General Geology of the Harold D. Roberts Tunnel, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 831-B

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ENGINEERING GEOLOGY OF THE HAROLD D. ROBERTS TUNNEL, COLORADO

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A review of the geologically complex area of the Front Range transected by the Roberts Tunnel

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GENERAL GEOLOGY OF THE HAROLD D. ROBERTS TUNNEL, COLORADO

By Charles S. Robinson, Lawrence A. Warner, and Ernest E. Wahlstrom

ABSTRACT

The Roberts Tunnel transects a geologically complex area in the Front Range of the Colorado Rocky Mountains. The area includes Precambrian igneous and metasedimentary rocks, Paleozoic and Mesozoic sedimentary rocks, and Tertiary igneous rocks. The structural history includes folding and faulting during Precambrian time and the Laramide orogeny.

The Precambrian rocks, which constitute about two-thirds of the area penetrated by the tunnel, consist of a sequence of metasedimentary rocks that were invaded by igneous rocks. The age relations among the metasedimentary rocks are still in doubt, owing to the complexity of the structure. These rocks are, from East Portal to West Portal, a sequence of amphibolite and related calc-silicate rocks, a migmatite unit, a microcline gneiss unit, a biotite gneiss and schist unit containing some amphibolite, a sillimanitic biotite gneiss and schist unit, and a hornblende gneiss unit.

The Precambrian metasedimentary rocks were intruded by granite of Precambrian age. The older granite, which is similar to the Boulder Creek Granite of other areas in the Front Range, is believed to have been emplaced at about the time of the metamorphism and plastic deformation of the Precambrian sedimentary rocks. The younger granite, which is similar to the Silver Plume Granite of other areas in the Front Range, is believed to have been intruded during a period of cataclastic deformation. Pegmatite and aplite of Precambrian age occur locally throughout the area.

Sedimentary rocks are exposed in the western quarter of the tunnel. These are the Entrada(?) Sandstone and Morrison Formation of Late Jurassic age, the Dakota Group of Early Cretaceous age, the Benton Shale of Early and Late Cretaceous age, and the Niobrara Formation and Pierre Shale of Late Cretaceous age. Underlying the sedimentary rocks exposed in the tunnel, and exposed to the west of the tunnel and intersected by drill holes along the tunnel line, are the Maroon Formation of Pennsylvanian and Permian age and the Lykins Formation of Permian and Triassic(?) age. These sedimentary rocks dip eastward toward the axis of the Front Range.

Early during the Laramide orogeny the Williams Range thrust fault developed, and Precambrian rocks were superimposed on the Pierre Shale along the fault. After the period of thrusting the Montezuma Quartz Monzonite stock was emplaced. The Williams Range thrust fault, as a result, was folded upward, and the tunnel intersects the fault zone at two places. Between the eastern exposure of the thrust and the Montezuma stock is a sequence of shale and siltstone that becomes more metamorphosed as the stock is approached. This sequence of shale and siltstone is believed to be equivalent, for the most part, to part of the Pierre Shale to the west of the Williams Range thrust.

Before and after the intrusion of the Montezuma stock, a series of dikes intruded the Precambrian units around the stock. The oldest dikes are augite and hornblende diorite. Other dikes contemporaneous in age and younger than the stock are latite porphyry and rhyolite porphyry.

The structural features recognized in the area were developed in Precambrian time and during the Laramide orogeny. The plastic deformation of the Precambrian metasedimentary rocks and the later cataclastic deformation were probably accompanied by jointing, but it was not possible to distinguish the joints formed in Precambrian time from those formed during the Laramide orogeny. The Laramide deformation resulted in the uplift of the Front Range, the development of the Williams Range thrust fault, and the development of the Front Range mineral belt. The mineral belt is a northeast-trending zone of faults, veins (with associated alteration), and igneous intrusions that extends diagonally across the range. The structural development of the mineral belt was in part controlled by the preexisting Precambrian structural features.

INTRODUCTION

The purpose of this chapter is to describe the general geology of the Harold D. Roberts Tunnel and the relation of the geology of the tunnel area to that of the region. The geology along the tunnel line was mapped prior to construction of the tunnel by E. E. Wahlstrom, and the geology of the tunnel during construction was mapped by L. A. Warner and V. Q. Hornback. Subsequent to the construction of the tunnel, the geology at the surface between the East Portal and the access shaft at Grant was remapped. This is an area of predominantly Precambrian rock, and the purpose of the remapping was to obtain additional detail on the Precambrian geology so that the surface geology could be related to that obtained in the underground mapping and to recent geologic mapping done in other parts of the Front Range. This remapping was done by Robinson with the guidance and advice of Warner and Wahlstrom, except for the area to the north and at the west end of the Montezuma stock, which was mapped by G. E. Ulrich

(1963) as part of an investigation for his Ph. D. thesis. The geology, as discussed in this chapter, is based primarily on the results of the surface mapping. Subsequent chapters will describe the geology of the tunnel in detail and the relation of the geology to the engineering practices.

The Roberts Tunnel passes beneath the Continental Divide at the crest of one of the most rugged parts of the Front Range. Relief is extreme along the tunnel line, with altitudes ranging from about 8,700 feet at the East Portal to more than 13,100 feet along the divide. The area has been extensively dissected by valley glaciers and torrential streams. The upper parts of the valleys are glacially scoured and terminate headward in steep-walled cirques. Valleys at lower altitudes are partially filled with glacial and fluvial deposits. High rolling areas above 10,000 feet are covered by blankets of mountaintop debris that has resulted from frost action and solifluction.

The area is relatively easily accessible. U.S. Highway 285 passes the East Portal and U.S. Highway 6 crosses the Dillon Dam about a mile north of the West Portal. Old mining and lumbering roads, still traversible by four-wheel-drive vehicle, follow most of the stream valleys to their headwalls and in some places climb to the divides.

Previous work in the area of the Roberts Tunnel includes that by Lovering (1935) in the Montezuma district, by Lovering and Goddard (1950) in the Front Range, and by Wahlstrom and Kim (1959) in Hall valley. Summaries of the geology of the tunnel area have been published by Wahlstrom and Hornback (1962) and Warner and Robinson (1967).

SUMMARY OF GENERAL GEOLOGY

The Roberts Tunnel transects a structurally complex area that is made up of Precambrian igneous and metasedimentary rocks, Paleozoic and Mesozoic sedimentary rocks, and Tertiary igneous rocks (pl. 1).

The Precambrian rocks, which constitute the area of the eastern two-thirds of the tunnel and the Williams Range thrust plate, are a sequence of metasedimentary rocks that have been intruded by two types of Precambrian granite and by Precambrian pegmatite and aplite. The metasedimentary rocks are divided into six units: a sequence of amphibolite and related calc-silicate rocks, a migmatite unit, a microcline gneiss unit, a biotite gneiss and schist unit containing some amphibolite, a sillimanitic biotite gneiss and schist unit, and a hornblende gneiss unit. The Precambrian igneous rocks are granitic rocks similar to the Boulder Creek and Silver Plume plutons.

The sedimentary rocks are of Mesozoic age and occur at the west end of the tunnel. They consist of the Entrada(?) Sandstone and the Morrison Formation of Late Jurassic age, the Dakota Group of Early Cretaceous age, the Benton Shale of Early and Late Cretaceous age, and the Niobrara Formation—which consists of the Fort Hays Limestone and the Smoky Hill Marl Members — and the Pierre Shale of Late Cretaceous age.

Igneous rocks of Tertiary age occur in the west-central part of the area. The largest of these igneous bodies is the Montezuma Quartz Monzonite stock. Intruded into the Precambrian rocks in the vicinity of the Montezuma stock are augite and hornblende diorite dikes believed to be older than the stock, latite porphyry dikes believed to be either older than or equivalent in age to the stock, and rhyolite porphyry dikes believed to be younger than the stock.

Surficial deposits of Quaternary age, which consist of morainal, glacial outwash, and fluvial deposits, occur along and in the stream valleys. These deposits have not been studied in any detail for the reason that they were not of significance in the engineering geology of the tunnel.

The geologic structure of the area is complex. At least two periods of Precambrian deformation are recognized. The older, a period of primarily plastic deformation, is believed to have been contemporaneous with the emplacement of the Boulder Creek Granite. The younger, primarily a cataclastic deformation, is believed to have been contemporaneous with the emplacement of the Silver Plume Granite. The next period of strong deformation (other than essentially vertical uplift) that can definitely be recognized is the Laramide orogeny. This deformation probably started with the uplift of the Front Range in latest Cretaceous or early Tertiary time and caused some of the folding of the sedimentary rocks. The uplift of the Front Range was probably followed by the formation of the Williams Range thrust fault, along which Precambrian rocks are superimposed on the Upper Cretaceous Pierre Shale. Igneous activity — the intrusion of the Montezuma stock and the dikes of the region — followed the development of the Williams Range thrust and was probably accompanied by some faulting. One or more periods of faulting occurred later than the emplacement of the igneous rocks. Some of these faults were mineralized to form veins. Jointing occurred during the Precambrian and Laramide periods of deformation.

Geologic structure is the most significant factor in the construction and design of a tunnel. For this reason, more emphasis has been placed in this report on structure than on any other geologic feature in the tunnel area.

PRECAMBRIAN ROCKS

Precambrian rocks occur along the eastern two-thirds of the tunnel route, north and south of the Montezuma stock, and in the Williams Range thrust plate (pl. 1). These rocks can be subdivided on the basis of their origin into metasedimentary rocks and igneous rocks. Mineralogically equivalent units have been mapped and studied in considerable detail by Harrison and Wells (1956, 1959), Sims and others (1963), Sims, Drake, and Tooker (1963), and Wahlstrom and Kim (1959) in the mineral belt north and south of the tunnel area.

METASEDIMENTARY ROCKS

The structural complexity of the area, as well as the limited area mapped, leads to some doubt as to the age relations of the metasedimentary rocks. These rocks, therefore, are described in the principal order in which they occur along the tunnel line from the East Portal westward. The rock units mapped in this order are amphibolite and related calc-silicate rocks, migmatite, microcline gneiss, biotite gneiss and schist and related amphibolite, sillimanitic biotite gneiss and schist, and hornblende gneiss.

The metasedimentary rocks in the Roberts Tunnel area and lithologically similar units in other parts of the Front Range have been referred to by a variety of names. Lovering and Goddard (1950, p. 19–21), using previously established nomenclature, included these rocks in two major units — the Idaho Springs Formation and the younger Swandyke Hornblende Gneiss. Wahlstrom and Kim (1959, p. 1220–1221) noted that the two sequences of layered rocks do not constitute formations in the usual sense and they suggested that intraregional correlations based on mineralogical similarities are probably in error. In describing the rocks of the Hall valley area, immediately south of the tunnel, Wahlstrom and Kim abandoned formation names in favor of letter designations, referring to a layered sequence predominantly of the Idaho Springs as the "A" series and to rocks corresponding to the Swandyke as the "B" series. They stated that the two series are separated by an angular unconformity.

In the work of Sims, Drake, and Tooker (1963) in the central Front Range, mineralogically similar units were named on the basis of their mineral composition. For example, their microcline-quartz-plagioclase-biotite gneiss is mineralogically similar to the microcline gneiss of this report. More recently, in the interest of brevity, simpler names have been used for rocks of the Front Range with the acknowledgment that minerals other than the ones named are present in significant amounts.

AMPHIBOLITE AND RELATED ROCKS

Amphibolite and related rocks crop out at the surface in discontinuous layers along the tunnel line from about station 1100+00 to the East Portal. At tunnel level these rocks are exposed at intervals between stations 1090+50 and the East Portal. Biotite gneiss and schist, migmatite, and bodies of Silver Plume Granite are interspersed with the amphibolite and related rocks.

This unit is equivalent to similar units in adjacent areas that were mapped by Lovering and Goddard (1950, pl. 2) as part of the Idaho Springs Formation. Regional reconnaissance suggests that these rocks are equivalent to one of the lime-silicate sequences of the "A series" of Wahlstrom and Kim (1959, pl. 4), as mapped by them to the southwest.

The amphibolite and related rocks weather out as lenticular knobs or ridges in an area of generally poor exposures. The unit is more resistant to weathering and erosion than the associated Silver Plume Granite and migmatite and commonly forms the outcrops in the heavily wooded area. The tunnel area has been intruded by numerous dikes and small bodies of Silver Plume Granite, and many of the outcrops of the amphibolite unit are inclusions within the granite, many too small to be shown at the map scale. There are really no large areas of amphibolite and related rocks that have not been extensively intruded by Silver Plume Granite. On plate 1 the areas shown as the amphibolite unit are those in which the bedrock has been estimated to consist of more than 50 percent of amphibolite and related rocks.

The contact of the amphibolite unit with the migmatite unit is believed — on the basis of the surface mapping — to be conformable and gradational. In nearly every underground exposure, a granitic dike occurs along the contact between the migmatite and the amphibolite unit, and the relations of migmatite and amphibolite are not clear. Around the amphibolite inclusions in the granite and between the granite dikes and bodies and the amphibolite unit is generally a layer of pegmatitic material. These layers of pegmatite have been attributed, by Warner and Robinson (1967, p. 98–100), to the differences in the expansion or contraction of the amphibolite and the cooling granite and to the physical-chemical changes in the granite as it cooled.

The amphibolite unit varies considerably in appearance and composition. Characteristically, it is

TABLE 1. — *Modes (volume percent) of varieties of rock in the amphibolite unit*

[Tr., trace. Leaders indicate looked for but not found]

Sample No.	1–CR60	2–CR60	5–CR60	8–CR60	10–CR60	14–CR60	15–CR60	20–CR60	1–CR61	2B–RD61
Microcline	6	....	....	....	....	....	1.2	2.3	....	3.5
Plagioclase	22	31	....	3.5	38	....	....	2.7	16	31
Quartz	18	Tr.	91	28	15	85	24	3.6	10	9
Biotite	....	....	....	....	....	....	....	....	....	11
Hornblende	22	65	....	65	....	....	....	35	38	40
Clinopyroxene	2.5	....	....	....	21	....	72	5	7	....
Epidote	1.2	Tr.	1.5	Tr.	21	....	....	....	13	1.3
Clinozoisite	....	....	....	....	....	....	2.7	16	....	....
Garnet	....	....	4.1	....	....	....	....	.9	....	....
Calcite	26	Tr.	....	Tr.	....	1.0	....	26	12	....
Tremolite	....	....	....	....	....	9	....	....	....	....
Sphene	2.4	....	....	2.0	2.4	....	....	7	1.8	....
Apatite	Tr.	.8	Tr.	Tr.	Tr.	....	Tr.	1.4	Tr.	1.7
Zircon	Tr.	Tr.	....	Tr.	....	Tr.	Tr.	....	....	Tr.
Opaque[1]	Tr.	2.8	3.4	Tr.	2.4	4.8	Tr.	Tr.	1.6	.5

[1]Predominantly magnetite.

DESCRIPTION OF SAMPLES

1–CR60. Calc-silicate gneiss. 1-ft-wide layer between layers of hornblende-plagioclase gneiss on nose on north side of Whiteside Gulch, about 500 ft above Geneva Creek.
2–CR60. Hornblende-plagioclase gneiss. From layer adjacent to sample 1–CR60.
5–CR60. Garnetiferous quartzite. From 50-ft-wide layer of banded quartzite (interlayered quartzite and garnetiferous quartzite) on southwest side of Whiteside Gulch, about 1,000 ft above Geneva Creek.
8–CR60. Quartz-rich amphibolite. 30-ft-wide layer of amphibolite west of head of Whiteside Gulch, about 1,150 ft above Geneva Creek.
10–CR60. Pyroxene gneiss. 5- to 10-ft-wide layer on ridge between Icy and Frenchman Gulches, at an altitude of 10,000 ft.
14–CR60. Quartzite. Outcrop of quartzite, 75–100 ft long and 20–30 ft wide, surrounded by pegmatite on knob, at an altitude of 10,200 ft, between Icy and Frenchman Gulches.
15–CR60. Pyroxene gneiss. Interlayered quartzite and pyroxene gneiss in small outcrop surrounded by migmatite and granite southwest of saddle between north branch of Callahan and Icy Gulches.
20–CR60. Marble. 5- to 10-ft layer of impure fine-grained marble in interlayered hornblende and pyroxene gneiss, in outcrop about 25 ft northeast of contact with granite, east of saddle between north branch of Callahan and Icy Gulches.
1–CR61. Calc-silicate gneiss. Outcrop 50–75 ft long, 10–25 ft wide about 1,000 ft west of triangulation point 10,205, between Callahan Gulch and the North Fork South Platte River.
2B–RD61. Hornblende-biotite-quartz-plagioclase gneiss. 100-ft inclusion in granite at top of cliff 1,500 ft north of the North Fork South Platte River and 2,750 ft northeast of Webster.

light to dark greenish gray, brownish gray, or black. Most layers contain some interlayered calcite, which has dissolved out on weathering to give the rock a rough and seamed appearance. In general, the rocks are fine to medium grained. Mineralogic layering is distinct, and the layers range in width from less than a millimeter to several centimeters.

Amphibolite, the dominant rock type, occurs in layers, a few feet to several tens of feet thick, that are well to poorly foliated. Some layers contain more than 65 percent yellow-green pleochroic hornblende, which, in places, is partly altered to chlorite. Plagioclase, ranging in composition from about An_{30} to An_{45}, is the only other major constituent present in all of the samples studied. Quartz, microcline, biotite, clinopyroxene, and epidote are locally abundant. The major accessory minerals are apatite, sphene, and magnetite.

Calc-silicate layers containing as much as 70 percent clinopyroxene (probably diopside) locally dominate the sequence. Most are massive, but some are distinctly banded and might be termed "pyroxene-plagioclase gneiss." Calcite is generally present, and small discontinuous lenses of marble occur sparingly. Scapolite is an important constituent in some of the more calcareous layers. Garnet, epidote, and amphibole (hornblende or tremolite) are locally abundant. Quartz and feldspar are generally sparse, and biotite was not observed.

Layers that contain 85–90 percent quartz (biotitic quartzite) are commonly associated with the calc-silicate members. Biotite-rich layers of schist and migmatite, from a few to several feet thick, occur sparingly throughout the sequence.

Table 1 lists modal analyses of samples collected from the surface and illustrates the variety of rocks in the amphibolite unit. Tables 1–9 and 11 and 12 give the modes, in volume percent, of the samples studied. In these tables the percentages greater than 5 percent are reported to the nearest percent; percentages from 0.5 to 4.9 percent are reported to the nearest 0.1 percent; and those which are less than 0.5 percent are reported as a trace.

MIGMATITE

On both sides of the amphibolite unit there is a sequence of schistose rocks that is rich in biotite and that contains numerous layers and lenses of granitic material. The granitic material varies greatly in abundance; in places it comprises thick sill-like bodies of pegmatite and aplite. Much of the unit consists of thin layers of biotite-rich and feldspar-rich material. It is convenient to refer to the entire sequence as migmatite, although, in places, the rock grades into biotite gneiss or schist that contains little or no granitic material. A few thin layers of amphibolite are present in the sequence.

This unit is not within the area mapped by Lovering and Goddard (1950, pl. 2), but they considered similar units in adjacent areas to be part of the Idaho Springs Formation. An equivalent unit to the south in Hall valley was classified by Wahlstrom and Kim (1959, pl. 4) as migmatite.

The migmatite unit is, in general, poorly exposed at the surface. The best exposures are along the northeast side of Geneva Creek, on the ridge between Geneva Creek and the North Fork South Platte River, and on the ridge between Frenchman and Icy Gulches. This part of the surface over the tunnel line is heavily forested, and outcrops are few. Adding to the difficulty in mapping is the fact that the unit has been intruded by numerous dikes and irregularly shaped bodies of Silver Plume Granite, pegmatite, and aplite. These granitic rocks, which are more resistant to weathering than the biotite schist and gneiss of the migmatite, form most of the outcrops of the area; float from these granitic rocks commonly masks the migmatite. Some of the migmatite bodies occur as lenses in larger masses of granitic rock.

The contact of the migmatite and the microcline gneiss to the northwest is nowhere clearly exposed. In most of the area, it may be located within a few feet on the basis of float, and it appears to be gradational, with conformable layers of microcline gneiss alternating with layers of biotite schist of the migmatite. A lens of biotite schist migmatite about 300 feet long and 50 feet wide occurs in the main mass of microcline gneiss about 1,500 feet north of the tunnel line just west of station 1000+00.

The migmatite unit varies widely in appearance and ranges from dark-gray, medium-grained biotite schist to light-gray fine-grained granite gneiss. The composition and appearance of the rocks of this unit are dependent upon the composition of the original rock and the degree of migmatization. Field evidence indicates that the original metasedimentary rock was predominantly biotite-quartz-plagioclase schist and sillimanitic biotite-quartz-plagioclase schist or gneiss interlayered with biotite-quartz-plagioclase gneiss. Now, granitic material ranging from layers less than 1 mm thick to dikes many feet thick is interlayered with biotite-rich gneiss and schist layers. The smaller granitic layers — those less than 1 foot thick — are in general conformable to the foliation, although they pinch and swell and fold the schist on either side. The granitic bodies thicker than 1 foot generally crosscut the foliation.

The migmatite is in places much contorted by minor convolute folds. Its position between amphibolite to the east and microcline gneiss to the west (pl. 1) suggests that in deformation the migmatite assumed the role of an incompetent unit between the relatively competent amphibolite and microcline gneiss units.

Microscopically, the minerals show the effect of shearing. The biotite, which is usually partly altered to chlorite, and the sillimanite, which is partly altered to muscovite, have streaked out along the foliation. Quartz and microcline have crushed and broken along their grain boundaries and are cut by microshears, which in general are parallel to the foliation. Microcline and quartz show graphic intergrowths along common boundaries. Locally, the microcline and plagioclase show perthitic intergrowths at their boundaries. The plagioclase grains, which are generally untwinned and show sericitic alteration along the grain boundaries and cleavage planes, are bent and broken. The composition of the plagioclase ranges from about An_{20} to An_{35} and averages about An_{25}. Common accessory minerals are zircon, apatite, allanite, and opaque minerals. The grains range in maximum dimension from less than 0.1 to 2 mm and average 0.2 mm. Table 2 lists the modes of six typical samples of the migmatite unit, which were collected at the surface.

TABLE 2. — *Modes (volume percent) of samples from the migmatite unit*

[Average grain size 0.2 mm. Leaders indicate looked for but not found]

Sample No.	7–CR61	9B–CR60	13–CR60	16–CR60	18–CR60	23–CR60
Microcline	......	5	23	23	13	19
Plagioclase	0.3	.6	16	.6	10	20
Quartz	23	63	43	25	30	40
Biotite[1]	48	18	13	24	26	17
Muscovite	1.6	2.4	4.5	3.7	5	1.5
Sillimanite	25	12	......	22	15	.6
Accessory minerals[2]	2.1	.5	1	2.5	.7	.8

[1]Includes biotite altered to chlorite.
[2]Apatite, zircon, allanite, and opaque minerals.

DESCRIPTION OF SAMPLES

7–CR61. Biotite-sillimanite schist. Outcrop of schist in area of migmatite, about 1,200 ft north of tunnel station 1197+00.

9B–CR60. Biotite-sillimanite schist and interlayered granite. Laminated rock; layers of biotite-sillimanite and quartz alternating with layers of microcline-quartz; layers less than 1 to 5 mm wide. From 200-ft-wide layer of migmatite on divide between Icy and Frenchman Gulches.

13–CR60. Biotite gneiss. Fine-grained gneiss interlayered with granite. From north side of Icy Gulch, at an altitude of about 10,100 ft.

16–CR60. Biotite-sillimanite schist interlayered with granite. From north side of Frenchman Gulch, at an altitude of about 10,200 ft.

18–CR60. Biotite-sillimanite gneiss. Sillimanite knots in laminated biotite-quartz-feldspar gneiss. Knots average 3×10 mm. From outcrop in streambed of Frenchman Gulch, at an altitude of 10,100 ft.

23–CR60. Biotite gneiss interlayered with granite. From knob, at an altitude of 10,550 ft, between branches of Callahan Gulch.

MICROCLINE GNEISS

The microcline gneiss crops out principally southeast of Burning Bear Creek and northwest of Frenchman Gulch and the head of Callahan Gulch. The main part of this unit was exposed at tunnel level between about stations 1014+00 and 1078+00. Two layers, each about 200 feet thick, consisting

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mainly of microcline gneiss, were penetrated by the tunnel below and east of the Continental Divide (pl. 1). These layers contain a little more biotite and muscovite, and somewhat less microcline, than the main microcline gneiss unit and are intimately interlayered with biotite gneiss and schist.

The microcline gneiss was mapped by Lovering (1935, pl. 3) and Lovering and Goddard (1950, pl. 2) as granite gneiss and was considered by Lovering and Goddard (1950, p. 25) to be a metamorphosed granite probably related to the Boulder Creek Granite. Similar rocks noted elsewhere in the mineral belt include the granulite of Koschmann (1960, p. 1361–1362, 1368), the microcline-quartz-plagioclase-biotite gneiss of Moench, Harrison, and Sims (1962, p. 37–39), and the microcline gneiss of Sims and Gable (1964, p. 10–14); these workers believed these rocks to be of sedimentary origin.

The exposures of this unit are poor. Except for a few cliffs along Burning Bear Creek and the top of the 11,275-foot hill at about station 1020+00, the exposures are small isolated outcrops, and the relation of this unit with other units is difficult to observe at the surface. Underground, the contacts of the migmatite with the gneiss are conformable. Layers of microcline gneiss of nearly uniform thickness occur in the schistose rocks and were folded with them. In a few places thin plastic dikes of schist penetrated fractures in the gneiss. No discordant bodies of microcline gneiss were noted.

Along the north side of Burning Bear Creek, mapping indicates that dikes of Boulder Creek Granite intruded the microcline gneiss. About 5,250 feet south of tunnel station 1025+00, small bodies of Silver Plume Granite intruded the microcline gneiss. A contact between a body of Silver Plume Granite and the gneiss is exposed here on the northeast side of the 11,349-foot hill and shows in detail that thin dikes of aplitic Silver Plume Granite — the chilled border facies—intruded the microcline gneiss. Dikes of Silver Plume Granite and related pegmatite, from a few inches to several feet wide, also occur in the microcline gneiss in other areas.

