Geology of Precambrian Rocks Central City District Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 474-C

Prepared partly on behalf of the U.S. Atomic Energy Commission

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

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GEOLOGY OF PRECAMBRIAN ROCKS, CENTRAL CITY DISTRICT, COLORADO

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

ABSTRACT

The Central City district, one of the major metal-mining areas in the Colorado mineral belt, is in the central part of the Front Range. It lies within a terrane of Precambrian rocks and is located at an intrusive center of early Tertiary (Laramide) porphyritic igneous rocks. The Precambrian rocks include a variety of metamorphic and igneous rocks that are representative of a large segment of the core of the Front Range.

The oldest Precambrian rocks in the district are interlayered gneisses that constitute part of a well-defined layered succession. The lowermost rock unit exposed in the district is microcline-quartz-plagioclase-biotite gneiss, which forms a layer about 3,000 feet thick. It is overlain by a biotite gneiss unit of comparable thickness. The biotite gneiss unit consists of two principal rock types: sillimanitic biotite-quartz gneiss and biotite-quartz-plagioclase gneiss, which are interlayered on different scales, and local lenses of garnetiferous biotite-quartz-plagioclase gneiss. All the biotite gneisses contain pegmatite, either as thin conformable stringers and layers, which constitute migmatite, or as larger discrete bodies. Associated with these major units are relatively small bodies of amphibolite, calc-silicate gneiss, and cordierite-amphibole gneiss. The amphibolite and the cordierite rocks are confined to the microcline-quartz-plagioclase-biotite gneiss unit.

The layered rocks are interpreted to be metamorphosed sedimentary rocks. The microcline-quartz-plagioclase biotite gneiss, which was considered by earlier investigators as a metamorphosed igneous rock, is interpreted to be a metamorphosed feldspathic sandstone that originally had a high Na_2O/K_2O ratio. The biotite gneisses—the Idaho Springs Formation of earlier investigators—are probably derived from an originally interbedded graywacke and shale or argillite succession. The biotite-quartz-plagioclase gneiss, which has an abnormally high Na_2O/K_2O ratio, may be metamorphosed graywacke; the sillimanite gneiss, which contains K_2O in excess of Na_2O, may be a metamorphosed shale. The close chemical similarity of the biotite gneisses with their presumed unmetamorphosed equivalents is interpreted to indicate that the mineral assemblages that were formed depended mainly upon the composition of the original sediments; probably little material was added or subtracted during metamorphism. The minor rock units are probably metamorphosed carbonate rocks of differing purity.

Three main types of Precambrian intrusive rocks—emplaced in the order (1) granodiorite and associated rocks, (2) quartz diorite and hornblendite, and (3) biotite-muscovite granite—cut the layered rocks of the district. The granodiorite occurs as subconcordant folded sheets and as phacoliths(?). Individual bodies range systematically in composition from quartz diorite to quartz monzonite but are dominantly granodiorite. The next younger intrusive, quartz diorite and hornblendite, forms small stubby lenses that also are subconcordant to the country rocks; hornblendite is the dominant phase in most of the bodies. The youngest Precambrian intrusive rock, biotite-muscovite granite, forms small irregular dikelike or slightly hook-shaped bodies that are discordant to the country rock. The granodiorite and probably also the quartz diorite and hornblendite are folded and partly or completely recrystallized. The biotite-muscovite granite, on the other hand, has a primary flow structure, yet it locally appears to form phacoliths.

The metamorphosed rocks contain mineral assemblages that accord in general with the upper range (sillimanite-almandine subfacies) of the almandine amphibolite facies.

The Precambrian rocks are folded along northeast-trending, nearly horizontal axes. The major fold is an upright, broad, gently arched anticline that bisects the district. Subparallel folds of lesser magnitude that are mainly open folds but include tight upright folds and recumbent folds occur on the limbs of the anticline. Locally, folds that trend nearly at right angles to the major folds are present, but these do not notably affect the structural and lithologic framework. Lineations that parallel the major fold axes and that are nearly normal to them are cogenetic with the folding.

The major folds, the minor folds that are normal to them, and the cogenetic lineations were formed during the older plastic deformation recognized in the central part of the Front Range. The mechanism of folding was almost entirely flexure slip; less resistant layers within the succession yielded in part by small-scale folding, resulting in drag folds.

The Precambrian intrusive rocks were emplaced during the deformation, and accordingly they can be classed as syntectonic. The older intrusive-rock units—granodiorite and quartz diorite and hornblende—were emplaced early during the period of tectonism and were deformed, whereas the younger biotite-muscovite granite was emplaced in the waning stages and escaped crushing and recrystallization.

INTRODUCTION

As one part of a comprehensive study of the Central City district, Colorado, the Precambrian bedrock was mapped in detail. The purpose of the detailed mapping was to determine the relation of these rocks to the younger (Laramide) ores and to obtain background information essential to projected studies in other parts of the Front Range. The reports on the economic phases of the study have been published (Sims, Drake, and Tooker, 1963; Sims and others, 1963). The present report describes the lithologic succession, petrography, chemical composition, and structure of the Precambrian rocks. It should prove useful in planning any future deep mining exploration in the district and will contribute to a better understanding of the geology of the central part of the range.

The Central City district is in south Gilpin County, in the central part of the Front Range (fig. 1). It lies

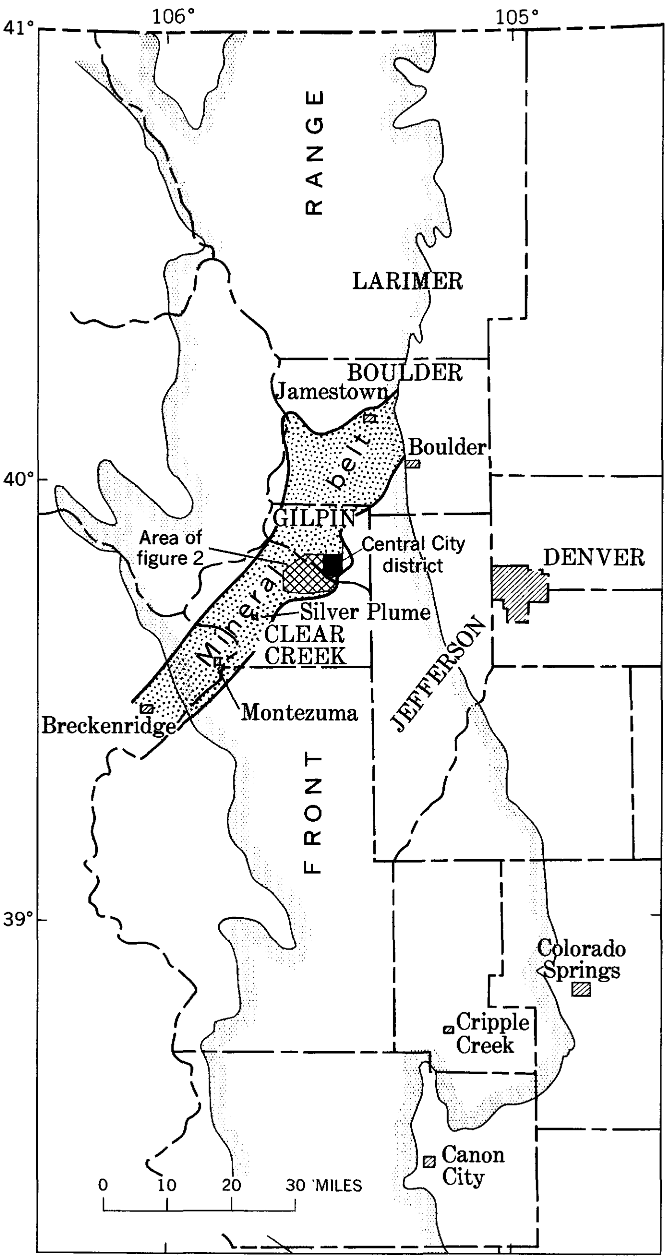


FIGURE 1.—Map of the Front Range, Colo., showing the location of the Central City district.

within the Colorado mineral belt, about midway between Jamestown on the northeast and Breckenridge on the southwest. The district, as defined by the U.S. Geological Survey, constitutes an area of about 12 square miles in the east-central part of the Central City 7½-minute quadrangle and the extreme west-central part of the Black Hawk 7½-minute quadrangle. It is about 12 miles east of the crest of the range, in a region characterized by a relatively gentle slope to the east and by many dissected upland surfaces. Altitudes range from 8,000 feet in the eastern part to about 9,600 feet on upland surfaces in the western part of the district; in the valley of North Clear Creek, the principal stream in the area, local relief is moderate. The bedrock is generally well exposed except on wooded north-facing slopes, on local upland surfaces having low relief, and in the southeastern part of the district.

This report is concerned primarily with description and interpretation of the Precambrian rocks, but the metalliferous veins, Tertiary intrusive rocks, and alluvium-colluvium deposits are shown on the geologic map (pl. 1) in order to make the map as complete as possible. For information concerning details of the Tertiary rocks and the veins, as well as locations and descriptions of the mines, the reader is referred to previously published reports (Sims, Drake, and Tooker, 1963; Wells, 1960; Sims and others, 1963).

PREVIOUS GEOLOGIC STUDIES

Many geologic studies, both local and regional, describe the Central City district and adjacent mining districts, but as might be expected because of the past economic importance of the region, most of these studies have emphasized the economic geology or some particular phase of the ore deposits. The studies dealing largely with the economic geology have been listed in a previous paper (Sims, Drake, and Tooker, 1963). The most authoritative studies that have dealt with the country rocks as well as with the ore deposits are those by Bastin and Hill (1917) and, more recently, Lovering and Goddard (1950). These investigations, published as Professional Papers by the U.S. Geological Survey, describe the gross features of the Precambrian rocks of the region and have provided an excellent framework for our more detailed investigations.

PRESENT INVESTIGATION AND ACKNOWLEDGMENTS

The fieldwork on which this report is based was done in the summers of 1952–55 as part of the U.S. Geological Survey's geologic investigations of the mining districts in the central part of the Front Range mineral belt on behalf of the Raw Materials Division of the U.S. Atomic Energy Commission. The mapping was done on a special topographic base (scale of 1:6,000 and a contour interval of 20 feet) prepared by the Topographic Division of the Geological Survey from aerial photographs taken in 1951. The mapping was done by P. K. Sims, R. H. Moench, A. A. Drake, Jr., E. W. Tooker, and A. E. Dearth; the areas of responsibility are shown by the index map, which appears on the geologic map of the district (pl. 1).

Concurrently with this investigation, the adjacent mining districts were mapped as follows: The Idaho Springs district by R. H. Moench and A. A. Drake; the Lawson-Dumont-Fall River district, by C. C. Hawley and F. B. Moore (written commun., 1961); the Freeland-Lamartine district, by Harrison and Wells (1956); and the Chicago Creek area, by Harrison and Wells (1959). Upon completing the district studies, the data were integrated into two geologic reports: a synoptic description of the uranium and associated ore deposits by Sims and others (1963) and a paper on the structure of the Precambrian rocks by Moench, Harrison, and Sims (1962).

As the Precambrian rocks in the central part of the Front Range had not been studied other than qualitatively prior to our investigations, we undertook quantitative mineralogic studies and limited chemical investigations of the major rock units. Modal analyses were made of standard thin sections that were cut generally normal to the lineation. In general, 800–1,000 counts were made of each section, but where more detailed analyses were desired—for example, to calculate a chemical composition of the rock from the mode—2,000–3,000 counts were made of a section. Modes determined in this way were found to be adequate for computation of chemical compositions, as the rocks are generally moderately homogeneous and equigranular and have grain sizes of a millimeter or less. Counting was done with a point-count mechanical stage and cell counter (Chayes, 1949). Fewer counts were made for the modes of three rock types: cordierite-amphibole gneiss, calc-silicate gneiss and related rocks, and granodiorite and associated rocks. Accordingly, the modes of these rocks are indicated in the tables as approximate.

The rocks that contain poorly twinned feldspars were prepared, as suggested by Chayes (1952), by use of hydrofluoric acid as an etching agent and sodium cobaltinitrite as a stain. Some pegmatites that are distinctly coarser grained than the other rocks were stained and counted by a superposed transparent grid.

To determine chemical compositions of certain of the rock units, emphasis was placed on calculating the composition from the modes, a method shown to be highly satisfactory by Engel and Engel (1958). For control, the chemical compositions of some representative samples of the important rock types and of some major components having variable composition, such as potassium feldspar and biotite, were determined by appropriate wet-chemical, spectrochemical, and X-ray analysis. Compositions of plagioclase were determined mainly by optical constants. Densities were determined directly by use of a micropycnometer or were calculated from compositional data.

The laboratory studies were carried on jointly by us. R. H. Moench assisted in the early stages of the mineralogic studies and was particularly helpful in the studies of cordierite-amphibole gneiss, calc-silicate gneiss, and granodiorite and associated rocks. E. J. Young, of the Geological Survey, determined the compositions of several potassium feldspars and garnets.

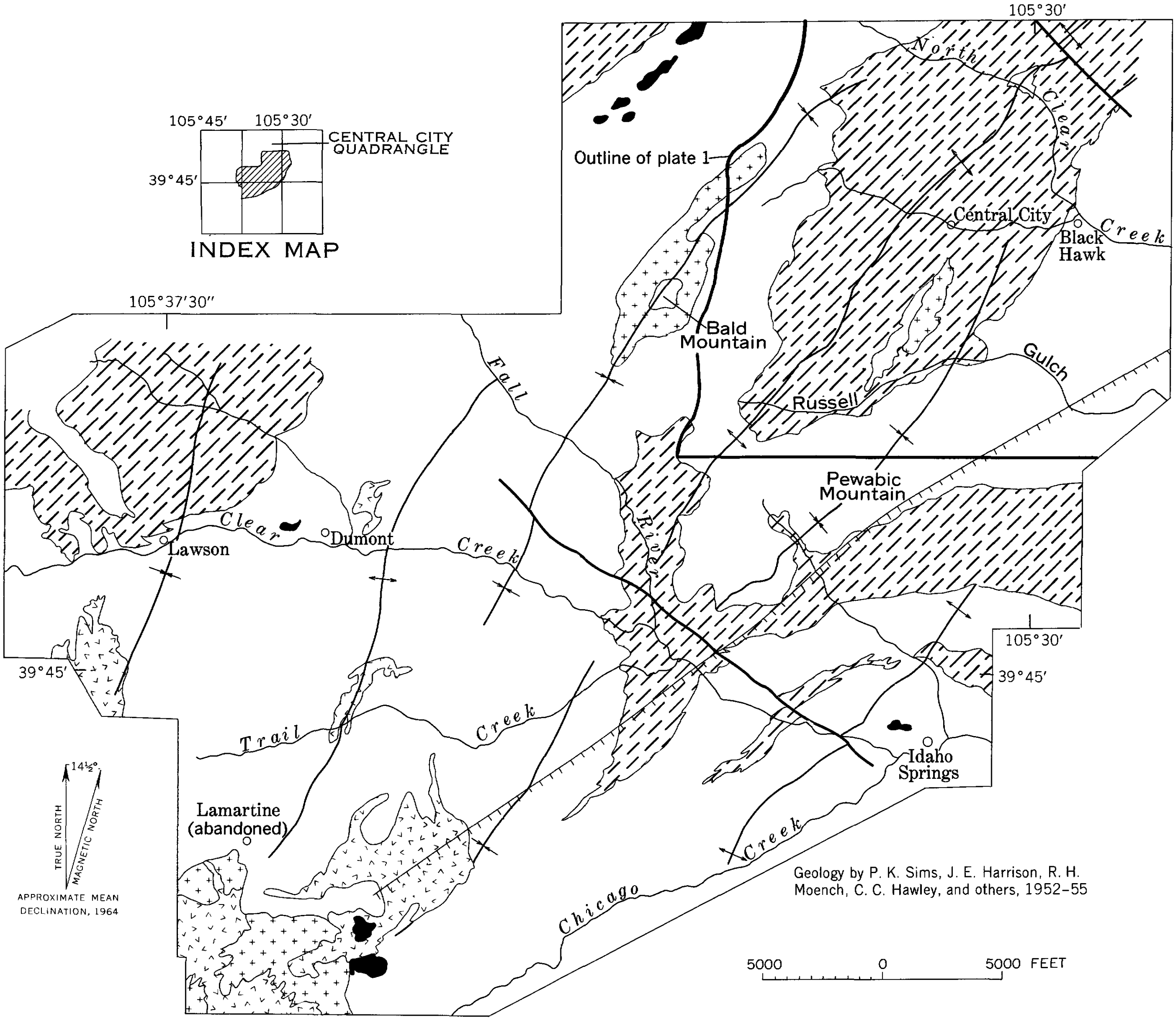
Thin sections and spectrochemical and chemical analyses were provided by many individuals in the Geological Survey. The individuals responsible for analyses are credited in the body of the report.

GEOLOGIC SETTING

The Front Range at the latitude of the Central City district consists of Precambrian rocks that are intruded by numerous small bodies of porphyritic igneous rocks of early Tertiary (Laramide) age. The Tertiary igneous rocks and associated ore deposits lie mainly within a narrow northeast-trending belt that constitutes the Front Range segment of the Colorado mineral belt. This belt contains all the important mining districts of the Front Range except Cripple Creek and a few uranium-bearing areas in Jefferson County (Sims and Sheridan, 1964).

The Precambrian rocks in the Central City district and immediate environs (fig. 2) are interlayered and generally conformable gneisses, migmatites, and intrusive igneous rocks, some of which are metamorphosed. The gneisses are high-grade metamorphic rocks that have been thoroughly recrystallized and reconstituted and, except for lithologic layering, have no recognizable primary structures and textures.

The oldest rocks in the area are a layered succession consisting mainly of migmatized biotite gneiss units and microcline-quartz-plagioclase-biotite gneiss (microcline gneiss) units. Associated with these rocks are relatively small bodies of amphibolite, calc-silicate gneiss and related skarn, cordierite-amphibole gneiss, quartz-spessartite-magnetite gneiss, and quartz gneiss. The biotite gneiss and the microcline gneiss are interlayered on a gross scale; the units of each of the rock types are repeated in the succession, as is shown in table 1 and on figure 3. The succession probably represents a normal stratigraphic order, for the recognized



EXPLANATION

Biotite-muscovite granite

Quartz diorite and associated hornblendite

Granodiorite

Microcline-quartz-plagioclase-biotite gneiss

Migmatitic biotite gneisses

Contact

Fault

Anticline

Syncline

Approximate northwest boundary intense cataclasis and younger folds

FIGURE 2.—Generalized geologic map of Precambrian rocks, central part of the Front Range mineral belt, Colorado.

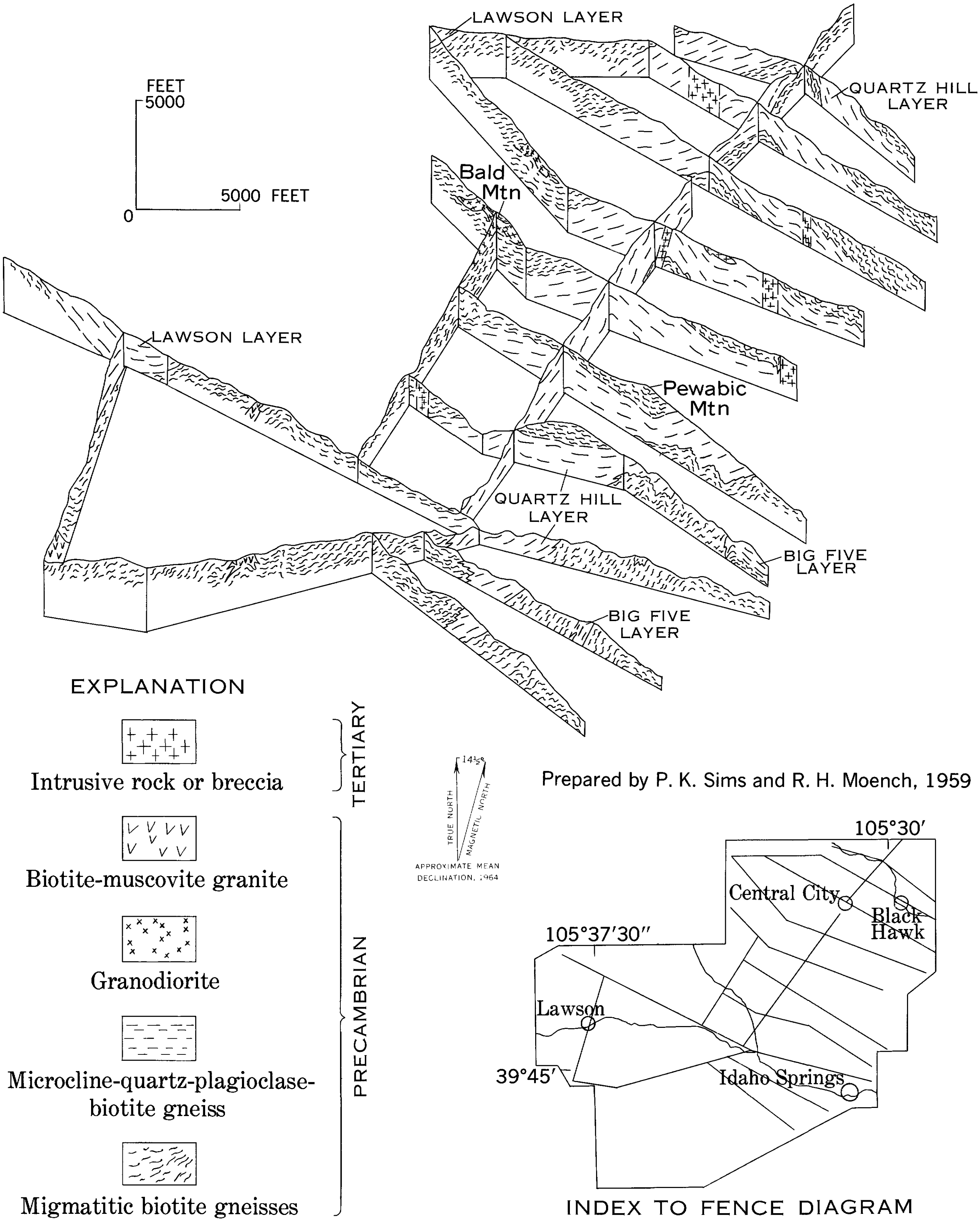


FIGURE 3.—Fence diagram showing structure of Precambrian rocks, central part of the Front Range mineral belt, Colorado.

rock units have a consistent vertical position throughout the area that has been mapped (Moench, Harrison, and Sims, 1962). We estimate that the layered strata exposed in the area have a maximum total thickness of 13,500 feet.

TABLE 1.—*Lithologic succession of Precambrian layered rocks, central part of Front Range mineral belt, Colorado*

[Based on Moench, Harrison, and Sims, 1962, table 1. Rock units are listed from youngest to oldest in the probable normal stratigraphic sequence]

Rock units	*Estimated maximum thickness (feet)*
Microcline gneiss (Lawson layer). Microcline-quartz-plagioclase-biotite gneiss; has average composition of quartz monzonite; contains several bodies of amphibolite	>2,500
Biotite gneiss. Consists of interlayered biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss; contains small bodies of garnetiferous biotite gneiss, quartz gneiss, and calc-silicate gneiss; migmatite, contains abundant granite gneiss and pegmatite in southern part of region	4,000
Microcline gneiss (Quartz Hill layer).[1] Microcline-quartz-plagioclase-biotite gneiss; has average composition of quartz monzonite; contains several thin layers and lenses of biotite gneiss, amphibolite, and calc-silicate gneiss and related rocks	3,000
Biotite gneiss. Similar in lithology to biotite gneiss unit described above. Unit probably pinches out to southwest	2,000
Microcline gneiss (Big Five layer).[2] Microcline-quartz, plagioclase-biotite gneiss; small bodies of amphibolite occur along margins; intercalated with granite gneiss and pegmatite	1,000
Biotite gneiss. Similar to biotite gneisses described above; south of Clear Creek, upper part of unit is largely replaced by granite gneiss and pegmatite	>1,000

[1] Central City layer of Moench, Harrison, and Sims.
[2] Idaho Springs layer of Moench, Harrison, and Sims.

Intruded into the layered rocks are—in order of their emplacement—granodiorite, quartz diorite and associated hornblendite, and biotite-muscovite granite.

The metamorphic rocks in the area are folded along northeast-trending axes and are also cataclastically deformed in the southeast part (fig. 2). The folding and cataclasis resulted from two distinct episodes of deformation: an older pervasive plastic deformation that took place under high confining pressures, and a younger deformation at shallower depths (Moench, Harrison, and Sims, 1962). Concurrently with the older deformation, the rocks were thoroughly recrystallized, the biotite gneisses—and to a lesser extent, other rocks—were migmatized, and the series of Precambrian intrusive rocks was emplaced. The older intrusive rocks of the series were deformed, in part at least, after crystallization; the youngest intrusive—biotite-muscovite granite—was emplaced sufficiently late in the period of deformation to escape recrystallization. All the intrusive rocks within the zone of cataclasis were locally granulated.

Folds formed during the earlier period of plastic deformation are outlined by the lithologic units and constitute the structural framework of the region (fig. 2). They are mainly broad open anticlines and synclines whose axes trend sinuously north-northeast and are spaced 1–2 miles apart. Without exception the axial planes are steep. In general, the fold axes are nearly horizontal or plunge at low angles, but to the south near the body of granodiorite exposed southwest of Idaho Springs (fig. 2), the axes plunge steeply to the northeast. Folds of similar trend but smaller magnitude are abundant on the limbs of the major folds. Many of these folds resemble the major folds because they are open and have gently dipping limbs; however, many others are upright to overturned closed folds, and a few are recumbent. Most folds, regardless of size, are disharmonic—that is, their configuration is not uniform throughout the stratigraphic column.

The younger deformation was largely confined to a zone about 2 miles wide that passes through the town of Idaho Springs (fig. 2). This zone has been called the Idaho Springs-Ralston shear zone (Tweto and Sims, 1963, p. 998). Within this zone, small folds formed in the relatively incompetent rocks—such as the biotite gneisses and migmatite—and the more competent rocks—such as the microcline gneiss and biotite-muscovite granite—were locally intensely granulated. The younger folds trend N. 55°–60° E. and are superposed on the older folds. Their form is controlled largely by their geometric relation to the preexisting rock attitude. Their axial planes are straight, and their asymmetry indicates that their northwest limbs moved upward relative to their southeast limbs. The largest known fold of this system has a wave length of about 400 feet.

Within the area (fig. 2) lineations in the Precambrian rocks can be related to the two fold systems, as is shown in table 2. The dominant lineations are nearly parallel to the axes of the major folds (B_o). Less abundant lineations are oriented nearly at right angles (A_o) to the major fold axes. In the zone of younger folding, lineations are both parallel to (B_y) and nearly at right angles to (A_y) the axes of the principal younger folds.

Both episodes of folding have been shown by regional relationships to be Precambrian in age (Tweto and Sims, 1963). Neither, however, has been dated as yet by absolute-age determination methods. Data on the age of a pegmatite at Central City, which is undeformed and cuts rocks folded during the plastic deformation, and of a granite that is equivalent to the biotite-muscovite granite of this report, however, indicate that the older deformation occurred not later than about 1,300 million years ago (table 3). The younger cataclastic deformation occurred necessarily less than 1,300 million years ago, at least in this area, for structures of this episode postdate emplacement of the biotite-muscovite granite. Studies that attempt to determine the absolute ages of the two deformations by different methods are now underway.

TABLE 2.—*Types, inferred genesis, and abundance of lineations related to the two fold systems*

[The bearings of the coordinates are averages; B_y and A_y, however, are remarkably consistent. The inferred genesis of each type of lineation is shown in parentheses]

	Lineation (genesis)	Abundance
	Older deformation	
B_o (N. 30° E.)	Folds (flexure)	Very abundant.
	Mineral alinements (recrystallization).	Do.
A_o (N. 60° W.)	Folds (flexure)	Common.
	Boudinage (tension)	Rare.
	Mineral alinements (recrystallization).	Do.
	Younger deformation	
B_y (N. 55° E.)	Folds (flexure)	Very abundant.
	Boudinage (tension)	Rare.
	Mineral alinements (recrystallization).	Do.
A_y (N. 25° W.)	Slickenside striae (stretching).	Very abundant.

