Petrology and Structure of Precambrian Rocks Central City Quadrangle Colorado

By P. K. SIMS *and* D. J. GABLE

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 554-E

A study of high-grade metamorphic and igneous rocks within the Colorado mineral belt

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1967

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

TABLES

PETROLOGY AND STRUCTURE OF PRECAMBRIAN ROCKS, CENTRAL CITY QUADRANGLE COLORADO

By P. K. SIMS and D. J. GABLE

ABSTRACT

The Central City quadrangle, in the east-central part of the Front Range, is underlain by Precambrian rocks which are intruded by abundant porphyritic igneous rocks of Tertiary age. The Central City district and parts of the Idaho Springs and Lawson-Dumont-Fall River mining districts, which are integral parts of the Front Range mineral belt, are located at intrusive centers of the Tertiary igneous rocks in the southern part of the quadrangle.

The Precambrian rocks are dominantly microcline-quartz-plagioclase-biotite gneiss and migmatitic biotite gneiss. These rocks contain layers and lenses of amphibolite, cordierite-amphibole gneiss, and calc-silicate gneiss and related rocks and are intruded by generally small bodies of several types of igneous rocks, some of which have been metamorphosed.

The metamorphic rocks constitute a well-defined lithologic succession that seems to represent a normal stratigraphic sequence. Three principal layers of microcline gneiss, each several hundred to a few thousand feet thick, are interlayered in alternate sequence with equally thick layers of biotite gneiss. An estimated maximum of 15,000–16,000 feet of strata is exposed in the quadrangle. The amphibolite forms concordant bodies as much as 500 feet wide and 3,000 feet long within and at the margins of major layers of microcline gneiss and local small bodies in the biotite gneiss. The cordierite-amphibole gneiss and calc-silicate rocks occur as small lenses within both microcline gneiss and biotite gneiss.

Common mineral assemblages of the metamorphic rocks, listed by rock types, are:

- Microcline gneiss:
  - Biotite-plagioclase-potassium feldspar-quartz
  - Biotite-muscovite-plagioclase-potassium feldspar-quartz
- Biotite gneiss:
  - Biotite-plagioclase-quartz
  - Biotite-garnet-plagioclase-quartz
  - Biotite-quartz-sillimanite
  - Biotite-plagioclase-quartz-sillimanite
  - Biotite-plagioclase-potassium feldspar-quartz-sillimanite
  - Biotite-muscovite-plagioclase-potassium feldspar-quartz-sillimanite
  - Biotite-garnet-plagioclase-potassium feldspar-quartz-sillimanite
  - Biotite-cordierite-garnet-magnetite-plagioclase-potassium feldspar-quartz-sillimanite
  - Biotite-cordierite-magnetite-plagioclase-quartz
- Amphibolite:
  - Andesine-hornblende-quartz
- Cordierite-amphibole gneiss:
  - Biotite-cordierite-garnet-gedrite-plagioclase-quartz
- Calc-silicate gneiss and related rocks:
  - Clinopyroxene-garnet-plagioclase-quartz-sphene
  - Garnet-magnetite-quartz
  - Clinopyroxene-epidote-hornblende-plagioclase-quartz

The metamorphic rocks are interpreted to be dominantly of metasedimentary origin. The microcline gneiss is thought to represent arkose, and the biotite gneiss, to represent interlayered shale and graywacke. Garnet- and cordierite-bearing varieties of biotite gneiss formed from shale that was somewhat enriched in iron and magnesium and deficient in calcium. Probably the minor metamorphic rocks also were derived mainly from sedimentary rocks.

The biotite gneisses are migmatized and contain an estimated 15–20 percent by volume of granite gneiss and pegmatite. Other rock types contain lesser amounts of similar material, as streaks or interlacing veinlets.

Four types of Precambrian intrusive rocks—granodiorite and associated rocks, gabbro and related rocks, quartz diorite and hornblendite, and biotite-muscovite quartz monzonite—each with associated pegmatites, intrude the layered rocks. From oldest to youngest, they are described as follows:

1. Granodiorite and associated rocks occur as subconcordant folded sheets and small plutons, some of which are phacoliths. Individual bodies range in composition from mafic quartz diorite to quartz monzonite. The bodies are satellite to the batholith of Boulder Creek Granite exposed northeast of the quadrangle.
2. Gabbro and related rocks also form subconcordant bodies; the large Elk Creek pluton probably is a compound phacolith. These rocks are distinguished by their content of both orthopyroxene and clinopyroxene and by their range in composition from melagabbro to quartz diorite, diorite being the dominant facies.
3. Quartz diorite and hornblendite grade locally into gabbroic rocks and are interpreted to have formed by retrograde metamorphism of gabbro and related rocks.
4. Biotite-muscovite quartz monzonite forms generally small crosscutting bodies that are peripheral to larger masses at Silver Plume, Colo., and vicinity. In contrast to the older intrusive rocks, it is remarkably uniform in composition.

The older intrusives were emplaced, synchronously with the major period of deformation, in the catazone of the crust; subsequent to crystallization they were deformed and were largely recrystallized. The biotite-muscovite quartz monzonite has a primary flow structure and is late syntectonic.

Progressive metamorphism developed mineral assemblages of the sillimanite zone in all but the youngest intrusive rocks. In rocks of suitable composition, sillimanite and potassium feldspar coexist; muscovite is stable with these minerals in rocks containing sufficient K_2O. Cordierite is stable in calcium-poor, magnesium- and iron-rich biotite gneisses and gedrite-bearing gneisses. Locally, adjacent to the Precambrian Elk Creek pluton the biotite gneiss assemblages are changed to the pyroxene hornfels facies. Adjacent to the largest of the Tertiary intrusive bodies the assemblages are modified also mainly by the conversion of highly triclinic microcline to orthoclase.

The quadrangle is in a region dominated by northeastward-trending folds; a narrow segment of the major Idaho Springs-Ralston shear zone extends across the extreme southeast corner of the quadrangle. The northeastward-trending folds are mainly open upright anticlines and synclines that have steeply dipping axial planes and gently plunging fold axes. Closed overturned folds occur in the west-central part of the quadrangle. Lineations that are parallel to the major fold axes (*B*) and that are nearly normal (*A*) to them are cogenetic with the folding. The Idaho Springs-Ralston shear zone trends N. 55° E. and is characterized by extreme cataclasis and minor folds that are subparallel to the zone itself.

The major folds and associated linear elements were formed during the principal episode of plastic deformation; the younger folding and cataclasis formed during a distinctly later deformation, but still in the Precambrian. This deformation was followed by an episode of faulting, the youngest known manifestation of Precambrian structural activity in this area.

INTRODUCTION

Geologic mapping of the Central City quadrangle was undertaken for two principal purposes: (1) To extend to a broader region the knowledge obtained through detailed mapping of the mining districts in the central part of the Front Range and (2) to form a nucleus for a program of quadrangle geologic mapping intended to result in a geologic section across the Front Range. The ultimate objective of this program was to gain a comprehensive knowledge of this segment of the Front Range in order to improve the understanding of the composition and structure of the range and of the factors controlling the localization and extent of the ore deposits of the Front Range mineral belt.

This report describes the Precambrian rocks of the quadrangle and places particular emphasis on their petrology and structure. Although the Tertiary porphyritic igneous rocks and metalliferous veins are shown on the geologic map (pl. 1), which was originally published by Sims (1964), they are not described herein because the main features of the rocks are discussed by Wells (1960) and the principal mining districts are described in reports by Sims, Drake, and Tooker (1963), Moench and Drake (1966), and Hawley and Moore (1967).

The Central City quadrangle lies astride the boundary between Gilpin and Clear Creek Counties, in the east-central part of the Front Range (fig. 1).

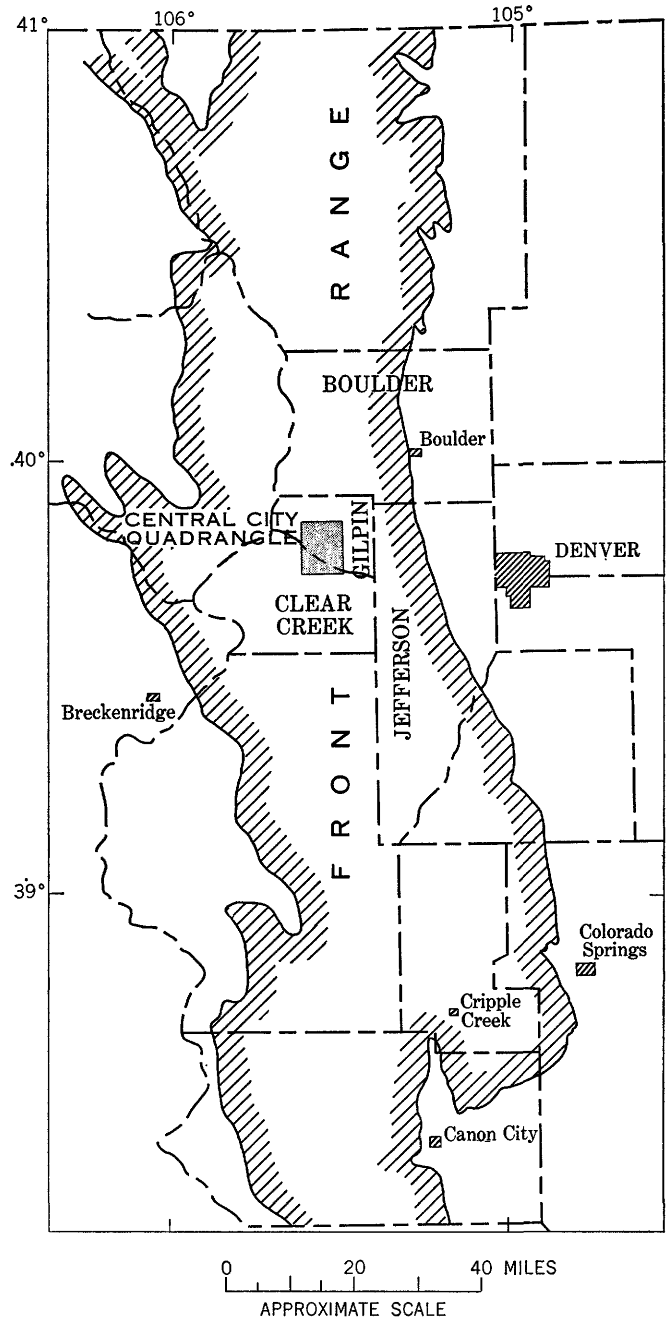


FIGURE 1.—Location of Central City quadrangle in the Front Range, Colo.

It is about 10 miles east of the crest of the range, in a region characterized by highly dissected, rolling upland surfaces that slope to the east. Altitudes range from 11,204 feet in the northwestern part of the quadrangle to 7,650 feet in the valley of Clear Creek at the south boundary. Local relief exceeds 1,000 feet in the vicinity of the major streams but is less along smaller stream valleys.

Bedrock is well exposed throughout most of the quadrangle. A notable exception is the extreme northwestern part, where the upland surfaces are largely mantled by a rubble of the underlying bedrock or are covered by thin deposits of colluvium or glacial materials and where the major stream valleys are largely filled with till left by retreat of the latest valley glaciers. Moraines deposited by these glaciers extend downstream to an altitude of about 9,100 feet in North Clear Creek in the northern part of the quadrangle and to about 8,600 feet in Fall River in the west-central part of the quadrangle.

The Precambrian rocks of the Central City quadrangle were first mapped early in the 20th century by E. S. Bastin (Bastin and Hill, 1917) at a scale of an inch to the mile. Later, the rocks within a segment of the area were remapped at the same scale by Lovering and Goddard (1950) as a part of their compilation of the geology of the entire Front Range. These studies provided an excellent framework for subsequent detailed mapping by the U.S. Geological Survey in the Central City (Sims and Gable, 1964), Idaho Springs (Moench, 1964), Freeland-Lamartine (Harrison and Wells, 1956), Chicago Creek (Harrison and Wells, 1959), and Lawson-Dumont-Fall River (Hawley and Moore, 1967) mining districts. A summary of the stratigraphy and a comprehensive discussion of the structure of the Precambrian rocks in the area of the detailed studies have been published by Moench, Harrison, and Sims (1962).

Geologic mapping of the Central City quadrangle was done in two stages. The southern part was compiled from the more detailed geologic maps (1:6,000) prepared for the Central City, Idaho Springs, and Lawson-Dumont-Fall River mining districts, and a small area in the central part was compiled from mapping at the same scale by E. W. Tooker and A. E. Dearth. The rest of the quadrangle was mapped at a scale of 1:20,000 during the field seasons of 1959 and 1960 by the authors and P. D. Lowman, Jr. The areas of responsibility for mapping are shown on the index map on plate 1. Both stages of the mapping were done under the supervision of P. K. Sims.

The laboratory studies were carried on jointly by both authors. D. J. Gable is responsible for most of the quantitative mineralogic data. Several colleagues in the U.S. Geological Survey assisted in the study by providing mineralogic and chemical data; these individuals are acknowledged at appropriate places in the report.

The compositions of plagioclase were determined by oil-immersion methods that determined indices of refraction to an accuracy of ± 0.003. Modal analyses were made from standard ¾- by 1-inch thin sections. Sections were cut normal to lineation, and grain counting was done by a point counter with spacing of 0.5 millimeter in one direction and 1 mm in the other (Chayes, 1949). On the average, 1,000 points were counted for each thin section.

Average grain diameters as reported in the tables were determined from the thin sections from which modal analyses were made. Each thin section was divided into six or eight equal parts, and an average grain diameter was observed and measured for each section. Then these six or eight averages were added and were then reaveraged to yield a grain diameter to represent the entire thin section.

Grain sizes given in the text are largely based on megascopic observation and are more meaningful for describing the physical appearance of the rock as a whole than are results from grain-size measurements determined in thin sections.

GEOLOGIC SETTING

The Front Range is a broad massive mountain unit 30–60 miles wide that extends from the vicinity of Canon City northward about 180 miles to the Wyoming State line (fig. 1). It has a Precambrian rock core which is flanked by steeply dipping Paleozoic and Mesozoic sedimentary rocks and which is locally overlapped by Cenozoic sedimentary and volcanic rocks (fig. 2). The range is crossed at about midlength by the Front Range mineral belt, a narrow northeast-trending belt of porphyritic igneous rocks and associated ore deposits of Laramide age. This belt contains all the important mining districts in the range, except Cripple Creek and the uranium mining areas in Jefferson County (Sims and Sheridan, 1964).

The Precambrian rocks of the Front Range consist of roughly equal amounts of metamorphic and igneous rocks. The dominant metamorphic rocks are metasedimentary biotite gneisses and schists of several types and associated migmatites that were mapped as the Idaho Springs Formation by Ball (1906) and by Lovering and Goddard (1950, p. 19–20, pls. 1, 2). Less common are (1) hornblende gneisses and amphibolites of uncertain derivation, which were mapped as the Swandyke Hornblende Gneiss by Lovering and Goddard (1950, pls. 1, 2), (2) quartzite as described by Wells, Sheridan, and Albee (1964), and (3) microcline paragneiss as described by Moench, Harrison, and Sims (1962). The microcline paragneiss previously was considered to be an orthogneiss by Lovering and Goddard (1950, p. 23). Estimates of the thicknesses of these formations and their correlations throughout the range cannot yet be made confidently because of complex folding and because of the lack of detailed mapping in many areas.

The igneous rocks are of several types and intrude the gneisses and schists. The dominant intrusive rocks

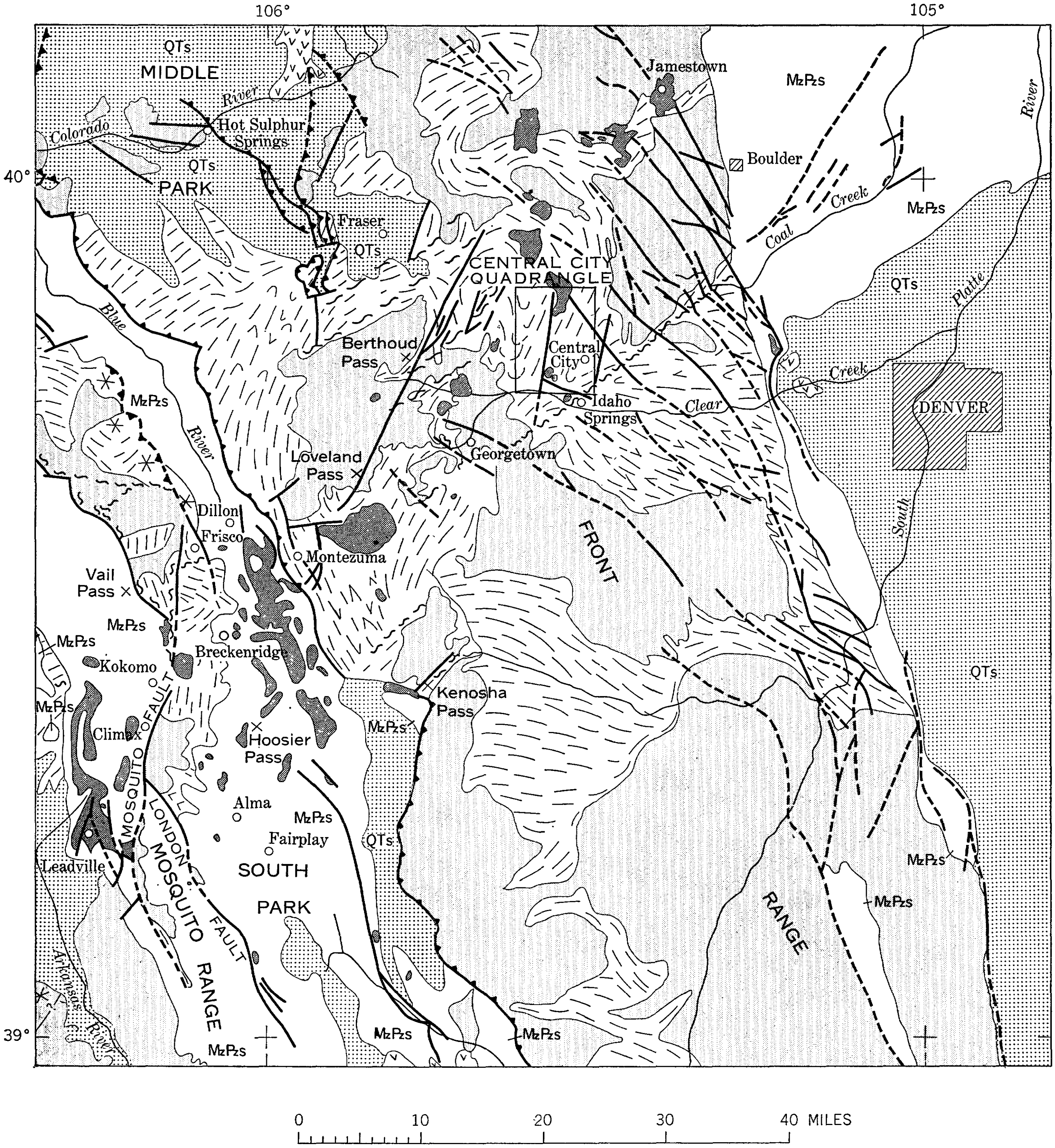


FIGURE 2.—Generalized geologic map of the central part of the Front Range and adjacent areas. Modified from Tweto and Sims (1963, pl. 1).

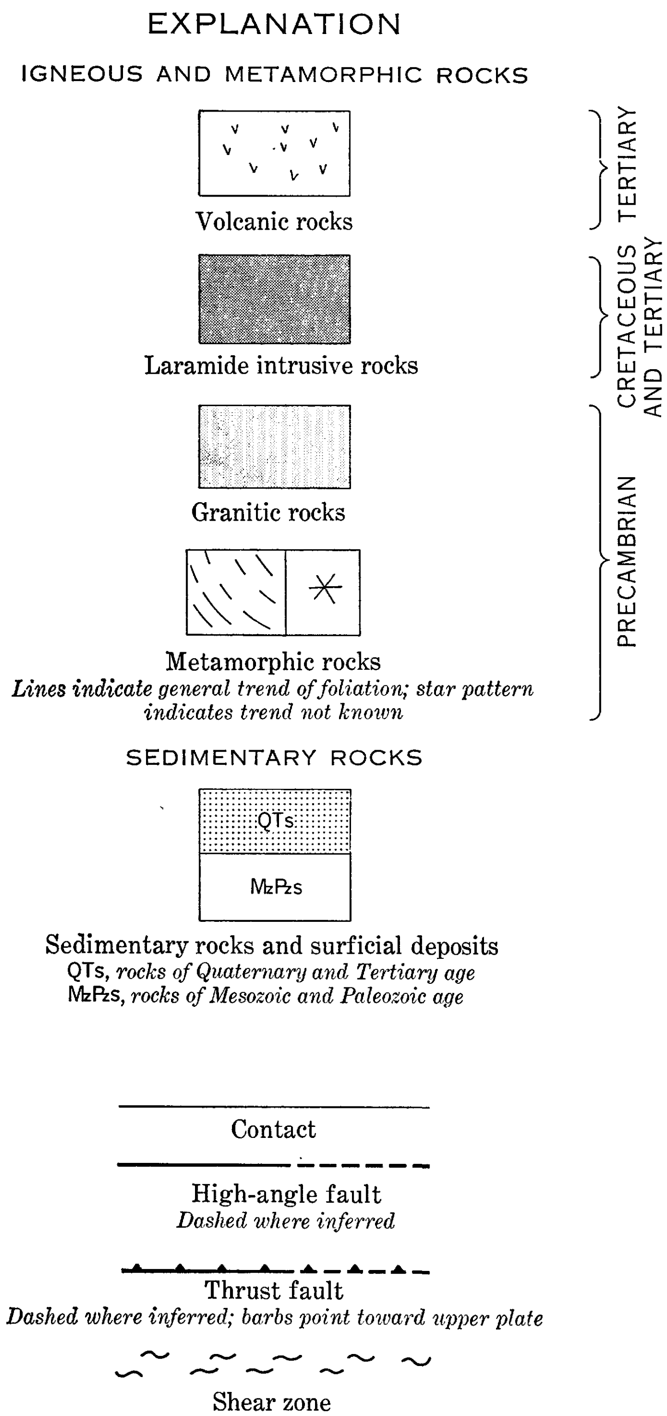


FIGURE 2.—Continued.

have been named the Boulder Creek Granite, the Silver Plume Granite, and the Pikes Peak Granite (Lovering and Goddard, 1950, p. 25–29); other intrusive rocks of smaller areal extent have been designated by lithologic terms. These lesser intrusive units include quartz diorite and hornblendite, which are known to form small bodies in the central part of the range, and gabbro and related rocks, which were described from the area of this report by Taylor and Sims (1962). The older igneous rocks of the intrusive sequence, gabbro and related rocks, granodiorite and associated rocks of Boulder Creek affinity, and quartz diorite and hornblendite are partly metamorphosed and are interpreted as syntectonic intrusives; the rocks of Silver Plume affinity are interpreted as late syntectonic; and the Pikes Peak Granite probably is posttectonic. Pegmatites of granitic composition are related to all intrusive rock types, and aplites are related to some.

The metamorphic rocks of the Front Range have mineral assemblages that conform generally with the almandine amphibolite facies of Turner and Verhoogen (1960, p. 544–550). The data from scattered localities indicate that the assemblages range from sillimanite-bearing assemblages, as in the region of this report, to lower grade biotite-chlorite-muscovite-quartz assemblages, as in the northern part of the range (W. A. Braddock, in U.S. Geological Survey, 1964, p. A94).

The internal structure of the Precambrian rocks that constitute the core of the Front Range developed largely in Precambrian time. The rocks were folded and regionally metamorphosed, were locally sheared, and were faulted and jointed. The regional folding was complex. Reconnaissance mapping, mainly by Lovering and Goddard (1950, pls. 1, 2), and later detailed mapping in selected areas indicate that the folds differ in trend from place to place but have systematic patterns locally. Details of the folding and metamorphism remain largely unknown except in the central part of the range, which has been mapped and studied intensively in recent years. (See particularly Moench, Harrison, and Sims, 1962; Tweto and Sims, 1963; Wells, Sheridan, and Albee, 1964.) In this area, the main structures in the Precambrian rocks resulted from three successive episodes of deformation. The oldest deformation created broad warps and smaller associated folds whose axes trend northwest; the deformation appears to be partly syntectonic with the Boulder Creek Granite. This deformation has been recognized (R. B. Taylor, oral commun., 1963) in the Black Hawk and adjacent quadrangles to the east of the Central City quadrangle, but its full extent beyond this area is not known. A second period of deformation, probably only slightly later than the first episode, developed folds trending north-northeast. This period is the dominant episode of deforma-

247–419—67——2

tion recognized in the Central City quadrangle. In the Central City area this deformation was accompanied by regional dynamothermal metamorphism and migmatization and was partly syntectonic with all the intrusive rocks of the area except perhaps the Silver Plume Granite. A third period of deformation began with folding on axes trending east-northeast and progressed into cataclasis along shear zones of the same trend. A major zone of shearing related to this deformation impinges on the southeast corner of the Central City quadrangle. The cataclastic deformation was followed by local faulting in at least two dominant directions trending northwest and north-northeast (Sims and others, 1963), which produced the initial structures containing the "breccia reefs" of the Front Range.

Data on the ages of Precambrian metamorphic and igneous events in the Front Range still are too meager for accurate dating. The determination of reliable ages is hindered by the multiple deformations during the Precambrian and, within the mineral belt, also by the thermal and structural events that accompanied the Laramide revolution. Presently available data indicate that the older deformations (episodes 1 and 2, preceding paragraph) probably took place about 1,700–1,800 m.y. (million years) ago, for George Phair (in U.S. Geological Survey, 1964, p. A95) obtained a zircon-isotope age of 1,730 m.y. for undeformed granitic rock within the Boulder Creek batholith west of Boulder. Rocks of Boulder Creek affinity are thought to be syntectonic with all or parts of the older deformations, and thus they should give ages approximating the time of these deformations. The age of the Silver Plume Granite should approximate the third deformation, for the granite is thought to be virtually syntectonic with the plastic stage of this deformation. K-Ar ages of 1,210 and 1,230 m.y. and Rb-Sr ages of 1,360 and 1,350 m.y. for muscovite and biotite were obtained on the Silver Plume Granite by Aldrich, Wetherill, Davis and Tilton (1958, p. 1130).

During the Laramide revolution, the core of the Front Range was uplifted and hypabyssal igneous rocks and attendant ores were emplaced within the mineral belt. Mountain building was accomplished without marked internal deformation. Except for the formation of some new fractures in the mineral belt (Sims, Armstrong, and others, 1963), the rejuvenation of older fractures, and the formation of a regional joint set (Harrison and Moench, 1961, p. B5–B12), the Precambrian core apparently was not appreciably deformed during the Laramide. Intrusion of the hypabyssal rocks was largely confined to the narrow strip of ground that constitutes the mineral belt. Most of the intrusives were emplaced as dikes, sills, and small stocks, larger stocks were emplaced along the northwest margin of the belt. The larger stocks are known, from study of the Tertiary stock at Eldora (Hart, 1964), to have contact metamorphic halos in which microcline in Precambrian gneisses is changed to orthoclase and isotopic mineral ages are reduced. Comparable mineralogic changes were observed by us adjacent to the stock near Apex in the Central City quadrangle. The full significance and extent of the thermal metamorphism of the Tertiary intrusives is not yet known, and further studies are needed to aid in interpreting the geochronology of the Precambrian rocks.

ROCK UNITS

The Precambrian rocks of the quadrangle are dominantly microcline-quartz-plagioclase-biotite gneiss and biotite gneiss units. These rocks contain small lenses of other metamorphic rocks and are intruded by generally small bodies of granodiorite and associated rocks, gabbro and related rocks, quartz diorite and hornblendite, biotite-muscovite quartz monzonite, and pegmatites of several types.

The terminology of the rock units described in this report accords generally with that used previously in the report on the Central City district (Sims and Gable, 1964). The lithologic names are assigned on the basis of quantitative mineral content and on the presence of diagnostic minerals. Where mineral assemblages are given, the minerals are listed in alphabetical order without regard to relative abundances.

METAMORPHIC ROCKS

Metamorphic rocks dominate the bedrock in the quadrangle. Microcline-quartz-plagioclase-biotite gneiss, hereafter called microcline gneiss in the text, is interlayered on a gross scale with biotite gneiss to constitute the lithologic framework of the district (pl. 1). Amphibolite, cordierite-amphibole gneiss, and calc-silicate gneiss and related rocks form small lenses and pods in the microcline gneiss units; and calc-silicate gneiss and associated quartzite and amphibolite occur sparsely in the biotite gneiss units. Internally, the biotite gneiss units are variable in composition and are migmatized. They consist dominantly of interlayered biotite-quartz-plagioclase gneiss, sillimanitic biotite gneiss, and garnet- and cordierite-bearing sillimanitic biotite gneiss. The garnet- and cordierite-bearing biotite gneiss is distinguished separately from the other biotite gneiss units on plate 1.

LITHOLOGIC SUCCESSION

The metamorphic rocks constitute a well-defined lithologic succession that seems to represent a normal stratigraphic sequence. Except for rocks in the upper part of the succession, the stratigraphic order has been defined previously in the summary report by Moench, Harrison, and Sims (1962, p. 38–39, pl. 2).

The succession consists of three principal layers of microcline gneiss, each at least 1,000 feet thick, separated by biotite gneiss units of comparable thickness, as summarized in table 1. The major microcline gneiss units are, from lowest to highest, the Big Five, the Quartz Hill, and the Lawson layers. In earlier reports the Big Five layer was called the Idaho Springs layer, and the Quartz Hill layer, the Central City layer. The biotite gneiss layers have not been similarly designated. An estimated maximum of 15,000–16,000 feet of strata is exposed in the quadrangle.

A biotite gneiss unit exposed on the crest of the Idaho Springs anticline, in the southeast corner of the quadrangle (pl. 1), is interpreted stratigraphically as the lowest unit in the area. The unit is estimated to exceed 1,000 feet in thickness, but its lower part is not exposed in the quadrangle. It consists mainly of sillimanitic biotite gneiss but contains layers of biotite-quartz-plagioclase gneiss and, locally, quartz gneiss.

TABLE 1.—*Lithologic succession of Precambrian metamorphic rocks, Central City quadrangle*

[From highest to lowest, stratigraphically]

Rock and description	*Estimated maximum thickness (feet)*
Biotite gneiss:	
Dominantly migmatized interlayered sillimanitic biotite gneiss and biotite-quartz-plagioclase gneiss, with lenticular zones of cordierite-bearing biotite gneiss, garnetiferous biotite gneiss, and garnetiferous sillimanitic biotite gneiss. Intertongues in lower part with microcline gneiss of Lawson layer. Top of unit not exposed in quadrangle	>2, 500
Microcline gneiss (Lawson layer):	
Ranges in composition from quartz monzonite to granodiorite; contains several small bodies of amphibolite and local lenses of biotite gneiss. Unit thins and is highly folded in the area between Fall River and Pecks Flat. In northern part of quadrangle, upper part of unit intertongues with overlying biotite gneiss unit	2, 500
Biotite gneiss:	
Consists dominantly of migmatized interlayered sillimanitic biotite gneiss and biotite-quartz-plagioclase gneiss with lenses of garnetiferous biotite gneiss and garnet- and cordierite-bearing sillimanitic biotite gneiss. Locally contains lenses of calc-silicate gneiss, amphibolite, and microcline gneiss	3, 000–4, 000
Microcline gneiss (Quartz Hill layer):	
Average composition is granodiorite; contains several thin layers and lenses of biotite-quartz-plagioclase gneiss and pods of amphibolite, calc-silicate gneiss, and cordierite-amphibole gneiss. Unit thins to south	3, 000
Biotite gneiss:	
Dominantly sillimanitic biotite gneiss; unit probably pinches to southwest	2, 000
Microcline gneiss (Big Five layer):	
Small lenses of amphibolite occur along margins; unit pinches out at depth and to southwest but thickens to east in adjacent quadrangles	1, 000
Biotite gneiss:	
Dominantly sillimanitic biotite gneiss. Bottom of unit not exposed im mapped area	>1, 000

Above the biotite gneiss unit is a discontinuous layer of microcline gneiss, designated the Big Five layer, which has an estimated maximum thickness of 1,000 feet. This layer is more felsic and generally more massive than the other major layers of microcline gneiss in the area. It pinches out at depth and toward the southwest on the northwest limb of the Idaho Springs anticline but thickens eastward.

The Big Five layer of microcline gneiss is overlain by a biotite gneiss unit that has an estimated maximum thickness of 2,000 feet. The biotite gneiss forms a curved outcrop pattern on the crest of the Idaho Springs anticline. It is lithologically similar to the lowest recognized biotite gneiss unit.

Above this biotite gneiss unit is the Quartz Hill layer of microcline gneiss, the dominant exposed unit in the eastern part of the quadrangle. It crops out on the axis of the Central City anticline and forms a shieldlike outcrop near Central City and an irregular prong-shaped mass along the steep slopes of the valleys of Clear Creek and Fall River. The structural configuration of the unit is clearly shown on plate 2 of the report by Moench, Harrison, and Sims (1962). The unit is known from studies in the Central City district (Sims, Drake, and Tooker, 1963; Sims and Gable, 1964) to have an average composition of granodiorite and a maximum thickness of about 3,000 feet.

The Quartz Hill layer is overlain by a biotite gneiss unit that crops out continuously in a 2-mile-wide northeastward-trending band across the central part of the quadrangle. The maximum thickness of the layer has been estimated from exposures along Clear Creek and Fall River to be about 4,000 feet (Moench, Harrison, and Sims, 1962, table 1). In the vicinity of North Clear Creek (see pl. 1, section *A–A′*), in the northern part of the quadrangle, the unit seems to be thinner and probably does not exceed 3,000 feet in thickness. This biotite gneiss unit is remarkably diverse in composition, as noted in table 1. A major zone of lenses of garnet- and cordierite-bearing biotite gneiss occurs locally in the middle of the unit, and a thin, discontinuous zone of lenses of the same rock type lies at or near the top.

Above this biotite gneiss unit is the Lawson layer of microcline gneiss, originally defined by Moench, Harrison, and Sims (1962) from exposures near Lawson (just west of the Central City quadrangle, in the valley of Clear Creek). The Lawson layer is inferred to extend discontinuously and irregularly northeastward across the quadrangle, its northern extremity in the quadrangle being in the vicinity of Gamble Gulch (pl. 1). According to this interpretation, the layer thins drastically from the west margin of the quadrangle, is intricately folded between Fall River and Pecks Flat, and apparently pinches out at Pecks Flat on the crest of Pecks Flat anticline. In the vicinity of Pecks Flat it is cut out by the Mount Pisgah pluton of granodiorite and associated rocks but reappears northeast of the pluton. The upper part of the microcline gneiss unit intertongues with the overlying biotite gneiss unit northeast of the pluton; possibly the microcline gneiss that encloses the body of gabbro and related rocks on the axis of the Arizona Mountain anticline is a major tongue of this unit. The unit is estimated from exposures near Lawson to exceed 2,500 feet in thickness. Mapping in the Central City quadrangle indicates that the maximum thickness in the vicinity of Blackhawk Peak also is about 2,500 feet.

Above the Lawson layer is a layer of biotite gneiss that is interpreted stratigraphically to be the highest unit in the map area. It occupies the northwest quarter of the quadrangle. We estimate that about 2,500 feet of strata in the unit is exposed in the quadrangle, but this estimate is less accurate than the estimates for other units because of complex folding and poor exposures—the top of the unit is not exposed. As indicated above, the lower part intertongues with the upper part of the Lawson layer of microcline gneiss. Lithologically, the unit resembles the biotite gneiss unit that underlies the Lawson layer. Garnet- and cordierite-bearing biotite gneisses occur locally throughout the unit. The major rock type is sillimanitic biotite gneiss.

MICROCLINE-QUARTZ-PLAGIOCLASE-BIOTITE GNEISS

Microcline gneiss forms three major stratigraphic layers—from oldest to youngest, the Big Five, Quartz Hill, and Lawson layers—and scattered smaller lenses and layers within larger masses of biotite gneiss. Although the layers differ somewhat in detail, the gross lithologies are similar, and the rock type is discussed as a unit herein.

GENERAL CHARACTER

The microcline gneiss is a distinctive rock unit, moderately variable in composition, that can be distinguished by its granitic appearance, generally conspicuous layering, and well-developed foliation.

It is a light- to medium-gray, fine- to medium-grained, equigranular, layered rock. Weathered surfaces are various shades of yellowish gray, gray orange pink, and very pale orange. Layering is the result of alternating layers of slightly different mineral composition and, at places, of regular paper-thin parallel streaks of biotite. The microcline gneiss contains less biotite and, accordingly, is lighter in color and has a more uniform and straighter layering than the associated biotite gneisses.

