Hornblendes from a Region of High-Grade Metamorphism, Front Range, Colorado

GEOLOGICAL SURVEY BULLETIN 1392

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By DOLORES J. GABLE *and* VERTIE C. SMITH

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Chemically analyzed Precambrian igneous and metamorphic hornblendes in general do not conform to the same patterns in a region of high-grade metamorphism where hornblende compositions are dependent primarily on the mineral assemblage

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HORNBLENDES FROM A REGION OF HIGH-GRADE METAMORPHISM, FRONT RANGE, COLORADO

By DOLORES J. GABLE and VERTIE C. SMITH

ABSTRACT

Calcic hornblendes from Precambrian metamorphic and igneous terranes in the central Front Range, Colo., were subjected to a sillimanite-grade metamorphism and have compositions that are more dependent on host-rock mineral assemblages than on host-rock chemical composition. The partitioning of the mafic oxides Mg, Fe^{+2}, Fe^{+3}, and Mn between biotite and hornblende is necessary in relating the total mineral assemblage to the composition of the host rocks. Orderly distribution of the mafic oxides between biotite and hornblende yields rather consistent distribution patterns, and these patterns appear to relate to the regional metamorphism. Fe^{+3} in the metamorphic host rocks controls, though perhaps imperfectly, the Mg content in hornblende, whereas Fe^{+3} in igneous host rocks only exerts partial control over Mg in accompanying hornblende. In general, oxidation-reduction ratios in the igneous hornblendes increase with increases in Fe^{+3} but decrease in metamorphic hornblendes with increasing Fe^{+3}.

INTRODUCTION

SCOPE AND PURPOSE

The crystalline core of the Front Range, which lies just west of Denver, Colo., contains many hornblende-bearing gneisses and syntectonically intrusive hornblende-bearing rocks, all Precambrian in age. Bulk rocks and the minerals hornblende and biotite separated from them were studied to compare the metamorphic effects on hornblende between rock types produced by a sillimanite-grade regional metamorphism. Hornblende, inasmuch as it occurred in all rocks chosen, was studied in the greatest detail to relate its physical and chemical properties to the metamorphism. Particular attention was given to hornblende and biotite in the intrusive Boulder Creek Granodiorite and associated rocks emplaced near the end of the major regional metamorphism in order to compare their chemical behavior with the hornblendes from adjacent Precambrian gneisses.

SAMPLE PREPARATION AND LABORATORY STUDIES

Chemical analyses were made in the Denver and Washington laboratories of the U.S. Geological Survey; analysts are credited in the appropriate tables in text. Standard rock analyses were made following

the procedures described by Peck (1964); rapid rock analyses and colorimetric and atomic-absorption studies were done following the procedures outlined by Shapiro and Brannock (1962). Spectrographic analyses are arbitrarily reported to the nearest number in the series 1, 0.7, 0.2, 0.15, and 0.1, whose numbers represent approximate midpoints of group data on a geometric scale. Precision of a reported value is approximately plus or minus one bracket at 68-percent confidence or two brackets at 95-percent confidence.

Pure mineral separates of hornblende and biotite were obtained by use of ultrasonic cleaner, heavy liquids (bromoform and methylene iodide), and a Frantz isodynamic magnetic separator. Purity of some separates also necessitated the use of centrifuge-separation procedures similar to those described by Schoen and Lee (1964). All samples, by binocular microscope, contained no more than 1 percent impurities.

Optical determinations were made on single grains and studied by modified spindle-stage procedures described by Wilcox (1959) and Wilcox and Izett (1968). Refractive indices were determined using the focal-masking techniques described in detail by Cherkasov (1955a, b; 1957). For each sample numerous grains were first observed in an index oil close to β, and the variability of index was observed. Indices were then run on an average of three grains for each of the samples. The range in indices for samples is due to zoning.

X-ray powder-diffraction data were obtained by using a Norelco X-ray diffractometer with Ni-filtered CuKα, radiation. Scans were made at 0.25° per minute in the range 8°–72°(2θ) with a chart speed of 1 inch per minute. An internal standard of CaF_2 was added to each sample and thoroughly mixed. Both an aluminum-mount holder and a collodion-membrane mount (Gude and Hathaway, 1961) were used for some of the runs, however, because most samples contained ample hornblende and because a sharper pattern resulted with the aluminum mount, most hornblendes were run in this way. The holders were carefully packed to reduce preferred orientation of grains. Observed interplanar (d) spacings for each sample were processed through the "least-squares unit-cell refinement" program on an IBM–360–65 computer to determine the major cell parameters (Evans and others, 1963). Mineral densities were measured by two different methods. Samples 2 and 16 were measured by sink-float in heavy liquids, range of accuracy ±0.002; the other samples were measured by taking a weighed 5-gram sample, heating it in water to drive off the absorbed air, and then weighing the sample again, range of accuracy, ±0.01.

GEOLOGIC SETTING

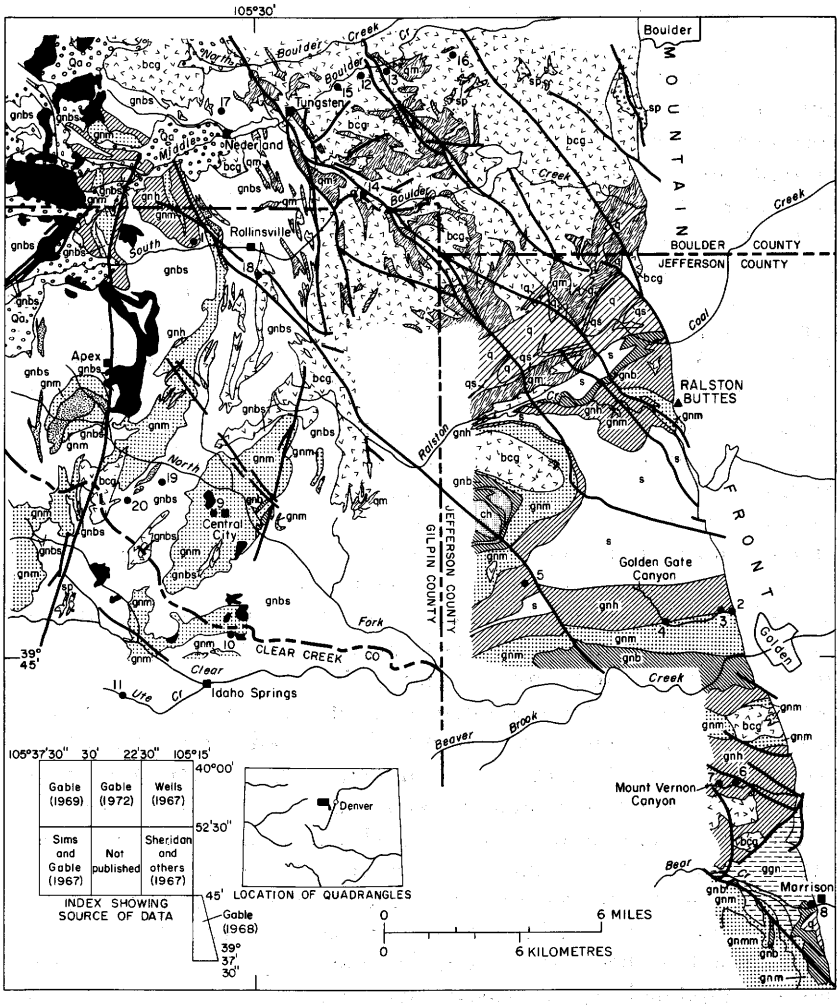
Precambrian metamorphic rocks form the major part of the crystalline core of the Front Range, where they occur as a thick layered

succession that is, in part, both migmatitic and pegmatitic. The most common and widespread layered rocks in the area are biotite gneisses (fig. 1). Interlayered with the biotite gneiss is a thick leucocratic gneiss unit, granitic in appearance, that is referred to as microline gneiss. Hornblende gneiss and amphibolite, a third unit, is generally well foliated and interlayered conformably with biotite gneiss and microcline gneiss units. Hornblende gneiss, biotite gneiss, and microcline gneiss are all finely interlayered with lesser units, including those of calc-silicate gneiss, garnet-quartz gneiss, and quartzite. Amphibolite, as small concordant lenses, is associated with all major rock units. It is more massive than hornblende gneiss, generally finer grained, and may have a well-developed foliation and lineation.

The intrusive rocks of the area are Precambrian and Cretaceous-Tertiary in age. Intrusives of Precambrian age are dominantly of two groups: (1) granodiorite, from the Boulder Creek Granodiorite (Boulder Creek Granite of Lovering and Goddard, 1950, pl. 2), and (2) biotite-muscovite-quartz monzonite which belongs to either Silver Plume Quartz Monzonite (Silver Plume Granite of Ball, 1906, p. 383) or quartz monzonite which is intimately associated with the Boulder Creek Granodiorite. Intrusive Precambrian rocks not named and in part associated with the Boulder Creek Granodiorite include quartz diorite, diorite, hornblende, and some gabbro. These rocks were metamorphosed to varying degrees during a 1,450- to 1,740-m.y. (million year) major regional metamorphism (Hedge and others, 1967). Intrusives not affected by the regional metamorphism and of no further concern to this report include Silver Plume Quartz Monzonite, 1,450 m.y. in age, and numerous Cretaceous-Tertiary igneous rocks that cut diagonally across the northern part of the study area.

