The Boulder Creek Batholith, Front Range, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1101

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By DOLORES J. GABLE

A study of differentiation, assimilation,
and origin of a granodiorite batholith
showing interrelated differences in
chemistry and mineralogy in the batholith
and cogenetic rock types

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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THE BOULDER CREEK BATHOLITH, FRONT RANGE, COLORADO

By Dolores J. Gable

ABSTRACT

The Boulder Creek batholith is the best known of several large Precambrian batholiths of similar rock composition that crop out across central Colorado. The rocks in the batholith belong to the calc-alkaline series and range in composition from granodiorite through quartz diorite (tonalite) to gneissic aplite. Two rock types dominate: the Boulder Creek Granodiorite, the major rock unit, and a more leucocratic and slightly younger unit herein named Twin Spruce Quartz Monzonite. Besides mafic inclusions, which occur mainly in hornblende-bearing phases of the Boulder Creek Granodiorite, there are cogenetic older and younger lenses, dikes, and small plutons of hornblende diorite, hornblendite, gabbro, and pyroxenite. Pyroxenite is not found in the batholith. The Boulder Creek Granodiorite in the batholith represents essentially two contemporaneous magmas, a northern body occurring in the Gold Hill and Boulder quadrangles and a larger southern body exposed in the Blackhawk and the greater parts of the Tungsten and Eldorado Springs quadrangles. The two bodies are chemically and mineralogically distinct. The northern body is richer in CaO and poorer in K_2O, is more mafic, and has a larger percentage of plagioclase than the southern body.

A crude sequence of rock types occurs from west to east in the batholith accompanied by a change in plagioclase composition from calcic plagioclase on the west to sodic on the east. Ore minerals tend to decrease, and the ratio potassium feldspar:plagioclase increases inward from the western contact of the batholith, indicating that the Boulder Creek batholith is similar to granodiorite batholiths the world over. Emplacement of the Boulder Creek batholith was contemporaneous with plastic deformation and high-grade regional metamorphism that folded the country rock and the batholith contact along west-northwest and north-northwest axes. Also, smaller satellitic granodiorite bodies tend to conform to the trends of foliation and fold axes in the country rock, suggesting that emplacement was controlled by preexisting structures in the country rock.

On a gross scale, chemical equilibrium in the Boulder Creek Granodiorite is expressed by a near 1:1 ratio, or straight-line relationship in the distribution of iron, magnesium, and manganese in biotite and hornblende. General mineralogical trends in the Boulder Creek Granodiorite indicate that modal biotite, hornblende, and plagioclase tend to increase and quartz and microcline tend to decrease as CaO increases. These trends were not found in the Twin Spruce Quartz Monzonite.

Differentiation is believed to have played a major role and assimilation a minor role in the development of the Boulder Creek batholith. The Boulder Creek Granodiorite is of probable mantle or lower crust origin, and, based on the scant data available, the Twin Spruce Quartz Monzonite may be of crustal origin, but the magma was extensively altered by contaminants of ambiguous origin. Mafic inclusions, possibly derived from a dioritic magma which was an early differentiate associated temporally with the Boulder Creek Granodiorite and (or) the Twin Spruce Quartz Monzonite, were injected into the Boulder Creek Granodiorite during the mush stage and before the batholith was completely crystallized.

Biotite, hornblende, and potassium feldspar were studied extensively. Their chemistry and petrology indicate a homogeneity throughout the batholith not believed possible by a casual observance of the batholithic rocks in the field. The accessory minerals, where investigated, also tend to indicate this same pervasive homogeneity.

INTRODUCTION

Geologic investigations, of which this report is a product, have been carried out in the Front Range of Colorado since the early 1950's when detailed geologic studies of the crystalline rocks west of Denver were begun. The Boulder Creek batholith, just west of Boulder, Colo., occupies an area 14 km by 27 km (fig. 1). The batholith is the type area of similar masses of granodiorite that constitute a major part of the Precambrian intrusive rocks of Colorado.

This report is a composite of some old and much new work, both published and unpublished. The Boulder Creek batholith was first briefly described by Boos and Boos (1934); in 1950, Lovering and Goddard mapped and presented a short description of the batholith; in 1953, Lovering and Tweto presented a more detailed description. More recently, mineralogic and geochemical aspects of the batholith have been described by George Phair and colleagues of the U.S. Geological Survey; these are discussed later in this report. This paper summarizes the field data concerning the batholith, gained by the quadrangle mapping of others as well as myself, and presents much new data on the overall mineralogy, geochemistry, and origin of the batholithic rocks.

Chemical, mineralogical, and structural data indicate that the Boulder Creek batholith is represented by two similar but chemically different granodiorite magmas and by a distinctly different quartz monzonite unit, the Twin Spruce Quartz Monzonite, that is in part the same age and in part younger than the Boulder Creek Granodiorite. Like the Boulder batholith in Montana (Tilling, 1973), the two similar but chemically different granodiorite magmas were

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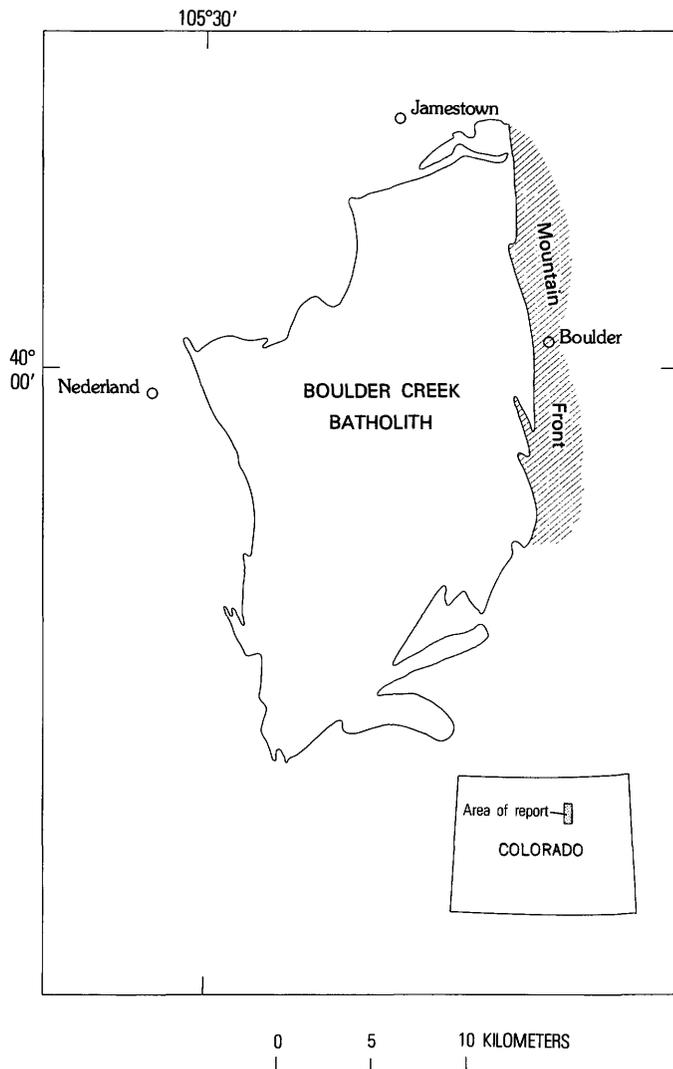
FIGURE 1.—Index map of the Boulder Creek batholith, Front Range, Colorado.

emplaced nearly contemporaneously. The Boulder Creek batholith was emplaced during the major regional metamorphism and sufficiently early for parts of the batholith to reflect this regional deformation.

PREVIOUS WORK

The early work of Boos and Boos (1934), Lovering and Goddard (1950), and Lovering and Tweto (1953) on the batholith was followed by detailed quadrangle mapping and by reports on various parts of the batholith. These reports are: Boulder quadrangle (Wrucke and Wilson, 1967); Nederland and Tungsten quadrangles (Gable, 1969, 1972); Ward quadrangle (Gable and Madole, 1976); Gold Hill quadrangle (Gable, 1977); Blackhawk quadrangle (Taylor, 1976);

Eldorado Springs quadrangle (Wells, 1967); and Ralston Buttes quadrangle (Sheridan and others, 1967). In addition, Sims and Gable (1964, 1967) described a few of the satellitic plutons in the metasedimentary rocks west and southwest of the batholith, and Pearson and Speltz (1975) mapped Boulder Creek Granodiorite in the Indian Peaks Wilderness area west of the Ward quadrangle.

Recent topical studies of minerals from the batholith include those by Wrucke (1965) on prehnite and hydrogarnet; Hickling, Phair, Moore, and Rose (1970) on allanite; Stern, Phair, and Newell (1971) on isotopic ages and morphology of zircon; and Phair, Stern, and Gottfried (1971) on fingerprinting discordant zircon ages.

TECHNIQUES USED IN THIS STUDY

The compositional classification and patterns of mineral distribution described in this report are based on modal analyses in which point counts of sufficient number (800–1,000 counts per thin section) were made to accurately represent the rock composition. Modes rounded to the nearest percent reflect less accuracy than those carried to the nearest tenth. Modal analyses of very coarse-grained rocks, such as were found in the central part of the batholith, were made using stained rock slabs, but a relatively small number of modes were made by this method. Only quartz, plagioclase, potassium feldspar, and total mafic minerals were counted on these slabs; the total mafic minerals were broken down by using a proportion determined by thin-section counts of the mafic minerals. Boundaries between composition fields in a triangular diagram (quartz, plagioclase, potassium feldspar) were determined as follows: granodiorite—5 to 20 percent dark minerals, more than 5 percent quartz, soda-lime feldspar at least equal to double the amount of the potassium feldspar; potassium feldspar may vary by 8 to 20 percent in rock of 60 percent feldspar. Below the granodiorite field the rock is a quartz diorite (tonalite); above it, the rock is a quartz monzonite. In quartz monzonite, alkali feldspar (microcline plus microperthite) ranges from 20 to 40 percent of a total of 60 percent feldspar. Rock units were named by using an average composition for the unit. Due to the large amount of quartz in these rocks the quartz monzonites generally fall in the granite or granitoid group of rocks according to Streckeisen's (1976) classification. Almost none of the rocks described in this report would be classified as quartz monzonite according to the classification of Streckeisen. Therefore only the more mafic rocks within this report generally are classified by the system of Streckeisen.

A total of 78 samples representative of all the rock types discussed here, excluding aplite and pegmatite, were chemically analyzed for both major and minor elements; 44 of the analyses have never been published before. Whole-rock samples were analyzed by standard (Peck, 1964) and rapid rock (Shapiro and Brannock, 1962) techniques. Minor elements were determined by semiquantitative spectrographic methods, and each result reported is the standard deviation of any single determination and should be taken as plus 50 percent and minus 33 percent.

Analyzed mineral concentrates were purified by first subjecting them to ultrasonic vibrations, then centrifuging in adjusted mixtures of methylene iodide and bromoform, and finally passed through an isodynamic separator. Samples were then examined under a binocular microscope. This process was repeated until only 1–2 percent impurities remained. Feldspar-concentrate powders were X-rayed for purity. Analytical procedures used for each mineral are given in the chemical tables (tables 10–13, 16, 18–20 and 22–26). Other procedures not applicable to all samples have been included at appropriate places in the text.

Composition of plagioclase was determined by measuring the refractive indices in index oils. Accuracy using this method is in the range of ±003. Another method that is less time consuming but not quite as accurate used extinction angles in conjunction with albite twinning (Deer and others, 1963, p. 135–139). Figure 6G was mostly compiled by this last method.

GEOLOGIC SETTING

Precambrian igneous and metamorphic rocks account for the greater part of the Colorado Front Range basement and are representative of the crystalline basement underlying the entire southern Rocky Mountain region.

The Boulder Creek batholith is the oldest (1,700 m.y.) of three extensive intrusive episodes of plutonic-rock emplacement in the Front Range. Its emplacement was syntectonic with the earlier major regional metamorphism. The Silver Plume Quartz Monzonite, a 1,450-m.y.-old intrusive suite, is exposed extensively north and west of the batholith but only occurs as small dikes and lenses within the batholith. Cataclasis affecting the batholith along the southeast contact (pl. 1), however, is related to the Silver Plume period of magmatism. The Pikes Peak Granite, representing the youngest Precambrian intrusive episode (1,040 m.y.), lies well outside the area of main concern and except for a few lamprophyre dikes in the batholith that are

perhaps of Pikes Peak Granite age, the batholith was not involved in that period of metamorphism.

Paleozoic and younger rocks upturned during the Laramide orogeny (Tweto and Sims, 1963) overlap the Boulder Creek batholith on the east. Elsewhere, Precambrian rocks representing a high-grade metamorphic gneiss terrane constitute the country rocks into which the batholith was emplaced. The country rock consists of biotite-sillimanite gneiss and schist for the most part, but layers of microcline gneiss and quartzite occur along the southeast contact. Interlayered with the schist and gneiss, but at some distance from the batholith, are several layers of hornblende gneiss that include some calc-silicate rocks and impure quartzite. Other than the mafic rocks shown on plate 1, only sparse, small dikes or sills of quartz diorite and hornblendite cut the schist and gneiss country rock.

Intrusive dikes and stocks of Cretaceous to Eocene age that are coextensive with the Colorado mineral belt occur mostly to the west of the batholith; a few smaller stocks and dikes occur along the contact, but only dikes are found within the batholith.

THE BATHOLITH

The Boulder Creek batholith crops out typically as pictured in figure 2, as a north-south-trending body along the eastern side of the Front Range just west of Boulder, Colo., and within the Colorado mineral belt. Extending from this centrally located batholith, both to the northwest and southwest across central Colorado, are lenses, plutons, and even other batholiths of similar composition.

The batholith was emplaced in the catazone, roughly at a depth of 12–20 km. As defined by Buddington (1959), the catazone is represented by an environment of intense pressure-temperature conditions. The batholith was emplaced partly by pushing aside the surrounding country rocks, as seen in outcrops on the west side of the batholith, partly by assimilation, and partly by passive magma emplacement into fold structures.

To the west of the batholith is a series of granodioritic and comagmatic mafic rocks that are crudely alined forming a continuous pattern of outcrop from the Strawberry Lake batholith to the northwest of the Boulder Creek batholith to the Mt. Evans batholith southeast of the Boulder Creek batholith (pl. 1). This pattern reflects a common tendency for associated mafic rocks to be satellitic to a major mass of granodiorite. Emplacement of the batholithic rocks apparently followed definite compositional trends as delineated in figure 3. The presumed concentric order
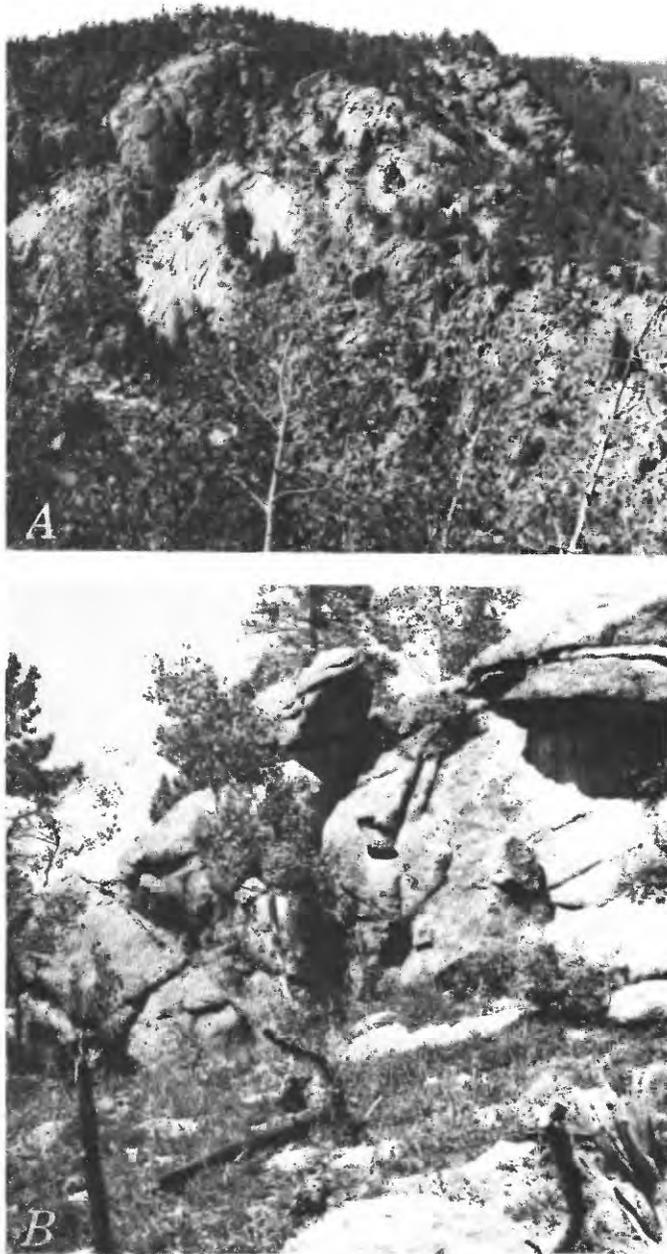
FIGURE 2.—Typical weathered bouldery outcrops of Boulder Creek Granodiorite, Pinecliffe area, Coal Creek Canyon, Colorado. A, view looking north across South Boulder Creek from turnout on Colorado Highway 72. B, an outcrop along dirt road leading to Gross Reservoir from Colorado Highway 72.

of emplacement was (1) quartz diorite, predominantly on the west; (2) quartz monzonite, to the east and adjacent to the batholith contact, followed in the batholith proper at the contact by mafic quartz diorite; inward in the batholith the quartz diorite grades into

granodiorite, quartz monzonite, and some granite. The eastern part of the batholith is buried, so it is not possible to comment on that part of the batholith. From figure 3 it appears that the three major rock types are nearly equally represented in the exposed part of the batholith. This crude zonal arrangement resembles that in plutons of similar composition the world over (Whitten, 1962; Nilssen and Smithson, 1965; Bateman and others, 1963).

CONSTITUTION OF THE BATHOLITH

The Boulder Creek batholith consists mainly of two rock types (pl. 2): (1) the Boulder Creek Granodiorite, generally the coarser grained, more mafic rock most often referred to in the literature and formally named by Sims and Gable (1964), and (2) quartz monzonite, a finer grained, often thinly slabbed, leucocratic rock that first was recognized as a distinct rock unit by Wells (1967, p. D24–D27) but not formally defined. In order to identify this rock type specifically and distinguish it from another variety of quartz monzonite in the Boulder Creek Granodiorite from the same area, the name Twin Spruce Quartz Monzonite is formally proposed for the unit later in this report.

Also included in the batholith are scattered smaller masses of darker plutonic rock that are both older and younger than the granodiorite, profuse large and small pegmatites, numerous aplites, and remnants of metamorphic rocks.

Approximately three-fourths of the Boulder Creek batholith consists of Boulder Creek Granodiorite, which is the name given a series of rocks that have the same macroscopic and microscopic characteristics and vary in composition from quartz diorite to quartz monzonite but average granodiorite. The granodiorite in the batholith appears to be related to two magma intrusions. A smaller northern intrusion is separated from a larger southern intrusion by quartz diorite similar in composition to that in the contact zones of the batholith. This area of quartz diorite is north of Magnolia (Magnolia is in the northeast quarter of section 6 in the Eldorado Springs quadrangle) and trends diagonally across the batholith in an east-southeast direction along the 40° latitude (fig. 3).

Twin Spruce Quartz Monzonite occurs predominantly in the central part of the batholith and along the southeast contact. Its composition is much less variable than that of the Boulder Creek Granodiorite. The extent to which the Twin Spruce Quartz Monzonite accompanies the Boulder Creek Granodiorite in plutons and batholiths other than the Boulder Creek batholith is unknown. It is found in the Mt. Evans batholith; the Rosalie lobe, studied by Bryant and Hedge, (1978), appears to be Twin Spruce Quartz Mon-
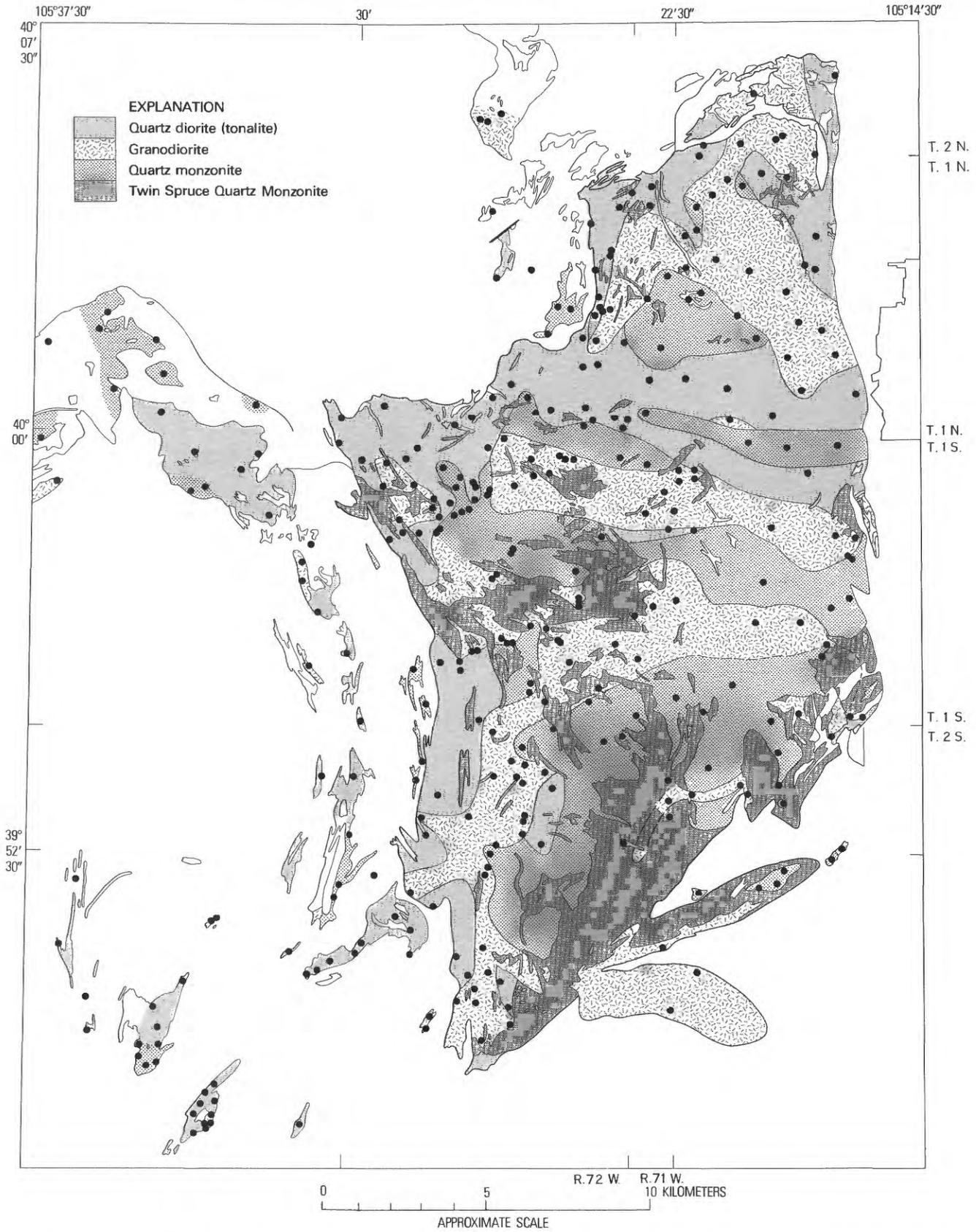
FIGURE 3.—Boulder Creek batholith showing rock types as indicated from modes. Dots are mode localities; dashes represent areas of insufficient data to place boundaries accurately.

zonite (pl. 1). The Boulder Creek Granodiorite on Rollins Pass (an area between the Boulder Creek batholith and the Strawberry Lake batholith) is also accompanied by large lenses of Twin Spruce Quartz Monzonite. Further detailed mapping, however, is needed to determine the extent of the Twin Spruce in all areas of Boulder Creek Granodiorite.

Gabbro, pyroxenite, hornblendite, and hornblende diorite (pl. 1) are believed to be associated in time and space with the Boulder Creek Granodiorite. Some of these mafic rocks appear to be older than the Boulder Creek Granodiorite because of their intense alteration; probably they belong to the same igneous event but were emplaced earlier than the granodiorite, as also suggested by Braddock in the Empire area (1969, p. 18). Other mafic bodies are probably the same age as the granodiorite, and still others probably are younger (Sims and Gable, 1967, p. E41).

CONTACT RELATIONS AND MODE OF EMPLACEMENT

Contacts of the Boulder Creek Granodiorite in the batholith with the country rocks are grossly sharp, and dips are steep to nearly vertical, although there are local variations. Foliations in the contact zone of the granodiorite are defined principally by the segregation of minerals into darker biotite-rich and lighter quartz-plagioclase-rich layers, and foliations in country rock and batholith are conformable, especially on the west side of the batholith. Forceful emplacement of the batholithic rocks is evident both along the west and south sides of the batholith; on the west, whereas foliations in the schist parallel the batholithic contact on a large scale, the schists are tightly folded on the scale of a hand specimen. Often chevron-type folding occurs at the contact with more open folds replacing the chevron folding out from the contact. Along the southern border of the batholith, as described by Taylor (1976), forceful emplacement of the Boulder Creek Granodiorite is suggested by the warping of adjacent gneiss into folds having overturned limbs and by the bending of the axial surfaces of older folds. To the north the schist-granodiorite contact from the Peak to Peak highway to just south of Gold Hill is folded along northwest-trending axes, and the granodiorite has been conformably emplaced along these fold axes giving the batholith contact an irregular or scalloped appearance (pl. 2). North of Gold Hill the trend of foliation in the batholith and in the gneiss and schist at the contact are parallel; however, the batholith and the adjoining metasedimentary rocks are folded along an east-northeast synclinal axis.

Interlensing of metasedimentary and batholithic rocks is common locally; at Nederland, for example, it is difficult to recognize and map a distinct, definite contact for the batholith. Along most of the western margin, however, the contact is relatively sharp, although bodies of pegmatite and aplite occur in the contact zone. The south and southeast contacts lie in the Idaho Springs–Ralston cataclastic zone (pl. 1); shearing in this zone produced a shear foliation in the rocks that extends into the batholith and masks original irregularities of the contact zone. On the north margin between the Peak to Peak highway and Sugarloaf Mountain (pl. 2), the contact zone is not nearly so foliated as on the west flank. Dips also vary only from 50° to 80° to the north, away from the batholith, whereas elsewhere dips are very steep. As the predominant country rock adjacent to the batholith is biotite schist and gneiss, it stands to reason most inclusions in the contact zone of the batholith are predominantly schist and gneiss; however, along the southeast batholith contact, there are inclusions of quartzite and microcline gneiss.

Contacts between Boulder Creek Granodiorite and the finer grained Twin Spruce Quartz Monzonite within the batholith are both gradational and sharp or they are locally separated by thin pegmatite lenses or mafic (biotitic) layers; also, occasional shearing may occur along the contact. Granodiorite in contact with quartz monzonite is commonly foliated, but elsewhere the contact may be blurred due to structural similarities between granodiorite and quartz monzonite. In the southern part of the batholith, north of Tremont Mountain and along South Boulder Creek, irregular-shaped inclusions of granodiorite are found in the finer grained quartz monzonite. Dips of the granodiorite-quartz monzonite contacts vary from near horizontal, as in the central part of the batholith, to vertical in the southern part.

The mineralogy of biotite gneiss and schist country rock is normally quite variable but from observations made while walking over contacts of metasedimentary rock and granodiorite it appears all gneiss and schist adjacent to the batholith are sillimanite bearing and abnormally rich in biotite. Along the west contact, the metasedimentary rocks in thin section are very rich in biotite, sillimanite, and quartz; plagioclase is very corroded, poorly twinned (the twins are indistinct and poorly developed), and very sparse as much as several tens of meters from the contact. Also, these rocks are ptygmatically folded. At Nederland, both plagioclase and potassium feldspar are noticeably absent, but as much as 10 or 15 percent kaolinite is present in the contact rocks. This alteration does not appear to be related to emplacement of the batholith but instead to processes associated with the Laramide mineralization in the Nederland-Tungsten district. Northward from Nederland, plagioclase in gneiss adjacent to the contact is very corroded, poorly twinned, and commonly

zoned (normal zoning), but is not diminished in quantity; potassium feldspar in the same rocks as indicated by modes varies no more than between samples from outcrops at a distance from the batholith.

In the Caribou pluton, a satellitic body between Boulder County Hill, Nederland quadrangle, and Mount Albion in the Ward quadrangle (pl. 1), granodiorite on the southeast side bears profuse biotite gneiss and schist inclusions. West of Overland Mountain in the Gold Hill quadrangle the Overland pluton is very coarse grained similar to coarse-grained, nonfoliated granodiorite from the central part of the batholith proper; it is less foliated than any of the other satellitic plutons. It also has a pronounced lineation due to the alinement and increase in length of the feldspar crystals in the granodiorite. In the Overland pluton biotite gneiss and schist inclusions occur throughout but are more profuse along the contact. In both these satellitic plutons, some gneiss and schist inclusions show alteration several millimeters in from the contact, especially where contacts are indistinct due to assimilation at the boundary of inclusion and granodiorite. South of the Ward and Gold Hill quadrangles and west of the batholith proper the metasedimentary rocks are pierced by many bodies of Boulder Creek Granodiorite. At Mt. Pisgah (Central City quadrangle), the Pisgah pluton has sharp contacts with the adjacent metasedimentary rocks except along the northeast margin where again assimilation of the gneiss by granodiorite is evident. At this locality biotite stringers derived from the gneiss occur abundantly in the granodiorite across a distance of several meters.

Emplacement of batholithic rocks, in general, appears to have been from west to east although nothing is known about the easternmost edge of the batholith. Most satellitic plutons and batholithic contact rocks were probably emplaced almost simultaneously. The contact magma was followed by core magma that is represented predominantly by hornblende-bearing rocks (fig. 6A). This core magma broke through the contact rocks at Gold Hill and just north and east of Nederland. The tongue of magma to the north of Nederland moved west and cut into the southern part of the Caribou pluton.

The larger structural features represented by foliation trends throughout the batholith (pl. 2) have been deflected to varying degrees by high-grade regional metamorphism. Lineations for the greater part of the batholith have conformed to foliation trends; however, lineation trends do not always agree with foliation trends especially in the area including Pinecliffe, Tremont Mountain, and Gross Reservoir. That lineations are askew of foliations may be because of late magma adjustments or there may be some other reason not

understood. These structural trends in the batholith led Lovering (Lovering and Tweto, 1953) to believe the magma for the entire batholith welled up from a conduit just east of Gold Hill and spread southward, rising at an angle of about 50° with the horizontal. It is possible that Lovering's conduit represents the final emplacement of magma for the smaller northern mass whose east-to-west compositional trend is not nearly as consistent as the trend in the southern part of the batholith (fig. 3).

Chemical and structural relationships tend to indicate that two magma intrusions may have been emplaced almost simultaneously in the batholith: a smaller northern mass that has not differentiated to the extent of a larger southern mass.

CONSTITUENT ROCKS OF THE BATHOLITH

BOULDER CREEK GRANODIORITE

The Boulder Creek Granodiorite in the batholith is a medium- to very coarse-grained (0.6–2.0+ mm), locally porphyritic rock that has both massive and foliated facies (fig. 4). Porphyritic granodiorite generally is found in the more mafic parts of the batholith or in those parts of the batholith and adjoining plutons that have been extensively sheared and perhaps locally metasomatized. The massive and coarser grained rocks are generally found near the center of the batholith (fig. 5D). Such an area lies north and east of Pinecliffe, where the rock is very coarse and generally nonfoliated, but the feldspars show a good lineation that appears to be a primary structure. The feldspars in the batholithic rocks also may be alined because of recrystallization accompanying shearing, but these textures are distinctly different because alined feldspars are accompanied by a foliation not found in the primary structure. Foliated, medium-grained, and nearly equigranular granodiorite, having perhaps both primary and secondary structures but chiefly secondary ones, generally occurs in marginal zones of the batholith, in lenses and plutons in adjacent metasedimentary rocks, or along the many faults within the batholith proper. This foliation results from oriented alined feldspar phenocrysts, stringers of biotite and less commonly hornblende, and a weak compositional layering due to segregation of biotite, quartz, and the feldspars. While the granodiorite appears to vary in texture and composition within a single outcrop, it has a surprising characteristic uniformity in texture and in mineral composition across the entire batholith.

The granodiorite is typically a mottled grayish-white and black rock on weathered surfaces but appears dark bluish gray on freshly broken surfaces. Weathered sur-
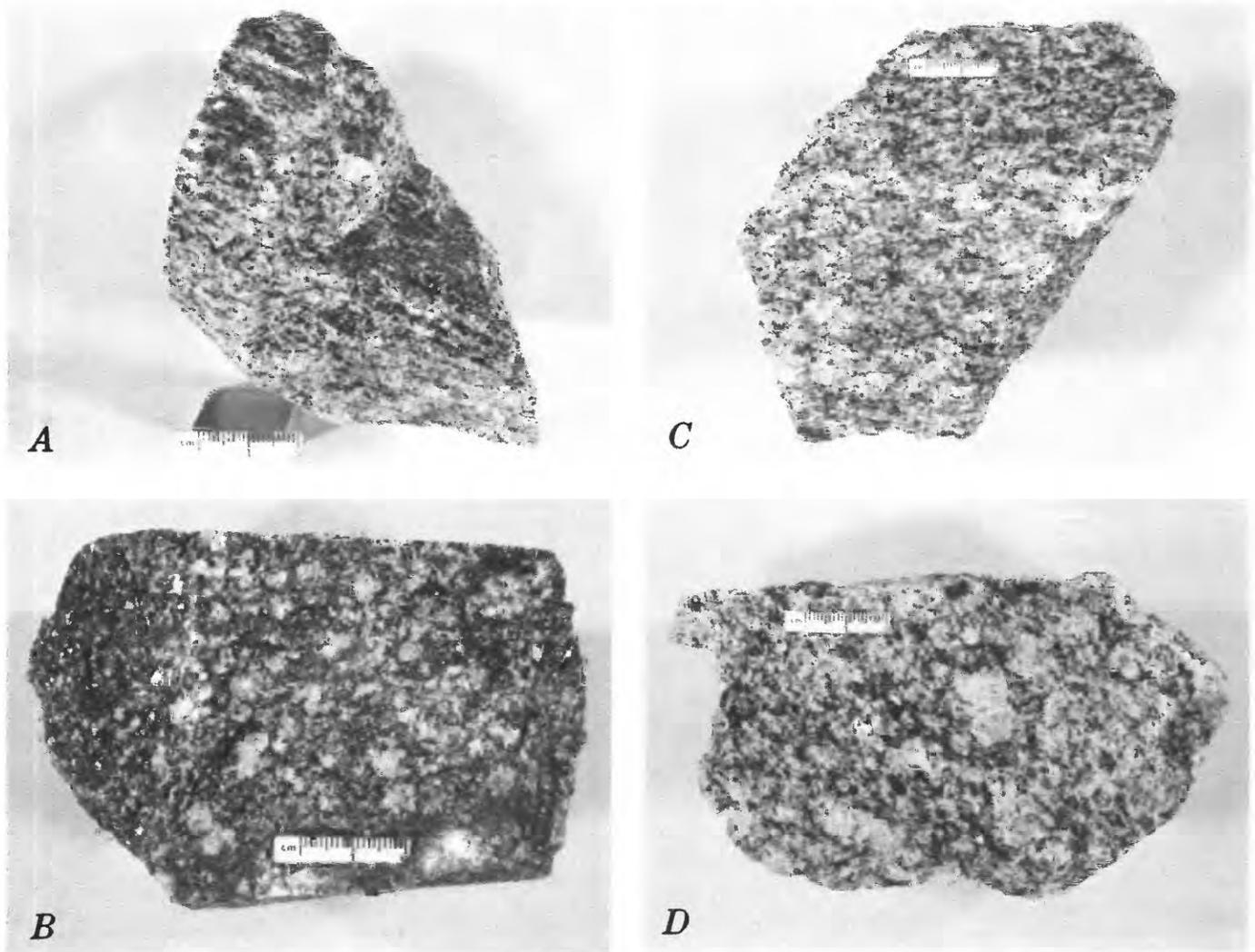
FIGURE 4.—Typical Boulder Creek Granodiorite. A, foliated granodiorite from west contact (29). B, biotitic, slightly porphyritic granodiorite from north contact (50). C, slightly foliated, medium-grained granodiorite with good lineation (129). D, medium-coarse-grained, slightly porphyritic granodiorite (41). Photographs by Louise Hedricks, U.S. Geological Survey. Numbers in parentheses are sample localities (tables 1 and 10). Scale in centimeters.

faces are commonly pitted by bowl-shaped depressions from 1 cm to 1 m in diameter and from several centimeters to several tens of centimeters in depth. Weathering also produces bouldery outcrops and a knobby topography, especially in areas where the finer grained, more easily weathered quartz monzonite has been weathered out of granodiorite. Jointing also causes differential weathering and is partly responsible for the development of the bouldery topography from which Boulder Creek derives its name.

The dominant minerals in the Boulder Creek Granodiorite include plagioclase, potassium feldspar (microcline and microperthite), quartz, and biotite. Hornblende is either disseminated throughout the rock, as is common in the central and northern part of the batholith (fig. 6), or occurs in spotty distribution as in the granodiorite in the southern part of the batholith. In figure 6 it can be seen that the ores, mainly magnetite, are more profuse to the west of the batholith as is to be expected because the mafic rocks related to the Boulder Creek batholith occur dominantly in this area. Probably both the ores and the mafic rocks represent an early phase of a differentiating magma. This trend also coincides with the trend in plagioclase composition and with the ratio potassium-feldspar:plagioclase. Alternatively, the north to northwest modal trend of the ores, quartz, feldspar proportions, and sphene also may have developed during emplacement of the batholith and represent a regional dynamic imprint for the batholith.

Modes representative of the Boulder Creek Granodiorite in the area of this report are given in
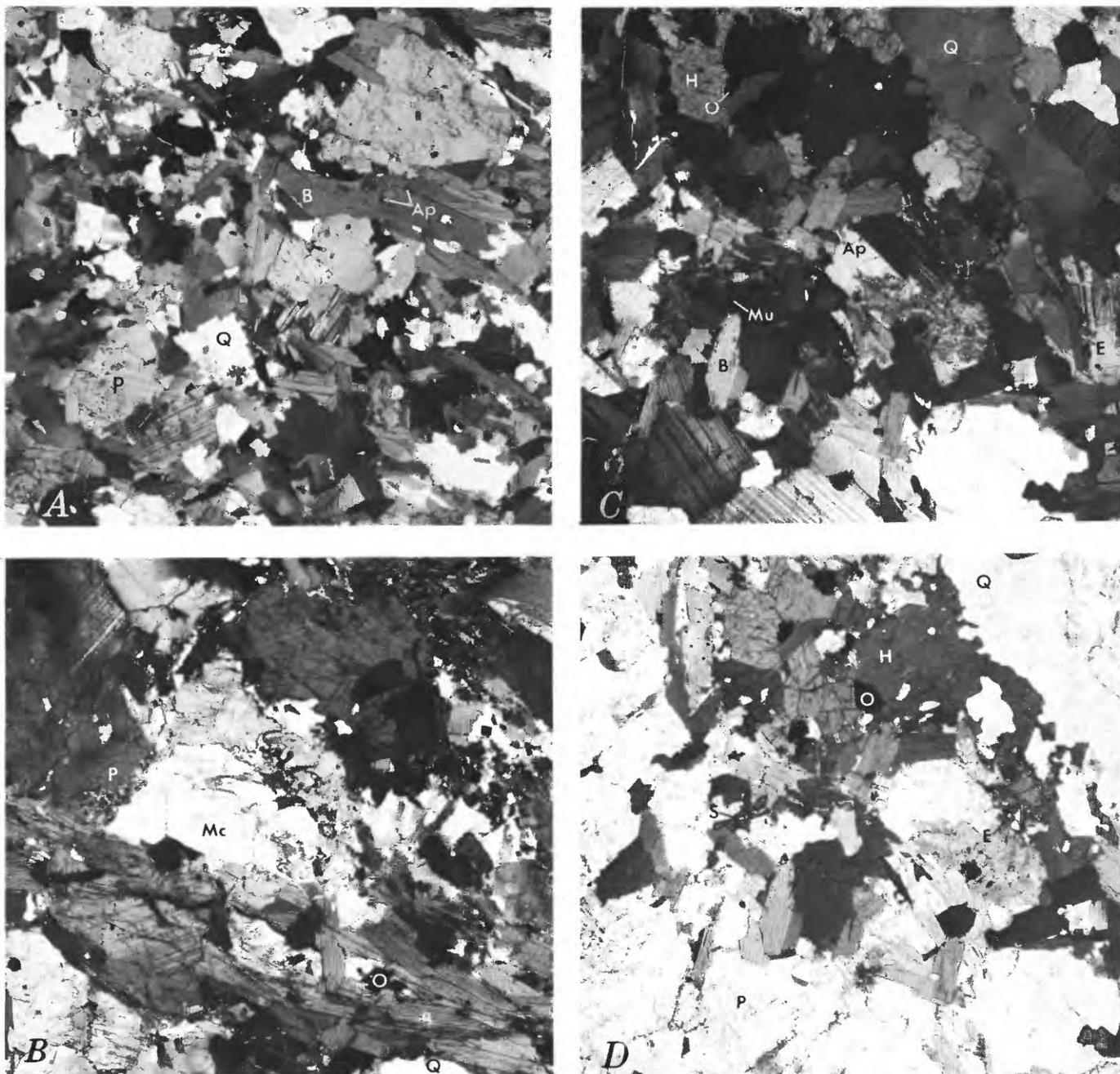
FIGURE 5.—Photomicrographs of Boulder Creek Granodiorite. *A,* near west contact with metasedimentary rocks (389), x-polarizers, ×10. *B,* shearing along crystal boundaries in granodiorite (47), x-polarizers ×12. *C,* granodiorite, medium grained from interior of batholith (50), x-polarizers, ×12. *D,* same section as in *C;* note clustering of mafic minerals, plain light, ×12. Photographs by Louise Hedricks, U.S. Geological Survey. Ap, apatite; E, epidote; B, biotite; H, hornblende; Mc, microcline; Mu, muscovite; O, ores; P, plagioclase; Q, quartz; S, sphene.

tables 1–5. In the tables, the modes are grouped in order to show variations in mineralogy to best advantage. A summary of the modal data is here, in two categories: (1) lenses and small plutons within metasedimentary rocks that are adjacent (contact zone) to the batholith; and (2) the batholith proper, with three groups; granodiorite from the contact zone, sheared and faulted segments, and the main bulk of the batholith.