The microcline gneiss within each of the major layers is associated with amphibolite and to a lesser extent with other metasedimentary rock units. The amphibolite forms thin, concordant lenses and stubby layers within, and at the margins, of the gneiss bodies. Some lenses, discontinuous along both strike and dip, appear to occur at similar stratigraphic positions within certain gneiss layers and probably constitute stratigraphic marker beds. The Quartz Hill layer, which has been studied in detail, contains small concordant bodies of calc-silicate rocks and cordierite-amphibole gneiss as well as amphibolite. It also has a few layers of biotite gneiss that are remarkably persistent (Sims and Gable, 1964). Contacts of the various rock units with the microcline gneiss generally appear sharp, but gradations across a few inches or a few feet are common. Biotite gneiss grades into microcline gneiss through gradual increases in microcline and diminution of biotite across the transition zone; adjacent to amphibolite, the microcline gneiss generally contains hornblende as the dominant mafic mineral rather than the more common biotite.

The northern segment of the Lawson layer is particularly heterogeneous. The contact zones are marked by interlayering of biotite gneiss with microcline gneiss and by intergradations, both along and across strike, of the two rock types. The gross interfingering of the two rock types is shown by the several tongues of boitite gneiss that extend into the Lawson layer on both sides of North Clear Creek (pl. 1). An intertonguing on finer scale is also present but could not be shown on plate 1. The central part of the layer is relatively homogeneous except in the area north of Blackhawk Peak where it contains numerous beds of amphibolite.

PETROGRAPHY

The microcline gneiss is generally an equigranular rock of allotriomorphic granular texture, but at a few places it is inequigranular and contains subhedral plagioclase and sparse potassium feldspar crystals as much as 5 mm in diameter. As detailed mineralogic data and modal analyses have been given previously for the rock unit within the Central City district, only that part of the region not covered previously is discussed herein; representative modes of the Lawson layer, particularly that part north of Fall River, and modes for other scattered bodies are listed in table 2. The modal data are summarized in the triangular diagram in figure 3. The earlier reports on the Central City district (Sims and Gable, 1964), Idaho Springs district (Moench, 1964), and the Lawson-Dumont-Fall River district (Hawley and Moore, 1967) contain additional information on this rock unit.

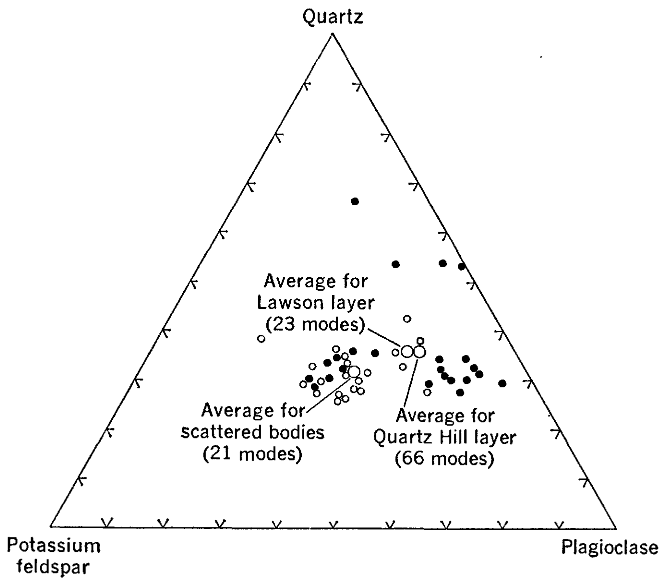


FIGURE 3.—Variation in composition (volume percent) of microcline gneiss but excluding Quartz Hill layer. ●, Lawson layer; ○, scattered bodies of microcline gneiss.

The microcline gneiss within each of the layers that have been mapped is similar in gross aspect to that described from the Quartz Hill layer (Sims and Gable, 1964). Plagioclase, quartz, and potassium feldspar, the dominant minerals, are intergrown in anhedral or rarely subhedral grains. Except locally, the plagioclase has well-defined albite twinning; Carlsbad twins and pericline twinning are less common. Narrow albitic rims or myrmekite are common at contacts of plagioclase with potassium feldspar. In general, the plagioclase contains a few percent of potassium feldspar as small patches alined parallel to the twin lamellae to constitute antiperthite. The quartz occurs mainly as irregular anastomosing grains, which show strain shadows and which are interstitial to the feldspar grains, and occurs also as small subrounded inclusions in other minerals or as myrmekitic intergrowths with biotite, plagioclase, and rarely muscovite. The potassium feldspar has both conspicuous grid twinning and fine perthitic intergrowths of plagioclase. The perthitic intergrowths constitute an estimated 10 percent by volume of the potassium feldspar grains. The potassium feldspar was determined in two specimens from the Quartz Hill layer to be near maximum microcline and to contain about 80 percent $KAlSi_3O_8$ (Sims and Gable, 1964). The biotite is a distinctly greenish strongly pleochroic type; optical data and chemical analyses of two specimens from the Quartz Hill layer have been reported by Sims and Gable (1964, p. C14). Muscovite has two modes of occurrence. Locally it is intergrown with biotite, plagioclase, and potassium feldspar and appears to be primary, but much of it occurs as patches in microcline and plagioclase and as overgrowths on biotite and appears to be secondary. Magnetite, zircon, and apatite are the most common accessory minerals. Hornblende is a local accessory mineral, occurring especially adjacent to amphibolite bodies. Garnet is a widespread accessory mineral in the northern part of the Lawson layer, particularly north of North Clear Creek (see samples 15, 17, 18, and 21 of table 2); it is most abundant and conspicuous along the northwest margin of the layer north of Blackhawk Peak (pl. 1). Typically, alteration of the rock is slight; the plagioclase is partly clouded by clay minerals. Chlorite, epidote, and calcite are local alteration products.

Typically, the microcline gneiss has a crystalloblastic texture, and the dominant minerals are intergrown in a mosaic pattern. Quartz and the feldspars are nearly equidimensional, and biotite forms plates that are slightly elongate parallel to the lineation of the rock.

On the east slope of Dakota Hill, east of the stock at Apex, the microcline gneiss in the extreme northwestern part of the Lawson layer is profoundly granulated and altered. Megascopically, the rock is noticeably finer grained and has a more pronounced foliation and lineation than elsewhere. In thin section, the gneiss is seen to be strongly granulated and recrystallized. In contrast to the common mosaic texture, the quartz forms elongate, amebiform aggregates of sutured grains as much as an inch long that form fingerlike projections through a finer grained groundmass of feldspar. Biotite is fine grained, typically frayed, and streaked out parallel to the quartz aggregates. The feldspars are strongly altered to clay minerals and sericite. The potassium feldspar has dark shadowy extinction, is microperthitic, and lacks the grid twinning which characterizes it elsewhere. Also, because twin lamellae in plagioclase are partly destroyed, distinction between the two feldspars is very difficult.

CHEMICAL COMPOSITION

That the microcline gneiss varies in chemical composition from a quartz diorite to a granite can be inferred from figure 3. Calculations made by Sims and Gable (1964) indicate that the Quartz Hill layer is mainly composed of granodiorite, if interbeds of other metamorphic rocks are excluded. The data presented in table 2 and figure 3 indicate that the Lawson layer is similar in composition. Judged from the modes reported in table 2, the smaller layers have the average composition of a quartz monzonite.

TABLE 2.—*Modes, in volume percent, of microcline-quartz-plagioclase-biotite gneiss*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Lawson layer

Mineral	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Potassium feldspar	Tr	3.6	11.4	34.0	34.5	35.9	36.6	17.1	22.6	29.9	12.8	28.3	11.4	25.6	13.0	13.8	8.9	8.2	4.8	13.3	14.0	10.5	8.9
Plagioclase	44.4	39.6	32.3	32.1	30.4	28.1	31.4	49.1	35.9	31.9	55.7	31.8	18.5	32.0	46.8	49.5	51.4	56.7	61.6	53.1	51.3	55.4	52.9
Quartz	50.4	50.1	50.0	29.4	30.8	27.8	27.2	27.8	32.1	32.6	26.8	28.5	58.0	32.0	31.5	29.8	31.4	29.6	28.2	29.4	30.2	27.9	29.6
Biotite	4.4	1.7	1.6	2.0	2.8	4.2	2.0	Tr	6.0	3.6	1.6	5.2	8.0	8.4	6.6	3.4	4.0	1.7	1.9	2.9	1.3	3.0	5.9
Muscovite	.8	.1	3.0	1.5	.6	3.3	1.5	1.2	1.8	1.4	.1	.9	.8	1.2	----	----	----	.4	.4	----	.1	----	.5
Opaque iron oxides	Tr	2.0	1.6	.9	.8	.5	1.0	2.2	.9	.6	2.6	3.1	1.1	.8	.4	.5	1.1	.6	2.0	1.2	1.1	2.5	1.6
Zircon	Tr	.1	.1	.1	.1	.2	Tr	Tr	.1	Tr	.4	Tr	.1	Tr	Tr	Tr	Tr	Tr	Tr	Tr	----	Tr	.1
Sphene	Tr	----	----	----	----	----	----	----	----	----	----	.8	----	----	----	----	----	----	----	----	----	----	----
Garnet	----	.1	----	----	----	----	Tr	----	----	----	----	----	.5	----	1.7	.9	3.1	2.7	.5	Tr	1.5	.7	.3
Sillimanite	----	----	----	----	----	----	Tr	----	----	----	----	----	1.6	----	----	----	----	----	----	----	----	----	----
Apatite	----	Tr	----	----	----	----	----	----	----	----	Tr	.9	----	----	Tr	.3	.1	Tr	Tr	----	----	Tr	.1
Epidote	----	----	----	Tr	----	----	----	1.4	----	----	----	----	----	Tr	----	----	----	.1	----	----	----	----	.1
Hornblende	----	2.7	----	----	----	----	----	----	----	----	----	----	----	----	----	1.8	----	----	----	----	----	----	----
Chlorite	Tr	----	----	Tr	Tr	Tr	.3	1.2	.6	----	Tr	Tr	----	Tr	----	Tr	Tr	----	.6	.1	.5	----	Tr
Allanite	----	----	----	----	----	----	----	----	----	----	----	.5	----	----	----	Tr	----	----	Tr	----	----	Tr	Tr
Calcite	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	Tr	----	----	----
Monazite	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	Tr	----	----	----	Tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{27}	An_{22}	Nd	Nd	Nd	Nd	Nd	Nd	An_{22}	An_{22}	An_{17}	An_{25}	Nd	An_{24}	An_{24}	An_{21}	Nd	Nd	Nd	Nd	Nd	Nd	An_{22}
Average grain diameter mm	0.5	0.5	0.8	0.4	0.6	0.6	0.5	Nd	Nd	Nd	Nd	Nd	0.4	0.6	0.6	0.6	0.4	0.4	0.5	0.4	0.4	0.4	0.4

Scattered bodies

Mineral	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
Potassium feldspar	33.7	20.0	30.0	29.0	18.9	14.5	28.9	32.5	25.5	15.0	29.6	29.2	18.5	41.6	36.0	36.1	30.3	28.2	35.8	32.9	39.4
Plagioclase	29.9	39.4	34.4	30.2	50.5	43.5	37.1	36.3	37.1	38.3	34.8	36.8	40.0	17.5	29.0	29.7	37.6	32.0	31.0	34.6	29.1
Quartz	26.5	32.6	32.2	33.3	26.6	34.5	25.8	24.8	28.7	39.0	29.3	28.1	28.3	36.1	31.0	27.2	26.9	32.6	25.9	24.9	28.5
Biotite	5.4	5.2	1.9	4.5	1.1	5.0	5.1	3.5	6.4	6.2	1.7	3.3	11.1	3.4	2.8	4.1	.7	.7	3.5	5.4	1.4
Muscovite	3.7	2.4	1.1	2.1	.9	Tr	1.2	1.1	.6	Tr	3.8	.4	----	.4	.6	2.3	2.4	5.2	2.6	1.4	.8
Opaque iron oxides	.4	.4	.4	.7	.9	2.0	1.8	.9	1.4	1.5	.8	1.0	1.0	9	.4	.6	.5	.2	.5	.7	.5
Zircon	Tr	Tr	Tr	Tr	.1	.1	Tr	.1	Tr	Tr	Tr	Tr	Tr	.1	.1	Tr	Tr	----	.1	.1	Tr
Sphene	----	----	----	----	----	----	----	----	----	----	----	----	.1	----	----	----	----	----	----	----	----
Garnet	----	----	----	----	.1	.3	----	----	----	----	----	----	----	----	.1	----	----	----	----	----	----
Sillimanite	----	Tr(?)	----	----	----	----	----	----	----	----	Tr	----	----	----	----	----	----	1.1	----	----	.3
Apatite	.4	----	----	.1	----	.1	.1	.8	.3	----	----	.1	.7	----	----	----	.1	----	----	Tr	----
Epidote	----	----	----	.1	.1	----	----	----	Tr(?)	----	----	Tr	----	Tr	----	----	----	----	----	----	----
Chlorite	Tr	----	Tr	----	.8	Tr	----	----	Tr	Tr	Tr	1.0	.3	----	Tr	Tr	1.5	Tr	.6	----	----
Allanite	----	----	----	----	----	----	----	----	----	----	----	Tr	----	----	----	----	----	----	----	----	----
Calcite	----	----	----	----	----	----	----	----	----	----	----	.1	----	----	----	----	----	----	----	----	----
Monazite	----	----	----	----	Tr	Tr	----	----	----	----	----	Tr	----	----	----	----	----	----	----	----	Tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{31}	An_{24}	An_{25}	Nd	An_{21}	An_{21}	An_{25}	An_{27}	An_{25}	An_{21}	An_{21}	Nd	An_{21}	An_{24}	An_{24}	Nd	An_{24}	Nd	An_{24}	An_{24}	An_{22}
Average grain diameter mm	0.5	0.5	0.5	0.5	0.6	0.4	0.6	0.6	0.5	0.4	0.8	Nd	Nd	0.5	0.4	0.9	Nd	Nd	Nd	Nd	0.6

1. Layered gneiss, from southeast flank of Sheridan Hill above Hamlin Gulch. (CC–196)
2. Layered gneiss, from outcrop east of Sheridan Hill summit. (CC–263)
3. Massive gneiss, from west edge of quadrangle in gulch north of Fall River road. (CC–20–1)
4. Gneiss, from outcrop 1.25 miles up Hamlin Gulch from Fall River road. (CC–291–2)
5. Gneiss, from float on Sheridan Hill, just above Pecks Gulch. (CC–307)
6. Gneiss, from North Clear Creek, west of Pecks Gulch. (CC–363–1A)
7. Typical microcline gneiss, from ridge between Pecks Gulch and Chase Gulch. (CC–368–1)
8. Layered gneiss, along North Clear Creek, east of Silver Creek. (CC–398–1)
9. Microcline gneiss interlayered with fine-grained biotite gneiss, from junction of Silver Creek and North Clear Creek. (CC–399–A)
10. Layered gneiss, from ridge between Chase Gulch and North Clear Creek. (CC–406)
11. Strongly foliated gneiss, from ridge west of Silver Creek and North Clear Creek. (CC–421)
12. Gneiss, from outcrop along North Clear Creek, south of Freeman Gulch. (CC–426–2)
13. Fine-grained strongly foliated gneiss, northeast of Pecks Flat. (CC–345–A)
14. Gneiss, from North Clear Creek just west of Pecks Gulch. (CC–364)
15. Gneiss, from dump 0.5 mile up Stewart Gulch from Missouri Gulch road. (JG–90)
16. Gneiss, from hill north of Stewart Gulch. (CC–1011–1)

17, 18. Garnet-bearing gneiss, from east slope of Dakota Hill. (CC–1027–1; CC–1027–B)

19. Gneiss associated with granite gneiss and pegmatite, from southeast slope of Dakota Hill. (CC–1030–1)
20. Microcline gneiss interlayered with sillimanitic biotite gneiss, from southeast slope of Oregon Hill. (CC–1036–B)
21. Garnet-bearing gneiss, from outcrop along Silver Creek northwest of Blackhawk Peak. (CC–1056–1)
22. Garnet-bearing gneiss from pit in saddle on southeast slope of Dakota Hill. (CC–1082)
23. Garnet-bearing gneiss, south of Gamble Gulch. (CC–1112)
24. Gneiss, from small folded lens on peak south of Ellsworth Creek northeastern part of quadrangle. (JG–111)
25. Gneiss, from thin layer southeast of Mount Pisgah. (CC–118)
26. Gneiss, from lens associated with quartz diorite and sillimanitic biotite-quartz gneiss, northeast of Mount Pisgah. (CC–245–AA)
27. Microcline gneiss inclusion in granodiorite, west of Pecks Flat. (CC–312–A)
28. Gneiss, from small lens, head of Montana Creek, northwest edge of quadrangle. (CC–1166)
29. Gneiss, from large crescent-shaped mass on southeast slope of Montana Mountain. (CC–1207–B)
30. Microcline gneiss, weakly layered, from small lens on top of ridge, 0.75 mile northwest of Missouri Lake. (JG–59)
31. Gneiss, from same general locality as that of sample 30, but taken 1,500 ft to the northeast. (JG–80)
32. Layered gneiss in contact with biotite gneiss, from south margin of crescent-shaped body on ridge west of Pine Creek and south of North Clear Creek. (CC–616–A)
33. Microcline gneiss, from small lens in migmatitic biotite gneiss, taken from ridge just north of Freeman Gulch. (CC–632–A)
34. Gneiss, from long narrow layer near west edge of mapped area, head of Miners Gulch. (CC–675)
35. Layered gneiss, from mine dump along North Clear Creek just west of its junction with Pine Creek. Gneiss is from the crescent-shaped layer that crosses North Clear Creek. (CC–922–A)
36. Gneiss, from mine dump on Elk Creek 1,800 ft from its junction with Pine Creek. (CC–948)
37. Gneiss lens, from head of Freeman Gulch. (CC–578)
38. Layered gneiss, east of the Elk Creek pluton, Miners Gulch, (CC–591)
39. Microcline gneiss, from long narrow layer within biotite gneiss, 0.5 mile south of Kingston. (CC–665–1)

40–42. Leucocratic gneiss, from crescent-shaped body southeast of Yankee Hill. (CC–487–1; CC–526; CC–529)

43. Gneiss, from lens extending northward from gneiss at site of sample 17. (CC–539)
44. Gneiss, from small lens near Kingston. (CC–1182–2)

AMPHIBOLITE

OCCURRENCE AND CHARACTER

In the quadrangle, amphibolite occurs as small concordant lenses widely dispersed in each of the microcline gneiss layers and less commonly as local lenses in the biotite gneiss layers. It also occurs as boudins in these rocks. Many of the lenses lie at or near the contact of major layers of microcline gneiss with biotite gneiss and range in width from a few inches to about 500 feet and in length from about a foot to at least 3,000 feet. Most are 1–20 feet thick and a few tens to a few hundred feet long. Accordingly, only the larger lenses can be shown at the scale of the geologic map (pl. 1).

Megascopically, contacts with the enclosing gneiss appear sharp, but in detail the amphibolite is seen to grade transitionally into the gneiss. Not uncommonly, pegmatite occurs along the contacts and intrudes both the amphibolite and the enclosing gneiss; the intruding pegmatite forms irregular crosscutting veinlets and stringers in the amphibolite and thus produces blocky forms that contrast sharply with the lit-par-lit structure of the migmatized biotite gneisses.

Within the Quartz Hill layer of microcline gneiss some bodies of amphibolite are associated with calc-silicate gneisses and cordierite-amphibole rocks. The amphibolite bodies in biotite gneiss layers commonly are associated with calc-silicate gneiss or skarn.

The amphibolite is a grayish black or medium gray, predominantly medium grained, generally homogeneous rock. Typical varieties have a uniform salt-and-pepper appearance; other varieties are finely layered as a result of segregation of the minerals into dark and light layers. The rock is more massive in appearance than other rock types in the region but has a moderately well developed foliation and lineation. Lineation is expressed mainly by the alinement of hornblende crystals.

PETROGRAPHY

Typical amphibolite in the quadrangle contains hornblende in excess of plagioclase, less than 10 percent quartz, and at places a few percent of clinopyroxene (samples 1, 2, and 5 of table 3). A variety of the rock herein referred to as hornblende gneiss contains about 25 percent hornblende, as much as 70 percent plagioclase, and generally sparse quartz (samples 6, 7, and 8 of table 3). Hornblende gneiss constitutes some of the mappable bodies within the Lawson layer of microcline gneiss on the east slope of Dakota Hill (pl. 1). All varieties of the rock have a dominantly hypidiomorphic granular texture.

The petrography of the amphibolite is similar to that described previously from the Central City district (Sims and Gable, 1964). The plagioclase is dominantly andesine and occurs as slightly cloudy anhedral or subhedral crystals. Most grains have well-developed simple twinning. Potassium feldspar occurs as tiny blebs in the plagioclase to constitute antiperthite; it occurs less commonly as small interstitial grains. Hornblende is the common green variety; it tends to

TABLE 3.—*Modes, in volume percent, of amphibolite*

[Tr, trace; Nd, not determined; ---, not found. Field number is in parentheses after description of sample. For chemical and spectrochemical analyses and norms of samples 1, 2, and 3 see corresponding numbered sample, table 4]

Mineral	1	2	3	4	5	6	7	8	Average of 19 modes, Central City district
Potassium feldspar	---	0.6	---	---	0.1	0.1	---	0.3	0.4
Plagioclase	30.5	36.1	40.4	13.1	35.5	70.0	70.6	55.5	43.0
Quartz	6.8	7.1	9.0	12.9	1.9	.8	---	9.4	4.8
Biotite	.3	1.0	---	3.1	.1	1.0	.1	.5	1.7
Hornblende	58.9	51.7	44.7	64.5	59.4	23.2	28.3	28.9	44.4
Clinopyroxene	1.9	2.2	---	---	---	2.7	---	---	1.3
Muscovite	---	---	---	3.4	---	---	Tr	---	
Opaque iron oxides	.4	Tr	3.0	.7	1.5	Tr	.6	4.6	
Zircon	---	.1	---	.4	---	.1	---	.1	
Sphene	---	.6	---	---	---	.4	Tr	.2	
Chlorite	---	---		1.1	.6	---	Tr	---	4.4
Epidote	---	Tr	---	Tr	.1	.4	.3	.1	
Calcite	.9	.1	2.6	.5	.5	1.3	---	---	
Apatite	.3	.5	.3	.3	.3	Tr	.1	.4	
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{48}	An_{30}	An_{48}	Nd	Nd	Nd	Nd	Nd	An_{34}
Average grain diameter mm	0.4	0.5	Nd	0.4	0.7	0.6	0.5	0.5	---

1. From mine dump south of the head of Pecks Gulch. (CC-309-B)
2. From thin layer of amphibolite in Central City layer of microcline gneiss, caved adit 0.5 mile northeast of Missouri Falls. (CC-730)
3. From dump of Grand Army shaft, Central City district. (S472-C-53)
4. From south margin of crescent-shaped microcline gneiss layer, nose of ridge south of North Clear Creek and west of Pine Creek. (CC-616-B)
5. From thick layer within the Lawson layer of microcline gneiss, south side of Stewart Gulch 0.5 mile west of Missouri Gulch. (CC-1001)
6, 7. Spotted plagioclase-hornblende gneiss, from layer within Lawson layer of microcline gneiss, crest of hill north of Stewart Gulch. (CC-984-1, CC-985)
8. Plagioclase-hornblende gneiss, from west margin of the Lawson layer of microcline gneiss, saddle west of Stewart Gulch. (CC-996)

be poikilitic and is intergrown with plagioclase to form a mosaic pattern. In a few samples clinopyroxene is intergrown with the hornblende; it is a very pale green, slightly pleochroic variety and is altered to hornblende along cleavage planes and grain boundaries. Quartz forms anhedral interstitial grains. Biotite is local in occurrence and is intergrown with but mainly secondary after hornblende. The biotite is partly altered to chlorite. Other alteration minerals include calcite, epidote, and muscovite. Opaque iron oxides, apatite, zircon, and sphene are common accessory minerals.

The amphibolite has a typical crystalloblastic texture, indicative of virtually contemporaneous crystallization of the dominant minerals—hornblende, plagioclase, and quartz. Pyroxene crystallized locally with the hornblende but subsequently was partly altered to hornblende. Biotite also apparently is secondary.

CHEMICAL COMPOSITION

Chemical and spectrochemical analyses of three typical specimens indicate some variation in chemical composition of the amphibolite (table 4). In general, the amphibolite is similar in composition to plateau basalt (Washington, 1922, p. 774), but it contains slightly more silica and alumina and less magnesia and titania; also, it overlaps the range in chemical composition of spilites (Reed, 1957, p. 37) but has less soda than does the typical spilite. The amphibolite contains less chromium and nickel than do most analyzed mafic igneous rocks (Engel and Engel, 1962, p. 65). The amphibolite from Central City is closely similar chemically to the para-amphibolites from North Carolina (Wilcox and Poldervaart, 1958, p. 1351).

Variations in alumina content of the rocks correlate directly with changes in the amount of modal plagioclase; the relatively low amount of calcium oxide in sample 3 (table 4) reflects a relatively small proportion of hornblende in the amphibolite.

TABLE 4.—*Chemical and spectrochemical analyses and norms of amphibolite*

[Laboratory number given in parentheses below sample number. Results of chemical analyses given in weight percent and of spectrochemical analyses, in parts per million. Normative composition or mesonorm computed by method of Barth (1959, 1962). For mode and sample description and locality, see corresponding numbered sample, table 3. Dorothy Powers and P. R. Barnett, analysts]

	Sample		
	1 (G3102)	2 (G3103)	3 (G3104)
Chemical analyses			
SiO_2	50.01	49.43	48.54
Al_2O_3	13.86	15.02	17.18
Fe_2O_3	2.95	3.11	3.61
FeO	10.35	8.73	10.61
MgO	5.99	5.88	5.42
CaO	10.33	10.18	7.87
Na_2O	2.57	3.38	3.14
K_2O	.57	1.06	.34
H_2O+	1.18	.95	1.46
H_2O-	.08	.06	.10
TiO_2	1.19	1.33	1.05
P_2O_5	.12	.20	.13
MnO	.22	.21	.29
CO_2	.33	.27	.27
Cl	.02	.05	.01
F	.07	.09	.09
S	.10	.01	.04
Subtotal	99.94	99.96	100.15
Less O	.08	.06	.06
Total	99.86	99.90	100.09
Bulk density	3.02	2.95	2.96
Powder density	3.06	3.04	3.01
Spectrochemical analyses			
Co	50	39	34
Cr	60	200	16
Cu	73	4	16
Ga	23	23	23
La	<100	<100	<100
Ni	44	49	12
Pb	<30	<30	<30
Sc	77	55	67
Sr	150	250	180
V	410	320	410
Y	50	50	40
Yb	5	4	4
Zr	90	140	100
Normative compositions			
Quartz	0.52	----------	2.66
Potassium feldspar	3.45	6.50	----------
Plagioclase:			
Albite	23.70	25.12	28.90
Anorthite	5.65	5.85	----------
Biotite	----------	----------	3.28
Hornblende:			
Actinolite	58.80	----------	----------
Edenite	----------	17.84	----------
Hornblende	----------	34.43	50.62
Pyroxene:			
Diopside	.52	2.84	----------
Hypersthene	----------	----------	1.06
Magnetite	3.16	3.28	3.85
Sphene (total titanium)	2.58	2.82	2.25
Apatite	.27	.43	.27
Pyrite	.27	.03	.09
Corundum	----------	----------	6.27
Calcite	.84	.68	.68

CORDIERITE-AMPHIBOLE GNEISS

Cordierite- and amphibole-bearing gneisses occur as scattered stubby lenses predominantly within the Quartz Hill layer of microcline gneiss. The lenses are elongate parallel to the regional foliation and range from a few tens of feet to 400 feet in length and from a few feet to about 125 feet in width. Most lenses are in direct contact with the enclosing gneiss or a pegmatite, but a few are adjacent to amphibolite, calc-silicate gneiss, or to hornblende-calcic plagioclase-quartz gneiss. The larger lenses are shown on plate 1 of this report but are given in more detail on the geologic map of the Central City district of Sims and Gable (1964). One small lens in biotite gneiss was mapped on the hill west of Missouri Lake (pl. 1).

The gneisses are variable in composition but consist mainly of three principal rock types, which in order of decreasing abundance are cordierite-gedrite rocks, hornblende- and cummingtonite-bearing rocks, and cordierite-biotite rocks. Previously (Sims and Gable, 1963) the cordierite-gedrite rocks were called cordierite-anthophyllite rocks. Commonly, the cordierite-gedrite rocks and the hornblende- and cummingtonite-bearing rocks are interlayered on different scales; cordierite-biotite rocks locally are intercalated with them. the complexity of the interlayering is shown schematically by the sketch in figure 4. In detail, the layering is still more complex, for each layer has a finer scale layering resulting from segregation of the constituent minerals in different proportions.

CORDIERITE-GEDRITE ROCKS

The cordierite-gedrite rocks are dark-gray or medium-gray and generally medium grained gneisses; but fine-grained and, locally, very coarse grained varieties are present. Freshly broken surfaces have a distinctly greasy, lustrous appearance, whereas weathered surfaces are grayish brown or reddish brown and are commonly ribbed. The layers rich in gedrite (for example, sample 1, table 5) tend to be coarse grained and to have a blocky appearance; the gedrite forms either radiating bundles or columnar aggregates as much as 5 centimeters long that radiate from a common center which contains abundant cordierite. The quartz-rich layers are finer grained and more inequigranular. Garnet and, to a lesser extent, cordierite typically are porphyroblastic and form crystals as much as 3 cm in diameter. Except for the fibrous gedrite, the tabular and fibrous minerals generally impart a conspicuous foliation and lineation to the rock.

The rocks typically have a granoblastic texture but locally are granulated. Where the rocks are granulated, quartz forms elongate plates parallel to the gedrite laths and has serrate grain boundaries against cordierite and plagioclase.

The cordierite-gedrite gneiss contains quartz, garnet, biotite, and plagioclase as well as the gedrite and the cordierite as major minerals, but the amounts and proportions of each of the minerals differ substantially from layer to layer (table 5). Magnetite-ilmenite, apatite,

TABLE 5.—*Modes, in volume percent, of representative varieties of cordierite-gedrite gneiss and associated rocks*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	Cordierite-gedrite rocks							Cordierite-biotite rocks	Hornblende- and cummingtonite-bearing rocks			
	1	2	3	4	5	6	7	8	9	10	11	12
Quartz	----	44.4	24.4	4.0	1.7	51.5	52.7	66.6	20.9	12.8	8.7	3.0
Plagioclase	----	----	.3	9.0	.4	----	14.5	----	16.7	31.7	54.1	52.2
Cordierite	3.8	29.6	29.7	29.3	38.6	27.1	29.6	25.5	----	----	----	----
Gedrite	90.0	2.2	23.4	37.9	44.3	10.4	1.3	----	----	----	----	----
Cummingtonite-hornblende	----	----	----	----	----	----	----	----	----	----	30.2	40.7
Hornblende	----	----	----	----	----	----	----	----	47.2	52.0	----	----
Magnetite-ilmenite	.1	.7	.2	1.6	----	.1	Tr	.1	2.8	3.0	2.0	3.5
Biotite	5.4	8.8	4.5	10.2	13.8	8.0	1.9	7.5	----	.2	----	----
Apatite	----	Tr	----	Tr	----	----	----	----	.1	.3	.9	.6
Zircon	.4	.1	Tr	.1	.1	Tr	Tr	Tr	----	----	----	----
Chlorite	----	.3	----	Tr	1.1	2.7	----	.2	4.3	----	2.6	----
Spinel	.3	----	----	Tr	----	----	----	----	----	----	----	----
Epidote	----	----	----	----	----	----	----	----	1.2	----	.4	----
Muscovite (secondary)	----	----	----	----	----	.2	Tr	.1	5.1	Tr	1.0	----
Garnet	----	13.9	17.5	7.9	----	----	----	----	1.7	Tr	.1	----
Sillimanite	----	Tr	----	----	----	----	Tr	Tr	----	----	----	----
Corundum	----	----	----	----	Tr	----	----	----	----	----	----	----
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	----	----	Nd	Nd	Nd	----	An_{26}	----	An_{78-80}	An_{65-69}	An_{61-65}	Nd
Average grain diameter ---- mm	Nd	0.5	1.7	0.6	0.6	0.5	Nd	0.6	0.3	0.4	0.3	0.6

1. Cordierite-gedrite-biotite gniess, from small body on crest of Negro Hill. (S 755-B-53)
2. Cordierite-garnet-gedrite-quartz gneiss, same locality as 1. (S 755-F-53)
3. Cordierite-gedrite-garnet-quartz-biotite gneiss, from small lens at margin of gedrite body on crest of Central City anticline, roadcut on north side of North Clear Creek. (B-17-1)
4. Cordierite-gedrite-garnet-biotite-plagioclase-quartz gneiss, from small body near crest of Quartz Hill. (S 53-A-52)
5. Cordierite-gedrite-biotite gneiss, from small body 1,800 ft south of the Patch, Quartz Hill. (S 257-1-52)
6. Cordierite-gedrite-quartz-biotite gneiss, same locality as 5. (S 257-7-52)
7. Cordierite-gedrite-plagioclase quartz gneiss, same locality as 5. (S 257-8-52)
8. Cordierite-quartz-biotite gneiss, from small body 1,500 ft south of the Patch, Quartz Hill. (S 251-B-52)
9. Garnet-hornblende-plagioclase-quartz gneiss, same locality as 5. (S 257-6-52)
10. Hornblende-plagioclase-quartz gneiss, same locality as 1 and 2. (S 754-1-53)
11. Cummingtonite-hornblende-plagioclase-quartz gneiss, same locality as 5. (S 257-5-52)
12. Cummingtonite-hornblende-plagioclase-quartz gneiss, same locality as 11. (S 257-1-52)

TABLE 6.—*Chemical analyses and modes of cordierite-gedrite gneiss and associated rocks*

[Serial number given in parentheses below sample number. Results of chemical analyses given in weight percent and modes, in volume percent. Tr, trace; Nd not determined; ----, not found. Analysis of sample 6 by C. L. Parker; all other analyses by E. L. Munson. Field number is in parentheses after description of sample]

	Cordierite-gedrite rocks					Cordierite-biotite rocks	Cummingtonite-bearing rocks
	1 (H3461)	2 (H3457)	3 (H3458)	4 (H3460)	5 (H3462)	6 (I4196)	7 (H3459)
Chemical analyses							
SiO_2	48.09	65.18	52.64	76.86	76.94	74.02	52.64
Al_2O_3	18.75	14.97	22.20	7.40	7.87	11.03	18.23
Fe_2O_3	2.04	.67	1.44	1.00	1.03	.63	1.23
FeO	17.55	7.76	9.73	6.11	7.27	4.50	11.12
MgO	8.76	6.75	7.85	5.85	4.68	5.04	4.86
CaO	.58	.31	.48	.06	.04	.07	6.53
Na_2O	.35	.25	1.91	.32	.41	.29	1.60
K_2O	.29	.12	.83	.22	.18	1.74	.40
MnO	.53	.13	.09	.04	.04	.04	.79
H_2O+	1.59	2.77	1.88	1.56	.95	1.83	1.12
H_2O-	.16	.15	.15	.29	.13	.17	.12
TiO_2	1.05	.76	.37	.09	.13	.19	1.17
P_2O_5	.14	.15	.01	.01	.01	.01	.32
CO_2	.01	.02	.01	.00	.01	.00	.03
Cl	----	----	----	----	----	.01	----
F	----	----	----	----	----	.18	----
Total	99.89	99.99	99.59	99.81	99.69	99.75	100.16
Modes							
Quartz	24	44	20	55	61	59	20
Cordierite	22	37	40	19	13	21	----
Gedrite	20	13	20	24	24	Tr	----
Cummingtonite	----	----	----	----	----	----	17
Biotite	2	Tr	9	2	2	17	1
Garnet	30	1	----	----	----	Tr	19
Plagioclase	----	----	6	----	----	2	43
Spinel	----	----	5	----	----	Tr	----
Apatite	Tr	Tr	----	----	----	Tr	Tr
Magnetite-ilmenite	2	2	Tr	Tr	Tr	----	Tr
Tourmaline	Tr	----	----	----	----	----	Tr
Alteration minerals	Tr	3	Tr	Tr	Tr	----	Tr
Pyrrhotite(?)	----	----	----	----	----	----	Tr
Zircon	----	----	Tr	Tr	Tr	----	----
Pyrite	----	----	----	----	----	Tr	----
Total accessory minerals	Tr	Tr	Tr	Tr	Tr	1	Tr
Total	100	100	100	100	100	100	100
Composition of plagioclase	----	----	Nd	----	----	Nd	An_{57}

1. Cordierite-garnet-gedrite-quartz gneiss, from small body on south slope of Quartz Hill, near Leavenworth mine. (S63–A–52)
2. Cordierite-gedrite-quartz gneiss, same locality as 1. This phase is interlayered with 1. (S63–C–52)
3. Cordierite-gedrite-plagioclase-quartz-spinel-biotite gneiss, from small body on west-southwest slope of Negro Hill at about the 8000-ft contour. (S682–A–53)
4. Cordierite-gedrite-quartz-biotite gneiss, from small body on crest of Negro Hill. (S754–A–53)
5. Cordierite-gedrite-quartz-biotite gneiss, from small body same locality as 4. (S755–C–53)
6. Biotite-cordierite-quartz gneiss, from small lens 0.25 mile south of the Glory Hole on east side of road. (S251–A–52)
7. Cummingtonite-garnet-plagioclase-quartz gneiss, from small body near crest of Quartz Hill. Cummingtonite is locally intergrown with hornblende. (S53–52)

zircon, spinel, sillimanite, and corundum are sparse local minerals.

