GEOLOGIC RELATIONSHIPS OF THE SALIDA AREA TO THE THIRTYNINE MILE VOLCANIC FIELD OF CENTRAL COLORADO

A Dissertation

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Doctor of Philosophy

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by

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ABSTRACT

Tertiary volcanism began in the Salida area between 35 and 40 million years ago in the early Oligocene Epoch. Ash-flow tuffs predominate in the lower two-thirds of a 3,000 to 3,500 foot thick volcanic pile; the remaining portion consists of intermediate to basic lava flows. In ascending stratigraphic order the major volcanic units are: ash flow-1 cooling unit, Antero Formation, tuff of Badger Creek, latite of East Badger Creek, ash flow-7 cooling unit, latite of Waugh Mountain, upper andesite, andesite of Big Baldy, and the interbedded gravels and basic lava flows of the Tenderfoot Hill volcanic sequence. The volcanic pile is unconformably overlain by the Dry Union Formation of early Pliocene age.

An extensive late Eocene erosion surface which extended from northern South Park to the Wet Mountain Valley and from Cripple Creek to Salida (Epis and Chapin, 1968, p. 56) allowed ash flows to spread throughout the Thirtynine Mile volcanic field and adjacent areas. An east-west trending drainage system, which crosses the Laramide structural grain and the present drainage at nearly a right angle, was carved into this erosion surface in the Salida area. These valleys were avenues of transport for the ash flows which now preserve the valleys.

Primary laminar flow structures in the ash flow-1 cooling unit and westward-forking tributaries indicate that these paleovalleys drained eastward off the Sawatch uplift prior to formation of the upper Arkansas graben and resultant separation of the Mosquito Range. A series of north trending postvolcanic faults have locally reversed the gradient of the paleovalleys and stepped the ash flows down into the Arkansas Valley where they occur at elevations1,500 to 2,000 feet lower than on the eastern rim.

Source areas for the extensive ash-flow sheets remain unknown. However, both the thickness and the number of ash flows in the Salida area exceed that in the remainder of the Thirtynine Mile volcanic field. This observation, combined with flow-structure data, distribution of ash-flow outcrops, and the postvolcanic development of the upper Arkansas graben, suggests that the eruptive centers were located west of Salida. Thus, the Thirtynine Mile field was an andesitic volcanic field which acted as a receiving area for silicic ash flows which erupted west of the field.

INTRODUCTION

Acknowledgments

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Statement of the Problem

The purpose of this investigation is to determine the geologic relationships of volcanic rocks in the Salida area to the regional structural and volcanic framework of central Colorado. Implicit to this end are:

(1) Delineation of the prevolcanic erosion surface and its paleodrainage in the southwestern portion of the Thirtynine Mile volcanic field;

(2) Determination of the stratigraphic relationships of volcanic rocks in the Salida area to volcanic formations of the Thirtynine Mile field;

(3) Evaluation of potential volcanic centers within the study area; and

(4) Evaluation of the structural setting of the upper Arkansas Valley in the Salida area.

Location and Accessibility

The area of investigation is located northeast of Salida, Colorado, in the southern Mosquito Range, an area referred to on some maps as the Arkansas Hills. The study area includes about 100 square miles within the southern half of the Cameron Mountain 15-minute quadrangle. Figure 1 shows the location of this area with respect to the Thirtynine Mile volcanic field. Adjacent communities include Salida, Howard, Cotopaxi, and Guffey. Accessibility is provided by the Ute Trail which connects Salida and Colorado State Highway 9 and by numerous logging and mining roads which branch from it. Throughout most of the study area 4-wheel drive transportation is desirable.

Methods of Investigation

A base for geologic mapping was prepared by enlarging the Cameron Mountain 15-minute quadrangle (1956) to a scale of 1 mile = 2 inches (1:31,680). Geologic mapping was done directly on a mylar copy of the enlargment. The

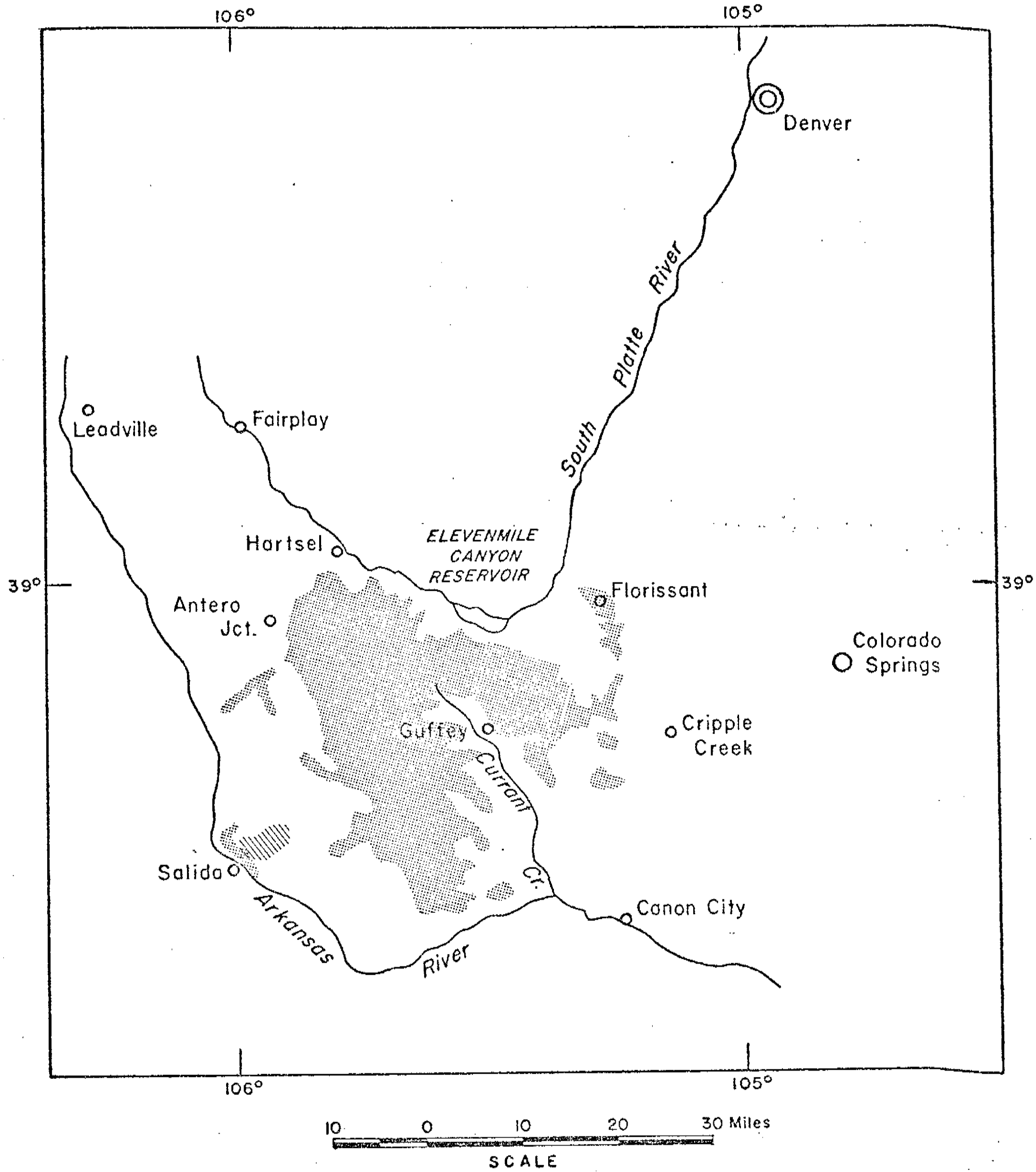
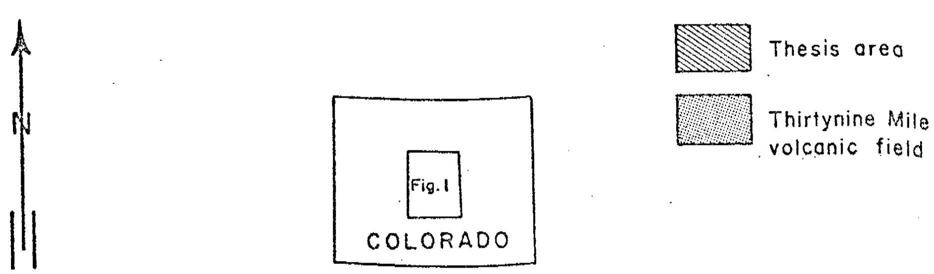


Figure I

LOCATION OF THIRTYNINE MILE VOLCANIC FIELD, CENTRAL COLORADO



Pueblo and Leadville sheets (1:250,000) of the Army Map Service provided regional topography and nomenclature. Aerial photographs U. S. F. S. (1956) were used as guides to the location and configuration of outcrops.

Ninety thin sections were examined on a standard petrographic microscope. The composition of plagioclase phenocrysts was determined by the Fouqué method; the method of Michel-Lévy was used to determine the composition of plagioclase microlites. Optic axial angles of sanidine crystals were measured orthoscopically on a four-axis universal stage. The optic axial angles of at least 20 sanidine crystals per thin section were measured and the median obtained by the method described by Chapin and Epis (1965). Point counts for modal analyses were made on a Swift automatic point counter and recording device. The point counting suggestions of Van der Plas and Tobi (1965) were followed.

Previous Investigations

The earliest studies in the Salida vicinity were those of the Hayden Survey (1874). Cross (1894) briefly studied the metamorphic rocks along the western edge of the Salida Region. A few years later, Lindgren (1908) described the Sedalia copper mine located a few miles northeast of Salida. Behre, Osborn, and Rainwater (1936) published a comprehensive report on the Calumet mining district. Johnson (1934) was the first to give a detailed account of the Paleozoic stratigraphy of the Mosquito Range.

Regional studies by Burbank and Goddard (1937), Lovering and Goddard (1950), Gableman (1952), and Boos and Boos (1957) have helped to elucidate the structural complexities of the central Colorado Rocky Mountains.

The Tertiary sediments near Salida have been described by Van Alstine and Lewis (1960). The stratigraphy of southwestern South Park was described by De Voto (1961, 1964) who has subsequently studied the Permian and Pennsylvanian stratigraphy in detail (1965, 1968).

The major stratigraphic and structural contributions to the geology of the Thirtynine Mile volcanic field have been made by Chapin and Epis (1964), Chapin (1965), and Epis and Chapin (1968). C. T. Wrucke is currently engaged in mapping the Cameron Mountain quadrangle for the U. S. Geological Survey.

A number of unpublished theses have been concerned with localities bordering or overlapping the present thesis area: these include Rold (1950) who studied the pre-Pennsylvanian strata of the Wellsville area; Bhutta (1954) who dealt with the general geology east of Salida with emphasis on nonmetallic ores associated with rocks of Precambrian age and pegmatites of Tertiary age; Rahman (1954) who studied the stratigraphy of the Wellsville-Calcite area in some detail; Skipp (1956) who was concerned with the Precambrian and Paleozoic stratigraphy in the Dead Horse Gulch area; Van Diver (1958) who primarily studied the ore deposits of the Calumet mining district; Quinlivan (1959) who discussed the geology of the Herring Park area; and Pierce (1968) who dealt exclusively with the Permo-Pennsylvanian strata of the Wellsville-Howard area.

ROCK UNITS

Prevolcanic Rocks

The prevolcanic rocks of the Salida area range in age from Precambrian to early Tertiary. A nearly complete Paleozoic stratigraphic section is present but rocks representing the Mesozoic Era are missing. The prevolcanic rocks have been studied in detail by a number of previous investigators and the following descriptions are largely abstracted from their work.

Precambrian Rocks

The Precambrian rocks of the Salida area consist, for the most part, of various metamorphic rocks which have been intruded by granitic and gabbroic bodies and invaded by their associated dikes and sills. The metamorphic rocks range from quartzites and hornblende mica schists to amphibolites and gneisses. Pegmatites are abundant in the northwestern part of the map area and farther west near the old ghost town of Turret (T.51N., R.9E., Sec. 29). The pegmatites of the Turret area have had considerable economic importance in the past but mining activity has slackened in recent years. For the best description of the Precambrian rocks, the reader is referred to Bhutta (1954, p. 28-50) where numerous petrographic data, maps, and stratigraphic descriptions are presented.

Paleozoic Rocks

All of the periods of the Paleozoic Era except the Cambrian and Silurian are represented in the Salida district. Generally speaking, the preservation of the Paleozoic stratigraphic sequence is attributable to down faulting during the Ancestral, Laramide, and late Tertiary periods of deformation.

Manitou Dolomite. Johnson (1934, p. 21) suggested the name Manitou for the dolomites and limestones of Early Ordovician age in central Colorado. Emmons (1882, p. 215-230), Eldridge (1894, p. 6), Cross (1894, p. 1-5), and Crawford (1913, p. 56-60) had described the unit previously under a variety of names. Berg and Ross (1959, p. 108) have described trilobites from the Manitou Dolomite of the Front Range which correlate with Lower Ordovician faunas of the Great Basin. In a recent publication concerning the development of the Canyon City embayment, Gerhard (1967, p. 2298) gave a detailed description of the formation.

Rahman (1954, p. 28) recognized three members of the Manitou Dolomite in the Wellsville area which he referred to as the basal portion, the middle portion, and the upper portion. The basal portion is a dark gray, thickly bedded, coarsely-crystalline dolomite displaying numerous lenses and beds of chert. The middle portion is lighter in color, more thinly bedded, and varies from sandy dolomite to dolomitic sandstone. The upper portion exhibits a light gray to buff color, bedding of intermediate thickness, and usually consists of dolomite containing thin beds of chert. The thickness of the formation varies greatly throughout central Colorado. At Wellsville, Rahman (1954, p. 30) measured sections which thickened from 161 feet in the north to 209 feet in the south. Other workers have measured 350-400 feet at Trout Creek Pass, 260 feet at Monarch Pass, and 130 feet at Calumet.

The Manitou-Precambrian contacts east of Badger Creek are erosional but most of those west of Badger Creek are fault contacts. No workers, including the present writer, have observed fossils in the general area of Wellsville and Salida. Correlation is based on stratigraphic position and lithologic similarity.

Harding Sandstone. Walcott (1892, p. 153) named the Harding Sandstone and described the type section near Canyon City, Colorado. Johnson (1945, p. 32) established the age of the formation as Middle Ordovician. The Harding is a gray to pinkish-gray quartzite which weathers brown to dark red. The thickness of bedding is variable and obscure but usually ranges between six inches and three feet. Thin interbeds of silicified shale or sandstone may be present. The formation is very resistant to erosion and often forms prominent ridges.

The stratigraphic thickness varies from zero to the maximum of 150 feet measured by Johnson (1944, p. 20) northwest of Canyon City. South of the project area, Rahman (1954, p. 33) measured a thickness of 64-78 feet. The Harding is prominent in the Trout Creek area but has not been mapped north of Buffalo Peaks (Chronic, 1964, p. 106).

According to previous workers, the Harding lies unconformably over the Manitou Dolomite and unconformably beneath the Fremont Dolomite. The Harding Sandstone is noted for the occurrence of fossil fish plates of Ostracodermi. In the Wellsville area, Rahman (1954, p. 33) described a number of these plates which closely resemble those studied by Johnson at the type locality and support the correlation.

Fremont Dolomite. The Fremont Dolomite was first described by Walcott (1892, p. 159) from the type locality near Canyon City, Colorado. The Fremont is a massive, dark-gray dolomite which contains chert nodules and weathers to light gray spiney surfaces. Bedding varies from less than one inch in thickness to more than five feet. The maximum stratigraphic thickness was determined by Johnson (1945, p. 25) in the Bonanza district where the Fremont overlies the Harding unconformably. According to Berg (1960, p. 16), the Fremont is separated from the Harding by an abrupt lithologic change, an irregular contact with as much as five feet of relief, and an angular discordance of one to two degrees. Pre-Fremont erosion places the Fremont directly on the Manitou Dolomite in some localities (Berg, 1960, p. 16).

At Wellsville, Rahman (1954, p. 29) measured thicknesses ranging from 134 feet to 165 feet. The lower part of the unit contains poorly preserved crinoid stems and corals; the upper part *Athyris* ? and *Ophelita* ?. Correlation into the present area of investigation is based on stratigraphic position and lithologic character.

Chaffee Formation. The rocks of Devonian age in central Colorado have been described under a variety of names. A nomenclatural review by Kirk (1930) resulted in the general acceptance of the term Chaffee. The Chaffee Formation has two distinctive members known as the Parting Quartzite and the Dyer Dolomite. The Parting is the lower member and consists of white quartzite interbedded with buff and pink sandstone, shale, dolomite and limestone. The Dyer Member is a gray to pinkish gray, fine-grained dolomite and dolomitic limestone which weathers to a light gray or yellowish brown. Bhutta (1954, p. 66) reports greenish-gray shale interbeds and thin lenses of brown chert in the member.

Thicknesses measured in the Chaffee Formation vary considerably on a regional scale. In the southern Mosquito Range, Chronic (1964, p. 107) reports a thickness of 20 to 75 feet for the Dyer Dolomite. Bhutta (1954, p. 66) measured a Parting thickness ranging from 25 to 45 feet and a Dyer thickness ranging from 98 to 99 feet. Rahman (1954, p. 51) determined a Parting thickness of 122 to 136 feet and a Dyer thickness of 85 to 100 feet. It is an unusual occurrence to find the Parting Member in greater thickness than the Dyer Member.

Recent workers, such as Chronic (1964, p. 107) and Baars and Campbell (1968, p. 37), have raised the Chaffee Formation to group status and the Parting and Dyer Members to formational status. This convention was not followed in the present study because the mapping scale prohibited separation of the Parting and Dyer units.