Structural and lithologic relationships suggest that the microcline gneiss of this area was derived from a sedimentary rock. The outcrop pattern obtained in surface mapping suggests that the gneiss is a stratigraphic unit in the layered sequence of metasedimentary rocks.

The typical microcline gneiss is a gray or brownish-gray rock streaked with black. The streaking results from wide discontinuous lenses of biotite that range in width from less than 1 to about 3 mm. In general, the rock is medium grained and slightly porphyroblastic. The quartz, plagioclase feldspar, and biotite are about equal in grain size and range in maximum dimension from less than 1 to about 3 mm. The microcline forms porphyroblasts that range in length from 1 to 40 mm. Locally, the rock is fine grained and aplitic. Near its northern contact with the biotite schist of the migmatite, the microcline gneiss is coarser grained and contains the largest porphyroblasts.

Microscopic examination shows that the microcline gneiss consists of anhedral grains of about equal proportions of microcline, plagioclase, and quartz, with a minor amount of biotite and a little muscovite. All the grains show considerable shearing with the shears healed with quartz. The plagioclase grains, which are both twinned and untwinned, are commonly bent and broken. Quartz and microcline are granulated along small shears that cut the grains and transect the grain boundaries. Perthitic intergrowths of microcline and plagioclase occur along their common boundaries. Quartz and microcline show graphic intergrowths, and quartz and plagioclase show myrmekitic intergrowths. The plagioclase is usually dusted with sericite; it ranges in composition from about An_{20} to An_{30} and averages about An_{25}. Much of the biotite has been partially to completely altered to chlorite. The common accessory minerals are zircon, apatite, monazite, sphene, allanite, hematite, and opaque minerals. Table 3 gives the modes of five typical samples of the microcline gneiss collected at the surface. The average modal composition is similar to that of the granitic plutons of the area.

TABLE 3. — *Modes (volume percent) of samples of microcline gneiss*

[Average grain size 2 mm]

Sample No.	24–CR60	25–CR60	28–CR60	29–CR60	33–CR60
Microcline	27	34	35	41	29
Plagioclase (An_{20}–An_{30})	35	27	28	28	33
Quartz	32	33	32	26	31
Biotite[1]	3.5	3.7	3.9	3.0	6
Muscovite	.8	2.3	.4	1.3	.6
Accessory Minerals[2]	1.7	.3	.6	.5	.5

[1]Includes biotite altered to chlorite.
[2]Apatite, zircon, monazite, allanite, sphene, and opaque minerals.

DESCRIPTION OF SAMPLES

24–CR60. Biotite-quartz-plagioclase-microcline gneiss from small area of gneiss southeast of saddle between Icy and Callahan Gulches.
25–CR60. Sheared outcrop on north side of saddle between Icy Gulch and Burning Bear Creek.
28–CR60. Sheared outcrop on north side of head of Frenchman Gulch, at an altitude of about 10,700 ft.
29–CR60. From base of 100-ft-high cliff, at an altitude of about 11,000 ft, on southeast side of hill 11,275.
33–CR60. Ungranulated sample from within 300 ft north of Burning Bear Creek, at an altitude of about 10,100 ft.

BIOTITE GNEISS AND SCHIST

The biotite gneiss and schist unit was mapped along the tunnel line from the Montezuma shear zone on the northwest to the stock of Boulder Creek Granite to the southeast. Included as part of this unit are a few lenses of amphibolite and of schist and gneiss in the Boulder Creek Granite on the northwest side of Burning Bear Creek. In the tunnel the unit is exposed between stations 690+00 and 880+50.

The biotite gneiss and schist is equivalent to part of the Idaho Springs Formation as mapped by Lovering (1935, pl. 3). The mapping along the Roberts Tunnel line overlaps on the south the mapping of Wahlstrom and Kim (1959, pl. 4). Much of this unit Wahlstrom and Kim termed "unclassified migmatized rocks of the A series," but they concluded (p. 1229) that the original metasedimentary rocks were quartz biotite gneiss, quartz schist, biotite-sillimanite gneiss, and quartzite.

The structure of the unit precludes any estimate of its probable thickness. It is cut to the northwest by the Montezuma shear zone, to the southeast by the North Fork fault, and it has been complexly folded. It has been intruded by numerous granitic bodies, and its relation with the other metasedimentary rocks to the southeast was destroyed by the intrusion of the Boulder Creek Granite stock. The layers of microcline gneiss within this unit as noted underground (p. B6) would indicate that it is part of the conformable sequence of metasedimentary rocks.

Intrusions of granitic rock in the biotite gneiss and schist unit are numerous, which partly explains why Wahlstrom and Kim (1959, p. 1228–1229) considered the unit to be a migmatite. The larger intrusives of Silver Plume Granite occur in the western part of the unit; the largest one forms the body at Geneva Peak. To the southeast mappable bodies of Silver Plume Granite are less abundant — possibly because of poor exposures — but granite and pegmatite dikes, a few inches to 25 feet wide, appear to be more abundant. Granitic material interlayered conformably with the foliation of the gneiss and schist is abundant throughout the unit. Wahlstrom and Kim (1959, p. 1228) attributed much of this material to metasomatism and local mobilization.

The biotite gneiss and schist unit consists of a variety of metasedimentary rocks: biotite-quartz-plagioclase gneiss and schist, biotite-microcline gneiss, thin layers of hornblende-plagioclase gneiss, and quartzite. The characteristic rock, which probably constitutes about 75 percent of the unit exclusive of the amphibolite, is a fine-grained biotite-quartz-plagioclase gneiss that contains variable amounts of microcline, muscovite, and sillimanite. On weathered surfaces the rock is light gray, brownish gray, or dark gray, and on fresh surfaces it is gray to dark gray. The foliation is indistinct in the fine-grained gneiss but more distinct in the coarser grained biotite or sillimanite gneiss and schist. The compositional layers of the unit range in thickness from a few millimeters to about 20 feet.

Microscopic examination shows that the mineral grains are generally anhedral and, except where granulated, about equal in size. Cataclastic structures, particularly granulation of the quartz and feldspar grains along their boundaries, are conspicuous. Grain sizes range from less than 0.1 to 2 mm, and average size is about 1 mm. The plagioclase feldspar is generally untwinned and is dusted with sericite along cleavage planes and grain boundaries. The composition of the plagioclase, exclusive of the plagioclase of the amphibolites, ranges from about An_{15} to An_{35} and averages about An_{25}. The distribution of microcline is erratic. None of the Precambrian rocks, either the biotite gneiss and schist or the Silver Plume Granite, contains microcline for 1,000 feet at the surface and 4,000 feet at tunnel level to the southeast of the Montezuma stock. The alkali feldspar is nonperthitic orthoclase. Warner and Robinson (1967, p. 101) believed that the heat of the stock converted the microcline to orthoclase. Beyond the area of thermal effects from the stock, the microcline in the biotite gneiss and schist unit occurs in the quartzose and biotite-poor rocks and near the intrusive granitic bodies. Wahlstrom and Kim (1959, p. 1233) attributed the presence of microcline in an equivalent unit to migmatization. The biotite is in part altered to chlorite. The chloritic alteration, associated with fine-grained pyrite, is conspicuous in the area west of station 800+00. The sillimanite and muscovite are associated, and their relations are similar to those of the sillimanitic biotite gneiss and schist unit. Common accessory minerals in the biotite gneiss and schist unit are zircon, apatite, sphene, epidote, and opaque minerals, including magnetite and pyrite. Table 4 gives the modes of nine representative samples from the surface of the biotite gneiss and schist unit.

AMPHIBOLITE

Interlayered with the biotite gneiss and schist are lenses of amphibolite. These lenses are most abundant at the surface along the tunnel line west of station 800+00, although they occur — generally too small to be shown at the map scale — throughout the unit. The amphibolite lenses are conformable to the enclosing schist or gneiss, and the contact is usually gradational, although locally the contacts appear sharp. The lenses are lenticular and, except for the thicker ones, can be followed for only rather short distances.

TABLE 4. — *Modes (volume percent) of samples of biotite gneiss and schist*

[Average grain size 1 mm. Tr., trace. Leaders indicate looked for but not found]

Sample No.	35B–CR60	35D–CR60	45–CR60	51–CR60	55–CR60	67–CR60	70–CR60	80–CR60	85–CR60
Microcline	35	13	13	2.2	2.0	....	8	9	11
Plagioclase	19	11	16	24	24.8	41	18	10	34
Quartz	38	68	58	44	60	28	41	68	33
Biotite[1]	7	6	9	22	9	29	15	7	19
Muscovite	.5	1.2	1.8	2.9	3.9	....	4.4	4.4	2.4
Sillimanite	....	....	1.7	....	....	....	11	Tr.	.3
Accessory minerals[2]	Tr.	.5	1.5	.9	1.1	1.8	1.3	1.0	.9

[1]Includes biotite altered to chlorite.
[2]Apatite, epidote, zircon, allanite, sphene, and opaque minerals.

DESCRIPTION OF SAMPLES

35B–CR60. Fine-grained biotite-quartz-plagioclase-microcline gneiss from within 10 ft of contact with Boulder Creek Granite, about 2,000 ft north of tunnel station 953+00.
35D–CR60. Quartzite from about 1-ft-wide layer, in gneiss from which 35B–CR60 was taken.
45–CR60. Fine-grained biotite-quartz-plagioclase-microcline gneiss from knob 11,262, about 200 ft south of tunnel station 936+50.
51–CR60. Fine-grained biotite-quartz plagioclase gneiss from sheared outcrop 1,200 ft north of tunnel station 892+50.
55–CR60. Fine-grained biotite-quartz plagioclase schist from end of nose, 1,500 ft south of tunnel station 884+50.
67–CR60. Fine-grained biotite-quartz-plagioclase gneiss from ungranulated outcrop, about 800 ft south of tunnel station 752+00.
70–CR60. Altered fine-grained sillimanitic biotite-quartz-plagioclase schist from sheared outcrop, 2,400 ft south of tunnel station 741+50.
80–CR60. Biotitic quartzite, 6-ft-wide layer, between layers of biotite-quartz-plagioclase gneiss, on north side of Kirby Gulch at an altitude of about 11,800 ft.
85–CR60. Fine-grained biotite-quartz-plagioclase gneiss from ungranulated outcrop at west end of knob 12,880, on ridge trending northeast from Landslide Peak.

On weathered surfaces the amphibolite is gray, greenish gray, or black. The foliation is usually distinct, resulting from the orientation of the hornblende and biotite and from the segregation of the hornblende and biotite into layers that alternate with layers of plagioclase and quartz. The layers range in thickness from about 1 millimeter to about 1 foot. The amphibolite grades into the adjacent gneiss by a decrease in the amount of hornblende, or in the number of hornblende-rich layers, and by an increase in the amount of biotite and quartz.

In thin sections the amphibolite is seen to be fine to medium grained. The grains range in maximum dimension from less than 0.1 to 2 mm and average about 1 mm. The hornblende is generally subhedral to anhedral. The plagioclase is generally twinned, much more so than in the adjacent gneiss, and ranges in composition from about An_{35} to An_{45}. In general, the plagioclase appears to be less altered to sericite than in the adjacent rocks. The biotite is partially altered to chlorite in most sections. Accessory minerals are zircon, apatite, epidote, and opaque minerals. Table 5 lists the modes of three samples of amphibolite from the biotite gneiss and schist unit.

TABLE 5. — *Modes (volume percent) of samples of amphibolite of the biotite gneiss and schist unit*

[Average grain size 0.1 mm. Tr., trace. Leaders indicate looked for but not found]

Sample No.	63–CR60	72A–CR60	72B–CR60
Microcline	....	....	Tr.
Plagioclase	22	40	20
Quartz	18	3.1	27
Biotite[1]	42	6	34
Muscovite	.7	....	....
Hornblende	16	48	19
Accessory minerals[2]	.7	1.8	.5

[1]Includes biotite altered to chlorite.
[2]Includes zircon, apatite, epidote, and opaque minerals.

DESCRIPTION OF SAMPLES

63–CR60. Laminated biotite-quartz plagioclase gneiss and hornblende-biotite-plagioclase gneiss, laminae <1–5 mm thick. From 2-ft-wide layer, at an altitude of 11,600 ft, north of lakes on north branch of Bruno Gulch.
72A–CR60. Fine-grained amphibolite gneiss from layer above tunnel line on ridge southeast of Landslide Peak.
72B–CR60. Fine-grained biotite-hornblende-plagioclase-quartz gneiss from layer adjacent to, and gradational with, layer of 72A–CR60.

SILLIMANITIC BIOTITE GNEISS AND SCHIST

The sillimanitic biotite gneiss and schist crops out principally along the Continental Divide between the Snake River to the south and the head of Geneva Creek to the north, along the ridge between the forks of the Snake River, and south of the Snake River between Keystone Gulch and Jones Gulch. Equivalent rocks are exposed at tunnel level for only a short distance between about station 620+50 and station 630+50. Most of the interval at the tunnel level that is equivalent to the exposures at the surface is made up of the Montezuma Quartz Monzonite.

This unit is part of the Idaho Springs Formation as mapped by Lovering (1935, pl. 3). The unit is probably equivalent in part to the "A series," as mapped by Wahlstrom and Kim (1959, p. 1243) to the south, in the Hall valley area.

The contact of the sillimanitic biotite gneiss and schist unit with the biotite gneiss and schist unit is probably conformable and gradational. The area of contact is obscured by the Montezuma shear zone. West of the shear zone, layers of sillimanitic biotite gneiss and schist predominate over layers of biotite gneiss and schist; east of the shear zone, the opposite is true. The occurrence of sillimanitic layers in the biotite gneiss and schist unit and the general mineralogic similarity of the two units would indicate that the two units are gradational.

Granite (similar to the Silver Plume Granite), pegmatite, and aplite were intruded into the sillimanitic biotite gneiss and schist. The intrusives range in size from large irregularly shaped bodies, such as the one that forms the top of Santa Fe Peak, to dikes and sills a few millimeters thick.

The unit is composed predominantly of biotite-quartz-plagioclase gneiss and schist but is characterized by the presence of numerous layers of sillimanitic biotite-quartz-plagioclase gneiss, which generally can be found within a few feet in any direction. It is distinguished from the hornblende gneiss not only by the general presence of sillimanite but also by the general absence of hornblendic layers, except near its contact with the hornblende gneiss. Except for the abundance of sillimanitic layers, it would be equivalent to the biotite gneiss and schist unit.

The typical rock is dark gray, brownish gray, or greenish gray on weathered surfaces and light to dark gray on freshly broken surfaces. The foliation, the result of the concentration and the parallel alinement of minerals in layers, is generally distinct. Those layers containing little or no sillimanite are gneissic. As the amount of sillimanite and biotite increases, the rock becomes schistose. The foliation of the schistose rocks is usually crenulated by many microfolds.

Under the microscope the compositional layering is seen to be distinct. Layers of biotite and plagioclase alternate with layers of quartz-sillimanite-muscovite and, if present, microcline. The minerals are anhedral and equigranular. The grain size ranges from 0.1 to 1 mm; it averages about 0.2 mm. The quartz and feldspar locally show granulation along their grain boundaries, but this cataclastic structure is not as distinct as in the other metasedimentary rock units. The plagioclase, which is generally untwinned, typically is dusted with sericite along cleavage planes and at grain boundaries. The composition of the plagioclase ranges from An_{20} to An_{35} and averages about An_{25}. The sillimanite is commonly partially altered to muscovite, and, as a result, it is difficult to tell whether any of the muscovite was primary. The biotite is partially to completely altered to chlorite. Common accessory minerals are zircon, apatite, epidote, calcite, and opaque minerals. Table 6 lists the modes of five varieties of the sillimanitic biotite gneiss and schist unit.

TABLE 6. — *Modes (volume percent) of samples of the sillimanitic biotite gneiss and schist unit*

[Average grain size 0.2 mm. Tr., trace. Leaders indicate looked for but not found]

Sample No.	15–CR61	17–CR61	13–CR62	14–CR62	17–CR62
Potassium feldspar	1.3	14	6	Tr.	3.1
Plagioclase	6	24	20	46	25
Quartz	5	24	32	35	38
Biotite[1]	40	25	24	18	18
Muscovite	3.6	7	4.5	....	7
Sillimanite	42	5	11	Tr.	8
Accessory minerals[2]	1.7	.3	2.6	1.5	.3

[1]Includes biotite altered to chlorite.
[2]Includes zircon, apatite, epidote, calcite, and opaque minerals.

DESCRIPTION OF SAMPLES

15–CR61. Biotite-sillimanite schist. From outcrop on section line south of Warden Gulch, at an altitude of 12,400 ft.
17–CR61. Biotite-sillimanite gneiss. Consists of alternating layers <1–5 mm thick of plagioclase-biotite-quartz and quartz-microcline-sillimanite. From outcrop on ridge that trends northwest from Santa Fe Peak, at an altitude of about 12,825 ft.
13–CR62. Sillimanitic biotite-quartz-plagioclase gneiss. From 150 ft southeast of Santa Fe Peak.
14–CR62. Biotite-quartz-plagioclase gneiss from outcrop 500 ft northwest of Santa Fe Peak.
17–CR62. Sillimanitic biotite-quartz plagioclase gneiss. From 50 ft southeast of where vein of Sarisfield mine crosses Collier Mountain.

HORNBLENDE GNEISS

The hornblende gneiss crops out along both sides of the Montezuma stock from about the longitude of Montezuma westward to the Williams Range thrust fault. This unit is lithologically similar to the Swandyke Hornblende Gneiss, as mapped by Lovering (1935, pl. 3) and named by him for exposures at the old town of Swandyke, on the Middle Fork Swan River about 5.5 miles south-southwest of Montezuma. More recently, Wahlstrom and Kim (1959, pl. 4) mapped similar rock as part of their "B series" in the area at the head of Hall valley, about 4 miles south-southeast of Montezuma. A more detailed subdivision into mineralogic units, such as the one made by Wahlstrom and Kim (1959, pl. 1, p. 1243–1244), was not attempted, because of the poor exposures and the limited area mapped.

The contact of the hornblende gneiss unit with the adjacent sillimanitic biotite-quartz-plagioclase gneiss and schist is not exposed, and the relationship of the two units could not easily be determined. The contact, as mapped about half a mile southeast of Montezuma, was based on limited float, and it could not be determined if this contact could be the unconformity between the "A" and "B series," as described by Wahlstrom and Kim (1959, p. 1221). The limited field evidence in this area indicates that the rock consists of alternating layers of the two units, for a distance of at least 1,000 feet on each side of the contact and that the contact is structurally conformable and gradational. This interpretation would agree with the interpretation of Lovering and Goddard (1950, p. 20) that the Swandyke Hornblende Gneiss was in part contemporaneous with, and in part younger than, the Idaho Springs Formation. Ulrich (1963), who mapped an area north of the Montezuma stock, also concluded that the sillimanitic biotite gneiss and the hornblende gneiss are conformable and gradational.

Granite (similar to that of the Silver Plume Granite), pegmatite, and aplite have intruded the hornblende gneiss locally. The intrusives range in size from unconformable stocks and large dikes to thin concordant dikes or sills a few millimeters thick, which locally gives this unit the appearance of the biotite gneiss and schist migmatite.

Megascopically, the hornblende gneiss unit is characterized by layers of hornblende gneiss and amphibolite, although, by volume, the largest percentage of the unit consists of biotite-quartz-plagioclase gneiss. Interlayered with these rock types are other mineralogic varieties, including biotite-hornblende-plagioclase gneiss, biotitic quartzite, and rocks intermediate to these types. Layers in the hornblende gneiss unit range in thickness from less than a millimeter to several meters. The amphibolite of this unit occurs in conformable layers, which are gradational with the adjacent mineralogic layers, and as crosscutting dikelike bodies that range in width from less than a foot to 20 feet and range in length from less than 10 to 500 feet. The amphibolite is distinguished from the hornblende gneiss by the general absence of quartz and the lower percentage of plagioclase feldspar.

The rocks of the hornblende gneiss unit are light gray to dark greenish gray on weathered surfaces. The foliation, which is the result of compositional layering and of parallel alinement of the ferromagnesium minerals and the feldspars, is distinct. Lineation is distinct in those rocks that contain megascopic biotite or hornblende. The rocks on fresh surfaces range in color from gray to dark green or black. The grain size ranges from less than 0.1 to 3 mm; it averages 0.3 mm.

Microscopically, the quartz and feldspar grains are seen locally to be crushed, particularly along their margins, and the biotite and hornblende grains are torn and stretched parallel to the foliation. The granulation and stretching of mineral grains is commonly visible megascopically. The feldspar, which is generally plagioclase feldspar only, ranges in composition from An_{20} to An_{40} and has an average composition of about An_{30}. It is generally untwinned or indistinctly twinned, except in the amphibolite, and the surfaces appear to be dusted with sericite. Most of the biotite and hornblende show partial to complete alteration to chlorite. Common accessory minerals are apatite, zircon, sphene, and opaque minerals (mostly magnetite and some pyrite). Table 7 lists the modes of seven samples of the hornblende gneiss unit.

TABLE 7. — *Modes (volume percent) of samples of hornblende gneiss unit*

[Average grain size 0.3 mm. Tr., trace. Leaders indicate looked for but not found]

Sample No.	26A–CR61	26B–CR61	8B–RD61	11–RD61	14–RD61	31C–RD61	38–RD61
Plagioclase	50	24	37	44	52	57	47
Quartz	44	2	....	32	39	4	38
Biotite[1]	4.6	20	12	22	8	....	14
Hornblende	....	52	50	....	....	39	....
Muscovite	.3	....	....	....	....	....	....
Epidote	....	1	....	....	.9	Tr.	....
Accessory minerals[2]	.7	.4	1.4	1.2	.5	.3	.4

[1]Includes biotite altered to chlorite.
[2]Includes apatite, zircon, sphene, and opaque minerals.

DESCRIPTION OF SAMPLES

26A–CR61. Biotite-quartz-plagioclase gneiss from outcrop about 650 ft south of tunnel station 587–50.
26B–CR61. Hornblende-biotite-plagioclase gneiss from same outcrop as sample 26A–CR61. Layers of hornblende-biotite-plagioclase gneiss alternate with layers of biotite-quartz-plagioclase gneiss; layers <0.1–3 ft thick.
8B–RD61. Hornblende-biotite-plagioclase gneiss from hornblendic layer in biotite-quartz-plagioclase gneiss about 10 cm thick. From outcrop on nose east of Burke-Martin mine, ½ mile southeast of Montezuma, at an altitude of 11,330 ft.
11–RD61. Biotite-quartz-plagioclase gneiss from interlayered biotite and hornblende gneiss; layers 2 mm to 1 m thick. From outcrop about 650 ft northwest of Equity mine, ⅓ mile south of Montezuma, altitude about 10,640 ft.
14–RD61. Biotite-quartz-plagioclase gneiss from interlayered biotite and hornblende gneiss; layers 1–50 mm thick. From outcrop about 450 ft southwest of Burke-Martin mine.
31C–RD61. Hornblende-quartz-plagioclase gneiss from outcrop of interlayered biotite- and hornblende-quartz plagioclase gneiss, layers <1 mm to 1 m thick. From outcrop about 2,200 ft due east of Hunkidori mine.
38–RD61. Biotite-quartz-plagioclase gneiss. From layered outcrop at contact of hornblende gneiss and Montezuma Quartz Monzonite, 2,400 ft northwest of Hunkidori mine.

IGNEOUS ROCKS

Irregularly shaped masses and dikes of Precambrian granite, pegmatite, and aplite are exposed in and along the tunnel. These masses—mineralogically, structurally, and in relative age — closely resemble those of the Silver Plume Granite and the Boulder Creek Granite exposed at other localities in the Front Range (Lovering and Goddard, 1950, p. 25–29). Recent workers in the Front Range (Harrison and Wells, 1959, p. 12–19; Moench and others, 1962), because of the genetic implication of the names Boulder Creek Granite and Silver Plume Granite, have distinguished similar granitic masses on the basis of their mineralogic classification as granodiorite or quartz monzonite and biotite-muscovite granite. For this report, however, the names Boulder Creek Granite and Silver Plume Granite are retained for descriptive purposes; however, a genetic relationship to all other bodies similarly classified is not intended.

BOULDER CREEK GRANITE

The Boulder Creek Granite crops out in the area between Burning Bear Creek and Bruno Gulch and on the north side of Bruno Gulch. This is part of a small body of about 3 square miles in extent that crops out from the head of Burning Bear Creek northward to Geneva Creek, just north of the mapped area. It is probably related to a larger body in the vicinity of Mount Evans (Lovering and Goddard, 1950, pl. 2), about 5 miles to the northeast. At the surface the mass is virtually separated into two segments by a thick septum of biotite gneiss and schist. At tunnel level the granite is exposed approximately between stations 880+50 and 975+00, and the septum at the surface is represented by a zone of large tabular inclusions between about stations 910+00 and 950+00.

The Boulder Creek Granite is the oldest of the Precambrian igneous rocks of the tunnel area. It cuts the enclosing metasedimentary rocks and has many inclusions of metasedimentary rocks, and it is, in turn, cut by dikes of Silver Plume Granite.

The exposures of the Boulder Creek Granite stock at the surface are few, except along the southeast side of Bruno Gulch. The dikes of Boulder Creek Granite in the metasedimentary rocks that surround the stock crop out conspicuously, for the granite is more resistant to weathering than the metasedimentary rocks.

On the west side of the stock, the contact of the Boulder Creek Granite and the biotite gneiss and schist unit is apparently sharp, and there is little interfingering or injection of granitic material of the stock with the metasedimentary rocks. The contact is rarely exposed, but at most places it can be located — on the basis of float — to within a few feet. On the east side of the stock, the contact is much more indefinite. Dikes and irregularly shaped bodies of Boulder Creek Granite intrude the metasedimentary rocks beyond the border of the stock, and inclusions of metasedimentary rock are common within the stock near its borders. A contact between biotite-quartz-plagioclase gneiss and a small body of Boulder Creek Granite is exposed on a small knob about 3,000 feet northeast of the tunnel line at station 932+50. At this point the contact is sharp, and the foliation of the granite and gneiss is conformable. For 6–12 inches from the contact, within the granite there are quartz veinlets 1–2 inches wide and biotite gneiss schlieren narrower than 1 inch. For 6–12 inches from the contact within the gneiss are conformable quartz and pegmatite stringers.