Cordierite occurs as equant grains about 0.3 mm in diameter that poikilitically include tiny subrounded crystals of quartz, magnetite-ilmenite, zircon, and spinel. It is nearly colorless or very pale blue in thin section but locally is deep blue and has a violet cast adjacent to spinel grains. Twinning consists both of interpenetration and of simple forms. Cordierite is partly

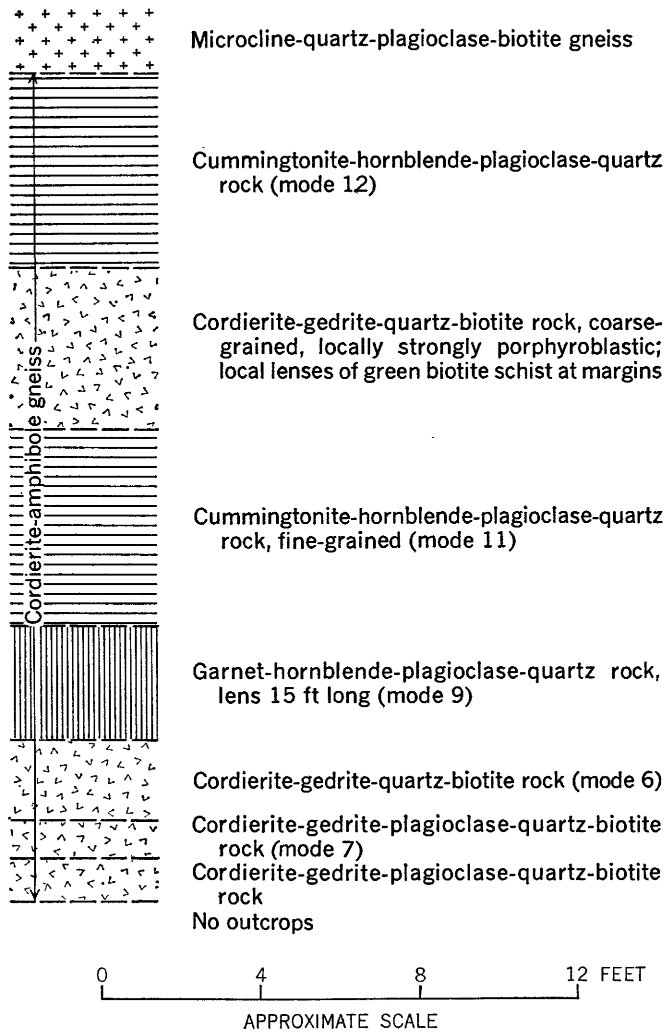


FIGURE 4.—Layering in a body of cordierite-amphibole gneiss, Quartz Hill. Mode number refers to table 5.

altered to chlorite and sericite (pinite) along grain boundaries. The zircon inclusions have strong pleochroic halos. Cordierite embays and corrodes biotite where the two are in contact. On eight grains of cordierite from different rock samples, n_y ranges from 1.541 to 1.548±0.003 and averages 1.545±0.003. It is biaxial positive or negative and has a very large but variable $2V$.

Gedrite forms subhedral or euhedral grains that tend to be slightly larger than the cordierite grains; for the most part it is oriented parallel to the lineation, but some occurs as radiating fibers. It is moderately or weakly pleochroic, and

X=pale yellow,
Y=pale yellow or pale greenish yellow, and
Z=pinkish gray or greenish gray.

It is positive and has a large $2V$. Three samples gave values for refractive index, n_z, as follows: 1.665±0.003, 1.674±0.003, and 1.676±0.003. Chlorite is a local alteration product. Commonly the gedrite is embayed by cordierite and quartz.

Garnet is local in occurrence and forms pale pinkish-orange or very pale lavender equant poikilitic grains, mainly containing inclusions of quartz and magnetite-ilmenite but also of sillimanite, cordierite, plagioclase, and biotite. Some crystals are skeletal. Characteristically the crystals have closely spaced intersecting fractures. The garnet has been determined from chemical analysis to be an almanditic variety; the range of n for five samples is 1.787±0.003 to 1.800 ±0.003. Biotite forms small ragged subhedral flakes and ranges from grayish yellow to orange brown. Many crystals have strong pleochroic halos around zircon inclusions. The biotite is embayed by both cordierite and gedrite. Plagioclase (calcic oligoclase) is subhedral, is twinned according to the albite and pericline laws (locally having complex twins), and is strongly embayed by cordierite and quartz. A later plagioclase that commonly encloses other minerals in the same sections is more sodic and anhedral and has weak albite twinning.

Green spinel occurs locally within cordierite crystals, mainly in association with magnetite-ilmenite. Magnetite-ilmenite forms anhedral grains in quartz, gedrite, and cordierite and between other mineral grains. Corundum was observed only in one section. Sillimanite occurs as inclusions in plagioclase and garnet and apparently is a relict mineral. The apatite in one specimen (S755–F–53) under crossed nicols has bright-blue polarization colors; as inferred by Vasileva (1958), it may be a manganese-rich apatite, for the interference color of apatite increases as Mn^{+2} increases.

CORDIERITE-BIOTITE ROCKS

Cordierite-biotite rocks are light gray, equigranular, fine to medium grained, and generally mottled because of the segregation of the light and dark minerals into clots. They constitute the bulk of one small body, and representative modes are given in table 5 (sample 8) and table 6 (sample 6). At places in this body a few percent of gedrite occurs in the cordierite-biotite rocks (Sims and Gable, 1964, table 20, sample 4). In another body described in this same report (see table 20, samples 5, 9, 10, 11, and 12), cordierite-biotite rocks are intercalated with thin layers of cordierite-gedrite rocks and cummingtonite- and hornblende-bearing rocks.

The cordierite-biotite rocks are granoblastic and, like the cordierite-gedrite rocks, are quite variable in composition. Typically, they consist mainly of quartz, cordierite, and biotite; some varieties contain more than 90 percent biotite and only traces of quartz and cordierite. The biotite has pleochroic colors ranging from light greenish orange brown to moderate reddish brown and is locally skeletal. In one specimen the biotite is olive green and

$$n_x=1.597\pm0.005,$$
$$n_y=n_z=1.612\pm0.005, \text{ and}$$
$$X>Y=Z.$$

Cordierite forms anhedral grains, has parallel twinning, and is locally intergrown myrmekitically with quartz. Zircon inclusions in the cordierite have strong pleochroic halos. In one specimen of cordierite n_y equals 1.549±0.003; the mineral is negative and has a very large $2V$. Sillimanite occurs locally in cordierite grains and is strongly embayed by it.

HORNBLENDE-CUMMINGTONITE ROCKS

Hornblende- and cummingtonite-bearing rocks, which occur as distinct layers intercalated with cordierite-gedrite gneiss, are of two types—one consisting of hornblende, calcic plagioclase, and quartz and the other of cummingtonite (with or without intergrown hornblende), calcic plagioclase, and quartz. Both hornblende- and cummingtonite-bearing rocks locally contain biotite.

The hornblende-plagioclase-quartz facies is a dark-gray fine- to medium-grained homogeneous rock. It resembles amphibolite but differs from it in containing more than 10 percent quartz and in having a much more calcic plagioclase. It has a typically granoblastic texture. The plagioclase is moderately to strongly zoned and has cores of labradorite or bytownite and rims of andesine or more sodic plagioclase. The hornblende is subhedral or euhedral and has a variable pleochroism. Commonly

X=brownish yellow,
Y=bluish green, and
Z=dark olive green.

In one specimen, n_y was 1.668±0.002. Because the mineral is negative and has a large $2V$, it is probably hastingsite. In some sections a little cummingtonite is intergrown with the hornblende.

The cummingtonite-bearing rocks are typically greenish gray, equigranular, and fine to medium grained and have a granoblastic texture. The rocks are characterized by intergrowths of cummingtonite and hornblende; the cummingtonite, which usually constitutes about 80 percent of the intergrowths, occurs in structural continuity with the hornblende and either surrounds it or forms irregular patches within it. In those rocks which contain cummingtonite without intergrowths of hornblende, the cummingtonite is peppered with inclusions of ilmenite. The cummingtonite is positive ($Z \wedge c \approx 20°$); n_z was determined in one specimen to be 1.664 ± 0.003. Garnet, which occurs sparsely, is pale pinkish orange and forms small clear anhedral grains or large irregular porphyroblasts with abundant inclusions of quartz and magnetite. Two separates of sample S53–52 that were X-rayed gave $A_0 = 11.557 \pm 0.0005$A and 11.532 ± 0.002A. Quantitative spectrochemical analyses by N. M. Conklin gave 2.4 percent manganese, 0.97 percent calcium, 3.4 percent magnesium, and 23 percent iron. The plagioclase is similar to that in the hornblende rocks described above. Biotite is rare except locally; it has a pleochroism almost identical to that in the associated rocks. In one specimen (S53–52), n_y was 1.629 ± 0.003.

CHEMICAL COMPOSITION

The rocks belonging to this unit vary in composition from layer to layer, and a chemical analysis is meaningful only with respect to a layer which has a specific mineralogy. Chemical analyses that represent the principal mineral associations are given in table 6. Five of the analyses in table 6 represent cordierite-gedrite rocks, one represents cordierite-biotite rock, and one represents cummingtonite-bearing rocks. Emphasis, therefore, is given to cordierite-bearing mineral associations.

The cordierite-gedrite rocks (analyses 1–5, table 6) vary widely in composition but are characterized by low content of CaO, Na_2O, and K_2O and moderate to high content of FeO and MgO. Cordierite-gedrite-quartz rocks, with or without garnet, have

$$\frac{FeO+MgO}{CaO+Na_2O+K_2O} \approx 20$$

With increasing amounts of Na_2O, sodic plagioclase forms (sample 3, table 6), and as K_2O increases, biotite forms in substantial amounts (sample 6, table 6). Garnet forms and both gedrite and cordierite decrease in those rocks which have an uncommonly high ratio of FeO to FeO+MgO (sample 1, table 6). In chemical composition, the rocks are similar to cordierite-anthophyllite rocks from many other localities. (See, for example, Tilley, 1937; Prider, 1940, p. 374.)

The cordierite-biotite rocks differ from the cordierite-gedrite rocks in having greater amounts of potassium and somewhat less magnesium and ferrous iron. The potassium favored the formation of biotite and inhibited the formation of gedrite as the available magnesium was used in the formation of cordierite and biotite.

The cummingtonite-bearing rocks intercalated with the cordierite-gedrite rocks have

$$\frac{FeO+MgO}{CaO+Na_2O+K_2O} < 2$$

and a high ratio of CaO to K_2O+Na_2O. The high content of CaO, Na_2O, and K_2O favored the formation of plagioclase. Some of the available CaO contributed to the formation of hornblende that is intergrown with the cummingtonite.

CALC-SILICATE GNEISS AND RELATED ROCKS

Rocks containing dominant calcium-iron silicates occur sporadically throughout the region as scattered small pods and discontinuous layers in all major layers of biotite gneiss and microcline gneiss. With few exceptions the bodies are a maximum of a few feet in thickness and a few hundred feet in length; most are too small to show at the scale of plate 1.

The rocks are extremely variable in composition but consist mainly of two types—skarns and calc-silicate rocks. Amphibolite is intercalated with many bodies throughout the quadrangle, and quartzite is associated with some bodies at Pewabic Mountain in the Central City district and on the northeast slope of Mount Pisgah.

Skarn is used in this report to designate dark-colored aggregates of calcium, magnesium, and iron silicates that resulted from metamorphism of interlayered impure calcareous and siliceous beds. The name embraces a group of rocks analogous to the reaction skarns of some Fennoscandian geologists (see discussion in Leonard and Buddington, 1964, p. 23–24) and does not imply an origin through metasomatism of carbonate rocks by emanations from a nearby cooling granitic body. The light-colored aggregates of similar mineralogy are referred to as calc-silicate rocks although some writers would also apply the term "skarn" to such masses.

The skarns have the following characteristic assemblages:

- Clinopyroxene-garnet
- Clinopyroxene-garnet-quartz
- Clinopyroxene-epidote-hornblende
- Garnet-magnetite-quartz

Lighter colored calc-silicate rocks commonly have the following assemblages:

- Clinopyroxene-garnet-plagioclase-quartz-sphene
- Calcite-clinopyroxene-garnet-quartz
- Clinopyroxene-epidote-hornblende-plagioclase-quartz
- Clinopyroxene-epidote-hornblende-quartz-scapolite
- Garnet-plagioclase-quartz

Epidote-opaque iron oxides-quartz-sphene
Epidote-hornblende-quartz-sphene
Epidote-plagioclase-quartz-sphene

Characteristically the rocks have crystalloblastic texture, indicative of virtually contemporaneous crystallization. Poikilitic textures are common in the garnets and less common in clinopyroxene and hornblende.

In an earlier report on the Central City district (Sims and Gable, 1964), garnet in the calc-silicate gneisses was reported in molecular percentages. Initial work on these garnets was completed in 1957–58, and at that time it was believed reasonable that percentages for garnets could be determined from combined X-ray and physical data. We now know that this assumption was erroneous. As no further work has been carried out on the garnets in calc-silicate gneisses since completion of the Central City district report, the type of garnet in these rocks is not designated in this report.

BIOTITE GNEISS

Biotite gneiss, the most abundant rock unit exposed in the quadrangle, occurs as thick layers intercalated on a gross scale with microcline gneiss. The layers have maximum thicknesses ranging from about 1,000 to 4,000 feet. Smaller bodies, from a few feet to a few hundred feet thick, occur at places within the major layers of microcline gneiss. Although the lithologies of each of the major biotite gneiss layers differ in detail, each layer is grossly similar, and accordingly the biotite gneisses are discussed as a unit herein.

The biotite gneiss can be divided on the basis of mineralogy into three principal rock types that are distinctive but to some extent gradational: (1) Biotite-quartz-plagioclase gneiss, (2) sillimanitic biotite gneiss, and (3) cordierite- and garnet-bearing sillimanitic biotite gneiss. All types of biotite gneiss contain moderate amounts of granite gneiss and pegmatite, either as thin streaks and concordant layers to constitute migmatite, or as larger discrete bodies.

Sillimanitic biotite gneiss and biotite-quartz-plagioclase gneiss are the dominant rock types and are intercalated in all the major biotite gneiss layers. Individual interlayers range in thickness from about an inch to several feet. Because of the intimate interlayering, mapping of the separate bodies of the two rock types was not practical at the scale of plate 1.

Cordierite- and garnet-bearing sillimantic biotite gneiss is mapped separately on plate 1. Contacts of the bodies of garnet- and cordierite-bearing gneiss are not shown, however, because the rock is gradational into sillimanitic biotite gneiss and it is difficult to delineate the different rock types in areas of sparse exposures. The garnet- and cordierite-bearing biotite gneiss occurs as discontinuous layers within the major biotite gneiss layers that lie above and below the Lawson layer of microcline gneiss. The largest body, about 1,000 feet thick and at least 2½ miles long, is stratigraphically near the middle of the lowermost of the two biotite gneiss layers. Discontinuous lenses occur in the upper part of the same layer and locally within the biotite gneiss layer overlying the Lawson layer.

The composition of the three principal types of biotite gneiss varies. Because abundant chemical data are lacking, the variations are shown in the text that follows by means of numerous modal analyses. The three types are subdivided for descriptive purposes into nine mineralogic groups.

Both the biotite-quartz-plagioclase gneiss and the sillimanitic biotite gneiss have been described in some detail from the Central City district (Sims and Gable, 1964), as well as from adjacent areas (Harrison and Wells, 1956, 1959; Moench, 1964), and are discussed only briefly on the following pages. The garnet- and cordierite-bearing rocks have not been described except in a short preliminary report (Sims and Gable, 1963) and accordingly are discussed more fully herein. A detailed report that will present additional data on the petrology and geochemistry of the cordierite-bearing rocks is now in preparation by the authors.

BIOTITE-QUARTZ-PLAGIOCLASE GNEISS

GENERAL CHARACTER

Biotite-quartz-plagioclase gneiss is a medium- or light-gray fine- to medium-grained equigranular rock. It weathers gray or brownish gray. Rarely, the rock is inequigranular with clots of felsic minerals as much as half an inch in diameter. Most varieties have a conspicuous compositional layering and a marked preferred planar and linear orientation of biotite and other tabular minerals. The mafic and felsic minerals are partly segregated into distinct layers. In many outcrops the biotite-rich layers are paper thin and impart a fissility to the rock, but in others the biotite is evenly dispersed. Some varieties resemble the more massive types of microcline gneiss but can be distinguished from the microcline gneiss because they are darker, finer grained, and richer in biotite.

Garnetiferous biotite-quartz-plagioclase gneiss, a local variety gradational into the major type and distinct from the garnetiferous sillimanitic biotite gneiss, forms scattered small bodies, especially in the northwestern part of the quadrangle and in the Central City district (Sims and Gable, 1964). The largest bodies that have been delineated are about 500 feet long and 100 feet wide. The gneiss has a conspicuous layering, the garnet tending to occur within the biotite-rich layers. It resembles the more common biotite-quartz-plagioclase gneiss megascopically except that is is darker and contains conspicuous garnet porphyroblasts. Commonly, weathering of the exposures forms a reddish stain that aids in distinguishing the rock.

PETROGRAPHY

The biotite-quartz-plagioclase gneiss contains plagioclase, biotite, and quartz as major minerals and a few percent of accessory minerals (table 7). It has an allotriomorphic granular texture. The plagioclase is dominantly sodic andesine but locally is labradorite; it varies more in composition than it does in other types of biotite gneiss. Most grains have narrow rims of albite. Twinning, of which the most prevalent is albite, is common but not ubiquitous, for about 15–20 percent of the grains in the sections examined appear to lack twinning. In sections that lack potassium feldspar the plagioclase grains tend to be poikilitic and to contain tiny inclusions of anhedral quartz; where potassium feldspar is present, the plagioclase is slightly antiperthitic and contains tiny irregular patches of microcline. Alteration of the plagioclase is slight and consists mainly of clay minerals oriented along twin lamellae and grain boundaries. Potassium feldspar occurs as grains smaller than those of plagioclase, is typically slightly perthitic (film and bleb perthite), and tends to be molded around plagioclase and quartz grains. Myrmekite occurs locally between the potassium feldspar and plagioclase grains. Quartz forms anhedral grains that show ubiquitous strain shadows; it contains abundant inclusions, at least locally, of magnetite-ilmenite, zircon, and plagioclase; some of the included magnetite has rims of muscovite(?). Strongly pleochroic biotite, ranging from pale yellow to deep reddish brown, typically occurs as fresh subhedral crystals having ragged terminations; zircon inclusions have pronounced pleochroic halos. At places the biotite is altered to chlorite and magnetite or to muscovite.

Magnetite-ilmenite, apatite, and zircon are nearly ubiquitous accessory minerals. The magnetite locally is altered to hematite. Hornblende, which is a strongly pleochroic olive-green variety, is a local accessory mineral that occurs mainly adjacent to amphibolite bodies. It forms anhedral grains, at places closely associated with biotite. Not uncommonly, traces of calcite occur with the hornblende.

The garnetiferous variety of biotite-quartz-plagioclase gneiss differs modally (table 8) from the more abundant variety, mainly in containing garnet. The

TABLE 7.—*Modes, in volume percent, of biotite-quartz-plagioclase gneiss*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	7	8	9	10	11	Average of 18 modes, Central City district
Potassium feldspar	----	----	----	----	----	10.5	4.0	2.4	Tr	0.8	1.0	----
Plagioclase	37.4	56.0	51.0	44.4	43.6	33.6	39.3	19.3	55.0	63.2	48.3	43.0
Quartz	31.7	22.6	32.2	17.7	24.8	30.8	51.0	66.0	17.5	18.6	22.0	40.0
Biotite	20.0	20.4	7.0	27.2	16.5	21.3	4.2	10.4	10.0	4.0	25.0	14.5
Muscovite	1.6	.5	----	Tr	----	----	.5	.7	----	----	.8	.5
Magnetite-ilmenite	7.1	.3	3.8	2.6	7.8	1.0	1.0	1.2	2.1	4.4	2.3	1.5
Garnet	----	----	----	----	----	----	----	----	Tr	Tr	----	
Chlorite	Tr	Tr	----	1.2	.3	Tr	Tr	----	----	----	----	
Epidote	Tr	----	----	Tr	----	----	----	----	.1	----	----	
Apatite	1.6	.2	.4	.7	.3	.4	----	----	.3	.5	.6	
Zircon	.1	Tr	Tr	Tr	.1	Tr	Tr	Tr	Tr	Tr	----	.5
Calcite	----	----	.1(?)	----	1.6	----	----	----	----	----	----	
Clinozoisite	.5	----	----	Tr	----	----	----	----	----	----	----	
Hornblende	----	----	5.5	6.1	4.9	2.0	----	----	15.0	8.2	----	
Sphene	----	----	----	.1	----	.4	----	----	Tr	.3	----	
Allanite	----	----	----	----	.1	Tr	----	----	----	Tr	----	
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{54}	Nd	An_{36}	An_{60}	An_{54}	Nd	Nd	Nd	An_{31}	An_{34}	Nd	----
Average grain diameter mm	0.3	0.5	0.5	0.3	0.2	0.6	0.4	0.4	0.4	0.3	0.5	----

1. Biotite gneiss, strongly foliated, homogeneous, from southwest flank of Mount Pisgah, between Hamlin Gulch and Woodpecker Gulch. (CC-155)
2. Biotite gneiss, thick layer, in migmatized biotite-sillimanite gneiss, from north side Fall River, 1.1 miles from west edge of quadrangle. (CC-162A)
3. Biotite gneiss, taken from 10-ft-thick layer adjacent to amphibolite in Lawson layer of microcline gneiss, north side of Fall River, 0.6 mile from west edge of quadrangle. (CC-21-1A)
4. Gneiss, from outcrop opposite the Fall River powerplant. (CC-103)
5. Biotite gneiss, fine-grained, interlayered with microcline gneiss, taken from near junction of Silver Creek and North Clear Creek. (CC-399-B)
6. Biotite gneiss, strongly foliated, from contact zone against microcline gneiss layer, head of Freeman Gulch. (CC-315-A)
7. Biotite-quartz-plagioclase gneiss, interlayered with microcline gneiss and sillimanitic biotite-quartz gneiss, from east slope of ridge, near head of Chase Gulch. (CC-443-A)
8. Biotite gneiss interlayered with granite gneiss and pegmatite, from hill southeast of Freeman Gulch, south of North Clear Creek. (CC-367-1B)
9. Biotite gneiss, from infolded lens about 100 ft from contact of microcline gneiss body in a saddle 1 mile east of Oregon Hill, on north side of Stewart Gulch. A small body of amphibolite is exposed about 200 ft to north. (CC-994-2)
10. Biotite gneiss, from layer within body of amphibolite on east slope of ridge between Stewart Gulch and Pickle Gulch. Grades transitionally into amphibolite. (CC-1009)
11. Biotite gneiss, from north slope Bald Mountain. (EWT-66B-54)

garnet forms porphyroblasts as much as 7 mm in diameter but more commonly occurs as grains about 2 mm across. Many grains are almond shaped, flattened in the plane of foliation, and elongated in the direction of dominant lineation. Many grains are broken or fractured roughly at right angles to the lineation. Biotite commonly forms thin sheaths around garnet porphyroblasts. The garnet is strongly poikilitic and contains abundant quartz and plagioclase and less biotite, magnetite-ilmenite, and apatite.

TABLE 8.—*Modes, in volume percent, of garnetiferous biotite-quartz-plagioclase gneiss*

[Tr, trace; Nd, not determined; ------, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	Average of 10 modes, Central City district
Potassium feldspar	2.3	------	------	0.1	------	------	------
Plagioclase	49.2	36.4	39.5	25.9	43.4	48.0	29.0
Quartz	35.3	45.4	34.2	50.4	15.6	41.0	38.0
Biotite	9.2	16.6	12.4	16.3	34.2	5.7	20.0
Muscovite	3.7	.2	.2	------	.3	------	------
Magnetite-ilmenite	Tr	.8	3.3	4.2	3.6	2.9	1.0
Garnet	.2	.4	10.3	2.5	2.9	1.0	10.0
Epidote	.1	------	------	------	Tr	------	2.0 (Epidote, apatite, zircon, amphibole)
Apatite	Tr	.2	.1	.5	Tr	.4	
Zircon	Tr	Tr	Tr	.1	Tr	Tr	
Amphibole (cummingtonite)	------	------	------	------	------	1.0	
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	Nd	Nd	An_{40}	An_{43}	An_{43}	An_{31}	------
Average grain diameter mm	0.5	0.4	0.4	0.3	0.4	0.2	------

1. Biotite gneiss, thin layer, associated with granite gneiss and pegmatite in Lawson layer of microcline gneiss; sample taken just north of Fall River, about 0.5 mile from west edge of quadrangle. (CC-24)
2. Migmatitic biotite gneiss intercalated with microcline gneiss; sample taken just below base of microcline gneiss layer, south slope of Blackhawk Peak near North Clear Creek. (CC-363-1B)
3. Migmatitic garnetiferous biotite gneiss; sample taken about 800 ft west of locality of sample 2. (CC-366-2)
4. Garnetiferous biotite gneiss, from ridge on north side of Miners Gulch, 1,100 ft from west edge of quadrangle. Gneiss is interlayered with biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss. (CC-677-1C)
5. Garnetiferous biotite gneiss, from thin layer of biotite gneiss in granodiorite body roadcut near head of Missouri Gulch. Garnetiferous biotite gneiss is intercalated with sillimanitic biotite-quartz gneiss, which locally is garnetiferous. (CC-855-A2)
6. Migmatitic garnetiferous biotite gneiss, adjacent to blunt layer of microcline gneiss; sample taken from steep westward-facing slope of Michigan Hill, 1,000 ft northeast of bend in North Clear Creek. (CC-889).

The rocks have a typical crystalloblastic texture; the plagioclase, quartz, and biotite are intergrown and show a well-defined mosaic texture. Hornblende and garnet, where present, appear to have crystallized almost simultaneously with the major minerals. Potassium feldspar apparently crystallized later. The albitic rims on plagioclase, and locally on myrmekite, indicate some modification subsequent to crystallization of most of the rock. The nearly complete absence of potassium feldspar, except in strongly migmatized biotite gneiss, and the apparently late paragenetic position are interpreted to indicate that the potassium feldspar was largely introduced during migmatization.

The assemblages of the biotite-quartz-plagioclase gneiss are:

Biotite-plagioclase-quartz
Biotite-plagioclase-potassium feldspar-quartz
Biotite-magnetite-plagioclase-potassium feldspar-quartz
Biotite-hornblende-magnetite-plagioclase-quartz

Muscovite is a local stable mineral in the preceding rock type as well as in the following assemblages of garnetiferous biotite-quartz-plagioclase gneiss:

Biotite-garnet-plagioclase-quartz
Biotite-garnet-magnetite-plagioclase-quartz

SILLIMANITIC BIOTITE GNEISS

GENERAL CHARACTER

Sillimanitic biotite gneiss consists of two varieties, sillimanitic biotite-quartz gneiss and sillimanitic biotite-quartz-plagioclase gneiss, which are gradational and inseparable in the field but differ somewhat in quantitative mineralogy. The rocks are light gray or bluish gray fine to medium grained and generally equigranular. Inequigranular porphyroblastic varieties occur locally. Weathered exposures are brownish gray and at places have a conspicuous silvery sheen. In most exposures the gneiss has a distinct layering consisting of alternating layers a fraction of an inch to a few inches thick of slightly different lithology or texture. Sillimanite is distinctive and conspicuous and occurs as alined needles and as aggregates of fibers as much as an inch in length, or less commonly as tabular discoid masses of about the same length.

PETROGRAPHY

The gneiss consists mainly of quartz, biotite, sillimanite, and plagioclase; minor minerals include potassium feldspar, magnetite-ilmenite, and muscovite. Sillimanitic biotite-quartz-plagioclase gneiss (table 9) is distinguished from sillimanitic biotite-quartz gneiss (table 10) in that it contains more than 15 percent plagioclase; it also has less biotite and more potassium feldspar. However, as can be seen by reference to the two tables of modes, each variety's mineral content varies considerably.

Both varieties of gneiss have an allotriomorphic granular and, locally, a lepidoblastic texture. Grains average about 0.4 mm in diameter; porphyroblasts are commonly 2.5–3.0 mm in diameter. Plagioclase of relatively uniform composition (An_{23-29}) forms anhedral or rarely subhedral grains and has three modes of occurrence: (1) Grains intergrown with the dominant minerals, (2) grains interstitial between larger crystals of quartz and biotite, and (3) poikilitic grains, generally untwinned, that poikilitically contain inclusions of biotite, magnetite, quartz, sillimanite, and zircon. In many sections nearly every plagioclase grain is twinned, whereas in other sections only about half the grains are twinned; albite twinning is dominant; Carlsbad and pericline twins are less common. Adjacent to potassium feldspar, the plagioclase has narrow rims of albite

TABLE 9.—*Modes, in volume percent, of sillimanitic biotite-quartz-plagioclase gneiss*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	7	8	9
Potassium feldspar	7.8	13.3	5.6	7.4	0.6	8.1	7.6	--------	9.5
Plagioclase	16.2	19.6	30.1	15.4	28.9	16.5	21.5	38.1	19.8
Quartz	49.1	54.2	47.5	53.2	57.6	52.1	47.2	23.4	54.6
Biotite	16.5	9.0	13.5	13.9	8.7	14.3	16.0	34.1	10.8
Muscovite	1.3	.4	.3	.9	1.5	3.3	.4	1.8	1.0
Magnetite-ilmenite	1.3	1.1	2.7	1.5	1.7	2.2	.8	.2	1.9
Sillimanite	7.8	2.2	Tr	7.7	1.0	3.5	6.5	2.2	2.4
Chlorite	Tr	Tr	--------	Tr	--------	--------	Tr	Tr	--------
Apatite	Tr	--------	--------	--------	--------	--------	--------	.2	--------
Zircon	Tr	.2	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Calcite	--------	--------	.3	Tr	--------	--------	--------	--------	--------
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	Nd	Nd	An_{29}	An_{25}	Nd	An_{24}	An_{25}	Nd	An_{23}
Average grain diameter mm	0.4	0.4	0.4	Nd	0.4	0.3	0.3	0.4	0.4

1. Sillimanitic biotite-quartz-plagioclase gneiss interlayered with granite gneiss and pegmatite; sample taken from outcrop north side of Fall River, 1.1 miles from west edge of quadrangle. (CC-226)
2. Sillimanitic biotite-quartz-plagioclase gneiss interlayered with biotite-quartz-plagioclase gneiss; outcrops on steep west slope of Michigan Hill opposite mouth of Freeman Gulch. (CC-243)
3. Gneiss from mine adit in eastward-trending gulch located between North Clear Creek and Freeman Gulch; rock is interlayered with rock represented by sample 4. (CC-611-A)
4. Sillimanitic biotite-quartz-plagioclase gneiss, from same locality as that of sample 3. (CC-611-B)
5. Gneiss from conspicuous outcrop near road on south slope of California Mountain, just north of Nugget; interlayered with rock like that of sample 6. (CC-1051-A)
6. Gneiss from same locality as that of sample 5. (CC-1051-B)
7. Gneiss from roadcut, west of entrance to Cold Spring campground, just east of quadrangle. (JG-84)

8, 9. Samples from north slope of Bald Mountain and vicinity. (EWT-53-54, EWT-89-54)

TABLE 10.—*Modes, in volume percent, of sillimanitic biotite-quartz gneiss*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	Average of 18 modes, Central City District
Potassium feldspar	------	0.9	8.0	------	0.6	------	0.5
Plagioclase	10.0	.5	7.8	10.2	9.2	5.3	14.0
Quartz	57.6	------	33.0	34.0	51.2	38.0	49.0
Biotite	22.1	58.9	34.4	23.3	24.8	31.5	23.5
Muscovite	1.8	1.2	Tr	.6	.5	1.6	4.0
Magnetite-ilmenite	2.2	.7	1.1	2.5	.4	2.1	1.0
Sillimanite	6.3	37.8	15.4	29.4	13.3	21.4	8.0
Chlorite	Tr	------	------	Tr	------	------	----------
Apatite	Tr	------	------	------	------	------	----------
Zircon	Tr	Tr	.3	Tr	Tr	.1	----------
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{29}	An_{25}	Nd	Nd	An_{28}	An_{26}	----------
Average grain diameter mm	0.4	Nd	Nd	Nd	0.3	0.2	----------

1. Sillimanitic biotite-quartz gneiss interlayered with biotite-quartz-plagioclase gneiss, sample taken from outcrop on north side of Fall River, about 1.1 miles from west edge of quadrangle. (CC-162-B)
2. Biotite- and sillimanite-rich variety of gneiss; thin layer in granodiorite body at head of Missouri Gulch; interlayered with garnetiferous biotite-quartz-plagioclase gneiss. (CC-855-A1)
3. Typical sillimanitic biotite-quartz gneiss from Missouri Gulch area. (JG-29b)

4, 5, 6. Samples from north slope of Bald Mountain and vicinity. (EWT-73-54, EWT-87-54, EWT-96-54)

and locally is myrmekitically intergrown with quartz. Some grains show a few percent of potassium feldspar in oriented patches, to constitute antiperthite. The potassium feldspar is dominantly microcline; it is slightly perthitic (string and film perthite), generally poorly twinned, and dominantly interstitial. Quartz forms anhedral grains and has strong strain shadows. The biotite is strongly pleochroic, ranging from light yellowish brown to dark reddish brown, and occurs as small stubby, ragged laths; at places it contains considerable sillimanite. Most sections show some alteration of the biotite to chlorite and magnetite. Optical and chemical data on a sample of biotite from the Central City district are reported by Sims and Gable (1964). Sillimanite occurs in sheaths and stringers and is generally associated with quartz and biotite. Muscovite forms overgrowths on and is intergrown with biotite, and it rims magnetite. Magnetite-ilmenite and zircon are common accessory minerals. Many sections show some alteration of magnetite to hematite. Biotite, quartz, potassium feldspar, muscovite, plagioclase, and sillimanite are intergrown and have sharp contacts with one another. Any one of them can be found in direct contact with any one of the others. Muscovite is dominantly a primary mineral. Sillimanite and potassium feldspar occur together and only locally have intervening muscovite. Chlorite and the clay mineral alteration of plagioclase are secondary in origin.

CORDIERITE- AND GARNET-BEARING SILLIMANITIC BIOTITE GNEISS

GENERAL CHARACTER

The rocks mapped as cordierite- and garnet-bearing sillimanitic biotite gneiss are distinguished from other types of biotite gneiss in that they contain cordierite and (or) garnet as well as sillimanite.

The cordierite- and garnet-bearing biotite gneiss varies in composition but consists mainly of three varieties: (1) Garnetiferous sillimanitic biotite-quartz-plagioclase gneiss (table 11), (2) cordierite-bearing garnet-sillimanite-biotite-quartz-plagioclase gneiss (table 12), and (3) cordierite-biotite-sillimanite-quartz-plagioclase gneiss (table 13). The varieties are gradational and were not distinguished separately in the field. Varieties 1 and 2 are difficult to distinguish megascopically except where cordierite occurs as distinct porphyroblasts; variety 3 is sparse and is generally intimately intermixed with variety 2.