The Chaffee Formation rests directly on the Fremont Dolomite of Ordovician age. A paraconformable contact is present as no irregular erosional surface has been observed. The Mississippian-Devonian contact, as observed by Rahman (1954, p. 56), is characterized by a well marked erosional surface. Johnson (1945, p. 42) established the age of the Chaffee Formation as late Middle Devonian to Late Devonian on fossil evidence but most subsequent workers have relied on stratigraphic position and lithology for correlation. Chronic (1964, p. 108) mentions the presence of algal heads on Horseshoe Mountain but states that other fossils are absent in the Chaffee Formation of the southern Mosquito Range.

Leadville Limestone. The term Leadville was first applied by Emmons (1882) in describing the ore-bearing limestones of the Leadville mining district. Eldridge (1894) later used the name for limestones in the Crested Butte quadrangle. Kirk (1931, p. 239) restricted the name to certain Mississippian rocks.

The Leadville is a gray to dark bluish gray, thin bedded to massive limestone. The unit weathers buff to pinkish gray and is noted for the presence of brecciated zones, thin white veinlets of calcite and dolomite, and occasional dark gray chert nodules. Bhutta (1954, p. 68) reported a basal conglomerate above the Chaffee Formation and a thickness ranging between 185 and 235 feet. Rahman (1954, p. 63) measured 235 to 243 feet at Wellsville. Chronic (1964, p. 108) reports localized zones of secondary dolomitization and a gradual southward increase in thickness from 150 feet in the southern Mosquito Range to 336 feet in the northern Sangre de Cristo Mountains. Conley (1965) reports 150 to 244 feet of section and the presence of fossils in the White River Plateau. No fossils have been observed in the Salida-Wellsville area. At other localities, Johnson (1945, p. 52) found fossils which indicate an Early Mississippian age.

Permo-Pennsylvanian Strata. Sedimentary rocks of Permian and Pennsylvanian age cover extensive portions of northern New Mexico and central Colorado. According to

Rahman (1954, p. 64), more than 40 stratigraphic names have been applied to these rocks. In central Colorado, the terms Maroon, Belden, and Minturn are in common but inconsistent usage. De Voto (1965) has reviewed the problems of Permo-Pennsylvanian nomenclature and postulated a depositional history to explain the complex facies relationships observed in central Colorado and northern New Mexico.

In general, the Permo-Pennsylvanian sequence in the thesis area consists of a basal unit of interbedded limestones and dark shales resting unconformably over the Leadville Limestone. The limestone interbeds are dark gray in color and superficially resemble the Leadville Limestone except for the presence of numerous fossils. Overlying the limestone and shale unit is a sequence of gray to greenish-gray grits, sandstones, siltstones, and limestones. The upper portion of the Permo-Pennsylvanian section usually consists of a thick sequence of red beds which include sandstones, siltstones, and conglomerates.

Bhutta (1954, p. 77) described a section of Permo-Pennsylvanian strata with a thickness of only 150 feet; however, at Wellsville, Rahman (1954, p. 64) measured over 13,000 feet of section. Recent work by De Voto (1968) and Pierce (1968 a, b) in the Wellsville area has disclosed the presence of an angular unconformity which truncates 5,000 feet of section in a distance of only three miles;

the angular unconformity and stratigraphic hiatus increase as the Pleasant Valley thrust is approached. These data imply that, at least within the southern portion of the map area, upward of 18,000 feet of Permo-Pennsylvanian sediments were deposited.

Tertiary Rocks

Whitehorn Stock. The Whitehorn stock was formed by the intrusion of granodioritic magma along the axial plane of the asymmetric Pleasant Valley syncline. Sills, dikes, and apophyses pierce the inclosing rocks, particularly the Permo-Pennsylvanian strata in which laterally continuous sills are common. Occasionally, as in the Calumet mining district, the igneous bodies are of economic importance. The nature and significance of the dikes and numerous basic and carbonate xenoliths have been discussed by Bhutta (1954, p. 85) and Osborn and Rainwater (1934, p. 33-35). Differentiates within the intrusive body have been studied by Behre, and others (1936, p. 789). Harris and Wilbanks (1966) have published an account of the effects of weathering on the zircon population.

Knobby, bouldery outcrops are characteristic of the central portion of the intrusion. Toward the contacts, sheet-like weathering is dominant. Typically, the rock has a bluish "salt and pepper" appearance on fresh surfaces and a dull greenish-gray cast on weathered or altered surfaces. The rock is holocrystalline and ranges from fine to coarse grained. Locally, the rock is magnetic enough to cause a strong deflection of a compass needle.

Petrographically, quartz and orthoclase surround and embay the earlier-formed plagioclase and ferromagnesian minerals. Accessory apatite, zircon, and sphene show up distinctively even in hand specimens. A complete petrographic analysis is given by Bhutta (1954, p. 89).

The Whitehorn stock is younger than all of the Paleozoic rocks and much of their structure, but is older than the last phase of Laramide tectonism and all volcanic rocks in the area. Most workers have assigned an Eocene age to the Whitehorn stock.

Volcanic Rocks

Volcanism had commenced in the area of investigation by early Oligocene time. Effusions from several volcanic centers rapidly accumulated on the prevolcanic erosion surface to form a thick pile of ash-flow tuffs, lava flows, flow breccias, and lahars.

Tertiary Rocks

Ash Flow-1 Cooling Unit. Ash flows-0.5, -1, and -2 are members of an extensive multiple ash-flow sheet known as the ash flow-1 cooling unit. This cooling unit represents the earliest known volcanic deposit in the Thirtynine Mile volcanic field. Previously, ash flows-1 and -2 were mapped and described by Chapin and Epis (1964). Evidence for another ash flow in the multiple flow cooling unit is afforded by a distinctly higher median 2V of sanidine crystals and by a higher plagioclase/sanidine ratio.

In outcrop, the member flows are indistinguishable. Generally, they form prominent, ledgelike, isolated outcrops in which a eutaxitic fabric is displayed. The fabric is made conspicuous by the presence of subparallel, elongated, pumice lapilli. Where the pumice lapilli have been removed by weathering, an even more distinctive "drill hole" appearance is imparted. The unit weathers to gray, buff, and dark brown.

The rock has an aphanitic reddish brown to purplish matrix containing angular and fractured phenocrysts of sanidine and plagioclase. The clear, unaltered sanidine crystals range upward in size to a maximum of about 7 mm. The plagioclase crystals are usually smaller and are typically altered to a dull white or yellowish color. Tiny flakes of biotite, 2 mm or less in size, are also present. Lithic inclusions are rare. Pumice forms about five percent of the rock.

Petrographically, the groundmass of the ash-flow members consists of devitrified glass shards and dust and contains phenocrysts of zoned sanidine, zoned and altered plagioclase, and partially oxidized to completely opaque biotite. Resorption of sanidine around pre-existing plagioclase grains is rather common.

Phenocryst grain counts were made to determine what, if any, modal differences exist between the formation members. The results are shown in Table I where the percentage of phenocrysts have been recalculated to 100. Table II summarizes sanidine optic angles and plagioclase compositions in the three members of the ash flow-1 cooling unit. Particular note should be given to the median 2V of the sanidine phenocrysts because this property is sufficiently distinctive to distinguish the member flows. It is definitely known from field evidence that ash flow-2 overlies ash flow-1. The stratigraphic relationship of ash flow-0.5 to the other member flows is not known with certainty; its median 2V suggests that it may be the earliest of the three members to be erupted. The data from Tables I and II provide a means of identifying rocks from the ash flow-1 cooling unit by their phenocryst content. Figure 2 shows these data plotted on a sanidine-plagioclase-ferromagnesian diagram. From this, it is seen that ash flow-0.5 is a latite, ash flow-1 varies from trachyte to latite; and the one sample of ash flow-2 lies on the boundary between trachyte and latite. A similar trend from latite to trachyte with ascending stratigraphic position has been observed by Eugene Tobey (1969, personal communication) in the ash flow-1 sheet near Cripple Creek.

Antero Formation. Johnson (1937), working in the Antero basin of southwestern South Park, described a thick

Table I. Modes in volume percent from the ash flow-1 cooling unit

Sample Number	Total pheno-crysts	Phenocryst proportions			Pheno-cryst points counted
		Sani-dine	Plagio-clase	Biotite & Opaques	
Ash flow-2					
L-617	27.4	65.9	28.1	5.8	691
Ash flow-1					
L-102	33.2	54.4	34.9	10.5	793
L-63	28.1	53.3	37.7	8.9	765
L-33	21.5	72.4	20.9	6.5	797
Ash flow-0.5					
L-622	24.4	50.0	41.8	8.2	608
L-621	24.8	48.0	44.0	8.0	690

Table II. Summary of phenocryst optics and compositions from the ash flow-1 cooling unit

	Phenocryst	Optics and compositions
Ash flow-2	Sanidine	2V = 30-42°, median = 33.5°, zoned 34.5-41.5° (24)
	Plagioclase	Avg. An 36, zoned An 31-38, norm. (3)
Ash flow-1	Sanidine	2V = 32-54°, median = 38°, zoned 34-48° (92)
	Plagioclase	Avg. An 41, zoned An 38-52, rev. & osc. (6)
Ash flow-0.5	Sanidine	2V = 35-54°, median = 42°, zoned 39.5-54° (48)
	Plagioclase	Avg. An 41, zoned An 32-51, osc. (5)

Bracketed quantities indicate number of determinations

ASH FLOW-1 COOLING UNIT

- o Ash flow-2
- △ Ash flow-1
- • Ash flow-0.5

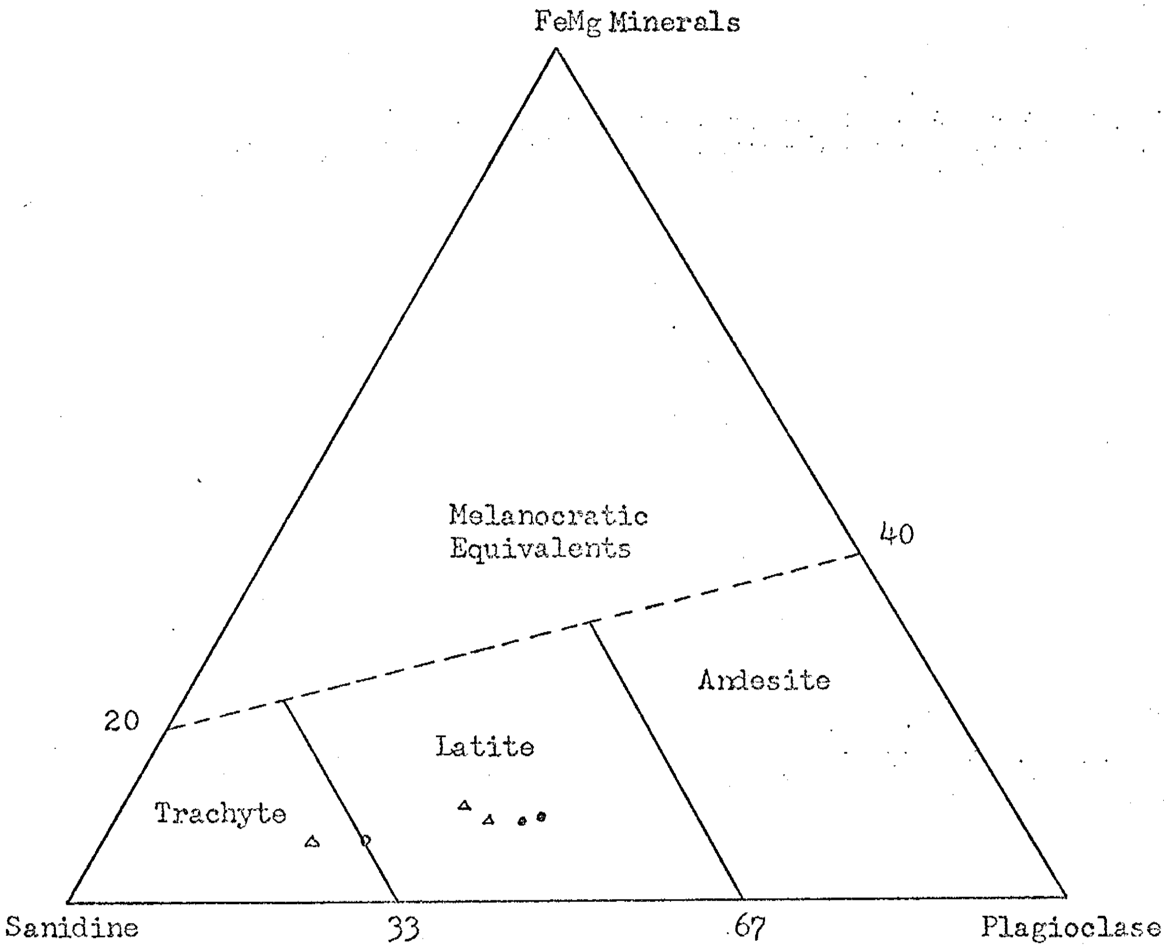


Fig. 2 Three component classification of common intermediate volcanic rocks (Based on AGI mineral ratios from data sheet 23a).

sequence of tuffs, volcaniclastic sediments, intercalated algal limestones, and overlying conglomerates to which he applied the name Antero Formation. De Voto (1964, p. 123-4) separated the Antero Formation into two members: the lower member consisted of tuffs and tuffaceous sediments with a maximum thickness of about 2,000 feet; the upper member consisted predominantly of coarse sandstone and conglomerate and is restricted to the Antero syncline where it reaches a thickness of 1,300 feet. According to Chapin and Epis (1964, p. 149), the lower tuff member of the Antero Formation extends southward as far as the canyon of the Arkansas River where it has a maximum thickness of 200 feet. The lower tuff member is also present in moderate thickness in the Salida area. The map scale of the present investigation did not permit a subdivision of the lower tuff member of geologic mapping. However, for the purposes of lithologic description, a two-fold division of the lower tuff member of the Antero Formation is recognized in the map area.

The two major lithologic types of Antero tuff present in the Salida region are termed the ash-flow tuff facies and the sedimentary tuff facies. The ash-flow tuff facies is the basal unit of the lower member named by De Voto and has a measured thickness of 368 feet east of Black's cabin (T.50N., R.11E., Sec. 7, SE 1/4). At this locality, the ash-flow tuff facies exhibits striking pinnacles of unwelded, pumice rich, ash-flow tuff. It is overlain by, and grades laterally into, the sedimentary tuff facies which consists of widespread, well stratified, pumice rich and biotite rich tuffaceous sediment.

In detail, the character of the sedimentary tuff facies varies from an indurated bluish sandstone containing altered biotite crystals and rock fragments to extremely friable beds of crystal-rich pumice lumps which nearly lack a clastic matrix. The sedimentary tuff facies is the predominant type in the Gribbles Park area (northeast portion of Plate I). Here the monotony of the subdued, grassy topography is relieved by occasional patches of whitish soil derived from the underlying sedimentary tuffs. The sedimentary tuff facies represents the deposition of water worked air-fall material combined with erosional debris from the earlier unwelded ash flows.

The basal facies consists of unwelded ash-flow tuffs with a whitish-gray matrix of glass shards and phenocrysts of plagioclase, biotite, sanidine, hornblende, and sphene. Lithic fragments, generally less than three inches in diameter, comprise approximately one percent of the rock and vary in lithology from Precambrian quartzite to Paleozoic clastics and carbonates to porphyritic volcanic rocks of intermediate composition. Subrounded pumice lumps ranging in size from 1/4 inch up to 14 inches in diameter may constitute as much as 60 percent of the rock and contain abundant fresh biotite and plagioclase crystals. Two types of pumice are present, one pinkish orange in color, and the other white. The size of the lithic inclusions and the pumice lumps tend to decrease upward through the unit; however, no vertical variations in abundance were detected. Outcrop limitations did not permit study of lateral variations. Frequently, the pumice lumps are slightly flattened which imparts a very crude compaction foliation to which lithic inclusions roughly conform. The rocks of the ash-flow tuff facies weather buff to light reddish brown in color and often have a distinctive sheetlike structure associated with weathered surfaces.

Petrographically, the Antero ash-flow tuffs consist of crystal-rich pumice, lithic inclusions, and phenocrysts of plagioclase, biotite, sanidine, hornblende, and sphene in a matrix of unwelded cuspate glass shards and dust. Table III is a compilation of phenocryst modal data collected through a measured section (T.50N., R.11E., Sec. 7) of Antero tuff. The sample numbers of Table III are plotted in Figure 3 which is a diagrammatic representation of the measured section. The modal data, plotted as histograms in Figure 3, reveal a remarkable uniformity through the measured section even though subtle partings and the presence of a fluvial stratum suggests a multiple flow origin. The section has been tentatively subdivided into four ash flows as indicated in Figure 3. The uppermost ash flow, friable in the extreme, could not be sampled adequately but resembled the lower flows in all other megascopic respects. Table IV summarizes the compositions of the plagioclase phenocrysts obtained from this measured section. The modal data from Table IV are plotted on a sanidine-plagioclase-ferromagnesian triangular diagram (Figure 4) which, together with the composition of the plagioclase, indicates an andesitic classification for the Antero tuffs.

