow Creek canyon, where the section appears free of faults and its base is not exposed. The overlying Campbell Mountain Member has an apparent thickness exceeding 1,100 feet on the south side of Nelson Mountain, and the top of the section is an unconformity. Mine workings in the Creede district, closer to the caldera rim, expose more than 800 feet of Campbell Mountain rocks, and the base of the section has not been seen. The uppermost, Windy Gulch Member is 800–900 feet thick on the southwest slopes of Bulldog Mountain (pl. 1), and the top of this section is an unconformity.

The main body of Bachelor Mountain Rhyolite in the Creede area has a volume of about 10 cu mi, and smaller bodies suggest an additional volume of 10–20 cu mi. Thus in the Creede area alone, the Bachelor Mountain Rhyolite is of magnitude 5 (10–100 cu km; multiplying cubic miles by 4 gives a rough conversion to cubic kilometers) in the classification of Smith (1960a, p. 819), and the entire sheet of Bachelor Mountain ash flows probably is one order of magnitude greater.

GENERAL LITHOLOGY

Ash flows of the Bachelor Mountain Rhyolite have a topographic expression dependent on the degree of welding. The Willow Creek Member, which is densely welded in most places, forms cliffs and precipitous canyon walls, and talus derived from it typically resembles wood chips, or, where the rocks are cut by closely spaced sheeting joints, it consists of flat plates. The Campbell Mountain Member, also densely welded in its lower part, in some places forms steep slopes continuous with the cliffs of Willow Creek and in others it marks a change to gentler slopes. Talus fragments from this member are blocky and irregular. The poorly welded to nonwelded Windy Gulch Member is more susceptible to weathering, soil formation, and erosion than the other two members, and it generally is poorly exposed.

The basal contact of the Bachelor Mountain is exposed at only a couple of places along Miners and East Willow Creeks. A few tens of feet of black splintery vitrophyre separates the Willow Creek Member from the underlying rhyolite of Miners Creek near locality 5, figure 2. The glass appears to intrude the underlying rhyolite in some places, but it also grades into the overlying devitrified welded tuff in the Willow Creek Member. Along East Willow Creek, dense devitrified Willow Creek welded tuff overlies a nonwelded tuff and breccia that may be either a poorly welded local basal facies of the Willow Creek Member or a part of the La Garita Quartz Latite. At both localities the rocks near the basal contact are less compacted than those higher in the Willow Creek.

The contacts between members of the Bachelor Mountain Rhyolite are completely gradational, and in field mapping they are placed within transition zones that generally are a few tens of feet thick. The transition zones are marked mainly by relatively sharp changes in compaction and welding, and in many places these changes are expressed also by breaks in the topography. Changes in color and in modal composition also characterize the transition zones in places.

The Bachelor Mountain Rhyolite intertongues with volcanic rocks from other source areas, and in places it shows lateral changes in lithology similar to the vertical changes that distinguish the members of the formation. These features are particularly evident near the margins of the body near Miners Creek. As shown at locality 1, figure 2, lava flows and flow breccia of the Shallow Creek Quartz Latite form a layer within the Windy Gulch Member. Both the Campbell Mountain Member and a lower lens of the Windy Gulch Member pinch out near this locality, and to the north Shallow Creek Quartz Latite rests directly on the Willow Creek Member. As mapped between localities 2 and 3 north of Miners Creek, the Shallow Creek Quartz Latite forms tongues both within and beneath the Windy Gulch Member. Near locality 4, moderately welded rocks of Campbell Mountain lithology grade laterally into poorly welded rocks of Windy Gulch lithology. Similarly, Bachelor Mountain rocks intertongue with La Garita Quartz Latite east of East Willow Creek, but the relations are poorly exposed.

At locality 5, figure 2, the Willow Creek Member consists of two cooling units separated by a few feet of vitrophyre. Beneath the vitrophyre, alternating zones of Willow Creek and Campbell Mountain lithology have the characteristics of a compound cooling unit. Above the vitrophyre, the rock is all of Campbell Mountain type, but it is too thin to be shown separately on the geologic map. This is the only locality at which we have observed a vitrophyre zone within the Bachelor Mountain Rhyolite. Alternating zones of Willow Creek and Campbell Mountain rock types occur also in other marginal areas of the formation, as west of Miners Creek (south of the area shown on fig. 2) and east of Creede between Dry Gulch and Farmers Creek.

SOURCE

Present exposures indicate that the thickest part of the Bachelor Mountain Rhyolite is centered near the town of Creede. Small bodies of intrusive rhyolite in

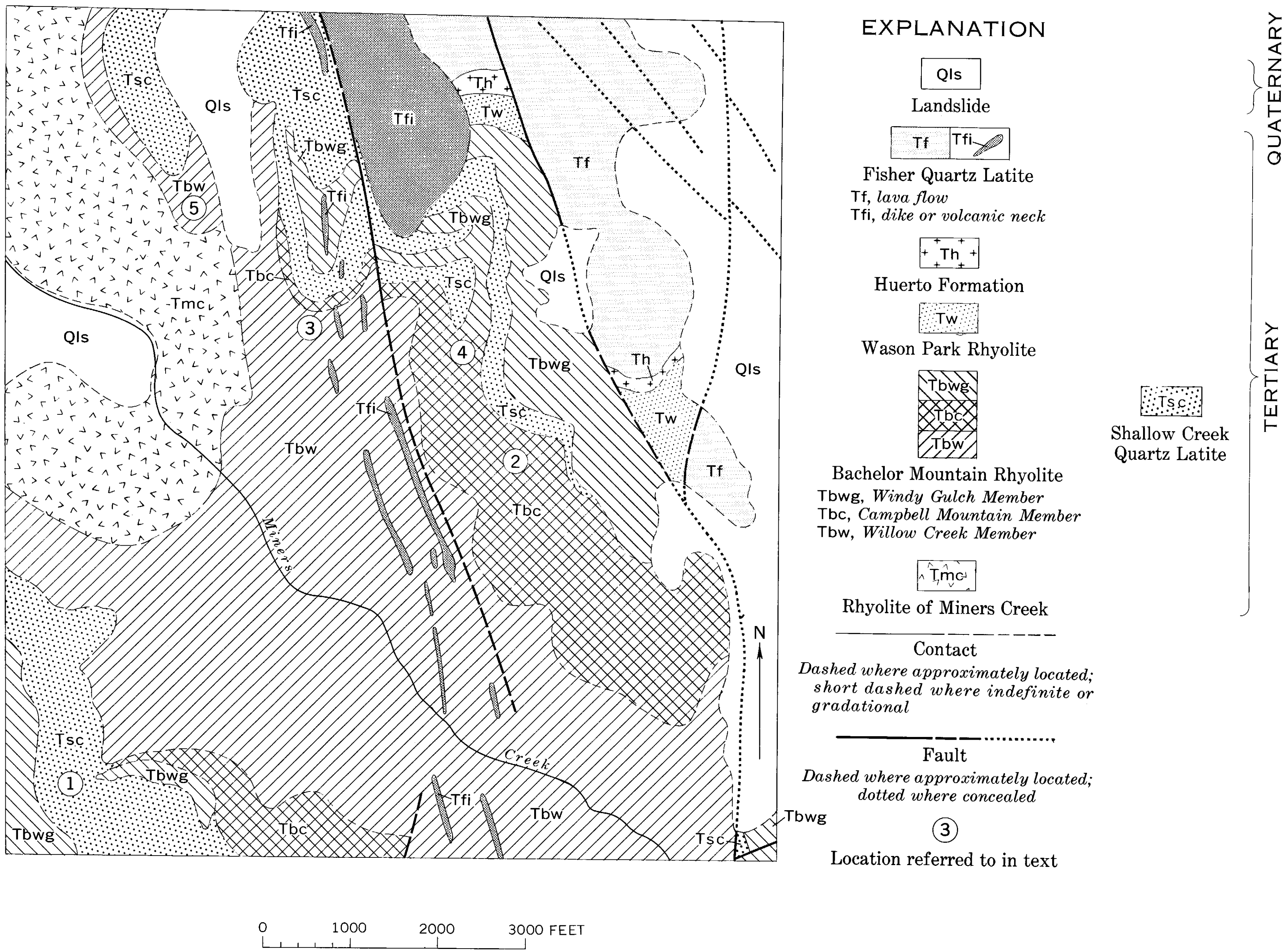


FIGURE 2.—Intertonguing and lateral facies changes in the Bachelor Mountain Rhyolite near Miners Creek. See plate 1 for location of area.

the Bachelor Mountain just north and west of Creede may mark plugged vents. The direction of intertonguing with volcanic rocks from other sources (fig. 2) and the direction of thinning and lateral changes in compaction and welding also indicate a source in the vicinity of the intrusive bodies or within the Creede subsidence area.

PETROGRAPHY

The Bachelor Mountain Rhyolite consists mainly of devitrified welded ash-flow tuff that generally contains 5–10 percent phenocrysts and from less than 1 to more than 20 percent foreign fragments of porphyritic volcanic rocks. Cognate pumice fragments are a major constituent of much of the rock, but they are not readily distinguished from the matrix except in the less welded parts of the Campbell Mountain and Windy Gulch Members.

Modes representing the three ash-flow members and the intrusive rhyolite are given in table 1. Modes in this report were made by the point-count method, and the number of points counted in each sample is indicated in the tables of modes. Foreign rock fragments were included in the modes because they characterize the rocks as field units, but they do not enter into the petrologic classification of the rocks. The magmatically derived constituents (matrix and phenocrysts) are accordingly recalculated to 100 percent.

The phenocrysts in the Bachelor Mountain are mostly sanidine and plagioclase but some are biotite, magnetite, and, rarely, clinopyroxene. They have maximum dimensions of 1–2 mm, but most are much smaller microphenocrysts. Sanidine generally predominates over plagioclase, although the ratio between the two minerals ranges widely. The sanidine crystals are mostly euhedral, zoned, and nonperthitic; they contain as much as 40–50 percent albite molecule as indicated by optical properties and X-ray analyses. The plagioclase phenocrysts are oligoclase-andesine in composition and commonly are replaced by unit pseudomorphs of clay minerals. (The composition of plagioclase cited in this report has been determined from extinction angles in sections approximately perpendicular to crystallographic "a" or approximately perpendicular to the optical bisectrix "x," using the high-temperature extinction-angle curves presented by Tröger 1952, p. 101, 111.)

Except for the glassy rocks at the base of the formation, the welded tuff has a microcrystalline to cryptocrystalline matrix that gives it a felsic or stony appearance in hand specimens. X-ray analyses show the matrix of the Willow Creek and Campbell Mountain Members to be mainly quartz and alkali feldspar, but some specimens of the Windy Gulch Member contain major quantities of the zeolites clinoptilolite and mordenite, and also montmorillonite, as alteration products of both the matrix and the pumice fragments.

The intrusive rhyolite in the Bachelor Mountain varies from bleached chalky white rock to gray to buff rock having a silicified appearance. Sanidine phenocrysts 1–2 mm long are prominent; they constitute as much as 10 percent of the rock and are practically the only phenocrysts except for a little biotite (mode 10, table 1). In thin sections, some of the sanidine phenocrysts show compositional zoning and faint perthitic structures, but others appear to be homogeneous. An increase in refractive indices toward the edges of zoned crystals indicates a higher albite content in the outer zones. One crystal, after being heated for 1 hour at

TABLE 1.—*Modes (volume percent) of Bachelor Mountain Rhyolite*

[Localities of samples are described with reference to Creede 15-minute quadrangle topographic map (1959). Leaders indicate mineral not found in thin section]

Rock unit and mode	Field No.	Matrix	Total phenocrysts	Plagioclase	Sanidine	Biotite	Pyroxene	Magnetite	Foreign rock fragments (percentage of total rock)	Total points (rock fragments excluded)
		Percentage of rock exclusive of foreign rock fragments								
Willow Creek Member:										
1	C-769-57D	96	4	1.7	1.5	0.3	0.2	0.1	2	1,110
2	CW-1	93	7	1.9	4.6	.5	.1	------	8	1,027
3	C-62B	94	6	1.5	4.6	.2	------	------	<1	1,015
4	C-480	94	6	2.5	3.0	.1	------	------	<1	1,131
Campbell Mountain Member:										
5	C-8	94	6	3.0	2.5	.4	------	------	5	965
6	C-62B	94	6	.8	4.4	.6	------	.1	6	1,048
7	C-843B	93	7	1.8	5.3	.5	------	.1	<1	1,096
Windy Gulch Member:										
8	C-859D	91	9	.6	6.8	.5	------	.7	21	1,051
9	C-944-59	89	11	7.3	2.8	.9	------	.4	15	1,089
Intrusive rhyolite:										
10	C-123	90	10	------	9.6	.4	.1	------	<1	963

1. Vitrophyre at base of Willow Creek Member about 900 ft east of elevation approximately 9,350 ft on Miners Creek.
2. Fluidal-eutaxitic, in Willow Creek Canyon, between Creede and North Creede.
3. In transition zone to Campbell Mountain Member at approximate 9,920-ft elevation on west side of East Willow Creek downslope from the Phoenix mine.
4. Fluidal Willow Creek Member in low outcrops on west side of Willow Creek Canyon between Creede and North Creede.
5. Eutaxitic Campbell Mountain Member at southeast end of McKenzie Mountain between Miners and Rat Creeks.
6. In transition zone to Willow Creek Member at approximate 9,920-ft elevation on west side of East Willow Creek downslope from the Phoenix mine.
7. Southwest side of Bulldog Mountain near Rat Creek at elevation approximately 9,200 ft.
8. South end of McKenzie Mountain between the Kreutzer and Corsair mines at elevation of about 9,700 ft.
9. West of Miners Creek, from outcrops at approximate 10,800-ft elevation near the McKenzie stock driveway.
10. At about 9,720-ft elevation on the ridge trending south from Bulldog Mountain, 1,000 ft west of road to Bachelor.

900°C, showed a homogeneous composition of $Or_{58}Ab_{42}$ as interpreted from its X-ray diffractometer pattern. The groundmass of the intrusive rhyolite has a micro-granophyre texture with tiny groups of quartz grains dispersed uniformly through it. These quartz grains may represent vesicle fillings and thus suggest near-surface intrusive bodies.

VERTICAL VARIATION

In a typical vertical section through the thickest part of the Bachelor Mountain Rhyolite, the three members form distinct lithologic facies having gradational boundaries (fig. 3). The differences are principally textural and are expressed by planar structures and porosity. Differences in color, modal composition, and degree of crystallization are locally conspicuous.

Certain terms used in describing the structural and textural features of the ash-flow tuffs, such as "fluidal," "eutaxitic," and "vitroclastic," are better understood from photographs than from words. Fluidal structure in a hand specimen is illustrated on figure 4*A*, and extreme fluidal structure in thin section on figure 5*B*. Eutaxitic structures in hand specimens are shown on figure 4*C*, *D*, and in thin section on figure 5*C*. Vestiges of vitroclastic texture with recognizable shards in thin sections are shown on figures 5*A*, and 6*A*, *C*. Fluidal structures grade into eutaxitic structures in some of the rocks (fig. 5*C*), a point discussed further below.

PLANAR STRUCTURES AND POROSITY

Progressive changes in planar structures and porosity from the base to the top of the Bachelor Mountain reflect a nearly continuous variation in the degree of compaction and welding of shards and pumice fragments. Where the base of the formation is vitrophyre or was markedly chilled, the welded tuff retains a semblance of vitroclastic texture (fig. 5*A*). However, most of the lower half of the Willow Creek Member is highly fluidal welded tuff (fig. 4*A*, *B*) which grades into mixed eutaxitic to fluidal rocks in the upper half (fig. 4*C*, *D*). In these mixed rocks, pumice fragments appear only as eutaxitic streaks and lack all vestiges of their original form and structure (figs. 5*C*, 7). The Campbell Mountain Member has a generally weak eutaxitic structure throughout (fig. 4*E*); although pumice lapilli are somewhat deformed, they commonly show relict vesicular structure (fig. 6*B*). The Windy Gulch Member has a weak eutaxitic structure in the zone of transition to the Campbell Mountain, but otherwise the pumice fragments in it are little deformed and they retain their original tubular structure (fig. 4*F*).

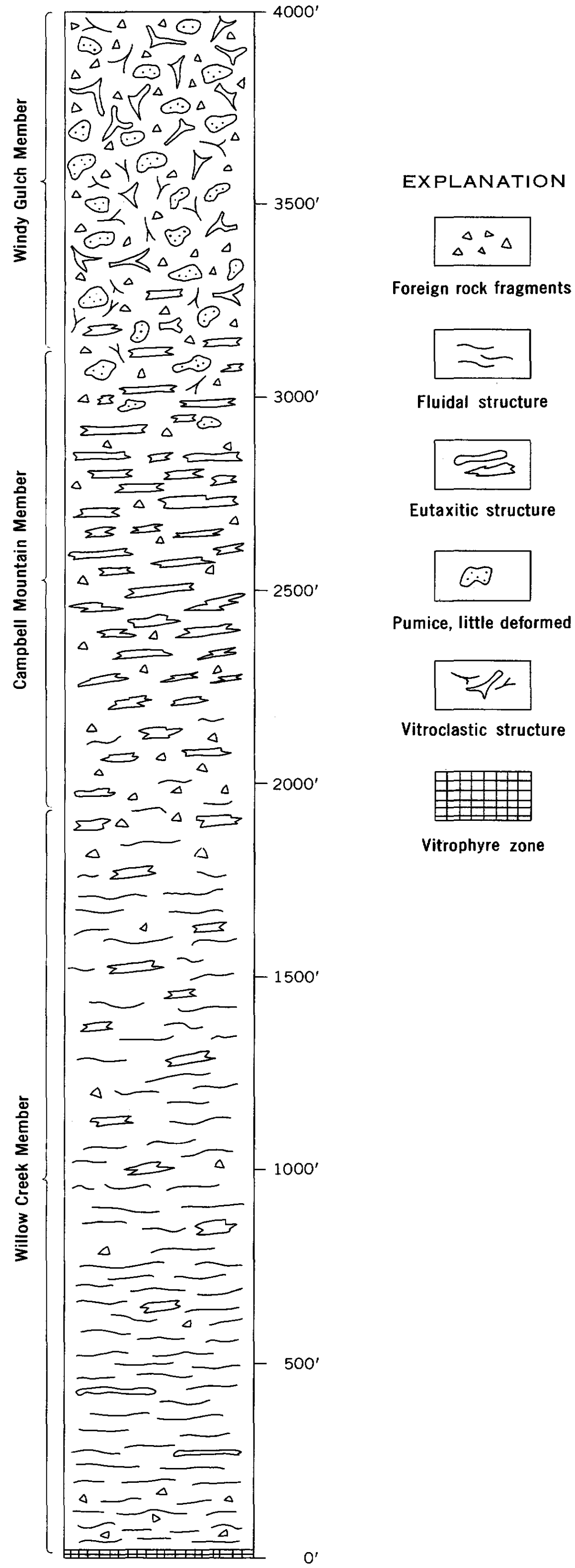


FIGURE 3.—Diagrammatic section of Bachelor Mountain Rhyolite.

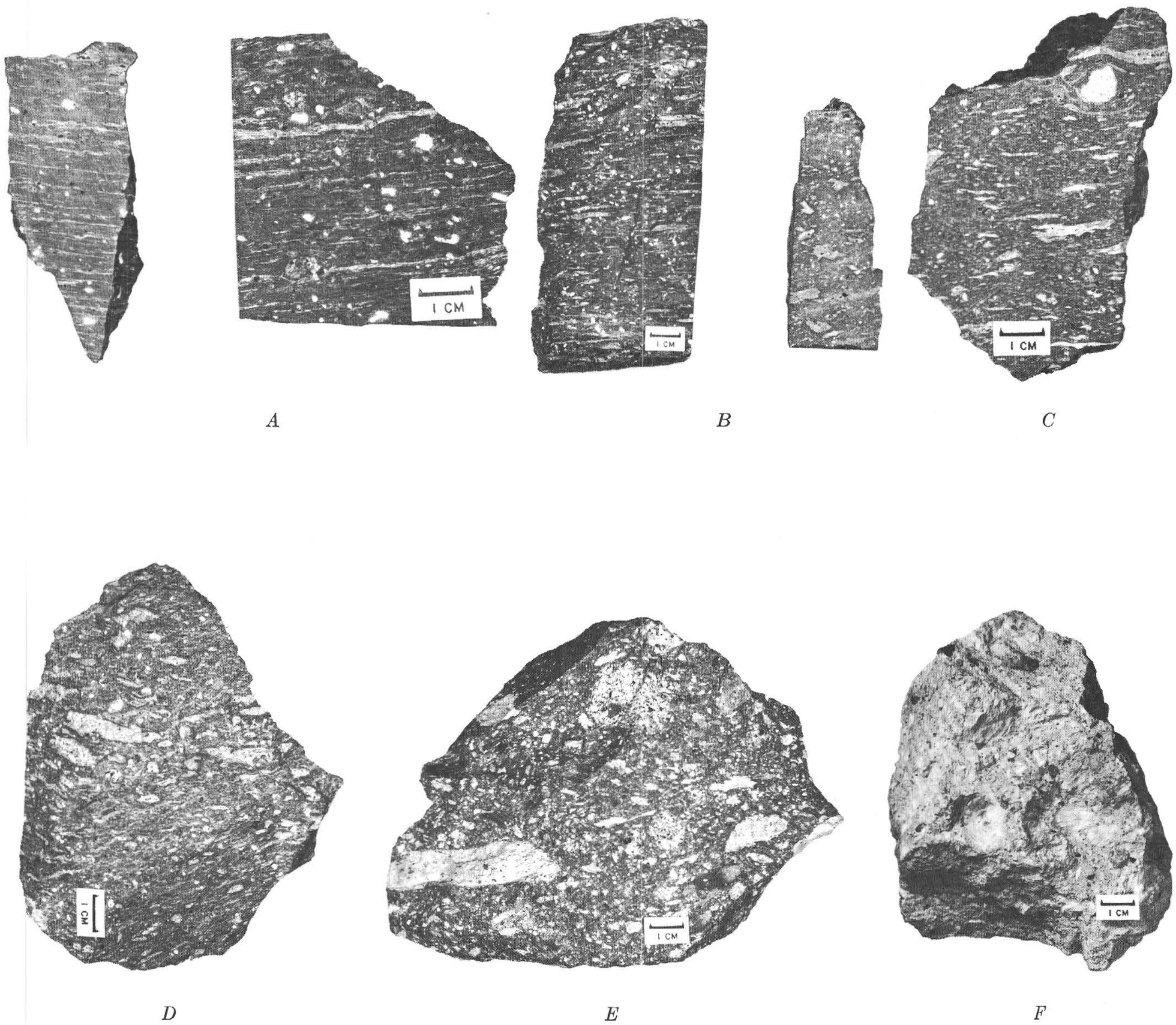
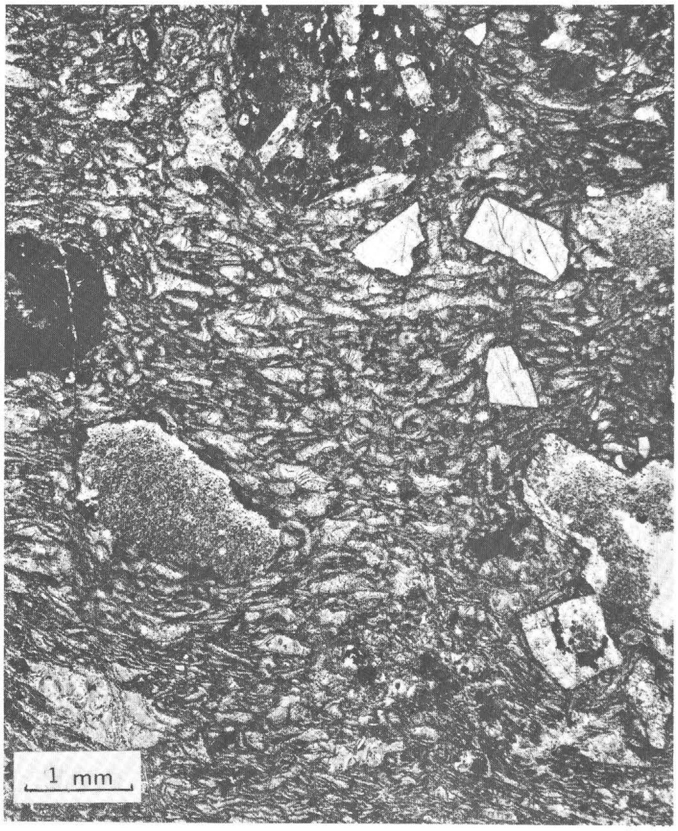
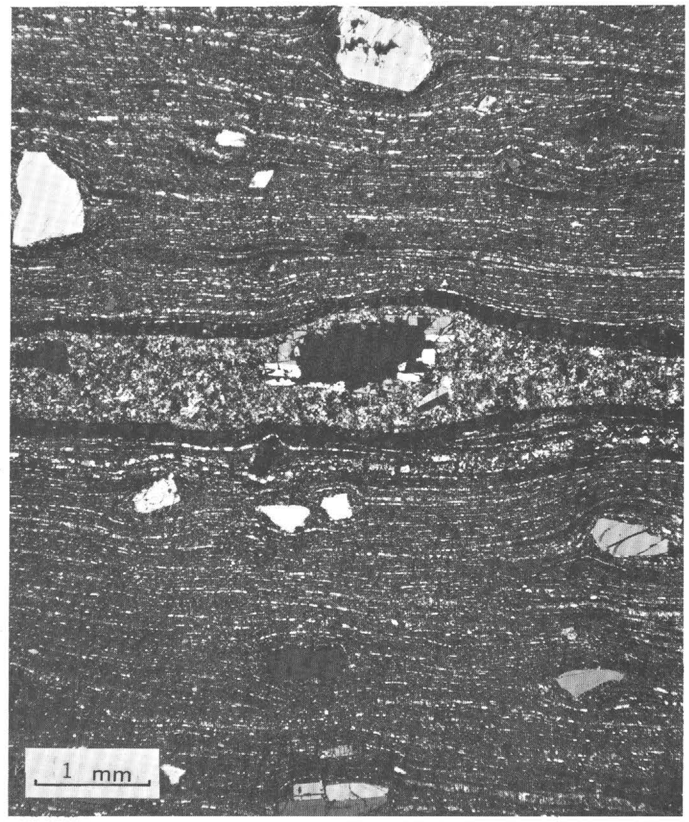


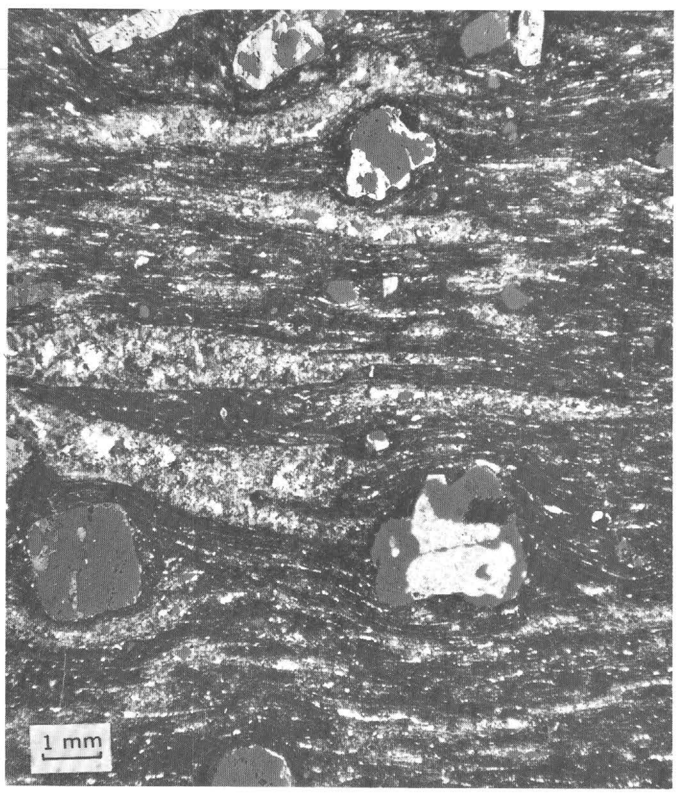
FIGURE 4.—Photographs of hand specimens of Bachelor Mountain Rhyolite showing changes in texture and structures between members of the formation, from bottom to top: *A*, Fluidal welded tuff near the bottom of the Willow Creek Member. *B*, Fluidal to eutaxitic welded tuff in the lower half of the Willow Creek Member. *C*, Eutaxitic to weakly fluidal welded tuff in the upper half of the Willow Creek Member. *D*, Eutaxitic welded tuff in the upper half of the Willow Creek Member. *E*, Weakly eutaxitic welded tuff in the Campbell Mountain Member. *F*, Poorly welded tuff in the Windy Gulch Member; tubular structure is preserved in many of the pumice fragments



A

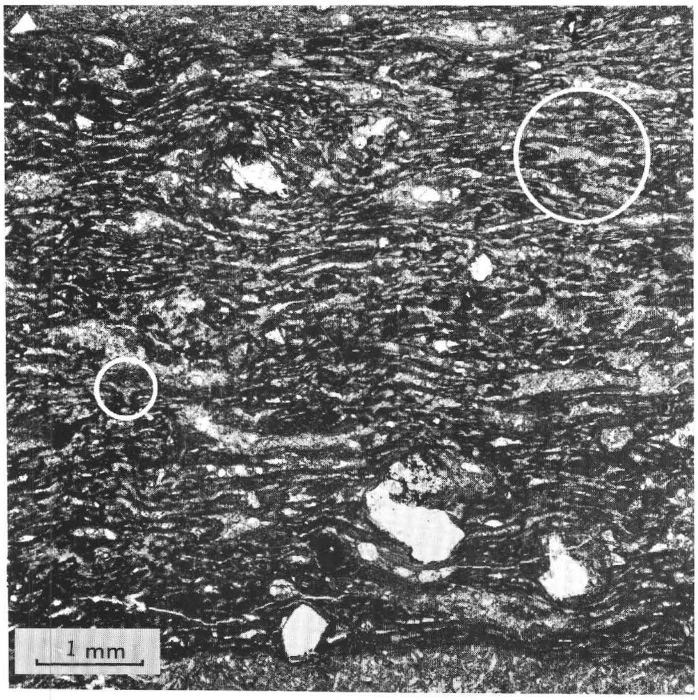


B

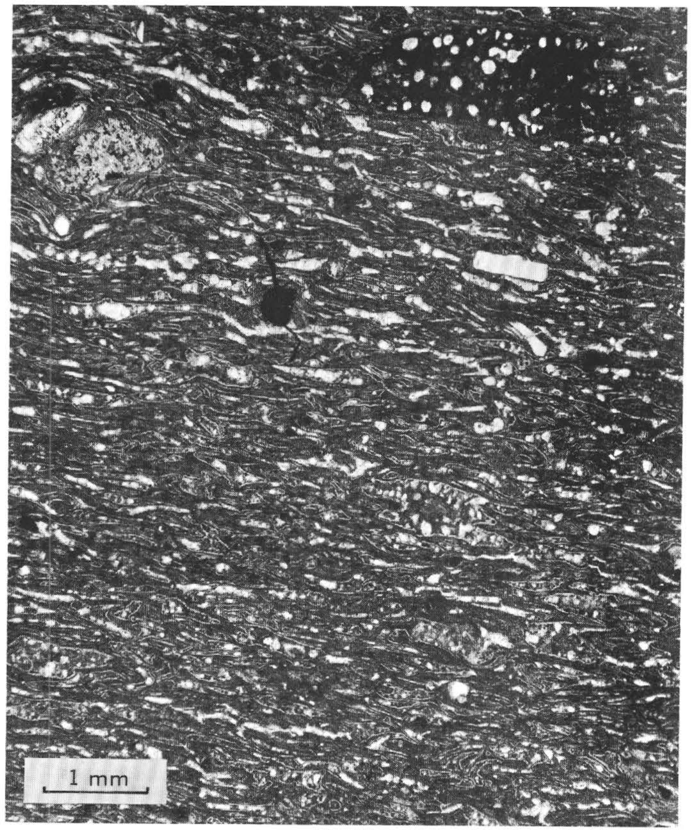


C

FIGURE 5.—Photomicrographs of microscopic structures in the Willow Creek Member of the Bachelor Mountain Rhyolite. *A*, Vitroclastic texture near the base of the member. *B*, Fluidal structure in the lower part of the member; granophyre layer (center) is part of a flattened pumice fragment that contains a plagioclase phenocryst. Crossed nicols. *C*, Eutaxitic structures showing weak fluidal characteristics, upper half of the member. Crossed nicols.