Dikes of Silver Plume Granite, and of pegmatite and aplite probably related to the Silver Plume Granite, cut the Boulder Creek Granite. The dikes range in width from a few inches to a few feet and are too small to be shown at the map scale. They are most abundant in the southeastern half of the stock and in the dikes of Boulder Creek Granite east of the stock. A large mass of Silver Plume Granite intruded the stock near the head of Burning Bear Creek and forms the south limit of the stock.

The Boulder Creek Granite is a medium- to coarse-grained locally porphyritic rock that consists predominantly of microcline, plagioclase, quartz, and biotite. In outcrop it weathers light gray or brownish gray, whereas on fresh surfaces it is light gray or light pinkish gray. Outcrops show a distinct foliation caused by the parallel orientation of biotite grains and biotite-rich aggregates. The microcline, which forms the phenocrysts in the porphyritic varieties, commonly is alined parallel to the biotite foliation. The microcline phenocrysts typically show simple Carlsbad twins. In some outcrops the quartz occurs in elongate rods oriented parallel to the foliation.

Under the microscope, a sample of the Boulder Creek Granite is seen to be composed of unequal-sized anhedral to subhedral grains of microcline, plagioclase, quartz, and biotite. The microcline grains are generally anhedral except where they form phenocrysts, which are usually subhedral. Grain size ranges from about 1 to 40 mm and averages about 3 mm. Simple twins are common. Some of the microcline is microperthitic and micrographic, and inclusions of red hematite are common. In the porphyritic varieties, the microcline phenocrysts are older than the plagioclase. The plagioclase is anhedral to subhedral and has an average grain size of about 3 mm. The grains are generally twinned (more so than is characteristic of the plagioclase of the enclosing metasedimentary rocks) and are dusted with sericite. The twins are commonly bent and broken. Some of the plagioclase grains show indistinct zoning. Intergrowths of plagioclase and microcline or quartz occur along their mutual boundaries. The anorthite composition of the plagioclase ranges from about An_{15} to An_{25} and averages about An_{20}. Quartz grains are anhedral and, in general, of smaller size than those of the feldspar; they average about 2 mm in diameter. Micrographic intergrowths of quartz and feldspar are common. The biotite, which is interstitial to the quartz and feldspar, occurs in anhedral to subhedral grains that are partially altered to chlorite. The blades of biotite are commonly bent and stretched in the direction of the foliation. The average length of the biotite grains is about 3 mm. Muscovite occurs in most thin sections in amounts of less than 2 percent. Accessory minerals, in euhedral to anhedral grains less than 1 mm in size, are apatite, zircon, monazite, allanite, and opaque minerals, principally magnetite.

Two varieties of Boulder Creek Granite were recognized in the surface and tunnel mapping. The eastern segment of the pluton at the surface is generally coarser grained than the western segment and is porphyritic and redder in outcrop as the result of the abundance of hematite inclusions in the microcline. Also, twinned microcline phenocrysts 10–40 mm long are commonly conspicuous. The modal analyses of the two varieties do not differ significantly, except that possibly the variety in the eastern segment, designated "type *A*" in the following table, contains

TABLE 8. — *Modes (volume percent) of samples of Boulder Creek Granite*

[Average grain size 3 mm. Tr., trace]

	Type *A* samples				Type *B* samples			
Sample No.	36–CR60	40–CR60	43–CR60	44–CR60	38–CR60	47–CR60	49–CR60	53–CR60
Microcline	32	24	39	47	32	41	26	38
Plagioclase	28	37	23	30	26	30	28	38
Quartz	34	34	34	18	40	20	43	24
Biotite[1]	2.6	4.1	2.7	3.5	2.8	6	.6	1.6
Muscovite	3.1	1.3	.6	.9	Tr.	1.6	2.1	Tr.
Accessory Minerals[2]	Tr.	Tr.	Tr.	.6	.5	1.2	Tr.	Tr.

[1]Includes biotite altered to chlorite.
[2]Includes apatite, zircon, monazite, allanite, and opaque minerals.

DESCRIPTION OF SAMPLES

36–CR60. Medium-grained sample from small outcrop 1,700 ft north of tunnel station 953+50.
40–CR60. Medium- to coarse-grained porphyritic sample from dike that cuts microcline gneiss, 3,400 ft north of tunnel station 968+00.
43–CR60. Medium- to coarse-grained porphyritic sample from sheared dike in biotite gneiss and schist outcrop 150 ft north of tunnel station 948+50.
44–CR60. Medium-grained porphyritic sample from dike in biotite gneiss and schist outcrop on the small knob 11,262, 200 ft south of tunnel station 937+00.
38–CR60. Medium-grained slightly porphyritic, moderately sheared outcrop, about 1,750 ft south of tunnel station 933+50.
47–CR60. Medium-grained slightly porphyritic sheared dike in biotite gneiss and schist, about 1,150 ft north of tunnel station 941+50.
49–CR60. Medium-grained equigranular outcrop of probable dike in biotite gneiss and schist, about 700 ft north of tunnel station 941+50.
53–CR60. Medium-grained quartz-rich variety from sharp knob about 100 ft north of tunnel station 911+00.

on the average more biotite and muscovite than does that of the western segment, designated "type *B*." The major difference is in the plagioclase, which averages An_{25} for type *A* and An_{15} for type *B*. Table 8 lists the modal analyses of eight samples of the Boulder Creek Granite.

SILVER PLUME GRANITE

The Silver Plume Granite is the most widely distributed of the Precambrian igneous rocks along the tunnel line. It, with associated pegmatite and aplite, occurs as dikes and irregular small bodies in the other Precambrian rocks throughout the area. Near the east end of the tunnel, the mapped area includes a part of the Kenosha batholith (Hutchinson, 1959; Badgley, 1960, p. 166), the main body of which lies to the southwest. The presence of the Silver Plume Granite in this area, and its correlation with the type area of Silver Plume, was first recognized by Lovering (1935, p. 14). Subsequently, Hutchinson (1960) and Badgley (1960) stated that the Kenosha batholith is older than the type Silver Plume and more nearly equivalent in age to the Boulder Creek Granite. The present authors agree with Lovering (1935), as shall be discussed in the section "Relative Age and Origin of the Precambrian Rocks" (p. B14).

The Silver Plume Granite, as well as the related pegmatite and aplite, is most abundant at the surface and at the tunnel level east of station 1080+00. Concordant and discordant dikes and irregularly shaped bodies are abundant in this area, and some of them may be traced directly back into the northeast end of the Kenosha batholith. The granite has intruded biotite gneiss and schist, migmatite, and the sequence of amphibolite and related rocks. Inclusions of the metasedimentary rocks in the granite are numerous, and small dikes (too small to be shown at the map scale) occur throughout the areas of the metasedimentary rocks. Most of the contacts of the granite with these rocks are sharp. Typically, a pegmatite layer occurs at the contacts of the granite and the amphibolite unit and around the inclusions of the amphibolite unit. The contacts of the discordant granite bodies with the migmatite are generally sharp, and there may be thin pegmatite or aplite border zones at the contact. The contacts of the concordant granite bodies are commonly gradational with layers of Silver Plume Granite alternating with layers of fine-grained biotite-quartz-plagioclase gneiss.

West of about station 1080+00 and east of the North Fork fault are numerous narrow dikes of Silver Plume Granite and pegmatite that are generally less than 5 feet wide. They cut the migmatite, the biotite gneiss and schist, the microcline gneiss, and the Boulder Creek Granite. Except in the migmatite, most of the dikes are discordant. The north end of a large mass of granite occurs near the head of Burning Bear Creek at the southwest edge of the mapped area, and numerous small bodies occur in the microcline gneiss east of this body.

From the North Fork fault west to the Montezuma stock are many irregularly shaped bodies and dikes of Silver Plume Granite. The dikes, particularly the pegmatitic dikes, are the most abundant for the first 5,000 feet west of the North Fork fault zone; then, larger and more even grained irregularly shaped bodies become the most abundant farther to the west. The contacts of the granite with the biotite gneiss and schist unit and the sillimanitic biotite gneiss and schist unit are generally sharp.

A few dikes and discordant bodies of Silver Plume Granite occur along the north and south margins of the Montezuma stock in the hornblende gneiss and the sillimanitic biotite gneiss and schist units; most of these bodies are too small to be shown at the map scale. Mappable areas occur in the vicinity of the Ida Belle mine (on Independence Mountain) and Jones Gulch, south of the tunnel line; in the vicinity of Porcupine Peak, north of the tunnel line; and between Frey Gulch and the North Fork Snake River, north of the tunnel line.

Underground, the distribution of the Silver Plume Granite and related pegmatite and aplite is similar to that at the surface. Dikes and irregularly shaped bodies are most abundant for about 15,000 feet west of the East Portal and for about 5,000 feet west of the North Fork fault zone. A few dikes occur in the Precambrian metasedimentary rock westward to the Montezuma stock.

The Silver Plume Granite is a slightly porphyritic, medium-grained, indistinctly foliated rock with an average composition of a quartz monzonite. In outcrop the rock weathers light gray, brownish gray, or reddish gray; on fresh surfaces it is generally light pinkish gray.

The primary foliation is the result of the subparallel arrangement of tabular microcline crystals. The biotite grains in the typical rock are not commonly oriented, but in some of the smaller bodies and near the borders of the larger bodies, or adjacent to inclusions within the larger bodies, the percentage of biotite increases, and the biotite is oriented parallel to the microcline foliation, imparting a distinct gneissic appearance. An apparent foliation is imparted to the rock locally by subparallel microscopic fractures, along which biotite may be streaked. These fractures, which are not always visible megascopically, commonly do not parallel the mineral foliation. Where they displace the mineral grains they may impart an apparent mineral foliation to the rock.

The foliation of the Silver Plume Granite, as pointed out by Lovering (1935, p. 14), is primarily the result of flow. Near the margins, the foliation is parallel to the contact, and in a concordant body it is parallel to the foliation of the metasedimentary rocks. In the central parts of the larger bodies, whether concordant or discordant, and in the discordant dikes, the foliation generally is not parallel to that of the country rock.

Under the microscope, a sample of the typical Silver Plume Granite is seen to consist predominantly of grains of microcline, plagioclase, quartz, biotite and of variable amounts of muscovite. The microcline is subhedral to anhedral and is generally coarser grained than the other minerals. Perthitic intergrowths of microcline and plagioclase and graphic intergrowths with quartz are common along their mutual grain boundaries. The plagioclase grains are anhedral and generally show complex twinning. Sericitic alteration along cleavage planes and grain boundaries is common. Myrmekite is common along mutual grain boundaries of plagioclase and quartz. The anorthite content of the plagioclase ranges from about An_{10} to An_{25} and averages about An_{15}. The quartz grains are anhedral and generally smaller than the feldspar grains. Biotite, which everywhere is partly altered to chlorite, is anhedral and is locally stretched parallel to the foliation. Some muscovite is found in most samples. It occurs in anhedral grains associated with the biotite. The common accessory minerals are apatite, zircon, allanite, monazite, and opaque minerals. Depending upon the type of metasedimentary rock cut by the Silver Plume Granite, such accessory minerals as hornblende, sillimanite, and garnet derived from the metasedimentary rocks are found in some samples. Table 9 gives the modes of eight samples of Silver Plume Granite.

Microscopic cataclastic features are common in most samples of the Silver Plume Granite but are the most abundant in those collected between Callahan Gulch and the East Portal. The most characteristic structures are microfractures, mortar structures along quartz-feldspar grain boundaries, and mortar trains that locally cut the grains. Some of the Silver Plume dikes in the vicinity of the East Portal have been so sheared that they are now essentially mylonites. The shearing, discussed in the section on the relative ages and origin of the Precambrian rocks, is believed to be nearly contemporaneous with the emplacement of the Kenosha batholith and related dikes.

PEGMATITE AND APLITE

Dikes and irregularly shaped bodies of pegmatite and aplite cut all the other Precambrian rocks of the mapped area; few are large enough to be shown at the map scale. Their distribution and relative abundance coincide in general with occurrences of the Silver Plume Granite and the Boulder Creek Granite. Lovering (1935, p. 15) recognized four ages, or associations, of pegmatites in this area. The limited mapping of this project precluded any general conclusion as to the age of most of the pegmatites.

Most of the pegmatite and aplite dikes are less than 1 foot wide and 10 feet long. A few are 10 feet or more wide, and may be followed for 100 feet or more.

The pegmatite and aplite near the east end of the tunnel occur at the contacts of Silver Plume Granite dikes with small bodies of the country rock and as

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TABLE 9. — *Modes (volume percent) of samples of Silver Plume Granite*

[Average grain size 2.5 mm]

Sample No.	26–CR60	78–CR60	86–CR60	90–CR60	93–CR60	5–CR61	6–CR61	28–CR61
Microcline	31	24	39	28	31	32	46	33
Plagioclase	32	28	26	30	29	32	29	23
Quartz	32	29	31	31	29	30	24	32
Biotite[1]	4.5	12	.8	5	6	2.7	1.0	5
Muscovite	.9	4.4	4.8	5	4.5	1.7	.2	6
Accessory minerals[2]	.3	2.3	.2	.2	.5	1.5	.2	.7

[1]Includes biotite altered to chlorite.
[2]Includes apatite, zircon, monazite, allanite, sillimanite, garnet, and opaque minerals.

DESCRIPTION OF SAMPLES

26–CR60. Ungranulated outcrop, with distinct biotite foliation, about 2,800 ft south of tunnel station 1049+50.
78–CR60. Biotite-rich variety. Porphyritic with euhedral microcline phenocrysts 5–10 mm long. From outcrop of dike crossing Kirby Gulch, about 1,850 ft north of tunnel station 758+50.
86–CR60. Biotite-poor variety. Medium-grained [equigranular] ungranulated outcrop (too small to be shown on pl. 1), about 1,850 ft north of tunnel station 739+50.
90–CR60. From outcrop at contact of granite and biotite gneiss and schist north of Landslide Peak, at an altitude of about 12,800 ft.
93–CR60. Ungranulated slightly porphyritic outcrop in saddle on Continental Divide between Geneva and Landslide Peaks.
5–CR61. From extension of Kenosha batholith, near contact with calc-silicate gneiss of amphibolite and related rock units, about 450 ft south of tunnel station 1170+50.
6–CR61. Garnetiferous and sillimanitic variety from contact of granite and amphibolite and related rocks. Outcrop on west side of Callahan Gulch at tunnel station 1159+25.
28–CR61. Granulated outcrop at top of Geneva Peak.

envelopes around inclusions of metasedimentary rock in larger bodies of Silver Plume Granite. Many of the concordant dikes of Silver Plume Granite grade into pegmatite dikes along their strikes. Small dikes of pegmatite and aplite cut the larger bodies of Silver Plume Granite. Similar relations were also observed around and in the dikes and bodies of Silver Plume Granite in the vicinity of the Montezuma stock. The conclusion is that these pegmatites and aplites are associated with emplacement of the Silver Plume Granite.

Pegmatitic and aplitic facies were observed in the Boulder Creek Granite, and their origin is believed to be related to that of the granite. These facies are also cut by small pegmatite and aplite dikes which resemble those cutting the Silver Plume Granite.

In field mapping, three types of pegmatite were originally distinguished: (1) pink quartz-feldspar pegmatite, (2) white quartz-feldspar pegmatite, and (3) quartz pegmatite. The pink quartz-feldspar pegmatite was most commonly found in association with the Silver Plume Granite, the white quartz-feldspar pegmatite was found only in the metasedimentary rocks, and the quartz pegmatite in the metasedimentary rocks and the granite.

Microscopic examination of the pink and white quartz-feldspar pegmatites showed that both are composed of microcline and quartz and smaller amounts of sodic plagioclase. The common mica is biotite or muscovite, biotite being the more abundant. The coloration of the pink pegmatites is due to inclusions of hematite in the microcline, which the microcline in the white pegmatites does not contain. Crystals of hematite as much as half an inch in diameter are common in the pink pegmatite locally, and small crystals of magnetite, generally less than a quarter of an inch in diameter, are common to pegmatite of both colors.

The quartz pegmatite consists of coarse-grained quartz and small amounts of white microcline and, locally, muscovite. The quartz pegmatite occurs as short dikes or pods generally less than 1 foot wide and a few feet long. Compared to the other types of pegmatite, it is rare, and seems to occur primarily along the Precambrian shear zones. Samples taken from these shear zones usually show that the quartz has been highly sheared.

The pink quartz-feldspar pegmatite is believed—because of its association with the Silver Plume Granite — to be related to the emplacement of the granite. The origin of the white quartz-feldspar pegmatite, which might be just an iron-free variety of the pink quartz-feldspar pegmatite, and the quartz pegmatite could not be determined.

RELATIVE AGE AND ORIGIN OF THE PRECAMBRIAN ROCKS

The age and origin of the Precambrian rocks of the Front Range have been the subject of considerable work for many years, and some differences of opinion still exist. Because of the limited area of investigation, work on the Roberts Tunnel can contribute little that is new. A summary of ideas concerning the age and origin of the Precambrian rocks as they apply to the rocks transected by the Roberts Tunnel follows.

METASEDIMENTARY ROCKS

The mineral assemblages of the metasedimentary rocks places them in the almandine-amphibolite facies of Fyfe, Turner, and Verhoogen (1958, p. 228–232). The gradation between the amphibolite and related rocks and the migmatite, and interlayering between the microcline gneiss and the biotite gneiss and schist, and between the biotite gneiss and schist and the hornblende gneiss suggest that the rocks were originally sedimentary rocks and that compositional differences are primarily the result of differences in original composition. The micaceous rocks represent a pelitic and quartzo-feldspathic composition, and the hornblendic rocks represent a calcareous or mafic composition.

The micaceous rocks, which account for the largest volume of metamorphic rock, are thought to have been derived mainly from argillaceous and arenaceous sedimentary rocks. Wahlstrom and Kim (1959, p. 1223–1228) showed the similarity between the average composition of a variety of argillaceous and arenaceous rocks and the composition, as shown by chemical analyses, of four samples from micaceous rocks from units equivalent to those of the Roberts Tunnel. Swann (1962, tables VI–VIII) also showed that chemical analyses of similar rocks in the northern Front Range compare favorably with those of graywacke and subgraywacke.

The hornblendic rocks occur mainly in two apparently distinct units — the amphibolite unit and hornblende gneiss. A few amphibolite layers occur in the migmatite and biotite gneiss units. Designating the ancestry of the hornblendic rocks is complicated by the fact that such rocks may result from recrystallization of either basaltic or impure calcareous sedimentary material (Engel and Engel, 1951; Poldervaart, 1953). The hornblendic layers of the amphibolite unit are intercalated with calc-silicate rock, marble, and quartzite, suggesting an original sequence of impure calcareous shale and sandstone with interlayers of orthoquartzite and relatively pure limestone. Calc-silicate layers are generally lacking in the amphibolites of the hornblende gneiss (or "B series" of Wahlstrom and Kim). Wahlstrom and Kim (1959, p. 1223–1225, fig. 2) concluded from chemical and petrologic data for similar rocks in Hall valley that amphibolites in the "A series" (amphibolite unit) were derived from impure calcareous sedimentary rocks and in the "B series" (hornblende gniess) from basaltic material, perhaps pyroclastic debris.

The original Precambrian sedimentary rocks have had a long and complex history. The principal period of metamorphism, which formed the chief constituents of the mineral assemblages as exposed today, is believed to have been about contemporaneous with the first period of major deformation (Moench, 1964, p. A43). During that period of deformation the buried Precambrian sediments were metamorphosed, plastically deformed, and intruded by plutonic rocks. The temperature-pressure conditions of formation of the metamorphic mineral assemblages must have been approximately the same as those attending the emplacement of the Precambrian plutons, as no significant contact effects were noted adjacent to the plutons. Turner and Verhoogen (1960, p. 553) suggested temperature-pressure values in the range of 550°–758°C and 4,000–8,000 bars for the formation of the almandine-amphibolite facies.

A younger period of Precambrian deformation, which was more limited in distribution and which was cataclastic in nature, probably took place at slightly lower temperatures and pressures and may have caused some slight retrogressive metamorphism (Moench, 1964, p. A66), such as the change of sillimanite to muscovite and biotite to chlorite.

GRANITE

The relative ages of the Silver Plume Granite and Boulder Creek Granite are known from field relations. In the Roberts Tunnel area, dikes of Silver Plume Granite cut the Boulder Creek Granite. It is generally believed that the Boulder Creek Granite — or equivalent rocks — was emplaced during the early period of plastic deformation of the metasedimentary rocks, and the Silver Plume Granite was emplaced during and after a later, and primarily cataclastic, period of deformation (Harrison and Wells, 1959, p. 33; Harrison and Moench, 1961, p. B2; Tweto and Sims, 1963, p. 1000). Hutchinson (1959) and Badgley (1960, p. 166) considered the Kenosha batholith to be older than the plutons that are equivalent in age to the Boulder Creek Granite and that are, therefore, older than the plutons equivalent in age to the Silver Plume Granite. Mapping of the northeast end of the Kenosha batholith (pl. 1), however, showed that dikes of the Kenosha batholith cut the Boulder Creek Granite stock, that the foliation of the Kenosha batholith is chiefly the result of flow, that dikes extending into the metasedimentary rocks follow what is considered to be a Precambrian shear zone, and that some of these dikes were sheared during and probably after their emplacement. These facts indicate that the Kenosha batholith was probably emplaced during the period of cataclastic deformation and is, therefore, equivalent in age to the Silver Plume Granite.

The modes of the Silver Plume Granite and those of the Boulder Creek Granite in the Roberts Tunnel area are similar (tables 8, 9), the chief difference between the two being textural. This similarity suggests a common mode of origin and perhaps a common source; the textural differences are probably due to differences in conditions of emplacement and crystallization and, possibly, in part, to metamorphism.

The Boulder Creek stock was emplaced between microcline gneiss and biotite gneiss and schist (pl. 1), either of which could conceivably yield a granitic melt. Dikes of Boulder Creek Granite, both concordant and discordant, intrude the gneisses; this intrusion suggests that the granite was emplaced as a fluid mass and that the gneisses to each side were not mobilized. Coexistence of the granite and gneisses at the present level of exposure is difficult to explain on the grounds that the granite formed by fusion of preexisting rocks in place.

Most of the Silver Plume Granite in the Roberts Tunnel area was emplaced along a zone occupied by the amphibolite unit, which appears to have been grossly brecciated during the emplacement of the granite. In this area the granite is in contact with amphibolite and contains blocks of amphibolite. Silver Plume Granite plutons and dikes are also common in the hornblende gneiss unit north, south, and west of the Montezuma stock. These relations would apparently preclude development of the granite by melting in situ.

These field relations indicate that the Silver Plume Granite and the Boulder Creek Granite were derived from magma formed below the level of the present terrain. The maximum relief in the area is on the order of 1 mile, and this distance probably represents a minimum interval through which the magma moved.

PALEOZOIC AND MESOZOIC SEDIMENTARY ROCKS

The sedimentary rocks exposed in the Roberts Tunnel are the Entrada (?) Sandstone and Morrison Formation of Late Jurassic age, the Dakota Group of Early Cretaceous age, the Benton Shale of Early and Late Cretaceous age, and the Niobrara Formation — consisting of the Fort Hays Limestone Member at the base and the Smoky Hill Marl Member at the top — and the Pierre Shale of Late Cretaceous age. These formations, except for the Entrada (?) Sandstone, crop out in the vicinity of the tunnel line between the West Portal and the Williams Range thrust fault (pl. 1). A part of the Pierre Shale, metamorphosed to a hornfels, crops out locally between the eastern part of the Williams Range thrust fault and the Montezuma stock. In addition, the Lykins Formation of Permian and Triassic (?) age and the Maroon Formation of Pennsylvanian and Permian age were penetrated in drill holes along the tunnel line and crop out west of the West Portal in the area of the Dillon Dam.

The formations exposed in the vicinity of the tunnel are structurally conformable and have an aggregate thickness of about 4,100 feet. The lower 750 feet consists of nonmarine and marginal marine sandstone and quartzite, claystone, shale, and thin beds of limestone. The upper 3,350 feet consists predominantly of marine shale and with lesser amounts of limestone, limy shale, silty shale and siltstone, and shaly sandstone. Table 10 gives a general summary of the sedimentary rocks exposed in the vicinity of the Roberts Tunnel.

MAROON AND LYKINS FORMATIONS

The Maroon and Lykins Formations are exposed west of the tunnel in the vicinity of the Dillon Dam and were penetrated in drill holes along the tunnel line that also penetrated the Entrada (?) Sandstone. Their position in relation to the tunnel is shown on the section on plate 1.

The Maroon Formation, of Pennsylvanian and Permian age, was tentatively identified in Middle Park by Lovering (1934, p. 4–6), as part of a Pennsylvanian and Permian sequence that ranges in thickness from 0 to 10,000 feet. Only about 100 feet of this sequence was penetrated by core holes drilled in conjunction with the construction of the Dillon Dam. The cores consist of pink and light-gray arkose and conglomeratic arkose and quartzose sandstone and a few thin layers of reddish-brown sandy siltstone.

Overlying the Maroon Formation and gradational with it are sedimentary rocks assigned to the Lykins Formation of Permian and Triassic (?) age. In earlier reports (Lovering and Goddard, 1950, p. 36–37) the Lykins has been mapped with the Maroon Formation and the overlying Entrada (?) Sandstone has been mapped with the Morrison Formation. Cores of the Lykins Formation, which is about 200 feet thick, consist of a succession of red to pink siltstone, sandy siltstone, silty sandstone, and thin siliceous beds of limestone and dolomite.

ENTRADA (?) SANDSTONE

The Entrada (?) Sandstone of Late Jurassic age is not exposed at the surface along the tunnel line. It is exposed, as a result of faulting, in the tunnel between stations 27+20 and 30+00 and between stations 32+80 and 33+70. Only the upper few feet of the formation near the contact with the overlying Morrison Formation is exposed in the tunnel, but, in the vicinity of the West Portal, complete sections and parts of the underlying Lykins Formation were recovered from core drill holes and surface exposures.