Tuff of Badger Creek. The tuff of Badger Creek is the informal name proposed by the author for the most extensive volcanic formation in the Salida area. This formation, with portions of the ash flow-1 cooling unit and the Antero Formation, fills the east-west trending valley (Salida-Waugh Mountain Paleovalley) nearly 11 miles long and about 1½ miles wide. Previous investigators, working mainly in the western portions of the Cameron Mountain quadrangle, have described parts of the unit with varying degrees of accuracy. Bhutta (1954, p. 102-104) described it in the Longs Gulch area (T.50N., R.9E., Sec. 3) as a rhyolite lava flow with microlites grading to phenocrysts in the amounts of 20 percent quartz, 15 percent orthoclase, and with biotite and interstitial devitrified glass common. Definite flow structures were also reported by Bhutta (1954, p. 104). Van Diver (1958, p. 64-70), working in

Table III. Modes in volume percent from the ash-flow tuff facies of the Antero Formation

Sample Number	Total pheno-crysts	Phenocryst proportions					Pheno-cryst points counted
		Plagio-clase	Sani-dine	Biotite Opaques	Hornblende Sphene	Lithics	
Top of unit							
1 S-2-7[o]	20.7	57.5	--	29.0	1.9	11.6	538
2 S-2-6	11.5	64.3	3.5	24.4	7.8	--	556
3 S-3-5	27.1	68.2	2.6	26.2	2.2	0.7	535
4 S-2-4	20.4	72.0	2.4	23.1	1.5	1.0	578
5 S-2-3	21.8	66.4	4.1	28.5	--	0.9	580
6 S-2-8	30.2	66.1	5.6	25.5	2.0	0.7	533
7 S-2-2	26.4	61.2	5.7	22.8	1.1	9.1	584
8 S-2-1	19.4	59.4	7.7	24.2	4.6	4.1	530
Base of unit							

[o] Water-worked strata

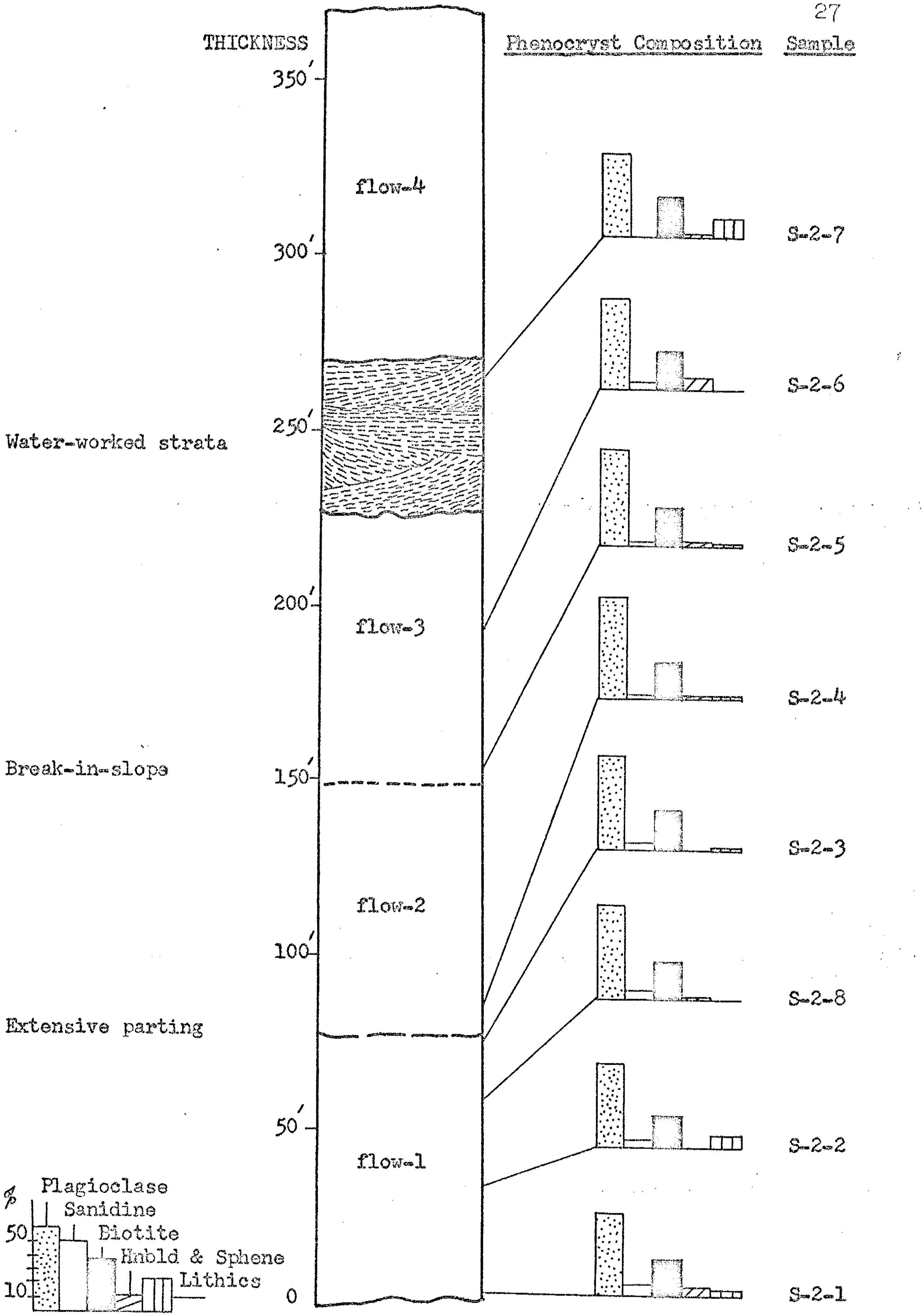


Fig. 3. Measured section of the ash-flow tuff facies of the Antero Formation showing mineralogical variations (data from Table III).

Table IV. Summary of plagioclase compositions from the ash-flow tuff facies of the Antero Formation

	Phenocryst	Composition
Flow-3	Plagioclase	Avg. An 28, zoned An 18-48, osc. (4)
Flow-2	Plagioclase	Avg. An 38, zoned An 20-48, osc. (2)
Flow-1	Plagioclase	Avg. An 38, zoned An 15-65, osc. (11)

Bracketed quantities indicate number of determinations

ANTERO FORMATION

• Ash-flow tuff facies of the Antero Formation

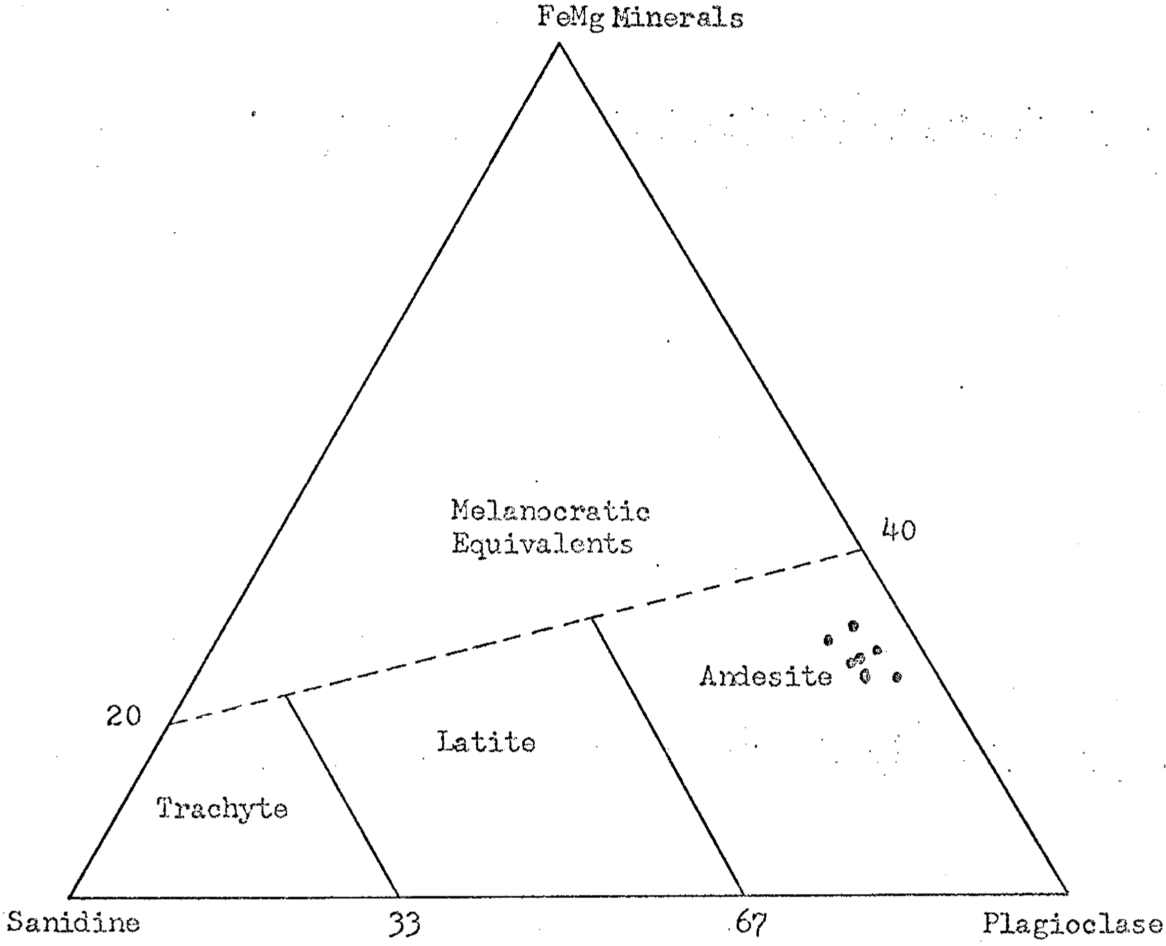


Fig. 4 Three component classification of common intermediate volcanic rocks (Based on AGI mineral ratios from data sheet 23a).

the same vicinity, correctly recognized the unit as an "ignimbrite" rather than a lava flow and described it as a welded rhyolite tuff breccia. This description notes the presence of angular fragments of sanidine, plagioclase, and euhedral quartz accompanied by uniformly distributed biotite in a matrix of partly devitrified glass shards. Van Diver states that "flow lineations" are absent but "flattened gas bubbles" are locally common.

The tuff of Badger Creek occasionally forms prominent cliff-like outcrops, particularly on southern exposures. The unit typically forms low rounded hills composed of sheetlike slabs of rock thoroughly imbedded in soil. The slabs measure a foot or two in diameter by three to four inches thick and are characteristic of the formation. Compaction foliations defined by flattened pumice are very common and lineations defined by pumice elongation during flow are observed occasionally. A number of dark gray to black vitrophyric zones have been observed at various horizons in the unit. These zones grade upward into moderately and slightly-welded zones where pumice is more conspicuous and thin streaks of pink, siliceous spherulites are present. When the pumice has been removed by weathering, numerous tubular cavities about one inch in diameter present a distinctive "Swiss cheese" appearance.

In hand specimen, the tuff of Badger Creek has a groundmass which varies from black to pinkish brown depending upon the degree of welding. Most specimens fall between these extremes and a "salt and pepper" aspect resulting from the high biotite content is common. Buff to yellowish gray is the usual color of weathered material. Locally, lithic inclusions may form as much as five percent of the rock but the average is about one percent. The lithic constituents range in size from microscopic fragments up to clasts five inches in diameter. A few Precambrian quartzite fragments have been observed but the most common lithic fragments are angular to subrounded volcanic rocks of intermediate composition and are less than two inches in diameter. Pumice, showing all degrees of welding, may form as much as five to 10 percent of the rocks above the vitrophyric zones. Black welded pumice lenses as much as six inches in diameter by one inch thick are not uncommon. Two types of pumice lumps have been observed in the less densely welded zones; these are a pinkish-orange pumice and a white pumice. Both are rich in biotite and plagioclase crystals. The pumice is strikingly similar to that in the tuffs of the underlying Antero Formation but occurs in lesser quantities and smaller lumps.

Petrographically, the tuff of Badger Creek consists of phenocrysts of plagioclase, biotite, sanidine, hornblende, and sphene combined with flattened pumice and a few lithic fragments in a matrix of cuspate glass shards which are welded and devitrified in varying degrees.

Modal mineralogical data from the tuff of Badger Creek are presented in Table V. Table VI contains a summary of optical and compositional data for plagioclase and hornblende.

A stratigraphic thickness of 313 feet was measured north of East Badger Creek (T.50N., R.11E., Sec. 12). The six vitrophyric zones encountered are shown diagrammatically in Figure 5 and suggest a multiple-flow origin and a compound-cooling history for the tuff of Badger Creek. Phenocryst variations and the sample locations are also shown in Figure 5. As in the ash-flow tuff facies of the Antero Formation, the phenocryst ratios and compositions are remarkably constant throughout the stratigraphic section. The modal data has been plotted on a sanidine-plagioclase-ferromagnesian diagram in Figure 6 which, together with the plagioclase composition, indicates an andesitic composition for the unit.

The tuff of Badger Creek and the unwelded ash-flow tuffs of the Antero Formation are very similar, both in modal mineralogy and in plagioclase composition, which suggests kinship of the two units even though their eruptions were separated by an interval of erosion and reworking.

Latite of East Badger Creek. The latite of East Badger Creek is a very distinctive cliff forming lava flow which appears to follow the east-west course of the Salida-Waugh Mountain paleovalley (T. 50N., R.11E.). The

Table V. Modes in volume percent from the tuff of Badger Creek

Sample Number	Total pheno-crysts	Phenocryst proportions					Pheno-cryst points counted
		Plagio-clase	Sani-dine	Biotite Opaques	Hornblende Sphene	Lithics	
Top of unit							
1 S-1-15	32.3	72.3	3.4	21.1	3.1	--	528
2 S-1-13	34.2	81.3	0.6	16.4	1.8	--	519
3 S-1-11	31.0	79.0	1.3	17.8	1.9	--	543
4 S-1-10	31.5	70.3	5.4[o]	19.4	4.8	--	529
5 S-1-8	33.6	73.5	2.1	18.2	4.2	2.1	553
6 S-1-6	35.3	72.5	1.7	19.0	6.2	0.6	534
7 S-1-3	34.8	75.2	1.7	17.5	5.5	--	528
8 S-1-1	36.6	72.2	0.5	19.2	6.6	1.4	588
Base of unit							

[o] Most counts from one very large grain

Table VI. Summary of phenocryst optics and compositions from the tuff of Badger Creek

	Phenocryst	Optics and composition
Flow-6	Plagioclase	Avg. An 40, zoned An 30-65, osc. & rev. (4)
Flow-5	Plagioclase	Avg. An 58, zoned An 40-53, norm. (3)
Flow-4	Plagioclase Hornblende	Avg. An 42, zoned An 28-34, norm. (2) Ext. 17° (2)
Flow-3	Plagioclase Hornblende Basaltic Hnbld.	Avg. An 40, zoned An 20-80, norm. (5) Ext. 24° (1) Ext. 3° (1)
Flow-2	Plagioclase	Avg. An 34, zoned An 30-42, osc. (2)
Flow-1	Plagioclase Hornblende	Avg. An 45, zoned An 23-65, osc., norm., & rev. (15) Ext. 16° (2)

Bracketed quantities indicate number of determinations

Extinction $c \wedge Z$

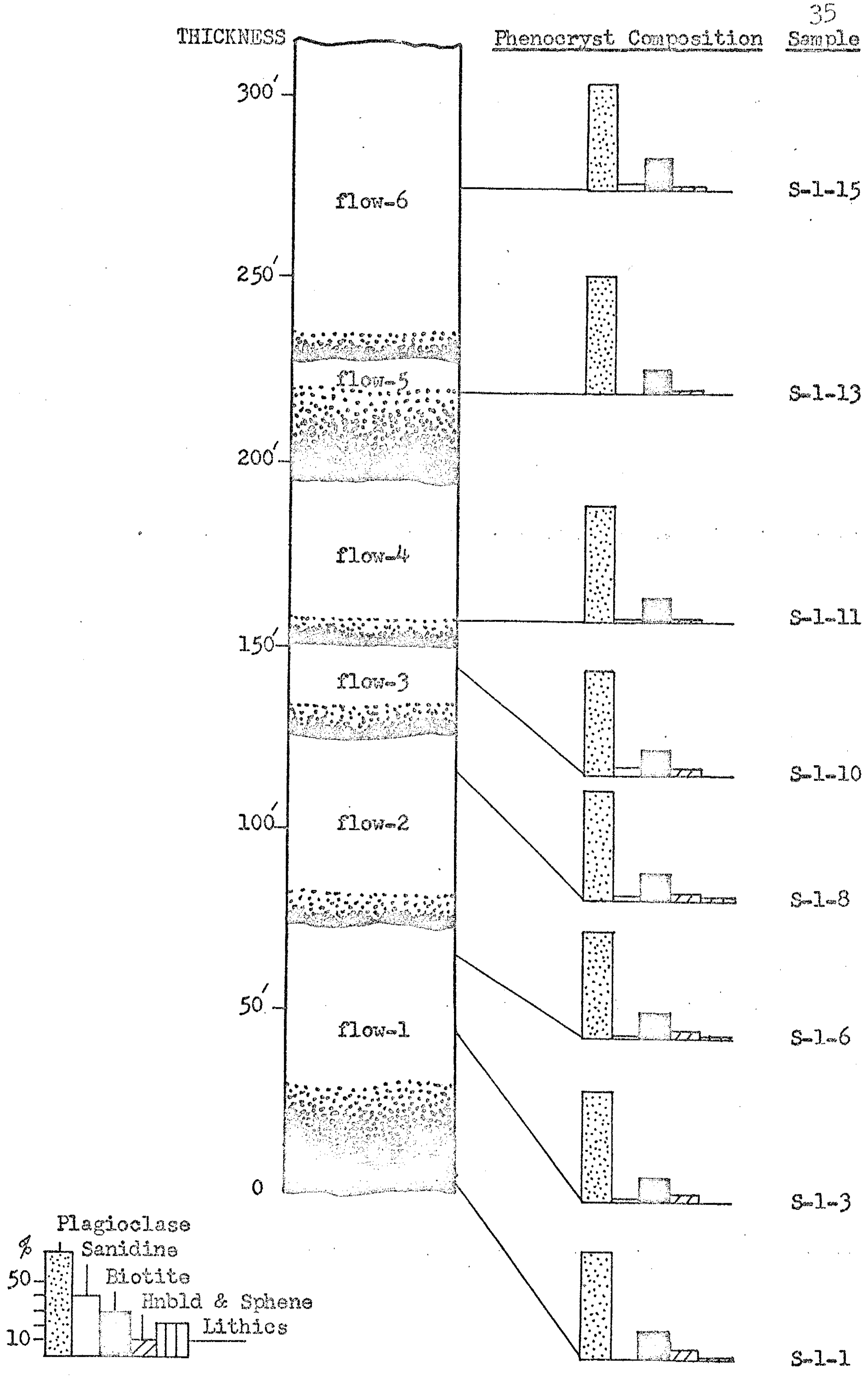


Fig. 5. Measured section of the tuff of Badger Creek showing mineralogical variations (data from Table V). Shading indicates approximate thickness of welded zones and degree of welding.