TABLE 11.—*Modes, in volume percent, of garnetiferous sillimanitic biotite-quartz-plagioclase gneiss*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	7	8	9
Potassium feldspar	26.6	1.4	9.5	0.1(?)	1.2	Tr(?)	18.5	3.0	--------
Plagioclase	18.5	23.8	40.8	2.5	60.4	41.8	31.5	22.9	11.8
Quartz	27.6	53.9	14.5	59.5	7.2	42.0	35.8	64.1	48.4
Biotite	16.3	14.3	26.0	24.0	28.5	13.6	12.2	7.7	8.5
Muscovite	--------	.1	.2	--------	.4	.5	.6	--------	1.0
Magnetite-ilmenite	.9	2.6	.8	1.0	.3	2.0	1.2	.9	3.9
Garnet	3.3	Tr	.5	1.9	.4	.1	Tr	.6	25.9
Sillimanite	6.5	3.9	7.7	11.0	1.6	Tr	.1	.8	.4
Apatite	--------	--------	--------	Tr	Tr	Tr	--------	--------	--------
Zircon	.3	Tr	Tr	Tr	Tr	Tr	.1	Tr	.1
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Composition of plagioclase	An_{27}	Nd	An_{21}	An_{34}	An_{27}	An_{24}	Nd	Nd	An_{32}
Average grain diameter ...mm	0.2	0.3	0.2	0.4	0.5	0.4	0.2	0.4	0.6

1. Gneiss layer in microcline gneiss; hill north of Pecks Flat, about 0.3 mile south of North Clear Creek. (CC-345-B)
2. Gneiss, from upper part of biotite gneiss layer, about 500 ft east of contact with microcline gneiss; ridge between Pecks Gulch and Chase Gulch. (CC-383-1)
3. Gneiss, from dump of caved adit on east side of Miners Gulch, just west of Elk Creek gabbro pluton. (CC-681)
4. Quartz-rich phase of gneiss, about 1,000 ft southwest of locality of sample 2, near head of Chase Gulch. (CC-367-B)
5. Gneiss, about 1,000 ft southeast of locality of sample 3. (CC-574)
6. Slightly migmatized gneiss, from ridge crest 0.5 mile south-southwest of Sheridan Hill. (CC-460)
7. Gneiss, interlayered with biotite-quartz-plagioclase gneiss, from ridge overlooking North Clear Creek, east of mouth of Freeman Gulch. (CC-425-1)
8. Gneiss, from south flank of Michigan Hill. (CC-911-2A)
9. Layered possibly sheared gneiss, from outcrop on east slope of Oregon Hill, 0.5 mile east of crest. (CC-1077-1B)

TABLE 12.—*Modes, in volume percent, of cordierite-bearing garnet-sillimanite-biotite gneiss*

[Tr, trace; Nd, not determined; --------, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	7	8	9	10
Potassium feldspar	3.9	14.2	.3	Tr	Tr(?)	Tr	--------	29.7	3.3	7.7
Plagioclase	2.2	2.2	6.0	12.1	11.9	5.7	.2	10.6	8.0	3.9
Quartz	30.4	24.5	27.0	27.3	40.9	52.7	22.2	1.2	29.6	26.7
Cordierite	26.7	19.2	27.9	5.9	11.2	1.9	39.9	10.0	4.3	11.7
Sillimanite	8.2	7.3	6.1	.1	7.8	10.6	17.5	20.1	5.7	3.2
Garnet	3.9	3.6	3.3	33.1	Tr	7.1	9.7	1.2	20.0	17.4
Biotite	22.0	25.0	24.6	15.2	25.0	21.0	7.0	20.8	28.9	27.7
Muscovite (secondary)	--------	Tr	--------	--------	--------	.2	--------	5.6	Tr	--------
Magnetite-ilmenite	2.7	3.9	4.6	6.3	3.2	.8	3.3	.5	.1	1.4
Zircon	Tr	Tr	.1	Tr	Tr	Tr	.2	.3	Tr	Tr
Apatite	--------	.1	.1	Tr	Tr	--------	--------	--------	--------	Tr
Spinel	--------	--------	Tr	Tr	--------	Tr	--------	--------	--------	--------
Chlorite	--------	--------	--------	--------	--------	--------	--------	--------	--------	.1
Andalusite	Tr	Tr	Tr	--------	Tr	--------	--------	--------	--------	.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	Nd	Nd	An_{30-32}	An_{38}	An_{25}	An_{38}	Nd	Nd	An_{30}	Nd
Average grain diameter ...mm	0.7	0.3	0.4	0.3	0.4	0.3	Nd	0.4	Nd	Nd

1. Migmatitic gneiss, outcrop 0.25 mile up Missouri Gulch road from State Highway 119, east side of Missouri Creek. (JG-12a)
2. Gneiss, from ridge, 0.5 mile northwest of Missouri Lake. (JG-30)
3. Gneiss, from outcrop in gulch, 0.5 mile west of Missouri Lake and 0.2 mile southwest of locality of sample 2. (JG-38a)
4. Biotite gneiss, adjacent to small lens of microcline gneiss, east slope of Yankee Hill. (CC-530-1)
5. Layer within interlayered migmatitic biotite gneisses, from east slope of hill at altitude of about 10,800 ft, 0.7 mile north of Yankee Hill. (CC-677-1B)
6. Layer within folded migmatitic biotite gneisses, from east of body of quartz diorite and hornblendite that crosses Pecks Gulch south of North Clear Creek, central part of quadrangle. (CC-783-4)
7. Biotite gneiss, from mine dump in eastward-draining gulch midway between Oregon Hill and Michigan Hill, 0.3 mile west of Silver Creek. (CC-789-A)
8. Gneiss, from southwest flank of Michigan Hill, 900 feet east of junction of North Clear Creek and Pine Creek. (CC-887)
9. Gneiss, from roadcut on north slope of hill, 1.5 miles west of the Bald Mountain Cemetery. (EWT-90)
10. Gneiss, from east side of small hill south of Chase Gulch and 1.5 miles north of Bald Mountain Cemetery. (D-168)

TABLE 13.—*Modes, in volume percent, of cordierite biotite-quartz-plagioclase gneiss*

Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3
Potassium feldspar	Tr	----	----
Plagioclase	18. 3	0. 1	15. 3
Quartz	24. 3	Tr	37. 2
Cordierite	24. 1	89. 0	31. 7
Biotite	28. 0	4. 3	8. 3
Magnetite-ilmenite	2. 7	3. 6	6. 0
Rutile	Tr	----	----
Apatite	. 6	----	Tr
Zircon	----	Tr	Tr
Muscovite	. 1	1. 3	----
Sillimanite	1. 9	1. 7	1. 5
Spinel	----	Tr	Tr
Garnet	----	Tr	Tr
Staurolite	Tr	----	----
Andalusite	1. 9	----	----
Total	100. 0	100. 0	100. 0
Composition of plagioclase	Nd	Nd	An_{26}
Average grain diameter____mm	0. 5	0. 9	0. 3

1. North slope Bald Mountain, about 2,200 ft west-southwest of sharp curve in road, upper Eureka Gulch. (EWT-66b-54)
2. Gneiss from top of ridge, 0.45 mile west-southwest of Missouri Lake. Sample taken 1,000 ft southeast of location of sample JG-38a, table 12. (JG-69)
3. Cordierite-biotite gneiss adjacent to hornblendite body, just north and east of junction of Mount Pisgah road with Forest Service road to experimental tree plot and dam. (CC-360-1)

The rocks are medium or dark gray, fine to medium grained and extremely variable in structure. They range from nearly massive, homogeneous-appearing rocks to strongly layered gneisses. The more massive rocks tend to be nearly equigranular, but locally they have conspicuous porphyroblasts of either intergrown garnet and sillimanite or cordierite. The strongly layered rocks tend to be coarser grained and inequigranular. Not uncommonly, the layered rocks have a pronounced crinkly foliation. All varieties contain some pegmatite that has potassium feldspar and that occurs as streaks or conformable pods. Amphibolite and calc-silicate gneisses are commonly found adjacent to the cordierite-bearing gneisses.

PETROGRAPHY

The principal minerals—cordierite, quartz, biotite, plagioclase, garnet, sillimanite, and potassium feldspar—occur in different amounts and proportions, as can be seen by comparing the modes in tables 11, 12, and 13.

Garnet occurs as porphyroblasts, from less than 1 mm to about 5 cm in diameter, that are strongly poikilitic and contain inclusions of biotite, sillimanite, plagioclase, quartz and, rarely, potassium feldspar. The porphyroblasts have two modes of occurrence: (1) Megacrysts that truncate biotite laths and (2) megacrysts that are enclosed by conformable biotite-sillimanite sheaths. Although generally subequant, some garnet megacrysts are elongate in the plane of foliation. In some cordierite-bearing varieties, the garnet is strongly embayed and corroded by cordierite and is surrounded by well-defined coronas of it; outside the coronas, biotite and sillimanite are profusely intergrown with quartz and plagioclase.

A reddish-brown biotite has the pleochroic formula in which

X=straw yellow,
Y=deep orange brown, and
Z=dark reddish brown.

It forms stubby, ragged laths, generally having a strong preferred orientation. The crystals are embayed by quartz, plagioclase, cordierite, and garnet and have grain boundaries that are fuzzy against cordierite. Myrmekitic intergrowths of quartz in biotite are associated with alteration of the biotite to andalusite. Zicron inclusions have strong pleochroic halos.

Sillimanite is generally associated with biotite, mainly as capillarylike needles and short stubby crystals in felted masses. Except rarely, sillimanite in contact with potassium feldspar lacks intervening muscovite.

Quartz, the dominant mineral in the rocks, forms anhedral grains that are slightly larger than all other minerals except garnet. The quartz contains a few tiny inclusions of sillimanite, plagioclase, biotite, and magnetite-ilmenite.

Plagioclase (oligoclase-andesine) is anhedral, and is embayed by quartz, potassium feldspar, and biotite. In a few sections it is slightly antiperthitic. The plagioclase is twinned according to the albite and pericline and, rarely, Carlsbad twin laws. Adjacent to potassium feldspar it commonly has albitic rims as much as 0.02 mm thick and locally has myrmekite rims. Typically, it is altered slightly to clay minerals.

Cordierite occurs as nearly colorless or as pale-blue equant grains of about the same diameter as those of plagioclase, as porphyroblasts as much as 5 mm in diameter, and as coronas around garnet, as previously noted. Nearly all grains are poikilitic and have inclusions of magnetite, biotite, quartz, garnet, and sillimanite. In some sections the cordierite has myrmekitic intergrowths of quartz and, rarely, potassium feldspar. The cordierite can be distinguished by its diagnostic alteration to pinite, twinning of both simple and interpenetration type, low birefringence, spongelike appearance, and by its content of abundant minute opaque(?) minerals and zircon which has strong radiohalos. Where cordierite coronas are well formed around garnet, they generally lack inclusions of other minerals except quartz and rarely potassium feldspar. These coronas separate the garnet from parts of the rock that are rich in biotite and sillimanite. The cordierite and associated quartz embay the garnet. The cordierite is biaxial negative (rarely biaxial positive) and has a $2V$ greater than 65°. Seven determinations of n_γ ranged from 1.548 ± 0.003 to 1.554 ± 0.003 and averaged 1.550 ± 0.003.

The potassium feldspar consists of grid-twinned microcline, orthoclase which has fine hairlike albitic twin lamellae, and vein and film microperthite. It forms small anhedral grains and, rarely, large poikilitic porphyroblasts which have inclusions of sillimanite (unaltered), clear quartz, plagioclase, and biotite. Both monoclinic and triclinic feldspars, as determined by X-ray, coexist in the cordierite-bearing gneiss units. Monoclinic feldspar is dominant in the lens that is continuous with the Dumont anticline in the northeastern part of the quadrangle, whereas triclinic feldspar is dominant in the lens that is due south of Michigan Hill. A small percentage of monoclinic orthoclase microperthite occurs with the triclinic feldspar. The triclinic feldspars have a distinct microcline grid twinning and contain about 75 ± 1 percent $KAlSi_3O_8$ by weight. Potassium feldspars in the other small, scattered, cordierite-bearing biotite gneiss bodies within the quadrangle, as observed in thin section, resemble those at Michigan Hill.

The minor minerals include magnetite-ilmenite, which is ubiquitous, and lesser amounts of andalusite, staurolite, spinel, apatite, and zircon. Magnetite-ilmenite occurs as poikilitic anhedral grains that have inclusions of quartz, biotite, sillimanite, and spinel or occurs as smaller anhedral grains closely associated with cordierite. Narrow coronas of slightly pleochroic, pale-green to pale-brown newly formed biotite were found in a few samples around magnetite in contact with cordierite grains. In those sections containing spinel, the spinel commonly is closely associated with the magnetite, and it may be surrounded by coronas of biotite similar to those around the magnetite. The spinel is an apple-green magnesian hercynite, as determined by chemical analysis. Andalusite occurs sparsely in many sections that contain cordierite. It forms irregular, parallel intergrowths with biotite in a few sections and embays and corrodes the biotite. It is negative and can be distinguished by its high relief, cleavage, low birefringence, very large $2V$, and weak dispersion. Most andalusite grains have vermicular rims adjacent to altered biotite. The biotite adjacent to the andalusite also is vermicular and commonly is altered to a greenish brown. Rounded relict grains of staurolite occur rarely as inclusions in both plagioclase and cordierite.

Alteration minerals that occur within or corrode and embay the major minerals include chlorite, muscovite, and clay minerals. The pinitic alteration of cordierite appears to consist of an intimate mixture of sericite and chlorite.

The textures of the cordierite-garnet gneisses are more complex than those in other biotite gneisses in the area. The presence of porphyroblasts and coronas and the rather common embayment and corrosion of minerals indicate some modification of the rock subsequent to original crystallization.

Cordierite, garnet, and, less commonly, potassium feldspar and magnetite-ilmenite occur as porphyroblasts in the rocks. The porphyroblasts nucleated and grew after some recrystallization had taken place. Garnet grew both by pushing aside surrounding mineral grains and by replacement. The common elongation in the plane of foliation indicates that the garnet grew during deformation; some of the garnet apparently continued to grow after the peak of maximum deformation, as garnet megacrysts truncate biotite laths. Cordierite evidently formed later than the garnet, for cordierite porphyroblasts commonly contain garnet, whereas cordierite has not been observed in garnet porphyroblasts. Cordierite occurs both as nearly equant grains and as coronas around garnet. Probably the cordierite in the coronas formed at the expense of garnet by the following reaction:

$$\text{Garnet} + \text{biotite} + \text{sillimanite} + \text{quartz} + O_2 \rightarrow \text{cordierite} + \text{magnetite} + \text{potassium feldspar} + H_2O.$$

This reaction has been suggested previously for similar rocks by Schreyer and Yoder (1961, p. 150). The virtual absence of biotite and sillimanite in the cordierite coronas supports the concept that this reaction is the actual one.

The rare occurrence of both spinel and quartz in the same thin section is indicative of local disequilibrium. The spinel evidently formed by the breakdown of magnetite and did not react with quartz because it was separated from it by intervening minerals. This association of spinel and quartz in the same rock is not uncommon and has been described, for example, from a gneiss north of Great Slave Lake, Northwest Territories, Canada (Folinsbee, 1940, 1941).

Andalusite, which so far as known is restricted to cordierite-garnet gneisses, seems to have formed at the expense of biotite, probably by the following reaction:

$$\text{Biotite} + O_2 \rightarrow \text{andalusite} + \text{magnetite-ilmenite} + \text{quartz} + \text{biotite (new)}.$$

The quartz released by the reaction formed vermicular intergrowths with both the biotite and the andalusite; magnetite-ilmenite formed discrete crystals.

CHEMICAL COMPOSITION OF THE BIOTITE GNEISSES

Because of the wide variation in mineralogy of the biotite gneisses, we have calculated approximate chemical compositions of the major rock types from the modes (table 14). The technique was described by Sims and Gable (1964) in the report on the Central City district. Although the samples are insufficient in number to give statistically meaningful bulk chemical compositions, they are adequate to give a reliable order of magnitude. Chemical analyses of five representative samples of biotite gneisses supplement the calculated analyses and are given in table 15.

The biotite gneisses are of two distinct chemical types, indicated mineralogically by the presence or absence of sillimanite. The biotite-quartz-plagioclase gneiss and the related garnetiferous variety are characterized by having an excess of Na_2O over K_2O and

$$\frac{Al_2O_3}{Fe_2O_3+FeO+MgO+CaO+Na_2O+K_2O}<1,$$

whereas the sillimanitic biotite gneisses have an excess of K_2O over Na_2O and

$$\frac{Al_2O_3}{Fe_2O_3+FeO+MgO+CaO+Na_2O+K_2O}>1 \text{ or } \approx 1.$$

Also, the sillimanitic biotite gneisses have a low CaO content. The close dependence of rock type on the Na_2O:K_2O ratio is shown graphically in figure 5, a plot of 23 analyzed samples. The Na_2O:K_2O ratios of biotite-quartz-plagioclase gneiss range from about 1:1 to slightly more than 2:1; the ratios of sillimanitic gneisses range upward to about 1:3. Garnet forms in the biotite-quartz-plagioclase gneiss when FeO exceeds the requirements for biotite. The available data indicate that it forms in those rocks having

$$\frac{FeO+MgO(+MnO)}{CaO+Na_2O+K_2O}>1$$

and a high ratio of FeO+MgO to Al_2O_3.

In general, the sillimanitic varieties of biotite gneiss are characterized chemically by having

$$\frac{FeO+MgO}{CaO+Na_2O+K_2O}>1$$

TABLE 14.—*Estimated chemical compositions and average modes of principal types of biotite gneiss*

[Tr, trace; ----, not found. Estimated chemical composition given in weight percent and average modes, in volume percent]

	1	2	3	4	5	6	7	8	9
Estimated chemical composition									
SiO_2	61.9	70.5	65.1	63.5	57.9	68.2	72.7	67.3	56.7
Al_2O_3	15.4	13.0	14.8	13.3	23.0	15.3	12.8	14.9	19.6
Fe_2O_3	4.2	2.3	3.5	1.9	2.4	2.1	2.2	2.2	3.8
FeO	5.0	3.5	6.2	9.4	7.0	5.4	3.9	5.8	11.1
MgO	2.0	1.6	1.4	2.1	2.8	2.1	1.4	1.8	3.6
CaO	4.4	2.5	3.3	1.6	.3	.7	1.1	1.5	.5
Na_2O	2.9	3.6	2.7	2.3	.7	1.2	2.0	2.4	.8
K_2O	1.9	1.6	1.7	1.9	3.5	2.8	2.8	2.6	2.8
H_2O (total)	.6	.5	.6	.7	1.2	1.0	.5	.6	.9
TiO_2	.6	.5	.4	.5	1.1	.8	.5	.6	.7
Total	98.9	99.6	99.7	97.2	99.9	99.6	99.9	99.7	100.5
Average modes									
Potassium feldspar	1.7	0.1	0.4	----	1.6	0.5	6.7	6.7	5.9
Plagioclase	44.7	43.1	40.4	29.0	7.2	13.9	22.9	28.2	6.3
Quartz	30.4	40.1	37.0	38.0	35.6	48.8	48.8	39.2	28.3
Cordierite	----	----	----	----	----	----	----	----	15.9
Biotite	15.1	14.4	15.8	20.0	32.5	23.5	15.2	16.8	21.7
Muscovite	.4	.4	.8	----	.9	3.7	1.2	.3	.6
Amphibole	3.8	----	----	----	----	----	----	----	----
Opaque iron oxides	3.0	1.5	2.5	1.0	1.5	1.3	1.5	1.5	2.7
Garnet	Tr	----	2.9	10.0	----	----	----	3.6	9.9
Sillimanite	----	----	----	----	20.6	8.2	3.7	3.6	8.7
Other minerals	.9	.4	.2	2.0	.1	.1	Tr	.1	Tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase (average)	An_{45}	An_{28}	An_{42}	An_{28}	An_{27}	An_{26}	An_{25}	An_{28}	An_{32}

1. Biotite-quartz-plagioclase gneiss. Analysis of biotite in S622-53 used for computation; composition of hornblende estimated. Average of 11 modes listed in table 7.
2. Biotite-quartz-plagioclase gneiss, from Central City district (Sims and Gable, 1964, table 11). Average of 18 modes.
3. Garnetiferous biotite-quartz-plagioclase gneiss. Analysis of garnet in EWT-90 used for computation. Average of 6 modes listed in table 8.
4. Garnetiferous biotite-quartz-plagioclase gneiss, from Central City district. Average of 10 modes listed in Sims and Gable (1964, table 14).
5. Sillimanitic biotite-quartz gneiss. Analysis of biotite in S378-53 used for computation. Average of 6 modes listed in table 10.
6. Sillimanitic biotite-quartz gneiss, from Central City district (Sims and Gable, 1964, table 13). Average of 18 modes.
7. Sillimanitic biotite-quartz-plagioclase gneiss. Analysis of biotite in S378-53 used for computation. Average of 9 modes listed in table 9.
8. Garnetiferous sillimanitic biotite-quartz-plagioclase gneiss. Analysis of biotite in JG12-A, and analysis of garnet in EWT-90 used for computations. Average of 9 modes listed in table 11.
9. Cordierite-bearing garnet-sillimanite-biotite-quartz gneiss. Analysis for cordierite and garnet in EWT-90 and analysis of biotite in JG12-A used for computation. Average of 10 modes listed in table 12.

TABLE 15.—*Chemical analyses and modes of cordierite-bearing garnet-sillimanite-biotite gneiss, sillimanitic biotite-quartz-plagioclase gneiss, and garnet-sillimanite-biotite-quartz-plagioclase gneiss*

[Serial number given in parentheses below sample number. Results of chemical analyses given in weight percent and modes, in volume percent. Tr, trace; Nd not determined; --------, not found. Analyses of samples 1-4 by C. L. Parker, 5 by E. S. Daniels. Field number is in parentheses after description of sample]

	1 (I4157)	2 (I4156)	3 (I4158)	4 (I4155)	5 (D100276)
Chemical analyses					
SiO_2	58.06	57.28	63.23	62.67	57.93
Al_2O_3	20.76	21.13	17.39	19.12	21.82
Fe_2O_3	1.55	2.22	3.03	2.11	1.08
FeO	9.72	7.90	5.95	5.13	7.02
MgO	3.23	3.04	2.67	2.44	2.91
CaO	.33	.65	.36	.29	.46
Na_2O	.39	.97	.62	.72	.94
K_2O	3.25	3.56	3.69	4.50	5.17
MnO	.10	.14	.09	.04	.05
H_2O+	1.10	1.47	1.30	1.48	1.21
H_2O-	.17	.20	.20	.17	.10
TiO_2	1.00	1.02	1.08	.95	1.09
P_2O_5	.07	.07	.06	.05	.07
CO_2	.01	.02	.01	.02	.01
Cl	.12	.11	.11	.11	.02
F	.01	.01	.01	.02	.14
Subtotal	99.87	99.79	99.80	99.82	100.02
Less O	.03	.03	.03	.03	.06
Total	99.84	99.76	99.77	99.79	99.96
Powder density	3.01	2.94	2.88	2.84	Nd
Modes					
Potassium feldspar	1.6	3.3	7.0	14.3	15.6
Plagioclase	2.0	8.0	7.1	5.4	7.4
Quartz	26.1	29.6	41.2	31.2	31.2
Cordierite	16.4	4.3	--------	--------	--------
Sillimanite	11.7	5.7	10.3	16.3	10.7
Garnet	17.3	20.1	.5	--------	4.8
Biotite	23.6	28.9	32.0	32.1	29.1
Muscovite (secondary)	--------	Tr	.2	Tr	.8
Magnetite-ilmenite	1.3	.1	1.7	.7	.4
Zircon	Tr	Tr	Tr	Tr	Tr
Apatite	--------	--------	Tr	--------	Tr
Spinel	Tr	--------	--------	--------	--------
Chlorite	--------	--------	--------	Tr	--------
Andalusite	Tr	--------	--------	--------	--------
Total	100.0	100.0	100.0	100.0	100.0

1. Cordierite-bearing garnet-sillimanite-biotite gneiss; at bottom of gulch 0.5 mile west of Missouri Lake and 0.3 mile west of fork in stream. (JG-38b)
2. Cordierite-bearing garnet-sillimanite-biotite gneiss; taken from outcrop 1.5 miles west-northwest of Bald Mountain Cemetery on Bald Mountain road. (EWT-90)
3. Sillimanitic biotite-quartz-plagioclase gneiss; taken from outcrop bordering locality of EWT-90 on the west. (EWT-90b)
4. Sillimanitic biotite-quartz-plagioclase gneiss; taken from outcrop on north side of North Clear Creek road 3,400 ft west of bench mark (alt 8,513 ft) and adjacent to garnet- and cordierite-bearing sillimanitic biotite-quartz gneiss. (CC-646)
5. Garnet-sillimanite-biotite-quartz-plagioclase gneiss from vicinity of Petunia mine, northeast corner of quadrangle. (CC-871-A)

and

$$\frac{Al_2O_3}{FeO+MgO}\approx 2.$$

The ratio Al_2O_3:FeO+MgO is slightly less for cordierite-bearing varieties than for varieties lacking cordierite. Garnet and cordierite occur in those sillimanitic rocks that contain high molecular proportions of MgO and FeO. Cordierite is dependent on a substantial content of MgO. Judged from the available analyses, it is restricted to those highly aluminous rocks that contain 32 percent or more

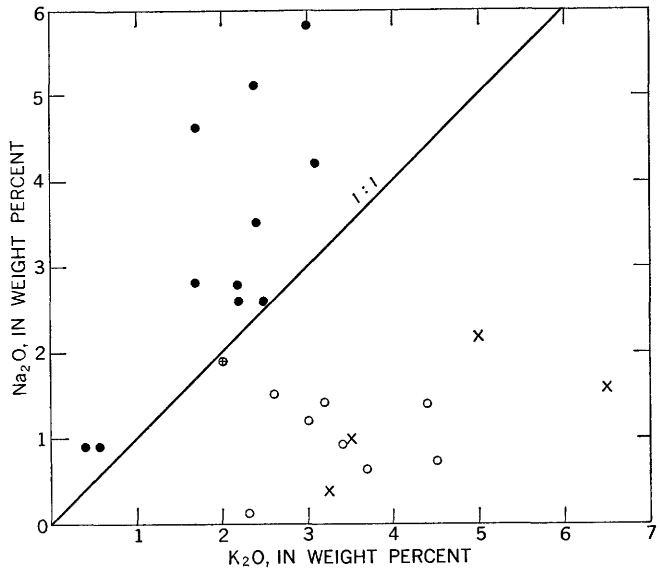


FIGURE 5.—Na_2O:K_2O ratios of biotite gneisses. ●, biotite-quartz-plagioclase gneiss; ○, sillimanitic biotite-quartz gneiss; ⊕, garnetiferous sillimanitic biotite-quartz gneiss; ×, garnet-cordierite-sillimanite-biotite-quartz gneiss. Flame photometer analyses by J. B. McHugh.

Al_2O_3+FeO+MgO, 11 percent or more FeO+MgO, and that have

$$\frac{Al_2O_3+FeO+MgO}{CaO+Na_2O+K_2O}>6$$

The control of the variables FeO and MgO on the mineralogy of the gneisses is summarized in figure 6. The occurrence of garnet and garnet plus cordierite is limited to rather well-defined fields.

Data on the minor element content of the various types of biotite gneisses are tabulated in table 16. In general, abundances are comparable in the different types, but barium, manganese, and strontium contents are somewhat greater and titanium content somewhat less in the biotite-quartz-plagioclase gneisses than in the sillimanitic biotite gneisses. The high manganese content of garnetiferous biotite-quartz-plagioclase gneiss reflects the presence of the spessartite molecule in the almanditic garnet. Zinc is somewhat more abundant in the garnetiferous biotite gneiss than in other rocks.

ORIGIN OF METAMORPHIC ROCKS

Data gathered during this study support our earlier interpretation (Sims and Gable, 1964) that the metamorphic rocks are dominantly of metasedimentary origin. The major rock units in the layered succession have the wide areal extent and the lithologic variations across layers that characterize many sedimentary rock sequences. The principal rock units, microcline gneiss and biotite gneiss, are thought to represent respectively arkose and interlayered shale and graywacke. Aside

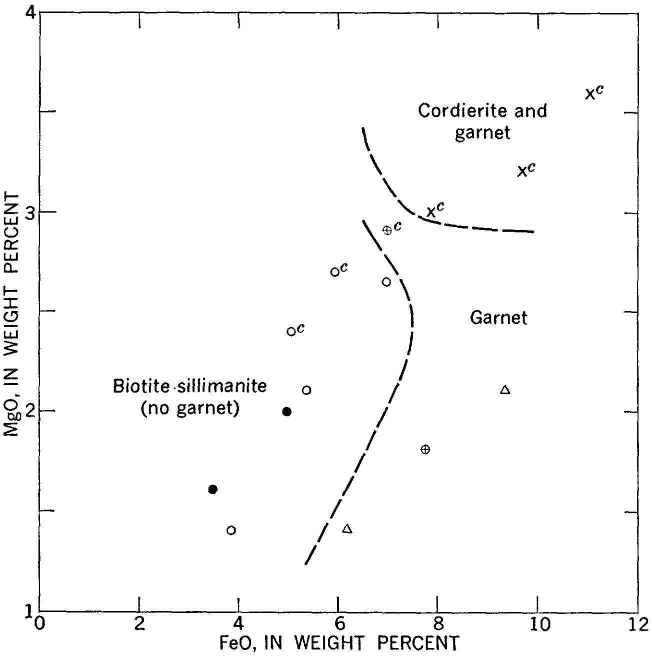


FIGURE 6.—FeO:MgO ratios of biotite gneisses. ●, biotite-quartz-plagioclase gneiss; △, garnetiferous biotite-quartz-plagioclase gneiss; ○, sillimanitic biotite-quartz-(plagioclase) gneiss; ⊕, garnetiferous sillimanitic biotite-quartz-plagioclase gneiss; ×, cordierite-bearing garnet-sillimanite-biotite-quartz-plagioclase gneiss; *c*, chemical analysis. Data from tables 14 and 15.

from amphibolite, whose origin is uncertain, the lesser rock units are considered to be metamorphosed sedimentary rocks. Metamorphism appears to have been virtually isochemical, although migmatization resulted in the local addition of some materials.

The biotite gneisses of the area have been interpreted, from lithologic and chemical resemblances to unmetamorphosed sedimentary rocks, to represent interlayered shales and graywackes. The biotite-quartz-plagioclase gneiss, which contains an excess of Na_2O over K_2O, is inferred to have been derived from original graywacke sediments, whereas the sillimanitic biotite gneisses, which have K_2O in excess of Na_2O, are presumed to have formed from original shales. Small differences in the chemical composition of the original sediments caused the variations in mineralogy and chemical composition observed in the metamorphic rocks. Those graywacke sediments that were somewhat rich in lime yielded hornblende-bearing biotite gneisses, as represented by sample 1, table 14, and those rich in iron (samples 3 and 4, table 14) yielded garnetiferous varieties. In the same way, the dominant facies of the shale yielded sillimanitic biotite gneiss; iron- and magnesium-rich and calcium-poor facies yielded garnet- and cordierite-bearing sillimanitic gneisses. Probably this facies was slightly more impoverished in feldspar than the normal shale; the relatively high iron and

TABLE 16.—*Semiquantitative spectrographic analyses, in parts per million, of minor elements in biotite gneisses*

[------ not found; Uteana Oda, analyst]

Sample	Serial No.	Ba	Be	Co	Cr	Cu	Ga	La	Mn	Mo	Nb	Ni	Pb	Sc	Sn	Sr	Ti	V	Y	Zn	Zr
Biotite-quartz-plagioclase gneiss																					
1-55	60-2832	700	2	20	200	50	30	70	500	<5	15	70	30	20	<10	1,000	7,000	200	15	<150	200
4-248-3	60-2833	300	2	10	150	50	10	<50	300	<5	10	70	<10	15	<10	500	5,000	70	30	<150	300
4-248-2	60-2834	200	2	<10	150	50	10	<50	1,000	5	10	15	<10	10	<10	150	5,000	70	30	<150	300
S622-53	60-2835	1,500	1	15	50	100	20	<50	500	<5	10	15	20	15	<10	1,500	5,000	100	10	<150	200
4-248-1	60-2836	150	1	<10	150	20	10	<50	1,000	<5	10	15	<10	15	<10	700	5,000	70	30	<150	300
S16-52-B	60-2837	1,500	1	20	30	70	20	100	500	<5	<10	15	<10	10	<10	2,000	5,000	100	20	<150	300
S291-B-53	60-2839	300	1	<10	<10	5	15	<50	300	<5	<10	<5	<10	<10	<10	70	1,500	<10	100	<150	200
CC-443-A	61-1308	500	<1	<10	5	3	20	<50	300	<2	------	5	30	<10	<10	300	3,000	15	30	<200	500
CC-103	61-1309	1,000	1	30	100	100	30	50	1,000	<2	------	70	30	20	<10	700	7,000	150	50	<200	200
Garnetiferous biotite-quartz-plagioclase gneiss																					
AE-4	60-2844	500	2	30	100	30	20	<50	5,000	5	10	50	15	15	<10	30	7,000	150	20	150	150
B-15-A	60-2845	500	<1	<10	<10	30	15	<50	3,000	5	<10	5	<10	20	<10	50	3,000	10	70	300	200
B-15-B	60-2846	500	1	<10	<10	10	15	<50	2,000	<5	<10	5	10	20	<10	100	3,000	<10	70	150	300
CC-670-1A	61-1301	300	2	20	70	70	15	70	3,000	5	------	30	20	20	<10	200	3,000	100	70	<200	200
Sillimanitic biotite-quartz gneiss																					
CC-611B	61-1302	500	<1	15	100	5	15	<50	300	<2	<10	50	20	10	<10	50	7,000	100	30	200	300
CC-1051-B	61-1303	300	<1	15	10	5	20	100	300	<2	<10	30	20	15	<10	50	7,000	100	100	200	700
5-137	60-2840	300	5	15	200	30	15	<50	300	<5	15	50	<10	15	<10	<20	15,000	100	20	200	300
S-4-245	60-2841	300	1	10	150	30	5	<50	300	<5	10	20	10	10	<10	300	500	50	20	<150	300
S116-1-53	60-2842	200	1	20	200	70	15	70	300	<5	15	70	<10	20	<10	70	10,000	100	50	<150	200
S379-A-53	60-2843	500	<1	50	200	10	20	150	300	<5	20	100	<10	30	<10	50	15,000	150	20	200	500
Garnetiferous sillimanitic biotite-quartz-plagioclase gneiss																					
CC-383-1	61-1304	300	<1	10	200	50	10	<50	200	<2	------	30	15	10	<10	150	7,000	70	10	<200	700
CC-858	61-1307	1,000	1	30	150	7	50	100	1,000	2	------	70	30	20	<10	100	7,000	200	50	300	200
Cordierite-bearing garnet-sillimanite-biotite gneiss																					
CC-789-A	61-1305	1,500	<1	30	200	5	50	<50	700	3	------	150	70	30	<10	200	10,000	300	50	300	500
CC-783-4	61-1306	700	<1	15	100	3	15	<50	500	<2	------	50	20	15	<10	70	7,000	100	30	<200	200

magnesium content can be attributed to a lack of prolonged weathering. The high $FeO:Fe_2O_3$ ratio compared with that of average shale probably resulted from reduction of the original Fe_2O_3 during metamorphism.

The lithologic layering and the heterogeneity and wide areal extent of the major layers suggest a metasedimentary origin for the microcline gneiss, as proposed earlier (Sims and Gable, 1964). Further support for this proposed origin is given by the intimate interlayering of biotite gneiss with microcline gneiss along both margins of the Lawson layer in the vicinity of North Clear Creek and Blackhawk Peak (pl. 1). Gradations both along and across strike near the contacts indicate gradual changes in lithology that can only result from original deposition. In addition to the gradual changes in sedimentation, repetition in the deposition of lithologically similar sediments occurred.

Special chemical and mineralogical studies were not made of the calc-silicate rocks, but from their gross composition, heterogeneity, and local association with quartz gneisses or quartzite, one may conclude that they were derived from impure carbonate rocks. The skarns may in part have resulted from iron metasomatism, as some are too rich in iron to have formed directly from any common carbonate rock, but this derivation is problematic and should be investigated further.

The amphibolite has been interpreted as mainly of sedimentary origin because of its association locally with calc-silicate gneiss and quartz gneiss and its gradation into microcline gneiss (Sims and Gable, 1964). However, it may in part be metamorphosed mafic igneous rocks, possibly spilite. The association of spilites with graywacke and shale sediments is not uncommon in eugeosynclinal terranes, as for example in the Wellington district of New Zealand (Reed, 1957).

The origin of the cordierite-amphibole gneiss is uncertain. If metamorphism was nearly isochemical, as seems probable from the data obtained on other metamorphic rocks in the sequence, the gneiss has no common unmetamorphosed equivalent. It has abnormally high percentages of both ferrous iron and magnesium and abnormally low amounts of calcium, sodium, and potassium compared with those in known sedimentary or igneous rocks. It most closely approximates iron-formations in composition, as these rocks are exceedingly low in alkalic content, but it contains substantially more magnesium than do typical iron-formations. Possibly it represents an unusual magnesium- and iron-rich chemical sediment of an origin similar to that of iron-formations.

GRANITE GNEISS AND PEGMATITE

Granite gneiss and pegmatite constitute the felsic material in migmatites and less commonly form discrete bodies a few feet to several feet wide. They are estimated to form 15–20 percent by volume of the migmatitic biotite gneisses, and in addition they occur as a network of veinlets in some amphibolite bodies and as irregular, generally conformable bodies in microcline gneiss. In general, granite gneiss and pegmatite decrease somewhat in abundance from the southern part of the quadrangle to the northern part, and concomitantly become coarser grained northward. Because of the generally small size and the abundance of the bodies, the granite gneiss and pegmatite were not mapped separately on plate 1; instead, they were included with the dominant rock units.