The framework of the area developed during a series of regional metamorphic events, all Precambrian in age. At least three periods of deformation have been recognized. The first two periods of deformation were accompanied by a pervasive high degree of metamorphism. The third period was largely cataclastic in character and local in extent and was superimposed on the two earlier plastic deformations. Migmatization and emplacement of the Boulder Creek Granodiorite took place late in the first period of deformation and continued into the second period, as indicated by forcible syntectonic emplacement of these rocks. Some quartz diorite, diorite, and hornblendite are intrusive in Boulder Creek Granodiorite and, in turn, are invaded by Silver Plume Quartz Monzonite; thus, an intermediate position in the intrusive sequence is reasonably well established for at least some of these mafic rocks.

Metamorphism throughout the area does not appear to have been particularly uniform but, in general, was of amphibolite to low-granulite grade. The highest grade of metamorphism appears to have been centered in the Central City–Morrison areas where muscovite,



EXPLANATION

Qa Alluvium, colluvium, and glacial deposits (Quaternary)

INTRUSIVE ROCKS

- Intrusive rocks (Tertiary and Cretaceous)
- sp Silver Plume Quartz Monzonite (Precambrian Y)
- gm Quartz monzonite of Boulder Creek affinity (Precambrian X)
- bcg Boulder Creek Granodiorite (Precambrian X)
- Diorite, gabbro, quartz diorite, and hornblendite undifferentiated (Precambrian)
- ggn Gneissic granodiorite (Precambrian)

METASEDIMENTARY ROCKS (PRECAMBRIAN X)

- gnm Microcline-quartz-plagioclase-biotite gneiss± hornblende± garnet
- gnmm Migmatitic microcline gneiss
- gnb Predominantly biotite-quartz-plagioclase gneiss
- gnbs Sillimanitic biotite-quartz-plagioclase gneiss — Both biotite and sillimanitic biotite-quartz-plagioclase gneiss may contain layers that are garnet, cordierite, gedrite, or hornblende bearing
- s Mica schist
- gnh Predominantly hornblende gneiss—Interlayered with amphibolite, calc-silicate gneiss, and biotite-quartz-plagioclase gneiss
- q Quartzite
- qs Schistose quartzite
- ch Calc-silicate gneiss

Contact

Fault

•11 Hornblende sample locality and number

sillimanite, and potassic feldspar appear to be in equilibrium (Gable and Sims, 1969, p. 3) in rocks of appropriate composition. At Ralston Buttes the lack of microline associated with sillimanite and muscovite may be due to lower grade or to rock composition. Sheridan, Maxwell, and Albee (1967, p. 37–38) believed that it is due to a lesser intensity of metamorphism.

HOST-ROCK DESCRIPTION

GENERAL CHARACTER

Hornblendes were separated from mafic layers in microcline gneiss, hornblende gneiss, and in amphibolite, intrusive Boulder Creek Granodiorite, hornblende diorite, and hornblendite, tables 1–3.

Microline gneiss layers contain only sparse, widely scattered, hornblende-bearing lenses (sample 10, table 3), some of which are mafic enough to be called amphibolite. These amphibolite lenses are interlayered with the gneiss generally near or adjacent to the contact of microcline gneiss with biotite gneiss. Microcline gneiss with singular scattered hornblende crystals occurs adjacent to nearly all hornblende-bearing gneiss contacts, whether the contacts are gradational or sharply defined. The hornblendes from microcline gneiss form ragged, generally subhedral grains, intergrown with or partly altered to biotite.

Hornblende gneiss (samples 1–7, table 2) is a fine- to medium-grained, nearly equigranular rock that is weakly to strongly foliated and possesses good mineral alinement, primarily of hornblende. The gneiss consists predominantly of hornblende and plagioclase and widely varying amounts of quartz, biotite, and pyroxene. Hornblende-plagioclase biotite and hornblende-plagioclase-pyroxene gneiss (samples 1, 5, 6, table 2) are common variants in hornblende gneiss. Interlayered within the hornblende-plagioclase gneiss are lenses of amphibolite, biotite gneiss, microcline gneiss, calc-silicate gneiss, and lesser amounts of quartz gneiss. Amphibolites in the hornblende gneiss unit are represented by samples 2, 3, 4, 7, and 8, table 2.

Hornblendes from the hornblende gneiss unit are 0.2–0.6 mm in size, rarely twinned, and only occasionally zoned. Biotite, where present, is subordinate in size to hornblende and in many places is interstitial. Plagioclase, the second most abundant mineral, ranges in composition from oligoclase to calcic andesine. Quartz is generally subordinate in size to hornblende and feldspar and is xenoblastic. It becomes elongated in strongly foliated rocks and shows a slight tendency to be segregated in the lighter layers.

Microcline gneiss and hornblende gneiss are believed to have been mostly of sedimentary origin, but some may have been of volcanic

FIGURE 1 (facing page). — Generalized geologic map of a part of the Front Range, Boulder, Gilpin, and Jefferson Counties, Colo.

TABLE 1. — *List of samples, field numbers, and locality descriptions used in this report*

[All localities in the Tungsten, Central City, and Ralston Buttes quadrangles are taken from the 1942 editions of the topographic maps; all localities in the Morrison quadrangle are from the 1957 edition]

Sample No.	Field No.	Description of sample locality
		Amphibolite and hornblende plagioclase gneiss in the rock unit hornblende gneiss (Amphibolite consists of hornblende and plagioclase and <15 percent of other minerals)
1	N-322A	Outcrop in hornblende gneiss layer, 1,150 feet southwest of Rollinsville Ranger Station warehouse on southeast slope of knob, sec. 35, T. 1 S., R. 73 W., Nederland quadrangle.
2	GG-1	Roadcut in hornblende gneiss layer, 1,250 feet west of sedimentary Precambrian contact on Golden Gate Canyon road, sec. 20, T. 3 S., R. 70 W., Golden quadrangle.
3	GG-2	Roadcut in hornblende gneiss layer, 1,450 feet west of elevation 6,618 feet on Golden Gate Canyon road, sec. 25, T. 3 S., R. 71 W., Ralston Buttes quadrangle.
4	GG-3	Roadcut in hornblende gneiss layer, 800 feet west of elevation 7,184 feet on Golden Gate Canyon road, sec. 23, T. 3 S., R. 71 W., Ralston Buttes quadrangle.
5	GG-4	Roadcut in hornblende gneiss layer on Robinson Hill road, 1,500 feet east of horseshoe curve and 1/4 mile southwest of intersection of Robinson Hill road with Golden Gate Canyon road, sec. 17, T. 3 S., R. 71 W., Ralston Buttes quadrangle.
6	M-276a	Roadcut in hornblende gneiss layer, 1,900 feet west of Mother Cabrini Shrine road on old U.S. Highway 40, Mount Vernon Canyon, sec. 16, T. 4 S., R. 70 W., Morrison quadrangle.
7	M-279a	Roadcut in hornblende gneiss layer, 1,300 feet east of BM7053, old U.S. Highway 40, Mount Vernon Canyon, sec. 17, T. 4 S., R. 70 W., Morrison quadrangle.
		Amphibolite lens in biotite-cordierite gneiss
8	M532-C2	Hornblende from amphibolite layer in garnet-cordierite-sillimanite-biotite gneiss; roadcut, 1,150 feet west of sedimentary Precambrian contact on Colorado Highway 74, Bear Creek Canyon, sec. 34, T. 4 S., R. 70 W., Morrison quadrangle.
9	S257-52X	Hornblende from amphibolite layer in cordierite-gedrite-biotite gneiss, 800 feet south of the Glory Hole, Quartz Hill area, Central City quadrangle.
		Microcline gneiss
10	St-5	Microcline gneiss, outcrop in Buttermilk Gulch, southeast corner of Central City quadrangle.
		Boulder Creek Granodiorite and associated rocks
11	St-3	Boulder Creek Granodiorite on Ute Creek, Idaho Springs quadrangle, sec. 7, T. 3 S., R. 73 W.
12	T-477-67	Boulder Creek Granodiorite from cut on aqueduct 1,800 feet southwest of BM7608, sec. 3, T. 1 S., R. 72 W., Tungsten quadrangle.
13	T-483-67	Quartz diorite phase of Boulder Creek Granodiorite, from cut on aqueduct, 1,750 feet northwest of quarter corner 8220, secs. 2 and 11, T. 1 S., R. 72 W., Tungsten quadrangle.
14	T415-67	Boulder Creek Granodiorite from roadcut 900 feet east of Winiger Ranch, sec. 27, T. 1 S., R. 72 W., Tungsten quadrangle.
15	T-467-67	Boulder Creek Granodiorite from cut along aqueduct 2,200 feet east of Castle Rock, sec. 9, T. 1 S., R. 72 W., Tungsten quadrangle.
16	T-170-68	Mafic phase of Boulder Creek Granodiorite, outcrop located approximately at 7,400-foot contour on ridge northwest of Calhoun Gulch, sec. 6, T. 1 S., R. 71 W., Tungsten quadrangle.
		Hornblende diorite
17	N-72-65	Hornblende diorite lens, 1,000 feet west of Colorado Highway 160 and 3,200 feet due north of Nederland Post Office, sec. 13, T. 1 S., R. 73 W., Nederland quadrangle.
18	T-219	Biotitic hornblende diorite lens in roadcut, 500 feet due northeast of BM8592 on Colorado Highway 119, sec. 6, T. 2 S., R. 72 W., Tungsten quadrangle.
		Hornblendite
19	D-245b	Hornblendite lens located approximately 400 feet south-southwest of section corner 8,904 feet between Chase Gulch and North Clear Creek, Central City quadrangle.
20	S376-1-53	Hornblendite lens on Pisgah road, 1/2 mile due east of Pisgah Lake, sec. 4, T. 3 S., R. 73 W., Central City quadrangle.

origin. The interlayered biotite gneisses are considered to be of sedimentary origin. Fine interlayering and conformity of the biotite, calc-silicate, quartzite, and hornblende gneiss, with no crosscutting relationships, lend support to all being of predominantly sedimentary origin.