From the summation above, the following conclusions appear valid: (1) the granodiorite in lenses and plutons in the metasedimentary rocks and in the batholith proper is similar in composition, except that ores are more common in the satellitic bodies and
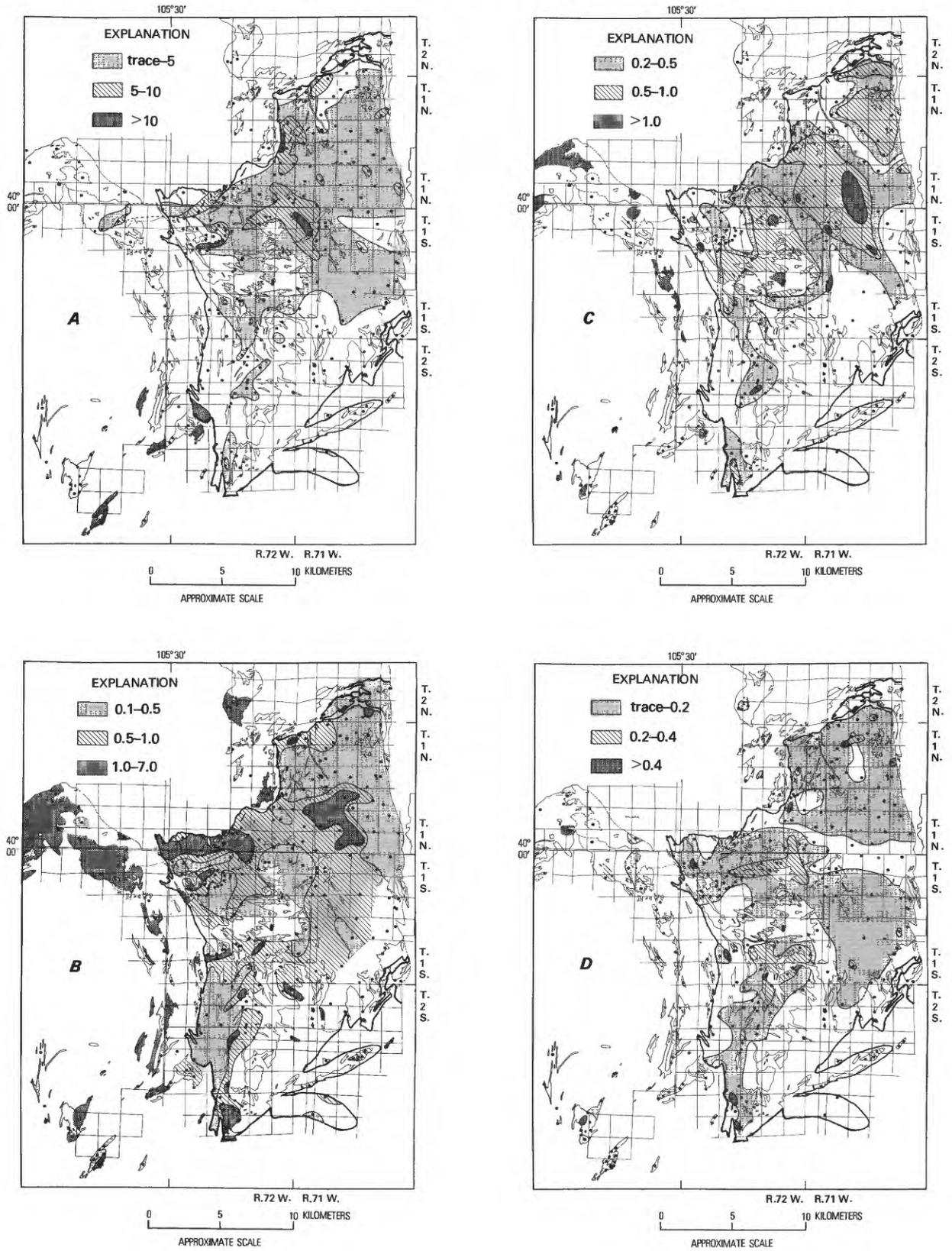
FIGURE 6.—Modal distribution of quartz, ores, sphene, allanite, hornblende, and potassium feldspar:plagioclase ratios and An content of plagioclase in Boulder Creek Granodiorite. Modal distribution, in percent, of *A*, hornblende; *B*, ores (mainly magnetite); *C*, sphene; *D*, allanite; *E*, quartz; *F*, apatite; *G*, composi-

tions of plagioclase in percent An; *H*, ratio of potassium feldspar to plagioclase. Hornblende in southeast part of batholith approximate, plotted from modes and text in Wells (1967). Areas shaded gray represent Twin Spruce Quartz Monzonite; dots indicate sample localities.
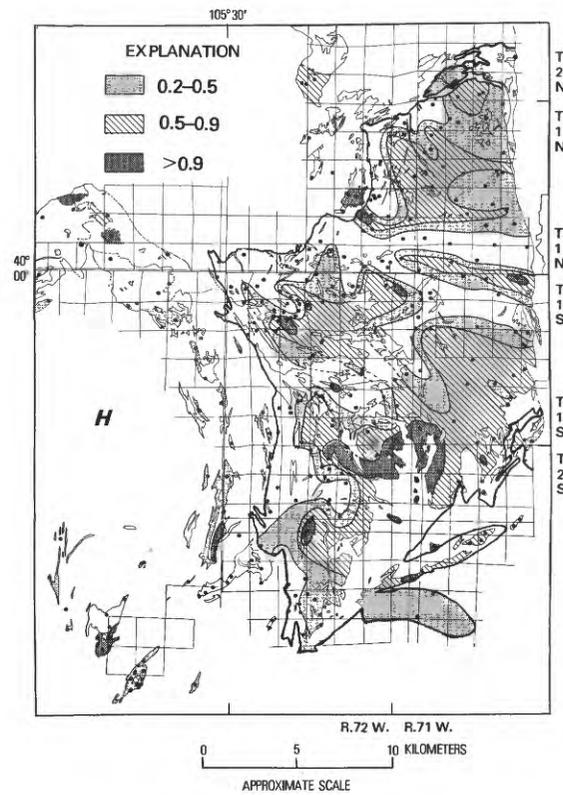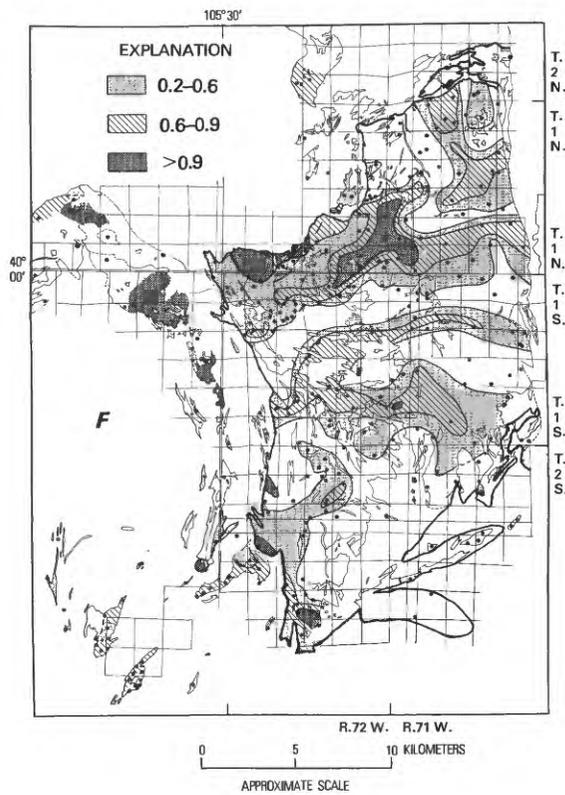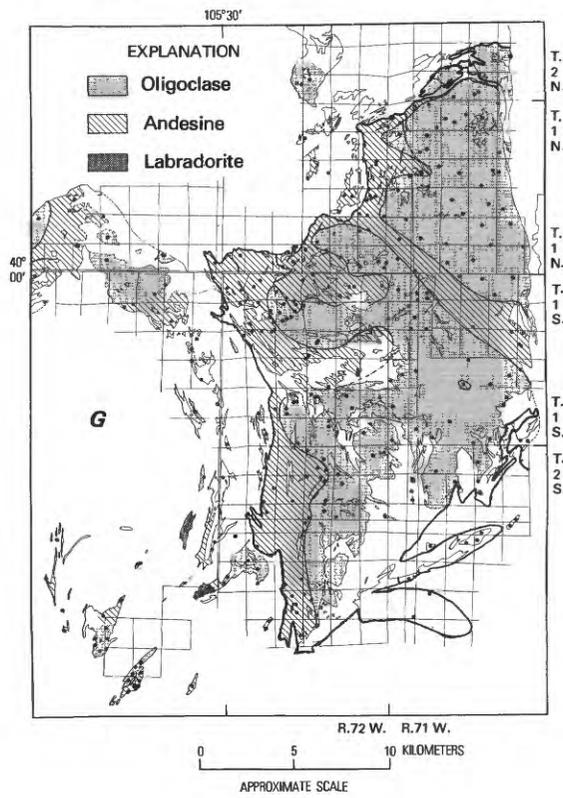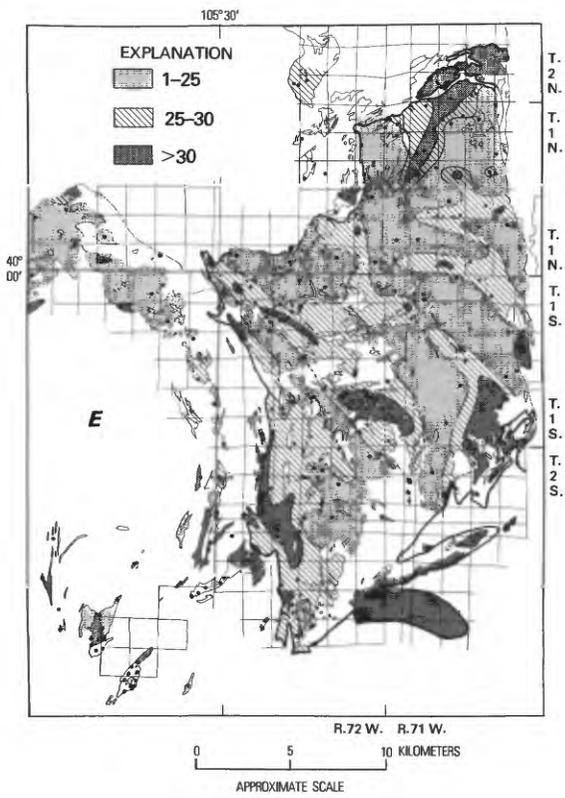
TABLE 1.—*Modes (volume percent) for Boulder Creek Granodiorite, from the batholith, Front Range, Colo.*

[(-), not found; Tr., trace; Tr.?, may be present; ores include all opaque minerals. Samples 1-76 and 192-217, Tungsten quadrangle; 99-131, Gold Hill quadrangle; 132-169, Boulder quadrangle; 170-191, Nederland quadrangle; 403-407, Ward quadrangle]

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Potassium feldspar	26.1	10.8	8.2	8.2	5.2	12.0	11.1	15.3	22.3	20.0	5.5	40.2	13.2	16.7
Plagioclase	33.4	41.1	53.0	43.4	47.0	46.3	41.5	45.1	36.6	41.4	46.0	32.0	39.0	47.0
Quartz	30.7	33.1	17.7	30.4	31.3	25.2	30.1	17.5	29.1	22.6	19.0	6.0	33.7	20.8
Biotite	8.1	12.9	17.3	15.5	15.0	15.3	15.2	19.8	9.1	13.3	18.7	4.5	13.5	10.6
Muscovite	0.1	0.1	--	0.1	--	0.1	0.2	0.1	--	--	--	--	--	--
Ores	0.5	1.2	0.8	0.8	0.6	0.5	0.8	1.0	0.4	0.5	1.0	0.3	0.1	1.0
Hornblende	--	--	1.8	--	--	--	--	--	--	0.5	8.5	14.6	--	Tr.
Allanite	Tr.	--	--	0.6	--	0.1	--	Tr.	Tr.	0.2	0.1	0.2	0.3	0.1
Apatite	0.2	0.2	0.3	0.7	0.6	0.3	0.4	0.5	0.3	0.3	0.5	0.6	--	0.5
Zircon	Tr.	Tr.	Tr.	0.1	Tr.	0.1	Tr.	Tr.	0.1	Tr.	0.2	0.1	0.1	Tr.
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	0.4	--	--	Tr.	--	--	--	--	--	--	--	--	--	--
Chlorite	0.2	--	--	0.1	--	--	--	0.1	--	--	--	--	--	0.4
Epidote-clinozoisite	0.3	0.1	0.1	0.1	Tr.	--	--	Tr.	1.5	0.8	--	0.4	0.1	2.0
Rutile	--	--	--	Tr.	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	0.5	0.8	Tr.	0.3	0.1	0.7	0.6	0.6	0.4	0.5	1.1	Tr.	0.9
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Potassium feldspar	15.3	15.0	13.1	22.5	.26.8	27.4	17.5	13.8	11.3	10.6	24.4	20.7	14.5	27.1
Plagioclase	49.3	41.8	46.7	35.1	33.6	28.0	40.3	37.7	46.5	46.6	36.3	41.9	44.4	36.3
Quartz	17.9	29.8	23.3	30.7	30.4	25.7	26.8	30.7	24.4	28.2	30.2	24.8	21.3	24.4
Biotite	13.4	11.8	11.5	9.1	5.5	14.1	10.4	13.2	13.2	12.8	6.7	9.9	16.0	10.6
Muscovite	--	0.1	--	0.1	1.8	0.1	--	--	--	0.3	0.2	--	--	--
Ores	2.0	0.1	2.4	1.2	1.1	0.7	0.5	0.6	0.3	0.1	1.1	0.4	0.4	0.8
Hornblende	--	--	0.3	--	--	2.8	1.9	1.3	1.9	--	--	0.2	0.5	--
Allenite	--	0.6	--	0.3	--	0.1	0.1	0.1	0.3	Tr.	--	--	Tr.	0.2
Apatite	0.5	0.4	0.6	0.6	0.8	0.7	0.5	0.1	0.3	0.2	0.7	0.6	0.7	0.2
Zircon	0.1	Tr.	0.1	Tr.	Tr.	0.1	Tr.	Tr.	0.1	Tr.	Tr.	0.1	Tr.	Tr.
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	--	--	0.4	0.1	--	--	--	--	--	0.3	--	--	0.1	--
Chlorite	0.6	0.2	0.1	0.1	Tr.	--	--	--	0.2	0.2	0.1	0.1	--	--
Epidote-clinozoisite	0.6	--	1.0	Tr.	Tr.	0.2	0.9	1.1	0.2	0.6	--	0.7	1.4	--
Rutile	--	--	--	Tr.	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	0.3	0.2	0.5	0.2	--	0.1	1.1	1.4	1.3	0.1	0.3	0.6	0.7	0.4
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 1.—*Modes (volume percent) for Boulder Creek Granodiorite, from the batholith, Front Range, Colo.*—Continued

Sample No.----------	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Potassium feldspar--	18.4	8.1	36.4	8.3	16.7	17.8	13.6	17.4	0.3	18.2	10.8	16.9	16.0	1.7
Plagioclase----------	37.8	48.2	27.4	47.4	36.1	46.6	47.5	42.1	47.2	38.3	48.3	37.5	43.0	62.1
Quartz--------------	29.0	26.9	25.9	23.2	23.3	22.7	25.1	21.8	32.3	31.6	27.8	26.6	22.0	11.1
Biotite-------------	14.0	15.7	8.1	14.5	15.8	10.5	11.8	15.9	18.2	9.8	11.2	17.3	14.7	15.9
Muscovite-----------	0.1	0.2	0.3	--	--	--	--	0.1	0.1	0.5	--	0.1	--	--
Ores----------------	0.5	0.3	1.0	0.2	0.8	0.2	0.7	0.9	0.8	0.4	0.9	0.5	0.9	0.5
Hornblende----------	--	--	--	5.3	4.7	0.9	--	--	--	--	--	--	1.4	7.4
Allanite------------	--	0.1	--	Tr.	0.1	Tr.	0.2	0.3	0.1	0.4	0.1	--	0.4	Tr.
Apatite-------------	0.2	Tr.	0.3	0.2	0.5	0.1	0.4	0.8	0.7	0.3	0.7	0.6	0.5	0.6
Zircon--------------	Tr.	Tr.	0.1	0.1	0.1	0.1	Tr.	0.1	--	Tr.	Tr.	Tr.	Tr.	Tr.
Monazite-xenotime---	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite-------------	--	--	--	--	--	--	--	--	--	0.4	--	--	0.2	--
Chlorite------------	--	0.1	0.3	--	0.1	--	--	--	--	Tr.	--	Tr.	--	--
Epidote-clinozoisite	--	0.2	0.2	0.4	1.5	0.9	0.3	--	--	0.1	--	Tr.	0.5	0.3
Rutile--------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite---------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet--------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene--------------	Tr.	0.2	Tr.	0.6	0.3	0.2	0.4	0.6	0.3	--	0.2	0.4	0.4	0.4
Kaolinite-----------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total-----------	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.-----------	43	44	45	46	47	48	49	50	51	52	53	54	55	56
Potassium feldspar--	37.6	23.4	34.5	21.1	10.6	16.6	19.0	2.5	19.4	17.1	11.8	14.0	9.2	25.3
Plagioclase----------	36.8	25.7	32.4	33.7	48.5	40.7	34.3	46.7	40.8	30.9	41.1	34.8	44.7	41.2
Quartz--------------	7.1	9.1	24.4	38.4	24.9	18.7	27.6	14.1	26.5	27.8	25.0	34.4	30.3	23.0
Biotite-------------	13.6	13.3	7.0	5.5	12.9	14.6	14.4	17.9	10.4	8.2	17.3	12.3	12.5	8.4
Muscovite-----------	--	--	--	0.2	--	--	--	--	0.5	--	0.1	--	0.4	--
Ores----------------	0.4	0.9	0.5	0.1	0.6	0.6	0.7	0.4	0.4	1.0	0.5	0.7	1.0	0.5
Hornblende----------	3.7	23.3	--	--	0.7	7.8	0.2	14.1	--	12.4	1.3	2.3	--	--
Allanite------------	Tr.	0.2	Tr.	--	Tr.	--	0.3	--	0.5	--	--	0.4	0.3	0.4
Apatite-------------	0.4	0.9	0.5	Tr.	0.4	0.5	0.7	1.1	0.2	0.3	0.6	0.2	0.5	0.4
Zircon--------------	0.1	0.1	0.1	0.1	0.1	Tr.	Tr.	Tr.	Tr.	0.1	0.1	Tr.	Tr.	Tr.
Monazite-xenotime---	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite-------------	--	0.2	--	0.2	0.2	--	0.5	0.4	--	Tr.	--	--	--	Tr.
Chlorite------------	--	--	0.1	0.1	--	--	--	0.1	0.2	--	--	Tr.	0.2	0.2
Epidote-clinozoisite	--	2.3	0.3	0.5	0.2	0.4	1.7	1.6	0.2	1.8	1.6	0.6	0.3	0.3
Rutile--------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite---------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet--------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene--------------	0.3	0.6	0.2	0.1	0.9	0.1	0.6	1.1	0.9	0.4	0.6	0.3	0.6	0.3
Kaolinite-----------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total-----------	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 1.—*Modes (volume percent) for Boulder Creek Granodiorite, from the batholith, Front Range, Colo.*—Continued

Sample No.	57	58	59	60	61	62	63	64	65	66	67	68	69	70
Potassium feldspar	6.2	0.7	27.6	27.8	18.6	14.0	5.6	15.2	30.5	25.6	31.9	12.1	29.7	26.7
Plagioclase	53.0	56.7	37.2	35.5	39.9	42.5	48.9	42.8	34.4	42.8	35.1	50.0	34.7	27.6
Quartz	3.0	17.3	28.7	31.5	33.0	31.6	17.5	24.9	24.8	20.4	26.8	19.3	25.0	31.3
Biotite	12.8	22.9	5.1	3.6	4.8	10.9	20.4	14.7	8.2	9.6	4.6	13.6	7.9	12.0
Muscovite	--	0.6	1.3	1.2	2.6	--	--	0.1	0.3	0.4	0.7	--	1.1	--
Ores	0.2	0.5	0.1	0.4	1.1	0.1	0.5	0.8	1.5	0.5	0.8	0.6	0.4	0.9
Hornblende	22.6	--	--	--	--	--	4.4	--	--	--	--	2.7	--	--
Allanite	--	Tr.	--	--	--	Tr.	0.2	0.2	Tr.	--	Tr.	0.3	0.3	0.3
Apatite	Tr.	0.2	Tr.	Tr.	Tr.	0.1	0.9	0.2	0.2	0.5	0.1	0.6	0.5	0.6
Zircon	Tr.	0.1	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	0.1	Tr.	Tr.
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	--	--	--	--	--	Tr.	Tr.	--	0.1	--	--	--	--	--
Chlorite	0.1	--	--	Tr.	--	0.2	--	0.2	Tr.	0.1	--	--	0.3	--
Epidote-clinozoisite	1.4	--	Tr.	--	Tr.	0.4	0.7	Tr.	--	0.1	--	0.3	--	--
Rutile	--	--	--	--	--	--	--	--	Tr.	Tr.	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	0.7	1.0	Tr.	--	--	0.2	0.9	0.9	Tr.	Tr.	--	0.4	0.1	0.3
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	71	72	73	74	75	76	99	100	101	102	103	104	105	106
Potassium feldspar	18.8	20.3	10.7	13.0	9.3	27.4	0.5	0.3	--	23.6	0.5	0.7	3.7	2.0
Plagioclase	43.5	36.3	52.9	42.2	51.6	31.1	59.6	47.3	41.6	38.2	44.5	50.1	52.6	54.7
Quartz	27.2	29.0	11.1	24.3	27.3	32.4	16.9	18.2	34.4	24.4	25.9	20.1	21.0	21.3
Biotite	10.0	12.7	14.0	17.3	9.5	6.9	19.4	21.7	21.5	10.4	27.5	19.3	13.3	15.3
Muscovite	--	0.1	0.1	0.6	--	0.3	--	--	--	--	--	--	--	--
Ores	0.3	0.5	1.0	0.8	0.5	0.5	0.6	Tr.	0.7	1.7	0.3	0.5	0.6	0.5
Hornblende	--	--	9.6	--	--	--	--	7.6	0.2	--	--	7.8	5.0	5.1
Allanite	0.1	--	--	0.1	0.3	Tr.	Tr.	0.1	Tr.	0.1	--	0.1	Tr.	Tr.
Apatite	0.1	0.4	0.1	0.7	1.1	1.0	1.3	0.8	0.4	0.1	0.6	1.0	0.7	0.3
Zircon	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	--	Tr.	0.2	Tr.	--	--	0.3	Tr.
Monazite-xenotime	--	--	--	--	0.1	--	--	--	--	--	--	--	--	--
Calcite	--	0.1	--	--	--	--	0.1	--	--	--	--	--	--	--
Chlorite	--	Tr.	--	--	--	Tr.	0.3	--	Tr.	--	--	--	--	--
Epidote-clinozoisite	--	--	0.1	Tr.	--	0.3	0.5	3.7	0.7	0.6	0.1	0.1	1.2	0.3
Rutile	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	Tr.	0.6	0.4	1.0	0.3	0.1	0.8	0.3	0.3	0.9	0.6	0.3	1.2	0.5
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	0.4	--
Prehnite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 1.—*Modes (volume percent) for Boulder Creek Granodiorite, from the batholith, Front Range, Colo.*—Continued

Sample No.	107	108	109	110	111	112	113	114	115	116	117	118	119	120
Potassium feldspar	23.5	0.3	1.4	0.4	0.2	25.3	17.5	7.8	7.1	--	28.0	37.4	--	--
Plagioclase	39.0	51.6	46.1	52.9	51.5	32.6	38.0	46.0	50.9	57.0	25.6	24.0	53.9	17.8
Quartz	24.6	16.6	27.0	19.5	12.2	30.6	13.6	20.0	20.5	4.4	34.5	32.0	22.6	47.3
Biotite	0.5	23.5	18.7	19.9	36.5	9.5	18.9	18.7	14.6	17.2	5.0	1.0	21.0	16.4
Muscovite	1.6	--	--	--	--	--	0.1	--	--	--	4.6	1.9	--	--
Ores	0.8	0.8	1.8	1.6	0.9	0.5	0.1	0.6	0.4	1.1	2.2	1.0	1.2	0.4
Hornblende	--	3.8	4.4	5.0	--	0.5	8.5	4.8	4.2	17.6	--	--	--	17.0
Allanite	--	--	0.1	Tr.	0.2	0.1	--	--	0.1	0.1	Tr.	--	Tr.	Tr.
Apatite	0.3	0.8	0.5	0.4	1.5	0.1	1.4	0.7	0.4	0.6	0.1	0.3	0.7	0.1
Zircon	Tr.	0.2	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	Tr.	0.2	--	Tr.	--	--	0.1	--	0.1	0.3	--	--	--	--
Chlorite	Tr.	--	--	Tr.	--	--	Tr.	--	0.3	0.6	--	2.2	0.1	--
Epidote-clinozoisite	0.3	1.7	Tr.	0.3	Tr.	0.7	0.9	0.8	Tr.	0.8	Tr.	0.1	0.5	0.6
Rutile	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	Tr.	--	--
Garnet	--	--	--	--	--	--	--	--	--	--	--	0.1	--	--
Sphene	0.6	0.5	--	Tr.	--	0.1	0.9	0.6	1.4	0.3	--	--	--	0.4
Kaolinite	[a]8.8	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	121	122	123	124	125	126	127	128	129	130	131	132	133	134
Potassium feldspar	--	--	--	37.5	Tr.	11.0	--	22.9	25.9	17.6	11.8	4.9	10.0	2.3
Plagioclase	44.4	55.2	47.5	25.8	48.6	37.0	53.6	33.3	36.8	34.6	40.6	46.0	44.3	55.7
Quartz	18.5	24.6	19.6	24.3	24.7	29.0	15.0	26.8	23.2	35.4	23.0	21.3	25.8	21.1
Biotite	24.5	19.5	30.4	10.7	23.6	18.8	22.8	13.3	11.0	9.7	13.3	20.3	16.4	3.1
Muscovite	--	--	--	--	0.4	--	--	0.6	0.6	0.7	--	--	0.1	--
Ores	0.7	0.3	1.3	0.2	1.8	0.4	0.3	2.3	1.8	1.4	0.4	0.5	0.3	2.4
Hornblende	8.9	--	--	--	--	2.9	7.0	--	--	--	6.2	5.0	1.0	1.9
Allanite	0.2	Tr.	0.1	Tr.	--	0.1	0.3	--	Tr.	--	Tr.	0.1	0.1	0.1
Apatite	1.2	0.3	Tr.	0.1	0.8	0.1	0.4	0.8	0.3	0.6	0.6	0.4	0.1	0.5
Zircon	Tr.	Tr.	Tr.	0.1	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	--	Tr.	--	--
Monazite-xenotime	--	--	--	--	--	--	--	Tr.	0.4	Tr.	--	--	--	--
Calcite	--	--	--	--	--	--	Tr.	--	--	--	0.2	--	--	Tr.
Chlorite	--	Tr.	0.2	0.4	--	0.3	0.3	Tr.	--	Tr.	0.6	Tr.	--	9.3
Epidote-clinozoisite	0.8	0.1	0.1	0.6	0.1	0.4	Tr.	--	--	Tr.	2.2	1.1	1.5	3.1
Rutile	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	0.8	--	--	--	--	--	--	--	--	--	--	--
Sphene	0.8	--	--	0.3	--	--	0.3	--	--	--	1.1	0.4	0.4	0.5
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	Tr.?	--	--	--	--	--	Tr.?	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 1.—*Modes (volume percent) for Boulder Creek Granodiorite, from the batholith, Front Range, Colo.*—Continued

Sample No.	135	136	137	138	139	140	141	142	143	144	145	146	147	148
Potassium feldspar	24.0	0.1	4.3	6.4	0.3	0.1	7.7	2.1	15.4	24.6	15.3	22.8	13.3	14.0
Plagioclase	29.4	53.3	43.8	46.9	39.5	61.6	35.4	40.4	40.3	36.2	37.5	38.8	35.5	40.5
Quartz	29.6	20.3	19.7	25.4	25.3	31.0	32.1	32.5	24.1	26.1	27.1	20.3	26.8	33.4
Biotite	7.9	22.5	20.6	12.2	24.3	5.8	18.5	22.8	8.6	0.7	9.9	13.3	21.1	10.5
Muscovite	--	--	--	--	--	--	[b]5.8	2.1	--	0.1	--	--	--	0.3
Ores	1.1	0.9	1.1	0.8	0.9	0.5	Tr.	0.1	0.3	0.3	1.6	Tr.	0.2	0.1
Hornblende	4.2	--	6.8	5.4	6.5	--	--	--	8.4	0.9	2.8	2.3	--	--
Allanite	--	Tr.	Tr.	0.1	Tr.	Tr.	--	--	--	Tr.	0.1	0.1	0.2	0.1
Apatite	0.3	1.0	0.6	0.9	0.8	0.1	0.1	Tr.	0.7	Tr.	0.7	0.1	0.2	0.1
Zircon	--	--	Tr.	--	Tr.	Tr.	0.3	Tr.	Tr.	0.1	Tr.	Tr.	0.1	0.3
Monazite-xenotime	--	--	--	--	--	Tr.	Tr.	Tr.	--	--	--	--	--	--
Calcite	0.1	--	--	0.1	--	0.6	--	--	--	--	1.2	0.3	Tr.	--
Chlorite	0.7	--	--	0.3	--	0.3	0.1	--	0.4	6.6	0.4	--	0.2	--
Epidote-clinozoisite	1.1	1.0	1.4	0.9	1.5	--	--	Tr.	--	1.2	3.2	1.6	0.9	0.3
Rutile	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	1.8	0.3	Tr.	--	0.3	--
Sphene	1.2	0.9	0.7	0.5	0.9	Tr.	--	--	Tr.	0.3	0.1	0.4	1.2	0.4
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	0.4	--	--	0.1	--	Tr.	--	--	Tr.	2.6	0.1	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	149	150	151	152	153	154	155	156	157	158	159	160	161	162
Potassium feldspar	0.3	27.0	8.3	18.1	12.8	8.8	17.3	16.2	9.4	5.6	15.2	12.9	14.6	7.6
Plagioclase	46.0	30.3	48.5	35.5	43.8	40.6	35.0	37.0	46.5	43.0	38.5	37.4	42.3	49.7
Quartz	31.8	31.7	24.2	34.6	23.8	26.9	32.0	23.8	23.0	31.0	33.0	32.3	30.2	20.5
Biotite	19.8	8.8	17.2	9.2	14.8	16.8	12.5	18.3	16.0	16.2	10.1	15.3	11.2	18.6
Muscovite	--	--	--	--	--	--	1.0	Tr.	--	--	0.7	--	0.6	Tr.
Ores	Tr.	1.3	0.7	0.2	0.4	0.9	0.4	0.2	0.1	0.4	1.3	0.1	0.4	0.2
Hornblende	0.5	--	--	1.1	1.7	4.4	Tr.	1.7	1.6	1.2	--	--	--	1.3
Allenite	--	Tr.	0.7	0.1	0.1	Tr.	Tr.	Tr.	0.1	0.4	--	Tr.	--	0.3
Apatite	0.5	0.7	0.1	0.2	0.7	0.4	Tr.	0.6	1.3	0.1	0.1	0.3	0.3	0.3
Zircon	0.3	--	0.3	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	--	--	--	--	--	0.4	0.7	0.1	--	--	0.1	--	--	--
Chlorite	--	0.1	--	--	0.3	--	0.3	0.4	--	0.1	Tr.	--	0.3	--
Epidote-clinozoisite	0.3	--	Tr.	0.5	0.9	0.1	0.6	1.1	1.4	1.6	Tr.	0.4	0.1	0.8
Rutile	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	0.5	0.1	Tr.	0.5	0.7	0.7	0.2	0.6	0.6	0.4	0.6	1.3	--	0.7
Kaolinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite	--	--	--	Tr.?	--	--	--	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 1.—*Modes (volume percent) for Boulder Creek Granodiorite, from the batholith, Front Range, Colo.*—Continued

Sample No.	163	164	165	166	167	168	169	403	404	405	406	407
Potassium feldspar—	20.3	11.2	5.1	11.0	21.2	19.3	--	Tr.	30.0	42.1	24.4	10.3
Plagioclase---------	40.8	42.3	43.2	43.5	39.5	43.1	49.7	34.4	35.0	9.9	22.1	42.8
Quartz--------------	24.8	26.3	20.8	23.2	21.0	23.3	23.8	49.2	27.0	21.0	32.9	28.3
Biotite-------------	11.1	14.9	21.9	18.1	15.4	10.4	21.4	14.9	6.0	26.5	18.3	6.8
Muscovite---------—	1.5	--	Tr.	Tr.	--	Tr.	--	Tr.	--	0.2	--	--
Ores---------------	0.4	0.4	0.3	0.2	Tr.	Tr.	0.4	1.5	1.0	0.3	1.3	1.8
Hornblende---------—	--	3.7	5.7	1.3	1.0	2.6	1.7	--	--	--	--	--
Allanite------------	Tr.	Tr.	0.5	Tr.	Tr.	--	0.1	--	0.5	--	0.1	--
Apatite-------------	0.4	Tr.	0.6	0.6	0.5	0.6	0.6	Tr.	0.5	--	0.6	0.5
Zircon-------------	Tr.	Tr.	--	Tr.	Tr.	Tr.	Tr.	Tr.	--	Tr.	--	Tr.
Monazite-xenotime---	--	--	--	--	--	--	--	--	--	--	--	--
Calcite-------------	--	--	0.4	--	Tr.	--	Tr.	--	--	--	--	--
Chlorite-----------—	--	--	0.1	0.1	0.2	--	0.3	--	--	--	--	--
Epidote-clinozoisite	0.4	0.7	0.8	1.7	0.5	0.7	1.6	--	--	--	--	8.3
Rutile--------------	--	--	--	--	--	--	--	--	--	--	--	--
Sillimanite---------	--	--	--	--	--	--	--	--	--	--	--	--
Garnet--------------	--	--	--	--	--	--	--	--	--	--	--	--
Sphene--------------	0.3	0.5	0.5	0.3	0.7	Tr.	0.4	Tr.	Tr.	--	0.3	1.2
Kaolinite-----------	--	--	--	--	--	--	--	--	--	--	--	--
Prehnite-----------	--	--	Tr.	Tr.?	--	--	--	--	--	--	--	--
Total-----------	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a]Includes some chlorite.   [b]Sillimanite altered to muscovite.

potassium feldspar and hornblende are more abundant within the batholith; (2) the contact zone and segments adjacent to faults are similar compositionally, suggesting that rocks in both environments have been recrystallized; the potassium went into biotite and the rest of the constituents into plagioclase.

The distribution of the major minerals of the Boulder Creek Granodiorite within the batholith and adjacent satellitic bodies may also be shown by the use of quartz-plagioclase-potassium feldspar triangular diagrams in figure 7. These diagrams show that the southeast part of the batholith is the most siliceous and the central part of the batholith the least siliceous. The abundance of quartz diorite in the triangular diagrams (fig. 7) for the Blackhawk, Tungsten, and Gold Hill quadrangles reflects border areas of the batholith. Most modes fall in the granodiorite-quartz monzonite fields; however, those for the Ward quadrangle plot on the granitic side of the quartz monzonite field.

Boulder Creek Granodiorite has a predominant hypidiomorphic granular texture in which the mafic minerals tend to cluster. The mafic clusters consist of biotite, hornblende, apatite, sphene, allanite, zircon, and the alteration mineral epidote. Plagioclase, quartz,

and some potassium feldspar form the largest crystals. Biotite and hornblende are the most prominent mafic minerals but only biotite is ubiquitous in granodiorite. Potassium feldspar, represented chiefly by microcline, forms both large crystals similar in size to plagioclase and smaller interstitial crystals.

Rocks of the batholith have been sheared and recrystallized and tend to have a preferred mineral alteration adjacent to faults and along much of the contact zone. Serrate quartz and anhedral feldspar (mostly microcline) occur interstitial to larger mineral grains in these rocks.

INCLUSIONS IN BOULDER CREEK GRANODIORITE

Inclusions in the Boulder Creek Granodiorite are mainly of three types: (1) lenses, some quite large, of biotite and sillimanite-biotite gneiss and schist; (2) massive to foliated mafic inclusions in discrete clots, spindles, and lenses consisting essentially of biotite, hornblende, and plagioclase and containing generally less than 10 percent quartz and 2 percent or less of potassium feldspar; (3) very old foliated and altered lamprophyres in eroded sills that are now rounded elongate bodies so altered that they often resemble mafic inclusions of type 2.

BOULDER CREEK BATHOLITH, FRONT RANGE, COLORADO

TABLE 2.—*Modes (volume percent) for Boulder Creek Granodiorite from small plutons and small lenses in biotite gneiss and schist, Front Range, Colo.*

[(-), not found; Tr., trace; ores include all opaque minerals. Samples 170-185 from Nederland quadrangle; 186-191 from Tungsten quadrangle]

Sample No.	170	171	172	173	174	175	176	177	178	179	180
Potassium feldspar	3.7	11.0	7.0	0.1	12.5	23.3	17.0	--	0.3	0.1	6.2
Plagioclase	43.9	46.5	40.8	34.6	44.9	36.4	44.0	49.2	54.8	48.8	49.6
Quartz	29.8	29.1	20.7	25.6	33.1	23.0	23.2	32.7	22.1	17.4	23.8
Biotite	[a]19.3	[a]11.3	22.3	30.0	[a]5.7	[a]11.4	11.0	**17.9**	[a]18.3	17.1	13.6
Muscovite	0.3	0.4	--	0.4	1.1	1.1	0.1	0.1	--	--	[b]1.0
Ores	2.0	1.6	4.2	4.8	1.3	1.9	2.0	0.1	2.7	5.6	3.1
Hornblende	--	--	--	--	--	--	--	--	--	6.4	--
Actinolite	--	--	--	--	--	--	--	--	--	--	--
Allanite	--	--	--	--	0.1	0.1	0.1	--	0.4	0.7	--
Apatite	0.3	0.1	1.8	1.7	--	0.7	0.8	Tr.	0.3	2.2	1.3
Zircon	Tr.	Tr.	0.1	--	Tr.	Tr.	0.1	Tr.	Tr.	--	Tr.
Calcite	--	--	--	--	Tr.	--	Tr.	--	--	0.4	--
Chlorite	--	--	--	--	--	--	--	--	--	0.3	--
Epidote	0.7	--	Tr.	--	1.3	--	0.1	--	0.7	--	1.4
Rutile	--	--	--	--	Tr.	--	--	--	--	--	Tr.
Sphene	--	--	3.1	2.8	--	2.1	1.6	--	0.4	1.0	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	181	182	183	184	185	186	187	188	189	190	191
Potassium feldspar	Tr.	1.7	Tr.	0.1	24.3	28.8	22.1	22.9	21.4	26.9	17.5
Plagioclase	46.8	53.5	40.3	46.2	34.8	24.9	30.3	30.6	36.2	28.5	38.1
Quartz	23.5	19.1	16.3	20.8	31.3	28.0	30.2	30.0	25.9	30.2	27.2
Biotite	19.0	17.7	21.8	25.7	5.1	12.6	10.4	11.0	9.8	11.0	13.2
Muscovite	[b]1.0	[b]1.9	[b]4.4	--	1.7	2.9	4.2	3.2	3.7	0.9	1.5
Ores	2.2	1.0	5.2	3.5	2.7	2.0	2.3	1.6	1.8	1.2	1.6
Hornblende	1.4	3.0	8.2	1.4	--	--	--	--	--	--	--
Actinolite	--	Tr.	--	--	--	--	--	--	--	--	--
Allanite	0.1	Tr.	0.1	0.3	--	--	--	0.1	0.1	0.5	--
Apatite	1.8	0.1	2.0	1.3	--	0.5	0.3	0.4	0.9	0.6	0.6
Zircon	Tr.	--	0.1	--	0.1	0.2	0.2	0.1	0.1	Tr.	0.3
Calcite	--	0.3	--	--	--	--	--	--	--	--	--
Chloirite	0.1	0.4	0.1	--	--	Tr.	--	--	0.1	0.1	--
Epidote	2.0	1.0	0.8	0.3	--	0.1	--.	0.1	--	0.1	--
Rutile	--	--	--	--	Tr.	--	--	--	--	--	--
Sphene	2.1	0.3	0.7	0.4	--	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a]Includes some chlorite.   [b]Includes sericite.

TABLE 3.—*Modes (volume percent) for Boulder Creek Granodiorite from contact area of batholith, Front Range, Colo.*

[(-), not found; Tr., trace; ores include all opaque minerals. Samples 192-199 from Tungsten quadrangle; 200-204 from Gold Hill quadrangle]

Sample No.	193	194	195	196	197	198	199	200	201	202	203	204
Potassium feldspar	4.0	0.2	--	--	7.7	0.2	--	0.5	--	--	--	1.3
Plagioclase	44.7	57.5	35.7	46.0	37.8	48.8	55.1	50.8	58.1	50.2	44.4	49.8
Quartz	28.1	5.0	23.3	25.0	38.6	31.8	11.8	18.8	22.1	23.4	24.7	25.8
Biotite	17.5	23.6	28.6	17.0	15.0	18.5	23.1	22.8	18.8	23.0	23.4	16.5
Muscovite	1.5	0.2	0.4	1.0	0.2	0.1	--	[a]0.7	--	0.1	Tr.	--
Ores	2.7	0.5	7.0	3.0	0.6	0.3	0.2	1.8	0.4	1.8	3.1	0.6
Hornblende	--	11.2	0.5	--	--	--	8.4	1.7	--	--	--	3.4
Allanite	0.1	0.1	0.1	Tr.	--	--	0.3	--	Tr.	0.1	Tr.	0.2
Apatite	1.1	0.8	1.4	Tr.	0.1	0.3	0.2	1.2	0.4	0.1	0.5	0.7
Zircon	0.3	Tr.	0.1	Tr.	Tr.	Tr.	Tr.	0.2	--	0.1	--	Tr.
Calcite	--	--	--	--	--	--	--	0.5	Tr.	--	0.1	--
Chlorite	--	0.3	0.2	5.0	--	--	0.1	--	0.1	0.3	1.8	--
Epidote	--	0.6	0.6	3.0	--	--	0.1	0.5	0.1	0.9	2.0	0.5
Clinozoisite	--	--	--	--	--	--	--	Tr.	Tr.	Tr.	Tr.	--
Sphene	--	--	2.1	--	--	--	0.7	0.5	--	Tr.	--	1.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a]Kaolin 0.2 percent of total muscovite.

TABLE 4.—*Modes (volume percent) for Boulder Creek Granodiorite adjacent to known faults, Front Range, Colo.*

[(-), not found; Tr., trace; ores include all opaque minerals. All samples are from Tungsten quadrangle]

Sample No.	205	206	207	208	209	210	211	212	213	214	215	216	217
Potassium feldspar	0.3	--	0.3	0.2	1.3	3.5	0.8	2.2	5.3	--	9.6	8.1	0.4
Plagioclase	59.3	55.2	52.0	54.4	38.3	51.9	57.8	49.0	42.8	63.3	47.7	45.6	48.2
Quartz	21.6	16.0	24.0	26.3	24.4	23.3	22.6	20.1	25.4	9.3	28.5	31.8	26.8
Biotite	13.1	27.8	21.1	16.9	18.7	14.9	13.1	23.9	16.8	25.4	12.6	12.7	23.2
Muscovite	--	--	--	--	--	--	--	0.2	--	--	--	1.2	--
Ores	1.4	0.2	1.1	0.2	5.6	0.1	1.1	1.2	0.4	0.8	0.5	0.2	0.2
Hornblende	--	--	--	1.5	7.1	5.1	3.0	--	5.9	--	--	--	--
Allanite	0.6	0.1	--	Tr.	--	0.2	0.2	--	0.3	Tr.	0.2	0.1	0.1
Apatite	0.7	0.5	0.6	0.2	1.5	0.5	0.4	0.7	0.7	0.6	0.1	0.2	1.1
Zircon	--	0.1	Tr.	0.1	0.1	Tr.	0.5	Tr.	Tr.	Tr.	--	Tr.	Tr.
Calcite	--	--	--	--	--	--	0.2	0.2	--	--	--	--	--
Chlorite	Tr.	--	--	Tr.	--	0.1	0.1	--	0.1	--	0.6	--	--
Epidote-clinozoisite	1.7	0.1	0.3	0.2	--	0.2	0.2	2.3	1.5	0.3	0.1	0.1	Tr.
Sphene	1.3	--	0.6	--	3.0	0.2	--	0.2	0.8	0.3	0.1	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 5.—*Summary of modal data (volume percent) for the Boulder Creek Granodiorite, Front Range, Colo.*

[Ores include all opaque minerals]

	Granodiorite in metasedimentary rocks	Granodiorite in batholith		
		Contact zone	Known fault areas	Remainder of batholith
Potassium feldspar----------	10.0	1.0	2.0	16.1
Plagioclase-----------------	42.0	47.0	51.0	40.5
Quartz----------------------	25.0	23.0	23.0	25.0
Biotite---------------------	16.0	21.0	19.0	13.6
Hornblende------------------	1.0	2.0	1.7	2.1
Ores------------------------	2.5	1.7	1.1	0.7
Allanite--------------------	0.1	0.1	0.1	0.2
Apatite---------------------	0.8	0.6	0.7	0.5
Epidote---------------------	0.4	0.6	0.5	0.5
Sphene----------------------	0.7	0.3	0.5	0.4
Muscovite-sericite----------	1.3	0.3	0.1	0.4

The mafic inclusions of type 2 (figs. 8 and 9 and samples 318–327, table 6) are believed to be plutonic in origin because of their physical characteristics and composition, especially trace-element composition, that is more nearly related to diorite-quartz diorite. These inclusions are found in the hornblende-bearing part of the batholith and are common in the roadcuts of Boulder Creek Granodiorite along Middle Boulder Creek, along the slopes north and south of Pinecliffe, and in roadcuts of the Salina–Gold Hill (County 89) and Gold Hill–Bighorn (County 52) mountain roads. While these mafic inclusions are widely scattered throughout the granodiorite, they are, or appear to be, more profuse in the central part of the batholith, extending from Thorodin Mountain to Bighorn Mountain.

The inclusions of type 2 occur in discrete clots, spindles, and lenses oriented either along the regional foliation or at an angle to it; their plunge is moderate to steep. Small inclusions as much as 0.5 m in size have blunt ends or rounded terminations and in cross section most are ellipsoidal; the larger inclusions range from a few meters to more than several hundred meters in length and have widths of as much as several tens of meters. Smaller inclusions can often be picked out with a hammer, leaving a somewhat smooth depression, especially in intensely weathered granodiorite. The larger inclusions are nearly always foliated and occur in irregular masses or lenticular bodies along foliation planes; some enclose small areas of granodiorite, forming augenlike segregations of the granodiorite (fig. 10). The larger inclusions are composite rocks that have a composition of diorite, quartz diorite, and may include some granodiorite; they are coarse to fine grained, dark gray to almost black. The smaller inclusions are finer grained and have a mottled texture due to a finer grained salt-and-pepper groundmass having large hornblende or feldspar crystals and clots of mafic minerals either alined or in random orientation throughout the groundmass. Whereas some inclusions have a mafic rim or a border of pegmatite, others grade into granodiorite with no distinct border. The larger inclusions are generally gradational with the Boulder Creek Granodiorite and often appear to interlens with the granodiorite for some distance along the contact.

Biotite and hornblende make up 26–65 percent by volume of the mafic inclusions (table 6). Quartz rarely exceeds 10 percent and generally is in the range of 2–8 percent. Apatite and ores each are in the range of 1–2 percent. In thin section the mafic inclusions have a xenomorphic granular texture (fig. 11).

The third type of inclusion is lamprophyre (samples 328, 329, 331, 332, table 6); it is not an inclusion like types 1 and 2 but occurs as eroded sills and dikes and is referred to as sills and dikes in the remainder of this report. The sills and dikes are of two ages. The older ones are generally found only in the central part of the batholith as altered and well-foliated stubby lenses from several meters to 300–400 m in length and are probably comagmatic with the Boulder Creek Granodiorite. The younger lamprophyre occurs as dikes and sills, is fresh looking, and may belong to the Pikes Peak Granite plutonism. The younger lamprophyre is of no further concern to this paper and is thus discussed no further.

The metamorphosed lamprophyre of concern to this report varies in composition from syenodiorite to melasyenodiorite, according to modes in samples 328, 329, 331, and 332 (table 6), and samples 387 and 388 (table 11). Biotite, hornblende, and pyroxene make up 48–86 percent by volume of the lamprophyre; a few bodies are pyroxene rich, and quartz is nearly absent. Allanite, apatite, and sphene average 6 percent. These altered and well-foliated lamprophyric dikes often take on the appearance of porphyritic microgranular inclusions of type 2, and the distinction between types 2 and 3 is made on texture and the presence or absence of potassium feldspar.

In thin section, the lamprophyre has a diabasic to xenomorphic texture depending on degree of metamorphism. Figure 11C shows a lamprophyre with xenomorphic texture.