TUFF OF BADGER CREEK

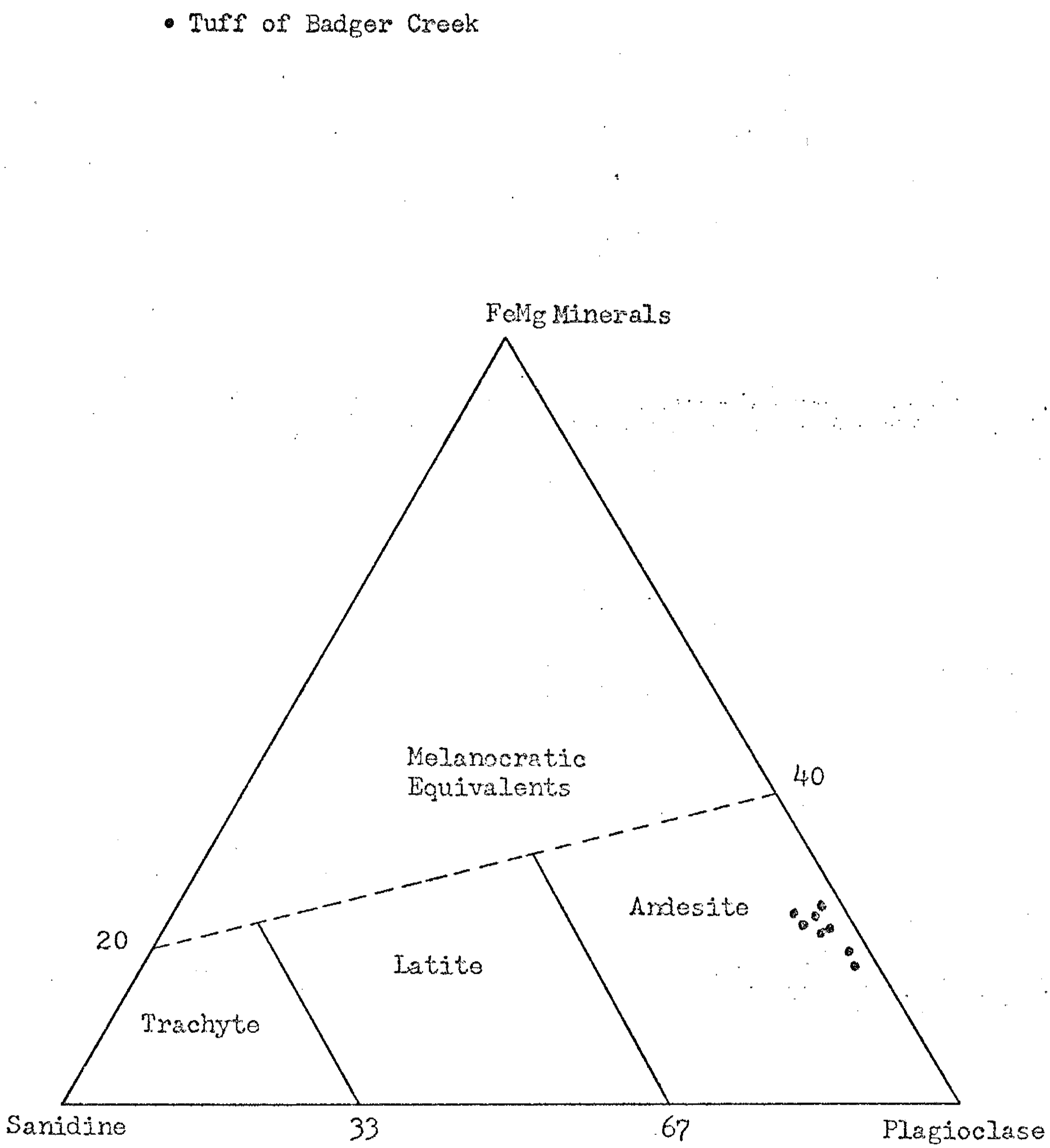


Fig. 6 Three component classification of common intermediate volcanic rocks (Based on AGI mineral ratios from data sheet 23a).

lava flow is 2 1/2 miles long, about one-half mile wide, and 250 to 300 feet thick. The unit exhibits a characteristic sheeting of one-eighth inch to four inches thick which is frequently paralleled by alignment of phenocrysts. Crude columnar jointing is present along the southern exposures. Close inspection of the joint surfaces reveal the presence of curious tiny grooves which apparently result from the intersection of joint surfaces with flow layers.

The aphanitic groundmass of this holocrystalline rock ranges from gray to purple in color and weathers yellowish brown. Seriate, microcrystalline feldspars comprise 80 percent of the rock and show a pilotaxitic texture in thin section. Plagioclase phenocrysts (An 37, average of three determinations) display splotchy, irregular zoning and constitute about 10 percent of the rock. Sanidine, or anorthoclase, with a median 2V of 49 degrees (22 determinations) forms about eight percent of the rock, partially oxidized biotite constitutes about two percent volumetrically.

One outcrop of the unit is worthy of special note. This elongate solitary body occurs in T.50N., R.11E., Sec. 8, SE 1/4. Here a megabreccia of rounded boulders, as much as one foot in diameter, of an intermediate porphyritic volcanic rock combined with smaller angular fragments of the same material are contained in a matrix of East Badger Creek latite. The breccia zone is small, probably less than 50 yards in diameter, roughly circular, and grades into the normal latite of East Badger Creek. Many of the large breccia blocks show contorted flow banding.

Ash Flow-7 Cooling Unit. A thick sequence of ash-flow tuffs, correlated with the multiple flow ash flow-7 cooling unit of the Thirtynine Mile volcanic field, has been mapped along the eastern margin of the Cameron Mountain quadrangle. Previous workers have studied the unit in South Park and in the Wet Mountain Valley (Chapin and Epis, 1964, p. 152; Epis and Chapin, 1968, p. 71).

In the area mapped by the present investigator, the ash flow-7 cooling unit exhibits massive cliffs along southern exposures and heavily wooded slopes strewn with slablike debris along the northern exposures. The rock varies from dark purplish brown to gray and shows moderate to well developed compaction structures.

Megascopic examination of the rock reveals the presence of phenocrysts of sanidine, biotite, hornblende, and sphene. Pumice lumps, welded and darkened in varying degrees, are flattened into lenses averaging one-fourth inch by three inches in size and constitute 10 percent or less of the rock. Angular lithic fragments up to one inch in diameter and consisting of red to black, aphanitic to porphyritic, volcanic rocks of intermediate composition are abundant. Bronzy biotite and blue chatoyant sanidine are characteristic of the entire formation.

Four members of the ash flow-7 cooling unit which may correspond to individual ash flows, have been recognized to date. These are termed P, O, G, and R in reference to their matrix colors of purple, orange, gray, and red respectively. Figure 7 represents a stratigraphic section measured north of Two Creek (T. 50N., R.11E., Sec. 5) and shows the relative positions and thicknesses of the members as well as their mineralogical variations. The basal member-P has a dark brownish-purple matrix which weathers to a lighter pinkish brown. The degree of welding decreases gradationally upward from a densely welded vitrophyric zone of uncertain thickness. Flattened pumice lenses as much as one-half inch by eight inches in size and lithic fragments as much as one inch by 10 inches in diameter are moderately abundant. Devitrification of glass shards increases upwards from the base of the unit. Spherulites of feldspar have developed within the pumice lenses near the top of the member.

Member-O, corresponding to a break in slope, has a distinctive pinkish-orange matrix which weathers buff to dark brown. The lithic and pumice content appears to be higher than in member-P; welding is much less intense. The glass shards of the matrix are strongly cuspate and are only slightly flattened. Chatoyant sanidine phenocrysts seem especially large and prominent in this member.

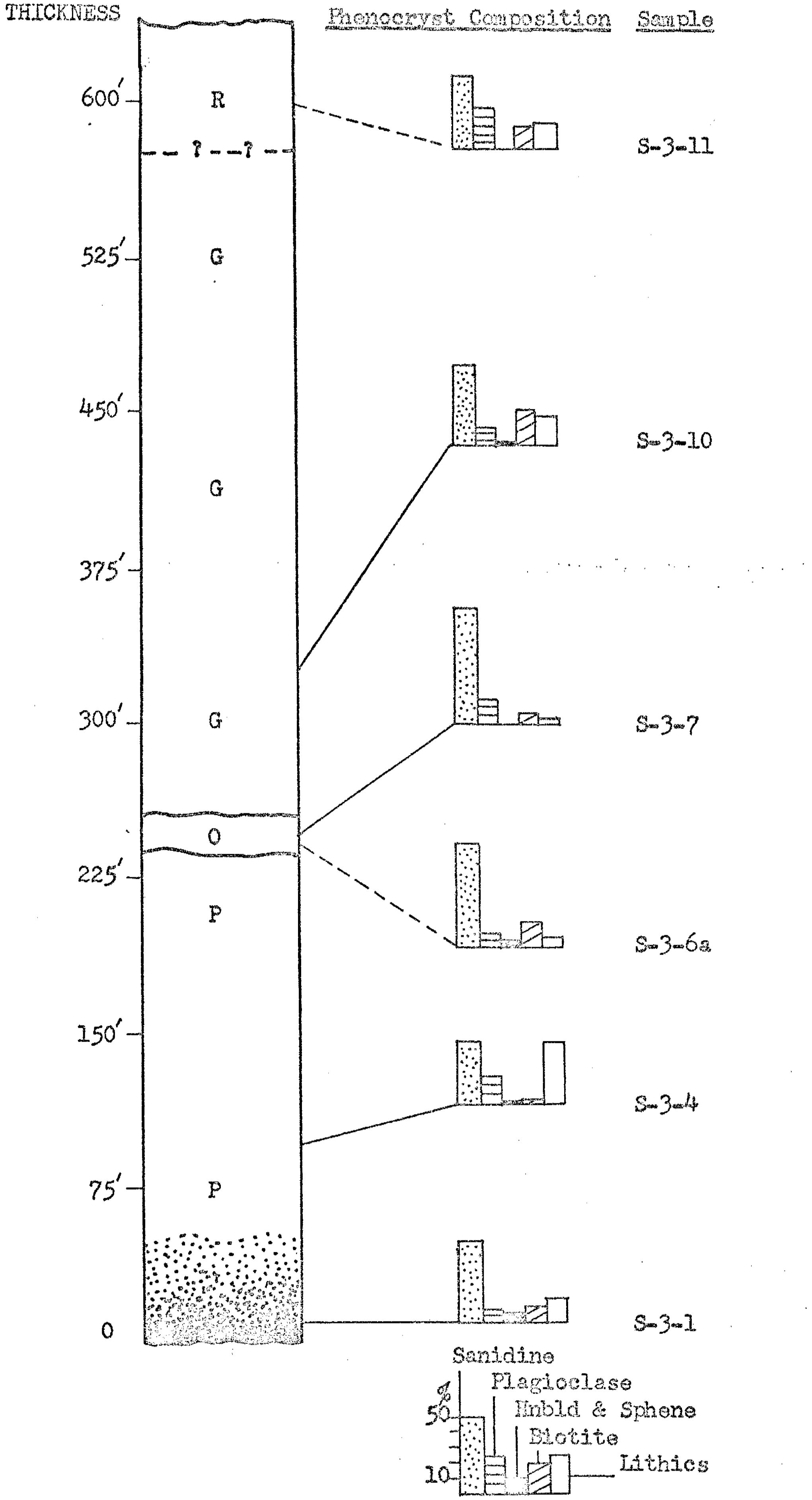


Fig. 7. Measured section of the ash flow-7 cooling unit showing mineralogical variations (data from Table VII). Shading indicates basal vitrophyric zone.

Member-G, accentuated by a slope change to the vertical, has a pinkish-gray to dark-gray matrix which weathers buff to reddish brown. Shard structures within the matrix are almost totally erased by crystallization of the glass to tiny irregular feldspar grains. Most of the ferromagnesian minerals show some degree of oxidation; bright coppery biotite is conspicuous. Resorption rims surround some plagioclase phenocrysts. A few pyroxene prisms with ragged terminations are present near the top of the member. Pumice lenses are strongly silicified. Welding varies from nil to moderate through the member. Most of the lithic fragments are somewhat rounded.

Member-R has a purplish-red matrix which weathers buff to brown. The matrix glass shards are reddish brown and are predominantly cuspate; most are slightly flattened and many show partial devitrification. The ferromagnesian phenocrysts are oxidized in varying degrees; bright coppery biotite crystals are conspicuous but not as abundant as in member-G. Tiny pyroxene prisms with ragged terminations but lacking overgrowths or alteration are present in trace amounts. Small, partially welded and slightly silicified, crystal-rich pumice lenses form approximately five percent of the rock. Small, angular, lithic fragments of volcanic rocks of intermediate composition are very prominent and may comprise as much as five percent of the rock.

Modal and optical data pertaining to the measured section of ash flow-7 are presented in Tables VII and VIII respectively. Figure 8 shows these data plotted on a sanidine-plagioclase-ferromagnesian triangular diagram from which it can be seen by the sanidine/plagioclase ratio that the ash flow-7 cooling unit varies from trachyte to latite.

Latite of Waugh Mountain. Waugh Mountain (11,718 feet), whose western flank lies along the boundary between the Black Mountain and Cameron Mountain quadrangles, forms the dominant topographic high in the southern portion of the Thirtynine Mile volcanic field. A poorly exposed volcanic center near the middle of Waugh Mountain is thought to be the source of a sequence of rhyolitic and latitic lava flows and flow breccias 200 to 700 feet thick which occur along its western flank (Epis and Chapin, 1968, p. 73). This flow sequence, termed the latite of Waugh Mountain, is present on three high ridges which extend one to two miles into the study area.

The latite of Waugh Mountain overlies the ash flow-7 cooling unit and caps the ridges at the head of Two Creek. The upper surface of this unit is characterized by discontinuous patchy outcrops of resistant knobs and boulders. The rocks form gray to pinkish-gray flows and autoclastic flow breccias which are commonly silicified. Flow bands, one to four inches thick, seem to be

Table VII. Modes in volume percent from the ash flow-7 cooling unit

Sample Number	Total pheno- crysts	Phenocryst proportions					Pheno- cryst points counted
		Sani- dine	Plagio- clase	Hornblende Sphene	Biotite Opaques	Lithics	
Top of unit							
1 S-3-11	32.3	43.9	25.1	0.6	14.6	15.8	529
2 S-3-10	12.9	50.0	10.8	1.6	20.9	16.3	587
3 S-3-7	19.5	73.8	15.4	1.0	6.7	3.1	530
4 S-3-6a	13.2	67.5	9.1	3.8	13.6	6.1	596
5 S-3-4	18.4	39.7	18.0	1.1	1.6	39.7	574
6 S-3-1	14.9	55.0	9.4	8.1	10.1	17.5	585
Base of unit							

Table VIII. Summary of phenocryst optics and compositions from the ash flow-7 cooling unit

	Phenocryst	Optics and composition
Member-R	Sanidine	2V = 28-48°, median 36° (21)
	Plagioclase	Avg. An 34.5, zoned An 27-47, osc. & rev. (3)
Member-G	Sanidine	2V = 28-48°, median 35.5° (42)
	Plagioclase	Avg. An 39, zoned An 33-47, osc. & rev. (7)
	Clinopyroxene	Ext. 43° (5)
Member-O	Sanidine	2V = 28-50°, median 35° (42)
	Plagioclase	Avg. An 38 (4)
Member-P	Sanidine	2V = 28-50°, median 36° (40)
	Plagioclase	Avg. An 30 (5)
	Hornblende	Ext. 20° (2)

Bracketed quantities indicate number of determinations

Extinction $c \wedge Z$

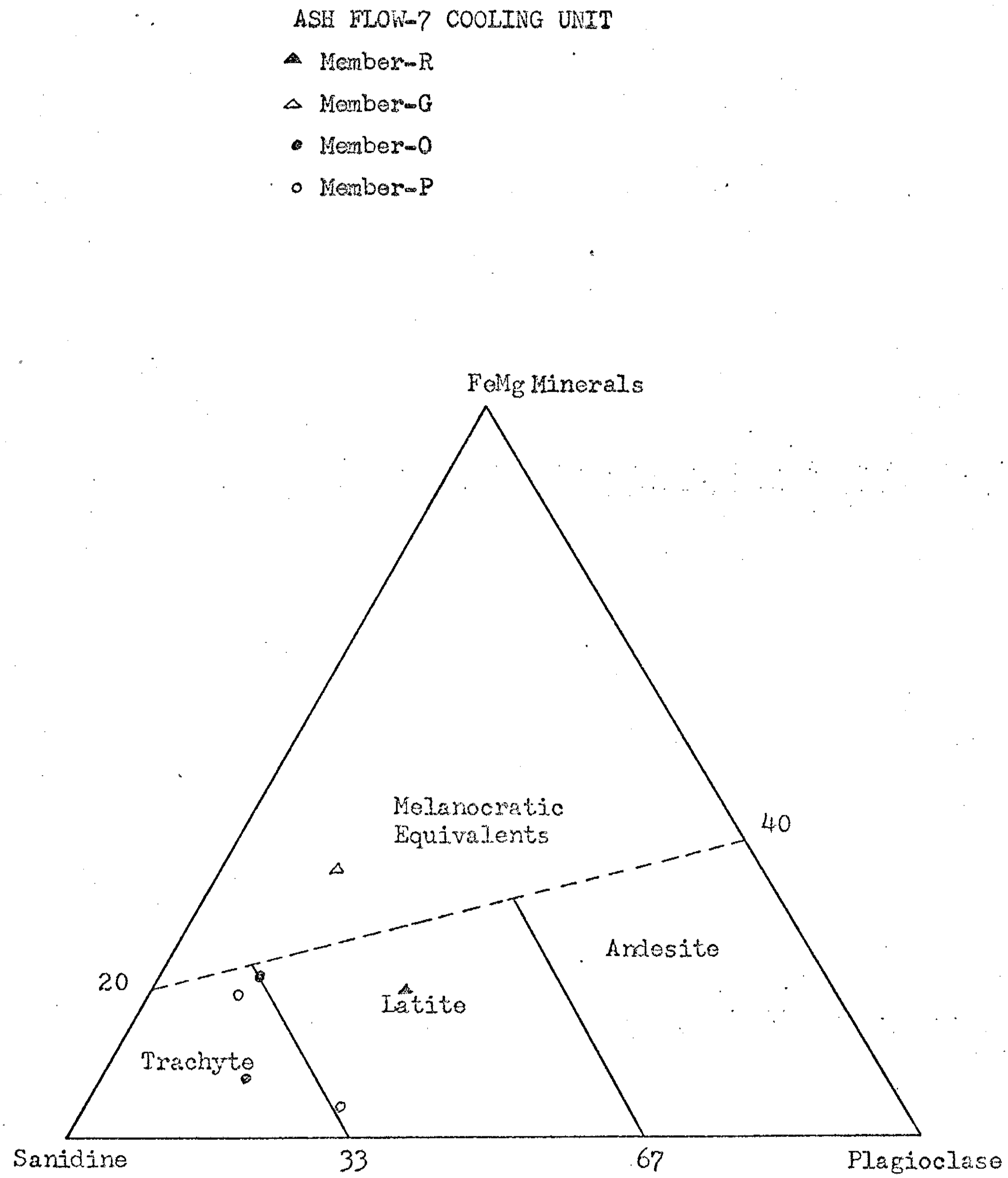


Fig. 8 Three component classification of common intermediate volcanic rocks (Based on AGI mineral ratios from data sheet 23a).

generally parallel to crudely oriented breccia fragments within the breccia zones.