The Entrada (?) in early reports (Lovering, 1935) was, often with parts of the underlying Lykins Formation, mapped with the Morrison Formation. Baker,

TABLE 10.—*Generalized section of the sedimentary rocks in the vicinity of the Roberts Tunnel*

System	Series	Stratigraphic unit		Thickness (ft)	Description
Cretaceous	Upper Cretaceous	Pierre Shale		2,500±	Dark-gray to black shale; weathers gray or brownish gray; interbedded with silty shale, siltstone, and shaly sandstone.
		Niobrara Formation	Smoky Hill Marl Member	460±	Dark-gray shale and calcareous shale; weathers light gray; interbedded with thin-bedded dark-gray to black limestone.
			Fort Hays Limestone Member	18±	Gray dense medium-bedded limestone; contains partings of calcareous shale.
	Upper Cretaceous / Lower Cretaceous	Benton Shale		350±	Dark-gray to black-shale; weathers dark gray; calcareous shale in upper part contains thin limestone beds, and a zone of sandy shale occurs at base.
	Lower Cretaceous	Dakota Group		200±	Upper unit, light- to dark-gray medium-bedded sandstone or quartzite interbedded with lenticular black shale. Middle unit, dark-gray to black shale and argillaceous sandstone. Lower unit, gray or brownish-gray sandstone or quartzite and thin beds of dark-gray shale; conglomerate at base locally.
Jurassic	Upper Jurassic	Morrison Formation		180±	Light-gray and greenish-gray claystone, with calcareous claystone and locally calcareous sandstone and limestone in lower part.
		Entrada(?) Sandstone		0–150	Light-gray medium-grained well-sorted crossbedded sandstone.
Permian and Triassic(?)		Lykins Formation		200±	Red and variegated dolomitic siltstone, sandy siltstone, and sandstone.
Pennsylvanian and Permian		Maroon Formation		100±	Red, pink, and gray arkose and conglomeratic arkose containing siltstone lenses. Base not exposed.

Dane, and Reeside (1947) and Heaton (1939) established the correlation and age of the Entrada Sandstone in Colorado with the type section in the San Rafael Swell, Utah, although they do not specifically mention a section in Middle Park. Lovering and Goddard (1950, p. 37), who recognized the Entrada Sandstone at Breckenridge, stated that it is not exposed north of Breckenridge, and they included the sandstone recognized here as the Entrada(?) Sandstone as part of the Morrison Formation. Detailed studies have not been made of the stratigraphy in the vicinity of the West Portal, and for this reason the formation in this area is queried. This sandstone may represent a sandstone lens at the base of the overlying Morrison Formation.

In the vicinity of the West Portal the thickness of the Entrada(?) Sandstone ranges from a few feet to about 150 feet. The variation in thickness of the Entrada(?) is attributed by Heaton (1939) to the amount of sediment deposited rather than to postdepositional erosion.

The contact of the Entrada(?) Sandstone with the underlying Lykins Formation is considered to be an unconformity that represents the systemic boundary between the Jurassic and Triassic(?) Periods. In the area of the West Portal, the contact is sharp and can be picked, where exposed, within inches. The contact of the Entrada(?) Sandstone with the overlying Morrison Formation, however, is gradational. Lenticular layers of Entrada-type sandstone, as much as 15 feet thick, are interbedded with calcareous claystone assigned to the Morrison Formation.

The Entrada(?) Sandstone is white to gray in outcrop and on fresh surfaces. Crossbedding is conspicuous, particularly in weathered outcrops. The sandstone consists predominantly of medium-grained well-sorted well-rounded frosted quartz grains. The quartz grains, where poorly cemented, are embedded in a matrix of clay minerals or, where firmly cemented, in a cement of silica and minor amounts of carbonates and clay minerals.

The following section is taken from Dillon damsite drill-hole 7W and illustrates the lithology of the Entrada(?) Sandstone in the vicinity of the West Portal of the Roberts Tunnel.

Dillon damsite drill-hole 7W, station 22+50

[Logged by Theodore Walker, 1955. Dip of Morrison average 20°]

Depth (ft)	*Description*	*Corrected thickness (ft)*
0.0– 51.4	Valley fill	51.4
	Morrison Formation (part):	
51.4– 53	Claystone, red, silty, sandy	1.5
53 – 61.7	Claystone; gray in lower part; oxidized to brown in upper part; silty	8.2
61.7–120	Claystone, gray to greenish-gray, silty; lacks conspicuous bedding; capable of holding open fractures through most of interval; commonly contains zones of slacking clay	54.8
120 –121	Clay, gray, swelling	.9
121 –169	Sandstone, gray to grayish-green, medium-grained; contains some coarse grains. Greenish-gray clay partings locally between sandstone beds	45.1
	Partial thickness of Morrison Formation	110.5
	Entrada(?) Sandstone (part):	
169 –172	Sandstone; color changes from gray to white as sandstone becomes coarser grained; coarse grains well rounded and frosted	2.8
172 –175	Sandstone; same as above but medium grained	2.8
175 –183	Quartzite, light-gray; (core badly broken)	7.5
183 –191	Sandstone, light-gray to white, fine-grained	7.5
191 –197.5	Sandstone, light-gray to white, poorly sorted; coarse grains well rounded and frosted	6.1
197.5–237	Sandstone, light-gray to white, fine- to medium-grained, well-sorted; medium grains well rounded and frosted. Between depths of 211 and 215 ft, grains somewhat coarser but not coarse grained	37.1
237 –281.5	Sandstone, light-gray, medium-grained; a little coarser and better sorted than above overlying unit; quartzitic between depths of 244 and 265 ft, 2–3 in. of swelling clay at depths of 274 and 277 ft	41.8
281.5–290	Sandstone, mottled light-gray and greenish-gray, fine-grained; core badly fractured	8.0
290 –301.3	Sandstone, light-brown and greenish-gray; grading to light gray in lower 2 ft; medium grained; quartzitic in lower 2 ft	10.6
301.3–307.8	Shale, dark-brown to black, silty and sandy; swelling clay at 304.5 ft; core badly broken	6.1
307.8–311.5	Sandstone, light-gray to white, greenish streaks locally. One-inch seam of swelling clay at 308.5 ft	3.5
	Partial thickness of Entrada(?) Sandstone (rounded)	134

MORRISON FORMATION

The sedimentary units assigned to the Morrison Formation, which is of Late Jurassic age, include all the units between the underlying Entrada(?) Sandstone and the overlying Dakota Group. In general, the formation consists of calcareous and noncalcareous claystone, lithographic limestone in the lower part, and sandstone near the base and top.

In the tunnel the upper part of the Morrison Formation is exposed at several intervals between stations 9+70 and 27+20, and the lower part is exposed between stations 30+20 and 38+50. South and southeast of the West Portal the upper part is exposed in scattered cuts along the Snake River (pl. 1). The entire formation was exposed during construction for the west abutment for the Dillon Dam and was intersected by core-drill holes along the line of the dam. From these exposures and the drilling, it was determined that the thickness of the Morrison Formation ranges from about 160 to 210 feet.

The Morrison Formation, as well as the Entrada(?) Sandstone, was first mapped and described in the vicinity of the West Portal by Lovering (1934, p. 6; 1935, p. 15) and Lovering and Goddard (1950, p. 38), who established the correlation with the type Morrison Formation along the east side of the Front Range. In later work (LeRoy, 1946; Van Horn, 1957) the equivalent stratigraphic interval on the east side of the Front Range was divided into the Ralston Creek and Morrison Formations. Without detailed stratigraphic studies, this division is not possible; so, for the purpose of this report, all the interval between the Entrada(?) Sandstone and the Dakota Group shall be considered Morrison Formation.

The formation consists for the most part of light-gray and greenish-gray claystone. Bedding, or shaly partings, is generally indistinct, and the rock breaks with a conchoidal or subconchoidal fracture. In the lower half are layers of calcareous claystone in which the bedding is more distinct. Interbedded locally with the calcareous claystone are beds of fine-grained lithographic limestone that have a maximum thickness of about 1 foot. Sandstone beds, as much as 15 feet thick that resemble those of the underlying Entrada(?) Sandstone, are interbedded with the claystone near the base of the formation, and a 5-foot-thick layer of sandstone that resembles the beds of the overlying Dakota Group occurs locally about 10 feet below the contact with the Dakota Group. The claystone adjacent to the sandstone beds is commonly sandy and silty.

The following log of Dillon damsite drill-hole B illustrates the lithology of the Morrison Formation in the vicinity of the West Portal of the tunnel.

A detailed study of the geochemistry and petrology of the Morrison Formation of the area of the Dillon Dam, made subsequent to the present investigation, has been published (Wahlstrom, 1966).

Dillon damsite drill-hole B

[Logged by E. E. Wahlstrom. Dip 5°–12°, avg 10°]

Depth (ft)	*Description*	*Corrected thickness (ft)*
	Dakota Group (part):	
0–31	Quartzite	30.4
	Morrison Formation:	
31–95	Claystone, light-gray and greenish-gray, bedding inconspicuous; numerous joints	62.7
95–128	Claystone, light-gray and greenish-gray, generally massive, but locally fractured	32.3
128–131	Claystone, light-gray and greenish-gray, limy, fractured	2.9
131–141	Claystone, light-gray and greenish-gray, fractured	9.8
141–153	Claystone, light-gray and greenish-gray, limy, fractured	11.8
153–162	Claystone, gray and dark-gray	8.8
162–163	Limestone, light-gray, fine-grained	1
163–175	Claystone, light-gray and greenish-gray, massive	11.8
175–176	Claystone, light-gray, limy	1
176–186	Claystone, light-gray and greenish-gray, fractured	9.8
186–192	Claystone, light-gray and light-greenish-gray, limy, massive	5.9
192–197	Claystone, light-gray and light-greenish-gray, massive	4.9
197–245	Claystone, light-gray and light-greenish-gray, limy, brittle	47
	Thickness of Morrison Formation (rounded)	210
	Entrada(?) Sandstone (part):	
245–276	Sandstone, light-gray, fine-grained, even-grained	30.4

DAKOTA GROUP

The Dakota Group, of Early Cretaceous age, consists of interbedded sandstone, quartzite, and shale. It is exposed on a low hill just above the West Portal and, with the overlying Benton Shale and underlying Morrison Formation, in the north bank of the Snake River south of the tunnel line (pl. 1). At the surface, sills of latite porphyry occur within the Dakota Group. In the tunnel, the lower part of the Dakota Group is exposed between stations 11+60 and 17+05 and between stations 22+50 and 30+30, and the upper part is exposed between stations 38+10 and 46+25.

The correlation of the Dakota Group in this area with equivalent rocks in other areas of Colorado has been established by Lovering and Goddard (1950, p. 39). Lovering (1935, p. 16–19) — for the Montezuma quadrangle to the east and for the Breckenridge district (1934, p. 7–10) to the south — referred to the strata of this stratigraphic interval as the Dakota Quartzite. Detailed stratigraphic studies, and the subdivision of the Dakota Group into formations, have been made east of the Front Range (Waagé, 1955) and in other areas of Colorado (Haun, 1959), but no detailed studies have been made in the south end of Middle Park. For this reason, the name Dakota Group will be used in this report, with no attempt at subdivision into formations.

The Dakota Group in the vicinity of the tunnel is about 200 feet thick. Sections measured along the Snake River south of the tunnel line, which include felsite porphyry sills, range in thickness from about 150 to 230 feet. Drill holes along the line of the Dillon damsite penetrated a maximum thickness of about 250 feet of the Dakota Group.

The Dakota Group can be subdivided into three lithologic units: a lower sandstone or quartzite unit, a middle shale unit, and an upper sandstone and quartzite unit. The lower unit is gradational with the underlying Morrison Formation, and the upper unit, with the overlying Benton Shale.

The lower unit, which makes up $\frac{1}{3}$–$\frac{1}{2}$ of the Dakota Group, consists of fine- to medium-grained massive to well-bedded, locally crossbedded, sandstone or quartzite and thin layers of gray, dark-gray, or reddish-brown shale. The sandstone beds range in thickness from less than 1 foot to about 10 feet. Commonly, the lower sandstone or quartzite beds are conglomeratic, containing pebbles of white, gray, or black chert. The shale beds range from thin partings less than an inch thick to beds 10 feet thick. The contact with the underlying Morrison Formation is usually picked at the base of the lowest sandstone or quartzite or at the top of the highest gray to greenish-gray claystone.

The middle unit consists of dark-gray to black shale and argillaceous sandstone. The shale beds range in thickness from less than 1 foot to about 10 feet, and the sandstone beds, from less than 1 foot to about 5 feet. The shale and sandstone typically are carbonaceous. The sandstone, in general, is finer grained than that in the upper or lower units.

The upper unit consists of light- to dark-gray massive- to medium-bedded sandstone or quartzite and thin lenticular black shale layers. The sandstone and quartzite are fine to medium grained and locally argillaceous. Pieces of organic plant material in the sandstone or quartzite beds are common, particularly near the base of a bed. The sandstone beds range in thickness from less than 1 foot to about 20 feet. The shale beds are dark gray to black, carbonaceous, and locally sandy and silty. They range in thickness from thin partings of less than an inch to beds as much as 5 feet thick. At the top of this unit is a transitional zone in which thin sandstone beds alternate with shale beds characteristic of the overlying Benton Shale.

The following log of drill-hole A of the Dillon damsite illustrates the lithology of the Dakota Group in the vicinity of the tunnel.

Dillon damsite drill-hole A

[Logged by Theodore Walker and E. E. Wahlstrom. Dip 20°–25°]

Depth (ft)	*Description*	*Corrected thickness (ft)*
0 – 3.5	Soil	3.5
	Dakota Group (part):	
3.5– 22	Quartzite, light- to dark-gray, medium-grained, equigranular	17
22 – 28	Shale, black, silty to fine-grained, sandy	5.5
28 – 39	Quartzite, light- to dark-gray, 0.5 ft of black argillaceous sandstone at 29 ft	10.1
39 – 41.5	Sandstone, dark-gray, very argillaceous	2.3
41.5– 48	Sandstone, light-gray; stained yellowish-brown; chips of organic matter	6
48 – 66.5	Sandstone, light- to dark-gray; abundant chips of organic matter. Black shaly sandstone between depths of 61 and 62 ft	17
66.5– 90	Shale, black; 1- to 2-in.-thick beds of sandstone locally. At depth of 88 ft, 0.5 ft gray sandstone	21.6
90 – 93	Sandstone, light-gray	2.8
93 – 93.7	Siltstone, light-gray	.6

Dillon damsite drill-holeA — Continued

Depth (ft)	*Description*	*Corrected thickness (ft)*
93.7–105	Quartzite, gray; some chips of organic material	10.4
105 –109	Quartzite, dark-gray, fine-grained; some chips of organic material; stylolites	3.7
109 –115	Shale, black; 1 ft of siltstone to fine-grained sandstone at 111.5 to 112.5	5.5
115 –117	Sandstone, dark-gray to black, fine-grained, argillaceous	1.8
117 –119	Shale, dark-gray to black; some swelling clay	1.8
119 –121	Sandstone, dark-gray, argillaceous	1.8
121 –131.5	Shale, dark-gray, silty; grades into argillic sandstone at 131.5 ft; swelling clay from depths of 127 to 129 ft	9.7
131.5–134	Sandstone, gray to dark-gray, argillaceous; grades into unit below	2.3
134 –154.5	Quartzite, light-gray; core shows evidence of much solution of quartz sand; black interbedded shale between depths of 148 and 150 ft	18.7
154.5–159	Quartzite, light-gray, medium-grained; conglomeratic between depths of 158 and 159 ft; some chips of organic material	4.1
159 –178.5	Quartzite, light-gray; argillaceous with some thin beds of clay which are interbedded and gradational	17.9
178.5–188	Quartzite, light-gray	9.2
188 –191.8	Shale, gray	3.5
191.8–193.9	Sandstone, light-gray; shale partings	1.9
193.9–195	Sandstone, light-gray	1
195 –207.7	Quartzite, light-gray	11.7
207.7–212	Shale, dark-gray, silty, calcareous	4
212 –218.5	Quartzite, light-gray	6
218.5–221	Shale, gray	2.3
221 –226	Shale; black with thin reddish layers	4.6
226 –235	Shale, gray	8.3
235 –236	Shale, reddish-brown	.9
236 –238	Shale, reddish-brown and gray	1.8
238 –247	Quartzite, light-gray	8.3
247 –259.5	Shale, reddish-brown and gray	11.5
	Partial thickness of Dakota Group (rounded)	236
	Morrison Formation (part):	
259.5–266	Claystone, light-gray, massive; bedding indistinct	6.0
266 –271	Shale, light-gray	4.6
271 –281	Claystone, light-gray; indistinct bedding; swelling clay between depths of 276 and 278.5 ft	9.2
	Partial thickness of Morrison Formation (rounded)	20

BENTON SHALE

The Benton Shale, of Early and Late Cretaceous age, consists of about 350 feet of predominantly black carbonaceous and calcareous shale. It is not exposed at the surface over the tunnel line, but along the Snake River south of the tunnel line, the lower part of it is exposed locally above the cliff of Dakota quartzite (pl. 1). Drill holes along the Dillon Dam line and the excavation for the emergency gate shaft to the tunnel intersected the lower part of the Benton Shale. In the Roberts Tunnel a complete section of the formation was exposed between stations 46+25 and 56+50. East of the Williams Range thrust fault, just east of the fault at station 339+30, is a calc-hornfels layer that is possibly the equivalent of the overlying basal limestone of the Niobrara Formation. If it is equivalent, then the metamorphosed shale between the base of the calc-hornfels layer and the Montezuma stock at station 343+00 is equivalent to the upper part of the Benton Shale just west of station 56+50. (See chap. C.)

The Benton Shale was mapped by Lovering (1934, pl. 3) in the Breckenridge mining district, south of the Roberts Tunnel. In that work, Lovering (1934, p. 13) established the correlation of the Benton Shale in the general area of the tunnel with that in other areas of Colorado.

The Benton Shale in the vicinity of the tunnel ranges in thickness from about 320 to 370 feet. The range in thickness is probably due in part to difficulty in picking the upper and lower contacts. The thickness as measured within the tunnel is about 320 feet. Lovering (1935, p. 22) reported a thickness of 370 feet on the north side of the Snake River about 1 mile west of the Montezuma quadrangle, which would be less than 1 mile south of the tunnel line.

The Benton Shale consists primarily of dark-gray to black shale. The lower two-thirds is carbonaceous and noncalcareous. At the base is a transitional zone 10–20 feet thick that consists of interbedded gray sandstone and dark-gray sandy or silty shale. In the vicinity of the West Portal, this transitional zone commonly contains (but not necessarily at the base) a conglomeratic sandstone that ranges in thickness from less than an inch to about 15 inches. The upper third of the formation consists of interbedded dark-gray and black carbonaceous shale, calcareous shale, and shaly calcareous sandstone. About 20 feet below the top of the formation is the top of a 10- to 20-foot-thick bed of calcareous shaly sandstone. Above this bed is a succession of alternating thin beds of shale, limestone, and limy shale. The top of the formation is picked at the base of a dense medium-bedded limestone, which has an undulating base that transects the laminae of the shaly limestone or calcareous shale at the top of the Benton Shale.

No significant section of the Benton Shale could be measured in the vicinity of the Roberts Tunnel.

NIOBRARA FORMATION

The Niobrara Formation, of Late Cretaceous age, consists of the Fort Hays Limestone Member and the overlying Smoky Hill Marl Member. The Fort Hays Limestone Member forms a low hogback that intersects the tunnel line at the surface at about station 51+00 and is the only part of the formation that is well exposed along the tunnel line. The Smoky Hill Marl Member forms low sage- and soil-covered rolling hills above the tunnel line. This member is best exposed at the surface in discontinuous outcrops at the north side of the Snake River about 1 mile south of the tunnel line (pl. 1).

West of the Williams Range thrust fault, the Niobrara Formation was exposed in the tunnel between about stations 56+50 and 80+60. The contact with the underlying Benton Shale is well exposed in the tunnel, but the upper part of the Niobrara in the tunnel is in fault contact with the lower part of the overlying Pierre Shale. East of the Williams Range thrust fault, just east of the fault at station 339+30, is a calc-hornfels layer that is possibly the equivalent of the Fort Hays Limestone Member. (See chap C.)

The Niobrara Formation in the area of the Roberts Tunnel was first studied by Lovering (1934, p. 11; 1935, p. 20), who established its age and correlation with other sections in Colorado. The term Timpas Limestone has been abandoned for the Fort Hays Limestone Member (Tweto, 1957, p. 21) and Apishapa Shale has been abandoned for the Smoky Hill Marl Member (Scott and Cobban, 1964).

The thickness of the Niobrara Formation in the vicinity of the tunnel is about 480 feet. The base of the Fort Hays Limestone Member can be picked relatively closely as the base of the dense medium-bedded limestone that overlies the alternating thin beds of shale, limestone, and limy shale assigned to the Benton Shale. The variation in thickness as reported (Tweto, 1957, p. 21; Holt, 1962, p. 23; Lovering, 1935, p. 21) is primarily the result of picking the upper contact, which is gradational with the overlying Pierre Shale. Generally, the contact is picked at the change from light-gray-weathering calcareous shale to brownish-gray-weathering noncalcareous shale.

The Fort Hays Limestone Member consists of 15–20 feet of limestone and interbedded shale. The limestone is gray, dense, and fine grained and occurs in beds less than 1 to about 3 feet thick. The beds of limestone are separated by beds of dark calcareous

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shale generally less than 1 inch thick. The Fort Hays Limestone Member grades into the overlying Smoky Hill Marl Member by a decrease in thickness and number of limestone beds.

The Smoky Hill Marl Member consists of about 460 feet of interbedded shale, calcareous shale, and limestone. The shale and limestone are generally dark gray and weather light gray; they occur in alternating beds less than 1 inch to 1 foot thick. Thin beds of bentonite, less than 1 to 6 inches thick, occur throughout the member. The shaly limestone beds are commonly black and rich in carbonaceous material and have a petroliferous odor when freshly broken.

No section of the Niobrara Formation was measured in the tunnel because of the extensive faulting. The following section of the Niobrara Formation is modified from that of Lovering (1935, p. 21–22) and was measured on the north side of the Snake River about 1 mile south of the tunnel line.

Niobrara Formation on the north side of the Snake River about 1 mile south of the Roberts Tunnel

[Modified from Lovering (1935, p. 21–22)]

	Thickness (feet)
Pierre Shale (part):	
9. Shale, dark-brown to black, brown weathering, fissile, noncalcareous	100+
Niobrara Formation:	
Smoky Hill Marl Member:	
8. Shale, black to dark-brown, calcareous and noncalcareous, fossiliferous	10
7. Shale, dark-gray to black; only locally calcareous	115
6. Shale, dark-gray; contains abundant secondary silica	30
5. Shale and limestone, gray to dark-gray; shale calcareous; limestone in beds 1 to 12 in. thick	30
4. Shale, dark-gray, calcareous; 3-in. layer of white calcite at top	40
3. Shale (partly covered), dark-gray, calcareous and noncalcareous	240
Thickness of Smoky Hill Marl Member	465
Fort Hays Limestone Member:	
2. Limestone, dark-gray to black; beds 1 to 3 ft thick, separated by less than 1-in.-thick beds of black shale; fossiliferous	10
Thickness of Niobrara Formation	475
Benton Shale (part):	
1. Limestone, gray, thin-bedded; grades downward into purplish calcareous shale	30

PIERRE SHALE

The Pierre Shale, of Late Cretaceous age, crops out and is intersected by the tunnel between the Niobrara Formation and the Williams Range thrust fault — along which Precambrian rocks were thrust over the upper part of the Pierre Shale — and as a hornfels, between the Williams Range thrust fault and the Tertiary Montezuma stock (pl. 1). In general, the formation is not well exposed at the surface along the tunnel line. Much of the Pierre forms soil- and sage-covered hills or, along the Snake River, is covered by fluvial deposits. Locally, however, parts of the formation are exposed in river or streamcut banks and in banks cut for irrigation ditches and roads.

In the tunnel the Pierre Shale was intersected between stations 80+60 and 180+00 west of the Williams Range thrust fault. Between stations 291+60 and 343+00, east of the Williams Range thrust fault, are baked shale, or hornfels, and lime silicate beds that originally were beds of shale and limy shale equivalent in part to the lower beds of the Pierre.

The Pierre Shale was recognized and mapped in the vicinity of the tunnel by Lovering (1935, p. 21–22), who also recognized the relation of the thickness of the Pierre Shale to the Williams Range thrust fault. Lovering (1935, p. 21) reported the Pierre Shale to be about 3,975 feet thick below the Williams Range thrust fault along the north side of the Snake River about 1 mile south of the tunnel line. Holt (1962, p. 23, 25) reported the Pierre Shale below the thrust to be about 3,300 feet thick east of Dillon and about 5,840 feet thick 13 miles north of Dillon at Ute Peak. In the tunnel the thickness of Pierre Shale exposed west of the thrust fault is an estimated 2,000–3,000 feet. The base of the Pierre Shale is not exposed in the tunnel, because the Pierre Shale is in fault contact with the underlying Niobrara Formation. East of the thrust fault, between it and the fault at station 339+30, an estimated 1,900 feet of metamorphosed shale is exposed, of which at least part is equivalent to the lower part of the Pierre.

The Pierre Shale consists predominantly of dark-gray to black shale that weathers light gray and brownish gray. Much of the shale is silty and sandy. On weathered surfaces the shale is fissile, but underground in some sections of the tunnel it broke with a subconchoidal fracture. Interbedded with it are several zones of shaly sandstone and siltstone, the lowest of which occurs in the tunnel about 750 feet stratigraphically above the Niobrara Formation. This shaly sandstone and siltstone is about 100 feet thick and consists of very fine to medium grained angular to subangular grains of quartz, chert, feldspar — both potassium feldspar and plagioclase — and rock fragments in a matrix of clay and minor amounts of calcite and dolomite.

No detailed sections of the Pierre Shale have been measured in the vicinity of the Roberts Tunnel.

Lovering (1935, p. 21), however, gave a general section measured along the Snake River about 1 mile south of the tunnel line. The lower 125 feet of his section would now be included in the Niobrara Formation. Holt (1962, p. 25) presented three generalized sections in the Blue River valley.

East of the Williams Range thrust fault, part of the Pierre Shale has been metamorphosed into hornfels. The correlation of the sections west and east of the Williams Range thrust plate underground is based on the 100-foot-thick shaly sandstone and siltstone near station 110+00 west of the thrust fault and a similar sandstone and siltstone near station 318+00 east of the thrust fault.