MAFIC PLUTONIC ROCKS

The mafic intrusive rocks, pyroxenite, gabbro, hornblendite, hornblende diorite, and quartz diorite, and related aplites and pegmatites, occur mainly in metasedimentary rocks as satellitic bodies, although a few scattered lenses of all rock types except pyroxenite occur within the batholith itself. Radiometric age determinations have not been made on any of the mafic intrusives, but field relations suggest that they are approximately the same age as the Boulder Creek
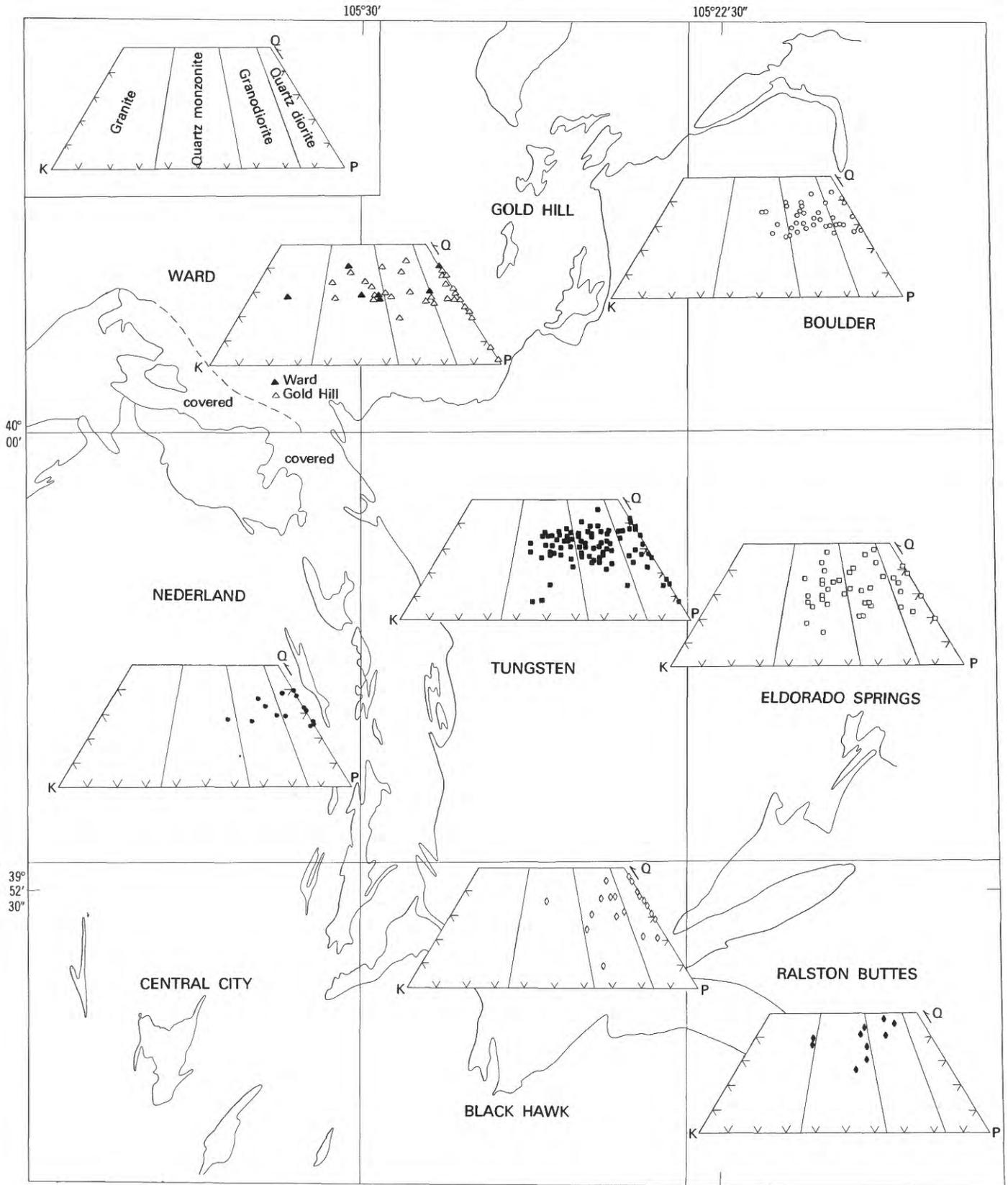
FIGURE 7.—Modal variation (in volume percent) of quartz, plagio-
clase, and potassium feldspar for Boulder Creek Granodiorite in
the batholith and adjacent lenses. Q, quartz; P, plagioclase; K,
potassium feldspar. Distribution of modes across the batholith
and in lenses indicated in figure 3. Each diagram occurs with its
corresponding 7½-minute quadrangle or quadrangles.
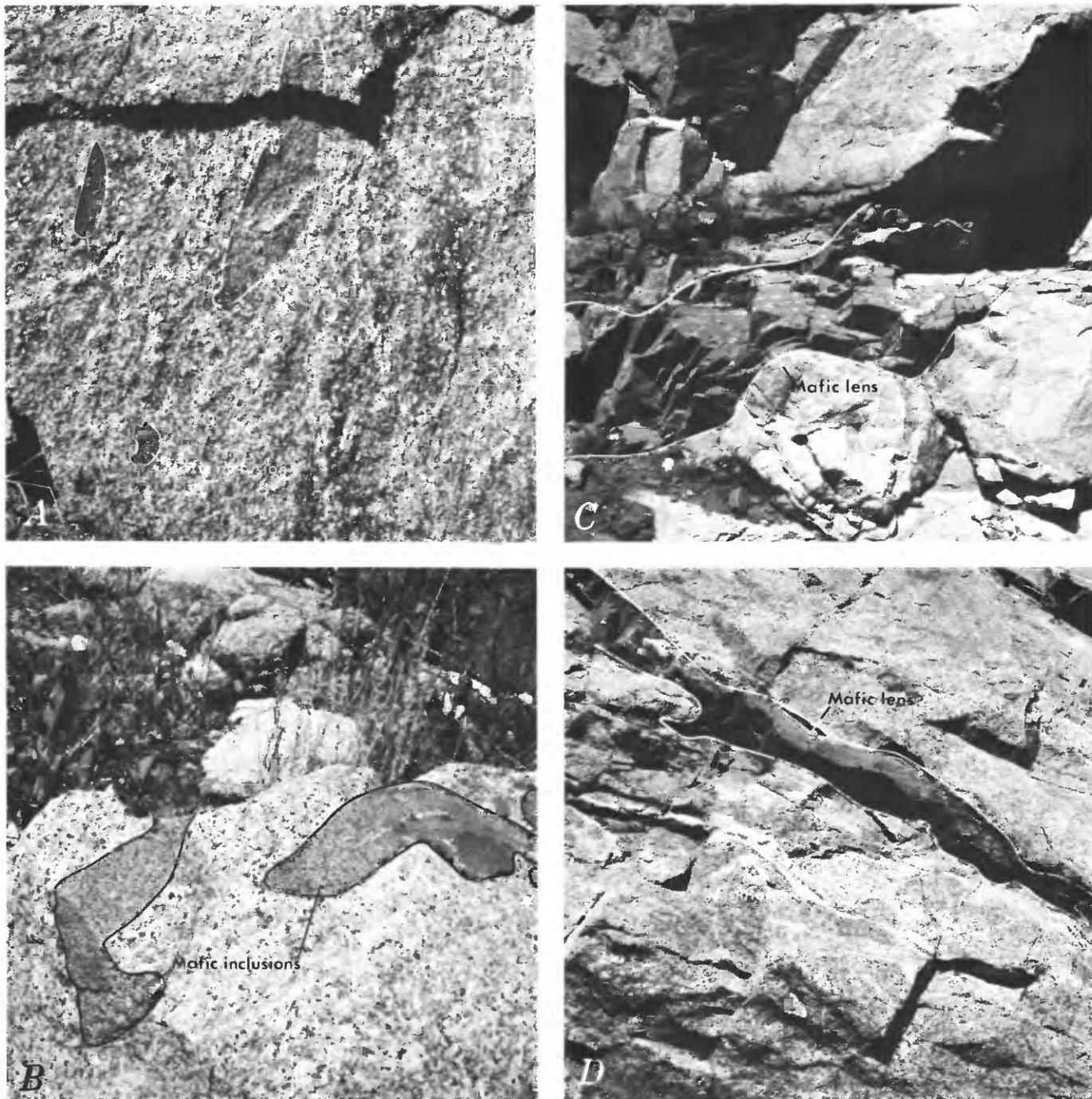
FIGURE 8.—Photographs of exposures of mafic inclusions in Boulder Creek Granodiorite, mainly from Boulder Canyon. *A,* mafic stringers in a biotitic phase of Boulder Creek. *B,* mafic clots in a more leucocratic Boulder Creek Granodiorite; note the leucocratic halo between granodiorite and inclusion. *C,* a foliated lens of dense biotite-quartz diorite and small pegmatite veins in granodiorite. *D,* a remanent, dense mafic lens; note the ghostlike leucocratic areas segregating darker granodiorite into patchy areas.

Granodiorite although some appear both older and younger (Sims and Gable, 1967, p. E29–E39; Braddock, 1969, p. 18). Most were emplaced in a period of deformation and metamorphism that attained sillimanite grade, and, accordingly, they were to some extent deformed and metamorphosed. Most plutonic bodies are massive to strongly foliated (fig. 12) and occur as stocks or blunt, narrow dikes and sills or lenses along Precambrian structures, especially in fold axes. Although they locally transect structures in the gneiss
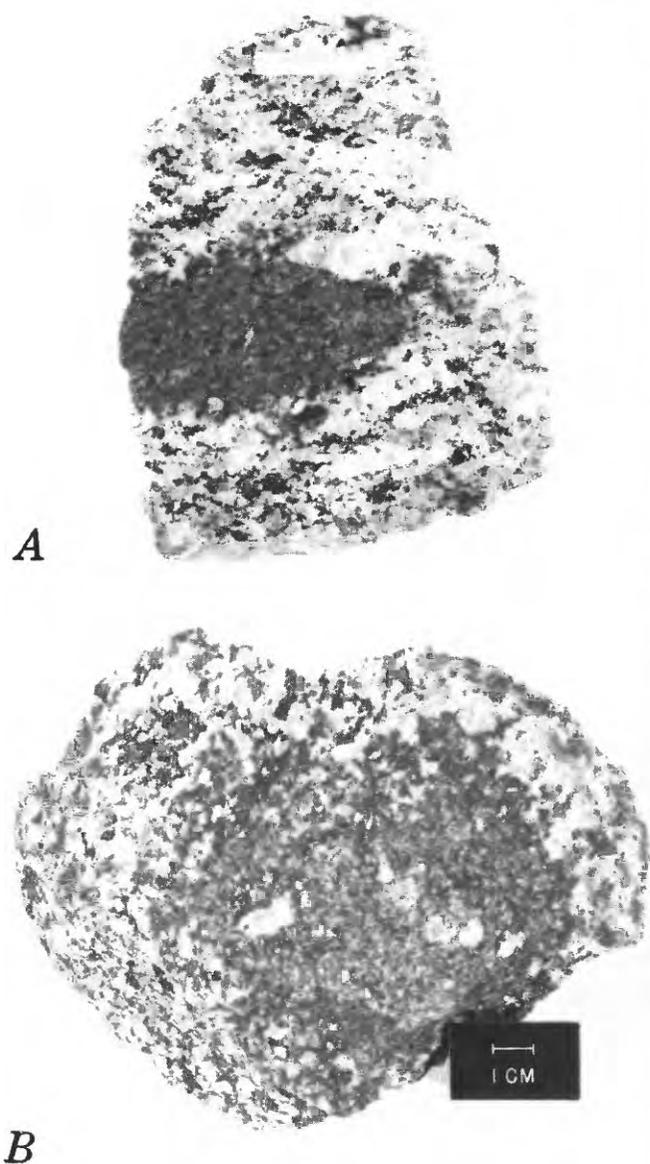
FIGURE 9.—Photographs of hand specimens of mafic inclusions in Boulder Creek Granodiorite. *A,* small bleb, regular outline with indentations of leucocratic minerals, biotite clusters at contact. *B,* inclusion, part of a larger mass of hornblende-bearing quartz diorite; assimilation is quite advanced. Photographs by Louise Hedricks, U.S. Geological Survey.

and schist country rock, they are subconformable to the regional foliation. Lineations within the rock are due to alined hornblende and biotite and are generally parallel to that in the enclosing gneiss. These mafic rocks compose a distinct belt west of the Boulder Creek batholith that is semicircular, as can be seen in plates 1 and 2. The bodies are small; the largest is less than 2 km in length. Most of the mafic bodies that were plotted on 7½-minute quadrangle maps are shown on plate 1, but hundreds of bodies observed in the field are too small to plot at the scale of a quadrangle map. The distribution of these rocks as shown on plate 1, however, is representative of their outcrop pattern.

GABBRO AND PYROXENITE

Gabbro is best known from its outcrop in the Elk Creek pluton in the northwest part of the Central City quadrangle (Taylor and Sims, 1962, p. D118; Sims and Gable, 1967, p. E35), but it also occurs in the southwest corner of the Nederland quadrangle—an extension of a lens from the Elk Creek pluton—and in two small bodies west of Gold Hill, both of which are strongly altered by a Tertiary diabase dike. Also, metagabbro was mapped by Wrucke and Wilson (1967) in the northern part of the Boulder Creek batholith.

The gabbro is a dark-gray, medium- to coarse-grained, massive, nearly equigranular rock that has a mottled texture due to large poikiloblastic mafic clusters. The matrix consists of interlocking plagioclase and pyroxene crystals. Typically the rock contains roughly 50 percent plagioclase. Where in contact with schist and gneiss, the smaller lenses are biotite rich and commonly weakly foliated. Samples 335–337 in table 7 are from a lens in the southwest corner of the Nederland quadrangle and vary little mineralogically from the Elk Creek pluton itself. Gabbro is characterized by calcic plagioclase (An_{41-54}), orthopyroxene, clinopyroxene, hornblende, biotite, ores, and about 5 percent quartz.

The pyroxenites are best developed in the Los Lagos lens, north of Rollinsville (pl. 2), in the southeast half of the Nederland quadrangle. Here contacts between pyroxenite and hornblende diorite with country rock or hornblende gneiss, where exposed, are indistinct, probably in part because of contact heating and in part because of retrograde metamorphism that occurred during or shortly after their emplacement. Another pyroxenite occurs west of Lakewood Reservoir and north of Nederland. It shows extensive alteration in thin section, in part due to thermal metamorphism caused by emplacement of younger hornblendite. The rock originally consisted almost wholly of pyroxene but now is composed of 50 percent pyroxene, about 40 percent hornblende, and 10 percent ores. Skeletal crystals in the rock consisting of serpentine and calcite probably were originally olivine. Olivine, however, never accounts for more than 2 percent of the total rock.

Hornblende pyroxenite is a grayish-black, medium-grained, massive rock that breaks with a glistening hackly surface. It occurs as clots in diorite or is gradational into hornblende diorite. The Los Lagos lens is representative of these gradational features. The

TABLE 6.—*Modes (volume percent) for mafic inclusions and metamorphosed lamprophyre dikes in Boulder Creek Granodiorite, Front Range, Colo.*

[(-), not found; Tr., trace; n.d., not determined; ores include all opaque minerals. Sample numbers 318–321, 323–331 from Tungsten quadrangle; 322, 332, 333 from Gold Hill quadrangle]

Sample No.	318	319	320	321	322	323	324	325	326	327	a328	a329	330	a331	a332	333
Potassium feldspar	--	--	--	--	0.8	--	--	0.1	2.0	11.4	26.0	19.1	15.2	13.0	27.9	4.3
Plagioclase	35.3	29.0	36.7	50.7	53.8	46.1	53.3	48.4	55.8	33.3	8.0	0.2	26.0	--	--	0.7
Quartz	8.5	6.3	7.9	5.3	14.3	1.5	1.2	4.8	0.6	2.7	--	0.2	7.7	--	0.9	--
Biotite	19.6	17.3	12.1	32.6	26.5	40.4	25.6	27.5	21.0	31.1	--	45.3	17.9	17.0	31.6	46.6
Hornblende	33.8	34.8	41.3	7.1	--	5.2	11.7	16.1	16.9	11.1	48.0	3.1	32.6	55.0	33.3	12.2
Cummingtonite	--	9.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Clinopyroxene	--	--	--	--	--	--	--	--	--	--	1.0	26.3	--	3.0	--	28.0
Ores	0.7	0.4	Tr.	1.0	1.1	1.3	1.3	Tr.	0.6	--	1.0	Tr.	Tr.	1.0	0.2	--
Allanite	--	--	--	--	Tr.	Tr.	0.2	0.2	0.1	0.2	1.0	1.3	Tr.	1.0	0.6	1.6
Apatite	2.1	Tr.	0.1	0.9	1.3	1.3	0.4	0.8	0.3	1.0	4.0	2.3	Tr.	4.0	3.2	1.9
Sphene	--	--	--	1.2	1.0	2.0	1.7	1.3	2.3	1.4	2.0	1.8	0.5	1.0	2.3	1.5
Zircon	Tr.	--	Tr.	Tr.	--	Tr.	0.1	0.1	0.2	0.1	--	Tr.	0.1	1.0	Tr.	--
Chlorite	--	1.0	0.8	--	0.1	--	--	--	--	--	8.0	--	--	--	Tr.	--
Epidote-clinozoisite	--	1.7	1.1	1.2	1.1	2.2	4.5	0.7	0.2	7.7	1.0	0.4	Tr.	4.0	--	3.2
Rutile	Tr.	--	--	--	--	--	--	--	--	--	--	Tr.	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An28	An42	An47	n.d.	n.d.	An32	n.d.	An28	An23	An28	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

a Metamorphosed lamprophyres.

FIGURE 10.—Oval-shaped lenses of Boulder Creek Granodiorite in mafic inclusion. Pegmatite occurs around periphery of granodiorite, especially at each end; roadcut, middle of Boulder Canyon, Tungsten quadrangle.

Severance lens (fig. 12; pl. 2), in the west half of the Tungsten quadrangle, was perhaps originally in part a pyroxenite; in a roadcut adjacent to the Bureau of Standards building on Colorado Highway 119, the more mafic part of the Severance lens is too crumbly and weathered to sample, but from outward appearances it is very probably an altered pyroxenite. If so, it too is gradational into hornblende-bearing quartz diorite and its outer border of biotitic hornblende-bearing quartz diorite is gradational into mafic Boulder Creek Granodiorite. These altered pyroxenites have a hornblende to pyroxene ratio that is quite variable, ranging from 1:1 to 1:4, and a few are pyroxene-bearing hornblendites (table 7, samples 347–355). The pyroxene minerals in pyroxenite are augite and bronzite. Biotite forms small slender laths and is reddish brown. Plagioclase is interstitial, and crystals are normally zoned and poorly twinned. In thin section, pyroxenites have a texture similar to the gabbro described earlier but are somewhat finer grained.

HORNBLENDITE, HORNBLENDE DIORITE, AND QUARTZ DIORITE

Black to mottled black and white, medium-grained, rarely slightly porphyritic rocks consisting principally of hornblende or of hornblende and plagioclase were mapped as hornblendite and diorite (pl. 2). The rocks are massive to foliated but lack the strong foliation characteristic of amphibolite of the area. Foliated diorite generally occurs at the margins of the larger dioritic bodies. Lighter colored, finer grained, foliated hornblende diorite has a salt-and-pepper appearance due predominantly to plagioclase in the rock. Quartz diorite, similar in appearance to hornblende diorite, consists of hornblende and plagioclase and at least 10 percent quartz.

The hornblendite in samples 338–340 (table 7) contains more than 70 percent hornblende; pyroxene and plagioclase account for most of the remaining 30 percent. Sample 339 contains 27 percent pyroxene and may be altered pyroxenite because its composition approaches that in the Severance lens, samples 352–354, table 7. In hornblendite, plagioclase is interstitial and is invariably altered to an aggregate of muscovite-sericite. The hornblende in thin section is generally brown, but some hornblendes are green; there is also some alteration of hornblende to actinolite or tremolite along cleavage. From optical data the pyroxene is probably diopside. Most pyroxene crystals are subrounded and are mantled somewhat by hornblende. The accessories are much the same as for the diorites and include ores, apatite, sphene, allanite, and zircon.

The diorites are principally hornblende and plagioclase bearing and contain less than 15 percent of other minerals including quartz, biotite, pyroxene, ores, and accessory minerals. Samples 341–344 (table 7) are representative of the diorites. Most diorites contain some chlorite, calcite, and secondary epidote.

The diorites have a hypautomorphic to allotriomorphic texture, depending upon degree of schistosity. The mafic minerals generally display the better developed crystal faces. The potassium feldspar in hornblende diorite is orthoclase. It forms small, subrounded, nontwinned, clear to partly cloudy grains that are easily misidentified as quartz. Plagioclase ranges in composition from andesine to labradorite and is normally zoned. Plagioclase from quartz diorite tends to be less calcic than from diorite and poikilitic with subrounded quartz inclusions. Plagioclase twinning includes Carlsbad, albite, pericline, and complex twins, with albite and pericline dominant. Alteration of plagioclase varies between diorites; in some the plagioclase is fresh, whereas in others it is completely altered to sericite and muscovite. Mafic minerals tend to cluster, similar to the texture in other Precambrian intrusive rocks in the area. Hornblende appears black in hand specimen and varies from grayish green to olive brown in thin section. It is often anhedral, and in a few sections traces of actinolite occur along grain boundaries and cleavage. In others, a twinning characteristic of cummingtonite indicates cum-
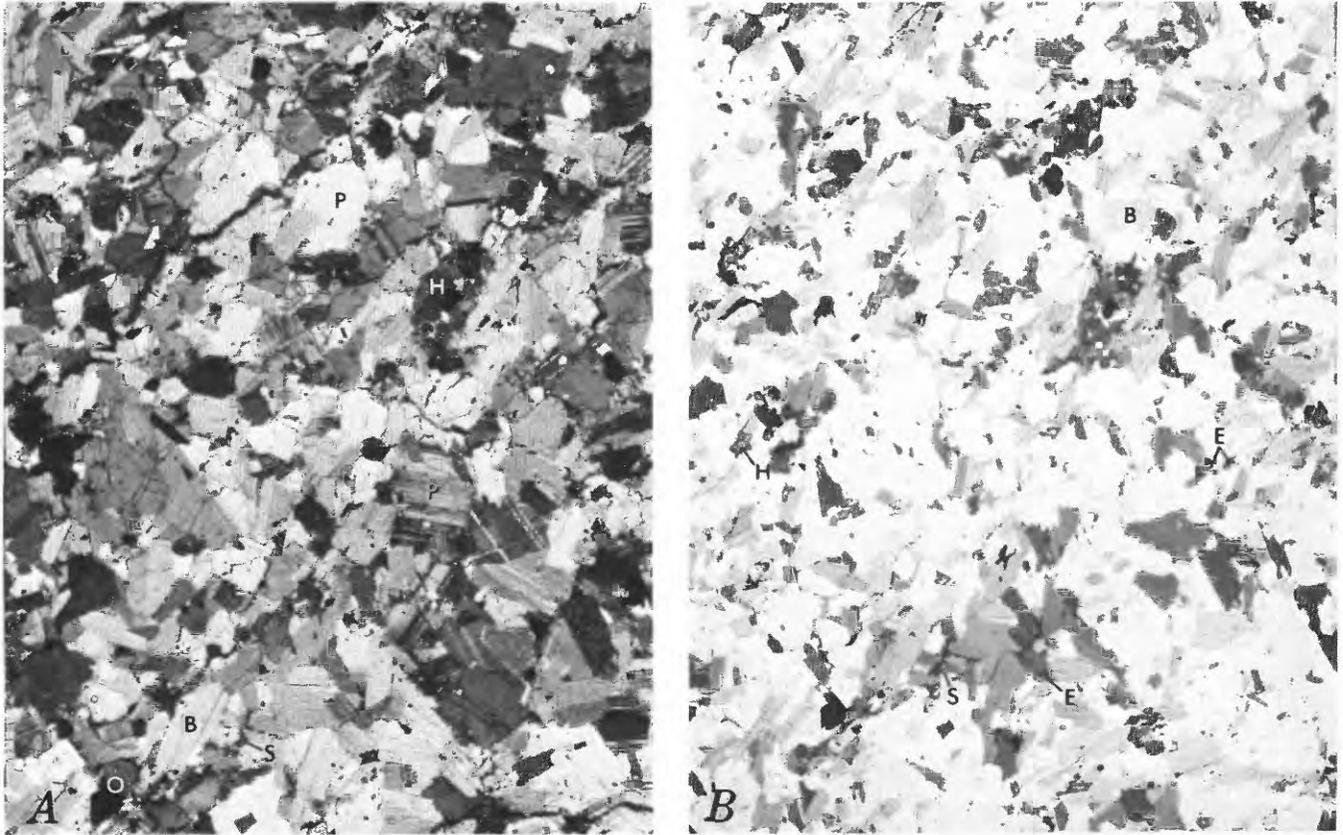
FIGURE 11.—Mafic inclusions in Boulder Creek Granodiorite. *A*, type 2 inclusion, biotitic quartz diorite inclusion (322); typical elongated clot but a little more leucocratic than in figure 8, x-polarizers, ×16. *B*, same section, plain light, ×12. *C*, type 3 inclusion, lamprophyre (331), plain light ×16. A, allanite; Ap, apatite; B, biotite; E, epidote; H, hornblende; O, ores; Or, orthoclase; P, plagioclase; Q, quartz; S, sphene. Photographs by Louise Hedricks, U.S. Geological Survey; sample numbers in parentheses.

mingtonite may be replacing hornblende on a small scale. Biotite varies in amount by as much as 20 percent in the more schistose diorites and is more prominent in the outer zones of the larger mafic bodies. It is reddish brown and is commonly of two generations: one generation forms stubby crystals that are in mutual contact with the other mafic minerals, whereas the other is more acicular and rarely forms radiating crystals that penetrate or sever hornblende and plagioclase crystals. Pyroxene in diorites occurs as relict grains that have been extensively replaced by hornblende. Where relict pyroxene exists, ores are in greater abundance and biotite is less common than in nonpyroxene-bearing diorites.

TWIN SPRUCE QUARTZ MONZONITE

The Twin Spruce Quartz Monzonite is herein named for the small settlement of Twin Spruce in the Eldorado Springs quadrangle. The type locality is just
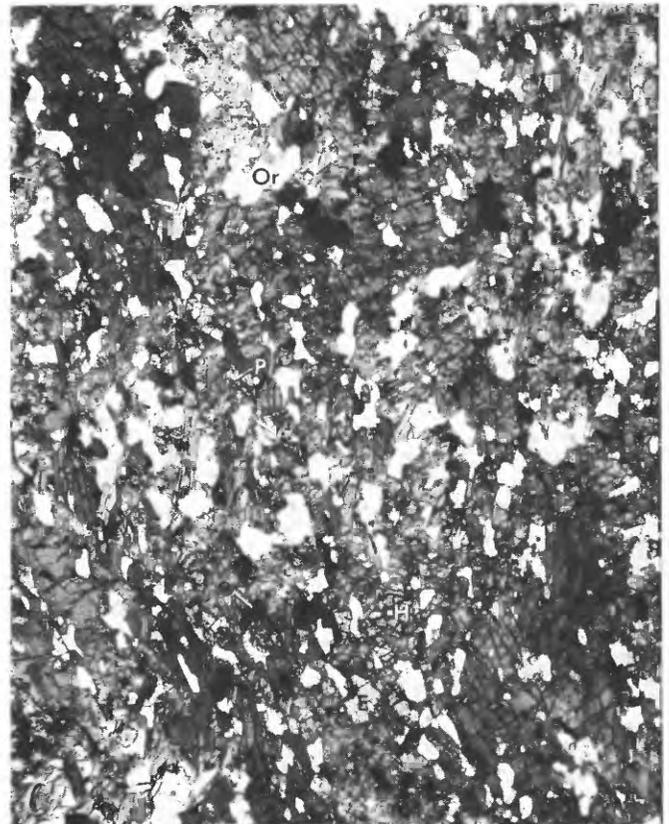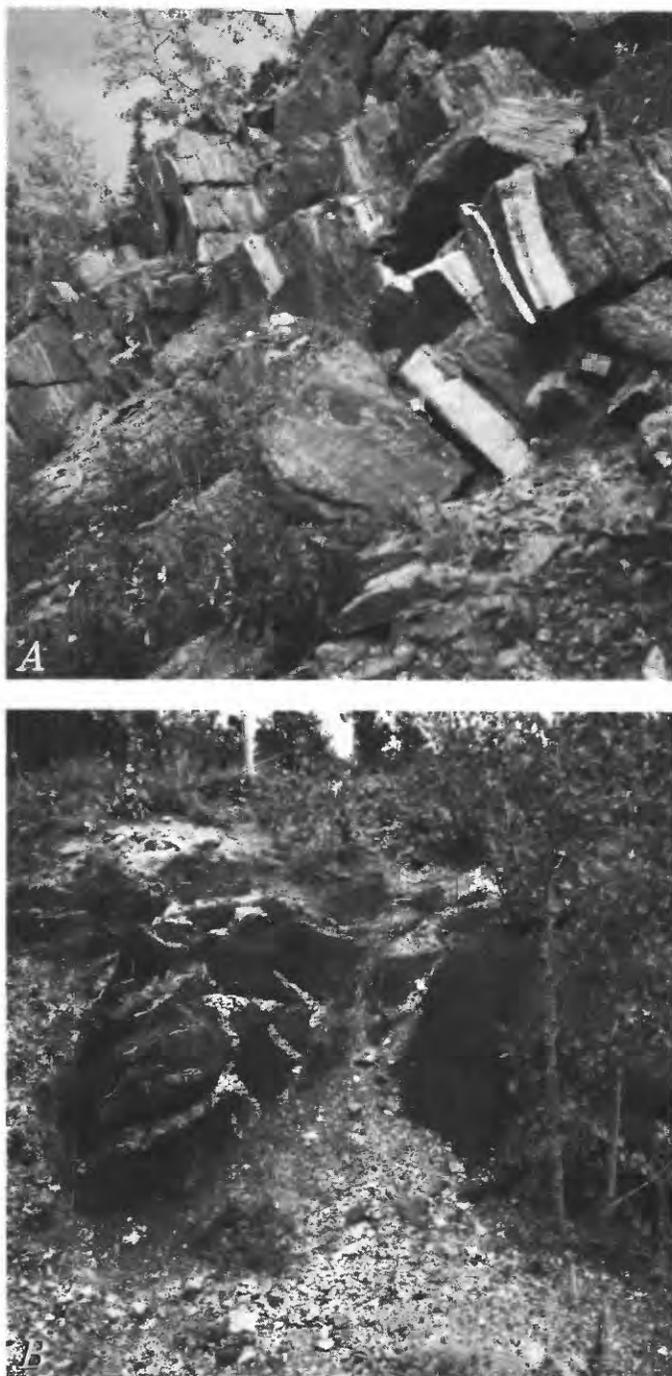
FIGURE 12.—Outcrops of layered and foliated biotitic hornblende diorite and massive pyroxenite(?): *A*, layered biotite-hornblende diorite in roadcut, Colorado 72 south of Rollinsville. *B*, same location as *A*, weathered rubble roadcut with resistant pyroxenite(?) cut by feldspar-rich pegmatites.

composition ranges from granite to quartz monzonite, it is chiefly quartz monzonite. The unit occupies nearly a quarter of the batholith and is more extensive and definitely more massive in the southern part of the batholith (pl. 2) adjacent to the schist and gneiss contact than farther north in the central part of the Tungsten quadrangle. Aplite, pegmatite, and rarely trondhjemite accompany the quartz monzonite. Although most bodies of quartz monzonite in the Boulder Creek Granodiorite are generally mappable, local thin lenses commonly are intermixed with the granodiorite or are gradational into it and cannot be mapped separately at a scale of 1:24,000.

Twin Spruce Quartz Monzonite was mapped by Lovering and Goddard (1950) as granite gneiss and gneissic aplite; however, recent mapping in the Front Range has shown that the granite gneiss and gneissic aplite unit of Lovering and Goddard includes more than one rock unit. In addition to the quartz monzonite delineated by Wells (1967), thick layers of older Precambrian microcline gneiss (microcline-quartz-plagioclase-biotite gneiss) conformably interlayered with biotite gneiss can also be distinguished locally (Moench and others, 1962; Sims and Gable, 1964; Hawley and Moore, 1967). Geologic mapping indicates the Twin Spruce Quartz Monzonite is certainly younger than the Boulder Creek Granodiorite in some places; elsewhere the field evidence is not as conclusive. Rb/Sr determinations on samples of this rock from the Eldorado Springs quadrangle indicate the ages isotopically fit the $1,710\pm40$ m.y. isochron of the Boulder Creek Granodiorite (Hedge 1969). Weighing all evidence, it appears safe to say that the Twin Spruce Quartz Monzonite is in part late Boulder Creek in age and in part younger than Boulder Creek.

Quartz monzonite is generally gray where fresh but has a characteristic zonal weathering pattern adjacent to joints that broke the rock into rough blocks that now weather into orange-brown and light-brown concentric zones. This form of weathering is typical of the quartz monzonite found in roadcuts in Middle Boulder Creek canyon. Joints or weathering also produce slabby rocks that break into thin layers much like shale, and these thin slabs tend to spread over weathered surfaces, obscuring contacts. One such area occurs in the extreme southeast corner of the Tungsten quadrangle; another is in the central part of the Tungsten mining district. Both areas are covered with pieces of quartz monzonite that give the ground a littered appearance. The monzonite in the batholith proper typically has a weak foliation and lineation produced by laths of biotite and tabular feldspar. In adjacent metasedimentary rocks, bodies of quartz monzonite have a pronounced gneissic structure; this structure is especially noticeable in the lens north and west of Nederland.

northeast of Twin Spruce where typical quartz monzonite crops out in Coal Creek Canyon. Twin Spruce Quartz Monzonite is a finer grained and more leucocratic rock than the Boulder Creek Granodiorite with which it is commonly associated, and although its

TABLE 7.—Modes (volume percent) for gabbro, hornblendite, hornblende diorite, quartz diorite, and hornblende pyroxenite, Boulder Creek batholith area, Front Range, Colo

[(—), not found; Tr., trace; ores include all opaque minerals. Samples 336, 338, 341, 343, 348, 349, 351, 352-354 from Tungsten quadrangle; 335, 337, 339, 340, 342, 343, 344, 345, 346, 347, 350, 355 from Nederland quadrangle]

| | Gabbro | | | Hornblendite | | | Hornblende diorite | | | | Quartz diorite | | Hornblende pyroxenite to biotite-hornblende diorite | | | | | | | | |
| | | | | | | | | | | | | | Los Lagos lens | | | | | Severance lens | | | |
Sample No.	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355
Potassium feldspar	—	—	—	—	—	—	—	Tr.	Tr.	—	—	—	—	—	—	—	—	—	4.0	—	—
Plagioclase	49	57	55	1	1	10	35.4	46	28.5	Tr.	29	39	5	Tr.	1	49	36	29.2	0.8	36.2	3
Quartz	5	Tr.	3	Tr.	1	2	—	3	5.3	2	17	17	—	—	—	Tr.	2	3.8	1.1	0.3	2
Hornblende	22	7	14	83	71	81	56.0	40	56.5	54	27	33	33	17	52	40	53	42.9	78.0	37.2	42
Actinolite-tremolite	2	Tr.	—	—	—	Tr.	—	—	—	—	Tr.	—	—	—	—	—	—	—	—	—	—
Clinopyroxene	6	15	6	5	27	} 1	2.1	—	—	—	Tr.	—	43	33	9	Tr.	1	—	3.9	0.3	} 49
Orthopyroxene	—	14	4	—	—		—	—	—	—	—	—	12	33	32	—	—	—	—	—	
Clinozoisite	—	—	—	—	—	—	—	—	—	—	—	—	—	10	—	1	—	—	—	—	—
Biotite	9	6	14	—	Tr.	1	4.9	10	—	7	12	8	2	—	Tr.	5	Tr.	20.8	—	21.4	2
Chlorite	4	—	1	—	—	1	—	—	—	5	3	Tr.	—	—	—	1	3	—	—	—	Tr.
Muscovite-sericite	—	—	1	8	—	4	—	—	8.2	29	8	—	—	6	—	4	3	—	4.3	—	1
Zircon	—	—	—	—	Tr.	—	Tr.	—	—	—	—	—	—	—	—	—	—	—	0.3	Tr.	Tr.
Allanite	—	—	—	—	—	Tr.	—	—	—	Tr.	—	Tr.	—	—	—	—	—	Tr.	—	Tr.	—
Ores	3	1	2	Tr.	Tr.	Tr.	0.8	1	—	Tr.	Tr.	3	3	1	2	—	1	0.3	0.7	—	Tr.
Apatite	Tr.	—	—	Tr.	Tr.	Tr.	0.1	Tr.	0.1	—	—	—	—	—	—	Tr.	Tr.	1.9	3.3	2.0	1
Rutile	Tr.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Prehnite[a]	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
Epidote	—	—	—	3	—	Tr.	0.6	Tr.	0.8	3	3	—	2	—	4	Tr.	1	1.0	1.5	2.6	—
Calcite	—	—	—	—	—	—	0.1	—	Tr.	—	—	—	—	—	—	—	—	—	—	—	—
Sphene	—	—	—	Tr.	—	—	—	—	—	—	—	—	—	—	—	—	—	0.1	2.1	—	Tr.
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a] Uncertain.

Twin Spruce Quartz Monzonite is chiefly a fine-grained rock having an average grain size of 4–5 mm (fig. 13A), but a medium-grained (0.6–0.8 mm) phase (fig. 13B) and a speckled phase occur locally. The speckled phase, not shown in figure 13, is due to clots of minerals surrounded by lighter haloes that are scattered randomly throughout the rock. These phases have not been mapped separately, especially as contacts are in general gradational.

Twin Spruce Quartz Monzonite is predominantly a microcline-, plagioclase-, and quartz-bearing rock with biotite, muscovite, and ores making up approximately 15 percent of the total rock (table 8). Accessory minerals are the same but are scarcer than in the Boulder Creek Granodiorite. Modally, quartz monzonite is restricted within the quartz monzonite field of a ternary quartz-potassium feldspar-plagioclase diagram; only a few modes plot in the granodiorite and granite fields (fig. 14). Quartz monzonite in the Eldorado Springs (Wells, 1967) and Ralston Buttes
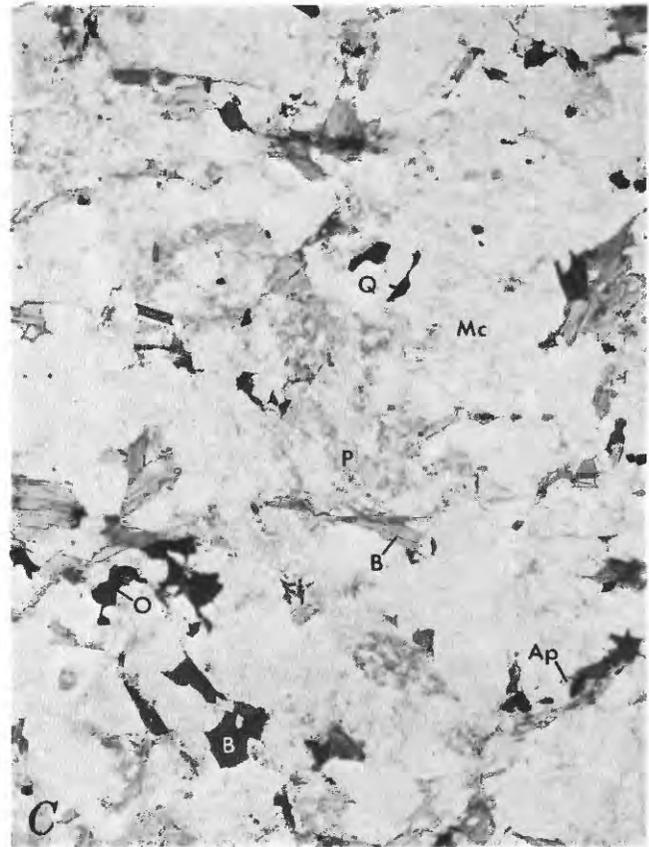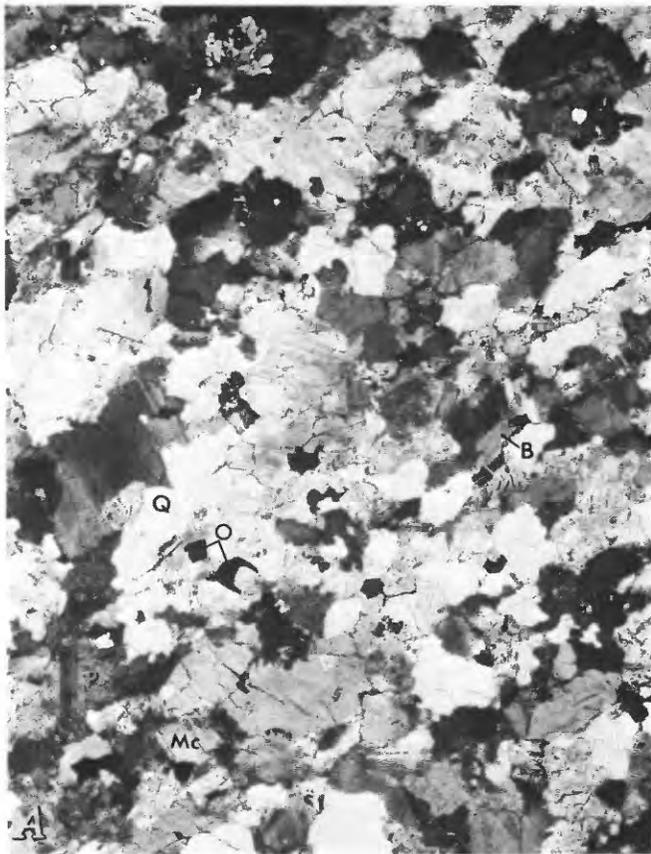
FIGURE 13.—Photomicrographs of Twin Spruce Quartz Monzonite. A, fine-grained quartz monzonite (sample 87, table 8), x-polarizers, ×12. B, coarse-grained quartz monzonite, slightly sheared (sample 380, table 13), x-polarizers, ×12. C, same section as B, except plain light. Ap, apatite; B, biotite; Mc, microcline; Mu, muscovite; O, ores; P, plagioclase; Q, quartz; Z, zircon. Photographs by Louise Hedricks, U.S. Geological Survey.

