GEOLOGIC AND PETROLOGIC RELATIONSHIPS BETWEEN THE THIRTYNINE MILE VOLCANIC FIELD AND THE CRIPPLE CREEK VOLCANIC CENTER

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ABSTRACT

The oldest volcanic rocks in the study area occuring in the Thirtynine Mile field and the Cripple Creek areas are a series of latitic ash-flow tuffs termed the ash flow - 1 cooling unit, and dated at between 35 and 40 million years. Immediately overlying that unit in the Cripple Creek area are latitic ash-flow tuffs probably associated with subsidence of the Cripple Creek cauldron.

An interval of intravolcanic erosion and aggradation of basins followed eruption of the latitic ash flows. The High Park and Bare Hills basins and the Cripple Creek cauldron received arkosic sediments from the erosion of surrounding granitic highs.

A major stream crossed the High Park basin and deposited conglomerates of varied lithology reflecting a larger source area, perhaps the South Park intermontane basin.

The youngest rocks in the Cripple Creek area are phonolite plugs and flows which intrude the lower andesite of the Thirtynine Mile field (dated at 34.1 t 1.1 m.y.). A minimum age for the volcanism at Cripple Creek has not been established.

Post-volcanic block faulting along the Fourmile Creek - Oil Creek fault zone and erosion have isolated the Cripple Creek center from the Thirtynine Mile field. Ash flow - 1 outcrops on the Front Range occur up to 1500 feet higher than outcrops in High Park. The Bare Hills basin has been uplifted 500 to 1000 feet above the High Park basin. These structural adjustments may be related to late Tertiary rise of the southern Front Range and Royal Gorge blocks.

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INTRODUCTION

The Problem

The purposes of this thesis are twofold: (1) to determine the stratigraphic and petrologic relationships between the rocks of the Cripple Creek volcanic center and those of the Thirtynine Mile volcanic field, and (2) to determine the nature of the crustal deformation which isolated the Cripple Creek volcanic center.

Acknowledgements

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R.C. Epis gave the author valuable assistance during the course of the field work. A.J. Budding, M.E. Willard, R.H. Weber, J.R. Renault and G.R. Lowell provided the author with ideas and information about various phases of the project during informal discussions in the office. Connie Woodruff, Heidimarie Warlies, and Loriann Lanphere assisted in the preparation of the map and the manuscript. Ranchers in the thesis area graciously allowed the author access to their lands.

Special thanks are due the thesis advisor, C.E. Chapin, for the original suggestion of the thesis problem, for valuable aid in the field

and in the office, and for patience during the writing of the thesis.

Location and Accessibility

The study area is located on the eastern edge of the Thirtynine Mile volcanic field (fig. 1) and extends eastward to include portions of the Cripple Creek volcanic center. It is situated on a high plateau at the northern edge of the Canon City embayment and the southern end of the Front Range. Colorado State Highway 67 and the county roads connecting Cripple Creek with Canon City provide useful access roads, but the majority of the area is accessible only in a four-wheel drive or similar vehicle.

Methods of Investigation

The field study was accomplished during the summer of 1968; geologic mapping was done directly on the United States Geological Survey Cripple Creek South 7.5-minute quadrangle and on a blue-line edition of the Pikes Peak No. 3 (A.F.C.) quadrangle. A mylar topographic base map for the compilation of data was prepared by joining copies of the Cripple Creek South 7.5-minute quadrangle and the Cover Mountain 15-minute quadrangle. Aerial photographs were used in the field as guides to the location and configuration of outcrops and to the trend of structural lineaments.

Axial angles of alkali feldspars in the ash-flow units were measured orthoscopically on a Leitz microscope and 5-axis universal stage using the method of Chapin and Epis (1965). Modal analyses of the ash-flow units were performed with the aid of a Swift point counter; for the other units, mineral ratios were obtained by visual estimation.

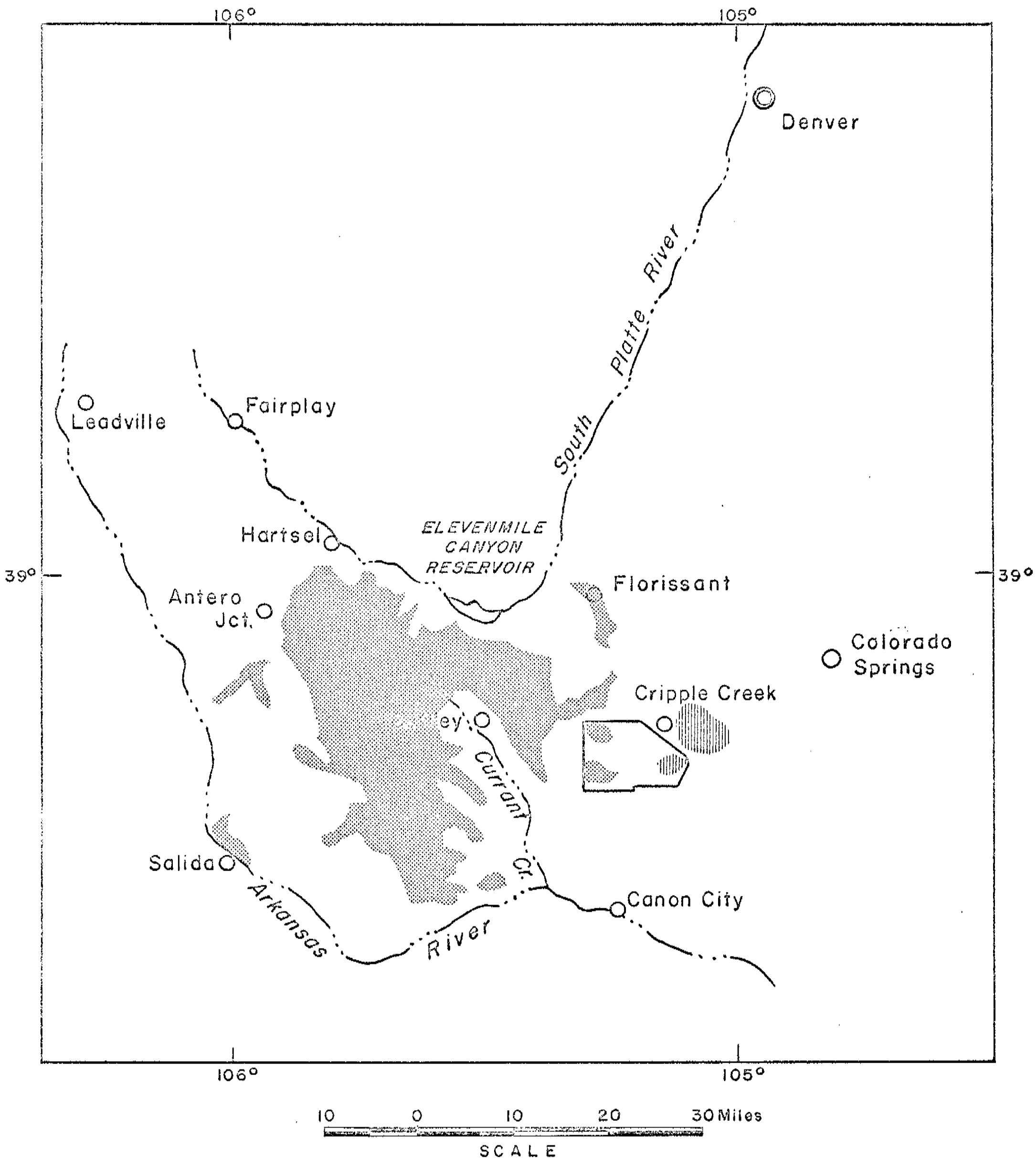
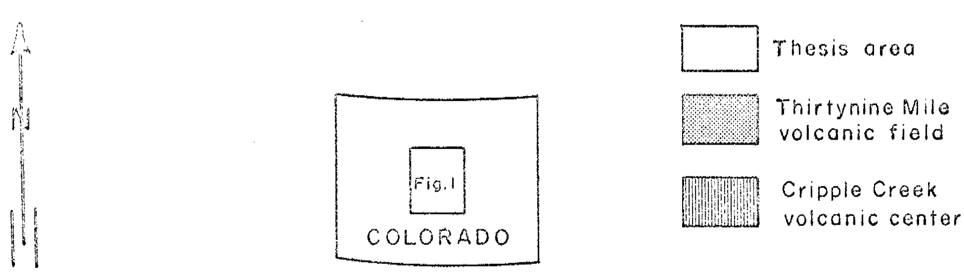


Figure I

LOCATION OF THIRTYNINE MILE VOLCANIC FIELD, CENTRAL COLORADO



Previous Investigations

Published papers on the geology of the thesis area are generally accurate, but most previous investigators were not primarily concerned with volcanology. Geologic exploration in the area began with reconnaissance work by members of the Hayden Survey in 1873 (Endlich, 1874, 1878). The most significant early contributions to understanding the volcanic stratigraphy were made by Whitman Cross (1894) during the mapping of the Pikes Peak area. Other early work by Cross and Penrose (1895) and Lindgren and Ransome (1906) dealt specifically with the mineralized portions of the Cripple Creek volcanic center. Since that time several papers have been written dealing with the economic geology and engineering geology of the Cripple Creek mining district (Loughlin, 1927; Loughlin and Koschmann, 1935; Koschmann, 1947, 1960; Lovering and Goddard, 1950).

In recent years, more detailed geologic work has been done in the Thirtynine Mile volcanic field by Chapin and Epis and by graduate students under their direction from the Colorado School of Mines and the New Mexico Institute of Mining and Technology (Chapin and Epis, 1964; Chapin, 1965; Chapin and Wyckoff, 1968; Epis and Chapin, 1968). In the course of this continuing work, the detailed volcanic stratigraphy and ages of most of the volcanic events in the Thirtynine Mile field have been worked out. Recent work on the stratigraphy and structure of Paleozoic rocks in the Oil Creek area has been done by Walter (1959) and Gerhard (1967, 1968). The Heavy Metals Division of the United States Geological Survey has recently conducted geochemical surveys in the Cripple Creek district to determine the feasibility of finding new gold telluride ore bodies (Nakagawa, et. al., 1968).