GENERAL CHARACTER

Granite gneiss and pegmatite constitute a light-gray or yellowish-gray medium- or coarse-grained rock that is somewhat inequigranular. They resemble microcline gneiss but generally can be distinguished from microcline gneiss both by their mode of occurrence and by their megascopic appearance. Granite gneiss and pegmatite typically occur as thin stringers and tabular bodies in biotite gneisses to constitute migmatite, whereas the microcline gneiss generally forms larger, more distinct layers. In appearance, most exposures of granite gneiss and pegmatite are leucocratic, nearly massive, and generally homogeneous, except for local wisps and streaks of biotite-rich gneiss, whereas the microcline gneiss characteristically has a conspicuous even layering. Contacts with adjacent rocks appear to be sharp megascopically but in detail are seen to be transitional.

PETROGRAPHY

The rock consists mainly of potassium feldspar, plagioclase, and quartz and contains biotite, magnetite-ilmenite, muscovite, zircon, sillimanite, garnet, and sphene as accessory minerals (table 17). Typically it has a granoblastic texture.

Potassium feldspar is perthitic and contains a few percent of plagioclase as film, string, and patch intergrowths. About two-thirds of the grains have a conspicuous grid twinning. In any given sample, crystals of potassium feldspar tend to be the coarsest grains in the rock. Plagioclase (oligoclase) is slightly antiperthitic and is twinned according to the albite and Carlsbad twin laws. Albitic rims as much as 0.03 mm wide are common where plagioclase is in contact with potassium feldspar. Myrmekite is present in many sections. Quartz that has conspicuous strain shadows forms irregular anastomosing grains and smaller subrounded grains. Biotite is nearly ubiquitous but sparse and commonly is intergrown with muscovite. It is a greenish-brown pleochroic variety, generally somewhat altered to chlorite, and in appearance resembles the biotite in the biotite gneiss units. Sillimanite and garnet are local accessory minerals. The sillimanite forms subhedral grains in stringers and clots; it is associated with muscovite and at places where in contact with potassium feldspar is separated from it by sheaths of muscovite. Zircon forms tiny anhedral grains, mainly in plagioclase and quartz. Xenotime and monazite occur locally in related pegmatites in the eastern part of the Central City district; their occurrence has been described previously by Young and Sims (1961).

Specimens from Dakota Hill and vicinity differ from typical samples in being finer grained and in having a cataclastic texture. Hand specimens appear sheared; the mafic minerals are in streaks and wisps and quartz occurs as discontinuous veinlets. In thin section the quartz is seen to form elongate aggregates, subparallel to cataclastic zones in which the plagioclase, in particular, is granulated. Most plagioclase grains are partly altered to clay minerals. The potassium feldspar has strain shadows and lacks grid twinning. Biotite is fresh and lies dominantly in the cataclastic zones.

Potassium feldspar from typical pegmatite belonging to this granite gneiss and pegmatite unit has been determined from two localities in the Central City district to contain about 78 percent $KAlSi_3O_8$ by weight after homogenization; it has a triclinicity index of 0.75 (Sims and Gable, 1964). An estimated chemical composition of the pegmatite was given in the same report. Flame photometer analysis by J. B. McHugh of three samples gave the following content, in percent:

Sample	NaO	K_2O
CC-1045-A	3. 0	7. 6
CC-1124-1	3. 9	4. 7
D-7	2. 6	7. 6

ORIGIN

The origin of granite gneiss and pegmatite was discussed in the report on the Central City district by Sims and Gable (1964) and need not be discussed in detail here. In brief, we infer that the granite gneiss and pegmatite formed from a fluid that was able to penetrate readily along the foliation planes of the biotite gneiss country rock, part of which it replaced. A source for the fluid through ultrametamorphism is favored, but an origin from a silicic melt cannot be dismissed from consideration. If the muscovite in the rock is primary, as seems probable from its textural relations, the pegmatite can be inferred from the experimental data of Yoder and Eugster (1955, p. 267) to have formed at more than 1,500 atmospheres of water pressure.

INTRUSIVE ROCKS

Four types of intrusive rocks—granodiorite and associated rocks, gabbro and related rocks, quartz

TABLE 17.—*Modes, in volume percent, of granite gneiss and pegmatite*

[Tr, trace; Nd, not determined; ----, not found. Field number is in parentheses after description of sample]

Mineral	1	2	3	4	5	6	7	8	9	10	11	12	13
Potassium feldspar	27. 8	36. 0	61. 0	52. 1	37. 5	35. 4	37. 9	30. 3	54. 2	28. 7	26. 5	50. 6	40. 0
Plagioclase	28. 9	25. 4	18. 6	19. 5	7. 3	33. 3	29. 5	32. 0	14. 4	34. 5	32. 4	22. 2	26. 8
Quartz	39. 8	35. 7	20. 0	27. 3	55. 0	27. 4	28. 8	30. 0	23. 9	30. 2	31. 6	23. 6	32. 6
Biotite	. 8	Tr	Tr	. 1	------	1. 9	1. 5	1. 8	. 8	. 6	1. 3	1. 6	. 1
Magnetite-ilmenite	. 1	. 7	------	. 2	Tr	Tr	. 7	. 6	. 3	. 7	. 6	Tr	. 1
Muscovite	1. 3	2. 2	. 4	. 7	. 2	1. 0	1. 6	4. 2	6. 2	4. 0	5. 5	1. 9	. 3
Zircon	Tr	Tr	------	Tr	------	Tr	Tr	Tr	. 1	Tr	Tr	Tr	. 1
Sillimanite	1. 3	------	------	------	------	1. 0	------	. 5	. 1	1. 3	2. 1	. 1	------
Chlorite	Tr	------	------	. 1	------	------	------	. 6	------	Tr	------	------	------
Garnet	Tr	------	------	------	------	------	------	------	------	------	------	------	------
Sphene	------	------	------	------	------	------	------	------	------	------	------	------	Tr
Total	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0	100. 0
Composition of plagioclase	Nd	Nd	Nd	Nd	Nd	Nd	An_{22}	An_{19}	An_{17}	An_{19}	An_{17}	Nd	Nd
Average grain diameter mm	0. 7	1. 3	1. 3	1. 7	1. 4	Nd	Nd	Nd	Nd	Nd	Nd	Nd	0. 5

1. Interlayered with sillimanitic biotite-quartz gneiss; collected north of Fall River 0.9 mile from west edge of quadrangle. (CC-61)
2. Interlayered with biotite gneiss, taken from nose of ridge north of Fall River and east of Hamlin Gulch. (CC-110)
3. From outcrop east side of Mount Pisgah. (CC-175)
4. Leucocratic granite gneiss and pegmatite from contact zone between granodiorite and migmatitic sillimanitic biotite-quartz gneiss, northwest tip of Mount Pisgah pluton. (CC-313A)
5. From just northwest of locality of sample 4; contains layers and streaks of sillimanitic biotite-quartz gneiss. (CC-316-1)
6. Sillimanitic granite gneiss and pegmatite, from outcrop along North Clear Creek on nose of Blackhawk Peak. (CC-366-1A)
7. From outcrop on north side of road, just below junction of North Clear Creek and Freeman Gulch. (CC-426A)
8. Interlayered with biotite-quartz-plagioclase gneiss, on old road along slope between Pecks Flat and North Clear Creek. (CC-443B)
9. Interlayered with biotite gneiss, taken 0.75 mile east of Yankee Hill. (CC-535)
10. Sillimanitic granite gneiss and pegmatite in biotite gneiss collected 0.5 mile south of Kingston, west margin of quadrangle. (CC-667-2)
11. From outcrop just west of locality of sample 10. (CC-669)
12. From just north of American City, northwestern part of quadrangle (CC-1045-A)
13. From ridge on west side of Dakota Hill, 0.5 mile northeast of Apex. Rock is sheared and granulated. (CC-1124-1)

diorite and hornblendite, and biotite-muscovite quartz monzonite—each with associated pegmatites, intrude the layered rocks of the quadrangle and constitute about 15 percent by volume of the exposed bedrock. Each intrusive rock type mapped in the quadrangle, except gabbro and related rocks, is widespread throughout the central part of the Front Range, and now the types can be correlated with confidence from one area to another.

The granodiorite and associated rocks of this report are equivalent to the intrusive rocks of the Boulder Creek batholith that are exposed just west of Boulder (Lovering and Goddard, 1950, pl. 2), the type area of the Boulder Creek Granite. The gabbro and related rocks are correlated with gabbro found southwest of Fraser in the Vasquez Mountains (Taylor and Sims, 1962). They are linked to the Vasquez Mountains occurrence by lithologic similarity and by age relative to known Precambrian events. Quartz diorite and hornblendite form numerous small scattered bodies in the region but have not been formally named. The biotite-muscovite quartz monzonite is equivalent to the Silver Plume Granite at the type area at Silver Plume, Colo., and to the biotite-muscovite granite recently described from nearby areas in Clear Creek County (Harrison and Wells, 1956, 1959).

GRANODIORITE AND ASSOCIATED ROCKS

DISTRIBUTION AND CHARACTER

Rocks that range in composition from a mafic quartz diorite to quartz monzonite but have a composition similar to granodiorite form scattered small or moderate-sized bodies in the quadrangle. The bodies are more abundant toward the northeast, and thus appear to be satellitic to the batholith of Boulder Creek Granite (Lovering and Goddard, 1950, pl. 2). Although the rocks vary rather widely in composition and overlap other intrusive rocks of the region, they constitute a diagnostic type that can be distinguished readily from biotite-muscovite quartz monzonite and from gabbro and related rocks.

The granodiorite and associated rocks typically form lenses in the apical areas of folds and sheets on the limbs of folds. Several of the bodies are notably thicker in the axial areas and are interpreted as phacoliths. The bodies dominantly lie within thick biotite gneiss units, but a few are in the contact zones between biotite gneiss and microcline gneiss units and at least one is at the contact between biotite gneiss and the Elk Creek pluton of gabbroic rocks. The contacts against the country rocks are sharp and only rarely are marked by a zone of interlayering a few feet wide. As a generalization, the contacts are grossly concordant with the gneissic structure of the country rocks, but in detail they can be seen to crosscut, and on the scale of the map (pl. 1) they locally appear to cut across some of the larger units, as in the vicinity of Pecks Gulch.

The internal structures of the bodies vary as widely as does the composition. All small bodies have a wholly gneissic structure. The larger bodies, however, tend to have weakly foliated interiors and moderately or strongly foliated borders. The foliation and lineation within the rocks is parallel to that in the metasedimentary country rocks and is interpreted to have resulted from syntectonic enplacement.

The largest body, exposed in the vicinity of Mount Pisgah (pl. 1), and herein called the Mount Pisgah pluton, has a surface area in excess of 1 square mile. It lies in the contact zone between the Lawson layer of microcline gneiss and the underlying unit of biotite gneisses. In most exposures the granodiorite is virtually conformable with the gneisses, but on a gross scale its east margin cuts across the internal gneissic structure of the microcline gneiss unit. In detail, prongs such as the one mapped on the south slope of Mount Pisgah (pl. 1) clearly transect the adjacent gneisses. The pluton is moderately thick in the trough of the syncline at Mount Pisgah and in the crest of the adjacent Pecks Flat anticline, but it pinches out abruptly on the limbs and accordingly is interpreted as a compound phacolith. The borders are strongly foliated and lineated, whereas the interior is nearly massive. Inclusions which are tabular lenses or pods and which conform to the internal structure of the body tend to be elongated parallel to the lineation and are more abundant than in other intrusive masses in the quadrangle. The inclusions are mainly biotite gneiss but include interlayered quartzite and calc-silicate gneiss. The body is cut by a few small dikes of biotite-muscovite quartz monzonite that are too small to be shown at the scale of plate 1. The pluton is more felsic than other bodies in the quadrangle (table 18). Apparently because of its relatively felsic composition, the body was mapped previously as Silver Plume Granite by Bastin and Hill (1917) and by Lovering and Goddard (1950, pl. 2).

Another body of moderate size is exposed on the upper slopes of Bald Mountain (pl. 1), within the biotite gneiss unit that lies between the Lawson and Quartz Hill layers of microcline gneiss. It contrasts sharply with the Mount Pisgah pluton in being more mafic in compositon (table 18) and in having a wholly gneissic structure. The body is either a folded sheet or a phacolith estimated to be about 700 feet thick. (See section *C–C′*, pl. 1.) It was mapped earlier by Bastin and Hill (1917) as granite gneiss, for they considered it to be equivalent to the granitic gneiss that we have named microcline-quartz-plagioclase-biotite gneiss (Sims and Gable, 1964). Lovering and Goddard (1950, pl. 2) showed the body to be quartz monzonite gneiss. Subsequently, in detailed mapping of the Lawson-Dumont-Fall River district, Hawley and Moore (1967) mapped the body as quartz diorite gneiss.

A thin layer of quartz diorite gneiss, considered to be a part of the granodiorite unit of this report, was mapped by Hawley and Moore (1967) in the Lawson area but is omitted from plate 1 because of its small size.

Several other bodies, mostly of small dimension, crop out in the quadrangle. A folded, subconcordant, composite sheet estimated to be about 400 feet thick is exposed south of Central City. It is strongly differentiated and ranges in composition from a quartz diorite to a fluorite-bearing quartz monzonite (Sims and Gable, 1964). A few moderate-sized conformable bodies and small lenses are exposed in the northeastern part of the quadrangle, within the biotite gneiss unit intruded by the Bald Mountain pluton. On the whole these bodies are relatively uniform in composition and contain very few parts as felsic as quartz monzonite. Some, as for example the curved body exposed along and adjacent to State Highway 119 at the east edge of the quadrangle, contain substantial amounts of biotite-hornblende quartz diorite. In the northwestern part of the quadrangle several long, thin, conformable sheets, some of which are probably folded, crop out within biotite gneisses, and a few tightly folded lenses or phacoliths occur in the biotite gneisses and at the contacts of biotite gneiss with microcline gneiss. These bodies are dominantly granodiorite and quartz diorite in composition and, like the small bodies in the northeastern part of the quadrangle, appear to be relatively uniform throughout.

PETROGRAPHY

The granodiorite and associated rocks are gray, mottled black and white, medium-grained, generally gneissic rocks that vary widely in composition and appearance. The more gneissic facies of the granodiorite is generally finer grained. In addition to the dominant facies—a medium-gray biotite granodiorite—a biotite-rich facies containing 20–30 percent biotite and a biotite- and hornblende-rich facies containing 30–50 percent dark minerals occurs. Where the field relations are clear cut, the dark facies are interlayered conformably with the light facies. In general, the dark facies has a more strongly developed foliation than does the light facies; the foliation is due to a subparallel alinement of biotite and hornblende crystals and to a weak compositional layering. Exposed bodies of the dark facies generally are associated with a coarse-grained felsic pegmatite.

Although the granodiorite apparently is medium grained and nearly equigranular, local coarse-grained facies contain microcline and plagioclase laths, which are as much as 2.5 cm long, in a finer grained matrix. A few small lenses just east of Yankee Hill contain scattered blue-gray plagioclase crystals as much as 10 cm long.

The granodiorite and associated rocks have a hypidiomorphic or less commonly an allotriomorphic granular texture. The most abundant mineral, plagioclase, ranges in composition from oligoclase to calcic andesine and rarely to labradorite and generally contains small patches and blebs of potassium feldspar. Commonly the crystals have a weak gradational normal zoning. The plagioclase forms subhedral or anhedral laths that have well-developed twinning—albite, Carlsbad, and albite-pericline twins being the most common. Albitic rims of an average width of 0.025–0.05 mm occur on some plagioclase crystals adjacent to microcline. Myrmekitic intergrowths of quartz and oligoclase-andesine are common. The potassium feldspar is perthitic microcline, which contains 30–50 percent by volume of plagioclase, or microcline that has a fairly well-developed grid twinning. Locally, however, as at Bald Mountain, it lacks visible microcline grid twinning and is difficult to identify unless it is stained. Quartz generally has conspicuous strain shadows. In some aggregates, quartz grains in contact with one another have serrated borders. Inclusions of subrounded clear quartz grains are common in the feldspars. The biotite is pleochroic, ranging from straw yellow to olive greenish brown. It forms laths that tend to be clustered with other mafic minerals, including magnetite-ilmenite, hornblende, allanite, sphene, and epidote. It cuts and embays hornblende. Hornblende forms euhedral to anhedral crystals and generally is altered somewhat to magnetite and biotite. Lamellar twinning is evident where the hornblende is bleached and altered. The pleochroism of the hornblende varies from pale brownish yellow to a dark olive green or dark bluish green. Allanite is a persistent and characteristic accessory mineral but never exceeds 1 percent by volume. Crystals of the mineral generally range in maximum dimension from 0.1 to 0.4 mm; in the Mount Pisgah body, however, one observed crystal was 3.1 mm in diameter. Commonly the allanite is zoned, with an outer dirty greenish-brown zone that grades inward to reddish brown or brown. The crystals are both positive and negative, have a large $2V$, and a moderate pleochroism ranging from light tan to a reddish brown. Magnetite-ilmenite commonly is rimmed by sphene Where abundant, sphene embays biotite.

Alteration minerals in the granodiorite and associated rocks formed subsequent to consolidation and include epidote, chlorite, magnetite, sericite, clay minerals, and muscovite.

Mineralogical variations of the rock unit in various bodies within the quadrangle are shown by the modes (in volume percent) in table 18. A summation of the mineralogic variations is given in figure 7. In brief, the Mount Pisgah pluton ranges in composition from a quartz diorite to felsic quartz monzonite and has an average composition, as determined from 18 modes, of 27 percent quartz, 38 percent plagioclase, 17 percent microcline, and 16 percent total mafic minerals. The Bald Mountain pluton has a similar range in mineralogy but is dominantly quartz diorite. The other smaller bodies in the quadrangle have comparable ranges in composition.

CHEMICAL COMPOSITION

Analyses of a sample of the quartz monzonite facies and of a hornblende-quartz diorite facies of the granodiorite unit are given in table 19. Analyses of two samples, a granodiorite and a quartz monzonite facies, from the Central City pluton were presented earlier

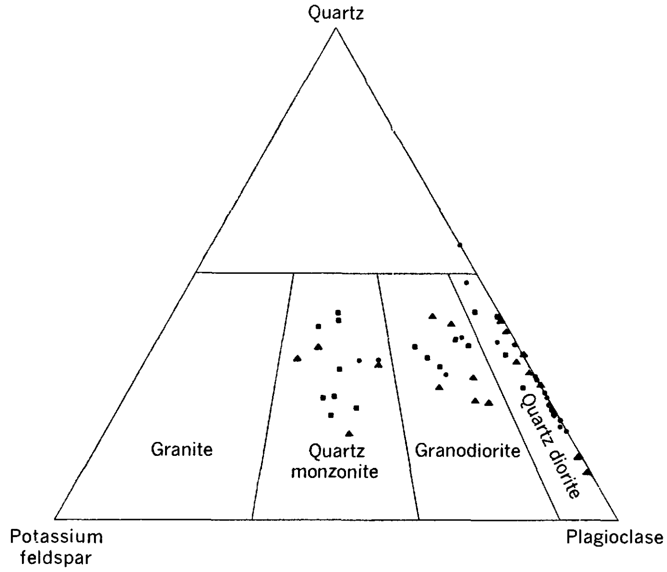


FIGURE 7.—Variation in composition (in volume percent) of granodiorite and associated rocks. ■, in the Mount Pisgah pluton; ●, in the Bald Mountain pluton; and ▲, in scattered small plutons (53 plots).

TABLE 18.—*Modes, in volume percent, of granodiorite and associated rocks*

[Tr, trace; Nd, not determined; ------, not found. Field number is in parentheses after description of sample]

Mount Pisgah pluton

Mineral	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Average (1–18)
Potassium feldspar	27.4	13.1	34.4	7.9	30.6	26.8	31.6	23.8	2.5	30.6	15.1	30.4	12.9	------	------	3.7	2.5	6.6	16.7
Plagioclase	28.6	39.1	32.9	41.8	27.1	28.0	38.8	24.3	56.4	30.0	37.9	25.5	45.1	46.5	45.1	39.5	51.9	44.0	38.0
Quartz	24.7	25.9	18.3	29.4	18.8	35.1	20.9	34.4	29.1	20.2	28.5	36.6	25.8	32.5	31.0	31.3	20.0	28.0	27.2
Biotite	13.3	19.9	11.9	17.7	17.5	6.1	1.0	13.5	7.8	13.1	13.1	5.5	9.5	15.5	16.8	18.3	19.4	14.3	13.1
Muscovite	1.5	.9	1.0	1.3	2.6	1.9	1.3	2.3	1.4	1.0	.8	.9	2.3	2.0	.6	2.6	.3	1.7	1.5
Magnetite-ilmenite	2.6	.5	.6	1.3	3.0	1.9	.6	1.7	1.6	4.0	2.2	.9	3.0	1.0	4.9	3.4	5.5	4.8	2.5
Apatite	.9	.2	.4	.6	.4	Tr	Tr	------	------	1.0	.2	------	.2	.4	1.0	1.0	.4	.5	.4
Sphene	1.0	Tr	------	------	Tr	------	------	Tr	Tr	------	2.2	------	.3	.5	------	------	------	Tr	.2
Calcite	------	------	.3	------	------	------	1.0	------	1.2	------	------	------	Tr	Tr	------	------	------	------	.1
Chlorite	------	.2	Tr	------	Tr	Tr	4.8	------	------	Tr	------	------	------	.5	Tr	------	Tr	------	.3
Zircon	Tr	Tr	.2	Tr	Tr	.2	Tr	Tr	Tr	Tr	------	Tr	Tr	Tr	.1	Tr	Tr	.1	Tr
Allanite	Tr	Tr	------	Tr	Tr	Tr	------	------	------	Tr	------	------	Tr	.6	.2	.1	Tr	Tr	Tr
Epidote	------	.2	------	------	Tr	Tr	------	------	------	Tr	------	------	Tr	.5	.3	------	Tr	Tr	Tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	100.0	99.8	99.1	100.0	100.0	99.9	100.0	100.0	100.0
Composition of plagioclase	An_{27}	An_{28}	An_{27}	An_{27}	An_{24}	An_{24}	An_{27}	An_{27}	An_{28}	An_{27}	An_{27}	An_{27}	An_{27}	An_{28}	An_{38}	An_{36}	An_{30}	Nd	An_{28}
Average grain diameter mm	0.6	0.8	1.5	1.3	0.7	0.5	1.6	0.5	1.2	0.7	1.0	1.5	0.9	0.6	0.4	0.4	Nd	Nd	0.9

Bald Mountain pluton

Mineral	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	Average (19–37)
Potassium feldspar	7.2	25.6	------	0.2	0.1	------	------	------	3.0	2.3	14.0	Tr	------	22.7	------	------	------	------	------	4.0
Plagioclase	43.5	33.5	54.6	49.7	56.5	52.2	39.5	54.1	52.0	39.4	49.0	51.1	40.7	35.3	53.3	54.5	52.4	38.7	45.4	47.0
Quartz	30.0	28.1	18.5	11.9	24.7	28.1	11.3	22.5	31.4	38.4	26.3	21.5	51.6	28.0	18.5	17.5	13.5	10.9	24.4	24.0
Biotite	16.8	10.4	22.6	13.2	17.2	18.5	19.0	21.4	12.5	16.1	9.8	25.6	6.5	12.1	14.6	3.2	18.5	21.8	12.1	15.3
Muscovite	1.8	1.9	.1	Tr	.4	.2	------	.1	.5	.6	.1	.5	.1	1.5	Tr	------	------	------	------	.4
Magnetite-ilmenite	.5	.3	2.5	1.2	.4	.5	Tr	1.3	.4	.3	.2	.6	.9	.1	2.3	3.8	1.2	Tr	.2	.9
Apatite	Tr	.1	1.0	Tr	.5	.2	.5	.6	.1	------	.2	.4	------	.1	.2	.5	.7	.3	.4	.3
Sphene	------	------	Tr	------	------	------	Tr	------	------	------	------	------	------	------	------	------	Tr	------	------	Tr
Chlorite	------	------	.1	Tr	.1	Tr	Tr	Tr	------	2.8	.2	------	.1	.1	.5	Tr	------	------	.1	.2
Hornblende	------	------	Tr	23.3	------	------	29.6	------	------	------	------	------	------	------	10.6	19.8	12.5	28.0	17.2	7.7
Zircon	.2	.1	Tr	Tr	Tr	.1	Tr	Tr	.1	Tr	.2	Tr	Tr	.1	Tr	------	------	Tr	------	Tr
Allanite	------	Tr	.3	Tr	------	Tr	.1	Tr	Tr	------	------	------	------	------	------	------	------	------	------	Tr
Epidote	------	Tr	.3	.5	.1	.2	Tr	Tr	------	------	Tr	.3	.1	------	------	.7	1.2	.3	.1	.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	100.0
Composition of plagioclase	An_{29}	An_{31}	An_{36}	An_{34}	An_{31}	An_{34}	An_{43}	An_{40}	An_{32}	An_{23}	An_{27}	An_{37}	An_{34}	An_{25}	An_{44}	Nd	An_{44}	An_{46}	An_{44}	An_{35}
Average grain diameter mm	0.8	0.5	0.6	0.5	0.6	0.5	0.4	0.6	0.8	Nd	Nd	0.3	Nd	0.6	0.5	0.6	0.4	0.4	0.6	0.5

See notes at end of table.

TABLE 18.—*Modes, in volume percent, of granodiorite and associated rocks*—Continued

Mineral	Smaller scattered bodies																					
	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	Average (38–58)
Potassium feldspar	------	------	------	13.6	9.6	31.4	------	38.2	------	------	9.7	------	------	10.4	1.4	8.0	9.0	------	22.1	6.5	------	7.7
Plagioclase	53.4	53.0	39.8	41.4	36.2	26.6	51.9	26.0	38.1	38.2	51.5	43.9	45.1	50.4	52.9	43.2	52.9	49.7	35.3	38.8	51.4	43.8
Quartz	30.4	29.5	22.0	20.1	32.0	31.4	29.3	31.2	8.0	15.4	25.0	17.8	5.4	19.9	26.0	30.0	19.4	30.6	26.9	27.5	17.7	23.6
Biotite	15.6	16.9	29.5	20.0	14.5	8.0	18.0	2.8	4.8	14.9	12.5	20.0	11.6	6.6	17.9	10.7	9.2	15.2	9.1	17.8	12.9	13.7
Muscovite	.2	Tr	Tr	.5	1.8	.1	.4	.7	------	.7	.5	3.3	------	------	1.2	1.8	Tr	.3	.4	------	------	.6
Magnetite-ilmenite	.2	.4	1.7	2.8	3.9	2.0	Tr	.3	1.5	1.6	.3	1.2	.6	3.2	.4	5.5	4.0	3.7	3.1	3.5	5.9	2.2
Apatite	.2	.1	.9	1.0	1.2	.4	.2	.1	.2	.1	.5	.5	Tr	1.9	------	.8	1.0	.5	.9	.9	1.0	.6
Sphene	------	------	1.5	------	------	------	------	Tr	------		------	------	------	1.9	------	------	2.2	------	1.8	2.7	3.4	.7
Calcite	------	------	------	------	------	------	------	------	.5	------	------	------	2.0	.4	------	------	------	------	------	------	------	.1
Chlorite	------	.1	------	Tr	------	Tr	Tr	Tr	1.0	2.3	Tr	Tr	Tr	------	------	Tr	------	------	------	------	.1	.2
Hornblende	------	------	4.0	------	------	------	------	------	45.9	24.1	------	12.5	35.3	5.0	------	------	------	------	Tr	.9	7.6	6.5
Zircon	Tr	Tr	------	Tr	.4	Tr	.1	Tr	Tr	Tr	Tr	Tr	Tr	Tr	.1	Tr	Tr	Tr	.1	Tr	Tr	------
Allanite	------	------	.6	.6	.4	.1	.1	Tr	------	------	------	Tr	Tr	Tr	------	Tr	Tr	Tr	------	.4	Tr	.1
Epodote	------	Tr	------	------	Tr	Tr	Tr	Tr	------	2.6	------	.8	------	.2	.1	Tr	.1	Tr	.3	1.0	------	.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0	97.8	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{31}	An_{24}	An_{46}	An_{43}	An_{46}	An_{31}	An_{40}	Nd	An_{56}	An_{46}	An_{25}	An_{48}	An_{56}	An_{29}	Nd	Nd	An_{32}	Nd	An_{25}	An_{34}	An_{36}	An_{38}
Average grain diameter (mm)	0.4	Nd	0.6	0.6	0.6	0.9	0.6	0.5	0.3	0.3	0.9	0.4	0.6	1.0	0.6	0.3	0.7	Nd	Nd	Nd	Nd	0.6

1. Quartz monzonite, from crest of Mount Pisgah. (1)
2. Granodiorite, from outcrop along south edge of pluton, 500 ft from contact with sillimanite-biotite-quartz gneiss. (4)
3. Fresh quartz diorite, from pit adjacent to roadcut in east edge of pluton. (13)
4. Quartz diorite, 500 ft northwest of locality of sample 3, adjacent to a sillimanite-biotite-quartz lens. (13b)
5. Quartz monzonite, from southeast slope, Mount Pisgah, 80 ft below crest. (18b)
6. Quartz monzonite, from outcrop 500 ft southeast of locality of sample 2, near biotite gneiss contact. (30)
7. Quartz monzonite, from outcrop just south of Lake Pisgah and west of the Pisgah road. (L1)
8. Quartz monzonite, from knob due east of Lake Pisgah and the Pisgah road. (L8)
9. Quartz diorite, from outcrop 1,000 ft west of Lake Pisgah. (L10)
10. Quartz monzonite, from outcrop on west slope, Mount Pisgah, 200 ft below crest. (R9)
11. Granodiorite, from outcrop 600 ft southwest of locality of sample 10. (R9a)
12. Quartz monzonite, from outcrop due west of midpoint between Lake Pisgah and the top of Mount Pisgah, just above flume. (R12)
13. Granodiorite, from outcrop 1,500 ft north of Lake Pisgah and 500 ft west of Pisgah road. (S21)
14. Quartz diorite, from outcrop on prominent knob northeast of Lake Pisgah. (S6)
15. Quartz diorite, from knob on Pecks Flat. (CC–330)
16. Quartz diorite, from outcrop 2,000 ft northeast of locality of sample 14. (CC–375)
17. Quartz diorite, from outcrop west of road, east slope of Mount Pisgah. (S373 A–53)
18. Quartz monzonite, from outcrop west of road, east slope of Mount Pisgah. (S374 B–53)
19. Quartz diorite, medium- to coarse-grained, from outcrop west of peak of Bald Mountain at an altitude of 9,750 ft. (CCH–24–B)
20. Granodiorite, from outcrop 1,000 ft downslope southeast from peak of Bald Mountain, adjacent to sillimanite-biotite-quartz gneiss contact. (CCH–91)
21. Biotite quartz diorite, from outcrop 1,000 ft due east of peak of Bald Mountain, and just north of well-defined east-west Tertiary dike. (ET–129)
22. Hornblende quartz diorite, from outcrop 1,000 ft south of locality of sample 21. (ET–219A)
23. Quartz diorite, from outcrop 2,500 ft northeast of peak of Bald Mountain. (ET–295)
24. Quartz diorite, from outcrop 500 ft southeast of locality of sample 20. (ET–220)
25. Hornblende quartz diorite, fine-grained, from outcrop 500 ft northwest of locality of sample 24 in the vicinity of biotite-muscovite quartz monzonite. (ET–296)
26. Biotite quartz diorite, from outcrop in the area of sample 19. (CCH–24–C)
27. Quartz diorite, medium- to coarse-grained, from outcrop 250 ft east-southeast of locality of sample 19. (CCH–25–A)
28. Quartz diorite, from pit along northeast edge of pluton, 0.5 mile north of Eureka Gulch. (EWT–45–54)
29. Granodiorite, from outcrop near center of pluton, just north-northwest of locality of sample 28. (EWT–46–54)
30. Biotite quartz diorite, fine-grained, from outcrop near center of pluton and north of Eureka Gulch. (EWT–52–54)
31. Quartz diorite, from outcrop adjacent to granite gneiss and pegmatite, 1,000 ft north of locality of sample 28. (EWT–58–54)
32. Granodiorite, from outcrop 600 ft due east of peak of Bald Mountain. (EWT–70–54)
33. Hornblende quartz diorite, from pit in the southeasternmost part of the bulge of the pluton. (EWT–63–54)
34. Hornblende quartz diorite, from outcrop 600 ft north of locality of sample 33. (EWT–71–54)
35. Hornblende quartz diorite, fine-grained, from pit south of Eureka Gulch; adjacent to migmatitic biotite-quartz gneiss lens. (EWT–80a–54)
36. Biotite-hornblende quartz diorite, fine-grained, from outcrop adjacent to biotite gneiss, about 250 ft west-northwest of locality of sample 35. (EWT–82–54)
37. Hornblende quartz diorite, from outcrop 2,500 ft northwest of peak of Bald Mountain and just south of Eureka Gulch. (EWT–83–54)
38. Quartz diorite, lens on ridge between Miners Gulch and North Clear Creek, northwest corner of mapped area. (CC–664)
39. Quartz diorite, southernmost tip of above lens. (CC–536)
40. Biotite-hornblende quartz diorite; cuts across Missouri Gulch road 1.5 miles north of junction of road with State Highway 119. (JG–9a)
41. Granodiorite, 0.25 mile north of locality of sample 40, associated with quartz diorite, hornblendite, and pegmatite. (JG–21)
42. Granodiorite, southwest prong of large body in northeast corner of mapped area. (JG–137)
43. Quartz monzonite, peak 10,383 ft north of bench mark 9101 on State Highway 119. (JG–112a)
44. Quartz diorite, northwest shoulder of peak from which sample 43 was taken. (CC–817)
45. Quartz monzonite, taken 0.25 mile east of locality of sample 44. (CC–818a)
46. Biotite-hornblende quartz diorite, lens west of Colorado Creek, northeast edge of mapped area. (CC–855–B)
47. Biotite-hornblende quartz diorite, along State Highway 119, and 0.25 mile northeast of Missouri Lake. (JG–148)
48. Quartz diorite, along State Highway 119, Cold Spring campground, near bench mark 9101. (JG–166)
49. Biotite-hornblende granodiorite; sample taken adjacent to locality of sample 48. (JG–166–1)
50. Biotite-hornblende quartz diorite, taken midway between localities of samples 47 and 48. (JG–172)
51. Biotite-hornblende granodiorite, taken midway between Blackhawk Peak and Oregon Hill. (CC–789–B)
52. Quartz diorite; same locality as that of sample 51. (CC–790–A)
53. Granodiorite, taken just east of locality of sample 52, along Silver Creek. (CC–791–D)
54. Granodiorite, lens just north of Montana Creek, northeast edge of mapped area; (CC–1165)
55. Quartz diorite, Michigan Hill area. (S381–A–53)
56. Quartz monzonite, small outcrop west of northernmost prong of Mount Pisgah along North Clear Creek road. (CC–431)
57. Biotite-hornblende granodiorite, from Sheridan Hill area. (CC–495)
58. Biotite-hornblende quartz diorite, from small body 1 mile east of Yankee Hill. (CC–566)

(Sims and Gable, 1964). The few chemical analyses reflect the same range in composition as that indicated by the modal analyses. Judged from a single analysis of quartz diorite from Bald Mountain (sample 2, table 19), the rock differs chemically from the quartz diorite facies in the Elk Creek pluton mainly in its higher aluminum and magnesium content and lower titanium and total iron content. Apparently the quartz diorite facies of the granodiorite unit can be distinguished chemically from the quartz diorite facies of the gabbro unit in the Elk Creek pluton by its significantly lower titanium content.

Chemical and spectrochemical analyses of a sample of biotite from the quartz monzonite phase at Mount Pisgah are given in table 20. The biotite differs slightly from a biotite in biotite-muscovite quartz monzonite, mainly in its higher aluminum and calcium content and lower total iron content. It contains more calcium than any biotite that has yet been analyzed from the district.

TABLE 19.—*Chemical and spectrochemical analyses and norms and modes of intrusive rocks*

[Laboratory number given in parentheses below sample number. Field number is in parentheses after description of sample. Results of chemical analyses given in weight percent and of spectrochemical analyses, in parts per million; modes given in volume percent. Tr, trace. Chemical analyses by Dorothy Powers and P. R. Barnett]

	Sample			
	1 (G-3098)	2 (G-3099)	3 (G-3100)	4 (G-3101)
Chemical analyses				
SiO_2	64.37	54.41	49.56	54.23
Al_2O_3	15.86	17.12	13.70	15.38
Fe_2O_3	1.78	3.14	6.17	4.66
FeO	3.04	5.60	9.27	6.84
MgO	1.69	5.18	4.09	3.70
CaO	2.37	7.25	7.46	6.14
Na_2O	3.09	2.98	2.46	2.97
K_2O	5.00	1.40	1.22	1.35
MnO	.05	.15	.17	.16
H_2O+	.52	1.23	.79	.95
H_2O-	.08	.07	.06	.08
TiO_2	.72	.85	3.75	2.26
P_2O_5	.32	.07	.41	.39
CO_2	.23	.08	.29	.36
Cl	.03	.07	.02	.03
F	.12	.07	.12	.11
S	.14	.10	.36	.18
BaO	.23	.06	.07	.11
Subtotal	99.64	99.83	99.97	99.90
Less O	.13	.10	.23	.15
Total	99.51	99.73	99.74	99.75
Bulk density	2.66	2.83	3.00	2.81
Powder density	2.73	2.89	3.06	2.92
Spectrochemical analyses				
Co	8	34	51	33
Cr	26	220	48	66
Cu	100	73	120	77
Ga	23	25	28	26
La	140	<100	<100	<100
Ni	20	85	44	58
Pb	50	<30	<30	<30
Sc	13	28	40	22
Sr	620	540	500	500
V	80	260	600	260
Y	50	30	50	50
Yb	4	3	4	4
Zr	700	130	280	360
Norms				
Quartz	19.44	7.20	10.20	13.26
Orthoclase	29.47	8.34	7.23	7.78
Albite	26.20	25.15	20.96	25.15
Anorthite	10.29	29.19	22.52	24.74
Diopside		4.73	7.85	.68
Hypersthene	6.34	17.04	11.56	13.85
Magnetite	2.55	4.64	9.05	6.73
Ilmenite	1.37	1.67	7.14	4.26
Corundum	1.63			
Apatite	.66		.96	.96
Pyrite	.48	.36	1.32	.72
Fluorite	.16	.16	.16	.16
Calcite (secondary)	.50	.20	.70	.80

See notes at end of table.