TABLE 8.—*Modes (volume percent) for Twin Spruce Quartz Monzonite, Front Range, Colo.*

[(--), not found; Tr., trace; ores include all opaque minerals. Samples 77-98 and 218-289 from Tungsten quadrangle; 290-303 from Nederland quadrangle; 304-311 from Ward quadrangle; 312-317 from Gold Hill quadrangle]

Sample No.	77	78	79	80	81	82	83	84	86	87	88	89	90	91
Potassium feldspar	47.8	35.5	37.7	36.8	44.8	36.5	38.5	35.8	42.6	40.4	34.5	33.6	28.6	21.8
Plagioclase	21.6	26.6	28.8	29.2	18.4	28.2	25.5	31.4	23.4	23.8	32.3	30.0	37.4	40.3
Quartz	28.8	27.5	26.6	28.1	35.8	29.5	32.4	31.2	24.1	29.5	27.3	30.6	29.1	27.4
Biotite	1.3	7.0	1.8	3.2	0.1	1.0	0.1	0.7	4.9	2.6	4.5	4.2	3.4	6.1
Muscovite	0.1	1.0	3.4	1.3	0.2	2.2	1.8	0.5	1.4	2.9	--	0.9	1.1	3.0
Ores	0.4	1.1	1.3	0.9	0.5	2.5	1.6	0.2	2.2	0.4	0.9	0.7	0.4	0.6
Apatite	Tr.	0.3	0.1	0.2	Tr.	Tr.	Tr.	0.1	0.4	0.4	0.4	--	Tr.	0.1
Allanite	Tr.	0.6	--	Tr.	--	--	--	--	0.6	Tr.	Tr.	--	--	0.4
Zircon	Tr.	0.1	--	0.1	--	Tr.	--	--	--	--	--	Tr.	Tr.	--
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Epidote	--	Tr.	--	0.1	--	--	--	--	0.1	--	--	Tr.	Tr.	0.1
Rutile	--	--	--	--	--	--	--	Tr.	--	--	--	--	--	--
Chlorite	--	0.3	0.3	0.1	0.2	0.1	0.1	0.1	0.3	--	--	--	--	0.1
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	--	--	--	--	--	--	--	Tr.	Tr.	0.1	--	--	0.1
Monazite-xenotime	--	--	--	--	--	--	--	Tr.	--	--	--	Tr.	Tr.	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	92	93	94	95	96	97	98	218	219	220	221	222	223	224
Potassium feldspar	17.8	33.6	42.7	31.3	37.8	5.9	37.3	32.7	48.0	32.1	37.8	33.7	7.8	26.5
Plagioclase	41.1	29.0	23.9	31.8	30.2	45.7	27.0	35.1	21.6	30.6	21.5	22.0	13.9	37.2
Quartz	24.9	20.2	29.4	32.6	30.0	40.9	26.5	27.7	26.7	25.7	35.3	38.4	67.6	26.9
Biotite	10.7	10.6	1.0	2.8	1.5	5.1	6.2	3.4	1.1	5.1	4.9	4.8	8.9	7.2
Muscovite	2.4	3.0	0.4	0.7	0.3	0.8	0.7	0.1	1.9	2.5	Tr.	0.6	0.3	1.0
Ores	1.9	2.9	1.2	0.8	0.1	1.0	2.3	0.9	0.7	2.1	0.4	0.5	1.5	1.1
Apatite	0.2	0.4	0.2	Tr.	0.1	0.4	Tr.	0.1	Tr.	0.7	0.1	--	--	0.1
Allanite	0.2	0.3	0.2	--	--	Tr.	--	--	Tr.	--	--	--	--	Tr.
Zircon	Tr.	Tr.	--	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Calcite	--	--	--	--	--	--	--	--	--	Tr.	--	--	--	Tr.
Epidote	--	--	--	--	--	--	--	Tr.	Tr.	--	--	--	--	Tr.
Rutile	Tr.	--	Tr.	--	--	--	--	--	Tr.	0.1	Tr.	--	--	Tr.
Chlorite	--	Tr.	1.0	Tr.	--	--	Tr.	--	Tr.	1.1	Tr.	--	--	Tr.
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	0.8	--	--	--	--	0.2	--	--	--	--	--	--	--	Tr.
Monazite-xenotime	--	--	--	Tr.	Tr.	--	--	--	Tr.	Tr.	--	Tr.	Tr.	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 8.—*Modes (volume percent) for Twin Spruce Quartz Monzonite, Front Range, Colo.*—Continued

Sample No.	225	226	227	228	229	230	231	232	233	234	235	236	237	238
Potassium feldspar	29.2	34.1	39.4	36.4	35.8	4.1	32.0	23.5	29.7	14.1	30.6	34.6	31.5	31.3
Plagioclase	28.2	24.8	24.0	24.7	12.9	14.3	30.3	18.5	32.4	27.7	31.0	27.5	16.2	28.4
Quartz	27.7	29.2	24.8	28.4	40.3	69.0	27.0	51.6	26.4	51.9	27.1	27.7	46.6	26.7
Biotite	6.8	7.5	7.2	6.9	6.2	7.5	6.4	3.3	5.9	2.8	1.1	6.0	3.1	9.5
Muscovite	6.2	3.0	2.9	2.2	3.5	3.8	2.1	2.2	2.2	2.5	1.8	1.9	1.6	1.9
Ores	1.1	1.0	1.3	1.2	1.1	Tr.	1.8	0.8	1.9	1.0	1.5	1.2	1.0	1.9
Apatite	0.1	0.3	0.3	0.1	--	--	Tr.	Tr.	0.2·	--	0.7	0.4	--	0.3
Allanite	0.5	0.1	--	--	--	--	--	--	--	--	0.3	0.1	--	--
Zircon	0.1	Tr.	0.1	0.1	0.2	Tr.	0.2	Tr.	Tr.	Tr.	Tr.	0.2	Tr.	Tr.
Calcite	--	--	--	--	--	--	Tr.	--	--	--	--	--	--	--
Epidote	Tr.	--	--	--	--	--	--	--	--	--	--	--	--	--
Rutile	--	Tr.	Tr.	--	--	--	--	--	Tr.	--	0.2	Tr.	--	Tr.
Chlorite	0.1	Tr.	Tr.	--	Tr.	--	0.2	--	1.3	--	5.7	0.4	--	--
Sillimanite	--	--	--	--	--	Tr.	Tr.	0.1	--	--	--	--	--	--
Sphene	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Monazite-xenotime	Tr.	Tr.	Tr.	Tr.	Tr.	--	Tr.	Tr.	Tr.	--	--	Tr.	Tr.	Tr.
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	239	240	241	242	243	244	245	246	247	248	249	250	251	252
Potassium feldspar	45.5	42.1	44.5	33.2	36.9	26.0	45.5	33.2	31.3	36.5	52.3	35.6	37.8	43.3
Plagioclase	21.4	25.2	22.8	25.3	27.6	39.4	23.4	29.7	31.1	24.8	16.2	25.5	21.1	22.4
Quartz	26.3	25.1	28.0	30.3	23.4	27.1	26.8	26.2	26.9	31.7	20.8	29.4	29.2	30.4
Biotite	3.5	2.0	2.0	7.7	8.5	4.9	2.2	7.2	6.4	4.1	4.0	7.4	3.1	1.5
Muscovite	1.4	1.4	1.2	0.4	2.1	0.6	1.0	1.2	2.5	0.3	1.9	1.8	7.7	2.0
Ores	1.3	1.3	1.0	2.1	0.9	1.2	0.8	1.6	1.6	1.0	3.3	0.2	0.7	0.1
Apatite	Tr.	0.1	Tr.	0.3	0.4	0.1	Tr.	0.7	0.2	0.2	Tr.	0.1	0.3	--
Allanite	--	0.1	0.3	0.6	Tr.	--	--	Tr.	--	--	0.3	--	--	--
Zircon	0.6	0.1	Tr.	Tr.	Tr.	Tr.	--	0.2	Tr.	0.1	Tr.	Tr.	0.1	--
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Epidote	--	--	--	--	--	--	--	--	--	0.7	--	--	--	--
Rutile	Tr.	--	--	--	--	--	Tr.	--	--	--	--	--	--	Tr.
Chlorite	Tr.	2.6	0.2	0.1	0.2	0.7	0.3	Tr.	--	0.6	1.2	--	--	0.3
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	--	--	--	--	--	--	--	Tr.	--	--	--	--	--
Monazite-xenotime	Tr.	--	--	--	Tr.	--	--	Tr.	--	--	--	--	--	Tr.
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 8.—*Modes (volume percent) for Twin Spruce Quartz Monzonite, Front Range, Colo.*—Continued

Sample No.	253	254	255	256	257	258	259	260	261	262	263	264	265	266
Potassium feldspar	28.8	35.3	38.9	23.9	32.4	38.9	48.2	30.2	41.4	41.7	33.3	34.8	34.7	34.5
Plagioclase	36.1	26.8	22.4	39.3	33.4	25.8	17.9	33.4	19.6	32.5	30.6	32.2	25.8	29.2
Quartz	30.3	34.9	28.9	25.3	28.4	30.2	32.8	30.2	30.0	21.7	31.2	28.0	25.7	30.6
Biotite	2.5	2.5	6.2	6.7	2.0	0.9	--	5.4	5.0	1.6	2.4	0.4	7.5	2.5
Muscovite	1.9	0.1	1.8	1.9	3.0	1.8	0.6	0.1	2.7	1.9	1.2	1.6	3.7	1.8
Ores	0.3	0.4	1.6	2.4	0.8	0.6	0.1	0.6	0.6	0.4	0.8	1.3	2.1	0.8
Apatite	Tr.	Tr.	Tr.	0.5	Tr.	Tr.	0.1	0.1	0.3	Tr.	Tr.	Tr.	0.4	0.1
Allanite	--	--	0.1	--	--	0.1	Tr.	--	Tr.	Tr.	Tr.	0.1	--	Tr.
Zircon	0.1	Tr.	Tr.	Tr.	Tr.	Tr.	--	Tr.	Tr.	0.1	0.2	Tr.	0.1	Tr.
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Epidote	--	--	--	--	--	--	--	--	--	--	--	0.1	--	0.4
Rutile	Tr.	--	--	--	--	0.2	--	--	--	Tr.	Tr.	Tr.	--	--
Chlorite	--	--	0.1	Tr.	--	1.5	0.3	--	0.4	0.1	0.3	1.5	--	0.1
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	--	--	--	--	--	--	--	--	--	--	--	--	Tr.
Monazite-xenotime	Tr.	Tr.	--	--	--	--	--	--	Tr.	--	Tr.	Tr.	Tr.	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	267	268	269	270	271	272	273	274	275	276	277	278	279	280
Potassium feldspar	47.8	35.5	37.7	36.8	44.8	36.5	38.5	35.8	42.6	40.4	34.5	33.6	28.6	21.8
Plagioclase	21.6	26.6	28.8	29.2	18.4	28.2	25.5	31.4	23.4	23.8	32.3	30.0	37.4	40.3
Quartz	28.8	27.5	26.6	28.1	35.8	29.5	32.4	31.2	24.1	29.5	27.3	30.6	29.1	27.4
Biotite	1.3	7.0	1.8	3.2	0.1	1.0	0.1	0.7	4.9	2.6	4.5	4.2	3.4	6.1
Muscovite	0.1	1.0	3.4	1.3	0.2	2.2	1.8	0.5	1.4	2.9	--	0.9	1.1	3.0
Ores	0.4	1.1	1.3	0.9	0.5	2.5	1.6	0.2	2.2	0.4	0.9	0.7	0.4	0.6
Apatite	Tr.	0.3	0.1	0.2	Tr.	Tr.	Tr.	0.1	0.4	0.4	0.4	--	Tr.	0.1
Allanite	Tr.	0.6	--	Tr.	--	--	--	--	0.6	Tr.	Tr.	--	--	0.4
Zircon	Tr.	0.1	--	0.1	--	Tr.	--	--	--	--	--	Tr.	Tr.	--
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Epidote	--	Tr.	--	0.1	--	--	--	--	0.1	--	--			0.1
Rutile	--	--	--	--	--	--	--	Tr.	--	--	--	--	--	--
Chlorite	--	0.3	0.3	0.1	0.2	0.1	0.1	0.1	0.3	--	--	--	--	0.1
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	--	--	--	--	--	--	--	Tr.	--	0.1	--	--	0.1
Monazite-xenotime	--	--	--	--	--	--	--	Tr.	--	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 8.—*Modes (volume percent) for Twin Spruce Quartz Monzonite, Front Range, Colo.*—Continued

Sample No.	281	282	283	284	285	286	287	288	289	290	291	292	293	294
Potassium feldspar	28.1	17.8	33.6	42.7	31.3	37.8	3.0	5.9	37.3	43.3	49.0	26.9	27.4	31.2
Plagioclase	33.2	41.1	29.0	23.9	31.8	30.2	48.6	45.7	27.0	23.9	21.0	35.6	32.8	29.3
Quartz	23.9	24.9	20.2	29.4	32.6	30.0	42.8	40.9	26.5	29.3	29.0	32.4	29.2	38.6
Biotite	9.7	10.7	10.6	1.0	2.8	1.5	Tr.	5.1	6.2	[a]2.0	[a]1.0	3.4	8.6	0.9
Muscovite	2.0	2.4	3.0	0.4	0.7	0.3	--	0.8	0.7	0.7	Tr.	0.9	0.8	Tr.
Ores	1.7	1.9	2.9	1.2	0.8	0.1	3.0	1.0	2.3	0.8	--	0.5	0.9	Tr.
Apatite	0.7	0.2	0.4	0.2	Tr.	0.1	0.4	0.4	Tr.	Tr.	--	--	0.3	--
Allanite	0.4	0.2	0.3	0.2	--	--	1.1	--	Tr.	--	--	--	--	--
Zircon	0.2	Tr.	Tr.	--	Tr.	Tr.	1.1	0.2	Tr.	0.1	Tr.	Tr.	Tr.	Tr.
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Epidote	Tr.	--	--	--	--	--	--	--	--	--	--	--	--	--
Rutile	--	Tr.	--	Tr.	--	--	--	--	--	Tr.	--	--	--	--
Chlorite	0.1	--	Tr.	1.0	Tr.	--	--	--	Tr.	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	--	--	--	0.3	--	--
Sphene	--	0.8	--	--	--	--	--	--	--	--	--	--	--	--
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--	--	--	Tr.
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	295	296	297	298	299	300	301	302	303	304	305	306	307	308
Potassium feldspar	31.5	43.0	22.7	24.7	35.3	24.9	44.4	43.6	31.9	41.9	47.9	41.1	34.6	43.7
Plagioclase	19.7	17.4	19.2	22.2	32.7	36.0	26.0	26.3	24.8	25.4	22.2	21.8	28.6	22.3
Quartz	39.4	36.5	54.0	47.7	27.7	27.9	24.6	26.8	38.6	23.5	26.2	26.3	26.6	26.5
Biotite	7.4	Tr.	3.1	3.8	1.3	[a]5.4	4.1	1.5	3.5	6.4	0.6	3.2	0.4	5.9
Muscovite	1.0	2.4	0.1	0.6	1.0	1.8	0.6	0.2	0.6	0.1	0.6	6.4	0.4	--
Ores	1.0	0.6	[b]0.9	0.7	1.0	3.6	0.3	--	0.6	2.0	0.8	0.2	1.4	1.3
Apatite	--	--	--	--	--	0.3	Tr.	Tr.	--	--	0.4	--	0.6	Tr.
Allanite	--	--	--	--	--	--	--	Tr.	--	0.3	--	--	--	--
Zircon	Tr.	0.1	Tr.	Tr.	Tr.	0.1	Tr.	Tr.	Tr.	Tr.	0.1	--	0.1	Tr.
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Epidote	--	--	--	--	--	--	--	Tr.	--	0.3	--	--	0.1	Tr.
Rutile	--	--	--	--	--	--	--	--	Tr.	--	--	Tr.	--	--
Chlorite	--	--	--	--	1.0	--	--	--	--	0.1	1.2	1.0	7.2	0.3
Sillimanite	--	--	--	Tr.	--	--	--	--	--	--	--	Tr.	Tr.	--
Sphene	--	--	--	--	--	--	--	--	--	--	--	--	Tr.	--
Monazite-xenotime	Tr.	Tr.	--	--	Tr.	Tr.	Tr.	--	Tr.	--	--	Tr.	Tr.	Tr.
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 8.—*Modes (volume percent) for Twin Spruce Quartz Monzonite, Front Range, Colo.*—Continued

Sample No.	309	310	311	312	313	314	315	316	317
Potassium feldspar	42.2	42.2	35.5	27.3	34.0	42.6	26.9	35.3	14.6
Plagioclase	22.0	29.1	31.4	34.7	34.0	27.8	30.2	34.3	44.8
Quartz	27.5	21.5	26.4	26.2	25.9	24.8	32.4	28.3	31.7
Biotite	4.8	3.9	4.6	6.9	1.9	3.2	7.5	1.3	7.0
Muscovite	1.3	0.4	0.1	1.8	3.3	1.0	0.7	—	0.5
Ores	1.3	1.6	1.5	1.4	0.7	0.1	1.5	0.7	0.3
Apatite	0.2	0.9	0.1	0.4	Tr.	0.1	0.3	0.1	0.3
Allanite	0.2	Tr.	0.1	—	Tr.	—	0.1	—	Tr.
Zircon	Tr.	0.1	Tr.	—	—	—	Tr.	—	—
Calcite	—	—	—	—	—	—	—	—	—
Epidote	Tr.	Tr.	—	Tr.	0.1	0.3	Tr.	Tr.	0.3
Rutile	—	Tr.	—	—	—	—	—	—	—
Chlorite	0.5	0.3	0.3	Tr.	0.1	0.1	Tr.	Tr.	0.5
Sillimanite	—	—	—	—	—	—	0.1	—	—
Sphene	—	Tr.	—	1.3	—	—	0.3	—	—
Monazite-xenotime	Tr.	Tr.	Tr.	—	Tr.	—	—	—	Tr.
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a]Biotite and chlorite undifferentiated.   [b]Traces of green spinel.

areas (Sheridan and others, 1967), in the southeastern part of the batholith, contains not only more quartz but also more plagioclase than similar rocks within the batholith. To the west of the batholith, within metasedimentary units, the quartz monzonite lenses also have a greater proportion of quartz, probably as a result of local contamination from the biotite gneiss and schist. In general, the speckled and fine-grained quartz monzonite phases have a greater spread in modal composition than does medium-grained quartz monzonite. Medium-grained quartz monzonite clusters imperfectly between 24 and 40 percent quartz, 35 and 45 percent microcline, and 20 and 35 percent plagioclase.

GRANITE GNEISS, GNEISSIC APLITE, AND PEGMATITE

Granite gneiss, gneissic aplite, and pegmatite occur as dikes and lenses in the batholith and in the adjacent metasedimentary rocks. Whereas these dikes and lenses are nearly all of Boulder Creek age (1,700 m.y.), it is possible some are of Silver Plume age (1,450 m.y.). Generally, but not always, they can be identified with one intrusive or the other.

Granite gneiss and pegmatite form topographically high ridges that can be easily mapped on the north and south sides of Lefthand Canyon, northeast of Gold Hill (pl. 2). At Gold Hill granite gneiss, gneissic aplite, and

pegmatite form profuse lenticular masses, dikes, and thin lenses that are generally associated with Boulder Creek Granodiorite adjacent to the batholith as well as in the batholith. An area of extensive pegmatite occurrence is north of Golden Gate Canyon for perhaps 2 or 3 m adjacent to the batholith in an area of large satellitic plutons. Granite gneiss and pegmatite are also present in the Central City quadrangle, especially the southern half.

Granite gneiss is a leucocratic, generally medium- to coarse-grained rock that is locally gradational into pegmatite and aplite. It is predominantly a feldspar rock containing 20–35 percent quartz and having less than 5 percent accessory minerals, including biotite, muscovite, and the ores (table 9). Locally, granite gneiss and pegmatite bear stringers of biotite gneiss or of biotite, muscovite, and sillimanite.

In thin section granite gneiss and pegmatite are leucocratic rocks having an allotriomorphic granular texture. The predominant minerals, microcline, plagioclase, and quartz, are equigranular in some of the finer grained granite gneisses, but more commonly microcline occurs as distinctly larger crystals. The microcline generally appears fresh, but the plagioclase is characteristically altered, and twinning is commonly indistinct and discontinuous. In a ternary quartz-plagioclase-potassium feldspar diagram (fig. 15) modal

distribution of granite gneiss extends form the quartz monzonite field into the granite field with a quartz range between 20 and 40 percent.
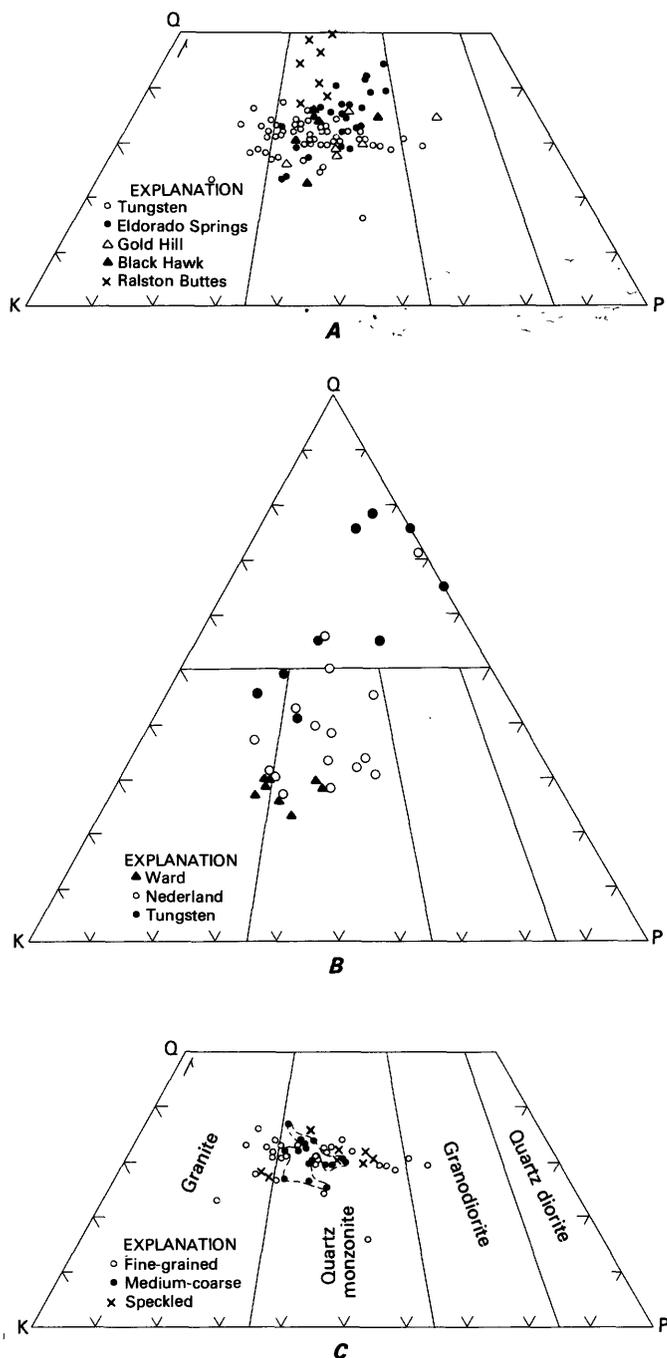
FIGURE 14.—Modal variation in quartz, plagioclase, and potassium feldspar (volume percent) for Twin Spruce Quartz Monzonite. *A*, composite of all Twin Spruce Quartz Monzonite modes for the batholith. *B*, variation in lens west of the Boulder Creek batholith. *C*, modes for the Tungsten quadrangle showing distribution of medium-grained quartz monzonite. Dashed area encloses medium-coarse-grained quartz monzonite. P, plagioclase; K, potassium feldspar; Q, quartz.

AGES OF BATHOLITHIC ROCKS

Both the Boulder Creek Granodiorite and the Twin Spruce Quartz Monzonite have been dated by determining Pb^{207}/Pb^{206} in zircons from the rock samples and by rubidium-strontium whole-rock methods. Perhaps the earliest reliable dates for the batholithic rocks were made by the U.S. Geological Survey (1964) on zircons and indicated an average age for the batholith of 1,730 m.y. Later, Stern, Phair, and Newell (1971) indicated an average age of the batholith based on six zircon samples to be 1,714 m.y. and emplacement age of the batholith, 1,725 m.y. Peterman, Hedge, and Braddock (1968) dated 13 samples from the batholith and smaller plutons of granodiorite to the north of the batholith. The results of their rubidium-strontium age determinations indicated the batholith was 1,700 m.y. years old. This age is in agreement with the zircon age of 1,714 m.y. obtained by Stern, Phair, and Newell (1971). Also, Peterman, Hedge, and Braddock (1968) indicated that a postcrystallization event was superimposed on the batholith as suggested by a Sr^{87}/Sr^{86} age of 1,340 m.y. Sr^{87} is suggested to have partly or completely re-equilibrated at that time. Several samples of Twin Spruce Quartz Monzonite from near the type area in the Eldorado Springs quadrangle were dated by Hedge (1969). He obtained rubidium-strontium whole-rock ages that isotopically fit the 1,700-m.y. isochron of the Boulder Creek Granodiorite.

Geologic mapping, principally by Wells (1967) and Gable (1972), indicated that Twin Spruce Quartz Monzonite is in part younger than the Boulder Creek Granodiorite. The field evidence indicates that the Twin Spruce Quartz Monzonite is in part the same age as the Boulder Creek Granodiorite, but the greater part of it is younger; the younger age is still within the limits of the isochron date (Hedge, 1969) determined for the quartz monzonite.

STRUCTURE

The Boulder Creek batholith was emplaced into a generally conformable sequence of high-grade metamorphic rocks that were folded into a series of complex antiforms and synforms and, locally, cataclastically deformed and faulted. Intrusion of the batholithic rock, metamorphism, folding, cataclasis, and major faulting in the area all took place during Precambrian time. Whereas Cretaceous to Tertiary intrusive stocks pierced the metasedimentary rocks to the north and northwest of the batholith, only dikes, sills, and small lenses occur within the batholith.

The Boulder Creek batholith and its satellitic plutons of similar composition and age shown on plate 1 compose a semicircular structural feature that is

TABLE 9.—*Modes (volume percent) for aplite, aplitic pegmatite, and granite gneiss from the map unit Granite Gneiss and Pegmatite (pl. 1), Boulder Creek batholith, Front Range, Colo*

[(-), not found; Tr., trace; ores include all opaque minerals. Sample 356 from Nederland quadrangle; 357-360 from Tungsten quadrangle; 361 from Ward quadrangle; 362-374 from Gold Hill quadrangle]

Sample No.	356	357	358	359	360	361	362	363	364	365	366
Potassium feldspar	33.4	52.9	34.6	56.4	38.7	52.0	46.0	38.6	45.3	39.0	35.4
Plagioclase	30.2	16.6	31.4	14.8	24.8	32.0	22.0	38.6	22.1	17.0	24.7
Quartz	32.7	29.3	30.9	26.9	33.7	12.0	30.0	22.8	31.9	34.0	33.9
Biotite	--	--	0.7	0.6	--	3.0	--	Tr.	--	2.0	4.4
Muscovite	2.2	[a]0.3	1.4	0.5	--	1.0	2.0	--	0.4	8.0	1.3
Ores	1.5	--	0.4	--	0.1	--	Tr.	Tr.	--	Tr.	0.3
Apatite	--	Tr.	Tr.	Tr.	0.4	Tr.	Tr.	--	--	--	--
Zircon	--	--	Tr.	--	--	Tr.	--	Tr.	--	--	--
Chlorite	--	--	0.6	0.8	1.1	--	--	--	--	--	--
Epidote	--	--	--	--	1.0	--	--	--	--	--	--
Rutile	--	--	--	--	--	--	--	--	--	--	--
Allanite	--	--	--	--	0.1	--	--	--	--	--	--
Monazite-xenotime	--	--	--	--	--	--	--	--	--	--	--
Calcite	--	--	--	--	0.1	--	--	--	--	--	--
Sillimanite	--	--	--	--	--	--	--	--	0.3	--	--
Total	100.0	100.0	100.0	100.0	99.3	100.0	100.0	100.0	100.0	100.0	100.0

Sample No.	367	368	369	370	371	372	373	374
Potassium feldspar	55.5	40.8	44.6	38.7	40.1	28.0	27.1	50.9
Plagioclase	17.8	25.5	30.1	25.7	20.4	34.4	33.9	20.5
Quartz	26.0	29.0	25.2	34.0	36.4	32.7	33.8	26.5
Biotite	--	0.9	--	--	Tr.	4.0	--	--
Muscovite	0.3	2.4	--	0.8	2.3	0.1	4.4	1.5
Ores	0.3	1.2	0.1	0.8	0.1	Tr.	Tr.	0.1
Apatite	Tr.	--	--	Tr.	Tr.	0.1	--	--
Zircon	--	--	--	Tr.	--	--	--	--
Chlorite	--	0.2	--	--	0.7	0.7	Tr.	--
Epidote	--	--	--	--	Tr.	Tr.	--	--
Rutile	--	Tr.	--	--	--	--	--	--
Allanite	--	--	--	Tr.	--	Tr.	Tr.	--
Monazite-xenotime	0.1	Tr.	--	--	--	--	--	--
Calcite	--	--	--	--	--	--	--	--
Sillimanite	Tr.	--	--	--	--	--	0.8	0.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a]Includes sericite.
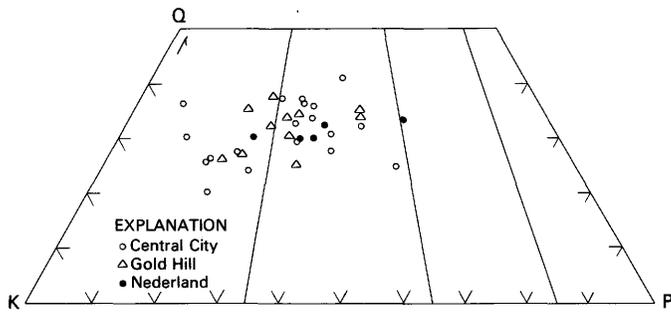
FIGURE 15.—Modal variation in quartz, plagioclase, and potassium feldspar (volume percent) for granite gneiss from the granite gneiss and pegmatite unit. P, plagioclase; K, potassium feldspar; Q, quartz.

midway between the Strawberry and Mt. Evans batholiths. In addition to Boulder Creek Granodiorite, ultramafic, mafic, and distinctly leucocratic rocks were emplaced as plugs, dikes, sills, lenses, and plutons along this semicircular feature. The smaller bodies of intrusive rocks roughly conform to the trends of foliation and fold axes in the older country rocks, suggesting that their emplacement was controlled, to a large degree at least, by preexisting structures in the country rocks.

Regional mapping has shown that the Precambrian country rocks of the batholith were deformed and metamorphosed during at least two episodes of regional metamorphism and deformation and a later episode of cataclastic deformation. Emplacement of the granodiorite apparently began late in the first period of synmetamorphic deformation and culminated during the second period. The first deformation formed tight to isoclinal folds that apparently have dominantly west- and northwest-trending axial surfaces. This fold set is represented by the overturned Buckeye Mountain anticline and the overturned Jenny Lind and Nederland synclines in the vicinity of Eldora and south of Gold Hill (pl. 2), where the granodiorite is subconformable to deformed country rocks that were folded on northwest-trending axes. Subsequently, the folds were refolded during a deformation that produced north- to northeast-trending folds, which are the dominant structures in the region (Sims and Gable, 1967; Gable, 1969; Gable and Madole 1976; Taylor, 1976). Both the northern and southern parts of the batholith have foliations that have been folded on east-northeast-trending axes that extend from the country rock into the batholith (pl. 2). Foliations along the west contact parallel the contact and vary sharply from those in the interior of the batholith where foliations undulate from northeast to northwest. Both trends in foliation are probably primary, that is, they were formed through flowage of magma that was still

plastic during the time of metamorphic deformation and presumably were caused by protoclastic deformation or by the differential flow of magma before complete consolidation. Continued shearing produced secondary foliations and recrystallization in the granodiorite along fault zones, particularly along the southern margin of the batholith. Both deformations took place under temperature-pressure conditions represented by 300–500 MPa [3–5 kb] at 620–710 °C (Gable and Sims, 1969) and are characteristic of a sillimanite-potassium feldspar grade metamorphism. The later and more restricted cataclastic deformation was confined mainly to a relatively narrow zone passing through the southeast part of the map area (pl. 1) and the southernmost part of the batholith and was accompanied by retrograde metamorphism. The cataclastic deformation has been dated at about 1,440 m.y. by Hedge (1969), which is approximately the time of emplacement of the Silver Plume Quartz Monzonite.

Jointing is well developed throughout the batholith but data are available for only the western half of the batholith. Joints mapped in the Tungsten and Gold Hill quadrangles are fairly uniform; figure 16 synthesizes the similarities.

Flat-lying joints (not shown in fig. 16) in the northern part of the batholith trend N. 72° E. and dip approximately 10° NW; this same joint set to the south has about the same trend, N. 80° E., and dips 15° SE. If these primary flat-lying joints formed when magmatic pressure decreased, they probably indicate a
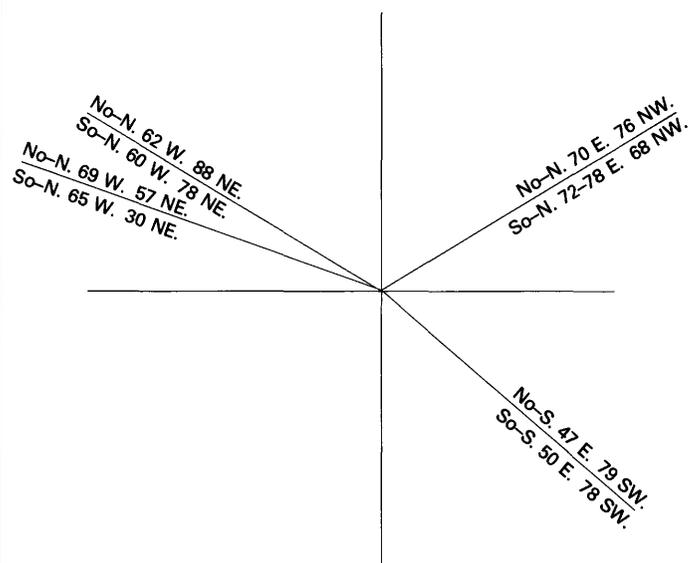
FIGURE 16.—Synthesis of the more prominent joint sets in the Tungsten and Gold Hill quadrangles, showing similarities in orientation; 963 poles represented. No, north half of batholith; So, south half of batholith.

doming of the batholith; another possibility is that the joints were related to contractions of the batholithic mass on cooling, or alternatively, represent fractures formed by release of pressure as the batholith was uncovered. Of the three possibilities, the last seems preferable, especially if the batholith does consist of two magma series. A joint set that dips to the west on the west slope of the southern part of the batholith (Gable, 1973) and a complementary set that dips east may also be related to the release of pressure.

GEOCHEMISTRY

Geochemical data indicate that the Boulder Creek Granodiorite consists of two magma sequences both regulated in part at least by CaO and SiO_2: (1) a northern sequence that has more SiO_2, CaO, and Na_2O than (2), a southern sequence that is richer in Al_2O_3, FeO, MgO, and K_2O. In the Twin Spruce Quartz Monzonite, however, CaO and SiO_2 do not appear to have influenced distribution of the oxides.

Chemical data were obtained for Boulder Creek Granodiorite and each of the significant rock types associated with the granodiorite. Major- and minor-element analyses of these rocks are given in tables 10, 11, 12, and 13. Data from analyses published since 1950, when usable, have also been used in many of the figures (for example, figs. 18–27), especially those from the Eldorado Springs quadrangle, in order to have more complete coverage of the batholith. Localities of chemically analyzed samples in this report are plotted in figure 17.

BOULDER CREEK GRANODIORITE

The Boulder Creek Granodiorite has two distinct chemical compositions based on the presence or absence of hornblende. Biotitic Boulder Creek Granodiorite generally has higher SiO_2 and CaO and lower TiO_2, FeO, and MgO than biotite-hornblende granodiorite. Chemically, Boulder Creek Granodiorite, on the average, shows the same variability in composition, based on the minerals biotite and hornblende, as do equivalent analyses of biotitic granodiorite and biotite-hornblende granodiorite published by Nockolds (1954, p. 1014); the Boulder Creek Granodiorite on the average, however, contains less SiO_2, Fe_2O_3, and Na_2O and more Al_2O_3, total iron as FeO, and MgO.

Chemical data on the mafic inclusions in the Boulder Creek Granodiorite are given in table 11. The small spindle type of mafic inclusion associated with the granodiorite, shown in figures 8A and 9 was not chemically analyzed; it is too greatly altered. All analyses are of larger dioritic inclusions (samples 334,

385, and 386, table 11). Trace-element data for the mafic inclusions are quite similar to data for Twin Spruce Quartz Monzonite (fig. 18). Trace elements for hornblende gneiss and amphibolite (fig. 18, col. 1), a rock type suggested as a source for the mafic inclusions and trace elements in the inclusions, vary widely.

Gabbro, hornblende pyroxenite, pyroxene-bearing hornblendite, hornblende diorite, and biotitic hornblende diorite, which are all spatially associated with the Boulder Creek Granodiorite, were also analyzed (table 12). Modes for these rocks are a part of table 7. Chemical analyses and modes indicate that these mafic rocks are composite and partly gradational into one another and even into granodiorite.

Twin Spruce Quartz Monzonite is a high-SiO_2, low-MgO rock, as indicated by 13 analyses from localities in the Nederland and Tungsten quadrangles (table 13). Average Twin Spruce Quartz Monzonite does not vary much from Nockolds' (1954) biotite adamellite or from his muscovite-biotite quartz monzonite. The Twin Spruce Quartz Monzonite has higher Fe_2O_3, due to oxidation, than Nockolds' average quartz monzonite. Amounts of K_2O in the Twin Spruce Quartz Monzonite are extremely variable between samples.

CHEMICAL TRENDS WITHIN THE BATHOLITH

Chemical trends occur from east to west across the southern part of the batholith as represented by samples from the Tungsten and Eldorado Springs quadrangles. However, in the northern part of the batholith, no east-west trend is indicated by the samples from the Gold Hill and Boulder quadrangles. Trends across the southern part of the batholith are defined by the percent of SiO_2 and (or) CaO in the rock in relation to most major oxides. In the northern part of the batholith the single east-to-west trend is replaced by two separate trends in which SiO_2 for both the border and interior of the batholith lie in exactly the same range. In general, the southern part of the batholith has more FeO, MgO, and K_2O and less CaO, P_2O_5, and possibly less Na_2O than the smaller northern part. Modal and chemical trends seem to indicate that there were two magmas involved in the batholith, the northern magma showing less differentiation from contact to central part of the batholith.

Chemical trends of CaO and SiO_2 to the major oxides in granodiorite from the Boulder Creek batholith are indicated in figures 19 and 20, and in general, as TiO_2, MgO, and FeO representing total iron increase, CaO increases, whereas K_2O and SiO_2 decrease as CaO increases. P_2O_5 and Na_2O show no direct relationship to CaO; no trend as such is indicated.

Chemical trends of calcic, sodic, and femic oxides relative to SiO_2 in the batholith (fig. 19) show con-

siderable scatter except for total iron, which has a nearly straight-line relationship to SiO_2, even within the satellitic plutons of granodiorite. Silica ranges from about 60–70 percent, and, as can be seen in figure 19, there is a distinct break in distribution of the oxides in the southern part of the batholith at about 64 weight-percent SiO_2, the greater part of the Eldorado Springs quadrangle samples (interior of the batholith) plotting between 60 and 65 percent SiO_2, and Tungsten samples (batholith border) plotting above 64 percent SiO_2. In the northern part of the batholith, Gold Hill and Boulder quadrangle samples each cover the entire range from 60 to 72 percent SiO_2. In the batholith, K_2O in relation to SiO_2 is steplike. Gold Hill quadrangle samples occupy mostly the 1–2.5 percent range of K_2O, Tungsten quadrangle samples occupy the 2.5–4.0 percent range, and Eldorado Springs quadrangle samples occupy the 3–4.5 percent range, but Boulder quadrangle samples cover nearly the entire range from 1.5 to nearly 5 percent. CaO and Na_2O in the northern part of the batholith represented by Boulder and Gold Hill quadrangle samples plot mostly above the Tungsten–Eldorado Springs samples from the southern part of the batholith, indicating greater CaO and Na_2O in the northern part of the batholith. CaO is the only oxide in which trends are readily defined in the two parts of the batholith and whereas the southern batholithic samples divide readily along the $CaO-SiO_2$ trend, those in the northern part of the batholith are separated by differences in amounts of SiO_2 rather than CaO.

Oxide distribution in relation to the percent of calcium present, especially between the northern and southern parts of the batholith, is expressed in figure 20. In the southern part of the batholith, analyses having greater than 4 percent CaO are represented predominantly by Tungsten quadrangle plots, and less than 4 percent CaO by Eldorado Springs quadrangle plots. In the northern part of the batholith no such zoning occurs; as the contact is approached, there is an increase in both sodium and calcium. Calcium apparently regulates a number of oxides, especially TiO_2 and MgO, and perhaps FeO, Al_2O_3, and fluorine, but virtually not Na_2O and P_2O_5 at all. Na_2O is relatively stable throughout the batholith and varies mostly between 3 and 4 percent of the total oxides. MgO in the southern part of the batholith follows a single trend, whereas in the northern part, represented by Boulder–Gold Hill quadrangle samples, it occurs in two separate trends, one representing the border area and the other the interior of the batholith. MgO trends are very distinct in comparison with trends for the other oxides in relation to CaO. Fluorine in the batholith is abnormally high for a granitic rock, but a relatively high fluorine content is characteristic of almost all granitic Precambrian Front Range rocks (Shawe, 1976, p. 25). Fluorine in at least the northern part of the batholith shows a regular distribution trend with calcium that indicates that calcium increases as fluorine increases. Lee and Van Loenen (1971, p. 21) noted also that with an increase in calcium, fluorine also increased in gneissic granitoid rocks in the southern Snake Range of Nevada. Unfortunately, in the southern part of the Boulder Creek batholith there are insufficient analyses to come to any conclusion.

In a ternary K_2O-Na_2O-CaO diagram (fig. 21), the trend (A) for the northern part of the batholith represented by the Boulder–Gold Hill quadrangle plots (non-shaded area) tends to increase in Na_2O as CaO increases, whereas in the Tungsten and Eldorado Springs quadrangles, the trend (B) shows a decrease in Na_2O as CaO increases. The Tungsten and Eldorado Springs plots from the southern part of the batholith are not only widely scattered but split at about 38 percent (on the basis of 100 percent) CaO and 32 percent for both K_2O and Na_2O. Tungsten quadrangle samples plot on the sodic side and those from the Eldorado Springs quadrangle on the potassic side of the diagram. The northern part of the batholith tends to be more calcic, the trend is well defined, and the scatter of points is small. The tendency of Na_2O to vary only between 25 and 35 percent on a K_2O-Na_2O-CaO ternary diagram is consistent with observations of many others. Bowen (1928, p. 100) was the first to note this close approach to a constant value for sodium in calc-alkaline rocks containing 55 to 75 percent SiO_2.

On a Q-Ab+An-Or (quartz-albite plus anorthite-orthoclase) diagram (fig. 22), samples from the Gold Hill quadrangle in the northern part of the batholith plot dominantly on the Ab+An side and to the left of the Tungsten and Eldorado Springs quadrangle samples from the southern part of the batholith. Samples from the Boulder quadrangle plot dominantly in the same field as those from the Tungsten and Eldorado Springs quadrangles. The trend of the granodiorite field is extended to the Ab+An corner by plotting the more mafic rocks associated with the granodiorite.

On a ternary variation diagram (fig. 23) the Tungsten and Eldorado Springs quadrangle samples fall closest to a line from the Na_2O-K_2O corner to the midpoint between the MgO, $FeO+Fe_2O_3+MnO$ side of the diagram, for a 1:1 ratio of total iron to magnesium. Differentiation trends for both the northern and southern parts of the batholith are indicated; however, the trend for the northern part plots closer to the $FeO+Fe_2O_3+MnO$ corner. Both trend lines flatten between 30 and 35 percent (based on 100 percent) $FeO+Fe_2O_3+MnO$ as MgO increases.

TABLE 10.—*Chemical and spectrographic analyses and modes for Boulder Creek Granodiorite, Front Range, Colo.*

[Rapid-rock chemical analyses for samples 106, 129, 132, 138, 140, 148, 150, 156, 162, 167, 394–402 by J. L. Harris and L. A. Bradley. Standard rock chemical analyses and spectrographic analyses for samples 4, 41, 44, 46–51, 192, 389 from Gable and Smith (1975). Standard rock chemical analyses and spectrographic analyses for samples 390–393 from Sims and Gable (1964, 1967). Sample 4 has a trace of rutile. N.d., not determined; (-) not found; Tr., trace; L, present but below limit of determination; <, less than; ores include all opaque minerals]

Sample No.	South half of Boulder Creek batholith											Satellitic plutons			
	4	41	44	46	47	48	49	50	51	192	389	390	391	392	393
	Chemical analyses[a], in weight percent														
SiO_2	66.40	62.25	61.3	74.5	62.99	63.5	64.9	61.8	67.9	61.2	60.8	54.29	54.41	64.37	64.09
Al_2O_3	15.88	16.88	15.8	12.9	17.05	16.7	16.8	16.8	15.7	16.9	17.1	13.53	17.12	15.86	14.03
Fe_2O_3	1.39	1.67	2.6	0.68	1.77	1.9	1.8	1.5	1.3	2.5	1.8	5.28	3.14	1.78	3.44
FeO	2.44	3.01	3.3	1.2	2.98	3.0	2.4	3.0	2.1	4.6	5.0	5.10	5.60	3.04	2.71
MgO	1.75	2.55	3.4	0.99	2.36	2.6	2.1	2.5	1.6	2.8	2.9	2.42	5.18	1.69	1.14
CaO	3.14	4.30	4.5	2.3	4.37	4.3	3.6	5.4	3.0	4.2	4.5	7.22	7.25	2.37	3.91
Na_2O	3.29	3.43	2.7	2.6	3.79	3.2	3.0	3.4	3.1	2.7	2.6	2.64	2.98	3.09	2.81
K_2O	3.72	3.84	3.9	3.6	2.95	3.0	3.6	3.1	3.7	2.7	2.7	2.40	1.40	5.00	4.18
H_2O^+	0.57	0.65	0.86	0.70	0.48	0.70	0.73	0.88	0.71	1.0	1.2	0.72	1.23	0.52	0.38
H_2O^-	0.04	0.07	0.24	0.04	0.02	0.03	0.05	0.06	0.07	0.15	0.08	0.22	0.07	0.08	0.16
TiO_2	0.51	0.59	0.64	0.28	0.63	0.62	0.49	0.75	0.46	0.93	0.95	2.37	0.85	0.72	1.31
P_2O_5	0.25	0.29	0.38	0.11	0.26	0.28	0.36	0.53	0.20	0.23	0.13	2.02	0.07	0.32	0.56
MnO	0.05	0.07	0.13	0.04	0.07	0.09	0.09	0.09	0.07	0.12	0.10	0.13	0.15	0.05	0.09
CO_2	0.01	0.14	0.11	0.10	0.06	0.05	<0.05	0.11	0.18	<0.05	<0.05	0.44	0.08	0.23	0.12
Cl	0.01	0.04	n.d.	n.d.	0.03	n.d.	n.d.	n.d.	n.d.	0.03	0.02	n.d.	0.07	0.03	0.05
F	0.16	0.15	n.d.	n.d.	0.13	n.d.	n.d.	n.d.	n.d.	0.14	0.16	0.43	0.07	0.12	0.59
S	n.d.	n.d.	n.d.	n.d.	n.d	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.36	0.10	0.14	0.03
BaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.17	0.06	0.23	0.24
Total	99.61	99.93	100.0	100.0	99.94	100.0	100.0	100.0	100.0	100.0	100.0	99.74	99.83	99.64	99.84
	Spectrographic analyses[a], in parts per million														
Ag	--	--	--	--	--	--	1	--	--	L	L	--	--	--	--
Ba	1,500	1,500	2,000	1,000	700	1,000	1,000	1,000	1,500	500	500	--	--	--	--
Be	3	2	3	3	2	3	3	3	3	--	--	--	--	--	--
Ce	150	L	500	--	L	300	--	300	--	--	--	--	--	--	--
Co	10	15	30	--	15	20	20	20	15	30	20	--	34	8	--
Cr	30	70	70	7	30	50	30	70	20	70	70	--	220	26	--
Cu	--	7	20	15	15	20	7	30	5	7	15	--	73	100	--
Ga	30	30	15	7	30	15	10	10	10	15	15	--	25	23	--
La	100	50	70	--	50	70	--	70	--	30	--	--	<100	140	--

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mo————	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nb————	10	L	7	3	L	3	3	3	3	7	5	—	—	—	—
Nd————	100	70	—	—	70	—	—	—	—	—	—	—	—	—	—
Ni————	20	30	70	<30	30	50	50	50	30	50	50	—	85	20	—
Pb————	30	15	7	10	15	7	7	7	7	7	7	—	<30	50	—
Sc————	10	15	3	3	15	10	7	10	3	20	20	—	28	13	—
Sr————	1,000	1,500	1,000	500	1,000	1,000	700	1,000	700	300	300	300	540	620	—
V————	100	70	100	30	70	70	70	70	50	100	100	100	260	80	—
Y————	30	30	70	10	15	30	30	50	10	30	30	30	30	50	—
Yb————	3	3	7	1	3	3	3	5	1	3	3	3	3	4	—
Zr————	300	150	30	5	70	10	15	30	20	150	300	300	130	700	—
Modes, in volume percent															
Potassium feldspar———	8.2	13.1	23.4	21.1	10.6	16.6	19.0	2.5	19.4	—	0.1	11.0	0.2	34.4	36.0
Plagioclase———	43.4	43.9	25.7	33.7	48.5	40.7	34.3	46.7	40.8	43.6	44.2	37.0	49.7	32.9	29.0
Quartz———	30.4	23.9	9.1	38.4	24.9	18.7	27.6	14.1	26.5	32.0	27.5	21.0	11.9	18.3	26.0
Biotite———	15.5	14.7	13.3	5.5	12.9	14.6	14.4	17.9	10.4	22.9	25.0	22.0	13.2	11.9	5.0
Hornblende———	—	1.4	23.3	—	0.7	7.8	0.2	14.1	—	—	—	—	23.3	—	—
Tremolite-actinolite———	—	—	—	—	—	—	—	Tr.	—	—	—	—	—	—	—
Ores———	0.8	0.9	0.9	0.1	0.6	0.6	0.7	0.4	0.4	1.4	2.0	8.0[b]	1.2	0.6	4.0[b]
Muscovite———	—	—	0.2	0.2	Tr.	—	0.3	—	0.5	0.1	0.3	[b]	Tr.	1.0	[b]
Sphene———	Tr.	0.4	0.6	0.1	0.9	0.1	0.6	1.1	0.9	—	—	[b]	—	—	[b]
Zircon———	0.1	Tr.	0.1	0.1	0.1	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	[b]	Tr.	0.2	[b]
Apatite———	0.7	0.5	0.9	Tr.	0.4	0.5	0.7	1.1	0.2	Tr.	0.7	Tr.	Tr.	0.4	Tr.
Allanite———	0.6	0.4	0.2	Tr.	Tr.	—	0.3	Tr.	0.5	—	—	Tr.	Tr.	Tr.	—
Kaolinite———	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Chlorite———	0.1	0.1	—	0.1	—	—	—	0.1	0.2	—	—	Tr.	Tr.	0.3	—
Calcite———	Tr.	0.2	0.2	0.2	0.2	—	0.5	0.4	—	—	0.1	—	0.5	—	—
Epidote-clinozoisite———	0.1	0.5	2.3	0.5	0.2	0.4	1.7	1.6	0.2	—	0.1	—	—	—	Tr.
Monzonite or xenotime———	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Prehnite———	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total———	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase———	An_{28}	An_{28}	An_{31}	An_{28}	An_{28}	An_{31}	An_{28}	An_{34}	An_{31}	An_{45}	**An_{42}**	n.d.	n.d.	An_{27}	n.d.