ROCK UNITS

Prevolcanic Rocks

Prevolcanic rocks in the thesis area range from Precambrian to early Tertiary in age. Rocks assigned to the Paleozoic era crop out in the Oil Creek embayment and Mesozoic rocks are present in the Bare Hills and in High Park. Early Tertiary prevolcanic rocks crop out in the High Park basin and perhaps in the Bare Hills.

Precambrian Rocks

Precambrian rocks in the study area consist of both metasedimentary rocks and granitic intrusive bodies. The metasedimentary rocks are made up of biotite and biotite sillimanite schists and the Cripple Creek augen gneiss of Hutchinson and Hedge (1967) which is dated at 1.70 b.y. The schists crop out as long lenselike bodies included in the granites and the augen gneiss occupies a large area near Victor. Precambrian intrusive rocks include those of the Cripple Creek and Pikes Peak batholiths. The Cripple Creek granite is fine to medium grained, reddish in color, and displays a planar flow structure caused by parallelism of tabular Carlsbad twins of potash feldspar in groundmass of finer grained feldspars and quartz (Ransome, et. al., 1906, p. 45). The Cripple Creek granite has been dated at 1.43 b.y. by the Rb/Sr method (Hutchinson and Hedge, 1967).

Although the southern boundary of the Pikes Peak batholith is north of Cripple Creek a small outcrop of the granite is present in the

High Park area. The rock is a coarse grained, pink to gray, biotite granite that weathers distinctively to a very coarse mineral gravel. The Pikes Peak granite has been dated at 1.04 b.y. by Rb/Sr methods (Hutchinson and Hedge, 1967).

Paleozoic Rocks

Rocks of the Paleozoic era are represented in the thesis area by the Ordovician and Pennsylvanian systems. For the purposes of the present study, the Ordovician rocks were mapped as undifferentiated and the following description of the Ordovician formations is largely a distillation of the reports of previous workers including Boos and Boos (1957) and Gerhard (1967-68). Three Ordovician formations exist in the study area; the Manitou Dolomite, the Harding Sandstone, and the Fremont Limestone. Rocks of Pennsylvanian age were mapped as the Fountain Formation.

Manitou Dolomite: The Manitou Dolomite was first described by Cross (1894, p. 2) at the type section near Manitou Springs, Colorado where it is 218 feet thick. In the Canon City embayment, the Manitou reaches a thickness of 113 feet and consists of 3 members, only two of which are present in the type locality (Gerhard, 1967, p. 2264). The basal member was named the Helena Canyon Member for exposures in Helena Canyon (T.16 S.-R.70W.) where it consists of about 10 feet of dolomite which contains no chert and weathers brick red. It is nonconformable on rocks of Precambrian age and has a basal conglomerate of rounded to subangular quartz cobbles in a limestone matrix (Gerhard, 1967, p. 2264).

The middle cherty member consists of thin-to medium-bedded, gray to pink dolomite with irregular interbeds of chert up to 10 inches in thickness (Walter, 1959, p. 15). The member reaches 45 feet in thickness and is conformable on the Helena Canyon member (Gerhard, 1967, p. 2264).

The upper member is composed of massive dolomitic limestone with thin shaly partings and reaches a maximum thickness of 75 feet in the thesis area (Gerhard, 1967, p. 2264). It is gray to light red when fresh and weathers dark red. Berg and Ross (1959, p. 110) have found trilobites of lowermost Ordovician age in the Manitou Dolomite north of Manitou Springs.

Harding Sandstone: The Harding Sandstone (Walcott, 1892, p. 153) disconformably overlies the Manitou Dolomite and reaches a thickness of 100 feet in the Canon City embayment (Gerhard, 1967, p. 2264). The Harding may be divided into at least three members, the lowest of which consists of thin-bedded to massive, white to greenish, quartzose sandstones alternating with greenish sandy shales. The basal 5 feet of this member often contain quartz pebbles as much as one-fourth inch in diameter. The middle member consists of a dark red, fissile, sandy shale with thin interbeds and lenses of green shale. This member contains disarticulated ostracodermi plates which were found by the author and by previous workers (Walter, 1959, p. 20; Gerhard, 1967, p. 2264). The upper member of the Harding contains massive to fissile, argillaceous sandstones with partings of red shale. The member is variable in color and ranges from green to pink or yellow.

Fremont Limestone: The Fremont Limestone disconformably overlies the Harding sandstone, and consists of massive, gray to yellow, dolomitic limestones. Most of the Fremont is noncherty but some chert is present in the lower part. The unit weathers cavernously and presents a spiny surface. Corals (principally Halysites, Gerhard, 1968, p. 113), and other fossils, including the cephalopod Gorbyoceras (Flower, 1964, personal communication), have been found and a late Ordovician age is assigned to the unit. The Fremont reaches a thickness of 80 feet in the thesis area (Walter, 1959, p. 22).

Fountain Formation: The Fountain Formation (Cross, 1894) overlies with angular unconformity Ordovician strata in the southern part of the study area. The Fountain is a large wedge of laterally intertonguing clastic sediments recognized as a series of coalescing alluvial fans derived from the Ancestral Rocky Mountains (Howard, 1966, p. 147). It consists of crossbedded, fissile to massive, arkosic conglomerates and coarse sandstones with interbeds of micaceous shales and siltstones. Sorting and rounding are poor but fluvial stratification is well developed. The red color of the Fountain is due to hematite which occurs both as stains on the grain surfaces and as interstitial cement. McLaughlin (1947, p. 1973) dates the Fountain as Pennsylvanian on the basis of invertebrate fossils found in limestone facies along the eastern margin of the Front Range.

Mesozoic Rocks

Rocks of the Mesozoic era are represented in the thesis area by the Morrison Formation of Jurassic age and the Dakota Group of Cretaceous age. These units crop out along the western boundary of the study area where they have been preserved, for the most part, as narrow slivers in fault zones.

Morrison Formation: The Morrison Formation was first described by Cross (1894) but was named by Eldridge and Emmons (1896) for a type section at the town of Morrison which is located a few miles west of Denver. It has been extensively studied in the western United States and its age and relationships to other units are the subject of much controversy (Stokes, 1952, p. 1770; Haun and Weimer, 1960, p. 59; Oriel and Craig, 1960, p. 55). The exposures of the Morrison Formation in the Canon City embayment are well known for excellent reptilian fossils of Jurassic age among which are: Allosaurus, Brachiosaurus, Camptosaurus, Dynosaurus, Stegosaurus, and six sauropod genera. Other fossils, including crocodile, turtle, and phytosaur remains as well as fecal pellets and gastroliths, are consistent with a Jurassic age (Stokes, 1952, p. 1969; Gerhard, 1967, p. 2268).

In the mapped area, the Morrison is nonconformable on rocks of Precambrian age and a basal white feldspathic conglomerate overlies the deeply weathered Precambrian surface. Above the conglomerate, the formation consists of variegated mudstones, siltstones, and sandstones with thin, nodular to lenticular, fresh-water limestones.

Dakota Group: In the Colorado Plateau region, rocks of lower Cretaceous age have been divided into a basal Burro Canyon Formation and an upper Dakota Group with the boundary set at the appearance of quartzose conglomerates (Stokes, 1952, p. 1772). In the thesis area, conglomeratic sandstones and marine shales are mapped as Dakota, although no clear cut boundary exists between the Dakota and Morrison Formations (Stokes, 1952, p. 1772; Haun and Weimer, 1960, p. 59). The Dakota was found only in the southwest corner of the thesis area where it consists of well-indurated, silica cemented, crossbedded, quartzose sands and conglomerates with some partings of shale.

Tertiary Rocks

Prevolcanic arkose: Prevolcanic arkose is an informal name applied to arkosic valley-fill deposits of probable Eocene or early Oligocene age in the Thirtynine Mile volcanic field. These immature sediments are older than all known volcanic units of the field (Epis and Chapin, 1868, p. 59). In the Tallahassee Creek region the arkose occupies a steep-walled, graben-like paleovalley and attains a thickness of as much as 1200 feet (Epis and Chapin, 1968, p. 59).

Similar arkose crops out in the High Park area as an unconsolidated, green to red and brown, sandy mudstone as much as 40 feet in thickness. Carbonaceous material is present in some of the beds. Consolidated basal arkosic conglomerates and sandstones grade upward into friable mudstones. The basal beds are cemented by clay with some patchy calcite. The grains are bimodally rounded with about 60% subangular to subrounded and slightly larger than average. These grains are composed of feldspars and other labile fragments; the other 40% of the grains are extremely well-rounded and spherical with frosted surfaces and are composed principally of quartz. Sorting is poor in all of the beds with boulders of regolithic granite present in the mudstones. Volcanic detritus is absent except for a few pebbles of a yellow rhyolite porphyry which contains double terminated quartz crystals as much as one-fourth inch in length. No fragments of any known Thirtynine Mile volcanic unit were found in the arkose.

Volcanic Rocks

The Ash Flow - 1 Cooling Unit: The earliest volcanic material deposited in the Thirtynine Mile field is a multiple-flow, simple cooling unit of welded ash-flow tuffs. Chapin and Epis (1964, p. 147) mapped and described two members of this unit which they termed ash flows-1 and 2. A third member of the sheet, recognized by the present author and by Gary R. Lowell in the Salida area (personal communication, 1969) has been informally designated ash flow-0.5. This member is distinguished by a higher median $2V_x$ of the sanidine phenocrysts and by a higher plagioclase to sanidine ratio. It may be the basal member of the ash flow-1 cooling unit; definite stratigraphic evidence, however, is not yet available.

In the study area, the most extensive outcrops of these ash flows occur in the High Park basin where a thickness of about 50 feet is attained. In the remainder of the area, the unit crops out as small isolated erosional remnants. The member flows of the cooling unit form ledge-like outcrops with a marked eutaxitic fabric imparted by stretched and compacted pumice fragments. The rock ranges in color from reddish-brown to purplish-brown and weathers to various shades of buff, brown and reddish-brown. Petrographically, the unit consists of a reddish-brown groundmass of devitrified glass shards containing broken crystals of clear unaltered sanidine, clay pseudomorphs after plagioclase, and crystals of biotite which are commonly oxidized to a dark red or are completely opaque. The sanidine ranges in length up to 5mm., the plagioclase seldom exceeds 3mm., and the biotite flakes have a maximum diameter of 2mm. The rock is made up of less than 20% crystal fragments with the remainder being matrix.