TABLE 19.—*Chemical and spectrochemical analyses and norms and modes of intrusive rocks*—Continued

	Sample			
	1 (G-3098)	2 (G-3099)	3 (G-3100)	4 (G-3101)
Modes				
Quartz	18.3	11.9	12.7	13.2
Potassium feldspar	34.4	0.2	1.5	
Plagioclase	32.9	49.7	46.1	55.1
Biotite	11.9	13.2	10.5	11.4
Muscovite	1.0	Tr		Tr
Hornblende		23.3	2.0	13.8
Magnetite-ilmenite	.6	1.2	10.0	3.7
Epidote		.5	.7	
Allanite		Tr	Tr	
Apatite	.4	Tr	.2	.3
Zircon	.2	Tr	Tr	Tr
Chlorite	Tr	Tr	1.6	1.2
Orthopyroxene			4.3	Tr
Clinopyroxene			10.4	
Sphene			Tr	
Calcite	.3		Tr	1.3
Composition of plagioclase	An_{27}	An_{34}	An_{41}	An_{38}

1. Quartz monzonite phase of granodiorite rock unit, dump east side of Mount Pisgah. Mode is average of three sections; total count is 3,000. (ST-8)
2. Quartz diorite phase of granodiorite rock unit, dump of small pit, east slope of Bald Mountain. Rock has strong foliation. (ET-219)
3. Pyroxene quartz diorite phase of gabbro rock unit, dump east side of Elk Creek pluton. (CC-1168-A)
4. Quartz diorite phase of gabbro rock unit, same locality as 3. (CC-1168-B)

Potassium feldspar from the same quartz monzonite facies of the Mount Pisgah pluton from which biotite was separated for chemical analysis was analyzed with the X-ray diffractometer by E. J. Young, who used the $(\bar{2}01)$ method of Bowen and Tuttle (1950). The method of homogenization and X-ray investigation used in our study was described in the earlier report on the Central City district (Sims and Gable, 1964). The composition of the feldspar before heating, expressed as weight percent $KAlSi_3O_8$, was 92 ± 1 percent; the composition after homogenization, expressed as weight percent $KAlSi_3O_8$, was 81 ± 1 percent. The triclinicity index of the feldspar determined by measuring the difference between $2\Theta_{CuK_\alpha}$ $(1\bar{3}0)$ and $2\Theta_{CuK_\alpha}$ (130) is 0.75 ± 0.02. Maximum microcline has an index of 0.84 (MacKenzie, 1954). Quantitative spectrographic analyses by J. C. Hamilton of certain elements in the same sample were determined as follows, in percent: calcium, 0.25; barium, 0.98; strontium, 0.13; rubidium, 0.035; iron, 0.047; and lead, 0.012.

PEGMATITE

The pegmatite characteristically found associated with the granodiorite, and presumably genetically related to it, forms homogeneous bodies which range in width from several feet to several hundred feet and which form ridges and knobs that tend to stand above the surface of the granodiorite. The pegmatite is

TABLE 20.—*Chemical and spectrochemical analyses of biotites from intrusive rocks*

[Laboratory number given in parentheses below sample numbers. Field number is in parentheses after description of sample. Results of chemical analyses given in weight percent and of spectrochemical analyses, in parts per million. Chemical analyses by E. L. Munson and P. R. Barnett]

	Sample	
	1 (H3381)	2 (H3382)
Chemical analyses		
SiO_2	35. 60	34. 84
Al_2O_3	17. 74	16. 49
Fe_2O_3	2. 28	3. 99
FeO	17. 68	19. 31
MgO	9. 78	9. 09
CaO	. 18	. 00
Na_2O	. 22	. 23
K_2O	9. 22	8. 26
MnO	. 22	. 18
H_2O+	3. 32	3. 83
H_2O-	. 04	. 17
TiO_2	2. 96	2. 55
P_2O_5	. 04	. 03
F	. 59	. 93
Subtotal	99. 87	99. 90
Less O	. 25	. 39
Total	99. 62	99. 51
Spectrochemical analyses		
Ba	1, 500	630
Co	30	40
Cr	100	30
Cu	41	24
Ga	50	60
Nb	90	80
Ni	80	30
Sc	60	40
Sr	20	10
V	280	180
Y	30	40
Zr	380	320

1. Quartz monzonite variety of granodiorite rock unit, dump east side of Mount Pisgah. (ST-8)
2. Biotite-muscovite quartz monzonite, Lawson area, just west of Central City quadrangle. (ST-11)

light gray, locally iron stained, coarse grained and biotitic, but the feldspar laths rarely exceed 2 inches in length. The bodies are composed dominantly of feldspar and commonly contain about 5 percent each of quartz and biotite. Microcline greatly exceeds plagioclase, which is randomly dispersed. The biotite tends to occur in small books scattered throughout the pegmatite; in appearance and composition the pegmatite is similar to that associated with biotite-muscovite quartz monzonite.

GABBRO AND RELATED ROCKS

OCCURRENCE AND GENERAL CHARACTER

The classification "gabbro and related rocks" is used in this report for rocks that contain an intermediate plagioclase and both orthopyroxene and clinopyroxene and range in composition from melagabbro to quartz diorite. Diorite is the most common rock type within the quadrangle. In composition the rocks overlap mafic phases of the granodiorite and associated rocks and certain phases of the quartz diorite and hornblendite unit. They can be distinguished from these units, however, by their megascopic appearance and by their diagnostic content of pyroxenes.

The gabbro and related rocks occur in the northwestern and central parts of the quadrangle. All known bodies lie northwest of a diagonal line drawn from the southwest to the northeast corner of the quadrangle. The largest body, referred to in this report as the Elk Creek pluton, is hook shaped and is about 2 miles in total length and three-fourths mile in maximum width; it is interpreted as a complex phacolith. Several smaller bodies less than 1,000 feet in maximum dimension occur near the Elk Creek pluton, particularly to the northwest, and masses a few tens of feet in width are associated with some of the quartz diorite and hornblendite bodies that were mapped sporadically northeastward from the vicinity of Mount Pisgah (pl. 1).

Contacts of the gabbro and related rocks against the older layered rocks are sharp. Transitional phases are absent except at one locality on the south slope of Arizona Mountain, near the axis of the Arizona Mountain anticline (pl. 1), where gabbroic rocks intertongue with microcline gneiss across a width of a few feet. Gabbro appears to crosscut a granodiorite dike at one locality in the northwest corner of the quadrangle; accordingly, the unit is interpreted to be younger than the granodiorite. Contacts between these units are poorly exposed elsewhere, however, and this age relation was not confirmed for other bodies. Gabbro is closely associated with and appears gradational into quartz diorite and hornblendite at a few localities.

The gabbro and related rocks are dark gray, generally medium or coarse grained, equigranular, and homogeneous; locally they are light gray or olive gray and mottled, are inequigranular, and contain feldspar crystals as much as 2 inches in diameter. The rocks tend to weather spheroidally to subrounded boulders, to coarse grus, or under forest cover, to a sticky dark-brown soil. Surfaces of the weathered rocks are commonly dark olive gray.

Typically the gabbro is massive and has interlocking plagioclase and pyroxene crystals. Local parts of the Elk Creek pluton, however, are foliated and lineated. On the southeast nose of Idaho Hill (pl. 1) a few subangular blocks or lenses of strongly foliated gabbro, as much as 25 feet in width and 50 feet in length, are enclosed within massive homogeneous gabbro of the pluton. The blocks occur near the outer margin of the pluton and have sharp contacts against the massive gabbro. In one block about 25 feet from the contact, the foliation within the block is subparallel to the outer contact of the pluton; in another the foliation within the block is virtually parallel to the contact with a large rotated inclusion of microcline gneiss.

In contrast to the other intrusive rocks, the country rocks adjacent to and included within the Elk Creek pluton are altered to hornfels through recrystallization and reconstitution and through shearing. The biotite gneisses in the contact zone across a width of a few tens of feet commonly are porphyroblastic and are coarser grained than the unmodified biotite gneisses. Sillimanite-bearing gneiss is changed to inequigranular rocks which contain discoidal sillimanite aggregates. Augen in one specimen consist of sillimanite, a phlogopitic mica, and a green spinel, which are surrounded by sericite. Biotite-quartz-plagioclase gneiss is reconstituted, at least in part, to an orthopyroxene-biotite-quartz-plagioclase rock of felted texture. Microcline gneiss in contact with the gabbro of the Elk Creek pluton on Arizona Mountain is altered to a flaser gneiss and is bleached for a distance of nearly 50 feet from the contact; quartz forms lens-shaped, strongly lineated aggegates, and biotite is altered to chlorite.

PETROGRAPHY

Composition of the gabbro and related rocks varies greatly, from a melagabbro to a quartz diorite, but it is dominantly diorite. In general, the small bodies scattered throughout the quadrangle and particularly those masses associated with the quartz diorite and hornblendite bodies are more mafic than the larger Elk Creek pluton. (See table 21.)

The rocks are hypidiomorphic or allotriomorphic granular and contain intermediate plagioclase, orthopyroxene, clinopyroxene, hornblende, biotite, quartz, and opaque iron oxides as principal constituents and potassium feldspar, muscovite, apatite, sphene, zircon, chlorite, epidote, allanite, calcite, and clay minerals as minor constituents. Plagioclase and pyroxene commonly are intergrown in interlocking grains, but at places they occur in aggregates with a synneusis texture.

Plagioclase, mainly calcic andesine but locally labradorite, is ubiquitous, constituting from about 2 percent to more than 70 percent of the rocks. It is dominantly anhedral, slightly clouded with alteration products, and twinned according to pericline and combination Carlsbad-albite twin laws. Most crystals appear homogeneous and slightly antiperthitic; a few show normal concentric zoning with a small range in composition from one zone to another. Dustlike inclusions, commonly oriented, of a dark-gray and red undetermined material are present in most grains. Myrmekitic intergrowths with quartz are fairly common, especially against biotite and potassium feldspar grains. Some plagioclase crystals contain subrounded blebs of quartz. At places the plagioclase has strain shadows; at others the laths are bent or fractured, and twin lamellae are discontinuous or are actually offset.

Both orthopyroxene and clinopyroxene occur in most sections, and at least one of them is present in all. The orthopyroxene occurs as dominantly subhedral crystals having a conspicuous schiller structure resulting from the alinement parallel to the optic plane of thin lamellae of brown, translucent, unidentified minerals and opaque iron oxides; other lamellae may be clinopyroxene or hornblende. Because augite lamellae at a small angle to the (101) plane in the orthopyroxene have not been noted, it is inferred that the original form of crystallization was orthopyroxene rather than pigeonite. Most grains are altered, and skeletal crystals have cores nearly completely changed to opaque iron oxides, hornblende, biotite, and quartz or to a fine aggregate of epidote, calcite, quartz, and chlorite; some crystals poikilitically contain blebs of quartz, opaque iron oxides, and hornblende. With few exceptions, the orthopyroxene has rims of, or is mottled by, green hornblende. The orthopyroxene is dominantly bronzite. It has a large $2V$;

X=moderate orange pink,
Y=colorless, and
Z=light greenish gray.

In three samples n_y ranged from 1.684 to 1.694. The clinopyroxene is a nearly colorless, slightly pleochroic variety of augite, which occurs in subhedral crystals, is generally skeletal, and has inclusions of opaque iron oxides. Its $2V$ is variable, ranging from about 40° to 60°; $c \wedge Z$ ranges from about 38° to 46°. In one sample $n_y = 1.684 \pm 0.005$. With few exceptions the clinopyroxene is partly replaced by hornblende that lies along grain boundaries or forms a cuneiform intergrowth which is inside the grain and is controlled by cleavage.

Hornblende is present throughout all the bodies. It is variable but seems to be dominantly of two types. One type that forms rims on pyroxene with straight, sharp contacts is green and moderately pleochroic. The pleochroism is generally

X=grayish yellow,
Y=olive green, and
Z=dark olive green or dark olive brown.

The hornblende tends to be poikilitic and contains blebs of quartz and locally, biotite, opaque iron oxides, and apatite. The other type of hornblende varies from a nearly colorless to a blue-green variety. It typically is anhedral with ragged outlines, embays pyroxene along cleavages, and forms blebs parallel to cleavage.

TABLE 21.—*Modes, in volume percent, of gabbro and related rocks*

[Tr, trace; Nd, not determined; --, not found. Color index is volume percent of dark minerals. Field number is in parentheses after description of sample]

Mineral	Elk Creek pluton																			Other bodies					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Potassium feldspar	--	--	--	--	Tr	--	--	0.5	--	--	--	1.5	--	--	--	--	--	--	--	--	--	--	Tr	1.9	1.0
Plagioclase	70.6	48.6	65.0	63.8	71.3	54.6	74.0	53.1	52.7	62.9	53.0	46.1	55.1	55.8	41.2	57.7	64.9	69.9	63.1	9.0	1.9	21.3	60.3	47.4	54.5
Quartz	4.0	4.0	4.5	4.5	4.7	5.6	6.4	6.5	6.8	7.0	12.3	12.7	13.2	14.6	20.3	8.1	5.2	5.4	5.8	--	--	--	8.1	6.9	12.3
Biotite	6.1	6.5	5.4	9.2	4.1	7.3	2.4	9.8	5.5	5.2	15.4	10.5	11.4	11.8	12.0	12.2	11.4	4.1	4.1	5.0	6.2	8.2	12.8	3.1	5.3
Opaque iron oxides	4.1	1.6	3.4	1.6	3.9	2.0	3.0	6.7	11.0	4.1	2.6	10.0	3.7	7.5	4.6	2.5	1.5	1.2	1.1	.4	1.3	.5	3.9	9.5	1.3
Amphibole (hornblende)	7.1	33.6	11.4	8.2	2.3	23.3	3.2	5.9	10.4	13.5	6.0	2.0	13.8	2.8	17.7	13.3	12.3	5.0	13.2	35.0	28.2	24.7	6.3	25.6	23.1
Orthopyroxene (bronzite)	7.0	--	1.1	8.3	7.5	Tr	4.9	10.2	--	3.1	7.0	4.3	Tr	--	Tr	1.5	.1	.1	--	50.6	43.3	29.5	5.2	.6	--
Clinopyroxene (augite(?))	.5	5.4	5.9	1.7	2.9	5.4	Tr	1.1	10.1	.9	2.9	10.4	--	6.8	--	.5	3.8	2.4	11.1	Tr	19.1	14.2	2.2	1.0	1.9
Apatite	Tr	.3	.1	.2	.6	.1	Tr	.4	3.5	.3	.1	.2	.3	.4	1.0	Tr	.1	.2	.3	--	--	.6	.6	.7	.1
Sphene	--	--	--	--	--	--	--	--	--	--	--	Tr	--	.1	.5	--	--	--	--	--	--	--	--	2.4	Tr
Zircon	Tr	--	--	Tr	Tr	Tr	Tr	Tr	--	--	--	Tr	Tr	--	Tr	Tr	Tr	Tr	Tr	--	--	--	--	--	.1
Chlorite	Tr	--	1.0	.6	1.0	1.7	1.5	1.0	--	.5	.1	1.6	1.2	--	1.2	1.5	.7	6.9	.5	--	--	--	Tr	.7	.2
Epidote	.3	Tr	2.2	1.9	1.7	--	4.6	4.8	--	2.5	.6	.7	--	--	1.5	2.5	--	2.9	.8	--	Tr	.5	.6	.2	.2
Allanite	--	--	--	Tr	--	--	--	--	--	--	Tr	Tr	--	.2	Tr	Tr	--	--	--	--	--	--	Tr	Tr	Tr
Calcite	.3	--	--	Tr	--	--	Tr	Tr	--	--	--	Tr	1.3	--	--	.2	--	.1	Tr	Tr	--	.5	--	Tr	--
Muscovite	Tr	--	--	--	--	--	--	--	--	--	--	--	Tr	--	Tr	--	--	1.8	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{46}	An_{43}	An_{46}	An_{43}	An_{43}	An_{43}	An_{48}	An_{41}	An_{41}	An_{41}	An_{38}	An_{41}	An_{38}	An_{38}	An_{36}	An_{46}	Nd	Nd	An_{43}	An_{56}	An_{54}	An_{41}	An_{46}	An_{38}	An_{43}
Color index	25	47	30	32	23	40	20	40	37	30	35	40	30	29	62	34	30	23	31	94	96	77	31	43	32
Average grain diameter ... mm	1.3	0.3	2.7	1.3	1.5	0.4	1.5	0.7	0.8	1.5	1.2	0.7	1.7	0.4	1.1	1.0	1.7	1.7	2.4	0.5	0.6	0.4	1.3	0.8	0.7

1. Diorite, from border, southern part of pluton. (CC-575)
2. Diorite, from east slope of Arizona Mountain. (CC-946)
3. Diorite, from border, south tip of pluton. (CC-571-3)
4. Diorite, from east margin of pluton, taken from nose of ridge on west side of Pine Creek. (CC-928-1A)
5. Diorite, from interior of pluton, taken in saddle between Arizona Mountain and Montana Mountain. (CC-1293-1)
6. Diorite, from eastern part of pluton, near junction of Elk Creek and Pine Creek. (CC-947-1)
7. Diorite, from interior of pluton, taken from dump of adit on south side of Elk Creek. (CC-954)
8. Contaminated diorite, from dump of adit near junction of Miners Gulch and North Clear Creek. Rock contains small inclusions of country rock that have 1/16-inch-thick bleached margins. (CC-1184B)
9. Diorite, from interior of pluton, taken from dump of adit on nose of ridge southwest of junction of Miners Gulch and Elk Creek. (CC-656)
10. Diorite, from margin of pluton, crest of Arizona Mountain. (CC-1233)
11. Quartz diorite, from border, taken 2 ft from contact with microcline gneiss, crest of Arizona Mountain. (CC-1232-C)
12. Pyroxene quartz diorite, taken from dump of adit in western part of pluton, north side of North Clear Creek. (CC-1168A)
13. Coarse-grained hornblende quartz diorite; same locality as that of sample 12. (CC-1168B)
14. Quartz diorite, from interior of pluton, east slope of ridge on south side of Miners Creek. (CC-589)
15. Quartz diorite, from contact zone against sillimanitic biotite-quartz gneiss. (CC-572-1)
16. Diorite, taken 400 ft northwest of locality of sample 11, crest of Arizona Mountain. (CC-1233-1)
17. Diorite, from interior of pluton, near top of Arizona Mountain. (CC-1236A)
18. Diorite, from interior of pluton, taken about 500 ft northwest of top of Arizona Mountain; rock has slight ophitic texture. (CC-1238)
19. Diorite, from border of pluton, north side of North Clear Creek. (CC-1241A)
20, 21. Hypersthene-bearing gabbro, from small bodies associated with bulbous mass of quartz diorite and hornblendite east of Mount Pisgah. (CC-244-1)
22. Pyroxene gabbro, from small lens southeast of Michigan Hill above Silver Creek. (CC-245-3)
23. Pyroxene-bearing diorite, from small body south of the Elk Creek pluton. (CC-906-1)
24. Hornblende diorite, an altered phase of gabbro, from small lens in northwest corner of quadrangle. (CC-1145A)
25. Hornblende quartz diorite, an altered phase of gabbro, from small lens in northwest corner of quadrangle. (CC-1147-1)

Red-brown biotite also is ubiquitous but variable in amount. It is closely associated with the hornblende and pyroxene as subhedral laths and as ill-defined rosettes that contain tiny inclusions of apatite, zircon, allanite, and opaque iron oxides. At places it surrounds and occurs along the cleavages of pyroxene and hornblende. The pleochroism is as follows:

X=very pale orange,
Y=light brown, and
Z=moderate reddish brown.

Potassium feldspar occurs sparsely as interstitial, anhedral grains clouded with alteration products. It is untwinned and slightly perthitic. Quartz is common, locally constituting as much as 20 percent of the rock. It occurs as anhedral interstitial grains, as blebs poikilitically included in the more abundant minerals, and as myrmekitic intergrowths with plagioclase and biotite. Allanite forms pleochroic subhedral crystals ranging from light brown to dark reddish brown; some crystals are zoned. Sphene is associated with biotite, hornblende, epidote, and opaque iron oxides. Apatite, as small subhedral crystals, is dispersed throughout the rock. Granular masses of epidote ranging from a very pale yellow to a pale yellow green occur with the mafic minerals, especially biotite; some crystals are zoned. Calcite typically occurs as small granular aggregates associated with epidote in grains of plagioclase and pyroxene. Chlorite, apparently of variable composition, locally surrounds hornblende and pyroxene, embays plagioclase along fractures and cleavages, and embays and replaces biotite. Muscovite and clay minerals occur as alteration products in intensely altered rocks and especially are associated with plagioclase.

CHEMICAL COMPOSITION

Chemical analyses of two typical samples from the Elk Creek pluton are given in table 19. The rocks differ from the quartz diorite phase of the granodiorite unit in containing more TiO_2, Fe_2O_3, and FeO and less Al_2O_3. In particular, a high titania content seems to be diagnostic of the rocks in the Elk Creek pluton. This content is reflected in the notable amounts of contained magnetite-ilmenite.

PEGMATITE

A distinctive pegmatite is associated with all the larger bodies of gabbroic rocks and occurs in the vicinity of many smaller bodies. The pegmatite forms irregular, crudely zoned bodies as much as a few hundred feet in maximum diameter. The bodies are coarse grained and consist generally of a milky quartz core and a perthite-biotite or perthite-muscovite border zone. Crystals of quartz and feldspar are as much as 12 inches long. The bodies, which contain abundant milky quartz, form conspicuous knobs that stand out prominently in the terrain. At a few localities syenitic pegmatite, which consists dominantly of plagioclase and biotite, forms inch-thin discontinuous tabular bodies along joints in the gabbro.

QUARTZ DIORITE AND HORNBLENDITE

OCCURRENCE AND GENERAL CHARACTER

The intrusive rocks that dominantly contain hornblende and plagioclase in varying amounts were mapped as quartz diorite and hornblendite. They occur in all parts of the quadrangle except the northwestern part within major units of both biotite gneiss and microcline gneiss. Most of the mappable bodies are alined at irregular intervals along a narrow zone which trends N. 45° E. from the southwest corner to the northeast corner of the quadrangle (pl. 1). Several bodies in the Central City district, which were mapped at a scale of 1:6,000 (Sims and Gable, 1964), were too small to show at the scale of plate 1 of this report.

The bodies are generally blunt lenses a few hundred feet in maximum dimension or are, less commonly, tabular bodies as much as 4,000 feet long and 500 feet wide. Contacts are poorly exposed, but observations at various points of the contact zones and the map patterns of separate bodies indicate that the bodies are subconformable to the older rocks. The age of the intrusive bodies relative to the ages of other intrusive rocks in the quadrangle has not been determined unequivocally. However, rocks of nearly identical lithology, texture, and structure in areas a few miles to the south (Harrison and Wells, 1959, p. 15) clearly intrude granodiorite and in turn are intruded by biotite-muscovite granite, the equivalent of the biotite-muscovite quartz monzonite of this report. Within the Central City quadrangle, several of the bodies of quartz diorite and hornblendite, especially in the northeastward-trending zone of intrusions that extend northeast from the vicinity of Mount Pisgah, are associated with small masses of gabbro. Small irregular masses of gabbro of a composition represented by samples 20, 21, and 22 (table 21) occur within and are intimately associated with quartz diorite and hornblendite in the bulbous mass on the east side of Mount Pisgah (pl. 1). Elsewhere, recognizable bodies of gabbro associated with quartz diorite and hornblendite bodies are less common. The field relations are best interpreted as indicating that the bodies of quartz diorite and hornblendite grade into gabbro.

The hornblendite is megascopically similar to that described from the Central City district (Sims and Gable, 1964). It is a black or greenish-black, medium-grained or rarely coarse grained, generally massive, equigranular rock.

The quartz diorite is a dark-gray, fine- to medium-grained, generally massive and equigranular rock. Locally it is inequigranular and contains clots of biotite as large as half an inch in diameter. Some of the smaller tabular bodies have border phases that are finer grained than the interiors. The quartz diorite lacks the strong foliation that characterizes the amphibolites of the area and thus is readily distinguishable from these rocks.

PETROGRAPHY

The quartz diorite and hornblendite of the quadrangle are similar mineralogically to that unit described previously by Sims and Gable (1964) from the Central City district but differ in that they contain substantially more pyroxene, which is partly altered to hornblende. Because of this difference and its significance in interpreting the origin of these rocks, some aspects of the petrography are discussed as follows.

The rocks contain dominant hornblende and plagioclase of intermediate composition, variable amounts of biotite and pyroxene, and lesser amounts of quartz, opaque iron oxides, and a variety of accessory minerals (table 22). Plagioclase (calcic andesine) forms subhedral and anhedral grains dominantly intergrown with pyroxene or, where pyroxene is absent, with hornblende or biotite. It is twinned according to the Carlsbad, albite, and pericline twin laws and shows weak concentric zoning. Both clinopyroxene and orthopyroxene occur sparsely in the rock. The orthopyroxene forms subhedral crystals that have a conspicuous schiller structure resulting from thin plates of an unidentified brown translucent material oriented parallel to the optic plane. Other lamellae of the same alinement may be clinopyroxene or a nearly colorless amphibole. With few exceptions, the orthopyroxene is embayed and rimmed by green hornblende, and contact between the minerals is sharp and ragged. Blebs of opaque iron oxides oriented in a crystallographic or a cleavage direction occur in the pyroxene that is partly altered to hornblende. The clinopyroxene occurs as irregular, shredded crystals that are partly altered to hornblende. The hornblende forms irregular patches and blades and wedges oriented in the plane of the cleavage and commonly is optically continuous with the clinopyroxene. Alined grains of magnetite occur in the altered clinopyroxene.

The hornblende is a green, strongly pleochroic variety having the following general pleochroic formula:

X=moderate greenish yellow,
Y=dark greenish yellow, and
Z=moderate olive brown.

TABLE 22.—*Modes, in volume percent, of quartz diorite and hornblendite*

[Tr, trace; Nd, not determined; ----, not found. Color index is volume percent of dark minerals. Field number is in parentheses after description of sample]

	1	2	3	4	5	6	7
Potassium feldspar	Tr	----	----	3.5	----	----	----
Plagioclase	51.8	43.5	21.8	39.5	52.7	33.6	0.2
Quartz	3.4	1.1	9.5	9.5	2.8	5.3	.5
Biotite	16.4	----	21.4	22.5	8.1	17.1	----
Muscovite	----	.1	----	----	----	----	----
Opaque iron oxides	4.9	3.6	1.1	4.6	6.8	4.2	Tr
Amphibole	15.5	47.8	43.1	16.1	3.3	37.9	99.2
Orthopyroxene	2.3	----	1.1	----	14.3	1.4	----
Clinopyroxene	5.0	.4	1.6	.5	7.4	----	----
Apatite	.3	Tr	.4	2.0	1.3	.2	.1
Sphene	----	Tr	----	.4	----	----	Tr
Zircon	Tr	Tr	Tr	Tr	----	----	----
Chlorite	----	2.7	----	1.0	.3	----	----
Epidote	.1	.8	----	Tr	3.0	.3	----
Allanite	.3	----	----	.4	----	----	----
Calcite	----	----	Tr	----	----	----	----
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{43}	Nd	An_{43}	Nd	An_{46}	An_{48}	Nd
Color index	45	55	68	55	43	61	99
Average grain diameter (mm)	Nd	Nd	0.5	0.3	0.1	0.2	Nd

1. Diorite, from lens-shaped body that cuts across Missouri Gulch near Stewart Gulch. (CC-1209)
2. Fine-grained phase of sample 1. (CC-1209-1)
3, 4, 5, 6. Succession of samples taken across strike of body exposed on south side of North Clear Creek, just east of mouth of Pecks Gulch. Sample 3, diorite that contains biotite clots; sample 4, similar to 3 but finer grained; sample 5, phase finer grained than 4; sample 6, fine-grained phase that occurs as ovoid blocks in normal phase. (CC-362-A; CC-362-B; CC-362-C; CC-362-D)
7. Hornblendite taken from small unmapped body on north slope of Bald Mountain. (EWT-54-54)

In addition to occurring as rims on pyroxene, it forms anhedral irregular grains, generally slightly larger than those of the pyroxene, that poikilitically include quartz, opaque iron oxides, and rarely apatite. Red-brown biotite is distributed irregularly. It has the following pleochroic formula:

X=grayish orange or very pale orange,
Y=dark yellowish orange or dark reddish orange, and
Z=moderate reddish brown.

It forms moderately large subhedral, generally poikilitic crystals. In general, a substantial proportion of quartz is associated with the biotite. The quartz is mainly in the interstices of the dominant minerals. Some sections which contain large amounts of biotite also contain myrmekitic intergrowths of quartz and potassium feldspar.

PEGMATITE

The pegmatite that is associated with bodies of quartz diorite and hornblendite is similar to that associated with the gabbro. It is coarse grained and forms crudely zoned bodies. White quartz cores typically grade laterally toward the walls into perthite-quartz-mica pegmatite. Sillimanite occurs locally in the pegmatite in areas where sillimanitic biotite gneisses occur.

BIOTITE-MUSCOVITE QUARTZ MONZONITE

Scattered small bodies of biotite-muscovite quartz monzonite, generally either in dike form or in crescentic masses thickened in apical areas and thinned or pinched on the limbs of folds, occur in the southwestern and central parts of the quadrangle. The bodies are peripheral to the large pluton of Silver Plume Granite exposed at and near Silver Plume, Colo. (Lovering and Goddard, 1950, pl. 3) and also to outlying smaller plutons such as at Alps Mountain in the Freeland-Lamartine and Chicago Creek areas (Harrison and Wells, 1956, 1959).

Nearly all the bodies exposed in the quadrangle lie within an ill-defined, relatively narrow, northeastward-trending zone that extends from the southwest corner of the quadrangle to the vicinity of Bald Mountain. The bodies are more numerous and larger in the southwestern part of the quadrangle than in the central part. They range in size from three-quarters of a mile to a few tens of feet in length and 1,000 feet to a few feet in width. They occur in biotite gneisses and to a lesser extent in microcline gneiss and granodiorite and associated rocks. Contacts of the quartz monzonite bodies with the country rock are sharp; however, several inches or feet of pegmatite may occur along the contacts.

The quartz monzonite is nearly massive except near the borders where it has weak foliation imparted by oriented biotite flakes and tabular feldspar crystals. The foliation is subparallel to the contacts, even where the contacts are discordant. Accordingly the foliation is interpreted as a primary flow structure.

The biotite-muscovite quartz monzonite is a light- or medium-gray rock that weathers to yellowish gray, pinkish gray, or buff. In this area it is dominantly fine or medium grained and virtually equigranular, but parts of the larger bodies are medium grained and seriate porphyritic in texture. The rock is closely similar in composition, fabric, and texture to the fine-grained varieties of the type area and of the nearby Freeland-Lamartine and Chicago Creek areas, but it has a slightly lower color index.

The rock contains roughly equal amounts of potassium feldspar, plagioclase, and quartz as essential minerals and biotite and muscovite as diagnostic varietal minerals (table 23). The proportions of the essential minerals vary somewhat, but the rock is dominantly quartz monzonite, which has a hypidiomorphic granular texture. As the petrography of the rock has been described previously from the Central City district (Sims and Gable, 1964) and the Lawson-Dumont-Fall River district (Hawley and Moore, 1967), only a brief description is given here. Typically, potassium feldspar, quartz and plagioclase form crystals that are 3–4 mm in diameter, but some tabular potassium feldspar crystals are as much as 6 mm in width. Interstitial to these grains are smaller crystals of biotite, muscovite, magnetite, and some of quartz and plagioclase. As a generalization, the quartz grains tend to be clustered at random. The plagioclase is typically cloudy and is partly altered to muscovite, sericite, and clay minerals. The potassium feldspar, however, tends to

TABLE 23.—*Modes, in volume percent, of biotite-muscovite quartz monzonite*

[Tr, trace; Nd, not determined; --------, not found]

	Scattered small bodies in Mount Pisgah and Bald Mountain areas							Lawson-Dumont-Fall River district [1]	Central City district [2]	Quarry, Silver Plume [3]	Chicago Creek area [4]
Field No.	S-12A-52	CC-296-2	CC-300A	EWT-50-54	EWT-81-54	EWT-95-54	Average	--------	--------	SPQ-1	--------
Potassium feldspar	27.2	32.0	39.4	35.6	41.0	21.5	32.8	30.0	25.8	31.7	34.4
Plagioclase	36.0	29.0	27.3	28.1	27.7	39.0	31.3	32.5	34.0	29.8	27.8
Quartz	24.9	26.3	23.4	26.0	20.9	26.5	24.6	29.0	30.1	24.0	29.6
Biotite	9.4	1.0	4.0	6.3	4.3	5.1	5.0	5 0	4.9	9.2	3.4
Magnetite-ilmenite	1.2	1.5	1.6	1.3	.2	.4	1.0	1.0	.7	1.4	.6
Muscovite	1.3	3.3	1.6	2.5	5.4	7.2	3.6	2.5	4.5	3.1	3.2
Apatite	Tr	.2	.3	.2	.3	Tr	.2	Tr	Tr	.6	Tr
Zircon and monazite	Tr	Tr	Tr	Tr	Tr	.3	Tr	Tr	Tr	.2	.4
Fluorite	--------	--------	--------	--------	--------	--------	--------	--------	--------	Tr	--------
Allanite	--------	.4	--------	Tr	--------	--------	Tr	Tr	--------	--------	--------
Epidote	--------	1.0	.7	--------	--------	--------	.3	--------	--------	--------	--------
Calcite	--------	--------	--------	--------	--------	--------	--------	--------	--------	Tr	--------
Chlorite	--------	5.3	1.7	Tr	.2	--------	1.2	--------	--------	--------	--------
Rutile	--------	--------	Tr	--------	--------	--------	--------	--------	--------	Tr	--------
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.4
Composition of plagioclase	An_{30}	Nd	An_{29}	An_{26}	An_{26}	Nd	An_{27}	Nd	An_{26}	An_{26}	Nd
Average grain diameter mm	Nd	0.6	0.6	0.6	0.4	0.3	0.5	Nd	Nd	0.6	Nd

[1] Average of 12 modes (C. C. Hawley, written commun., 1961).
[2] Average of 5 modes (Sims and Gable, 1964).
[3] Type section of Silver Plume granite.
[4] Average of 29 modes (Harrison and Wells, 1959, p. 19).

be clear and little altered. The biotite is dominantly the brown variety; the chemical composition of a typical sample is given in table 20. Associated with the biotite are traces of allanite, zircon, and monazite, which all produce pleochroic halos. Muscovite generally appears shredded and occurs as overgrowths on feldspars and biotite and locally as aggregates and stringers between the larger quartz and feldspar grains. As zircon and monazite are virtually identical in appearance in thin section, they are grouped together in the table of modes. Monazite is sufficiently abundant to produce anomalously high radioactivity.

Potassium feldspar from the same rock (ST–11) from which biotite was separated for chemical analysis (table 20) was analyzed with the X-ray diffractometer by E. J. Young, who used the ($\bar{2}01$) method of Bowen and Tuttle (1950). The composition of feldspar before it was heated, expressed as weight percent $KAlSi_3O_8$ was 91.5$\pm$1 percent; the composition after it was heated, expressed as weight percent $KAlSi_3O_8$ was 82$\pm$1 percent. The triclinicity index of the feldspar determined by measurement of the difference between $2\Theta_{CuK_\alpha}$ ($1\bar{3}0$) and $2\Theta_{CuK_\alpha}$ (130) was 0.84$\pm$0.02; this index is equivalent to maximum microcline as defined by MacKenzie (1954). Quantitative spectrographic analyses by J. C. Hamilton of certain elements were determined on the same material and were, in percent—calcium, 0.15; barium, 0.37; strontium, 0.049; rubidium, 0.046; iron, 0.075; and lead, 0.017.