Petrographically, the rock contains 10 to 20 percent phenocrysts of plagioclase, sanidine, and biotite in a glassy to microcrystalline groundmass. Plagioclase, the predominant feldspar, has a composition ranging from An 28 to An 42; it is frequently zoned and is often fragmented. The plagioclase crystals are distinctly corroded either on the periphery or within the core, but rarely both. Sanidine phenocrysts are generally larger in size, freer of alteration effects, and less fragmental than those of plagioclase. Small biotite phenocrysts, forming less than two percent of the rock, are nearly always partially oxidized. Trace amounts of anorthoclase, hornblende, and sphene may also be present. Lensoid axiolitic and spherulitic zones, more or less paralleled by the tabular and lath-shaped minerals, define the flow structure. Where brecciation has occurred, thin stringers of calcium carbonate may envelope some of the breccia clasts. Accidental lithic fragments are rare, but types ranging from Precambrian gneiss to Tertiary andesite (?) have been observed. Phenocryst paucity renders the assignment of a rock name from petrographic data difficult. Mineralogically, these flows are andesites but because of their light color and the presence of sanidine, a more silicic composition seems likely; hence the author is using the term latite until chemical data is available.

Upper Andesite. Overlying the latite of Waugh Mountain is a sequence of andesitic and basaltic flows, flow breccias, and minor lahars and tuffs which have been informally named the upper andesite by Epis and Chapin (1968, p. 76). These workers estimate a thickness of about 1,200 feet near Waugh Mountain which diminishes to less than 300 feet in the southern part of the volcanic field. Waugh Mountain is the presumed source of the rocks. Although outcrops of the upper andesite are rare within the study area, erosional debris of the unit is widely scattered over most of the eastern half of the quadrangle.

In the Cameron Mountain quadrangle, rocks representing the upper andesite are present along the extreme eastern margin (T.50N., R.11E., Secs. 10, 15, and 16). This densely wooded area is nearly barren of outcrops; formational distribution is inferred from the distribution of rock types in the colluvium. A brownish purple aphanitic andesite (?) which weathers to buff and contains a few phenocrysts of plagioclase, pyroxene, and biotite crops out on hill "10,660 feet"; these outcrops display a distinctive, but erratic, sheeting structure. Overlying the andesite (?) is a black, vesicular, olivine basalt of unknown thickness and areal extent. Some of the vesicles were filled with amygdules of pinkish-white calcite.

A small outcrop of unwelded lithic ash-flow tuff, superfically resembling the lower member of the Antero

Formation, but stratigraphically higher, occurs along the eastern margin of the quadrangle (T.50N., R.11E., Sec. 10). The rock weathers to buff and reddish brown and forms stubby pinnacles. Rounded biotite-rich pumice lumps, as much as six inches in diameter, form an estimated 30 to 40 percent of the rock. Two pumice types are present, one is grayish white and the other pinkish orange. The grayish-white pumice is more abundant and generally larger in size. The lithic content is extremely high (20 percent by volume estimated in outcrop) and distinctively different from that of the lower member of the Antero Formation. All of the angular to rounded lithic fragments are of volcanic origin and range up to six inches in diameter. The lithic constituents strongly resemble the upper andesite and the latite of Waugh Mountain. The major phenocrysts are feldspar and biotite but a few crystals of hornblende (?) are present. The matrix is gray to slightly pinkish gray and very friable. Because of the geographic occurrence and stratigraphic position of the outcrop and the distinctive lithic content, the rock is assigned to the upper andesite until further mapping reveals a better designation.

Andesite of Big Baldy. In the southwestern portion of the map area, a number of isolated patches of similar appearing basaltic andesites have been grouped under the name andesite of Big Baldy. These rocks are younger than the Antero Formation but complete stratigraphic information is not available. Because of dissimilar petrologic characteristics and appreciable geographic separation, no direct genetic relationship to the upper andesite is postulated.

The best outcrops of this formation are those in the vicinity of Big Baldy Mountain (T.50N., R.10E., Sec. 29). At this locality, andesitic lava flows, autobrecciated and silicified in part, are interstratified with minor, variegated, andesitic boulder breccias. The breccias contain red and black porphyritic andesite boulders ranging up to four feet in diameter and are restricted to two small outcrops west and south of Big Baldy Mountain.

The major portion of the unit consists of purplish porphyritic basaltic andesite which weathers brown to black. Phenocrysts of altered and zoned plagioclase containing tiny apatite inclusions form 25 to 40 percent of the rock. Compositionally, the plagioclase phenocrysts range from An 30 to An 70 with an average of An 50. Small altered hypersthene phenocrysts may constitute as much as five percent. A few phenocrysts of basaltic hornblende and clinopyroxene may be present. Opaque grains, probably magnetite and oxidized biotite, are present in trace amounts. The matrix elements are brownish glass and plagioclase microlites which vary in textural arrangement from hyalopilitic to pilotaxitic.

Silicic Felsite of Section 36. A highly silicified lava flow which rests on prevolcanic rocks or on the andesite of Big Baldy has been mapped in the southwest portion of the study area. This flow, previously described as pitchstone (Bhutta, 1954, p. 109), is referred to by the present investigator as the silicic felsite of section 36.

The purplish gray, massive flow which is locally fractured and brecciated forms resistant cliffs along its mile-long length. In outcrop, flow structures and phenocryst foliations are vague and extremely erratic. White, fractured phenocrysts of zoned plagioclase range in composition from An 35 to An 58 but constitute less than 10 percent of the rock. A few scattered phenocrysts of oxidized biotite and other opaque grains are present. Most of the rock consists of pinkish-brown glass which displays a crude flow banding in thin section. The phenocrysts do not appear to conform to this structure. Minor devitrification has formed a few faintly birefringent arborescent microlites.

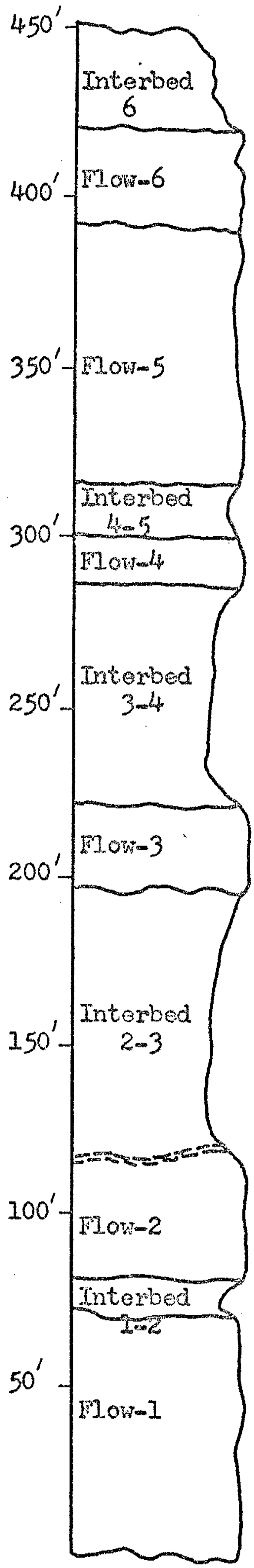
Tenderfoot Hill Volcanic Sequence. In 1954, Bhutta described a unit called the andesite porphyry within which he included the basic volcanic rocks of the Tenderfoot Hill locality just northeast of Salida. That worker, referring to Figure 32, p. 106 (photograph of Tenderfoot Hill), stated that, "The conical surface expression may suggest a near-surface intrusive origin of the rock".

The present writer interprets these same rocks as being part of a steep, west dipping, interstratified sequence of basaltic lava flows and unconsolidated boulder gravels of Tertiary age. In accordance with this view, the name Tenderfoot Hill volcanic sequence is proposed for these rocks.

A composite stratigraphic section was measured in the gulches surrounding Tenderfoot Hill. Six basaltic lava flows and five interflow boulder gravel deposits are present and total 450 feet in thickness. The stratigraphic picture, however, is clouded by landslides, alluvium, and faulting; thus the measured thickness must be regarded as minimal. The composite stratigraphic section is presented diagrammatically in Figure 9.

Flows-1 and -2 are similar, black, porphyritic basalts which weather reddish brown. Approximately 25 percent of the rock is composed of phenocrysts of plagioclase, clinopyroxene, and opaque minerals. The plagioclase phenocrysts form about 20 percent of the rock and are pitted, altered, strongly zoned, and frequently contain a few tiny apatite crystals. The clinopyroxene phenocrysts, probably augite, may reach a length of one inch and are characterized by twinning and sarcophagus-like rims of hornblende (?). The opaque minerals are probably magnetite and highly oxidized biotite. The phenocryst optics of flows-1 and -5 are summarized in

THICKNESS DESCRIPTION



Poorly and crudely stratified boulder gravel with boulders up to 3 ft. in diameter. Metamorphic and plutonic rocks, flow-5, and flows-1 and -2 in order of decreasing abundance form the detritus.

Andesite breccia with clasts up to 1.5 ft. in diameter.

Aphanitic basalt, strongly jointed and sheeted. Autobrecciated at top; yellowish and reddish brecciated zones common. Outcrops rubbly and weathered to reddish-brown color. Resembles cap-rock of Tenderfoot Hill.

Outcrops nil, distinct break in slope and lithology.

Altered, poorly exposed andesite or basalt flow.

Poorly and crudely stratified boulder gravel with grayish-white matrix containing subrounded boulders metamorphic, plutonic, and volcanic rock up to 1.5 ft. in diameter.

Several thin andesite (?) flows separated by thin yellowish-brown soil horizons. Poor outcrops.

Poorly sorted boulder gravel similar to those above. Boulders range up to 4 ft. in diameter with metamorphic and plutonic rocks dominant. A few boulders representing flows-1 and -2 are present. Matrix is ashy-gray silt. Poor outcrops.

Soil horizon containing chips of flow-2.

Similar to flow-1.

Topographic and lithologic break. No outcrops.

Coarsely porphyritic basalt; dark gray to black in color. Weathers to reddish-brown color.

Fig. 9. Measured section of the Tenderfoot Hill volcanic sequence.

Table IX. The pilotaxitic matrix is composed of subequal amounts of brown glass and plagioclase microlites whose composition is about An 50 (method of Michel-Levy using 10 grains).

Flow-3 consists of several thin, gray to bluish gray, porphyritic flows separated by yellowish-brown soil horizons. The rock weathers to a brownish-black color and contains coarse, grayish white, altered plagioclase phenocrysts.

Flow-4 is a thin flow of basaltic andesite or basalt whose outcrops are less resistant to weathering than other flows in the sequence. The rock varies from bluish gray to black in color and weathers to dark brown. Conspicuous greenish and purplish altered zones are present in the rock. Plagioclase and pyroxene (?) crystals, perceptible by hand lens, are highly altered.

Flow-5 is an aphanitic, gray to black basalt which weathers to a reddish-brown color and is characterized by rubbly outcrops. The rock is strongly jointed and sheeted and exhibits numerous, small, discontinuous, red and yellow brecciated zones. Petrographically, flow-5 contains a few phenocrysts (less than five percent) of plagioclase, clinopyroxene, and opaque grains. The plagioclase crystals commonly display combined carlsbad-albite twinning and may contain a few tiny apatite inclusions. The matrix is hyalopilitic with subequal quantities of brownish glass

Table IX. Summary of phenocryst optics and compositions in flows 1 and 5 of the Tenderfoot Hill volcanic sequence

	Phenocryst	Optics and compositions
Flow-5	Plagioclase Augite (?)	Avg. An 53 (2) Ext. 39° (3)
Flow-1	Plagioclase Augite (?)	Avg. An 70, zoned An 63-75, rev. (3) Ext. 40° (3)

Bracketed quantities indicate number of determinations

Extinction $c \wedge Z$

and plagioclase microlites with a composition of An 50 (method of Michel-Levy using 10 grains). The thin basaltic cap of Tenderfoot Hill is thought to be a remnant of flow-5.

Flow-6 is a reddish brown to black, porphyritic, amygdaloidal, andesitic or basaltic breccia. Fragments as much as 1 1/2 feet in diameter are contained in a matrix of similar appearing material. Yellowish-white amygdules as much as one inch in length and thin, irregular stringers of calcium carbonate are abundant. Large, highly altered and zoned phenocrysts of plagioclase are typical.

The sediments interbedded with these flows are poorly sorted, crudely stratified, unconsolidated boulder gravels apparently of fluvial origin. Boulders of Precambrian metamorphic rocks and Tertiary volcanic rocks, ranging up to four feet in diameter, form as much as 60 to 70 percent of these interbeds. Some of the volcanic constituents can be recognized as belonging to the underlying lava flows; others are from formations unfamiliar to the author. The matrix is composed of greenish-gray to yellowish-gray silt and sand. Limonitic staining is common. Van Alstine (1968, personal communication) has regarded similar sediments as a facies of the Dry Union Formation of Tertiary age.

Miscellaneous Volcanic Rocks. Three different volcanic rocks of unknown stratigraphic position occur in very small isolated outcrops within the study area. For convenience, these rocks appear on the geologic map (Plate I) with the symbol Tm (Tertiary miscellaneous) but brief individual descriptions follow below.

An unusual tuffaceous body, restricted to a single, small, circular outcrop, occurs along the upper reaches of Dead Horse Gulch (T.50N., R.9E., Sec. 22, NE 1/4). The rock is iron stained to a bright yellow color and forms pinnacles. The lithic constituents of this body are particularly noteworthy: (1) yellow chert is extremely abundant; (2) Paleozoic rock fragments of all shapes, sizes, and formations are numerous; and (3) these are accompanied by amygdaloidal and vesicular, angular blocks of porphyritic rock up to one foot in diameter which resemble the andesite of Big Baldy. No signs of stratification or sorting were observed in the limited outcrop available. The area north and east of the body is mapped as the andesite of Big Baldy but the nature of the contacts is obscured by copious rounded boulders of red- and yellow-stained scoria and normal andesitic debris. It is thought that this body may be a portion of a small localized lahar emplaced during or following extrusion of the andesite of Big Baldy.

A small body of intrusive breccia has been mapped within the granodiorite of the Whitehorn stock (T.49N., R.10E., Sec. 31). The breccia consists of angular fragments of gray porphyritic volcanic rock of intermediate composition and Whitehorn granodioite contained in a matrix of clay. The clay matrix is yellowish in color and is apparently an alteration product. Rock fragments predominate over the matrix and appear to be arranged in steeply dipping, alternately coarse and fine breccia zones. A number of mineral prospects are associated with the intrusive breccia and the narrow elongate ridge on which it occurs. These features are thought to be localized by the post-Laramide Maverick fault

Slightly less than one mile south of the intrusive breccia and on the strike of the Maverick fault is an isolated body of altered felsite. The felsite exhibits a pinkish orange, flow-banded groundmass which contains a few highly altered feldspar phenocrysts. A greenish-yellow alteration product pervades the entire outcrop. Tiny quartz-filled vugs are abundant. The rock is extensively brecciated and may represent either a small intrusive or a flow remnant.