Tables 1 and 2 summarize the optical and mineralogical data obtained by thin-section study of the cooling unit. Table 1 lists modal analyses of each of the member flows with phenocryst percentages recalculated to 100%. Table 2 tabulates the axial angles of sanidine phenocrysts. The median axial angles are sufficiently constant in each flow to provide a basis for correlation when used in conjunction with the gross lithologic characteristics and mineral percentages (Chapin and Epis, 1965; Chapin, 1965).

The modal analyses were plotted on a three component diagram, Figure 2, with end members sanidine, plagioclase, and biotite plus opaques. It can be seen from this diagram that ash flows-0.5, 1 and 2 are latites and that the composition becomes progressively more trachytic from ash flow-0.5 to ash flow-2 which also suggests that ash flow-0.5 is probably the basal member even though definite stratigraphic relationships have not yet been established in the field.

<u>The Ash Flow of Cripple Creek</u>: The ash flow of Cripple Creek consists of at least two members in a multiple flow unit which overlies the more extensive ash flow - 1 cooling unit. Both cooling units were previously mapped as Tertiary rhyolite by Cross (1894) and Koschmann (1947). In this study, the Cripple Creek unit will be divided into a basal member known as ash flow-G (gray) and an upper member designated ash flow-S (squiggly).

The ash flow of Cripple Creek crops out on Grouse Mountain and Little Pisgah Peak and as large xenoliths in the phonolite on Grouse Mountain. Rather than forming ledges as does the ash flow - 1 cooling unit, a typical outcrop consists of a meadow strewn with rounded boul-

Table 1. Modes in volume percent of phenocrysts (recalculated to 100%) from the ash flow - 1 cooling unit

Sample #	Percent phenocrysts	Sanidine	Plag.	Biotite	Plagioclase / Sanidine	Points Counted
Ash-Flow 2						
T - 38	14.2	62.5	35.5	2	.55	755
Ash-Flow 1						
T - 27	19	57	38	5	.67	730
T - 34	17.8	50	42	8	.84	878
T - 35	15	57	36	7	.63	730
Ash-Flow 0.5						
T - 13 - 2	17.5	45	45	10	1.00	637
T - 13 - 3	14.8	48.5	46.5	5	.96	756
T - 23	17	50	42	8	.84	637

Table 2. Axial angles ($2V_x$) of sanidine from ash flows-0.5, 1 and 2

Ash-flow	Range	Median	Range of zoning	Number of determinations
2	28.5 - 42	32.5	37.5 - 42	21
1	29.5 - 52	36.6	39 - 52	62
0.5	31.5 - 52	40.7	32 - 46.5	70

ASH FLOW - 1 COOLING UNIT

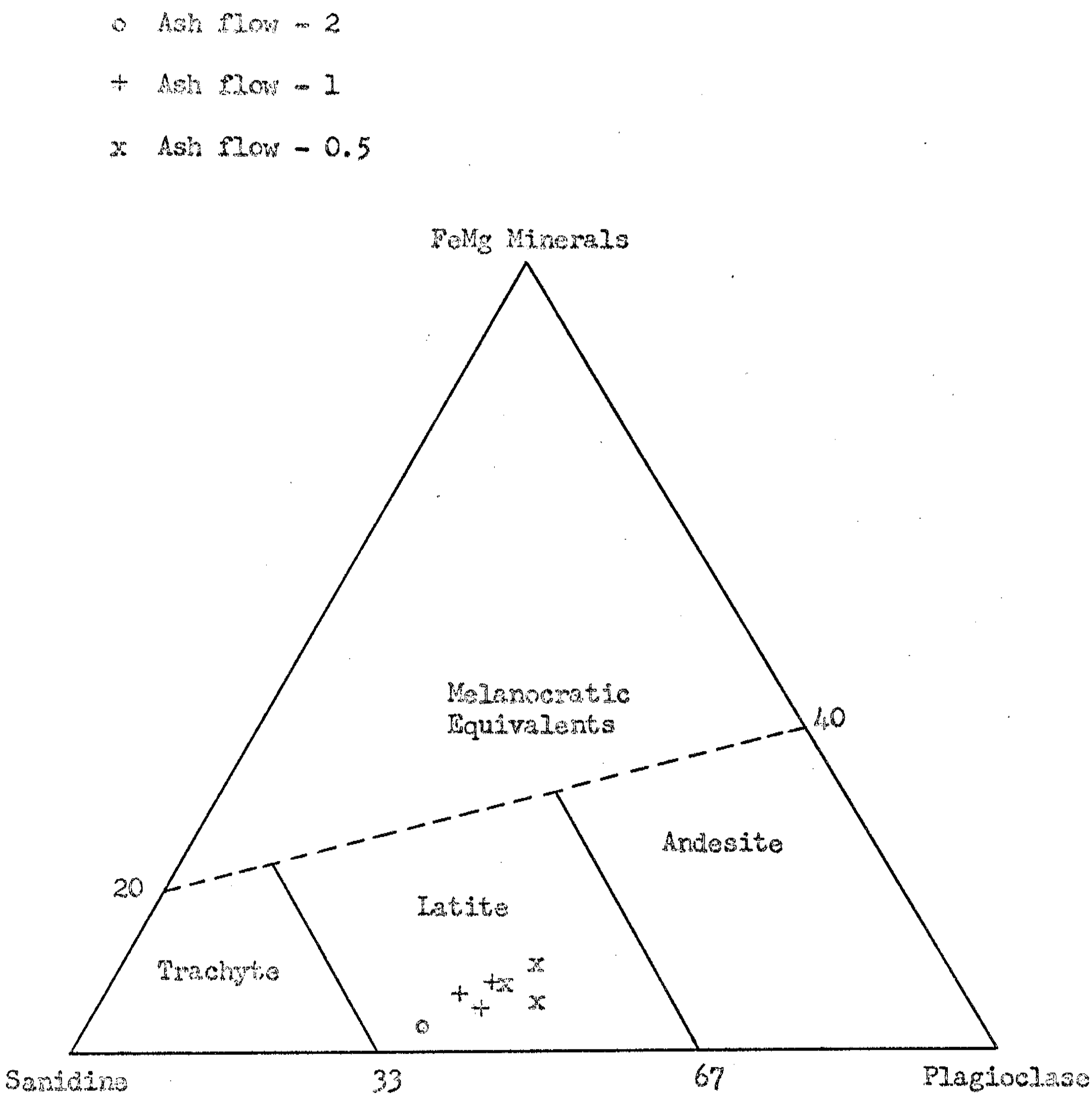


Fig. 2 Three component classification of common intermediate volcanic rocks (Based on AGI mineral ratios from data sheet 23a).

ders. In the valley between Grouse Mountain and Little Pisgah Peak, the ash flow of Cripple Creek attains a thickness of at least 100 feet. The member flows may be distinguished in the field by their color and fabric. Ash flow-G has a purplish-gray to pinkish-gray color and does not display a marked eutaxitic fabric. Ash flow-S is yellowish-brown to dark reddish-brown in color and exhibits a squiggly or wormy eutaxitic fabric imparted by smeared and devitrified glass shards. The upper portion of ash flow-S is an extremely fine grained, crudely-stratified deposit of volcanic dust and glass shards that may represent the last pulses of ash-flow activity (Schminke and Swanson, 1967, p. 648).

Petrographically, rocks of both members consist of fractured crystals of plagioclase, sanidine, and biotite set in a fine grained matrix. Plagioclase is completely replaced by pseudomorphs of white clay whereas the sanidine is largely clear and unaltered. Biotite has a bronzy color and is often oxidized to hematite and other iron oxides. Sanidine crystals reach a length of 5mm. and are more blocky than the smaller plagioclase crystals; biotite occurs as minute flakes with some larger flakes having diameters up to 7mm. The rocks consist of about 15% crystals with the remainder composed of glass shards, a small percentage of lithic fragments, and pumice lapilli which are largely replaced by vapor phase minerals. Ash flow-G contains numerous, small, accessory lithic fragments of quartz and microcline derived from prevolcanic rocks.

Tables 3 and 4 summarize the optical and mineralogical data obtained by thin section study of the member flows. Table 3 lists modal analyses of the ash flows with the phenocryst percentages recalculated to 100%. Table 4 summarizes the axial angles of sanidine phenocrysts.

Table 3. Modes in volume percent of phenocrysts (recalculated to 100%) from the ash flows of Cripple Creek

Sample #	Percent phenocrysts	Sanidine	Plag.	Biotite	Plagioclase / Sanidine	Points Counted
Ash-flow S						
T - 2	12.5	56	33	11	.59	636
T - 14 - 2	14.8	63	33	5	.52	668
Ash-flow G						
T - 13 - 1	15.6	51	37	12	.72	685
T - 14 - 3	16.2	56	32	12	.57	784
Altered Samples						
T - 1	20.4	56	39	5	.70	629
T - 5	21	55	33	12	.60	589

Table 4. Axial angles ($2V_x$) of sanidine from the ash flows of Cripple Creek

Ash-flow	Range	Median	Range of zoning	Number of determinations
S	24 - 54	38	36 - 46	48
G	29.5-51.5	34.7	37 - 44	51
Altered				
T - 1	46 - 56	47	-	21
T - 5	38 - 51	42	-	17

Figure 3 shows the modal analyses plotted on a three component diagram. It can be seen from this diagram that ash flow-G is a latite and that ash flow-S is a trachytic latite; this trend from latite toward trachyte with ascending stratigraphic position is similar to that observed in the ash flow - 1 cooling unit.

Some of the ash-flow outcrops represent rafted blocks in the later phonolite flows. In these outcrops, the tuffs were bleached nearly white, the sanidine was strongly corroded, and the biotite was almost completely oxidized to iron oxides. These samples gave distinctly higher median $2V_x$ values of sanidine and were plotted as altered tuffs since they could not be definitely correlated. It is interesting to observe that deuteric vapor-phase activity in the cooling ash flows failed to alter the sanidine axial angles, whereas they were appreciably altered by hydrothermal fluids from an external source.