Mineral associations and rock fabrics indicate a gradual increase in the intensity of the metamorphism as the Montezuma stock is approached. The shale just east of the Williams Range thrust fault is brittle and sandy, with mineral assemblages and fabrics similar to those of its counterpart west of the Williams Range thrust fault. Nearer the Montezuma stock the grain size has increased as a result of recrystallization of some fine-grained constituents, additional minerals have been formed, and some minerals have disappeared as a result of baking. The metamorphic effects of the Montezuma stock on the Pierre Shale are described in detail in chapter C of this Professional Paper.

TERTIARY IGNEOUS ROCKS

The Tertiary igneous rocks at the surface in the Roberts Tunnel area and those intersected by the tunnel include the Montezuma Quartz Monzonite stock and a series of dikes. The dogleg route of the tunnel was selected to take advantage of the relatively competent rock of the Montezuma stock, as compared with the highly sheared and altered Precambrian rock at the Continental Divide along a straight-line route. (See chap. A.)

MONTEZUMA QUARTZ MONZONITE AND ASSOCIATED APLITIC ROCK

The Montezuma Quartz Monzonite comprises a stock of about 16 square miles in areal extent at the surface near the center of the Montezuma quadrangle (Lovering, 1935, pl. 3). This stock, the largest in the Front Range, is one of the many quartz monzonite intrusive bodies of Tertiary age that are found in the Front Range mineral belt (Lovering and Goddard, 1950, pl. 2). The Montezuma stock was first studied by Lovering (1935, p. 32–34), who described in detail this stock and its relation to the other Tertiary intrusives of the Front Range mineral belt.

The Montezuma Quartz Monzonite crops out at the surface along the tunnel line between about stations 353+50 and 571+20. In the valleys of the Snake River and Peru Creek are glacier-polished knobs of quartz monzonite that are surrounded by glacial deposits. Above about 11,000 feet in altitude, the quartz monzonite crops out as weathered knobs, as along Collier Mountain, or as small peaks, such as Tiptop and Morgan Peaks, and in cirque walls, as at the head of Grizzly and Warden Gulches.

Underground, the tunnel was driven in stock approximately between stations 343+00 and 690+00, with the exception of an interval of Precambrian gneiss, believed to be a large inclusion or roof pendant, between stations 625+00 and 637+00.

The stock at the surface within the mapped area is in contact with Precambrian rocks, except for a small area at its westernmost edge in and along the Snake River valley, where it is in contact with hornfels. The contact is rarely exposed; at most places it is covered by slope wash, talus, or glacial deposits. It may be located within a foot or so on the divide between Morgan and Warden Gulches and at several places near the head of Warden Gulch (pl. 1). The contact is exposed in several small outcrops for a distance of about 500 feet southwest of Montezuma and northwest of the Equity mine. It is also exposed in scattered outcrops near the head of Grizzly Gulch southwest of the Hunkidori mine.

The contact of the stock and the enclosing rock is generally sharp. Locally, the contact is parallel to the foliation or bedding of the enclosing rock, but within a few inches or feet it crosscuts the structures. Abrupt changes in the strike of the contact are common and were apparently caused by the quartz monzonite intruding along preexisting joints. Inclusions of the country rock are common within the stock along the contact. The inclusions range from thin slivers less than half an inch wide to blocks several feet in maximum dimension. Most of the inclusions, however, are less than 1 foot in maximum dimension and occur within 3 feet of the contact. Dikes of quartz monzonite or aplite, which extend into the country rock, range in size from less than an inch wide and a few inches long to about 50 feet wide and 200 feet long. The larger dikes were best observed near the head of Warden Gulch. Most of the smaller dikes near the contact parallel the contact or the foliation of the country rock. The larger dikes are radial to the contact, and their emplacement was probably in part controlled by the preexisting jointing.

QUARTZ MONZONITE

The typical Montezuma Quartz Monzonite is a medium-grained porphyritic rock, which on fresh exposures is light gray with pinkish-gray tabular patches and black specks. It weathers to a brownish-gray coarsely granular surface. The phenocrysts, which give the rock its pinkish-gray tabular patches, are orthoclase and generally range in length from 10 to 25 mm, but can be as much as 50 mm long. They comprise about 10–25 percent of the rock and are typically Carlsbad twins. The black specks, so conspicuous in fresh outcrops, are subhedral to euhedral crystals of black biotite that range in diameter from about 1 to 3 mm. The groundmass consists of grains, from 3 to 5 mm in maximum dimension, of light-gray subhedral plagioclase feldspar, pink subhedral to anhedral orthoclase, and gray anhedral quartz. Grains of black magnetite about 1 mm in diameter and of yellow sphene about 0.5 mm in diameter are conspicuous when examined with a hand lens in most fresh hand specimens.

In thin section the rock is seen to consist of approximately equal amounts of plagioclase and orthoclase and a somewhat lesser amount of quartz. The plagioclase is generally twinned, subhedral, and fresh. Zoned crystals are common, and the cores of such crystals are altered, at least in part, to sericite. Perthitic intergrowths of plagioclase and orthoclase occur along mutual grain boundaries. The composition of the plagioclase ranges from An_{30} to An_{45}; the more basic plagioclase occurs in the center of the zoned crystals and as badly corroded crystals. The orthoclase in the groundmass is generally anhedral; some grains show simple Carlsbad twins, and most grains are somewhat altered. Micrographic intergrowths of orthoclase and quartz occur along their mutual boundaries. The quartz is anhedral and contains numerous minute fluid inclusions. Brown biotite is the common ferromagnesian mineral, but some specimens contain traces of common dark-green hornblende. The biotite is subhedral and contains inclusions of apatite and, rarely, allanite. The biotite, generally, shows some alteration to chlorite and, in some places, to epidote near the grain boundaries; however, in some specimens most of the biotite has been altered to chlorite. The common accessory minerals are apatite, sphene, and magnetite. In addition, a few grains of zircon can be seen in most slides.

At the surface the composition and grain size of the stock are remarkably uniform, except for local areas of nonporphyritic quartz monzonite and near the contacts. Locally, within the stock are areas of several hundred square feet that do not contain the usually conspicuous phenocrysts of orthoclase. Except for appearance, there is no difference in composition and grain size between the porphyritic and nonporphyritic varieties.

Near the contact of the stock, except where bordered by aplite, is a zone of finer grained quartz monzonite 1 to 3 feet thick. Within this zone are partially assimilated pieces of the Precambrian country rock, and the composition of the stock has also been changed by the assimilation of some of the country rock. The typical change has been an increase in the percentage of plagioclase and biotite. Also, muscovite and sillimanite occur in the stock near its contact with the Precambrian gneiss.

Table 11 lists the modes (volume percent) of five samples of the Montezuma Quartz Monzonite, one sample of the aplitic border zone of the stock, and the one sample from an aplitic dike within the stock.

APLITIC ROCK

Associated with the Montezuma Quartz Monzonite is aplitic rock, which occurs locally along the contacts and as dikes within the main part of the stock and in the Precambrian country rock. The aplitic rock at the border of the stock is best exposed at the surface near the head of Warden Gulch. Under-

TABLE 11. — *Modes (volume percent) of samples of Montezuma Quartz Monzonite and associated aplitic rock*

[Average grain size of samples: Quartz monzonite, 3 mm; aplitic border zone, 1 mm; aplitic dike in stock, 0.5 mm. Leaders indicate looked for but not found]

	Quartz monzonite					Aplitic border zone	Aplitic dike in stock
Sample No.	127–CR60	10–RD61	13–CR61	15–RD61	25B–CR61	19–CR61	45–CR61
Orthoclase	39	37	32	32	32	42	45
Plagioclase	28	35	34	34	34	20	19
Quartz	26	25	26	23	25	36	35
Biotite	4.0	2.6	6	8	6	1.8	1.7
Hornblende	......	......	......	.2	......	......	......
Accessory minerals[1]	2.4	.5	2.1	2.8	2.8	.9	.2

[1]Includes sphene, apatite, zircon, calcite, chlorite, and opaque minerals — principally magnetite and pyrite.

DESCRIPTION OF SAMPLES

127–CR60. From outcrop about 500 ft northwest of contact between stock and sillimanitic biotite gneiss and schist on Collier Mountain.
10–RD61. From outcrop just below contact of stock and hornblende gneiss unit about 800 ft west of the lower adit of the Equity mine.
13–CR61. From outcrop 175 ft west of contact of stock where the contact crosses the divide between Warden and Morgan Gulches.
15–RD61. From outcrop at lower adit of Equity mine.
25–CR61. Outcrop at top of Tiptop Peak.
19–CR61. Outcrop adjacent to contact about 150 ft northeast of stream in Warden Gulch.
45–CR61. From aplitic dike on northwest side of Tiptop Peak.

ground, a border zone of aplitic rock about 300 feet wide occurs between the Montezuma Quartz Monzonite and the Precambrian rocks at the east contact at about station 686+50. A dike of aplitic rock, about 100 feet wide, within the stock was mapped at the surface on the nose between the Snake River and Peru Creek. Underground, three dikes of aplitic rock, ranging in width from 50 to about 400 feet, were intersected by the tunnel at about station 600+00 and to the east.

The contacts of the aplitic rock with quartz monzonite are either sharp or gradational and are sharp with the Precambrian country rock. The aplitic rock at the border of the stock may be either a chilled facies of the stock or a dike. Where the aplite is a chilled facies, the grain size gradually increases toward the main mass of the stock; where it is a dike, the contact is sharp, and the dike material adjacent to the quartz monzonite stock is finer grained than that near the center of the dike. The contact of the aplitic rock at the border of the stock with the Precambrian country rock is irregular because dikes of aplitic rock have intruded the country rock beyond the contact, and inclusions of country rock commonly occur within the aplitic rock.

The aplitic rock is typically fine to very fine grained and porphyritic. The average grain size is about 0.5 mm. The phenocrysts consist of subhedral or anhedral grains of orthoclase, subhedral or anhedral plagioclase, and anhedral quartz that range in maximum dimension from 0.1 to 1 mm. The groundmass consists of anhedral orthoclase and quartz, subhedral and anhedral plagioclase and biotite, and minor accessory minerals. As compared with the quartz monzonite, the aplitic rock has more orthoclase and quartz and less plagioclase, biotite, and accessory minerals. The modes (volume percent) of two samples of aplitic rock are listed with those of the quartz monzonite in table 11.

The quartz monzonite and the aplitic rock are spatially and mineralogically related and, therefore, are considered to have essentially the same origin and age. Some of the aplitic rock is a chilled border facies of the Montezuma Quartz Monzonite stock and some is considered to be younger than the quartz monzonite because dikes of aplitic rock cut the quartz monzonite. Probably, the aplitic dikes represent the intrusion of magma late in the period of the emplacement and cooling of the Montezuma stock.

DIKES

A series of small dikes, consisting of rhyolite porphyry, latite porphyry, and augite or hornblende diorite, all considered to be of Tertiary age, occur at the surface in the vicinity of the tunnel line. Most of the dikes were emplaced in the Precambrian rocks around the Montezuma stock. The exceptions are latite porphyry sills in the Dakota Group near the West Portal and augite diorite dikes near the southern mapped limit of the North Fork fault. (The distribution of the dikes more than 10 feet wide is shown on pl. 1.) Two dikes were intersected by the tunnel: a rhyolite porphyry dike near station 258+00 and an augite diorite dike near station 773+00.

The dikes range in width from less than 1 to 200 feet and in length from about 1 to 2,000 feet. The average dike is about 10 feet wide and 100–200 feet long.

The dikes were emplaced primarily in the Precambrian metasedimentary rocks. One exception is two small dikes that were noted in the Precambrian granite about 1,000 feet southwest of Geneva Lake. The other exception is the sills in the Dakota Group mentioned above. The contacts of the dikes with the country rock are sharp, and there is commonly a chilled zone, less than half an inch wide, at the border of the dike. The emplacement of the dikes was controlled by preexisting structure. The chief control was the foliation of the Precambrian rocks. This is shown by the strike-frequency diagram (fig. 1) of 18 dikes measured between the Montezuma stock and the Montezuma shear zone. Most dikes in this area strike between N. 10° and 50° E., which is the same as the strike of the foliation as shown by the contour diagram, figure 4*A*. Joints and shear zones also controlled the attitude of some of the dikes. An example of joint control of dike emplacement is the dike about 2,000 feet west of the Buena Vista mine (about station 600+00). At its south end the dike is parallel to the foliation. At about half its length the strike changes abruptly at that point and parallels a major direction of jointing. Dikes, most of them too small

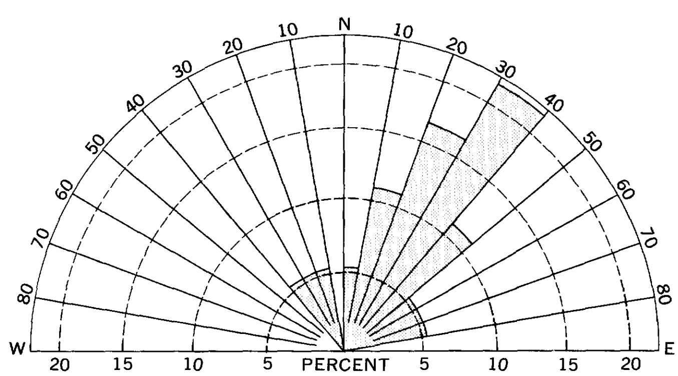


FIGURE 1.—Strike-frequency diagram of 18 Tertiary dikes that cut Precambrian rocks between the Montezuma stock and the Montezuma shear zone.

to be shown at the map scale, commonly occur in and parallel to the major shear zones. An example is the small dike on the Continental Divide between Santa Fe Peak and Sullivan Mountain.

The dikes may be classified on the basis of their mineralogy and relative age into three groups: augite and hornblende diorite, latite porphyry, and rhyolite porphyry. In mapping (pl. 1), distinction was made only between the diorite dikes and the rhyolite-latite porphyry dikes.

AUGITE AND HORNBLENDE DIORITE

The augite and hornblende diorite dikes occur as a series of short dikes along a northwest-trending line from the south end of the North Fork fault, as mapped, to the east shoulder of Landslide Peak, on the northeast and southwest sides of Collier Mountain farther west, and on the southwest-trending ridge from Porcupine Peak. In outcrop, the rock is dark brownish gray or dark greenish gray. On fresh surfaces the rock is dark gray. The texture is fine grained to aphanitic and equigranular to porphyritic. The phenocrysts are laths of plagioclase feldspar and subhedral crystals of augite or hornblende, with maximum dimension of about 4 mm.

Under the microscope, the rock is seen to consist of almost equal proportions of plagioclase and ferromagnesian minerals and 5–10 percent magnetite. The plagioclase is anhedral to subhedral, twinned, and commonly altered, at least in part, to sericite. Grain size of the plagioclase, exclusive of the phenocrysts, is as much as 2 mm in maximum dimension and averages 0.5 mm. The composition of the plagioclase ranges from An_{40} to An_{50}, the more basic plagioclase generally forming the phenocrysts. The ferromagnesian minerals are augite or amphibole. They occur in anhedral to subhedral crystals and have a maximum length of 2 mm and an average length of about 0.2 mm. Augite is the most abundant ferromagnesian mineral in the eastern dikes. What hornblende (uralite) is present is apparently the result of the alteration of the augite. The hornblende, in turn, has been partly altered to chlorite. Hornblende is most abundant in the two dikes on Collier Mountain; no augite was noted in these dikes. Magnetite — both as a primary constituent in subhedral grains up to 1 mm in diameter and as an alteration product of the augite or hornblende in very fine grains of less than 0.1 mm in diameter — constitutes 5–10 percent of the rock. Scattered anhedral grains of quartz, generally less than 0.1 mm in diameter, usually constitute less than 1 percent of the rock. Anhedral to subhedral apatite occurs in trace amounts.

Table 12 gives the modes (volume percent) of three samples of the augite and hornblende diorite. In determining the modes, the alteration products were included with the primary mineral from which they were derived.

TABLE 12. — *Modes (volume percent) of samples of augite and hornblende diorite*

[Leaders indicate looked for but not found; Tr., trace]

Sample No.	57–CR60	81–CR60	14–CR61
Plagioclase	46	48	44
Augite	45	42	....
Hornblende	....	....	44
Quartz	1.1	.2	.9
Magnetite	8	9	11
Apatite	Tr.	Tr.	Tr.

DESCRIPTION OF SAMPLES

57–CR60. From dike at south end of North Fork fault.
81–CR60. From dike on south side of the head of Kirby Gulch.
14–CR61. From dike on southwest side of Collier Mountain.

LATITE PORPHYRY

The distinction between the latite porphyry and the rhyolite porphyry dikes was made on the basis of the megascopically visible phenocrysts. In the latite porphyries the predominant phenocrysts are plagioclase feldspar; in the rhyolite porphyries the predominant phenocrysts are quartz.

The latite porphyry dikes are light to dark gray or greenish gray and fine grained to aphanitic and porphyritic. The typical phenocrysts are plagioclase feldspar and quartz, but some dikes also contain phenocrysts or orthoclase, biotite, hornblende, and sphene. The phenocrysts comprise from 10 to 75 percent (by volume) of the rock. The groundmass consists of orthoclase, quartz, and plagioclase with lesser amounts of biotite and sometimes hornblende. The plagioclase in the phenocrysts ranges in composition from An_{20} to An_{35}. All the plagioclase shows some alteration, and most of the ferromagnesian minerals are usually altered, at least in part, to chlorite. The common accessory minerals are magnetite, apatite, and sphene.

RHYOLITE PORPHYRY

The rhyolite porphyry dikes are characterized by phenocrysts of quartz. These dikes are light gray or light brownish gray, aphanitic and porphyritic. In addition to the quartz phenocrysts, phenocrysts of orthoclase, biotite, and plagioclase may be present. The quartz phenocrysts are generally less than 2 mm in diameter. The other minerals that occur as phenocrysts may have a maximum dimension as much as 4 mm. The phenocrysts comprise about 5 to 25 percent of the rock. The groundmass consists of a microgranular mixture of quartz and orthoclase and lesser amounts of plagioclase and biotite. The common accessory minerals are apatite and magnetite. Commonly, the feldspar of the groundmass is somewhat altered to clay minerals, and the biotite, at least in part, to chlorite.

AGE

The geologic and relative age of the Tertiary igneous rocks of the Front Range have been discussed in considerable detail by Lovering (1935, p. 26–42) and by Lovering and Goddard (1938, p. 38–68; 1950, p. 44–50). The limited extent of this investigation can contribute little to their conclusions. According to Lovering and Goddard (1950, pl. 2), the oldest Tertiary igneous rocks are the augite and hornblende diorite dikes. These dikes are correlative with some of the oldest Tertiary igneous rocks in the Front Range and are included in their group 2. The latite porphyry dikes are within their groups 4, 5, and 6. Their group 6 also includes the Montezuma stock. The rhyolite porphyry dikes are within their group 7. They (1950, p. 47) concluded that the intrusion of the igneous rocks of the Front Range took place in Paleocene and early Eocene time.

SURFICIAL DEPOSITS

Surficial deposits are shown on the geologic map (pl. 1) in only those areas, such as the major stream valleys, in which they completely obscure the bedrock. Because the purpose of this investigation was to study the character and structure of the bedrock, no effort was made to classify and map the surficial deposits where there was reasonable assurance of the character of the bedrock below. The surficial deposits include alluvial, glaciofluvial, morainal, talus, landslide, and swamp deposits and mountain-top debris that has resulted from frost action and solifluction. Thin alluvial deposits occur along the lower reaches of the stream valleys and generally overlie older glacial deposits. Glaciofluvial and morainal deposits occur in most of the mountain valleys. Talus deposits have formed at the base of most steep slopes that were oversteepened by glaciation. Landslides have occurred where glacial materials were deposited along valley walls against too steep slopes and where streams undercut glacial deposits or altered and broken bedrock. Swamp deposits have formed in most of the stream valleys as a result of the damming of the drainage by glacial deposits and by beavers. At most places above the level of glaciation, the mountain slopes are covered by broken rock and soil that have been derived from frost action and solifluction.

STRUCTURE

The rocks along the route of the Roberts Tunnel are extensively folded and faulted. Joints were formed as a result of the folding and faulting, and some faults were mineralized to form veins. The structures of the rocks are primarily the result of tectonic activity during Precambrian and Tertiary time. At least two periods of tectonic activity can be recognized as having occurred during the Precambrian. A sequence of tectonic events — the Laramide revolution — can be recognized as having occurred in Late Cretaceous and Tertiary time. The emplacement of igneous rock accompanied the folding and faulting in both Precambrian and Tertiary time and not only was influenced by the preexisting structural features but also modified them. The location and attitudes of the veins were also controlled by preexisting structural features.

The geologic structure along the route of the Roberts Tunnel has been discussed by Wahlstrom and Hornback (1962) and by Warner and Robinson (1967). The reader is referred to these reports for more detailed discussions of the origin of the major structural features.

In the following discussion of these features, the Precambrian and Laramide folds and faults are considered separately. In the study of the jointing, it was not possible to distinguish Precambrian from Laramide joints, so all joints are discussed together. The veins and associated wallrock alteration are considered also in this section on structure.

One purpose of the Roberts Tunnel project was to compare the geology as determined at the surface with the geology as determined in the tunnel. In order to make the comparison between the geology at the surface and that in the tunnel, data for structural elements were compiled on statistical diagrams for different geologic domains which are defined chiefly on the basis of rock units. The diagrams include strike-frequency diagrams and Schmidt equal-area diagrams constructed according to methods described for joints by Billings (1942, p. 108–114).

PRECAMBRIAN STRUCTURAL FEATURES

Most of the route of the Roberts Tunnel traverses rocks of Precambrian age. The construction of the tunnel and the resulting geologic studies have afforded an unusual opportunity to study the Precambrian structural features of the Front Range in three dimensions.

The Precambrian structures recognized are folds and faults and the probable associated joints. The folds are defined by the distribution of lithologic units and, more importantly, by the foliation and lineation of the layered Precambrian rocks. The Precambrian faulting is difficult to recognize because Laramide faulting has often occurred along the same zones. Precambrian faults can be recognized in several areas by the offset of lithologic units, intrusion of Precambrian igneous rocks along well-defined zones, and by cataclasis and recrystallization of the Precambrian rocks. Precambrian joints are difficult to recognize and can only be definitely established where they have controlled the emplacement of Precambrian igneous rocks. The Precambrian Boulder Creek and Silver Plume Granites show cataclastic or flow foliation, which, in general, is related to the structure of the enclosing metasedimentary rocks.

The work by Moench, Harrison, and Sims (1962), and others, in the Idaho Springs–Central City area in the Front Range has clearly demonstrated the relations of two periods of Precambrian deformation. Their interpretation of the two periods of deformation was chiefly based on the geometric distribution of the lithologic units, the mineralogic and geometric relationships of folds and related linear elements, and the age relationships of the intrusive rocks to each of the fold systems. They concluded that the older period of deformation was characterized by a major fold system with axes that bear north-northeast and that the younger period of deformation was characterized by a relatively minor fold system, with axes that bear N. 55° E., and intense cataclasis (Moench and others, 1962, p. 56–57).

In the Roberts Tunnel area the two periods of Precambrian deformation, as described by Moench, Harrison, and Sims (1962), cannot be recognized. An older fold system is not well defined, and at least two principal directions of folding can be recognized; these may represent different periods of folding or a major difference in the principal direction of stress in different areas during a single period of deformation. A younger period of deformation was chiefly a period of cataclasis, and no folds can be definitely attributed to it.

The terminology used in this report for the structural elements recognized in the Precambrian rocks corresponds to the definitions of Moench, Harrison, and Sims (1962, p. 39–40).

FOLDS

The outcrop pattern of the layered Precambrian rocks suggests a broad, asymmetrical, plunging fold complex. The linear elements associated with the folds indicate that the major fold axes plunge north-northeast or northwest. The tunnel trends northwest, which is both parallel and at a right angle to the axes of the major folds. The limited mapping at the surface, which was controlled by the location of the tunnel, does not, on the basis of the geometry of the lithologic units, clearly define the major folds. The directions of the trends of the principal fold axes have, therefore, been determined chiefly from the mapping and from the statistical plots of the planar and linear elements. The planar elements that are mapped and compiled include the foliation, which is the preferred mineral orientation of the layered rocks (and is in nearly all instances parallel to the compositional layering); the primary flow structure in the intrusive rocks, which is expressed by the planar alinement of tabular minerals or inclusions of wallrock; and the subparallel closely spaced fractures, which are characteristic of the rocks that have been sheared. The linear elements that are mapped and compiled include elongate minerals (or mineral aggregates), axes of minor folds, boudinage, and rodding of minerals.

The only major fold that could be clearly defined in the field is an asymmetrical syncline between the Montezuma stock and the Montezuma shear zone. This fold is in the sillimanitic biotite gneiss and schist and is defined by the attitude of the foliation and the plunge of the lineation. Another major fold is suggested by the outcrop pattern, the foliation, and the lineation of the migmatite unit at the East Portal and to the west. The data available are interpreted as indicating this fold to be a large northeastward-plunging anticline with the amphibolite and related rocks forming the core of the anticline.

Minor folds are abundant throughout the area. Their distribution and geometry are chiefly related to the relative competency of the different layered units. The minor folds in the amphibolite and related rocks, the biotite gneiss and schist, and the hornblende gneiss range from a few inches to several feet across. Typically, these folds are open, and, although their axial planes dip steeply, they are rarely overturned or recumbent. The minor folds in the migmatite, in the sillimanitic biotite gneiss and schist, and in the schist bands of the other units are typically closed, the axial planes range in dip from 0° to 90°, and they are commonly overturned. The widths of the minor folds in the schistose unit range from less than an inch to a few feet. Many of the minor folds are considered to be drag folds that resulted from differential movement between units of different competency during the period of major folding.