Boulder Creek Granodiorite ranges in composition from mafic quartz diorite to quartz monzonite, but its average composition is granodiorite (samples 12–16, table 2). The rock is medium to very coarse grained with a predominantly hypautomorphic-granular texture. Leucocratic minerals are as much as 4 cm long. Biotite, hornblende, and iron oxides commonly cluster together, and accessory minerals, sphene, allanite, epidote, and some apatite are generally associated with them. Hornblende forms euhedral to anhedral crystals, as much as 1.5 cm long, which may be embayed by biotite. Rare local hornblende crystals have altered pyroxene centers. Traces of iron oxides occur along fractures and grain boundaries of hornblende. Plagioclase is oligoclase-andesine; potassic feldspar is microcline.

Hornblendite (samples 19, 20, tables 2, 4) occurs in intrusive pods and lenses; it is generally fine to medium grained, weakly foliated to nonfoliated, and equigranular and consists mainly of hornblende and subordinate plagioclase. The hornblende is in euhedral to subhedral grains. In sample 19 anhedral pyroxene is subordinate in size to hornblende and is partly altered to chlorite. The hornblende in sample 20 is of two generations; the larger crystals display a clustering of opaque oxides along the cleavage. The centers of a few of these crystals have colorless patches which are probably remnants of pyroxene. The second-generation hornblende crystals are subhedral, are smaller in size, and have no inclusions.

Hornblende diorite, a medium-grained to rarely coarse grained intrusive rock, is found in elongated lenses as much as 2 km long and less than 1 km wide, although most lenses are considerably smaller. The diorite is generally massive and equigranular; however, biotitic phases are somewhat foliated but generally lack the strong foliation that characterizes the amphibolites of the area. Hornblende and plagioclase with variable amounts of pyroxene and biotite make up the bulk of the rock (table 2, samples 17, 18). The hornblende is euhedral to anhedral, nearly free of inclusions, and equigranular with the plagioclase. Locally, hornblende alters to epidote. The plagioclase is andesine to labradorite and well twinned. The iron oxides are magnetite and hematite that occur in single and intergrown crystals.

CHEMICAL COMPOSITION

Because of the different rock types involved, the chemical and spectrographic analyses (table 2) cannot be compared exactly, but there are

TABLE 2. — *Chemical and spectrographic analyses and modes of hornblende-bearing rocks, central Front Range, Colo.*

[Samples 1, 8, 14 by standard rock analyses; E. S. Daniels analyzed sample 1; G. O. Riddle, sample 8; E. Engleman, sample 14. Samples 2–7, 12, 13, 15–19, rapid rock analyses; analysts, Paul Elmore, Sam Botts, Gillison Chloe, Lowell Artis, H. Smith, J. Kelsey, J. Glenn, Joseph Budinsky. nd, not determined; Tr., trace; L, detected but below limit of determination; ---, not looked for. Sample localities are listed in table 1]

Sample No.	1	2	3	4	5	6	7	8	12	13	14	15	16	17	18	19
Rock name	Amphibolite and hornblende plagioclase gneiss in the rock unit hornblende gneiss[1]							Amphibolite lens in biotite-cordierite gneiss		Boulder Creek Granodiorite and associated rocks				Hornblende diorite		Hornblendite
Chemical analyses, in weight percent																
SiO_2	44.75	52.3	53.1	61.4	51.2	48.9	49.6	49.34	64.9	61.8	62.25	63.5	52.2	55.1	47.4	51.2
Al_2O_3	14.34	13.4	14.5	11.3	13.7	13.8	15.9	14.52	16.8	16.8	16.88	16.7	19	13.4	14.4	12
Fe_2O_3	3.70	3.7	2.7	2.5	2.7	2.7	2.1	3.89	1.8	1.5	1.67	1.9	2.6	3.8	3.5	2.6
FeO	8.30	11.5	10.6	6.6	8.1	9.7	9.5	9.00	2.4	3	3.01	3	4.9	6.1	7.2	6.6
MgO	8.50	4.4	3.7	3.9	7.7	7.1	5.6	7.43	2.1	2.5	2.55	2.6	5	7.7	9.7	10.5
CaO	13.63	8.7	8.5	9	9.6	11	10.9	9.68	3.6	5.4	4.30	4.3	7.4	8.6	9.3	11.1
Na_2O	1.74	2.6	3.1	2.2	3	2.2	2.4	2.04	3	3.4	3.43	3.2	3.9	1.9	2	.90
K_2O	1.24	.28	.45	.59	.91	1.4	.49	.65	3.6	3.1	3.84	3	2.4	1.1	2.2	1.1
H_2O+	1.78	.87	.81	.69	.77	1	1	1.70	.73	.88	.65	.70	1.2	.51	1.1	1.3
H_2O-	.07	.13	.09	.09	.07	.08	.09	.06	.05	.06	.07	.03	.14	.10	.16	.13
TiO_2	.95	1.4	1.6	.82	1	.92	.95	1.17	.49	.75	.59	.62	.82	.55	1.2	.97
P_2O_5	.20	.17	.24	.52	.18	.12	.15	.12	.36	.53	.29	.28	.23	.09	.73	.48
MnO	.22	.27	.26	.18	.22	.26	.23	.25	.09	.09	.07	.09	.15	.24	.26	.21
CO_2	.40	<.05	<.05	.30	.06	.08	.40	.04	<.05	.11	.14	.05	<.05	<.05	<.05	<.05
Cl	.02	nd	nd	nd	nd	nd	nd	.04	nd	nd	.04	nd	.04	.03	.10	.02
F	.12	nd	nd	nd	nd	nd	nd	.06	nd	nd	.15	nd	.19	.13	.39	.25
S	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	nd	nd	0
Subtotal	99.96	100	100	100	99	99	99	99.99	100	100	99.93	100	100	99	99	99
Less O	.05	nd	nd	nd	nd	nd	nd	.04	nd	nd	.07	nd	nd	nd	nd	nd
Total	99.91	100	100	100	99	99	99	99.95	100	100	99.86	100	100	99	99	99
Powder density	nd	[2]3.08	[2]3.08	[2]2.98	[2]3.05	[2]3.10	[2]3.05	3.03	[2]2.95	[2]2.95	nd	[2]2.95	[2]3	[2]3.08	[2]3.08	[2]2.92
Oxidation ratios																
mol $\frac{2(Fe_2O_3)\times 100}{2(Fe_2O_3)+FeO}$ = (percent)	29	23	19	26	23	20	17	30	40	31	32	36	32	39	31	27
Spectrographic analyses, in parts per million																
Ag	0	<1	<1	<1	<1	<1	<1	0	1	0	0	0	0	L	L	0
Ba	500	500	200	700	300	200	150	70	1,000	1,000	1,500	1,000	500	150	700	100
Be	0	0	0	2	1	0	0	0	3	3	2	3	1	0	0	0
Ce	0	0	0	0	0	0	0	0	0	300	L	300	500	0	500	100
Co	50	30	30	30	50	30	50	30	20	20	15	20	30	50	50	70