Lower Volcanic Conglomerate: Arkosic conglomerates and volcanic conglomerates overlie and channel through the ash flow - 1 cooling unit in meandering valley-fill deposits in the central and southern portions of the Thirtynine Mile volcanic field (Epis and Chapin, 1968, p. 62). These deposits are overlain by laharic breccias of the lower andesite. Deposits of similar stratigraphic position and composition are present throughout the study area but exhibit local variations. Sedimentary rocks in the High Park and Cripple Creek vicinities have previously been mapped as High Park Lake Beds (Cross, 1894; Koschmann, 1947). These strata outcrop as low rounded hills with grassy, boulder-strewn slopes. A lag concentrate of boulders on the surface gives an illusion of greater coarseness.

ASH FLOW OF CRIPPLE CREEK

o Ash flow - S

\+ Ash flow - G

x Altered ash flow

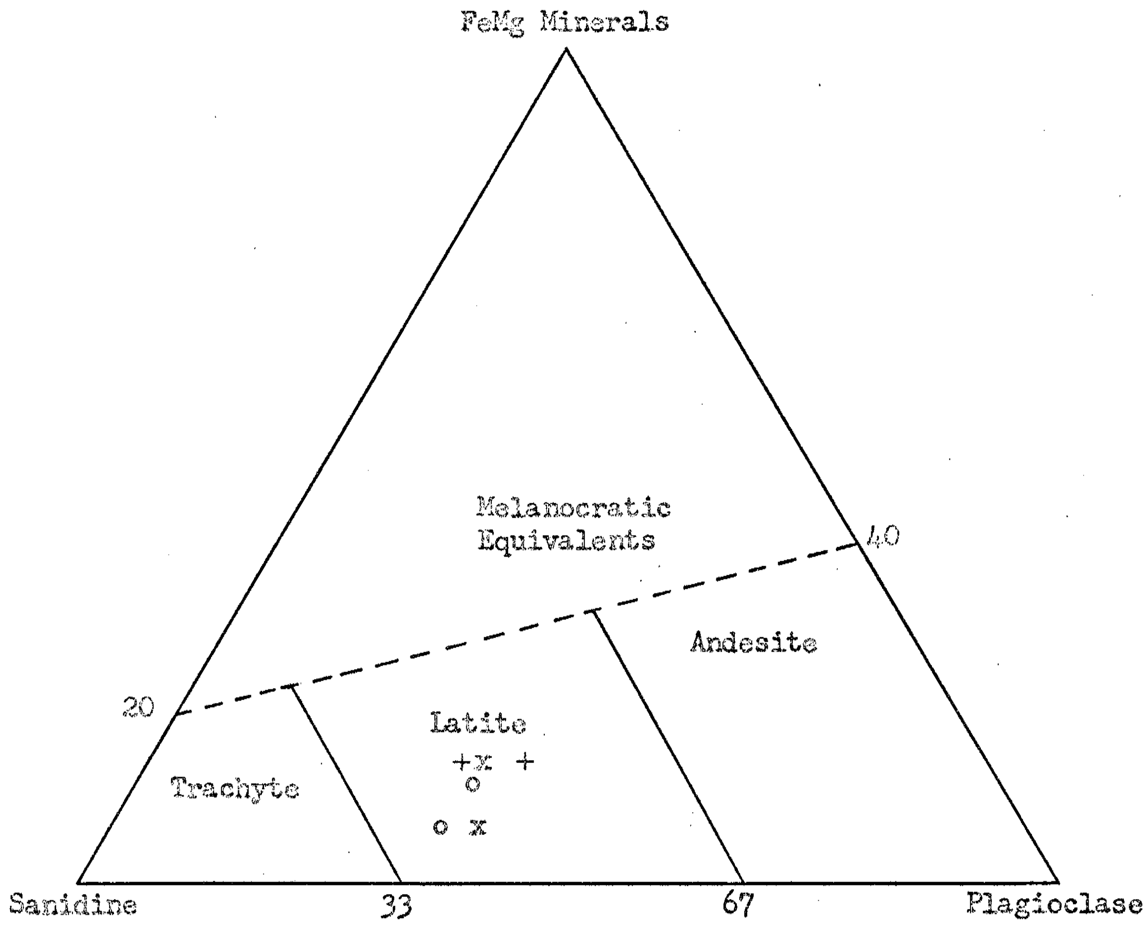


Fig. 3 Three component classification of common intermediate volcanic rocks (Based on AGI mineral ratios from data sheet 23a).

In High Park, the deposits consist in decreasing order of importance of boulder conglomerates, coarse sands, and siltstones with a total thickness of about 100 feet. Bedding in the finer materials is sub-parallel and in the coarser material is usually lenselike with distinct crossbedding. Imbrications of boulders at the Cotter Corporation uranium prospect imply a southeasterly direction of flow (Fig.4). The poorly-sorted deposits are usually unconsolidated but become more indurated near intrusive bodies. Smooth, spherical boulders and pebbles of gray to green quartzite make up about 10% of the total deposit. Granite and other plutonic fragments, which account for 75% of the deposits, are subrounded to rounded. Less well rounded fragments of the ash flow - 1 cooling unit make up about 10% of the unit. The remaining 5% consists of intermediate volcanic fragments of unknown derivation.

In the Cripple Creek area, deposits of arkosic grits and conglomerates as much as 300 feet thick occur on Grouse and Straub Mountains. The deposits are largely unconsolidated and consist of subangular grains of quartz and feldspar with fragments of Precambrian plutonic and metamorphic rocks, Paleozoic and Mesozoic sediments, and near the base, fragments of the ash flow of Cripple Creek. Locally the rocks are very well indurated, usually with hematite cement. This is especially true of the blocks of grits rafted in the phonolite flows; in some cases the feldspars have been completely removed.

The Bare Hills are completely underlain by basin-fill arkosic deposits as much as 250 feet thick. The unit grades upward from fine-grained, red and green mudstones, which contain boulders of Precambrian granite and Mesozoic clastic sediment rocks, to sandstones and boulder

Figure 4: View of the lower volcanic conglomerate exposed in a cut of the Cotter Corporation uranium prospect in High Park (SW/4, NE/4, sec. 36, T.15S., R.71W.). Note the imbrication of boulders and cobbles which indicates a southeasterly direction of transport (facing northeast, field of view 10 feet). A large elongate and angular boulder of welded tuff in the center of the picture stands in sharp contrast to the well-rounded boulders of Precambrian rocks.

conglomerates (Fig.5). The basal portion is similar in aspect to the prevolcanic arkose but without the ash flow - 1 cooling unit as a datum plane the two arkoses are difficult to separate. Most of the boulders are of local derivation; quartzite boulders are rare in the Bare Hills and become increasingly scarce to the south and west. The boulder strewn slopes of locally derived granite fragments can be distinguished from slopes underlain by Precambrian rocks by the high albedo of the rounded and whitened boulders. Volcanic fragments (composed entirely of the ash flow - 1 cooling unit) comprise less than 5% of the deposit. The locally-derived arkosic deposits between Currant Creek and High Park (Epis and Chapin, 1968, p. 63) are contiguous with the Bare Hills deposits and may represent drainage into the basin.

Lower Andesite: The lower andesite is comprised of a series of breccias and flows of dark andesitic rocks which have been divided into a lower member of chaotically-stratified laharic breccias and an upper member of well-stratified flows and flow breccias (Epis and Chapin, 1968, p. 65). The lower member is the most extensive and voluminous volcanic unit in the Thirtynine Mile field and was erupted from numerous small vents randomly scattered throughout the area. Lateral distribution of the fragmental material was mainly accomplished by volcanic mudflows; flow breccias rarely flowed more than a few hundred yards from the vents (Chapin and Wyckoff, 1968). Outcrops of the lower member of the lower andesite occur in High Park, the Bare Hills, and on Little Pisgah Peak. The upper member is absent in the thesis area.

In the High Park area, the lower andesite consists of both heterolithic and monolithic lahars. Angular fragments of pyroxene

Figure 5: View of red and white mudstones of the lower volcanic conglomerate in the Bare Hills (SE/4, NE/4, sec. 10, T.16S., R.71W.). Note the volcanic boulders in soil above unit. Field of view 15 feet.

andesite, as much as 12 inches in diameter, comprise the monolithic breccias. Individual pyroxene crystals are as much as one-fourth inch in length. The heterolithic breccias contain more rounded fragments and a greater diversity of rock types. Some lahars near the base of the unit are composed of as much as 85% granite fragments picked up from the Precambrian basement rocks over which they flowed (Fig.6). Laharic breccias of more siliceous composition make up about 2% of the unit; these breccias form thin, white deposits composed of fragments of hornblende trachyte and Precambrian granites. The fragments and the matrix display differing oxidation states; in breccias with a high percentage of matrix, the fragments are purple-black and the matrix is reddish. Breccias with less matrix are green-gray to dark gray and weather brown.

A small breccia vent was found at the north end of High Park and is marked by short, steeply-dipping flows and flow breccias of pyroxene and hornblende andesites. Faulting and hydrothermal alteration is present in the vent area.