[b] Ores, muscovite, sphene, and zircon combined.

TABLE 10.—*Chemical and spectrographic analyses and modes for Boulder Creek Granodiorite, Front Range, Colo.*—Continued

North half of Boulder Creek batholith

Chemical analyses,[a] in weight percent

Sample No.	394	395	396	397	398	399	400	401	402	106	129	132	138	140	148	150	156	162	167
SiO_2	63.5	61.1	62.3	65.6	71.0	65.1	65.2	69.2	61.1	62.3	68.1	62.8	63.1	63.5	69.7	68.5	67.8	64.8	66.9
Al_2O_3	14.4	14.9	15.5	16.2	14.8	15.8	17.3	15.4	16.3	17.0	15.6	15.4	16.2	16.4	14.4	15.5	15.1	15.6	15.6
Fe_2O_3	3.7	4.2	3.5	1.7	1.0	1.8	1.5	1.6	3.5	1.8	2.0	2.1	1.8	1.0	0.74	1.6	1.3	1.6	1.5
FeO	2.6	3.4	2.2	3.2	1.0	1.8	1.7	1.3	3.8	2.0	2.3	2.8	2.7	3.0	1.9	1.7	2.1	2.6	2.1
MgO	1.5	1.0	1.1	1.6	0.72	1.5	1.3	1.2	2.4	1.5	0.84	3.0	2.2	2.4	1.5	1.0	1.8	2.0	1.9
CaO	4.6	6.3	4.4	4.4	3.2	5.7	5.9	4.1	6.2	5.8	3.3	4.9	5.4	5.1	3.2	2.8	3.7	4.6	3.9
Na_2O	3.1	3.2	3.2	3.0	3.1	3.5	4.0	3.2	3.0	3.8	3.0	3.4	3.8	3.7	3.0	3.3	3.3	3.7	3.8
K_2O	3.1	2.3	3.4	1.8	3.7	1.8	1.3	3.1	1.3	2.2	4.3	3.1	2.6	1.9	4.5	4.7	3.8	2.9	3.4
H_2O^+	0.48	0.68	0.94	1.0	0.40	0.76	0.78	0.50	1.2	0.60	0.38	1.1	0.65	0.74	0.79	0.55	0.83	0.84	0.92
H_2O^-	0.26	0.29	0.16	0.16	0.18	0.10	0.12	0.07	0.09	0.10	0.18	0.32	0.12	0.31	0.24	0.16	0.14	0.18	0.11
TiO_2	1.1	1.7	0.93	0.68	0.43	0.67	0.59	0.52	0.83	0.71	0.81	0.79	0.67	0.65	0.49	0.47	0.64	0.88	0.61
P_2O_5	0.82	1.1	0.74	0.44	0.52	0.63	0.78	0.43	0.68	0.66	0.46	0.70	0.54	0.50	0.44	0.42	0.49	0.55	0.50
MnO	0.08	0.08	0.06	0.05	0.04	0.06	0.04	0.05	0.08	0.06	0.06	0.08	0.06	0.05	0.02	0.02	0.04	0.05	0.05
CO_2	0.13	0.08	0.08	0.06	0.04	0.08	0.12	0.03	0.15	0.08	0.08	0.22	0.08	0.36	0.25	0.07	0.08	0.04	0.07
Cl	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.03	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.01
F	0.31	0.40	0.27	0.13	0.04	0.09	0.12	0.07	0.11	0.09	0.12	0.15	0.07	0.12	0.01	—	—	0.03	0.06
S	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
BaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.00	100.00	99.00	100.00	100.00	99.00	101.00	101.00	101.00	99.00	101.00	101.00	100.00	100.00	101.00	101.00	101.00	101.00	101.00

Spectrographic analyses,[a] in parts per million

Sample No.	394	395	396	397	398	399	400	401	402	106	129	132	138	140	148	150	156	162	167
Ag	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Ba	700	700	700	700	700	700	700	700	700	700	2,000	700	700	1,000	1,500	1,500	1,000	1,000	1,500
Be	2	2	2	n.d.	1	2	2	2	1	3	2	3	2	2	2	2	3	2	2
Ce	300	300	150	L	L	L	L	L	L	150	300	n.d.	L	L	L	L	L	L	L
Co	10	10	10	7	2	7	7	L	10	7	7	15	15	15	7	7	10	10	10
Cr	20	35	20	20	20	30	20	20	70	30	5	70	70	70	50	30	70	50	50
Cu	20	30	30	70	n.d.	20	300	n.d.	50	15	10	20	20	2	2	7	10	15	30
Ga	7	15	15	7	7	7	15	7	7	15	20	20	20	20	15	15	15	15	15
La	100	100	50	30	L	30	30	n.d.	L	50	150	L	50	70	50	70	50	70	50
Mo	1	1	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3	7	3	5	—	—	L	L	L

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Nb	15	7	5	3	n.d.	3	7	3	3	n.d.	15	10	L	L	L	L	10	L	L
Nd	100	150	100	L	n.d.	L	70	70	L	L	150	70	70	70	70	70	70	70	70
Ni	5	20	5	20	5	20	20	20	5	20	5	30	30	30	30	30	30	30	30
Pb	10	20	15	15	10	10	10	10	10	7	30	30	20	15	30	30	30	20	20
Sc	5	15	7	10	3	7	20	20	15	15	10	15	20	15	7	L	10	10	10
Sr	500	500	500	500	500	700	700	700	500	500	500	1,000	1,000	700	1,000	1,000	1,000	700	700
V	70	70	70	50	50	50	50	50	50	70	50	100	100	100	70	70	70	70	70
Y	30	30	30	20	10	15	15	50	15	15	20	15	20	15	10	10	15	15	10
Yb	7	3	3	2	2	3	2	5	2	2	2	2	2	2	1	L	2	2	2
Zr	500	<500	<500	200	50	200	200	200	150	150	100	70	100	70	70	150	70	100	100

Modes, in volume percent

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Potassium feldspar	22.1	7.0	22.7	—	21.0	8.0	6.3	2.0	21.0	0.5	25.9	4.9	6.4	0.1	14.0	27.0	16.2	7.9	21.2
Plagioclase	36.4	48.0	37.6	44.6	39.7	49.9	45.0	54.7	43.8	50.8	36.8	46.0	46.9	61.6	40.5	30.3	37.0	49.7	39.5
Quartz	23.0	24.0	22.8	31.0	25.1	19.3	17.6	21.3	25.7	18.8	23.2	21.3	25.4	31.0	33.4	31.7	23.8	20.5	21.0
Biotite	12.7	16.0	10.8	22.0	12.3	15.3	23.3	15.3	7.3	22.8	10.5	20.3	12.2	5.8	10.5	8.8	18.3	18.3	15.5
Hornblende	—	—	—	—	—	3.7	4.2	5.1	0.3	1.7	—	5.0	5.4	—	—	—	1.7	1.3	0.9
Tremolite-actinolite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Ores	2.7	3.0	2.2	2.0	0.6	0.5	0.9	0.5	Tr.	1.8	1.8	0.5	0.8	0.5	0.1	1.3	0.2	0.2	Tr.
Muscovite	0.4	—	0.5	—	—	0.1	—	—	—	0.5	0.6	—	—	—	0.3	—	Tr.	Tr.	—
Sphene	1.6	1.0	2.0	—	0.6	0.5	0.6	0.5	0.3	0.5	—	0.4	0.5	Tr.	0.4	0.1	0.6	0.7	0.7
Zircon	—	—	—	—	Tr.	Tr.	Tr.	Tr.	—	0.2	Tr.	Tr.	—	Tr.	0.3	—	Tr.	Tr.	Tr.
Apatite	1.0	1.0	0.5	0.4	0.3	0.1	1.8	0.3	0.2	1.2	0.3	0.4	0.9	0.1	0.1	0.7	0.6	0.3	0.5
Allanite	—	—	0.3	—	0.1	0.6	Tr.	Tr.	0.1	—	Tr.	0.1	0.1	Tr.	0.1	Tr.	Tr.	0.3	—
Kaolinite	—	—	—	—	—	0.6	—	—	—	0.2	—	—	—	—	—	—	—	—	—
Chlorite	—	—	0.5	—	—	—	—	—	—	—	—	Tr.	0.3	0.3	—	0.1	0.4	—	0.2
Calcite	0.1	—	—	—	Tr.	Tr.	—	—	0.1	0.5	—	—	0.1	0.6	—	—	0.1	—	—
Epidote-clinozoisite	—	—	0.1	Tr.	0.3	1.4	0.3	0.3	1.2	0.5	—	1.1	0.9	—	0.3	—	1.1	0.8	0.5
Xenotime or monazite	—	—	—	—	—	—	—	—	—	—	0.4	—	—	Tr.	—	—	—	—	—
Prehnite	—	—	—	—	—	—	—	—	0.1	Tr.	—	—	0.1	Tr.	—	—	—	—	—
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{35}	An_{32}	An_{28}	An_{32}	An_{25}	n.d.	An_{31}	n.d.	n.d.	An_{38}	n.d.	An_{28}	An_{30}	An_{29}	An_{27}	An_{28}	An_{31}	An_{26}	An_{28}

a Lab Nos. for unpublished analyses: 394, W182999; 395, W183000; 396, W183001; 397, W183002; 398, W183003; 399, W183004; 400, W183005; 106, W183006; 401, W183007; 402, W183008; 129, D173346W; 132, D173347W; 138, D173348W; 140, D173349W; 148, D173350W; 150, D173351W; 156, D173352W; 162, D173353W; 167, D173354W.

b Undifferentiated accessory minerals.

TABLE 11.—*Chemical and spectrographic analyses and modes for mafic inclusions and lamprophyre dikes in Boulder Creek Granodiorite, Front Range, Colo.*

[Rapid-rock chemical analyses by P. L. D. Elmore, Gillison Chloe, Hezekiah Smith, James Kelsey, J. L. Glenn, S. D. Botts, J. W. Budinsky; semiquantitative spectrographic analyses by J. L. Harris. N.d., not determined; (--), not found; Tr., trace; <, less than; ores include all opaque minerals]

	Mafic inclusions			Lamprophyre dikes	
Sample No.------------	334	385	386	387	388
Lab. No.-------------	W171193	W185231	W171834	W171832	W171833
SiO_2---------------	52.6	53.6	52.2	43.8	50.7
Al_2O_3-------------	16.6	15.6	19.0	12.5	13.3
Fe_2O_3-------------	4.7	2.9	2.6	2.7	3.0
FeO------------------	5.0	5.5	4.9	5.2	5.7
MgO------------------	3.0	4.4	5.0	8.4	7.9
CaO------------------	5.4	7.9	7.4	9.6	7.8
Na_2O--------------	3.3	3.1	3.9	1.5	1.7
K_2O---------------	3.7	2.6	2.4	5.9	6.6
H_2O^--------------	0.11	1.3	1.2	0.14	0.15
H_2O^+-------------	1.1	0.09	0.14	1.3	0.40
TiO_2--------------	2.7	0.64	0.82	1.7	1.3
P_2O_5-------------	1.1	0.71	0.23	1.2	1.2
MnO------------------	0.12	0.18	0.15	0.09	0.16
CO_2---------------	<0.05	0.02	<0.05	<0.05	<0.05
F--------------------	0.20	n.d.	0.19	0.62	0.59
Cl-------------------	0.03	n.d.	0.04	0.04	0.04
Total----------	99.00	99.00	100.00	99.00	100.00
Powder density-------	n.d.	n.d.	3.00	3.00	3.00
Semiquantitative spectrographic analyses, in parts per million					
Ba-------------------	2,000	1,120	500	1,000	1,000
Be-------------------	1	4	1	5	5
Ce-------------------	2,000	191	500	1,500	3,000
Co-------------------	20	31	30	30	30
Cr-------------------	70	153	150	200	200
Cu-------------------	20	123	200	20	30
Ga-------------------	20	36	15	10	10
La-------------------	500	80	70	500	1,000
Mo-------------------	5	--	10	5	5
Nb-------------------	20	--	100	15	15
Nd-------------------	500	--	--	1,000	1,500
Ni-------------------	30	102	100	300	200
Pb-------------------	--	--	7	--	--
Sc-------------------	10	46	20	15	15
Sm-------------------	--	14	--	100	100
Sr-------------------	1,000	660	1,000	2,000	2,000
V--------------------	150	136	150	150	150
Y--------------------	50	67	50	100	100

TABLE 11.—*Chemical and spectrographic analyses and modes for mafic inclusions and lamprophyre dikes in Boulder Creek Granodiorite, Front Range, Colo.*—Continued

	Mafic inclusions			Lamprophyre dikes	
Sample No.------------	334	385	386	387	388
Lab. No.-------------	W171193	W185231	W171834	W171832	W171833
Yb-------------------	5	9	5	10	10
Zr-------------------	1,000	734	150	700	500
Modes, in volume percent					
Potassium feldspar---	15.6	1.9	6.2	31.5	39.2
Plagioclase----------	42.7	46.7	53.0	0.2	0.6
Quartz---------------	15.5	7.7	3.0	--	0.2
Biotite--------------	19.0	14.8	12.8	19.6	14.5
Hornblende-----------	--	23.5	22.6	41.9	37.0
Pyroxene-------------	--	Tr.	--	0.2	--
Ores-----------------	3.0	--	0.2	--	0.9
Allanite-------------	0.3	--	Tr.	0.6	1.1
Apatite--------------	0.9	1.2	Tr.	2.8	2.4
Sphene---------------	2.6	0.5	0.7	3.2	3.9
Zircon---------------	--	--	Tr.	--	--
Calcite--------------	--	0.3	--	--	--
Chlorite-------------	0.2	1.3	0.1	--	--
Prehnite-------------	--	Tr.	--	--	--
Muscovite------------	0.2	--	--	--	--
Epidote-clinozoisite------	--	2.1	1.4	Tr.	0.2
Total----------	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase-------	An_{26}	An_{30}	An_{31}	n.d.	An_{43}

Whereas the major elements vary rather systematically with SiO_2 or CaO, this is not particularly true for the trace elements. Of 20 minor elements only chromium, nickel, and vanadium appear to vary directly with CaO or SiO_2 content. Chromium, nickel, and vanadium increase as CaO increases and all three decrease as SiO_2 increases.

MINERALOGY IN RELATION TO CHEMICAL TRENDS

Chemical trends in the granodiorite (fig. 20) are more definitely related to calcium than they are to silicon and are better defined than those related to silicon (fig. 19); therefore, weight percents of essential minerals were plotted against calcium (fig. 24) to determine related mineralogical trends. Modes are not available for chemically analyzed samples from the Eldorado Springs quadrangle, and accordingly these samples do not appear on any of the plots. All trends have widely scattered points except biotite in biotitic granodiorite and hornblende in biotite-hornblende granodiorite.

Trends for modal potassium feldspar and quartz are inversely related to CaO in the rock, and from figure 24, those trends for potassium feldspar are more consistent. Microcline accounts for the greater part of the potassium feldspar in the granodiorite, and, accordingly, trends approximate those of quartz; however, with an increase in the amount of biotite, the K_2O is used first to form biotite and less K_2O is left to form potassium feldspar, causing some scattering of plots. Modal biotite, hornblende, and plagioclase increase as CaO increases (although biotite uses no CaO), and their trends are opposite to those of quartz and microcline.

TABLE 12.—*Chemical and spectrographic analyses for gabbro, hornblende, pyroxenite, pyroxene-bearing hornblendite, hornblende diorite, biotitic hornblende diorite, Boulder Creek batholith area, Front Range, Colo.*

[Rapid-rock analyses by Joseph Budinsky, P. L. D. Elmore, Lowell Artis, J. L. Glenn, Gillison Chloe, Hezekiah Smith, and James Kelsey for sample 343, all other samples by Leung Mei. Spectrographic analysis for sample 343 by J. L. Harris; all other samples by H. W. Worthing. (--), not found]

	Gabbro	Hornblende pyroxenite		Pyroxene-bearing hornblendite		Hornblende diorite		Biotitic hornblende diorite
Sample No.-------	336	348	349	353	338	[a]351	343	352
Lab. No.---------	W179527	W179530	W179528	W179533	W179529	W179531	W173309	W179532

Chemical composition, in weight percent								
SiO_2------------	53.3	52.9	50.1	50.5	50.2	50.0	55.1	47.8
Al_2O_3------------	17.8	5.8	5.4	8.8	9.9	17.1	13.4	14.3
Fe_2O_3------------	1.4	2.0	4.8	2.9	2.9	2.8	3.8	3.6
FeO-------------	6.4	6.3	5.6	5.8	5.9	6.7	6.1	7.0
MgO-------------	7.8	17.0	17.3	13.4	13.1	7.5	7.7	9.7
CaO-------------	7.6	13.2	12.1	12.4	13.2	10.0	8.6	9.8
Na_2O------------	3.4	0.43	0.53	0.73	1.2	2.7	1.9	2.0
K_2O------------	0.68	0.16	0.20	1.6	0.79	0.56	1.1	2.5
H_2O^+------------	0.77	0.40	1.1	0.61	0.59	1.3	0.51	1.1
H_2O^-------------	0.07	0.02	0.02	0.09	0.01	0.08	0.10	0.16
TiO_2------------	0.49	0.31	0.35	0.84	0.82	0.95	0.55	1.1
P_2O_5------------	0.24	0.10	0.24	1.10	0.16	0.11	0.09	0.86
MnO-------------	0.11	0.17	0.21	0.21	0.16	0.15	0.24	0.18
CO_2------------	0.01	0.08	0.08	0.03	0.01	0.05	0.05	0.05
Cl-------------	0.04	0.02	0.02	0.03	0.01	0.04	0.03	0.09
F-------------	0.05	--	0.01	0.24	0.17	0.53	0.13	0.32
Total------	100.00	99.00	99.00	99.00	99.00	100.00	99.00	100.00

Semiquantitative spectrographic analyses, in parts per million								
Ba---------------	700	1,500	70	1,500	200	150	150	500
Be---------------	1	1	1	1	1	--	--	1
Ce---------------	70	--	70	200	100	--	--	325
Co---------------	30	70	70	30	50	60	50	40
Cr---------------	300	1,500	2,000	1,500	500	175	500	300
Cu---------------	70	200	200	20	50	100	10	7
Ga---------------	20	7	7	10	10	12	10	17
La---------------	--	--	--	200	50	--	30	125
Ni---------------	150	500	700	200	500	135	150	200
Pb---------------	5	5	5	5	5	5	5	5
Sc---------------	15	70	70	70	50	30	70	60
Sn---------------	--	7	10	7	--	--	--	--
Sr---------------	1,000	200	100	1,500	1,000	300	300	700
V---------------	100	150	150	100	150	200	150	150
Y---------------	15	15	20	50	30	25	30	60
Yb---------------	1.5	1.5	2	5	3	2	3	6
Zr---------------	50	50	50	200	100	40	150	125

[a]Average of two analyses.

TABLE 13.—*Chemical and spectrographic analyses and modes for Twin Spruce Quartz Monzonite, Front Range, Colo.*

[Wet chemical analyses for samples 1 and 2 by C. L. Parker; rapid-rock analyses for samples 3, 4, and 5 by P. L. D. Elmore, Lowell Artis, Gillison Chloe, J. L. Glenn, S. D. Botts, Hezekiah Smith, James Kelsey; spectrographic analyses for samples 1 and 2 by G. W. Sears, Jr., for samples 3-5, J. L. Harris, for samples 9-13, H. W. Worthing. N.d., not determined; <, less than; (--), not found; Tr., trace; L, present but below limit of determination; ores include all opaque minerals unless stated otherwise]

Sample No.	[a]232	[a]235	375	85	376	377	378	379	380	[a]381	[a]382	[a]383	[a,b]384
Lab. No.	D101719	D10172D	W170101	W171192	W171191	W173306	W173307	W173308	W177080	W177081	W177083	W177084	W177082
SiO_2	75.06	68.91	69.4	71.9	62.0	72.4	71.5	72.4	69.4	68.7	78.9	70.9	69.7
Al_2O_3	12.27	14.72	15.7	14.9	16.9	14.0	14.5	14.8	14.9	16.1	9.7	13.3	14.2
Fe_2O_3	1.34	1.62	0.89	0.42	3.2	0.34	0.62	0.93	2.0	2.6	1.8	1.8	2.4
FeO	1.71	1.96	0.92	1.2	2.7	1.9	1.8	0.88	1.3	1.1	2.5	3.3	2.1
MgO	0.67	0.84	0.38	0.38	1.6	0.45	0.53	0.38	0.54	0.24	1.1	1.0	0.5
CaO	0.93	1.6	1.5	1.4	3.2	0.92	1.9	1.7	1.7	2.4	1.3	1.1	1.5
Na_2O	2.85	2.57	3.4	2.3	3.0	3.0	3.8	3.7	2.7	4.4	1.7	2.3	2.5
K_2O	3.9	5.89	6.2	6.6	5.3	5.3	4.2	4.5	5.5	2.4	1.3	3.6	5.3
H_2O^+	0.34	0.51	0.48	0.39	0.51	0.69	0.41	--	0.8	0.66	0.84	1.1	0.78
H_2O^-	0.03	0.02	0.04	0.07	0.1	0.17	0.03	0.1	0.07	0.08	0.05	0.11	0.08
TiO_2	0.35	0.6	0.18	0.19	0.96	0.36	0.31	0.24	0.53	0.21	0.57	0.75	0.56
P_2O_5	0.04	0.26	0.09	0.06	0.34	0.07	0.09	0.05	0.33	0.03	0.09	0.04	0.12
MnO	0.05	0.04	0.04	0.04	0.09	0.07	0.06	0.05	0.05	0.09	0.03	0.12	0.09
CO_2	0.05	0.02	0.09	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cl	0.01	0.02	n.d.	0.001	0.02	0.011	0.006	0.004	<0.001	<0.001	0.012	0.010	0.010
F	0.06	0.12	n.d.	0.02	0.12	0.06	0.05	0.04	0.05	0.01	0.01	0.03	0.02
S	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.02	--	--	--	0.02
Subtotal	99.66	99.70	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	100.0	99.0	100.0
Less O	0.03	0.05	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.63	99.65	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	100.0	99.0	100.0
Powder density	2.69	2.70	[c]2.63	n.d.	n.d.	[c]2.56	[c]2.56	[c]2.56	n.d.	n.d.	n.d.	n.d.	n.d.

Spectrographic analyses, in parts per million													
Ba	1,500	1,500	2,000	2,000	2,000	700	700	700	1,500	1,000	300	1,500	2,000
Be	--	--	2	1	1	--	--	--	<1	1	<1	<1	<1
Ce	<150	700	500	500	1,000	500	200	500	500	100	100	150	200
Co	5	5	--	--	10	--	--	--	5	3	10	10	5
Cr	30	10	3	3	20	7	10	10	15	1	310	50	5
Cu	1	30	10	7	500	50	2	3	50	3	3	3	5
Ga	30	30	10	15	20	15	15	15	20	30	20	20	20
La	70	300	150	150	500	150	70	100	500	100	70	100	200
Mo	--	--	--	--	--	3	3	3	--	5	--	3	L
Nb	10	10	3	--	5	20	7	10	20	--	--	7	7
Nd	70	300	--	--	300	--	--	--	500	--	--	--	200
Ni	10	5	--	--	L	--	--	L	5	--	30	10	7
Pb	50	70	30	30	20	50	30	50	50	15	10	20	20
Pr	--	<100	--	--	--	--	--	--	50	--	--	--	--
Sc	10	5	3	3	10	10	7	5	10	5	10	15	7
Sr	300	500	300	3 000	1,000	200	200	200	300	300	100	200	500
V	30	70	10	20	70	30	30	20	70	10	100	70	30
Y	70	50	10	20	30	20	20	20	50	100	50	100	70
Yb	10	3	1	2	3	2	2	2	3	15	5	10	5
Zr	500	500	15	200	700	700	300	150	1,000	200	200	700	1,000

TABLE 13.—*Chemical and spectrographic analyses and modes for Twin Spruce Quartz Monzonite, Front Range, Colo.*—Continued

Sample No.	[a]232	[a]235	375	85	376	377	378	379	380	[a]381	[a]382	[a]383	[a,b]384
Lab. No.	D101719	D10172D	W170101	W171192	W171191	W173306	W173307	W173308	W177080	W177081	W177083	W177084	W177082
Modes, in volume percent													
Potassium feldspar	23.5	34.6	34.3	45.5	31.6	31.2	28.4	34.3	35.1	15.1	0.9	18.0	36.2
Plagioclase	18.5	27.5	31.5	21.2	39.3	29.1	33.4	33.9	31.4	51.8	23.4	28.3	27.4
Quartz	51.6	27.7	31.3	27.0	13.6	32.6	30.0	25.2	22.6	27.9	62.5	39.3	28.1
Biotite	3.3	6.0	0.5	3.6	10.3	4.4	6.4	2.9	8.4	3.2	12.0	11.1	5.3
Muscovite	2.2	1.9	0.1	1.5	0.6	2.0	0.8	2.9	0.8	--	--	0.3	1.2
Ores	0.8	1.2	0.5	0.4	2.4	0.7	0.8	0.4	1.2	1.5	1.0	0.8	1.7
Sillimanite	0.1	--	--	--	--	--	--	--	--	--	--	Tr.	--
Apatite	Tr.	0.4	0.1	Tr.	0.4	--	0.1	Tr.	0.1	Tr.	0.1	--	Tr.
Xenotime	Tr.	Tr.	--	--	--	--	--	--	Tr.	--	--	--	--
Monazite	--	--	--	--	Tr.	--	--	Tr.	--	--	Tr.	--	Tr.
Zircon	Tr.	0.2	Tr.	--	--	Tr.	0.1	Tr.	Tr.	Tr.	0.1	0.1	0.1
Chlorite	--	0.4	1.6	--	Tr.	--	--	0.4	0.3	--	--	--	([d])
Calcite	--	--	0.1	--	--	--	--	--	--	--	--	--	--
Allanite	--	0.1	Tr.	0.3	0.1	--	--	--	0.1	--	--	--	Tr.
Rutile	--	Tr.	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	--	--	0.1	1.6	--	--	--	--	--	--	--	--
Epidote	--	--	--	0.4	0.1	--	--	--	--	--	--	--	--
Garnet	--	--	--	--	--	--	--	--	--	0.5	--	2.1	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Composition of plagioclase	An_{14}	An_{24}	An_{18}	An_{22}	An_{19}	An_{23}	n.d.	n.d.	An_{28}	An_{19}	An_{28}	An_{24}	An_{22}

[a]Samples 232, 235, 381, 382, 383, 384 are from quartz monzonite in metasedimentary rocks.

[b]Ores in separate include molybdenum, pyrite, chalcopyrite, and magnetite.

[c]Bulk density.

[d]Biotite and chlorite undifferentiated.

The spread in points, however, is so great that systematic relationships are nearly impossible to define except for hornblende in biotite-hornblende granodiorite and biotite in biotite granodiorite (fig. 24).

Chemical differences between the granodioritic rocks in the northern and southern parts of the batholith, especially in calcium, potassium, and to a lesser degree sodium, are indicated by larger percentages of plagioclase, biotite, hornblende, and apatite in the northern part. In the chemical variation diagram (fig. 23) the ratio of iron to magnesium in the northern part of the batholith is expressed in a differentiation trend that distinctly differs from the differentiation trend for the southern part of the batholith. The presence of more biotite and hornblende and less potassium feldspar in the northern part of the batholith reflects this chemical difference as indicated by the following modes (in percent): for the southern part of the batholith, potassium feldspar, 20; plagioclase, 39; quartz, 26; biotite, 11; hornblende, 1.4; for the northern part of the batholith, potassium feldspar, 10; plagioclase, 44; quartz, 24; biotite, 15; hornblende, 2.9.

CHEMICAL TRENDS IN MAFIC INCLUSIONS

The mafic inclusions (table 11, nos. 334, 385, 386) are, according to their major oxides, allied to the hornblende diorite, but the inclusions have larger amounts of sodium and potassium and less calcium and magnesium than the hornblende diorite. The lamprophyre represented by samples 387 and 388 in table 11 is chemically distinct from the mafic inclusions in that it has low aluminum and high magnesium, calcium, and potassium.

The major chemical characteristics of inclusions are compared with the Boulder Creek Granodiorite and associated rocks in a Q-Ab+An-Or variation diagram (fig. 22). The analyzed inclusions plot with diorite in the Ab+An part of the diagram. On an AFM diagram (fig. 23) of the same rocks the inclusions plot farther
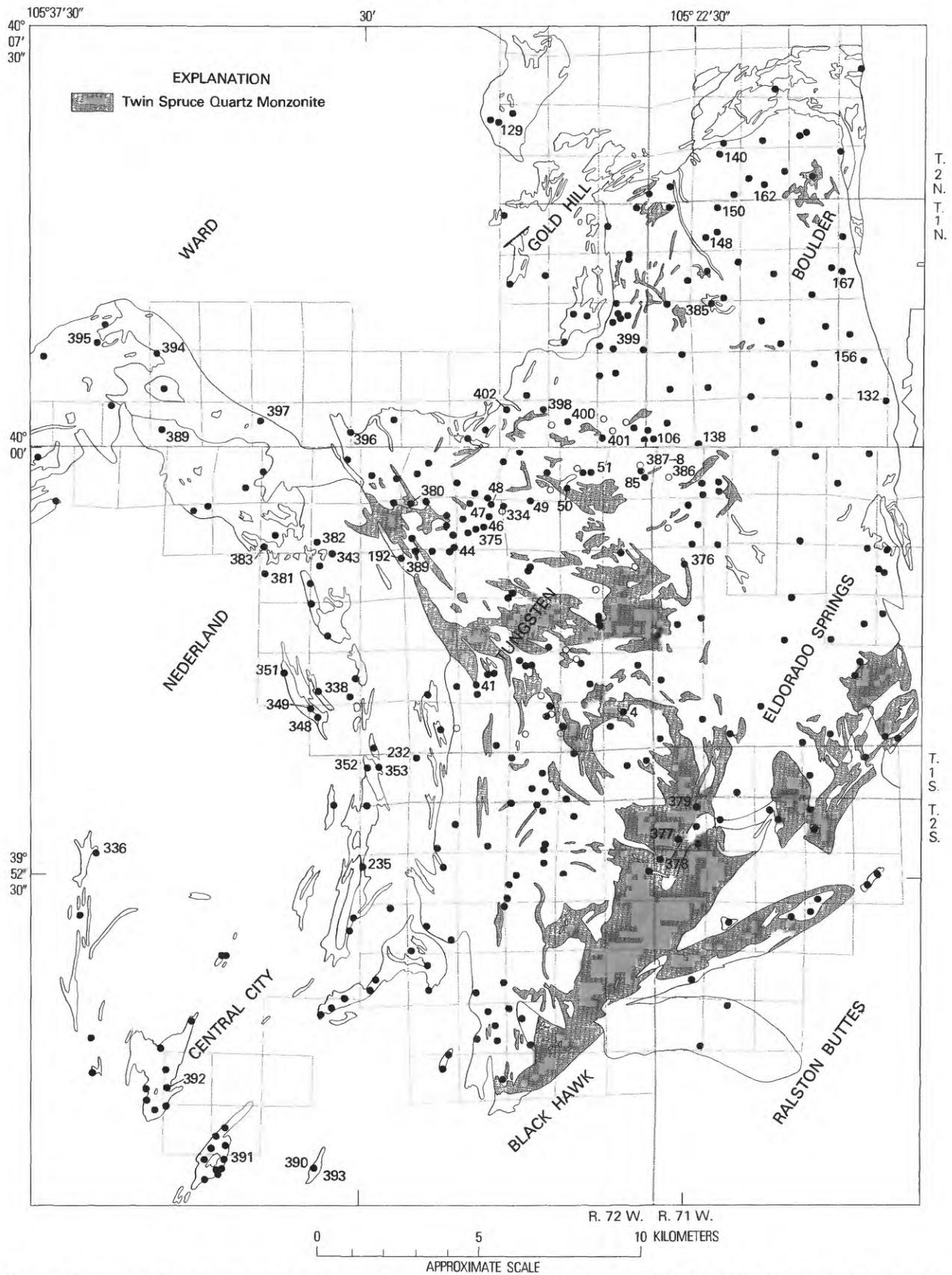
FIGURE 17.—Sample localities for rock and mineral analyses shown in tables in this report. Batholith covered by grid showing section, township, and range. Dots without numbers indicate samples for which modes have been made but which have no chemical data.
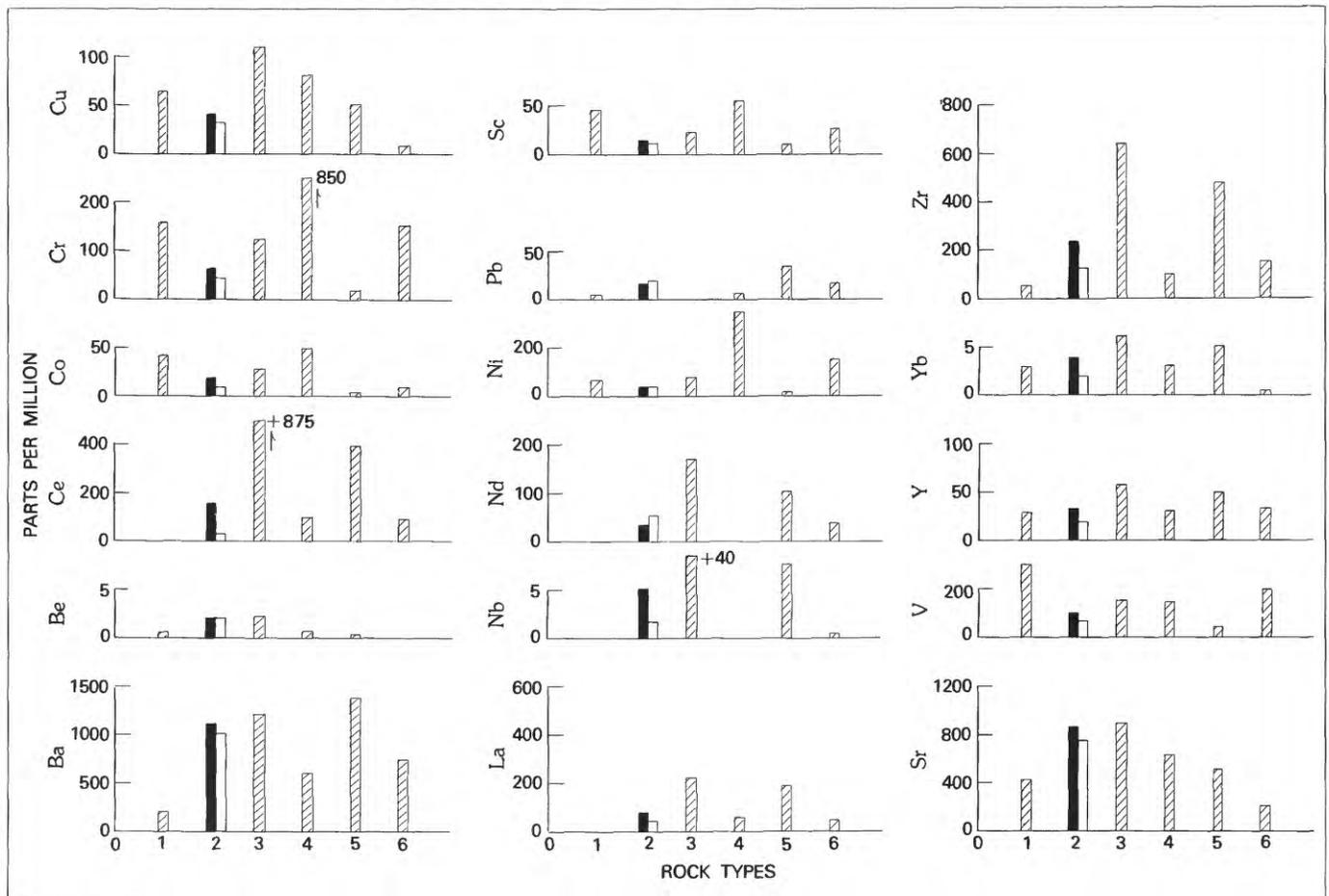
FIGURE 18.—Abundances of minor elements for 1, hornblende gneiss and amphibolite, average of 20 analyses; 2, Boulder Creek Granodiorite (white bar, northern part of batholith, average of 15 analyses; black bar, rest of batholith, average of 16 analyses); 3, inclusions in Boulder Creek Granodiorite, average of three analyses excluding the lamprophyres; 4, mafic rocks, average of eight analyses; 5, Twin Spruce Quartz Monzonite, average of 13 analyses; 6, biotite gneiss, average of 27 analyses. Number beside bar indicates length bar should have been.

from the M corner and closer to the F corner of the diagram than do other major rock types, indicating less MgO and more FeO than in the Boulder Creek Granodiorite or Twin Spruce Quartz Monzonite. Inclusions, however, plot closer to the quartz monzonite trend with one inclusion plotting on the quartz monzonite trend (see fig. 27).

The trace elements in the inclusions are more nearly allied to hornblende diorite and the Twin Spruce Quartz Monzonite (fig. 18) than to the Boulder Creek Granodiorite. The mafic inclusions are richer in cerium, copper, lanthanum, nickel, niobium, neodymium, and zirconium than are granodiorite rocks.

CHEMICAL TRENDS IN GABBRO, PYROXENITE, AND HORNBLENDE DIORITE

The composition of gabbro (sample 336, table 12) is similar to that of hornblende diorite (samples 351, 343) and probably reflects a common origin for the two.

Biotitic hornblende diorite (sample 352) is an altered hornblende diorite; potassium apparently was introduced at the time of alteration. Hornblende pyroxenite and the pyroxene-bearing hornblendite (sample 338, table 7; and samples 348, 349, and 353, table 12) are chemically similar and reflect degrees of alteration indicated by the amount of hornblende present.

Except for copper, cobalt, chromium, nickel, and scandium, the trace elements in gabbro, pyroxenite, and diorite are very similar to those in the Boulder Creek Granodiorite and differ greatly from the mafic inclusions in the granodiorite (fig. 18). Chromium and nickel are especially abundant in these mafic rocks while all are devoid of niobium and neodymium.

CHEMICAL AND MINERALOGICAL TRENDS IN THE TWIN SPRUCE QUARTZ MONZONITE

In the Twin Spruce Quartz Monzonite, MgO, FeO, SiO_2, and Na_2O generally increase as K_2O and Al_2O_3 decrease. Most oxide relationships are graphically

shown in: (1) a K_2O-Na_2O-CaO diagram where most quartz monzonite samples plot on the K_2O side of the Boulder Creek Granodiorite samples and Na_2O in quartz monzonite samples is more variable than in granodiorite samples (fig. 25); (2) a Q-Ab+An-Or diagram where quartz monzonite samples plot in the same quartz range as Boulder Creek Granodiorite samples (figs. 22, 26); and (3) an AFM diagram where as iron decreases MgO also decreases forming an orderly trend toward the Na_2O+K_2O corner of the diagram (fig. 27).

Chemical trends are difficult to define in the quartz monzonite because neither SiO_2 nor CaO appear to have controlled oxide distribution. In a ternary plot of K_2O-Na_2O-CaO (fig. 25), Na_2O was more important in the distribution of other oxides than it was in the Boulder Creek Granodiorite. The general trend indicates that as Na_2O increases, CaO also increases, and points are widely scattered on the K_2O side of the diagram and to the left of those for Boulder Creek Granodiorite.

In the Q-Ab+An-Or ternary diagram (fig. 26), Twin Spruce Quartz Monzonite points are scattered but do tend top cluster around 25–40 percent for normative quartz and are centered between the normative orthoclase and plagioclase fields. Normative values agree quite well with modal values (fig. 14) for the same areas. On the AFM diagram (fig. 27), all quartz monzonite samples plot close to a curved trend line that is parallel to that of the Boulder Creek Granodiorite in figure 23, especially the trend line of samples from the Boulder and Gold Hill quadrangles in the northern part of the batholith. The quartz monzonite samples, however, plot closer to the FeO+Fe_2O_3+MnO side, reflecting the low MgO content of quartz monzonite.

Plagioclase having an anorthite content averaging 21–22 percent is the only major mineral in quartz monzonite that plots in a trend that is characteristic of a differentiated intrusion. Plagioclase generally increases as CaO increases (fig. 28).

In Twin Spruce Quartz Monzonite, minor elements, especially barium, cerium, lanthanum, strontium, and zirconium, are surprisingly abundant. In addition, quartz monzonite lenses in schist and gneiss also appear to have high amounts of chromium, yttrium, and nickel (table 13). Analyses indicate that quartz monzonite is poorer in the trace elements beryllium, cobalt, chromium, and strontium than the Boulder Creek Granodiorite, but quartz monzonite is richer in barium, lanthanum, lead, and zirconium. Quartz monzonite and the mafic inclusions in granodiorite have similar amounts of trace elements (fig. 18), but quartz monzonite contains more copper, vanadium, and strontium, and, to a lesser extent, more chromium. Lead

does not occur in the mafic inclusions but does in quartz monzonite.

CHEMICAL EQUILIBRIUM IN THE BOULDER CREEK GRANODIORITE

On a gross scale the major minerals hornblende, biotite, potassium feldspar, and perhaps plagioclase are in imperfect chemical equilibrium with one another, as indicated by similar mineral compositions in samples throughout the batholith (see mineral descriptions in the section on "Mineralogy, petrology, and chemistry of minerals in the batholith"). On a microscale, however, inequilibrium apparently exists locally between most major minerals, because some plagioclase is normally zoned, myrmekite appears between plagioclase and potassium feldspar crystals, and hornblende has bleached contacts and is corroded and replaced by biotite and iron oxides. Where altered, biotite contains irregular crystals of allanite that commonly are rimmed by epidote; also, chlorite, sphene, and tiny red-brown blebs (probably hematite) occur along cleavage and grain boundaries. Hornblende, biotite, allanite, and plagioclase have been locally replaced by some epidote. Muscovite forms rims on magnetite, occurs in veins, or is associated with sericite in replacing plagioclase. Sparse muscovite occurs in hornblende-bearing granodiorite, even where sheared or foliated and considerably altered; under the same circumstances, biotite-bearing granodiorite may contain substantial muscovite. As suggested by Kretz (1959, p. 374), primary muscovite does not occur with hornblende; the only muscovite present occurs as an alteration mineral in biotite or plagioclase, and in quartz. In the recrystallized border zones of the batholith muscovite in non–hornblende-bearing granodiorite has cross-cutting characteristics of a primary mineral. Most indications of inequilibrium found between minerals, however, are believed to be related to retrograde and, locally, later hydrothermal metamorphism.