A



B

C

FIGURE 6.—Photomicrographs of microscopic structures typical of the Campbell Mountain Member of the Bachelor Mountain Rhyolite. *A*, Microeutaxitic structure in transition rock between Willow Creek and Campbell Mountain Members; relict shards are circled. *B*, Curlicue or maze texture formed by compaction of shards and small pumice fragments; this texture is characteristic of the member. *C*, Part of the thin section shown in *B* enlarged to show shard details.

FIGURE 7.—Flattened pumice fragment (light streak in center of block) in fluidal welded tuff of the Willow Creek Member.

A highly flattened pumice fragment in fluidal welded tuff in the Willow Creek Member is illustrated in figure 7. This particular fragment had planar dimensions in outcrop of at least 32 by 10 cm and a thickness of 1 mm. If restored to a more nearly equidimensional form and reinflated to about twice its nonporous volume, it would make a cubical pumice lapilli 4 cm on a side. In its present form, the pumice has an apparent flatness, a ratio of maximum and minimum dimensions (Peterson, 1961) of about 300:1. Pumice masses of this size in the Willow Creek commonly contain phenocrysts, which help to identify them as discrete samples of the parent magma.

Devitrified welded tuff in the Willow Creek Member has a cryptocrystalline matrix with fluidal streaks and eutaxitic bodies of granophyre (fig. 5*C*). The fluidal streaks commonly number 40–50 per cm (fig. 5*B*), and many consist virtually of a single line of quartz grains without appreciable alkali feldspar. Some of the eutaxitic lenses consist of crudely zoned micropegmatite, in which a border zone of pectinate alkali feldspar fibers gives way to a central zone of quartz and euhedral alkali feldspar tablets. (See Emmons and Larsen, 1923, pls. 5–7.) Some feldspar crystals have the typical rhombic form of adularia. Other granophyric intergrowths occur in the central part of axiolites and shards in the groundmass of Bachelor Mountain rocks.

OTHER PROPERTIES

The changes in structure through a vertical section of Bachelor Mountain Rhyolite may be accompanied by changes in the color of the rocks. Rocks of the Willow Creek Member are generally gray to bluish gray or violet; those of the Campbell Mountain are typically reddish brown, yellowish brown, tan, or brick red, and, near the lateral margins of the member, gray to brown. Tuff of the Windy Gulch also is red to brown or yellow, but commonly is much lighter in color than rocks of the lower members because of abundant light-colored clay minerals that replace many of the pumice fragments. In hydrothermally altered areas, any of the rocks may be bleached.

Changes in the modal composition of the members through a vertical section are probably slight, as indicated by the modes of table 1, although there is an increase of foreign rock fragments from the bottom toward the top of the deposit. In addition, the transition between the Willow Creek and Campbell Mountain Members is characterized by a notable concentration of such xenoliths. This feature is particularly noticeable in exposures near Creede, from Miners Creek to Dry Gulch, and appears to coincide more or less with the color change from grays and purples in the Willow Creek Member to the reds and browns of the Campbell Mountain Member and with the most marked change from fluidal to eutaxitic textures.

The groundmass of Bachelor Mountain Rhyolite shows a variety of textures but in general it consists of cryptocrystalline to microcrystalline intergrowths. The Willow Creek Member represents a zone of granophyric crystallization in contrast with the Campbell Mountain Member, in which spherulites, including axiolites and branching crystal aggregates, are prevalent. Spherulitic structure is common also in the Windy Gulch Member, but in these rocks the matrix textures are largely obscured by secondary minerals, mainly clays, zeolites, and quartz. Quartz is the only silica mineral we have identified in the Bachelor Mountain Rhyolite, except in one sample from the Windy Gulch Member which, as shown by X-ray analysis, contains abundant cristobalite as well as the zeolite mordenite and minor amounts of montmorillonite. The predominance of quartz is in accord with the findings of Smith (1960a), who noted that quartz is to be expected as the silica mineral in the groundmass in simple cooling units of rhyolitic welded tuffs more than about 600 feet thick, except that quartz should yield to cristobalite or tridymite in the upper part of the sheets unless it is replaced by secondary silica. Because much of the groundmass silica in the Bachelor Mountain Rhyolite probably has been recrystallized during deuteric and hydrothermal alteration, the silica minerals in this deposit have little significance as indicators of the conditions during primary crystallization of the ash flows.

CHEMICAL COMPOSITION AND ALTERATION

The chemical composition of Bachelor Mountain Rhyolite is represented by the analyses in table 2. Although the analyzed rocks all were altered in one way or another, they are all classified as rhyolites or alkali rhyolites in the chemical system of Rittmann (1952). Analysis 2–R, table 2, of the basal vitrophyre of the formation, probably closely approximates the composition of the original rock. It was derived by recalculating analysis 1 on a water-free basis on the assumption that the original glass probably contained only a few tenths percent water (Ross and Smith, 1955, p. 1071). The minor element content of the rocks conforms generally to the values expected in rhyolites, and the values for cobalt, chromium, and nickel are particularly low in comparison to those in the quartz latitic rocks of the younger parts of the Creede caldera sequence.

The range in chemical composition, the presence of secondary minerals in the mode, and the secondary textures are evidence that much of the Bachelor Mountain Rhyolite is altered. Whereas sodium, calcium, magnesium, and iron have been pervasively leached from much of the rhyolite, potassium has been pref-

TABLE 2.—*Chemical analyses, norms, and spectrographic analyses of Bachelor Mountain Rhyolite*

[Sample localities described with reference to Creede 15-minute quadrangle topographic map (1959)]

Sample No.	1	2R	3	4	5	6	7	8	9	10	11	12	13	14R	15
Laboratory No.	153631	--------	C–1166	C–1167	C–1169	--------	--------	--------	--------	151482	151483	C–1168	154778	--------	151481
Field No.	C–769	C–769	C–988	C–990	C–992	--------	--------	--------	La G–481	C–41	C–69A	C–991	C–944	C–944	C–123
Rock unit	Willow Creek Member									Campbell Mountain Member			Windy Gulch Member		Intrusive rhyolite

Chemical analyses (weight percent)

Nos. 2R and 14R are recalculated analyses. Type of analysis: R, rapid rock, by methods similar to those described by Shapiro and Brannock (1956); S, standard rock. Analysts: 1, P. L. D. Elmore; 2, I. H. Barlow; 3, S. D. Botts; 4, Gillison Chloe; 5, M. D. Mack; 6, Dorothy Taylor; 7, Faye H. Neuerburg; 8, W. C. Wheeler; 9, F. A Gonyer]

	1	2R	3	4	5	6	7	8	9	10	11	12	13	14R	15
SiO_2	71.7	75.0	75.40	73.61	76.03	73.53	76.26	77.36	72.96	72.8	72.4	71.28	66.2	70.6	72.0
Al_2O_3	13.0	13.6	12.66	13.99	12.03	12.87	11.30	11.37	14.14	14.2	14.2	13.86	14.5	15.5	15.2
Fe_2O_3	.8	.8	.88	.93	1.00	.88	.52	.31	1.24	1.0	1.3	1.66	1.9	2.0	.38
FeO	.85	.9	.12	.18	.18	.64	.34	.36	.28	.28	.44	.18	.42	.4	.15
MgO	.22	.2	.20	.20	.04	.56	.02	.14	.36	.18	.18	.04	.84	.9	.12
CaO	.78	.8	.12	.35	.19	.07	.23	.30	.24	.20	.22	.20	2.2	2.3	.27
Na_2O	3.4	3.6	.40	2.18	1.01	.63	2.81	1.38	1.14	.89	.86	.57	1.3	1.4	1.1
K_2O	4.7	4.9	9.05	7.18	8.88	8.92	6.77	7.28	8.39	9.5	9.1	11.35	5.8	6.2	9.1
H_2O+	4.0	--------	.23	.45	.15	.70	.14	.26	.93	.9	1.2	.17	3.4	--------	1.2
H_2O-	.37	--------	.55	.50	.07	.40	.39	.55	--------	.21	.26	.12	3.0	--------	.32
TiO_2	.19	.2	.19	.21	.20	.19	.15	.16	.18	.26	.28	.27	.32	.3	.22
P_2O_5	--------	--------	.01	.02	.03	Tr.	.01	.03	--------	.06	.08	.07	.12	.1	.05
MnO	.11	.1	.02	.02	.02	.09	.05	.03	--------	.01	.01	.02	.04	--------	.01
CO_2	<.05	--------	.02	--------	--------	.23	.19	.06	--------	.08	<.05	.01	<.05	--------	<.05
S	--------	--------	--------	--------	--------	.02	.26	.33	--------	--------	--------	--------	--------	--------	--------
BaO	--------	--------	--------	--------	--------	--------	.49	.05	--------	--------	--------	--------	--------	--------	--------
SrO	--------	--------	--------	--------	--------	.05	--------	--------	--------	--------	--------	--------	--------	--------	--------
F	--------	--------	.02	.04	.01	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Cl	--------	--------	.02	.01	.02	--------	--------	--------	--------	--------	--------	.01	--------	--------	--------
Subtotal	--------	--------	99.89	99.87	99.86	--------	--------	--------	--------	--------	--------	99.81	--------	--------	--------
Less O	--------	--------	.01	.02	0.00	--------	--------	--------	--------	--------	--------	.00	--------	--------	--------
Total	100	100	99.88	99.85	99.86	99.78	99.93	99.97	99.86	100	100	99.81	100	100	100
Density (powder)	2.40	--------	2.62	2.60	2.63	--------	--------	--------	--------	2.55	2.50	2.61	2.55	--------	2.51
Density (bulk)	2.38	--------	--------	--------	--------	--------	--------	--------	--------	2.29	2.39	--------	2.29	--------	1.92
Analysts	1, 2, 3	--------	6, 7	6, 7	6, 7	8	8	8	9	1, 3, 5	1, 3, 5	6, 7	1, 2, 3, 4	--------	1, 3, 5
Type of analysis	R	--------	S	S	S	--------	--------	--------	--------	R	R	S	R	--------	R
Date	1959	--------	1957	1957	1957	1913	1913	1913	1942	1957	1957	1957	1959	--------	1957

Norms

	1	2R	3	4	5	6	7	8	9	10	11	12	13	14R	15
Q	--------	33.2	38.5	33.0	35.9	34.6	35.2	41.1	33.42	31.0	32.4	24.4	--------	31.6	30.7
or	--------	29.0	54.0	43.0	52.8	53.7	40.0	43.4	50.3	56.2	54.2	67.3	--------	38.1	54.6
ab	--------	29.6	3.3	18.6	8.4	5.4	20.4	11.8	9.7	7.5	7.3	4.7	--------	11.8	9.5
an	--------	4.0	.3	1.4	.7	--------	--------	.5	1.2	.6	.6	.3	--------	10.6	.8
C	--------	1.1	2.1	2.1	.5	2.1	.5	1.0	2.8	2.2	2.7	.5	--------	2.2	3.2
wo	--------	--------	--------	--------	--------	--------	.3	--------	--------	--------	--------	--------	--------	--------	--------
en	--------	.5	.5	.5	.1	1.4	--------	.4	.9	.5	.5	.1	--------	2.2	.3
fs	--------	.8	--------	--------	--------	.3	--------	--------	--------	--------	--------	--------	--------	--------	--------
mt	--------	1.2	--------	--------	--------	1.3	--------	--------	.2	.9	.6	--------	--------	.6	--------
hm	--------	--------	.9	.9	1.0	--------	.2	.3	1.0	.2	.9	1.7	--------	1.6	.4
il	--------	.4	.3	.4	.4	.4	--------	--------	.4	.5	.5	.4	--------	.7	.3
ap	--------	--------	--------	--------	.1	--------	--------	--------	--------	.1	.2	.2	--------	.3	.1
sp	--------	--------	--------	--------	--------	--------	--------	.2	--------	--------	--------	.1	--------	--------	.1
ac	--------	--------	--------	--------	--------	--------	1.5	--------	--------	--------	--------	--------	--------	--------	--------
py	--------	--------	--------	--------	--------	--------	1.0	1.2	--------	--------	--------	--------	--------	--------	--------

See footnotes at end of table.

TABLE 2.—*Chemical analyses, norms, and spectographic analyses of Bachelor Mountain Rhyolite*—Continued

Sample No.	1	2R	3	4	5	6	7	8	9	10	11	12	13	14R	15
Laboratory No.	153631	--------	C–1166	C–1167	C–1169	--------	--------	--------	--------	151482	151483	C–1168	154778	--------	151481
Field No.	C–769	C–769	C–988	C–990	C–992	--------	--------	--------	La G–481	C–41	C–69A	C–991	C–944	C–944	C–123
Rock unit	Willow Creek Member									Campbell Mountain Member			Windy Gulch Member		Intrusive rhyolite

Quantitative spectrographic analyses

[These results have an overall accuracy of ±15 percent, except that they are less accurate near limits of detection where only one digit is reported. nd, not detected. Analysts: 1, N. M. Conklin; 2, P. R. Barnett; 3, J. C. Hamilton]

	1	2R	3	4	5	6	7	8	9	10	11	12	13	14R	15
B	0.004	--------	nd	nd	nd	--------	--------	--------	--------	nd	0.003	nd	nd	--------	nd
Ba	.025	--------	0.1	0.07	0.05	--------	--------	--------	--------	0.11	.086	0.1	0.17	--------	0.098
Be	.0002	--------	nd	nd	nd	--------	--------	--------	--------	nd	.0001	nd	<.0002	--------	.0001
Ce	nd	--------	nd	nd	nd	--------	--------	--------	--------	.0001	.0001	nd	nd	--------	nd
Co	<.0005	--------	nd	nd	nd	--------	--------	--------	--------	.0001	.0001	nd	.0014	--------	nd
Cr	.0002	--------	.0002	nd	.0004	--------	--------	--------	--------	.0001	.0001	.0003	.0005	--------	nd
Cu	.0003	--------	.0002	.002	.001	--------	--------	--------	--------	.00036	.0013	.001	.0011	--------	.00040
Ga	.0014	--------	.0009	.001	.0009	--------	--------	--------	--------	.0015	.0014	.0009	.0010	--------	.0016
La	.008	--------	.01	.01	.01	--------	--------	--------	--------	.0069	.0052	.01	<.007	--------	.0064
Mo	.0004	--------	nd	nd	nd	--------	--------	--------	--------	nd	nd	nd	<.001	--------	nd
Nb	.002	--------	.002	.002	.002	--------	--------	--------	--------	.001	.001	.002	.003	--------	.0024
Ni	<.0002	--------	nd	nd	nd	--------	--------	--------	--------	nd	nd	nd	.0005	--------	nd
Pb	.002	--------	.003	.004	.008	--------	--------	--------	--------	.0028	.0049	.03	.002	--------	.0038
Sc	.0005	--------	nd	nd	nd	--------	--------	--------	--------	.0005	.0005	.0008	<.001	--------	.0005
Sr	.0096	--------	.01	.01	.006	--------	--------	--------	--------	.011	.009	.01	.039	--------	.010
V	.0008	--------	.0007	.0007	.0006	--------	--------	--------	--------	.0014	.0020	.003	.003	--------	.0010
Y	.004	--------	.003	.003	.003	--------	--------	--------	--------	.0034	.0034	003	.002	--------	.0033
Yb	.0003	--------	.0003	.0003	.0003	--------	--------	--------	--------	.00039	.00036	.0003	.0002	--------	.00034
Zr	.018	--------	.02	.02	.02	--------	--------	--------	--------	.017	.021	.02	.027	--------	.026
Analyst	1	--------	2	2	2	--------	--------	--------	--------	2, 3	2, 3	2	3	--------	2, 3
Date	1959	--------	1958	1958	1958	--------	--------	--------	--------	1958	1958	1958	1960	--------	1958

1–2R. Basal vitrophyre tuff; black splintery glass containing a few percent tiny feldspar phenocrysts; approximately 900 ft east of elevation 9,350 ft on Miners Creek, at contact between rhyolite of Miners Creek and overlying Willow Creek Member of Bachelor Mountain Rhyolite.
3. Eutaxitic densely welded tuff containing partially argillized phenocrysts and pumice fragments, 150 ft from portal of Holy Moses No. 2 adit on west side of East Willow Creek.
4. Massive silicified(?) densely welded tuff, 1,000 ft from portal of main haulage tunnel, Commodore mine, on west side of lower West Willow Creek.
5. Dark silicified(?) densely welded tuff, 55 ft from portal of Amethyst mine on west side of West Willow Creek.
6. Somewhat altered rhyolite from Solomon adit west of East Willow Creek (Larsen and Cross, 1956, table 21, No. 51).
7. Altered rhyolite about 25 ft from vein in the Bachelor shaft at the Nelson adit on the west side of lower West Willow Creek (Larsen and Cross, 1956, table 21, No. 52).
8. Near sample 6 (Larsen and Cross, 1956, table 21, No. 53).
9. Near sample 6 (Larsen and Cross, 1956, table 21, No. 54).
10. Eutaxitic densely welded tuff, at elevation of about 9,300 ft, above clearing west of elevation about 9,120 ft on Rat Creek.
11. Densely welded tuff a few feet beneath black glass in Phoenix Park Member of La Garita Quartz Latite, at elevation of about 9,800 ft east of East Willow Creek opposite Holy Moses mine.
12. Densely welded tuff, about 50 ft southwest of ancestral Amethyst fault, where the fault is cut by the McClure drift in the Commodore mine, main haulage level, west side of lower West Willow Creek.
13–14R. Light-colored pumiceous poorly welded tuff containing 5–10 percent dark dacitic rock fragments. Pumice lapilli partly altered to clay; west of Miners Creek, at about 10,800-ft elevation, on slabby talus slope near McKenzie stock driveway.
15. Intrusive rhyolite; bleached white rock containing purplish streaks and glassy sanidine phenocrysts as much as 5 mm long, at elevation of approximately 9,720 ft, on ridge trending south from Bulldog Mountain, 1,000 ft west of road to Bachelor.

erentially concentrated (table 2). The secondary minerals and the transfer of chemical constituents may have resulted alternatively from devitrification and deuteric processes during cooling of the ash-flow deposit, from hydrothermal alteration associated with the mineralized structures of the Creede mining district, or from weathering processes. Effects of the different alteration processes are not all distinguishable from one another, but, because rhyolitic ash flows of the overlying Mammoth Mountain and Farmers Creek Rhyolites are not comparably altered, we believe that the Bachelor Mountain Rhyolite was pervasively altered during the cooling of the ash flows and before the eruption of the rocks that overlie it. The most highly altered rocks occur in the vicinity of cauldron border structures, and these structures may have provided access for the altering fluids. Whether these were hydrothermal fluids from magma at depth or fluids derived from the ash-flow deposit itself is not known.

DEPOSITIONAL AND MODIFYING PROCESSES

The fragmental origin of the Bachelor Mountain Rhyolite is apparent from the vitroclastic textures of the less welded parts of the formation and from the gradation from slightly to densely welded tuff. Complete gradations between the members and the lack of any recognizable evidence for individual ash flows or compound cooling characteristics near the probable vent area indicate both rapidity of eruption and high temperature of emplacement. Eruptions at the vent and accumulation nearby may well have been virtually continuous. Away from the source area, the three members change laterally into less welded and less compacted facies, and alternating zones of densely welded and partially welded tuff mark the change from a simple cooling unit to compound cooling units; also near the margins of the deposit, the ash flows become interlayered with volcanic rocks from other sources. A vitrophyre zone high in the section near Miners Creek marks a local boundary between separate ash flows and cooling units near the edge of the ash-flow body. These features indicate episodic accumulation near the margins and possibly reflect variations in the intensity of the eruptions at the source. The decrease in the overall thickness of the ash flows away from their place of origin and the increase in cooling with distance of transport account for the lateral differences in compaction and welding.

The abrupt increase in the size and abundance of lithic fragments that marks the Willow Creek-Campbell Mountain transition in the thickest sections of the formation probably represents a significant change in the eruptive system. The increased porosity and reddening of the rocks in and above the transition may be related to the same change. Possibly, enlargement of vents during eruption caused the magma to vesiculate more rapidly, increasing the violence of the eruption and, thereby, the content of wallrock material in the magma. Other effects of more violent eruptions might be greater dispersal of fragmented materials and consequently greater cooling during transport, both resulting in a less welded, more porous deposit in which oxidation reactions could cause the reddening of the rocks.

ORIGIN OF EUTAXITIC AND FLUIDAL STRUCTURES

Eutaxitic structures in the Willow Creek and Campbell Mountain Members reflect progressively greater compaction and flattening of pumice fragments and ash downward in the Bachelor Mountain welded tuff. The successive changes from nearly undeformed vesicular pumice blocks to structureless streaks or blotches can be traced both in outcrop and in thin sections. Some relict pumice fragments (see figs. 5*B*, 7) appear to be flattened beyond the simple compaction necessary for the complete elimination of pore space, and they must have been involved in what Smith (1960a, p. 807) has described as radial stretching. Ross and Smith (1961, p. 25) suggested that stretching is indicated whenever the elongation of a fragment is greater than 20 times its smallest dimension. Some of the larger pumice blocks in the Willow Creek Member have long dimensions a few hundred times their thickness. Stretching of this magnitude can be considered as secondary flow.

The fluidal structures in the deepest parts of the Willow Creek Member are believed to signify an approach to a completely homogenized welded tuff. Fine fluidal streaks like those shown in figure 5*B* might be interpreted as the ultimate in compaction and stretching of small pumice fragments or as discontinuities related to laminar flow of reconstituted ash-flow materials. Extreme compaction is suggested by the occurrence of eutaxitic pumice and fine discontinuous streaks in the same thin section, as shown in figure 5*C*. Accordingly the contrasting structures may reflect only differences in size of the original fragments. However, laminar flow is suggested by the continuity of fluidal structures such as the layers of quartz grains shown in figure 5*B*. These layers may represent the concentration of a volatile fluid, rich in silica, along minute discontinuities between flow laminae.

In a very thick section of rapidly deposited ash flows, secondary laminar flow of reconstituted ash-flow materials conceivably could cause significant lateral extensions of the deposit as secondary flows. However, we have found no evidence of such flows in the Bachelor Mountain Rhyolite. Rather, the secondary flowage evidently is a feature of the general flattening of the deposit by compaction.

FARMERS CREEK RHYOLITE

Farmers Creek Rhyolite in and adjacent to the type locality along Farmers Creek (Steven and Ratté, 1964) is a heterogeneous assemblage of ash flows and pumice breccia, minor lava flows, and flow breccia or agglomerate. Near Wagon Wheel Gap, the formation includes a complex of hypabyssal intrusive rocks, lava flows, pyroclastic breccia, and local volcanic sediments, as well as pumiceous welded tuff. The following discussion refers principally to Farmers Creek Rhyolite in the type locality, where the rocks crop out along southwest-facing slopes in the Farmers Creek drainage basin, and on both sides of West Bellows Creek (pl. 1). These rocks were included by Larsen and Cross (1956, p. 146) in the basal part of the lower rhyolite member of their Piedra Rhyolite.

DISTRIBUTION AND SOURCE

Present exposures of the Farmers Creek Rhyolite are limited to the northeastern rim of the Creede caldera, from Farmers Creek to Goose Creek (pl. 1). The formation was deposited on an irregular topography cut on older rocks, and it is irregularly overlapped by the younger Mammoth Mountain Rhyolite in most places. Lenses of La Garita Quartz Latite are interlayered locally with the Farmers Creek, and west of West Bellows Creek, La Garita welded tuffs and breccia form a wedge between the Farmers Creek and the overlying Mammoth Mountain Rhyolite. Maximum thicknesses of the Farmers Creek are exposed in sections along Farmers Creek and West Bellows Creek, where roughly 1,000 feet of rock is exposed, but the bottom is concealed. A minimum of 5–10 cu mi of Farmers Creek Rhyolite is exposed or inferred beneath the younger rocks on the east side of the caldera. These figures may represent only a small fraction of the original volume.

The distribution of the Farmers Creek Rhyolite along the northeast flank of the Creede caldera, lateral changes in the degree of welding, and some small intrusive bodies are the only evidence for the source of this formation. Between Farmers Creek and West Bellows Creek (pl. 1) a northeastward reduction in the degree of welding of some of the Farmers Creek ash flows indicates a source in the direction of the Creede caldera. Vents have not been positively identified, but several small dikes and irregular intrusive bodies of vitrophyric welded tuff cut the ash flows along the north bank of Farmers Creek. The intrusives probably fed some of the adjacent ash flows, although direct gradations between intrusive vitrophyre and the layered ash flows were not observed. The many dikes and other small intrusives in the Farmers Creek Rhyolite in the Goose Creek sector of the caldera rim suggest local vents in that area.

The eruptive activity in Farmers Creek time may have been localized by marginal faults or ring fractures formed during collapse of the Bachelor Mountain cauldron. On the other hand, the present exposures of Farmers Creek Rhyolite may represent only the marginal facies of a more extensive ash-flow sequence, the remains of which are buried within the Creede caldera along with their source.

FIGURE 8.—Cavernous pumice breccia in the lower part of the Farmers Creek Rhyolite. White scale in center of photograph is 6 inches long.

GENERAL LITHOLOGY

In the type locality, the Farmers Creek Rhyolite has been divided into two parts roughly equal in thickness. The lower half consists mainly of cavernous-weathering pumice breccia (fig. 8) the base of which is not exposed. The pumice breccia is widely obscured by landslides, but where exposed in place, it comprises layers a few feet to several tens of feet thick, which are interpreted as individual ash flows. Separate layers show differences in color and texture and in the relative abundance of glass and devitrified material. Internal stratification or sorting is absent from the layers. A few lenses of red porphyritic flow breccia or agglomerate, probably tongues of La Garita Quartz Latite, are present in the pumice breccia, and several small masses of black vitrophyre intrude this unit near the base of the slopes along the north bank of Farmers Creek.

The upper half of the Farmers Creek consists of a series of nonwelded to welded ash flows that form cooling units a few feet to several tens of feet thick. Many, if not most, of these are simple cooling units, embracing probably a single avalanche or ash flow. These ash flows exhibit more rapid changes in welding and compaction than any other ash flows in the Creede caldera sequence. Lateral changes in the direction of strike are exposed for about 4 miles from lower West Bellows Creek to upper Farmers Creek, and changes in the direction of dip can be seen along the west side of West Bellows Creek. Conspicuous massive dark-brown ledges in this part of the formation are zones of densely welded tuff in simple cooling units that commonly have a vitrophyre zone near the base and a zone of partially welded tuff at the top. At least four such ledges of densely welded tuff, 50–100 feet thick, are present along the slopes north of Farmers Creek. The upper two appear to be continuous through most of the 4 miles of exposures along this slope, except as they are offset by small faults. Interlayered with these ash flows are one or two discontinuous layers or lenses of flow breccia consisting of a homogeneous rubble of small agglutinated blocks of lava without any obvious pyroclastic material. The layered units dip generally 15°–30° NE. in the Farmers Creek area. These dips, which probably are too steep to be original, are believed to result from rotation of fault blocks marginal to the Creede caldera.

PETROGRAPHY AND COMPOSITION

Typical pumice breccia in the lower half of the Farmers Creek is a porous light-colored rock studded with foreign rock fragments ranging from microscopic size to blocks several inches long. The fragments, which constitute about 15–25 percent of the pumice breccia, consist mainly of dark-red to blue-gray porphyries in an aphanitic matrix. They resemble rocks in the Shallow Creek and La Garita Quartz Latites. The remainder of the pumice breccia consists of pumice blocks and lapilli and fine-grained pyroclastic materials, all of which appear completely devitrified. Some of the pumice fragments are altered to clay minerals, but in general, the matrix is firm, and it is probably cemented by secondary zeolites and silica. There is little if any distortion of the pumice blocks, and the pumice breccia is virtually nonwelded.

A typical cooling unit of ash-flow tuff in the upper half of the Farmers Creek Rhyolite has a thin basal zone of poorly welded tuff that grades upward into vitrophyre a few feet thick, and this in turn grades upward into dark-brown devitrified densely welded tuff several tens of feet thick. The densely welded tuff grades into an upper zone of partially welded tuff which commonly is difficult to distinguish from the poorly welded material at the bottom of the next higher cooling unit. Traced downdip away from the Creede caldera, the densely welded tuff changes to moderately welded, and similar changes take place along the strike of the cooling units. Rocks in the zone of dense welding are devitrified and generally uniform in appearance. They do not show conspicuous eutaxitic structure or compaction foliation, but they commonly have abundant pinhole vesicles and a few stringy pumice fragments. In contrast, the partially welded tuffs are glassy or partly devitrified and relatively porous; they have a shard matrix that encloses pumice fragments which give the rocks a blotchy to eutaxitic appearance. Some of this rock resembles the Campbell Mountain Member of the Bachelor Mountain Rhyolite, though generally it is less densely welded and has a more vitroclastic texture.

Modes 1–4, table 3, show that the ash flows in the upper half of the formation are crystal-poor rocks containing 5–10 percent phenocrysts. The phenocrysts have maximum dimensions of 1–2 mm, but many are microphenocrysts and tiny crystal chips. Plagioclase (oligoclase-andesine) and sanidine phenocrysts are almost equal in abundance and together make up most of the phenocrysts. Biotite is the chief mafic mineral. Less than 5 percent foreign rock fragments are shown in the modes, but samples from the basal parts of individual ash flows contain a much greater proportion of fragments. The matrix texture of the densely welded tuffs ranges from a tight intricate maze, with micro-eutaxitic structure, to a dense vitroclastic form in which the constituents are completely welded and the pumice is collapsed, but the shards are not greatly flattened. The partially welded tuffs have a vitroclastic matrix in which the glass shards are even less deformed and pumice fragments are in various stages of collapse and compaction.

Most of the lithic inclusions in the upper part of the Farmers Creek Rhyolite are similar to those in the lower pumice breccia, but some are of welded tuff from older ash flows, and others are a distinctive light-brown rock having a uniform granitic texture of crystals 1–5 mm long. A point count of one thin section indicates this rock consists of quartz, 20 percent; alkali feldspar, 26 percent; plagioclase (An^{35}) 38 percent; biotite, 5 percent; clinopyroxene, 3 percent; green hornblende, 1 percent; magnetite, 1 percent; and sphene, <1 percent; the remaining 6 percent of the rock is a brown cryptocrystalline material that occurs in fractures and along grain boundaries throughout the rock. The pyroxene replaces both the hornblende and the biotite.

The composition of the granitic fragments and their unique occurrence in this formation suggest that they are an intrusive phase of the Farmers Creek Rhyolite. Thin-section relations show that the rock was pervasively broken on a granular or subgranular scale, and the fractures filled by a liquid which probably chilled as glass and later devitrified. The granitic inclusions may have been part of a crystallized border facies in the magma chamber that was shattered during the eruption of the Farmers Creek Rhyolite and then incorporated in the rising magma. The original hornblende and biotite, both hydrous minerals, apparently became unstable during or after the eruption and were partly replaced by anhydrous pyroxene.

Intrusive vitrophyre in the Farmers Creek Rhyolite, as represented by the largest body along upper Farmers Creek, consists of splintery black glass very much like the vitrophyre at the base of the Bachelor Mountain Rhyolite along Miners Creek. The Farmers Creek vitrophyre contains a few foreign lithic fragments and about 5 percent small phenocrysts and microphenocrysts, mainly sanidine and sodic plagioclase but including biotite and magnetite (mode 4, table 3). The matrix is densely welded but recognizably vitroclastic,

TABLE 3.—*Modes (volume percent) of Farmers Creek Rhyolite*

[P, constituent present but not found in point count; leaders, constituent not found in thin section. Localities of samples are described with reference to Creede 15-minute quadrangle topographic map (1959)]

Mode	Field No.	Matrix	Total phenocrysts	Plagioclase	Sanidine	Quartz	Biotite	Pyroxene	Hornblende	Magnetite	Foreign rock fragments	Points counted
1	R-103D	91	9	3.5	3.6	----------	1.1	0.3	0.1	0.3	1.4	1,061
2	R-86A	90	10	5.1	3.4	P	.9	.1	.6	.3	2.7	1,041
3	R-86B	90	10	3.6	4.9	.1	.6	P	.3	.5	1.6	1,015
4	R-40-59A	95	5	2.5	1.4	----------	.4	----------	----------	.2	<1	1,039

1. Devitrified densely welded tuff in middle third of Farmers Creek Rhyolite at approximate 9,665-ft elevation on the north bank of upper Farmers Creek where creek level is at about 9,500-ft elevation.
2, 3. Specimens of partially welded tuff in middle third of Farmers Creek Rhyolite at about 9,350-ft elevation on the slopes west of West Bellows Creek where the elevation at creek level is about 9,200 ft.
4. Densely welded intrusive vitrophyre tuff from the largest of the small intrusive bodies on the north bank of upper Farmers Creek. Elevation at creek level downslope from the vitrophyre is approximately 9,520 ft.