Two small outcrops of lower andesite in the Cripple Creek area are composed of highly altered volcanic and granitic fragments in a finely comminuted matrix. The volcanic fragments range from biotite and pyroxene andesites to olivine (?) basalts. Alteration is extreme and pyroxenes have been replaced by calcite or iron oxides so that their identification was based largely on the euhedral outlines of the calcite pseudomorphs. The lower andesite was intruded by a phonolite plug on Little Pisgah Peak and near the contact the rock is baked and oxidized a bright red. The red coloration is due to disseminated hematite. The phonolite neck on Mount Pisgah, northwest of the town of Cripple Creek,

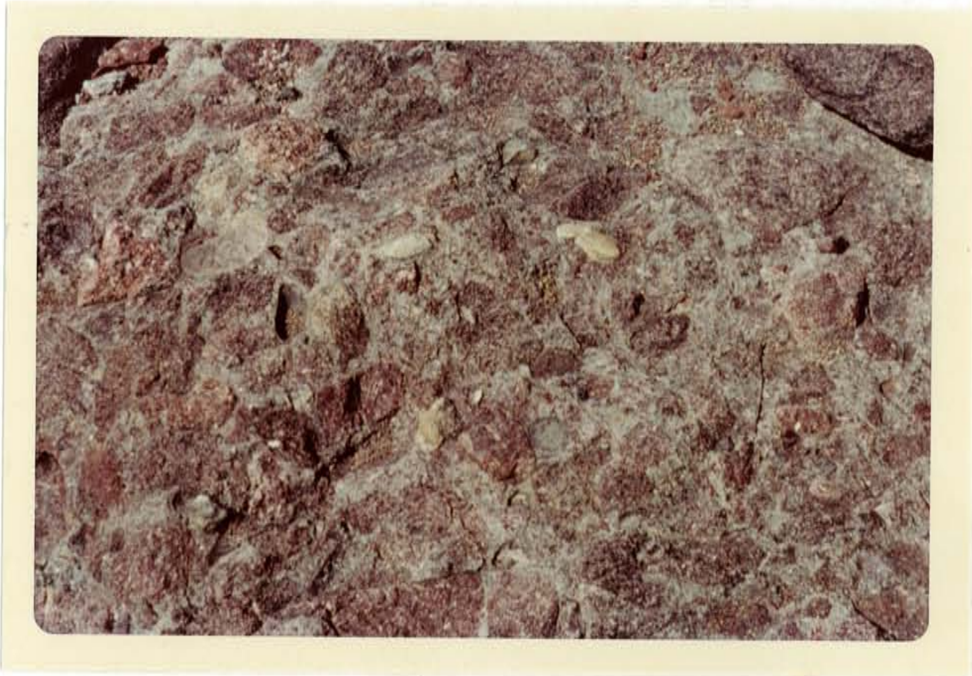


Figure 6: Close up of a laharic breccia composed primarily of Precambrian granitic fragments in an andesitic matrix. The breccia occurs near the base of the lower member of the lower andesite in High Park (SW/4, SW/4, sec. 4, T.15S., R.71W.). Field of view 4 feet.

has also intruded and altered laharic breccias of the lower andesite (Chapin, 1969, personal communication).

The lower andesite differs markedly in character in the Bare Hills due to the presence of a local eruptive center which contributed pumice lapilli and ash. The unit is composed of 50% epiclastic lahars with tuffaceous matrix, 40% bedded tuffaceous sands and siltstones, and 10% lapilli tuffs. The epiclastic lahars are crudely stratified and unsorted deposits which consist of rounded to subangular fragments ranging in size from clay to boulders 12 inches in diameter. Most of the fragments range from one-eighth inch to one-half inch in diameter. Dark fragments consist of andesites and other intermediate to basic volcanic rocks which were probably derived from the Thirtynine Mile field (Fig.7). Granitic fragments and quartz and microcline grains are also present. Pumice lapilli constitute about 10% of rock. The gray-white matrix is composed of finely comminuted rock material and crushed pumice lapilli. Boulders weathered out of the tuffaceous matrix cover the slopes and prevent recognition of unit boundaries. Only in recent gullies may the true nature of the deposits be seen.

Bedded sands and very finely laminated siltstones and shales crop out in the northern half of the Bare Hills. The sands have the same composition as the epiclastic lahars. The siltstones are composed of laminae containing euhedral biotite and green hornblende crystals in a clay matrix alternating with laminae containing quartz, microcline, and crystal fragments of volcanic origin in a clay matrix. Decomposed pumice lapilli form the clay matrix. The rock displays a marked fissility and breaks along bedding planes into fragments with lateral dimensions many times their thickness.

Figure 7: View of andesitic boulders weathering out of a tuffaceous matrix in an epiclastic laharic breccia exposed in the Bare Hills (NE/4, SW/4, sec. 10, T.16S., R.71W.). Field of view 5 feet.

The lapilli tuffs are composed of pumice lapilli as much as one-half inch in diameter set in a matrix of quartz, microcline, plagioclase, and biotite grains. The plagioclase and biotite grains often display euhedral outlines whereas the quartz and microcline are broken crystal fragments. Euhedral hornblende crystals as much as one-fourth inch in length were also observed in some of the pumice lapilli.

Table 5 presents some of the mineralogical and compositional variations of the lower andesite in the thesis area. The data is based on visual estimates in thin section.

Trachyte of Bare Hills: The cap rocks of the Bare Hills, mapped as hornblende andesite by Cross (1894), are designated on Plate 1 as the trachyte of Bare Hills. The unit crops out as one large plug with radiating dikes, numerous smaller plug-like masses and dikes (Fig.8), and as slabby talus-like remnants of flows. The rock shows a marked fissility due to very fine flow banding and breaks into platy fragments which slide down over the lower units and mask the contacts. In hand specimen, the rocks are very fine-grained with few visible phenocrysts and conchoidal fracture. Fresh surfaces are gray to black; weathered surfaces are light gray to reddish-brown. Some of the extrusive phases are agglomerates of trachytic and andesitic fragments with quartz and microcline grains between the fragments. That some of the fragments were still molten at the time of impact is shown by alignment of microlites parallel to fragment boundaries.

Petrographically, the rocks have a trachytic texture and consist of microlites of sodic plagioclase and sodic amphibole set in glassy matrix. Some biotite, magnetite, and green hornblende is present and

Sample #	Matrix %	Nonvolcanic fragments %	Volcanic fragments %	Volcanic minerals	Alteration
T - 9	60	-	40	plag. ----- 70 pyrox. ----- 20 iron oxides --- 10	pyrox. calcite plagic. calcite + sericite
T - 15	40	5	55	plag. ----- 80 pyrox. ----- 15 biot. ----- 5	plag. clay pyrox.+ biot. iron ox. calcite veins reddening and oxidation
T - 42	20	15	65	plag. ----- 50 pyrox. ----- 30 iron ox. --- 15 biot. ----- 5	groundmass + augite aegerine + chlorite
T - 44	15	-	85	plag. ----- 50 lamp. ----- 25 biot. ----- 12 iron ox. --- 12 horn. ----- 1	horn. lamp. biot. iron oxides plag. sericite
T - 48	50	-	50	plag. ----- 75 iron ox. --- 5	pyrox. iddingsite plag. clay zeolitization calcite veins

Table 5 Compositional variations of lower andesite in the Cripple Creek (T - 9, 15); High Park (T - 42, 44, 48, 50); and Bare Hills area (T - 32, 32 - 2, 33).
(continued on next page)

Sample #	Matrix %	Nonvolcanic fragments %	Volcanic fragments %	Volcanic minerals	Alteration
T - 50	25	55	20	plag. ---- 60 pyrox. ---- 20 iron ox. -- 20	pyroxene iddingsite plag. clay zeolitization
T - 32	20	10	70	plag. ---- 55 san. ---- 35 biot. ---- 10	pumice clay
T-32-2	35	-	65	plag. ---- 70 pyrox. ---- 20 iron ox. -- 10	pumice clay pyrox. iron ox. plag. sericite
T - 33	75	5	20	san. ---- 35 biot. ---- 25 horn. ---- 20 plag. ---- 15 iron ox. -- 5	pumice clay

Table 5 (cont.)

Figure 8: View looking east at a bifurcating trachyte dike cutting granite in the Bare Hills (SW/4, NW/4, sec. 2, T.16S., R.71W.). Grassy knob in background is Big Baldy.

xenocrysts of microcline and quartz are fairly common. In some samples of the flow material, analcite forms up to 3% of the rock and appears to be a primary mineral occurring as small blebs in the groundmass and as vein fillings. Plagioclase microlites show oscillatory zoning and wavy extinction. Their refractive indices range from 1.538 to 1.551± .002 indicating an average composition of An_{27} (oligoclase); they are often mantled with a clear rim of sanidine or untwinned albite. The rim does not alter with the rest of the lath yielding sarcophagus-like phenocryst outlines.

The sodic amphibole represents as much as 15% of the rock and forms long acicular crystals and radiating clusters of tiny needles. In the more oxidized samples it is largely replaced by limonitic material. The mineral is pleochroic, varying from light yellow to greenish-yellow and displays an anomalous blue birefringence on the order of .015 (maximum). The maximum extinction angle of the prisms measured z to c is 38°.

Biotite and green hornblende are present in small amounts and are usually oxidized and partially replaced by iron oxides. The refractive index of the brown glass, which forms up to 55% of the rock, is 1.523± .002 and indicates a minimum SiO_2 content of about 62%.

Phonolite: The characteristic rock type of the Cripple Creek district is phonolite, which has been studied in some detail by Cross (1894), Ransome, and others (1906), and Koschmann (1947). The phonolite occurs as irregular intrusive masses, dikes and sills, and as remnants of flows. In the thesis area, flows crop out on Straub Mountain, Grouse Mountain, and Booger Red Hill while intrusive bodies occur on Mitre

Peak, Little Pisgah Peak, and south of Straub Mountain. Outside the thesis area, phonolite occurs in the Cripple Creek cauldron on Nipple Mountain, Pisgah Mountain, Rhyolite Mountain, and on the south slope of Pikes Peak to an elevation of 11,000 feet (Ransome et. al., 1906, p. 58).

The characteristic geomorphic expression of the phonolite flows is rounded, grassy hills with shingled surfaces of large plates of phonolite. Sheeting imparts a high degree of fissility to the rock and causes it to break into large platy fragments (Fig.9). The phonolite flows on Grouse Mountain contain rafted bodies of lower conglomerate and the ash flow of Cripple Creek. Near these bodies the phonolite contains numerous inclusions of quartz and microcline. Intrusive bodies are expressed as steep-sided, irregularly-shaped masses with nearly vertical sheeting.

In hand specimen, fresh rocks are olive-gray to dark gray and when weathered become greenish-yellow to yellow-brown or white in color. Pitting caused by leaching of phenocrysts is common on weathered surfaces; a mottled surface also results from the contrast between whitened feldspars and the darker groundmass. Flow-aligned crystals of alkali feldspar are common. Some flows on Grouse Mountain contain prisms of red nepheline as much as one-fourth inch in length, but more commonly the nepheline occurs in the groundmass and imparts a greasy luster to the whole rock. Coarsely crystalline inclusions of feldspar and pyroxene are common in the intrusive masses.