Flame photometer analyses by J. B. McHugh of representative samples of biotite-muscovite quartz monzonite gave the following compositions, in percent:

Sample	Na_2O	K_2O
CC–296–2	2.8	5.5
CC–300–A	2.7	5.9
S606B–53	3.2	6.0
CC–1042	3.1	6.4
SPQ–1	3.1	5.6

All samples except SPQ–1 were collected in the Central City quadrangle; SPQ–1 was from the Silver Plume Granite quarry in Silver Plume, Colo.

Pegmatite that is associated with biotite-muscovite quartz monzonite is unzoned and consists dominantly of perthitic microcline, sodic plagioclase, quartz, and biotite. It is characterized by the presence of biotite as irregularly shaped books that have little or no preferred orientation and that tend to be clustered. Uraninite-bearing pegmatites within a northeastward-trending belt that extends across Virginia Canyon in the southeastern part of the quadrangle possibly are related to the granite; they have been described in some detail in an earlier report (Sims, Armstrong, and others, 1963, p. 10–12). Flame photometer analyses by J. B. McHugh of two samples from the Highlander claim in Virginia Canyon gave the following compositions, in percent:

Sample	Na_2O	K_2O
H–1	2.8	11.8
A–13–9	3.0	8.0

EMPLACEMENT AND ORIGIN OF THE INTRUSIVE ROCKS

The Precambrian intrusive rocks in the Central City quadrangle part of the Front Range were emplaced synchronously with the major period of folding and metamorphism in the catazone of the earth's crust. The texture, structure, and lithology of the rocks are interpreted to indicate that the intrusives crystallized largely from magma.

The sequence of emplacement of the major intrusive rocks in the central part of the Front Range has been established with certainty by the previous detailed geologic studies of Harrison and Wells (1959), Sims and Gable (1964), and Moench, Harrison, and Sims (1962). The order from oldest to youngest, as determined by crosscutting relations and by internal structures of the intrusive bodies, is granodiorite and associated rocks, quartz diorite and hornblendite, and biotite-muscovite quartz monzonite. Our study has established that the gabbro and related rocks, which were not noted in the adjacent area mapped previously by Harrison and Wells (1959), are intermediate in the succession—between the granodiorite and associated rocks and the biotite-muscovite quartz monzonite. It has also established that the quartz diorite and hornblendite bodies which are so profusely scattered through the adjacent terranes probably were formed by the retrograde metamorphism of the gabbro and related rocks.

The oldest intrusive bodies, granodiorite and associated rocks, were intruded early in the episode of plastic deformation. They were emplaced subsequent to the development of most of the migmatite, for inclusions of migmatized biotite gneiss are found scattered through the granodiorite bodies, and were emplaced after folding had begun, for inclusions commonly are folded more intricately than the enclosing granodiorite. The subconcordant contacts and local phacolithic forms are interpreted to indicate that the rock formed from a magma or a fluid that welled up between and along foliation planes and that followed preexisting structures. Magma moved into relatively low pressure sites in the crests of anticlines and the troughs of synclines as folding progressed, and phacoliths resulted. Except locally, the magma was not able to penetrate for long distances along the limbs of the folds, and as a result the limbs of phacoliths are short and the sheets generally are lenticular. Crystallization took place under directed compressive stresses, and the result was a foliation and lineation subconcordant to that in the country rock. Continued stress after consolidation caused recrystallization in the borders of the bodies, and a secondary foliation and lineation resulted. A concept of magmatic origin for all or most of the rock is supported by the crosscutting contacts on both a small scale and a regional scale, by sharp contacts, by a composition consistent with that expectable from a differentiating magma, and by a probable flow structure marked locally by tabular inclusions oriented parallel to crosscutting contacts (Harrison and Wells, 1959, p. 13–15).

Gabbro and related rocks are inferred to be younger than the granodiorite because of the apparent crosscutting relations in the northwest corner of the quadrangle (pl. 1) on the northwest slope of the Montana Mountain. This interpretation of age is supported by marked differences in the internal structures of the bodies of the two rock types; the gabbroic rocks have a more massive structure than the granodiorite, and thus they probably crystallized later in the episode of deformation under less intense deforming stresses. The Elk Creek pluton, the principal body of gabbroic rocks, is interpreted to be a compound phacolith. In some aspects, it resembles the "pine tree" structures described by Boos and Boos (1934) from the granitic rocks in the Longs Peak-St. Vrain batholith in the northern part of the Front Range. Smaller bodies are stubby sheets or lenses, wholly conformable to the country rock. Presumably the mechanism of emplacement was similar to that of the granodiorite bodies—the magma was injected under directed compressive stresses but except locally was not recrystallized sufficiently to produce a secondary foliation and lineation. The blocks of foliated gabbro observed near the east margin of the Elk Creek pluton suggest that an early consolidated phase of the magma, which crystallized under directed compressive stresses, was broken and engulfed within still-fluid magma. At least one of these xenoliths was oriented, presumably by flow of the magma, parallel to the pluton walls. The gabbroic rocks are interpreted to have formed from a normal gabbroic magma. A temperature difference between the magma and the country rocks, which may be estimated at possibly as much as 500°C., was sufficient to produce a narrow halo of metamorphism in the country rock and, possibly, a chilling of the margins of the bodies. After crystallization, green hornblende formed at the expense of pyroxene and plagioclase. Later biotite and probably other minerals replaced the older minerals. We are not able, however, with our present knowledge to distinguish confidently all phases of igneous or deuteric and metamorphic stages of crystallization.

Bodies of quartz diorite and hornblendite are widely distributed in the region, and their equivalence has been established by detailed studies in several areas. All the bodies are small and either podlike or lenslike. That some have border phases that are finer grained than the interiors indicates probable chilling during intrusion. The bodies intrude granodiorite and associated rocks and in turn are intruded by biotite-muscovite quartz monzonite. An intermediate position in the intrusive sequence, therefore, is firmly established for the rock unit.

The regional variations in the mineralogy and structure of the quartz diorite and hornblendite rock unit and its close association with and gradation into gabbroic rocks in the central and northwestern parts of the Central City quadrangle are interpreted to indicate that the unit was derived from gabbro through retrograde metamorphism. From localities south of the Central City quadrangle and extending northward into the quadrangle there is a systematic change in the character of the quartz diorite and hornblendite bodies. In the area at and south of Idaho Springs, the bodies are foliated and lineated and contain hornblende and biotite as the major mafic minerals. The strongly foliated masses contain as much as 20 percent microcline and plagioclase in the range An_{23}–An_{32}; the less foliated ones have virtually no microcline and contain calcic andesine or labradorite (Harrison and Wells, 1959, p. 16). In the Central City district, on the east side of the Central City quadrangle, bodies of the same rock are weakly foliated and contain a few percent of clinopyroxene as well as the principal constituents hornblende and andesine (Sims and Gable, 1964). Similar bodies in the central part of the quadrangle, and particularly those extending northeastward from Mount Pisgah, are weakly foliated or nearly massive and contain some orthopyroxene as well as clinopyroxene (table 22). The hornblende appears to have formed largely at the expense of pyroxene; biotite, too, is a secondary mineral. The hornblende is similar in color and optical properties to that formed after pyroxene in the gabbroic rocks. These mineralogic data, together with the apparent gradation in the field between gabbroic rocks and quartz diorite and hornblendite, are consistent with a view that the quartz diorite and hornblendite formed in some manner from the gabbroic rocks. Evidently the smaller bodies of gabbro were more susceptible to change than were the larger bodies, and some were so completely modified that all remnants of the original texture and mineralogy were destroyed. The regional pattern of distribution of gabbro and quartz diorite and hornblendite is consistent with an interpretation that original gabbroic rocks were modified by the deforming stresses, the younger episode of Precambrian deformation (see p. E49) that produced the Idaho Springs-

Ralston shear zone. This deformation was intense in the shear zone and weak elsewhere. Probably all bodies of original gabbro within the shear zone would be modified by retrograde metamorphism because the pressure-temperature environment was one of cataclasis with little recrystallization. Outside the zone, modification by the new metamorphic environment was less intense, and some of the primary features of the gabbro were not destroyed. The same episode of metamorphism can account for the mineral changes in the Elk Creek pluton of gabbro and related rocks, as discussed previously.

The biotite-muscovite quartz monzonite, the youngest of the Precambrian intrusive rocks, was emplaced at about the same time as or after the cessation of the deforming stresses that produced the major folds of the region. Evidence for a late-syntectonic origin is provided by occurrence of the quartz monzonite as phacoliths in small folds, previously documented for the Chicago Creek area (Harrison and Wells, 1959, p. 20), a few miles south of the quadrangle. Within the quadrangle, the rock occurs as small subconcordant bodies or more commonly as crosscutting dikes. Some of the subconcordant bodies along Clear Creek are possibly phacolithic. The mineralogic homogeneity, crosscutting contacts, and primary foliation of the rocks support the theory for a wholly magmatic origin.

The Precambrian intrusive rocks were emplaced in the catazone, as defined by Buddington (1959), in an environment of intense pressure-temperature conditions. The thickness of cover can be presumed, from the estimates of Buddington for the catazone, to be in the range of from 7 to 12 miles. The earliest intrusive rocks—granodiorite and associated rocks—crystallized after or near the thermal maximum, which was equivalent to the upper sillimanite grade of metamorphism of the older, major Precambrian deformation. By this time regional migmatization of the country rock had been largely accomplished. Later in the deformation the gabbroic rocks were emplaced under similar pressure-temperature conditions. Temperatures in the Elk Creek pluton of gabbro, the largest intrusive body in the region, were sufficiently greater than the country rock to form a narrow metamorphic halo. Evidently a substantial interval of time preceded emplacement of the biotite-muscovite quartz monzonite. The deforming stress had lessened and probably a substantial thickness of cover had been eroded. Although mild compressive stresses were still active, emplacement was controlled to a considerable degree by cross fractures. The physical conditions of emplacement in some respects were transitional to the mesozone environment. Metamorphism under decreasing pressure-temperature conditions may have begun soon after emplacement of the biotite-muscovite quartz monzonite but more likely took place concomitantly with the younger Precambrian deformation.

METAMORPHIC FACIES

Progressive metamorphism of the rocks of the region produced mineral assemblages characteristic of the sillimanite grade. In rocks of suitable composition, potassium feldspar, sillimanite, and muscovite are stable; this stability indicates that the rocks are above the sillimanite-potassium feldspar isograd, as defined by Guidotti (1963).

Judged from the mineral assemblages, regional metamorphism was virtually uniform in the quadrangle. The assemblages can be related to the metamorphism that accompanied the episode of dominant regional deformation; the younger Precambrian deformation apparently did not appreciably modify the assemblages, except locally in the southeastern part of the quadrangle, within the Idaho Springs-Ralston shear zone. The younger episode of deformation mainly resulted in cataclasis and the formation of new structures.

The assemblages of the regionally metamorphosed Precambrian rocks adjacent to the Tertiary stock near Apex were modified in a manner similar to that described recently by Hart (1964) from the adjacent Nederland quadrangle.

The mafic metamorphic rocks of the quadrangle, represented by amphibolite, dominantly contain the assemblage andesine-hornblende-quartz; clinopyroxene is a local constituent. These minerals crystallized near equilibrium during the highest grade of metamorphism in the area. Some of the hornblende and biotite may have resulted, however, from a later retrograde metamorphism. Apparently the rocks formed under conditions of progressive metamorphism that approximate the transition in which sphene disappears and clinopyroxene appears, as represented by the amphibolites in the zones of progressive metamorphism in the northwest Adirondack Mountains, New York (Buddington, 1963, p. 1163; Engel and Engel, 1962, p. 69). The hornblende gneiss in the Lawson layer of microcline gneiss, in the northeastern part of the quadrangle, represents rocks which had an original bulk composition that was different from that of the normal amphibolite.

Microcline gneiss contains the common assemblages biotite-plagioclase-potassium feldspar-quartz and biotite-muscovite-plagioclase-potassium feldspar-quartz. Garnet, sillimanite, and hornblende are local constituents. None of the assemblages are diagnostic of a particular grade of metamorphism.

Metamorphism of the pelitic rocks produced several mineral assemblages, the composition of which depends upon the original bulk chemical composition. The principal assemblages of the dominant biotite gneisses—biotite-quartz-plagioclase gneiss and sillimanitic biotite gneiss—are as follows:

1. Biotite-plagioclase-quartz
2. Biotite-garnet-plagioclase-quartz
3. Biotite-quartz-sillimanite
4. Biotite-plagioclase-quartz-sillimanite
5. Biotite-plagioclase-potassium feldspar-quartz-sillimanite
6. Biotite-muscovite-plagioclase-potassium feldspar-quartz-sillimanite

Muscovite formed in those rocks that had a sufficiently high K:Na ratio. The plagioclase is consistently An_{23-29}; the average composition is about An_{27}. Rarely muscovite apparently formed also as a product from the reaction between sillimanite and potassium feldspar.

Metamorphism of pelitic sediments rich in $Al_2O_3+FeO+MgO$ produced the following common assemblages:

1. Biotite-garnet-magnetite-plagioclase-potassium feldspar-quartz-sillimanite
2. Biotite-cordierite-garnet-magnetite-plagioclase-potassium feldspar-quartz-sillimanite
3. Biotite-cordierite-magnetite-plagioclase-quartz

Assemblage 1, characteristic of the gneisses listed in table 11, locally lacks potassium feldspar, magnetite ilmenite, and sillimanite. Assemblage 2 may lack or show only traces of magnetite, potassium feldspar, and plagioclase (table 12). Cordierite commonly forms coronas around garnet, as indicated on page E23. The potassium feldspar is dominantly microcline and microperthite but locally is orthoclase. Andalusite-biotite-quartz and biotite-cordierite-magnetite-sillimanite-spinel form local subassemblages. Assemblage 3, characteristic of the rocks listed in table 13, may contain garnet or sillimanite or both. It apparently is more restricted in occurrence than the other two major assemblages.

The magnesian cordierite-amphibole gneiss consists of the following several stable mineral assemblages, the composition of which depends upon the bulk chemical compositions:

1. Biotite-cordierite-gedrite
2. Biotite-cordierite-gedrite-quartz
3. Biotite-cordierite-garnet-gedrite-quartz
4. Cordierite-plagioclase-quartz
5. Biotite-cordierite-quartz

Except for the occurrence of quartz and spinel in the same rock, evidences of disequilibrium are lacking.

The calc-silicate rocks contain a variety of assemblages. (See p. E17.) They contain epidote as an apparent stable mineral phase and thus differ from the common calcareous assemblages in the sillimanite-almandine subfacies (Fyfe, Turner, and Verhoogen, 1958, p. 231).

In a narrow zone surrounding the Elk Creek pluton the assemblages of the biotite gneisses were changed to the pyroxene hornfels facies. The biotite gneisses were reconstituted and recrystallized to a coarser grained hornfels. Sillimanitic biotite gneisses were changed to inequigranular rocks which contain discoidal aggregates of sillimanite, phlogopitic mica, quartz, plagioclase, and spinel; biotite-quartz-plagioclase gneiss was converted to orthopyroxene-biotite-quartz-plagioclase rocks of felted texture. A small amount of clinopyroxene formed with the orthopyroxene.

The thermal metamorphism related to the larger Tertiary intrusive bodies in this area cannot be entirely separated from the hydrothermal effects; further studies of the contact metamorphic aureoles are needed.

STRUCTURE

The main structures of the Precambrian rocks of the Central City quadrangle are interpreted to have resulted from two episodes of Precambrian deformation. Northeastward-trending folds and associated lineations—the dominant structures of the area—formed during an older plastic deformation; and shearing and related folds and lineations trending east-northeast formed during a distinctly younger deformation. The older deformation was pervasive and virtually contemporaneous with emplacement of most of the Precambrian intrusive bodies, whereas the younger one was more local in extent, and megascopically visible effects of it are mainly confined to the southeastern part of the quadrangle. The principal manifestation of the younger deformation is the Idaho Springs Ralston shear zone (Tweto and Sims, 1963). This and other structures related to the younger deformation have been described in considerable detail previously (Moench and others, 1962) and are only discussed briefly in this report. A still older deformation that has been recognized in similar rocks to the east of Central City (p. E5) has not been distinguished in the Central City quadrangle.

In accord with previous reports on the region (Moench, Harrison, and Sims, 1962; Sims and Gable, 1964), we refer the linear elements associated with the fold systems to directional coordinates. In this report, *B* refers to the major fold axes and to linear elements parallel to them, and *A* refers to the minor fold axes and associated linear elements that are nearly at right angles to the axes of the major folds. *A* and *B* are, therefore, used in a geometric sense. However, *B* conforms to established petrofabric terminology in which *b* refers to the axis of internal rotation, which commonly is parallel to fold axes and normal to *a*, the direction of tectonic transport (Fairbairn, 1949, p. 6). *A* has the required geometric relations of an *a* fabric direction to *b* but is also a direction of folding. In the commonly established petrofabric terminology, therefore, it is a *b* fabric direction and might be termed accordingly b^1 or b_2.

TERMINOLOGY

The Precambrian rocks have a well-defined foliation and lineation that is analagous to the "gneissic structure" of high-grade metamorphic rocks throughout the world. As these structures have been described previously for rocks in this region (Sims and Gable, 1964; Moench, 1964), only brief discussions of the terms are given herein.

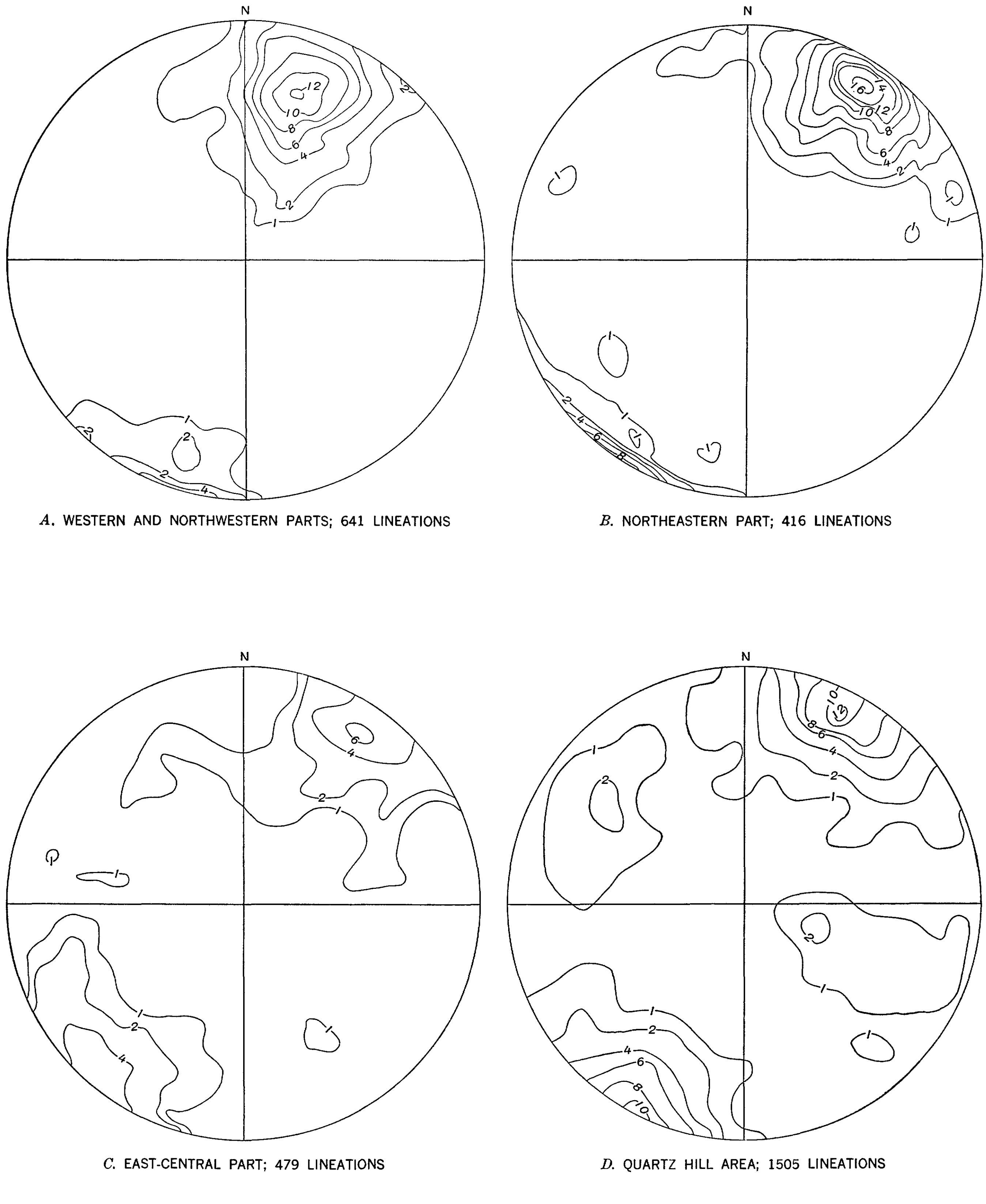
Foliation.—Foliation is the term used for a preferred planar mineral orientation as well as for a compositional layering. In the metamorphic rocks the mineral orientation is subparallel to the compositional layering, except for a few scattered outcrops where a planar mineral orientation is parallel to axial planes of small folds and is at a large angle to the lithologic layering. Except for the exceptions noted above, the foliation is secondary and formed prior to the culmination of folding. In the intrusive rocks the foliation is dominantly a planar mineral orientation and is in part secondary and in part primary. Foliation in the granodiorite and associated rocks, and to a lesser degree in the gabbro and related rocks and in the quartz diorite and associated hornblendite, is largely secondary, for it conforms to and is continuous with the foliation in the layered gneissic country rocks. It formed during the regional plastic deformation, subsequent to crystallization. However, as these rocks were emplaced during the deformation, an original primary foliation probably was also induced, and this foliation probably was modified by postconsolidation recrystallization. The foliation in the biotite-muscovite quartz monzonite is wholly primary and formed as a flow structure, for it is parallel to the walls of the intrusive bodies even where they crosscut the gneissic structure of the country rock. In the sheared rocks of the Idaho Springs-Ralston shear zone, foliation at places is due to a subparallel mesh of closely spaced fractures, with or without a planar mineral orientation.

Lineation.—Lineation is defined (Cloos, 1946, p. 1) as "a descriptive and nongenetic term for any kind of linear structure within or on a rock." In this area lineation is expressed by the axes of small folds, elongate minerals and mineral aggregates, boudinage, and rarely slickenside striae and rodding. With a few exceptions the observed lineations were formed by secondary flowage that accompanied the older, plastic deformation of the region. Consequently the lineations are parallel to the major fold axes (*B*) or are nearly normal (*A*) to them. Slickenside striae and rodding and rarely other linear elements are related, however, mainly to the cataclastic deformation that produced the Idaho Springs-Ralston shear zone. These lineations are parallel to folds of the younger deformation or are nearly normal to them.

To summarize the lineation data for the quadrangle, lineations measured in surface exposures were plotted on the lower hemisphere of Schmidt equal-area nets. Four diagrams were constructed according to the method described by Billings (1942, p. 119–121) for the poles of joints, except that the lower hemisphere was used. Figure 8*A* represents measurements made in the western and northwestern parts of the quadrangle, in an area roughly bounded on the east by a straight line passing through Oregon Hill and Mount Pisgah. Most measurements in this area were made north of Fall River; lineation data on the area south of Fall River are given in the report on the Lawson-Dumont-Fall River mining district by Hawley and Moore (1967). Figure 8*B* represents measurements in the northeastern part of the quadrangle, in the area north of North Clear Creek and east of Blackhawk Peak. Figure 8*C* covers the east-central part of the quadrangle; it includes measurements from Bald Mountain and vicinity northward to North Clear Creek, west of the Central City district. Figure 8*D* represents measurements made from the southern and central parts of the Central City mining district, in an area centering at Quartz Hill. Many additional data are given for this area in the report on the Central City district by Sims and Gable (1964). Lineation data for the extreme southeastern part of the quadrangle are not presented herein as these are given in the report on the Idaho Springs district by Moench (1964) and in summation, in the report by Moench, Harrison, and Sims (1962, p. 43).

FOLDS

The northeastward-trending folds are the most conspicuous structural feature of the region and provide the structural framework of the quadrangle (pl. 1). They are dominantly open, upright anticlines and synclines which have steeply dipping axial planes and gently plunging axes. Closed, overturned folds of intermediate size occur in the west-central part of the quadrangle in the vicinity of Hamlin Gulch. According to our interpretation of the lithologic succession, the dominant folds of the quadrangle are the Central City anticline in the east and the Lawson syncline in the west. The Idaho Springs anticline in the extreme southeastern part of the quadrangle is similarly a major structure, but it does not affect the distribution of the rocks within the quadrangle to the same extent as do



A. WESTERN AND NORTHWESTERN PARTS; 641 LINEATIONS

B. NORTHEASTERN PART; 416 LINEATIONS

C. EAST-CENTRAL PART; 479 LINEATIONS

D. QUARTZ HILL AREA; 1505 LINEATIONS

FIGURE 8.—Contour diagrams of lineations in the Central City quadrangle. Lower hemisphere plots, contoured in percent.

the other two folds. In general the strata dip westward from the axis of the Central City anticline to the axis of the Lawson syncline; a structural rise of more than 2 miles occurs from the Lawson syncline southeastward across strike to the southeast corner of the quadrangle.

MAJOR FOLDS

CENTRAL CITY ANTICLINE

The dominant fold in the eastern part of the quadrangle, the Central City anticline, is a broad, open, nearly symmetrical, upright fold outlined by the Quartz Hill layer of microcline gneiss and the overlying biotite gneiss unit (pl. 1). It has been traced along its axis for a distance of about 10 miles and extends 5 miles northeastward beyond the east border of the Central City quadrangle. Near Central City the fold has a breadth in excess of 3 miles; southwestward it decreases in both breadth and amplitude and near Clear Creek becomes a gently dipping, westward-facing monocline. The axial plane is interpreted from both surface and subsurface data in the Central City mining district to dip about 85° SE. (Sims and Gable, 1964). The trace of the axial plane trends N. 40° E. on the average but is sinuous in detail. The deflections in the trace of the axial plane account largely for the spread in the maximums of lineations in the northeast and southwest quadrants of the diagram in figure 8*D*. In the same way the plunge of the axis varies. On the whole the plunge is southwestward within the quadrangle, but locally it is northeastward; small reversals in plunge along the axis are characteristic and can be seen in section *E–E′* of plate 2 in the report on the Central City district by Sims and Gable (1964). The limbs dip 40° away from the crest on the average, but in detail they are corrugated by minor folds of several types. The principal minor folds are open, upright anticlines and synclines that have breadths that exceed heights. Many are nearly symmetrical; others are asymmetrical and have the normal relations of drag folds. Fold axes for the most part are nearly parallel to the axis of the Central City anticline. Locally, tight folds whose heights exceed breadths occur on the limbs, particularly near the crest. One such fold belt is marked by the zigzag pattern of the calc-silicate rocks on the northeast slope of Quartz Hill. Less commonly small recumbent folds whose axes are subparallel to the major fold axes occur. The folds that were observed during detailed mapping of the Central City district are at most a few feet across (breadth) and a few tens of feet from crest to crest. Without exception the axial planes of the recumbent folds are subparallel to the foliation planes of the overlying and underlying rocks.

Small-scale folds that trend nearly at right angles to the major fold axis are uncommonly abundant on the flanks of the Central City anticline. They are small undulations that do not modify the structural framework at the scale of plate 1 but warp or crinkle the foliation planes and the *B* lineation. Rarely, in biotite-rich rocks, these folds are accompanied by a subparallel mineral alinement (*A*). The folds differ in form within rocks of different lithology. Within the relatively competent microcline gneiss, they are typically open, low-amplitude warps and irregular undulations that range in breadth from a few inches to at least several tens of feet. They are commonly nearly symmetrical but at places are strongly asymmetrical; the axes are poorly defined and discontinuous and generally are arranged en echelon. At places pegmatite streaks and boudins or incipient boudinage are subparallel to the fold axes. The folds within relatively incompetent biotite gneiss, however, are more sharply contorted and commonly are more strongly asymmetrical. They range in breadth from tiny crinkles to folds several feet across; commonly their heights are nearly as great or are greater than their breadths. The crinkles are mostly of chevron type and are most common in biotite-rich layers. They bend the biotite flakes and sillimanite needles; rarely the biotite flakes are broken at the crest of the chevrons. The axial planes of the crinkles and of other small-scale folds typically converge upward toward the axes of larger anticlines trending in the *A* direction.

IDAHO SPRINGS ANTICLINE

The Idaho Springs anticline, in the southeast corner of the quadrangle, is strongly asymmetrical and has a steep northwest limb and a gentle southeast limb. Its axial plane dips steeply southeastward as noted in section *D–D′*, plate 1. The axis plunges 25°–50° NE., which is steeper than the plunge of the axes of most other folds in the quadrangle. The fold has been traced with certainty southwestward from the quadrangle for a distance of about 2 miles and, judged from the regional map of Lovering and Goddard (1950, pl. 2), extends still farther south; probably the bulbous, northeastward-projecting mass of Boulder Creek Granite mapped by Lovering and Goddard (1950) along Barbour Fork is on the axis of this anticline. Details of the fold, including the superposed folds imposed by the younger deformation within the Idaho Springs-Ralston shear zone, are described by Moench (1964).

LAWSON SYNCLINE

The Lawson syncline, the dominant fold in the western part of the quadrangle, is a complex, broad, open, upright structure outlined by the Lawson layer of microcline gneiss and adjacent units of biotite gneiss (pl. 1). It has been traced along its axis with certainty for about 5 miles, from south of Clear Creek northeastward to the thick lens of microcline gneiss east of Yankee Hill (pl. 1). The axial plane dips nearly vertically; the trace of the axial plane trends N. 15°–20° E. and is moderately straight. The axis plunges northeastward at a moderate angle, except for local small reversals. Judged from measurement of minor folds and related lineations at and near the major fold axis, the axis plunges on the average about 25° NE. (fig. 8*A*). The limbs dip gently inward toward the axis. According to our interpretation of the lithologic succession, the east limb, marked by microcline gneiss, extends irregularly northward into the adjacent Nederland quadrangle. The west limb lies outside the quadrangle in the Empire quadrangle; W. A. Braddock (written commun., 1963), who mapped this quadrangle, reported that the microcline gneiss on the west limb pinches out abruptly a short distance west of the boundary of the Central City quadrangle, possibly as a result of a stratigraphic pinchout.

Within the trough and on the east limb of the syncline, between Clear Creek and Fall River, the microcline gneiss and adjacent biotite gneiss are warped by a series of small, subparallel folds that plunge gently either about N. 70° E. or S. 70° W. The folds are accompanied by a mineral lineation and boudinage. A second lineation direction marked by small-scale folds and a mineral alinement plunges about N. 20° W. or S. 20° E., approximately at right angles to the other fold axes. Folds in the N. 20° W. direction locally contain elongate pods and larger phacolithlike bodies of biotite-muscovite quartz monzonite; at other localities these folds are crosscut by dikes of biotite-muscovite granite and were apparently formed prior to the emplacement of the intrusive rock.

The axis of the Lawson syncline can be traced from the Lawson layer of microcline gneiss northward into biotite gneiss but apparently terminates abruptly in the area of the small body of microcline gneiss on the ridge on the east flank of Yankee Hill (pl. 1). The reason for the abrupt termination is not known. From what can be seen at the sparse outcrops the fold axis is interpreted to pass into a slightly overturned fold in biotite gneiss which contains thin stringers of microcline gneiss, or it dies out in these beds. Equally uncertain is the reason for the layers of microcline gneiss which trend north-northwest on the north slope of Sheridan Hill. Although the layers conform to the foliated biotite gneiss, on a gross scale they appear to transect stratigraphic units within the biotite gneiss. The uncertainties in the structure of the Yankee Hill area are reflected by the very generalized form lines within biotite gneiss in section *B–B′* of plate 1.

INTERMEDIATE-SCALE FOLDS

Several folds of intermediate size, subparallel to the major folds, occur between the axes of the larger folds. These are described as follows in order of their succession from southeast to northwest.

PEWABIC MOUNTAIN SYNCLINE

The Pewabic Mountain syncline, a relatively small, virtually symmetrical flexure midway between the Idaho Springs and Central City anticlines, has been traced along its strike for about 5 miles. Throughout most of its length it is an open, upright syncline, which plunges gently in either direction. Southwestward, on the east flank of Bellevue Mountain, the fold tightens and locally is overturned to the southeast.

BALD MOUNTAIN SYNCLINE

The Bald Mountain syncline is a relatively narrow fold that is outlined in part at Bald Mountain by a folded sheet or phacolith of granodiorite. The axis of the syncline trends about N. 40° E. and plunges gently or moderately northeast on the average. Associated small folds and *B* lineations plunge variably either northeast or southwest (fig. 8*C*). Although the syncline is dominantly an open fold, tight folds plicate the limbs, as shown by the detailed map in the report on the Lawson-Fall River-Dumont district (Hawley and Moore, 1967).

DUMONT ANTICLINE

The Dumont anticline is a tight, upright fold in biotite gneiss about midway between the Quartz Hill and Lawson layers of microcline gneiss. It is inferred to extend from Clear Creek nearly to Missouri Creek, but because of widely scattered exposures and the absence of definitive stratigraphic markers in the biotite gneiss unit, its validity as a single fold is not certain. Observations of small-scale folds and related lineations indicate reversals in plunge along the length of the fold (fig. 8*C*). The crest of the fold is marked nearly everywhere by abundant, tight, nearly symmetrical folds of small size. As mapped, phacolithlike bodies of biotite-muscovite quartz monzonite occur locally along the fold axis.

SYNCLINE AT MOUNT PISGAH

The syncline at Mount Pisgah is relatively tight and contains a phacolithic body of granodiorite and associated rocks. The fold is well defined on Mount Pisgah but apparently dies out within a mile to the southwest; it can be traced only a short distance into the pluton. Judged from lineation measurements within the pluton and the biotite gneisses, the fold plunges about 30° NE.

PECKS FLAT ANTICLINE AND ADJACENT OVERTURNED FOLDS

Between the syncline at Mount Pisgah and the major Lawson syncline to the west are several small, tight, overturned folds that are spaced about 1,000 feet apart and that produce sharp plications in the Lawson layer of microcline gneiss and the underlying and overlying units of biotite gneiss. The folds are dominantly closed and slightly asymmetrical and are overturned to the west. Details of the folds are not well known; they occur in a structurally complex area, which is complicated by drastic thickening and thinning of the Lawson layer of microcline gneiss, the dominant stratigraphic marker of the area.

The Pecks Flat anticline, the easternmost of the folds, is a complex tight fold in Hamlin Gulch and becomes more open and upright northward along its axis. The axial plane dips steeply eastward, and its trace trends north. The axis plunges about 30° NE. on the average. At the head of Hamlin Gulch the granodiorite that constitutes the western part of the Mount Pisgah pluton is substantially thickened on the crest of the anticline and greatly thinned on the west, overturned limb.

About 1,000 feet west of the Pecks Flat anticline, an irregular, narrow tongue of microcline gneiss (Lawson layer) appears to mark the trace of a closed, overturned syncline, the limbs of which probably dip about 50°–60° SE. A parallel, overturned anticline is inferred to lie just west of the syncline; it bisects the narrow tongue of biotite gneiss that lies west of the microcline gneiss.

Two other folds, which are dominantly open and upright, have been mapped on the north side of Fall River, just west of the overturned folds (pl. 1). They appear to have relatively small amplitudes and to be of restricted length. The syncline on the east is open in the microcline gneiss but becomes closed southward along the fold axis in the biotite gneisses. This change in the character of the fold is a manifestation of disharmonic folding.

LINEAR ELEMENTS RELATED TO FOLDS

Linear elements that are subparallel to the major fold axes (*B*) are ubiquitous in the metamorphic rocks and are present locally in all intrusive rocks except the biotite-muscovite quartz monzonite. Less commonly lineations are oriented nearly at right angles (*A*) to major fold axes.

More than 90 percent of the visible lineations in the Precambrian rocks are subparallel to the major fold axes, or the (*B*) axis. These are mainly mineral alinements and the axes of small-scale folds but include boudinage. The lineations are represented by the strong maximums in the northeast quadrants of the lineation plots and by the weaker maximums in the southwest quadrants (*A*, *B*, *C*, and *D* of fig. 8). As the statistical plots indicate, the lineations in the *B* direction vary somewhat both in orientation and angle of plunge throughout the quadrangle. In the northwestern and western parts of the quadrangle (fig. 8*A*), the lineation "high" is rather sharply defined and symmetrical. The maximum is 28° N. 17° E.; a moderate spread in bearing from about N. 10° W. to N. 50° E. and a substantial variance in angle of plunge occur. In the northeastern part of the quadrangle (fig. 8*B*) the maximum is 12° N. 32° E. However, the bearing of the measurements varies in orientation about 90°, but the variance in the angle of plunge is less than in the western part of the mapped area (fig. 8*A*). The wide spread in the lineations is accounted for by fold axes that range in bearing from about north to east, as described in the Central City district report (Sims and Gable, 1964) for the area on the north side of North Clear Creek. Except for local areas near North Clear Creek and west of State Highway 119, it is doubtful that lineations related to the younger deformation can account for the east-northeast bulge in the northeast segment of the diagram (fig. 8*B*), for other than in these areas, superposed folds have not been recognized. Lineations in the east-central part of the quadrangle (fig. 8*C*) are comparable in bearing and angle of plunge to those in the northeastern part of the quadrangle but have less spread in orientation. Lineations in the Central City district, as indicated by the measurements plotted on figure 8*D* vary substantially in bearing; the mean value is 10° N. 27° E. The spread in orientation is mainly a reflection of a marked spread in the bearing of the major fold axes which can be seen on the geologic map of the Central City district (Sims and Gable, 1964, pl. 1); the 1- to 2-percent bulge at N. 60° E., however, mainly reflects lineations related to the younger deformation.