TABLE 3.—*Absolute ages of rocks from the central part of the Front Range, Colo.*

Location	Rock	Mineral	Age (millions of years)		
			Pb-U Pb-Th	K-Ar	Rb-Sr
Silver Plume [1]	Biotite-muscovite granite.	Biotite		1,230	1,350
	do	Muscovite		1,210	1,360
Central City [2]	Pegmatite	Uraninite	1,300±100		

[1] Source: Aldrich and others (1958, p. 1130).
[2] Source: Phair and Gottfried (1958); George Phair (written commun., 1960).

ROCK UNITS

The Precambrian rocks exposed in the Central City district are dominantly microcline-quartz-plagioclase-biotite gneiss (microcline gneiss) and biotite gneiss (pl. 1). These rocks are associated with small lenses and layers of other types of metamorphic rocks and are intruded by a few small generally concordant bodies of granodiorite, quartz diorite and hornblendite, biotite-muscovite granite, and pegmatites of several types.

The gneisses form a layered sequence that probably formed from a former dominantly sedimentary sequence. They attained their present character through dynamothermal metamorphism and, locally, modification by the addition or subtraction of rock-forming materials.

The intrusive rocks are interpreted from their field relationships and compositions to have been emplaced mainly as magmas and attendant mobile phases. Emplacement of each distinct type of intrusive rock was contemporaneous with the dominant (plastic) episode of deformation, and accordingly they are classed as syntectonic intrusives.

TERMINOLOGY USED IN THIS REPORT

The terminology used in this report differs from that commonly found in earlier publications describing the Precambrian rocks of the Front Range. Accordingly, a review of the terminology and the reasons for adopting a different nomenclature are given in this section. It should be noted that a terminology similar to that used in this report has been used in reports on adjacent mining districts that were studied concurrently with the Central City district. (See Harrison and Wells, 1956, 1959.) Also, the problem of terminology as applied to rocks in the Front Range has been considered in a recent paper by Wahlstrom and Kim (1959, p. 1218–1219).

Heretofore, the Precambrian rocks of the Front Range have commonly been assigned to formations, mainly on the basis of gross similarities in lithology. The terminology that has been in common usage is summarized in the report by Lovering and Goddard (1950, p. 19–29). The principal formations of metamorphic rocks as distinguished in the Front Range are the Idaho Springs and the Swandyke, each of which shows approximately the same degree of metamorphism. The Idaho Springs Formation was originally defined by Ball (1906) to include the biotite gneisses and schists and closely associated rocks in the Idaho Springs region (Spurr, Garrey, and Ball, 1908), which he considered to be metamorphosed sediments. The Swandyke Hornblende Gneiss was named by Lovering (1935, p. 10) from the Montezuma quadrangle, on the west side of the Front Range, to include dominant hornblendic gneisses and schists and some interlayered quartz schists. Lovering (1935, p. 11) considered the rock to be a metamorphosed igneous rock intermediate between gabbro and diorite in composition and considered it to be younger than the Idaho Springs Formation. Later, Lovering and Goddard (1950, p. 20) interpreted the Swandyke Hornblende Gneiss as mainly the product of metamorphism of quartz diorite flows or sills interbedded with clastic sedimentary rocks and suggested that it was in part contemporaneous and in part younger than the upper part of the Idaho Springs Formation. In recent years, these two formations have commonly been extended to include all the biotite gneisses and all the hornblende gneisses, respectively, in the Front Range.

In the same way, the intrusive rocks in the Front Range have been classified on the basis of lithology and gross characteristics into three types: the Boulder Creek Granite and associated quartz monzonite, the Silver Plume Granite, and the Pikes Peak Granite. Internal structures of the intrusive bodies and contact relations have generally not been defined carefully because of a lack of detailed mapping. Other rock units that have been distinguished as informal cartographic units by Lovering and Goddard (1950) are quartz monzonite gneiss and gneissic pegmatite, granite gneiss and gneissic aplite, and quartz diorite and hornblendite. Each has been interpreted to be of igneous derivation.

The recent geologic mapping in the central part of the Front Range has shown that the Idaho Springs Formation and the Swandyke Hornblende Gneiss, as mapped by Lovering and Goddard (1950, pl. 2), are not time-stratigraphic units. Instead, they each consist of lithologic units that are repeated in the section but that can probably be mapped as individual stratigraphic units. In the same way, the granite gneiss of Bastin and Hill (1917) and the quartz monzonite gneiss of Lovering and Goddard (1950) in this area, which erroneously have been considered igneous in origin, have no time-stratigraphic significance. These rocks are interlayered repeatedly with biotite gneisses. (See fig. 3.) Further, confusion has resulted from erroneous correlations of individual masses of these granitic-appearing gneisses, as can be seen by comparing the map of Lovering and Goddard (1950, fig. 2) with figure 2 of this report.

The existing terminology for the major igneous rock types is less equivocal than that for the metamorphic rocks, but until further geologic mapping is done and many absolute age determinations become available, it seems advisable to use these terms with caution; however, the designation of a specific petrographic rock type could perhaps be made without implication as to probable stratigraphic equivalence among rock types. We know, however, that the biotite-muscovite granite of this area is equivalent to the Silver Plume Granite at the type section at Silver Plume, Colo., for the rock can be traced nearly continuously from the type area through the Lawson-Dumont-Fall River district (C. C. Hawley and F. B. Moore, written commun., 1961) into the Central City district. Correlation with the other two-mica granites in the Front Range and elsewhere in central Colorado, though, is at present problematical. Also, the granodiorite of this report almost certainly is equivalent to the intrusive granitic rocks in the Boulder Creek pluton, west of Boulder (Lovering and Goddard, 1950, pl. 2), for rocks from the two localities are similar both lithologically and structurally.

The need for discrimination of more precise cartographic units and, where possible, of time-equivalent units has led us to not use the existing terminology and to define the units in terms of lithology without formal designation. Later, upon completing geologic mapping in a much larger area, a new stratigraphic nomenclature can possibly be proposed, at least for many of the rock units in the Precambrian complex. The lithologic names used herein are assigned on the basis of quantitative mineral content and on the presence of diagnostic minerals. The rock units used in this report and the equivalent units distinguished, at least for cartographic purposes, by earlier investigators are listed in table 4.

TABLE 4.—*Correlation of rock units used in this report with those of previous investigators*

This report	Bastin and Hill (1917)	Lovering and Goddard (1950, pl. 2)
Biotite-muscovite granite	Not mapped	Silver Plume granite
Quartz diorite and associated hornblendite	Hornblende schist of Idaho Springs formation	Quartz diorite and hornblendite
Granodiorite and associated rocks	Biotite granite, probably a phase of Silver Plume granite; granite gneiss	Boulder Creek granite and quartz monzonite
Pegmatite	Granite pegmatite	Pegmatite
Biotite gneiss	Quartz-biotite schist of Idaho Springs formation	Idaho Springs formation
Amphibolite	Hornblende schist of Idaho Springs formation	Swandyke hornblende gneiss
Calc-silicate gneiss and related rocks; Cordierite-amphibole gneiss	Not mapped as separate units	Not mapped as separate unit; generally included in Idaho Springs formation
Microcline-quartz-plagioclase-biotite gneiss	Granite gneiss	Granite gneiss and gneissic aplite or quartz monzonite gneiss and gneissic pegmatite

METAMORPHOSED LAYERED ROCKS

Metamorphic rocks constitute more than 90 percent of the bedrock (pl. 1) and thus dominate the lithology of the district. Microcline gneiss, the principal rock type, is exposed in the core of the major anticline of the district; it crops out as a shieldlike northeast-trending body that tapers to the southwest. Biotite gneisses conformably overlie and, except to the north, flank the microcline gneiss; they contain a thin layer of microcline gneiss near the base. Amphibolite, cordierite-amphibole gneiss, and calc-silicate gneiss and related rocks occur as small bodies within the main mass of microcline gneiss, and calc-silicate gneiss occurs also in the larger body of biotite gneisses. All the biotite gneisses contain varying amounts of pegmatite, both as thin conformable wisps and streaks that form migmatite and as larger discrete mappable bodies. The microcline gneiss contains irregularly defined bodies of pegmatite.

A lithologic succession for the gross rock units at Central City can be established with confidence, because the pattern of folding is relatively simple and the rocks dip at low angles. The succession is based on the assumption that the exposed rocks are upright, a condition which seems certain from the regional structural and stratigraphic patterns (Moench, Harrison, and Sims, 1962). Further, the gross lithologic layering probably represents an originally bedded succession; on a large scale as well as on a small scale, layering in the rocks appears to represent relict bedding. Unquestionably, metamorphic differentiation cannot be demonstrated to operate on such a scale as to yield units several hundred feet or more thick.

In the sections that follow, we first discuss the stratigraphic relationships of the metamorphic rocks and then describe the various rock types. Insofar as possible the rocks are described in order of relative age, but it should be kept in mind that many of the rock types appear more than once in the stratigraphic succession.

LITHOLOGIC SUCCESSION OF LAYERED ROCKS

The gross succession of layered Precambrian rocks in the Central City district consists of a thick unit of microcline gneiss overlain and underlain by units of biotite gneiss (pl. 2). The position of these rock units relative to the sequence in the larger area mapped during related investigations can be seen by reference to figure 3 or to the more detailed sections published in an earlier paper (Moench, Harrison, and Sims, 1962).

The areally widespread microcline gneiss unit, designated informally as the Quartz Hill layer on figure 3, extends southward at the surface into the adjacent Idaho Springs district and thence for several miles to the east. The unit is probably about 3,000 feet thick in the Central City district; it pinches out to the southwest but probably thickens eastward from Idaho Springs.

The layer of biotite gneiss that overlies the Quartz Hill layer is equally widespread, extending to the west and east for a few miles. It has an estimated maximum thickness of 4,000 feet regionally, but only a few hundred feet of the lower part of the unit is exposed within the Central City district. The layer of biotite gneiss that lies stratigraphically below the Quartz Hill layer of microcline gneiss is not exposed within the Central City district but was intersected in the Argo tunnel (section *C–C′*, pl. 2, this report; Sims, Drake, and Tooker, 1963, fig. 20) at a vertical depth of about 1,500 feet below the surface. It probably lies immediately below the amphibolite lens mapped along the axis of the Central City anticline in the valley of North Clear Creek, as is shown in sections *A–A′* and *E–E′*, plate 2. This biotite gneiss layer is estimated from exposures just north of Idaho Springs (figs. 2 and 3) to be as much as 2,000 feet thick.

The microcline gneiss layer contains numerous lenses and layers of other metamorphic rocks, some of which appear to constitute local stratigraphic marker beds (pls. 1 and 2). Amphibolite is widely distributed through the Quartz Hill layer and is abundant at the upper and lower contacts. Within the layer, several amphibolite bodies and associated calc-silicate gneiss bodies can be traced almost continuously for distances of a few hundred to several hundred feet along the strike. Cordierite-amphibole gneiss bodies are sparse and apparently erratically distributed. Biotite gneiss, on the other hand, forms some persistent but thin layers that constitute excellent marker beds in the layer. A layer 200–250 feet thick that is 900–1,000 feet below the top of the microcline gneiss layer (sections *D–D′* and *E–E′*, pl. 2) underlies most of Quartz Hill and probably extends over an area of more than a square mile. It has been traced through the mine workings on Quartz Hill; it should intersect the surface on the north slope of the hill, as can be seen in section *E–E′*, plate 2, but it has not been identified there because of the cover of colluvium that obscures the bedrock. Another thin layer of biotite gneiss has been noted locally on Quartz Hill about 650 feet vertically below this layer (see section *D–D′*, pl. 2), and still others, apparently of much lesser areal extent, lie above it. These layers have been exposed at shallow depths in some of the mine workings in the Quartz Hill-Upper Russell Gulch area (Sims, Drake, and Tooker, 1963).

The biotite gneiss layer that lies above the microcline gneiss consists dominantly of sillimanitic biotite-quartz gneiss and biotite-quartz-plagioclase gneiss that are interlayered in beds a few inches to several tens of feet thick. This biotite gneiss layer contains lenticular layers of garnetiferous biotite-quartz-plagioclase gneiss and local lenses and pods of calc-silicate gneiss and cordierite-amphibole gneiss. The biotite gneisses are migmatitic and contain abundant discrete bodies of pegmatite, as is shown on plate 1. A layer of microcline-quartz-plagioclase-biotite gneiss, less than 100 feet thick, lies about 200 feet above the base of the biotite gneiss unit on Silver Hill (pl. 1). Local concentrations of xenotime and monazite occur at three localities in the biotite gneiss layer in the eastern part of the district

(Young and Sims, 1961); each occurrence is about 100 feet stratigraphically above the base of the layer.

The biotite gneiss layer that lies beneath the microcline gneiss unit is relatively unknown from studies in the district, but R. H. Moench's investigations in the adjacent Idaho Springs district indicate that it is similar lithologically to the upper layer. This layer is not discussed in the pages that follow.

MICROCLINE GNEISS

Microcline gneiss, technically microcline-quartz-plagioclase-biotite gneiss, is a granitic-appearing rock that was earlier called granite gneiss, both by previous investigators (table 4) and by Sims (Sims, Osterwald, and Tooker, 1955, p. 8). Sims (1956, p. 742, table 1) referred to it also as quartz monzonite gneiss.

GENERAL CHARACTER

The contacts between microcline gneiss and included bodies of biotite gneiss and amphibolite and also the overlying layer of biotite gneiss are conformable and typically gradational across a few inchs. The gradation between microcline gneiss and amphibolite is marked locally by the presence of hornblende dispersed through the gneiss immediately adjacent to and as much as a few inches away from the amphibolite. The gradation from microcline gneiss to biotite gneiss is marked dominantly by a decrease in microcline and an increase in biotite across a width of a few inches. In addition, the rock becomes noticeably finer grained near the biotite gneiss. Also, adjacent to garnetiferous varieties of biotite gneiss, the microcline gneiss contains a few scattered disseminated garnets, as is shown by the modes given in table 5.

The microcline gneiss is a very light gray to medium gray [1] generally medium grained equigranular layered rock. It weathers to yellowish gray, gray orange pink, very pale orange, or intermediate hues of these colors. Outcrops of the gneiss are typically smooth and form more or less rounded low knobs or rolling surfaces; where joints are numerous, the rock forms angular bold exposures. The rock has a well-defined foliation given by the segregation of the minerals into light and dark layers and by a subparallel arrangement of the tabular and platy minerals. Most phases have a conspicuous layering marked by regular paper-thin parallel streaks and wisps of biotite. Some phases, however, are poorly foliated because they contain irregularly dispersed, unoriented plates of biotite, and still others contain so little biotite that they appear massive. The perfection of the layering depends to a large extent upon the amount of biotite in the rock and the degree to which it is concentrated in layers.

[1] In this report, colors are determined from the National Research Council "Rock-Color Chart" of Goddard and others (1948).

PETROGRAPHY

The microcline-quartz-plagioclase-biotite gneiss is equigranular and has an allotriomorphic granular texture. The principal minerals vary in amounts and proportions, as shown in table 5 and on figure 4.

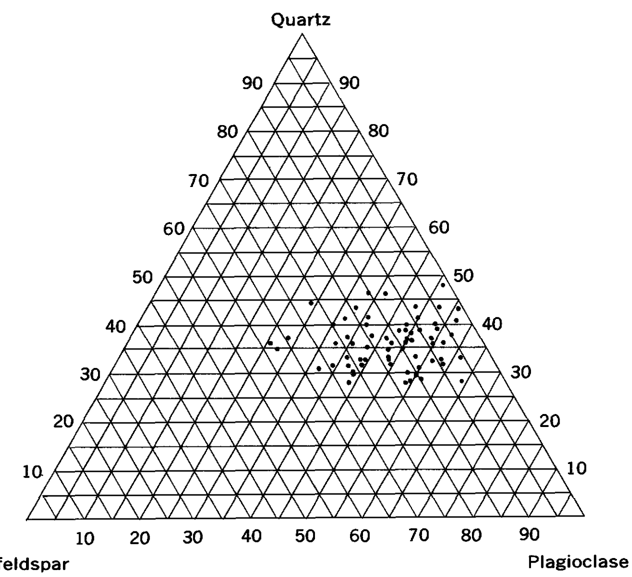


FIGURE 4.—Triangular diagram showing variations in composition, in volume percent, of microline gneiss. (Field of associated biotite-plagioclase gneiss is along QP boundary.) 66 plots.

Plagioclase (oligoclase), the most abundant mineral, forms anhedral or, rarely, subhedral grains as much as 3 or 4 mm in diameter that tend to be surrounded by the other dominant minerals. Characteristically, the plagioclase has simple albite twinning that is moderately well formed, but some grains have no visible twinning and others show a patchy twinning. Where in contact with microcline grains, narrow albitic rims or myrmekite are common. Except for the rims, most of the plagioclase crystals are clouded with alteration products, mainly clay minerals but locally sericite. In a few sections, small patches of microcline (patch antiperthite) were observed in the plagioclase grains.

Quartz occurs as anhedral grains that generally show strain shadows and as myrmekitic intergrowths with plagioclase and biotite. The larger quartz grains have two principal modes of occurrence: (a) subrounded grains in plagioclase or, less commonly, in other mineral grains, and (b) irregular anastamosing grains that embay plagioclase in particular or are largely interstitial to feldspar grains. Some quartz has visible fluid inclusions, and some contains fine hairlike rutile(?).

TABLE 5.—*Modes, in volume percent, of microcline-quartz-plagioclase-biotite gneiss from Quartz Hill layer*

[Tr., trace. Sample localities are listed at top of p. C12]

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Field No.	4-55	S436-53	S3-53	S270-53	S288A-53	4-56	462-B	S215-52	S667-52	S656-1-52	S301-A-53	S651-52	S392-53	S575-1-53	S484-53	S482-53
Microcline	6.2	29.0	12.5	8.1	8.7	22.9	26.6	15.8	22.2	23.4	17.8	25.9	11.6	18.5	6.2	34.0
Plagioclase	49.5	38.5	49.1	51.2	53.5	32.8	28.9	43.7	37.9	43.6	46.7	36.3	49.6	39.8	51.8	28.3
Quartz	32.1	31.0	30.9	34.9	29.1	37.6	44.1	35.2	34.1	31.1	32.0	35.0	37.7	38.8	37.4	36.8
Biotite	7.3	1.3	7.3	3.3	5.9	4.9	Tr.	3.2	4.8	Tr.	.9	1.9	Tr.	2.2	4.5	Tr.
Muscovite			.1	.3	1.4	.6	.2	.1	.5	.9	1.9	Tr.			.1	.5
Magnetite		.1	.1	2.0	1.3	1.0	.2	1.9	.4	1.0	.7	.9	1.1	.6	Tr.	.4
Hematite																
Zircon		.1	Tr.	Tr.	Tr.	.2		.1				Tr.		Tr.		
Sphene	.1			.2	.1	Tr.	Tr.		.1	Tr.			Tr.		Tr.	Tr.
Apatite	.1								Tr.			Tr.		Tr.		
Hornblende	4.7															
Epidote					Tr.	Tr.									Tr.	
Chlorite												Tr.				
Garnet										Tr.			Tr.			
Allanite														.1	Tr.	
Monazite(?)						Tr.										
Calcite																
Fluorite(?)																
Spinel(?)																
Composition of plagioclase			An_{18}		An_{18}					An_{19}						
Average grain size millimeters	0.35	0.5	0.5	0.5	0.3	0.5	0.5	0.45	0.3		0.6	0.35	0.5	0.35	0.6	0.6

Sample	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Field No.	S486-53	S51-52	S82-52	S122-52	S129A-52	S149-52	S171-A-52	S171-B-52	M477-1	M409	M418	10-55	58-55	S42-55	S290-53
Microcline	20.9	16.3	25	16	12	13	27	23	9	12	15	18.1	17.3	24.9	24.7
Plagioclase	42.6	47.8	47	52	45	44	42	38	55	46	48	35.6	46.2	39.8	40.6
Quartz	34.5	30.2	30	27	36	31	27	36	31	34	27	40.8	32.7	32.1	28.3
Biotite	.6	4.7	3	5	6	8	3	2	3	6	2	3.7	3.6	2.5	3.3
Muscovite	.8	1.0	2	Tr.								.8	Tr.	Tr.	3.1
Magnetite	.6	Tr.	Tr.	Tr.	1	Tr.	1	1	2	Tr.	Tr.	1.0	Tr.	.7	Tr.
Hematite															
Zircon		Tr.									Tr.				
Sphene	Tr.				Tr.	Tr.			Tr.		Tr.	Tr.	.2	Tr.	
Apatite		Tr.		Tr.	Tr.		Tr.		Tr.	Tr.	Tr.		Tr.	Tr.	Tr.
Hornblende				Tr.		2					6				
Epidote		Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.					
Chlorite															
Garnet					Tr.					Tr.	Tr.				
Allanite															
Monazite(?)															
Calcite						Tr.									
Fluorite(?)															
Spinel(?)															
Composition of plagioclase		An_{20}	An_{20}	An_{19-22}	An_{19-22}	An_{18-19}	An_{19-22}	An_{16-17}	An_{17}	An_{18}	An_{14-15}	An_{19}	An_{19}		
Average grain size millimeters	0.7	0.5–1.0	0.6	0.2	0.5	0.5	1.0	0.8	0.9		1.0	0.35	0.65	0.35	0.3

Sample	32	33	34	35	36	37	38	39	40	41	42	43	44	45	Average of 66 modes [1]
Field No.	S522-52	S452-52	S416-52	M455	M458	M475	M492-1	M563	M587	M-773	EWT 102-54	EWT 107-54	EWT 109-54	EWT 110-54	
Microcline	20.6	22.8	19.0	6	13	6	25	12	15	Tr.	13.0	19.5	22.6	2.0	15.8
Plagioclase	36.4	43.8	43.1	53	51	48	41	42	54	58	45.9	39.7	45.5	46.7	44.2
Quartz	39.9	32.4	34.1	32	29	36	29	34	29	37	35.3	36.2	27.6	46.3	33.9
Biotite	2.7	.1	2.5	7	6	9	4	12	2	Tr.	.6	Tr.	2.9	5.0	4.2
Muscovite	.2	.1	.1				Tr.				.2	.5	1.3		1.0
Magnetite	.2	.8	1.0	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	3.0	3.5	.1	Tr.	.5
Hematite														Tr.	}
Zircon				Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	}
Sphene	Tr.	Tr.	.1	Tr.	Tr.	Tr.	Tr.			Tr.					}
Apatite			.1	Tr.	Tr.	Tr.	Tr.	Tr.					Tr.		}
Hornblende										3					}
Epidote															}
Chlorite											2.0	.6	Tr.		} .4
Garnet															}
Allanite							Tr.								}
Monazite(?)															}
Calcite															}
Fluorite(?)															}
Spinel(?)															}
Composition of plagioclase			An_{16}	An_{13-17}	An_{16-17}	An_{16}	An_{16}	An_{15}		An_{14}	An_{15}	An_{12}	An_{17}	An_{25}	$\approx An_{20}$
Average grain size millimeters	0.65	0.3	0.5	1.0							0.5	0.5	0.5	0.6	

[1] Includes modes for 21 samples not listed in this table.

LOCALITIES OF SAMPLES LISTED IN TABLE 5

1. West of Central City just north of Eureka Gulch.
2. Southeast slope of Nevada Hill, north of Eureka Gulch.
3. Near Kent County mine, north slope of Quartz Hill.
4. Top of Nevada Hill.
5. Near Oranbako mine, Kings Flat.
6. Outcrop 500 ft northwest of loc. 1.
7. North of Main Street in Central City.
8. South slope of ridge between Leavenworth Gulch and Russell Gulch.
9. Northeast slope of Quartz Hill, above large bend in Nevada Gulch, just west of Central City.
10. Near small mine south of Nevada Gulch, along axis of syncline northeast of Patch.
11. Just off top of Nevada Hill, along north slope.
12. Outcrop 500 ft northwest of loc. 10.
13. Area along south slope of Nevada Hill, just above Eureka Gulch.
14. Outcrop along west slope of Nigger Hill, 750 ft above Eureka Gulch.
15. Outcrop 600 ft north of loc. 16.
16. Outcrop north of Nevada Gulch road and west of the cemetery.
17. Area south of Grand Army shaft, north of loc. 15.
18. Pit near Alps shaft, Quartz Hill area.
19. Outcrop northwest of loc. 8, about 1,500 ft along nose of ridge.
20. Outcrop north of head of Russell Gulch.
21. Nose of ridge, east slope of Alps Hill.
22. Slope south of Alps Hill above Russell Gulch.
23. Outcrops approximately 500 ft south and slightly west of loc. 8.
24. Same as loc. 23.
25. North side of Illinois Gulch, just east of granodiorite body.
26. South side of Russell Gulch, 1,200 ft above loc. 27.
27. South side of Russell Gulch, 1,000 ft west of junction with Illinois Gulch.
28. Dump of 16-1 mine, north edge of district.
29. Area at junction of Missouri Canyon and stream from Missouri Falls.
30. Top of hill southwest of Missouri Falls.
31. About 500 ft due west of loc. 11.
32. Outcrop 750 ft southwest of Patch.
33. About 1,000 ft due south of Patch.
34. Southwest of Patch, near Egyptian mine.
35. Nose of ridge between Illinois Gulch and Russell Gulch.
36. About 500 ft north of loc. 35.
37. Approximately 500 ft downslope from loc. 25.
38. About 300 ft east of State Highway 279, about 1,000 ft below junction north of Illinois Gulch.
39. Near top of hill northeast of Illinois Gulch.
40. Southeast slope of hill mentioned for sample loc. 39.
41. Southeast slope of Quartz Hill.
42. Old mine at head of Eureka Gulch.
43. Outcrop 1,000 ft southwest of loc. 42.
44. Outcrop north of Kings Flat and southeast of Eureka Gulch.
45. Outcrop 600 ft south of loc. 44.

Microcline forms anhedral crystals that commonly embay plagioclase or are interstitial to it. It has both conspicuous grid twinning and undulating extinction and contains fine film perthitic intergrowths of plagioclase.

Biotite forms ragged subhedral stubby laths, and generally has a well-defined planar and crystallographic orientation. At places it is intergrown with muscovite, and commonly it is altered to some extent to a green chlorite having anomalous blue interference colors and associated opaque iron oxides. It is a distinctly greenish variety, generally having grayish-yellow to olive-green pleochroism, but it varies slightly and locally is olive brown. Optical data and composition of two biotites are given in table 7.

The gneiss contains many minor minerals. Magnetite occurs throughout, and in some varieties of the rock it is more conspicuous than biotite; it is associated with hematite, sparse ilmenite, and, locally, pyrite. Similarly, zircon and apatite are very common. Zircon forms tiny euhedral or anhedral crystals, commonly distinctly pink, that are dispersed through the rock and form distinct pleochroic halos in biotite. A few grains are clearly zoned and consist of pink cores and nearly colorless outer zones. Hornblende is locally common (sample 1, table 5). It forms ragged generally subhedral crystals, typically intergrown with or altered to biotite, that have a greenish-yellow to dark yellowish-green or bluish-green pleochroism. Red garnet, probably almandine, is local in occurrence. Allanite is a local mineral. It occurs as subhedral crystals as much as 3 mm in maximum diameter that are mottled orange and reddish brown and are strongly pleochroic. Epidote, chlorite, and calcite are local alteration products.

In general, the rocks have typical crystaloblastic textures indicative of nearly simultaneous crystallization, but evidence exists that at least some minerals crystallized late. Typically, the microcline is interstitial to and extensively embays the more abundant plagioclase. Not uncommonly, ramifying irregular bodies of microcline extend across the boundaries of several older grains, a fact indicating that the microcline crystallized after these grains. The albitic rims on the oligoclase, as well as on the myrmekite, occur only adjacent to microcline, a fact indicating modification of the plagioclase. Rarely, myrmekite also extends into microcline. In the same way, some quartz extensively embays plagioclase. Also, at least part of the muscovite crystallized late, and not uncommonly, large ragged grains transect several older grains of other minerals, including microcline.

CHEMICAL COMPOSITION

An approximate chemical composition of the microcline gneiss unit has been calculated from the modes by use of the technique applied by Engel and Engel (1958) to similar rocks in the Adirondack Mountains. To aid in the calculation, total rock analyses were made of two selected samples, and the compositions of the major minerals in the same two samples were determined separately.