Cr	150	0	10	150	300	70	50	150	30	70	70	50	150	500	300	150
Cu	70	50	2	15	20	20	30	70	7	30	7	20	200	10	5	150
Ga	15	20	20	10	15	15	15	20	10	10	30	15	15	10	15	10
La	0	0	0	100	0	0	0	0	0	70	50	70	70	30	150	0
Mo	0	5	3	3	3	3	3	0	5	0	0	7	5	5	5	5
Nb	0	0	0	3	0	0	0	0	3	3	L	3	10	0	3	7
Nd	---	---	---	---	100	---	---	---	---	0	70	0	0	0	0	0
Ni	150	10	15	50	70	50	30	50	50	50	30	50	100	150	200	200
Pb	15	0	0	0	0	0	0	10	7	7	15	7	7	5	1	0
Sc	30	20	30	20	50	50	50	100	7	10	15	10	20	70	70	30
Sr	1,500	150	200	500	300	300	300	300	700	1,000	1,500	1,000	1,000	300	700	300
V	200	150	200	150	200	150	300	200	70	70	70	70	150	150	150	200
Y	20	30	50	30	30	20	30	30	30	50	30	30	50	30	50	30
Yb	2	3	5	2	3	2	3	5	3	5	3	3	5	3	5	3
Zr	30	50	70	150	70	30	50	50	15	30	150	10	150	150	100	30
Modes, in volume percent																
Potassic feldspar	---	---	---	---	---	---	---	---	19	2.5	18.1	16.6	6.2	Tr.	---	---
Plagioclase	4.4	26.8	35.4	12.6	34.9	35.6	40.7	21.5	34.3	46.7	43.9	40.7	53	28.5	29.2	1
Quartz	.2	10.9	9.9	44	3.1	Tr.	.9	2.7	27.6	14.1	23.9	18.7	3	5.3	3.8	6
Biotite	---	.5	.1	.4	2.5	---	---	6.3	14.4	17.9	14.7	14.6	12.8	---	20.8	Tr.
Muscovite-sericite	15.5	---	---	---	---	---	---	---	---	---	---	---	---	8.2	.1	---
Hornblende	65.1	60.6	52.3	30.8	56.9	56.6	56.5	68.2	.2	14.1	1.4	7.8	22.6	56.5	42.8	79
Clinopyroxene	14.4	---	---	2	---	7.4	---	---	---	---	---	---	---	---	---	---
Orthopyroxene	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	10
Apatite	.4	.4	.4	.7	.1	.2	Tr.	.1	.7	---	.5	.5	Tr.	.1	1.9	2
Iron oxides	Tr.	.8	1.2	Tr.	.3	Tr.	.1	1.2	.7	.4	.9	.6	.2	.6	.3	Tr.
Allanite	Tr.	---	---	---	---	---	---	---	.3	1.1	.4	---	---	---	Tr.	1
Sphene	---	---	.7	1.9	1.1	.1	.7	---	.6	1.1	.4	.1	.7	---	.1	Tr.
Zircon	---	---	---	---	---	---	---	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	---	---	---
Calcite	Tr.	Tr.	4.1	1.1	.1	.8	Tr.		.5	.4	.2	---	---	Tr.	---	---
Chlorite	---	---	---	---	---	---	---	---	---	.1	.1	---	.1	---	---	Tr.
Epidote	---	---	---	.7	---	---	.3	---	1.7	1.6	.5	.4	1.4	.8	1	---
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Composition of plagioclase[3]	An_{41}	An_{33}	An_{34}	An_{34}	An_{33-34}	An_{46}	An_{50}	An_{43}	An_{28}	An_{34}	An_{28}	An_{31}	An_{31}	An_{57}	An_{40}	nd

[1]Amphibolite consists of hornblende and plagioclase and less than 15 percent of other minerals.
[2]Powder density by sink/float — estimated accuracy ±0.002.
[3]Chayes (1952).

Sample No.	*Lab. No.*	*Sample No.*	*Lab. No.*
1	D100280	12	W170105
2	W170057	13	W170106
3	W170058	14	D101974
4	W170059	15	W170104
5	W170060	16	W171834
6	W170054	17	W173309
7	W170055	18	W173310
8	D100505	19	W171836

TABLE 3. — *Modes of hornblende-bearing rocks for which no chemical analyses are available*

[Sample localities are listed in table 1. Tr., trace; nd, not determined]

Sample No.	9	[1]10	[1]11	20
Potassium feldspar	---	15	4	---
Plagioclase	.5	30	40	Tr.
Quartz	---	35	35	---
Clinopyroxene	---	---	---	Tr.
Hornblende	99.5	5	1	100
Biotite	---	15	14	Tr.
Apatite	Tr.	---	1	---
Iron oxides	Tr.	Tr.	1	Tr.
Sphene	---	Tr.	3	---
Epidote	---	---	1	---
Zircon	---	---	Tr.	---
Allanite	---	---	Tr.	---
Total	100.0	100	100	100
Composition of plagioclase	nd	An_{14-16}	An_{30-32}	nd

[1]Approximate mode by visual estimates.

some similarities. Samples 12, 13, and 15, Boulder Creek Granodiorite, are very similar, whereas sample 16, also Boulder Creek Granodiorite but a diorite in composition, is more mafic and intermediate to hornblende diorite of samples 17 and 18. The highest MgO, CaO, and lowest Al_2O_3 values belong to hornblendite sample 19. Hornblende-plagioclase gneiss and amphibolite (samples 1–8) have a composition similar to hornblende diorites. Spectrographic analyses of trace elements are very similar between rock types except for vanadium, which dominantly is found in hornblende gneiss and amphibolite, and nickel, which is predominantly in hornblende diorite and hornblendite. Barium is variable between rock types but is highest in hornblende gneiss, amphibolite, and Boulder Creek Granodiorite.

HORNBLENDE

CHEMICAL COMPOSITION OF HORNBLENDE

Chemical analyses of 20 hornblende samples are presented in table 4; only the analysis of sample 9 has been published earlier (Gable and Sims, 1969, p. 54). Structural formulas were calculated on the basis of 24 (O, OH, F, Cl), using a computer program and assuming a structural formula of $A_{0-1}X_2Y_5Z_8O_{22}$. The current trend is to calculate hornblende formulas on the basis of 23 oxygens, but 24 was used here inasmuch as Phillips (1963, p. 701) stated that a possible deficiency in hydrogen in OH sites can be overlooked if the anhydrous method of calculating a formula is followed. Although Dodge, Papike, and Mays (1968, p. 400) found that hydrogen deficiency is unimportant in the calculation of a structural formula for common hornblende, they did find that specific gravities calculated on "conventionally" analyzed hornblendes, on the

basis of 24 oxygens, agreed better with observed specific gravities. Three of the hornblendes in table 4 have less than 1.70 weight percent H_2O, but these hornblendes were still computed on the basis of 24 oxygens because the hydrogen deficiency appeared real for the hornblendes from the igneous rocks in comparison with those from metamorphic gneisses (table 4).

All hornblendes are calcic and plot between the two end-member series tremolite–ferrotremolite and pargasite + magnesiohastingsite–ferropargasite + hastingsite (fig. 2).

Major element variation between hornblendes of the various rock types of table 4 is shown in figure 3. CaO, Na_2O and K_2O vary little in hornblendes, whereas Fe_2O_3 is somewhat more variable, with the highest Fe_2O_3 values represented by Boulder Creek and hornblende diorite analyses. FeO and Al_2O_3, in general, increase as SiO_2 and MgO

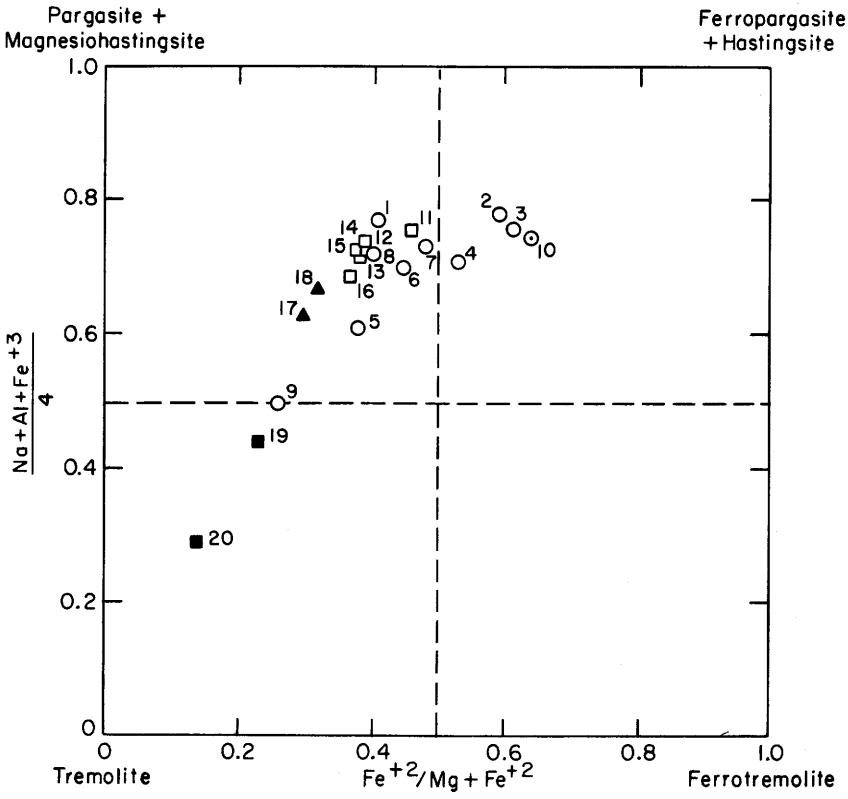


FIGURE 2.— Chemical variations of some Front Range hornblendes expressed as the numbers of ($Fe^{+2}/Mg+Fe^{+2}$) and $Na+Al+Fe^{+3}/4$ atoms per formula unit. From Colville, Ernst, and Gilbert (1966, p. 1734): □, Boulder Creek Granodiorite; ▲, hornblende diorite; ■, hornblendite; ○, hornblende gneiss; ⊙, microcline gneiss.