Petrographically, the phonolites are holocrystalline, porphyritic, with an aphanitic groundmass of feldspar microlites. The microlites are obliquely oriented to flow planes which have produced the

Figure 9: View of phonolite flow rock with prominent horizontal sheeting exposed on Booger Red Hill (NW/4, NW/4, sec. 32, T.15S., R.70W.). Note platy nature of weathered phonolite fragments on ground.

fissility of the rock. Feldspar displays twinning only according to the Carlsbad law and has been described as soda orthoclase (Ransome et. al., 1906, p. 59). Seven thin sections of the phonolites yielded the following average mineral percentages: 65% feldspar, 15% nepheline, 10% pyroxene, 5% analcite, and 5% minor constituents such as nosean, zeolites, other feldspathoids and accessory minerals.

The feldspar occurs as euhedral laths and as microlites with poorly-defined crystal boundaries which are usually in a state of turbid decomposition. Clay and zeolites are common alteration products of the feldspar. The principle pyroxene is aegirine, some of which have aegirine-augite cores. The crystal habit of the aegirine varies from euhedral crystals to clusters of radiating crystals and feathery aggregates. The radiating clusters frequently penetrate analcite but seldom penetrate nepheline or feldspar. Analcite occurs as veinlets and with nosean as small rounded blebs in the groundmass. In the coarse-grained inclusions of intrusive bodies, the phonolite consists of euhedral aegirine, nepheline, soda orthoclase, sphene, and dark biotite crystals set in an analcite matrix.

Silicic Intrusives: Koschmann (1947) mapped as Tertiary rhyolite the ash-flow sheets and four, small, irregularly-shaped intrusive bodies in the granite between Cripple Creek and Wilson Creek. These intrusives were emplaced along a shear zone that parallels the Oil Creek fault. The rock consists of a few euhedral feldspar crystals and many granitic fragments set in a purple-brown, aphanitic, silicic groundmass. Microcline in the fragments is largely altered to clay. The abundance and size of the granitic fragments increases toward the borders of the intrusives giving a gradational appearance to their contacts. Small purple masses of earthy fluorite are present in cavities in the rock.

Postvolcanic Deposits

Quaternary Mass Waste Deposits: The term Quaternary landslide has been used in this study for mass waste deposits which include slump blocks, talus, landslides, and colluvium. Landslides and slump blocks are particularly abundant in areas where competent volcanic strata overlie unconsolidated sediments. The deposits may be recognized by their characteristic hummocky topography and by the mixing of chaotically jumbled blocks of various rock units. Colluvium is important where plates of fissile phonolite or andesite creep downslope covering all contacts and greatly exaggerating the thickness of the parent unit. Talus slopes exist on Mitre Peak and Little Pisgah Peak where intrusions of fissile phonolite stand in high relief above deep canyons.

STRUCTURAL GEOLOGY

Regional Structural Setting

The Thirtynine Mile volcanic field occupies a structural plateau situated within a belt of north-trending synclinal basins which include North, Middle, South and Huerfano Parks; the Wet Mountain Valley; and the Trinidad and Raton Basins (Eardley, 1962, p. 391; Chapin and Epis, 1964, p. 155). The field is bounded on the west by the Mosquito and Sawatch Mountains, on the east by the southern Front Range, on the north by South Park and on the south by the Wet Mountain Valley.

Pre-Tertiary structure has been largely masked by Laramide activity and regionally a picture of Laramide uplift and thrusting in two directions is presented. The trend of the Laramide faulting has been shown to be partly controlled by reactivated Precambrian and Paleozoic belts of weakness (Boos and Boos, 1957, p. 2635; Hudson, 1969, p. 294), and partly to assert tectonic independence (Eardley, 1962, p. 392; Harms, 1964, p. 93). The origin of the Laramide uplifts in the Rocky Mountains is controversial and the author will present the two principle hypotheses.

Vertical Tectonics

During consideration of the bounding fault systems of the Laramide and Ancestral uplifts, Harms (1964) and Eardley (1963, 1968, 1969) have independently arrived at the conclusion that the uplifts are the result of the vertical rise of large crustal blocks. Vertical tectonics explains the mild deformation of the intermontane basins as contrasted to greatly deformed basins in crustally shortened areas (Harms, 1964, p. 97).

Eardley (1968) related the vertical tectonic control of the Ancestral and Laramide Rockies to widespread magmatism in the following manner:

1) rise of megalaccoliths of basalt in scattered places from the upper mantle to the base of the silicic crust
2) doming of the crust and the sedimentary veneer
3) creation of the surficial features by gravity induced mass movement along the flanks of the uplifts and folding of the Paleozoic synclinoria between the uplifts.

Horizontal Compression

The other school of thought holds that the Ancestral and Laramide structures are the result of thrusting in two directions in a belt of horizontal compression (Boos and Boos 1957, p. 2673; Sales, 1968). Recent regional analyses and model studies by Sales (1968) have shown that all the major tectonic features of the Rocky Mountain region can be accounted for by horizontal compression caused by the Pacific block being driven under the North American craton along a megashear. The basic differences in the Canadian, United States, and Central American segments of the Cordillera are accounted for by the manner with which the stress from the west was resisted by the crust to the east of the Cordillera. An east-west couple was set up in the western United States between the stable Canadian craton and the relatively plastic Gulf Coast region. Crustal shortening in the Front Range-Denver Basin area was transferred to the Texas craton by left lateral yield along the Wichita lineament. The local configuration of the deformation was strongly controlled by isostasy and gravity tectonics.

Some investigators believe that both mechanisms were active during the deformation period. Hudson (1969, p. 283) concluded from a study of faulting and joint patterns in Precambrian and Paleozoic rocks of the Bighorn Mountains in Wyoming that early Laramide deformation was compressive and that vertical uplift predominated in the later stages.

Prevolcanic Structure

The thesis area lies in a region of mobility that has undergone repeated periods of deformation since the Precambrian. In High Park and the Bare Hills, the Morrison Formation rests directly on Precambrian rocks, indicating that uplift and erosion stripped away the Paleozoic rocks prior to Jurassic deposition. In the Oil Creek embayment, however, the Paleozoic formations escaped erosion suggesting that the Oil Creek structure was also a graben during the Ancestral uplift. The presence of only Ordovician and Pennsylvanian strata to represent the Paleozoic era, as well as unconformities between the Ordovician formations, attests to earlier periods of deformation.

Major structural units in the study area are the Cripple Creek arch, the Oil Creek graben and its northward extension along the Fourmile Creek - Oil Creek fault zone, and the Rice Mountain horst of Boos and Boos (1957, p. 2668). The Cripple Creek arch is the southern extension of the Colorado Front Range and is bounded on both sides by north-trending, high-angle, reverse faults. The Rice Mountain horst is the northern extention of the Royal Gorge arch and is bounded by high-angle, broadly-curving, reverse faults which trend east to northeast. The Oil Creek graben is a v-shaped structural re-entrant at the head of the Canon City embayment and is bounded on the east by the western fault boundary of the Cripple Creek arch and on the west by the eastern fault boundary of the Rice Mountain horst (Boos and Boos, 1957, p. 2669).

In the area under investigation, the western boundary of the Cripple Creek arch is formed by a series of high-angle, step-down faults between the Cooper Mountain fault of Boos and Boos (1957, p. 2668) and the Oil Creek fault of Cross (1894). These faults trend north-northwest through the thesis area from sec. 27, T.16S., to sec. 2, T.15S., R.70W. and are termed, along with newly discovered faults, the Fourmile Creek - Oil Creek fault zone. The narrow steps dropping down to the graben are locally capped by remnants of nearly flat Palezoic beds which dip steeply westward adjacent to the faults.

The western boundary of the Oil Creek graben is the Twin Mountain fault (Boos and Boos, 1957, p. 2669), which disappears under graben-fill sediments in the thesis area. Faults in the Rice Mountain area immediately south of the thesis area trend east-northeast and probably offset the Precambrian basement in the Oil Creek graben (Boos and Boos, 1957, p. 2669). Numerous small faults offset Palezoic strata in the Red Ridge area, Sec. 8-16, T.16S., R.70W.; some of these faults are pre-Pennsylvanian in age and some are Laramide or younger.

Post-volcanic Structure

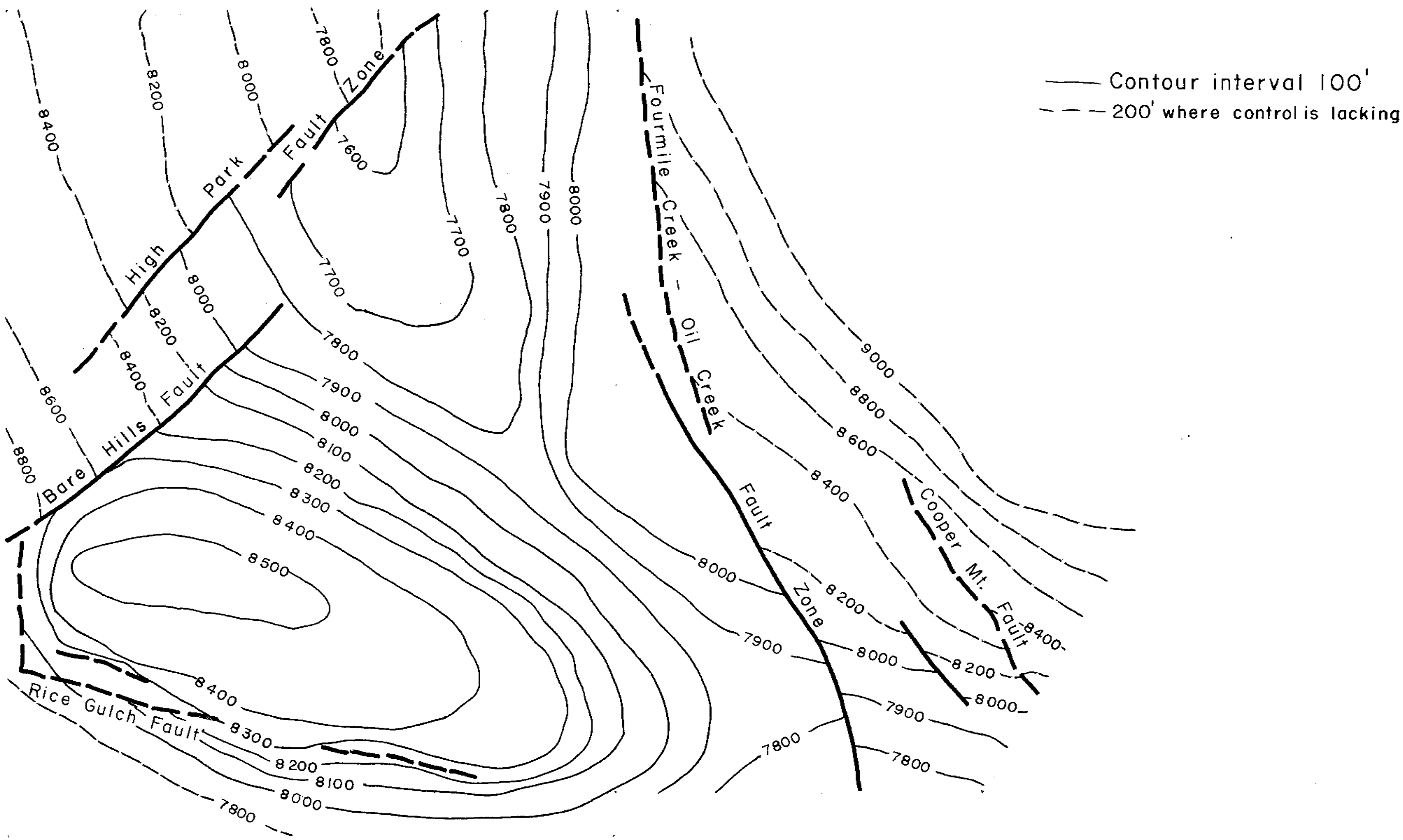
Structural deformation which began after the onset of volcanic activity in the Thirtynine Mile and Cripple Creek volcanic fields is termed post-volcanic for the purposes of this study. In the Bare Hills area, post-volcanic faulting was largely controlled by local northeast-trending shear zones in the Precambrian rocks. These fault zones characteristically contain small slivers of rocks belonging to the Morrison and Dakota Formations. Post-volcanic faulting in the Victor and Oil Creek areas was also influenced by pre-existing faults, however these trend north-northwest. Koschmann (1947, 1960) reports that structural control of the Cripple Creek cauldron was mainly along pre-existing north-northeast zones of weakness and that the mineralized veins are both parallel to and at right angles to the walls of the caldera. Re-entrants of the subsided basin with east-west and north-northeast trends also serve as points of localization for the gold telluride deposits.