Microcline from two samples assumed to be representative of the rock was analyzed by use of the X-ray diffractometer; the composition was determined by using the (201) method of Bowen and Tuttle (1950). This method, which relates the lattice spacing to the Or/Ab ratio for synthetic feldspars, has been shown by Hewlett (1959, p. 527–528) and others to give results that compare closely with chemical analyses of natural alkali feldspars. Before the feldspars are X-rayed, they must be homogenized in the laboratory by heating. Heating at a high temperature for a short period of time causes the sodium feldspar of the perthitic lamellae to disappear and form a solid solution with the potassium feldspar component. (See Bowen and Tuttle, 1950.) Data on the microcline from Central City are given in table 6. The two samples of microcline were found, after homogenization, to contain 78±3 percent and 81±3 percent $KAlSi_3O_8$ respectively, or an average of about 80 percent $KAlSi_3O_8$. (Samples were homogenized by heating for 48 hours at 900° C. To learn something of the nature of the microperthite, the samples were X-rayed also before they were homogenized. The X-ray analyses indicated that the potassium feldspar phase contains an average of 95 percent $KAlSi_3O_8$.) The remaining 20 percent consists mainly of soda feldspar but also includes some calcium feldspar. To obtain an estimate of the amount of calcium feldspar, quantitative analyses for calcium were made of the same samples that were X-rayed. The data are given in table 7. The other elements that were determined by analysis were not included in the calculations. The combined data indicate that the microcline in the samples has an average mineral composition of approximately $Or_{80}Ab_{14}An_6$.

Biotites from the same two samples also were analyzed. The major oxides were determined by wet-chemical methods, and the trace elements were determined by spectrochemical analysis (table 8). For comparison, the atomic ratios of elements in each sample are given in table 9.

TABLE 6.—*Optical and X-ray data for microcline from microcline-quartz-plagioclase-biotite gneiss*

[Data by E. J. Young]

	Field No.[1]	
	10–55	S416–52
Composition determined before heating (expressed as weight percent $KAlSi_3O_8$)	94±2	96±2
Composition determined after heating (expressed as weight percent $KAlSi_3O_8$)	78±3	81±3
Triclinicity index	0.85°	0.81°
n_x	1.5183±0.0005	1.5178±0.0005
n_y	1.5232±0.0005	1.5223±0.0005
n_z	1.5247±0.0005	1.5239±0.0005
Birefringence	0.0064±0.001	0.0061±0.001
Optic angle (2V)	84±2	84±2
Optic sign	(−)	(−)
Orientation optic plane	⊥(010)	⊥(010)

[1] See samples 28 and 34, table 5, for descriptions and locations.

TABLE 7.—*Quantitative spectrochemical analyses, in percent, of certain elements in microcline from microcline-quartz-plagioclase-biotite gneiss*

[Analyst: J. C. Hamilton]

	Serial No. (field No. [1])	
	278037 (10–55)	278038 (s416–52)
Ca	0.47	0.31
Ba	.40	.41
Sr	.030	.023
Rb	.052	.039
Fe	.060	.046
Pb	.010	.005

[1] See samples 28 and 34, table 5, for descriptions and locations.

The plagioclase in the unit, as determined by oil immersion methods on feldspars from 45 samples, ranges from An_{12} to An_{26}. We have chosen an average of An_{20} for the composition of the plagioclase. Data are not available on potassium and other constituents in the plagioclase.

The calculated average composition of the Quartz Hill layer of microcline gneiss determined from the modes and chemical data given in tables 5, 8, and 9 is listed in table 10 together with the results of total-rock analyses of four selected samples of the rock. Two of the four samples analyzed (columns 3 and 4, table 10) are the same as those from which potassium feldspar and biotite were separated for analysis; they have modal compositions near the average determined for the Quartz Hill layer. Columns 1 and 2, table 10, list values for phases of the gneiss that are richer in quartz than the average. The calculated composition (table 10) probably approximates the average composition of the gneiss in the area of study. The precision of the calculated mean was first checked by calculating the percentage chemical composition of sample S416–52 (column 3, table 10) and sample 10–55 (column 4, table 10) from their modes, by use of the physical and chemical data of component minerals, and by comparing these percentages with those obtained from the wet-chemical total-rock analyses. The deviation between the composition values determined by chemical analysis and those calculated from modes for the two samples was less than 1 percent for the major oxides SiO_2 and Al_2O_3 and less than 0.5 percent for the alkalies.

In calculating the average chemical composition from the modes, we did not take into account the quartz that is finely intergrown in myrmekite, nor did we allow for the albite in the albitic rims. Myrmekite could account for as much as 1 percent of the rock, and the rims could comprise more than 1 percent by volume of the plagioclase.

TABLE 8.—*Chemical and spectrochemical analyses and optical properties of biotite from microcline-quartz-plagioclase-biotite gneiss*

[Analysts: V. C. Smith and R. P. Barnett]

	Laboratory No. (field No.[1])	
	F2724 (S416-52)	F2725 (10-55)
Chemical analyses, in weight percent		
SiO_2	35.04	34.71
Al_2O_3	17.58	18.37
Fe_2O_3	2.50	1.95
FeO	21.90	21.87
Mgo	7.29	7.07
CaO	.10	.00
Na_2O	.20	.31
K_2O	8.60	9.02
H_2O+	3.73	3.50
H_2O-	.03	.06
TiO_2	2.14	2.43
MnO	.64	.44
F	.49	.38
Subtotal	100.24	100.11
Less Oxygen	.21	.16
Total	100.03	99.95
Spectrochemical analyses, in parts per million		
Ba	530	500
Co	38	35
Cr	7	7
Cu	10	13
Ga	80	90
Nb	160	120
Ni	29	16
Sc	90	80
V	87	85
Y	50	60
Zr	340	390
Powder density	3.13	3.13
Optical properties		
n_x	1.596±0.001	1.595±0.001
$n_y \cong n_z$	1.648±0.001	1.647±0.001
Color for β or γ	Grayish olive	Moderate brown.

[1] See samples 34 and 28, table 5, for descriptions and locations.

TABLE 9.—*Composition of biotites in microcline gneiss and biotite gneiss, expressed in atomic ratios* [1]

	Field No.				
	S416-52	10-55	S378-53	5-228	S622-53
Tetrahedral:					
Si	2.70	2.68	2.69	2.69	2.74
Al	1.30	1.32	1.31	1.31	1.26
Total	4.00	4.00	4.00	4.00	4.00
Octahedral:					
Al	0.29	0.35	0.40	0.43	0.32
Fe^{+3}	.15	.11	.12	.14	.15
Fe^{+2}	.141	1.42	1.19	1.35	1.10
Mg	.84	.82	.96	.82	1.15
Mn	.04	.03	.01	.01	.02
Ti	.12	.14	.18	.14	.19
Total	2.85	2.87	2.86	2.89	2.93
Large cations:					
Ca	0.01				
Na	.03	0.05	0.03	0.03	0.02
K	.85	.89	.93	.92	.94
Total	.89	.94	.96	.95	.96
OH	1.91	1.80	1.67	1.69	1.54
F	.12	.09	.09	.07	.11
Total	2.03	1.89	1.76	1.76	1.65

[1] For method of calculation of atomic ratios see Stevens (1946).

S416-52, 10-55. Microcline-qnartz-plagioclase-biotite gneiss. (See samples 34 and 28, table 5, for description and locality.)
S378-53. Sillimanitic biotite-quartz gneiss, northwestern part of district.
5-228. Garnetiferons biotite-quartz-plagioclase gneiss. (See sample 8, table 14, for description and locality.)
S622-53. Biotite-quartz-plagioclase gneiss, from top of hill just north of Catholic Cemetery.

BIOTITE GNEISS

The biotite gneiss in the Central City district comprises two main varieties—biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss—but it includes also garnetiferous biotite-quartz-plagioclase gneiss. Within the biotite gneiss unit, the two principal types of gneiss are interlayered in various thicknesses and are somewhat gradational, and accordingly they are not distinguished separately on the geologic map (pl. 1). The thin layers of biotite gneiss within the microcline gneiss unit are entirely biotite-quartz-plagioclase gneiss, which is locally garnetiferous. All varieties of biotite gneiss contain moderate or abundant pegmatite, either as thin concordant layers typical of migmatite or as larger discrete bodies; migmatite was not mapped as a separate rock unit. The biotite gneisses were mapped previously as the Idaho Springs Formation (Bastin and Hill, 1917; Lovering and Goddard, 1950).

Calc-silicate gneiss occurs in the biotite gneiss as scattered small concordant podlike masses that grade transitionally into the biotite gneiss.

BIOTITE-QUARTZ-PLAGIOCLASE GNEISS

Biotite-quartz-plagioclase gneiss is a medium-gray—locally light-gray or dark-gray—fine- to medium-grained nearly equigranular layered rock. It weathers to gray or brownish gray and typically forms scattered low more or less rounded outcrops in larger areas of soft decomposed material. The gneiss is generally darker, finer grained, and richer in biotite than is the microcline gneiss, but some light-colored varieties closely resemble the microcline gneiss and can be distinguished with certainty only under the microscope. These light-colored varieties occur principally within the Quartz Hill layer of microcline gneiss. Most phases of the biotite gneiss have a pronounced composi-

TABLE 10.—*Chemical analyses, calculated composition, and modes of microcline gneiss, Quartz Hill layer*

[Tr., trace]

	1	2	3	4	Calculated average composition
Chemical analyses, in weight percent					
SiO_2	76.30	71.76	74.79	75.56	73.7
Al_2O_3	12.20	14.37	12.95	12.88	14.4
Fe_2O_3	.90	1.13	1.20	1.03	.7
FeO	2.00	1.80	1.35	.93	1.4
MgO	.48	.58	.33	.22	.3
CaO	1.70	2.05	1.66	1.79	1.9
Na_2O	3.70	4.95	4.03	3.82	4.4
K_2O	1.10	2.02	2.67	2.58	2.5
MnO	.02	.06	.04	.03	.02
H_2O^+	}	{ .03	.16	.24	.2
H_2O^-	.83	.33	.08	.05	----------
TiO_2	.22	.27	.20	.18	.1
P_2O_5	.96	.04	.04	.02	----------
CO_2	.20	.54	.10	.29	----------
F	----------	----------	.02	.01	.01
Subtotal	----------	----------	99.62	99.63	----------
Less Oxygen	----------	----------	.01	.00	----------
Total	99.71	99.93	99.61	99.63	99.63
Bulk density	----------	2.67	2.64	2.64	----------
Powder density	----------	2.65	2.70	2.69	----------
Modes, in volume percent					
Microcline	4.0	11.1	18.8	16.7	15.8
Plagioclase	36.0	42.0	42.8	41.1	44.2
Quartz	45.0	38.5	34.2	36.9	33.9
Biotite	14.0	5.3	3.4	3.4	4.2
Magnetite	.3	----------	.8	1.1	.5
Apatite	.5	.4	Tr.	Tr.	----------
Zircon	.2	----------	Tr.	Tr.	----------
Muscovite	----------	----------	----------	.8	1.0
Calcite	----------	.7	----------	Tr.	----------
Allanite	----------	----------	Tr.	----------	----------
Pyrite	----------	.1	----------	----------	----------
Leucoxene	----------	.9	----------	----------	----------
Total	100.0	99.9	100.0	100.0	[1] 99.6

[1] Remainder of 0.4 percent is total of all other accessory minerals.

1. From sixth level, East Calhoun mine. Field No. EWT–51a–53; lab. No. 147561. Chemical analysis by P. L. D. Elmore, K. E. White, and S. D. Botts. Mode determined by E. W. Tooker.
2. From Essex mine. Lab. No. A–13. Chemical analysis by L. N. Tarrant. Mode determined by E. W. Tooker. Plagioclase considerably altered to clay minerals.
3. From dump of Egyptian mine. Field No. S416–52; lab. No. 5F762. Chemical analysis by D. F. Powers. Mode is average of two sections; total number of counts is 4,240.
4. From dump of 16–1 mine. Field No. 10–55; lab. No. F2763. Chemical analysis by D. F. Powers. Biotite contains traces of chlorite. Mode is average of two sections; total number of counts is 4,537.
5. Mode is average of 66 modes of samples collected throughout Central City layer. (See table 5.) Composition of plagioclase estimated to be An_{30}.

tional layering and show a marked preferred orientation of biotite and other tabular minerals. The layering is marked by a partial segregation of the mafic and felsic minerals into separate layers, and where coarser it is marked by intercalation of typical biotite-quartz-plagioclase gneiss with either sillimanite-bearing biotite gneiss or quartz-rich biotite gneiss. Commonly, the biotite layers are paper thin and impart a fair fissility to the rock; at other places the biotite is dispersed more evenly. The layering is accentuated in many outcrops in thin conformable layers of pegmatite.

The biotite-quartz-plagioclase gneiss is equigranular and has an allotriomorphic granular texture. Individual grains are generally less than 0.5 mm in diameter. Phases that contain no visible pegmatitic material consist dominantly of plagioclase, quartz, and biotite. The proportions of the principal minerals vary considerably in amount, both within the main body of biotite gneiss (table 11) and in the lenses within the Quartz Hill layer of microcline gneiss (table 12). The plagioclase is dominantly calcic oligoclase, but locally it is andesine. It occurs as fresh or slightly altered anhedral crystals that are intergrown with quartz. Albite and pericline twinning is well defined in most grains; zoning is generally not visible. Typical crystals have a small amount of potassium-feldspar in bleb-type antiperthitic intergrowths. Myrmekite is present locally. Quartz forms anhedral grains, all of which show strain shadows, and commonly has abundant conspicuous tiny fluid inclusions. Brown biotite occurs as subhedral crystals that generally have a well-defined planar and crystallographic orientation. At places it is intergrown with muscovite. Optical data and composition of one sample of biotite from a biotite gneiss are given in table 15.

Hornblende and garnet occur locally in the biotite gneiss layers within the Quartz Hill layer of microcline gneiss. The hornblende is present near bodies of amphibolite. It forms nearly equant anhedral grains that are intergrown with biotite and plagioclase; it is very pleochroic, ranging from light olive brown to dusky green. The garnet is a pale-red almanditic variety that forms anhedral grains intergrown with plagioclase.

The accessory minerals are dominantly magnetite, zircon, apatite, and muscovite but include microcline, tourmaline, allanite, sphene, clinozoisite, chlorite, muscovite, and a variety of clay minerals. Microcline is scarce, except in those phases that contain introduced granitic material. Tourmaline (schorl) was observed locally in the biotite gneisses along North Clear Creek at the eastern margin of the district in close association with tourmaline-bearing pegmatites.

The rock typically has crystalloblastic textures indicative of nearly simultaneous crystallization. Quartz and plagioclase are intergrown in a well-defined mosaic pattern. Biotite laths tend to occur along boundaries of quartz and plagioclase grains, but they also transect the grains; at places the biotite is associated with muscovite. Microcline is interstitial, except where introduced during migmatization of the rock.

SILLIMANITIC BIOTITE-QUARTZ GNEISS

Sillimanitic biotite-quartz gneiss is similar in general appearance to biotite-quartz-plagioclase gneiss but differs in detail. The sillimanitic gneiss is generally lighter gray than the biotite-quartz-plagioclase gneiss, and where it contains moderately abundant sillimanite

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

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10
Field No.	M625-1	M679	M789-1	1-55	4-253A	4-253B	4-188	S117-53	4-237B	S621-53
Plagioclase	29	41	37	65.8	42.6	44.8	48.1	53.1	54.6	56.2
Quartz	44	45	49	1.7	46.2	42.9	40.1	22.7	26.0	21.7
Biotite	27	13	13	29.9	7.7	8.3	9.2	20.9	16.8	20.8
Muscovite				1.0	.6	1.5		.4	.1	.1
Magnetite	Tr.	1	1	1.6	2.6	2.2	1.4	1.8	1.6	1.0
Hematite				Tr.	Tr.	.1		.1	.1	
Zircon	Tr.	Tr.	Tr.		Tr.	.1	Tr.		Tr.	
Sphene				Tr.				.1		
Apatite		Tr.	Tr.		.3	.1	.9		.8	.2
Clinozoisite							Tr.			
Chlorite										
Allanite	Tr.			Tr.			.3	.2		
Tourmaline						Tr.				
Microcline								.7		
Composition of plagioclase	An_{27}	An_{20}	An_{25}	An_{28}		An_{36}			An_{30}	An_{34}
Average grain size (millimeters)				0.4					0.45	0.7

Sample	11	12	13	14	15	16	17	18	Average of 18 modes
Field No.	S625-53	S113-53	S120-2-53	4-245	4-248B	4-248-1	4-248-2	4-248-3	
Plagioclase	66.7	33.5	48.9	27.5	40.0	24.6	32.3	30.4	43
Quartz	16.3	54.3	35.2	58.1	44.5	65.2	57.2	51.4	40
Biotite	15.5	10.6	14.7	11.0	13.1	6.3	5.9	15.5	14.5
Muscovite	.8			.9	.1	.9		.8	.5
Magnetite	.7	1.4	.7	1.0	1.8	2.1	3.9	1.4	1.5
Hematite	Tr.				Tr.			Tr.	
Zircon	Tr.	Tr.		Tr.	Tr.		Tr.	.2	
Sphene						.1			
Apatite		.2	.5	.1	.5	.6	.5		
Clinozoisite									
Chlorite	Tr.						.2		.5
Allanite								.2	
Tourmaline						.2		.1	
Microcline				1.4					
Composition of plagioclase	An_{27}	An_{34}				An_{78}	An_{38}	An_{28}	
Average grain size (millimeters)	0.85	0.25			0.2	0.2	0.2	0.25	

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 11

1, 2. Gneiss near Knickerbocker shaft, southwest part of district.
3. Infolded body of biotite gneiss north of Illinois Gulch. It is finely interlayered with sillimanitic biotite-quartz gneiss. (See column 7, table 13.)
4. Gneiss in roadcut on State Highway 119 just north of north edge of map area.
5, 6. Gneiss on hill on east side of State Highway 119 about 1,000 ft southeast of east edge of map area.
7. Gneiss from Silver Hill, opposite the American Eagle tunnel.
8. Migmatitic biotite gneiss at head of Nevada Gulch near west edge of district.
9. Gneiss from thin layer included in small phacolith of granodiorite and associated rocks along State Highway 119 one-half mile southeast of Black Hawk.
10. Medium-grained biotite gneiss, 1,600 ft north of Boodle mine, northwest part of district. Resembles typical foliated granodiorite in hand specimen.
11. Similar biotite gneiss as from loc. 10.
12. Massive fine-grained biotite gneiss interlayered with sillimanitic biotite-quartz gneiss, head of Nevada Gulch.
13. Gneiss near King mine, western part of district.
14. Gneiss interlayered with sillimanitic biotite-quartz gneiss, northeast side of State Highway 119 just west of Silver Gulch.
15. Fine-grained massive gneiss from hill east of Silver Gulch, east edge of map area.
16. Fine-grained quartz-rich gneiss from loc. 15.
17, 18. Same as loc. 15.

and muscovite, it tends to have a distinctly silvery sheen. In an interlayered succession of the two types of biotite gneisses, the sillimanitic gneiss is commonly somewhat coarser grained than the associated biotite-quartz-plagioclase gneiss. Also, the sillimanitic variety is typically more schistose and more highly migmatized. The sillimanite, the most conspicuous and distinctive mineral in the rock, occurs as alined needles and aggregates of fibers as much as an inch in length or, less commonly, as tabular discoid masses of about the same length. In most exposures the sillimanite is more or less evenly dispersed through the rock, but in places it is concentrated in layers a fraction of an inch thick. Adjacent to pegmatitic streaks and layers the sillimanite locally occurs as coarse-grained aggregates.

In thin section the rock is seen to be nearly equigranular and to have a crystalloblastic texture. It contains quartz as the dominant mineral and variable amounts of biotite, sillimanite, muscovite, and plagioclase (table 13). The quartz is anhedral, has very conspicuous strain shadows, and commonly is intergrown with the plagioclase and biotite to form a mosaic pattern; locally it is myrmekitically intergrown with biotite and muscovite. The plagioclase (calcic oligoclase) forms an-

TABLE 12.—*Modes, in volume percent, of biotite-quartz-plagioclase gneiss in Quartz Hill layer of microcline gneiss*

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10	11	Average of 11 modes
Field No.	M780-A	M780-B	G-1E-2	BM-4	EC-6-4	AD-6	AD-7	ED-3	53-1	S51-B-52	EWT-5A-54	
Plagioclase	25	42	37.1	37.9	75.0	56.8	46.6	53.1	18.3	34.0	34.6	41.9
Microcline	------	------	------	------	------	.1	------	------	------	------	1.5	.2
Quartz	42	36	53.6	52.1	13.8	26.0	18.5	15.6	22.5	37.8	49.7	33.4
Biotite	33	22	8.7	8.2	7.0	13.4	25	11.1	6.1	23.6	12.6	15.5
Muscovite	------	------	------	.4	------	------	------	------	------	------	------	
Magnetite	------	------	Tr.	.6	4.0	.9	.7	1.9	1.4	1.2	.2	
Hematite	------	------	------	------	------	------	------	------	------	------	1.0	
Zircon	Tr.	Tr.	------	------	.1	Tr.	.3	.6	------	------	------	
Sphene	------	------	------	------	------	.5	------	------	.5	.1	------	
Apatite	------	------	Tr.	Tr.	.1	.5	.4	.7	.9	.2	.4	9.0
Hornblende	------	------	------	------	------	1.5	------	16.6	14.9	------	------	
Epidote	------	------	------	------	------	.2	------	------	------	------	------	
Clinozoisite(?)	------	------	.5	------	------	------	------	------	------	------	------	
Chlorite	------	------	------	------	------	------	8.5	------	------	.9	------	
Garnet	------	------	.1	.6	------	------	------	------	------	------	------	
Calcite	------	Tr.	------	.2	------	.1	------	.2	------	2.2	------	
Composition of plagioclase	------	An_{20-25}	------	An_{44}	------	------	------	An_{27}	------	An_{25-27}	------	------
Average grain size (millimeters)	------	------	------	0.4	------	------	------	0.2	0.3	0.3	------	------

LOCALITIES OF SAMPLES LISTED IN TABLE 12

1, 2. Small body north of Hecla mine, eastern part of Quartz Hill.
3. Thin layer exposed in German mine, Quartz Hill.
4. Thin lens in Blanche M mine, Quartz Hill.
5–9. Lenses in Wood-East Calhoun mine, Quartz Hill.
10. Thin layer adjacent to cordierite-amphibole gneiss body, top of Quartz Hill.
11. Thin layer in McKay shaft, RHD mine, Nigger Hill. Altered phases of the gneiss locally contain secondary uranium minerals (Sims, Osterwald, and Tooker, 1955).

hedral grains, has moderately distinct albite and pericline twins, and is generally slightly cloudy because of alteration products. The crystals have no apparent zoning except locally adjacent to microcline where narrow albitic rims are formed. Sillimanite occurs in sheaths or aggregates of fibers and as fibers and needles included within and transecting quartz, plagioclase, and microcline. In places the sillimanite aggregates are intergrown with biotite and muscovite. The sillimanite in contact with microcline only rarely has intervening muscovite. The biotite is a moderate-brown highly pleochroic variety. Optical data and chemical data on one biotite (S378–53, column 3) are given in table 15. Microcline is mainly interstitial to the dominant minerals, but in places it is intergrown with quartz and plagioclase in an interlocking texture. It is slightly perthitic and contains blebs of irregular plumelike veinlets of plagioclase. Probably most of the biotite, sillimanite, plagioclase, and microcline crystallized contemporaneously. The muscovite very likely crystallized later than these minerals, but this fact is not certain.

GARNETIFEROUS BIOTITE-QUARTZ-PLAGIOCLASE GNEISS

Garnetiferous biotite-quartz-plagioclase gneiss resembles biotite-quartz-plagioclase gneiss but is somewhat darker and contains visible garnets. The garnets are commonly a few millimeters in diameter but are locally as much as one-half inch across. They tend to be dispersed evenly through the rock. Weathering imparts to outcrop surfaces a red-tinted stain that is useful in distinguishing this rock from other biotite gneisses.

The garnetiferous gneiss forms scattered small bodies as much as 75 feet by 500 feet in the biotite gneiss unit, and it forms thin lenses intercalated with amphibolite near the axis of the Central City anticline along State Highway 119 (pl. 1).

The gneiss consists predominantly of quartz, plagioclase, biotite, and garnet (table 14). The quartz forms anhedral grains that show conspicuous strain shadows and contain abundant tiny fluid inclusions. The plagioclase (An_{25-30}) is anhedral; it has moderately well formed twinning in accord with the albite and pericline laws and is slightly clouded by alteration products. Garnet is anhedral or rarely subhedral and forms crystals of approximately the same size as those of the quartz and feldspar. It is moderately poikilitic and contains subrounded inclusions of quartz, magnetite, and biotite. In contrast to the other minerals in the rock, it is fractured, commonly in two intersecting sets of fractures. In some specimens the fractures contain biotite flakes. The garnets are almanditic varieties, as is indicated by the data in table 15. The biotite is a highly pleochroic variety ranging from light yellow to yellow brown or dark reddish brown. It has optical properties and a chemical composition similar to biotites from other biotite gneisses in the district (table 16). Microcline is scarce except in samples containing peg-

TABLE 13.—*Modes, in volume percent, of sillimanitic biotite-quartz gneiss from biotite gneiss unit*

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10
Field No.	S131-52	M536-1	M347	M606-2	M625-2	M670	M789-2	4-248c	4-246-2	S116-1-53
Plagioclase	10.5		35		5	13	8	6.1	11.4	16.3
Microcline						3	Tr.	2.0	2.0	
Quartz	58.0	31	30	37	51	55	49	52.0	37.8	56.0
Biotite	23.3	37	28	48	30	18	27	21.2	24.9	18.7
Sillimanite	6.5	27	2	11	8	5	9	14.5	13.8	7.3
Muscovite	1.2	2	4	Tr.	6	5	4	2.9	8.9	1.0
Magnetite	.5	3	Tr.	3	Tr.	1	3	1.3	.7	.7
Hematite									.1	
Zircon	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	
Apatite		Tr.		Tr.		Tr.	Tr.		.4	Tr.
Chlorite	Tr.									
Calcite										
Allanite(?)										
Sulfides			Tr.							
Composition of plagioclase	An_{27}					An_{22}	An_{22}	An_{25-26}		
Average grain size millimeters	0.25							0.25		0.15

Sample	11	12	13	14	15	16	17	18	Average of 18 modes
Field No.	S99-53	5-137	4-31B	2-302A	1-190	2-302B	1-421	S97-A-53	
Plagioclase	2.9	1.0	19.5	24.6	28.1	17.2	24.1	25.9	14
Microcline	Tr.		Tr.		1.0		.4		.5
Quartz	56.2	55.1	59.0	45.2	40.6	56.8	57.9	51.9	49
Biotite	26.0	26.0	10.7	15.4	19.0	18.7	12.1	19.0	23.5
Sillimanite	12.9	11.0	6.2	7.7	2.9	1.3	.6	.4	8
Muscovite	1.2	4.5	4.5	5.0	6.8	5.1	3.0	2.1	4
Magnetite	.6	2.3	.1	2.1	1.6	.9	1.9	.7	1
Hematite	.2			Tr.	Tr.	Tr.	Tr.	Tr.	
Zircon	Tr.	.1	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	
Apatite		Tr.		Tr.	Tr.				
Chlorite									
Calcite									
Allanite(?)				Tr.					
Sulfides									
Composition of plagioclase	An_{28}	An_{25-26}							
Average grain size millimeters	0.35	0.25	0.7			0.45			

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 13

1. Alps Hill, west of Delmonico mine.
2. Infolded body of biotite gneiss, north of Illinois Gulch.
3. Low hill 1,200 ft southwest of Holland mine.
4-6. Near Old Town mine.
7. Infolded body of biotite gneiss east of Gauntlet mine.
8. Roadcut along State Highway 119 about 300 ft east of Silver Gulch. The gneiss is finely interlayered with quartz-rich biotite gneiss (see table 11); both type gneisses are migmatized.
9. Exposures along State Highway 119 about 200 ft west of Silver Gulch. Gneiss contains conspicuous tabular crystals of sillimanite as much as one-half inch long.
10. Migmatitized biotite gneisses head of Nevada Gulch near west edge of district. Gneiss is interlayered with biotite-quartz-plagioclase gneiss.
11. Migmatized biotite gneiss north of Hawkeye mine, near loc. 10.
12. Exposures at mouth of Silver Gulch north of State Highway 119.
13. Near Albert mine on hill east of Fourmile Gulch, about one-half mile north of North Clear Creek.
14. Biotite gneiss layer in the southeast part of district.
15. South of village of Russell Gulch.
16. Same as loc. 14.
17. Near loc. 15.
18. Dump of Hawkeye mine, west side of district.

matitic material. Muscovite is also sparse; it was observed in abundance only in one sample, which also contained considerable microcline.