Postvolcanic Deposits

Tertiary Deposits

Dry Union Formation. The Tenderfoot Hill volcanic sequence is unconformably overlain at the north end of its exposures by sediments thought correlative with the Dry Union Formation. The Dry Union Formation was named by Tweto (1961, B-133) for its type locality in Dry Union Gulch, a few miles south of Leadville, Colorado. Van Alstine and Lewis (1960) studied these sediments and their fossils in the Salida area and concluded that they were of early Pliocene age. The sediments are also present in the Poncha Pass area (Van Alstine, 1968). The present correlation is based on lithologic similarity and stratigraphic position.

The sediments of the Dry Union Formation are similar to those within the Tenderfoot Hill volcanic sequence but are not interbedded with volcanic rocks. They consist of friable, poorly consolidated, tuffaceous and arkosic silts, sands, and gravels. Thin intercalated clays and calcareous zones are occasionally present. Pumice and biotite occur in the tuffaceous strata. Lithic constituents consist of Precambrian metamorphic and granitic rocks and Tertiary volcanic rocks ranging from sand-size grains to pebbles. The formation lies unconformably above the Precambrian rocks and has subsequently been faulted. The strata dip 15 to 18 degrees to the west which is more gentle than the westerly dip of 22 to 65 degrees for the rocks of the Tenderfoot Hill volcanic sequence. In two localities along the Ute Trail sand has been quarried from the formation for commercial purposes.

Boulder Gravels. After the termination of the major phases of volcanism in the Salida area, boulder gravels were deposited in the Salida-Waugh Mountain paleo-valley where they occur as isolated erosional remnants resting on the tuff of Badger Creek, on the Antero Formation, or on prevolcanic rocks. The gravels consist of unstratified angular to rounded boulders of various rock types of Precambrian, Paleozoic, and Tertiary age which range upward in size to four feet in diameter. Sub-sequent erosion has apparently removed the original matrix material so that rounded knobs of boulder-strewn debris remain. The areal distribution of these gravel patches suggest that their distribution was largely restricted to the Salida-Waugh Mountain paleovalley.

Quaternary Deposits

Landslides, Slump Blocks, and Colluvial Deposits. For the purposes of this study landslides, slump blocks, and colluvial deposits were mapped collectively as mass wasting deposits. A number of such bodies are present in the area of investigation. The landslide associated with the feature named "The Crater" (T.50N., R.9E., Sec. 24, SW 1/4) is worthy of individual discussion. At this lo-cality, the dark-purplish andesite of Big Baldy overlies the white ash-flow tuff facies of the Antero Formation with a striking contrast of color. The downslope area west and southwest of The Crater is covered by loose andesitic debris which is characterized by a hummocky and rubbly appearance. The author views the scooped-out depression adjacent to the in situ volcanic rocks as a landslide scar rather than a volcanic crater.

Alluvium. In this report, alluvium is used to indicate detrital stream desposits of recent origin. Such deposits would include sediments laid down in stream beds, alluvial fans, flood plains, and valley fill. In the interest of map clarity, only a portion of these deposits are shown on Plate I. In general, they are shown on the geologic map only where they have a particularly obscuring effect on the bedrock geology.

PALEOVALLEYS IN THE PREVOLCANIC EROSION SURFACE

Prevolcanic Erosion Surface

The study area lies on the western edge of an extensive prevolcanic erosion surface described by Epis and Chapin (1968, p. 56-59). This surface covers an area of about 5,000 square miles and extends from the foot of Kenosha Pass in northeastern South Park to the northern Wet Mountains and Wet Mountain Valley. In an east-west direction, it stretches from the upper Arkansas Valley to the Cripple Creek area, a distance of about 50 miles.

According to Epis and Chapin (1968, p. 57), the prevolcanic surface was a relatively smooth plain of low relief on which small hills, as much as 800 feet high, were present. The surface slopes southward from an elevation of about 9,500 feet in South Park to about 8,500 feet in the northern Wet Mountains. The prevolcanic erosion surface appears to have been formed in middle or late Eocene time and subsequently broken by late Cenozoic faulting (Epis and Chapin, 1968, p. 59).

Paleovalleys

In the study area, volcanic rocks preserve an anomalous drainage pattern which trends east-west and crosses the Laramide structural grain and the present drainage at nearly a right angle. The axes of these paleovalleys mark the two possible directions of stream flow but post-Laramide tectonism has disrupted the original gradients leaving the flow direction of both the streams and the volcanic rocks open to interpretation.

Salida-Waugh Mountain Paleovalley. By early Oligocene time, a prominent east-west trending valley with westward-forking tributaries had developed on the prevolcanic erosion surface in the Salida area. It is not known if the valley was carved in response to Oligocene uplift after the formation of the prevolcanic surface or simply represents a stream entrenchment contemporaneous with the formation of that surface. This valley, now preserved by the ash flow-1 cooling unit, the Antero Formation, and the tuff of Badger Creek, was presumably of erosional origin because it crosses the Laramide structural grain at nearly a right angle and preceded post-Laramide faulting. The eastern end of the paleovalley disappears beneath younger volcanic rocks associated with the Waugh Mountain volcanic center. Chapin (1969, oral communication) has suggested that the paleovalley may extend eastward beyond Waugh Mountain into the Tallahassee Creek area where the tuff of Badger Creek caps a mesa one-half mile southeast of Thorn's ranch house (T.17S., R.73W., Secs. 22 and 23). Thick unwelded ash flows are present in the Antero Formation along the projected trend of this valley as far east as the pinnacles at the head of

Twelvemile Hole (T.17S., R.72W., Sec. 30, NW 1/4). The traceable length of the paleovalley in the Cameron Mountain quadrangle is about 11 miles and the average width is about 1.5 miles.

Plate II is a composite map constructed from present topographic highs of prevolcanic rocks and, where available, the prevolcanic topography. It serves as a paleotopographic map of the prevolcanic surface on which the volcanic rocks rest. The map outlines the geometry of the Salida-Waugh Mountain paleovalley and indicates that the valley was on the order of 1,000 feet deep.

Gribbles Run Paleovalley. The Gribbles Run paleovalley is located in the northeastern portion of the thesis area (T.51N., Rs. 10 and 11E.). The east-west trending paleovalley is about 4 miles long and 1/4 to 1/2 mile wide and is preserved by the ash flow-1 cooling unit.

Flow structures in the Gribbles Run paleovalley are described and interpreted in a later section (p. 76); for the purposes of the present discussion it may be useful for the reader to refer to the paleotopographic map (Figure 15, p. 85) which shows the configuration of the Gribbles Run paleovalley. The post-Laramide Badger Creek fault (see Plate I) has broken the paleovalley into two segments with opposing dips. However, it is clear that the original valley was at least 500 feet deep and that it had westward and northwestward forking tributaries.

Regional Geomorphic Implications

Van Diver (1958, p. 70), working along the extreme northwestern portion of the Salida-Waugh Mountain paleovalley, did not recognize any post volcanic structural deformation and postulated that the volcanic rocks flowed into the paleovalley from the east. This conclusion is based on the elevation changes of the prevolcanic surface from about 9,800 feet in the east to about 8,500 feet in the west. The present author reaches the opposite conclusion regarding the direction of volcanic flowage.

Present evidence suggests that the paleovalleys in the Salida area were carved in the prevolcanic erosion surface before formation of the upper Arkansas graben. Further, it is postulated that these paleovalleys are the remains of a drainage system which drained eastward from the Sawatch Range and across the present southern Mosquito Range. Data supporting this contention are: (1) the tributaries of the Salida-Waugh Mountain and Gribbles Run paleovalleys fork to the west as do tributaries of similar un-named paleovalleys north of the study area (De Voto, 1961, plate 3); (2) directional data within the ash flow-1 cooling unit in the Gribbles Run paleovalley indicate that flowage was from west to east (see p. 83); (3) volcanic rocks filling the Salida-Waugh Mountain paleovalley range from 9,800 feet to 8,200 feet where they cross Badger Creek in the eastern third of the map area; (4) pronounced topographic lineaments which correspond to sharp elevation changes in the prevolcanic surface support the presence of north trending postvolcanic faults (the Maverick and Badger Creek faults on Plates I and II) which have broken the Salida-Waugh Mountain paleovalley into three main sections each marked by a dip reversal. Two additional faults, the Dead Goat and Dead Horse faults, drop the volcanic rocks of the Salida-Waugh Mountain paleovalley down into the upper Arkansas graben; (5) outcrops of the ash flow-1 cooling unit are present on the west side of the upper Arkansas Valley at Poncha Pass (Chapin, 1969, oral communication). The younger ash flow-7 cooling unit is also present at Poncha Pass and has been steeply tilted into the graben and buried beneath several thousand feet of graben-fill sediments (Chapin, 1969, oral communication); and (6) paleontologic evidence (Van Alstine and Lewis, 1960) suggests a Pliocene age for the sediments deposited in the upper Arkansas graben near Salida.

STRUCTURAL GEOLOGY

Regional Structural Development

A number of workers have studied the structural development of central Colorado. Among these are: Burbank and Goddard (1937), Stark and others (1949), Gableman (1952), Boos and Boos (1957), Badgley (1960), Tweto and Sims (1963), Harms (1964), Sawatzsky (1964), Munger (1965), and Eardley (1968). According to these writers, the Front Range and the Wet Mountains represent the easternmost of a series of large north-northwest trending uplifts bounded by steeply dipping thrust faults. West of these ranges are a series of downfaulted intermontane basins, or parks, which also trend north-northwest. From southeast to northwest these basins are Huerfano Park, the Wet Mountain Valley, South Park, Middle Park, and North Park. West of these basins, and arranged in an echelon fashion, are the Sangre de Cristo Mountains, Mosquito Range, Ten Mile Range, and Gore Range. The Sawatch Range, west of the Mosquito Range, is separated from it by the Arkansas Valley.

Eardley (1963) and Osterwald (see explanation in Eardley, 1963, p. 209) have explained the structural features of the modern Rocky Mountains as the result of vertical uplift. Formerly, the Rocky Mountains were generally regarded as a system of folded and thrust faulted mountain ranges formed by horizontal compression. Authors favoring the latter view include Burbank and Goddard (1937), Stark and others (1949), Lovering and Goddard (1950), Gableman (1952), Boos and Boos (1957), and Blackstone (1963). These investigators feel that, during Late Cretaceous time, westward-directed compression resulted in regional folds which were finally broken by high angle east dipping thrust faults in early Eocene time. These folds, representing the early phases of the Laramide Orogeny, were intruded by stocks and batholiths of early Tertiary age. Laramide activity was then completed by a phase of eastward-directed compression resulting in steep west dipping thrust faults.

Sawatzsky (1964, p. 138) working in South Park, and Harms (1964, p. 100) working in the southern Front Range, have supported the postulates of Eardley (1963) regarding the role of vertical uplift in forming the major structures of the Rocky Mountains. Eardley (1968) has summarized his views on this important form of tectonism as follows: (1) uplifts are caused by the rise of basalt from the mantle to the base of the silicic crust; (2) the silicic crust and sedimentary veneer are domed by this rise; and (3) surficial structures are caused by gravity-induced mass movements along the flanks of the uplifts toward the synclinoria of Paleozoic strata between them.

Eardley (1969) has developed a convincing case for Laramide vertical uplift and attendant thrusting in the Wasatch Mountains.

In spite of recent support of mechanisms of vertical tectonics, some investigators, such as Munger (1965, p. 18) have continued to favor the theory of horizontal compression; others, such as Armstrong and Oriel (1965, p. 45), point out deficiencies in both theories. Hudson (1969, p. 283), has recently sought to explain Laramide structural features in the central Rocky Mountains as the result of an initial stage of horizontal compression followed by a stage of vertical uplift. Sales (1968), utilizing models and recent data from oceanography, crustal geophysics, and rock mechanics, has presented an integrated hypothesis for the deformation of the Cordilleran foreland. According to Sales (1968, p. 2043), "Laramide and pre-Laramide deformation of the entire western United States and much of the Mid-Continent is a mechanically integrated tectonic system which resulted from the Pacific block being relatively driven under the North American craton."

Subsequent to Laramide orogenic activity, a period of regional block faulting began in late Oligocene time and continued through the Tertiary Period (Burbank and Goddard, 1937, p. 965; Gableman, 1952, p. 1578-1579; Eardley, 1962, p. 395-397). Armstrong and Oriel (1965,

p. 46) suggest that the period of block faulting probably continued up until the present time. Tertiary effusive rocks and sediments (early Oligocene age and younger) have been offset by these faults. Burbank and Goddard (1937, p. 965) demonstrated that the San Luis Valley was formed by post-Laramide block faulting. Van Alstine (1968) has shown that the Arkansas Valley and the San Luis Valley are connected by a structural trough containing volcanic rocks and sediments of Tertiary age. The existence of this trough indicates that the Rio Grande depression extends continuously northward into the upper Arkansas Valley (Van Alstine, 1968). This evidence confirms earlier ideas of Gableman (1952, p. 1607-1609), Tweto (1958, plate 7 and 1961, p. B135), and Chapin and Epis (1964 b, p. 158) who postulated a block fault origin for the Arkansas Valley. Munger (1965, p. 20) believes that the Wet Mountain Valley is also a graben structure rather than an intermontane synclinal depression as previously supposed by Burbank and Goddard (1937, p. 938) and many subsequent writers.

Prevolcanic Structures

The project area, northeast of Salida, Colorado, is located in the southernmost portion of the Mosquito Range, an area referred to on some maps as the Arkansas Hills. Several Laramide structures of regional importance pass through this area; these are the Pleasant Valley syncline, Pleasant Valley thrust, and the Wellsville-Orient thrust.

Pleasant Valley Syncline. The Pleasant Valley syncline represents a major synclinal fold in strata of Paleozoic age. The steeply dipping to slightly overturned eastern limb of the syncline is truncated by the high angle Pleasant Valley thrust (see Plate I). The western limb of the syncline dips less steeply and is cut by the northern extension of the Wellsville-Orient thrust (Gableman, 1952, p. 1580; De Voto, 1961, p. 204). Locally, small anticlinal and synclinal folds are superimposed on the synclinal limbs; these are particularly well developed in the Permo-Pennsylvanian strata. The Whitehorn stock was intruded along the eastward dipping axial plane of the syncline and nearly obliterates this major structure in the study area. However, according to Gableman (1952, p. 1590) the Pleasant Valley syncline extends northward into Bassam Park and finally dies out just south of Trout Creek Pass. Gableman also projected the Pleasant Valley syncline southward beneath the fill at the northwest end of the Wet Mountain Valley and suggested that it might be the true structural continuation of the Wet Mountain Valley. Munger (1965, p. 6) dissents and projects the axis of the Pleasant Valley syncline into the Spread Eagle Peak area on the eastern flank of the Sangre de Cristo Mountains rather than into the Wet Mountain Valley.

Pleasant Valley Thrust. The Pleasant Valley thrust was named by Gableman (1952, p. 936) but was first described by Burbank and Goddard (1937, p. 936). The fault is a north trending, east dipping, high-angle thrust which brings Precambrian metamorphic and igneous rocks into contact with sedimentary rocks of Permo-Pennsylvanian age along most of its length. Apparently, the fault dies out north of the study area before reaching South Park. Gableman's (1952, p. 1596) correlation of the fault with the London-Weston fault zone is not supported by De Voto (1961, p. 204). Burbank and Goddard (1937, p. 936) state that the fault continues southward from the study area to form the east boundary of the Wet Mountain Valley. Munger (1965, p. 10) contends that, rather than bending to the southeast under the gravels of the Wet Mountain Valley, the fault continues southward into the Sangre de Cristo Mountains. In the Spread Eagle Peak area, Munger (1965, p. 4) shows the Pleasant Valley thrust extending diagonally from northwest to southeast along the east flank of the range.

The Pleasant Valley thrust extends north from the southern boundary of the study area along Badger Creek and Willow Creek and crosses the northern boundary west of Gribbles Park (see Plate I). The dip varies from about 60 degrees east to vertical along this length. Precambrian metamorphic rocks have been thrust into contact with steeply dipping Manitou Dolomite within most of this region and the fault is offset by a number of small cross faults.

Wellsville-Orient Thrust. The western boundary of the Pleasant Valley syncline is truncated by a steeply-dipping fault displaying both normal and thrust fault characteristics. This fault is postulated to be the northward continuation of the Wellsville-Orient thrust described by Gableman (1952, p. 1596). Within most of the thesis area, the fault appears to be a near vertical fault (see Plate I). However, in some places, such as in the upper reaches of Cottonwood Gulch (T.49N., R.9E., Sec. 28), Precambrian metamorphic rocks are thrust eastward over the Manitou Dolomite; at this locality, the thrust plane dips about 15 degrees west. Similar variations have been described in the north along the Mosquito-Weston fault by Gableman (1952, p. 1597) and De Voto (1961, p. 206). It is suggested that the northward extension of the Wellsville-Orient thrust into the Salida area provides the previously postulated link between the Mosquito-Weston fault and the Wellsville-Orient fault (Burbank and Goddard, 1937, p. 938). Gableman suggested (1952, p. 1597) that post-Laramide normal faulting along former Laramide thrust zones, accompanied by cross faulting and rotation, could account for the variable nature of the fault.

Postvolcanic Block Faulting and Formation of the Upper Arkansas Graben

A series of north trending normal faults have been mapped in the study area. These faults offset the volcanic sequence with step-down displacements toward the west. The trend of the normal faults parallels that of the upper Arkansas graben and it is postulated that these faults played a role in the down dropping of that major structure.