Gable and Smith (1975) determined manganese, iron, and magnesium contents of hornblende and biotite while making a study of hornblende coexisting with biotite in a part of the Boulder Creek batholith. The amount of iron in both biotite and hornblende was nearly identical in the batholith and mafic inclusion samples, as shown in table 14. Manganese in both minerals, expressed as Mn/Fe^{+2}+Mg+Mn+Ti, is in equilibrium as shown in figure 29. Magnesium in biotite and hornblende has a straight-line relationship to ferric iron; as magnesium increases, ferric iron decreases. Alkali feldspar from the same samples also
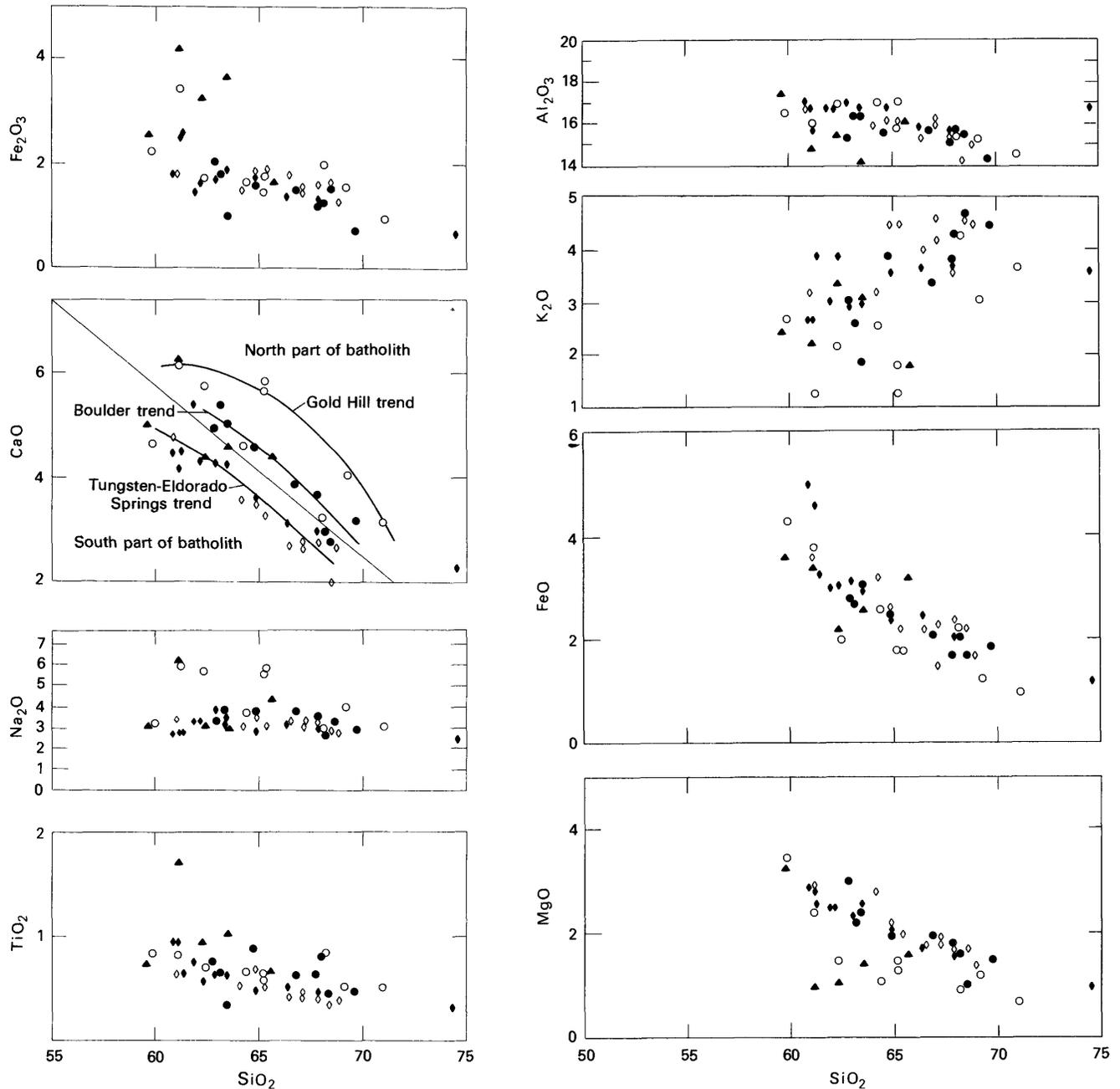
FIGURE 19 (above and right).—Variation diagrams of common oxides plotted against SiO_2 for Boulder Creek Granodiorite (in weight percent).

has a range in composition of Ab, An, and Or that is very similar (see table 22). Ab, An, and Or contents for alkali feldspar from the Twin Spruce Quartz Monzonite, on the other hand, are quite variable (see table 24). Judged by the limited data available (see tables 25 and 26), sphene and allanite do not vary noticeably in composition in the Boulder Creek Granodiorite but do vary between it and associated rock types. Plagioclase is the single mineral, according to our data, that changes in composition zonally across the batholith (fig. 6G) from oligoclase in the central part of the

batholith to andesine along its contacts with metasedimentary rocks to labradorite in plutons of granodiorite in the metasedimentary rocks west of the batholith.

ASSIMILATION AND DIFFERENTIATION IN THE BOULDER CREEK GRANODIORITE

Geochemical data, as presented, indicates that differentiation and not large-scale assimilation of country rock was responsible for producing the Boulder Creek
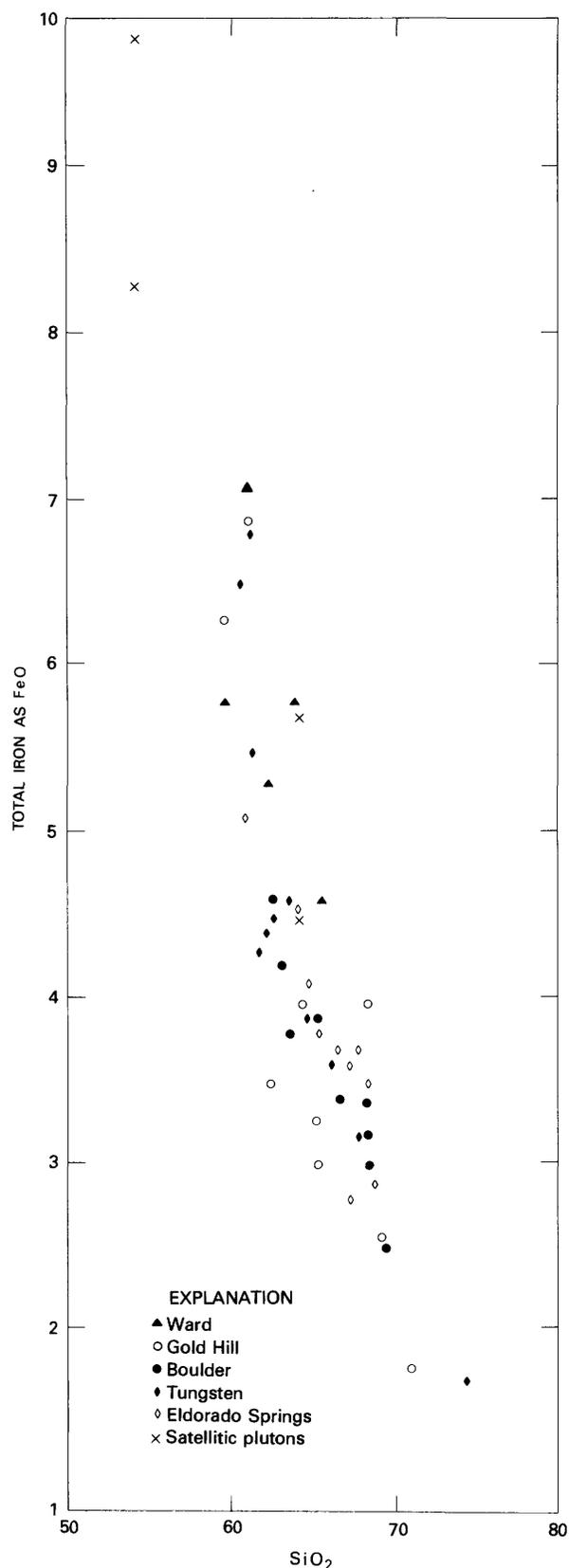
orderliness in the distribution of the major oxides within the batholithic rocks.

In an attempt to determine whether assimilation or contamination by country rock played a major role in the makeup of the batholith, samples of metasedimentary rock west of the batholith, and granodiorite at the contact, within the batholith, and across the batholith were collected and chemically analyzed. A summation of these data is given in table 15. The biotite-sillimanite gneiss and schist samples (col. 1, table 15), typical of the gneiss and schist west of the batholith, were taken at some distance from the batholith. The granodiorite samples listed in column 2 were taken from 100 to 1,000 m from the contact. Columns 3 and 4 are averaged analyses for granodiorite samples grouped into biotite-bearing and biotite-hornblende-bearing granodiorite from the central part of the batholith. Columns 5 through 7 are averaged granodiorite samples that are grouped to facilitate comparison of compositional variations within the batholith.

From the data in table 15 it would seem that the role assimilation played in the generation of Boulder Creek Granodiorite in the batholith is mainly confined to local border phases. Sillimanite-biotite gneiss, the country rock to the west of the batholith, is typically impoverished in both CaO and Na_2O with respect to rocks of the batholith. Both oxides occur in amounts of less than 1 percent in the gneiss and schist country rock and contrast sharply with amounts of these oxides in granodiorite from the contact and the batholith proper (table 15). Also, the contact zone of the batholith has less K_2O than the main part of the batholith or the average sillimanite-biotite gneiss country rock. Whereas both FeO and MgO are higher in the contact zone than in the rest of the batholith, only FeO is considerably higher in comparison with the rest of the batholith. In the satellitic plutons on the west (col. 7, table 15) FeO is high as in the contact zone, but MgO is low. A transfer of iron to the batholith from the contact rocks cannot be ruled out, but the data in figure 6 suggest that the high amounts of iron may be due in large part to an early, more mafic magma. Granodiorite from the contact zone along the west side of the batholith in the Tungsten quadrangle (col. 2, table 15) is quite different from averaged granodiorite samples from the Tungsten and Eldorado Springs quadrangles in the south-central part of the batholith (col. 5) and the Boulder quadrangle samples from the north-central part of the batholith (col. 6b).

This lack of large-scale assimilation may be explained if, as suggested by Vance (1961), crystallization of a granite pluton begins from the border against

Granodiorite. Despite variations within the granodiorite, apparent even within a single outcrop, definite chemical trends occur, indicating considerable
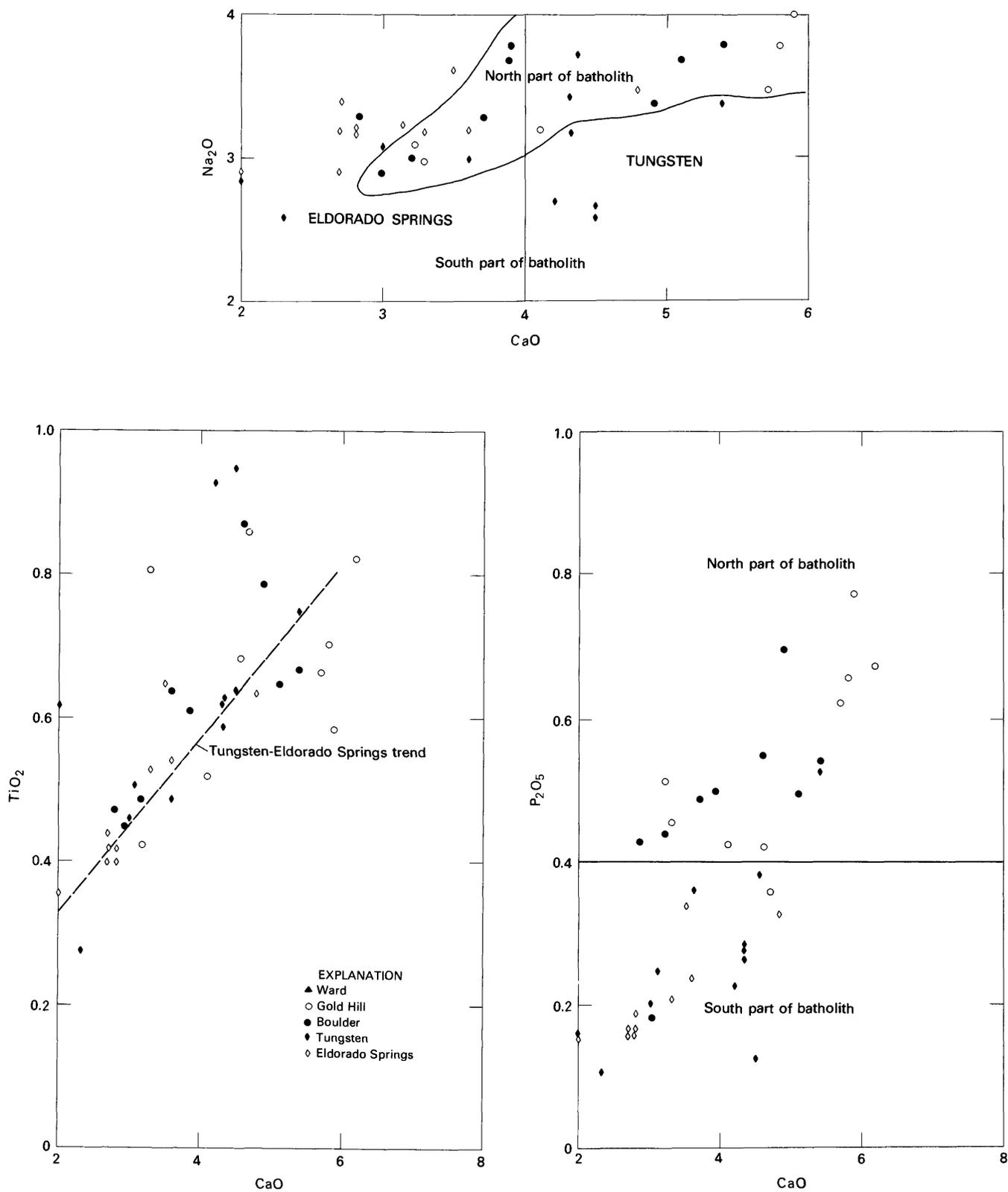
FIGURE 20.—Variation diagrams of CaO plotted against other oxides
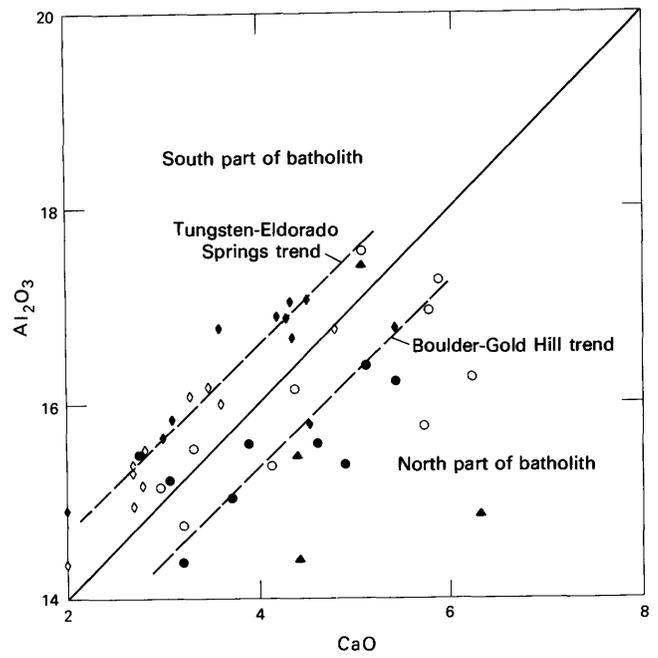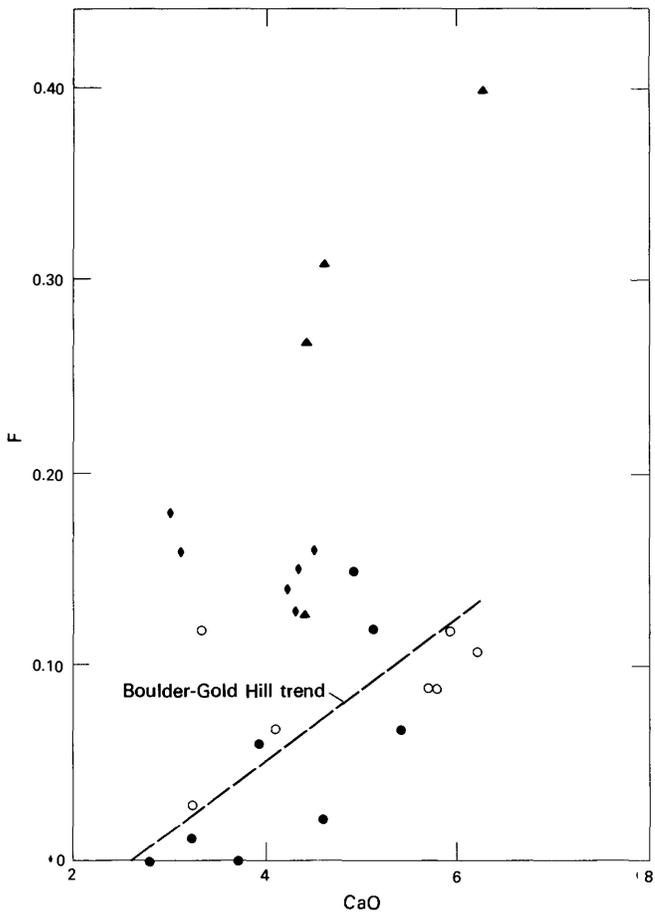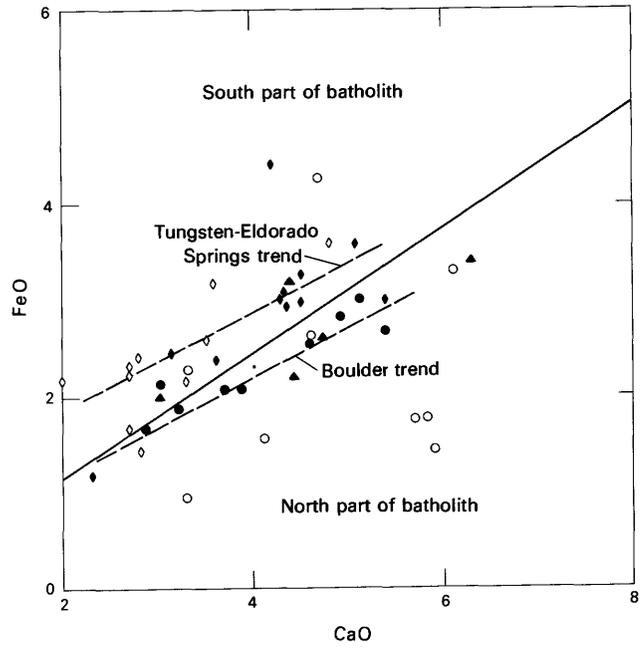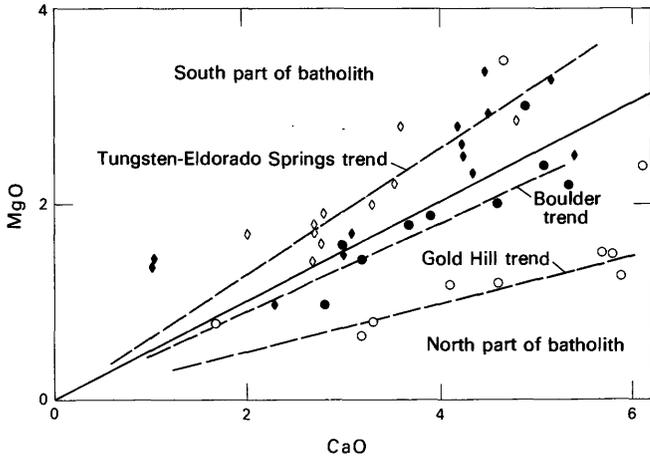
and fluorine for Boulder Creek Granodiorite (in weight percent).
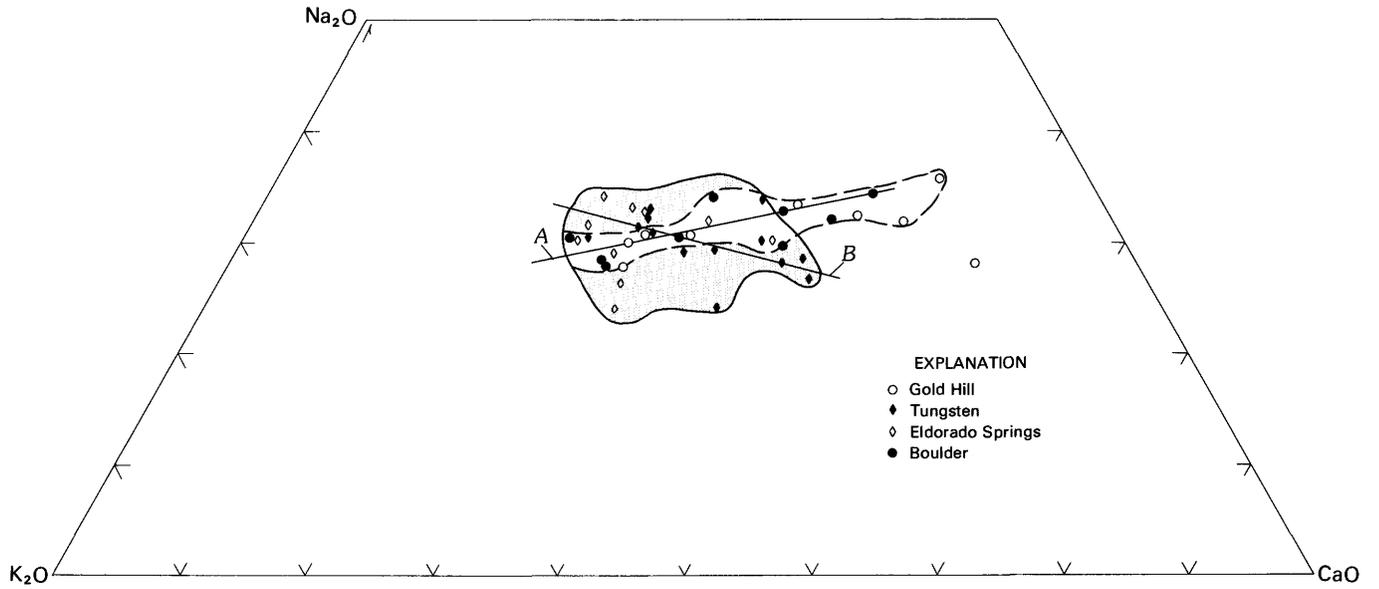
FIGURE 21.—Ternary diagrams of K_2O-Na_2O-CaO chemical variation of Boulder Creek Granodiorite (recalculated to 100 percent). Dashed outline enclosed total area covered by Boulder-Gold Hill area; shaded area represents total area analyses cover for Tungsten and Eldorado Springs; A, trend for Boulder-Gold Hill analyses. B, trend for Tungsten and Eldorado Springs analyses.
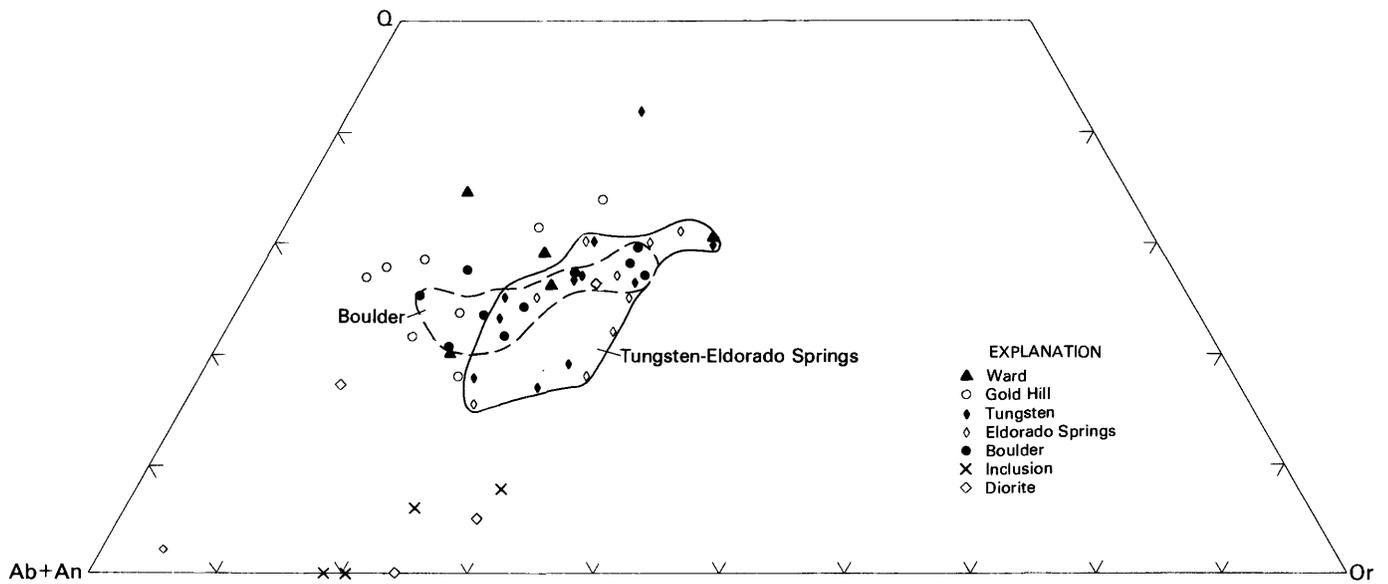
FIGURE 22.—Ternary diagrams of chemical variation of Boulder Creek Granodiorite expressed in terms of normative $Q-Ab+An-Or$ (recalculated to 100 percent).

cooler country rock that tends to seal in released volatiles. Accordingly, other elements will be sealed in and out preventing an interchange of elements be-

tween country rock and the batholith magma. In the Boulder Creek batholith, there may have been some movement of oxides into the country rock from the

batholith because migmatite and pegmatite are more prevalent near the batholith contact and appear to be related to the Boulder Creek Granodiorite, indicating that the magma, at least in its later stages, was probably saturated in H_2O that partly escaped into the country rock. Except for water, mobilization and recrystallization in the Boulder Creek Granodiorite along the contact may be only slightly related to chemical exchanges such as iron between the batholith and country rock. Assimilation of quartz from the quartzite unit (pl. 2) in the southeastern part of the batholith is possible and was likely caused by cataclasis and recrystallization due to proximity to the large Idaho Springs–Ralston shear zone. This assimilation of quartz by the granodiorite is related to retrograde metamorphism rather than to processes in the batholith itself.

Differentiation trends in figures 19, 20, 21, and 23 for the Boulder Creek Granodiorite, based on major-oxide chemistry, are typical for a calc-alkaline series and suggest that the analyzed rocks are comagmatic. Mineralogical data, especially for biotite and hornblende, in the section on "Mineralogy, petrology, and chemistry of minerals in the batholith," support this

assumption. Fractionation trends in the Boulder Creek Granodiorite, expressed by fractionation curves (Tuttle and Bowen, 1958) and phase relationships (Winkler and others, 1975) of crystallizing granitic and granodioritic melts in the system SiO_2-$NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-H_2O are analyzed below. Both fractionation trends and phase relationships are important in the interpretation of the origin of the Boulder Creek Granodiorite.

Comparisons of Boulder Creek Granodiorite with Tuttle and Bowen's (1958) fractionation curves that are based on a rock containing 80 percent or more Ab-Or-Q (albite-orthoclase-quartz) are risky, especially because Boulder Creek samples have a fairly large An content and Ab-Or-Q totals less than 80 percent. However, representative Boulder Creek samples from the interior of the batholith concentrate in Bowen's (1937) thermal valley in the area represented by the lower phase boundary (fig. 30A). Here the two feldspars, plagioclase and potassium feldspar, are dominant, but because of the high• An content in plagioclase, plots occur predominantly in the plagioclase field rather than in the orthoclase field of granite. Analyzed samples from the Ward quadrangle and from the contact areas of the Tungsten, Boulder,
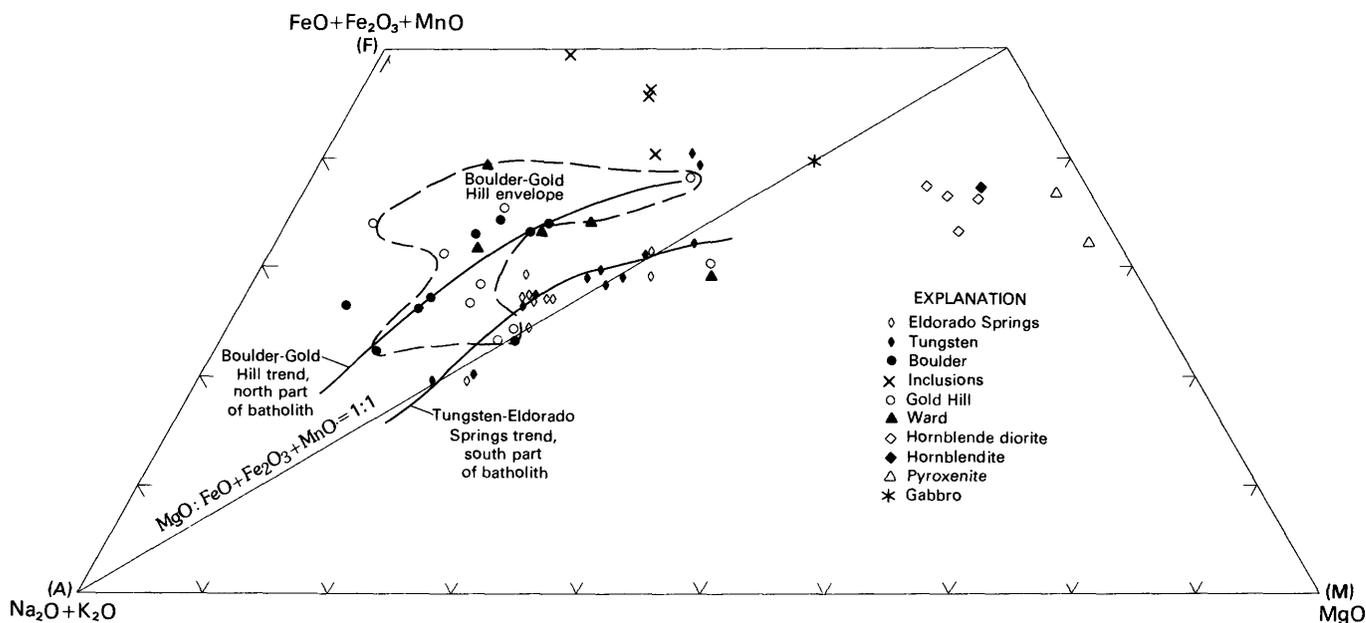
FIGURE 23.—Mole precent variation in an AFM diagram for Boulder Creek Granodiorite and the more mafic rocks associated with the granodiorite.
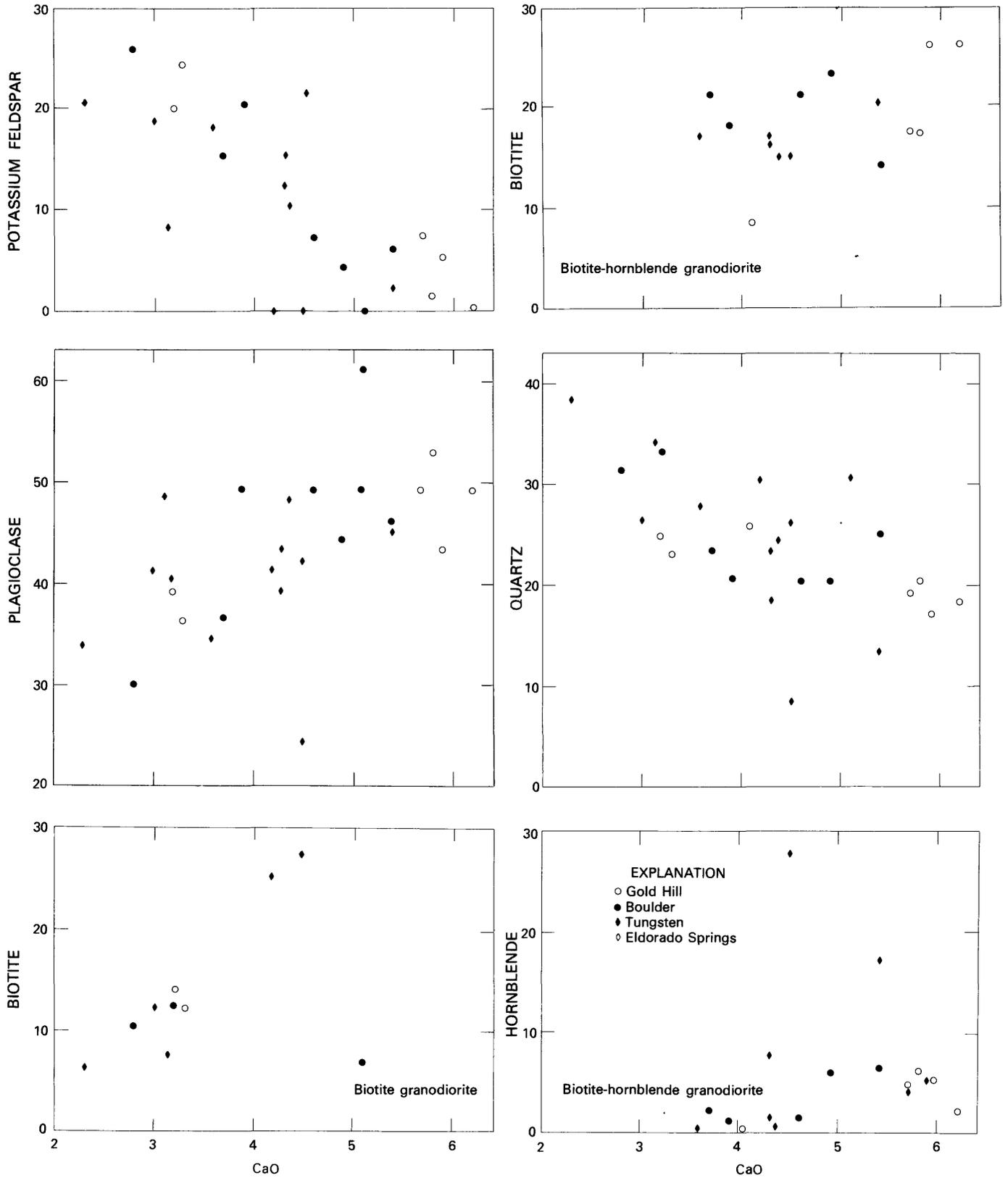
FIGURE 24.—CaO content (in weight percent) plotted against weight percent of rock-forming minerals (weight percent calculated from modal percent) in the Boulder Creek Granodiorite.
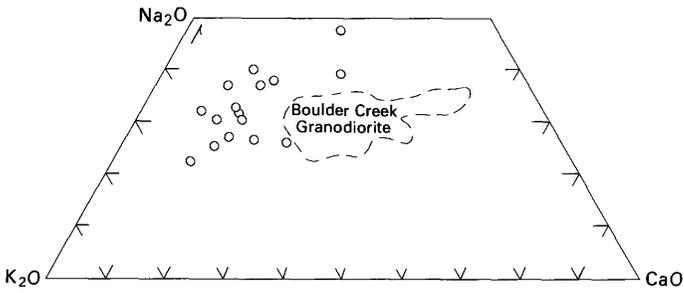
FIGURE 25.—Ternary plot of the oxides K₂O-Na₂O-CaO showing chemical variation for Twin Spruce Quartz Monzonite (open circle). Dashed outline encloses field occupied by Boulder Creek Granodiorite samples.

and Gold Hill quadrangles, from within the batholith, do not fall in the thermal valley, but most do define differentiation trends (figs. 19 and 20). That the older contact samples fall on the Ab side, or plagioclase side, of figure 30*A*, and outside the thermal valley, is to be expected in samples that contain less K₂O than CaO. Contact rocks (table 14) are in this category, and, as indicated by Chayes (1952, p. 243), "crystallization of a liquid whose initial composition lies in the diagram [Tuttle and Bowen's equilibrium diagram] generates a liquid residue which approaches and finally enters the thermal valley; and unless heat is added, the liquid cannot escape the valley, once it has entered. The composition of adequate samples of such a crystallizing mass would necessarily fall either in the valley or outside it on the side nearest the initial composition."
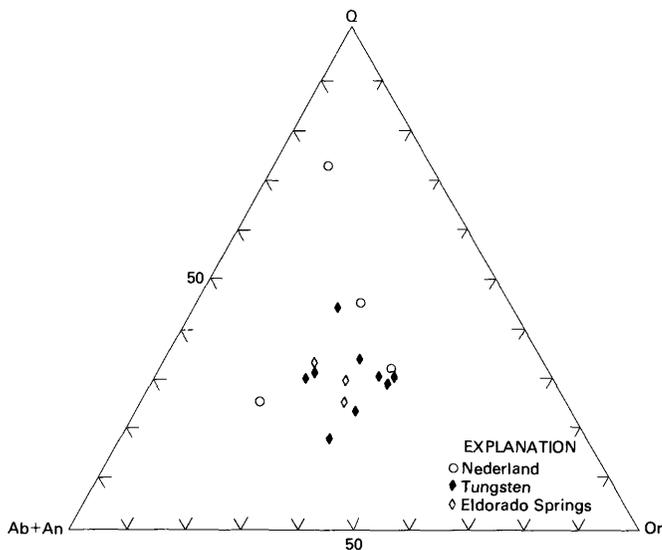
FIGURE 26.—Ternary plot of normative Q-Ab+An-Or showing chemical variation for Twin Spruce Quartz Monzonite (recalculated to 100 percent).
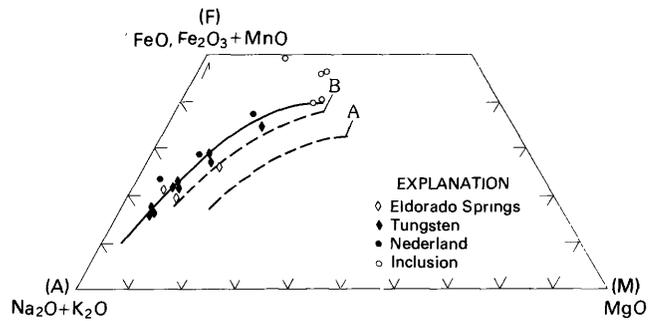
FIGURE 27.—AFM diagram showing molar variation for Twin Spruce Quartz Monzonite (in weight percent). Dashed lines are trends for Boulder Creek Granodiorite from figure 23; trend *A* represents the southern part of the batholith, trend *B* represents the northern part of the batholith.

New research on low-temperature granitic melts has been carried out in the system SiO₂-NaAlSi₃O₈-KAlSi₃O₈-CaAl₂Si₂O₈-H₂O (Winkler and others, 1975; Winkler, 1976). Winkler, Boese, and Marcopoulos
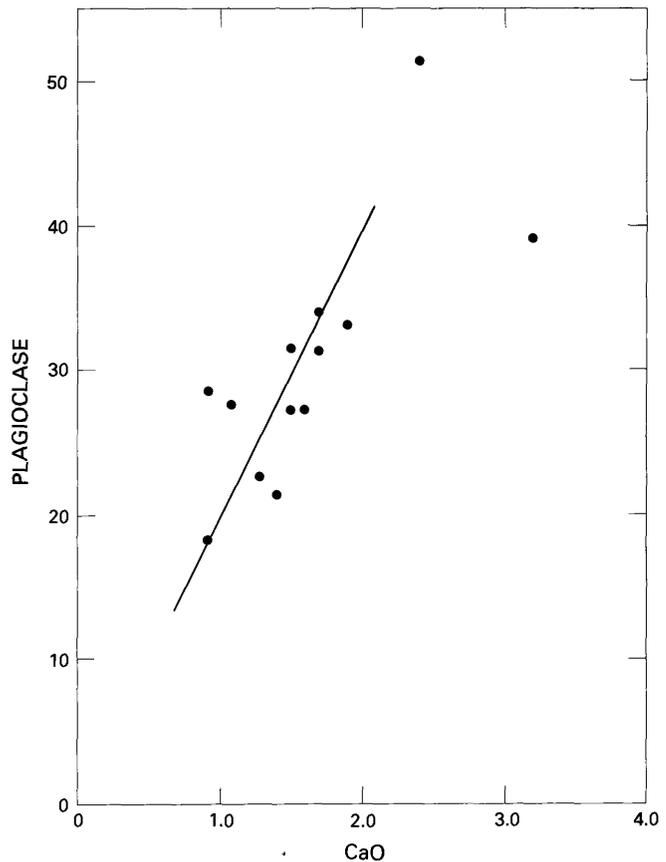
FIGURE 28.—Sample variation of plagioclase (calculated in weight percent from the mode) in relation to CaO (weight percent) in Twin Spruce Quartz Monzonite. Straight line is statistical trend of data.

TABLE 14.—*Total iron expressed as FeO (in percent) in biotite and hornblende, Boulder Creek batholith area, Front Range, Colo.*

Sample No.-----	Boulder Creek Granodiorite			Mafic inclusions		Hornblende diorite
	41	48	50	385	386	352
Hornblende-----	17.3	17.0	17.1	17.0	16.8	14.6
Biotite--------	17.0	17.1	17.2	17.6	16.8	15.7

(1975) have done considerable research on phase relations in the system Q-Ab-Or-An-H$_2$O, especially on low-temperature granitic melts, and they believe from their data that two fundamentally different processes of granitic magma generation—magmatic or anatectic—can be recognized, although Winkler (1976) now believes all granitic-granodiorite rocks were derived by anatexis. Tuttle and Bowen's research (1958) ignored the An content of feldspar. Winkler, Boese, and Marcopoulos (1975), took into consideration the An con-

tent of the feldspar, and, by making certain assumptions, presented a Q-Ab-Or diagram (fig. 30*B*) in which the An content in weight percent is shown as a radial projection onto the Q-Ab-Or surface.
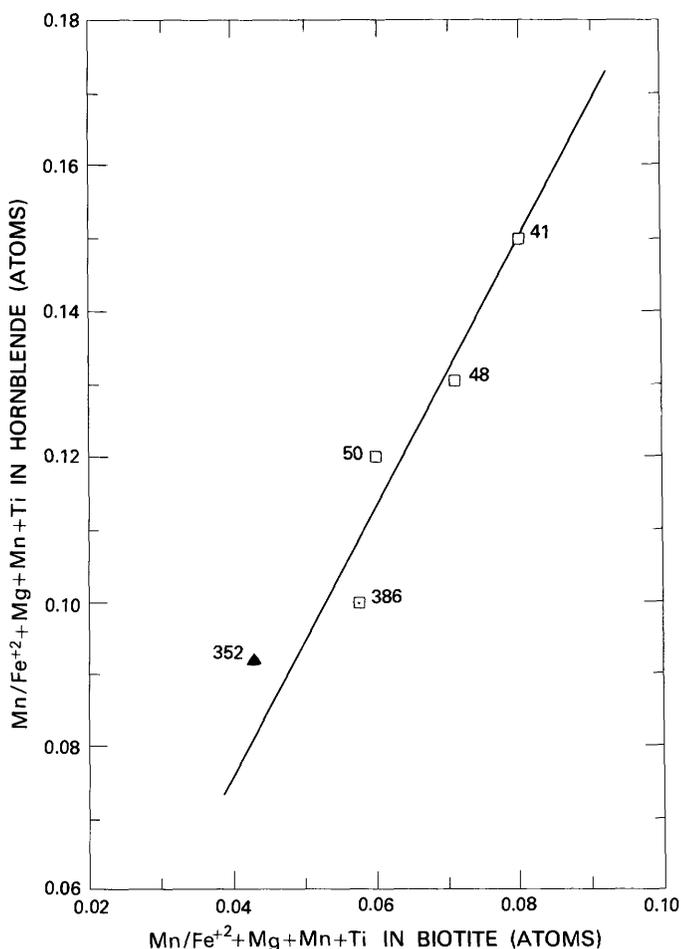
Nine samples of Boulder Creek Granodiorite, where data are complete, have been plotted on the 500 MPa (mega pascals) phase diagram presented by Winkler, (1976) (fig. 30*B*). In application of the system to natural rocks, Winkler, Boese, and Marcopoulos (1975), and Winkler (1976) ignored the potassium in biotite and the calcium in hornblende because, according to their experiments, it did not affect the overall conclusions concerning the crystallization or melting history of plagioclase, alkali feldspar, or quartz. The data, as plotted in figure 30*B*, are from modes, An was determined on plagioclase in thin section, and the alkali-feldspar minerals were chemically analyzed. Normative data derived from whole-rock chemical analyses indicate that plagioclase seldom contains more than a small amount of potassium so that points as plotted would only shift slightly to the Or side of the diagram, and the An content would decrease only slightly. In applying the 500 MPa water pressure Q-Ab-Or diagram to Boulder Creek rocks it must be remembered that Winkler (1976) found that the compositions determined at 500 MPa water pressure were also a good approximation of conditions at somewhat lower (300–400 MPa) and higher (700 MPa) pressures. Temperatures at 300–400 MPa pressure were about 5°–10°C higher and the An composition was 1 or 2 percent lower; the opposite was true at 700 MPa pressure. Boulder Creek Granodiorite plots in the plagioclase-quartz field of the Q-Ab-Or diagram (fig. 30*B*) and pierces the cotectic surface quartz+plagioclase+liquid+vapor with a somewhat higher An content than that shown on the isotherms. For larger departures from the cotectic plane, as in Boulder Creek rocks, there is a marked increase in temperature. Most Boulder Creek plots lie between 660° and 685°C (as projected onto the isotherms) where the An on the isotherms is between 4 and 6 percent. However, as all but one Boulder Creek sample has more than 10 percent An above the An indicated on the nearest isotherm, nearly all crystallized at higher temperatures than the 660°–685°C indicated. From the experiments of Winkler, Boese, and Marcopoulos (1975, fig. 11, p. 264) the temperature for crystallization of Boulder Creek plagioclase appears to be in the range of or above 750°C at 500 MPa water pressure. This temperature suggests that plagioclase in the Boulder Creek batholith is of magmatic origin and it tends to support the data in figure 30*A* wherein most samples lie in Bowen's thermal valley. From figure 30*B*, the stages of crystallization for plagioclase, alkali feldspar, and quartz appear to be:

FIGURE 29.—Distribution of manganese in biotite and hornblende in Boulder Creek Granodiorite and hornblende diorite. Square, Boulder Creek Granodiorite; solid triangle, hornblende diorite from Gable and Smith (1975, table 9); square with dot, mafic inclusion (this report); straight line is statistical trend of data (table 14).

TABLE 15.—*Comparison of sillimanite-biotite gneiss and schist country rocks with averaged compositions of Boulder Creek Granodiorite, Front Range, Colo.*

Column	1	2	3	4	Batholith				7
					South		North		
					5		6		
					(a)	(b)	(a)	(b)	
Oxides	Sillimanite-biotite gneiss and schist	Contact biotite granodiorite	Average biotite granodiorite	Average biotite-hornblende granodiorite	Tungsten quadrangle granodiorite	Eldorado Springs quadrangle granodiorite	Gold Hill quadrangle granodiorite	Boulder quadrangle granodiorite	Satellitic plutons granodiorite
SiO_2	61.0	61.6	67.2	64.1	63.8	66.2	66.0	65.8	60.6
Al_2O_3	19.2	16.7	15.5	16.2	16.4	15.6	16.0	15.4	15.1
Fe_2O_3	2.1	2.2	1.4	1.9	1.7	1.6	1.9	1.5	3.6
FeO	6.5	4.1	2.5	2.5	2.8	2.5	2.0	2.4	3.5
MgO	2.8	2.6	1.6	2.1	2.5	2.0	1.4	1.9	2.0
CaO	0.7	5.0	3.5	4.8	4.2	3.1	4.8	4.2	5.2
Na_2O	0.8	3.0	3.0	3.4	3.2	3.2	3.3	3.4	3.0
K_2O	4.1	2.1	3.6	2.9	3.4	4.1	2.5	3.4	3.1
MnO	0.1	0.1	Tr.	0.1	0.1	0.1	0.1	0.1	0.1
H_2O^+	1.1	1.1	0.7	0.8	0.7	0.9	0.7	0.8	0.7
TiO_2	1.0	1.0	0.6	0.7	0.6	0.5	0.7	0.6	1.3
P_2O_5	0.1	0.4	0.3	0.5	0.3	0.2	0.6	0.5	0.8
Total	99.5	99.9	99.9	100.0	99.7	100.0	100.5	100.6	98.7
Averaged analyses	10	4	10	16	10	10	7	8	7

first, plagioclase, then plagioclase+quartz, and then plagioclase+quartz+alkali feldspar; this is essentially the paragenetic sequence observed in thin section.