The accessory minerals are mainly magnetite, zircon, sphene, apatite, iron sulfides (pyrite?), and sillimanite. Hematite occurs as a local alteration product of magnetite.

CHEMICAL COMPOSITION

The biotite gneisses are known from modal analyses and from a few chemical analyses to vary widely in chemical composition. Rather than resort to more total-rock chemical analyses of samples, we calculated approximate chemical compositions of the two main rock types—biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss—from average modal analyses. For purposes of calculation the compositions of the biotites were assumed to be the same as those determined by chemical analysis of selected samples from each rock type (table 16). A composition of An_{28} for the plagioclase, as determined by oil immersion methods, was used in calculating the composition of the biotite-quartz-plagioclase gneiss; An_{26} was used for the sillimanitic biotite-quartz gneiss. Microcline was assumed to consist wholly of the potassium feldspar molecule. Some of the minor mineral components in the rocks were ignored in the computations.

The calculated average chemical compositions of the two rock types together with the results of chemical analyses of two selected samples are given in table 17. The average biotite-quartz-plagioclase gneiss contains more SiO_2, CaO, and Na_2O and less Al_2O_3, FeO, MgO, and K_2O than does the average sillimanitic

TABLE 14.—*Modes, in volume percent, of garnetiferous biotite-quartz-plagioclase gneiss from biotite gneiss unit*

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10	Average of 10 modes
Field No.	M609-1	M-668-1	M668-2	M668-3	B-20-B	B-15-A	B-15-B	5-228	S101-53	S299-52	
Plagioclase	21	10	26	21	50.0	21.2	43.8	33.4	26.6	35.2	29
Microcline	Tr.	---	---	---	---	---	---	.1	---	13.5	---
Quartz	38	44	38	29	41.1	45.4	40.6	33.1	36.1	32.4	38
Biotite	30	24	26	30	5.7	18.0	8.5	22.6	26.5	6.5	20
Muscovite	---	---	---	Tr.	---	---	.6	---	.1	9.8	---
Magnetite	3	---	3	Tr.	Tr.	.1	2.0	.6	1.5	.3	1
Hematite	---	---	---	---	---	.5	---	Tr.	---	---	---
Zircon	Tr.	Tr.	Tr.	Tr.	---	---	Tr.	Tr.	Tr.	---	---
Sphene	---	---	---	---	Tr.	Tr.	---	---	---	---	---
Apatite	Tr.	Tr.	Tr.	Tr.	---	---	.1	.1	.1	---	---
Sillimanite	---	---	---	---	---	Tr.	---	---	---	---	---
Garnet	8	22	7	15	3.2	14.8	4.0	10.1	9.1	2.3	10
Sulfides	Tr.	---	---	Tr.	---	---	---	---	---	---	---
Composition of plagioclase	An_{25}	An_{30}	An_{25-26}	An_{25}	---	---	---	An_{28}	---	An_{25}	---
Average grain size, millimeters	---	---	---	---	0.45	0.45	0.4	0.45	0.25	0.8	---

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 14

1–4. Gneiss associated with small bodies of garnet skarn, biotite gneiss unit, southwest part of district.
5. Gneiss intercalated with amphibolite in amphibolite body along crest of Central City anticline on State Highway 119.
6. Gneiss intercalated with amphibolite in amphibolite body west of loc. 5.
7. Same as loc. 6.
8. West slope of hill on east side of Fourmile Gulch about 3,200 ft north of North Clear Creek.
9. Thirty-foot layer of garnetiferous biotite-quartz-plagioclase gneiss in biotite gneiss unit at the head of Nevada Gulch.
10. Thin layer infolded body of biotite gneiss on the south side of Leavenworth Gulch northwest of Holland mine.

TABLE 15.—*Composition of garnet from garnetiferous biotite-quartz-plagioclase gneiss*

Field No.	5-228 [1]	AE-4 [2]
Unit cell edge (A_o)	11.539±0.002	11.547±0.003
Molecular composition [3]		
Almandite	61	49
Spessartite	24	34
Pyrope	15	17
Quantitative spectrochemical analyses, in percent [4]		
Manganese	2.6	4.5

[1] See sample 8, table 14, for description and locality.
[2] From American Eagle mine, Fourmile Gulch area.
[3] In percentage of end members, as calculated from data on synthetic end members by Skinner (1956): determined by E. J. Young.
[4] Analyst: N. M. Conklin.

biotite-quartz gneiss. Whereas the Na_2O/K_2O ratio is more than 2:1 in the biotite-quartz-plagioclase gneiss, it is less than 1:2 in the sillimanitic gneiss. In general, the biotite-quartz-plagioclase gneiss is a little less felsic than is the microcline gneiss (table 10).

AMPHIBOLITE

OCCURRENCE AND CHARACTER

Except as a minor constituent of rocks mapped as calc-silicate gneiss, amphibolite occurs only within the Quartz Hill layer of microcline gneiss, where it forms scattered bodies at certain stratigraphic positions and discontinuous lenses at the upper and lower contacts of the miocrocline gneiss unit. Possibly the rock constitutes 2 or 3 percent by volume of the Quartz Hill layer, but bodies mappable at the scale of plate 1 are not abundant. The bodies within the microcline gneiss range from lenses a few inches in maximum dimensions to layers as much as half a mile long and about 300 feet thick, but a body at the contact in the Fourmile Gulch area has an exposed length of about 3,500 feet.

With the notable exception of two bodies that lie along or near the axis of the Central City anticline in North Clear Creek, the mappable amphibolite bodies (pl. 1) consist almost entirely of the one rock type and some associated pegmatite. The lenses in North Clear Creek contain some intercalated garnetiferous biotite gneiss and rocks gradational between amphibolite and biotite gneiss; also, at one locality they contain a small body of cordierite-amphibole gneiss.

The contacts of amphibolite with adjacent rocks are conformable and commonly gradational. At many localities the amphibolite can be seen to grade into microcline gneiss across a width of a few inches by a gradual decrease in the abundance of hornblende and a concomitant increase in quartz and microcline. In a similar way, amphibolite grades into calc-silicate gneisses by changes in the mineralogy across the contacts.

The amphibolites are dark-gray or grayish-black fine- to medium-grained equigranular rocks. Commonly, they are mottled black and white, are nearly homogeneous, and have a distinct planar structure imparted by suparallel plagioclase and hornblende crystals. Lineation is less pronounced than the foliation, except in scarce bodies containing somewhat acicular hornblende crystals. Some bodies of amphibolite have a distinct fine-scale layering that is marked by a partial segregation of the mafic and felsic minerals into separate bands; the layers are generally only a few millimeters thick.

TABLE 16.—*Chemical and spectrochemical analyses and optical properties of biotite from biotite gneisses*

[Analysts: V. C. Smith and P. R. Barnett]

Laboratory No. / Field No.	F2783 / S622–53	F2784 / 5–228	F2785 / S378–53
Chemical analyses, in weight percent			
SiO_2	35.73	34.74	35.14
Al_2O_3	17.44	19.14	19.10
Fe_2O_3	2.57	2.46	2.08
FeO	17.10	20.89	18.63
MgO	10.06	7.08	8.39
CaO	0	0	0
Na_2O	.16	.18	.21
K_2O	9.63	9.39	9.56
H_2O+	3.01	3.29	3.29
H_2O-	.03	.03	.03
TiO_2	3.20	2.35	3.19
MnO	.24	.08	.13
F	.43	.30	.37
Subtotal	99.60	99.93	100.12
Less oxygen	.18	.13	.16
Total	99.42	99.80	99.96
Spectrochemical analyses, in parts per million			
Barium	2,000	1,300	1,200
Cobalt	56	43	52
Chromium	150	280	420
Copper	130	58	14
Gallium	50	60	40
Niobium	70	60	80
Nickel	120	110	240
Scandium	80	20	80
Vanadium	380	240	380
Yttrium	20	<20	<20
Zirconium	340	190	120
Optical properties			
n_x	1.592 ± 0.001	1.594 ± 0.001	1.590 ± 0.001
$n_y \cong n_z$	1.645 ± 0.001	1.646 ± 0.001	1.643 ± 0.001
Color for β or γ	Dusky yellowish brown	Dusky yellowish brown	Moderate brown

F2783. Biotite-quartz-plagioclase gneiss, northwestern part of district.
F2784. Garnetiferous biotite-quartz-plagioclase gneiss, Fourmile Gulch area.
F2785. Sillimanitic biotite-quartz gneiss, western part of district.

The pegmatite associated with the amphibolite forms irregular ramifying veinlets that tend to form a blocky structure. Thus, the structure differs markedly from the intimate interlayering of pegmatite in the foliated migmatitic biotite gneisses.

TABLE 17.—*Chemical analyses, in percent, and calculated composition of biotite gneisses*

[Tr., trace]

	Analyzed samples		Average composition calculated from modes	
	1	2	3	4
SiO_2	76.33	64.23	70.54	68.23
Al_2O_3	12.30	16.45	12.97	15.32
Fe_2O_3	1.08	2.40	2.30	2.11
FeO	1.75	4.31	3.52	5.36
MgO	.59	1.68	1.58	2.10
CaO	2.41	3.11	2.49	.69
Na_2O	3.13	3.75	3.55	1.19
K_2O	1.02	2.14	1.57	2.84
H_2O-	.17	.02		
H_2O+	.42	.89	.49	1.00
TiO_2	.27	.80	.50	.80
CO_2	.01	0		
P_2O_5	.03	.10	.12	.01
MnO	.03	.08		
BaO		.02		
SrO		Tr.		
S		.03		
Total	99.54	100.01	99.63	99.65
Bulk density	2.65			
Powder density	2.69			

1. Biotite-quartz-plagioclase gneiss from McKay shaft, RHD mine, Nigger Hill. Field No. EWT–5A–54; lab. No. A1. Analyst: L. N. Tarrant. Mode given in table 12. The gneiss is from a thin layer included within the Central City layer of microcline gneiss.
2. Quartz-biotite schist from the biotite gneiss unit near former site of Penn Mill just below Black Hawk. Analyst: George Steiger. Reference: Bastin and Hill (1917, p. 27).
3. Biotite-quartz-plagioclase gneiss. Calculated from average of 18 modes given in table 11.
4. Sillimanitic biotite-quartz gneiss. Calculated from average of 18 modes given in table 13.

PETROGRAPHY

The amphibolite consists principally of plagioclase and hornblende but locally contains clinopyroxene or biotite and generally a little quartz (table 18). Plagioclase occurs as slightly cloudy anhedral or subhedral crystals, averaging about 0.4 or 0.5 mm in diameter, arranged in a mosaic pattern. It is generally oligoclase or andesine but locally is more calcic; the average of 27 determinations is An_{34}. The crystals are commonly unzoned and well twinned in accord with the albite and pericline twin laws. Some crystals have a slight normal zonation, and others have narrow albitic rims, particularly adjacent to microcline grains. A small amount of microcline occurs as tiny blebs in the plagioclase and constitutes antiperthite.

Hornblende forms anhedral or, rarely, subhedral crystals generally 0.3 to 0.5 mm in maximum length that are intergrown with the plagioclase. Commonly, aggregates of crystals are somewhat segregated into indistinct crude laminae. At places pyroxene is intergrown with the hornblende, and in the rocks containing biotite, the biotite also is closely associated with the hornblende. The hornblende is highly pleochroic, having the general pleochroic formula: X=yellow or greenish brown, Y=olive green, and Z=dark green or dark bluish green. The range is from 1.670 to 1.682, to judge from four separate determinations. The clinopyroxene occurs as equant grains that are intergrown with hornblende; it is pale green and slightly pleochroic and has an n_γ of about 1.708. Its optical properties indicate that it is an augitic pyroxene.

Ragged subhedral grains of biotite that are intergrown with hornblende or aggregated in clusters are present in small amounts in most sections and constitute as much as 10 percent of some amphibolites. The biotite is pleochroic, ranging from light yellow to olive green; n_γ of one sample (S483–D–53, column 9, table 18) is 1.614±0.003. Quartz occurs in most of the amphibolite but is variable in amount; it forms anhedral grains having strain shadows and is associated predominantly with plagioclase. Microcline forms rare equant interstitial grains. Calcite, chlorite, epidote, and muscovite are common alteration products. Magnetite, apatite, sphene, and zircon are common accessory minerals.

The amphibolite is nearly equigranular and has a typical granoblastic texture. The textures are interpreted to indicate that plagioclase, hornblende, and quartz crystallized almost contemporaneously. At places pyroxene crystallized with plagioclase, but sub-

TABLE 18.—*Modes, in volume percent, of amphibolite*

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10	11
Field No.	M562	M551	M246-1	ET99-54	S77-52	S403-1-53	S41-53	S52-53	S483-D-53	S638-C-52	4-136
Plagioclase	45.6	46.7	48.3	40.5	26.5	37.0	44.3	30.1	25.3	49.9	52.6
Microcline			.2	.6	1.0					1.9	
Quartz	1.0	8.7	19.9	.1	7.0	.8	.1	9.2	.1	.3	4.4
Hornblende	40.0	39.9	24.4	48.0	51.5	54.9	53.1	54.9	63.7	44.4	41.8
Clinopyroxene											.2
Biotite	10.8		1.2	6.4	4.2	3.1	.4	1.7	8.5	.4	Tr.
Magnetite-ilmenite	1.3	1.5	2.1	Tr.	4.4	.2	Tr.	1.7		.3	
Zircon	.1		.4		Tr.	.6			.1	1.5	
Apatite	.3	Tr.	.5	Tr.	1.7	.1	.1	.4	Tr.	.5	Tr.
Calcite					1.0	1.7	.8	Tr.	.8		
Sphene	.8	.3	2.6	1.1		.1	1.2		.1	.6	.4
Chlorite		.1	.1	1.8	2.0			2.0		.1	
Epidote	.1	2.8	.3			1.5	Tr.		1.4	.1	.6
Muscovite					.7						
Composition of plagioclase	An_{26}	An_{42}	An_{37}	An_{30}	An_{56}		An_{34}			An_{29}	An_{37}
Grain size, millimeters							0.25			0.40	0.35

Sample	12	13	14	15	16	17	18	19	20	21	Average of 21 modes
Field No.	S472-C-53	S475-53	S152-A-52	S153-2-52	S153-1-52	M246-2	S10-53	M221	B-17-C	B-20-A	
Plagioclase	40.4	32.5	47.1	54.9	56.3	41.8	47.8	59.9	36.7	41.6	43.0
Microcline		.3	1.1	.3	1.0	.2	.2	.6			.4
Quartz	9.0	.8	.3	3.9	1.9	4.6	13.5	.9	5.6	8.6	4.8
Hornblende	44.7	65.8	47.6	24.0	35.4	40.8	37.7	22.8	56.2	41.3	44.4
Clinopyroxene			1.4	13.7	2.8			9.1			1.3
Biotite					Tr.						1.7
Magnetite-ilmenite	3.0	.3	Tr.		Tr.	1.3	Tr.		1.4	8.5	} 4.4 (Magnetite-ilmenite through Muscovite)
Zircon		.3	.5	Tr.	Tr.	Tr.	Tr.	Tr.	.1		
Apatite	.3	Tr.	.3	.2	Tr.	.3	.2	.2		Tr.	
Calcite	2.6			.7							
Sphene			.5	.5	2.0	1.3	Tr.	3.0			
Chlorite		Tr.									
Epidote			.6	1.8	.6	9.7	.6	3.5			
Muscovite											
Composition of plagioclase	An_{48}	An_{32}	An_{26}	An_{32}	An_{34}	An_{37}	An_{29}	An_{36}	An_{73}	An_{46}	An_{34}
Grain size, millimeters		0.40	0.45	0.30	0.35		0.30		0.35	0.25	

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 18

1. Biotitic amphibolite from dump of Gladstone mine, three-quarters of a mile south of Central City.
2. Small body just east of granodiorite body, three-quarters of a mile south of Central City.
3. Small body at upper contact of Quartz Hill layer of microcline-quartz-plagioclase biotite gneiss 1,100 ft east of Minnesota mine.
4. Amphibolite from thin layer in Quartz Hill layer of microcline-quartz-plagioclase-biotite gneiss, north side North Clear Creek, 3,000 ft northwest of Black Hawk.
5. Dump of Bon Ton shaft, Quartz Hill.
6. Thin layer of amphibolite north side Nevada Gulch opposite LaCrosse tunnel.
7. Amphibolite that is associated with calc-silicate gneiss west of Barker mine, north slope of Quartz Hill.
8. Dump of shaft 500 ft west of Treasure Vault mine, north slope of Quartz Hill.
9. Biotitic amphibolite from same layer as in loc. 6.
10. Zigzag-shaped body of calc-silicate geniss northeast of the Patch, Quartz Hill.
11. Large body of amphibolite southeast side of Silver Hill.
12. Dump of Grand Army shaft, north slope of Nevada Hill.
13. Amphibolite layer north side of Nevada Gulch, 800 ft north-northeast of LaCrosse tunnel.
14. Folded amphibolite layer west side of Quartz Hill, 600 ft southwest of Jefferson-Calhoun shaft.
15-16. Near sample loc. 14.
17. Same layer as in loc. 3.
18. Small body just west of crest of Quartz Hill.
19. Layer of amphibolite near axis of Central City anticline on south side of Russell Gulch.
20. Amphibolite body exposed in North Clear Creek 1,000 ft northwest of axis of Central City anticline.
21. Amphibolite body along axis of Central City anticline on North Clear Creek. The body probably lies at the base of the Quartz Hilll layer of microcline-quartz-plagioclase-biotite gneiss.

sequently it was locally altered to hornblende. Probably some of the biotite crystallized with the dominant minerals, but it could be a late mineral.

CHEMICAL COMPOSITION

Total-rock analyses of two samples of the amphibolite from the Central City district (table 19) indicate that the rock has the chemical composition of a slightly oversaturated basalt. Sample S472–C–53 (G3104, table 19) contains slightly more quartz and somewhat less hornblende than the average amphibolite in the district (table 18).

CORDIERITE-AMPHIBOLE GNEISS

DISTRIBUTION AND CHARACTER

Rocks that contain cordierite and either gedrite or cummingtonite as principal constituents were mapped as cordierite-amphibole gneiss. These rocks were first recognized in the Front Range during the current studies and were described briefly in an earlier report (Sims, Osterwald, and Tooker, 1955, p. 7). Previously, gedrite was called anthophyllite.

The cordierite-amphibole gneiss occurs as small widely scattered bodies within the Quartz Hill layer of microcline gneiss. Nine separate bodies have been recognized in the district. Four bodies on Quartz Hill and one on Nigger Hill are shown on plate 1. The other four, all too small to show on the map, are located at (1) the east margin of the amphibolite body just northwest of the amphibolite body along the axis of the Central City anticline in North Clear Creek, (2) the Grand Army mine workings (identified on the basis of specimens taken from the dump), (3) 1,000 feet southwest of the mapped body on Nigger Hill (a small body), and (4) 1,400 feet northeast of the Patch (a small body associated with biotite gneiss). The maximum width of any of the exposed bodies is about 300 feet. Several of the bodies are associated with amphibolite, and a few are associated with biotite gneiss. Pegmatite is commonly present adjacent to the bodies but rarely occurs within them.

The cordierite-amphibole gneiss is a dark-gray or medium-gray fine- to medium-grained layered rock. It can be distinguished readily from the other metamorphic rocks of the district by a conspicuous blue-tinted hue given by cordierite, a somewhat greasy lustrous appearance, and megascopically visible orthoamphibole and garnet. The layering is marked by alternating bands of different mineralogy that range in width from less than an inch to several inches. Garnet varies widely in abundance from layer to layer; coarse matted gedrite occurs in some layers. Weathering emphasizes the layering and commonly produces pronouncedly ribbed surfaces on which the cordierite-rich layers stand out in relief. Except for local thin layers of coarse gedrite, the rock has a well-defined foliation and lineation that conforms to such features in adjacent rocks.

TABLE 19.—*Chemical and spectrochemical analyses of amphibolite*

Laboratory No. / Field No.	A4 / EWT-10-54	G3104 / S472-C-53
Chemical analyses, in weight percent		
SiO_2	48.19	48.54
Al_2O_3	15.66	17.18
Fe_2O_3	3.86	3.61
FeO	9.08	10.61
MgO	7.17	5.42
CaO	8.68	7.87
Na_2O	.92	3.14
K_2O	1.07	.34
H_2O+	3.17	1.46
H_2O-	.67	.10
TiO_2	.75	1.05
P_2O_5	.12	.13
MnO	.26	.29
CO_2	.01	.27
Cl	----------	.01
F	----------	.09
S	----------	.04
Subtotal	----------	100.15
Less oxygen	----------	.06
Total	99.61	100.09
Spectrochemical analyses, in parts per million		
Cobalt	----------	34
Chromium	----------	16
Copper	----------	16
Gallium	----------	23
Lanthanum	----------	<100
Nickel	----------	12
Lead	----------	<30
Scandium	----------	67
Strontium	----------	180
Vanadium	----------	410
Yttrium	----------	40
Ytterbium	----------	4
Zirconium	----------	100
Bulk density	2.80	2.96
Powder density	3.02	3.01

A4. Partly altered amphibolite from McKay shaft, Nigger Hill; contains 48.8 percent hornblende, 38.3 percent plagioclase, and 12.9 percent quartz. Analyst: L. N. Tarrant.

G3104. Fresh amphibolite from dump of Grand Army shaft, Nevada Hill. Mode given in table 16. Analysts: D. F. Powers and P. R. Barnett.

PETROGRAPHY

The cordierite-amphibole gneiss varies in composition from layer to layer but consists dominantly of the assemblage cordierite-gedrite-quartz-garnet-biotite (table 20). The principal minerals, especially quartz and gedrite, vary within rather wide limits. Oligoclase and spinel are local varietal minerals. A second assemblage that is intercalated with the dominant one contains cummingtonite, calcic plagioclase, and quartz as major minerals and garnet and hornblende as varietal minerals. To judge from the selected samples, in table 20, cordierite does not occur with cummingtonite. A third assemblage that probably is a variant of the dominant one contains abundant quartz, cordierite, and biotite. It is represented by samples listed in table 20, columns 9 and 10. The assemblage given in column 4 of table 20 may represent a transitional phase between the dominant cordierite-gedrite-quartz assemblage and the assemblage given in column 9.

TABLE 20.—*Approximate modes, in volume percent, of cordierite-amphibole gneiss*

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Field No.	S63-B-52	S63-A-52	S682-A-53	S251-52	M829E	S59-52	B17A	S472-B53	M829A	M829D	M829C	M829B	S53-52
Quartz	Tr.	24	20	48	45	17	62	43	64	56	2	2	20
Cordierite	45	22	40	22	19	39	17	6	23	27			
Gedrite	22	20	20	3	17	37	2	4					
Cummingtonite										Tr.	24	35	17
Hornblende											35	17	
Biotite	4	2	9	21	19	4	8	9	13	11			1
Garnet	8	30		3			11	29		6			19
Plagioclase			6	3		2		9	Tr.		34	41	43
Spinel			5										
Apatite	4	Tr.				Tr.						Tr.	Tr.
Tourmaline		Tr.											Tr.
Pyrrhotite(?)											Tr.	Tr.	Tr.
Calcite													Tr.
Zircon			Tr.	Tr.	Tr.				Tr.	Tr.			
Monazite					Tr.				Tr.	Tr.			
Magnetite-ilmenite	1	2	Tr.	Tr.		1					Tr.	Tr.	Tr.
Alteration minerals	16	Tr.	Tr.	Tr.	Tr.	Tr.		Tr.	Tr.	Tr.			
Total accessory minerals											5	5	
Composition of plagioclase						An_{27}			An_{23}		An_{33}	An_{33}	An_{57}

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 20

1. Small body exposed near Leavenworth mine, 500 ft south of Leavenworth Gulch on south slope of Quartz Hill.
2. Garnet-rich gneiss at loc. 1.
3. Dump of shallow prospect pit on southwest slope of Nigger Hill.
4. Small body 1,500 ft south of the Patch and 400 ft north of mapped body on Quartz Hill.
5. Lens associated with mapped body of biotite gneiss 1,300 ft east-northeast of the Patch on the east side of Quartz Hill.
6. Near north margin of crescentic body exposed just east of crest of Quartz Hill, 300 ft northeast of Alps mine shaft.
7. East edge of body mapped as amphibolite immediately northwest of crest of the Central City anticline on North Clear Creek.
8. Dump of Grand Army mine.

9–12. Same as loc. 5.

13. South-central part of same body in loc. 6.

The rocks generally have a granoblastic texture but are locally porphyroblastic. The garnets and locally the cordierite and plagioclase tend to be poikilitic. Characteristically, the major minerals tend to be concentrated in crude, ill-defined layers. At some places the tabular minerals, such as gedrite and biotite, show a definite preferred orientation.

The major minerals are anhedral and are intergrown in a mosaic pattern. The cordierite forms equant nearly colorless grains about 0.3 mm in diameter that are slightly poikilitic and contain small subrounded inclusions of quartz, magnetite-ilmenite, zircon, and, rarely, other accessory minerals. The zircons have narrow pleochroic halos. All cordierite is partly clouded, veined, or rimmed by alteration minerals (pinite), and some is intensely altered. The cordierite from two specimens (columns 1 and 6, table 19) has an n_y of 1.545 ± 0.003, is optically negative, and has a large optic angle. It generally can be distinguished from plagioclase by its higher refringence, cloudy appearance, and pinitization and from quartz by its cloudy appearance, alteration, and absence of strain shadows. Gedrite forms subhedral, anhedral, or, rarely, fibrous grains that are commonly slightly larger than the associated cordierite grains. It is faintly pleochroic, ranging from colorless or light yellowish brown to light brown. Three samples gave the following range in refractive index: $n_z = 1.665 \pm 0.003$, 1.674 ± 0.003, and 1.676 ± 0.003. Locally the mineral is partly altered to chlorite. Quartz has moderately well defined strain shadows and commonly forms discrete anhedral grains; locally it is poikilitically intergrown with cordierite.

Garnet, which varies widely in amount, is a pink or lavender variety that is nearly colorless or pale pink in this section; it is very poikilitic and contains abundant subrounded grains of quartz, feldspar, cordierite, and magnetite-ilmenite; locally it contains ragged flakes of biotite. Some crystals are skeletal. Commonly the garnets contain intersecting tiny fractures. The garnet specimen listed in column 13 of table 20 was determined by E. J. Young to have the following composition: 42 percent almandite, 30 percent pyrope, and 28 percent spessartite. It contains 2.4 percent Mn, 0.97 percent Ca, 3.4 percent Mg, and 23 percent Fe. (Quantitative spectrochemical analyses by Nancy M. Conklin, 1960.)

The biotite is a light pleochroic variety that ranges generally from grayish yellow to moderate reddish brown and forms ragged small subhedral flakes. The biotite specimen listed in column 6 of table 20 has an n_y of 1.615±0.003 and that listed in column 13 has an n_y of 1.629±0.003. Cummingtonite forms nearly colorless faintly pleochroic anhedral or subhedral crystals that are commonly intergrown poikilitically with quartz and plagioclase. It is optically positive and has a large optic angle: $Z \wedge c = 20°$. The specimen listed in column 13 contains cummingtonite having a $n_z =$ 1.664±0.003. The plagioclase in the cordierite-gedrite assemblage is oligoclase in roughly equant anhedral grains that are intergrown with quartz and cordierite. The plagioclase that occurs in the cummingtonite-bearing assemblage is calcic and in three specimens ranges from An_{57} to An_{83}. It forms clear anhedral crystals having generally well defined albite or pericline twins, or combinations of the two. Some grains are poikilitic and contain small subrounded inclusions of quartz and magnetite-ilmenite.

Hornblende was noted in two thin sections (table 20). It forms anhedral or subhedral crystals and is pleochroic, ranging from light yellow to moderate bluish green. It is intimately intergrown with cummingtonite, and some grains consist of the two minerals in structural continuity. The boundaries between the minerals appear to be sharply transitive. Dusky-green spinel occurs as a local anhedral mineral scattered through the inner parts of some cordierite grains. Apatite, tourmaline, pyrrhotite, calcite, zircon, monazite, and magnetite-ilmenite are common accessory minerals.

The textures of the cordierite-amphibole geniss are interpreted to indicate that the constitutent minerals crystallized almost simultaneously. During crystallization, garnet, cordierite, and, at places, other major minerals poikilitically incorporated the minor minerals to produce the commonly observed poikiloblastic textures.