A

B

FIGURE 9.—Spherulites and "devitrification dikes" in vitrophyre of the Farmers Creek Rhyolite. *A*, A collection of spherulites that have weathered out of the vitrophyre upslope; keel on some of the larger spherulites represents the central rib or "divitrification dike." *B*, Spherulites in place, showing their relation to the "devitrification dike"; pencil in line with dike shows scale.

containing distinct glass shards and a few collapsed pumice fragments. The glass is devitrified in patches, and microspherulites radiate from the corners or edges of most phenocrysts. Large spherulites weather out of the vitrophyre and roll to the bottom of the slope (fig. 9*A*). Where found in place, they occur along dikelike ribs of devitrified glass (fig. 9*B*); the ribs are 1–2 inches wide, and the spherulites may be as large as 12–18 inches in diameter. Where they are equal in size and symmetrically disposed on opposite sides of a rib, they form dumbbell-shaped spherulites. The form of the spherulites and their localization along ribs of devitrified glass suggest that the devitrification was induced by emanations that traversed fractures in the vitrophyre. The growth of spherulites may have been controlled by irregularities in the ribs or by inhomogeneities in the adjacent vitrophyre. Similar devitrification features in Tertiary ash flows in Arizona were termed "devitrification dikes" by Simons (1962).

Chemical analyses and norms of Farmers Creek Rhyolite are presented in table 4.

MAMMOTH MOUNTAIN RHYOLITE

The Mammoth Mountain Rhyolite was named in the Creede mining district by Emmons and Larsen (1923, p. 40), who described it as a single thick flow of rather uniform character which they traced eastward as far as Bellows Creek. They also mapped a separate unit of rhyolite tuff, including thin rhyolite flows and flow breccia, above the Mammoth Mountain. As redefined by Steven and Ratté (1964), the Mammoth Mountain Rhyolite is a widespread ash-flow unit, largely densely welded, that includes both the original Mammoth Mountain Rhyolite and the overlying rhyolite tuff unit of Emmons and Larsen. Representative sections of the formation discussed in the following pages are identified on plate 1 as sections *A–I*.

The Mammoth Mountain Rhyolite is a composite ash-flow sheet that evidently once extended almost completely around the Creede caldera. It has been mapped two-thirds of the way around the caldera, from near Bristol Head on the west through the Wagon Wheel Gap area to upper Goose Creek on the south (pl. 1). It is absent locally on the north margin of the caldera, near West Willow Creek and Miners Creek,

TABLE 4.—*Chemical analyses, norms, and spectrographic analyses of Farmers Creek Rhyolite*

[Sample localities described with reference to Creede 15-minute quadrangle topographic map (1959). Chemical analyses by P. L. D. Elmore, I. H. Barlow, S. D. Botts, G. Chloe, 1959 and 1960, by methods similar to those described by Shapiro and Brannock (1956). Spectrographic analyses by J. C. Hamilton, 1959, 1960]

Sample No.	1	2	3
Laboratory No.	154777	156563	270736A
Field No.	R-40	R-103d	R-103C
Chemical analyses (weight percent)			
SiO_2	72.5	72.7	----------
Al_2O_3	13.7	13.7	----------
Fe_2O_3	.6	1.6	----------
FeO	.52	.20	----------
MgO	.11	.30	----------
CaO	.67	.72	----------
Na_2O	3.6	3.4	----------
K_2O	5.1	5.7	----------
H_2O^+	3.1	} .78	----------
H_2O^-	.1	}	----------
TiO_2	.18	.26	----------
P_2O_5	.02	.06	----------
MnO	.08	.06	----------
CO_2	<.05	<.05	----------
Total	100	100	----------
Norms			
Q	31.2	27.6	----------
or	31.0	37.1	----------
ab	31.0	29.0	----------
an	3.3	3.2	----------
C	1.1	.2	----------
en	.3	.8	----------
fs	.3	----------	----------
mt	.9	.4	----------
il	.3	.3	----------
hm	----------	1.4	----------
ap	----------	.2	----------

Spectrographic analyses

[Q, quantitative analysis; overall accuracy ±15 percent, except that analyses are less accurate near limits of detection where only one digit is reported. SQ, semiquantitative analysis, in percent to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, . . . The assigned group includes the quantitative value about 60 percent of the time. nd, not detected; d, barely detected and concentration uncertain]

Type of analysis	Q		SQ
B	nd	----------	0.003
Ba	.031	----------	.07
Be	<.0002	----------	.00015
Ce	nd	----------	d
Co	.001	----------	nd
Cr	.0002	----------	.00015
Cu	.0010	----------	.0007
Ga	.0010	----------	.0007
La	<.007	----------	.007
Mo	.0014	----------	nd
Nb	.003	----------	.0015
Nd	nd	----------	d
Ni	<.0005	----------	nd
Pb	.004	----------	.0015
Sc	<.001	----------	.0007
Sr	.0061	----------	.015
V	<.001	----------	.0015
Y	.003	----------	.003
Yb	.0003	----------	.0003
Zr	.017	----------	.015

1. Densely welded intrusive vitrophyre tuff from the largest of the small instrusive bodies on the north bank of upper Farmers Creek. Elevation at creek level downslope from the vitrophyre is approximately 9,520 ft.

2, 3. Devitrified densely welded tuff in the middle third of the Farmers Creek Rhyolite at approximately 9,665-ft elevation on the north bank of upper Farmers Creek, where creek level is at about 9,500-ft elevation.

where the older Bachelor Mountain Rhyolite apparently stood as a topographic high at the time the Mammoth Mountain rocks were deposited.[1]

[1] After this report was prepared, further reconnaissance mapping in the central San Juan region by Steven and others has raised doubts of the correlation of sections *A* and *B* (pl. 1) with the Mammoth Mountain Rhyolite. If sections *A* and *B* are not Mammoth Mountain, then that formation was not deposited in the area west of the Creede Caldera; however, the descriptions of rock units and interpretations of magmatic history in this report are not affected.

The thickness of the Mammoth Mountain Rhyolite is controlled largely by the configuration of a rough underlying topography. The formation is 800–1,000 feet thick under Bristol Head, west of the caldera (section *A*, pl. 1), but it is more than 1,700 feet thick between Bristol Head and Shallow Creek (section *B*). It pinches out completely between Shallow Creek and West Willow Creek. On Campbell Mountain, between East and West Willow Creeks, the formation is 0 to nearly 600 feet thick (section *C*), and just east of East Willow Creek, in what is called the First Fork section (section *D*), it is 1,500–1,600 feet thick. To the southeast the thickness diminishes to about 800 feet in the Farmers Creek drainage basin (sections *E* and *F*) and to 300–500 feet in the basins of East and West Bellows Creeks (section *G*). From the mouth of Blue Creek (section *H*) southward to a locality east of upper Goose Creek (section *I*), the formation is 800–1,000 feet thick.

The Mammoth Mountain Rhyolite has an indicated volume of 10–25 cu mi (40–100 cu km) in the mapped area. However, it is known to extend far beyond the mapped area, and it probably also blanketed the core of the caldera. Its total volume is at least of magnitude 6 in the classification of Smith (1960a, p. 819), that is, 100–1,000 cu km (25–250 cu mi).

SOURCE

The Mammoth Mountain Rhyolite probably was erupted from vents that now are buried by younger deposits within the Creede caldera. Distinct petrographic facies of the rhyolite radiate from the caldera, suggesting a source within the subsided block. Mammoth Mountain rocks north of the caldera along East Willow Creek are mainly crystal-poor rhyolite welded tuffs. To the east and southeast, these change to crystal-rich quartz latitic welded tuffs, and to the southwest to crystal-rich welded tuffs intermediate in phenocryst content between the other main facies. A change from dominantly simple cooling characteristics near the caldera to compound cooling features at greater distances indicates that the cooling histories of different parts of the deposit are related to distance from the caldera. Mammoth Mountain rocks are less densely welded southeastward down the palisades of the Rio Grande from Wagon Wheel Gap, and northeastward from the caldera toward the head of West Bellows Creek.

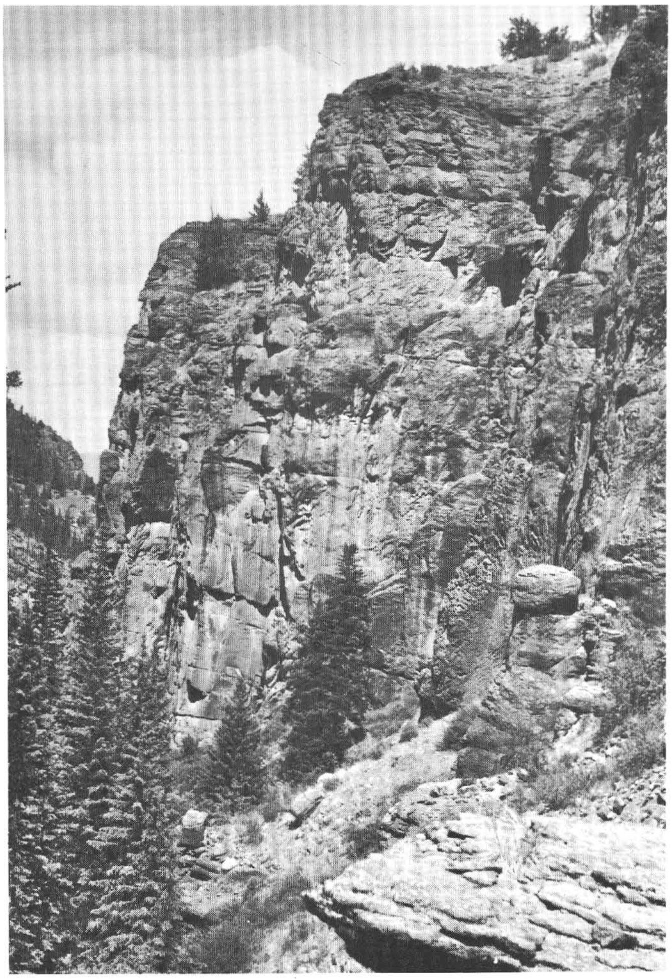
GENERAL LITHOLOGY

Many thick sections of Mammoth Mountain Rhyolite in the Creede area consist of single cooling units, simple to compound in character and composed largely of densely welded and devitrified ash flows. In most places, partially welded materials constitute less than

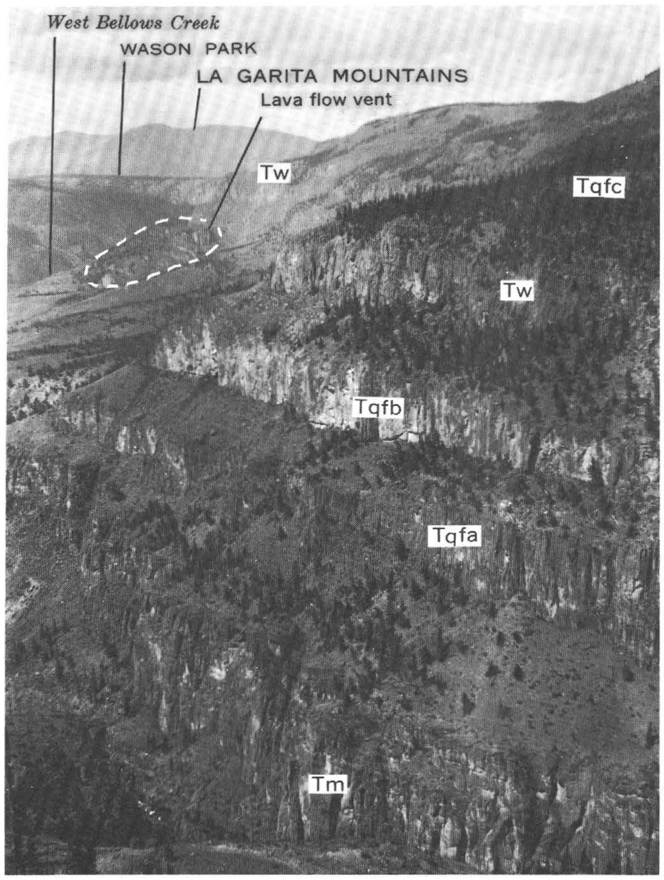
10 percent of the formation and occur mainly in a thin zone at its top, although in some places partings of partially welded tuff separate distinct cooling units, and in others, lenticular zones of partially welded rock are isolated completely in densely welded tuff. South of the Rio Grande, near Elk Creek (pl. 1), however, the whole upper third of the formation is soft and only partially welded.

The base of the Mammoth Mountain Rhyolite is generally covered in the Creede area, but in most places where the base is exposed either a basal vitrophyre or densely welded devitrified tuff is in contact with the older rocks. In some places, however, as near the head of West Bellows Creek (section *G*, pl. 1) and southeast of Blue Creek, poorly welded to nonwelded tuff lies between the vitrophyre and the older rocks and may represent the earliest eruptions of the Mammoth Mountain at this locality.

Densely welded Mammoth Mountain Rhyolite commonly stands in massive cliffs several hundred feet high (fig. 10). The cliffs bench abruptly where densely welded tuff grades into partially welded tuff (fig. 10*A*). Most outcrops display vertical or nearly vertical joint sets and a set of subhorizontal joints. Steep joints range widely in strike, but most can be assigned to two or three major joint sets. The joints are spaced several feet apart, and the joint blocks consequently are large. When viewed from a distance, they give the cliffs a crude columnar structure (fig. 10). Rarely do the steep joints show any evidence of movement or cementation, and they almost certainly formed as contraction joints during the cooling of the thick



A



B

FIGURE 10.—Mammoth Mountain Rhyolite and associated units north of East Bellows Creek. *A*, Mammoth Mountain Rhyolite along lower East Bellows Creek. Note change from coarse, nearly vertical prismatic joints in lower cliffs to closely spaced subhorizontal release joints that parallel compaction foliation near the top of the cliffs; bench at top of cliffs marks transition from densely welded to partially welded tuff. *B*, Palisades north of East Bellows Creek. Tm, Mammoth Mountain Rhyolite; Tqfa, a local quartz latite flow; Tqfb, rhyolite flow which pinches out beyond area shown in right-hand side of photograph; Tw, Wason Park Rhyolite; Tqfc, quartz latite lava flow. Photographs by J. F. Hunter.

section of homogeneous welded tuff. The subhorizontal joints in outcrops of Mammoth Mountain Rhyolite parallel the compaction foliation in the welded tuff. They are widely spaced and inconspicuous near the base of thick outcrops, but become more closely spaced and accentuated by weathering near the top of the outcrops (fig. 10). Partially welded tuff is not so well jointed but tends to display eutaxitic structures in the form of lenticular cavities and flattened masses of pumice.

Pronounced vertical jointing or columnar structure has been cited by Marshall (1935), Gilbert (1938), and many others as a characteristic feature of ash flows that aids in distinguishing them from lava flows. This criterion is not particularly reliable in the Creede area. Where thick sections of densely welded tuff and lava flows are interlayered, as along the north side of East Bellows Creek, columnar structure is about equally developed in both extrusive rock types (fig. 10*B*).

The Mammoth Mountain Rhyolite consists of a phenocryst-poor welded tuff facies (crystal-poor tuff) and a phenocryst-rich quartz latitic welded tuff facies (crystal-rich tuff). In some areas, the formation is made up entirely of one or the other facies; in other areas, both facies as well as gradations between them are represented in what is here termed a composite section. Gradations between facies are both vertical and lateral. Major vertical gradations are all from crystal-poor welded tuff below to crystal-rich welded tuff above. Crystal-poor welded tuff occurs mainly in the thickest sections of the formation.

Distribution of the facies around the Creede caldera is summarized below by reference to the lettered sections indicated on plate 1.

Section(s)	*Description*
A, B	Rocks near the top of the formation are typical crystal-rich welded tuffs; in the lower part of the formation the phenocrysts range widely in abundance and size, and the rocks appear intermediate in aspect between typical crystal-poor and crystal-rich facies. In the lowest exposures the rocks contain abundant dark dacitic inclusions.
C	Typical crystal-poor facies.
D	Composite section, 1,500–1,600 feet thick; crystal-poor facies composes lower 1,000 feet; crystal-rich facies composes upper 500–600 feet.
E	Composite section; consists of a lower part of crystal-poor rocks a few tens of feet to a few hundred feet thick; remainder of section consists entirely of crystal-rich welded tuff.
F	Composite section; crystal-poor rocks in lower part are exposed only in a few places and apparently are cut out to the south and east by the overlap of younger crystal-rich tuff onto tilted Farmers Creek Rhyolite.
G, H, I	Entirely crystal-rich welded tuff.

Locality *D* (pl. 1), which we call the First Fork section, illustrates a composite section of Mammoth Mountain Rhyolite. The rocks of this section belong to a simple cooling unit that consists of a densely welded zone approximately 1,200 feet thick that grades upward into a partially welded zone 300–400 feet thick. The transition from densely welded to partially welded tuff is marked by a bench at the top of a 20–30-foot cliff of densely welded tuff. Vitrophyre several feet thick lies at the bottom of the section and is overlain by completely devitrified welded tuff. The lower 1,000 feet of the section belongs to the crystal-poor facies, which grades into the crystal-rich facies about 200 feet below the transition from densely welded tuff to partially welded tuff. Partings marking the boundaries of individual ash flows were not recognized in the densely welded part of the section, but in the partially welded upper part, partings that are weakly manifested by minor variations in composition and texture, suggest the presence of multiple ash flows.

Foreign lithic fragments are most abundant near the bottom of the Mammoth Mountain Rhyolite, but they occur also in the rocks that form the cliff at the transition between the densely welded and the partially welded tuff of the First Fork section, and are abundant in some of the partially welded tuff above the transition. In most places, the inclusions can be identified as fragments of older volcanic rocks that are exposed nearby.

The distribution and interrelations of the facies in the Mammoth Mountain indicate that the early crystal-poor rhyolitic ash flows filled in much of the preexisting rough topography adjacent to the source area, and spread over some of the lower interfluves in the early phases of the eruption. Younger ash flows changed gradually to crystal-rich quartz latite, which filled the remainder of the valleys and spread a thick blanket of ash flows over most of the region surrounding the central source. In part of this region, it spread beyond the early crystal-poor tuff, and in such places the Mammoth Mountain consists only of crystal-rich ash flows.

PETROGRAPHY

A summary of the modal composition of the Mammoth Mountain Rhyolite is given in table 5. The modes show mainly the differences in abundance of phenocrysts and the contrasting mineralogy of the crystal-poor and crystal-rich facies. The crystal-poor rocks generally have less than 10 percent phenocrysts, and the crystal-rich rocks generally have 20 percent or more phenocrysts. Foreign lithic fragments generally constitute less than 5 percent of the rock, but they may form as much as 10 percent of some local varieties of Mammoth Mountain.

TABLE 5.—*Modes (volume percent) of Mammoth Mountain Rhyolite from throughout the Creede area*

[P, mineral present in trace amounts; 0, mineral not found in point count, or quantity too small to be noted]

Modes	Description and location of samples (location given by nearest section(s), pl. 1)		Percentage of rock, excluding lithic fragments: Matrix	Total phenocrysts	Plagioclase [1]	Sanidine [1]	Biotite	Pyroxene	Hornblende	Magnetite	Quartz	Foreign rock fragments (percentage of total rock)	Points counted
13	Crystal-poor densely welded tuff from samples near sections *C, D, E, F*.	Average	92	8	4 (50)	3 (37)	<1	P	P	<1	0	5	1,022
		Range	89–95	5–11	2–5	2–4						1–10	740–1,340
2	Crystal-rich densely welded tuff in the First Fork section, section *D*.	Average	69	31	16.5 (53.5)	11.5 (37)	2.5	0	P	1	0	1.5	770
		Range	67–71	29–33	15–18	11–12						1–2	639–900
4	From transition cliff between densely welded and partially welded tuffs in the First Fork section, section *D*.	Average	91	9	5 (54)	3.5 (41)	<1	0	0	<1	0	5	937
		Range	88–94	6–12	3–8	3–5						P–11	643–1,126
2	Partially welded tuff from samples near the top of the First Fork section, section *D*.	Average	78	22	11 (50)	8.5 (38.5)	2	0	<1	<1	0	3.5	1,029
		Range	72–84	16–28	8–14	6–11						2–5	938–1,120
2	Crystal-rich welded tuff from samples in section *G*.	Average	73	27	21 (78)	0 (0)	3.5	1	0	1	0	<1	903
		Range	72–74	26–28	20–22	0 to P						0–<1	900–905
41	Crystal-rich welded tuff from samples of the Blue Creek section, section *H* (see table 9).	Average	57	43	34 (79)	0 (0)	5	1	0	2	0	3	1,230
		Range	47–70	30–53	25–44	0–P						<1–12	762–1,604
6	Crystal-rich welded tuff from samples in the Bristol Head-Shallow Creek areas, sections *A, B*.	Average	61	39	29 (73)	4 (11)	4	<1	0	2	0	3	834
		Range	42–82	18–58	11–45	P–6						<1–7	591–1,131

[1] Numbers in parentheses show percentage of item relative to total phenocrysts.

The phenocrysts in the Mammoth Mountain rocks are 75–95 percent plagioclase and sanidine; the remainder are mostly biotite and magnetite, some pyroxene, and rare amphibole. Apatite and zircon are common as small accessory crystals; quartz and sphene are rare and may have been derived from included foreign rock fragments. The phenocrysts generally are no larger than 1–2 mm in diameter, but a few are as large as 5 mm, and many are tiny microphenocrysts. Sanidine and plagioclase phenocrysts are in nearly equal amounts in the crystal-poor facies, but sanidine is virtually absent in the crystal-rich welded tuff, which contains a greater proportion of mafic phenocrysts, particularly biotite, pyroxene, and magnetite. The feldspar crystals are generally euhedral, but as the abundance of phenocrysts increases from the crystal-poor to the crystal-rich facies, there is a marked increase in the resorption and corrosion of individual crystals.

Sanidine phenocrysts range from tiny chips to tabular crystals as much as 5 mm long. The crystals are commonly twinned and some show a faint grid structure. A history of alternating growth and resorption is shown by compositional zoning in some of the phenocrysts. The cores of zoned crystals are more sodic than outer zones. The sanidine crystals have small to moderate axial angles, the optic plane consistently oriented about perpendicular to 010.

Plagioclase phenocrysts, like sanidine, range from tiny chips to euhedral crystals and crystal intergrowths having maximum dimensions of about 5 mm. The plagioclase averages sodic andesine in composition, and ranges from An_{26} in some homogeneous crystals to An_{40-50} in the cores of some of the larger zoned crystals. Zoned crystals typically show ranges in composition of only 5–10 percent anorthite.

Mafic phenocrysts are generally smaller than the feldspar crystals. Biotite is conspicuous in hand specimens of most Mammoth Mountain rocks, and light-green pyroxene crystals commonly are visible in specimens of the crystal-rich facies. Magnetite or magnetite-ilmenite(?) grains are subhedral to anhedral and are confined largely to the microscopic fraction of the rock.

Biotite phenocrysts are mostly euhedral plates and books in various stages of resorption and oxidation. In the final stage of resorption, the biotite is reduced to a skeletal outline of opaque iron oxide grains. Pleochroic colors vary between unaltered and oxidized biotite as follows: X=straw yellow to bright yellow orange; $Y \approx Z$=dark brown to reddish brown and orange red. The absorption formula is $X < Y \approx Z$.

Pyroxene phenocrysts, generally less than 1–2 mm in diameter, are light-green euhedral to subhedral monoclinic crystals. They probably belong to the diopside or augite series, but their composition has not been determined. The pyroxene grains commonly are altered to clay minerals at their borders, and consequently tend to be plucked out of the rock in the preparation of thin sections. Some crystals also show incomplete replacement by carbonate, presumably during weathering.

The matrix of the basal vitrophyre is black glass, but in all other parts of the Mammoth Mountain Rhyolite, the matrix is completely devitrified. The matrix of the densely welded tuff is largely cryptocrystalline, and much of it is a formless aggregate obscured by a dark-reddish-brown pigment. Elsewhere, spherulitic texture is common and in some thin sections spherulites in the matrix have the form of individual units, but more commonly they are plumose segments or ramified branching crystal aggregates of the type described and illustrated by Iddings (1909, p. 224–240). The constituent particles in the matrix are ash-sized shards, pumice fragments, and interstitial dust which form a tightly compacted maze in densely welded tuff, but which grade into true vitroclastic textures in partially welded tuff.

Lapilli and coarse ash-sized fragments of pumice are common throughout the Mammoth Mountain Rhyolite, but they are most abundant in the crystal-poor facies where they constitute as much as 25 percent of the rock. Large pumice fragments generally can be differentiated from the matrix in crystal-poor welded tuff by their relatively unbroken phenocrysts and their coarser matrix texture, which ranges from microcrystalline to granophyric. Some of the different textures of coarse pumice fragments seen in thin sections are sketched in figure 11. Parallel trains of opaque dust-sized particles give many of the pumice chunks a ruled structure (fig. 11*A, B*). Most pumice fragments also have numerous tiny round to ovoid vesicles that are commonly filled with tridymite and other, unidentified, minerals. The vesicles are the dominant structure in some pumice fragments as shown in figure 11*C*. The ruled structure commonly is visible through a mask of radial and concentric spherulitic structure, but it tends to be destroyed in more advanced stages of devitrification. The ovoid vesicles, however, are obscured only by fairly coarse crystallization. In figure 11*D*, the ruled structure is preserved in a narrow border zone and as relict patches within the pumice. The dark border zone is a distinctive feature of pumice fragments in hand specimens of crystal-poor Mammoth Mountain Rhyolite.

The ruled structure is interpreted as collapsed vesicle tubes of the original pumice. The preservation of this structure in a border zone on many pumice fragments suggests that chilling of the borders inhibited devitrification. If so, the round to ovoid vesicles must represent a secondary vesiculation, because they appear undistorted in pumice fragments whose primary vesicle tubes are collapsed completely (fig. 11*B*). Minerals in the secondary vesicles probably crystallized from gases that were trapped in individual pumice fragments during compaction and welding.

CHEMICAL COMPOSITION

Chemical and spectrochemical analyses and norms of four samples of Mammoth Mountain Rhyolite are presented in table 6. Analyses 1 and 2 represent

TABLE 6.—*Chemical analyses, norms, and spectrographic analyses of Mammoth Mountain Rhyolite*

[Sample localities described with reference to Creede 15-minute quadrangle topographic map (1959)]

Sample No.	1	2	3	4
Laboratory No.	C-1163	C-1164	151484	D100-029
Field No.	C-985A	C-985B	C-539A	R299U

Chemical analyses (weight percent)

[S, standard rock analysis; R, rapid rock analysis by methods similar to those described by Shapiro and Brannock (1956). Analysts: 1, Dorothy Taylor and F. H. Neuerburg; 2, P. L. D. Elmore, S. D. Botts, and M. D. Mack; 3, Christel L. Parker]

Type of analysis	S	S	R	S
SiO_2	69.93	72.69	67.0	63.17
Al_2O_3	13.86	13.85	16.7	16.81
Fe_2O_3	1.90	1.51	2.0	3.13
FeO	.18	.18	.32	.67
MgO	.67	.40	.72	.84
CaO	1.12	.89	2.0	4.56
Na_2O	1.93	3.11	4.1	3.84
K_2O	5.94	5.46	4.7	4.25
H_2O+	2.35	.70	1.2	.34
H_2O-	1.27	.49	.57	.45
TiO_2	.28	.25	.44	.62
P_2O_5	.06	.05	.12	.22
MnO	.09	.04	.04	.09
CO_2	.09	0	.05	.81
Cl	.01	.03	--	.02
F	.06	.05	--	.10
Subtotal	99.74	99.70	--	99.92
Less O	.03	.03	--	.04
Total	99.71	99.67	101.0	99.88
Density (powder)	2.56	2.52	2.55	2.62
Density (bulk)	--	--	2.44	--
Analysts	1	1	2	3
Date	1957	1957	1957	1963

Norms

Q	34.1	31.6	17.3	15.2
or	36.7	33.0	27.6	25.5
ab	17.3	26.9	34.3	33.0
an	5.2	3.9	9.9	16.4
C	2.3	1.4	1.2	--
wo	--	--	--	2.7
en	1.7	1.0	1.8	2.1
Fs	--	--	4.1	--
mt	.1	--	3.0	.6
hm	2.0	1.5	--	2.7
il	.5	.5	.9	1.2
ap	.1	.1	--	.5

Spectrographic analyses

[Q, quantitative analysis; overall accuracy ±15 percent, except that analyses are less accurate near limits of detection where only one digit is reported. SQ, semiquantitative analysis, in percent, to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, . . .; numbers represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 30 percent of the time. nd, not detected. Analysts: 1, P. R. Barnett; 2, P. R. Barnett and J. C. Hamilton; 3, J. C. Hamilton]

Type of analysis	Q	Q	Q	SQ
Ba	0.07	0.07	0.27	0.2
Be	.0002	.0002	.0001	.0002
Ce	nd	nd	nd	.02
Co	nd	nd	.0002	.0007
Cr	.0003	.0002	.0002	.0007
Cu	.0009	.0006	.00071	.002
Ga	.0009	.001	.0018	.003
La	.01	.01	.0047	.007
Nb	.003	.002	nd	.001
Nd	nd	nd	nd	.015
Ni	nd	nd	nd	nd
Pb	.004	.006	.0030	.002
Sc	.0009	.0008	.0006	.0015
Sr	.02	.01	.079	.1
V	.002	.002	.0026	.01
Y	.004	.004	.0024	.003
Yb	.0004	.0003	.00024	.0003
Zr	.03	.02	.026	.02
Analysts	1	2	2	3
Date of analysis	1958	1958	1958	1963

1. Crystal-poor densely welded tuff a few feet above the basal vitrophyre approximately 500 ft from portal of Gormax mine west of East Willow Creek.
2. Crystal-poor densely welded tuff at elevation approximately 10,500 ft on nose of ridge east of East Willow Creek and about 1,800 ft southeast of portal of Outlet mine.
3. Crystal-rich densely welded tuff about 15 ft below transition to partially welded tuff in First Fork section about 4,100 ft east of portal of Outlet mine at an elevation of approximately 11,000 ft.
4. Crystal-rich densely welded tuff at elevation approximately 9,220 ft near middle of Blue Creek section about 1,000 ft east of Wagon Wheel Gap at mouth of Blue Creek.

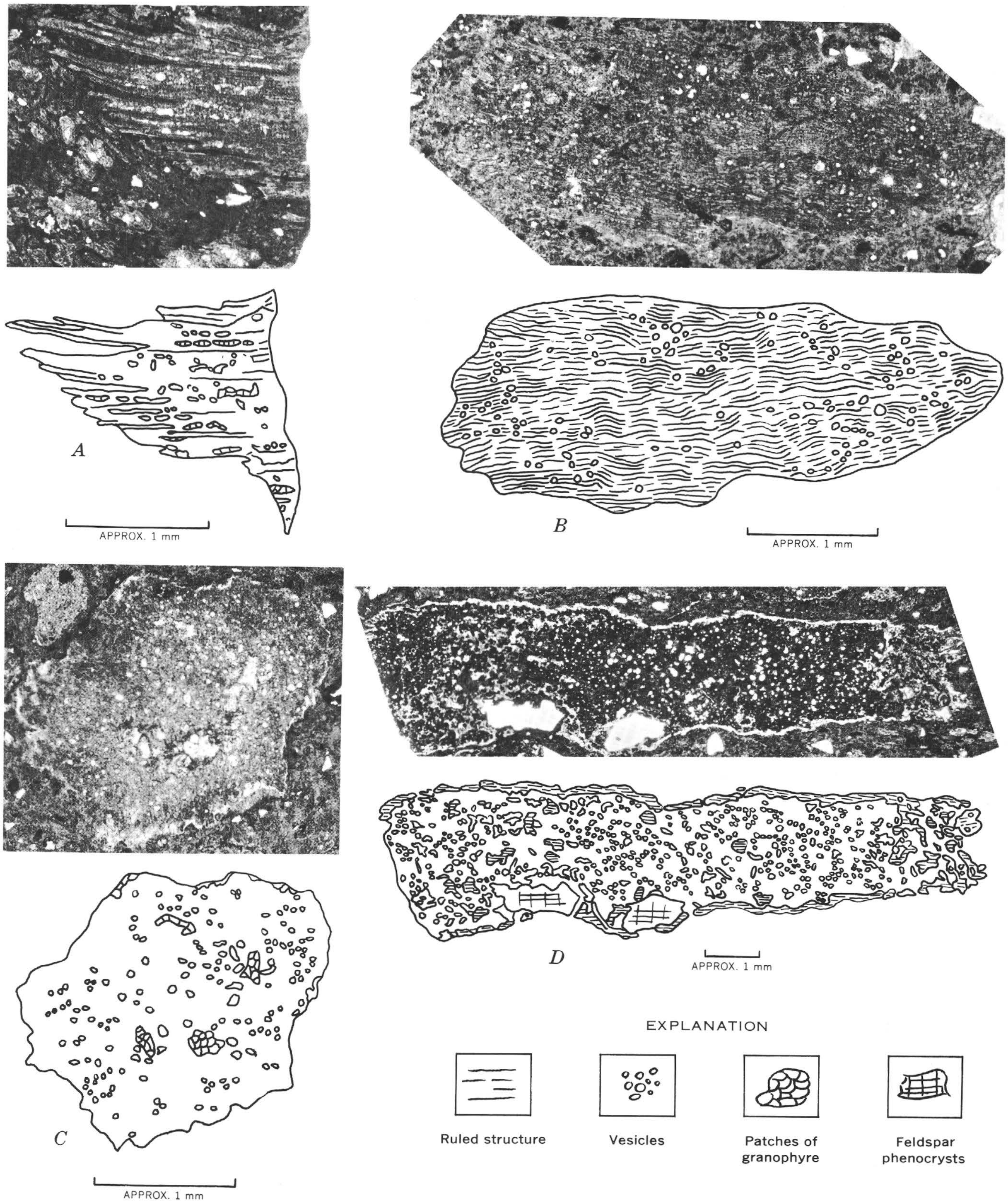


FIGURE 11.—Large pumice fragments in the Mammoth Mountain Rhyolite. *A*, Pumice showing frayed edges, minor ruled structure, and streaks of granophyre. *B*, Pumice showing ruled structure and vesicles. *C*, Pumice showing vesicles and patches of granophyre. *D*, Vesicles and patches of granophyre in pumice showing ruled border, and relict patches showing ruled structure within the pumice.

crystal-poor welded tuff in the lower part of the First Fork section (locality *D*, pl. 1). When recalculated water-free, the silica content of these samples is similar. Other differences, particularly in the alkalies, are believed to reflect clay alteration of plagioclase phenocrysts and the presence of several percent of foreign quartz latitic fragments in the rock of analysis 1. Analysis 3 is from a specimen of crystal-rich welded tuff in the First Fork section, and analysis 4 represents crystal-rich welded tuff in the middle part of the Blue Creek section (locality *H*, pl. 1). Both of the crystal-poor rocks are rhyolites according to the chemical classification of Rittmann (1952); the two crystal-rich welded tuffs are quartz latites, but the one from the First Fork section plots close to the rhyolite field, whereas the one from the Blue Creek section plots near the center of the quartz latite field. The spectrochemical analyses show greater contents of cobalt, chromium, copper, and vanadium in the quartz latites than in the rhyolites.