Fractionation trends based on strontium and rubidium in granodiorite rocks are inconclusive. Fractionation as indicated by a decrease in strontium values as normative Or/Ab increases does not exist in the Boulder Creek Granodiorite (table 16, fig. 31), but because strontium is much more mobile than the major mineral-forming elements, this reversal of trend could be expected. Rubidium trends are normal; as normative Or/Ab increases so does rubidium, but this increase could also have occurred during alkali exchange in which rubidium accompanied potassium in the feldspar.
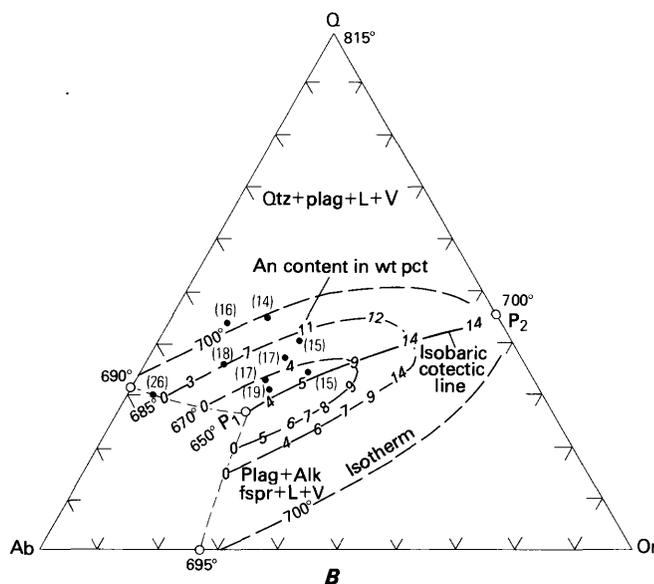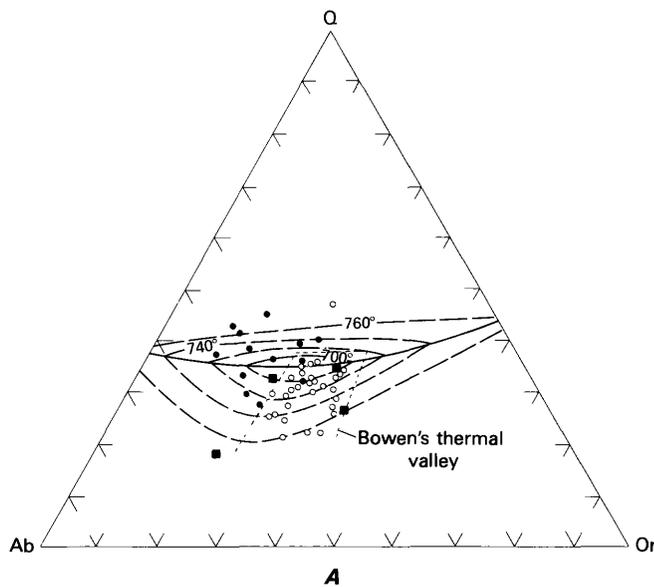
ORIGIN OF THE BOULDER CREEK GRANODIORITE AND THE TWIN SPRUCE QUARTZ MONZONITE

Data from the Boulder Creek Granodiorite are consistent with the theory of a calc-alkaline magma derivation from the mantle or lower crust, as suggested by modeling and experimental studies of Cawthorn and Brown (1976) and Green and Ringwood (1968) for the genesis of calc-alkaline magmas. The Twin Spruce Quartz Monzonite probably is of crustal origin, but the magma was greatly contaminated either by a deep-seated source or by country rock, as suggested by the lack of differentiation trends. The mafic inclusions in the Boulder Creek Granodiorite could perhaps have been refractory material that remained after partial fusion of mantle or lower crust and that was reconstituted as it was carried upward as part of the magma, as suggested by Presnall and Bateman (1973, p. 3197) in the Sierra Nevada batholith. Trace elements in the Twin Spruce Quartz Monzonite and in the inclusion are similar. Data suggest that the refractory material was injected into the Boulder Creek Granodiorite during the mush stage and before the batholith was completely crystallized.

Evidence supporting the above conclusions, especially for the Boulder Creek Granodiorite, is as follows:

1. Analyses from the major part of the batholith (in the Boulder, Eldorado Springs, and Tungsten quadrangles) plot in Bowen's (1937) low-temperature thermal valley for granites, suggesting fractional crystallization in a system

FIGURE 30.—Phase relations for Boulder Creek Granodiorite in the system SiO_2-$NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-H_2O, where modes and chemical and optical data are available. A, Ternary diagram of normative Q, Ab, and Or in Boulder Creek Granodiorite from the Boulder Creek batholith and adjacent plutons. Dotted area, position of thermal valley (Bowen, 1937, Chayes, 1952); dashed lines represent isotherms, in °C, on liquidus in the system albite-orthoclase-quartz at P_{H_2O}=2,000 kg/cm² (Tuttle and Bowen, 1958, p. 55). Open circle, analyzed samples from main part of the batholith; solid dot, analyzed samples from the batholith contact; solid square, analyzed samples from plutons in metasedimentary rocks. B, Isobaric system, Q-Ab-Or-An-H_2O with excess H_2O-rich vapor at P_{H_2O}=5 Kb (500 MPa or megapascals) for low-temperature granitic melts from Winkler (1976). Projection of cotectic line P_1-P_2 and isotherms, in °C, (showing weight percent An where it pierces isotherms), on cotectic surfaces: quartz+plagioclase+liquid+vapor, plagioclase+alkali feldspar+liquid+vapor. Figures in parentheses adjacent to solid dot, calculated weight percent An (this report). Open circle, location of experimentally determined temperature.

TABLE 16.—*Rubidium, strontium, and potassium analyses (in ppm) of Boulder Creek Granodiorite samples, Front Range, Colo.*

[Rb analyses by flame emission spectrography; Sr analyses by atomic-absorption spectrography. Analysts: L. P. Greenland, Roosevelt Moore, and M. M. Schnepfe; K values from table 10]

Sample No.	[a]129	132	138	140	148	150	156	162	167
Lab. No.	D173346W	D173347W	D173348W	D173349W	D173350W	D173351W	D173352W	D173353W	D173354W
Rb	170	120	74	95	120	150	120	92	98
Sr	300	580	710	670	690	630	620	510	550
K	31,000	22,000	18,000	13,000	32,000	33,000	27,000	21,000	24,000
K/Rb	182	183	243	137	267	220	225	228	245
Rb/Sr	0.57	0.20	0.10	0.14	0.17	0.24	0.19	0.18	0.18

[a]From pluton in metasedimentary rocks northwest of batholith.

similar to that used by Tuttle and Bowen (1958), $Na_2AlSi_3O_3$-$KAlSi_3O_8$-SiO_2-H_2O (fig. 30A). In the experimental ternary phase diagram of Winkler (1976) and Winkler, Boese, and Marcopoulos (1975) (fig. 30B) $CaAl_2Si_2O_8$ is also considered in the system, and the sequence in the crystallization history of plagioclase in the Boulder Creek Granodiorite appears to have begun with high temperatures, thus further substantiating fractional crystallization.

2. In their model for the formation of corundum-normative calc-alkaline magmas, Cawthorn and
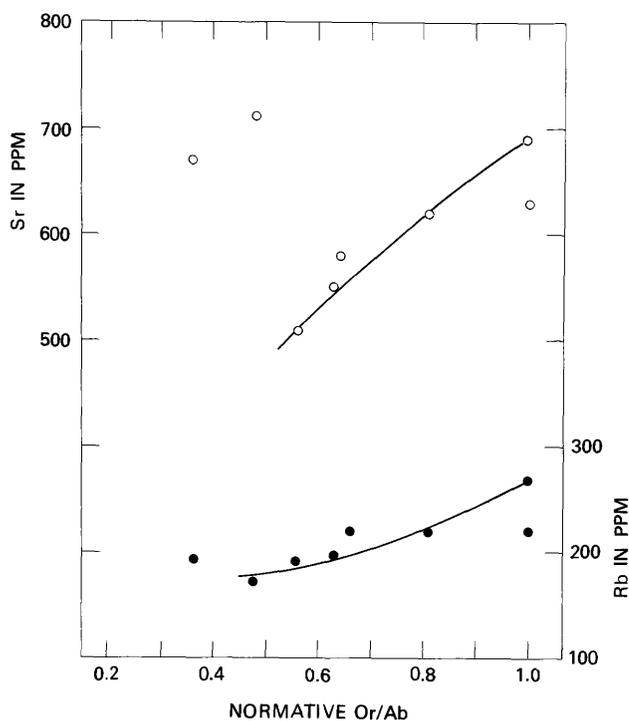
FIGURE 31.—Strontium (circle), rubidium (solid dot), and potassium feldspar analyses (in ppm) of Boulder Creek Granodiorite samples from the northern part of the batholith; data from table 16. Lines represent median of values as plotted.

Brown (1976) showed a trend in the calc-alkaline suite from diopside normative to corundum normative as SiO_2 increases. Whereas the magmas they used in their model frequently contained almandine-spessartine garnet, garnet of almandine-spessartine composition is known from only one locality in the Boulder Creek Granodiorite, and that is a pegmatite, an association not unlike that described by them (1976, p. 474). A most interesting relationship described by them can be related to the Boulder Creek Granodiorite as well and that is the indication that the formation and crystallization of corundum-normative calc-alkaline magmas through amphibole fractionation may be explained by the crystallization of hornblende in a hydrous magma. They interpret the crystallization trend from diopside-normative to corundum-normative rocks as the result of fractionation (crystallization or melting) of hornblende from a diopside-normative basic magma; normative-corundum trends depend in part on the $Na/(Na+K)$ ratio of the magma. Both the Boulder Creek Granodiorite rocks and the Sierra Nevada batholithic rocks (Bateman and others, 1963) became corundum-normative at about 60 percent SiO_2.

3. Experimentally determined fractionation trends in an AFM plot for a calc-alkaline province at 2,700–3,600 MPa under dry conditions determined by Green and Ringwood (1968, p. 153) are similar to the one determined in this report for Boulder Creek Granodiorite (fig. 23). In both plots there is no marked iron enrichment relative to magnesium in the more basic compositions. Alternatively, according to Green and Ringwood, the same fractionation trend may be obtained experimentally at 900–1,000 MPa under wet conditions ($P_{H_2O}<P_{Load}$). Calculated liquid fractionates at 900–1,000 MPa follow the same calc-alkaline

trends whereby partial melting of amphibolite at lower crustal depths under wet conditions yields rocks of the calc-alkaline series.

4. Initial Sr^{87}/Sr^{86} ratios of 0.7034 ± 0.0010 for the Boulder Creek Granodiorite (Peterman and others, 1968) fall in the oceanic volcanic field. Such moderately low initial strontium-isotope ratios could be derived from short-lived crustal material or from the mantle. Green and Ringwood (1968, p. 156) indicated that there is increasing evidence that initial Sr^{87}/Sr^{86} ratios found in the calc-alkaline series characteristically fall in the range of about 0.704–0.708 owing to derivation from basaltic material having low initial Sr^{87}/Sr^{86} ratios. Melting of old crystalline or miogeosynclinal sedimentary rocks would produce higher strontium ratios and greater variability than possessed by Boulder Creek rocks. Thus, an origin of upper mantle or lower crust seems plausible for the Boulder Creek Granodiorite, especially in relation to data presented here.

The Twin Spruce Quartz Monzonite in many respects appears to be a later differentiate of the magma that produced the Boulder Creek Granodiorite, but additional data may be needed to confirm this opinion. In figure 25, variations in K_2O, Na_2O, and CaO suggest a differentiation trend; also, AFM diagrams (figs. 23 and 27) show that iron-magnesium trends are complementary for both rock types. In biotite analyses from both rock types (see fig. 34), the major oxides MgO, FeO, Al_2O_3, and SiO_2 show definite compositional relationships. For example, all Boulder Creek Granodiorite biotite analyses contain greater than 12 percent MgO, and Twin Spruce Quartz Monzonite biotite analyses contain less than 12 percent MgO. Boulder Creek Granodiorite biotite has more MgO and SiO_2 and less Al_2O_3 and FeO than Twin Spruce Quartz Monzonite. K_2O, however, is just as variable in one rock type as in the other. Variation diagrams for Twin Spruce Quartz Monzonite appear to be meaningless because of contamination; SiO_2 appears to have exerted no control over the other oxides and CaO very little control. Plagioclase, however, has a definite trend relative to the CaO content in rock (fig. 28); calcium increases directly as weight percent of plagioclase increases. Other than the plagioclase and potassium feldspar, no major calcium-bearing mineral occurs in the Twin Spruce Quartz Monzonite; thus, as in the Boulder Creek Granodiorite, crystallization was dominated by plagioclase; potassic feldspar crystallized later for both rock types. It may be that the Twin Spruce Quartz Monzonite is a differentiate of the Boulder Creek Granodiorite magma, but the variation indicated by oxides in relation to SiO_2 and calcium sug-

gests that the magma was contaminated. In some instances contamination appears local in origin, whereas in other instances the contaminants are of ambiguous origin and may be from a deep-seated source.

MINERALOGY, PETROLOGY, AND CHEMISTRY OF MINERALS IN THE BATHOLITH

BIOTITE

BOULDER CREEK GRANODIORITE

General description. Biotite, along with hornblende and, locally, plagioclase and quartz, defines the foliation in the Boulder Creek batholith. Biotite in recrystallized contact rocks, unlike in the central part of the batholith where it clusters with the other mafic and accessory minerals, may form stringers and thin wispy layers with the mafic and accessory minerals. Biotite in the batholith proper averages slightly greater than 15 percent; the west contact and sheared and recrystallized areas adjacent to faults average 22 percent. In granodiorite, potassium feldspar decreases as biotite increases (fig. 32 and table 17).

Biotite from granodiorite lenses in schist and gneiss country rock is grayish red brown in color, always ragged, and commonly oxidized to an orangish color along grain boundaries and cleavage. At the contact in gneiss and schist, biotites are moderate reddish brown and within the batholith are a dark reddish brown or dark yellowish brown. Biotite cuts and embays hornblende but also appears frayed, ragged, and sometimes zoned. Inclusions consist of ores, monazite and (or) xenotime, and allanite. Biotite typically alters to chlorite, iron oxides, epidote, sphene, and allanite. In the northern part of the batholith biotite is part of a reaction in which hydrogarnets formed locally.

Chemistry. In a very general way biotite can be related to the bulk chemistry of the rock. Modal biotite increases as CaO in the host rock increases. The CaO, however, is localized in the plagioclase and (or) hornblende and as hornblende increases in the rock, biotite decreases. Also, biotite decreases as SiO_2 increases (fig. 33), but there are many exceptions and the trend is quite general.

Major elements were determined by standard wet chemical analyses described by Peck (1964) and structural formulas were calculated (tables 18 and 19) on the basis of 24 (O, OH, Cl, F) atoms to the general mica formula $X_2Y_{4-6}Z_8O_{20}(OH, F, Cl)_4$, using a computer program described by Jackson, Stevens, and Bowen (1967). Totals for the octahedral sites are 5.67–5.85 out of a possible 6 atoms per formula unit and the large cations (Ca, Na, K) in the X group range from 1.88 to
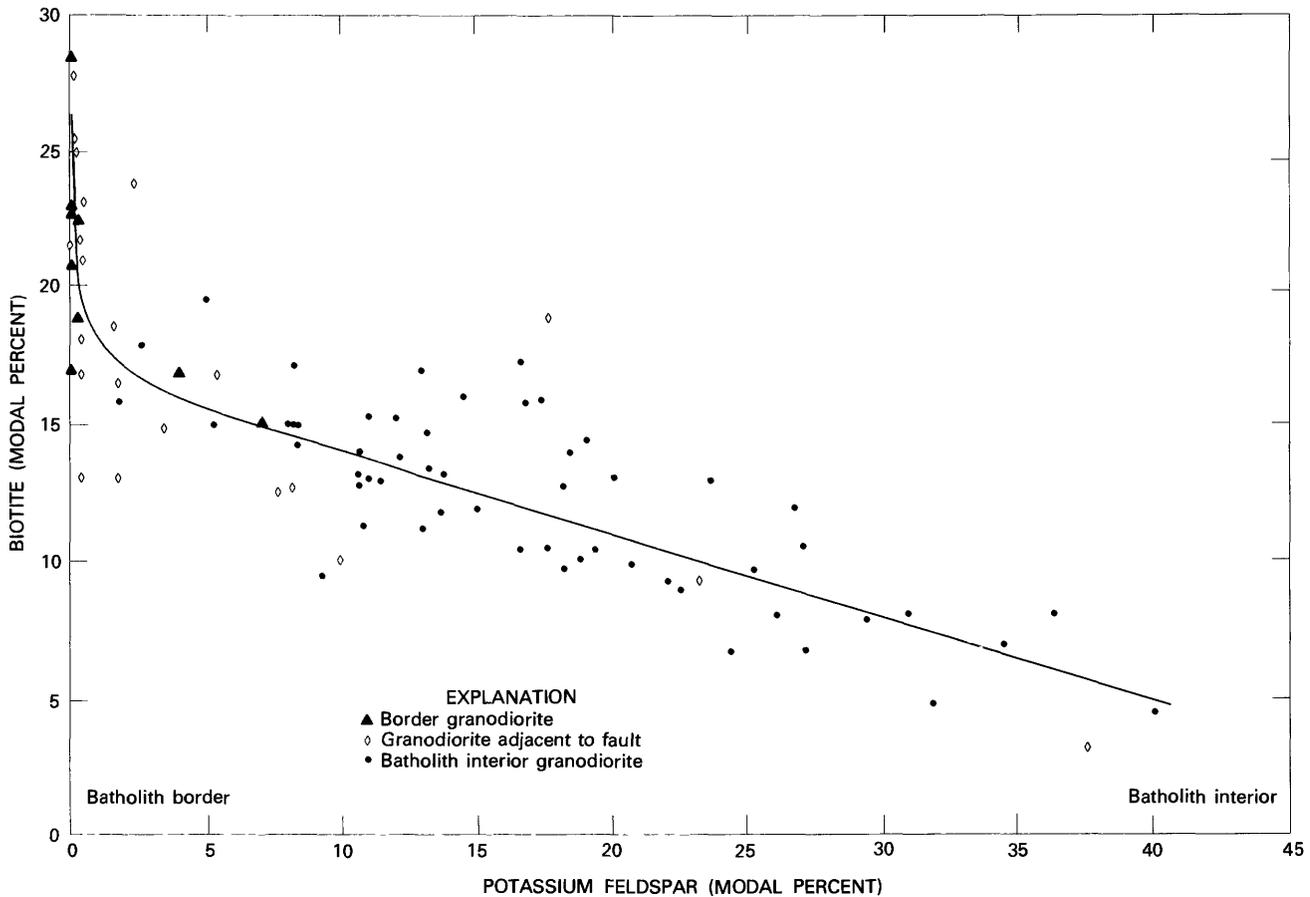
FIGURE 32.—Modal biotite plotted against potassium feldspar for the border and the interior of the batholith. No linear distance across batholith indicated. Curve represents statistical trend of data.

1.99, fairly close to the ideal 2.00. Chemical variations between granodiorite biotites are quite similar if sample 392, a biotite from the satellitic Pisgah pluton, is excluded. The Pisgah biotite is higher in FeO and lower in MgO than batholithic biotites. Chemical trends in biotite are rather inconsistent due to the presence of hornblende in many samples. Trends for Na_2O in biotite relate in a general way to the anorthite content of plagioclase coexisting with biotite, but the presence of hornblende seems to interfere in the relationship because it too is a calcium and sodium-bearing mineral.

TABLE 17.—Mode summary (volume percent) of major minerals in the Boulder Creek batholith, Front Range, Colo.

	Contact area	Adjacent to faults	Entire batholith	Batholith south of lat 40 N.	Batholith north of lat 40 N.
Potassium feldspar---	1	2	14	18	11
Plagioclase----------	47	51	42	40	46
Quartz---------------	23	23	25	26	24
Biotite--------------	21	19	15	14	15
Hornblende----------	2	2	2	2	3
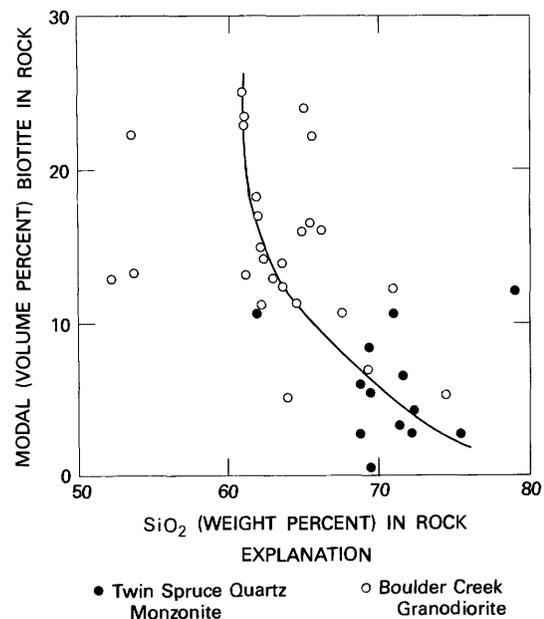
FIGURE 33.—Percent biotite in Boulder Creek Granodiorite and Twin Spruce Quartz Monzonite in relation to percent SiO_2 in rock. Curve drawn on median of plots.

TABLE 18.—*Chemical and spectrographic analyses and mineral formula for biotite from Boulder Creek Granodiorite, hornblende diorite, mafic inclusions, and a lamprophyre dike, Boulder Creek batholith area, Front Range, Colo.*

[Sampled areas located on figure 17. (–), not looked for; N, not detected; L, detected but below the limit of determination; N.d., not determined. Standard rock analyses by V. C. Smith except sample 385 by E. L. Brandt. Spectrographic analyses by L. A. Bradley except sample 385 by Ray Havens. Results are based on their identity with geometric brackets whose boundaries are 1.2, 0.83, 0.56, 0.38, 0.26, 0.18, 0.12, and so forth, and are reported arbitrarily as midpoints of these brackets: 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, respectively. Precision of a reported value is approximately plus or minus one bracket at 68-percent confidence, or two brackets at 95-percent confidence. Samples 41, 48, 49, 50, 352, 386 from Gable and Smith (1975), 392 from Sims and Gable (1967)]

Sample No. [a]	Boulder Creek Granodiorite							Hornblende diorite	Mafic inclusions			Lamprophyre dike
	4	47	392	49	50	41	48	352	334	385	386	388
	Chemical composition, in weight percent											
SiO_2	37.49	37.38	35.60	37.67	37.50	37.88	37.34	36.97	36.31	36.81	37.43	39.01
Al_2O_3	16.19	15.82	17.74	15.53	15.32	15.08	15.55	15.09	16.06	16.08	15.51	13.55
Fe_2O_3	2.53	2.79	2.28	3.16	2.21	2.78	2.86	3.30	2.41	2.57	3.81	2.57
FeO	14.81	14.59	17.68	14.34	15.21	14.51	14.52	12.69	16.15	15.30	13.33	12.49
MgO	11.72	12.96	9.78	13.05	13.21	12.83	12.67	14.10	11.75	12.86	13.60	15.72
CaO	0.49	0.13	0.18	0.25	0.52	1.34	0.47	0.41	0.52	0.67	0.98	1.00
Na_2O	0.33	0.22	0.22	0.28	0.29	0.24	0.22	0.13	0.22	0.14	0.28	0.27
K_2O	9.36	9.57	9.22	9.43	9.04	8.79	9.29	8.87	9.00	8.64	8.58	9.29
H_2O^+	3.07	3.07	3.32	3.02	3.41	2.85	2.98	3.31	3.19	3.96	3.55	2.48
H_2O^-	0.15	0.05	0.04	0.10	0.11	0.15	0.04	0.23	0.05	0.04	0.17	0.12
TiO_2	2.61	2.27	2.96	1.90	1.95	2.23	2.84	3.34	2.99	2.19	1.58	1.12
P_2O_5	0.05	0.02	0.04	0.02	0.01	0.05	0.07	0.10	0.09	0.05	0.07	0.26
MnO	0.30	0.31	0.22	0.34	0.26	0.30	0.26	0.17	0.25	0.29	0.22	0.22
Cl	0.07	0.14	n.d.	0.12	0.14	0.13	0.15	0.15	0.21	0.13	0.09	0.14
F	0.98	0.68	0.59	0.58	0.56	0.81	0.61	0.67	0.63	0.45	0.75	1.93
Subtotal	100.20	100.00	99.87	99.79	99.74	99.97	99.87	99.53	99.83	100.18	99.95	100.17
Less O	0.43	0.32	0.25	0.27	0.27	0.37	0.29	0.31	0.32	0.22	0.34	0.84
Total	99.77	99.68	99.62	99.52	99.47	99.60	99.58	99.22	99.51	99.96	99.61	99.33

Number of atoms on the basis of 24 (O, OH, F, Cl) in the general formula $X_2Y_6Z_8(O, OH, F, Cl)_{24}$

Z	Si	5.669	5.649	5.44	5.700	5.669	5.751	5.655	5.560	5.523	5.488	5.599	5.876
	Al IV	2.331	2.351	2.56	2.300	2.331	2.249	2.345	2.440	2.477	2.512	2.401	2.124
Octahedral		8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	Al VI	0.555	0.468	0.062	0.470	0.399	0.449	0.431	0.235	0.420	0.313	0.333	0.282
Tetrahedral	Ti	0.297	0.258	0.34	0.216	0.222	0.255	0.323	0.378	0.342	0.246	0.178	0.127
	Fe^{+3}	0.294	0.317	0.26	0.360	0.251	0.318	0.326	0.374	0.276	0.288	0.429	0.291
	Fe^{+2}	1.873	1.844	2.26	1.815	1.923	1.842	1.839	1.596	2.054	1.908	1.667	1.574
	Mn	0.038	0.040	0.02	0.044	0.033	0.039	0.033	0.022	0.032	0.037	0.028	0.028
	Mg	2.642	2.920	2.22	2.943	2.977	2.903	2.860	3.161	2.664	2.858	3.032	3.530
		5.70	5.85	5.72	5.85	5.81	5.81	5.81	5.77	5.79	5.65	5.67	5.83
X	Ca	0.079	0.021	0.02	0.041	0.084	0.218	0.076	0.066	0.085	0.107	0.157	0.161
Ca+Na=2	Na	0.097	0.065	0.06	0.082	0.085	0.071	0.065	0.038	0.065	0.041	0.081	0.079
	K	1.806	1.845	1.80	1.820	1.743	1.702	1.795	1.702	1.746	1.643	1.637	1.785
		1.98	1.93	1.88	1.94	1.91	1.99	1.94	1.81	1.90	1.79	1.88	2.02
	F	0.469	0.325	0.28	0.278	0.268	0.389	0.292	0.319	0.303	0.212	0.355	0.920
	Cl	0.018	0.036	--	0.031	0.036	0.033	0.039	0.038	0.054	0.033	0.023	0.036
	OH	2.945	3.045	3.34	3.048	3.328	2.734	2.970	3.320	3.237	3.938	3.542	2.492
		3.43	3.41	3.62	3.36	3.63	3.16	3.30	3.68	3.59	4.18	3.92	3.45
$b_{100} Fe^+/Fe^+ + Mg=$		45.1	42.5	53.2	42.5	42.2	42.7	43.1	38.4	46.7	43.6	40.9	34.6

TABLE 18—*Chemical and spectrographic analyses and mineral formula for biotite from Boulder Creek Granodiorite, hornblende diorite, mafic inclusions, and a lamprophyre dike, Boulder Creek batholith area, Front Range, Colo.—Continued*

Sample No.[a]	Boulder Creek Granodiorite							Hornblende diorite	Mafic inclusions			Lamprophyre dike
	4	47	392	49	50	41	48	352	334	385	386	388
	Semiquantitative spectrographic analyses, in parts per million											
Ba	1,000	700	1,500	1,000	1,000	1,000	1,000	5,000	3,000	700	1,000	3,000
Co	50	70	30	100	100	100	100	70	70	50	100	100
Cr	100	100	100	100	200	150	150	30	N	200	200	N
Cu	10	50	41	20	150	15	100	200	30	150	300	10
Ga	50	50	50	50	50	50	50	50	100	50	50	70
La	30	N	N	N	N	N	N	N	N	50	N	N
Mo	5	20	N	5	20	5	5	7	7	N	7	7
Nb	20	N	90	N	N	N	10	20	L	N	N	N
Ni	70	70	80	100	100	100	100	500	150	150	300	700
Pb	20	N	N	N	N	N	N	N	10	N	10	10
Sc	50	20	60	20	10	30	20	7	30	15	10	7
Sr	20	15	20	20	15	20	20	70	30	30	50	150
V	300	300	280	300	300	300	300	300	300	300	300	300
Y	N	N	30	N	N	20	N	L	N	N	N	15
Yb	3	2	N	1	2	2	N	N	N	N	N	N
Zn	N	N	N	N	N	N	N	300	700	300	N	500
Zr	100	50	380	50	30	100	70	N	300	30	20	150

[a] Lab. numbers not published previously: sample 4, D102146; 47, D102147; 334, D102519; 385, D103822; 388, D102520.

[b] $Fe^+ = Fe^{+2} + Fe^{+3}$.

Minor elements in biotite were determined by semi-quantitative spectrographic analysis and it was found that the trace elements in biotites were fairly consistent from one sample to another. Trace amounts of zirconium are probably due to tiny zircons not completely removed from the samples during separation and purification.

TWIN SPRUCE QUARTZ MONZONITE

General description. Biotite in the Twin Spruce Quartz Monzonite occurs mostly as an interstitial mineral to plagioclase, microcline, and quartz, and, unlike biotite laths in granodiorite, the laths are generally smaller and quite ragged. Their color is similar to that of biotite in Boulder Creek Granodiorite. Accessory minerals in the Boulder Creek Granodiorite tend to cluster with the biotite and other mafic minerals whereas in the quartz monzonite accessories occur both with biotite or completely separated but in foliation trends with biotite. Accessories associated with biotite in quartz monzonite include apatite, ores, zircon, monazite or xenotime and allanite. Biotite alters somewhat to chlorite, contains many opaque blebs, and enters into a reaction forming allanite. Biotite in quartz monzonite varies in abundance between outcrops but is rarely more than 10 percent of the rock and averages close to 6 percent.

Chemistry. Nine biotite samples separated from quartz monzonite were chemically analyzed (table 19) by the same methods used for the biotite from granodiorite. Quartz monzonite biotites are richer in Al_2O_3, TiO_2, and FeO but contain less MgO and SiO_2 than Boulder Creek Granodiorite biotites (fig. 34; TiO_2 not shown). CaO, K_2O, and Na_2O are nearly constant in biotites from both rock types. Biotites from Twin Spruce Quartz Monzonite also appear to be much more uniform in major-element composition than the host-rock composition would indicate; this uniformity was also true for biotites in the Boulder Creek Granodiorite.

The minor elements cerium, neodymium, and zinc, though occurring in quartz monzonite biotites, are not found in the granodiorite biotites. Lead and tin are reported in most quartz monzonite biotites and rarely in granodiorite biotites; chromium, however, is consistently higher in Boulder Creek Granodiorite biotite than in biotite in quartz monzonite.

X-ray of the basal (005) interplanar spacing of biotite from quartz monzonite indicates an increase in fluorine as d_{005} spacings decrease that is similar to the findings of Dodge, Smith, and Mays (1969), and Lee and Van Loenen (1971). In figure 35 biotite in quartz monzonite occurs in two trends that are subparallel. Both trends definitely show an increase in fluorine as d_{005} spacings increase. Why the quartz monzonite biotites plot in two distinct trends is not obvious. The only consistent variation is in the number of potassium atoms in biotite (table 19); those biotite samples having the higher potassium values plot in a lower range of d_{005} spacings, but this may not be a complete explanation. Biotite from the younger Silver Plume Quartz Monzonite was plotted and the d_{005} spacings also formed a single straight line indicating again that the d_{005} spacings increase as fluorine increases. Biotite in the Boulder Creek Granodiorite is plotted on the same figure but it shows no such relationship; points cluster between 0.20140 and 0.20180 nm (nanometers) for 0.5 to 1.0 weight percent fluorine.

MAFIC INCLUSIONS AND LAMPROPHYRE DIKES IN THE BOULDER CREEK GRANODIORITE

General description. Thin sections show that biotite and hornblende do not tend to cluster in most inclusions as they do in the Boulder Creek Granodiorite. Biotite replaces both hornblende and pyroxene and it can be generally assumed that even though some biotite may be primary, the greater the percentage of biotite the greater the alteration of the inclusion. Some biotite is reddish and some is greenish brown in color, is frayed and eroded, and, in general, its habit and form of alteration is similar to that of biotite in the Boulder Creek Granodiorite.

Chemistry. The distribution of the major oxides in biotite from the syenodiorite or lamprophyre (sample 388, table 18) is not much different from that in biotite from mafic inclusions; however, TiO_2, P_2O_5, and fluorine do not follow this distribution. Both P_2O_5 and fluorine amounts are higher in the lamprophyre; TiO_2 is lower. Other oxides vary as much between the various mafic inclusions as between rock types. Biotite from inclusions tends to contain more nickel, zinc, and lithium than granodiorite biotite.

X-ray determination of the d_{005} spacing (fig. 35) indicates that biotites from inclusions plot near biotites from the Boulder Creek Granodiorite and Twin Spruce Quartz Monzonite whereas the biotite from a lamprophyre is isolated owing to its high fluorine content.

PETROGENESIS

Figure 36 shows that biotites from the Boulder Creek Granodiorite, the Twin Spruce Quartz Monzonite, and the inclusions all belong to the assemblage magnetite-potassium feldspar-biotite and plot along a

TABLE 19.—*Chemical and spectrographic analyses and mineral formula for biotite from Twin Spruce Quartz Monzonite, Front Range, Colo.*

[Standard rock wet chemical analyses by V. C. Smith; spectrographic analyses by L. A. Bradley; (--), not found; N.d., not determined]

Sample No.		232	235	85	376	380	381	382	383	384
Lab No.		D102154	D102153	D102513	D102514	D102155	D102157	D102156	D102152	D102158
Chemical analyses, in weight percent										
SiO_2		35.79	35.74	36.90	36.99	36.62	35.56	35.50	35.86	36.69
Al_2O_3		18.47	16.52	16.52	16.31	16.63	16.19	17.16	18.35	17.19
Fe_2O_3		2.63	2.70	2.81	2.57	4.32	2.85	2.58	2.36	2.38
FeO		17.44	18.10	17.10	15.82	15.51	18.94	17.89	17.91	17.26
MgO		8.86	10.06	10.17	11.42	9.99	9.03	9.27	8.30	9.63
CaO		0.00	0.61	0.73	0.38	0.00	0.00	0.00	0.00	0.19
Na_2O		0.15	0.24	0.32	0.24	0.28	0.22	0.19	0.19	0.27
K_2O		9.41	8.52	8.51	9.36	9.28	8.85	9.44	9.10	9.23
H_2O^+		2.84	3.08	3.75	3.13	3.21	3.09	2.89	2.86	2.89
H_2O^-		0.02	0.20	0.09	0.07	0.13	0.15	0.05	0.08	0.11
TiO_2		3.22	2.50	2.10	2.41	2.76	3.50	4.15	3.78	2.88
P_2O_5		0.01	0.04	0.02	0.04	0.04	0.03	0.03	(^{a})	(^{a})
MnO		0.32	0.16	0.33	0.38	0.16	0.39	0.22	0.08	0.38
Cl		0.07	0.19	0.05	0.08	0.18	0.14	0.10	0.11	n.d.
F		0.73	1.41	0.47	0.83	1.11	1.23	0.47	0.88	1.12
Subtotal		99.96	100.07	99.87	100.03	100.22	100.17	99.93	99.86	100.22
Less O		.33	.63	.21	.37	.51	.55	.22	.39	.47
Total		99.63	99.44	99.66	99.66	99.71	99.62	99.71	99.47	99.75
Powder density		n.d.	n.d.	3.05	3.04	n.d.	n.d.	n.d.	n.d.	n.d.
Number of atoms on the basis of 24 (O, OH, F, Cl) in the general formula $X_2Y_6Z_8(O,OH,F,Cl)_{24}$										
Z Octahedral	Si	5.476	5.496	5.574	5.607	5.561	5.486	5.463	5.493	5.612
	Al	2.524	2.504	2.426	2.393	2.439	2.514	2.537	2.507	2.388
		8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y Tetrahedral	Al	0.806	0.490	0.515	0.520	0.538	0.429	0.576	0.806	0.693
	Ti	0.371	0.289	0.239	0.275	0.275	0.406	0.479	0.435	0.330
	Fe^{+3}	0.303	0.312	0.319	0.293	0.494	0.331	0.299	0.272	0.275
	Fe^{+2}	2.231	2.328	2.160	2.005	1.970	2.443	2.302	2.294	2.200
	Mn	0.042	0.021	0.042	0.049	0.021	0.051	0.029	0.010	0.046
	Mg	2.020	2.306	2.290	2.580	2.261	2.076	2.127	1.895	2.200
		5.77	5.75	5.57	5.72	5.60	5.74	5.81	5.71	5.75
X	Ca	--	0.101	0.118	0.062	--	--	--	--	0.028
	Na	0.044	0.072	0.094	0.071	0.082	0.066	0.057	0.056	0.073
	K	1.836	1.671	1.640	1.810	1.798	1.741	1.853	1.778	1.797
		1.88	1.84	1.85	1.94	1.88	1.81	1.91	1.83	1.89
	F	0.353	0.686	0.225	0.398	0.533	0.600	0.229	0.426	0.541
	Cl	0.018	0.049	0.013	0.021	0.046	0.037	0.026	0.029	--
	OH	2.878	2.954	3.778	3.165	3.120	3.025	2.916	2.841	2.824
		3.25	3.69	4.02	3.58	3.70	3.66	3.17	3.30	3.36
$100(Fe^+/Fe^++Mg)$		55.60	53.40	52.00	47.00	52.10	57.20	55.00	57.50	52.90

TABLE 19.—*Chemical and spectrographic analyses and mineral formula for biotite from Twin Spruce Quartz Monzonite, Front Range, Colo.—*
Continued

Sample No.	232	235	85	376	380	381	382	383	384
Lab No.	D102154	D102153	D102513	D102514	D102155	D102157	D102156	D102152	D102158
Spectrographic analyses, in parts per million									
Ba	700	700	700	1,000	700	2,000	1,000	1,000	700
Ce	--	300	1	--	--	--	--	--	200
Co	50	50	100	100	50	50	70	70	50
Cr	150	50	10	30	50	50	500	100	10
Cu	10	150	50	700	200	20	10	10	30
Ga	100	100	70	100	100	50	50	100	100
La	30	200	70	--	70	--	--	30	200
Li	--	--	700	300	--	--	--	--	--
Mo	20	10	10	7	5	5	5	7	5
Nb	20	20	20	--	20	10	10	20	10
Nd	70	200	70	--	150	--	--	100	150
Ni	50	50	50	100	30	10	100	50	20
Pb	20	50	30	--	20	10	10	--	20
Sc	70	50	15	30	50	30	50	50	50
Sn	20	50	--	--	50	20	20	20	20
Sr	15	70	70	30	15	20	10	20	15
V	100	300	300	300	300	300	300	200	100
Y	200	20	15	--	--	--	20	20	30
Yb	7	2	--	--	2	5	5	5	5
Zn	1,000	1,000	500	700	1,000	500	500	500	500
Zr	200	50	300	500	50	50	70	100	200

[a]P_2O_5 included in Al_2O_3.

trend paralleling the compositions of "buffered" biotites in the ternary system $K Fe_3^{+3} AlSi_3 O_{12} (H_{-1})$-$KFe_3^{+2}AlSi_3O_{10}(OH)_2$ (Wones and Eugster, 1965, p. 1232). This trend suggests that oxygen fugacities in biotite of the Boulder Creek Granodiorite are slightly greater than those of the Ni-NiO buffer. One granodiorite sample was not plotted on the ternary diagram; it, too, would have plotted in the concentration of points for granodiorite.

In the presence of magnetite acting as a buffer, oxygen fugacities in a crystallizing magma decrease as temperatures decrease and generally as FeT:FeT+Mg ratios increase. Boulder Creek Granodiorite biotites have FeT:FeT+Mg values of 42.5-45.1 (the Mt. Pisgah pluton sample having a ratio of 53.2 is excluded because the granodiorite lies outside the batholith), inclusions have values of 38.4-46.7, and Twin Spruce Quartz Monzonite from the batholith only, 47.0-52.1; these values appear consistent for the Boulder Creek

Granodiorite and the Twin Spruce Quartz Monzonite because the quartz monzonite was emplaced later in the sequence, after the Boulder Creek Granodiorite, when temperatures would be expected to be somewhat lower. Biotites in the inclusions have Fe:Fe+Mg values that indicate some inclusions are younger and some older than Boulder Creek Granodiorite. These data substantiate the belief stated earlier that some of the inclusions are younger and some older than the granodiorite.

HORNBLENDE

BOULDER CREEK GRANODIORITE

General description. The approximate extent of hornblende-bearing granodiorite is outlined in figure 6A. Hornblende is not common in Boulder Creek Granodiorite lenses and plutons that are satellitic to
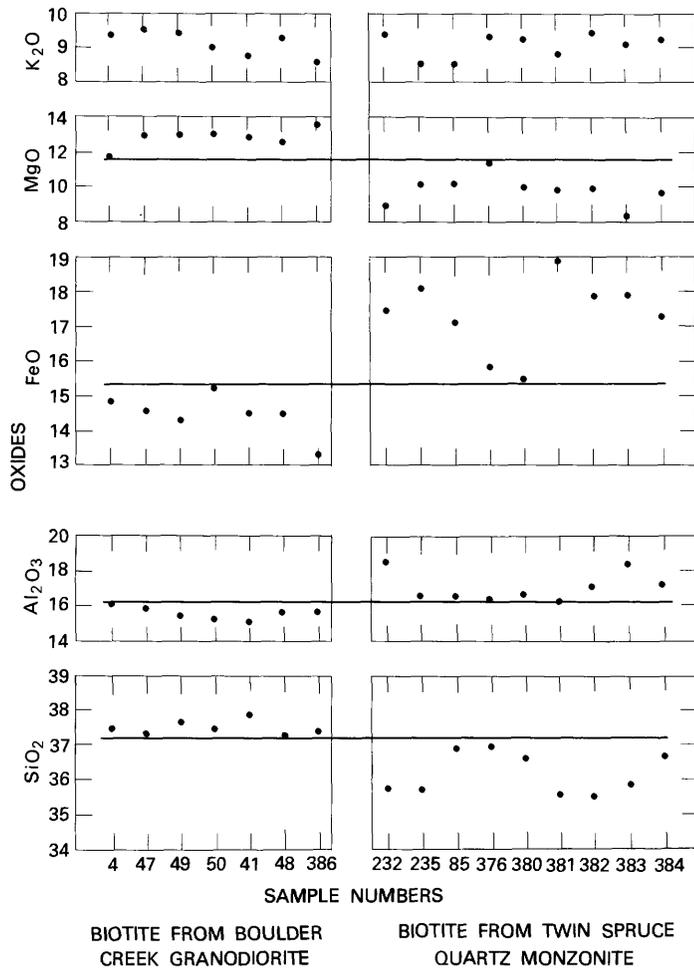
FIGURE 34.—Compositional variations of K_2O, MgO, FeO, Al_2O_3, and SiO_2 in biotites from Boulder Creek Granodiorite and Twin Spruce Quartz Monzonite. Horizontal lines show median separation of each element, except K_2O, between Boulder Creek Granodiorite and Twin Spruce Quartz Monzonite. Oxides in weight percent.

FIGURE 35.—Fluorine in biotite plotted against d_{005} spacing of biotite.

green and crystals are as much as 1.5 cm in length, but most hornblende is in smaller crystals, some of which are slightly zoned (zoning is principally by color and index difference) and often eroded by other minerals. Magnetite, sphene, calcite, and allanite have replaced hornblende, in some areas extensively. Physical and chemical properties for most of these hornblendes have already been published (Gable and Smith, 1975) and will not be included here except for pertinent chemical data.

Chemistry. The hornblendes analyzed are calcic, and the batholith proper; one exception lies in the southernmost part of the map area (pl. 1). Here the northeast-trending Bald Mountain pluton, if extended northeastward from its outcrop, lies along a trend of hornblende-rich granodiorite which extends into the batholith proper (fig. 6A). Another exception lies north of Nederland in the easternmost part of the Caribou pluton.

Hornblende in the batholith proper occurs as disseminated crystals in granodiorite and in clusters containing, besides hornblende, apatite, allanite, biotite, and ores; the occurrence in clusters is more common. About half of the granodiorite samples collected were hornblende bearing and contained as much as 23.3 percent hornblende (table 1).