CALC-SILICATE GNEISS AND RELATED ROCKS

CHARACTER AND OCCURRENCE

Rocks that consist dominantly of calcium-iron silicates are called calc-silicate gneiss in this report. They include a variety of rocks of widely variable composition and structure that can be grouped into two broad general types. One type—skarn—consists mainly of dark silicate minerals, principally garnet, clinopyroxene, hornblende, and epidote. These rocks are nearly massive and somewhat variable in grain size, and tend to form rather small podlike bodies. The other type—light-colored calc-silicate rocks—consists of light-colored silicate minerals or of both light- and dark-colored silicate minerals that are conspicuously interlayered. Quartz, epidote, plagioclase, and scapolite as well as garnet, hornblende, clinopyroxene, and epidote are characteristic minerals. This type tends to form rather long, thin layers but also occurs in blunt masses. In general, the two types of rocks occur together in the district, although one type or the other is generally predominant in any particular body. The separate types are not distinguished separately on plate 1. Both types of rocks and particularly the distinctly layered calc-silicate gneiss are intimately associated with amphibolite; accordingly, some amphibolite is present within most of the bodies that are mapped as calc-silicate gneiss on plate 1. Quartzite is intercalated with some of the calc-silicate gneiss bodies on the north slope of Pewabic Mountain, in the south-central part of the district (pl. 1).

The calc-silicate gneisses are scattered throughout the microcline and biotite gneiss units as concordant pods or layers that range from a few inches to almost a mile in length. Many podlike bodies occupy the crests of small folds; the more continuous layers locally constitute stratigraphic marker beds on fold limbs. The contacts with the enclosing rocks are gradational, particularly with amphibolite. At many localities massive aggregates of dark silicate minerals grade laterally into distinctly layered conformable calc-silicate rocks and thence into biotite gneiss. Possibly the calc-silicate gneisses also grade into microcline gneiss, but such relationships have not been definitely proved because of poor exposures and the presence of pegmatite at nearly all the contacts.

The calc-silicate gneisses are the most variable rocks in the district; indeed, their variability is one of the diagnostic features by which they can be distinguished from other rock types. Their compositions vary not only from body to body but also from layer to layer within an outcrop. The skarns are red and dark gray or greenish black generally massive rocks. At most localities they are fine or medium grained and nearly equigranular, but some garnet skarn is coarse grained and inequigranular. The layered light-colored rocks are green, brown, and white or are conspicuously color banded; they are generally fine or medium grained and equigranular. The layers range from a fraction of an inch to as much as a foot in thickness, and contacts between layers may be either sharp or gradational.

PETROGRAPHY

The principal minerals in the calc-silicate gneisses are combined in almost any proportions, but in general they can be grouped into a few characteristic mineral assemblages. The skarns have the assemblages andraditic garnet-clinopyroxene, andraditic garnet-clinopyroxene-quartz, and clinopyroxene-hornblende-epidote; these rocks grade into feldspathic skarns containing both garnet and pyroxene. A variety of skarn that occurs in the biotite gneiss unit in the southwestern part of the district has the assemblage spessartite-quartz-magnetite and contains varietal hornblende and cummingtonite(?). Similar rocks have been noted in the adjacent Idaho Springs district (R.H. Moench, oral commun., 1961) and in the Chicago Creek district (Harrison and Wells, 1959, p. 8–9). A common variety of layered calc-silicate gneiss in the district has the assemblage clinopyroxene-hornblende-epidote-plagioclase-quartz; locally scapolite occurs instead of all or part of the plagioclase and quartz. Other calc-silicate gneisses contain garnets that consist mainly of the grossularite molecule, quartz, and plagioclase. Approximate modes of selected samples that are representative of the assemblages are given in table 21, along with modes of quartzite that is associated locally with the calc-silicate gneisses.

Garnets from the calc-silicate gneiss are typically anhedral and moderately or highly poikilitic, enclosing small grains of pyroxene, hornblende, epidote, quartz, and, locally, other minerals. They vary widely in chemical composition (table 22). Most are andradite-grossularite varieties, and their compositions range from 56 percent andradite, 30 percent grossularite, and 44 percent spessartite to 11 percent andradite, 87 percent grossularite, and 2 percent spessartite. The garnets in the spessartite-quartz-magnetite rocks consist of more than 80 percent of the spessartite molecule.

Pyroxene forms anhedral grains; commonly it is partly altered to hornblende. In the skarns it is a moderate-green or moderate bluish-green monoclinic variety having moderate pleochroism. It has extinction angles ($Z \wedge c$) of 50° or more and optic angles (2V) of slightly more than 60°. In the layered lighter calc-silicate gneisses, it is a moderate or pale-green variety having smaller extinction angles. The chemical compositions of the pyroxenes are not known, but they probably belong mainly in the diopside-hedenbergite fields.

Hornblende occurs as anhedral or subhedral grains and as a patchy alteration product of pyroxene. In the skarns it is characteristically a dusky-green or bluish-green very pleochroic variety, but in the more felsic rocks it is a lighter green variety. Quartz as irregular anhedral grains intergrown with other major minerals occurs nearly everywhere in the calc-silicate gneisses; at places it fills interstices between or within garnet, pyroxene, or hornblende. Epidote also is nearly as prevalent. It occurs as granular grains, commonly aggregated, that form a mosaic pattern with other minerals.

Plagioclase is a major mineral in all calc-silicate gneisses except skarn. It has well-defined albite and pericline twins, is moderately clear, and ranges in composition from calcic oligoclase to bytownite. Scapolite occurs as anhedral grains that are intergrown with pyroxene in a mosaic pattern in a few calc-silicate gneisses in the south part of the district and occurs sparsely in the calc-silicate gneiss body on the east slope of Nevada Hill about 1,000 feet west of Central City (pl. 1). The n_o of scapolite from five separate localities ranges from 1.586 to 1.589, indicating a composition of approximately Me_{65} Ma_{35}, according to the data of Winchell (1948, p. 294). Microcline and magnetite-ilmenite are variable components, sphene is less common, and calcite occurs in small amounts in some rocks, especially those containing scapolite and sparse quartz. Other minor accessory minerals are unidentified sulfides, apatite, and zircon.

The rocks are nearly equigranular and have wholly crystalloblastic textures; these characteristics indicate virtually contemporaneous crystallization. The major minerals are intergrown typically to form mosaic patterns. Garnet and, less commonly, pyroxene and hornblende tend to be poikilitic and include a wide variety of other minerals.

ORIGIN OF LAYERED ROCKS

The layered rocks of the Central City district are interpreted by us to be of metasedimentary origin. The mineralogic assemblages that formed depended mainly upon the aggregate composition of the original rocks and probably only to a minor extent on the addition and subtraction of materials by fluids of ultrametamorphic and magmatic origin. Probably the microcline gneiss was derived from feldspathic sandstones (arkose?), and the biotite gneisses were derived from graywacke sandstones and shaly sediments. The origin of the other less abundant rocks intercalated with the dominant gneiss units is less certain, but the amphibolite, calc-silicate gneisses, and cordierite-amphibole gneisses were formed probably from carbonate-rich sediments. Because the rocks have been thoroughly recrystallized and reconstituted during intense dynamothermal metamorphism, however, some aspects of the origin of the rocks remain largely conjectural. Possibly studies in other parts of the Front Range and in adjacent mountain ranges of layered rocks of lower metamorphic grade will provide more definitive answers to questions on the nature of the original materials and the kind and extent of the metamorphic changes.

The conclusions on origin reached in this report differ in some important details from those of earlier workers, particularly with respect to the derivation of the microcline gneiss. The biotite gneisses of the Idaho

TABLE 21.—*Approximate modes, in volume percent, of representative assemblages of calc-silicate gneiss and related rocks*

[Tr., trace]

Sample	1	2	3	4	5	6	7	8	9	10	11
Field No.	S47-C-52	S191-52	S47-A-52	S47-B-52	S47-D-52	S48-52	S49-52	S463-1-52	S214-A-52	S212-B-52-1	S212-B-52-2
Garnet	92	68	35	1		19		7		2	
Clinopyroxene	4		23	11	2	1	Tr.	30	57	33	1
Hornblende	Tr.		1	14	64		15	3.5	9	3	6
Quartz	4	24	40	Tr.	2	35	39	25		23	59
Epidote	Tr.	8		42	2	12	2	5.5	7	10	8
Plagioclase				26	26	33	43	24.5	24	27	26
Scapolite											
Microcline						Tr.	1				
Sphene	Tr.			Tr.	2	Tr.				Tr.	Tr.
Calcite											
Sulfides	Tr.		Tr.								
Magnetite-ilmenite		Tr.	1	6	2	Tr.	Tr.	4.5	3	2	Tr.
Apatite				Tr.	Tr.	Tr.	Tr.		Tr.		
Zircon					Tr.	Tr.	Tr.				
Chlorite						Tr.					
Composition of plagioclase				An_{25-58}	An_{34}	An_{35-47}			An_{93}	An_{77}	Calcic
Average grain size millimeters			0.5		0.5	0.45			0.05–1.0	0.3	0.3

Sample	12	13	14	15	16	17	18	19	20	21
Field No.	S639-B-52	S638-A-52	S41-A-53	1-160	1-60	2-198	2-225	2-259	2-307	2-308
Garnet								0.5	6	
Clinopyroxene		7	15	46	36	34	29	10		
Hornblende	11	5	1		10	Tr.	11	11		
Quartz	24	43	39	Tr.	6	Tr.	Tr.	5	94	94
Epidote	Tr.	5	2	30	4.5	11	15	22	Tr.	
Plagioclase	62	40	42	8	3	17	34	40	Tr.	
Scapolite					31	32	.5	7		
Microcline	1	Tr.	Tr.	13	Tr.		6	Tr.	Tr.	
Sphene	1	Tr.	1	2	5	2	4	3		
Calcite					4	4	.5	Tr.		
Sulfides										
Magnetite-ilmenite			Tr.			Tr.		1		6
Apatite	.5				.5	Tr.	Tr.	.5		
Zircon									Tr.	
Chlorite	.5			1	Tr.	Tr.		Tr.	Tr.	
Composition of plagioclase		An_{25}								
Average grain size millimeters									0.5	0.3

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 21

1. Garnet skarn from crest of Quartz Hill. The rock contains a reddish-orange garnet and a moderate-green pyroxene; quartz appears to fill vugs in garnet. Garnet has a composition of 56 percent andradite, 30 percent grossularite, and 14 percent spessartite and contains 0.66 percent manganese.
2. Garnet-quartz-epidote rock from Quartz Hill southeast of Wyandotte mine. Garnet is reddish orange and has a composition of 52 percent grossularite, 39 percent andradite, and 9 percent spessartite.
3. Garnet-pyroxene-quartz rock; locality same as loc. 1. Clinopyroxene is yellowish green to bluish green and has a large optic angle.
4. Epidote-plagioclase-hornblende-pyroxene rock; locality same as loc. 1. Hornblende is very pleochroic, ranging from light yellowish green to dusky bluish green. Pyroxene has the following partial optical properties: $Z\wedge c$=ca.54°; 2V=ca. 64°. n_z of epidote=1.733±0.003.
5. Hornblende-plagioclase-pyroxene rock; locality same as loc. 1. Hornblende appears same as in loc. 4 n_y=1.693±0.003.
6. Quartz-plagioclase-garnet-epidote rock from same body as in loc. 1.
7. Plagioclase-quartz-hornblende rock from outer part of calc-silicate gneiss body at loc. 1. Rock is adjacent to a quartz-rich amphibolite that nearly surrounds skarn and related rocks.
8. Calc-silicate gneiss from float near Wood mine, Quartz Hill. Garnet is reddish orange; clinopyroxene is moderate to brilliant green and partly altered to hornblende.
9. Feldspathic pyroxene skarn from mapped irregular-shaped body of layered calc-silicate gneisses on south slope of Quartz Hill. Contains graphic intergrowths of vermicular pyroxene in plagioclase. Clinopyroxene has the following partial optical properties: n_y=1.733±0.003; 2V=ca. 66°; X=light yellowish green, Y=moderate bluish green, Z=moderate green. Pyroxene is partly altered to hornblende. Hornblende is very pleochroic, ranging from yellowish green to dusky bluish green n_y=1.719±0.003, n_z=1.725±0.003; optic angle is small.
10. Pyroxene-plagioclase-quartz rock from western part of same body as in loc. 9. Clinopyroxene is light yellowish green to light bluish green; n_y=1.733±0.003; 2V=ca. 65°. Hornblende is pleochroic, ranging from light yellowish green to dark brownish green; n_y=1.698±0.003.
11. Felsic layer from same outcrop as in loc. 10.
12. Plagioclase-quartz-hornblende gneiss from zigzag-shaped body of calc-silicate gneiss northeast of the Patch, Quartz Hill. Rock is interlayered with green epidote-rich rocks, garnet-bearing rocks, and amphibolite.
13. Light-brown felsic gneiss from the same calc-silicate gneiss body in as loc. 12.
14. Greenish-gray calc-silicate gneiss from dump of shaft 150 ft west of Barker shaft, northwest slope of Quartz Hill. Clinopyroxene is a moderate-green slightly pleochroic variety; hornblende is a dusky-green variety. Rock is probably interlayered with amphibolite.
15. Pyroxene-epidote rock from north slope of Pewabic Mountain.
16. Pyroxene-scapolite-hornblende rock locality, same as loc. 15. Scapolite is meionite of approximate composition $Ma_{20}Me_{80}$.
17. Pyroxene-scapolite-plagioclase-epidote rock from north slope of Pewabic Mountain.
18. Layered pyroxene-plagioclase-epidote-hornblende rock from Pleasant Valley area, southeast part of district.
19. Layered feldspathic epidote-pyroxene-hornblende rock near loc. 18. The hornblende is a dusky-green variety; the pyroxene is moderate green.
20. Quartzite from north slope of Pewabic Mountain. Rock is associated with calc-silicate gneiss.
21. Quartzite from same rock body as in loc. 20.

Springs Formation were considered by everyone who has mapped in the Front Range to be metamorphosed shaly sediments (Lovering and Goddard, 1950, p. 20). The calc-silicate gneisses were generally considered to represent limy layers of variable composition within the main bulk of shaly sediments that formed the Idaho Springs Formation (Spurr, Garrey, and Ball, 1908, p. 44). The hornblende gneisses (amphibolites of this report), on the other hand, were considered by some as metamorphosed igneous rocks (Spurr, Garrey, and Ball, 1908, p. 45–46; Lovering and Goddard, 1950, p. 20); and by others, mainly as metamorphosed sedimentary rocks (Wahlstrom and Kim, 1959, chart opposite p. 1222). All earlier workers in the central part

TABLE 22.—*Composition of garnets from calc-silicate gneisses*

Sample	1	2	3	4	5	6	7
Field No.	EWT-192-53	S648-53	S630-1-52	S191-52	S3-103	Mx-408	M607-1B
Unit cell edge (A_0)	11.928±0.005	11.906±0.003	11.920±0.003	11.908±0.0005	11.869±0.003	11.614±0.002	11.600±0.002
Refractive index	1.830±0.003	1.820±0.003	1.810±0.003	1.799±0.003	1.755±0.0005	1.805±0.004	1.798±0.004
Assemblage	Garnet-clino-pyroxene.	Garnet-clino-pyroxene-quartz.	Garnet-epidote-quartz-clino-pyroxene-horn-blende.	Garnet-quartz-epidote.	Garnet-quartz-plagio-clase-scapolite.	Garnet-quartz-magnetite.	Garnet-quartz-magnetite.
Molecular composition [1]							
Grossularite	30	34	46	52	87	------------	------------
Spessartite	14	17	8	9	2	[2] 92	[2] 82
Andradite	56	49	46	39	11	------------	------------
Quantitative spectrochemical analyses, in percent [3]							
Manganese	0.66	1.3	1.2	------------	.26	12.1	31.5
Calcium	------------	24.0	28.0	------------	27.0	------------	------------
Magnesium	------------	.043	.04	------------	.24	------------	------------
Iron	------------	12.0	14.0	------------	3.8	------------	------------

[1] In percentage of end members, as calculated from data on synthetic end members by Skinner (1956) and using method of Stockwell (1927); determined by E. J. Young.

[2] Remainder is mainly almandite and pyrope molecules.

[3] Analyst: N. M. Conklin.

DESCRIPTIONS

1. Skarn body on crest of Quartz Hill.
2. Small body of skarn half a mile west of crest of Nigger Hill.
3. Zigzag body of calc-silicate gneiss on north slope of Quartz Hill.
4. Small body on south slope of Quartz Hill southeast of Wyandotte mine.
5. Calc-silicate gneiss body on east slope of Nevada Hill 1,000 ft west of Central City.
6. Skarn body from Bellevue Mountain, 1 mile southwest of Central City district.
7. Small skarn body in pegmatite 1,000 ft west of head of Russell Gulch, southwestern part of district.

of the Front Range considered the microcline gneiss (of this report) as a metamorphosed igneous rock, but we class it as metasedimentary. Bastin and Hill (1917, p. 31) called the rock granite gneiss and stated: "The granite gneiss is believed to be a granitic intrusive rock that has received a foliated structure as a result of dynamic metamorphism subsequent to its intrusion." In the field, these writers apparently failed to clearly distinguish the microcline gneiss from pegmatite and associated granite gneiss and accordingly erroneously interpreted apophyses of the microcline gneiss to penetrate the biotite gneisses of the Idaho Springs Formation. Later, Lovering and Goddard (1950, p. 23) similarly considered the microcline gneiss as igneous in origin. They show the microcline gneiss on their map of the Front Range mineral belt (Lovering and Goddard, 1950, pl. 2) as granite gneiss.

BIOTITE GNEISS

Unquestionably the biotite gneisses are metasedimentary in origin, for they have the wide areal extent and the lithologic variations across layers that are characteristic of many sedimentary-rock successions. In general they satisfy the requirements for blanket-type sedimentary units (Krynine, 1948). Although mapping on a regional scale is inadequate to determine width-to-thickness ratios for units of the biotite gneisses, the regional maps of Lovering and Goddard (1950, pls. 1 and 2) and our own reconnaissance investigations are adequate to show that the ratios are large and hence are similar to those of more recent sedimentary-rock units. The interlayering of biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss on different scales and the local thin layers of garnetiferous biotite gneiss and quartz-rich biotite gneiss indicate that the original sediments were moderately well bedded. Some of the gradations across strike may represent original graded bedding, but if so, the graded bedding has been so modified by subsequent deformation and reconstitution that it cannot be distinguished with certainty.

The biotite-quartz-plagioclase gneiss from the Central City district is distinguished chemically by having an excess of Na_2O over K_2O (table 23 and fig. 5). Such an excess of Na_2O over K_2O is characteristic of certain graywackes (columns 3 and 4, table 23; Pettijohn and Bastron, 1959, p. 596–597), particularly in the eugeosynclinal environment, and distinguishes these rocks chemically from shales or sandy sediments derived as residual weathering products. In detail, the biotite-quartz-plagioclase gneiss is remarkably similar chemically to graywacke sandstones of Mesozoic age in the Wellington district, New Zealand (column 2, table 23). The correlation with these rocks is even more remarkable when it is noted that the graywackes in New Zealand contain shaly interlayers that are equivalent chemically to the sillimanitic biotite-quartz gneisses of the Central City district, as discussed in following paragraphs. Further, the biotite-quartz-plagioclase gneiss at Central City is similar chemically to the "least altered paragneiss" of Engel and Engel (1953) in the Adirondack Mountains (column 8, table 23).

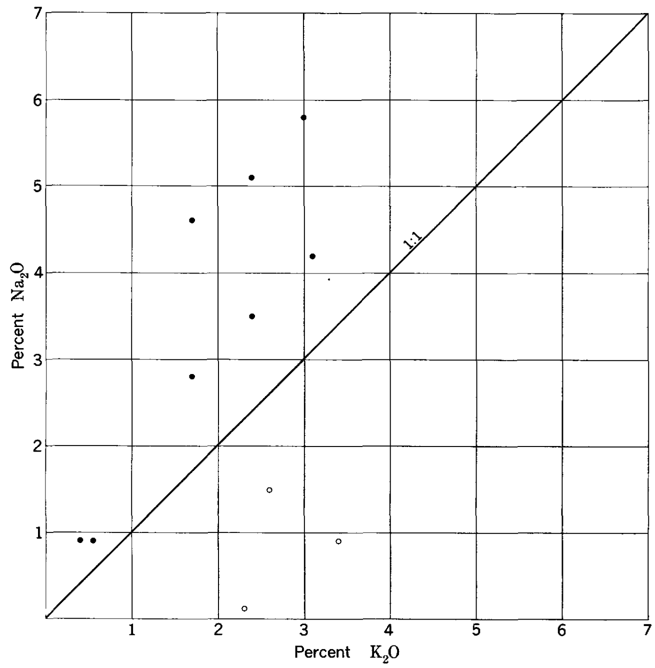


FIGURE 5.—Na_2O/K_2O content of samples of biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss. Solid circles: biotite-quartz-plagioclase gneiss; open circles: sillimanitic biotite-quartz gneiss. Analyses by flame photometer; analyst: J. B. McHugh.

The sillimanitic biotite-quartz gneiss that is interlayered with the biotite-quartz-plagioclase gneiss, on the other hand, contains K_2O in excess of Na_2O. Otherwise the rock differs but little chemically from biotite-quartz-plagioclase gneiss. The sillimanitic biotite-quartz gneiss closely resembles shaly sediments in chemical composition (column 7, table 23), and as stated previously, it is remarkably similar chemically to the argillite interlayered with graywacke in New Zealand (column 6, table 23).

The similarities in composition of the biotite gneisses from the Central City district with unmetamorphosed graywackes and shaly sediments may be indicative that the parent sediments of the biotite gneisses were deposited in an environment such as that common to graywacke and argillite deposition. The sediments could have been derived from either granitic or metamorphic terranes. The alteration of biotite-quartz-plagioclase

TABLE 23.—*Comparison of average chemical composition, in percent, of biotite gneisses from the Central City district with some graywacke sandstones, argillites, average pelitic rock, and a paragneiss*

[Tr., trace]

Analysis	1	2	3	4	5	6	7	8
SiO_2	70.54	71.1	69	64.7	68.23	64.2	60.76	70.90
Al_2O_3	12.97	13.9	13	14.8	15.32	16.3	16.73	12.17
Fe_2O_3	2.30	Tr.	} 5.4	{ 1.5	2.11	.72	2.53	1.31
FeO	3.52	2.7		3.9	5.36	4.1	3.85	4.12
MgO	1.58	1.3	2.5	2.2	2.10	1.9	2.49	2.32
CaO	2.49	1.8	4.4	3.1	.69	1.4	1.74	1.55
Na_2O	3.55	3.7	3.2	3.1	1.19	2.2	1.82	3.74
K_2O	1.57	2.3	2	1.9	2.84	3.7	3.41	2.87
H_2O+	.49	1.9	----------	2.4	1.00	3.4	3.43	.21
H_2O-	----------	.26	----------	.7	----------	.55	----------	.05
TiO_2	.50	.50	----------	.05	.80	.70	.81	.32
P_2O_5	.12	.10	----------	.2	.01	.14	----------	----------
MnO	----------	.05	----------	.1	----------	.06	----------	.04
CO_2	----------	.12	----------	1.3	----------	Tr.	1.65	----------
SO_3	----------	----------	----------	.4	----------	----------	----------	----------
S	----------	Tr.	----------	.2	----------	.24	----------	----------
C	----------	.09	----------	----------	----------	.44	----------	----------
Total	99.63	99.8	99.5	101.0	99.65	100.1	99.22	99.60

1. Calculated chemical composition of average biotite-quartz-plagioclase gneiss from Central City district. (See also table 16.)
2. Composite graywacke sample from Wellington district, New Zealand (Reed, 1957, p. 16).
3. Average composition of sandstones (graywackes) from eugeosynclinal environments arithmetic mean of 7 major oxides (Middleton, 1960, p. 1011).
4. Average graywacke (Pettijohn, 1957, 23 analyses).
5. Calculated chemical composition of average sillimanitic biotite-quartz gneiss from Central City district. (See also table 16.)
6. Composite argillite sample from Wellington district, New Zealand (Reed, 1957, p. 28). Argillite is intercalated with graywacke represented by analysis 2 above.
7. Average pelitic rock (Shaw, 1956, p. 928).
8. Analysis of composite sample of 24 least altered layers of quartz-biotite-oligoclase gneiss (sample No. Q6A) from Adirondack Mountains, N.Y. (Engel and Engel, 1953, p. 1085).

gneiss and sillimanitic biotite-quartz gneiss may reflect deposition on a shelf area adjacent to a rising foreland of plutonic rocks, during which the shaly and sandy phases were separated largely by lateral transportation in a manner similar to that postulated by Reed (1957, p. 46) for the New Zealand rocks. In this environment the sediments could have been transported from relatively shallow water and redeposited by turbidity currents in deep water. Such an interpretation is consistent with the evidence provided by the varying scale of interlayering of the two types of gneisses and by the lenticularity and gradation of particular layers of each rock type.

The sodic nature of the parent graywackes can be accounted for in several ways, as discussed by Engel and Engel (1953, p. 1086–1091) and Pettijohn and Bastron (1959, p. 596–598), but it seems probable to us that the sodic content was inherited from the parent sedimentary rocks. The parent rock of the biotite-quartz-plagioclase gneiss probably was coarser grained and contained more detrital feldspar than that of the sillimanite-bearing gneiss. In contrast, the parent rock of the sillimanite-bearing gneiss probably contained notably greater amounts of clay minerals or mica than that of the biotite-quartz-plagioclase gneiss. These differences in mineralogy of the original sediments are reflected closely by the mineralogy of the respective metamorphic rocks observed today.

MICROCLINE GNEISS

The microcline gneiss is interpreted from field relations and chemical composition to be of metasedimentary derivation also. Probably the original sedimentary rock was a feldspathic sandstone that had a high Na_2O/K_2O ratio.

Relations observed in the field strongly support a sedimentary origin for the microcline gneiss. As a whole, the unit forms a thick persistent layer that resembles known sedimentary rocks. The layer is as much as 3,000 feet thick, perhaps more, and extends along a strike length of at least 15 miles. Thus, it approaches the dimensions of a blanket-type deposit. Other layers of the same rock in the environs of Central City are less persistent but are nevertheless generally widespread. Both on a regional scale and in small detail, the microcline gneiss units are wholly conformable to adjacent rocks. The contacts against biotite gneiss and other rocks are relatively sharp but gradational across a few inches. Pinches and swells, which are common, have no apparent relation to their structural position on folds and thus appear to reflect original thicknesses of sedimentary rocks rather than variations resulting from intrusive mechanisms—for example, in phacoliths. Pinchouts are abrupt, lacking apparent interfingering, evidence which suggests that the units are wedge-shaped deposits.

Internally, the units of microcline gneiss are layered on different scales and contain moderate or abundant lenses of other rocks, which also apear to be predominantly metasedimentary in origin. The layering is both thick and thin. The thick layering is on a scale of tens of feet and consists of compositional differences between layers equivalent to the range from a quartz monzonite to a quartz diorite. The thin layering is marked by segregations of the light- and dark-colored minerals into layers an inch or less thick.

The included rocks are biotite-quartz-plagioclase gneiss having a high Na_2O/K_2O ratio, amphibolite, calc-silicate gneiss, and cordierite-amphibole gneiss. The biotite gneiss forms a few layers of considerable areal extent and local lenses. One layer is about 250 feet thick and persists over an area of at least a square mile; it grades transitionally into the microcline gneiss. Amphibolite is widespread and is confined to units of the microcline gneiss. It increases in abundance and in proportion to the microcline gneiss eastward along the Quartz Hill layer. Calc-silicate gneiss and cordierite-amphibolite gneiss form local, small lenses. The included rocks are widely dispersed through the Quartz Hill layer of microcline gneiss, but each rock type appears to occur at certain stratigraphic positions in the unit.

The microcline gneiss has an average mineralogic composition of a granodiorite. It resembles the biotite-quartz-plagioclase gneiss chemically but it contains more silica and less (total) iron, magnesia, and calcium and has a similar Na_2O/K_2O ratio (fig. 6).

The composition of the microcline gneiss indicates that it was probably derived from a feldspathic sandstone. If the metamorphism was mostly isochemical, as seems probable, the sandstone must have contained sodic feldspar in excess of potassic feldspar; thus, it differed from typical arkoses (Pettijohn, 1957) in containing Na_2O in excess of K_2O.

The environment of deposition must have been similar to that for the graywackes and shaly sediments that yielded the biotite gneiss but was such that the sediments were cleaner sorted and probably were slightly coarser grained. The deposits could have formed relatively close to rising landmasses of acid plutonic rocks. Thus, they might represent sediments deposited nearer the shore than were the graywackes and associated rocks.