Differences in the composition of welded tuffs in the Mammoth Mountain in different parts of the Creede area are shown further by a comparison of $K_2O:Na_2O$ ratios (table 7). Analyses 1–8 are from samples of crystal-poor welded tuff between West Willow Creek and Dry Gulch (pl. 1). The $K_2O:Na_2O$ ratios of these samples range from 1.54 to 3.08 and average 1.70. Analyses 9–21 represent samples of crystal-rich welded tuffs from other parts of the Creede area. They have $K_2O:Na_2O$ ratios ranging from 1.04 to 1.39 and average 1.18.

In harmony with the modal data, the chemical data indicate that the early formed crystal-poor ash flows are rhyolitic and that the younger ash flows are quartz latitic.

ASH FLOW BOUNDARIES AND PARTINGS

At most places in the Creede area, the Mammoth Mountain Rhyolite is a simple cooling unit of unusually great thickness. Near the caldera only scattered and localized partings are visible in it, and it appears to be a single great flow. Away from the caldera, a series of flows is suggested by the division of the rhyolite into compound and multiple cooling units. These relationships could be accounted for by either (1) a mechanism of pulsating but virtually continuous eruption near the source and discontinuous deposition at a distance, or (2) sequential deposition of a series of ash flows whose boundaries were obliterated by intense welding near their source. To appraise these two possibilities, detailed studies were made, first, of one of the local partings in the Mammoth Mountain, and then of a nearly complete vertical section of the entire formation at Blue Creek (section *H*, pl. 1) where no partings are visible. Variations in petrography and physical properties of the welded tuffs in the Blue Creek section are interpreted as subtle evidence of ash-flow boundaries.

TABLE 7.—K_2O *and* Na_2O *(percent) in selected samples of Mammoth Mountain Rhyolite*

[Localities of samples described with reference to Creede (samples 1–15) and Bristol Head (samples 16–21) 15-minute quadrangle topographic maps (1959). Analyzed by Wayne Mountjoy and G. T. Burrow, by flame photometer, internal standard method]

Sample No.	Field No.	Laboratory No.	K_2O	Na_2O	$K_2O:Na_2O$	Approximate elevation (ft)	Location
				Crystal-poor welded tuff			
1	C-985A	C-1163	5.94	1.93	3.08	10,320	Gormax mine, west of East Willow Creek.
2	C-985B	C-1164	5.46	3.11	1.76	10,400	East of East Willow Creek, about 1,800 ft southeast of Outlet mine.
3	R-MM-NaK	273849	5.54	3.34	1.65	10,800	Along Dry Gulch.
4	R-19-NaK-2	273853	5.65	3.10	1.82	10,040	East of east fork of Dry Gulch on top of sharp ridge.
5	R-19-NaK-4	273855	5.41	3.19	1.70	10,040	Approximately same as 4.
6	C-268-NaK-2	273862	5.20	2.90	1.79	10,450	About 1,600 ft northeast of junction of West Willow and Nelson Creeks on west slope of Campbell Mountain.
7	C-266-NaK-1	273863	4.65	3.02	1.54	10,400	About 500 ft north-northwest of sample 6 locality.
8	C-538-NaK-2	273869	5.18	3.24	1.60	11,000	On northwest spur of Mammoth Mountain.
				Crystal-rich welded tuff			
9	C-539A	151484	4.7	4.1	1.25	11,000	First Fork section, about 4,100 ft east of Outlet mine.
10	R-299C	282272	4.11	3.87	1.06	8,860	Blue Creek section, about 1,000 ft east of Wagon Wheel Gap, at mouth of Blue Creek; about 60 ft above base of exposures.
11	R-299U	D-100-029	4.25	3.84	1.11	9,200	Same as 10, but about 400 ft above base of exposures.
12	R-299V	282273	4.31	3.81	1.13	9,240	Same as 10, but about 440 ft above base of exposures.
13	R-299MM	282274	4.05	3.91	1.04	9,580	Same as 10, but about 780 ft above base of exposures.
14	R-76A	282270	4.83	3.90	1.24	10,250	West of upper west Bellows Creek where creek forks at elevation about 11,120 ft.
15	R-76B	282271	4.21	3.96	1.06	10,250	Do.
16	C-1084D	282264	4.36	3.70	1.18	9,800	West side of Horsethief Creek, south of Shallow Creek, NW¼ sec. 17, T. 41 N., R. 1 W.
17	C-1074A	282265	4.15	3.74	1.11	10,800	On main ridge trending southeast from Bristol Head, NE¼ sec. 36, T. 41 N., R. 2 W.
18	C-1075	282266	4.88	3.50	1.39	10,600	On west side of ridge trending southeast from Bristol Head, NW¼ sec. 36, T. 41 N., R. 2 W.
19	C-1035	282267	4.61	3.80	1.21	10,400	Along the north fork of Sevenmile Creek, SW¼ sec. 18, T. 41 N., R. 1 W.
20	C-1102	282268	5.05	3.74	1.35	10,000	Near pack trail north of Shallow Creek, NE¼ sec. 6, T. 41 N., R. 1 W.
21	C-1078A	282269	4.32	3.92	1.10	11,200	On west side of Bristol Head, NE¼ sec. 26, T. 41 N., R. 2 W.

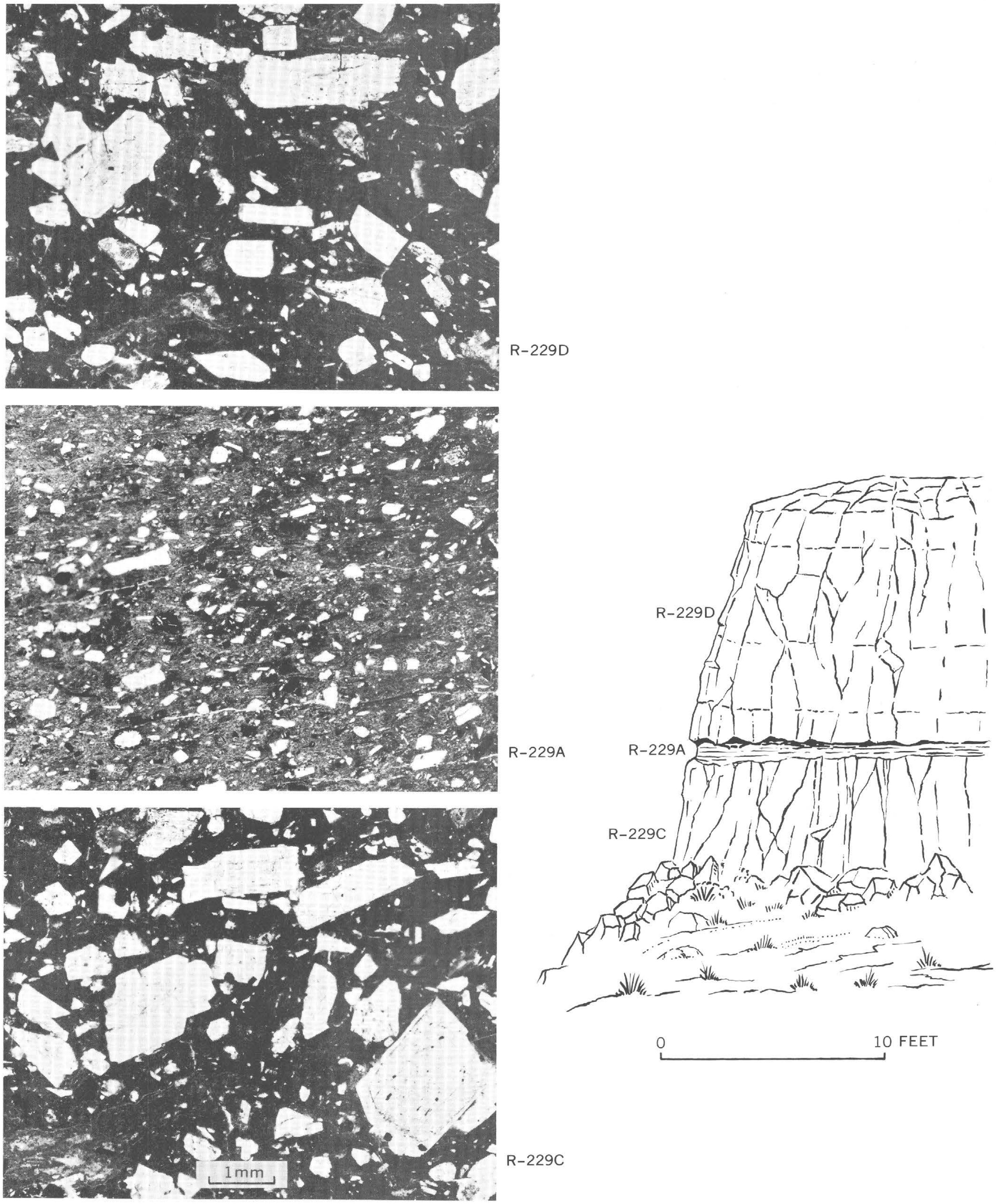


FIGURE 12.—Changes in texture across a parting in Mammoth Mountain Rhyolite about 1 mile north of the Blue Creek section. Sketch shows location of specimens relative to niche in cliff face. Photomicrographs show texture of corresponding thin sections.

CHARACTERISTICS OF A VISIBLE PARTING

A visible parting near the base of the cliffs of Mammoth Mountain Rhyolite on the east side of Blue Creek about 1 mile north of the Blue Creek section (section *H*, pl. 1) was selected for detailed study. The parting is expressed as a discontinuous shallow weathered recess or niche having a maximum width of about 6 inches (fig. 12). The niche parallels the subhorizontal compaction foliation of the rocks, and it can be traced laterally for a few hundred feet before it becomes indistinguishable in the enclosing rocks. Densely welded rocks above and below the recess are dark gray and crystal rich; the rock within the niche is reddish brown, appears to be crystal poor, and has a discontinuous compaction foliation that is much more closely spaced than the foliation in the enclosing rocks. There is no discernible change in the degree of welding across the parting.

Thin sections from a suite of specimens collected across the parting show that the rock in the niche differs from the enclosing rocks mainly in the abundance and size of phenocrysts (table 8*A*, *B*; fig. 12). Specimen C–229a, from within the niche, contains less than half as many crystals as the specimens from above and below the niche. There is also a disproportionate increase in biotite flakes within the parting, where biotite constitutes almost one-third of the phenocrysts, in contrast to less than one-fifth of the phenocrysts of the other two specimens (table 8*A*). The crystals and lithic fragments in the sample from the niche are finer than in the rocks above and below (table 8*B*). Eighty percent of the crystals and rock fragments in the parting are in the two smallest size classes, whereas only 40–50 percent of the particles in the two adjoining specimens are in those size classes, and the median size of fragments in the parting is close to ⅛ compared to ¼–½ mm in the other two specimens. (The median fragment size was determined graphically on semilogarithmic graph paper by using the approximate midpoints of the size classes, 1.25 mm, 0.75 mm, 0.375 mm, 0.188 mm, and 0.085 mm, and the grain count in cumulative percent.) The rock in the parting is less dense than the rocks above and below (table 8*C*). This difference can be attributed partly to a difference in the porosity of the rocks, but the difference in grain density suggests that the bulk density changes are also in part the result of the greater abundance of plagioclase phenocrysts in the rocks above and below the parting. Properties of this suite of rocks are plotted in profile form in figure 13.

TABLE 8.—*Petrographic differences across a parting in the Mammoth Mountain Rhyolite*

	Sample		
	R 229C (4 ft below parting)	R 229A (rock in parting)	R 229D (6 ft above parting)
A. Modal composition (volume percent)			
Lithic fragments	3	3	3
Matrix	60	80	61
Phenocrysts	37	17	38
Total	100	100	100
Plagioclase	28	10	29
Biotite	6	6	6
Pyroxene	1	0	1
Magnetite	2	1	2
Total	37	17	38
B. Size analysis (percent) [Median size is the midpoint of size distribution by grain count]			
Millimeter			
>1	17	1	12
½–1	19	4	16
¼–½	19	15	22
⅛–¼	25	33	21
<⅛	20	47	29
Median size	.45	.18	.33
C. Density (g per cc) and porosity (percent)			
Bulk density	2.49	2.41	2.49
Grain density	2.63	2.56	2.62
Porosity	5.1	5.7	5.2

Partings of the type just described are not to be confused with discontinuous zones of partially welded tuff such as are conspicuous in cliffs of Mammoth Mountain Rhyolite south of the Rio Grande opposite the mouth of Blue Creek. These lenticular zones of partially welded tuff are a few inches to a few feet thick and extend laterally a few tens of feet or a few hundred feet before pinching out in densely welded tuff. The partially welded tuff represents interruptions in the cooling of the deposit, and by definition is characteristic of compound cooling units (Smith, 1960a) rather than of simple cooling of multiple ash flows.

BLUE CREEK SECTION

In order to determine whether flow boundaries expressed by variations in petrographic and physical properties as just described exist in the Blue Creek section, 41 specimens of Mammoth Mountain Rhyolite were collected at vertical intervals of approximately 20 feet through 800 feet of section. Modes and the size distribution of phenocrysts and lithic fragments were counted in thin sections, and density-porosity measurements and calculations were made for each specimen.

LITHOLOGY AND PETROGRAPHY

The Mammoth Mountain Rhyolite at the Blue Creek section consists principally of dark-brown densely welded crystal-rich ash-flow tuff that stands in cliffs nearly 800 feet high. The cliffs show a faint layered structure that dips 5°–10°N. The base of

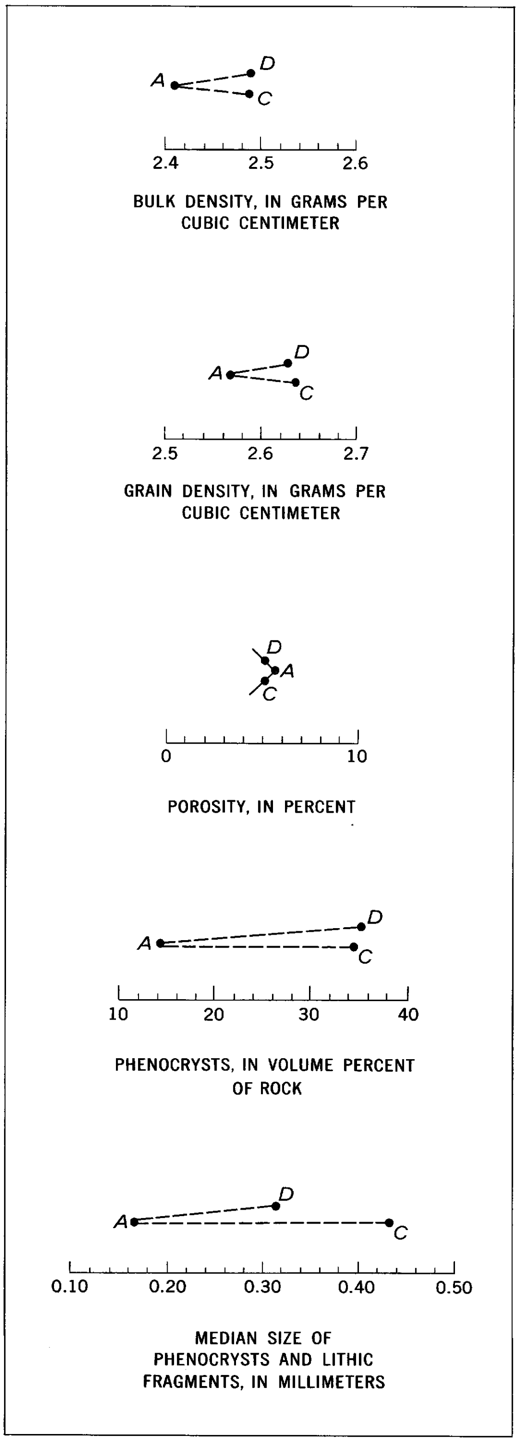


FIGURE 13.—Profiles across a parting in Mammoth Mountain welded tuff. Sample D 10 feet above sample C.

the formation, although here covered by talus, probably lies within a few tens of feet beneath the lowest exposures, as indicated by the presence of a basal vitrophyre a short distance to the southeast. The upper 50–100 feet of the section consists of partially welded tuff that is poorly exposed beneath cliffs of quartz latite lava flows. An erosional bench covered by landslide and talus debris marks the transition from the zone of densely welded tuff to the zone of partially welded tuff. The exposed part of the section is entirely devitrified. The following lithologic variations were observed in traversing the cliffs: The densely welded rocks are dark gray in the lower half of the section and reddish brown in the upper half. Partially welded tuff at the top of the section is light brown to pinkish white. Lithic inclusions are most abundant near the bottom of the section. Poorly bounded zones of closely spaced compaction foliation and well developed eutaxitic streaks occur in the upper half of the cliffs. Except for the transition to less welded rocks at the top of the cliffs, clear-cut changes in the degree of welding were not observed, nor was any trace of a parting.

Modes of the 41 specimens from the Blue Creek section (table 9) show that phenocrysts constitute 30–53 percent of the rock. The phenocrysts are mostly plagioclase, biotite, clinopyroxene, and magnetite but include rare sanidine and hornblende. The near-absence of sanidine, the relative abundance of clinopyroxene, and a slightly more calcic composition of plagioclase distinguish these rocks from more rhyolitic facies of the formation. The plagioclase phenocrysts are somewhat more complex in form and zoning than those in the more rhyolitic rocks. Biotite phenocrysts are weakly to moderately oxidized in the lower half of the section, and are generally strongly oxidized in the upper half.

The lithic inclusions in the Blue Creek section consist of porphyritic and microlitic lavas and welded tuff fragments. Biotite-rich fragments with a micrograniitic fabric have been noted in Mammoth Mountain Rhyolite in this area only; they resemble the granitic inclusions in the Farmers Creek Rhyolite, but are finer grained. Pumice lapilli occur throughout the section, and relict vesicular structures are visible in thin sections of some of the larger pumice fragments, even in the lower parts of the unit. In the upper part of the formation, the larger pumice fragments commonly contain unbroken phenocrysts and have miarolitic cavities filled with coarse tridymite in wedge-shaped twins.

The matrix of the rocks displays progressive changes in texture and crystallinity from the bottom to the top of the section. The matrix is dark and lacks a clearly defined microtexture in the lower 50–100 feet of the exposures. Higher in the section, to about 300 feet above the base of the outcrops, a tight maze structure having some microeutaxitic texture is characteristic, and, rarely, true vitroclastic shards can be observed. Microeutaxitic texture increases upward and becomes prevalent in the upper half of the section.

TABLE 9.—*Modes (volume percent) of Mammoth Mountain Rhyolite in the Blue Creek section*

[P, mineral present in trace amounts. 0, mineral not found in point count. Samples listed in stratigraphic order. Degree of welding: PW, partially welded; leaders, densely welded]

Field No.	Degree of welding	Matrix	Phenocrysts	Plagioclase (percentage of phenocrysts)	Sanidine	Biotite	Pyroxene	Hornblende	Magnetite	Foreign rock fragments (percentage of total rock)	Points counted
		Percentage of rock without lithic fragments									
R-299OO	PW	70	30	25(83)	P	5	0	0	P	1	1,108
NN	PW	61	39	32(82)	P	5	0	P	2	<1	1,165
MM	----------	59	41	33(81)	P	5	1	P	2	<1	1,302
LL	----------	59	41	34(83)	P	4	1	P	2	2	1,284
KK	----------	61	39	30(77)	P	5	1	0	3	<1	762
JJ	----------	63	37	29(77)	P	5	P	0	3	1	1,180
II	----------	55	45	35(78)	0	6	2	0	2	2	1,229
HH	----------	52	48	38(79)	P	6	2	0	2	4	1,465
GG	----------	60	40	31(77)	P	5	2	P	2	2	1,415
FF	----------	53	47	38(81)	P	5	2	0	2	1	1,405
EE	----------	52	48	36(75)	0	6	2	0	4	5	1,274
DD	----------	53	47	38(81)	P	5	2	0	2	4	1,106
CC	----------	56	44	34(77)	0	7	1	0	2	2	1,257
BB	----------	61	39	31(79)	P	5	1	0	2	5	1,378
AA	----------	60	40	30(75)	0	6	2	0	2	2	1,373
Z	----------	60	40	33(82)	P	5	0	0	2	<1	1,320
Y	----------	63	37	30(81)	P	6	P	0	1	1	1,333
X	----------	60	40	30(75)	0	6	2	P	2	<1	1,347
W	----------	60	40	32(80)	0	5	1	0	2	1	1,350
V	----------	64	36	30(83)	P	4	P	0	2	1	1,296
U	----------	61	39	32(82)	P	3	2	P	2	<1	1,394
T	----------	53	47	38(81)	0	5	2	P	2	9	1,275
S	----------	49	51	42(82)	P	4	3	P	2	4	1,339
R	----------	52	48	38(79)	0	6	2	0	2	1	1,376
Q	----------	49	51	42(82)	0	5	2	P	2	2	1,330
P	----------	47	53	44(83)	0	5	2	P	2	6	1,396
O	----------	52	48	38(79)	0	5	3	P	2	3	873
N	----------	52	48	40(83)	0	4	2	0	2	6	1,157
M	----------	52	48	40(83)	0	4	2	0	2	4	1,604
L	----------	56	44	35(80)	0	5	2	0	2	12	1,303
K	----------	55	45	38(84)	0	5	P	0	2	6	1,415
J	----------	57	43	36(84)	0	6	0	P	1	4	1,385
I	----------	62	38	32(84)	0	4	0	0	2	3	1,388
H	----------	60	40	34(85)	0	4	0	P	2	5	1,354
G	----------	60	40	32(80)	0	6	P	0	2	4	1,198
F	----------	56	44	35(79)	0	7	P	0	2	4	1,462
E	----------	61	39	31(79)	0	6	0	0	2	2	1,373
D	PW	65	35	28(80)	0	5	0	0	2	4	1,443
C	----------	58	42	32(76)	P	6	2	P	2	5	1,227
B	----------	60	40	30(75)	0	6	2	0	2	7	1,055
A	----------	56	44	35(80)	0	5	2	0	2	6	1,563
Average		57	43	34(79)	P	5	1	P	2	3	1,230
Range		47–70	30–53	25–44(75–85)	0–P	3–7	0–3	0–P	P–4	<1–12	762–1,604

Crystallinity of the matrix changes upward in the formation from a formless cryptocrystalline type to an increasingly pervasive spherulitic type. Granophyric material occurs mainly in the interiors of the larger pumice fragments.

PARTICLE SIZES

The parting discussed on page— showed finer grain size than the rocks above and below, and as differences in grain size are evident in thin sections from the Blue Creek section, a statistical study was made of the size distribution of phenocrysts and crystal and lithic fragments. Size analysis presents a problem in welded rocks such as these because the constituents cannot be separated into sieve sizes by mechanical disintegration. The technique used was to measure the maximum diameter of crystals and fragments found along parallel traverses of the thin sections by using a micrometer eyepiece. Large fragments that were cut by adjacent traverses were counted only once. The fragments were assigned to one of five size classes according to the length of their maximum diameters:

Class	*Size (mm)*
1	>1
2	<1; >½
3	<½; >¼
4	<¼; >⅛
5	<⅛; but >1 division on the micrometer occular (about 0.05 mm).

Results of the size analysis are shown in table 10.

DENSITY AND POROSITY

The density of each of the 41 specimens from the Blue Creek section was determined by standard water-absorption techniques. Sample fragments, ranging from 55 to about 150 grams, were oven dried at 105°–115°C for 24 hours. After cooling in a desiccator, they were weighed to determine the dry weight in air (M_1). The samples were next placed in a desiccator from which the air was evacuated to a pressure of about 1.5 mm of mercury. The desiccator was then flooded with deaerated water and the specimens were left to absorb water in the available pore space for 3 days. At the end of this time, the samples were removed from the water and quickly weighed in

TABLE 10.—*Size analysis of phenocrysts and lithic fragments in the Mammoth Mountain Rhyolite of the Blue Creek section*

[Samples listed in stratigraphic order. Median size is midpoint of size distribution by grain count]

Field No.	Percentage of individual fragments by size class (mm)						Grains counted
	>1	½–1	¼–½	⅛–¼	<⅛	Median size	
R-299OO	6	16	28	28	23	0.38	432
NN	10	19	27	24	20	.43	415
MM	13	22	27	23	15	.49	462
LL	18	22	27	19	14	.53	402
KK	13	21	27	19	20	.47	269
JJ	10	18	26	24	22	.42	311
II	17	19	24	21	19	.48	405
HH	16	21	22	21	20	.48	384
GG	18	19	26	19	19	.51	448
FF	21	23	26	19	11	.60	442
EE	18	22	23	21	16	.52	400
DD	18	19	21	20	21	.47	289
CC	15	22	24	21	18	50	470
BB	14	17	24	25	20	.43	391
AA	17	19	26	18	21	.50	361
Z	16	22	20	19	22	.48	275
Y	13	23	22	23	19	.47	327
X	17	21	21	20	22	.48	373
W	19	16	20	22	22	.44	402
V	15	19	24	21	20	.46	407
U	17	20	21	23	18	.49	266
T	17	19	21	24	18	.48	304
S	13	15	23	27	22	.38	458
R	14	13	25	30	18	.39	419
Q	14	18	28	25	14	.48	443
P	11	23	23	26	18	.45	481
O	11	14	28	26	22	.38	558
N	11	14	25	26	23	.37	499
M	14	18	24	22	22	.43	462
L	19	18	20	21	21	.46	390
K	21	20	21	19	19	.52	418
J	11	19	20	26	23	.39	492
I	15	18	22	23	22	.42	320
H	17	17	23	27	16	.47	330
G	18	16	27	19	20	.47	353
F	14	21	23	22	21	.47	524
E	14	16	22	23	24	.40	365
D	13	20	25	22	20	.45	368
C	16	18	25	21	20	.46	357
B	10	19	25	25	21	.41	500
A	14	19	24	23	21	.44	716

TABLE 11.—*Bulk density, grain density, and porosity of Mammoth Mountain Rhyolite in the Blue Creek section*

[Samples listed in stratigraphic order. Measurements by William Allen, 1959]

Field No.	Bulk density (g per cc)	Grain density (g per cc)	Porosity (percent)
R-299OO	1.86	2.57	27.6
NN	2.21	2.65	17.2
MM	2.48	2.63	5.7
LL	2.49	2.64	5.6
KK	2.49	2.63	5.6
JJ	2.45	2.62	6.6
II	2.49	2.64	5.8
HH	2.50	2.64	5.3
GG	2.50	2.64	5.5
FF	2.53	2.65	4.5
EE	2.51	2.65	5.4
DD	2.53	2.64	4.5
CC	2.49	2.64	5.9
BB	2.49	2.64	5.8
AA	2.51	2.64	4.7
Z	2.44	2.62	7.0
Y	2.48	2.62	5.6
X	2.49	2.64	5.4
W	2.50	2.64	5.1
V	2.50	2.63	4.8
U	2.52	2.62	3.8
T	2.53	2.66	5.1
S	2.55	2.67	4.5
R	2.49	2.67	6.7
Q	2.51	2.66	5.7
P	2.45	2.68	8.9
O	2.53	2.66	4.9
N	2.41	2.65	8.9
M	2.50	2.66	6.1
L	2.50	2.65	5.8
K	2.51	2.65	5.7
J	2.55	2.65	3.9
I	2.47	2.63	6.2
H	2.49	2.64	5.6
G	2.52	2.64	4.7
F	2.50	2.63	5.0
E	2.49	2.62	4.9
D	2.24	2.63	14.9
C	2.47	2.64	6.7
B	2.48	2.63	5.9
A	2.50	2.64	5.2
Average	2.47	2.64	6.7

air, after the excess water was removed from the outside of the samples, to get the wet weight in air (M_2). The wet sample was then weighed in water to obtain the wet weight in water (M_3). From the weights M_1, M_2, and M_3, the bulk density, grain density, and percent porosity were calculated for each specimen by the following formulas: bulk density$=\frac{M_1}{M_2-M_3}$; grain density (essentially equivalent to powder density) $=\frac{M_1}{M_1-M_3}$; and porosity (in percent)$=\frac{M_2-M_1}{M_2-M_3}\times 100$. Results of the measurements are listed in table 11.

The bulk density of the 41 specimens of the Blue Creek section ranges from 1.86 to 2.55 g per cc (grams per cubic centimeter), with the bulk density of 90 percent of the samples between 2.45 and 2.55 g per cc. The grain density of the specimens ranges from 2.57 to 2.68 g per cc, with the grain density of 80 percent of the samples between 2.62 and 2.66 g per cc.

As a check, the density measurements were made on a second sample of each of 13 of the welded tuff specimens. In seven paired samples there was no detectable difference in the calculated densities, and in five pairs the difference between samples was 0.01 g per cc; the maximum difference between two samples of the same specimen was 0.04 g per cc. In addition, the precision of the measurements was checked by several reruns of the same samples and found to be within 0.01 g per cc. The difference of 0.04 g per cc between two samples of specimen R-299Z probably represents a real variation in density within the specimen. Errors inherent in this method, such as possible differences in the abundance of sealed pore space within the samples, cannot be evaluated but are believed to be unimportant because the rocks are tightly welded and uniform in texture.

EVIDENCE OF FLOW BOUNDARIES

In an attempt to identify flow boundaries, the density and petrographic data from the Blue Creek section are plotted in a series of profiles showing variations in density, porosity, modal composition, and the size distribution of phenocrysts and lithic fragments (fig. 14).