Badger Creek Fault. The Badger Creek fault is the easternmost of a series of north trending normal faults which offset the volcanic sequence in the study area. It is regarded as a post-Laramide normal fault reactivated, in part, along the pre-existing Pleasant Valley thrust. At the confluence of Willow Creek and Badger Creek (T.50N., R.10E., Sec. 15), the Badger Creek fault branches north-northeast from the older Pleasant Valley thrust and follows Badger Creek. The fault crosses the Gribbles Run paleovalley but appears to die out before reaching the Paleozoic strata bordering Gribbles Park. East of the fault, the prevolcanic surface dips from 9,800 feet at the eastern boundary of the map area to 8,200 feet at Badger Creek in a distance of about 4 miles. It is postulated that normal faulting, perhaps accompanied by doming associated with the Waugh Mountain volcanic center, has caused the westward rotation of the block east of the Badger

Creek fault and a corresponding dip reversal of the eastern portion of the Salida-Waugh Mountain paleovalley and the Gribbles Run paleovalley (see Plate II and Figure 15).

Maverick Fault. The Maverick fault is a north trending normal fault which accounts for the presence of similar volcanic rocks differing in elevation by 600 to 1,000 feet in a distance of 1 to 2 miles (see Plate II). Rotation of the block west of the Maverick fault has tilted the volcanic rocks down towards the Arkansas Valley producing an overall decrease in elevation of 1,500 to 2,000 feet in 3 to 4 miles. The Maverick fault follows a pronounced topographic lineament along which occur intrusive breccia, altered felsite, hydrothermal alteration, landslides, numerous mineral prospects, and fresh-water springs.

Dead Horse Fault. Dead Horse fault is a north trending normal fault similar to the Maverick fault and has displaced the prevolcanic surface by at least 400 feet in a distance of 0.5 mile (see Plate II). The block west of the fault has been stepped down and rotated to the west thus inverting the gradient of the western tributaries of the Salida-Waugh Mountain paleovalley. This structure also coincides with a prominent topographic lineament.

Dead Goat Fault. Dead Goat fault is a north trending normal fault of small vertical displacement with the west side down. The fault is characterized by a strong topographic lineament and the truncation of Tertiary rocks as young as the Dry Union Formation of Pliocene age. Thus, formation of the upper Arkansas graben was probably accomplished by recurrent down dropping along normal faults similar to those observed in the study area.

EVIDENCE FOR PRIMARY AND SECONDARY LAMINAR FLOWAGE IN THE ASH FLOW-1 COOLING UNIT

Introduction

A number of authors have noted the existence of structures resulting from laminar flowage in ash-flow tuff deposits (Rittman, 1958; 1962, p. 81; Mackin, 1960, p. 99; Smith, 1960, p. 807; Cook, 1963, p. 95; 1966a, p. 165; 1966b, p. 97, 110, 114, 115, 117; Hoover, 1964; Hamilton, 1965, p. 4, 5, 10, 15; Schmincke and Swanson, 1966; 1967; Noble, 1968; and additional references cited in Schmincke and Swanson, 1967, p. 657). These structures, which include folds, lineations, and flow banding, have most commonly been attributed to secondary flowage (movement subsequent to the halt of the ash flow). Postulated causes for secondary flowage, after or contemporaneous with welding are: (1) deposition on moderately steep slopes; (2) oversteepening of slopes; and (3) earthquakes.

Recently, Schmincke and Swanson (1967) have described a sequence of late Miocene to early Pliocene ash flows on Gran Canaria, Canary Islands, which contain numerous laminar flow structures shown by these authors to be of primary origin. These primary structures are: (1) stretched pumice fragments; (2) broken and rotated pumice fragments; (3) tension cracks in the matrix; (4) hollows around rotated inclusions; (5) folds; (6) imbricated pumice fragments; and (7) ramp structures (Schmincke and Swanson, 1967, p. 649).

The structures mapped by Schmincke and Swanson occur throughout at least 15 recognizable cooling units distributed over 350 sq. km and are found as near to, and as far from, the source caldera as outcrops permit. No lateral gradation into welded rocks without the laminar structures have been observed. Directionally significant structures show uniform radial flowage away from the caldera. Major deviations from the flow direction caused by the underlying topography were not observed. Flat-lying ash flows within the caldera also contain laminar flow structures and thus indicate that laminar flowage in these units did not require steep gradients. Schmincke and Swanson conclude that the observed structures resulted from laminar flowage during the last stage of continuous movement of each cooling unit and did not require the remobilization of a stationary welded tuff as suggested by other investigators. Recent observations by Noble (1968) concerning numerous ash-flow tuffs in the western United States lend additional strength to the arguments of Schmincke and Swanson. Furthermore, Noble's gas flotation hypothesis may elucidate the mechanism by which late-stage laminar flowage occurs.

Flow Structures in the Ash Flow-1 Cooling Unit

Flow structures are present in virtually every outcrop of the ash flow-1 cooling unit within the project area. These features are prominently displayed in the Gribbles Run paleovalley (T.51N., Rs. 10 and 11E.) which is a narrow, sinuous feature nearly four miles in length preserved by deposition of the ash flow-0.5 member of the ash flow-1 cooling unit (tentative identification of the member is based on the method of sanidine optic axial angles, Chapin and Epis, 1965). This body was selected for detailed study because it lies in a narrow paleovalley whose axis marks the two possible flow directions.

Stretched Pumice Fragments. The most common flow structures in the Gribbles Run paleovalley are elongate pumice ellipsoids and cavities left by removal of pumice during weathering. Adjacent pumice fragments and cavities are subparallel in alignment of their major axes forming a strong lineation. The stretched pumice elements taper gently away from a slightly bulged center in cigar-like fashion. Figures 10-13 are photographs of lineated pumice fragments. Dimensional data pertaining to the distortion of pumice fragments were not obtained in this study. However, data presented by Schmincke and Swanson (1967, p. 650-651) indicated that pumice distortion varied between cooling units but that, "generally the fragments are at most 1.5-3.0 times as wide and 30 times as long as thick."

Figure 10. View of the ash flow-1 cooling unit showing the compaction foliation and lineated pumice cavities.

Figure 11. Side view of lineated pumice in the ash flow-1 cooling unit.

Figure 12. End view of lineated pumice cavities in the ash flow-1 cooling unit. (Note size range).

Figure 13. Steep asymmetric fold in the ash flow-1 cooling unit formed by secondary flowage toward the axis of the paleovalley. The direction of secondary flowage is approximately at 90 degrees to the direction of primary flowage. (fold axis trend parallel to pumice lineation)

The second-order lineations mentioned by Schmincke and Swanson (1967, p. 649-650) were also observed by the present investigator. These consist of parallel ridges and grooves on the surfaces of the flattened pumice fragments where the plane of the compaction foliation is exposed. The ridges and grooves are parallel to the long axis of the stretched pumice fragments. These second-order lineations are probably the result of scouring by phenocrysts during laminar flow (Schmincke and Swanson, 1967, p. 650).

Imbricated Pumice Fragments. Most of the measured pumice lineations lie in the plane of the compaction foliation but approximately one-fourth plunge at angles which differ from the dip component of the foliation for that azimuth. Such occurrences are thought to result from imbrication of pumice fragments as postulated by Schmincke and Swanson (1967, p. 655-656). According to those authors, imbrication is probably caused by upward ramping of cooler more viscuous material under stresses induced by faster flowage of hotter material in the flow center. The imbricated pumice fragments studied by Schmincke and Swanson (1967, p. 655) consistently dipped sourceward and were a reliable indication of flow direction.

Figure 14 shows the flow-structure data obtained in this study. Trends and plunges of lineated pumice fragments are shown with the strike and dip of the compaction

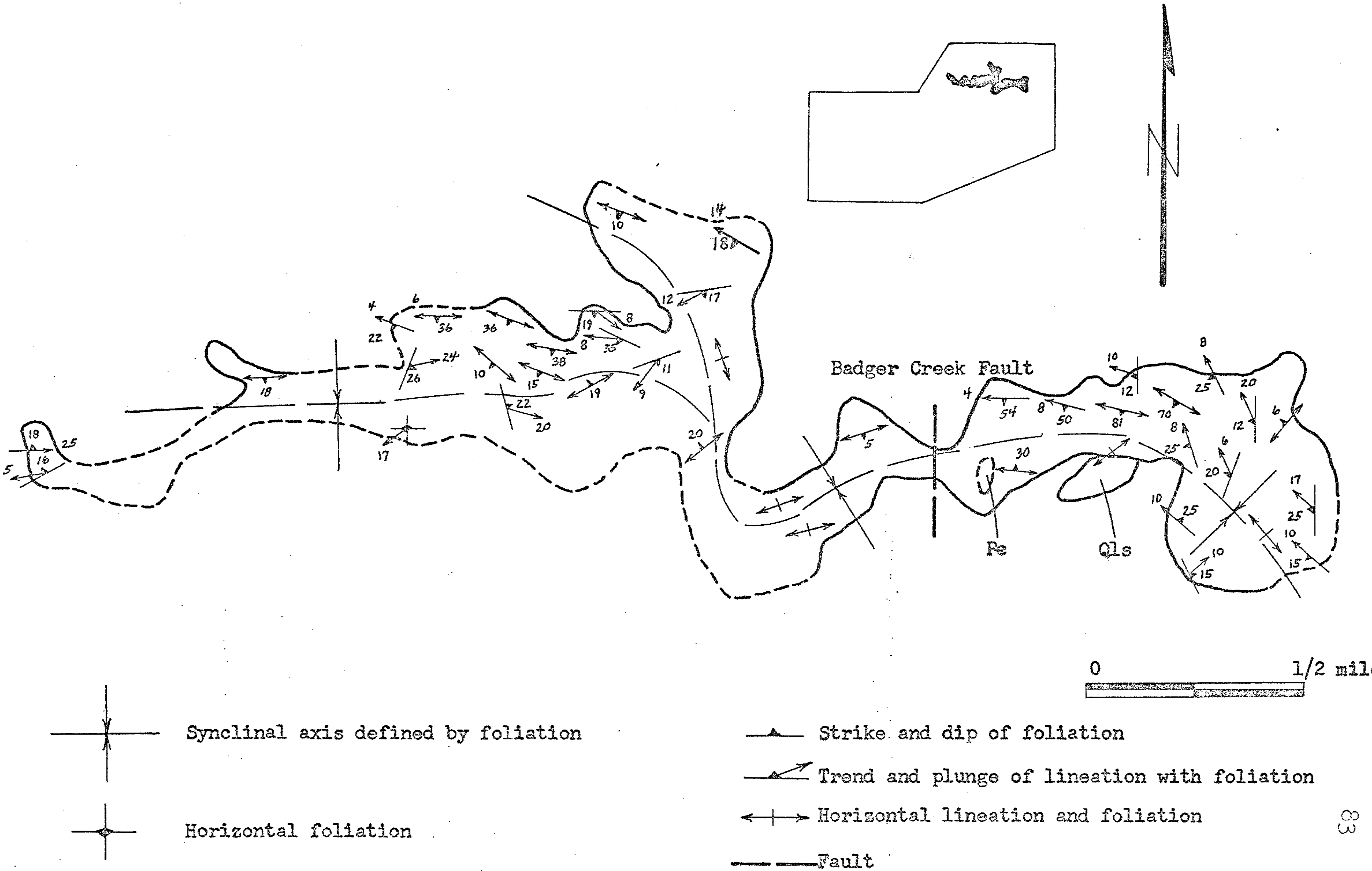


Fig. 14. Pumice lineations and compaction foliations in the ash flow-1 cooling unit of Gribbles Run paleovalley.

foliation. Of the 14 measurements of imbricated pumice, all plunge westward suggesting that the ash flow travelled eastward through the valley.

Folds. The major structure present in the rock body studied is a four mile long, bifurcating syncline defined by the compaction foliations shown in Figure 14. Superimposed on the limbs of this syncline are a number of small anticlines, synclines, and recumbent folds, the amplitudes of which range from a fraction of an inch to several feet (see Figure 13). The axes of these folds are subparallel to the axial lineation of the pumice fragments and to the strike of the compaction foliation suggesting that they are secondary structures due to flowage towards the valley axis during compaction (see Figure 15). Both pumice fragments and welded ash-flow matrix are involved in the smaller folds.

Folds have been described in ash-flow tuffs by a number of previous workers. Hoover (1964) found that the axes of isoclinal and asymmetric folds were parallel to the strike of the flow banding but that the axes of crenulated folds tended to parallel the dip of the flow banding and were parallel to secondary lineations caused by flowage toward topographic lows. Schmincke and Swanson (1967, p. 655), however, found different fold orientations in the ash flows of Gran Canaria. They report two main types of folding: (1) those which have been localized by the

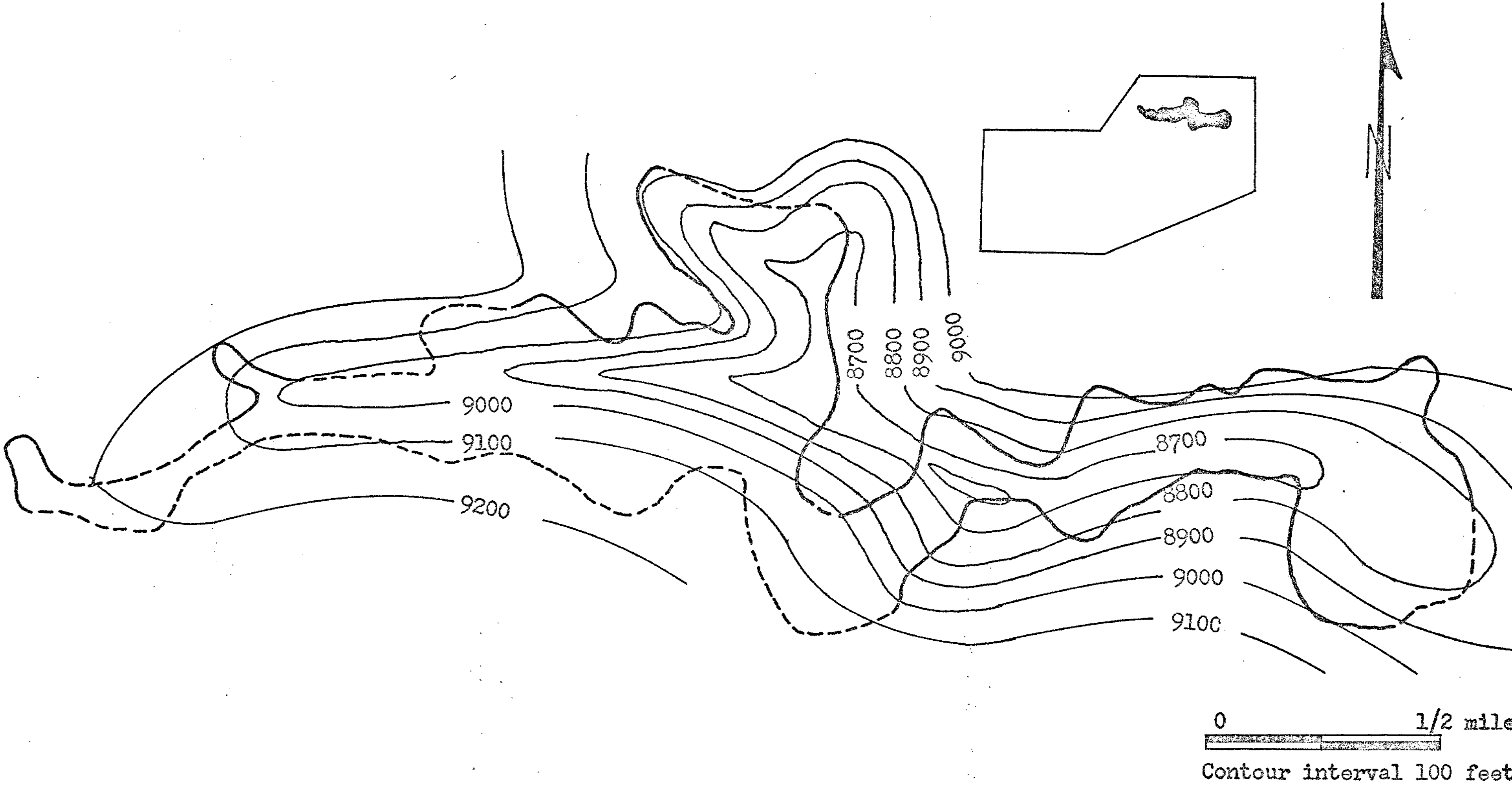


Fig. 15. Paleotopographic map showing basal configuration of the ash flow-1 cooling unit in the Gribbles Run paleovalley.

presence of rigid inclusions and show no preferred orientation; and (2) those adjacent to ramp structures which usually trend normal to the primary flow direction and are asymmetric with the gentle limbs dipping 10 to 30 degrees sourceward. In both studies, the axes of major folds were normal to the direction of primary (Schmincke and Swanson) or secondary (Hoover) flowage as marked by the lineations.

Ramp Structures. Ramp structures, so named by Schmincke and Swanson (1967, p. 656) for the resemblance to viscous lava-flow ramp structures, form by compressional deformation of the upper part of an ash flow over its hot fluidal interior. Large scale ramping which forms broad warps and thrusting in the foliation may not have occurred in the ash-flow body filling the Gribbles Run paleovalley but small scale ramping, such as that responsible for the imbrication of lineated pumice fragments, probably occurred in the body during the late stages of laminar flow.

Summary and Conclusions

Summary. Evidence suggesting that primary laminar flowage occurred after cessation of turbulent flowage but before the ash-flow body came to a complete forward halt is:

(1) Elongation of partially collapsed pumice fragments parallel to the axis of the Gribbles Run paleovalley along which the ash flow travelled; further, pumice lineations occur in virtually every outcrop of the ash flow-1 cooling unit within the thesis area (see Plate I) and are generally not parallel to the compaction;

(2) Lineations on the surfaces of stretched pumice fragments parallel their axial lineation; and

(3) Imbrication of pumice fragments with a consistent plunge to the west.

Evidence indicating that secondary laminar flowage towards topographic lows occurred after, or near the end of, primary flowage is:

(1) Orientation of minor fold axes perpendicular to the compaction dip; the fold axes are also parallel to the lineation of pumice fragments and the axis of Gribbles Run paleovalley; and

(2) Folding of lineated and imbricated pumice fragments.