OTHER ROCKS

The origin of the minor rock units in the district—amphibolite, calc-silicate gneiss, and cordierite-amphi-

732-809 O—64——3

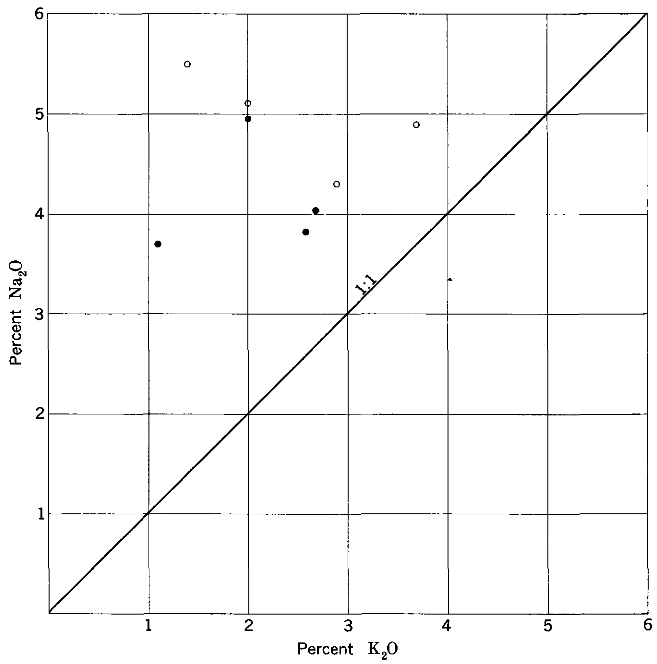


FIGURE 6.—Na_2O/K_2O content of samples of microcline gneiss. Solid circles: chemical analyses by L. C. Peck laboratory. Open circles: analyses by flame photometer; analyst: J. B. McHugh.

bole gneiss—is uncertain, and further studies are needed. However, the rocks were derived probably from calcareous sedimentary rocks of varied composition. In contrast to rocks of the major units, metasomatism may have changed the original compositions of these minor rocks substantially. If so, the metasomatism probably took place during recrystallization and reconstitution that accompanied the plastic deformation.

Amphibolite is interpreted from its field associations to be of probably metasedimentary origin, but it could be a metamorphosed mafic igneous rock (basalt?) or a metasomatic product. Possibly, it has more than one mode of formation. The close association of amphibolite with calc-silicate gneisses suggests that the two rocks have a common mode of origin. Perhaps the amphibolite was derived mainly by metamorphism of rather homogeneous calcareous and magnesian rocks, whereas the calc-silicate gneisses were derived from cogenetic siliceous impure calcareous rocks. Evidence for such a mode of origin is supported by the close association of quartz gneisses, which undoubtedly represent orthoquartzites and calc-silicate rocks. (See table 21.)

Iron metasomatism may have been a significant factor in producing the skarns of the district. Some of the rocks consist mainly of an andraditic garnet and, accordingly, are too rich in iron to have formed from any common carbonate rock. They resemble skarns from other areas that are clearly of metasomatic origin, as in the Adirondack Mountains (Leonard and Buddington, 1964), the New Jersey-New York Highlands (Sims and Leonard, 1952), and central Sweden (Geijer, 1917). As the skarns are not spatially associated with observed igneous rocks, the postulated metasomatic solutions must have been derived from mobile volatile phases that accompanied the plastic deformation of the region. Such solutions could have selectively replaced carbonate rocks, perhaps in a manner similar to the metasomatic replacement of carbonate rocks by iron in the Triassic lowlands of New Jersey and Pennsylvania. (See Hotz, 1950, for a discussion of origin.)

The origin of the cordierite-amphibole gneisses is equally if not even more puzzling than that of the amphibolites and calc-silicate gneisses. These gneisses are highly magnesian rocks that have no common unmetamorphosed analog. Tentatively it is inferred that they were formed by metasomatism of amphibolites or closely associated mafic rocks by solutions derived during deformation and migmatization, but an origin through metamorphism of uncommon magnesia- and iron-rich chemical sediments cannot be ruled out. The source of the magnesia needed for a metasomatic origin is highly conjectural, but it could have been derived by leaching from the amphibolites during metamorphism in a manner similar to that proposed by Bugge (1943, p. 99–103) for the cordierite-anthophyllite rocks of the Arendal district, Norway. Isochemical metamorphism of original magnesia-rich sedimentary rocks has been proposed by Hietanen (1943, 1947) for cordierite-rich rocks (kinzigites) in the Kalanti and Turkin districts, Finland.

PEGMATITE

Pegmatite of simple mineralogy is very prevalent in the Central City district. It is interleaved with the biotite gneisses to form migmatite and occurs as discrete bodies in these and other metamorphic rocks. To a lesser extent it forms small bodies associated with each of the intrusive rocks.

Nearly all the pegmatite shown on plate 1 is in the biotite gneiss units and other layered rocks. It is equivalent to the unit of granite gneiss and pegmatite recognized in the central part of the Front Range (Moench, Harrison, and Sims, 1962, pl. 1) but differs from that unit as defined by Harrison and Wells (1956; 1959) by being coarser grained and less foliated. Much of the pegmatite is contemporaneous with or older than granodiorite and associated intrusive rocks, but the age of some is uncertain. Possibly some of the bodies in the gneisses are genetically related to the various intrusive rocks, each of which has cogenetic pegmatites, but identification of specific pegmatites is difficult because of a general lack of diagnostic lithologic and structural features.

PEGMATITE AND ASSOCIATED GRANITE GNEISS

OCCURRENCE AND CHARACTER

Pegmatite and associated granite gneiss constitutes at least 20 percent and probably more of the volume of the biotite gneiss unit and an estimated 5 percent or more of the microcline gneiss unit in the district. It occurs in a variety of forms, but typically as (1) thin, lenticular stringers and vein-form bodies along the foliation of the biotite gneisses to constitute migmatite, (2) discrete generally conformable tabular bodies of varying size in the same schistose rocks, (3) generally thin stringers that anastamose through the relative massive rocks such as amphibolite and calc-silicate gneiss, and (4) conformable lens-shaped bodies along contacts of all the layered rocks. Most of the bodies mapped on plate 1 are the larger discrete masses in biotite gneisses.

The pegmatite forms less distinct units than other rock types in the district as a result of being intermixed in different degrees with the layered rocks. Such intermixtures are especially characteristic in the biotite gneiss unit. Consequently, except for some small bodies that can be readily delineated, the contacts of separate bodies commonly must be established arbitrarily. On the geologic map (pl. 1), we have drawn the contacts between pegmatite and biotite gneiss at the transition from rock containing distinctly more than 50 percent pegmatite to rock containing distinctly less than 50 percent pegmatite. For the most part the transition is relatively sharp and takes place across a width of a few feet or even a few inches. At places, though, the transition is gradual through several feet of migmatite into slightly migmatized biotite gneisses, as is typical in the Freeland-Lamartine district (Harrison and Wells, 1956).

As a consequence of containing biotite gneiss in varying proportions—as layers of various sizes or as shredded wispy streaks or lenses—the fabric of the pegmatite varies from massive to highly foliated. Relatively uncontaminated varieties are nearly massive and medium grained to coarse grained, although some medium-grained varieties have a slight foliation imparted by crudely alined tabular feldspar crystals. Where it contains intercalated biotite gneiss, the pegmatite generally has a distinct foliation, the degree of distinction depending on the amount of biotite and the abundance of wisps of country rock. The biotite has a well-defined preferred planar arrangement and tends to be concentrated in streaks; rarely, it is disseminated through the rock. The more gneissic varieties of pegmatite resemble the microcline gneiss in some respects, but they can generally be distinguished from it megascopically by having a much less regular layering and by the tendency for the mafic minerals to occur as lenticular wispy streaks in a leucocratic granite groundmass. Furthermore, the pegmatite differs petrographically by being generally more felsic than the microcline gneiss, as can be seen by comparing the modes of the two rocks.

PETROGRAPHY

The pegmatite and associated granite gneiss is a light-gray, yellowish-gray, or grayish-pink medium- to coarse-grained rock of variable grain size that consists predominantly of microcline, quartz, and plagioclase and contains minor amounts of biotite, muscovite, sillimanite, and, rarely, tourmaline, garnet, and other minerals. It ranges widely in composition—from potassic leucogranite to quartz monzonite—and includes rare magnetite-bearing silexites. In most places, however, it has the composition of a normal leucocratic granite. The modal variations of representative specimens of the rocks are listed in tables 24 and 25. Observations reported in table 24 were made from thin sections in the manner described on page C3. Observations reported in table 25 were made by modal analysis of sawed slabs a few inches in diameter. The flat surfaces were immersed in hydrofluoric acid for 5 seconds, washed in water, stained with sodium cobaltinitrite, and washed again. After staining, a point count was made by superposing a 1.5-mm grid on the smooth surfaces and using reflected light and a binocular microscope.

The rocks have an allotriomorphic granular texture. Microcline in anhedral laths forms crystals that are commonly 1–15 mm long. In most specimens it embays or veins plagioclase. The grains contain soda feldspar in perthitic intergrowths as strings, blebs, or irregular veinlets. In many samples microcline grains have narrow partial rims of albite. Plagioclase occurs as partly altered anhedral crystals that have approximately the same range in size as microcline. Typically the grains have simple twins. All grains have clear albite rims a fraction of a millimeter to a millimeter in width where the plagioclase is in contact with microcline. Myrmekite is well formed at places in parts of the albite rims. Quartz in anhedral crystals as much as 10 mm long embays both plagioclase and microcline; rarely it forms amoeboid grains. Without exception, it has conspicuous strain shadows. The varietal minerals are commonly associated more closely with plagioclase than with microcline. Biotite in subhedral plates is very common but rare in leucocratic massive varieties. It ranges from pale yellow to brownish red and is commonly partly altered to a green chlorite and iron oxides. Similarly, magnetite is very common. It is the dominant or only mafic mineral in some of the rocks, espe-

TABLE 24.—*Modes, in volume percent, of pegmatite and granite gneiss*

[Tr., trace]

	Granite gneiss					Pegmatite		
Sample	1	2	3	4	5	6	7	8
Field No.	2-55	78-55	S325-53	S449-53	D7	S636-A-53	4-247-1	S4-41
Microcline	37. 4	34. 7	36. 4	40. 0	54. 6	56. 5	56. 5	26. 7
Plagioclase	28. 6	27. 6	25. 4	22. 5	9. 3	6. 4	15. 6	43. 1
Quartz	34. 0	36. 2	37. 5	37. 3	28. 3	36. 3	25. 8	23. 7
Biotite	Tr.	. 2	. 1	Tr.	---	---	---	5. 9
Muscovite	---	. 5	---	---	7. 5	. 8	. 9	Tr.
Magnetite	Tr.	. 8	. 6	. 2	. 3	---	---	. 4
Tourmaline	---	---	---	---	---	---	. 4	---
Sillimanite	---	---	---	---	Tr.	---	. 8	. 1
Sphene	Tr.	Tr.	---	---	---	---	---	---
Zircon	---	---	---	---	---	---	Tr.	Tr.
Apatite	---				Tr.	---	Tr.	Tr.
Epidote	Tr.	---	---	---	Tr.	Tr.	---	---
Xenotime	---	---	---	---	---	---	---	. 1
Composition of plagioclase	An_{20}	An_{18}	An_{18}	An_{18}	---	---	---	---
Average grain size....millimeters	0. 7	0. 7	0. 3	0. 5	1. 0	2. 0	1. 0	0. 8

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 24

1. Pinkish-gray leucocratic granite gneiss from narrow body exposed at curve along State Highway 119 on the north edge of the district. The gneiss layer contains wisps of biotite gneiss.
2. Same layer as in loc. 1, but 700 ft northeast of highway.
3. Light-gray leucocratic granite gneiss within microcline-quartz-plagioclase-biotite gneiss unit near head of Prosser Gulch.
4. Granite gneiss similar to that in loc. 3 near head of Prosser Gulch.
5. Pinkish-gray leucocratic granite gneiss within biotite gneiss unit; collected from small body along road 3,000 ft west of top of Nigger Hill. Body contains common wisps of sillimanite.
6. Leucocratic pegmatite from large body on west side of Nigger Hill.
7. Yellowish-gray nearly massive pegmatite from hook-shaped body exposed in roadcut along State Highway 119 about 500 ft west of mouth of Silver Gulch.
8. Pegmatite adjacent to amphibolite north of Black Hawk.

TABLE 25.—*Approximate modes, in volume percent, of pegmatite*

[Tr., trace. Determined from flat slabs; 1,000 counts or more]

Sample / Field No.	1 S636-53	2 4-247-1	3 4-245	4 4-247	5 4-199	6 D-9	7 4-199-1	8 JC	9 S360-52
Microcline	74	69	48	43	45	30	28	5	---
Plagioclase	1	3	22	26	27	30	40	77	---
Quartz	24	27	25	29	27	40	31	4	80
Biotite	Tr.	Tr.	4	---	---	Tr.	. 5	10	---
Magnetite	Tr.	Tr.	Tr.	Tr.	1	---	. 5	---	20
Muscovite	1	Tr.	1	1	Tr.	Tr.	Tr.	1	---
Pyrite	---	---	---	---	---	---	Tr.	---	---
Sillimanite	Tr.	Tr.	Tr.	---	---	---	---	---	---
Tourmaline	---	1	---	1	---	---	---	---	---
Garnet	---	---	---	---	---	---	---	3	---
Xenotime	---	---	---	---	---	---	---	Tr.	---
Monazite	---	---	---	---	---	---	---	Tr.	---
Range in grain size millimeters	1-10	1-20	1-5	1-12	1-7	1-12	1-11	2-12	3-20
Average grain size do	3	3	2	3	3	4	2	5	6

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 25

1. Yellowish-gray massive leucocratic potassic granite pegmatite a few streaks of mafic minerals from dump of Monitor mine, Eureka Gulch area.
2. Yellowish-gray nearly massive leucocratic granite pegmatite from hook-shaped body exposed in roadcut along State Highway 119 about 500 ft west of mouth of Silver Gulch.
3. Yellowish-gray slightly foliated leucocratic granite pegmatite from mouth of Silver Gulch. Biotite concentrated mainly in streaks.
4. Yellowish-gray nearly massive leucocratic granite pegmatite; locally same a loc. 2.
5. Yellowish-gray massive leucocratic granite pegmatite from large body exposed on hill just west of mouth of Fourmile Gulch.
6. Grayish-yellow massive leucocratic granite pegmatite from long hook-shaped body in northwest part of district 1,500 ft north of Eureka Gulch.
7. Same as loc. 5.
8. White to very light gray massive syenitic pegmatite from Jasper Cuts area, four-fifths mile south of Central City. Biotite is coarse grained and occurs in streaks and clots. Xenotime and monazite form tiny crystals in biotite.
9. Magnetite-bearing silexite from upper Russell Gulch area.

cially in pegmatite within the microcline gneiss, and it is a minor component associated with biotite in other rocks.

Sillimanite occurs sparsely in pegmatite that lies within bodies of sillimanitic biotite-quartz gneiss. It forms irregular aggregates, generally intergrown with muscovite, or forms needles dispersed through plagioclase. Where it is in contact with microcline, the sillimanite locally has sheaths of muscovite; rarely, it has sheaths of quartz. Tourmaline is present in pegmatite within tourmaline-bearing biotite gneisses in a small area along North Clear Creek at the east edge of the district (columns 2 and 4, table 4). It is very pleochroic, ranging from pink to dark green, and forms subhedral crystals as much as 5 mm long. Sphene and epidote are local, scarce minerals.

A variety of pegmatite that is apparently closely related in age to the common pegmatite described in foregoing paragraphs but that differs from it in containing substantial xenotime and monazite and containing plagioclase almost to the exclusion of microcline occurs in an area of about a quarter of a square mile near Jasper Cuts, four-fifths of a mile south of Central City. This pegmatite is light gray to nearly white, massive, and generally coarse grained. It contains biotite and, locally, garnet and muscovite as varietal minerals. (See column 8, table 25.) Locally, xenotime and monazite are abundantly dispersed through coarse-grained biotite aggregates, but they are still more abundant in migmatite associated with the pegmatite. These deposits of rare-earth minerals are of some economic interest and have been described in a previous paper (Young and Sims, 1961).

In order to compare the microcline of the pegmatite and associated granite gneiss unit with that in the microcline gneiss, quantitative studies were made of two samples (table 26). Optical data were determined on two separate fractions for each sample. As can be seen by comparing these data with those in table 6, the microcline in the pegmatite unit contains approximately the same amount of $NaAlSi_3O_8$ as the microcline in the microcline gneiss, but it has a lower triclinicity index. The optical constants of the microclines are similar in both units. Quantitative spectrochemical analyses for the minor elements in the microcline from the pegmatite unit (table 27) indicate less calcium in the pegmatite than in the microcline gneiss; the amounts of barium, strontium, rubidium, iron, and lead in the microcline of the two rocks are roughly equal.

CHEMICAL COMPOSITION

The pegmatite and associated granite gneiss have estimated chemical compositions (table 28) nearly equivalent to those of the alkali granites of Nockolds (1954, p. 1012). The composition of the rocks was calculated from the modes in tables 24 and 25 by use of the method described previously in the text for the microcline gneiss (p. C3). The composition of the microcline was determined from the data given in tables

TABLE 26.—*Optical and X-ray data for microcline from pegmatite and associated granite gneiss unit*

[Data by E. J. Young]

Field No.	4-247-1 [1]		S636-A-53 [2]	
Composition determined before heating (expressed as weight percent $KAlSi_3O_8$)	93±2		91±1	
Composition determined after heating (expressed as weight percent $KAlSi_3O_8$)	77±1		79±1	
Triclinicity index	0.75		0.75	
	a [3]	b	a	b
n_x (±0.0005)	1.5186	1.5176	1.5186	1.5185
n_y (±0.0005)	1.5235	1.5230	1.5235	1.5235
n_z (±0.0005)	1.5248	1.5247	1.5257	1.5247
Birefringence (±0.001)	0.0062	0.0071	0.0071	0.0062
Optic angle (2V)	80±2	83±2	83±2	80±2
Optic sign	(−)	(−)	(−)	(−)
Orientation optic plane	⊥(010)	⊥(101)	⊥(010)	⊥(010)

[1] See sample 2, table 25, for description and location.
[2] See sample 6, table 24, for description and location.
[3] a and b represent individual grains within the same sample.

TABLE 27.—*Quantitative spectrochemical analyses, in percent, of certain elements in microcline from pegmatite and associated granite gneiss unit*

Serial No. Field No.	278703 [1] 4-247-1	278704 [2] S636-A-53
Ca	0.12	0.080
Ba	.27	.33
Sr	.043	.052
Rb	.05	.05
Fe	.030	.011
Pb	.025	.018

[1] See sample 2, table 25, for description and location.
[2] See sample 6, table 24, for description and location.

TABLE 28.—*Estimated chemical composition, in percent, of pegmatite and associated granite gneiss*

[Calculated from the average of 17 modes in tables 24 and 25]

Constituent	*Composition*
SiO_2	74.0
Al_2O_3	14.0
Fe_2O_3	1.5
FeO	.7
MgO	.1
CaO	1.0
Na_2O	3.0
K_2O	5.5
Others	.2
Total	100.0

26 and 27; an average content of 78 percent $KAlSi_3O_8$ was used for the homogenized feldspar. The plagioclase was assumed from several determinations to be An_{20}; chemically, the biotite was assumed to be equivalent to the analyzed biotite sample from sillimanitic biotite-quartz gneiss (table 17).

ORIGIN

The field relationships at Central City and in adjacent areas clearly indicate that the pegmatite and associated granite gneiss formed during the episode of plastic deformation of the region, but the mode of formation of the rocks is problematic. Probably, the pegmatite and associated granite gneiss were formed largely by metamorphic processes, the granitic material having been introduced into the original country rock either from below or laterally, but an origin from a silicate melt having a bulk composition corresponding to minimum melting compositions in the synthetic granite system (Tuttle and Bowen, 1958) cannot be dismissed entirely.

The occurrence of narrow lenses and layers of pegmatite and associated granite gneiss along foliation planes and contacts in the biotite gneisses suggests that the rock formed from a fluid that could intimately penetrate the layered country rock. Apparently the fluid could permeate the biotite gneisses without disrupting or displacing them. Further, to judge from observations that the pegmatite grades both laterally and longitudinally into the gneiss and contains ill-defined remnants of the gneiss, the pegmatite derived from the fluid probably replaced the country rock, at least in part. Many of the inclusions are wispy aggregates of biotite and sillimanite; others are ghostlike bodies that have gradational contacts and can be recognized mainly because they are darker and more gneissic than the pegmatite. In sillimanitic biotite-quartz gneiss terranes, the pegmatite commonly contains local aggregates of sillimanite that are associated with clots of oligoclase and muscovite; in tourmaline-bearing biotite gneisses, the pegmatite commonly contains local concentrations of this mineral. Undoubtedly, these minerals are contaminants derived from the original country rock.

Chemically, the pegmatite and associated granite gneiss contains more potassium and silicon and less aluminum, ferrous iron, ferric iron, magnesium, and, probably, calcium than the surrounding unaltered biotite gneisses (compare tables 28 and 17). Thus, potassium and silicon must have been introduced and aluminum, iron, magnesium, and calcium must have been removed in the formation of the pegmatite. The introduction of the potassium and silicon could have been either from below or laterally; the mafic constituents may have been removed from the system.

A clue to the ultimate origin of the pegmatite and associated granite gneiss is given by the distribution of the rock relative to the large pluton of syntectonic granodiorite that crops out south of Idaho Springs (fig. 2). On a regional scale, pegmatite and associated granite gneiss decreases in abundance away from the margin of the pluton. This decrease is accompanied by an increase in the grain-size of the pegmatite, a decrease in the degree of migmatization of the gneiss, and a corresponding increase in discrete bodies of pegmatite. This pattern of distribution and the changes in texture and structure suggest that the pegmatite may be a product of the formation of plutons of igneous rock during plastic deformation. Possibly the felsic component of the biotite gneiss country rock was mobilized (remelted?) near the sites of magma generation and moved upward and laterally away from the "hot spot" into cooler rock. In the presence of a temperature gradient, potassium and silicon would probably be enriched in the cooler rock away from the "hot spot." Nearly identical relations have been demonstrated by field observations in the Grenville province of the Adirondack Mountains (Engel and Engel, 1958). More recently, such relations have been shown by experimental data (Orville, 1960). Presumably, the metamorphic fluid responsible for the granitization would be rich in water and volatiles and capable of transporting materials to and from the sites of precipitation. As shown experimentally by Orville (1960, p. 107), alkali-bearing vapor in equilibrium with two alkali feldspars at high temperature is, on cooling, capable of replacing sodium feldspar with potassium feldspar. Thus, the dominant sodium feldspar of the biotite gneisses may have been replaced by potassium feldspar, the ratio of potassium to sodium in the rock was changed. If so, the fate of the displaced sodium is unknown.

URANINITE-BEARING PEGMATITE

A uraninite-bearing pegmatite that has been dated by absolute age methods (see table 3) is abundant on the dump of the Waterloo mine in the upper Russell Gulch area, which is within the biotite gneiss unit. It has not been recognized elsewhere in the district but is similar lithologically to uraninite-bearing pegmatites that are rather widely spread in a narrow northeast-trending belt in the Idaho Springs district, about a mile to the south (Sims and others, 1963). These pegmatites resemble radioactive pegmatites that cut, and that are demonstrably related to, the biotite-muscovite granite of the area.

The uraninite-bearing pegmatite is a pinkish-gray nearly massive coarse-grained rock composed mostly of plagioclase, microcline, and biotite. It is distinctively radioactive; individual hand specimens give readings of as much as 5 mr (milliroentgens) per hour. The biotite is irregularly dispersed and forms books a quarter of an inch or less thick and as much as an inch in diameter and, locally, elongate aggregates of books as much as 6 inches long. The biotite in the form of clots of books shows little or no preferred orientation, but that in the elongate aggregates tends to have a preferred orientation that imparts a local crude planar structure to the pegmatite. Microcline and plagioclase in subhedral crystals as much as an inch in diameter are intergrown in varying proportions. The microcline is perthitic; it contains a few percent of albite as strings and blebs. The plagioclase (An_{15}) has well-defined polysynthetic twinning. Quartz occurs as much smaller anhedral grains that are largely interstitial to the feldspars. It constitutes as much as 15 percent by volume of the rock. Uraninite in euhedral cubes that average about 0.5 mm on a side are dispersed through the rock but are apparently concentrated slightly in the more biotitic parts. Zircon that has a distinctive white color and a waxy luster is sparsely dispersed through the rock.

OTHER PEGMATITES

An elongate pegmatite that cuts a quartz-feldspar pegmatite on Kings Flat (pl. 1) is of interest because it has a crude zoning. The pegmatite trends northwestward and is a maximum of about 25 feet wide and 200 feet long. Despite the fact that it cuts an older conformable pegmatite, it too is nearly conformable to the foliation in the country rock; possibly it occurs in a cross fold. The pegmatite has a 1- to 2-foot border zone consisting of feldspar (dominantly perthite), white mica, and quartz and a massive coarser grained core consisting of white milky quartz, coarse books of white mica, and black tourmaline. The mica books are as much as 2 inches thick, and they appear to have a random orientation.

INTRUSIVE ROCKS

Three main types of Precambrian intrusive rocks—emplaced in the order: granodiorite and associated rocks, quartz diorite and hornblendite, and biotite-muscovite granite—cut the metasedimentary rocks of the district. They form generally small slightly discordant bodies in the layered rocks and constitute only a few percent of the exposed bedrock.

GRANODIORITE AND ASSOCIATED ROCKS

DISTRIBUTION AND CHARACTER

Granodiorite bodies that contain related quartz diorite and quartz monzonite are exposed at three localities in the Central City district (pl. 1). A folded subconcordant composite sheet that has an exposed length of 4,300 feet, a maximum width of 1,000 feet, and an estimated thickness of less than 400 feet crops out south of Central City. It lies within the Quartz Hill layer of microcline gneiss at the contract with an infolded body of biotite gneiss (pl. 2, section *C-C′*). Earlier, it was mapped both by Bastin and Hill (1917) and by Lovering and Goddard (1950, pl. 2) as Silver Plume Granite. A second body, exposed in the roadcut along State Highway 119, half a mile east of Black Hawk, is possibly a small phacolith. It is 500 feet wide and probably does not exceed 200 feet in thickness. It is in biotite gneiss and is cut by numerous pegmatites that apparently are cogenetic with it. A third body, the northeast segment of a moderately large folded composite sheet, crops out on the crest and flanks of Bald Mountain at the western edge of the district. It lies within biotite gneisses and is cut by small bodies of pegmatite and biotite-muscovite granite.

Each of the granodiorite bodies is slightly discordant, at least locally, with the foliation in the country rock. In addition, the contacts are commonly serrate and marked by intertonguing of granodiorite into the host gneisses. The following discussion is concerned primarily with the body of granodiorite that crops out south of Central City.

The sheet exposed near Central City consists dominantly of granodiorite but has a marginal phase of quartz diorite, generally not more than 10 or 20 feet thick, and a local quartz monzonite phase. The quartz monzonite is confined to a small knob near the south end of the body in the topographically highest part of the sheet. The quartz diorite and quartz monzonite grade into the main mass of granodiorite. The body contains a few sharply defined concordant inclusions of biotite gneiss and microcline gneiss, two of which are large enough to be shown on plate 1.

The granodiorite and quartz diorite that constitute the bulk of the sheet are dark-gray medium-grained nearly equigranular homogeneous rocks. They tend to weather to spheroidal masses that have brown or reddish-brown exteriors. Foliation and lineation are well defined near the borders of the body but become less pronounced toward the interior. They are due mainly to a definite planar and linear orientation of biotite. The foliation and lineation are continuous with those in the country rock, and a few small folds can be traced through the granodiorite into the adjacent country rock (pl. 1). The quartz monzonite is lighter and coarser grained than the granodiorite. It contains crystals as much as 5 mm in diameter, whereas the maximum grain size in the granodiorite is 2 or 3 mm. All phases of the body are distinctly coarser grained than the metamorphic rocks of the district. The granodiorite can be distinguished readily from biotite-muscovite granite as it is darker and coarser grained and contains abundant biotite and little or no muscovite.