TABLE 4. — *Chemical and spectrographic*

[Sample numbers 1–8 and 12–20 by standard rock analysis; Vertie C. Smith analyzed samples 1, 8, 16–19; George O. atomic absorption, Na_2O and K_2O by flame photometer, analyst Wayne Mountjoy; SiO_2 and Al_2O_3 determined Gillison Chloe, Lowell Artis, and H. Smith. Spectrographic analyses for samples 1, 8, 20, Harriet Neiman; 2–7, not found. Sample localities are listed in table 1]

Rock name	Amphibolite and hornblende-plagioclase gneiss in the rock unit hornblende gneiss						
Sample No.	1	2	3	4	5	6	7
Chemical analyses, in weight percent							
SiO_2	41.18	41.86	41.13	42.99	45.57	42.90	44.14
Al_2O_3	12	11.93	11.55	11.03	9.73	11.65	10.61
Fe_2O_3	5	5.31	4.91	5.37	3.94	3.90	3.73
FeO	12.53	17.30	18.04	15.56	12.25	13.99	15.15
MgO	10.05	6.74	6.68	7.78	11.44	9.46	9.06
CaO	12.12	11.24	11.10	11.85	11.92	12.10	11.92
Na_2O	1.36	1.32	1.27	1.14	1.05	1.08	1.04
K_2O	1.37	.81	.72	.81	.82	1.29	.66
H_2O+	1.86	1.97	1.92	1.87	1.94	1.84	1.90
H_2O-	.01	.00	.00	.01	.00	.00	.01
TiO_2	1.81	1.14	2.12	.85	.91	1.27	1.20
P_2O_5	.07	.05	.10	.15	.06	.03	.02
MnO	.28	.35	.39	.34	.30	.33	.33
Cl	.04	.01	.01	.01	.01	.05	.03
F	.18	.05	.06	.08	.11	.12	.06
Subtotal	99.86	100.08	100.00	99.84	100.05	100.01	99.86
Less 0	.09	.02	.03	.03	.05	.06	.04
Total	99.77	100.06	99.97	99.81	100.00	99.95	99.82
Semiquantitative spectrographic analyses, in parts per million (Looked for but not found — Ag, As, Au, B, Bi, Cd, Ge, Hf, In, Li, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn)							
Ba	700	100	100	200	70	100	70
Be	0	0	0	0	0	0	0
Co	50	50	50	50	50	50	50
Cr	150	5	10	200	300	50	50
Cu	50	20	5	5	15	10	20
Ga	20	20	20	20	20	20	20
La	0	0	0	0	0	0	0
Mo	0	7	7	7	7	7	0
Nb	0	0	0	0	0	0	0
Nd	0	0	0	0	0	0	0
Ni	150	10	15	50	100	50	50
Pb	0	0	0	0	0	0	0
Sc	50	70	70	50	70	70	70
Sr	500	50	50	70	20	50	50
V	500	500	500	300	300	500	300
Y	30	100	100	20	50	50	50
Yb	3	10	10	5	5	5	5
Zr	30	50	70	100	70	70	50
Mineral formulas, number of ions on the basis of 24 oxygens (O, OH, F, Cl)							
(Z) Tetrahedral: Si	6.203	6.366	6.293	6.515	6.723	6.435	6.616
Tetrahedral: Al IV	1.797	1.634	1.707	1.485	1.277	1.565	1.384
	8.00	8.00	8.00	8.00	8.00	8.00	8.00
(Y) Octahedral: Al IV	.333	.504	.375	.485	.415	.495	.490
Octahedral: Ti	.205	.130	.244	.097	.101	.143	.135
Octahedral: Fe^{+3}	.567	.608	.565	.612	.437	.440	.421
Octahedral: Mg	2.256	1.528	1.523	1.757	2.516	2.115	2.024
Octahedral: Fe^{+2}	1.578	2.200	2.308	1.972	1.511	1.755	1.899
Octahedral: Mn	.036	.045	.051	.044	.038	.042	.042
	4.98	5.02	5.07	4.97	5.02	4.99	5.01
X = Ca + Na = 2.0, A = Remaining Na + K: Na	.397	.389	.377	.335	.300	.314	.302
X = Ca + Na = 2.0, A = Remaining Na + K: Ca	1.956	1.831	1.820	1.924	1.884	1.945	1.914
X = Ca + Na = 2.0, A = Remaining Na + K: K	.263	.157	.140	.157	.154	.247	.126
	2.62	2.38	2.34	2.42	2.34	2.51	2.34

See footnotes at end of table.

analyses of hornblende and mineral formulas

Riddle analyzed samples 2–7, 13–15; Elaine L. Brandt analyzed sample 20. Samples 10–12, Fe, MgO, and CaO by colorimetrically by G.T. Burrow. Sample 9 is by rapid rock analysis, analysts include Paul Elmore, Sam Botts, 13–15, Leon A. Bradley; 9, John C. Hamilton; 16–19, Bruce W. Lauthorn. Nd, not determined; 0, looked for but

Amphibolite in biotite cordierite gneiss		Microcline gneiss		Boulder Creek Granodiorite and associated rocks					Hornblende diorite		Hornblendite	
8	9	*10	*11	*12	13	14	15	16	17	18	19	20
Chemical analyses, in weight percent												
44.47	48.6	44.1	46.1	45.2	43.43	42.84	43.13	43.85	46.42	44.48	49.38	52.89
11.58	8.4	11.7	12.3	11.4	10.29	10.44	10.57	10.12	10.14	10.27	7.32	5.05
4.85	3	[1]25.5	[1]21.5	[1]18.6	5.93	6.19	5.99	5.80	4.09	4.83	2.94	2.01
12.51	9.6				11.80	11.71	11.62	11.61	10.09	10.22	8.19	5.40
10.36	15.7	5.9	9	10	10.79	10.37	10.66	10.92	13.40	12.34	15.52	18.67
11.47	10.4	10.7	11.4	11.6	11.85	11.83	11.83	11.98	11.26	12.10	12.49	12.69
1.07	1	1.30	1.11	1.16	1.20	1.19	1.09	1.10	1.16	1.17	.67	.44
.38	.22	1.37	1.26	1.34	1.17	1.34	1.31	1.14	.53	1.07	.41	.27
1.89	[2]2.3	---	---	---	1.70	1.64	1.57	1.69	1.84	1.62	1.54	2.16
.03	Nd	---	---	---	.02	.03	.08	.05	.00	.02	.01	.00
.78	.36	---	---	---	1.13	1.20	1.24	.96	.83	1.06	.74	.29
.01	.12	---	---	---	.02	.31	.06	.08	.01	.11	.04	.00
.34	.31	---	---	---	.37	.46	.40	.31	.30	.30	.21	.18
.05	Nd	---	---	---	.14	.13	.14	.10	.06	.17	.04	Nd
.07	Nd	---	---	---	.25	.35	.27	.32	.17	.30	.44	.06
99.86	100.01	---	---	---	100.09	100.03	99.96	100.03	100.30	100.06	99.94	100.11
.04	---	---	---	---	.14	.18	.14	.15	.08	.17	.20	.03
99.82	100.01	---	---	---	99.95	99.85	99.82	99.88	100.22	99.89	99.74	100.08
Semiquantitative spectrographic analyses, in parts per million (Looked for but not found — Ag, As, Au, B, Bi, Cd, Ge, Hf, In, Li, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn)												
30	30	---	---	---	50	50	50	70	50	150	200	50
0	0				3	5	2	2	0	2	0	0
50	50	---	---	---	50	50	50	70	70	50	30	30
300	500	---	---	---	70	100	100	150	300	200	700	150
30	30	---	---	---	20	2	10	30	20	15	20	15
20	<20	---	---	---	20	20	20	30	20	30	15	7
0	30	---	---	---	0	0	70	0	0	70	0	0
0	0	---	---	---	0	0	7	0	0	0	0	0
0	0	---	---	---	10	10	10	10	10	10	0	0
0	0	---	---	---	0	0	200	0	0	200	0	0
70	500	---	---	---	100	100	100	150	300	300	500	500
0	70	---	---	---	0	0	0	0	0	0	0	20
70	50	---	---	---	70	150	150	100	70	100	20	70
20	50	---	---	---	70	100	100	100	50	200	500	100
500	500	---	---	---	200	300	300	500	300	200	200	150
30	15	---	---	---	150	300	300	30	30	100	0	30
3	0	---	---	---	10	20	20	3	3	7	0	3
20	15	---	---	---	50	50	100	70	30	70	0	30
Mineral formulas, number of ions on the basis of 24 oxygens (O, OH, F, Cl)												
6.581	6.960	6.603	6.624	6.645	6.497	6.455	6.486	6.549	6.741	6.583	7.120	7.406
1.419	1.040	1.397	1.376	1.355	1.503	1.545	1.514	1.451	1.259	1.417	.880	.594
8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
.601	.377	.668	.708	.620	.311	.309	.359	.331	.476	.375	.364	.239
.087	.039	.135	.130	.133	.127	.136	.140	.108	.091	.118	.080	.031
.540	.323	[3].552	[3].643	[3].658	.668	.702	.678	.652	.447	.538	.319	.212
2.285	3.351	1.317	1.928	2.191	2.406	2.329	2.389	2.431	2.900	2.722	3.336	3.897
1.548	1.150	[3]2.317	[3]1.682	[3]1.402	1.476	1.476	1.461	1.450	1.225	1.265	.988	.632
.043	.038	---	---	---	.047	.059	.051	.039	.037	.038	.026	.021
5.10	5.28	4.99	5.09	5.00	5.04	5.01	5.08	5.01	5.18	5.06	5.11	5.03
.307	.278	.377	.309	.331	.348	.348	.318	.318	.327	.336	.187	.120
1.819	1.596	1.717	1.755	1.827	1.899	1.910	1.906	1.917	1.752	1.919	1.930	1.904
.072	.040	.262	.231	.251	.223	.258	.251	.217	.098	.202	.075	.048
2.20	1.91	2.36	2.30	2.41	2.47	2.52	2.48	2.45	2.18	2.46	2.19	2.07