The data on Precambrian folding, as well as on other Precambrian structures, were compiled by geologic domains. The domains include the Williams Range thrust plate, the areas north and south of the Montezuma stock, the area between the Montezuma stock and the Montezuma shear zone, the area between the Montezuma shear zone and the North Fork fault zone, and the area between the North Fork fault zone and the East Portal (which includes the Boulder Creek stock). Plots of the poles of the lineations and foliations were compiled for each do-

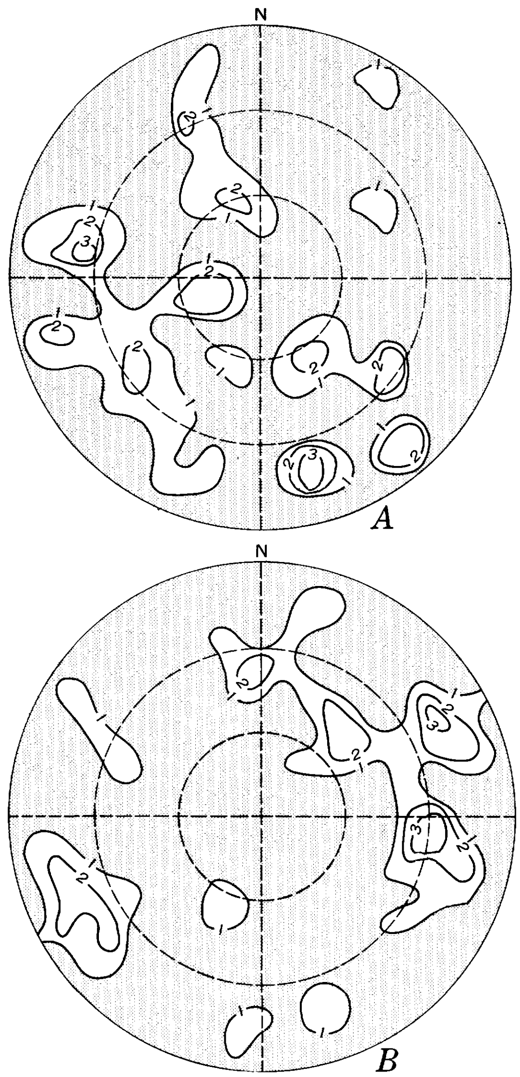


FIGURE 2. — Contour diagrams of the foliation and mineral lineation of the Precambrian metasedimentary rocks of the Williams Range thrust plate. *A*, Foliation (contoured on number of poles, 39 poles, lower hemisphere). *B*, Mineral lineation (contoured on number of poles, 34 poles, lower hemisphere).

main. Where minor folds occurred, plots of poles of the axial planes and the plunge of the axes were compiled.

The Williams Range thrust plate consists of a sequence of interlayered hornblende gneiss and sillimanitic gneiss and schist and Silver Plume Granite, which are considerably altered and poorly exposed. No major fold structure could be determined in this area. In general, the foliation strikes northwest and dips northeast or southwest or strikes northeast and dips northwest (fig. 2*A*). Mineral lineations plunge 20°–50°, N. 50°–70° E. or S. 50°–70° W.; and 35° E. to S. 80° E. (fig. 2*B*). The relative ages of the lineations, as determined by the superposition of biotite on hornblende lineation, indicate that the southwest- or northeast-plunging lineations is older than the east to southeast lineation.

The Precambrian folds north and south of the Montezuma stock and east of the eastern exposure of the Williams Range thrust fault have been modified by numerous Tertiary faults and by the intrusion of the stock. The rocks in the area are the hornblende gneiss, the sillimanitic biotite gneiss and schist, and the Silver Plume Granite. The foliation south of the stock, in general, strikes north or northeast (pl. 1; fig. 3*A*) and dips either east or west.

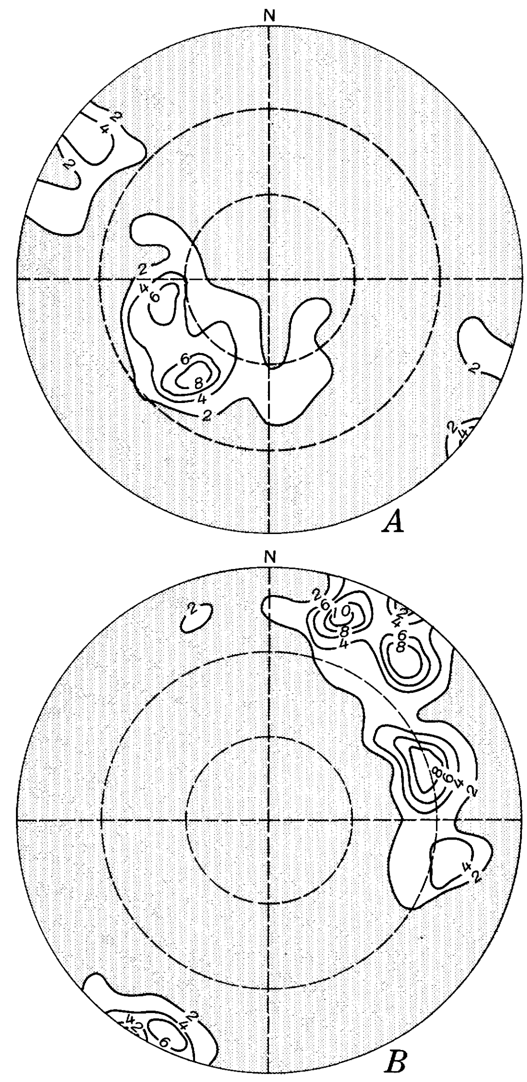


FIGURE 3. — Contour diagrams of the foliation and mineral lineation of the Precambrian rocks north and south of the Montezuma stock. *A*, Foliation (contoured in percent, 169 poles, lower hemisphere). *B*, Mineral lineation (contoured in percent, 98 poles, lower hemisphere).

The lineations plunge at low angles southwest or northeast (fig. 3*B*). North of the stock the foliation strikes more northwestward and dips northeast. The linear elements plunge northeast. Observations south of the stock indicate that the linear elements which plunge about 20°, N. 20° E. or S. 30° W., are older than the linear elements which plunge about 35°, N. 70° E.

Between the Montezuma stock and the Montezuma shear zone, the chief Precambrian unit is the sillimanitic biotite gneiss and schist. In this area the unit contains only small masses of Silver Plume Granite. The foliation defines an asymmetrical syncline (pl. 1), the axis of which trends about N. 10° E. across the tunnel line. Within half a mile north or south of the tunnel line the axis turns and trends more northwestward. The foliation on the southeast limb of the syncline dips less steeply than on the northwest limb (fig. 4*A*). The mineral lineations plunge 40°, N. 10° E. and are believed to represent the plunge of the axis of the syncline at about the tunnel line (fig. 4*B*). The attitude of the axial planes of minor folds (fig. 4*C*) on either limb of the syncline, in general, is parallel to the attitude of the foliation, and the axes of minor folds plunge about parallel to the plunge of the mineral lineations.

The Precambrian unit between the Montezuma shear zone and the North Fork fault zone at the surface is the biotite gneiss and schist unit, which is intruded by several bodies of Silver Plume Granite. Because of the intrusion of the granite, which probably complicated the Precambrian folds, and the general lack of exposures in the eastern part of this domain, no major fold axis was identified at the surface, although several small folds were noted. In this interval underground, however, there is an overturned anticline outlined by two layers of microcline gneiss that do not crop out at the surface (pl. 1).

The foliation of metasedimentary rock in the central and western parts of this domain strikes northwest and dips southwest (fig. 5*A*). In the eastern third of this domain, the foliation is more north or northeast, at about right angles to the trend of the tunnel, and has a westerly dip.

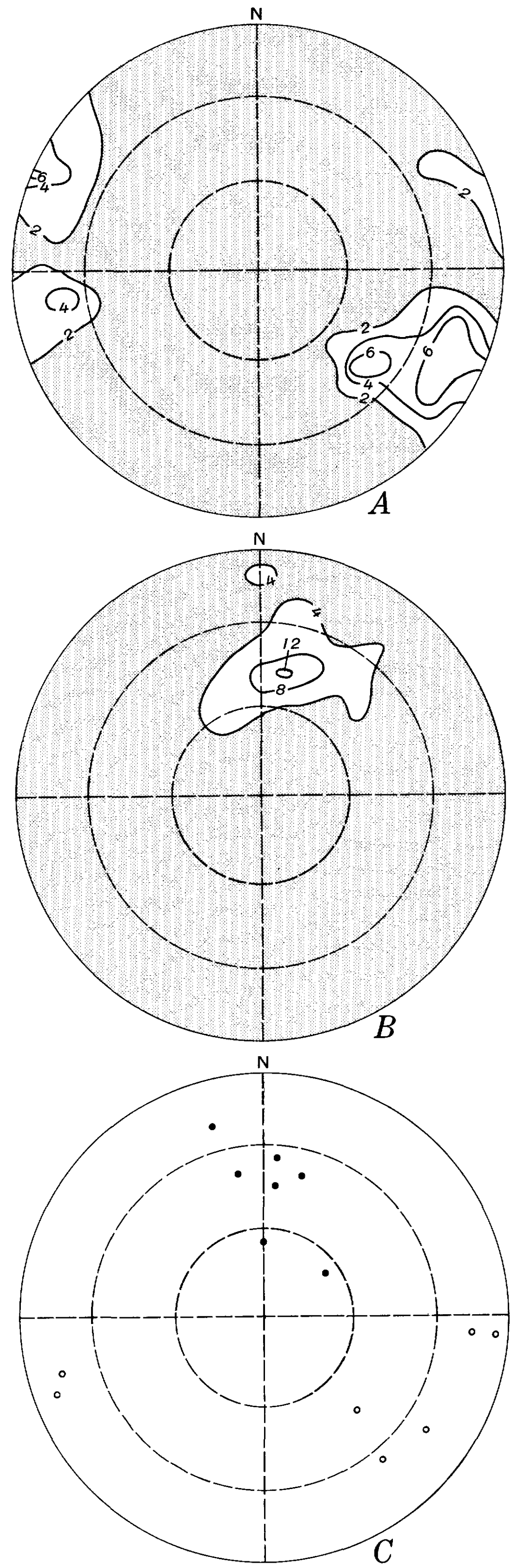


FIGURE 4. — Contour diagrams of the foliation and mineral lineation and point diagram of minor folds in the Precambrian rocks between the Montezuma stock and the Montezuma shear zone. *A*, Foliation (contoured in percent, 167 poles, lower hemisphere). *B*, Mineral lineation (contoured in percent, 154 poles, lower hemisphere). *C*, Point diagram of axes of minor folds (circles indicate attitude of axial planes, 7 poles; dots indicate plunge of axes, 7 poles).

Mineral lineations at the surface plunge 45°, N. 70° W. (fig. 5*B*) and are in agreement with the 50°,

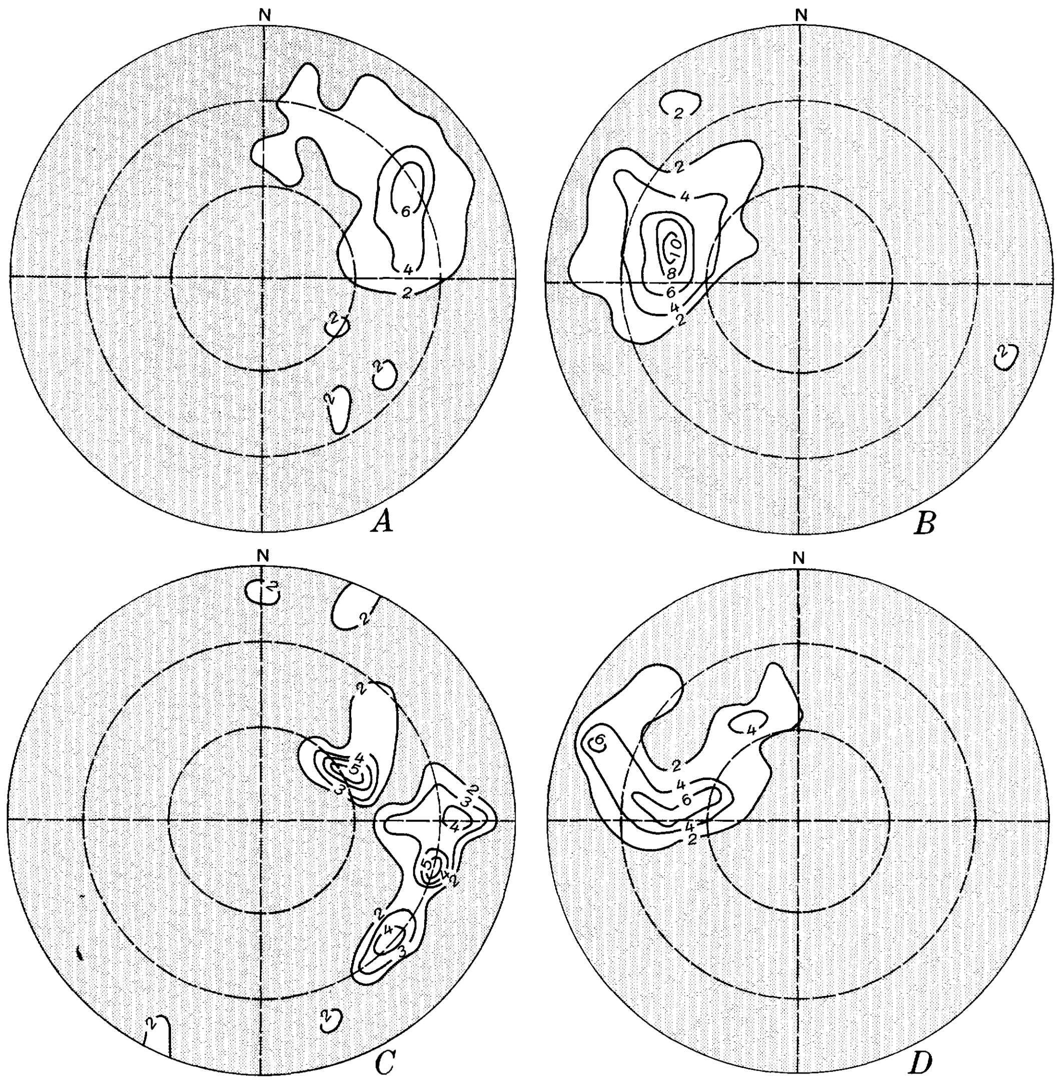


FIGURE 5. — Contour diagrams of the foliation, mineral lineation, and axial planes and plunge of the axes of minor folds in the Precambrian rocks between the Montezuma shear zone and the North Fork fault zone. *A*, Foliation (contoured in percent, 338 poles, lower hemisphere). *B*, Mineral lineation (contoured in percent, 291 poles, lower hemisphere). *C*, Axial planes of minor folds (contoured on number of poles, 51 poles, lower hemisphere). *D*, Plunge of axes of minor folds (contoured on number of poles, 56 poles, lower hemisphere).

N. 70° W. axis of the fold outlined by the layers of microcline gneiss mapped underground. Unfortunately, the trace of the axial plane of this fold could not be identified at the surface.

The attitudes of the axial planes (fig. 5*C*) and the plunge of the axes (fig. 5*D*) of the minor folds are not all approximately parallel to the major fold axis, as defined by the foliation and lineation at the surface and the mapping in the tunnel. The axial planes of several of the folds strike northeast and dip northwest, and the axes plunge about 70°, N. 30° W. One of these minor folds is partly outlined by the layer of amphibolite at the tunnel line between stations 750+00 and 800+00. From the field evidence—chiefly the superposition of mineral lineations — the folds represented by axes plunging N. 30° W. are inferred to be younger than the folds represented by axes plunging N. 70° W.

Between the North Fork fault zone and the east contact of the Boulder Creek Granite stock are few outcrops in those areas mapped as biotite gneiss and schist. Underground, between the stock and the North Fork fault zone, the mapping indicated that the structural feature in this area was probably the east limb of the overturned anticline west of the fault. The outcrops in the area of the large inclusion in the stock are mostly of dikes of granite, and the structure of the inclusion could not be determined.

Between the Boulder Creek stock and the East Portal of the tunnel, the folding is complicated by the intrusion of Silver Plume Granite and by extensive faulting, and evidence is obscured by much cover. The migmatite unit is folded into what appears to be a north- to northeast-plunging overturned anticline, with the amphibolite and related rocks forming the core. The plots of the foliations and the lineations (fig. 6*A*, *B*) measured in the migmatite show that statistically the foliation strikes northwest to northeast and dips northeast or northwest. The mineral lineations plunge mostly 45°, N. 5° E. The plots of the foliations and the lineations (fig. 6*C*, *D*) measured in the amphibolite and related rocks show that statistically the foliation strikes from about N. 10°W. to N. 30° E. and dips steeply in either direction, and that most of the mineral lineations plunge about 10°, N. 10° W.; 40°, N. 40° W.; and 45°, S. 35° W. No superimposed lineations were noted, and it could not be clearly determined if the different directions of the plunge of the lineations represented more than one period of folding.

The structure in the microcline gneiss unit between the migmatite unit and the Boulder Creek stock is, in general, similar to that in the migmatite unit. Only one direction of plunge of a mineral lineation was observed in the area of microcline gneiss and that was noted on a schist layer. The foliation of the microcline gneiss strikes, in general, east to north-northeast and dips northwest (fig. 6*E*).

The Precambrian folds at the east end of the Roberts Tunnel, on the basis of the above observations, is assumed to have produced a slightly overturned anticline that plunges northward. The proof of the existence of this fold will depend upon additional regional mapping.

FAULTS

The Precambrian faults are difficult to recognize, and ages of most cannot be established by direct evidence. The faults or shear zones are wide areas of cataclasis or granulation, mylonite, or recrystallized gneiss cut by sharply defined faults. Superimposed on the Precambrian faults or shear zones are faults of probable Tertiary age, along many of which have occurred mineralization and hydrothermal alteration that mask the features attributed to the Precambrian faulting. A summary of the distribution and characteristics of the Precambrian faults or shear zones along the Colorado mineral belt, including a discussion of their origin and basis of age, was published by Tweto and Sims (1963).

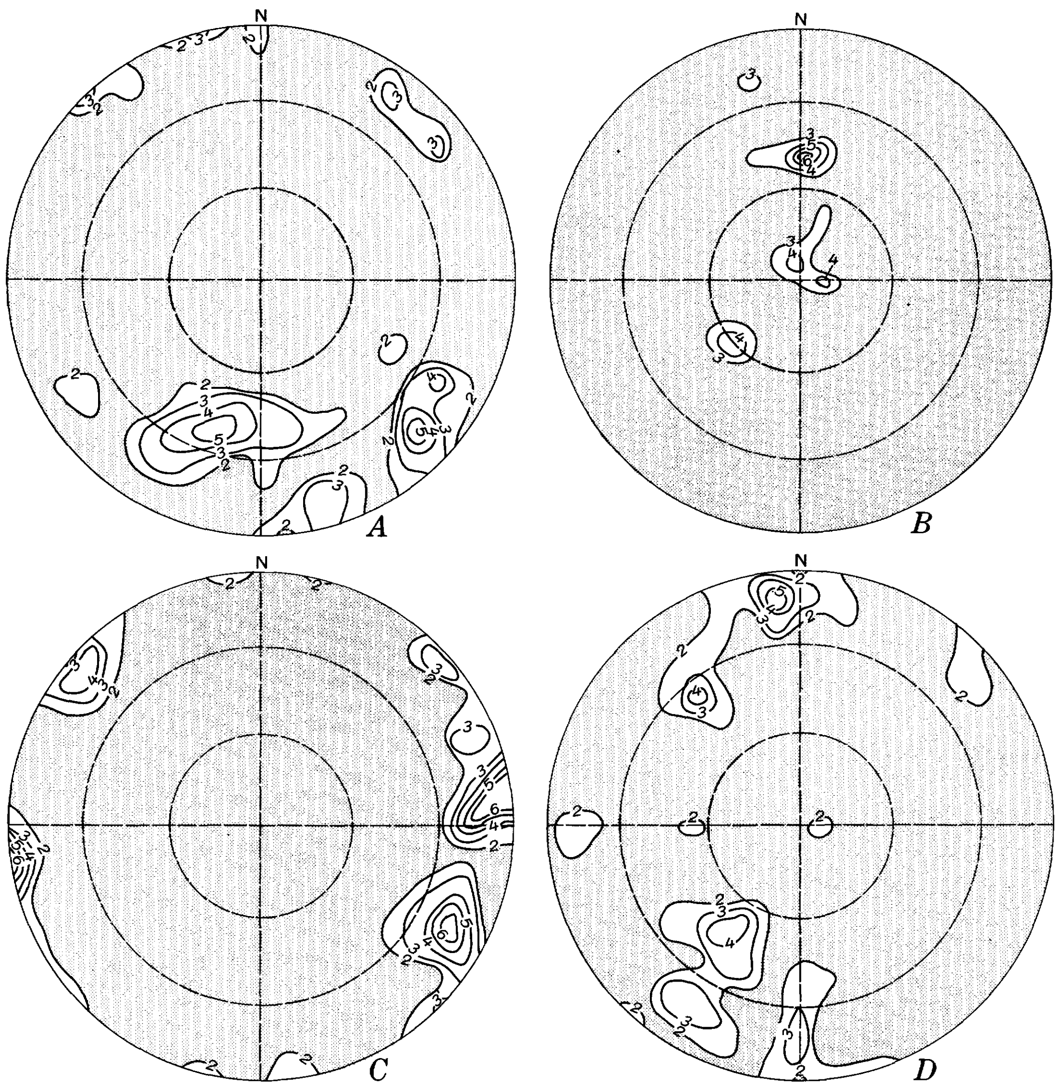
The typical Precambrian fault or shear zone of this area is a zone, a few hundred feet to several thousand feet wide, of moderate to intense faulting and shearing. Most determinations of the contacts with the country rock were made arbitrarily — that is, most contacts were picked where the cataclasis has not significantly altered the original fabric or mineralogy of the rock. Locally, the contact may be a sharp fault or a zone of mylonite. The rock within the zone is commonly sheared, altered, and recrystallized. Within a fault or shear zone may be blocks of relatively unsheared or altered country rock with maximum dimensions of as much as several hundred feet. Typically, dikes of Precambrian igneous rock (that may or may not show evidence of cataclasis), dikes of Tertiary igneous rocks, and Tertiary faults and veins occur in and parallel to these Precambrian fault or shear zones.

Four major zones of Precambrian faulting or shearing were recognized in the Roberts Tunnel area (pl. 1). These are in the Williams Range thrust plate along Frey Gulch and to the south, between Santa Fe Peak and Sullivan Mountain east of the Montezuma stock, along Bruno Gulch west of the Boulder Creek stock, and near the East Portal of the Roberts Tunnel. Other Precambrian faults or shear zones probably exist but were not recognized because of the limited area mapped or because they were masked by the Laramide faulting and mineralization.

FREY GULCH SHEAR ZONE

The Frey Gulch shear zone trends almost due north, or a little west of north, across the tunnel line just east of the Williams Range thrust fault. The zone is about 1,500 feet wide and has indefinite boundaries. The age of the zone is inferred from the characteristics of the faulting, shearing, and recrystallization of the rock along the zone, and even these characteristics are not distinct because of later shearing and alteration that occurred along this zone during and after the formation of the Williams Range thrust fault (pl. 1).

The Precambrian units in the shear zone are the hornblende gneiss and small irregular bodies of Silver Plume Granite and pegmatite. The hornblende gneiss, which in this area consists of alternating 1- to 10-foot-wide layers of medium-grained hornblende-biotite-plagioclase gneiss and biotite-quartz-plagioclase gneiss, has been intensively sheared and locally altered. South of the Snake River the original foliation of the hornblende gneiss layers can be recognized locally; it has an average attitude of about N. 25° W., 50° E. Each mineral grain in this rock,



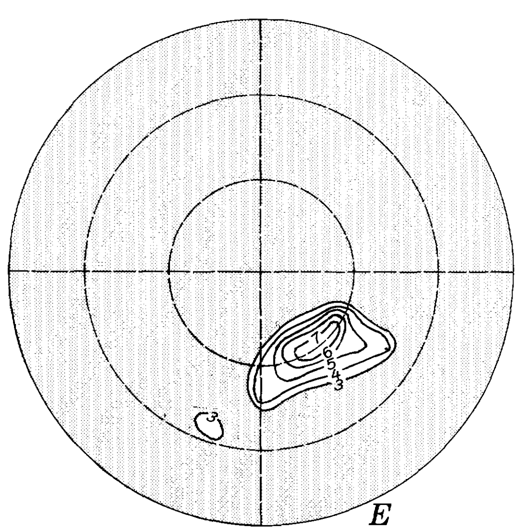


FIGURE 6. — Contour diagrams of the foliation and mineral lineation of the Precambrian rocks between the Boulder Creek Granite stock and the East Portal. *A*, Foliation in migmatite (contoured in percent, 130 poles, lower hemisphere). *B*, Mineral lineation in migmatite (contoured on number of poles, 65 poles, lower hemisphere). *C*, Foliation in amphibolite and related rocks (contoured in percent, 208 poles, lower hemisphere). *D*, Mineral lineation in amphibolite and related rock (contoured in percent, 136 poles, lower hemisphere). *E*, Foliation in microcline gneiss (contoured on number of poles, 54 poles, lower hemisphere).

however, has been streaked almost north-south along numerous microscopic shears. The biotite of the biotite gneiss has been rotated and reoriented as a result of shearing, and the original foliation is rarely recognizable. The quartz and feldspar in both rock types show microscopic fracturing across the grains and granulation along the grain boundaries. The grains have been recrystallized and recemented. North of the Snake River most of the rock in the shear zone is a mylonite, and only locally can the original characteristics of the rock be recognized. In one outcrop the characteristic mineral assemblage of the Silver Plume Granite could be recognized, but the typical tabular microcline grains and the biotite had been sheared, reoriented, and recrystallized, giving the rock a distinct cataclastic foliation.

MONTEZUMA SHEAR ZONE

The Montezuma shear zone, which is 600 feet or more wide, trends about N. 20°–30° E. across the tunnel line between Santa Fe Peak and Sullivan Mountain. This shear zone is not exposed in the tunnel; it apparently terminates against the eastward extension of the Montezuma stock. North of the tunnel line the shear zone parallels the east boundary of the Montezuma stock, and in part probably controlled its emplacement, and is a continuation of the Decatur-Peruvian shear zone of Ulrich (1963) farther to the north.

The shear zone is considered to be the boundary between the sillimanitic biotite gneiss and schist on the west and the biotite gneiss and schist to the east. It is not possible from a study of the rocks along the shear zone (exposures are extremely poor, as would be expected) to tell whether this change from one rock type to the other is the result of offset along the fault, or whether the units are gradational, as it would appear from their composition (tables 4, 6), and the change in lithologies and the position of the fault are coincidental. The attitudes of the foliation and lineation of the metasedimentary units on each side of the fault are strikingly different (figs. 4, 5). This, again, may be the result of faulting or may be merely the result of folding.