PETROGRAPHY

The granodiorite contains 15–25 percent quartz, 35–49 percent plagioclase, 3–12 percent microcline, 18–26 percent biotite, and 7–10 percent total accessory minerals (table 29). The texture is hypidiomorphic granular. Plagioclase occurs as anhedral or subhedral crystals that are generally 1–2 mm in maximum diameter and are considerably embayed by microcline and quartz. Many grains have well-formed albite and pericline twins, which may occur separately or in combination, and a few have combined Carlsbad-albite-pericline twins. In contrast to those in other common rock types in the district, some grains of plagioclase have a moderate gradational normal zonation; the maximum zonation observed is from An_{41} at the center to An_{28} at the margin. Grains of plagioclase that are in contact with microcline have narrow rims of either clear albite or myrmekite. Except for the albitic rims, all the plagioclase and particularly the inner zones of zoned crystals show some alteration, apparently dominantly saussuritic in type. Microcline forms anhedral crystals that are generally cloudy and rather poorly twinned. Grid twinning within individual crystals varies greatly and is generally most conspicuous adjacent to inclusions of other minerals. A few percent of albite occurs as strings and blebs in the microcline and constitutes a film type of microperthite.

Quartz occurs as anhedral grains that show strain shadows and also as myrmekitic intergrowths in plagioclase. Biotite occurs as anhedral crystals, locally having a well-defined planar orientation. It is pleochroic, ranging from pale yellow to moderate olive brown or moderate brown. In one section, muscovite was observed to cut biotite. Fresh hornblende in subhedral or anhedral generally ragged crystals constitutes as much as 3 percent of one rock specimen (column 4, table 29). It has a pleochroic formula: X=yellowish green, Y=green, Z=bluish green.

Sphene and magnetite are the most abundant accessory minerals, and they are present in nearly equal amounts. Both tend to be closely associated with biotite; in many places sphene can be seen to occur as narrow rims on magnetite. Apatite is next in abundance; it forms tiny euhedral rods in biotite, quartz, plagioclase, and microcline and forms larger subrounded grains along grain boundaries of the major minerals. Allanite occurs everywhere; it forms anhedral to subhedral grains, which in part are rimmed by epidote. Hematite rims pyrite at places. Calcite and chlorite are commonly intergrown and occur along grain boundaries.

TABLE 29.—*Approximate modes, in volume percent, of granodiorite and associated quartz diorite and quartz monzonite from body south of Central City*

[X, major accessory mineral; (X), minor accessory mineral; Tr., trace]

Sample / Field No.	1 M507	2 M508-1	3 M477-3	4 M854	5 M853	6 M690	7 M549	8 M528-1	9 M520	10 M510	11 M487-1	12 M484	13 M548	14 M511	15 M477-4	16 M477-2
Major minerals																
Quartz	29	25	15	21	20	22	20	24	18	24	25	19	20	17	27	18
Plagioclase	34	27	45	43	48	49	42	43	40	38	35	49	47	51	41	53
Microcline	29	36	8	3	3	4	3	6	12	5	10	6	5	1	1	Tr.
Biotite	4	8	22	20	21	18	25	19	21	26	23	20	19	25	23	25
Accessory minerals																
Total accessory minerals	4	4	9	10	8	7	9	8	9	7	7	7	9	6	8	4
Sphene	X	X	X	X	X	X	X	X	X	(X)	Tr.	X	X	X	(X)	(X)
Magnetite	X	X	X	X	X	X	X	X	X	(X)	X	X	X	X	X	X
Apatite	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	X	(X)	(X)	(X)	(X)	X	X
Allanite	(X)	(X)	(X)	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	(X)	Tr.	Tr.	Tr.	Tr.	Tr.
Fluorite	Tr.	Tr.														
Muscovite	Tr.	Tr.									(X)					
Epidote		Tr.		Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.			Tr.	Tr.	Tr.	
Pyrite		Tr.		Tr.				Tr.				Tr.	Tr.			
Hornblende				3	Tr.	Tr.	Tr.									
Calcite								Tr.					Tr.			
Chlorite								Tr.	Tr.				Tr.			
Plagioclase																
Composition	An_{21-26}	An_{25-28}	An_{26-26}	An_{26-30}	An_{29-30}	An_{31}	An_{29-32}	An_{31}	An_{26}	An_{35-37}	An_{37-41}	An_{27-39}	An_{30-32}	An_{26-26}	An_{26-26}	An_{22-27}

The paragenetic sequence of the major minerals, as determined from studies of about 20 thin sections, is, from oldest to youngest: plagioclase, microcline, quartz, and biotite. Allanite, pyrite, magnetite, and sphene—in the order named—appear to have crystallized later than biotite, possibly almost contemporaneously with the formation of the albitic rims. Calcite, chlorite, and epidote are late alteration products.

The petrography of the quartz diorite phase is similar in most respects to that of the granodiorite. An indication of the range in composition of the quartz diorite is shown in columns 14, 15, and 16 in table 29. The biotite in the quartz diorite phase is darker and commonly finer grained than that in the granodiorite. Probably these differences resulted from recrystallization or reconstitution due to the more intense deformation near the border of the body, where the quartz diorite occurs.

A local quartz monzonite phase, represented in colums 1 and 2, table 28, is notably more felsic, coarser grained, and lighter colored than is the granodiorite phase. It is characterized by megascopically visible disseminated purple fluorite and sphene. Also, myrmekite and clear late albite are more abundant, and the biotite is lighter in color than in granodiorite. The fluorite is later than but probably nearly contemporaneous with sphene.

The mineralogic variation in the composite body of granodiorite and associated rocks near Central City, as determined from 17 samples, is shown on figure 7.

The chemical composition of a sample of granodiorite and of a sample of fluorite-bearing quartz monzonite from the upper part of the rock body are given in table 30.

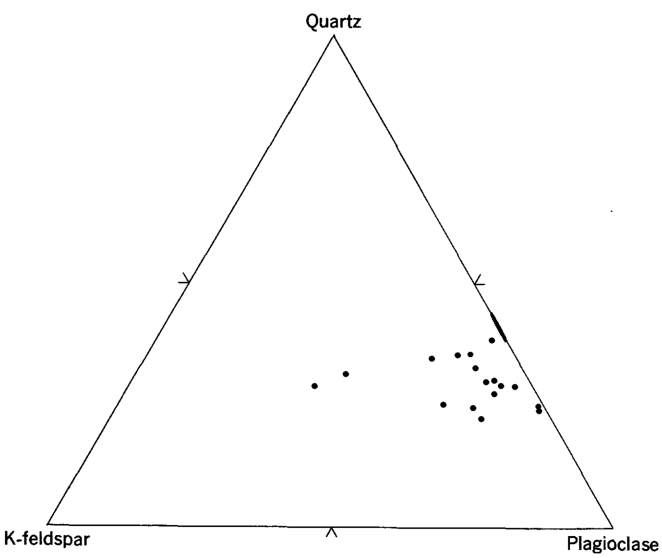


FIGURE 7.—Triangular diagram showing variations in composition (volume percent) of granodiorite body south of Central City; 17 plots.

TABLE 30.—*Chemical analyses, in percent, of granodiorite and quartz monzonite from an intrusive body south of Central City*

Field No.	A-179	A-180
SiO_2	64.09	54.29
Al_2O_3	14.03	13.53
Fe_2O_3	3.44	5.28
FeO[1]	2.71	5.10
MgO	1.14	2.42
CaO	3.91	7.22
Na_2O	2.81	2.64
K_2O	4.18	2.40
H_2O+	.38	.72
H_2O-	.16	.22
TiO_2	1.31	2.37
P_2O_5	.56	2.02
MnO	.09	.13
CO_2	.12	.44
Cl	.05	----------
F	.59	.43
S	.03	.36
BaO	.24	.17
Subtotal	99.84	99.74
Less Oxygen	.25	.27
Total	99.59	99.47
Bulk density	2.70	2.80
Powder density	2.73	2.85

[1] A calculated correction was made for FeO present as pyrite based on percentage of sulfur. In making the correction, all sulfur was assumed to be present as pyrite.

A-179. Quartz monzonite; contains visible fluorite. Taken from same outcrop as were samples 1 and 2, table 29.
A-180. Sample of granodiorite.

QUARTZ DIORITE AND HORNBLENDITE

OCCURRENCE AND CHARACTER

Small bodies of quartz diorite and hornblendite are widely scattered in the western part of the district within both the biotite and the microcline gneiss units (pl. 1). In contrast to adjacent areas to the south, such as the Chicago Creek district (Harrison and Wells, 1959), hornblendite and associated diorite are more abundant than quartz diorite.

The rocks form small generally blunt irregular lenses that are a maximum of 500 feet by 200 feet. They are poorly exposed in the Central City district and are generally characterized by a rubble of large subrounded boulders; consequently, their relation to the associated host rocks was not determined. Observations in adjacent areas (Harrison and Wells, 1959, p. 15), however, indicate that the rocks intrude granodiorite and older rocks, partly as slightly discordant bodies, and that they are in turn intruded by biotite-muscovite granite and some pegmatites.

Hornblendite and associated diorite are black or greenish-black massive or slightly foliated equigranular medium-grained rocks. Feldspar is sparse, and where present it occurs generally as anastamosing veinlets about one-eighth inch wide or as thin oriented aggregates that impart a poor foliation. The rocks are readily distinguishable megascopically from amphibolite by being coarser grained and richer in hornblende and from granodiorite by containing much larger quantities of hornblende. Diorite resembles hornblendite megascopically in all respects, except that it contains visibly more feldspar.

Quartz diorite is a dark-gray, mottled black and white, commonly slightly foliated medium-grained nearly equigranular rock. In contrast to the hornblendite, most of the plagioclase in this phase is regularly distributed through the rock or occurs in discontinuous streaks. Microscopically, the plagioclase is complexly twinned, as noted earlier by Harrison and Wells (1959, p. 16–17).

PETROGRAPHY

The quartz diorite and hornblendite contain hornblende, plagioclase, and, at places, clinopyroxene as major constituents and small but variable amounts of quartz, biotite, sphene, apatite, and zircon (table 31). Chlorite, epidote, and magnetite are common alteration minerals. The texture is hypidiomorphic granular or allotriomorphic granular. Hornblende, the most abundant mineral in all rocks of this group, occurs as subhedral crystals from less than 1 mm to as much as 4 mm in diameter. It is green and has the color and optical properties of hastingsite. It is highly pleochroic and has a weak dispersion of the optic axes; the dispersion formula is $r>v$; X=yellow or greenish yellow, Y=light green, and Z=green or dark green. The optic angle is estimated at 60°–75°. Two samples of hornblende from hornblendite were determined by oil immersion to have an index $n_y=1.664\pm0.003$ and 1.673 ± 0.003 respectively. Hornblende from the dioritic body exposed on Quartz Hill, near the Blanche M mine (pl. 1), has an index $n_y=1.665\pm0.003$; $Z\wedge c=18°$; $2V=71°$ (determined by universal stage). A dark hornblende from the quartz diorite (column 4, table 31) has an index $n_y=1.698\pm0.005$.

The clinopyroxene commonly contains scattered remnants of hornblende that are mutually oriented; the cleavage in the hornblende continues as a parting in the clinopyroxene. In some rocks, however, the clinopyroxene forms anhedral crystals enclosed within hornblende or mutually intergrown with it. The pyroxene is nearly colorless to pale green. A specimen from the body exposed near the Blanche M mine (column 3, table 31) has the following partial optical properties: +, $2V=60°\pm5°$; $r>v$, weak; $Z\wedge c=43°$ $n_y=1.705\pm0.003$. The optical properties indicate that this clinopyroxene is diopside having an approximate composition $Di_{80}Hed_{20}$ (Winchell, 1951, p. 413). Another

TABLE 31.—*Modes, in volume percent, of quartz diorite and hornblendite*

[Tr., trace]

Sample	1	2	3	4	5
Field No	S301B–53	S319–53	S75A–52	S72A–52	EWT 57–54
Plagioclase	Tr.	13.2	16.1	46.4	0.1
Quartz	----	----	----	4.1	3.6
Hornblende	93.7	84.0	64.5	45.9	96.2
Biotite	----	----	----	1.9	----
Magnetite	.9	1.3	Tr.	Tr.	Tr.
Pyroxene	5.4	1.5	17.6	----	----
Apatite	----	----	.3	Tr.	.1
Sphene	----	----	.5	.3	Tr.
Zircon	----	----	.5	.2	Tr.
Epidote	----	----	.5	.3	Tr.
Microcline	----	----	----	Tr.	----
Chlorite	----	----	----	.9	----
Total	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{27}	An_{30-35}	An_{28}	An_{29}	----

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 31

1. Hornblendite from small body of float at head of Prosser Gulch 500 ft south of gulch.
2. Diorite from small body of float at head of Prosser Gulch; plagioclase is irregularly distributed and occurs as anastamosing thin stringers in rock.
3. Diorite from body on south slope of Quartz Hill adjacent to Blanche M mine; plagioclase is in discontinuous parallel streaks.
4. Foliated quartz diorite from dump of Topeka mine, south slope of Quartz Hill.
5. Hornblendite from narrow elongate body in northwestern part of district 2,000 ft northwest of Eureka Gulch.

pyroxene of similar color and pleochroism has an index $n_y=1.681\pm0.002$.

Plagioclase forms subhedral or anhedral crystals, commonly interstitial to hornblende and pyroxene, that are distinguished by complex twins. Combination albite-pericline (acline) twins are the most common type, but Carlsbad-albite, Carlsbad-pericline, or more complex varieties are noted in a few specimens. The plagioclase is altered to various degrees to clay minerals. Quartz occurs generally as small anhedral grains interstitial to the major minerals or as subrounded crystals in hornblende or plagioclase. Biotite ranging from yellow brown to greenish brown is intergrown locally with hornblende; generally it has a distinct preferred orientation. In most specimens the biotite is partly altered to chlorite (penninite?) and magnetite. Sphene, the most abundant accessory mineral, is moderately pleochroic. It generally occurs in aggregates that are within or at the margins of hornblende crystals.

BIOTITE-MUSCOVITE GRANITE

OCCURRENCE AND CHARACTER

Small bodies of biotite-muscovite granite that are satellitic to larger stocks exposed near Silver Plume, Colo. (Lovering and Goddard, 1950, pl. 2), about 12 miles to the southwest, crop out in the western part of the district within the biotite gneiss unit and the body of granodiorite and associated rocks at Bald Mountain (pl. 1). The distribution of the granite is thus similar to that of the quartz diorite and hornblendite.

The granite occurs as irregular dikelike or slightly hook-shaped bodies that are, at least locally, discordant to the country rock. The bodies range in size from small lenses a few tens of feet in length and a few feet wide to larger bodies as much as 1,000 feet by 300 feet. Without exception the bodies have sharp contacts against the host rocks, although a few inches or a few feet of pegmatite may occur at the contacts.

The granite is nearly massive except near the contacts, where it has a poorly defined foliation. The foliation, imparted by oriented biotite flakes and to a lesser extent by tabular feldspar crystals, is subparallel to the contacts, even where the contacts are discordant.

Within the Central City district, the biotite-muscovite granite is a yellowish-gray or gray fine-grained nearly equigranular homogenous rock. It is similar in composition as well as in fabric and texture to the fine-grained variety of biotite-muscovite granite in the nearby Freeland-Lamartine and Chicago Creek districts (Harrison and Wells, 1956, 1959), which are peripheral to the type locality at Silver Plume, Colo. In these districts as well as at Silver Plume, however, the fine-grained variety is subordinate to the dominant medium-grained seriate porphyritic variety. The biotite-muscovite granite at Central City is more calcic than in these other areas, a fact indicated by the few modes listed in table 32. A local leucocratic variety, which grades into the more common phase, is a true granite, however.

TABLE 32.—*Modes, in volume percent, of biotite-muscovite granite*

[Tr., trace]

Sample	1	2	3	4	5	6	Average of 5 modes
Field No.	S23-53	S114-A-53	S114-B-53	ET-6	S174-53	S171-53 [1]	
Potassium feldspar	22.5	22.4	38.6	25.9	19.7	36	25.8
Plagioclase	35.1	35.5	30.5	34.1	34.1	18	33.9
Quartz	31.5	31.3	27.9	27.0	32.8	32	30.1
Biotite	5.9	5.6	.2	5.9	6.7	3	4.9
Muscovite	4.0	4.8	2.0	5.9	5.7	8	4.5
Magnetite	.9	.3	.8	1.0	.6	Tr.	.7
Zircon; monazite	----	----	----	.2	.1	Tr.	
Hematite	----	.1	----	----	----	----	
Apatite	.1	----	----	Tr.	----	Tr.	1.1
Chlorite	----	----	----	----	.3	----	
Epidote	----	----	----	----	----	Tr.	
Sillimanite	----	----	----	----	----	3	
Total	100.0	100.0	100.0	100.0	100.0	100	100.0
Composition of plagioclase	----	----	----	An_{26}	An_{26}	An_{26}	----

[1] Composition is approximate; sample is not included in the average.

DESCRIPTIONS AND LOCALITIES OF SAMPLES LISTED IN TABLE 32

1. Fine-grained biotite-muscovite granite from long narrow dike near head of Nevada Gulch 800 ft south of the gulch.
2. Fine-grained biotite-muscovite granite from small body at head of Nevada Gulch.
3. Leucocratic phase of granite from loc. 2.; grades abruptly into normal phase of granite.
4. Fine-grained biotite-muscovite granite from large body in western part of district northwest of Eureka Gulch.
5. Fine-grained biotite-muscovite granite from small hook-shaped body of granite near head of Nevada Gulch 1,000 ft north of the gulch.
6. Contaminated granite from small body near head of Nevada Gulch 700 ft north of the gulch.

PETROGRAPHY

Observed in thin section, the biotite-muscovite granite has a hypidiomorphic granular texture. Microcline in subhedral to anhedral laths forms crystals that average about 1 mm in diameter but are as much as 4 mm long, plagioclase and quartz form anhedral and rarely subhedral crystals from less than 1 to about 3 mm in diameter, and biotite and muscovite form subhedral crystals that are generally not more than a millimeter long. The major minerals appear to have crystallized in the following order: Plagioclase, microcline, quartz, biotite, and muscovite. The microcline contains a few percent of perthitic albite as strings and blebs, which are commonly oriented nearly at right angles to the twin plane of Carlsbad twins. The grid twinning that characterizes microcline generally is well defined but is irregular and blotchy in many grains. Quartz grains, a fraction of a millimeter in diameter and subrounded in shape, are found locally in the microcline. Most of the quartz, however, is in aggregates that anastamose through the rock or are interstitial to the feldspars. Except for a few tiny grains, all the quartz shows conspicuous strain shadows. The plagioclase generally has moderately or slightly formed polysynthetic twinning, dominantly of the albite type; rarely, combination twins of albite-pericline (or acline) or well-defined Carlsbad twins are observed. Albite rims, a small fraction of a millimeter in thickness, are found around nearly all the plagioclase grains, and myrmekite is commonly formed where the plagioclase is in contact with microcline. The plagioclase is altered in different degrees to sericite and clay minerals.

Biotite is moderate olive brown to dusky brown and is in irregular ragged grains partly altered to chlorite and magnetite; it contains tiny zircon and monazite crystals that have well-defined dark pleochroic halos. Some muscovite is intergrown with biotite, and some embays the feldspars and grades into sericitic shreds on altered plagioclase crystals. A few crystals of muscovite have myrmekitic intergrowths of quartz. In one specimen (column 6, table 32), muscovite is intergrown with and contains needles of sillimanite, which is presumably derived from the sillimanitic biotite-quartz gneiss country rock. Magnetite, zircon, monazite, and apatite are the principal accessory minerals. Because of the difficulty of distinguishing zircon from monazite in thin section, data for the two minerals are combined in table 32. The monazite content of the biotite-muscovite granite is generally sufficient to give the rock an anomalously high radioactivity, which distinguishes it from other granitic rocks in the region.

ORIGIN OF INTRUSIVE ROCKS

The intrusive rocks are inferred to have crystallized from magmas. The rather close spatial and temporal relationships of the separate types of intrusive rocks could indicate that they were related in origin, but the present data make this conclusion highly conjectural.

The variations in composition and the structural relationships of the granodiorite and related rocks at Central City are similar to those of rocks in the Chicago Creek area and support the conclusion of Harrison and Wells (1959, p. 13 and 15) that the granodiorite and related rocks were emplaced as magma during the episode of plastic deformation. At Central City, bodies of these rocks have sharp locally crosscutting contacts with the gneisses, and they contain a secondary foliation and lineation. Furthermore, in the body exposed south of Central City, the composition varies systematically, and phases having different composition intergrade as do typical igneous rocks. These features must have originated vertically in place by differentiation. The crescent-shaped body exposed along North Clear Creek is probably a phacolith (see the discussion on page C19), but this probably has not been proved. Subsequent to emplacement, the bodies were deformed and recrystallized by stresses that continued after consolidation and produced the secondary foliation and lineation and the metamorphic texture of the rocks.

Data regarding the origin of the quartz diorite and hornblendite are meager at Central City because the rock is poorly exposed and contacts were not observed. In adjacent areas, however, the rocks form discordant dikes (Harrison and Wells, 1959, p. 15) that cut both the layered rocks and the granodiorite; also, they are accompanied by a characteristic pegmatite that appears to be a differentiation product; they have internal features that indicate probable magmatic emplacement.

The biotite-muscovite granite crystallized almost certainly from a magma, as is indicated by its internal homogeneity, the close similarities between bodies, the very discordant contacts, and the presence of a primary foliation parallel to the walls even where the bodies are crosscutting. This view is in agreement with that of Harrison and Wells (1959, p. 20) for rocks in the Chicago Creek area, where the rock is more abundant and better exposed.

A discussion of the genesis of the intrusive rocks as a group is premature, for many more data are needed over a large segment of the range and adjacent areas to the west. However, the close geographic grouping (Lovering and Goddard, 1950, pls. 1 and 2) and close temporal relationships of the rocks indicates that the various intrusive rocks probably have a common mode of origin. The oldest igneous phase—granodiorite and related rocks—was emplaced during earlier stages of the plastic deformation, probably when temperatures in the level of the crust now exposed were generally near the temperature range of magma. The precise time of the intrusive activity relative to the migmatization and folding that accompanied the deformation remains unknown. We do know, however, that granodiorite was intruded after the formation of at least some migmatite, for rotated blocks of migmatite locally occur as inclusions in it (Harrison and Wells, 1959, p. 12–13), and that it was intruded before the folding stresses relaxed. Later, the quartz diorite and hornblendite were emplaced, and then, near the end of the deformation and probably after the regional isotherms had lowered, the biotite-muscovite granite was emplaced. The granodiorite has a composition similar to the country rock composed of biotite and microcline gneisses and could have been derived directly from it by selective melting. The biotite-muscovite granite, on the other hand, is more felsic than the country rock; its origin may have been more complex.

METAMORPHIC FACIES

The mineral assemblages of the metamorphic rocks conform in general with those of the upper range (sillimanite-almandine subfacies) of the almandine amphibolite facies as defined by Fyfe, Turner, and Verhoogen (1958).

The biotite gneisses consist of three dominant mineral assemblages: (1) biotite-quartz-calcic oligoclase, (2) biotite-quartz-oligoclase-sillimanite-microcline, and (3) biotite-quartz-oligoclase-almandine-(sillimanite). The occurrence of the pair sillimanite plus potassium feldspar indicates that the rocks were formed at temperatures above the "orthoclase" isograd of Heald (1950, p. 74–79). Muscovite is generally associated with the pair. The estimated chemical composition of the biotite-quartz-plagioclase gneiss and the compositions of its component minerals closely approximate those of the intermediate range of the metamorphosed paragneisses in the northwest Adirondack Mountains (Engel and Engel, 1953; 1958; 1960).

The amphibolites contain the assemblage hornblende-andesine-quartz but locally also contain clinopyroxene. Probably the clinopyroxene reflects local original differences in composition rather than a higher grade of metamorphism. Epidote is common but appears to be wholly of secondary origin.

In the magnesian rocks the mineral assemblages are (1) cordierite-gedrite-quartz-almandine-biotite and (2) cummingtonite-calcic plagioclase-quartz-almandine-hornblende. Green spinel is locally associated with cordierite. The almandine garnet contains about 30 percent of the pyrope molecule.

The calcareous rocks vary widely in composition and contain a variety of calcium-iron silicates. They differ from the calcareous assemblages of the sillimanite-almandine subfacies as reported by Fyfe, Turner, and Verhoogen (1958, p. 231) in that nearly all contain epidote.

The metamorphic mineral assemblages were formed in association with migmatites and intrusive igneous rocks in an environment of granite injection and granitization. The pegmatite that permeated the gneisses contains the same stable pair—microcline plus sillimanite—as do the gneisses and thus was subjected to approximately the same temperature and pressure conditions as the associated country rock; also, it contains a potassium feldspar having approximately the same composition and triclinicity (compare with data in tables 6 and 26) as does that in the gneisses. The pegmatite appears to have been introduced into the rocks rather than to have been formed primarily in place; but its source probably was not far removed, and thus temperatures were in or near the temperature range of magma. The intrusive igneous rocks were emplaced into the metamorphic host rocks without noticeably altering them, and subsequently most of the igneous rocks were metamorphosed under approximately the same conditions at the host rocks. The biotite in the granodiorite is similar petrographically and chemically to that in the biotite gneisses and thus presumably formed under similar conditions.

Evidence of retrograde metamorphism is widespread; it consists of local replacement of biotite by musovite and replacement of hornblende by biotite and epidote; also, the muscovite associated with the sillimanite-microline assemblage is probably secondary. Possibly the retrograde changes were caused by late(?) solutions related to migmatization or to the formation of granodiorite. Similar evidence of retrograding has been observed in the nearby Chicago Creek area (Harrison and Wells, 1959), but at that locality retrograding could have resulted from the later cataclasis and related deformation rather than from earlier events.

STRUCTURE

The distribution of the Precambrian rock units and the attitudes of foliation and lineation indicate that the rocks of the district are folded along northeast-trending nearly horizontal axes. Traces of the axial planes of the major folds are shown on the geologic map (pl. 1). Locally, folds that trend nearly at right angles to the major folds form undulations on the limbs of the major folds, but these are too small to deflect the contacts noticeably at the scale of plate 1. Lineations that parallel the major fold axes or that are nearly normal to them are cogenetic with the folding.

The major folds and the minor folds that are normal to the general trend were formed during the older plastic deformation in this part of the Front Range (Moench, Harrison, and Sims, 1962; p. C39, this report).

The younger deformation that intensely disturbed the rocks in a narrow linear belt to the south (see p. C39) did not notably affect the rocks of the Central City district, and accordingly, this episode of folding is not discussed separately in this report. Some evidence of the younger deformation—sparse, widely scattered slickenside striae and folds and associated lineations that trend nearly parallel to known younger folds—is discussed briefly, however, in the pages that follow.

It is useful to refer the linear elements of a fold system to directional coordinates. Accordingly, in this paper B refers to the coordinate direction of major fold axes and to linear elements nearly parallel to them, and A refers to the coordinate direction of minor fold axes and associated linear elements that are nearly at right angles to the axes of the major folds. The relation between A and B therefore is geometric. However, B is similar to established petrofabric terminology in which *b* refers to the axis of internal rotation, which is commonly parallel to fold axes and normal to *a; a* is the direction of tectonic transport (Fairbairn, 1949, p. 6; Turner and Verhoogen, 1951, p. 532). A has the required geometric relations of an *a* fabric direction to a *b* direction but is also a direction of folding. In the commonly established petrofabric terminology, therefore, it is a *b* fabric direction and might be designated accordingly b_1 or b_2.

STRUCTURAL FEATURES IN THE PRECAMBRIAN ROCKS

FOLIATION

The Precambrian rocks of the district have a generally well-defined foliation. The foliation is conspicuous in the layered rocks and is marked by a well-defined preferred mineral orientation and by a compositional layering. It occurs in different degrees in the intrusive rocks, where it is expressed by a dimensional orientation of the platy minerals.

The dimensional orientation of the mineral components is nearly parallel to the lithologic layering, and accordingly the foliation can confidently be presumed to be parallel to bedding in the original rocks. One exception has been noted in thinly interlayered quartz-rich and sillimanite-rich biotite gneisses at the mouth of Silver Gulch (pl. 1). At this locality, steeply inclined foliation planes locally cut the layering in the crests of small folds. These foliation planes are nearly parallel to the axial planes of the folds.

The foliation in the layered rocks is secondary. A preferred mineral orientation was formed parallel to the compositional layering subsequent to consolidation of the original rocks. The locally observed axial plane-type foliation apparently formed late during the period of the plastic deformation that produced the pervasive gneissic structure; it formed in the crest of folds where the rocks were tightly compressed.