TABLE 4. — *Chemical and spectrographic analyses*

Rock name	Amphibolite and hornblende-plagioclase gneiss in the rock unit hornblende gneiss						
Sample No.	1	2	3	4	5	6	7
Mineral formulas, number of ions on the basis of 24 oxygens (O, OH, F, Cl) — Con.							
OH	1.869	1.998	1.959	1.880	1.909	1.841	1.890
F	.086	.024	.029	.038	.051	.057	.028
Cl	.010	.003	.003	.003	.003	.013	.008
	1.97	2.03	1.99	1.92	1.96	1.91	1.93
$100Mg/(Mg+Fe^{+2}+Fe^{+3}+Mn)$	35.6	34.9	34.3	40.1	55.9	48.5	46.1

*Partial analysis only.
[1]Total iron reported as FeO.
[2]Total H_2O reported only.
[3]Estimated, using similar hornblende composition for breakdown of FeO and Fe_2O_3 from total reported FeO.

Sample No.	*Lab. No.*	*Sample No.*	*Lab. No.*	*Sample No.*	*Lab. No.*
1	D100966	8	D100968	14	D102180
2	D102173	9	161528	15	D102181
3	D102174		304835	16	D102510
4	D102175	10	D132492	17	D102509
5	D102176	11	D132491	18	D102512
6	D102177	12	D132489	19	D100967
7	D102178	13	D102179	20	D100504

decrease, however the fluctuations in Al_2O_3 are not as great as in the oxides FeO and MgO.

Trace elements in hornblendes (table 4) vary in relation to rock type. Barium, chromium, nickel, strontium, and vanadium are consistently high in all hornblendes. Nickel and niobium are more abundant in the igneous hornblendes with one exception — sample 15. In sample 9, the trace-element content is more characteristic of the igneous hornblendes. Lanthanum and lead found in igneous hornblendes occur in sample 9 as well.

In a perusal of the hornblende mineral formulas (table 4) certain characteristics become evident:

"Z" site. — The amount of tetrahedrally coordinated aluminum varies widely due to the high silica content of some hornblendes. In the igneous hornblendes alumina values for granodiorite range from 1.38 to 1.54; in diorite, from 1.23 to 1.42; and in hornblendite, from 0.59 to 0.88. Low alumina–high silica values in the hornblendites are probably due to the presence of the end-member tremolite. In the metamorphic gneisses, alumina values range from 1.04 to 1.80. Samples 9, 19, and 20, because of their low iron and alumina and high silica and magnesia content (table 4), probably belong to the "rare" group described by Dodge, Papike, and Mays (1968, p. 407) and Nockolds (1941, p. 457). Nockolds proposed that the hornblende may have formed at the expense of preexisting hornblende and pyroxene by the action of later fluids.

"Y" site. — The magnesium and iron cation substitutions in the octahedral site are gross replacements of Fe^{+2} by Mg (fig. 4). In the plot of Fe^{+2}:Mg, metamorphic hornblendes plot below a Mg of 2.5 and above

of hornblende and mineral formulas — Continued

Amphibolite in biotite cordierite gneiss		Microcline gneiss		Boulder Creek Granodiorite and associated rocks					Hornblende diorite		Hornblendite	
8	9	*10	*11	*12	13	14	15	16	17	18	19	20
Mineral formulas, number of ions on the basis of 24 oxygens (O, OH, F, Cl) — Con.												
1.836	2.197	---	---	---	1.676	1.618	1.495	1.684	1.782	1.599	1.481	2.017
.033	---	---	---	---	.118	.167	.128	.151	.078	.140	.201	.027
.013	---	---	---	---	.036	.033	.036	.025	.015	.043	.010	---
1.88	2.20	---	---	---	1.83	1.82	1.66	1.86	1.88	1.78	1.69	2.04
51.7	68.9	31.4	45.4	51.5	52.3	51	52.2	53.2	62.9	59.6	71.4	81.8

an Fe of 1.5; most igneous hornblendes plot at Mg 2.0 or above and below an Fe^{+2} of 1.5. Titanium and manganese influences on the hornblende structure are not readily understood, but [here] titanium in the unit cell in hornblende from gneiss appears to be dependent on the mineral assemblage and is lower in the hornblendes associated with biotite and sphene.

"X" site. — In all samples but No. 9, calcium plus sodium equals two positions in the hornblende structure. In sample 9, there is excess hydrogen and, because the "A" site, as believed by some, can accommodate hydrogen ions (two hydrogen ions are counted as one in calculating the cation numbers), the excess hydrogen values are probably in the "A" site as H_3O+ (hydronium ion) (?) thus balancing the "X" position (2) and the OH, F, Cl position.

OH, F, Cl sites. — There are two hydroxyl positions and, according to Phillips (1963, p. 701), if there are not enough hydrogen atoms in the OH position and if there is no error in the water analysis, the balance is made up with oxygen atoms. Ferric ions equal to this number of oxygens are required in the "Y" site to balance the substitution (accomplished by the oxidation of ferrous ions to ferric iron). In table 4 there is an inverse relationship between OH− and Fe^{+3} values (the higher the $OH-^{1}$, the smaller the Fe^{+3} values) except in sample 19. The water analysis in sample 19 may be low inasmuch as there is no appreciable increase in Fe^{+3} even though OH− values are low.

PHYSICAL PROPERTIES OF HORNBLENDE

Physical properties — refractive indices, birefringence, pleochroism, unit-cell parameters, and density — for hornblendes measured are compared in table 5. In a general way the refractive indices of the hornblendes vary systematically with compositional changes (fig. 5*A–C*). A plot of indices of refraction against the replacement of Mg by Fe^{+2}, expressed as the ratio 100 $Mg:Mg+Fe^{+2}+Fe^{+3}+Mn$ (fig. 5*D*), shows a well-defined correlation which is similar to the magnesium-iron substitution observed by Binns (1965, p. 314). The scatter of points in figure 5*D* indicates the importance of other ionic substitutions. All but

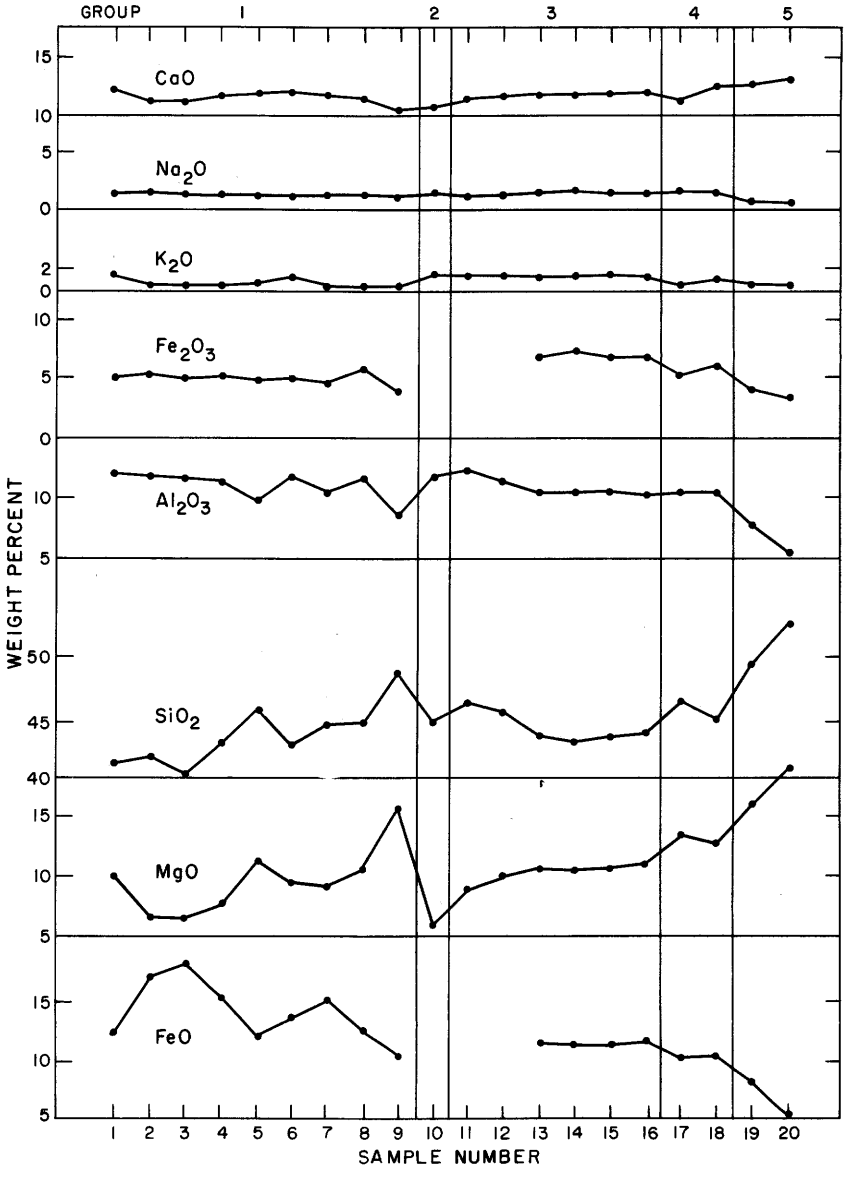


FIGURE 3. — Comparison of major oxides in hornblendes, grouped according to the source rocks. Group 1, amphibolite and hornblende gneiss; 2, microcline gneiss; 3, Boulder Creek Granodiorite; 4, hornblende diorite; 5, hornblendite. For chemical analyses of numbered samples, see table 4.