Lineations in the *A* direction, oriented nearly at right angles to the major fold axes, occur sporadically throughout the quadrangle but are statistically sufficiently abundant to be shown by the contour lines only on figures 8*B*, 8*C*, and 8*D*. Lineations in the *A* direction are mainly small folds but include rare mineral alinements, boudinage, and slickenside striae. In figure 8*D*, the maximums in the northwest quadrant reflect measurements made on the northwest limb of the Central City anticline, and the maximums in the southeast quadrant reflect measurements made on the southeast limb, for the plunge, of course, is controlled by the dip of the limbs.

IDAHO SPRINGS-RALSTON SHEAR ZONE

The Idaho Springs-Ralston shear zone, which impinges on the southeast corner of the quadrangle, is the largest of several Precambrian shear zones known in the Front Range (Tweto and Sims, 1963, p. 998–1000). It extends from a point a few miles south of the quadrangle northeastward to the mountain front, a distance of about 23 miles. To the northeast it disappears beneath the Fountain Formation of Pennsylvanian and Permian age; to the southwest it dies out, apparently in a large pluton of granodiorite of Boulder Creek affinity. The northwest boundary of the shear zone, which is southeast of the crest of Bellevue Mountain, marks the approximate limit of intense cataclastic deformation (pl. 1).

Within the quadrangle the shear zone is characterized by extreme cataclasis, minor folds and related linear elements, and weak local recrystallization. The relatively competent rock units, as microcline gneiss and granite gneiss and pegmatite, are nearly pervasively cataclastically deformed, whereas the less competent rock units, although sheared parallel to their foliation, are folded. The folds and cataclasis are superposed on the folds formed by the older, plastic deformation.

The folds within the shear zone trend about N. 55° E., subparallel to the zone itself, and plunge at various angles, depending upon the attitude of the older, larger folds. They range from about a foot in breadth to about 400 feet and consequently are too small to show at the scale of plate 1. The axial planes dip steeply southeastward and are remarkably straight and persistent. The folds tend to be sharp crested and are either simple or complex structural terraces or closed chevron folds; with few exceptions they are strongly asymmetrical and have steep, generally long northwest limbs and short, crumpled southeast limbs. The form depends largely on the geometry of superposition and to a lesser extent on the type of movements that produced the folds. The distribution and character of the folds are shown in the report on the Idaho Springs mining district (Moench, 1964), and the geometry of superposition is discussed in the report by Moench, Harrison, and Sims (1962, p. 49–55).

Cataclasis is nearly pervasive in the shear zone and takes several forms, each form depending on the intensity of shearing and the nature of the rock. The effects of shearing range from incipient granulation and mortar textures, visible only in thin sections, to flaser structures and, locally, to mylonite. In general the shearing was localized along preexisting foliation surfaces, especially in the biotite gneisses. Biotite tends to be smeared out and locally chloritized in such rocks, and quartz tends to be elongate or amoebiform. On the crests of minor folds the micas are bent and sillimanite needles are broken. In the more competent and homogeneous rocks the original foliation planes are transected in places and locally obliterated by shear planes which have produced a new foliation—a meshwork of subparallel, interconnecting fractures. In general these shear planes dip roughly parallel to the contact of the Big Five layer of microcline gneiss and the overlying biotite gneiss unit—about 35°–50° NW. Linear elements on the shear surfaces include slickenside striae, mineral streaking, and rodding, and all are oriented northwest, nearly at right angles to the associated fold axis.

SHEARING AND ASSOCIATED ALTERATION IN DAKOTA HILL AREA

Adjacent to the Tertiary intrusive porphyry at Apex, the Precambrian rocks are sheared as well as altered. Details of the shearing are obscure because of poor exposures, but the general character of the shearing is known from scattered surface exposures and from openings in the tunnel of the Nye-Mathews molybdenum prospect on the west flank of Dakota Hill. On the west slope of Dakota Hill the rocks are sheared and cataclasized for a distance of at least 2,000 feet from the porphyry contact; shearing is most intense within a few hundred feet of the contact and decreases westward. Adjacent to the contact the Precambrian rocks are profoundly altered as well as sheared and are cut by quartz veins that locally contain molybdenite. Some quartz veins near the contact and within the porphyry, which similarly is sheared, are as much as 8 inches thick, but most are less than an inch. On the crest and east slope of Dakota Hill shearing and veining is somewhat less intense except near the contact.

Megascopically, the sheared rocks are bleached to a grayish white and are locally veined by milky quartz. They have a well-developed gneissic structure and a distinctly granulated appearance, and thus individual rock types are difficult to distinguish separately. The predominant textural changes are a decrease in average grain size and a destruction of the common granoblastic texture by cataclasis and recrystallization. Quartz forms sutured, elongate aggregates of grains that have a marked linear fabric in a fine-grained matrix composed mainly of feldspars.

The close association of both shearing and alteration with the Tertiary stock suggest that both were produced by the emplacement and attendant thermal effects of the igneous body. However the stock may have been intruded into a previously deformed zone, for it occurs at the approximate junction of the northward-trending Apex fault and the northwestward-trending Blackhawk fault—faults believed to have originated during the Precambrian (Sims, Drake, and Tooker, 1963, p. 20–22). The shearing may, therefore, be partly of Precambrian age. Some of the deformation is of definite Tertiary age, however, for the stock itself is locally broken by a complex set of fractures, some of which contain quartz and molybdenite. Further studies of the Tertiary intrusive bodies are needed.

FAULTS

Faults that formed initially in the Precambrian, subsequent to the development of the Idaho Springs-Ralston shear zone, are widely spaced in the quadrangle. These are northwestward-trending faults, which belong to the group of faults known in the Front Range as breccia reefs (Lovering and Goddard, 1950), and faults trending north-northeast. Other faults, which are far more abundant and which contain most of the ore deposits, formed later during the Laramide orogeny; these form a meshlike pattern in the Central City district (Sims, Drake, and Tooker, 1963).

The northwestward-trending faults are characteristically long and persistent; some have been traced across the full width of the mineral belt and for many miles on either side. They are spaced 1–6 miles apart. Within the quadrangle the faults have a left-lateral displacement of as much as 600 feet; they commonly contain porphyry dikes of Laramide age along a part of their length. In detail the faults are complex sheared zones consisting of one or more subparallel major strands and intervening branching and interconnecting fractures. Most have a complex history of movement. The Idaho Springs and Blackhawk faults, the principal faults of this set in the quadrangle, show predominant strike-slip movement of several generations, probably Precambrian, and relatively late vertical and oblique movements of Laramide age. Local concentrations of base-metal sulfides in the faults are related to openings formed by recurrent movements in Laramide time (Sims, Drake, and Tooker, 1963; Sims, Armstrong, and others, 1963).

The faults trending north-northeast are likewise long and persistent but are more widely spaced than are the northwestward-trending faults. The only significant fault of this trend in the quadrangle is the Wild Wagoner-Apex fault, a conspicuous fracture zone that extends northward through the western part of the quadrangle. It is poorly exposed but appears to consist dominantly of a single, major strand and subordinate subparallel fractures. It is filled mainly by gouge and breccia but locally by siliceous breccia and quartz-sulfide veins. At places it contains porphyry dikes. Movement along the fault is right lateral; also the east wall is dropped relative to the west wall. The apparent displacement is determined mainly by the offset of the Tertiary bostonite porphyry dike in the Pecks Flat area (pl. 1).

Evidence of a Precambrian origin for both sets of faults is strong in the Front Range as a whole (Tweto and Sims, 1963) but is not definitive within the Central City quadrangle itself. Within the quadrangle the Idaho Springs fault equally displaces the young folds and the older features of the Idaho Springs-Ralston shear zone; this indicates that the displacement is younger than the cataclasis and the younger folding. The Precambrian age is inferred from the local presence of mylonite, a product of a relatively deep-seated environment, and of Precambrian aplite and pegmatite dikes along faults of similar attitude and habit in adjacent areas to the north (Lovering and Tweto, 1953, pl. 1) and east. Many of the faults disappear beneath the Paleozoic and sedimentary rocks at the mountain front, and even those that were rejuvenated in Laramide time apparently die out rapidly in the sedimentary rocks (Lovering and Goddard, 1950, pls. 1–2; Boos and Boos, 1957, figs. 3–10).

JOINTS

Joints were measured in the quadrangle to supplement the data compiled earlier by Harrison and Moench (1961) for the Central City-Idaho Springs area. The joints were plotted on Schmidt equal-area nets to show statistically their orientation. Figure 9*A* includes measurements from the northwestern and western parts of the quadrangle and covers the same area as figure 8*A*, a plot of lineations; figure 9*B* includes measurements from the northeastern part and covers the same area as figure 8*B*. Diagrams are not included for those parts of the quadrangle that were mapped previously at a more detailed scale; these are given in the earlier summary report by Harrison and Moench (1961). The joint diagrams were constructed according to the method described by Billings (1942, p. 119–121). In such diagrams each pronounced maximum represents the approximate attitude of the poles of many joints.

The most pronounced and abundant joint set in both the areas (*A* and *B* of fig. 9) strikes northwestward and dips steeply either to the northeast or to the southwest. That the maximum for this set is broad and irregular in both diagrams indicates a substantial spread in both strike and dip. In the northwestern part of the quadrangle (fig. 9*A*), the joint set has an average strike of N. 50°–65° W., and dips 85° NE. to 87° SW.; in the northeastern part it has an average strike of N. 45°–55° W. and dips 80° NE. to 85° SW.

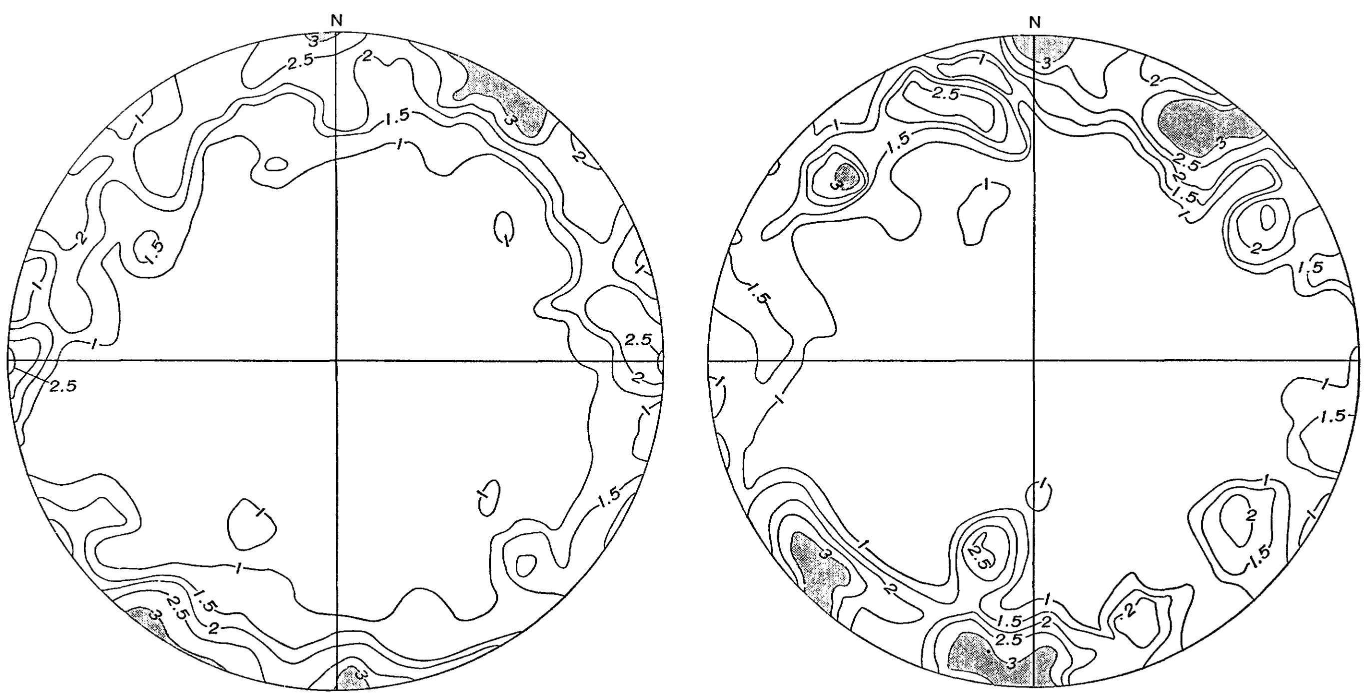
The second most abundant joint set trends roughly east and dips steeply either to the north or the south. The concentration of poles in figure 9*A* indicates an average attitude of N. 85°–90° E., vertical; similarly, the average attitude in figure 9*B* is N. 85°–90° W., 85° S. to 85° N.

Other less conspicuous joint sets, judged from the contour diagrams, are not equally developed in both parts of the region. A joint set that strikes N. to N. 5° W. and dips vertically is represented by the 2.5- to 3-percent concentration of poles at the east and west axes of the contour diagram for the northwestern part of the quadrangle (fig. 9*A*); the set is not evident in the northeastern part of the map area (fig. 9*B*). A joint set that has an average strike of N. 45° E. and dips 70° NW. is indicated by the 3-percent maximum in figure 9*B*; it probably is represented by the bulge in the 2-percent concentration of poles at the same location in figure 9*A*. A joint set that is conspicuous in the northeastern part of the quadrangle has an average strike of N. 70°–80° E. and dips 70°–80° NW. but apparently is not present in the northwestern part, unless it is represented by the westward bulge of the 2.5- to 3-percent contour at the top of figure 9*A*. If so, it probably overlaps the more conspicuous set striking N. 85°–90° E. and dipping vertically. Another joint set striking N. 32° W. and dipping 72° NE. is represented by the 2.5- to 3-percent "bulls eye" in figure 9*B*; this set is not evident in figure 9*A*.

The joint pattern in the Precambrian rocks of the region can be interpreted to have resulted mainly from stresses related to the major episode of Precambrian folding and to the uplift of the Front Range highland in the Laramide orogeny (Harrison and Moench, 1961). The prominent northwestward-trending joint set can be inferred to be a cross joint to the major folds. Comparison of figures 8*B* and 9*B* shows that the position of the joint set striking N. 45°–50° W. corresponds exactly to the theoretical position of a cross joint to the major folds; that is, the joint set is perpendicular to the average plunge of the fold axes as represented by the lineation "high" in figure 8*B*. The northwestward-trending joint set in the northwestern part of the quadrangle is not quite at right angles to the mean value for the plunge of the fold axes, as indicated in figure 8*A*; instead it is steeper and differs in strike by a few degrees. The rest of the joint sets represented by the concentrations of poles in the diagrams can be related to the regional joint system distinguished by Harrison and Moench (1961, p. B12–B14). The north-south joint set in the northwestern part of the map area (fig. 9*A*) has approximately the relationship of a regional longitudinal joint; the set striking N. 70°–80° E. in the northeastern part (fig. 9*B*) perhaps represents a regional cross joint, and the set striking N. 45° E. represents a regional diagonal joint. Although these interpretations may be speculative, they are consistent with the earlier conclusion of Harrison and Moench (1961), which was derived from a study of the joint data in the southern part of the quadrangle and adjacent areas to the south. Their conclusion was that the regional joint system was formed during the uplift of the Front Range highland.

CHARACTER AND ENVIRONMENT OF DEFORMATION

The gneissic structure, granoblastic texture, and folds and related lineations can all be related to the episode of plastic deformation that affected the central part of



A. WESTERN AND NORTHWESTERN PARTS; 522 POLES

B. NORTHEASTERN PART; 386 POLES

FIGURE 9.—Contour diagrams of poles to joints in the Central City quadrangle. Upper hemisphere plots, contoured in percent.

the Front Range. Deformation occurred in an environment in which metamorphic temperatures overlapped the magmatic range. The Idaho Springs-Ralston shear zone, which resulted from a younger deformation, formed in a less intense pressure-temperature environment. In contrast to the earlier pervasive deformation, this deformation was local in extent and resulted from shearing along a linear zone subparallel to the Colorado mineral belt (Tweto and Sims, 1963).

The parallelism of foliation with original bedding, evident in nearly every outcrop in the region, is characteristic of high-grade metamorphic rocks in all parts of the world. The parallelism cannot be accounted for by an hypothesis of load metamorphism, for the fabric resulting from such metamorphism should show axial symmetry about the axis of loading, whereas the observed fabric shows symmetry about the axes of folding. The origin of the fabric, therefore, must be directly connected with the regional stresses that produced the folding. To account for the foliation and lineation we suggest that initially compacted rocks, buried under a substantial thickness of cover, recrystallized under high temperatures and pressures along slip planes that followed original bedding. Both foliation and lineation were formed by penetrative movement along the planes, probably involving both external rotation and microfolding about the *B* lineation direction. Microfolding was a significant mechanism only in the relatively incompetent biotite gneisses. Studies of the space-lattice orientation of mineral grains were not made specifically to determine the mechanism of deformation, but petrofabric diagrams of quartz and xenotime from unoriented samples made for other purposes (Young and Sims, 1961, p. 292–293) indicate maximums in the foliation plane. This suggests that movement was in the plane of the foliation. The relatively uniform character of foliation and lineation in all the metamorphic rocks of the region, regardless of the intensity of the associated folds, shows that movements along the slip planes need not be large to produce strong foliation. The relative abundances of platy and tabular minerals are more significant than the intensity of folding in determining whether a specific rock is weakly or strongly foliated.

The axial-plane flow cleavage noted locally in the area formed only in incompetent rocks. At the previously described locality at the mouth of Silver Creek, in the eastern part of the Central City district (Sims and Gable, 1964), well-oriented sillimanite and mica, in particular, formed in shear planes that were parallel to axial planes of small folds in biotite gneiss. These shears do not cut the more massive rock layers. Evidently the compression that produced the folds in these incompetent rocks also produced parallel shear planes that were perpendicular to the greatest stress axis and an extension parallel to the least stress axis. In more competent, intercalated rocks it produced concentric shears and slippage along bedding planes.

The folding was accomplished largely by flexure slip. The thick layers of relatively competent microcline gneisses, which were separated by relatively incompetent biotite gneisses, favored the formation of broad open folds. Tight and locally overturned folds of short wavelength formed mainly within the relatively incompetent biotite gneisses. Throughout the interval of folding the competent layers, especially the microcline gneiss layers, probably yielded dominantly by concentric folding. Elastic bending was accompanied by the formation of subparallel concentric shearplanes on the flanks and, to a lesser extent, on the crests. The less competent biotite gneisses in the succession also yielded by slip movements along concentric shear planes. In contrast to the competent microcline gneisses, however, the biotite gneisses were deformed partly by small-scale folding that produced drag folds, the attitudes of which reflect the direction of relative displacement of the overlying and underlying more competent layers. Transfer of material from the limbs to the crests in the incompetent layers was accomplished largely by this type of folding. Possibly to a certain degree it was accomplished also by solution and redeposition. In addition the potential open spaces in the crests of several folds of intermediate scale were filled by syntectonic intrusive rocks.

To a considerable degree the folding is disharmonic. Disharmonic folds of different types are visible on a small scale at scattered localities throughout the region and can confidently be inferred to exist on a larger scale. A small-scale example of a strongly disharmonic fold characterized by extreme attenuation of a relatively incompetent layer within amphibolite has been illustrated by Moench, Harrison, and Sims (1962, pl. 3, fig. 2). Larger scale folds of a similar type are manifested by the local belts of tight folds within broader areas of open folding, as shown, for example, by map patterns in the Central City district (Sims and Gable, 1964, pl. 1). Within the quadrangle pronounced disharmonic folds on a relatively small scale can be observed in the syncline along Fall River, just west of Hamlin Gulch. As the fold axis is traced southward from microcline gneiss into underlying biotite gneisses, the fold tightens and the axial area is characterized by abundant small chevron folds as much as a few feet in width. Insofar as known, the contact between the microcline gneiss and the biotite gneiss, which must be a detachment zone, is relatively smooth and even. Larger scale disharmonic folds of a similar type are suggested by the map patterns (pl. 1).

The northeastward-trending fabric of the Precambrian rocks has been interpreted to have resulted from a horizontal couple (Sims and Gable, 1964). Such a stress pattern can account for the bends in the fold axes and for the minor warps in the *A* direction as well as for the major fold pattern. Knowledge of the folds within a larger area is needed, however, to confidently interpret the stress pattern.

The Idaho Springs-Ralston shear zone is one of several northeastward-trending shear zones in the Front Range. The folding within the shear zone has many characteristics of slip or shear folds, as defined by Turner (1948, p. 165–174) and others but lacks an associated distinct fracture cleavage (Moench, Harrison, and Sims, 1962, p. 54). Associated cataclasis indicates deformation under less intense pressure-temperature conditions than for the older, plastic folding and metamorphism. The shearing is a manifestation of regional stresses that produced major shear zones which are approximately coextensive with the Colorado mineral belt. The shear zones are interpreted as a dominant controlling structure responsible for localizing the mineral belt (Tweto and Sims, 1963).

GEOLOGIC HISTORY

The natural history recorded by the rocks in the central part of the Front Range is moderately well known as the result of investigations carried on in recent years. Nevertheless many details are lacking, and knowledge particularly of events that preceded the major episode of Precambrian metamorphism and deformation is lacking. Accurate knowledge of the ages of deformation and attendant metamorphism as well as of the intrusive igneous rocks still is meager. Until reliable information secured by dating methods is available, correlation of events in this area with those in other parts of the Rocky Mountain region is not feasible.

The first event that was recognized in the area was deposition of the sediments that subsequently yielded the metamorphic rock succession. Thick units of interbedded graywacke and shale and of feldspathic sandstone were deposited repeatedly. An estimated 15,000 feet of sediments was formed, apparently without a major break in deposition, for major unconformities have not been recognized in the succession. Lesser bodies of carbonate(?) sediments and clean quartz sands were deposited within the major sedimentary deposits. Judged from the layered rocks now visible, the character of sedimentation did not change materially with time, for units of the two major rock types throughout the succession are similar both in composition and in structure. The nature and source of the sediments are conjectural. Inferrence can be drawn from their present compositions that the source materials were either felsic metamorphic rocks or felsic or intermediate intrusive rocks, but an older succession of this lithologic character has not been identified within the Front Range. Regardless of source it is probable by analogy with more recent sediments resembling wacke that the sediments were deposited in a eugeosynclinal environment. Possibly the area was transitional to a miogeosynclinal environment, for the rocks preserved in areas immediately to the east are more typical of those formed in a miogeosyncline (D. M. Sheridan, written commun., 1965).

Subsequent to deposition the sediments undoubtedly were buried under a substantial cover of younger strata, probably to depths in the range of 7 to 12 miles. As a consequence of the superincumbent load, the materials must have been largely dewatered. Original bedding probably was accentuated by the formation first of clay minerals, then of micas, and perhaps also by incipient growth of other platy or tabular minerals. No evidence has been found to indicate that the strata were deformed by other than mild load metamorphism during this interval; apparently at the onset of regional deformation the succession was subhorizontal and lacked any notable cleavage.

The episode of regional metamorphism and plastic deformation that impressed upon the rocks most of the features visible today took place at high temperatures and pressures in the catazone of the crust as defined by Buddington (1959). The foliation and lineation and the mineral phases characteristic of the sillimanite zone were accomplished relatively early in the deformation. Migmatites formed at or near the culmination of the thermal cycle, in the interval during which metamorphic temperatures overlapped the igneous range of temperatures. Presumably they formed from the relatively low melting components of the country rocks, which were mobilized in the deeper parts of the sequence and moved upward and outward as a fluid phase along the foliation of the biotite gneisses and, to a lesser extent, into the other metamorphic rocks.

During the episode of deformation the intrusive igneous rocks were emplaced. Granodiorite intruded early in the episode, probably near the thermal maximum, but after most or all of the migmatization. The granodiorite moved upward from depth, probably as a magma, and along foliation planes and into the crests and troughs of active folds. Intrusion apparently was largely passive; the magma entered potential open spaces in the apical areas of the folds without notable disruption of the walls. Continuing stresses after consolidation of the granodiorite produced a secondary foliation and lineation, subparallel to the primary flow structures, in the borders of the intrusive bodies. The smaller bodies, and probably also those emplaced relatively early in the intrusive interval, were completely recrystallized and folded. After the thermal maximum was reached, gabbroic magma was emplaced, also largely by a phacolithic mechanism. The rocks in a narrow halo around the larger Elk Creek pluton were progressively metamorphosed, but the latent heat in the smaller bodies was not sufficient to noticeably change the mineral compositions of their wallrocks. After cessation of the major deforming stresses, biotite-muscovite quartz monzonite was emplaced mainly along crosscutting structures or across the gneissic structure of the wallrocks to yield markedly crosscutting bodies, but to a small degree it was emplaced by a phacolithic mechanism. The quartz monzonite was emplaced sufficiently late in the deformation to escape crushing and recrystallization; it has a wholly primary flow texture and was probably the biotite-muscovite quartz monzonite crystallized from a magma.

Probably a period of relative quiescence during which the region was undergoing erosion preceded the next event that has been recognized—cataclastic deformation. The Idaho Springs-Ralston shear zone and scattered lesser shear zones were formed as a result of shearing along linear belts which were coincident with the present site of the Colorado mineral belt. Judged from the pervasive cataclasis and minor recrystallization, the deformation took place under much lower pressure-temperature conditions than did the earlier regional deformation, perhaps at a significantly lesser depth. Possibly the deformation caused the retrograde metamorphism evident in many parts of the region and even outside the shear zone. Later, but still in the Precambrian, faults trending northwest and northeast and related breccia reefs were formed.

The post-Precambrian history of the central part of the Front Range has been discussed by several geologists (Lovering and Goddard, 1950; Sims, Armstrong, and others, 1963; Sims, Drake, and Tooker, 1963; and Harrison and Moench, 1961) and except for the events of the Laramide orogeny need not be reiterated here. Uplift of the Front Range along an axis trending north-northwest began in Late Cretaceous time and continued, probably intermittently, into the Tertiary. In early Tertiary time several varieties of porphyritic igneous rocks (Lovering and Goddard, 1938; Wells, 1960) were emplaced as small plutons and dikes within and adjacent to the present mineral belt. In large part the porphyries were intruded, probably passively, into joints, faults, and other planes of structural weakness in the Precambrian country rocks, but in part the intrusions appear to have been accompanied by explosive activity to yield breccias. Near the close of the hypabyssal igneous activity, three main sets of faults that make a complex intersecting network formed within the mineral belt, and the older (Precambrian) faults were rejuvenated. Mineralization of these fissures yielded gold- and silver-bearing base-metal sulfide ores. These are described and discussed in the report by Sims, Drake, and Tooker (1963). Subsequent uplift, erosion, and weathering have altered the veins to shallow depths, and locally rich supergene ores and placers have resulted.

REFERENCES CITED

Aldrich, L. T., Wetherill, G. W., Davis, G. L., and Tilton, G. R., 1958, Radioactive ages of micas from granitic rocks by Rb-Sr and K-A methods: Am. Geophys. Union Trans., v. 39, no. 6, p. 1124–1134.

Ball, S. H., 1906, Pre-Cambrian rocks of the Georgetown quadrangle, Colorado: Am. Jour. Sci., 4th ser., v. 21, p. 371–389.

Barth, T. F. W., 1959, Principles of classification and norm calculations of metamorphic rocks: Jour. Geology, v. 67, no. 2, p. 135–152.

———1962, A final proposal for calculating the mesonorm of metamorphic rocks: Jour. Geology, v. 70, p. 497–498.

Bastin, E. S., and Hill, J. H., 1917, Economic geology of Gilpin County and adjacent parts of Clear Creek and Boulder Counties, Colorado: U.S. Geol. Survey Prof. Paper 94, 379 p.

Billings, M. P., 1942, Structural geology: New York, Prentice-Hall, Inc., 473 p.

Boos, C. M., and Boos, M. F., 1957, Tectonics of eastern flank and foothills of Front Range, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 12, p. 2603–2676.

Boos, M. F., and Boos, C. M., 1934, Granites of the Front Range—the Longs Peak-St. Vrain batholith: Geol. Soc. America Bull., v. 45, no. 2, p. 303–332.

Bowen, N. L., and Tuttle, O. F., 1950, The system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O: Jour. Geology, v. 58, no. 5, p. 489–511.

Buddington, A. F., 1959, Granite emplacement with special reference to North America: Geol. Soc. America Bull., v. 70, no. 6, p. 671–747.

———1963, Isograds and the role of H_2O in metamorphic facies of orthogneisses of the northwest Adirondack area, New York: Geol. Soc. America Bull., v. 74, no. 9, p. 1155–1182.

Chayes, F. A., 1949, A simple point counter for thin-section analysis: Am. Mineralogist, v. 34, nos. 1–2, p 1–11.

Cloos, Ernst, 1946, Lineation, a critical review and annotated bibliography: Geol. Soc. America Mem. 18, 122 p.

Engel, A. E. J., and Engel, C. G., 1962, Progressive metamorphism of amphibolite, northwest Adirondack Mountains, New York, *in* Engel, A. E. J., James, H. L., and Leonard, B. F., eds. of Buddington volume, Petrologic studies: New York, Geol. Soc. America, p. 37–82.

Fairbairn, H. W., 1949, Structural petrology of deformed rocks [2d ed.]: Cambridge, Addison-Wesley Press, 344 p.

Folinsbee, R. E., 1940, Gem cordierite from the Great Slave Lake area, N.W.T., Canada [abs.]: Am. Mineralogists, v. 25, p. 216.

———1941, The chemical composition of garnet associated with cordierite: Am. Mineralogist, v. 26, no. 1, p. 50–53.

Fyfe, W. S , Turner, F. J , and Verhoogen, Jean, 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. America Mem. 73, 259 p.

Guidotti, C. V., 1963, Metamorphism of the pelitic schists in the Bryant Pond quadrangle, Maine: Am. Mineralogist, v. 48, p. 772–791.

Harrison, J. E., and Moench, R. H., 1961, Joints in Precambrian rocks, Central City-Idaho Springs area, Colorado, *in* Shorter contributions to general geology: U.S. Geol. Survey Prof. Paper 374–B, p. B1–B14.

Harrison, J. E., and Wells, J. D., 1956, Geology and ore deposits of the Freeland-Lamartine district, Clear Creek County, Colorado: U.S. Geol. Survey Bull. 1032–B, p. 33–127.

——— 1959, Geology and ore deposits of the Chicago Creek area, Clear Creek County, Colorado: U.S. Geol. Survey Prof. Paper 319, 92 p.

Hart, S. R., 1964, The petrology and isotopic-mineral age relations of a contact zone in the Front Range, Colorado: Jour. Geology, v. 72, no. 5, p. 493–525.

Hawley, C. C., and Moore, F. B., 1967, Geology and ore deposits of the Lawson-Dumont-Fall River district, Clear Creek County, Colorado: U.S. Geol. Survey Bull. 1231 (in press).

Leonard, B. F., and Buddington, A. F., 1964, Ore deposits of the St. Lawrence County magnetite district, northwest Adirondacks, New York: U.S. Geol. Survey Prof. Paper 377, 259 p.

Lovering, T. S., and Goddard, E. N., 1938, Laramide igneous sequence and differentiation in the Front Range, Colorado: Geol. Soc. America Bull., v. 49, no. 1, p. 35–68.

——— 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geol. Survey Prof. Paper 223, 319 p. [1951].

Lovering, T. S., and Tweto, Ogden, 1953, Geology and ore deposits of the Boulder County tungsten district, Colorado: U.S. Geol. Survey Prof. Paper 245, 199 p.

Mackenzie, W. S., 1954, The orthoclase-microline inversion: Mineralog. Mag., v. 30, no. 225, p. 354–366.

Moench, R. H., 1964, Geology of Precambrian rocks, Idaho Springs district, Colorado: U.S. Geol. Survey Bull. 1182–A. p. A1–A70.

Moench, R. H., and Drake, A. A., Jr., 1966, Economic geology of the Idaho Springs district, Clear Creek County, Colorado: U.S. Geol. Survey Bull. 1208, 91 p.

Moench, R. H., Harrison, J. E., and Sims, P. K., 1962, Precambrian folding in the Idaho Springs-Central City area, Front Range, Colorado: Geol. Soc. America Bull., v. 73, no.1, p. 35–58.

Prider, R. T., 1940, Cordierite-anthophyllite rocks associated with spinel-hypersthenites from Toodyay, Western Australia: Geol. Mag. [Great Britain], v. 77, no. 5, p. 364–382.

Reed, J. J., 1957, Petrology of the lower Mesozoic rocks of the Wellington district [New Zealand]: New Zealand Geol. Survey Bull. 57, new ser., 60 p.

Schreyer, W. F., and Yoder, H. S., Jr., 1961, Petrographic guides to the experimental petrology of cordierite: Carnegie Inst. Washington Year Book 1960–61, p. 147–152.

Sims, P. K., 1964, Geology of the Central City quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ–267.

Sims, P. K., Armstrong, F. C., Drake, A. A., Jr., Harrison, J. E., Hawley, C. C., Moench, R. H., Moore, F. B., Tooker, E. W., and Wells, J. D., 1963, Geology of uranium and associated ore deposits, central part of the Front Range mineral belt, Colorado: U. S. Geol. Survey Prof. Paper 371, 119 p.

Sims, P. K., Drake, A. A., Jr., and Tooker, E. W., 1963, Economic geology of the Central City district, Gilpin County, Colorado: U.S. Geol. Survey Prof. Paper 359, 231 p.

Sims, P. K., and Gable, D. J., 1963, Cordierite-bearing mineral assemblages in Precambrian rocks, Central City quadrangle, Colorado, *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–B, p. B35–B37.

——— 1964, Geology of Precambrian rocks, Central City district, Colorado: U.S. Geol. Survey Prof. Paper 474–C, p. C1–C52 [1965].

Sims, P. K., and Sheridan, D. M., 1964, Geology of uranium deposits in the Front Range, Colorado: U.S. Geol. Survey Bull. 1159, 116 p.

Taylor, R. B., and Sims, P. K., 1962, Precambrian gabbro in the central Front Range, Colorado, *in* Short papers in geology, hydrology, and topography: U.S. Geol. Survey Prof. Paper 450–D, p. D118–D122.

Tilley, C. E., 1937, Anthophyllite-cordierite-granulites of the Lizard [Cornwall, England]: Geol. Mag. [Great Britain], v. 74, no. 7, p. 300–309.

Turner, F. J., 1948, Mineralogical and structural evolution of the metamorphic rocks: Geol. Soc. America Mem. 30, 342 p.

Turner, F. J., and Verhoogen, John, 1960, Igneous and metamorphic petrology [2d ed.]: New York, McGraw-Hill Book Co., Inc., 694 p.

Tweto, Ogden, and Sims, P. K., 1963, Precambrian ancestry of the Colorado mineral belt: Geol. Soc. America Bull., v. 74, no. 8, p. 991–1014.

U.S. Geological Survey, 1964, Geological Survey Research 1964: U.S. Geol. Survey Prof. Paper 501–A, 367 p.

Vasileva, Z. V., 1958, On the role of manganese in apatites: Akad. Nauk SSSR, Vses. Mineral. Obshch. Zapiski, v. 87, no. 4, p. 455–468.

Washington, H. S., 1922, Deccan traps and other plateau basalts: Geol. Soc. America Bull., v. 33, p. 765–804.

Wells, J. D., 1960, Petrography of radioactive Tertiary igneous rocks, Front Range mineral belt, Gilpin and Clear Creek Counties, Colorado: U.S. Geol. Survey Bull. 1032–E, p. 223–272.

Wells, J. D., Sheridan, D. M., and Albee, A. L., 1964, Relationship of Precambrian quartzite-schist sequence along Coal Creek to Idaho Springs Formation, Front Range, Colorado: U.S. Geol. Survey Prof. Paper 454–O, p. O1–O25.

Wilcox, R. E., and Poldervaart, Arie, 1958, Metadolerite dike swarm in the Bakersville-Roan Mountain area, North Carolina: Geol. Soc. America Bull., v. 69, p. 1323–1368.

Yoder, H. S., and Eugster, H. P., 1955, Synthetic and natural muscovites: Geochim. et Cosmochim. Acta, v. 8, nos. 5–6, p. 225–280.

Young, E. J., and Sims, P. K., 1961, Petrography and origin of xenotine and monazite concentrations, Central City district, Colorado: U.S. Geol. Survey Bull. 1032–F, 273–299.