The Precambrian rocks within the shear zone are intensely sheared biotite gneiss and schist and Silver Plume Granite. The intensity of shearing along and across the shear zone varies from outcrops of gneiss or granite only slightly sheared, in which the original foliation and lineation may be recognized, to cataclastic gneiss, in which the foliation is the result of the shearing, to a mylonite, in which the original composition and foliation cannot be recognized. Several dikes of Silver Plume Granite too small to be shown at the map scale (pl. 1) occur in, and trend parallel to, the shear zone, which would indicate that the shear zone controlled their emplacement. All these dikes show some degree of cataclastic structure, which would indicate that movement continued along the zone after their emplacement.

NORTH FORK FAULT ZONE

The North Fork fault zone is not clearly exposed on the surface above the Roberts Tunnel, but the trace of a probable Laramide fault along this zone is discernible on aerial photographs of the region and is indicated by offset of a diorite dike. The general trend of the fault zone is about N. 40° E. The flaser gneisses, breccia, and mylonite that characterize the zone in Hall valley (Wahlstrom and Kim, 1959, p. 1235) were not observed at the surface in the vicinity of the tunnel, an area of poor exposures, nor in the tunnel below the fault trace.

The character of the Precambrian rocks and their structure make the identification of the North Fork fault zone in the vicinity of the tunnel difficult. The metasedimentary rocks on either side of the projection of the fault zone from Hall valley are biotite gneiss and schist. In Hall valley the fault is nearly normal to the foliation, and movement was confined to a relatively narrow zone. In the vicinity of the tunnel the foliation is parallel to the trend of the shear zone, and the movement was possibly dispersed over a wide zone along the overturned limb of the large anticline west of the Boulder Creek stock. The many slip surfaces parallel to the foliation noted in this part of the tunnel may be due in part to Precambrian faulting. The Boulder Creek stock east of the projection of the shear zone has the characteristic structure of many Boulder Creek plutons, which some authors (Wells and others, 1964, p. O12) have considered to be cataclastic; however, this structure is considered to be contemporaneous with, and a result of, the intrusion, not a result of movement along the shear zone. A few small dikes of Silver Plume Granite and pegmatite occur within the area of projection of the fault zone, but they do not exhibit the cataclasis of some such dikes in the other Precambrian shear zones.

The presence of the North Fork fault zone in the vicinity of the tunnel is presumed on the basis of projection of the strong fault zone exposed in the Hall valley area and on the probable occurrence of the Laramide fault along this projection in the vicinity of the tunnel.

EAST PORTAL SHEAR ZONE

A broad zone of shearing and cataclasis was delineated by surface mapping in the vicinity of the East Portal. The zone is poorly defined in the tunnel because of later, probably Laramide, faulting along the zone. The zone trends about N. 70° E., and on the north side of the North Fork South Platte River is about 2,000 feet wide. The southern limit was not mapped. The zone is characterized by poorly to well-defined shears parallel, and about 60°, to the foliation of the migmatite unit, and by cataclastic zones in the Silver Plume Granite. Dikes and irregularly shaped bodies of Silver Plume Granite and pegmatite lie in the shear zone. The dikes, in general, trend parallel to the zone and have a distinct flow foliation parallel to the zone, factors which suggest that their emplacement was controlled by the presence of the shear zone. The shearing and recrystallization of some dikes is indicative that some movement took place along the zone after the emplacement of the dikes. In the tunnel the rock in the shear zone is mainly migmatite that is cut by numerous faults, some of which may be of Precambrian origin. The larger faults show gouge and alteration characteristic of faults of Laramide age.

IGNEOUS ROCKS

The Precambrian igneous rock units are similar in mineral composition (p. B10) but are different in structure, which is the main basis for differentiating them in the field. The structure is also one of the criteria used to interpret their age in relation to the major periods of Precambrian deformation.

The foliation in the Boulder Creek Granite stock is the result of the parallel orientation of grains of biotite, the streaking of concentrations of biotite, the stretching (or rodding) of quartz, and (or) the stretching of quartz and feldspar aggregates. Superimposed on these types of foliation is a shear, or cataclastic, foliation that results from the offset of fragments of a single mineral grain along numerous almost microscopic shears. The cataclastic foliation is commonly at an angle to the mineral foliation and is considered to be younger.

The mineral foliation in the Boulder Creek Granite stock is shown on plate 1, and foliation data have been statistically compiled in figure 7*A*. In general, the foliation strikes northeast and dips northwest, about parallel to the foliation of the surrounding metasedimentary rocks. The contacts of the stock are concordant and discordant, yet the foliation of the country rock and of the stock are generally subparallel on each side of both types of contact. Because of relationships such as these and the similarity in the plunge of the lineations in the country rock and the igneous rocks that are equivalent to the Boulder Creek Granite, Harrison and Wells (1959,

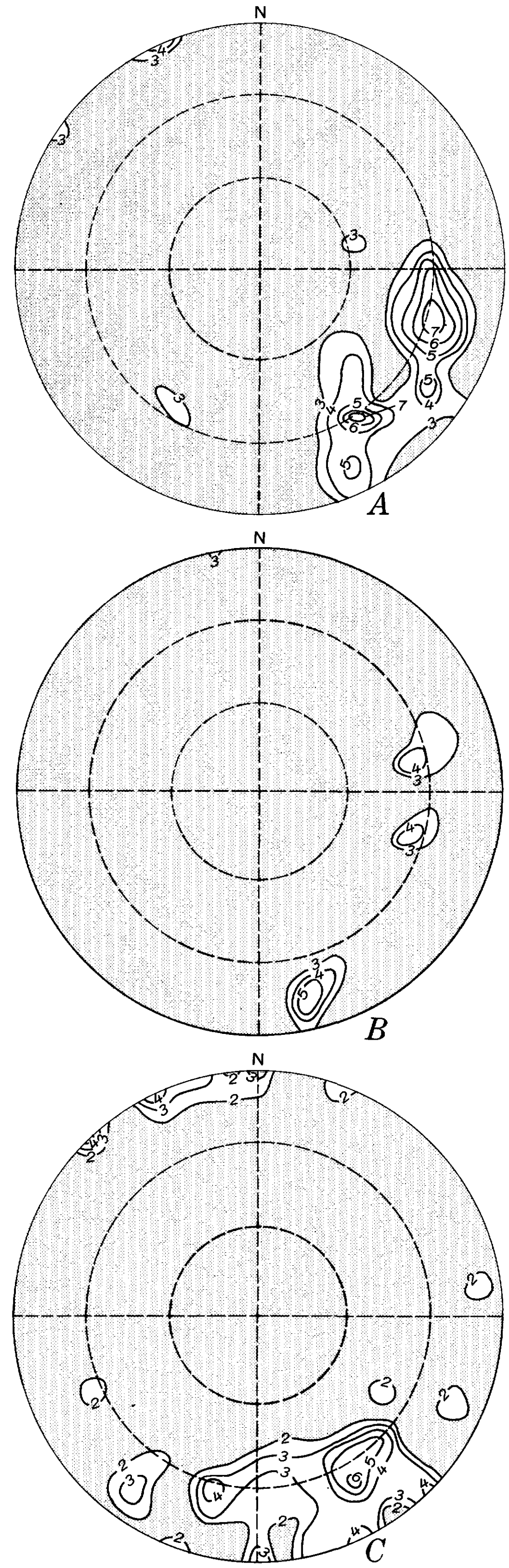


FIGURE 7. — Contour diagrams of the foliation of the Boulder Creek Granite and the Silver Plume Granite. *A*, Boulder Creek Granite (contoured on number of poles, 94 poles, lower hemisphere). *B*, Silver Plume Granite, Montezuma shear zone to North Fork fault zone (contoured on number of poles, 56 poles, lower hemisphere). *C*, Silver Plume Granite, North Fork fault zone to East Portal (contoured in percent, 121 poles, lower hemisphere).

p. 12, 13) and Moench (1964, p. A40) concluded that the foliation was the result in part of plastic deformation during an early period of Precambrian deformation. They also recognized that the foliation in part might have resulted from flow at the time of emplacement of the igneous rock. Wells, Sheridan, and Albee (1964, p. O11, O12) considered the foliation of the Boulder Creek Granite to be largely of cataclastic origin at the time of intrusion of the granite.

The foliation in the numerous bodies of Silver Plume Granite is chiefly the result of the parallel orientation of feldspar laths. Adjacent to contacts of the granite with the country rock, where the granite has apparently assimilated some of the country rock, the percentage of biotite increases, and the biotite grains are generally oriented parallel. In the central parts of the thicker bodies of Silver Plume Granite, the biotite is generally unoriented. Superimposed locally on the feldspar and biotite foliation is a cataclastic foliation in which the mineral grains have been offset along numerous microscopic shears. The cataclastic foliation is commonly at an angle to the mineral foliation.

The mineral foliation of the Silver Plume Granite bodies is shown on plate 1, and the data have been compiled in figure 7*B* and *C*. Figure 7*B* represents the foliation in the Silver Plume Granite bodies between the Montezuma shear zone and the North Fork fault zone; figure 7*C* represents the foliation of the Silver Plume Granite bodies between the North Fork fault zone and the East Portal. The mineral foliation in the smaller bodies and adjacent to the contacts in the larger bodies of Silver Plume Granite is generally parallel to the contacts, whether these contacts are concordant or discordant. In the central part of the larger bodies, however, the foliation may show diverse attitudes. The maximums on the statistical plots of the foliation, in general, represent the attitudes of the bodies of Silver Plume Granite. The mineral foliation in the Silver Plume Granite is believed to represent a flow foliation (Lovering and Goddard, 1950, p. 28).

LARAMIDE STRUCTURAL FEATURES

The Laramide structural features discussed are the folds and faults that probably had their origin in Late Cretaceous and Tertiary time. The folding, principally the result of the uplift of the mountains and the emplacement of the Montezuma stock, was, in general, simple. The faulting, which occurred over a considerable period of time, was probably also associated with uplift of the mountains and emplacement of the Montezuma stock; faulting continued into late Tertiary time (Holt, 1962).

FOLDS

Folding during the Laramide orogeny, other than drag along faults or that which resulted from the intrusion of the Montezuma stock, can be recognized only in the Jurassic and Cretaceous rocks west of the Williams Range thrust in the western part of the Roberts Tunnel area (pl. 1). The sedimentary rocks along the tunnel line in this area in general strike northwest and dip northeast, about parallel to the strike and dip of the Williams Range thrust (pl. 1). South of the Snake River in the mapped area, the strike of the beds changes to northeast, and the dip, to southeast. This indicates the existence of an anticlinal axis south of the tunnel line that approximately follows the fluvial filled valley of the Snake River west of the projection of the Williams Range thrust fault. The axis probably plunges gently about N. 45° E. The anticline is more clearly illustrated on Lovering and Goddard's plate 2 (1950). Minor flexures, with amplitudes of only a few feet, may be recognized in any of these stratigraphic units.

Between the Williams Range thrust plate and the Montezuma stock, the Cretaceous sedimentary rocks, which have been converted to a brittle hornfels, strike northeast and dip gently northwest (pl. 1). This hornfels unit is correlated in part with the Pierre Shale west of the Williams Range thrust and is believed to have originally dipped east. The intrusion by the Montezuma stock, which metamorphosed this shale, is believed to have reversed the dip of the Williams Range thrust and the shale (Wahlstrom and Hornback, 1962, p. 1493–1498).

FAULTS

Faults mapped at the surface are fractures along which there is evidence of movement, as indicated by gouge, striae, or offset of intersected rock. The faults are considered to be related to the Laramide orogeny if they intersect rock units younger than Precambrian, or if they contain gouge or uncemented or unrecrystallized breccia, or if they are open or show evidence of mineralization or hydrothermal alteration. For the purpose of description the faults — both unmineralized and mineralized — will be considered for different geologic domains along the tunnel line from west to east: these are the faults (1) in the sedimentary rocks from the West Portal to the Williams Range thrust, (2) in the Williams Range thrust, (3) in the Williams Range thrust plate, and (4) east of the Williams Range thrust and west of the Montezuma stock; the faults and veins (5) in the Montezuma stock, (6) in the Precambrian rocks surrounding the stock and west of the Montezuma shear zone, and (7) between the Montezuma shear zone and the North Fork fault zone; and the faults (8) between the North Fork fault zone and the East Portal. The attitude of faults or veins could rarely be observed at the surface, so equal-area diagrams could not be prepared. Underground mapping showed, however, that most of the faults dip steeply; therefore, the strike-frequency diagrams based on the geologic mapping would represent the structural trends of the area.

The faults mapped at the surface between the West Portal and the Williams Range thrust are predominantly high-angle fractures that trend north to northwest parallel to the trend of the Front Range or that trend northeast parallel to the mineral belt (Wahlstrom and Hornback, 1962). They can be recognized chiefly near the West Portal where they intersect sandstone or quartzite of the Dakota Group. In the thick Cretaceous shale between the Dakota Group and the Williams Range thrust fault are an equivalent number of faults (Wahlstrom and Hornback, 1962, p. 1482), but they could not be recognized at the surface. Figure 8 is a strike-frequency diagram of the faults measured at the surface between the West Portal and the Williams Range thrust fault. Only 17 faults were measured at the surface in this interval; however, Wahlstrom and Hornback (1962, p. 1482) reported 688 faults in this interval at tunnel level.

The Williams Range thrust fault is the principal structural feature along the west side of the Front Range and can be mapped for nearly 60 miles, from about 5 miles east of Breckenridge south of the tunnel to north of Kremmling, in Middle Park. Along most of the fault, Precambrian rocks have been superimposed on Cretaceous sedimentary rocks, principally the Pierre Shale. Exposures along the thrust and to either side are generally poor and the location of the thrust is determined chiefly on the basis of

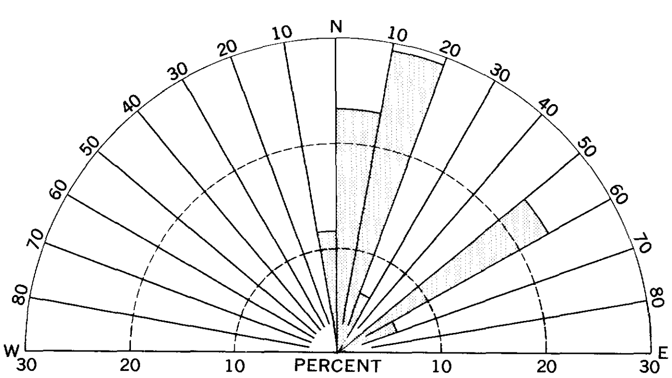


FIGURE 8. — Strike-frequency diagram of 17 faults at the surface in the sedimentary rocks between the West Portal and the Williams Range thrust fault.

float. The relation between the surface trace of the fault and the topography indicates that the fault strikes N. to N. 45° W. and dips 30°–50° NE. for most of its length (Holt, 1962).

The Williams Range thrust fault is crossed by the tunnel line at two places, the fault plane forming a broad syncline between the two points. At the surface and in the tunnel at the western intersection, the thrust is offset by a younger high-angle normal fault, and the thrust fault cannot be directly observed. In the tunnel west of the high-angle fault is a strong flat shear zone, which indicates that the shearing, probably as a result of thrusting, extended at least 120 feet below the thrust. The normal fault contains a breccia of rock fragments that probably were formed as a result of thrusting prior to the formation of the normal fault. Surface mapping north and south of the Snake River indicates that the strike of the thrust prior to the normal faulting was about N. 30° W.

The Williams Range thrust fault crosses the tunnel line again at the surface near the junction of the Snake River with the North Fork Snake River. Cretaceous shale, altered to hornfels and overlain by Precambrian gneiss, crops out on the nose between the two streams and south of the Snake River. The mapping by Ulrich (1963) indicated that the metamorphosed shale is a window with the thrust dipping away in all directions. Near the center of the window the thrust is offset by a north-trending high-angle fault, and on the east the thrust has been destroyed by the intrusion of the Montezuma stock. Ulrich's (1963) mapping also indicated that the thrust was not a simple plane in this area but probably was at least two parallel planes of thrusting. On the ridge extending west from Porcupine Peak is a sliver of Cretaceous shale overlain and underlain by Precambrian rock.

Underground, at station 291+60, the tunnel intersected the east side of the Williams Range thrust. There, Precambrian gneiss abuts against highly fractured, brittle, baked shale. Except for the fracturing in the shale, there is little evidence of any extensive movement, such as breccia or thick gouge at the contact of the gneiss and baked shale. There, the thrust plane strikes northeast and dips about 30° NW.

Faults that cut the thrust plate are generally high-angle normal faults. Few faults were mapped at the surface in this interval because of the extensive valley fill along the tunnel lines. Wahlstrom and Hornback (1962, p. 1484–1485) reported 1,037 faults in the thrust plate at tunnel level that have diverse strikes and an average dip of 60° or more. They reported that 35.2 percent of the rock intersected by the tunnel in the thrust plate consists of brecciated, shattered, and altered rock, most of which is associated with faults. Figure 9 is a strike-frequency diagram showing the strikes of the faults mapped at the surface in the thrust plate.

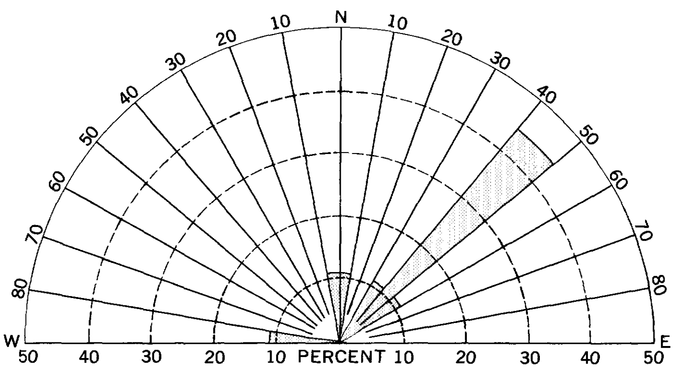


FIGURE 9. — Strike-frequency diagram of nine faults in the Williams Range thrust plate.

Few faults were noted in the metamorphosed shale at the surface east of the Williams Range thrust fault because of poor exposures. The more conspicuous faults were those that offset the thrust plane. In general, these strike north to northeast and dip steeply northwest or southeast. Underground, in the interval between the Williams Range thrust and the Montezuma stock, Wahlstrom and Hornback (1962) reported 189 faults. The average attitude of these is N. 10° E., 35° NW., or approximately the same as the attitude of the Williams Range fault.

Faults and veins in the Montezuma stock range from fractures a few inches wide and a few feet long to shear zones as much as 100 feet wide and a mile long. Most of the faults and veins are 1–2 feet wide and less than 1,000 feet long. The mineralized part of a fault that comprises a vein is rarely more than 2 feet thick, although the associated alteration can extend several feet into the wallrock beyond the fault and vein. From surface mapping it was determined that most faults and veins have a west or east-northeast strike and steep northerly or westerly dips. At tunnel level, the faults and veins have much the same attitudes, although there is more variation (probably as a result of more measurements) as shown by Warner and Robinson (1967). Figure 10 is a strike-frequency diagram of 64 faults and veins measured in the Montezuma stock at the surface.

Numerous faults, shear zones, and veins occur in the Precambrian rock surrounding the Montezuma stock at the surface. It probably can be assumed that

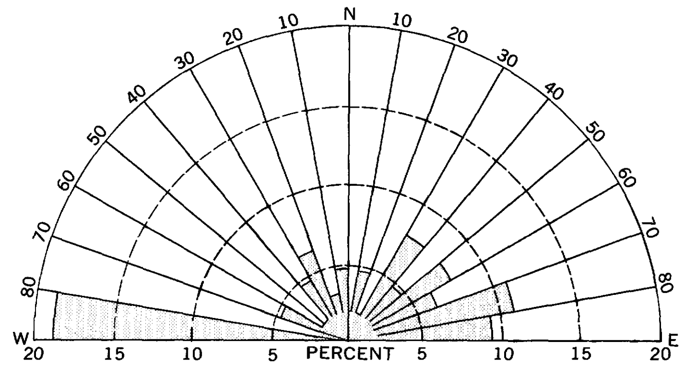


FIGURE 10. — Strike-frequency diagram of 64 faults and veins in the Montezuma stock.

most of the area mapped around the stock — for example, to as far east as station 690+00 — is underlain at depth by the stock, as was shown by the driving of the tunnel. The faults and shear zones mapped in the Precambrian rocks around the stock show evidence of recent movement, such as gouge, breccia, mineralization, and alteration. This interval is in the stock at tunnel level.

Most of the faults and veins in the area surrounding the stock are small, similar in dimension to the faults and veins in the stock. In no place could the amount of displacement along the faults or veins be determined.

Figure 11 is a strike-frequency diagram showing the strike of 97 faults, shear zones, and veins in the Precambrian rocks around the stock and west of the Montezuma shear zone. Figure 12 shows contour diagrams of the attitude of 23 faults and veins in the stock and 75 faults and veins in the surrounding rock. In general, the faults and veins strike northeast and dip northwest or southeast.

Between the Montezuma shear zone and the North Fork fault zone, the number of faults, shear zones, and veins decreases toward the east. During the sur-

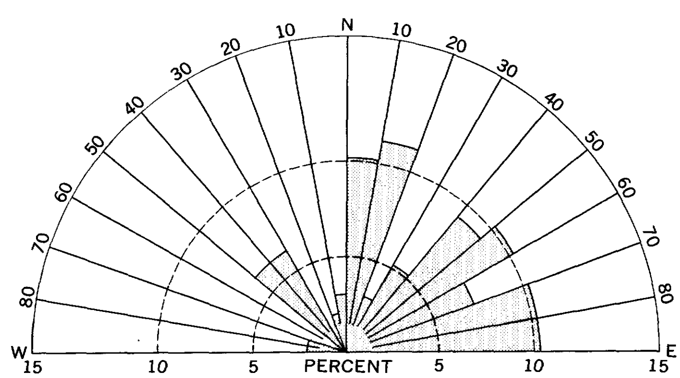


FIGURE 11. — Strike-frequency diagram of 97 faults, shear zones, and veins in the Precambrian rocks around the Montezuma stock and west of the Montezuma shear zone.

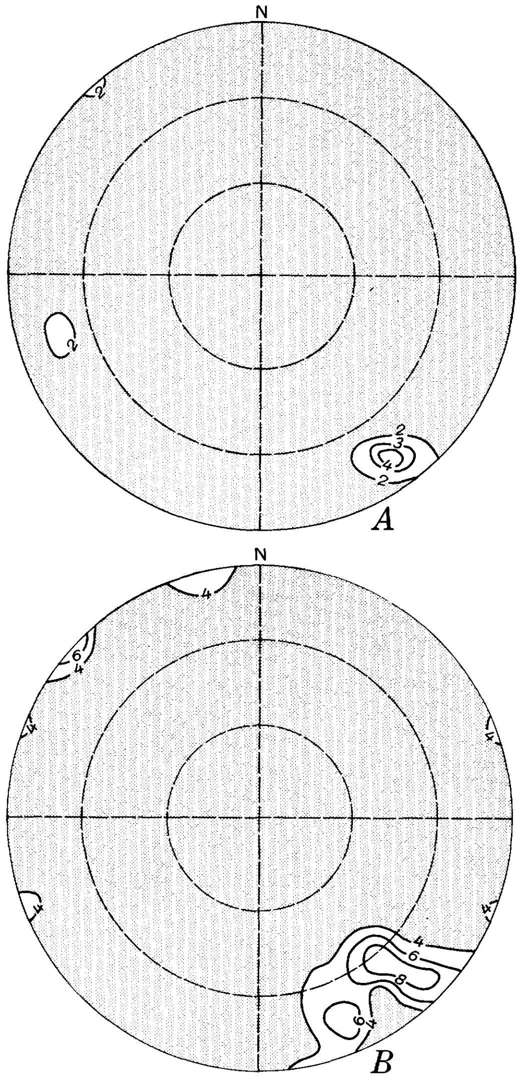


FIGURE 12. — Contour diagrams of faults and veins in the Montezuma stock and in the Precambrian rocks surrounding the stock and west of the Montezuma shear zone. *A*, Faults and veins in the Montezuma stock (contoured on number of poles, 23 poles, lower hemisphere). *B*, Faults and veins in the Precambrian rocks surrounding the stock (contoured in percent, 75 poles, lower hemisphere).

face mapping, this decrease was thought to be primarily the result of poor exposures which, in turn, are due to lower relief, but the decrease was also noted during the mapping of the tunnel (Warner and Robinson, 1967). Most of the faults in this interval are small, similar in dimensions to those west of the Montezuma shear zone. Major faults occur east of Sullivan Mountain, across the ridge that extends southeast from Landslide Peak, and along the North Fork shear zone.

The shear zone east of Sullivan Mountain was traced across the mapped area as a zone of shearing and brecciation as much as 200 feet wide. Only Precambrian rocks were involved in the shearing, but a Tertiary dike, too small to be shown at the map scale, was intruded along the zone, and its emplacement was probably controlled by the presence of the zone. Along the contacts of the dike are slickensides, which indicate that some movement has occurred along this zone since the emplacement of the dike.

A large fault crosses the ridge extending southeast from Landslide Peak and can be traced across the mapped area. The fault zone is as much as 50 feet wide, and gouge as much as 2 feet wide was observed along it near the crest of the ridge. A layer of amphibolite terminates against the fault, and it is assumed that the fault offsets this layer, although the extension of the layer east of the fault could not be found.

A supposed Tertiary fault extends along the projection of the North Fork shear zone of Hall valley. At no place is this fault exposed, but it was mapped on the basis of the offset of an augite diorite dike and a faultline scarp (pl. 1). The dike is offset about 100 feet at a point about 1¼ miles south of the tunnel line. North of this dike a layer of amphibolite terminates abruptly in a low scarp. This scarp, which is very distinct on aerial photographs, may be traced northward to within 1,000 feet of Bruno Gulch.

Figure 13 is a strike-frequency diagram of the faults and veins mapped at the surface between the Montezuma shear zone and North Fork fault zone. The faults and veins, in general, strike north-northeastward or east-northeastward, the same as they do in the area to the west, including in the Montezuma stock.