Figure 10 is a structure contour map drawn on the base of the ash flow - 1 cooling unit which was deposited on a pre-volcanic erosion surface of low relief (Chapin and Epis, 1964, p. 147). The basin structure of High Park and the domed aspect of the Bare Hills may be easily seen from the figure. It is also evident that the Victor area has undergone considerable post-volcanic uplift with respect to the High Park and Mitre Peak areas. These features have resulted from activity along the following faults and fault systems:

1) High Park fault zone

2) Bare Hills fault and Rice Gulch fault

3) Fourmile Creek - Oil Creek Fault zone



Contour interval 100'
200' where control is lacking
Fourmile Creek - Oil Creek Fault Zone
Cooper Mt. Fault
High Park Fault Zone
Bare Hills Fault
Rice Gulch Fault
9000
8800
8600
8400
8200
8000
7900
7800
7700
7600
8500
8300
8100

High Park fault zone

High Park is a v-shaped graben bounded on the west by the High Park fault zone, secs. 24-33, T.15S., R.71W., and on the east by the Fourmile Creek - Oil Creek fault zone, secs. 4-20, T.15S., R.70W. The High Park fault zone is marked by northeast-trending, nearly vertical faults which are geomorphically expressed by reddened and subdued topography in the Precambrian rocks. Shearing is commonly parallel to the foliation of included lensoid bodies of sillimanite and biotite schists. The fault zone contains sheared slivers of the Morrison Formation of Jurassic age; lineaments on aerial photographs suggest that the fault zone is made up of a series of subparallel segments. Slivers of Precambrian granite upthrown into the breccias of the lower andesite indicate that some movement followed deposition of that unit.

Bare Hills and Rice Gulch faults

The Bare Hills are a horst-like structural unit bounded on the northwest by the Bare Hills fault, secs. 3-8, T.16S., R.71W.,; on the west by a small fault in sec. 20, T.16S., R.71W.; and on the south by the Rice Gulch fault in secs. 21-23, T.16S., R.71W. The faults may be recognized on aerial photographs as lineaments; in the field they are marked by subdued topography, reddening of the Precambrian granite, and by upturning and shearing of the Morrison and Dakota Formations. The ash flow - 1 cooling unit is offset more than 250 feet in some localities and is steeply tilted in sec. 21.

Prior to post-volcanic faulting, the Bare Hills area was a basin in which a thick sequence of arkosic and volcanic conglomerates accumulated. Now the basin fill deposits are topographically high and dip northward into the High Park basin. Lower volcanic conglomerate which was deposited in a channel draining southeastward from the Cap Rock Ridge area (Epis and Chapin, 1968, p. 63) is now at least 150 feet lower than the old Bare Hills basin into which it drained. Vertical uplift in the Bare Hills may be related to faulting or to doming associated with the rise of magma beneath the Bare Hills volcanic center, or both.

Fourmile Creek - Oil Creek fault zone

Post-volcanic uplift of 1000 to 1400 feet in the Victor area with respect to the High Park and Mitre Peak areas is presumed to have taken place along reactivated Laramide faults of predominant north-northwest trend. The extension of the Oil Creek fault zone through sec. 4-20, T.15S., R.70W., passing just east of Booger Red Hill shows up as a prominent lineament on aerial photographs and the combined fault system will be called in this study the Fourmile Creek - Oil Creek fault zone. The aligrment of the Oil Creek graben, High Park, and to the north of the thesis area, the Alnwick and Florissant basins plus the existence of a prominent excarpment along their east sides suggests that the Fourmile Creek - Oil Creek fault zone extends northward as far as Florissant.

GEOLOGIC HISTORY

Prevolcanic History

A thick sequence of clastic sediments and interbedded volcanic rocks was deposited in central Colorado during Precambrian time (Peterman, and others, 1968, p. 2277). In the course of two or more orogenies, regional metamorphism produced rocks of varying rank. A whole rock Rb-Sr age of 1.8 billion years for the last metamorphic event was obtained by Hedge and others (1967, p. 551).

A long period of emergence and erosion preceeded the deposition of the first Paleozoic sediments in the thesis area. Seas began to advance into Colorado in the late Cambrian but they transgressed very slowly across the Sierra Grande highland in south central Colorado (Berg, 1960, p. 10) so that the first sedimentary unit deposited in the study area was the Manitou Dolomite of Lower Ordovician age. Lack of clastic material in the Manitou indicates that the region was either completely submerged or of very low relief. A slight uplift took place at the end of Manitou time and post-Manitou - pre-Harding erosion and channeling took place (Gerhard, 1968, p. 2271). The shaly sands of the Harding Formation suggest that the uplifted source area was probably of low relief. Renewed uplift and erosion occurred after deposition of the Harding. Following resubmergence of the area, the Fremont Limestone was deposited in shallow seas favorable for the growth of corals and other quiet water organisms.

Nothing is known of the depositional record in the study area from the end of the Ordovician to the Pennsylvanian period. If sediments were deposited they were removed by subsequent erosion.

In late Mississippian or early Pennsylvanian time, orogenic activity associated with the Ancestral Rockies commenced (Kaun and Kent, 1965) and debris resulted from erosion of these highlands accumulated in the Oil Creek graben as the Fountain Formation. Erosion was again the dominant force in the region from the time deposition of the Fountain ceased until the upper Jurassic when the terrigenous sandstones, siltstones, and mudstones of the Morrison Formation were deposited. This erosional period beveled most of the study area and allowed the Morrison to be deposited directly on the Precambrian basement everywhere in the thesis area except in the Oil Creek graben, where down-dropped blocks of the Paleozoic formations were preserved.

Laramide orogenic activity beginning in late Cretaceous time resulted in regional uplift of central Colorado and formation of the Front Range and other high lands. Subsequent erosion carved a regional surface of moderate relief between the Laramide uplifts (Epis and Chapin, 1968, p. 56) and stripped away most of the Paleozoic and Mesozoic sedimentary veneer in the thesis area. Topographic lows on the surface were filled by material derived from the erosion of basement rocks. Such deposits are found in the Cottonwood Creek area (Epis and Chapin, 1968, p. 59) and in the High Park area of the present study.

Volcanic History

The presence of this erosion surface, which beveled topography produced by Laramide faulting, allowed the earliest volcanic material, the ash flow - 1 cooling unit of the Thirtynine Mile Field, to be emplaced throughout most of the study area. This ash-flow unit spread laterally from an unknown vent area across the erosion surface and filled meandering valleys on that surface (Epis and Chapin, 1968, p. 57). Outcrops of the unit have been identified in the Victor area as well as 50 miles to the west in the Salida area (Lowell, 1969, personal communication) and 20 miles to the north in the Florissant area (Niesen, 1969, personal communication). A K/Ar date of 40.0 ± 1.2 million years or earliest Oligocene has been reported for the ash flow - 1 cooling unit by Epis and Chapin (1968, p. 52).

Eruption of the ash flow - 1 cooling unit was followed closely by eruption in the Cripple Creek area of at least two latitic ash flows which marked the beginning of volcanism in that area. Eruption of these ash flows may have started subsidence of the Cripple Creek cauldron, as thick stratified deposits of sandstone similar to the lower conglomerate (grits of Cross and Koschmann) have been reported from deep within the cauldron (Koschmann, 1960, p. 186).

A period of erosion then ensued and the ash-flow sheets were largely stripped away. Small remnants were left along the sides of paleovalleys and more extensive remnants were preserved in the larger basins where deposition of the lower volcanic conglomerate mantled the ash flows. Detrital products of this erosional cycle accumulated in basins in the High Park, Bare Hills and Victor areas and in meandering valleys throughout the volcanic field (Epis and Chapin, 1968, p. 62-63). The presence of well-rounded quartzite boulders of unknown derivation in the High Park deposits indicates the presence of a major through-going drainage system. The southeasterly direction of flow and the presence of lithologically and stratigraphically similar deposits in the Alnwick and West Fourmile creek areas suggests that this may have been the drainage for the South Park basin. Material of predominantly local derivation in the conglomerates of the Bare Hills and Victor areas indicates that these basins were not on the main drainage but were fed detritus by local tributaries.