two plots on each of the graphs in figure 5 fall into either an igneous or a metamorphic field. Sample 9, an amphibolite, generally plots in the ig-

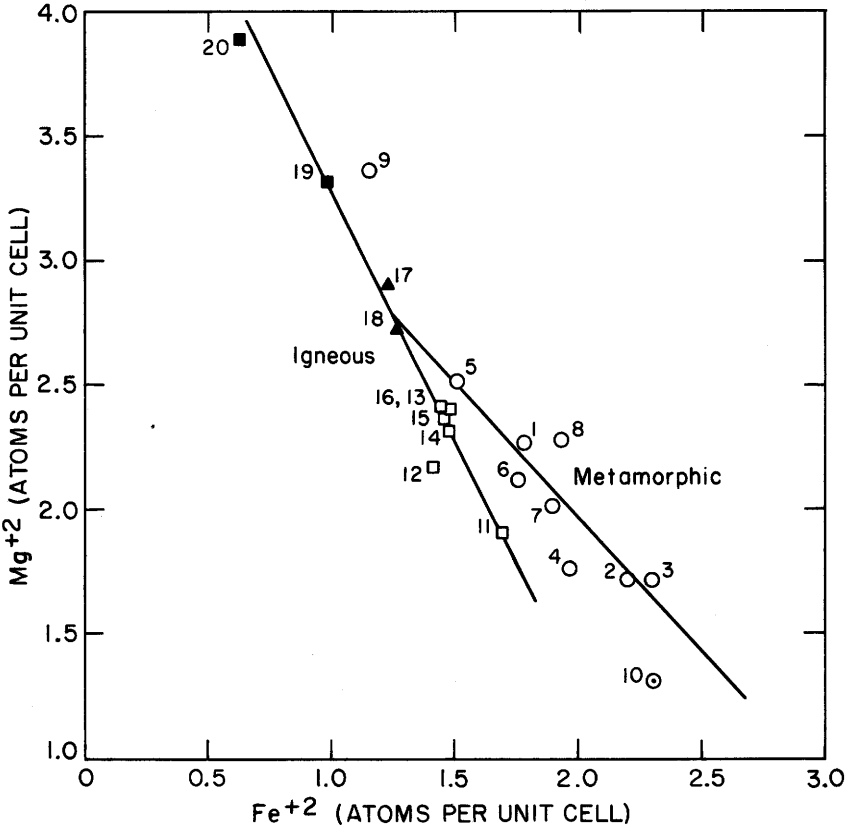


FIGURE 4. — Replacement of Fe^{+2} by Mg^{+2} in hornblende. □, Boulder Creek Granodiorite; ▲, hornblende diorite; ■, hornblendite; ○, hornblende gneiss; ⊙, microcline gneiss.

neous field while sample 1 plots in both the igneous and the metamorphic fields.

Pleochroism was observed in oils and recorded in table 5. The green or blue-green color of hornblende in metamorphic gneiss is commonly referred to as indicative of high-grade metamorphism, and the browner colors are reserved for the highest grades of metamorphism. With rising temperatures, titanium (Engel and Engel, 1962) and, to a certain extent, ferric iron (Henderson, 1968) produce the browner shades. In the rocks of this area many of the hornblendes must share titanium with biotite and sphene; therefore, color as a temperature indicator must be used with caution. Correlation of birefringence, 2V, and extinction angles in hornblende with rock types is not possible. These physical properties vary between hornblendes with no particular regard to composition.

TABLE 5. — *Optical and physical properties of hornblendes*

[Nd, no data]

Sample No.	1	2	3	4	5	6	7	8	9
Optical properties									
Indices									
α^1	1.669	1.668	1.662	1.664 and 1.672	1.652	1.656 and 1.660	1.651	1.634 and 1.654	1.639 and 1.648
β^1	1.678	1.684	1.669	1.674 and 1.684	1.661	1.668 and 1.671	1.668	1.649 and 1.668	1.651 and 1.660
γ^1	1.685	1.691	1.688	1.682 and 1.692	1.673	1.676 and 1.679	1.676	1.657 and 1.676	1.654 and 1.668
Birefringence[1]	.016	.023	.026	.018-.020	.021	.019-.021	.025	.022-.025	.018
$2Va(-)$	74°±1°	62°±1°	68°±4°	58°-79°	70°±2°	65°-75°	74°±3°	74°-86°	78°±1°
$Z \wedge c$	16°	18°	16°	15°-16°	13°	11°-13°	21°	16°-18°	20°
Pleochroism[2] *(in oil)*									
α	po	lo	dy	mgny	pyg	po	myeg	gry	grg
β	dyg	dyg	dylg	myg	grg	pg	dyg	dylg	pyeg
γ	grg	mg	grbg	grbg	grbg	grg	bg	bg	bg
Density (calculated)	3.35	3.30	3.32	3.28	3.20	3.25	3.25	3.29	3.19
Density (measured)	Nd	3.30	3.32	3.29	3.21	3.27	3.25	Nd	Nd
Unit-cell parameters									
a, Å	9.868±0.004	9.862±0.002	9.862±0.004	9.874±0.002	9.863±0.002	Nd	9.858±0.004	9.816±0.002	9.834±0.002
b, Å	18.107± .009	18.121± .003	18.102± .007	18.075± .004	18.096± .004	Nd	18.080± .007	18.044± .007	18.039± .006
c, Å	5.30± .002	5.324± .001	5.335± .002	5.292± .001	5.319± .002	Nd	5.339± .001	5.334± .002	5.304± .002
β°,-degree	104°32′±1.1′	104°34′ ± .8′	104°35′±1.1	104°31′± .09′	105°05′±1.2′	Nd	104°31′± .9′	104°36′± .8′	104°33′±1′
$\alpha \sin \beta$	9.552	9.545	9.544	9.559	9.523	Nd	9.541	9.499	9.518
Cell volume (A^3)	915.6± .37	919.2± .26	920.2± .39	912.9± .28	917± .34	Nd	919.7± .32	912.6± .41	902.2± .38

Sample No	10	11	13	14	15	16	17	18	19	20
Optical properties										
Indices										
α[1]	1.678	1.669	1.665	Nd	1.664	1.658	1.653	1.653	1.648	1.625
β[1]	1.692	1.683	1.677	Nd	1.675	1.667	1.663	1.666	1.656	1.637
γ[1]	1.700	1.688	1.683	Nd	1.683	1.675	1.672	1.675	1.668	1.645
Birefringence[1]	.022	.019	.018	Nd	.019	.023	.019	.022	.020	.020
$2Va(-)$	78°±3°	66°±2°	66°±3°	Nd	66°±2°	69°±3°	75°±4°	66°±2°	80°±1°	80°±2°
$Z \wedge c$	23°	15°–17°	25°	Nd	14°	22°–26°	17°–19°	14°	10°–17°	15°–17°
Pleochroism[2] *(in oil)*										
α	lo	pg	myeg	Nd	pyeg	lo	gry	dy-lobr	pg	grg
β	dylg	dyg	dyg	Nd	dyg	dyg	grg	dyg-po	grg	pyeg
γ	mg	mg	mg	Nd	mg	grbg	pg	grg-lo	po	bg
Density (calculated)	3.30	3.24	3.24	3.25	3.25	3.32	3.24	3.29	3.20	3.12
Density (measured)	Nd	Nd	3.24	3.23	3.26	3.30	Nd	Nd	Nd	Nd
Unit-cell parameters										
a, Å	9.880±0.005	Nd	Nd	9.872±0.006	9.874±0.003	Nd	9.827±0.003	9.873±0.002	9.845±0.004	9.839±0.002
b, Å	18.057± .012	Nd	Nd	18.044± .002	18.079± .006	Nd	18.072± .004	18.089± .004	18.074± .008	18.057± .002
c, Å	5.292± .004	Nd	Nd	5.327± .006	5.328± .003	Nd	5.312± .003	5.320± .002	5.305± .004	5.283± .002
β°,-degree	104°34′ ±1.5′	Nd	Nd	104°16′±3.4′	105°04′±1.5′	Nd	104°32′ ±1.1′	105°01′± .8′	104°34′±1.1′	104°27′±1.4
$\alpha \sin \beta$	9.563	Nd	Nd	9.568	9.534	Nd	9.513	9.536	9.529	9.528
Cell volume (A^3)	912.2± .48	Nd	Nd	918.8± .95	918.2± .46	Nd	911.6± .42	917.5± .34	912.1± .56	907.6± .44

[1]Accuracy of determination estimated as ±0.001.
[2]br, brown; b, blue; d, dusky; dyl, dark yellowish; g, green; gn, greenish; gr, grayish; l, light; m, moderate; o, olive; p, pale; y, yellow; ye, yellowish.