Southeast of the North Fork fault zone to the East Portal of the tunnel, exposures are generally poor,

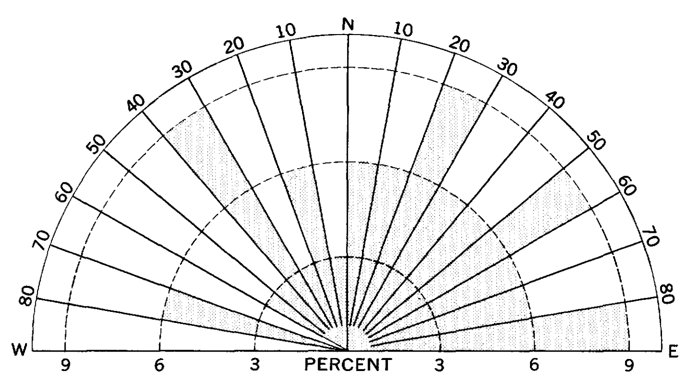


FIGURE 13. — Strike-frequency diagram of 32 faults and veins between the Montezuma shear zone and the North Fork fault zone.

and faults at the surface could be recognized only where they offset lithologic units. A few faults, whose locations are based principally on topographic relations, are indicated on the surface map. A fault such as these is shown trending down Bruno Gulch. The straightness of Bruno Gulch and the apparent eastward offset of the contact of the Boulder Creek stock are the bases for determination of the location of this fault. Other faults occur on both sides of Burning Bear Creek, at the head of Frenchman Gulch, in the Callahan Gulch area, and on the hill west of the East Portal.

Relatively large faults offset the contacts of the Boulder Creek stock northwest of Burning Bear Creek and the contacts of the microcline gneiss and migmatite between Frenchman and Callahan Gulches. The faults are 5 to about 50 feet wide, and they can be recognized by the sharp depressions they form where they cross ridges, as well as by the offset of contacts along their traces.

The faults at the surface between the North Fork fault zone and the East Portal, in general, strike northeast or east-northeast, as shown in figure 14. The north-northeasterly trending faults, so conspicuous west of this domain, were not recognized either at the surface or at tunnel level.

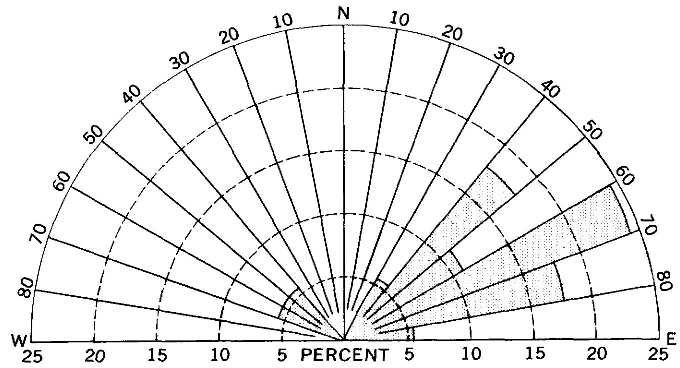


FIGURE 14. — Strike-frequency diagram of 17 faults between the North Fork fault zone and the East Portal.

JOINTS

Joints are common in all rocks along the route of the tunnel, and their attitudes and number are apparently related to rock type and the proximity to major structural elements, such as the Williams Range thrust and the Front Range mineral belt. The age of any particular joint set is difficult to determine and can only be inferred from geometric relations to major structural features that can be dated, or from parallelism to dikes of known age.

The only joints considered here are fractures that could be traced across the tunnel, or a comparable distance along the tunnel, or that could be traced on the surface for at least 10 feet. For purpose of later discussion, the joints are described as the faults have been described — by geologic domains.

Joints in the sedimentary rocks between the West Portal and the Williams Range thrust are not conspicuous at the surface because of the nature of the rock. They were observed only in the sandstone and quartzite outcrops of the Dakota Group and in stream-cut cliffs of the other formations. In general, the joints dip at high angles and are parallel or at right angles to the strike of the beds. Observations made at the surface were too few to be of any significance. In the tunnel in this interval, Wahlstrom and Hornback (1962, p. 1482–1483) noted that in general the joints dip steeply and strike north to northwest parallel to the axis of the Front Range or northeast nearly parallel to the mineral belt. No systematic distribution of joints in relation to the Williams Range thrust was observed.

In the Williams Range thrust plate no attempt was made to record the attitudes of individual joints or joint sets at the surface or underground. Joints in this interval are numerous and closely related to zones of faulting, brecciation, and mylonitization and, as a result, they occur at attitudes so diverse that neither would it have been practical nor would the data have had sufficient significance to have attempted to record them.

The metamorphosed shale interval between the Williams Range thrust and the Montezuma stock is highly jointed. At the surface, however, few observations could be made because of the lack of outcrops. At tunnel level, according to Wahlstrom and Hornback (1962, fig. 3), two maximums were obtained from equal-area plots of joints: one representing joints that strike about N. 55° W. and dip about 80° NE., and another representing joints that strike about N. 10° E. and dip about 35° SE.

The joints in the Montezuma stock have a wide range in attitude. Figure 15, a contour diagram of the joints measured at the surface, however, shows that most of the joints strike N. 10°–20° E. and dip steeply northwest or southeast, or strike N. 40°–60° E. and dip 45°–90° NW. or SE. The wide spread in the attitude of the joints at the surface may be the result of plotting all the joints measured in the stock on one diagram. Wahlstrom and Hornback (1962, p. 1489–1490) noted that in different sections in the tunnel within the Montezuma stock the joint maximums are different. In some areas the joints parallel the faults and veins associated with the mineral belt, and in other areas the joints have a more diverse orientation and probably are related to the cooling

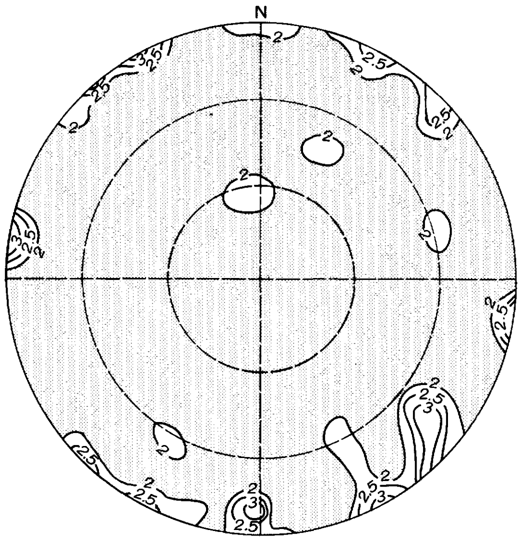


FIGURE 15. — Contour diagram of the joints in the Montezuma stock (contoured in percent, 249 poles, lower hemisphere).

of the stock. Warner and Robinson (1967, p. 113) noted that joints in the eastern part of the stock tend to parallel the faults.

Joints measured at the surface in the Precambrian rock around the stock are not represented at the tunnel level because of the enlargement of the stock with depth. Figure 16 is a contour diagram of the joints measured at the surface around the stock. The figure shows maximums of joints that strike N. 70° W. and dip about 75° SW., that strike N. 55° W.

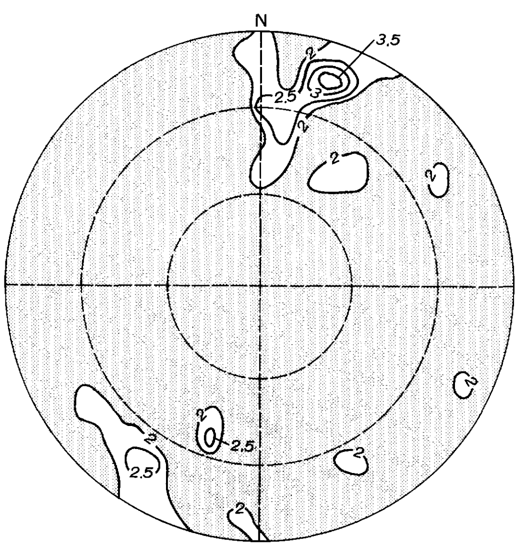


FIGURE 16. — Contour diagram of the joints in the Precambrian rocks around the Montezuma stock and west of the Montezuma shear zone (contoured in percent, 593 poles, lower hemisphere).

and dip about 70° NE., and that strike N. 70° W. and dip 50° NE.

East of the Montezuma shear zone and west of the North Fork fault zone, the joint measurements at the surface were compiled separately for the Precambrian metasedimentary rocks and the Silver Plume Granite (fig. 17). Both diagrams indicate joint sets that strike northeast and dip 50°–60° NW. and that strike northwest and dip 80°–90° NE. or SW. In addition, the Silver Plume Granite contains a joint set that strikes almost east and dips 80°–90° N. or S., and the metasedimentary rocks contain

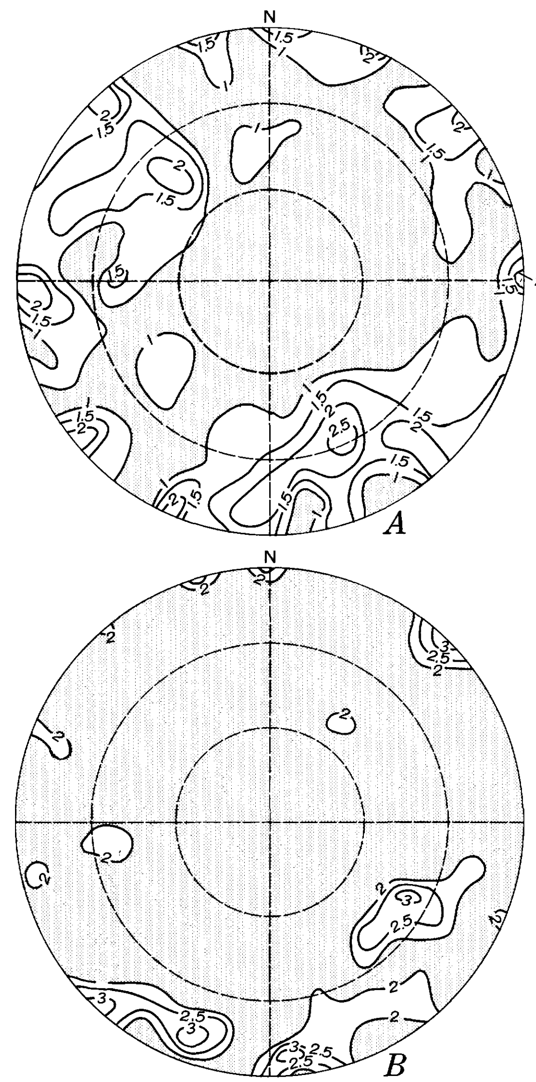


FIGURE 17. — Contour diagrams of joints in the Precambrian rocks between the Montezuma shear zone and the North Fork fault zone. *A*, Metasedimentary rocks (contoured in percent, 656 poles, lower hemisphere). *B*, Silver Plume Granite (contoured in percent, 241 poles, lower hemisphere).

joint sets that strike northeast and dip about 45° SE. and that strike north and dip 80°–90° E. or W. The dispersion of the attitude of the joints in the metasedimentary rocks is greater than in the Silver Plume Granite. This probably can be attributed to the greater number of observations made for the metasedimentary rocks.

The attitudes of joints measured at the surface between the North Fork fault zone and the East Portal were compiled separately for the different rock types: Boulder Creek Granite, Silver Plume Granite, microcline gneiss, migmatite, and amphibolite and related rocks.

Most of the joints in the Boulder Creek Granite strike west-northwest to north-northwest and dip 70°–90° SW. or NE. (fig. 18*A*). In addition, a strong set strikes about northeast and has an average dip of 30° SE., and a minor set strikes about east-northeast and dips about 70° NW.

Most attitudes of the joints in the Silver Plume Granite were measured in small irregularly shaped bodies of granite or dikes of granite that were intruded into and around inclusions of metasedimentary rocks between the Boulder Creek stock and the East Portal. Two distinct maximums were obtained from the plots of poles of these joints (fig. 18*B*). These maximums represent joints that strike northwest and dip 75°–90° SW. or NE. and that strike north-northwest to north-northeast and dip 70°–90° E. or W.

The microcline gneiss crops out in a relatively small area, much of which is well wooded. Because of this, the attitudes of only 92 joints were observed. The plots of the poles of these joints (fig. 18*C*) show one strong maximum which represents joints that strike northwest and dip 80°–90° SW. or NE.; also, they show minor maximums which represent joints that strike east-northeast and dip about 80° SE., that strike northeast and dip about 80° SE., that strike west-northwest and dip 70°–90° SW., and that strike northeast and dip about 60° SE.

The attitudes of the joints in the migmatite were measured at the surface across a relatively large area from about station 1050+00 to northeast of the East Portal. These joints, if the interpretation of the folding is correct, were measured on both limbs of an overturned anticline. The maximums of the polar plots (fig. 18*D*) represent joints that strike north-northwest and dip 80°–90° NE. or SW., that strike north-northeast and dip about 70° SE., and that strike generally northwest and dip 70°–90° NE. or SW. The limited number of observations made over such a wide area should probably limit the significance of the 3-percent maximum.

Most of the attitudes of the joints measured in the amphibolite and related rocks were measured on inclusions of considerable range in size in the Silver Plume Granite. The maximums of the polar plots (fig. 18*E*) represent, in general, joints that strike west-northwest to east-northeast and dip 70°–90° N. or S. and joints that strike northeast or northwest and dip 80°–90° in either direction.

Joint patterns in deformed rocks in the Front Range have been interpreted by Harrison and Moench (1961). In their study, Harrison and Moench were able to determine the relation of folding to faulting from the detailed mapping of the distribution of lithologic units, and they were able to relate the joint patterns to the structural evolution of the area. It is possible, where differences between shear and tension joints can be recognized and the relative age of joints is determined, to work out the principal stress directions and probable relative ages of folding from the statistical compilation of data on the joints. In the study of the Roberts Tunnel, however, particularly in the Precambrian rocks where the relation of the periods of folding could not definitely be determined from field mapping, the compilation of the joint patterns does not clearly define the relation of joints to folding (Warner and Robinson, 1967, p. 114).

VEINS AND WALLROCK ALTERATION

The Roberts Tunnel passes under the old mining district of Montezuma. Exposed at the surface and penetrated by the tunnel are numerous small veins with their associated wallrock alteration. The veins and alteration are considered to be of Tertiary age (Lovering, 1935, p. 50). No deposits of commercial significance were found.

The veins penetrated by the tunnel occur in the interval between stations 460+00 and 800+00 (pl. 1) and are mainly in the Montezuma stock. At the surface, veins along the tunnel line occur in the stock and southeast of it for about 4 miles; they are the most abundant in the Precambrian rock above the extension of the Montezuma stock at tunnel level. The veins are generally less than 1 foot wide and 200 feet long; the largest vein noted at the surface averages about 2 feet in thickness and can be traced for about 3,000 feet. Sulfide minerals — chiefly pyrite and sphalerite, with some galena, chalcopyrite, and molybdenite — are contained in a gangue composed chiefly of quartz and rhodochrosite. Calcite and gypsum are common locally. A detailed description of the Montezuma mining district and of the ore deposits was given by Lovering (1935, p. 51–63).

A halo of chloritic and pyritic alteration surrounds the Montezuma stock, and argillic alteration

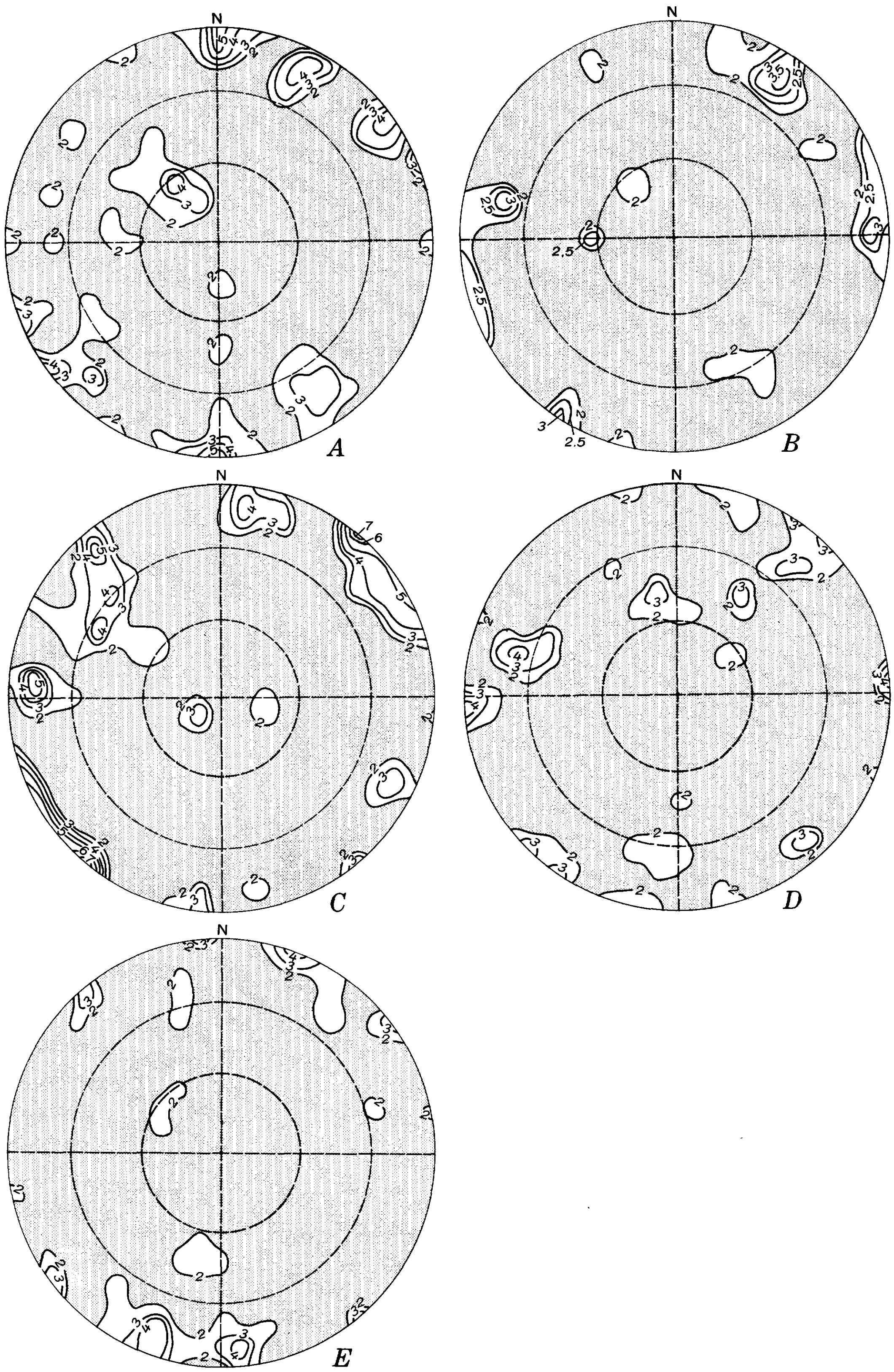


FIGURE 18. — Contour diagrams of joints in Precambrian rocks between the North Fork fault zone and the East Portal. *A*, Boulder Creek Granite (contoured in percent, 173 poles, lower hemisphere). *B*, Silver Plume Granite (contoured in percent, 249 poles, lower hemisphere). *C*, Microcline gneiss (contoured on number of poles, 92 poles, lower hemisphere). *D*, Migmatite (contoured in percent, 132 poles, lower hemisphere). *E*, Amphibolite and related rocks (contoured in percent, 173 poles, lower hemisphere).

occurs along the veins, faults, and some joints in and adjacent to the Montezuma stock. The chloritic and pyritic alteration halo extends for 2–3 miles southeast of the contact of the Montezuma stock and the Precambrian rocks. This alteration is most easily distinguished at the surface where the weathering of the pyrite has iron stained the rock. The chlorite was derived from the partial to complete alteration of the biotite and hornblende in the metasedimentary rocks and the Silver Plume Granite. The pyrite occurs as very fine disseminated grains, usually along the foliation planes.

The width of zones of argillic alteration along veins and fractures — as well as the intensity of the alteration — is, in general, proportional to the width of the veins and fractures or fracture zones. For a distance of an inch or less to a foot on each side of minor fractures or veins, the plagioclase has been partially to completely altered to aggregates of montmorillonite and kaolinite. Along the major fractures and in the major shear zones, most of the minerals of the country rock, except quartz, have been altered to montmorillonite and kaolinite. A narrow zone, rarely more than a few inches wide, adjacent to the fractures contains silica and sericite (Wahlstrom and Hornback, 1962, p. 1490).

SUMMARY OF STRUCTURAL GEOLOGY

The Front Range in Colorado has been a subject of considerable geologic research during the past few years, most of the results of which have already been published (Harrison and Wells, 1956, 1959; Wahlstrom and Kim, 1959; Harrison and Moench, 1961; Moench and others, 1962; Sims and others, 1963; Sims, Drake, and Tooker, 1963; Wells and others, 1964; Moench, 1964). Most of this work has been done in the Front Range mineral belt north of the Roberts Tunnel. At least two major periods of Precambrian and one period of Laramide structural deformation have been recognized. As Tweto and Sims (1963) have noted, the Precambrian structures, at least in part, controlled the development of the Laramide structures.

The oldest structural features in the Roberts Tunnel area are folds in the Precambrian metasedimentary rocks. Some of the folds are believed to have been contemporaneous with the metamorphism of the metasedimentary rocks and the intrusion of the Boulder Creek stock because the foliation in the stock is probably, in part, the result of the metamorphism. The surface mapping and the equal-area plots of the lineation measurements indicate at least two principal trends for the Precambrian fold axes. If we exclude the lineations measured in the Williams Range thrust plate, those north and south of the Montezuma stock, and those in the amphibolite and related rocks unit, the principal trends would be about N. to N. 10° E. and N. 80° W. If we include the maximums for the Williams Range thrust plate and the amphibolite and related rocks, the principal trends of the axes would range from N. 5° W. to N. 20° E. and from N. 80° W. to S. 60° W., with minor trends of about N. 30° to 40° E. and of about N. 30° to 40° W. Two interpretations as to the origin of these trends are possible: (1) they represent only one period of folding and the different directions represent changes in the direction of the principal stress during the folding and (2) they represent two or more separate periods of folding.

Other workers in the central Front Range who have noted two directions of Precambrian folding have attributed these directions to two different periods of folding (Harrison and Wells, 1956, p. 63; 1959, p. 27; Moench and others, 1962, p. 39, 55). The older, major fold axes trend about N. 5°–40° E., and the younger axes, associated with cataclasis, trend about N. 55° E. Wells, Sheridan, and Albee (1964, p. O15, O16) recognized three periods of folding: (1) the oldest one, recognized by the folding of an old lineation set; (2) the Coal Creek syncline and related folds, which trend N. 60°–80° E.; and (3) the folds associated with the Idaho Springs-Ralston shear zone, which trends about N. 50° E. In the Roberts Tunnel area the superposition of lineation in the Williams Range thrust plate indicates that the lineation that plunges either S. 65° W. or N. 65° E. is older than the lineations that plunge N. or S. 70° E. North and south of the Montezuma stock, the lineations that plunge about S. 35° W. and N. 35° E. are older than lineations that plunge N. 20° E. or N. 70° E. to S. 80° E. In the area between the Montezuma shear zone and the North Fork fault zone, the lineations that plunge about N. 80° W. are older than those that plunge N. 35° W. to N. 35° E. From these relationships it could be assumed that there were three principal directions of folding — the oldest represented by lineations trending about N. 35° E., the next oldest by lineations trending about N. 65° E. to S. 80° E., and the youngest by lineations trending about N. 35° W. to N. 35° E. The measurements of superimposed lineations, however, are few in number, and the domains in which the different sets were observed are separated by major geologic disconformities; consequently, the interpretation of the regional significance of these observations is limited. The solution to the sequence of folding in the Roberts Tunnel area and the correlation with other areas in the central Front Range will require additional mapping between the area mapped to the north and the area mapped in the vicinity of the Roberts Tunnel.

Faulting and cataclastic deformation of the metasedimentary and igneous rocks occurred in Precambrian time and are believed to have been contemporaneous, in part, with the emplacement of the Silver Plume Granite. Dikes of Silver Plume Granite were intruded along the Montezuma shear zone and the East Portal shear zone, and some of these dikes have been sheared and recrystallized. The Precambrian shear zones strike N. 60°–80° E. and N. 20°–45° E.

Joints undoubtedly were formed during periods of Precambrian folding and faulting. Subsequent jointing, however, has so masked the probable Precambrian jointing that it is impossible to recognize joints that were formed during Precambrian time.

The Ancestral Rocky Mountains developed in central Colorado approximately along the axis of the present Front Range during Pennsylvanian and Permian time (Curtis, 1958). Erosion before and during the development of the Ancestral Rocky Mountains stripped away the older Paleozoic sedimentary rocks and formed thick sedimentary deposits along the flanks of the mountains. No evidence of this period of deformation was noted in the Roberts Tunnel area.

The next period of major structural development in the Roberts Tunnel area started in Late Cretaceous time with the uplift of the area and the cessation of deposition of Mesozoic marine sediments. At some time after the uplift, the Williams Range thrust fault developed. Wahlstrom and Hornback (1962, p. 1493-1497) concluded that the thrust had its origin in gravity sliding that resulted from vertical uplift. They recognized that the faults and joints in the thrust plate and those to the west in the sedimentary rocks are parallel in trend (but not in dip) to the thrust and to the mineral belt. The Montezuma Quartz Monzonite stock was emplaced approximately at the intersection of the structural trend of the Williams Range thrust fault and the Colorado mineral belt.

The emplacement of the Montezuma stock was both preceded and succeeded by faulting, jointing, and intrusion of dikes, which were followed by mineralization and alteration. Wahlstrom and Hornback (1962, p. 1497) noted that the attitudes of concentrations of fractures within the stock are similar to those in the surrounding rock, and they attributed this similarity to similar forces being active during and after the intrusion of the stock.

The Laramide fractures in the Precambrian rocks east of the Montezuma stock do not show a significant regional pattern. Warner and Robinson (1967) concluded that the faults were probably developed by wrench faulting along the Front Range mineral belt and as a result of upthrusting of the basement core of the range, and that the trends of the more prominent joint sets suggest a relation to the major fault development.

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