Following this period of erosion and aggradation of basins, volcanism was renewed in the Thirtynine Mile field. An enormous sheet of andesitic breccias was erupted from many small, randomly-scattered, vents (Chapin and Wyckoff, 1968), one of which is located in the High Park area (sec. 25, T.15S., R.71W.). The upper member of the lower andesite (not present in thesis area) has been dated by K-Ar methods at 34.1 ± 1.1 million years (Epis and Chapin, 1968, p. 52). That much of the previous volcanic material had been removed by erosion is evident from the fact that some basal lahars in the lower andesite contain up to 85% granitic fragments picked up from the terrain over which they swept. Eruptions of pumice lapilli tuffs were also occurring at local vents in the Bare Hills and material from these vents mixed with the laharic breccias. Finely-laminated pumice deposits of small areal extent were formed in the Bare Hills where ponding occurred along blocked drainages.

At some time following the eruption of the lower andesite, volcanic activity again commenced in the Bare Hills with the emplacement of necks and flows of trachytic composition. The continuing subsidence of the Cripple Creek cauldron was accompanied by the eruption of volcanic breccias of varying composition and phonolite domes and flows. The time relationship of these events is not positively known; however, the mineralogical and physical similarities of the trachyte of Bare Hills to the phonolite suggests that the eruptions were closely related in time and space. Activity in both regions consisted of the eruption of fissile flow rock accompanied by the emplacement of numerous small plugs and dikes.

Postvolcanic History

Renewed structural activity during (?) and after the volcanic interval took place along old Laramide faults and probably along new faults. The study area was divided into blocks separated by considerable relief when the basins of the Bare Hills and Victor areas were uplifted into their present topographically high positions. The age of these structural events is not known but may be Miocene (Eardley, 1963). The geologic history of the area since the last volcanic activity has been one of dominant denudation in which mass-wasting processes have played an important role.

CONCLUSIONS

Several important conclusions, which throw some light on the stratigraphic and structural relationships between the Cripple Creek volcanic center and the Thirtynine Mile volcanic field, may be drawn from the data accumulated during field and laboratory investigation of the rocks in the study area.

Onset of Volcanism

The oldest rocks in the study area related to the Cripple Creek volcanic center are ash-flow tuffs immediately overlying the ash flow - 1 cooling unit. This unit, the oldest volcanic rock in the Thirtynine Mile field, has been dated by K-Ar methods at 40.0 ± 1.2 m.y. (sanidine) (Epis and Chapin, 1968, p.52). More recently, outcrops in the Brown's Canyon fluorspar district north of Salida have been tentatively correlated with the ash flow - 1 sheet by Lowell (1969, personal communication). Van Alstine (1967, personal communication) has obtained K-Ar dates of 35.4 ± 1.1 m.y. (sanidine) and 37.3 ± 1.9 m.y. (biotite) for these rocks. Thus volcanism of the Cripple Creek center probably began between 35 and 40 million years ago in the early Oligocene.

Intravolcanic Period of Aggradation

At least two main periods of volcanism occurred at Cripple Creek and were separated by a period of erosion and aggradation of basins. Subsidence of the Cripple Creek cauldron probably commenced with eruption of the ash flow of Cripple Creek; the cauldron then served as a basin of aggradation during the ensuing erosional interval and received at least 2000 feet of arkosic and volcanic sediments (Koschmann, 1960, p. 186). Pebbles composed of the ash flow of Cripple Creek were found in arkosic grits on Grouse Mountain. These deposits are correlative with the High Park Lake Beds of Cross (1894), and the lower volcanic conglomerate (Epis and Chapin, 1968, p. 62-63) of the Thirtynine Mile field. Basin fill sediments correlated with the lower volcanic conglomerate consist primarily of locally derived material in the Bare Hills and Victor areas, whereas deposits of similar stratigraphic position in the High Park area contain a greater variety of rock types, including abundant boulders of quartzite and volcanic material not indigenous to the Thirtynine Mile field. Imbrication of boulders in the High Park deposits indicates a southeasterly direction of flow and conglomerates of similar lithology occur to the north in the Alnwick and West Fourmile Creek areas. This suggests that the South Park intermontane basin may have drained through High Park prior to volcanism in the Guffey area.

Cessation of Volcanism

The youngest rocks in the study area related to the Cripple Creek center are phonolite plugs and flows which intrude and overlie the lower member of the lower andesite of the Thirtynine Mile field. The upper member of the lower andesite has been dated at 34.1 ± 1.1 m.y. (whole rock) by the K-Ar method (Epis and Chapin, 1968, p. 52). No rocks in the study area were found to intrude or overlie the phonolite; thus, a minimum age for the volcanism at Cripple Creek has not been established.

The Bare Hills contain a minor volcanic center as suggested by Cross (1894); however, the bulk of Tertiary rocks exposed in the area are arkosic conglomerates and mudstones correlative with the lower volcanic conglomerate of the Thirtynine Mile field. Trachytic flows and intrusions of the Bare Hills are mineralogically and texturally similar to phonolites of the Cripple Creek center (both contain sodic feldspars, sodic ferromagnesian minerals, and primary analcite). They occupy similar stratigraphic positions and are probably related in time.

Postvolcanic Structural Activity

The Cripple Creek volcanic center was separated from the Thirtynine Mile field during late Tertiary, post-volcanic block faulting along the Fourmile Creek - Oil Creek fault zone. This fault zone is believed to extend northward from the Oil Creek graben through the High Park, Alnwick, and Florissant areas. The ash flow - 1 sheet occurs 1000 to 1500 feet lower in the High Park area than in the Victor area and 500 to 1000 feet lower than in the southern Bare Hills. Faulting along the west and south sides of the Bare Hills has raised and tilted that basin to its present high topographic position. Both structural adjustments may be related to late Tertiary rise of the southern Front Range and Royal Gorge blocks. Alternatively, doming related to rise of magma in the Cripple Creek and Bare Hills areas may have influenced the adjustments. The High Park area occupies a graben situated between these two uplifts and probably represents a northward extension of the Oil Creek graben.

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Appendix I

Optic axial angles, measured in degrees, of sanidine phenocrysts in the ash flow - 1 cooling unit and in the ash flows of Cripple Creek

Ash flow - 0.5

Sample T - 23 SE/4, NW/4, sec. 23 T. 16S., R. 70W. moderately welded 20 crystals 24 values	Sample T - 13 - 2 NW/4, SW/4, sec. 12 T. 16S., R. 70W. moderately welded 20 crystals 25 values	Sample T - 13 - 3 NW/4, SW/4, sec. 12 T. 16S., R. 70W. moderately welded 20 crystals 21 values
40	40, 48	41
42	40	41.5
40.5	38, 46.5	44.5
38	38	38.5
42.5, 45	36.5, 42.5	39
44.5	46	41
41	39	52
33, 43.5	40	40.5
34, 41.5	34	43.5
43	35, 47	42.5
36.5	46	46.5
40	40	32, 46.5
44.5	41	42
40.5	35.5, 45.5	31.5
38	42.5	42.5
40.5	40.5	37.5
41.5	43.5	49.5
37, 46	43	46
41.5	45	40
40.5	42	37.5

Ash flow – 1

Sample T – 27 SE/4, NE/4, sec. 17 T. 16S., R. 71W. moderately welded 20 crystals 20 values	Sample T – 34 SE/4, NW/4, sec. 36 T. 15S., R. 71W. moderately welded 20 crystals 22 values	Sample T – 35 SW/4, SW/4, sec. 25 T. 15S., R. 71W. moderately welded 20 crystals 20 values
40.5	42.5	39
34.5	35.5	37.5
35	31, 43	39
43	36	36.5
45.5	30	36.5
37	39, 52	34.5
33.5	39	40
35	42.5	36
38.5	31.5	38
34	29.5	32
42	36	34
48.5	33	39
38	40.5	36
32.5	41	45.5
33.5	41.5	34
37	40	36.5
33.5	38	40.5
33	43	41
44.5	33	41.5
36	34	32.5

Ash flow - 2

Sample T - 38
SW/4, SE/4, sec. 30
T. 15S., R. 70W.
moderately welded
20 crystals
21 values

40
32.5
31
32.5
27.5
37.5, 42
31.5
38
32.5
33
34.5
33
32.5
34
33
32
34
36
35
41.5

Ash flow - G

Sample T - 13 - 1 NW/4, SW/4, sec. 12 T. 16S., R. 70W. moderatley welded 22 crystels 24 values	Sample T - 14 - 2 NW/4, SW/4, sec. 1 T. 16S., R. 70W. moderately welded 23 crystals 24 values
34.5	34.5
30.5	33
36.5	36.5
46.5, 51.5	33.5
37, 44	33.5
36.5	35
34.5	37.5
37.5	32
35.5	36.5
31	35
32.5	34.5
35	37
33.5	32
37	34
29.5	35, 30.5
35.5	35
37	36.5
35	34.5
31.5	36.5
37.5	33.5
33	38.5
35.5	37.5
	35

Ash flow - S

Sample T - 2
SE/4, SE/4 sec. 36
T. 15S., R. 70W.
moderately welded
20 crystals
21 values

39.5
38, 47.5
45
39
40
39
38.5
38
38.5
45
41
25
40.5
36.5
34.5
42.5
37.5
36
39
37

Sample T - 24 - 2
NW/4, SW/4, sec. 1
T. 16S., R. 70W.
moderately welded
27 crystals
30 values

41
36.5
40
38.5
42
41
34.5
45
37
54
36.5
36
37.5
35.5
39.5
37
36, 46
39.5
40.5
35
39.5, 47.5
38.5
35
36.5
45.5
39.5, 46.5
39

Altered ash flows

Sample T - 1
SE/4, NE/4, sec. 36
T. 15S., R. 70W.
highly bleached and altered
21 crystals
21 values

46
48
54.5
52
47
46.5
46
48.5
47
46.5
48.5
50.5
52
47
47.5
56
47.5
48
51
50.5
49

Sample T - 5
SE/4, SW/4, sec. 36
T. 15S., R. 70W.
altered and bleached
17 crystals
17 values

38.5
51
42
42.5
40
40.5
44
45.5
38
40
41.5
42.5
43.5
40
44.5
40
42.5