The reliability of the different types of data differs considerably. The density and porosity data are believed to be very reliable because of the precision with which results have been reproduced. The data dependent upon modal counts are not as precise as the density measurements, but the greater magnitude

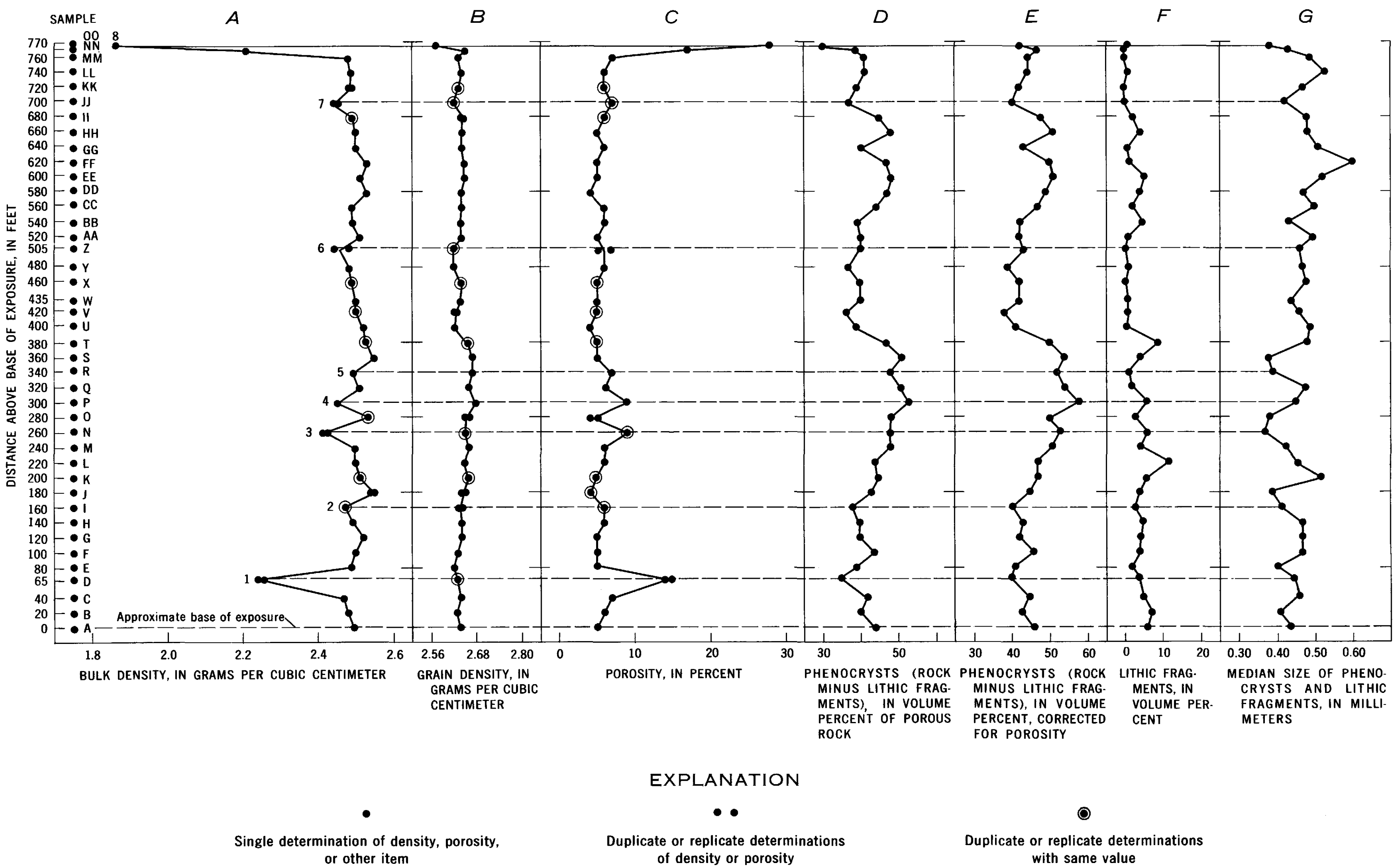


FIGURE 14.—Profiles summarizing physical and petrographic properties of Mammoth Mountain Rhyolite in the Blue Creek section. Numbers on profile *A* indicate breaks in density profile discussed in text.

of variations in the modal analyses permits small errors of 1–2 percent without seriously affecting the shape of the profiles. The least reliable data are those expressing grain or fragment size because of the difficulties in defining small chips and fragments and the relatively small number of grains counted per thin section.

Sharp breaks or discontinuities in the bulk-density profile that might represent ash-flow boundaries are numbered 1 to 8 in figure 14. The changes in bulk density at each break exceed the probable error of the density measurements shown by repeated measurement. That the breaks do not reflect merely expectable variation within single flows is supported by multiple measurements and by the relatively uniform variation between some breaks. The lack of corresponding discontinuities in grain density eliminates the influence of changes in modal composition as the major cause of sharp breaks in bulk density.

The grain density of specimens in the Blue Creek section is nearly constant within the limits of error of the measurements, and it probably indicates a nearly uniform modal composition. However, there is a small but perceptible decrease in the average grain density from the lower half to the upper half of the section, and a moderately sharp decrease at the top of the section (profile *B*). These changes and smaller irregularities in the grain-density profile probably do correspond to small changes in modal composition. Contrasting amounts of silica polymorphs (quartz, specific gravity 2.65; tridymite, sp gr 2.36; and cristobalite, sp gr 2.30) or the presence of zeolites of low specific gravity in the more porous rocks could account for small differences in grain density. Spot checks of the section were made by X-ray and no zeolites were found, but tridymite is conspicuous in some thin sections, particularly from the upper half of the section. The higher grain density near the top of the lower half of the section probably reflects the greater abundance of phenocrysts in this part of the section. (See profiles *D* and *E*.) The phenocrysts, which are largely andesine with minor biotite and pyroxene, all have specific gravity greater than the silica minerals and alkali feldspar that make up most of the rock matrix.

The porosity (profile *C*) ranges from 4 to 28 percent, but about 90 percent of the specimens have a porosity of less than 8 percent. The porosity profile is almost a mirror image of the bulk-density profile, indicating that changes in bulk density probably are to a large degree dependent on changes in porosity.

Variations in the abundance of phenocrysts through the section are shown in profiles *D* and *E* (fig. 14). Profile *E* includes a correction for the porosity of the rocks, but this correction does not alter significantly the form of the profile. The phenocrysts are most abundant near the middle of the section, and the profile shows several breaks or discontinuities that may be related to differences in modal composition of separate ash flows.

Variations in the abundance of foreign lithic fragments through the section are shown in profile *F*. Lithic inclusions are somewhat more abundant in the lower than in the upper half of the section, and they are anomalously abundant in several places, as in specimens L and T.

Variation in the median size of the phenocrysts and lithic fragments is shown in profile *G*. The median sizes are presented as a summary of the size analysis, details of which are given in table 10.

The numbers on profile *A* (fig. 14) mark conspicuous discontinuities or breaks in the bulk-density profile, and discontinuities 1–7 are projected across the other profiles by means of broken lines. Thus projected, some discontinuities correlate with discontinuities on the other profiles, but some do not.

In the basic ash-flow unit defined by Smith (1960b), in which zones of welding are completely developed, the bulk density of the rocks is greatest in the zone of dense welding, which is sandwiched between zones of partially welded to nonwelded ash-flow tuff having low bulk densities. In the zone of dense welding, where ash-flow materials theoretically are completely welded and compacted, there should be no variations in bulk density. However, as outlined by Smith (1960b, p. 156), density and porosity gradients generally are present in the zone of dense welding of an actual cooling unit because of trapped or exsolved gases and a lithostatic pressure gradient.

Thus the changes in bulk density through the Blue Creek cooling unit (profile A) may reflect either zones of greater and lesser welding or the boundaries of ash-flow units. Discontinuity 8 (profile A) clearly reflects differences in welding near an ash-flow boundary, inasmuch as it lies in the transition between zones of dense and partial welding as observed in the field. The other seven discontinuities all lie in what appears to be uniformly welded rock, and they are regarded as possible flow boundaries that have been almost obliterated by welding. In support of this interpretation, the bulk-density profile does not show a general trend from top to bottom as evidence of a pressure gradient in the zone of dense welding. It does, however, show such a trend in segments of the profile, as between discontinuities 2 and 3, 5 and 6, and 6 and 7, which would be consistent with separate ash flows and incipient cooling units.

Data based on phenocrysts and lithic fragments only partly support the identifications of flow boundaries suggested by bulk densities. Certain discontinuities, such as 1, 2, 5, and 7 (profiles *D*–*G*, fig. 14), fit well with the bulk-density breaks. A correspondence is to be expected in some degree at least, because a decrease in the relatively heavy constituents should decrease the density, but calculation shows that the reductions in phenocrysts and lithic fragments are not enough to produce the reductions in density. Moreover, certain breaks, such as No. 4, and possibly No. 6, occur near samples that combine relatively low bulk density with relatively high phenocryst and rock fragment content. Thus, contents of phenocrysts and lithic fragments are at least in part independently variable.

Most of the numbered breaks express discontinuities in phenocrysts and fragments compatible with ash-flow tops. Many ash flows in the Creede area, as well as ash flows in other places (Enlows, 1955; Boyd, 1961), show a decrease in number and size of phenocrysts and lithic fragments toward the tops of the flows. This decrease is attributed primarily to a so-called "fallout" mechanism, by which the upper part of an ash flow is enriched in fines settled from the ash cloud above the ash avalanche. From study of the historic eruption of glowing avalanche deposits on St. Vincent, British West Indies, Hay (1959) concluded that as much as one-third of the material discharged in an eruption is dissipated in such clouds.

In general, lithic fragments are most abundant near the bottoms of ash flows because they are in part debris swept up from the surface of deposition by turbulence of the ash flow and in part the leavings from the creation of the eruptive vent. Profile *F* (fig. 14) shows a general decrease in lithic fragments upward in the Mammoth Mountain, and two abrupt breaks that suggest bottoms of flows, but neither of these breaks corresponds with the conspicuous breaks in the other profiles. It is possible, of course, that such concentrations of lithic fragments merely reflect sudden enlargements of the vent during eruption.

To test the conclusions suggested by visual inspection of the profiles (fig. 14), simple statistical tests were made, using Spearman's rank correlation coefficient (r_s), and the students' *t* test (Siegel, 1956, p. 202–212). Spearman's rank correlation coefficient is a measure of the similarity between two ranked sets of variable data; the larger the coefficient, the greater the inferred correlation of the two sets of data. The students' *t* test translates the correlation coefficients into values that are related to levels of significance or probabilities. The results of these tests (table 12) indicate a high probability of a relationship between bulk density and the abundance of phenocrysts in the Blue Creek section. The independent nature of the relationship is shown by the high probability of a relationship after the effects of compaction were eliminated by correcting for the porosity of the samples. The tests also show a fairly

TABLE 12.—*Statistical correlation of bulk density with the abundance and size distribution of phenocrysts and lithic fragments in the Blue Creek section of the Mammoth Mountain Rhyolite*

[r_s, Spearman's rank correlation coefficient, $r_s=1-\frac{6d^2}{n(n^2-1)}$, where d=difference in rank value for a sample with respect to the two sets of data being tested, and n=number of samples. *t* test of Siegel, $t=r_s\sqrt{\frac{n-2}{1-r_s^2}}$]

Profiles correlated (fig. 14)	r_s	*t* test of Siegel	Level of significance	Chances of a fortuitous relation
Profiles *A* and *D:* Bulk density and abundance of phenocrysts, not corrected for porosity	0.465	3.3	0.99	1 in 100
Profiles *A* and *E:* Bulk density and abundance of phenocrysts with correction for porosity	.315	2.1	.95	1 in 20
Profiles *A* and *F:* Bulk density and abundance of lithic fragments	.247	1.6	.80	1 in 5
Profiles *A* and *G:* Bulk density and median size of phenocrysts and lithic fragments	.308	2.0	.95	1 in 20

strong statistical probability of a relationship between bulk density and the median size of fragments, but the probability of a reliable relationship between bulk density and the abundance of lithic fragments is relatively weak.

CONCLUSIONS

The detailed study of the Blue Creek section of the Mammoth Mountain Rhyolite indicates that, although the formation here is a simple cooling unit, it consists of several individual ash flows, just as it does in areas more distant from the source. Boundaries of these flows are expressed in part by differences in bulk density and porosity and in the abundance and size distribution of phenocrysts and lithic fragments, but from the data available, we hesitate to specify the precise number, thickness, and characteristics of individual flows. The changes described for a visible parting in densely welded tuff (p. H27) suggest that sampling at smaller intervals across indicated flow boundaries in the Blue Creek section might bring the boundaries into sharper focus.

An incidental conclusion from the study of the Blue Creek section is that a numerical value of porosity more accurately expresses degree of welding than undefined terms such as "densely welded" or "partly welded." All samples in the densely welded zone of the Blue Creek cooling unit except sample D (profile *A*, fig. 14) have a porosity of less than 10 percent, and most have porosities of only 7–8 percent. Sample D shows relict vitroclastic texture in thin section, and it probably is not completely welded. Rocks having less than 10 percent porosity might, therefore, be classed as densely welded, and those having more than 10 percent porosity as partly welded.

WASON PARK RHYOLITE

The Wason Park Rhyolite is an extensive welded ash-flow sheet that was named (Steven and Ratté,

1964) for its exposures along the rim of Wason Park in the northeastern part of the Creede area (pl. 1). It lies conformably on the Mammoth Mountain Rhyolite in most of the mapped area, but near Creede, where the Mammoth Mountain is absent, it lies on the Bachelor Mountain Rhyolite. North of Shallow Creek and east of the Creede caldera, one or more lava flows separate the Wason Park and Mammoth Mountain. Small amounts of volcanic sandstone and conglomerate occupy local stream channels at the base of the Wason Park Rhyolite west of Miners Creek and east of East Willow Creek. Thus there was at least local erosion and reworking of volcanic materials as well as eruption of lava in the interval between the Mammoth Mountain and Wason Park eruptions.

DISTRIBUTION AND SOURCE

Wason Park Rhyolite is exposed almost continuously around the north half of the Creede caldera, where it is largely coextensive with the Mammoth Mountain Rhyolite. It extends south along the east side of the caldera at least to the south margin of the mapped area, and southeast along the north side of the Rio Grande for at least 5 miles from the mouth of Blue Creek (pl. 1). Reconnaissance has shown that it is present also near Spring Creek Pass, 17 miles northwest of the caldera; under Sagauche Park, 25 miles northeast of the caldera center; near the head of Trout Creek, just south of the area of plate 1; and in the headwaters of the West Fork of the San Juan River about 14 miles south of the caldera center.

From Bristol Head to the area southeast of Blue Creek (pl. 1), Wason Park Rhyolite has an average thickness of about 600 feet and it has a maximum thickness, near the margin of the caldera, of 700–800 feet. It is about 400 feet thick on Bulldog Mountain, and appears to thin toward the head of Miners Creek. It is less than 200 feet thick west of East Willow Creek on the east flanks of Nelson Mountain (pl. 1), and it wedges out to the north against a rough underlying surface on older rocks.

Bodies of Wason Park Rhyolite bordering the Creede caldera total at least 25 cu mi (100 cu km), and, considering its occurrence in more distant areas and the probability that it once covered the entire area of the caldera, its volume is well within the 100–1,000 cu km range, comparable to or greater than the volume of the Mammoth Mountain Rhyolite.

The source of the Wason Park Rhyolite is inferred to have been within the area of the Creede caldera because of the distribution of the formation around the caldera and because the degree of welding decreases slightly away from the caldera, especially to the southeast and southwest.

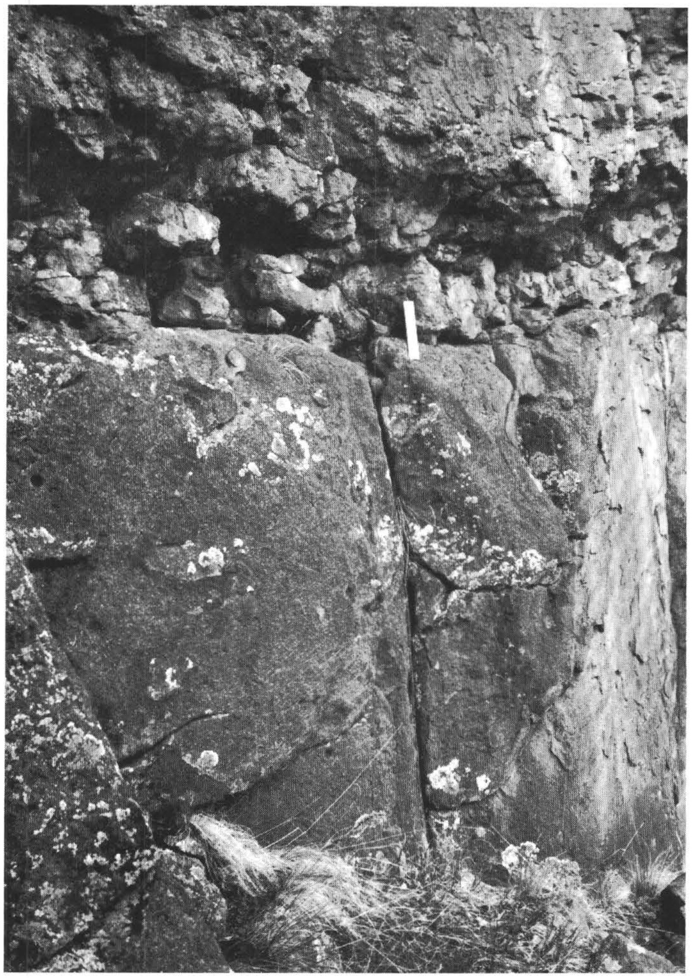
GENERAL LITHOLOGY

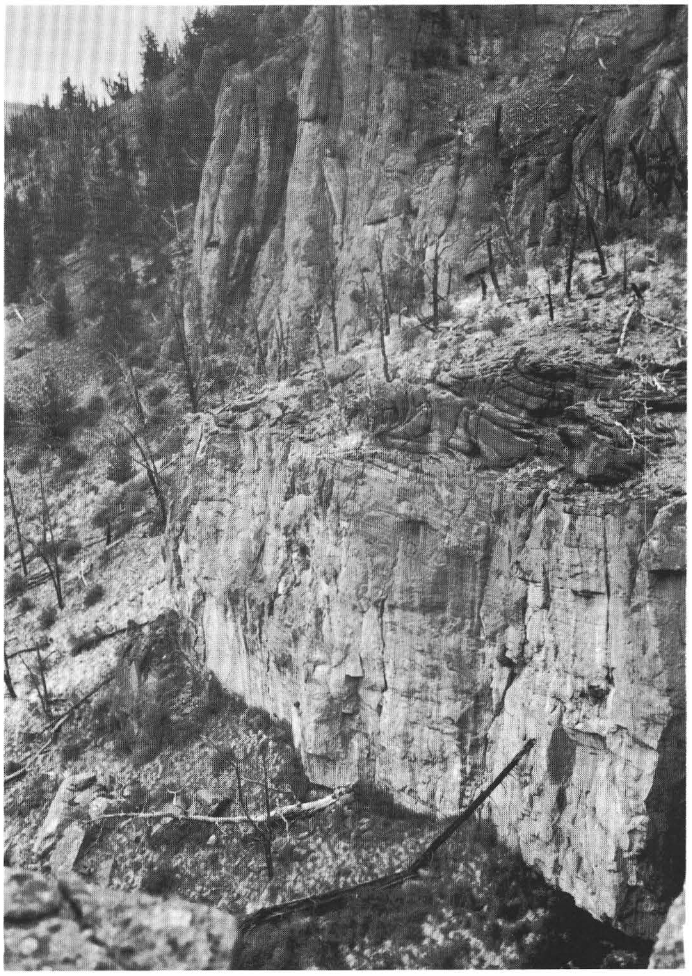
The Wason Park Rhyolite consists of a thick simple cooling unit of welded ash flows in the Creede area. Dense black vitrophyre 10–15 feet thick, is nearly everywhere present at the base of the formation. In most places, the change upward from vitrophyre to devitrified rocks is a sharp transition, but locally it is marked by a thin lithophysal zone containing irregular pockets of devitrified rock and some spherulites or thunder eggs that enclose masses of opal or chalcedony (fig. 15*A*). Above the vitrophyre, and extending to within a few tens of feet of the top of the formation, densely welded devitrified tuff stands in massive to columnar cliffs (fig. 15*B*). The upper part of the formation is partially welded tuff that is almost everywhere obscured by talus and landslide debris or has been partly eroded.

The Wason Park Rhyolite is a distinctive ash-flow tuff in the Creede area. In the zone of dense welding, it contains 20–30 percent white feldspar phenocrysts 2–4 mm long, smaller books of black to copper-colored biotite, and scattered crystals of green pyroxene in a brick-red lithoidal matrix. The matrix also includes characteristic white blocks and schlieren of collapsed pumice, which have a maximum length of more than 4 feet and a maximum thickness of about 3 inches (fig. 16*A*). More commonly the pumice streaks, which appear to be largest in the upper third of the densely welded zone, are a few inches in diameter and one-half an inch or less thick, and in many places are marked by open miarolitic cavities (fig. 16*B*). Foreign rock fragments are small and occur mainly in the vitrophyre or in the lower few tens of feet of the devitrified zone; they generally constitute less than 5 percent of the rock. Partially welded ash-flow material in the upper part of the formation is light pink to gray, relatively porous, and it generally contains fewer and smaller phenocrysts and pumice masses than the densely welded tuff. Locally, Wason Park welded tuff near the bottom of the devitrified zone lacks conspicuous pumice schlieren and it resembles reddish-brown densely welded tuff in the Mammoth Mountain Rhyolite. Similarly, certain local crystal-rich phases of the Wason Park and Mammoth Mountain are virtually identical.

PETROGRAPHY AND COMPOSITION

Modal analyses of specimens from two stratigraphic sections of Wason Park Rhyolite, one east of upper West Bellows Creek and the other north of East Bellows Creek, are presented in table 13. Each section is about 600 feet thick. The average modes of the two sections agree closely, and the average of all 29 modes shows that Wason Park welded tuff in the Bellows Creek area contains about 30 percent phenocrysts, chiefly plagio-





A B

FIGURE 15.—Lithologic features of the Wason Park Rhyolite east of West Bellows Creek. *A*. Lithophysal zone in the transition between vitrophyre below and devitrified welded tuff above; white scale is 6 inches long. *B*. Rhyolite lava flow and overlying Wason Park Rhyolite; lower cliffs are lava flow that has contorted flow layers in a vesicular zone at top; columnar cliffs above are Wason Park welded tuff having lithophysal zone and vitrophyre (shown in *A*) at its base; dip is low, away from observer; rhyolite lava flow pinches out abruptly westward (left) beneath the Wason Park Rhyolite.

clase (18 percent) and sanidine (8 percent), about 2 percent biotite, 1 percent magnetite, and minor green pyroxene and sparse crystals of brown hornblende. The partially welded rocks at the top of the Wason Park contain only about half as many phenocrysts as the densely welded rocks. Lithic fragments are common throughout the lower third of the East Bellows Creek section, but in the West Bellows Creek section they are abundant in the basal vitrophyre only.

Plagioclase phenocrysts generally range in composition from about An_{25} to An_{40}, although the cores of some of the larger and more complexly zoned crystals are as calcic as An_{50}. The average composition is estimated to be sodic andesine between An_{30} and An_{35}. The crystals are subhedral to euhedral and show some resorption. On the whole, plagioclase crystals and other phenocrysts in the Wason Park Rhyolite are not badly broken, although most of the larger crystals have chipped corners.

Sanidine phenocrysts are more resorbed than plagioclase. They seem to be optically homogeneous and only rarely show evidence of compositional zoning or unmixing. Carlsbad twins are common but other forms were not observed. The optical axial angle is estimated to be small to moderate and the optic plane is consistently about perpendicular to (010). Sanidine from the Wason Park vitrophyre 10 miles west of Creede, analyzed by F. Gonyer (Larsen and others, 1938, p. 418, 421), has the calculated composition Or_{62}, Ab_{35}, An_3. X-ray analysis of the same specimen (MacKenzie and Smith, 1956, p. 411) gave the composition $Or_{59.5}$ and showed the sanidine to be slightly unmixed.

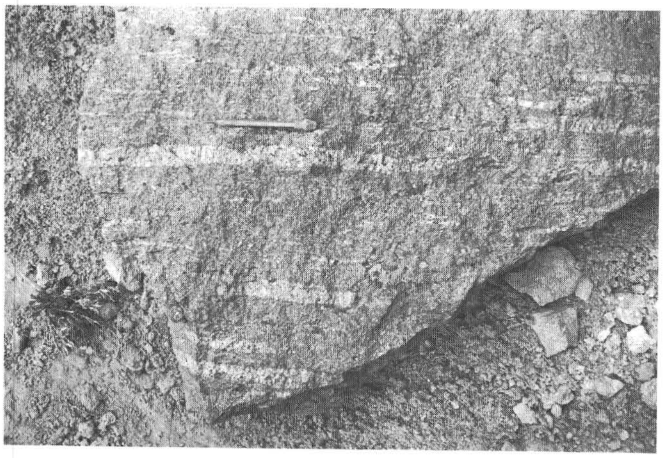
TABLE 13.—*Modes (volume percent) of Wason Park Rhyolite*

[P, mineral present in trace amounts: 0, mineral not found in point count. Samples listed in stratigraphic order. Degree of welding: PW, partially welded; leaders, densely welded]

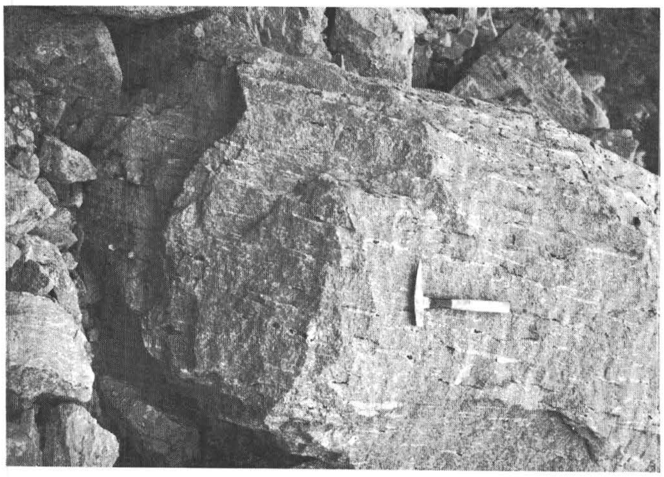
Field No.	Degree of welding	Matrix	Phenocrysts (not corrected for porosity)	Plagioclase	Sanidine	Biotite	Pyroxene	Hornblende	Magnetite	Foreign rock fragments	Points counted
				(Percentage of phenocrysts)							
A. **Section east of West Bellows Creek** [Modes by William Thordarson]											
R-122L	PW	84	16	10 (63)	4 (25)	1	0	0	<1	0	1,419
K	PW	85	15	10 (67)	2 (13)	1	0	P	1	P	1,495
J		67	33	22 (67)	7 (21)	3	P	P	<1	1	1,038
I		68	32	22 (69)	7 (22)	2	P	P	P	0	1,234
H		71	29	19 (65)	8 (28)	2	P	0	<1	0	1,317
G		67	33	23 (70)	8 (24)	2	P	0	<1	P	1,060
F		66	34	22 (65)	9 (26)	3	<1	0	<1	P	1,336
E		72	28	17 (61)	9 (32)	1	P	0	<1	0	1,073
D		71	29	16 (55)	9 (31)	3	P	P	1	0	1,018
C		74	26	15 (58)	8 (31)	2	P	0	1	0	1,356
B		69	31	21 (67)	8 (27)	2	0	0	P	1	1,437
A		69	31	20 (65)	8 (26)	1	P	P	1	14	1,283
Average		72	28	18 (64)	7 (25)	2	P	P	<1	P	1,255
Range		66-85	15-34	10-23 (55-70)	9 (13-32)	1-3	0-P	0-P	P-1	0-14	1,038-1,495
B. **Section north of East Bellows Creek**											
R-286Q	PW	86	14	9 (64)	4 (29)	2	P	P	<1	<1	1,439
P	PW	75	25	14 (56)	8 (32)	2	P	0	1	<1	1,240
O	PW	75	25	14 (56)	9 (36)	1	<1	0	1	0	1,425
N		71	29	17 (59)	7 (24)	3	1	0	1	P	1,328
M		71	29	18 (62)	8 (38)	2	P	0	1	P	1,269
L		71	29	15 (52)	10 (34)	2	1	P	1	0	1,271
K		68	32	20 (62)	8 (25)	1	<1	0	2	1	1,320
J		71	29	18 (62)	9 (31)	1	<1	0	1	0	1,402
I		66	34	19 (56)	12 (35)	2	<1	0	<1	0	1,181
H		65	35	19 (54)	11 (31)	3	<1	0	2	<1	1,277
G		63	37	23 (60)	11 (29)	2	<1	0	1	1	1,100
F		68	32	18 (56)	10 (31)	2	<1	0	1	5	1,437
E		62	38	27 (71)	9 (24)	1	P	0	1	3	1,376
D		64	36	23 (64)	11 (31)	1	P	0	<1	P	1,333
C		64	36	24 (67)	8 (22)	3	P	0	1	5	1,849
B		70	30	20 (64)	7 (23)	2	P	0	1	1	1,623
A		67	33	21 (62)	8 (24)	3	P	0	1	<1	1,403
Average		69	31	18 (60)	9 (29)	2	<1	P	1	<1	1,369
Range		62-86	14-38	9-27 (52-71)	4-12 (22-36)	1-3	P-1	0-P	<1-2	0-5	1,100-1,849
Combined average of A and B		70	30	18 (62)	8 (28)	2	<1	P	<1	<1	
C. **Comparison of densely welded tuff and an enclosed pumice fragment**											
R-46A		71	29	16 (55)	10 (35)	2	<1	0	1	0	549
R-46B	Enclosed pumice	76	34	15 (62)	7 (21)	1	<1	0	1	0	749

Mafic phenocrysts constitute only a small percentage of the rocks and are generally much smaller in average size than those of feldspar. They are chiefly biotite and magnetite. Biotite is brown to pale-yellowish brown in thin sections of the vitrophyre but is oxidized throughout the rest of the deposit, so it has reddish-brown and deep-red pleochroic colors. The biotite books are commonly partly resorbed. Iron oxide occurs as anhedral to subhedral crystals and more abundantly as dusty opaque grains throughout the matrix. Clinopyroxene phenocrysts are colorless to greenish yellow in thin section and are mainly subhedral to euhedral. Reddish-brown oxyhornblende grains are tiny and sparsely distributed. A few small zircons and tiny apatite crystals occur in most thin sections.

Pumice fragments in the Wason Park Rhyolite contain practically no vestiges of their original internal structures, but they can be distinguished from the matrix by their coarser crystallinity and by the unbroken character of their phenocrysts. The pumice fragments are largest and least squashed in the upper part of the devitrified and densely welded zone: the zone of partial welding at the top of the deposit generally does not contain large pumice fragments. Pumice fragments in the lower part of the devitrified zone are coarsely spherulitic to granophyric, but in the higher part the pumice is devitrified to granophyric aggregates that are progressively coarser toward the top of the deposit. In about the upper 50 feet of the densely welded zone, coarse elongate crystals form comb structures around lenticular cavities along the centers of many pumice fragments. Wedge-shaped twins and prismatic crystals of tridymite commonly line the central cavity or form a medial lens in completely crystalline pumices that lack central cavities. The tridymite probably formed from a vapor phase migrating through the deposit and from residual vapors in the large pumice fragments. There does not appear



A



B

FIGURE 16.—Flattened pumice blocks in Wason Park Rhyolite in landslide area west of upper West Bellows Creek. *A*, Exceptionally large pumice blocks. *B*, Streaked pumice with miarolitic cavities in a block of typical eutaxitic welded tuff.

to be a well-defined vapor-phase zone such as described by Smith (1960b, p. 155–156).

The phenocryst contents of pumice blocks and rock matrix are compared in table 13*C*. The pumice contains 5 percent fewer phenocrysts than the matrix. Phenocrysts in the pumice are mostly euhedral and whole, whereas those in the matrix are represented by many crystal chips and broken crystal fragments. The differences in phenocryst abundance may be caused by differential compaction between fine ash and shards in the matrix and gas-rich pumice fragments, many of which retain miarolitic cavities as evidence of incomplete compaction. The contrast in abundance of crystal fragments between matrix and pumice attests to the cushioning effect of the pumice on phenocrysts included within it.

The matrix of Wason Park Rhyolite ranges from glass to granophyre. In the basal vitrophyre, densely welded and tightly compressed glass shards have a vitroclastic-to maze-type texture. The glass itself is colorless in thin section, but it is crowded with a myriad of tiny crystallites that color the vitrophyre black in hand specimen. In the densely welded devitrified zone, the matrix is a fine cryptocrystalline aggregate so clouded by reddish-iron oxide pigment that no evidence of original texture can be recognized in many thin sections. In the zone of partial welding at the top of the formation, the matrix is largely cryptocrystalline with vitroclastic texture. Several X-ray analyses of both the densely welded and the partially welded tuff indicate that cristobalite and potassium feldspar are generally the major minerals in the matrix. Tridymite was not identified as a matrix constituent; it appears to be restricted to pumice fragments as a vapor-phase mineral.

Chemical analyses of the Wason Park Rhyolite include two analyses reported by Larsen and Cross (1956, table 21; analyses 43, 48) and five new analyses obtained during the current investigations, all of which are presented in table 14 together with calculated normative minerals and spectrochemical analyses. Analyses 1, 2, 5, 6, and 7 represent rocks that are rhyolites in the Rittmann classification of volcanic rocks; analyses 3 and 4 are in the quartz latite field, but are very close to the rhyolite field.