In thin section, the hornblende is green or bluish

FIGURE 36.—Relation of Fe^{+3}-Fe^{+2}-Mg (atomic ratios) between biotites of Boulder Creek Granodiorite and Twin Spruce Quartz Monzonite. Dashed lines represent compositions of buffered biotites in ternary system $KFe_3^{+3}AlSi_3O_{12}H_{-1}$-$KFe_3^{+2}AlSiO_{10}(OH)_2$-$KMg_3AlSi_3O_{10}(OH)_2$ depicted by Wones and Eugster (1965, fig. 1). Solid circle, Boulder Creek Granodiorite; solid circle with tail, inclusion; x, Twin Spruce Quartz Monzonite. Line through plotted biotites represents composition of buffered biotites. Buffers are: Fe_3O_4-Fe_2O_3, Ni-NiO,Fe_2SiO_4-Fe_3O_4-SiO_2.

chemical variations among hornblendes in the granodiorite are small, except for SiO_2, FeO, Al_2O_3, and MgO. FeO and Al_2O_3, in general, increase as MgO and SiO_2 decrease. Table 20 has been reproduced in part from Gable and Smith (1975).[1] The same trace elements, except for beryllium occur in both biotite and hornblende in granodiorite rocks. Beryllium, however, occurs only in hornblende.

MAFIC INCLUSIONS AND LAMPROPHYRE DIKES IN THE BOULDER CREEK GRANODIORITE

General description. Hornblende-rich mafic inclusions are particularly abundant in the south-central part of the batholith but are present nearly everywhere in the northern half. The west contact and the Caribou pluton in the Nederland and Ward quadrangles are nearly free of hornblende. Mafic inclusions in the Caribou pluton are biotitic due to alteration and rarely contain hornblende.

Hornblende in the lamprophyric rocks is generally poikilitic and has inclusions of potassium feldspar (orthoclase), apatite, ores, biotite, and allanite. Pyroxene in the lamprophyre is in small subrounded crystals that accompany hornblende or occur as inclusions in hornblende. In the foliated and porphyritic microgranular mafic inclusions, the occurrence of hornblende is not much different from that in hornblende diorite. In pyroxene-bearing hornblende diorite, however, hornblendes are generally very large and typically poikilitic, containing subrounded pyroxene crystals.

Chemistry. The hornblende from the mafic inclusion has a composition similar to hornblendes from the Boulder Creek Granodiorite and hornblende diorite (table 20) except for fluorine, which is a little higher in inclusion hornblendes. Cerium and zirconium found in the hornblende inclusion may be due to small inclusions of allanite and zircon crystals within the hornblende. Hornblendes in the inclusions also contain more chromium, nickel, and strontium than hornblendes from the granodiorite.

HORNBLENDE DIORITE AND HORNBLENDITE

Hornblendes from hornblende diorite and hornblendite are also calcic. These hornblendes are generally higher in SiO_2 than Boulder Creek Granodiorite hornblendes or inclusion hornblendes. This higher SiO_2 content may be due to a small excess amount of SiO_2 occurring in the hornblende initially and then not being available to form quartz or enter into reactions forming other minerals. In hornblendite, high SiO_2 is ac-

companied by low Al_2O_3, a combination discussed below. Of the minor elements, chromium and nickel are both higher in hornblende from hornblende diorite and hornblendite rocks whereas yttrium is lower.

PETROGENESIS

Hornblende from granodiorite, inclusions, and hornblende diorite is chemically similar. Hornblende from lamprophyre and hornblendite contains less Al_2O_3 than the more leucocratic rocks; hornblende from hornblendite carries greater SiO_2 and MgO but less $FeO + Fe_2O_3$.

In an investigation of aluminum replacement of silicon in the amphibole lattice, Harry (1950) indicated that the higher the temperature of formation, the higher the solid solubility, and at high temperatures aluminum substitutes for silicon and the substitution is controlled by magmatic temperatures at time of crystallization. On the basis of tetrahedrally and octahedrally coordinated aluminum, early formed hornblendes from rocks of appinitic type belong to Harry's (1950) type I, hornblendes in diorites and trondhjemites to type II and hornblendes of late crystallization to type III (table 21).

Silicon-aluminum relationships in hornblendes from the Boulder Creek Granodiorite, mafic inclusions, and hornblende diorite place the hornblende composition of the rock in this report between Harry's types I and II, which are primary hornblendes; hornblendes from hornblendites of this report belong to type III, which are hornblendes of late crystallization.

In a study of Caledonian amphiboles, Nockolds and Mitchell (1946) found that rocks rich in amphibole, that is, hornblendite, have different trace elements in hornblendes in comparison to hornblendes from hornblende diorites, quartz diorites, and granodiorites. Trace-element abundances vary between hornblendes in this report but not significantly; perhaps more analyses are needed to identify real differences. Lead occurs only in hornblendite; and lanthanum, niobium, and neodymium, although not found in hornblendites, do occur in the hornblendes of other rocks (table 20).

PLAGIOCLASE
BOULDER CREEK GRANODIORITE

Plagioclase is neither as fresh nor as free of inclusions as accompanying potassium feldspars, and eroded hemihedral to anhedral crystals of plagioclase are about the same size as the potassium feldspars. Plagioclase may be antiperthitic and normally zoned; the zoned crystals have rims ranging in composition from oligoclase to albite. Reaction rims are broader

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[1]Hornblende from sample 386 (Gable and Smith, 1975, sample T 170–68) was originally included with hornblende of granodiorite but is now believed to be part of a very mafic inclusion that is gradational into normal Boulder Creek Granodiorite.

TABLE 20.—*Chemical and spectrographic analyses and mineral formula for hornblende from Boulder Creek Granodiorite, mafic inclusions, a lamprophyre dike, hornblende diorite, and hornblendite, Boulder Creek batholith area, Front Range, Colo.*

[Analyst for standard rock analyses on hornblende in sample 385, E. L. Brandt; 388, V. C. Smith; all others credited in Gable and Smith (1975). Spectrographic analyst for samples 385 and 388, Ray Havens; all others credited in Gable and Smith (1975). N.d., not determined; (-), looked for but not found]

Chemical analyses, in weight percent

Sample No.	Boulder Creek Granodiorite				Mafic Inclusions		Lamprophyre dike	Hornblende diorite		Hornblendite	
	49	50	41	48	[a]385	386	[a]388	343	352	411	412
SiO_2	45.2	43.43	42.84	43.13	44.03	43.85	46.08	46.42	44.48	49.38	52.89
Al_2O_3	11.4	10.29	10.44	10.57	10.04	10.12	8.39	10.14	10.27	7.32	5.05
Fe_2O_3		5.93	6.19	5.99	5.70	5.80	4.82	4.09	4.83	2.94	2.01
FeO	[b]18.6	11.80	11.71	11.62	11.88	11.61	10.33	10.09	10.22	8.19	5.40
MgO	10.0	10.79	10.37	10.66	10.71	10.92	12.69	13.40	12.34	15.52	18.67
CaO	11.6	11.85	11.83	11.83	11.92	11.98	12.01	11.26	12.10	12.49	12.69
Na_2O	1.16	1.20	1.19	1.09	1.02	1.10	1.33	1.16	1.17	0.67	0.44
K_2O	1.34	1.17	1.34	1.31	1.07	1.14	0.95	0.53	1.07	0.41	0.27
H_2O^+	n.d.	1.70	1.64	1.57	1.75	1.69	1.56	1.84	1.62	1.54	2.16
H_2O^-	n.d.	0.02	0.03	0.08	0.00	0.05	0.01	0.00	0.02	0.01	0.00
TiO_2	n.d.	1.13	1.20	1.24	1.10	0.96	0.75	0.83	1.06	0.74	0.29
P_2O_5	n.d.	0.02	0.31	0.06	0.12	0.08	0.19	0.01	0.11	0.04	0.00
MnO	n.d.	0.37	0.46	0.40	0.45	0.31	0.30	0.30	0.30	0.21	0.18
Cl	n.d.	0.14	0.13	0.14	0.12	0.10	0.07	0.06	0.17	0.04	n.d.
F	n.d.	0.25	0.35	0.27	0.22	0.32	0.66	0.17	0.30	0.44	0.06
Subtotal	n.d.	100.09	100.03	99.96	100.13	100.03	100.14	100.30	100.06	99.94	100.11
Less O	n.d.	0.14	0.18	0.14	0.12	0.15	0.30	0.08	0.17	0.20	0.03
Total	n.d.	99.95	99.85	99.82	100.01	99.88	99.84	100.22	99.89	99.74	100.08

Number of atoms on the basis of 24 (O, OH, F, Cl) in the general formula $A_{0-1}X_2Y_5Z_8O_{22}$

(Z) Tetrahedral											
Si	6.645	6.497	6.455	6.486	6.567	6.549	6.808	6.741	6.583	7.120	7.406
Al IV	1.355	1.503	1.545	1.514	1.433	1.451	1.192	1.259	1.417	0.880	0.594
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
(Y)											
Al VI	0.620	0.311	0.309	0.359	0.332	0.331	0.269	0.476	0.375	0.364	0.239
Ti	0.133	0.127	0.136	0.140	0.123	0.108	0.083	0.091	0.118	0.080	0.031
Fe^{+3}	0.658[c]	0.668	0.702	0.678	0.640	0.652	0.536	0.447	0.538	0.319	0.212
Octahedral											
Mg	2.191	2.406	2.329	2.389	1.482	2.431	2.795	2.900	2.722	3.336	3.897
Fe^{+2}	1.402[c]	1.476	1.476	1.461	0.057	1.450	1.276	1.225	1.265	0.988	0.632
Mn	--	0.047	0.059	0.051	2.381	0.039	0.038	0.037	0.038	0.026	0.021
	5.00	5.04	5.01	5.08	5.02	5.01	5.00	5.18	5.06	5.11	5.03
Na	0.331	0.348	0.348	0.318	1.905	0.318	0.381	0.327	0.336	0.187	0.120
Ca (X=Ca+Na=2.0)	1.827	1.899	1.910	1.906	0.295	1.917	1.901	1.752	1.919	1.930	1.904
K (A=Na+K)	0.251	0.223	0.258	0.251	0.204	0.217	0.179	0.098	0.202	0.075	0.048
	2.41	2.47	2.52	2.48	2.40	2.45	2.46	2.18	2.46	2.19	2.07
OH	--	1.676	1.618	1.495	0.104	1.684	1.537	1.782	1.599	1.481	2.017
F	--	0.118	0.167	0.128	0.030	0.151	0.308	0.078	0.140	0.201	0.027
Cl	--	0.036	0.033	0.036	1.741	0.025	0.018	0.015	0.043	0.010	--
	1.83	1.82	1.82	1.66	1.88	1.86	1.88	1.88	1.78	1.69	2.04
Ratio: $100Mg/(Mg+Fe^{+2}+Fe^{+3}+Mn)$	51.5	52.3	51.0	52.2	32.5	53.2	60.2	62.9	59.6	71.4	81.8

TABLE 20.—*Chemical and spectrographic analyses and mineral formula for hornblende from Boulder Creek Granodiorite, mafic inclusions, a lamprophyre dike, hornblende diorite, and hornblendite, Boulder Creek batholith area, Front Range, Colo.—Continued*

	Boulder Creek Granodiorite				Mafic Inclusions		Lamprophyre dike	Hornblende diorite		Hornblendite	
Sample No.—	49	50	41	48	[a]385	386	[a]388	343	352	411	412
	Semiquantitative spectrographic analyses, in parts per million										
Ba—	—	50	50	50	30	70	100	50	150	200	50
Be—	—	3	5	2	3	2	7	—	2	—	—
Ce—	—	—	—	—	—	—	150	—	—	—	—
Co—	—	50	50	50	50	70	50	70	50	30	30
Cr—	—	70	100	100	150	150	500	300	200	700	150
Cu—	—	20	2	10	20	30	7	20	15	20	15
Ga—	—	20	20	20	30	30	30	20	30	15	7
La—	—	—	—	70	50	—	100	—	70	—	—
Mo—	—	—	—	7	—	—	—	—	—	—	—
Nb—	—	10	10	10	10	10	—	10	10	—	—
Nd—	—	—	—	200	150	—	100	—	200	—	—
Ni—	—	100	100	100	100	150	300	300	300	500	500
Pb—	—	—	—	—	—	—	—	—	—	—	20
Sc—	—	70	150	150	150	100	70	70	100	20	70
Sr—	—	70	100	100	70	100	300	50	200	500	100
V—	—	200	300	300	300	500	200	300	200	200	150
Y—	—	150	300	300	150	30	30	30	100	—	30
Yb—	—	10	20	20	15	3	2	3	7	—	3
Zn—	—	—	—	—	200	—	—	—	—	—	—
Zr—	—	50	50	100	70	70	150	30	70	—	30

[a] Lab. number for sample 385 is D103823; for sample 388, D1025116.

[b] Total iron reported as FeO.

[c] Used sample 50 hornblende composition for breakdown of FeO and Fe_2O_3 from total reported FeO.

TABLE 21.—*Comparison of partial hornblende lattice structures*
[Columns 1, 5, and 6 from Harry (1950)]

		Type I	Grano-diorite	Hornblende Inclusions diorite		Type II	Type III	Hornblendite
		1	2	3	4	5	6	7
Z group	Si----	6.31	6.52	6.55	6.64	6.79	7.12	7.23
	Al----	1.69	1.48	1.51	1.34	1.21	0.88	0.74
Y group	Al----	0.22	0.40	0.33	0.43	0.11	0.15	0.30

and mild cataclasis prevails in plagioclase from rocks in which muscovite occurs. Albite twinning is predominant, but Carlsbad, pericline, and minor complex twins were also observed in thin section. Composition varies from labradorite to oligoclase, but labradorite occurs only in a few lenses satellitic to the batholith, east of the zone of more mafic rocks. Plagioclase in the batholith is of oligoclase-andesine composition (fig. 6G). Figure 6G indicates widespread erratic zoning of plagioclase in the granodiorite from west to east. Plagioclase at the batholith contact is andesine and plagioclase in the main part of the batholith is oligoclase. Plagioclase in a northwest-trending wide band in the central northern half of the batholith, like the border rocks, is andesine. It appears that plagioclase in the batholith has had a long crystallization history because subrounded crystals of plagioclase appear in both biotite and hornblende, suggesting that plagioclase may have been the earliest mineral to crystallize or that it formed nearly simultaneously with hornblende and biotite. Locally, smaller and more altered plagioclase crystals occur in younger, larger, and clearer plagioclase crystals. Twinning in smaller altered crystals and newer crystals is different; twinning by the same law is disoriented between the older and younger crystals, and twinning by two different laws occurs in the older and host crystals. The younger crystals contain biotite, quartz, and other inclusions, and crystal shape is well defined to subrounded.

TWIN SPRUCE QUARTZ MONZONITE

Plagioclase in the quartz monzonite is more altered than plagioclase in the granodiorite and composition is much more limited, ranging from sodic to calcic oligoclase. Zoning is normal, and the thin outer zone ranges from calcic albite to sodic oligoclase. Generally plagioclase is the host mineral for myrmekite that is well developed adjacent to potassium feldspar crystals, but myrmekite forms adjacent to potassium feldspars in the absence of plagioclase.

MAFIC INCLUSIONS IN THE BOULDER CREEK GRANODIORITE

Plagioclase is both fresh looking and sericitized, and crystals are generally subordinate in size to those of the mafic minerals, but the rocks generally contain a few scattered porphyritic plagioclase crystals. Twinning is predominantly albite and complex albite-pericline types. Plagioclase unzoned to normally zoned has a composition that varies from calcic oligoclase to calcic andesine.

POTASSIUM FELDSPAR

BOULDER CREEK GRANODIORITE

General description. The alkali feldspars in the granodiorite consist of microcline and microperthite crystals that are slightly smaller to equal in size to the larger plagioclase crystals. Microcline crystals are generally subhedral to anhedral and show good microcline grid twinning. Large crystals are often poikilitic, having inclusions of zoned plagioclase, subhedral quartz, anhedral ores, and frayed, somewhat altered biotite. Myrmekitic intergrowths are particularly common near fault zones or wherever rocks have been sheared and recrystallized; muscovite may also occur in these rocks. Microperthite is more local and seems to be more prevalent near the more mafic lenses that are gradational with granodiorite. Some perthites, as in the southeast part of the batholith, have clear polysynthetic twinned albite rims that formed where two or more potassium feldspars have common grain boundaries.

Chemistry. Six potassium feldspars were chemically analyzed (table 22). Feldspar composition ranges from $Or_{86.5-87.9}Ab_{10.7-11.9}An_{1.2-2.1}$. Six of the seven analyses have a compositional range of only 1 percent for any one component, indicating a quite uniform composition of potassium feldspar throughout the batholith. The minor elements are also fairly consistent in amounts between potassium feldspars with only barium and strontium in more than trace amounts. Determination of triclinicity from X-ray diffraction powder patterns using the 131-1$\overline{3}$1 peaks (Goldsmith and Lavas, 1954) indicates that all chemically analyzed potassium feldspars from the Boulder Creek Granodiorite have a triclinicity (obliquity) of 0.60-0.82±0.05. Nilssen and Smithson (1965) found that low triclinicity values are generally from more mafic rocks. This relationship is true for the Boulder Creek Granodiorite as well; potassium feldspar in the more mafic granodiorite adjacent to the larger mafic inclusions is often a microcline-microperthite having a triclinicity of 0.60-0.65. Elsewhere in the granodiorite

TABLE 22.—*Chemical and semiquantitative spectrographic analyses of potassium feldspar from Boulder Creek Granodiorite, Front Range, Colo.*

[Total Fe and CaO determined by atomic absorption methods, Na_2O and K_2O by flame photometric methods; Wayne Mountjoy, analyst. SiO_2 and Al_2O_3 determined by rapid-rock techniques, Sam Botts, analyst; semiquantitative spectrographic analyses by L. A. Bradley. N, not found; L, detected but below limit of determination; N.d., not done]

Sample No.	4	41	47	48	49	50
Lab. No.[a]	D138923	D138924	D138925	D138926	D138927	D138928
	W173436	W173441	W173437	W173431	W173442	W173439
Chemical analyses, in weight percent						
SiO_2	64.40	64.40	64.40	64.40	64.40	64.40
Al_2O_3	18.60	18.60	18.40	18.60	18.60	18.60
FeO[b]	0.05	0.09	0.05	0.05	0.05	0.05
CaO	0.11	0.17	0.24	0.17	0.13	0.18
Na_2O	1.31	1.26	1.34	1.26	1.25	1.34
K_2O	14.80	14.10	14.40	14.50	14.40	14.10
Total	99.27	98.62	98.83	98.98	98.83	98.67
Semiquantitative spectrographic analyses, in parts per million						
Ba	5,000	5,000	3,000	5,000	5,000	5,000
Cr	N	N	N	N	N	N
Cu	7	7	15	100	5	10
Ga	20	20	20	20	20	20
Ni	N	L	5	5	N	N
Pb	70	70	70	70	50	100
Sr	1,000	1,500	1,000	1,000	1,000	1,000
Composition ratios						
Ab	10.96	10.97	11.40	10.71	10.74	11.59
An	1.17	1.91	2.10	1.60	1.33	1.70
Or	87.87	87.12	86.50	87.69	87.93	86.71

[a] "W" numbers for Al_2O_3 and SiO_2; "D" numbers for all other oxides.   [b] Total Fe as FeO.

the triclinicity averages 0.80–0.85, maximum microcline (microcline having maximum obliquity). Investigators (Kuroda, 1958; Marmo and others, 1963; Nilssen and Smithson, 1965) have concluded that low triclinicity or low-delta potassium feldspars may be related to porphyroblastesis and metasomatism. They suggest that rocks containing feldspars having low triclinicity may have undergone a change in bulk composition due to introduced potassium, and the process was arrested before the potassium feldspars were completely inverted to the higher delta values. This explanation may be valid for the Boulder Creek Granodiorite as well; it explains the large potassium feldspar crystals often found in the vicinity of mafic areas. It is possible that remobilized potassium, due to shearing, caused this local metasomatism.

Variation in distribution of potassium feldspars for the batholith is summarized in figure 6H. The ratio of potassium feldspar to plagioclase in granodiorite has been plotted and contoured for the batholith and a zonal arrangement of areas lacking alkali feldspars and areas rich in potassium feldspars became apparent. The absence of potassium feldspar along the western contact of the batholith and metasedimentary rocks and along a west-northwest trending area between the northern and southern parts of the batholith is evident

in figure 6H. From areas devoid of potassium feldspar there is an increase in potassium feldspar toward the centers of the north and south halves of the batholith.

An Ab content of potassium feldspars of less than 15 percent is generally believed to indicate that the rocks completed crystallization or were recrystallized at low temperatures (Tuttle and Bowen, 1958, p. 129). Granodiorite having an 0.80–0.85 triclinicity is believed by some to have crystallized in the presence of excess water vapor. The presence of excess water vapor during the latter stages of crystallization is possible for the Boulder Creek Granodiorite, especially because large pegmatites accompany the batholithic rocks.

MAFIC INCLUSIONS AND LAMPROPHYRE DIKES IN THE BOULDER CREEK GRANODIORITE

Potassium feldspars in the mafic inclusions are either orthoclase or microcline, and in the lamprophyre are orthoclase. These feldspars are generally anhedral, poorly twinned to nontwinned, cloudy in appearance, and contain profuse small apatite crystals. Potassium feldspars also occur in rounded blebs as inclusions in other minerals, including hornblende. Analyses of the feldspars (table 23) indicate a composition range of $Or_{86.8-88.5}Ab_{9.7-11.7}An_{1.5-1.8}$ in the mafic inclusions. A potassium feldspar from lamprophyre has a composition of $Or_{77}Ab_{18}An_5$. The composition of potassium feldspar from the mafic inclusions is more nearly that of the feldspars from more mafic Boulder Creek Granodiorite.

TWIN SPRUCE QUARTZ MONZONITE

General description. Microcline occurs throughout the Twin Spruce Quartz Monzonite in subhedral to anhedral grid-twinned crystals. Medium-grained quartz monzonite has a variable grain size and chiefly bears large Carlsbad-twinned poikilitic crystals that show good grid twinning or are perthitic. The poikilitic crystals contain inclusions of predominantly zoned plagioclase, biotite, subrounded quartz, and eroded perthitic microcline crystals. Alkali feldspar in fine-grained and speckled quartz monzonite is more nearly equigranular, and plagioclase in the rock appears more altered.

Chemistry. The composition of the potassium feldspars in quartz monzonite is more variable than in the Boulder Creek Granodiorite (tables 22 and 24). The potassium feldspar in sample 384 (table 24) is orthoclase and in sample 381 microcline microperthite; all other analyzed alkali feldspars from quartz monzonite are microcline. The range in composition is from $Or_{84.7-89.6}Ab_{9.5-14.6}An_{0.9-2.2}$. Triclinicity of the analyzed

TABLE 23.—*Chemical and semiquantitative spectrographic analyses of potassium feldspar from mafic inclusions and a lamprophyre dike in Boulder Creek Granodiorite, Front Range, Colo.*

[Total Fe and CaO determined by atomic absorption methods, Na₂O and K₂O determined by flame photometric methods, Wayne Mountjoy, analyst; SiO₂ and Al₂O₃ determined by rapid-rock techniques, Sam Botts, analyst; semiquantitative spectrographic analyses by L. A. Bradley. L, detected but below limit of determination; N, not found; N.d., not done]

| | Mafic inclusions | | Lamprophyre |
	Orthoclase	Microcline	Microperthite
Sample No.---------	334	386	388
Lab. No.[a]---------	D138909	D138929	D139810
	W173440		W173444

Chemical analyses, in weight percent			
SiO₂--------------	63.80	n.d.	62.50
Al₂O₃------------	18.60	n.d.	19.20
FeO[b]--------------	0.05	0.05	0.09
CaO--------------	0.12	0.15	0.28
Na₂O--------------	1.12	1.38	2.09
K₂O--------------	14.10	14.10	12.40
Total------	97.79	(c)	96.56

Semiquantitative spectrographic analyses, in parts per million			
Ba----------------	10,000	10,000	15,000
Cr----------------	N	1	N
Cu----------------	15	15	10
Ga----------------	30	20	30
Ni----------------	5	N	L
Pb----------------	70	70	100
Sr----------------	2,000	1,000	7,000
Zr----------------	100	N	50

Composition ratios			
Ab----------------	9.71	11.74	17.59
An----------------	1.78	1.46	5.03
Or----------------	88.51	86.80	77.38

[a]"W" numbers for Al₂O₃ and SiO₂; "D" numbers for all other oxides and for Al₂O₃ and SiO₂ where there are no "W" numbers.

[b]Total Fe as FeO.

[c]Analysis incomplete.

feldspars varies from 0.65 to 0.82±0.05. Minor elements, especially lead and strontium, are more variable in potassium feldspars from quartz monzonite than in those from granodiorite.

QUARTZ

Most quartz and feldspars in the Boulder Creek Granodiorite are nearly equigranular; however, larger feldspar crystals are common throughout the granodiorite. In areas of cataclasis smaller quartz crystals cluster in rounded or serrate contact with larger quartz crystals or with other minerals. In general, quartz is conspicuously strained and generally free of inclusions. Inclusions of quartz, especially in the feldspars, are subrounded, clear, and locally abundant. As in many of the isopleth maps of other minerals in figure 6 (B, C, E, H), quartz amounts show

TABLE 24.—*Chemical and semiquantitative analyses of potassium feldspar in Twin Spruce Quartz Monzonite, Front Range, Colo.*

[Total Fe and CaO determined by atomic absorption methods, Na₂O and K₂O by flame photometric methods, Wayne Mountjoy, analyst; SiO₂ and Al₂O₃ determined by rapid-rock techniques, H. H. Lipp, analyst for sample 384, Sam Botts for all others; semiquantitative spectrographic analyses, L. A. Bradley, analyst. N, not detected]

Sample No.	[b]381	383	384	380	232	235	85	376
Lab. No.[a]	D138912	D138913		D138717	D138915	D138916	D138918	D138921
	W173448	W173443	D138914	W173435	W173434	W173438	W173445	W173446

Chemical analyses, in weight percent								
SiO_2	63.80	64.40	67.90	65.70	64.40	65.10	64.40	64.40
Al_2O_3	18.60	18.80	17.20	18.40	18.60	18.20	18.80	18.60
FeO[c]	0.07	0.05	0.05	0.11	0.04	0.07	0.05	0.05
CaO	0.13	0.13	0.15	0.18	0.16	0.11	0.10	0.10
Na_2O	1.13	1.51	1.54	1.14	1.64	1.24	1.18	1.11
K_2O	14.20	14.10	13.60	13.80	14.10	14.50	14.70	14.80
Total	97.93	98.99	100.44	99.33	99.24	99.22	99.23	99.06

Semiquantitative spectrographic analyses, in parts per million								
Ba	7,000	3,000	3,000	10,000	2,000	3,000	5,000	3,000
Cu	15	30	5	15	15	15	2	10
Ga	50	20	30	20	30	30	20	20
Ni	N	N	5	N	N	N	N	N
Pb	200	100	50	70	100	100	70	70
Sr	1,000	500	500	2,000	500	500	1,000	500
Zr	150	100	70	20	50	N	70	50

Composition ratios								
Ab	9.84	13.02	13.63	10.01	14.00	10.69	10.03	9.52
An	1.35	1.14	1.32	2.21	1.34	0.99	1.10	0.92
Or	88.81	85.84	85.05	87.78	84.66	88.32	88.87	89.56

[a]"W" numbers for Al_2O_3 and SiO_2; "D" numbers for all other oxides and for Al_2O_3 and SiO_2 where there are no "W" numbers.

[b]Sample has low total oxides; SiO_2 may be low.

[c]Total Fe reported as FeO.

a strong west to northwest regional percent distribution pattern in the central and southwestern part of the batholith (fig. 6E).

In the Twin Spruce Quartz Monzonite, quartz and the feldspars are equigranular. Quartz contacts are mutual, serrate, or embayed; it is always strained, and small blebs of quartz along mineral boundaries are particularly noticeable in strained and altered rocks. Quartz averages about 29 percent of the quartz monzonite, except in the Nederland quadrangle and in the lens in schist and gneiss adjacent to the west contact of the Boulder Creek Granodiorite (pl. 2) where it averages 35 percent.

ACCESSORY MINERALS

Accessory minerals including the ores, allanite, apatite, and sphene, are common and characteristic of the Boulder Creek Granodiorite and associated mafic inclusions but are relatively sparse in the Twin Spruce

Quartz Monzonite and the more mafic rocks. Apatite, sphene, allanite, zircon, and monazite and (or) xenotime are abundant in that order.

Ores. Ores include iron oxides (magnetite, hematite, ilmenite) and the sulfides (pyrite, chalcopyrite, molybdenite). In the Boulder Creek Granodiorite the ores are predominantly magnetite and some hematite and pyrite; other ore minerals are extremely rare. Hematite is generally in the range of 15–20 percent of the ores in Twin Spruce Quartz Monzonite; it occurs as individual grains, as an intergrowth in magnetite, or as an overgrowth on the magnetite. Iron oxides in the Twin Spruce Quartz Monzonite are more complex because ilmenite is also present. Ilmenite is less abundant than magnetite or hematite, but, where present, it is associated with magnetite or hematite as single grains or intergrown with hematite. The speckled appearance of quartz monzonite is caused by the clustering of ores and adjacent leucocratic haloes. The dominant iron oxide in the clusters is hematite.

Sphene. Sphene in the Boulder Creek Granodiorite occurs predominantly along the trend of hornblende-bearing Boulder Creek Granodiorite (fig. 6A and C). Sphene in the batholith proper averages 1.5 percent but along the western contact it is nearly absent. Granodiorite lenses within the metasedimentary rocks, along the western contact, bear almost no sphene but further to the west in lenses of granodiorite associated with the more mafic rocks, sphene averages 3 percent; these lenses are also rich in ores. The occurrence of sphene is twofold: (1) as primary sphene in hemihedral to anhedral crystals clustered with the mafic minerals and the accessory minerals apatite, allanite, and zircon; or (2) as secondary sphene, which rims magnetite, forms small exsolved blebs in biotite and replaces biotite along cleavage and grain boundaries. Sphene is often bleached along magnetite-sphene contacts.

Sphene in the Twin Spruce Quartz Monzonite is generally anhedral and is dominantly a product of the alteration of some plagioclase, magnetite, and biotite; it corrodes magnetite grains and is often in bleached contact with magnetite.

Both a light greenish-yellow and a grayish-yellow sphene can be found in a single hand specimen. No effort was made to separate the two for chemical analysis but the greenish-yellow variety is more common and is represented in the chemical analysis. According to partial chemical analysis of CaO and TiO_2 (table 25), all sphene samples are very similar in regard to CaO and TiO_2. Spectrographic analyses, however, indicate that the sphene from Twin Spruce Quartz Monzonite is richer in the trace elements cerium, copper, lead, yttrium, zirconium, and neodymium than sphene in Boulder Creek Granodiorite (table 25). Spec-

TABLE 25.—*Chemical and semiquantitative spectrographic analyses of sphene in Boulder Creek Granodiorite, inclusions in granodiorite, and Twin Spruce Quartz Monzonite, Front Range, Colo.*

[CaO determined by atomic absorption methods, TiO_2 colorimetrically determined, John Gardner, analyst; spectrographic analyses by L. A. Bradley. N, not determined]

	Boulder Creek Granodiorite		Inclusions		Twin Spruce Quartz Monzonite
Sample No.	47	49	386	334	376
Lab. No.	D138953	D138956	D138954	D138955	D138957
Chemical analyses, in weight percent					
CaO	29.3	28.8	29.8	27.9	28.3
TiO_2	35.8	35.4	35.4	36.0	35.4
Semiquantitative spectrographic analyses, in parts per million					
Ba	10	30	30	10	150
Ce	2,000	2,000	3,000	7,000	5,000
Cr	150	100	150	50	50
Cu	30	20	150	20	1,000
Dy	200	200	200	300	150
Ga	N	N	N	10	7
La	300	200	700	2,000	1,500
Mo	15	30	15	20	15
Nb	300	200	100	300	300
Nd	3,000	3,000	3,000	7,000	5,000
Ni	N	N	5	N	N
Pb	20	70	50	50	150
Pr	500	200	500	1,500	1,000
Sc	20	15	20	20	50
Sm	700	700	500	1,500	1,000
Sn	200	150	100	200	150
Sr	70	100	70	150	150
V	700	700	700	300	500
Y	1,500	1,500	1,500	2,000	3,000
Yb	70	70	70	50	70
Zr	300	500	200	500	1,000

trographic analyses of trace elements in sphene from inclusions indicate that some sphene has trace elements similar to sphene in Twin Spruce Quartz Monzonite and other sphene is more closely allied to Boulder Creek Granodiorite.

Apatite. Apatite occurs as small euhedral to anhedral crystals that, according to X-ray powder patterns, are fluorapatite. It is very pale greenish in hand specimen, colorless in thin section, and is predominantly associated with the mafic clusters in the granodiorite. Its modal distribution indicates that apatite is partly controlled by rock type. (Compare figs. 3 and 6E). In the Boulder Creek Granodiorite apatite tends to concentrate in the rocks of quartz diorite (tonalite) or granodiorite composition and is nearly absent in those of quartz monzonite composition.

Allanite. Allanite is rare in the mafic rocks to the west of the batholith proper, including the Los Lagos and Severance lenses (table 7) but is a common accessory mineral in mafic inclusions in the batholith (table 6, samples 318–327, 333) and also in the lam-

prophyre (table 6, samples 328, 329, 331, 332). Allanite in the Twin Spruce Quartz Monzonite, however, rarely exceeds 0.2 modal percent and normally if present is in trace amounts only. The distribution of allanite in the Boulder Creek Granodiorite is outlined in figure 6D. The distribution pattern in figure 6D does not agree with the one presented by Hickling, Phair, Moore, and Rose (1970, p. 1976). Their pattern was based on fewer than one-third of the observation points used here. Areas where allanite is more abundant, greater than 0.2 percent, correspond to areas that are in the trend of hornblende-bearing Boulder Creek Granodiorite. Allanite, however, is not confined to hornblende-bearing rocks, but where it does occur without hornblende it is found always in less than 0.2 percent amounts. This relationship is also true of the scattered plutons to the west of the batholith. The Pisgah pluton is a good example; large allanite crystals occur in it but no hornblende thus far has been found in the pluton.

Physical properties of allanite in the Boulder Creek batholith have been studied extensively by Hickling, Phair, Moore, and Rose (1970) and will only be mentioned briefly here for consistency in mineral description. Allanite in thin section is yellowish brown to reddish brown and commonly is zoned and rimmed by epidote. The centers of crystals are commonly isotopic, and epidote usually occurs between biotite-allanite contacts. Hickling, Phair, Moore, and Rose (1970) reported high-birefringent allanite in the northwest part of the batholith but high-birefringent allanite is also found sparsely scattered throughout the central part of the batholith extending to the southern border. In separating allanite from rock samples, it was found that allanite is also locally associated with pyrite. Pyrite attached to or as an inclusion in allanite is euhedral to anhedral. This association is rarely seen in thin section. An explanation may be that the small allanite and still smaller pyrite crystals are plucked out in grinding of the section.

It is here proposed that both primary and secondary allanite exists in these rocks. This interpretation differs from that of Hickling, Phair, Moore, and Rose (1970), who proposed that allanite was all of secondary origin, principally an alteration product of biotite. True primary allanite is not readily distinguishable because of the large amount of allanite replacing biotite, but small euhedral crystals of allanite in plagioclase and hornblende, hemihedral allanite crystals cutting biotite at an angle, and large allanite crystals in granodiorite plutons well out from the batholith all suggest that some of the allanite is primary. It is suspected that a considerable amount of the larger allanite crystals in the batholith is also primary. The modal distribution pattern of allanite,

which follows that of hornblende in a general way, suggests that primary allanite is characteristic of the batholith.

Allanites in Twin Spruce Quartz Monzonite are often zoned (sometimes as many as five or more distinct zones can be counted) but have sharp contacts against adjacent minerals (fig. 37). Almost no epidote occurs at the contact of allanite and biotite as is commonly
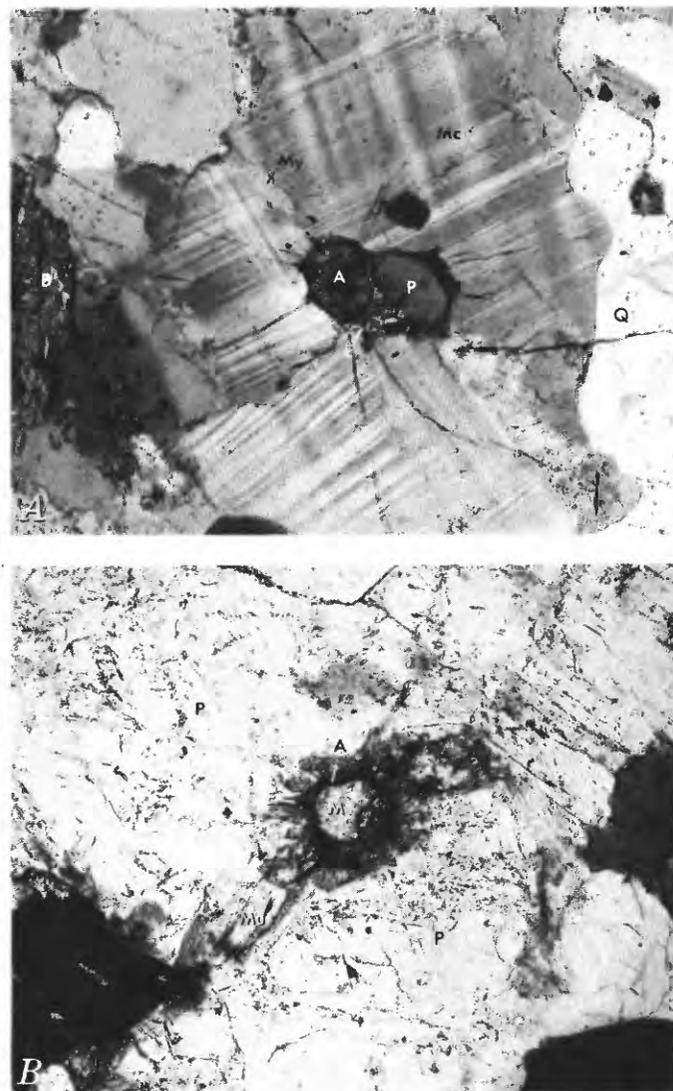
FIGURE 37.—Allanite and monazite in Twin Spruce Monzonite. A, Allanite crystal slightly altered to epidote with growth pressure cracks radiating away from it. Allanite may be late primary crystal in Twin Spruce Quartz Monzonite (sample 85, table 13). Plain light, ×100. B, Monazite crystal with brown, almost isotropic alteration zone that may be allanite. Epidote occurs in radiating growths on allanite (sample 89, table 8). Plain light, ×100. A, allanite; B, biotite; E, epidote; M, monazite; Mu, muscovite; My, myrmekite; P, zoned plagioclase; Mc, microcline; Q, quartz. Photographs by Louise Hedricks, U.S. Geological Survey.

observed in the Boulder Creek Granodiorite. In quartz monzonite, monazite locally alters to what appears to be allanite (fig. 37B). It appears that allanite from hornblende diorite may be richer in copper, yttrium, neodymium, samarium, gadolinium, and dysprosium than allanite from either granodiorite or its inclusions (table 26).

Allanite in a quartz monzonite lens along the crest of the ridge north of Boulder County Hill in the Caribou pluton (pl. 1) appears to have formed from the reaction of monazite and biotite. Within the batholith proper, quartz monzonite lenses locally bear monazite that has coronas of what may be secondary allanite (fig. 37B). This secondary allanite is mantled by epidote crystals formed by the reaction biotite+plagioclase?+mona-zite→allanite+epidote+iron oxides. Dietrich (1961) noted similar coronas of monazite altering to epidote in the Mount Airy Granite.

Monazite and (or) xenotime. Both monazite and xenotime are rare accessory minerals in the Boulder Creek Granodiorite and Twin Spruce Quartz Monzonite. Both minerals are difficult to identify in thin section because they usually occur as very small subhedral to subrounded crystals that are associated with apatite, biotite, allanite, and ores. Xenotime has a faint yellow pleochroism and monazite a faint brown pleochroism, but this pleochroism is difficult to observe unless the minerals are isolated in leucocratic areas of the thin section.

ALTERATION MINERALS

Muscovite-sericite. Muscovite never occurs with hornblende except as small flakes totally within plagioclase crystals. Wells (1967, p. D22) also noted this characteristic from his work in the Eldorado Springs quadrangle.

Muscovite laths in Boulder Creek Granodiorite lenses adjacent to the batholith are at large angles to biotite with no evident reaction between them. This muscovite is older than most microcline and quartz and is perhaps a primary muscovite as both microcline and quartz embay it. In addition to this early muscovite, a later muscovite occurs in large lathlike patches that extend across microcline crystals. Within the batholith, all muscovite is clearly secondary; it forms thin rims on the ores, and occurs as overgrowths on biotite, as growths along biotite cleavage, or forms in plagioclase where plagioclase is intensely altered. Epidote and (or) calcite may accompany the muscovite in recrystallized parts of the batholith.

Muscovite appears to be both primary and secondary in the Twin Spruce Quartz Monzonite. Primary muscovite appears to be the same age as biotite and

the ores, or younger, and has had a long and complex history. In the southeast part of the batholith, along the granodiorite-quartz monzonite contact, rocks that have been recrystallized contain secondary musocovite laths that are larger than anywhere else in the batholith. In the field muscovite is plainly visible and often profuse. In thin section the large laths appear eroded again by potassium feldspar and quartz. The laths are characteristically bent and strained and dendritic-like. Muscovite having a single orientation has grown in the host mineral, feldspar.

Prehnite and hydrogarnet. Both minerals were first described by Wrucke (1965) as occurring in the north-east part of the exposed batholith. This study confirms that this is also the only area of the batholith in which they occur. Prehnite alone has been found only along the northwest contact of the batholith and along its most northern contact in Left Hand Canyon. Growth of prehnite is due to the release of calcium in the altera-tion of plagioclase and hornblende. Prehnite in lens-shaped aggregates parallel to the (001) cleavage in biotite is perhaps epitaxial; the 001 surface provides suitable nucleation sites (Moore, 1976, p. 527). Prehnite was associated with quartz in only one thin section and this was in a small vein cutting other minerals, indicating mobility of Ca^{2+} ions. Hydrogarnet replaces prehnite but is more likely part of the reaction involving hornblende and (or) biotite+plagioclase.

The experiments of Coombs, Ellis, Fyfe, and Taylor (1959) showed that prehnite is not stable above 450 °C at water pressure of as much as 500 MPa; thus a magmatic origin is not likely. A calcium or potassium metasomatism accompanying faulting, shearing, and recrystallization may be possible.

Epidote, clinozoisite, and piedmontite. Very little clinozoisite has been identified in the southern two-thirds of the batholith because of its similar occurrence to epidote and the difficulty in distinguishing it from epidote; therefore the two are reported together in modes. Piedmontite was only recognized at one local-ity, north of Wallstreet, Gold Hill quadrangle, in a pegmatite outcrop. The piedmontite gives the rock a very pink color. Crystallization was probably from hydrothermal solutions.

Like sphene, epidote is nearly absent from grano-diorite lenses in metasedimentary rocks adjacent to the Boulder Creek batholith and from the batholith near its contact, except in areas where hornblende-bearing rocks occur along the contact (fig. 6A). Epidote chiefly replaces biotite or hornblende associated with biotite; hornblende only weakly alters to epidote. Replacement is along crystal boundaries or in aggregates along biotite cleavage. Also, epidote

TABLE 26.—*Chemical and spectrographic analyses of allanite in Boulder Creek Granodiorite, inclusions, and biotitic hornblende diorite, Boulder Creek batholith area, Front Range, Colo.*

[Oxides determined by lithium borate fusion, X-ray methods by J. S. Wahlberg; spectrographic analysis by J. C. Hamilton. >, greater than, (-), not found; N.D. not done]

	Boulder Creek Granodiorite		Inclusion		Hornblende diorite
Sample No.—————	[a]49	47	385	334	352
Lab. No.—————	D138960	D138961	D172033	D138962	D138963
Chemical analyses, in weight percent					
CaO—————————	13.5	12.1	17.0	12.1	10.6
Ce_2O_3—————————	9.0	9.0	12.0	10.5	8.9
FeO[b]—————————	12.0	12.2	16.2	12.0	11.5
La_2O_3—————————	5.5	5.5	3.4	7.2	4.3
MnO—————————	0.2	1.3	0.2	0.3	0.3
Spectrographic analyses, in parts per million					
B—————————	n.d.	——	50	——	30
Ba—————————	n.d.	70	500	150	300
Co—————————	n.d.	20	20	15	30
Cr—————————	n.d.	150	700	70	70
Cu—————————	n.d.	100	100	70	1,500
Dy—————————	n.d.	70	——	70	500
Er—————————	n.d.	70	——	70	100
Eu—————————	n.d.	150	100	150	150
Ga—————————	n.d.	50	50	30	30
Gd—————————	n.d.	150	300	200	1,500
Ho—————————	n.d.	100	70	70	100
Mo—————————	n.d.	15	——	——	——
Nd—————————	n.d.	>20,000	30,000	30,000	70,000
Ni—————————	n.d.	20	50	7	——
Pb—————————	n.d.	300	900	150	500
Pr—————————	n.d.	>10,000	10,000	10,000	15,000
Sc—————————	n.d.	500	1,000	700	1,000
Sm—————————	n.d.	3,000	2,000	3,000	7,000
Sr—————————	n.d.	700	1,500	1,000	1,500
Th—————————	n.d.	5,000	10,000	2,000	5,000
V—————————	n.d.	700	500	700	500
Y—————————	n.d.	500	700	700	2,000
Yb—————————	n.d.	50	50	15	70
Zr—————————	n.d.	300	150	300	500

[a]Usual limits of detection do not apply due to dilution technique. [b]Total Fe as FeO.

replaces allanite, sometimes leaving only an allanite core. Allanite-biotite contacts are generally separated by a zone or layer of epidote, and incomplete reactions involving epidote are: biotite→epidote+sphene; hornblende+biotite→sphene+epidote+magnetite; hornblende→epidote±magnetite; allanite+biotite→epidote.

Epidote in the batholith modally occurs in numerous small epidote islands that are difficult to correlate with any of the other mineral trends, but if allanite and epidote modes are combined, there is a distinct pattern that again mimics the distribution of hornblende-bearing rocks in the batholith. The higher values of allanite are not in epidote-rich areas but appear to be coincident with the more mafic inclusions in the Boulder Creek batholith.

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