The foliation in the intrusive rocks, on the other hand, is in part secondary and in part primary. That in the granodiorite and associated rocks and to a lesser degree in the quartz diorite and associated hornblendite is largely if not entirely secondary, for it conforms to and is continuous with the foliation in the layered gneiss 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 was possibly induced and was modified and largely destroyed by postconsolidation recrystallization. The foliation in the biotite-muscovite granite, however, 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.

The foliation in all rocks tends to be moderately regular within an outcrop, although it may vary widely in attitude from outcrop to outcrop. In some outcrops, however, especially in the apical areas of small folds, it is exceedingly diverse, and a "trend" is the only significant determination that can be made.

LINEATION

Lineation is conspicuous in the rocks and can be measured in nearly every outcrop. Within the district, lineation is expressed by the axes of small-scale folds, elongate minerals and mineral aggregates (mineral alinements), boudinage, and, rarely, slickenside striae. With few exceptions, the observed linear elements formed by secondary flowage that accompanied the plastic deformation of the region. The lineations are parallel to the axes of the major folds (B direction) or are nearly normal to them (A direction).

Lineations in the B direction are found in all the layered rocks and in the intrusive granodiorite and associated rocks and constitute more than 90 percent of the linear elements observed in the district. They consist dominantly of mineral alinements and small fold axes. The most commonly observed elongate minerals are hornblende in amphibolite and other mafic rocks and sillimanite in the biotite gneisses. Also, biotite flakes and aggregates and quartz aggregates tend to be elongated in the B direction. Studies were not made specifically of the space-lattice orientation of mineral grains, but petrofabric diagrams of quartz and accessory xenotime from a locality in Fourmile Gulch (pl. 1) show a moderate preferred orientation (Young and Sims, 1961, p. 292–293). Small folds ranging in size from minute crinkles and warps to larger folds that are small-scale replicas of major folds are observed to be parallel both to mineral alinements in the B direction and to the axes of major folds in the B direction. They are formed in all the layered rocks but are more commonly observed in the biotite gneisses; indeed, crinkles are confined almost only to the biotite-rich parts of the biotite gneisses.

Lineations in the A direction are relatively uncommon, and in contrast to lineations in the B direction, they exist only locally. They consist dominantly of axes of small folds but include mineral alinements, boudinage, and slickenside striae. The folds occur locally in all rock types but differ in type within rocks of different competency.

Slickenside striae that are in the A coordinate direction of the younger deformation of the region (see table 2) are visible locally in the district. They are most common on gently dipping foliation planes in the microcline gneiss on the northwest flank of the Central City anticline.

All the lineations that were measured in surface exposures in the district were plotted on Schmidt equal-area nets to show statistically their orientation (pl. 3). Eight diagrams were prepared to show the similarity in the gross pattern within different segments of the district and the minor variations in it. A total of about 2,300 lineation readings was plotted. Each of the diagrams in plate 3 is located at the approximate geographic center of the area it represents. The lineation diagrams were constructed according to the method described by Billings (1942, p. 119–121) for the poles of joints, except that the lower hemisphere is used here. Each pronounced maximum, therefore, represents the approximate bearing and plunge of many field observations. Interpretation of the diagrams is discussed in the subsection on "Folds" (p. C44).

JOINTS

All the Precambrian rocks are jointed, and at least one and commonly two or three conspicuous joint sets are visible at nearly all exposures. The joint pattern for the district has been described in a previous paper (Sims, Drake, and Tooker, 1963) and has been interpreted regionally by Harrison and Moench (1961); it will be discussed only briefly here.

Four principal joint sets and several minor sets are present in the rocks of the district. The principal sets have average attitudes of (1) N. 30° W., 80° NE., (2) N. 45° W., 80° NE., (3) N. 76° E., 80° N., and (4) N. 75° W., 80° N. The minor joint sets have average attitudes of (1) N. 55° E., 75° NW., (2) N. 10°–15° W., vertical, and (3) N. 90° E., 80° N.

The regional joint pattern in the rocks of this area has been interpreted by Harrison and Moench (1961) to have resulted mainly from stresses related to the two episodes of Precambrian folding and to the uplift of the Front Range Highland during the Laramide orogeny. Specifically, they (1961, table 1) interpret the N. 76° E. set as a cross joint related to the axis of Laramide uplift and the N. 75° W. set as a diagonal joint related to the uplift; they interpret the N. 30° W. set as a cross joint to the younger episode of Precambrian deformation. The interpretation of the N. 30° W. set as a cross joint related to the younger deformation is possible even though the rocks of the Central City district were not folded during this deformation, for strains related to this deformation could have been weakly transmitted through the rocks without folding them. It seems probable to us that the N. 45° W. joint set is a cross joint related to the older Precambrian deformation.

FOLDS

The structural framework of the district is provided by the Central City anticline, a broad gently arched fold containing a core of microcline gneiss that bisects the district (pls. 1 and 3). Folds of lesser magnitude whose axes are subparallel to the axis of the anticline occur on the limbs, but only a few of these are sufficiently large to be mapped at the scale of the geologic map. The larger subsidiary folds produce slight bends in the pattern of the lithologic contacts and corrugate the limbs, but they do not appreciably modify the structural framework. The cross folds (A) that trend nearly at right angles to the axes of the major folds (B) are small relative to the major folds and rarely cause noticeable deflections in contacts (pl. 1).

MAJOR FOLDS AND RELATED LINEATIONS

The northeast-trending folds are mainly open upright anticlines and synclines but include upright tight folds and, locally, recumbent folds. Linear elements related to these folds are pervasive in all the folded rocks.

The principal fold, the Central City anticline, is a broad open nearly symmetrical upright structural feature that trends through the district and for short distances beyond. It has been traced for about 2 miles beyond the district to the northeast, where it dies out adjacent to the Boulder Creek batholith (Lovering and Goddard, 1950, pl. 2), and for about the same distance to the southwest, where it passes into a gently dipping homocline (Moench, 1964, pl. 1). The axial plane of the anticline is presumed to dip about 85° SE. This inclination was determined mainly by comparing the position of the trace of the axis at the surface with that at the level of the Argo tunnel, as mapped by Lovering and Goddard (1950, pl. 16), and accordingly is only approximate. The trace of the axial plane trends on the average about N. 40° E., but it is highly sinuous in detail and bends locally to more northerly or easterly trends, as can be seen on plate 1. The most notable bends in the axis are on Quartz Hill and Silver Hill (pl. 1). In the same way, the plunge of the axis varies, but to a lesser extent. On the whole, the plunge is gentle to the southwest; but locally it is to the northeast, and small-scale reversals are common and indeed characteristic. The changes in the plunge are shown diagrammatically in section *E–E′* (pl. 2), a section along the approximate axis of the anticline, and in more detail by the lineation measurements shown on plate 1. The limbs of the anticline dip on the average about 40° away from the crest, but they are corrugated by folds of various sizes and of several types, as is discussed in the following paragraphs.

The principal folds on the limbs of the Central City anticline are open upright synclines and anticlines whose breadths exceed their heights. Many of the larger ones are nearly symmetrical, but many also are asymmetrical and have the characteristics of drag folds. The axes of several of the larger subordinate folds are shown on plate 1; others that are smaller and less continuous are shown by special fold symbols. It can be seen on plate 1 that a few of these folds—for example, the Pewabic Mountain syncline—slightly deflect the contact between the microcline gneiss unit and the overlying biotite gneiss unit. The axes of most of the traceable folds are subparallel to the axis of the Central City anticline. However, the trace of the axial planes of several mappable folds in the eastern part of the district (pls. 1 and 3) converge slightly to the north with the axis of the Central City anticline. The drag folds on the limbs are useful in determining the gross structural pattern, but they must be used with caution as they merely indicate the position of the axis of the next larger fold. For the most part the axial planes of the drag folds converge upward on the flanks of the Central City anticline in the manner of "abnormal anticlinoria," as defined by Billings (1942, p. 50–51).

Locally, tight folds whose heights exceed their widths occur on the limbs of the Central City anticline. These folds are shown by the zigzag pattern of some rock units, as on the north slope of Quartz Hill about 1,000 feet northeast of the Patch (pl. 1). They occur within belts of steeply dipping foliation; their presence is shown diagrammatically on the geologic sections on plate 2. Detailed mapping in mines with areas of good surface exposures indicate that the folds are definitely second-order structural features—that is, they do not appreciably modify the gross structural framework. The belts of tight folds are fairly well defined and trend subparallel to the major fold axes (pl. 1). On the southeast flank of the Central City anticline, a belt of tight folds extends from the vicinity of Leavenworth Gulch northeastward beyond the limits of the district. The northwest boundary of the belt is about 300–500 feet southeast of the axis of the main anticline; the belt is about 1,700 feet wide on Quartz Hill and widens northeastward. In places, and particularly on Winnebago Hill and Maryland Mountain, terrace folds are associated with the closed folds. The bends in the strata at the base and top of the individual terraces are sharp, the angle of deflection commonly exceeding 60°. The axial planes of the closed folds and of the terrace folds dip nearly vertically but they may dip steeply either to the northwest or the southeast. Another belt of tight folds occurs on the northwest limb of the anticline, but because of generally poor exposures, it is poorly known. On Nigger Hill this belt extends northwestward from the elongate body of calc-silicate gneiss exposed near the junction of Prosser Gulch with Eureka Gulch for a distance of at least 1,000 feet, but its full longitudinal extent is unknown. Dips of the gneisss within this belt commonly exceed 70°. Still another belt of tight folds occurs in the Justice Hill area in the southeastern part of the district. This belt extends without interruption southwestward into the Idaho Springs district (Moench, 1964, pl. 1); it passes abruptly northwestward (across strike) into a belt of open folds (Sims and others, 1963, pl. 8).

Recumbent folds whose axes are subparallel to the major fold axes are present locally. They are shown on plate 1 by a special fold symbol. The folds that were observed measure only a few feet or at most a few tens of feet from crest to crest; the axial plains lie subparallel to the foliation. The crests of the folds are subrounded or sharp, depending somewhat on the relative competency of the country rock, and generally are marked by a slight thickening. In other parts of the region (Harrison and Wells, 1959, p. 29), this type of fold is characteristic of the crestal region of large folds. However, the folds generally do not have this characteristic in the Central City district; instead, recumbent folds seems to occur mainly on the gentle limbs of broad open folds.

Lineations in the B direction are represented by the maximums in the northeast and southwest quadrants of each of the diagrams shown on plate 3; and accord closely with the bearing and plunge of the folds. In most diagrams the "highs" are well defined, and the maximums are represented by "bulls eyes" of 10 percent or more. The contour lines on all diagrams, however, are somewhat spread, and the contour lines on some diagrams—such as G, H, and, to a lesser extent, C and D—have a wide spread. The interval in the contour lines that represents variations in bearing of lineations reflects observed deflections in fold axes; for example, in many areas where the folds axes trend more eastward than average, the lineations are observed also to bear more eastward. In the district, the bearing of fold axes has been observed to range from about north to nearly east. Variations of this order of magnitude are observed most commonly in the northeastern part of the district, as can be seen by the fold axes and lineation measurements on plate 1. Folds and cogenetic lineations at most places in this area bear about N. 40° E. (see diagram H, pl. 3), but locally the bearing swings sharply and almost entirely to the east; the swing to an easterly direction is accompanied by a steepening of plunge. It could be argued that the areas containing abundant lineations that bear approximately N. 50°–70° E., as represented by diagrams C and D (pl. 3), contain rocks that were folded by both the older and the younger episodes of deformation recognized in this region. (See p. C6 and table 2.) However, the absence of recognized superposed folding in these areas, the similarities in type of folding throughout, the lack of cataclasis, and the observed gradual changes in traces of fold axes at many places indicate that the linear elements that trend east-northeast almost certainly were formed during the older plastic deformation, at the same time as were the dominant northeast-trending folds. Folds in the extreme southeast corner of the district, which are in the area shown in diagram C (pl. 3), are possible exceptions. Possibly, as inferred on figure 2, this area was deformed during the younger deformations; exposures in this part of the district are too poor, however, to determine such a deformation with certainty.

MINOR FOLDS AND RELATED LINEATIONS

Folds that trend nearly at right angles to the major fold axes are widely distributed but do not occur everywhere, and do not appreciably modify the structural framework. They are small undulations that locally warp or crinkle the foliation planes and the lineation in the B direction. At places in biotite-rich phases of the biotite gneiss unit, the folds are accompanied by a subparallel mineral alinement.

The folds in the A direction occur locally in all rock types except biotite-muscovite granite but differ in form within rocks of different competency. Within the more highly competent rocks, such as the microcline gneiss unit, the folds are typically open low-amplitude warps and irregular undulations that range in breadth from a few inches to several tens of feet or perhaps more. They are generally almost symmetric but at places are very asymmetric; the axes are poorly defined and discontinuous and are generally arranged in echelon. At places pegmatite streaks and boudins or incipient boudinage are subparallel to the fold axes. One of the folds that irregularly warps the contact between the microcline gneiss unit and the overlying biotite gneiss unit just north of Nevada Gulch (pl. 1) is so large that it is expressed as a noticeable deflection of the contact on a map at the scale of 1:6,000. The folds within relatively incompetent rocks, such as highly biotitic phases of the sillimanitic biotite-quartz gneiss, on the other hand, are more sharply contorted and commonly more highly asymmetric. They range in breadth from tiny crinkles to folds several feet across; commonly their heights are nearly as great or greater than their breadths. The crinkles are commonly of a 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 the larger anticlines that are in the A direction.

The folds in the A direction are apparently accompanied by relative shortening of the axes of major folds (folds lying in the B direction) and appear to be most abundant adjacent to bends in the axial planes of these folds. On Quartz Hill near the head of Leavenworth Gulch, for example, abundant complex cross warps in the A direction occur on the concave sides of arcs in the axial planes of the Central City anticline. Both to the north and south, where the trace of the axial plane is more northerly and more nearly straight, cross warps are much less conspicuous. Possibly the abundant west-trending cross folds along the north side of Eureka Gulch in the western part of the district also having a similar tectonic setting, but this possibility is uncertain. In the same way, folds in the A direction appear to accompany reversals in the plunge of the major fold axes. As might be expected they are abundant in dish-shaped segments (concave upward) along the axes, where maximum shortening takes place. Cloos (1946, p. 27–28) suggested a similar mechanism to account for folds in the *a* direction.

The folds and related lineations in the A direction vary sympathetically with changes in direction of the folds in the B direction. Lineations in the A direction, where sufficiently abundant statistically to be contoured at a 1-percent interval on the diagrams, are represented by maximums in the northwest or southeast quadrants of the diagrams in plate 3. Because of relatively persistent dips away from the crest of the Central City anticline, the diagrams for the northwest limb contain maximums only in the northwest quadrants, whereas those for the southeast limb contain maximums only in the southeast quadrant. The plunge of the maximums is, of course, controlled by the dip of the limbs. Diagram G differs substantially from the other diagrams and deserves comment. The principal maximum (3 percent) in A is in the northwest quadrant; its bearing is nearly at right angles to the 6-percent "high" at N. 40° E., which is the B linear direction. Another 3-percent maximum (S. 70° W.) reflects the many measurements of tight chevron folds and accompanying mineral alinements of biotite in the upper part of Eureka Gulch. (See pl. 1.) These lineations are presumed to be in the A direction of folding, but this fact has not been fully substantiated.

CHARACTER OF DEFORMATION

The texture and structure of the metamorphic rocks and the types of folds indicate that the Precambrian rocks were deformed by plastic flowage. The mineral assemblages indicate further that the plastic deformation took place at relatively high temperatures and pressure, while the rocks were buried under a substantial cover.

The deep-seated environment in which the rocks were deformed caused the foliation to form nearly parallel to the original bedding and the lineation to form in the foliation plane. The preferred mineral orientation must have resulted largely from mimetic crystallization during molecular plastic flowage. The absence, except at one known locality, of visibly divergent cleavages indicates that the original layering was not subjected to severe dynamic metamorphism. The axial plane foliation that contains oriented crystals of sillimanite and other minerals in the B coordinate direction at the locality near Silver Gulch indicates some shearing during the episode of deformation, however. At this locality, where the rocks are closely folded, shearing was sufficiently strong to refoliate the layering but not so intense as to destroy it. Thus, the foliation and associated lineation are analogous to the gneissic structure that characterizes the high-grade metamorphic rocks of the Precambrian shield areas.

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The folding was accomplished almost entirely by flexure slip. The slippage that necessarily accompanied folding occurred parallel to the fold limbs and the foliation planes. Less resistant (incompetent) layers within the succession yielded in part by small-scale folding, forming drag folds, the attitudes of which reflect the relative displacement of the competent layers above and below. At many places potential low pressure areas formed in the crests of the folds, and these were filled by pegmatite. Deformation did not result in the shearing out of folds and refoliation of the rocks at any locality.

On a small scale the folding was disharmonic (Billings, 1942, p. 53). The disharmonic folding is expressed by marked changes in the amplitude and tightness of small folds involving rocks of different relative competency; an extreme example can be seen in a photograph in the report by Moench, Harrison, and Sims (1962, pl. 3, fig. 2). The relatively competent rock layers tend to have round crests, whereas the less competent layers tend to be drawn out into sharp elongate crests. Possibly, the belts of tight folds in the district are an expression of disharmonic folding on a larger scale, but this possibility is uncertain. Instead, at least one belt of tight folds—on the southeast limb of the Central City anticline—appears more likely to have resulted from shortening perpendicular to strike that was necessitated by the convergence of the subordinate fold axes on this limb with the axis of the Central City anticline. Such relationships could result from anisotropism in the microcline gneiss unit; the rocks within the belt of tight folds may have been less resistant than the adjacent rocks. Possibly also the sheet of granodiorite and related rocks along part of the southeast margin of the belt behaved as a rigid body against which the less competent rocks were smashed.

The northeast-trending fabric of the rocks is inferred to have resulted from a horizontal(?) couple, for such a mechanism can readily account for the marked bends in the axes of folds lying in the B direction and the accompanying lineations in the A direction. If stresses having a strong shear component acting in a northerly direction on the east side of a block of ground containing the district and in a southerly direction on the west side continued intermittently subsequent to the formation of the main folds, the fold axes would have been warped as a result of a reorientation of the principal stresses. In effect, the continuing stresses would have compressed the folds along the axial planes in a longitudinal direction and, thus, relatively shortened the axis. As the compression at this stage appears to have been plastic rather than elastic deformation, the buckling of the axes may have taken place in stages: one segment would have been buckled; then after a decrease in its plasticity, another segment would have been buckled. At this late(?) stage of the deformation, the folds and other lineations in the A direction would have been formed, for these folds clearly warp the foliation surfaces and the lineation and only rarely have cogenetic mineral alinements.

STRUCTURE OF INTRUSIVE ROCKS

The intrusive rocks of the district are interpreted from observations in this and adjacent area to be syntectonic with the plastic deformation. The granodiorite and related rocks form concordant bodies that have a secondary foliation and lineation that can be traced into the adjacent layered rocks, a fact indicating that they were deformed by the same stresses that deformed the country rocks. The body south of Central City (pls. 1 and 2), for example, which is interpreted as an intrusive sheet, is folded along axes that can be traced longitudinally into the layered rocks. Evidence for emplacement of the granodiorite contemporaneously with the deformation at Central City is not clear, however, and is based partly on observations in adjacent areas. Mapping in areas to the west of the district by one of us and in the Chicago Creek area by Harrison and Wells (1959, p. 33) has shown that the granodiorite was emplaced during the deformation, for it contains inclusions of folded layered rocks and forms distinct phacoliths in the crests of folds lying in the B direction. Some inclusions in the Chicago Creek area are oriented parallel to the walls of the granodiorite body. The quartz diorite and hornblendite unit also forms concordant bodies, and, as it is folded and contains B lineations and is known to be younger than the granodiorite and older than the biotite-muscovite granite (Harrison and Wells, 1959, p. 16–17 and 33), it is necessarily also syntectonic. The biotite-muscovite granite is undeformed, forms small very discordant bodies, and has a slight foliation that is parallel to the walls, even where they crosscut older rocks, facts indicating that the granite is either late syntectonic or post tectonic. In the nearby Freeland-Lamartine and Chicago Creek districts (Harrison and Wells, 1959, p. 33, 54), and the Idaho Springs district (Moench, 1964), bodies of the same granite locally form distinct phacoliths lying in the B direction, a fact indicating that the granite is at least in part syntectonic.

Some bodies of intrusive rocks are classed as phacoliths because they occur as generally concordant lenses in the axial regions of anticlines and synclines; their internal structure seems to have originated prior to complete consolidation but after the formation of foliation in the wallrocks. The bodies of granodiorite and related rocks, which typically form phacoliths in this area, have characteristically deformed highly foliated margins and slightly foliated interior parts. The interpretation of these relationships that is most consistent with the available data is that the borders of the masses were foliated prior to consolidation, probably during emplacement, whereas the inner parts, which were removed farther from the confining walls at the time of intrusion, remained nearly massive. Such an interpretation is supported by textures observed in thin sections. The minerals in the highly foliated margins appear to have been recrystallized, at least in part, whereas those in the interiors appear to have a primary texture. Evidence that the bodies are intrusive rather than pretectonic-folded sills or sheets is indicated by local crosscutting contacts and by the local presence of rotated blocks of foliated country rocks (Harrison and Wells, 1959, p. 13). The magma in this environment probably made room for itself in part by entering potential low-pressure zones in the axial areas of plunging folds. The gneissic country rock yielded mainly by flowage; the magma in conjunction with the fold stresses created openings.

RELATION OF GROSS STRUCTURE AND LITHOLOGY OF PRECAMBRIAN ROCK UNITS TO METALLIFEROUS VEINS

Since publication of the important paper by Lovering (1930) on the localization of ore in the schists and gneisses of the Front Range mineral belt, the distribution and continuity of the vein deposits in the mining districts have been recognized to be greatly influenced by gross lithologic and structural features of the Precambrian rocks. Lovering (1930, p. 248–250) emphasized the effect of structure and kind of wallrock on the localization of ore shoots and pointed out for the first time the importance of the gross structure of the Precambrian rocks in causing the "bottoming-out" of ore. Later, Lovering (1942) amplified his discussion of many aspects of the structural controls of the ore bodies. Our mapping provides new data on the localization of the ore deposits. Most of the detailed information has been given previously (Sims, Drake, and Tooker, 1963; Sims and others, 1963); this section is mainly concerned with the probable persistence of fissures and ore deposits at depth.

The depth to which the ore deposits at Central City extend depends on several geologic factors but probably mainly on the type of wallrock. Observations in this and adjacent mining districts indicate that as depth increases, fissures in the less rigid rocks tend to become tighter because of higher confining pressures, whereas those in stronger wallrocks tend to remain open. At Central City most of the successful deep mining has been where the veins have walls consisting of microcline gneiss; in contrast, the veins at depth within the biotite gneisses have generally been thin and unprofitable to work (Sims, Drake, and Tooker, 1963). Thus, successful deep mining at Central City will probably be dependent upon the presence of the microcline gneiss unit as wallrocks.

The geologic sections accompanying this report (pl. 2) indicate in a broad way the disposition of the microcline gneiss unit relative to potentially workable veins that are known from surface exposures and underground workings. These data indicate that at the level of the Argo tunnel (alt approx. 7,650 ft), the deepest tunnel in the area, the microcline gneiss unit should form the walls of veins in nearly all parts of the district, except locally along the axis of the Central City anticline. Thus, except for the relatively thin biotite gneiss layers within the unit, microcline gneiss should constitute the walls in laterals extending from the main tunnel. Accordingly, other factors being favorable, this ground should be favorable for exploration. At depths below the tunnel level near the axis of the Central City anticline, the veins should be in biotite gneiss. Most of the known productive veins on Quartz Hill should enter the biotite gneiss unit that lies below the Quartz Hill layer of microcline gneiss at altitudes between 7,000 and 7,500 feet; northeastward along the axis of the Central City anticline, depths to the biotite gneiss unit should be even less, as is shown in section *E–E′*, plate 2. The veins in areas on the limbs of the anticline should remain in the microcline gneiss unit to substantially lower altitudes.

SUMMARY OF GEOLOGIC HISTORY

The geologic history that can be discerned from the rocks of the district and immediately adjacent areas is long and complex and includes events dating from the Precambrian to the present. Some of these events can be confidently inferred; others are highly conjectural.

The first event that can be reasonably inferred in the Precambrian was deposition of the sediments that yielded the layered rocks. Thick successions of interbedded graywacke and argillite or shale were deposited alternately with feldspathic sandstone. Except for the shales, the rocks apparently had high Na_2O/K_2O ratios, which may have been inherited from highly sodic parent rocks. Small lenses of carbonate(?) rocks and quartz sands were deposited with the dominant sediments—principally with the feldspathic sandstones. By analogy with more recent sediments of graywacke affinity, the sediments are inferred to have been deposited in a marine environment, probably on a shelf area adjacent to a terrane of granite or felsic metamorphic rocks.

Subsequently, the sedimentary rocks were deeply buried or exposed to a hot environment where they were reconstituted to high-grade metamorphic rocks that characterize the upper range (sillimanite-almandine subfacies) of the almandine amphibolite facies as defined by Fyfe, Turner, and Verhoogen (1958, p. 228–230). The graywackes were changed to biotite-quartz-plagioclase gneiss; the shaly sedimentary rocks, to sillimanitic biotite-quartz gneiss; and the feldspathic sandstone, to the granitic-appearing microcline-quartz-plagicoclase-biotite gneiss (microcline gneiss). Evidently, the clastic sediments were reconstituted without appreciable change in composition. The compositions of the carbonate(?) rocks, however, were changed probably during reconstitution through the addition and subtraction of elements. Iron may have been added to yield the skarns, and magnesia may have been added to form the cordierite-amphibole gneiss.

Reconstitution of the sedimentary rocks was probably closely followed by or perhaps partly accompanied by pervasive deformation by plastic flowage. The major northeast-trending folds and associated lineations were formed, and this event was followed closely by the formation of local small-scale folds and related linear elements nearly at right angles to the major fold axes. During earlier stages of the deformation, granitic solutions(?) thoroughly permeated the biotite gneisses and to a lesser extent the other rocks and formed migmatites. The migmatization was followed or perhaps in part accompanied by the emplacement of a succession of syntectonic intrusive igneous rocks. Granodiorite and associated quartz diorite and quartz monzonite were emplaced first as large generally concordant plutons and as smaller crescent-shaped bodies and dikes. The mode of emplacement is not fully understood, but intrusion by a phacolithic mechanism was probably dominant. The emplacement of the granodiorite and related rocks was followed by emplacement of quartz diorite and hornblendite in a manner similar to that of the granodiorite. The quartz diorite, hornblendite, and granodiorite were partly deformed and recrystallized late in the stage of plastic deformation. Locally, folds that can be traced into the adjacent country rock were formed in these rocks. As the last episode of intrusion, biotite-muscovite granite was emplaced as crosscutting dikes and, rarely, as phacoliths. The granite, however, was emplaced sufficiently late in the deformation to escape crushing and recrystallization. The granite appears to have been emplaced about 1,300 million years ago.

The Precambrian events that occurred after the emplacement of the biotite-muscovite granite are not clearly discernible in the Central City district but can be reconstructed in part from observations in adjacent areas and in the broader region of central Colorado. Studies in the Idaho Springs area (Moench, Harrison, and Sims, 1962) indicate that the rocks were locally deformed cataclastically after the intrusion of the granite. This deformation was confined mostly to the area now known as the Colorado mineral belt and was probably a significant factor in localizing this belt (Tweto and Sims, 1963). It did not appreciably affect the rocks of the Central City district, and except for an area in the extreme southeast part of the district, it appears to have produced only widely scattered slickenside striae and folds and possibly some joints. At a later time, but still in the Precambrian, large persistent faults having northwest and north-northeast trends were formed throughout the length of the Front Range (Sims and others, 1963; Tweto and Sims, 1963). These faults belong to the well-known "breccia reef" fault system (Lovering and Goddard, 1950).

The post-Precambrian history of that part of the Front Range containing the Central City district has been discussed by Lovering and Goddard (1950) and Sims, Drake, and Tooker (1963), and except for the events of the Laramide orogeny, it 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 a variety 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 time of the hypabyssal igneous activity, three main sets of faults that form a complex intersecting network formed within the mineral belt, and the older (Precambrian) faults were rejuvenated. Mineralization of these fissures yielded the gold- and silver-bearing base-metal sulfide ores for which the district is famous. These ores are described and discussed in the report by Sims, Drake, and Tooker (1963). Subsequent uplift, erosion, and weathering has altered the veins to shallow depths and locally provide rich supergene ores and placers.

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