Conclusions. Although the source area of the ash flow-1 cooling unit is not presently known, imbrication of pumice fragments suggests that the ash flow entered the Gribbles Run paleovalley from the west and northwest in early Oligocene time. Because the formation of the upper Arkansas graben did not occur until near the end of the Tertiary Period, the ash flow eruptive center might be located in the Sawatch Range or in the Bonanza district. Potential volcanic centers in the Sawatch Range include the Grizzly Mountain area near Independence Pass, and the Tertiary intrusive center described by Dings and Robinson (1957, p. 19) in the Garfield quadrangle.

In order to account for the flow structures present in the ash-flow body, turbulent flow must have entirely given way to laminar flow for at least a short distance before the ash flow came to rest. After primary flowage ceased, differential compaction warped the compaction foliation into the general configuration of the enclosing Gribbles Run paleovalley. Differential compaction was accompanied locally by secondary flowage toward the valley axis. This flowage deformed the compaction foliation into small anticlines, synclines, and recumbent folds whose axes trend semiparallel to the valley walls and to the primary pumice lineations.

GEOLOGIC HISTORY

Prevolcanic History

The deposition, intrusion, and metamorphism of Precambrian sediments was followed by uplift and a long period of erosion. During the early and middle portion of the Paleozoic Era, Colorado was a relatively stable region which was periodically inundated by shallow seas. Pre-Pennsylvanian sedimentation, once regarded as being restricted to a narrow belt between the Siouxia and the Sierra Grande highlands, was much widerspread in occurrence than previously thought (Chronic and Ferris, 1961, p. 146). The oldest record of sedimentation in the study area is the Manitou Dolomite of Early Ordovician age. Middle and Late Ordovician transgressions followed withdrawal of the Manitou seas and partial erosion of Manitou sediments. The Harding Sandstone and the Fremont Dolomite were deposited during marine transgressions in Middle and Late Ordovician time.

Sediments of Silurian age were probably deposited in Colorado (Chronic, 1961, p. 98) and subsequently eroded prior to the advance of shallow, Late Devonian seas which deposited the conglomerates, sandstones, and carbonates of the Chaffee Formation.

A period of Late Devonian erosion occurred and was followed by the invasion of shallow Mississippian seas which deposited the Leadville Limestone. The Mississippian seas covered nearly all of Colorado before withdrawing and the sediments were deposited higher on the flanks of the Siouxia and Sierra Grande highlands than during earlier transgressions (De Voto, 1961, p. 70).

Late Mississippian regional uplift caused erosion to prevail throughout most of Colorado. During this period, lateritic soils and a karst topography developed (Skipp, 1956, p. 55; De Voto, 1961, p. 69).

Uplift of the Ancestral Rocky Mountains formed the central Colorado depositional trough in Early Pennsylvanian time. Sedimentation resulted in deposition of thin, fossiliferous limestone and great thicknesses of sandstone, conglomerate, and shale. The depositional trough was broken during the Pennsylvanian Period by positive fault blocks which were subsequently onlapped in Permian time by red clastics derived from the active Uncompahgre Highland to the west (De Voto, 1968).

The occurrence of Mesozoic sediments in South Park and the Front Range suggest that they were probably once present in the study area; however, they appear to have been completely removed by erosion prior to volcanism.

Late Cretaceous time marked the beginning of the Laramide Orogeny in central Colorado. Early deformation produced the Pleasant Valley syncline and its bounding faults, the Pleasant Valley thrust and the Wellsville-

Orient thrust. These early Laramide structures were nearly obliterated by emplacement of the Whithorn stock in Eocene time. A final phase of Laramide activity formed west-dipping thrusts subsequent to plutonism.

The last stage of Laramide tectonism was followed by a period of relative quiescence in the Salida region marked by erosion and development of east-west trending drainages, such as the Salida-Waugh Mountain and Gribbles Run paleovalleys. The Salida-Waugh Mountain paleovalley probably headed in the Sawatch Range and drained eastward across the study area before formation of the upper Arkansas graben.

Volcanic History

Volcanism in the Thirtynine Mile volcanic field commenced in late Eocene or early Oligocene time (ash flow-1 cooling unit, 40.0 ± 1.4 m.y., Epis and Chapin, 1968, p. 52; 35.4 ± 1.1 m.y. or 37.3 ± 1.9 m.y., Van Alstine, 1967, personal communication*) and resulted in deposition of a thick sequence of ash flows, lavas, and breccias erupted from several volcanic centers. The youngest volcanic rocks known in the field are late Miocene in age (upper andesite, 18.9 ± 1.2 m.y., Epis and Chapin, 1968, p. 52), hence the entire volcanic episode,

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*Sanidine optic axial angles of these rocks from the Browns Canyon area suggest that they are not ash flow-4 as postulated by Van Alstine.

including the time required for interformational erosion, took place in about 15 to 20 million years. The bulk of the volcanic pile, however, was emplaced during about two to six million years of early Oligocene time.

The earliest volcanic event in the thesis area was the eruption of the ash flow-1 cooling unit in early Oligocene time. This series of at least three ash flows is believed to have been erupted west (possibly northwest or southwest) of the Salida area from whence they spread eastward over the broad, flat prevolcanic surface of the Thirtynine Mile volcanic field at least as far as the Cripple Creek area (Eugene Tobey, oral communication, 1969). The Salida-Waugh Mountain and Gribbles Run paleovalleys represent prevolcanic drainages which were filled and overrun by these ash flows. Differential compaction and severe erosion led to the re-establishment of much of the pre-eruption topography following deposition of the ash flow-1 cooling unit. The basal unwelded ash flows of the Antero Formation were then erupted. These ash flows again filled the Salida-Waugh Mountain paleovalley and overflowed onto the adjacent erosional plateaus. Subsequently, erosion of the friable unwelded ash flows led to widespread deposition of tuffaceous sediments on the adjacent plateaus and rapid exhuming of the Salida-Waugh Mountain paleovalley.

Renewal of volcanic activity in the vent area of the Antero Formation (locality as yet unknown) refilled the Salida-Waugh Mountain paleovalley with a sequence of at least six welded ash flows which comprise the tuff of Badger Creek. These welded ash flows were sufficiently resistant to preserve the Salida-Waugh Mountain paleovalley until the present time.

Subsequent to emplacement of the tuff of Badger Creek, initial activity of the Waugh Mountain volcanic center began east of the study area. Eruption of the latite of East Badger Creek, probably accompanied by doming and westward tilting of the block east of Badger Creek, signaled the first stage of Waugh Mountain volcanism.

Contemporaneous with Waugh Mountain volcanic activity, a thick sequence of ash flows, correlated with the ash flow-7 cooling unit of the Thirtynine Mile field, was deposited in the eastern and northeastern portion of the map area. These ash flows have been identified at Poncha Pass, Tallahassee Creek, the northern Wet Mountain Valley, and the upper Badger Creek drainage (Epis and Chapin, 1968, p. 71-72), however, their source is presently unknown. A K/Ar date of 34.8 ± 1.4 m.y. has been reported by Epis and Chapin (1968, p. 52) for these rocks.

Continuing eruptions from the Waugh Mountain volcanic center deposited the latite of Waugh Mountain above the ash flow-7 cooling unit along the eastern border of the study area. The andesitic and basaltic flows, flow breccias, and tuffs of the upper andesite then covered the latite of Waugh Mountain and marked the end of Waugh Mountain activity.

At about the time that Waugh Mountain volcanism was occurring, the andesite of Big Baldy was deposited in the southwestern portion of the study area from an unknown volcanic source. This same source may also have erupted the silicic felsite of Section 36 which was deposited some time after the andesite of Big Baldy.

The Tenderfoot Hill volcanic sequence at the city limits of Salida is thought to represent the last stage of extrusive activity in the project area. The basaltic flows of the sequence are interstratified with sediments which closely resemble those of the Dry Union Formation of early Pliocene age. The flows of the Tenderfoot Hill volcanic sequence are of small areal extent (probably due to subsequent faulting) and their eruptive source is unknown.

Postvolcanic History

Late Tertiary time was a period of structural and geomorphic modification in central Colorado. Block faulting formed the San Luis Valley, the northern Wet Mountain Valley, and the upper Arkansas Valley; the latter is the northern continuation of the Rio Grande depression.

In the area of investigation, faulting began shortly after, or perhaps during, the last stages of effusive activity. Step faulting, related to formation of the upper Arkansas graben, reversed drainage directions from eastward off the Sawatch Range to westward into the graben. The Salida-Waugh Mountain paleovalley was broken into three segments; the Gribbles Run paleovalley was broken into two segments.

Deposition of the sediments which comprise the Dry Union Formation probably occurred contemporaneously with the down faulting of the Arkansas graben. Deposition of boulder gravels in the Salida-Waugh Mountain paleovalley may have occurred at this time.

In Quaternary time, uplift and resultant erosion has caused deep dissection of the late Tertiary topography. Alluvium has formed along the present stream beds while landslides, slump blocks, and colluvium have formed along the steeper slopes.

CONCLUSIONS

Several important conclusions, which help to clarify the geologic relationships of volcanic rocks in the Salida area to the regional structural and volcanic framework of Colorado, may be drawn from data accumulated during field and laboratory investigation of rocks in the study area.

Paleovalleys on the Prevolcanic Erosion Surface

The prevolcanic erosion surface occurs at elevations ranging from at least 10,600 to 8,200 feet along the crest of the Arkansas Hills east of Salida. During late Eocene time, drainage was dominantly eastward off the Sawatch Range as evidenced by several east-west trending paleovalleys whose tributaries branch to the west. Directional features in the ash flow-1 cooling unit also indicate an eastward direction of volcanic flowage.

Volcanic Stratigraphy

The oldest volcanic rocks of Tertiary age in the Salida area are welded tuffs of the ash flow-1 cooling unit which have been dated at between 35.4 ± 1.1 m.y. and 40.0 ± 1.2 m.y. These rocks occur mainly along the bottoms and sides of paleovalleys and are overlain by unwelded ash flows belonging to the Antero Formation of early Oligocene age. The tuff of Badger Creek, a new ash-flow unit described in this study, rests on the Antero tuffs and is, in turn, overlain by the latite of East Badger Creek, the ash flow-7 cooling unit, the latite of Waugh Mountain, and the upper andesite (18.9 ± 1.2 m.y.). The youngest volcanic rocks are a series of andesitic to basaltic flows interbedded with gravels of the upper Arkansas graben in the Tenderfoot Hill area. Thus volcanism affecting the Salida area began between 35 and 40 million years ago in earliest Oligocene time and continued intermittently into late Miocene or early Pliocene time with eruption of basic lava flows into the aggrading upper Arkansas graben.

Potential Eruptive Centers

Major volcanic centers in the Thirtynine Mile field have been described near Guffey and at Waugh Mountain (Epis and Chapin, 1968, p. 73) and numerous small vents have been located in the lower andesite breccia sheet (Chapin and Wyckoff, 1968). Source areas for the extensive ash-flow sheets, however, remain unknown. No vents of any size were found in the Salida area; the feature labeled "The Crater" on the Cameron Mountain 15-minute quadrangle map was found to be a landslide scar.

Lineated and imbricated pumice in the ash flow-1 sheet and the presence of these rocks at Poncha Pass and in the bottom of the Arkansas Valley north of Salida indicates that these ash flows swept down the east-trending paleovalleys from vents west of the Salida area. Possible source areas are the Bonanza volcanic center, an intrusive center in the Sawatch Range described by Dings and Robinson (1957, p. 19), or the Grizzly Mountain area near Independence Pass.

Both the thickness and the number of ash flows in the Antero Formation, the tuff of Badger Creek, and the ash flow-7 cooling unit are greater in the Salida area than anywhere else in the Thirtynine Mile volcanic field. Thus, it appears that most, if not all, of the ash flows of the Thirtynine Mile field may have been erupted west of the Salida area. If true, the Thirtynine Mile field was a dominantly andesitic volcanic field which acted as a receiving area for silicic ash flows erupted from outside the field; the broad prevolcanic erosion surface and the leveling effect of the lower andesite breccia sheet (Chapin and Wyckoff, 1968) may have been important factors in such a development.

Structural Development of the Upper Arkansas Valley

Rocks of the ash flow-1 cooling unit have been stepped down into the upper Arkansas Valley by a series of north trending postvolcanic faults. In the Browns Canyon area north of Salida, these rocks occur at elevations of 8,000 to 7,600 feet, whereas along the crest of the Arkansas Hills east of Salida the same rocks crop out at elevations of 10,100 to 8,200 feet. The east-trending paleovalleys in which the ash flow-1 cooling unit was deposited headed in the Sawatch Range in early Oligocene time and extended eastward across the present site of the upper Arkansas Valley.

R. E. Van Alstine (1968) has recently shown that the upper Arkansas Valley is structurally continuous with the San Luis Valley to the south. Several thousand feet of basin-fill sediments are present on Poncha Pass and overlie westward tilted ash-flow outcrops which have been recently identified by C. E. Chapin (1969, personal communication) as belonging to the ash flow-1 and ash flow-7 cooling units. Thus, the upper Arkansas Valley is a post-Oligocene graben containing early Pliocene sediments (Van Alstine and Lewis, 1960) and, as such, it probably represents the northernmost segment of the Rio Grande rift zone. Several periods of faulting (Tweto, 1961) are indicated; locally, the relief of the valley floor may reach 1,000 feet.

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APPENDIX I

MEASUREMENTS OF SANDINE OPTIC AXIAL ANGLES $2V_x$

Ash Flow-1 Cooling Unit

sample L-33 T.50N., R.11E., Sec. 18, NW/4, NE/16. moderately welded 17 crystals 17 measurements*	sample L-63 T.51N., R.11E., Sec. 30, NE/4, NW/16. moderately welded 22 crystals 23 measurements
43	40
36	42.5
37.5	39
36	40
39	40, 46
41	41
36	39
32	42.5
39.5	37.5
37	42.5
38.5	42
38	37
43	35
33	40.5
47.5	39.5
46	38.5
42	39
	43
	41
	37.5
	39
	49.5

*All angles measured in degrees.

Ash Flow-1 Cooling Unit

sample L-102
T.50N., R.10E., Sec. 10,
center
moderately welded
22 crystals
24 measurements

41
37
43
43.5
42
38
36, 40
44
39
41
42.5
40
47.5, 42.5
39
41
53
35
37.5
37.5
50.5
37
49

sample L-617 bv
T.50N., R.10E., Sec. 32,
NW/4, NE/16
moderately welded
19 crystals
28 measurements

53.5
40.5
36.5, 43.5, 34.5
46, 37
33
33.5
38
32.5
36.5
40
47.5
40.5
38.5, 48
41, 37.5, 39, 34, 37
40.5
34
34
46, 38
38

Ash Flow-1 Cooling Unit

sample L-617 av
T.50N., R.10E., Sec. 32,
NW/4, NE/16
moderately welded
20 crystals
24 measurements

36
33
29.5
42
31
42
32.5
35.5
35
36
34
37
30.5
31
34, 39, 32.5
41.5, 37
34.5
39.5, 32
32
29.5

sample L-621
T.50N., R.9E., Sec. 28,
SE/4, SW/16
moderately welded
19 crystals
19 measurements

41
40
41
35
44.5
40.5
39
41
47.5
42
46
42.5
44
42
44
38
38.5
48
42

Ash Flow-1 Cooling Unit

sample L-622
T.51N., R.11E., Sec. 19,
SE/4, center
moderately welded
20 crystals
29 measurements

43
41
40.5
40
43
45, 48, 42.5, 48.5, 43
43
40.5
45
49
54, 43.5, 39.5
47
42.5
46, 44.5, 43
51.5
41.5
45
48, 42
42
43

Ash Flow-7 Cooling Unit

sample S-3-1
T.50N., R.11E., Sec. 5,
center
densely welded
20 crystals
20 measurements

45
36
40.5
32
36
36.5
37
33
34.5
35.5
38
36
38.5
35
35
35.5
36
36
37
29

Ash Flow-7 Cooling Unit

sample S-3-4
T.50N., R.11E., Sec. 5,
center
slightly welded
16 crystals
20 measurements

50.5
43
42
33, 48
30
35
38
29
28
40, 36, 42
38
34.5
32
43
34, 36
45

sample S-3-6a
T.50N., R.11E., Sec. 5,
center
moderately welded
20 crystals
21 measurements

36
33
28
32
39
37
35
33
29
41, 42
42
37.5
34
38
36.5
34.5
37.5, 36
33
35.5

Ash Flow-7 Cooling Unit

sample S-3-7
T.50N., R.11E., Sec. 5,
center
slightly welded
20 crystals
20 measurements

35
35
34
35
35
34
35
37
35
34
40
32
36
40
35
35
38
49.5
40
31.5

sample S-3-10
T.50N., R.11E., Sec. 5,
center
slightly welded
20 crystals
21 measurements

36
31
31.5
35
40
38
37
35
30
35.5
34.5
38, 44
46
35
35
37
33
35
28
34

Ash Flow-7 Cooling Unit

sample S-3-11
T.50N., R.11E., Sec. 5, center
moderately welded
20 crystals
21 measurements

42.5, 28
42.5
48
28
39
35
35
44
34
43.5
34
35
35
37
36.5
35.5
38
38
43
38.5

Latite of Two Creek

sample L-120
T.50N., R.11E., Sec. 7, NW corner
lava flow
20 crystals
22 measurements

51
49.5
54
45.5
52
48
46
51.5
48.5
44.5
52.5
51.5
46, 46
52
52, 47
41.5
54.5
50
58
52

This thesis is accepted on behalf of the faculty of the Institute by the following committee:

Christina L. Balk

Date: 25 July 1969