EVIDENCE OF FLOW BOUNDARIES

As was done for the Mammoth Mountain Rhyolite, detailed studies of physical properties and petrography were made for evidence of ash-flow boundaries in the Wason Park Rhyolite. The studies were made on suites of samples from the West Bellows Creek and East Bellows Creek sections of the formation, where there is no visual evidence of multiple ash flows. Bulk density, grain density, and porosity of the samples from these two sections are shown in table 15. Density measurements were made of replicate specimens of 13 of the samples, and of these, 4 showed no difference in bulk density, 6 showed a difference of only 0.01 g per cc, 1 showed a difference of 0.02 g per cc, and 2 showed a difference of 0.04 g per cc. The larger differences occurred in the most porous rocks, and probably represent true differences in the bulk density of the samples.

Data on the size distribution of phenocrysts and lithic fragments are shown in table 16.

TABLE 14.—*Chemical analyses, norms, and spectrographic analyses of Wason Park Rhyolite*

[Localities of samples described with reference to the Creede 15-minute quadrangle topographic map (1959), except that sample 7 is with reference to San Cristobal 30-minute quadrangle topographic map (1905)]

Sample No	1	2	3	4	5	6	7
Laboratory No	D1423	151486	151487	151488	D100030	----	----
Field No	C-341B	C-741	C-816	C-224B	R-306-59	La G-48	Scxx

Chemical analyses (weight percent)

[S, standard rock analysis; R, rapid rock analysis by methods similar to those described by Shapiro and Brannock (1956) Analysts: 1, M. Seerveld; 2, P.L.D. Moore; 3, S. D. Botts; 4, M. D. Mack; 5, C. L. Parker; 6, George Steiger; 7, F. A. Gonyer]

Type of analysis	S	R	R	R	S	----	----
SiO_2	69.24	70.9	66.9	67.0	66.72	67.76	70.84
Al_2O_3	13.96	14.1	17.0	16.7	15.89	16.08	13.53
Fe_2O_3	1.15	2.4	1.9	2.0	1.34	2.22	1.16
FeO	.72	.30	.32	.32	.78	.23	.52
MgO	.49	.58	.46	.72	.60	.43	0
CaO	1.18	1.6	2.2	2.0	2.07	2.59	.86
Na_2O	3.19	3.6	4.3	4.1	3.95	4.06	3.51
K_2O	6.06	4.6	4.8	4.7	5.35	4.91	5.57
H_2O+	2.65	1.2	1.0	1.2	2.14	.54	3.13
H_2O-	.27	.42	.61	.57	.15	.94	----
TiO_2	.35	.45	.40	.44	.40	.45	.22
P_2O_5	.07	.12	.11	.12	.08	.11	0
MnO	.08	.04	.03	.04	.08	.04	.09
CO_2	.04	.11	.08	<.05	.01	0	----
ZrO_2	----	----	----	----	----	.02	----
Cl	.12	----	----	----	.10	----	----
F	.05	----	----	----	.08	----	----
Subtotal	99.62	----	----	----	99.74	----	----
Less O	.05	----	----	----	.05	----	----
Total	99.57	100	100	100	99.69	100.38	99.43
Density (powder)	2.49	2.50	2.50	2.50	----	----	----
Density (bulk)	2.38	2.25	2.38	2.44	2.47	----	----
Analysts	1	2, 3, 4	2, 3, 4	2, 3, 4	5	6	7
Date	1957	1957	1957	1957	1963	1920	1932

Norms

Q	26.1	28.7	18.7	20.1	20.0	20.6	28.3
or	37.2	27.6	28.9	28.0	32.4	29.0	34.2
ab	27.0	30.8	37.1	35.2	32.9	34.4	30.9
an	5.1	7.3	10.4	9.2	9.1	11.2	4.4
C	.5	.6	1.0	1.5	.6	----	.2
Wo	----	----	----	----	----	.2	----
en	1.2	1.4	1.1	1.8	1.5	1.7	----
mt	1.7	----	----	----	2.0	----	1.4
hm	.1	2.4	1.7	2.0	.1	2.2	.2
il	.7	.9	.7	.9	.8	.6	.4
ap	.2	.3	.3	.3	.2	.3	----
sp	----	----	----	----	----	.4	----

Spectrographic analyses

[Q, quantitative analysis; overall accuracy ±15 percent, except that analyses are less accurate near limits of detection where only one digit is reported. SQ, semiquantitative analysis, in percent, to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, . . .; numbers represent approximate midpoints of group data on a geometric scale. The assigned groups for semiquantitative results include the quantitative value about 30 percent of the time. nd, not detected. Analysts: 1, P. R. Barnett; 2, J. C. Hamilton]

Type of analysis	Q	Q	Q	Q	SQ		
Ba	0.1	0.13	0.18	0.17	0.2	----	----
Be	nd	.0001	.0001	.0001	.0002	----	----
Co	nd	.0002	nd	nd	nd	----	----
Cr	.0003	.00030	.0001	.0002	.0002	----	----
Cu	.0003	.00076	.00076	.00045	.0005	----	----
Ga	.001	.0015	.0019	.0020	.003	----	----
La	.01	.0055	.0056	.0066	.007	----	----
Nb	.003	nd	nd	nd	.0015	----	----
Ni	nd	nd	nd	nd	nd	----	----
Pb	.0004	.0038	.0048	.0036	.003	----	----
Sc	nd	.0006	.0007	.0007	.001	----	----
Sr	.02	.048	.072	.068	.07	----	----
V	.002	.0028	.0044	.0028	.003	----	----
Y	.004	.0030	.0032	.0025	.003	----	----
Yb	.0003	.00028	.00026	.00025	.0003	----	----
Zr	.02	.034	.025	.029	.03	----	----
Analysts	1	1, 2	1, 2	1, 2	2	----	----
Date	1958	1958	1958	1958	1963	----	----

1. Vitrophyre at base of densely welded tuff at about 11,300-ft elevation north of the second fork of East Willow Creek.
2. Devitrified densely welded tuff on west side of McKenzie Mountain, at elevation of about 11,200+ ft, about 4,000 ft north-northwest of bench mark 11,756.
3. Devitrified densely welded tuff from the west side of Bulldog Mountain, at elevation of about 10,500 ft.
4. Devitrified densely welded tuff above the stock driveway at elevation of about 10,950 ft on the southeast slope of Nelson Mountain.
5. Vitrophyre at base of densely welded tuff at elevation of approximately 10,680 ft, east of West Bellows Creek at the foot of the cliffs about 5,800 ft slightly north of east from the SE cor. sec. 1, T. 41 N., R. 1 E.
6. Devitrified welded tuff, elevation about 10,500 ft, near the town of Bachelor between Bulldog Mountain and Bachelor Mountain northwest of Creede. Collected and described by Larsen and Cross (1956, table 21, No. 43).
7. Glass believed to be from Wason Park vitrophyre in roadcut 2 miles west of Antelope Spring. Collected and described by Larsen and Cross (1956, table 21, No. 48).

TABLE 15.—*Bulk density, grain density, and porosity of Wason Park Rhyolite*

[Samples listed in stratigraphic order. Measured and calculated by William Allen]

Field No.	Bulk density (g per cc)	Grain density (g per cc)	Porosity (percent)
Section east of West Bellows Creek			
R-122L	1.91	2.51	24
K	2.15	2.38	10
J	2.22	2.55	13
I	2.32	2.58	10
H	2.33	2.55	9
G	2.33	2.56	9
F	2.33	2.57	9
E	2.31	2.55	10
D	2.33	2.57	9
C	2.37	2.57	8
B	2.44	2.55	2
A	2.45	2.50	2
Section north of East Bellows Creek			
R-122Q	2.05	2.42	15
P	1.94	2.49	22
O	2.05	2.54	20
N	2.42	2.55	5
M	2.29	2.56	11
L	2.40	2.56	6
K	2.38	2.57	8
J	2.46	2.56	4
I	2.44	2.55	4
H	2.47	2.57	4
G	2.34	2.56	8
F	2.45	2.57	5
E	2.46	2.58	5
D	2.46	2.58	5
C	2.46	2.59	5
B	2.40	2.58	7
A	2.43	2.58	6

TABLE 16.—*Size analysis (millimeters) of phenocrysts and lithic fragments in the Wason Park Rhyolite*

[Median size is midpoint of size distribution by grain count]

Field No.	>1	½–1	¼–½	⅛–¼	<⅛	Median size	Grains counted
Section East of West Bellows Creek							
R-122L	7	10	24	20	38	0.27	268
K	10	11	15	18	46	.20	287
J	22	26	18	15	18	.60	175
I	27	23	22	14	15	.68	254
H	20	22	23	19	19	.52	223
G	31	24	25	10	11	.80	160
F	27	22	22	15	14	.68	269
E	18	25	18	16	23	.50	238
D	18	26	18	18	20	.54	227
C	22	18	21	12	27	.56	276
B	18	23	21	14	23	.50	337
A	19	23	20	17	21	.50	201
Section north of East Bellows Creek							
R-286Q	9	16	16	19	40	0.25	437
P	15	19	17	19	30	.37	358
O	19	17	19	13	32	.40	382
M	21	24	18	19	18	.50	370
N	26	22	20	15	17	.64	336
L	27	21	19	16	17	.64	344
K	27	21	21	16	15	.64	395
J	32	22	19	13	14	.82	301
I	32	22	18	13	15	.74	406
H	24	20	20	17	19	.56	443
G	28	26	18	16	12	.72	394
F	32	24	14	14	16	.71	321
E	35	21	15	14	15	.82	323
D	27	24	17	14	18	.68	404
C	33	19	18	12	18	.72	419
B	23	22	19	15	21	.56	330
A	21	24	19	14	22	.55	429

WEST BELLOWS CREEK SECTION

The section east of West Bellows Creek was sampled at irregular intervals where subtle changes in lithology suggested the possibility of ash-flow boundaries. The data for this section are plotted in profile form in figure 17. The bulk density (profile *A*) shows a maximum of 2.45 g per cc in the vitrophyre at the base of the section (sample A). It decreases steadily to 2.33 g per cc 150 feet above the vitrophyre (samples B–D), and then remains approximately uniform, between 2.31 and 2.35 g per cc, throughout the rest of the densely welded zone (samples E–I). The density then decreases rapidly to less than 2.0 g per cc in the partially welded rocks in the upper 50–100 feet of the formation (samples J and L). Samples K and L were taken from approximately the same position near the top of the section, but they differ greatly in the measured values of density and porosity. The differences are attributed to irregular silicification of the porous partially welded tuff of sample K, which was close to a weathered surface.

The grain density (profile *B*) is nearly constant throughout the densely welded zone. Lower densities occur near the base, where the sample is largely glass, and near the top, where the rocks are only partially welded and feldspar phenocrysts are least abundant.

The porosity (profile *C*) ranges from only 2 percent in the vitrophyre to as much as 25 percent in partially welded rocks. The rocks in the densely welded zone generally have less than 10 percent porosity.

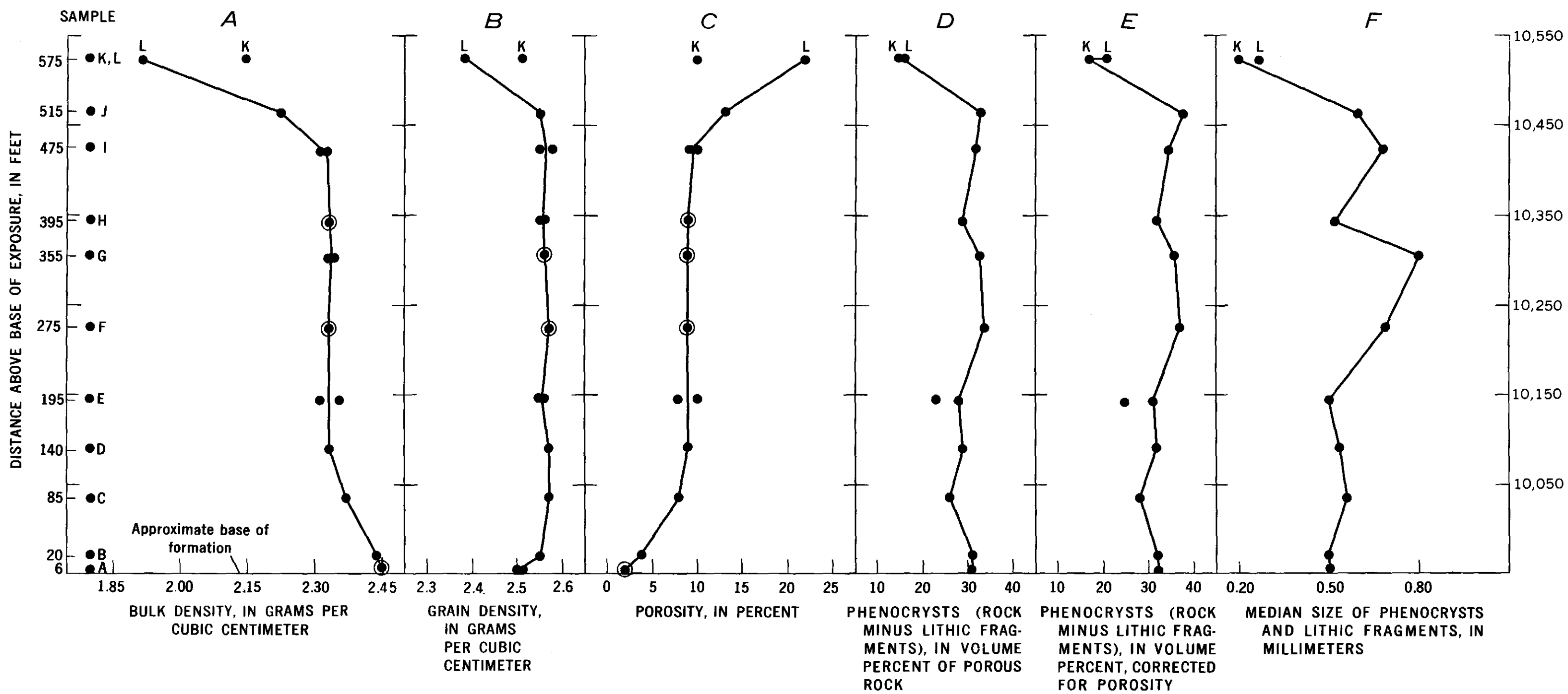
Phenocryst content (profile *D*) ranges from 23 to 34 percent in the zone of dense welding; it increases slightly toward the top of the zone and then decreases abruptly in the zone of partial welding. Phenocryst content corrected for porosity is shown in profile *E*.

Variation in the median size of phenocrysts and lithic fragments is shown in profile *F*. Comparison of this profile with profiles *D* and *E* shows a general parallelism between the abundance and size of phenocrysts in the section.

There are no breaks in the density, porosity, or phenocryst-abundance profiles for this section that can be interpreted confidently as partings between separate ash flows. A possible discontinuity in phenocryst abundance at position E, from 195 feet above the base of the section, was not confirmed by counting a second mode of the same specimen. The first mode was probably biased by a large pumice lapilli which made up about 25 percent of the thin section. The profile for the median size of phenocrysts and lithic fragments (profile *F*, fig. 17) can be divided into three parts by discontinuities in fragment size at samples E and H, but because stronger indications of discontinuities in the other profiles at these positions are lacking, flow boundaries are not postulated.

EAST BELLOWS CREEK SECTION

The section north of East Bellows Creek was sampled at intervals of approximately 40 feet. The base of



EXPLANATION

● Single determination of density, porosity, or other item

●● Duplicate or replicate determinations of density or porosity

◉ Duplicate or replicate determinations with same value

FIGURE 17.—Profiles summarizing physical and petrographic properties of Wason Park Rhyolite in stratigraphic section east of West Bellows Creek. Density measurements and calculations by William Allen.

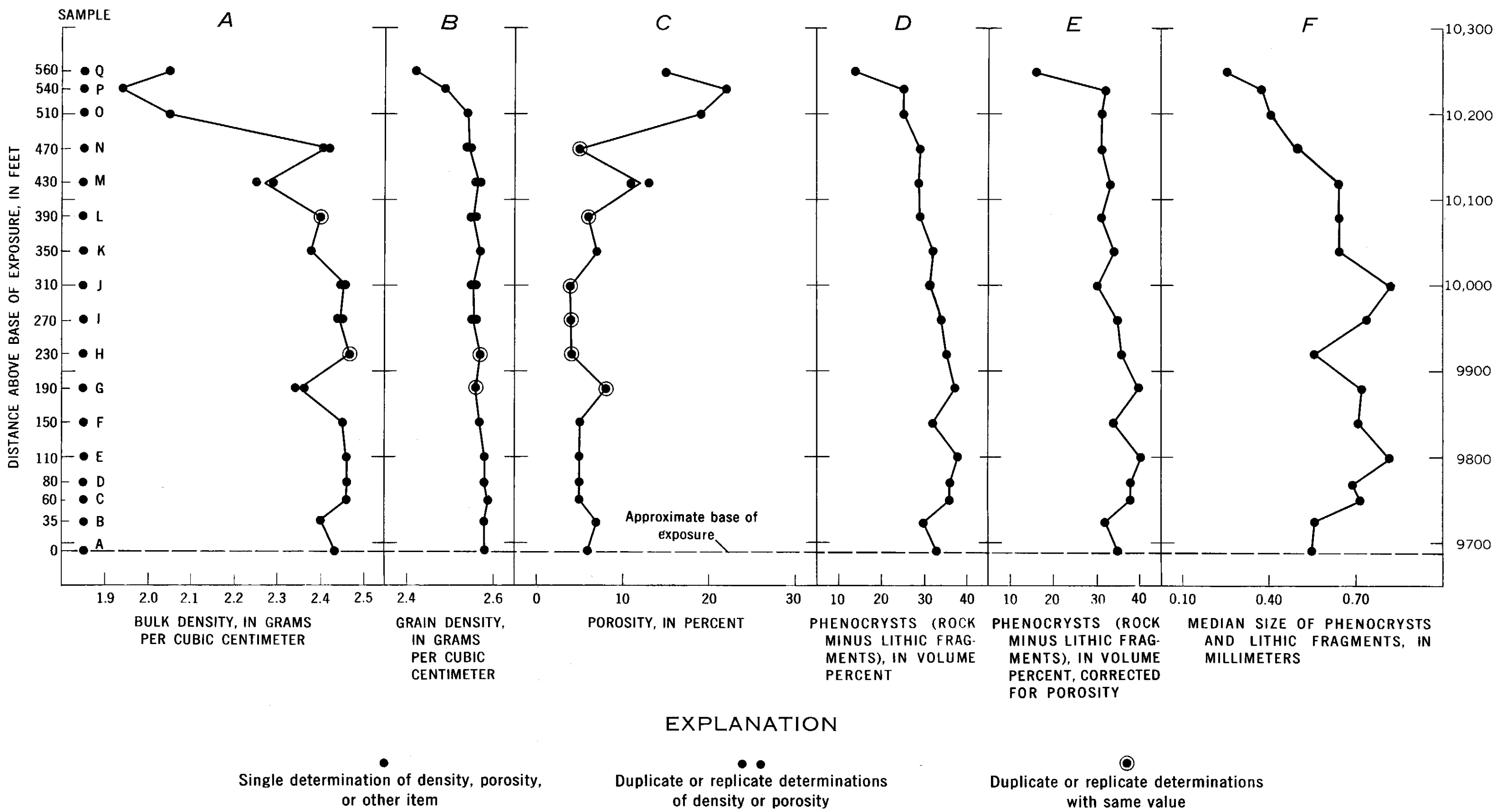


FIGURE 18.—Profiles summarizing physical and petrographic properties of the Wason Park Rhyolite in stratigraphic section north of East Bellows Creek. Density measurements and calculations by William Allen.

the Wason Park Rhyolite is not exposed at this place, but there can be at most only a few tens of feet of section beneath the lowest sampled outcrops. The physical and petrographic variations in this stratigraphic section are summarized in figure 18. Discontinuities in density and porosity (profiles *A* and *C*) indicate the possibility of three ash-flow boundaries near samples B, G, and M. Discontinuities in profiles *D*, *E*, and *F* are generally displaced up or down with respect to the breaks in porosity and density, except at sample B. Discontinuities between 150 and 230 feet (samples F and H) in all of the profiles except *B* correlate roughly with weak lithologic changes in the outcrops. Thus between 190 and 230 feet above the base of the section a concentration of coarse collapsed pumice fragments with miarolitic lenses grades upward into more massive rock containing fewer and smaller pumice fragments. This change is accompanied by a general decrease in the abundance of lithic inclusions in the upper half of the section, which also contains zones of particularly massive welded tuff.

In summary, a comparison of profiles of stratigraphic sections along East and West Bellows Creeks shows little correlation between Wason Park sections 2½ miles apart, although weak discontinuities occur in some profiles of both sections. Any one or all of the discontinuities could be related to changes in the materials or mechanics of a single continuous eruption, and thus are not necessarily indicative of ash-flow boundaries. However, it is difficult for us to conceive of a single ash flow having the volume of the Wason Park Rhyolite. Thus we consider the discontnuities in the profiles to be a first approximation in the breakdown of the Wason Park cooling unit into ash-flow units. The lack of breaks in the density and porosity profiles of the West Bellows Creek section suggests very rapid deposition and complete welding of hot ash flows if the section is a multiple-flow simple cooling unit as indicated by the corresponding profiles of the East Bellows Creek section.

SNOWSHOE MOUNTAIN QUARTZ LATITE

DISTRIBUTION AND SOURCE

The Snowshoe Mountain Quartz Latite forms a cylindrical block of crystal-rich ash flows which occur only in the central core of the Creede caldera. Larsen and Cross (1956, p. 132, 138) considered these rocks to be the product of a local volcano, possibly a single large lava flow; they assigned them to the upper rhyolite latite member of their Alboroto Rhyolite and thus placed the rocks within one of the older formations of their sequence. However, we have found that the Snowshoe Mountain rocks represent one of the youngest units in the volcanic sequence of the Creede area (Steven and Ratté, 1964).

Snowshoe Mountain Quartz Latite is presently confined to the core of the Creede caldera, where it apparently accumulated concurrently with caldera subsidence. Thus, it seems reasonable to conclude that the formation was erupted somewhere within this same subsided block. Careful mapping of all exposed parts of the caldera core has failed to disclose a vent, and we can only conclude that the source of the ash flows was not within the exposed part of the caldera core. The margin of the subsided block, on the other hand, is almost everywhere covered by postcaldera rocks (Creede Formation and Fisher Quartz Latite) or by surficial deposits which may mask the vent or vents through which the Snowshoe Mountain Quartz Latite was erupted. Deductively, ring fractures along the broken margin of the subsiding block would provide a route for ready access of magma to the surface, and there is some evidence that the source of the ash flows was so localized. A zone of partially welded tuff at the top of the Snowshoe Mountain thickens southward around the east half of the caldera, and partially welded partings deeper in the formation grade northward into densely welded tuff. Inasmuch as lateral transitions from partially welded to densely welded tuff theoretically point toward the source, a source along the covered north margin of the caldera is indicated.

Subsidence of the caldera evidently accompanied eruption of the Snowshoe Mountain, and crumbling of the caldera walls caused avalanches that spread into the caldera. Blocks of Wason Park Rhyolite can be recognized in some tongues of avalanche debris that extend as much as a mile into the pile of Snowshoe Mountain Quartz Latite, indicating that the Snowshoe Mountain ash flows are younger than the Wason Park Rhyolite.

Quartz latite ash flows from other sources, as the Rat Creek Quartz Latite and Nelson Mountain Quartz Latite, which crop out north of Creede, also are younger than the Wason Park Rhyolite. They are thought to be of the same general age as the Snowshoe Mountain (fig. 11), but they were derived from the San Luis Peak cauldron and are nowhere in contact with the Snowshoe Mountain.

The Snowshoe Mountain Quartz Latite is of great but unknown thickness—its base is nowhere exposed. At least 4,000–6,000 feet of it is exposed on the sides of a complex graben that extends south across the caldera core in the vicinity of Deep Creek (pl. 1). The exposed Snowshoe Mountain rocks in the caldera core can be represented by a cylinder 10 miles in diameter, at least 1 mile thick, and having a volume of about 78.5 cu mi or 330 cu km. Thus, although the volume of the unexposed part is unknown, the Snowshoe Mountain is of magnitude 6 in the scale of Smith

(1960a), and is comparable in volume with the other large ash-flow sheets of the Creede caldera.

GENERAL LITHOLOGY

The Snowshoe Mountain Quartz Latite, which consists mainly of densely welded crystal-rich ash flows, is clearly an example of a composite ash-flow sheet. The ash flows were deposited in rapid succession within the subsiding core of the Creede caldera, where most of them were welded together without visible partings. The absence of vitrophyres from the pile further indicates the rapidity with which most of the ash flows succeeded one another. Locally, however, the formation shows compound cooling characteristics with vertical and lateral changes in welding and changes in the abundance and size of phenocrysts, and along the west flank of the core of the caldera tongues of talus and landslide breccia from the caldera walls intertongue with the ash flows and confirm the composite character of the deposit.

When observed from a distance, the upturned edges of several thousand feet of Snowshoe Mountain ash flows on the northwest flank of the caldera core present a distinct layered aspect. This layering occurs in densely welded rocks, which on close inspection show only a faint compaction foliation and parallel discontinuous joints. The gross layering that is so clear from a distance is of no help in subdividing the outcrops into ash-flow units.

In other parts of the deposit, however, vertical and lateral changes from densely to partially welded rocks indicate that the thick mass of Snowshoe Mountain welded tuffs resulted from the accumulation of many successive ash flows. Most important is a zone of relatively soft partially welded tuff that forms the upper part of the deposit. The soft tuff occurs on the northwest flank of the caldera core only in scattered patches, but it is almost continuous along the outer edge of the core in the eastern half of the caldera. Small patches of similar tuff are present at the top of some deeply infaulted blocks in a graben across the central part of the caldera. This transition from a zone of dense welding to one of partial welding at the top of the formation is the only lithologic change that can be followed throughout the body of Snowshoe Mountain Quartz Latite. The base of the partially welded zone shifts up and down along the east flank of the caldera but in general descends stratigraphically to the south and east, and the zone of partially welded rocks thickens correspondingly.

Other partings marked by partially welded tuff can be recognized deeper within the body, and in three areas significant thicknesses of Snowshoe Mountain ash flows change laterally from densely to partially welded tuff. The partings are generally only a few feet to a few tens of feet thick; in places they extend as much as 2 miles before they fade out into densely welded rock, but elsewhere they can be followed only a few tens of feet. In places, the partings separate rocks that contain phenocrysts of contrasting size, but more commonly they separate identical rock types. Some of the partially welded rocks were traced into breccia tongues near the margin of the deposit and others contain scattered fragments from older formations exposed outside the caldera.

The zones of partially welded tuff are the only mappable units in the formation, and the partially welded zone at the top of the deposit provides the main stratigraphic control for structural interpretations in the caldera core.

Local variations in the size and abundance of phenocrysts in Snowshoe Mountain rocks probably are related in part at least to ash-flow boundaries. The phenocrysts are more conspicuous in some rocks than in others, but their prominence generally reflects their average size rather than their relative abundance. However, certain layers in the upper part of the ash-flow sequence, along the western fllank of the caldera core, contain fewer as well as smaller crystals than the average. Rocks containing phenocrysts of distinctive size locally form vague units having gradational contacts that were traced for distances of a few hundred feet to more than a mile. These units are several tens to several hundreds of feet thick, and they parallel the general layering of the ash flows. Changes in the abundance or size of phenocrysts appear to be associated with changes in welding in some places, but, more commonly, no such relationship was observed. The phenocryst content of the rocks is most variable in the northern and western parts of the caldera core.

Mixed breccias derived by avalanching of older rocks from the caldera walls (Steven and Ratté, 1960, p. B14) form several tongues extending into the Snowshoe Mountain Quartz Latite along the western flank of the caldera, and they also cap the Snowshoe Mountain ash flows in some of the fault blocks in the graben along Deep Creek. Avalanche breccias probably are intertongued with ash flows in other parts of the core also, but they have been recognized only in the western half, where the ash-flow sequence is most completely exposed. Small pods and individual fragments of similar breccia occur here and there in local partings within the ash-flow deposit, and some partings of partially welded rocks can be traced into larger tongues and masses of the avalanche breccia. These relations have been interpreted (Steven and Ratté, 1960, p. B14) as indicating subsidence concurrent with deposition of the Snowshoe Mountain ash flows and as requiring episodic accumulation of the ash flows within the caldera walls. The Snowshoe Mountain ash flows above and below the tongues of breccia must have cooled independently, and thus, at least locally, have formed separate cooling units. Toward the center of the caldera, the breccia tongues pinch out along tuffaceous partings, which in turn grade into densely welded rocks that apparently cooled as a unit.

PETROGRAPHY AND COMPOSITION

Snowshoe Mountain Quartz Latite consists largely of crystal-rich welded tuff in which phenocrysts constitute about half the rock and give it a gross granular appearance. The matrix of the welded tuff determines its general color. Densely welded rocks range from red to shades of gray, depending on the degree of oxidation of the matrix. Less welded rocks range from light red to pink or are streaked with pink, cream, and light-gray colors. Most phases of the Snowshoe Mountain Quartz Latite have virtually identical counterparts in the Rat Creek and Nelson Mountain Quartz Latites outside the caldera.

Pumice fragments in densely welded Snowshoe Mountain rocks are represented generally by obscure clots that are nearly indistinguishable from the rest of the rock except in thin sections, where they can be recognized by larger and less broken phenocrysts than those in the matrix of the welded tuff. In some outcrops, however, pumice blocks are distinctvely lighter in color than the rest of the rock (fig. 19), particularly in less welded tuffs, where vestiges of original tubular structure may be preserved in the pumice.

All the Snowshoe Mountain ash flows observed have a completely devitrified matrix that is structureless in hand specimens but microeutaxitic in thin sections. This devitrified matrix consists of cryptocrystalline spherulitic to microgranular aggregates having a unit index of refraction less than that of Canada balsam. Former pumice fragments range from clearly defined clots containing coarser devitrification products than the rest of the matrix to vague masses that are difficult to distinguish from the enclosing matrix. Some of the fragments have a "ruled" structure that may represent collapsed tubular vesicles. The original fragmental texture of many of the densely welded rocks has been largely destroyed by spherulitic crystallization or is concealed by a brown cloud of fine dusty granules, but it is preserved in some of the less welded tuffs. Although partially welded tuff lacks a strong eutaxitic structure, it is relatively porous except as irregularly streaked by densely welded materials.

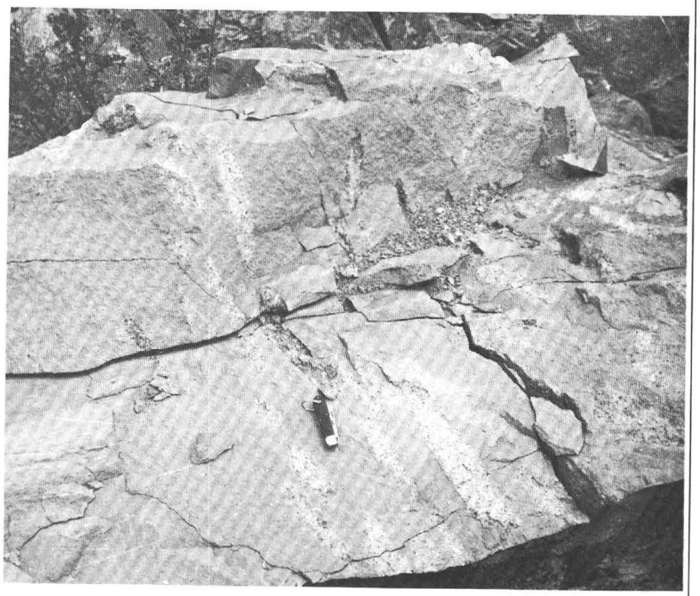


FIGURE 19.—Pumice blocks (light-colored masses) in welded tuff of the Snowshoe Mountain Quartz Latite.

A summary of 35 modes of Snowshoe Mountain Quartz Latite is shown in table 17A. The modes represent suites of samples from several different parts of the formation, and therefore are deemed representative of the entire formation. The greater range in modal composition within suites than between averages of suites indicates a moderately uniform modal composition throughout the deposit. This uniformity is further documented by the small range in the abundance of different phenocrysts throughout the deposit. Thus, only the average mode and the range in composition for the formation as a whole is given in table 17*A*.

Phenocryst content of the Snowshoe Mountain rocks ranges from 34 to 58 percent and averages 48 percent. Poorly welded rocks commonly contain fewer phenocrysts than the associated densely welded rocks, which are much more voluminous. Three-fourths of the phenocrysts are plagioclase. Biotite, the most abundant mafic phenocryst, makes up about 5 percent of the average rock. Sanidine, quartz, clinopyroxene, and magnetite are all common but minor phenocrystic minerals in the average Snowshoe Mountain rock; hornblende, sphene, apatite, and zircon occur in accessory amounts.

Plagioclase phenocrysts range from euhedral tablets 2–3 mm long to tiny crystal chips. Crystals of small to intermediate size generally predominate and give most of the rocks an overall fragmental appearance. The average composition of the plagioclase is sodic andesine (about An_{36}), and the composition of individual unzoned phenocrysts ranges from An_{30} to An_{50}. However, most of the phenocrysts show progressive or irregular oscillatory zoning and a difference of about 10 percent in anorthite content between core and rim.

TABLE 17.—*Modes (volume percent) of Snowshoe Mountain, Rat Creek, and Nelson Mountain Quartz Latites*

[P, present in trace amounts]

	Matrix	Phenocrysts	Plagioclase (percentage of phenocrysts)	Sanidine	Quartz	Biotite	Pyroxene	Hornblende	Magnetite	Points counted
***A.* Snowshoe Mountain Quartz Latite** [Summary of 35 modes]										
Average	52	48	35(75)	1.3	2.2	5.4	1.5	<1	1.8	1,073
Range	42–66	34–58	25–42(72–74)	.5–2.6	1.2–4.2	1.6–9.3	0–3.5	0–1.8	.7–3.0	640–1,340
***B.* Comparison of modes of densely welded Snowshoe Mountain Quartz Latite and an included pumice lapilli**										
Densely welded tuff	48	52	35(67)	2.9	2.5	6.5	3.0	0	2.1	1,098
Pumice lapilli	60	40	29(73)	P	.2	4.4	3.2	.4	2.4	889
***C.* Rat Creek Quartz Latite** [Summary of 18 modes]										
Average	69	31	24(77)	<1	<1	3.5	<1	<1	1	972
Range	56–76	24–44	17–34(68–83)	0–3	0–1	2–5	0–2	0–3	1–4	584–1,258
[Summary of 10 modes of lavas from cone complex along West Willow Creek]										
Average	76	24	19(79)	<1	<1	4	<1	<1	1	683
Range	68–80	20–32	16–22(69–83)	0–1	0–1	2–5	0–1	0–1	0–2	568–1,046
***D.* Nelson Mountain Quartz Latite** [Summary of 27 modes]										
Average	68	32	24(75)	1	P	4	1	P	1	809
Range	55–79	21–45	11–35(58–84)	0–7	0–2	2–7	0–4	0–2	0–2	493–1,083

Biotite constitutes about 10 percent of the phenocrysts. It occurs as euhedral books and bent to broken plates, and commonly is partly or completely oxidized. Fresh crystals are yellowish brown to brown; oxidized crystals are reddish brown to deep red, and contain opaque granules and colorless mica at their borders and along cleavage planes. Completely oxidized biotite is an aggregate of opaque granules that can be recognized as former biotite only by the form of the opaque aggregate.

Sanidine and quartz phenocrysts are common in all the Snowshoe Mountain rocks. The sanidine is in nearly euhedral rectangular crystals, crystal fragments, and deeply embayed grains, and in places it is intergrown with plagioclase crystals. Quartz phenocrysts are commonly rounded and are also deeply embayed, and some are the doubly terminated short prisms typical of high temperature quartz.

Euhedral crystals of augitic pyroxene are present in nearly all of the thin sections, and where absent, are inferred to have been lost in the preparation of the sections. Some pyroxene phenocrysts in Snowshoe Mountain rocks have overgrowths of hornblende; one grain was observed to have a core of pyroxene and a mantle of hornblende, which in turn had a reaction rim of pyroxene and magnetite.

Euhedral hornblende phenocrysts are widespread in this formation but generally are much less common than pyroxene phenocrysts. They range from yellow-green hornblende to brown oxyhornblende, and are represented also by aggregates of hematite, pyroxene, and other materials. Some hornblende phenocrysts have reaction rims of pyroxene and magnetite.

The euhedral form of most of the mafic phenocrysts indicates that they formed largely within the magma chamber. By analogy with other ash-flow units in the Creede area, the alteration and reaction relations are later phenomena associated with the eruptive stage of the magma or the cooling history of the ash flows. These other units contain altered mafic phenocrysts similar to those in the Snowshoe Mountain, but the mafic crystals in their vitrophyres are virtually unaltered. The Snowshoe Mountain contains no vitrophyre.

In all the crystal-rich ash-flow deposits in the Creede area, we have noticed that collapsed pumice lapilli contain fewer and less broken phenocrysts than do the welded fragmental material enclosing them. Similar relations elsewhere have been ascribed to a winnowing action that takes place during eruption, when the pyroclastic debris may separate into a dense ash flow and a superincumbent ash cloud (Hay, 1959). By means of this mechanism, part of the finer crystal fragments and vitric ash form the cloud, whereas the coarser pumice fragments and most of the phenocrysts are concentrated in the ash flow. Thus the matrix of the ash flow is depleted somewhat of fine constituents, but the original ratio of phenocrysts to matrix is preserved in the larger pumice blocks, except as modified by welding and compaction. Modes in table 17*B* represent densely welded tuff and an enclosed pumice lapilli in the Snowshoe Mountain that show this relationship. The relative abundance of the phenocrysts, with the exception of sanidine and quartz, is virtually the same in both phases.

Chemical analyses, norms, and spectrographic analyses of three samples of Snowshoe Mountain Quartz Latite are presented in table 18. Samples 1 and 2 represent densely welded tuff in the upper part of the formation. Sample 3 represents an inclusion believed to be a cognate pumice block in the welded tuff of sample 2; it contains some secondary calcite replacing plagioclase and pyroxene. All three samples are quartz latites in Rittmann's chemical classification of volcanic rocks.

COMPARISON WITH SIMILAR ASH FLOWS OUTSIDE THE CREEDE CALDERA

Welded ash flows of the Rat Creek and Nelson Mountain Quartz Latites, which cap many of the high ridges north of Creede and extend to within 2 miles of the Creede caldera (pl. 1), are similar petrographically and chemically to the Snowshoe Mountain Quartz Latite. All three formations are younger than the Wason Park Rhyolite and older than the Fisher Quartz Latite and thus are similar in stratigraphic position also. These similarities indicate a possible close genetic relation, but field relationships suggest a source for the Rat Creek and Nelson Mountain to the north of the Creede caldera, even though all three units may be comagmatic.

The Rat Creek Quartz Latite forms a sheet of nonwelded to densely welded ash-flow tuffs and air-fall pyroclastic rocks ranging in thickness from a few hundred feet to as much as 800 feet over a wide area near the Continental Divide, from Wheeler Monument, near the head of Bellows Creek, to Spring Creek Pass, 4–5 miles west of the head of Miners Creek (pl. 1). An ash-flow cooling unit 100–200 feet thick occurs at the top of the formation, from East Willow Creek to Miners Creek. This unit has a basal vitrophyre zone a few feet thick that is in gradational contact with underlying nonwelded tuff. The vitrophyre grades upward into devitrified densely welded tuff 50–100 feet thick, which in turn grades into partially welded tuff in a thin zone at the top of the formation. A local cone of intrusive and extrusive rocks on upper West Willow Creek has a central plug of perlitic obsidian flanked by air-fall tuffs and porphyritic lavas that intertongue laterally with the ash-flow sheet. This vent may have supplied some of the ash-flow tuffs as well as the local cone deposits.

The Nelson Mountain Quartz Latite forms a widespread composite ash-flow sheet 300–400 feet thick that overlies the Rat Creek Quartz Latite throughout much

TABLE 18.—*Chemical analyses, norms, and spectrographic anlayses of the Snowshoe Mountain, Rat Creek, and Nelson Mountain Quartz Latites*

[Sample localities described with reference to Creede and Spar City 15-minute quadrangle topographic maps (1959)]

Formation	Snowshoe Mountain Quartz Latite			Rat Creek Quartz Latite			Nelson Mountain Quartz Latite				
Sample No.	1	2	3	1	2	3	1	2	3	4	5
Field No.	S-54-13	S-56A	S-56B	C-375A	C-590	S-269	C-583	C-980	C-1047C	C-1048	La G-174
Laboratory No.	D1422	153105	153106	D1424	D100038	D100037	D1298	D1299	D1300	D1301	----------
Chemical analyses (weight percent)											
[Leaders indicate not determined. Analysts: 1, M. Seerveld; 2, S. D. Botts; 3, H. H. Thomas; 4, M. D. Mack; 5, Christel L. Parker; 6, George Steiger (Larsen and Cross, 1956)]											
SiO_2	61.71	66.0	62.4	69.88	66.67	62.71	65.05	64.28	63.51	66.65	65.34
Al_2O_3	16.45	15.4	15.4	12.70	14.45	16.01	15.20	16.13	15.60	15.66	16.00
Fe_2O_3	4.58	2.6	2.9	3.71	1.78	3.41	2.79	4.01	2.74	3.52	3.96
FeO	.99	2.0	2.1	.41	1.04	.99	.99	.54	1.80	.30	.61
MgO	1.75	1.3	1.3	.77	.95	1.62	1.26	1.02	1.61	.63	.78
CaO	4.28	3.2	5.4	2.59	2.64	3.65	3.25	3.36	3.67	2.57	3.61
Na_2O	3.60	3.5	3.5	2.69	3.28	3.00	3.25	3.52	3.58	3.47	3.96
K_2O	3.55	4.3	3.6	3.17	3.90	4.30	4.00	3.99	3.72	4.44	3.59
H_2O+	.92	} .88	} 1.1	.87	3.31	2.48	1.13	.75	2.15	.77	.38
H_2O-	.50			1.98	1.00	.72	1.16	.90	.28	.75	.52
TiO_2	.68	.55	.54	.50	.40	.57	.51	.60	.59	.52	.59
P_2O_5	.29	.22	.24	.20	.15	.25	.20	.25	.26	.21	.18
MnO	.09	.10	.14	.03	.10	.11	.11	.05	.10	.05	.09
ZrO_2	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	.04
CO_2	.04	.13	1.4	.03	.02	.01	.83	.05	.01	.05	0
Cl	.03	----------	----------	.02	.05	.05	.02	.02	.07	.01	----------
F	.10	----------	----------	.07	.07	.08	.07	.08	.07	.07	----------
Subtotal	99.56	----------	----------	99.62	99.81	99.97	99.82	99.55	99.76	99.67	----------
Less 0	.05	----------	----------	.04	.04	.04	.03	.03	.05	.03	----------
Total	99.51	100	100	99.58	99.77	99.93	99.79	99.52	99.71	99.64	99.73
Density (powder)	2.72	2.58	2.61	2.48	2.45	2.54	----------	----------	----------	----------	----------
Density (bulk)	2.57	2.39	2.46	2.20	----------	----------	----------	----------	----------	----------	----------
Analysts	1	2, 3, 4	2, 3	1	5	5	1	1	1	1	6
Date of analysis	1957	1958	1958	1957	1963	1963	1957	1957	1957	1957	1925

TABLE 18.—*Chemical analyses, norms, and spectrographic analyses of the Snowshoe Mountain, Rat Creek, and Nelson Mountain Quartz Latites*—Continued

Formation	Snowshoe Mountain Quartz Latite			Rat Creek Quartz Latite			Nelson Mountain Quartz Latite				
Sample No.	1	2	3	1	2	3	1	2	3	4	5
Field No.	S-54-13	S-56A	S-56B	C-375A	C-590	S-269	C-583	C-980	C-1047C	C-1048	La G-174
Laboratory No.	D1422	153105	153106	D1424	D100038	D100037	D1298	D1299	D1300	D1301	----------
Norms											
[Secondary calcite in mode replacing plagioclase and pyroxene]											
Q	17.1	20.1	19.7	37.3	27.2	19.8	23.4	21.1	20.0	24.3	20.8
or	21.4	25.7	22.3	19.4	24.2	26.1	24.6	24.2	22.7	26.8	21.6
ab	30.9	30.8	31.0	23.6	29.2	26.1	28.6	30.5	30.7	30.0	33.9
an	18.7	13.4	16.3	11.7	12.4	17.5	15.1	15.1	16.3	11.0	15.4
C	----------	----------	----------	.7	.5	.5	.1	.6	----------	1.2	----------
wo	.3	.6	.4	----------	----------	----------	----------	----------	.2	----------	.7
en	4.4	3.2	3.3	2.0	2.5	4.1	3.1	2.6	4.1	1.6	1.9
fs	----------	.8	.8	----------	----------	----------	----------	----------	.2	----------	----------
mt	1.5	3.9	4.4	----------	2.7	2.0	2.1	.2	4.1	----------	.6
il	1.3	1.0	1.0	.9	.8	1.1	1.0	1.1	1.1	.7	1.1
hm	3.6	----------	----------	3.8	----------	2.2	1.3	4.0	----------	3.5	3.6
ap	.7	.5	.6	.5	.4	.6	.5	.6	.6	.5	.4
tn	----------	----------	----------	----------	----------	----------	----------	----------	----------	.3	----------

Spectrographic analyses

[Q, quantitative analyses in percent; overall accuracy ±15 percent, except that analyses are less accurate near limits of detection where only one digit is reported. SQ, semiquantitative analyses in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15 and 0.1, . . .; numbers represent approximate midpoints of data on a geometric scale. The assigned group for semiguantitative results will include the quantitative value about 30 percent of the time. nd, not detected; leaders, not looked for. Analysts: 1, P. R. Barnett; 2, N. M. Conklin; 3, J. C. Hamilton]

Type of analysis	Q	Q	Q	Q	SQ	SQ	Q	Q	Q	Q	----------
B	nd	0.002	0.001	nd	nd	nd	nd	nd	nd	nd	----------
Ba	.1	.074	.082	.1	.15	.2	.1	.1	.1	.1	----------
Be	nd	.0001	.0001	nd	.0003	.0002	nd	nd	nd	nd	----------
Co	.001	.0009	.001	.001	.0007	.001	.0009	.001	.001	.0009	----------
Cr	.001	.0018	.0018	.001	.0003	.0005	.0008	.001	.001	.0005	----------
Cu	.002	.0024	.0019	.001	.0015	.003	.002	.002	.002	.001	----------
Ga	.002	.0016	.0018	.0008	.003	.003	.001	.001	.001	.001	----------
La	nd	<.005	<.005	.01	.007	.007	.01	.01	.01	.01	----------
Mo	nd	<.0002	.0002	nd	nd	nd	nd	nd	nd	nd	----------
Nb	.002	.002	.002	.002	.0015	.0015	.002	.002	.002	.002	----------
Nd	----------	----------	----------	----------	.015	.015	----------	----------	----------	----------	----------
Ni	.0009	.0006	.0005	.0008	.0003	.0005	.0007	.0008	.0007	.0006	----------
Pb	.003	.001	.001	.006	.003	.002	.003	.003	.003	.004	----------
Sc	.002	.0008	.0010	.001	.0007	.001	.001	.001	.001	.001	----------
Sr	.07	.056	.084	.05	.1	.1	.05	.07	.06	.04	----------
V	.01	.0090	.010	.007	.005	.01	.007	.009	.009	.006	----------
Y	.004	.003	.003	.003	.003	.003	.005	.004	.004	.003	----------
Yb	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0002	----------
Zr	.02	.015	.014	.02	.015	.02	.02	.02	.02	.02	----------
Analyst	1	2	2	1	3	3	1	1	1	1	----------
Date	1958	1959	1959	1958	1963	1963	1958	1958	1958	1958	----------

Snowshoe Mountain Quartz Latite:
1. Devitrified densely welded tuff from the southwest flank of Snowshoe Mountain at an elevation of about 10,800 ft, and approximately 4,000 ft east-southeast of NE cor. sec. 8, T. 40 N., R. 1 W., Spar City quadrangle.
2. Devitrified densely welded tuff from talus blocks beneath cliffs in NE¼ sec. 28, T. 41 N., R. 1 W.
3. Collapsed pumice block included in the densely welded tuff of sample 2.

Rat Creek Quartz Latite:
1. Partially welded tuff near top of Rat Creek welded tuff, at elevation of approximately 11,800 ft, on southwest slope of Nelson Mountain.
2. Perlitic vitrophyre in plug of Rat Creek cone east of upper West Willow Creek.
3. Devitrified densely welded tuff containing eutaxitic streaks of black vitrophyre from the middle part of formation, elevation about 11,400 ft; ½ mile west of Wheeler Monument.

Nelson Mountain Quartz Latite:
1. Devitrified densely welded tuff in lower part of formation at elevation of about 11,400 ft, on east side of upper West Willow Creek, at top of clearing about 1 mile south of Equity mine.
2. Devitrified densely welded tuff at elevation of about 12,400 ft, 7,000± ft east of the Equity mine.
3. Perlitic vitrophyre from possible vent area near Continental Divide at head of west fork of East Willow Creek; elevation about 12,600 ft.
4. Partially welded tuff near top of formation, from flat-topped surface at about 12,200-ft elevation, between Whited Creek and upper East Willow Creek.
5. Densely welded(?) tuff from south-facing cliffs near top of Nelson Mountain; collected and described by Larsen and Cross (1956, table 21, No. 40).

of the area north of the Creede caldera. It also occurs as a large mass of densely welded tuff at least 3,500 feet thick in the San Luis Peak area, where it apparently fills a large cauldron structure (Steven and Ratté, 1963, 1964). The history of formation of the San Luis Peak caldera is complex and not well understood, but the subsidence, in part at least, resulted from eruption of the Nelson Mountain Quartz Latite.

The petrographic character of the crystal-rich Nelson Mountain ash flows, as shown in figures 20 and 21, is typical of most of the quartz latitic ash flows in the Creede area, including the Snowshoe Mountain Quartz Latite. Particularly common in both the Nelson Mountain and Snowshoe Mountain are crystal-rich densely welded rocks like those shown in figure 20 *A*, *B*, and *F* and in thin section in figure 21*E*. Figure 20*C* shows fine-grained partially welded tuff near the top of the Nelson Mountain Quartz Latite; its vitroclastic texture and axiolitic structure are shown in figure 21*F*. Figure 20 *D*, *E*, and *F* shows the nature of deformed pumice fragments in hand specimens of devitrified welded tuff, and photomicrographs of deformed pumice in both devitrified and glassy welded tuffs are shown in figure 21 *A*–*D*. Figure 21 *B* and *C* shows how obscure microtextures in densely welded tuffs may be delineated better by use of reflected light than by transmitted light in thin-section studies. In photomicrographs *D* and *E* (fig. 21), phenocrysts can be seen included within some pumice fragments. In general, the pumice fragments do not contain the abundant tiny chips and crystal fragments that are scattered throughout the rest of the rock.

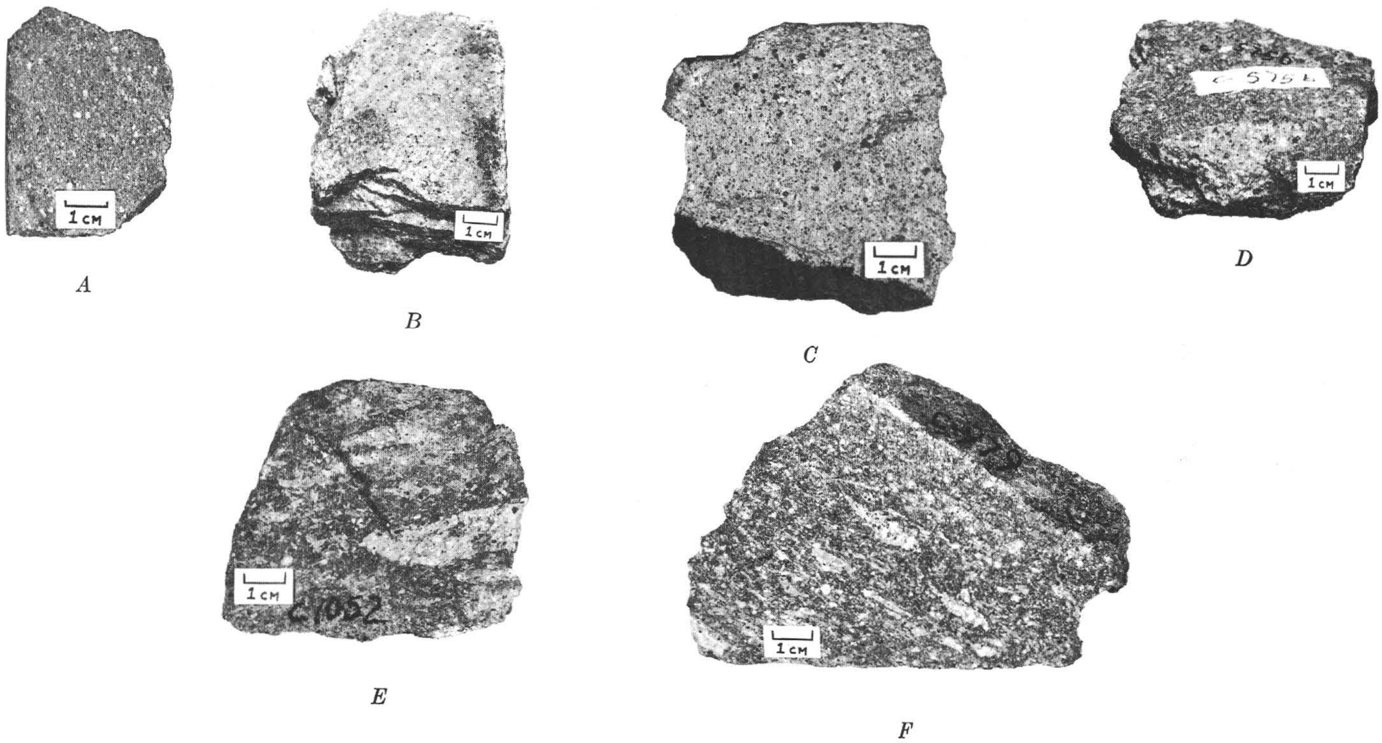
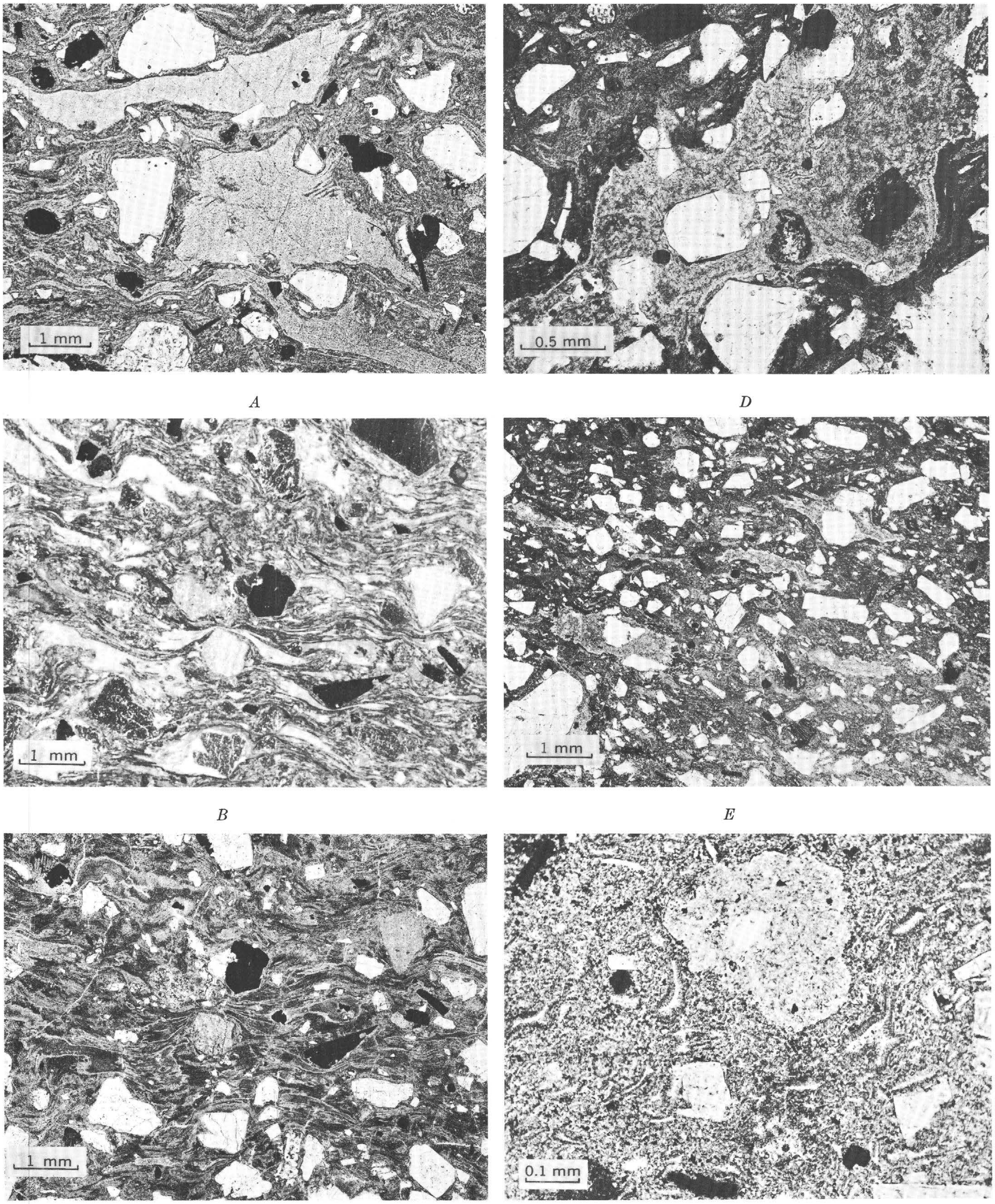


FIGURE 20.—Typical textures and structures in quartz latite welded tuffs in the Creede area as shown by specimens of Nelson Mountain Quartz Latite. *A, B,* Fine-grained crystal-rich densely welded tuff with strong compaction foliation and weak eutaxitic structure, from the upper part of the densely welded zone. *C,* Fine-grained partially welded tuff from the vapor-phase zone in the upper part of the Nelson Mountain Quartz Latite. *D, E, F,* Eutaxitic structure and deformed pumice lapilli in specimens of densely welded tuff.

Average modes of Rat Creek Quartz Latite and Nelson Mountain Quartz Latite (table 17 *C, D*) show that the rocks of both formations contain about 30 percent phenocrysts. Three-fourths of the phenocrysts are plagioclase; the rest are mainly biotite and magnetite and small amounts of quartz, clinopyroxene, and hornblende. As compared with average Snowshoe Mountain Quartz Latite (table 17*A*), these formations contain fewer phenocrysts and disproportionately fewer quartz phenocrysts.

Chemical and spectrographic analyses and norms of the three quartz latite welded tuff formations are listed in table 18. All the analyzed rocks are quartz latites, according to Rittmann's chemical classification, but the Rat Creek Quartz Latite and, to a lesser extent, the Nelson Mountain are slightly more rhyolitic than the Snowshoe Mountain Quartz Latite. The average ratio of $CaO:Na_2O+K_2O$ for the Rat Creek and Nelson Mountain is 0.44, in contrast to 0.59 for the Snowshoe Mountain. Rat Creek samples 1 and 2 and Nelson Mountain sample 4 also contain relatively high SiO_2 and normative quartz. For Rat Creek sample 1 and the Nelson Mountain sample, the anomaly may represent secondary silica, because both rocks were exposed close to the top of their respective formations near a weathered surface. Rat Creek sample 3, however, represents a glassy rock which is virtually unaltered except for hydration of the glass. The spectrochemical analyses show all of the quartz latites to be similar in minor-element content. The high

FIGURE 21.—Typical microscopic textures and structures of quartz latite welded tuffs in the Creede area as illustrated by Nelson Mountain Quartz Latite. *A,* Basal vitrophyre with eutaxitic matrix of squashed pumice; large pumice blobs are not greatly flattened. *B,* Eutaxitic structure in lower part of formation; pumice fragment shown near center of picture is attenuated in the middle by compaction against a lithic fragment. (Reflected light.) *C,* Thin section of *B* observed in transmitted light; note the relatively poor definition of eutaxitic pumice fragments as contrasted with *B*. *D,* Pumice fragment containing phenocrysts in densely welded tuff; crystal chips are most abundant in matrix outside the pumice, but feldspar phenocryst in center of pumice also is broken; pumice matrix consists of fine granophyre with a narrow pectinate border. *E,* Weak eutaxitic structure in the upper part of the densely welded zone; rock is littered with crystal debris; some wispy pumice fragments contain feldspar phenocrysts. *F,* Vitroclastic poorly welded tuff in the vapor-phase zone at the top of the formation; note axiolitic structure of relict shards.



A *D*

B *E*

C *F*

FIGURE 21.—For explanation see opposite page.

barium content of two of the Snowshoe Mountain rocks possibly reflects some secondary barite, although that mineral was not detected in the modes.

FISHER QUARTZ LATITE AND OTHER LAVAS

Coarsely porphyritic lava flows are locally interlayered with the ash-flow sheets of the Creede caldera sequence; similar flows and lava domes were erupted after the final collapse and subsequent uplift of the Creede caldera to form the Fisher Quartz Latite (Steven and Ratté, 1964). The flows range from rhyolite to rhyodacite in composition, but most are crystal-rich quartz latite.

DISTRIBUTION

The general distribution of the interlayered lava flows and the Fisher Quartz Latite is shown on plate 1. The distribution of most of the flows and known vents around the margin of the Creede caldera suggests that the eruptions were localized largely by caldera ring fractures.

The oldest of the interlayered lavas forms a neck and related quartz latite flows beneath the Mammoth Mountain Rhyolite in the Goose Creek area. Other quartz latite flows separate the Mammoth Mountain and Wason Park Rhyolites between Goose Creek and West Bellows Creek, and a distinctive rhyolite flow underlies the Wason Park between East and West Bellows Creeks. A quartz latite flow overlies the Wason Park from Blue Creek to West Bellows Creek, and the source vent is exposed along the slopes between East and West Bellows Creeks. A light-colored rhyolite flow of much different appearance underlies the Wason Park Rhyolite between Shallow Creek and Miners Creek northwest of the caldera, and the related vent is exposed nearby along Shallow Creek. The interlayered flows are generally 200–400 feet thick. A few may have flowed as far as 5 miles from their vents, but most appear to have a more restricted distribution.

The Fisher Quartz Latite forms lava flows and domes with associated pyroclastic breccia around the margins of the resurgent Creede caldera and north of the caldera between Rat Creek and Miners Creek (pl. 1). Similar flows are widespread along the Continental Divide northwest of Creede, where they are localized near the western margin of the San Luis Peak caldera. The largest accumulation of all is south of the Creede caldera, from the Fisher Mountain-Copper Mountain area southward. The Fisher lavas range from flows a few hundred feet thick to domical masses 1,000 feet or more thick. Associated necks have been mapped along the west flank of the caldera core and between Miners and Rat Creeks, and many of the bulbous flows and volcanic domes in the Wagon Wheel Gap and Fisher Mountain-Copper Mountain areas show evidence of buried local sources.

The volume of flow lava in the Fisher and interlayered with the ash-flow deposits of the Creede caldera sequence is small relative to the volume of the ash-flow sheets. In general, the proportion of lava flows increases upward in the caldera sequence.

LITHOLOGY AND PETROGRAPHY

Lava flows in the Creede caldera volcanic sequence are porphyritic rocks that can be distinguished readily from the associated pyroclastic rocks by structures typical of flows such as flow banding, basal flow breccia and vesicular zones, and by frothy flow tops. Some of these features, as present in the rhyolite flow beneath the Wason Park Rhyolite on the north side of East Bellows Creek, are shown in figure 22. Large-scale flow structures are visible in aerial photographs of domes and flows of Fisher Quartz Latite in the Wagon Wheel Gap area.

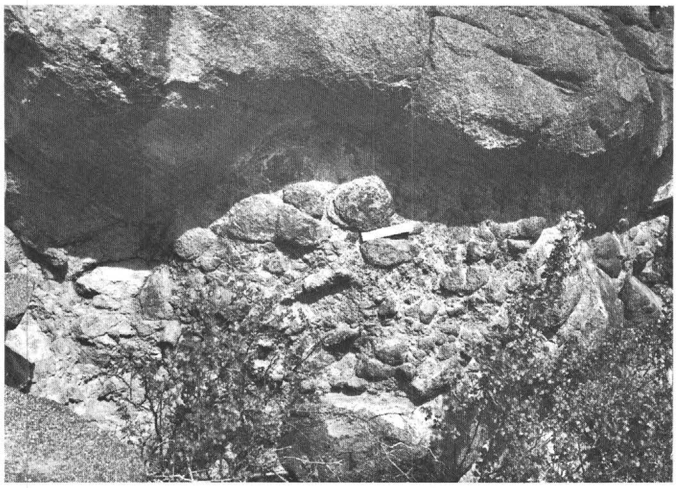
PETROGRAPHY

Modes of the interlayered lava flows and the Fisher Quartz Latite are presented in tables 19 and 20. The

TABLE 19.—*Modes (volume percent) of lava flows interlayered with the Creede caldera ash-flow sequence*

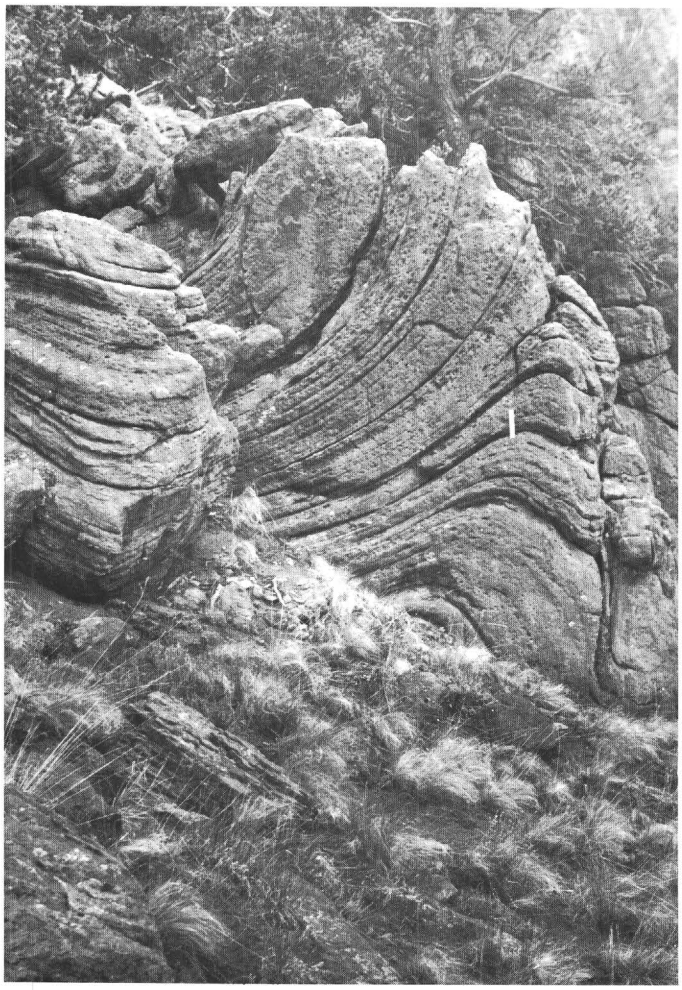
[P, present in trace amounts; O, constituent not found in thin section]

Locality	Field No.	Matrix	Phenocrysts	Plagioclase	Sanidine	Biotite	Pyroxene	Hornblende	Magnetite	Points counted
Lava flow underlying Wason Park Rhyolite between East Bellows and West Bellows Creeks.	Average of 5	77	23	18	1	3	<1	0	1	897
	Range	74–80	20–26	15–20	<1–1	2–3	P–<1	0	<1–1	741–1,064
Rhyolitic flow underlying Wason Park Rhyolite north of Shallow Creek and west of Miners Creek.	C–945	86	14	5.2	8.2	6.2	0	0	.5	1,126
	C–954	53	47	21	22	2.8	0	0	.6	1,026
Two flows overlying the Mammoth Mountain Rhyolite in the Blue Creek section.	Average of 27	67	33	25	0	2	3	0	2	1,028
	Range	58–76	24–42	18–34	0	<1–5	1–6.5	0–P	1.5–3	790–1,111
Lava flow overlying the Wason Park Rhyolite north of East Bellows Creek.	R–287	71	29	20	0	2	5	P	2	578
Lava flows north of Nelson Mountain	C–553B	61	39	34	0	3	0	P	1.5	499
	C–703C	72	28	19	0	4	3	0	3.0	198
	C–703F	74	26	21	0	2	2	0	1.5	532
	C–704B	65	35	27	0	5	1	P	2.5	215
Lava flow near the head of Goose Creek		74	26	16	0	.4	1.6	5.6	2.4	1,085



A

B



C

FIGURE 22.—Lithologic features of the rhyolite lava flow beneath welded tuff of Wason Park Rhyolite on the north side of lower East Bellows Creek; scales are 6 inches long. *A*, Vitrophyre flow breccia at the base of the lava flow with massive vitrophyre above. *B*, Recumbent drag folds above the massive vitrophyre; folds are outlined by alternating thin layers of black vitrophyre and red felsite. *C*, Scoriaceous top of lava flow containing contorted flow layers.

TABLE 20.—*Modes (volume percent) of Fisher Quartz Latite in the Creede area*

[0, constituent not found in thin section]

Locality	Field No.	Matrix	Phenocrysts	Plagioclase	Sinidine	Quartz	Biotite	Pyroxene	Hornblende	Magnetite	Points, counted (vesicles excluded)
West of Rat Creek	C-715	59	41	32	0.9	1.1	5.2	0.1	0	1.9	1,057
	C-744C	54	46	36	0	0	3.7	3.1	0	2.5	1,059
	C-748C	55	45	33	0	0	6.9	2.8	0.1	2.1	1,160
East of Rat Creek	C-667B	57	43	32	0	0	5.2	4.2	0	1.8	840
	C-669B	62	38	30	0	0	4.8	1.9	0	1.3	956
Southwest Snowshoe Mountain	S-60A	56	44	31	1.2	.7	4.1	1.8	3.0	2.5	1,022
	S-60C	54	46	30	2.0	.6	7.2	1.1	3.3	1.7	1,111
	S-61	63	37	27	.6	.2	5.2	.2	2.3	1.4	1,020
Dome west of West Bellows Creek	R-140A	68	32	23	0	0	3.0	.7	2.9	1.2	1,074
	R-144C	55	45	34	0	0	5.0	.5	2.8	2.4	1,110
Dome north of East Bellows Creek	R-157B	65	35	22	0	0	5.2	2.1	4.0	1.8	614
	R-161	59	41	29	.6	0	5.1	1.3	3.9	1.0	1,114
Flow south of East Bellows Creek	R-204	65	35	26	0	0	1.8	1.4	4.6	.9	775
	R-206C	67	33	22	1.9	.3	5.3	.6	1.8	1.1	1,075
	R-298	61	39	22	.5	0	5.3	.5	3.9	1.5	1,063
Dome and flow south of lower Bellows Creek	R-170	62	38	27	0	0	5.2	.8	4.0	1.2	1,511
	R-171	58	42	31	0	0	2.7	.5	5.5	1.9	1,067
	R-173	58	42	34	0	0	5.0	0	2.6	.8	1,101
Wagon Wheel Gap dome and flow	R-218A	69	31	24	0	0	1.9	.3	3.1	1.8	1,188
	R-284	58	42	21	0	0	2.2	.4	15.0	3.5	739
Average		60	40	29	.4	.2	4.5	1.3	3.1	1.7	1,033
Range		54–69	31–46	21–36	0–2.0	0–1.1	1.8–7.2	0–4.2	.1–15	.8–3.5	614–1,511

interlayered flows average about 30 percent phenocrysts, and these have maximum dimensions of a few millimeters. About three-fourths of the phenocrysts are plagioclase crystals, except in the rhyolite near Shallow Creek, where sanidine and plagioclase are nearly equal in abundance. Most of the plagioclase crystals in the flows have oscillatory zones; their average composition is sodic andesine to midandesine in the rhyolite flow of Shallow Creek, and midandesine to calcic andesine in the quartz latite flows and in the rhyolite flow in the Bellows Creek area. Some of the most calcic zones in the plagioclase of the quartz latites are sodic labradorite. Sanidine is present only in the rhyolite, and quartz is absent as phenocrysts. Tridymite plates are commonly visible in miarolitic cavities. Biotite and magnetite are the chief mafic phenocrysts in the rhyolite flows; some clinopyroxene is in the rhyolite north of East Bellows Creek. In the quartz latite flows, biotite, magnetite, and clinopyroxene all are common, and hornblende, which is generally present in minor amounts, is the dominant mafic phenocryst in one of the samples (table 19). Hornblende is conspicuous in lavas associated with a local vent southeast of the Creede caldera.

The Fisher Quartz Latite (table 20) has an average of 40 percent phenocrysts, of which about three-fourths are zoned plagioclase having an average composition of midandesine. Biotite, clinopyroxene, and magnetite are common in all the Fisher flows, and hornblende is one of the most abundant mafic phenocrysts in all the flows considered here except those northwest of Creede between lower Rat Creek and Miners Creek. A small dome on the west side of the Creede caldera contains conspicuous sanidine and quartz, as do some of the flows northwest of Creede and in the Bellows Creek area. Some Fisher flows in the Fisher Mountain-Copper Mountain area on the south side of the caldera contain abundant coarse sanidine phenocrysts 1–2 cm long, but these flows have not been studied petrographically.

A pair of dark flow-banded quartz latitic lava flows overlying the Mammoth Mountain Rhyolite in the Blue Creek section (location *H*, pl. 1) was selected for detailed study in stratigraphic section. The lower flow is about 400 feet thick; both the top and the bottom of the flow are mantled with talus, but part of the scoriaceous upper part of the flow is visible through the debris. The upper flow is about 300 feet thick and is exposed from the upper part of a basal vitrophyre layer to its scoriaceous top. Twenty-seven samples were collected at intervals ranging from 20 to 40 feet from the exposed parts of the two flows. The phenocryst content, bulk density, grain density and porosity of these samples were measured (table 21) and are plotted in figure 23.

Phenocrysts are more abundant in the lower flow, but within each flow they show a rather uniform distribution, with one or two possible exceptions for which we have no explanation. Both flows show a general decrease in bulk density from bottom to top, but the lower flow shows a reversal in bulk-density trend in its lower half. This reversal is in a zone of relatively high porosity and abundant tridymite, and could represent an interval of vesiculation at a temporary top of the flow between surges of lava. The grain-density profiles of both flows are rather irregular, and they generally vary in sympathy with the bulk-density profile. The porosity profiles vary inversely with both the bulk-density and grain-density profiles, but the magnitude of the variations is more on the order of that of the grain-density profile.

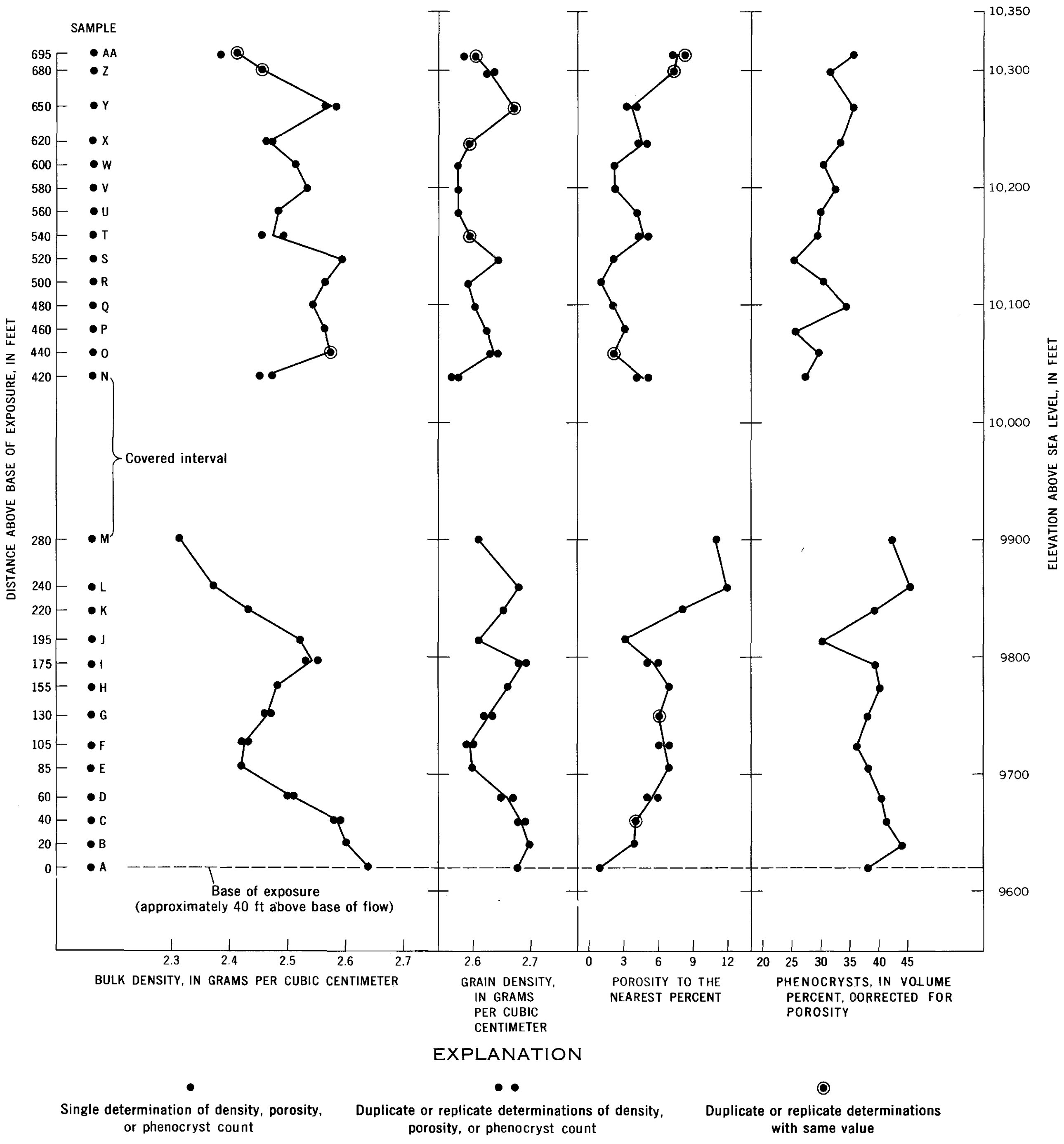


FIGURE 23.—Profiles showing variations in density and phenocryst abundance in quartz latite lava flows east of Blue Creek.

These data on the lava flows were compiled mainly for comparison with similar data on the welded tuffs in the Mammoth Mountain and Wason Park Rhyolites. Among the profiles plotted for the two kinds of rocks (figs. 14, 17, 18, 23), those representing grain density show the greatest contrast. Grain density is uniform throughout the densely welded zones of the welded tuff but decreases in partially welded rocks at the top of the ash-flow sheets. The uniformity of grain densities in the welded tuffs has been used in this report as evidence that variations in corresponding bulk-density profiles reflect varying porosity rather, than changes in composition. This interpretation is supported by the form of the porosity profiles of the welded tuffs, which are nearly mirror images of the bulk-density profiles. In the lava flows, in contrast, grain density generally varies more directly with bulk density, and the porosity profiles of the flows are rela-

TABLE 21.—*Density, porosity, and phenocrysts in two quartz latite flows in the Blue Creek area*

[Density and porosity measured by Gary Curtin]

	Field No.	Bulk density (g per cc)	Grain density (g per cc)	Porosity (percent)	Phenocrysts (volume percent corrected for porosity)
Top of upper flow	R-300AA	2.41 2.41 2.38	2.60 2.60 2.58	7.5 7.5 7.9	35
	Z	2.45 2.45	2.62 2.63	6.6 6.7	31
	Y	2.56 2.58	2.67 2.67	3.9 3.3	35
	X	2.47 2.46	2.59 2.59	4.5 5.2	33
	W	2.51	2.57	2.4	30
	V	2.53	2.57	1.7	32
	U	2.48	2.57	3.6	29
	T	2.45 2.49	2.59 2.59	5.1 3.8	29
	S	2.59	2.64	2.0	25
	R	2.56	2.59	1.4	30
	Q	2.54	2.60	2.2	34
	P	2.56	2.62	2.6	25
	O	2.57 2.57	2.64 2.63	2.4 2.4	29
Vitrophyre near base of upper flow.	N	2.45 2.47	2.57 2.56	4.8 3.6	27
Covered interval					
Scoria near top of upper flow.	M	2.31	2.61	11.3	42
	L	2.37	2.68	11.8	45
	K	2.43	2.65	8.2	39
	J	2.52	2.61	3.5	30
	I	2.55 2.53	2.68 2.69	5.1 6.0	39
	H	2.48	2.66	7.1	40
	G	2.46 2.47	2.62 2.63	6.2 5.9	38
	F	2.42 2.43	2.59 2.60	6.5 6.6	36
	E	2.42	2.60	7.0	38
	D	2.50 2.51	2.67 2.65	6.3 5.1	40
	C	2.59 2.58	2.68 2.69	3.6 3.9	41
	B	2.60	2.70	3.8	44
Approximately 40 ft above covered base of flow.	R-300A	2.64	2.68	1.4	38
Upper flow:					
Average					30
Range					25–35
Lower flow:					
Average					39
Range					30–45

tively weak mirror images of the bulk-density and grain-density profiles. These relationships indicate that the bulk density of the lavas is controlled not by porosity alone but also by phenocryst content and by the filling of vesicles and miarolitic cavities with vapor-phase minerals such as tridymite, which influences both the porosity and the bulk density of the rocks and causes irregular variations in grain density.

CHEMICAL COMPOSITION

Chemical analyses, norms, and spectrographic analyses of some of the interlayered flows and Fisher Quartz Latite are shown in table 22. The interlayered flows range from rhyolite to quartz latite and the Fisher flows from quartz latite to dark rhyodacite in Rittmann's chemical classification.

EVOLUTION OF THE CREEDE CALDERA SEQUENCE

The ash flows and other volcanic rocks of the Creede caldera sequence show a general change with time from alkali-rich rhyolite to quartz latite and rhyodacite. Ash flows of the early rhyolitic formations, such as the Bachelor Mountain, Farmers Creek, and Mammoth Mountain, are typically pumice rich and phenocryst poor. Quartz latite ash flows in the upper part of the Mammoth Mountain, and in the Wason Park and Snowshoe Mountain, are generally phenocryst rich. Lava flows interlayered with the ash flows occur largely in the younger half the sequence and are invariably rich in phenocrysts.

General observations on similar parallel changes in chemical composition and crystal content of ash flows were made by Roberts and Peterson (1961) and Smith (1960a, p. 833–834.)

Crystallization trends during the eruptive history of the sequence are interpreted with the aid of two plots of normative minerals as shown on a triangular diagram (fig. 24). Both plots show a progressive change to a greater abundance of mafic minerals in the younger formations. Bachelor Mountain Rhyolite is represented in figure 24 by an average normative composition and also by the composition of its basal vitrophyre.

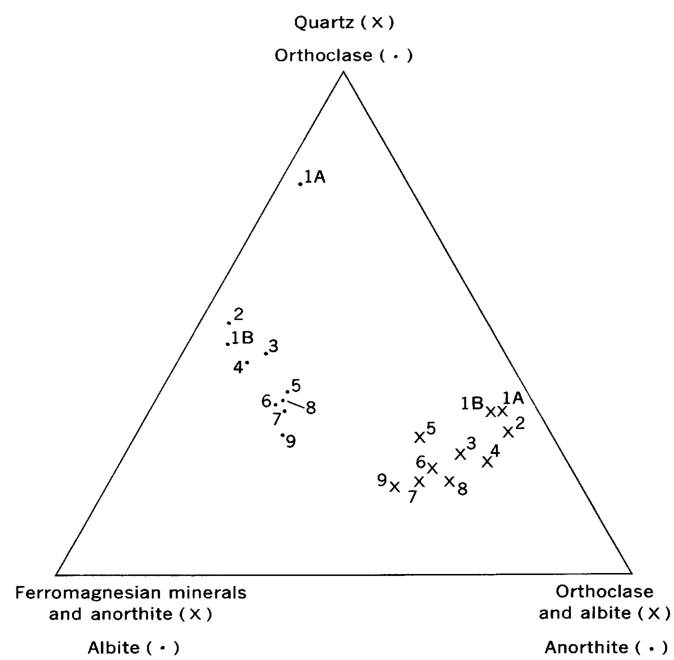


FIGURE 24.—Normative minerals in the Creede caldera sequence and some associated formations. Numbers show relative stratigraphic position in sequence, except 8, which represents lava flows interlayered between 2 and 7. 1A, Bachelor Mountain Rhyolite (average of 13 norms); 1B, Bachelor Mountain Rhyolite (basal vitrophyre; C–769, table 2); 2, Farmers Creek Rhyolite (average of 2 norms); 3, Mammoth Mountain Rhyolite (average of 4 norms); 4, Wason Park Rhyolite (average of 7 norms); 5, Rat Creek Quartz Latite (average of 3 norms); 6, Nelson Mountain Quartz Latite (average of 5 norms); 7, Snowshoe Mountain Quartz Latite (average of 3 norms); 8, Interlayered lava flows (average of 5 norms); 9, Fisher Quartz Latite (average of 2 norms).

TABLE 22.—*Chemical analyses, norms, and spectrographic analyses of the Fisher Quartz Latite and other lava flows in the Creede caldera sequence*

[Specimen localities described with reference to Creede 15-minute quadrangle topographic map (1959). Chemical analyses: 1-3, by C. L. Parker 1963; 4, by R. E. Bailey, 1923, and F. A. Gonyer, 1942 (in Larsen and Cross, 1956); 5, by J. G. Fairchild, 1925 (in Larsen and Cross, 1956); 6, by P. L. D. Elmore, I. H. Barlow, and S. D. Botts, 1959; 7, by R. K. Bailey, 1923 (in Larsen and Cross, 1956). Spectrographic analyses: 1-3, by J. C. Hamilton, 1963; 6, by N. M. Conklin, 1959]

Sample No.	1	2	3	4	5	6	7
Laboratory No.	D100035	D100033	D100034			153630	
Field No.	R-185A	S-175B	R-300N	La G-1027	La G-1598	R-284	La G-1021
Chemical analyses (weight percent)							
SiO_2	65.50	59.28	62.53	60.54	65.29	60.0	64.59
Al_2O_3	15.82	16.94	15.76	16.01	15.56	15.5	15.22
Fe_2O_3	1.92	3.97	3.18	3.63	4.13	3.6	2.73
FeO	.70	1.91	1.35	2.34	.55	2.8	1.79
MgO	.90	1.67	1.79	2.49	.78	3.0	1.83
CaO	2.69	5.55	3.77	5.44	3.41	5.1	3.91
Na_2O	3.25	3.81	3.46	3.69	3.66	3.6	3.52
K_2O	5.14	3.61	3.97	3.80	4.61	2.6	3.72
H_2O^+	2.54	.39	1.89	1.07	.94	2.1	1.27
H_2O^-	.48	.59	.87	.23	.60	.25	.59
TiO_2	.45	.86	.66	1.10	.85	.78	.70
P_2O_5	.12	.38	.24	.51	.26	.25	.29
MnO	.06	.11	.09			.16	
CO_2	.01	.63	.02			<.05	
Cl	.08	.02	.09				
F	.10	.10	.10				
Subtotal	99.76	99.82	99.77				
Less O	.06	.04	.06				
Total	99.70	99.78	99.71	100.85	100.64	100	100.16
Bulk density						2.52	
Powder density	2.49	2.69	2.57			2.66	
Norms							
Q	21.3	11.6	18.1	12.3	19.4	15.4	20.6
or	31.4	21.9	24.3	22.5	27.5	15.8	22.4
ab	28.4	32.9	30.3	31.2	31.4	31.2	30.4
an	12.6	18.8	16.2	15.9	12.5	19.0	15.0
C	.4						
wo		2.8	.4	3.3	.8	2.3	1.2
en	2.3	4.2	4.5	6.2	1.9	7.6	4.5
fs						1.2	
mt	1.0	4.1	2.8	4.4		5.3	3.7
hm	1.3	1.2	1.3	.6	4.1		.2
il	.9	1.6	1.3	2.1	1.2	1.5	1.3
ap	.3	.9	.6	1.2	.6	.6	.7
ti					.6		

Spectrographic analyses

[Semiquantitative analyses in percent to nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1 . . .; numbers represent approximate midpoints of data on a geometric scale and will include the quantitative value about 30 percent of the time. Quantitative analyses in percent; overall accuracy ±15 percent, except that analyses are less accurate near limits of detection if only one digit is reported. nd, not detected]

	Semiquantitative					Quantitative	
B	0.003	nd	nd			<0.001	
Ba	.2	0.2	0.2			.081	
Be	.0002	.0002	.0003			<.0001	
Ce	.02	.02	.02			nd	
Co	.0007	.0015	.001			.001	
Cr	.0007	.002	.0015			.0076	
Cu	.0015	.005	.01			.0035	
Ga	.003	.003	.003			.0018	
La	.007	.007	.007			<.005	
Mo	nd	nd	nd			.0004	
Nb	.002	.0015	.002			.001	
Nd	.015	.015	.015				
Ni	0	.001	.0007			.0014	
Pb	.003	.002	.002			.001	
Sc	.001	.0015	.0015			.0010	
Sr	.1	.15	.15			.078	
V	.007	.03	.01			.013	
Y	.003	.003	.003			.002	
Yb	.0005	.0005	.0003			.0002	
Zr	.02	.02	.02			.013	

1. Vitrophyre at base of lava flow in cliffs north of East Bellows Creek, elevation about 9,850 ft, approximately 2 miles above junction of East and West Bellows Creeks.
2. Vitrophyre at base of flow in cliffs southeast of Lake Humphreys, elevation about 9,440 ft, Spar City quadrangle.
3. Vitrophyre breccia near top of upper lava flow, elevation about 10,040 ft, about 1,000 ft east of Wagon Wheel Gap at the mouth of Blue Creek.
4. Dark lava from flow east of West Bellows Creek in Silver Park just north of bench mark 11,534. Collected and described by Larson and Cross (1956, table 23, No. 6).
5. Porous lava from southeast slope of McClelland Mountain, at elevation of 10,650 ft. Collected and described by Larsen and Cross (1956, table 23, No. 14).
6. Vitrophyre at base of Fisher Quartz Latite, elevation about 8,600 ft, in the cliffs east of the Rio Grande about 2,000 ft downstream from the gap at Wagon Wheel Gap.
7. Phenocryst-rich lava of Fisher Quartz Latite from 9741 hill between Farmers and Bellows Creeks, NE¼ sec. 11, T. 41 N., R. 1 E. Collected and described by Larsen and Cross (1956, table 23, No. 12).

The vitrophyre (point 1B) plots near the siliceous end of the sequence, but the average Bachelor Mountain rock (point 1A) is anomalously rich in orthoclase. If normative orthoclase and albite are combined (x's on fig. 24), the average Bachelor Mountain rock also plots at the siliceous end of the sequence. These relationships indicate the character of the pervasive alteration of the Bachelor Mountain Rhyolite, which is primarily a fixation of potassium and loss of sodium. Also noteworthy in the diagram is the position of the average interlayered lava flow near the mafic end of the trend, although the flows themselves range from 2 to 7 in the stratigraphic sequence.

The averaged analyses smooth the variations considerably, as can be seen by considering the separate analyses in the tables.

A certain cyclic effect has been noted in the sequence, and as an example of this the rhyolitic and quartz latitic facies of the Mammoth Mountain Rhyolite and the average Wason Park Rhyolite are shown by a plot of normative minerals on a separate triangular diagram (fig. 25). Points 1–4 represent changes in composition of the Mammoth Mountain Rhyolite within a single ash-flow sheet from early phenocryst-poor rhyolite (points 1 and 2) to later phenocryst-rich quartz latite (points 3 and 4). The next ash flows erupted, the Wason Park Rhyolite (point 5, fig. 25), are more rhyolitic in composition than the upper part of the

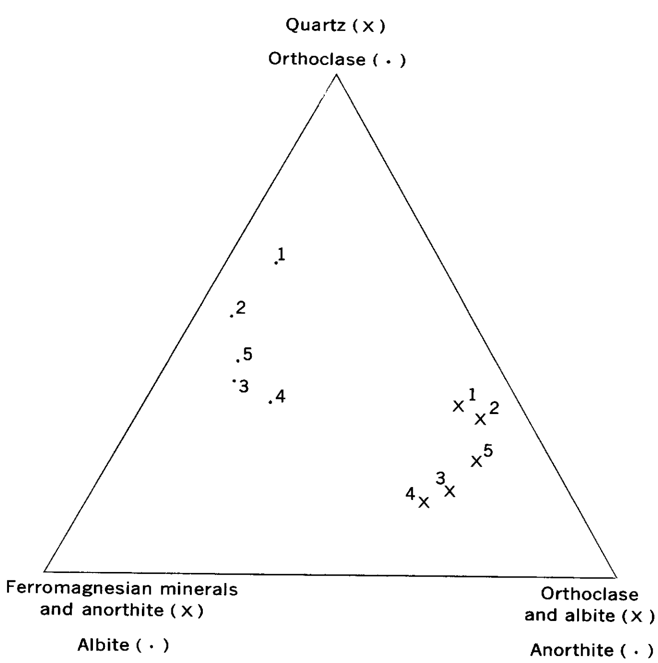


FIGURE 25.—Normative minerals in the Mammoth Mountain and Wason Park Rhyolites. 1 and 2, Mammoth Mountain Rhyolite, rhyolitic facies; 3 and 4, Mammoth Mountain Rhyolite, quartz latitic facies; 5 Wason Park Rhyolite, average of 7 norms.

Mammoth Mountain; thus the trend toward less siliceous rocks in the younger units was reversed. The trend was reestablished, however, in the succeeding Snowshoe Mountain Quartz Latite ash flows (compare fig. 24).

Points 5 and 6 (fig. 24) represent the Rat Creek Quartz Latite and the Nelson Mountain Quartz Latite, respectively. As discussed on p. H46, these ash flows have a source different from that of the Creede caldera sequence, but it is probably significant to the origin of all the rocks related to the central San Juan cauldron complex that the norms of these rocks fit into the crystallization trend for the Creede caldera sequence. The Rat Creek and Nelson Mountain Quartz Latites appear to be intimately related to one another in time of eruption, source, and distribution. The more rhyolitic Rat Creek rocks and the younger Nelson Mountain Quartz Latite may represent part of another local eruptive cycle.

Considering this evolution, we conceive of the Creede caldera sequence as having been derived from a local body of fractionating magma, perhaps a cupola extending above the general level of a larger body of magma that must have underlain the cauldron complex in the central San Juan Mountains (Steven and Ratté, 1963). Prior to the first eruptions of the Creede caldera sequence, the top of this magma column consisted of volatile-rich crystal-poor magma having the composition of alkali rhyolite. When the roof failed, as when increasing gas pressure exceeded the confining strength, the volatile-rich magma was rapidly expelled as pumice and ash that accumulated and welded as the Bachelor Mountain Rhyolite, and the Bachelor Mountain cauldron collapsed into the partially evacuated magma chamber. The body of Bachelor Mountain Rhyolite was then pervaded by magmatic fluids and converted to a highly potassic rock; incomplete evidence suggests that fractures formed by cauldron collapse may have guided these fluids.

After a period of quiescence of unknown length, additional eruptions of gas-rich crystal-poor rhyolite ash flows formed the Farmers Creek Rhyolite. Succeeding volcanic activity alternated between eruption of small lava flows and great ash flows. The ash flows record differences in composition with time, and because of the great volume of the flows these differences are correlated with differences in level of origin within the magma chamber. Some individual ash flows, as the Mammoth Mountain, show on a smaller scale the same type of evolution as the caldera sequence as a whole. The initial material of the Mammoth Mountain eruptions was crystal-poor rhyolitic ash, presumably from the top of the magma chamber, and this ash was followed by progressively more crystal-rich and quartz latitic magma from deeper within the chamber. The time interval between the Mammoth Mountain and Wason Park ash-flow eruptions apparently was sufficient for a new body of rhyolitic magma to be generated at the top of the magma column, and the succeeding Wason Park ash flows are rhyolitic. In contrast to older rhyolitic ash flows of the sequence, the Wason Park Rhyolite has abundant phenocrysts, whose presence indicates a general advance in the crystallization of the magma. The last major ash-flow eruptions deposited the Snowshoe Mountain Quartz Latite, the least silicic and most crystal-rich of all the ash flow deposits in the Creede caldera sequence. The succeeding Fisher Quartz Latite, although somewhat poorer in phenocrysts, was even more latitic.

The local lava flows interlayered with the ash-flow deposits do not reflect comparable compositional changes with time; they are generally quartz latitic but have a few rhyolite flows interspersed irregularly throughout the sequence. The composition of the lavas possibly can be explained by the common occurrence of lava flows as the last event in an individual eruptive cycle. In many volcanic fields, ash-flow eruptions related to cauldron subsidence were followed by viscous lavas which rose along ring fractures and other faults formed during the collapse. The magma available for eruption shortly after a major ash-flow eruption should be from a lower level within the magma chamber and thus presumably somewhat less silicic than that which formed the ash flows.

Less speculative is the increasing ratio of lava flows to ash flows upward in the Creede caldera sequence. The change from ash flow to lava flow probably reflects progressive depletion of volatile components by recurrent eruptions of ash from the top of a fractionating column. Eruptions removed the gas-rich top of the column more rapidly than fractionation could replenish it, and finally, the magma became too poor in volatiles to vesiculate to ash, and eruption took the form of flows which solidified as the Fisher Quartz Latite.

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