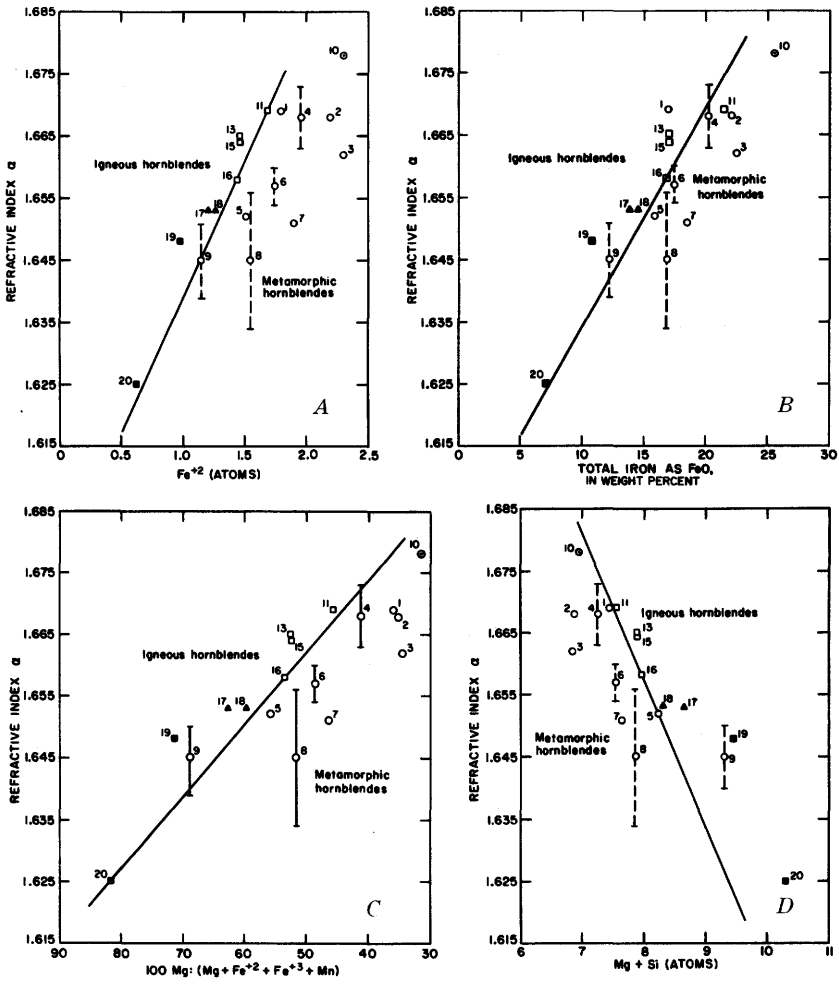


FIGURE 5. — Variations in hornblende composition and its relations to refractive index alpha. *A*, Variations of ferrous iron; *B*, total iron ($FeO+Fe_2O_3$); *C*, replacement of magnesium by iron expressed as the ratio 100 Mg : ($Mg+Fe^{+2}+Fe^{+3}+Mn$); *D*, magnesium and silicon in the unit cell in relation to refractive-index α. ○, amphibolite and hornblende-plagioclase gneiss; ⊙, microcline gneiss; □, Boulder Creek Granodiorite, ▲, hornblende diorite; ■, hornblendite. Vertical dashed lines indicate range of refractive indices.

Unit-cell parameters (table 5) correlate in a general way with the chemistry of the hornblendes. The interrelationship of iron and magnesium is broadly reflected in the parameters *a*, Å and cell volume (Å^3) which are both generally reduced in size with an increase in magnesium over iron. No apparent correlation of *b* or *c* Å, or β with

composition is readily indicated. The hornblendes do have a similar crystal structure relationship to four of the six hornblendes investigated by Heritsch, Paulitsch, and Walitzi (1957), Heritsch, Bertoldi, and Walitzi (1959), Heritsch and Kahler (1959), and Heritsch and Reichert (1959) and tabulated by Deer, Howie, and Zussman (1963, p. 267).

Densities, both measured and calculated (table 5), agree fairly well and are within 0.02 of one another. The lowest hornblende densities belong to those in the hornblendites and the highest to those in the hornblende gneiss. Densities are a crude measurement of the substitution of Mg for Fe^{+2} in hornblende.

TEXTURAL RELATIONS OF HORNBLENDE

Textural relations between minerals can be related more or less to the environment in which the minerals developed. In metamorphic rocks, growth of hornblende and biotite is related to the major Precambrian thermal event, and, in samples containing both biotite and hornblende, the hornblende is clearly older or the same age as the biotite.

In hornblende gneiss, biotite is interstitial or forms overgrowths on hornblende. Iron oxides and (or) sphene may occur along the grain boundaries or fractures in hornblende (samples 2, 7), especially where biotite is sparse or not observed at all. In samples 1 and 6, hornblende has been partly replaced by pyroxene, and wide reaction zones occur in the hornblende at the contact with pyroxene.

Hornblende from Boulder Creek Granodiorite, diorite, and hornblendite, where modified, contain new biotite as overgrowths on hornblende or along fractures or cleavage in hornblende. Sphene overgrowths on magnetite in these same rocks are common and appear, also, to be related to the regional metamorphism. In general the hornblende in the diorite and hornblendite (samples 17–20) shows the least replacement. In sample 18 the biotite and hornblende are in hemihedral to euhedral crystals, free of inclusions; almost no reaction between mafic minerals is observed in thin section. Exsolution is finely developed in the hornblendes from sample 9 where oriented exsolution lamallae (on 100) is observed. These lamallae are best observed in grains immersed in oil; they are extremely narrow and appear to be exsolved cummingtonite. Binns (1965, p. 314) recognized exsolved cummingtonite in hornblendes where the "Y" group of cations ranges from 5.15 to 5.30 and calcium is less than 1.75 cations per formula unit; sample 9 lies within this range. With exsolution cummingtonite in hornblendes of sample 9, it seems reasonable that the systematic anomalous position of sample 9 in every plot of chemical and optical properties may be due to a compositional change in hornblende and, therefore, the hornblende is related to an igneous origin rather than a metamorphic one.

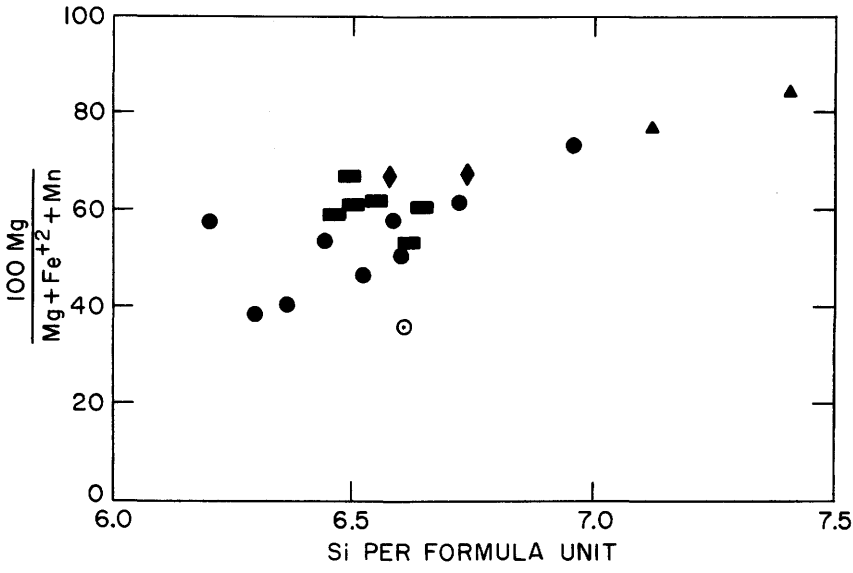


FIGURE 6. — Composition of hornblende showing major element variations. The number of silicon atoms per formula unit is a direct function of the amount of aluminum in tetrahedral coordination. ▬, Boulder Creek Granodiorite; ♦, diorite; ▲, hornblendite; ●, hornblende gneiss and amphibolite; ⊙, microcline gneiss.

PETROLOGY

Previous workers have demonstrated that the bulk chemistry of the host rocks, the mineral assemblage, and the metamorphic history are important factors in determining the composition of hornblende. Many of the hornblende-bearing rocks of this report have been subjected in varying degrees to a regional metamorphism; therefore, it is understandable that the major-element variation in hornblende should cluster (fig. 6). The hornblendes from the Boulder Creek Granodiorite and associated rocks and the diorite plot much closer to the main cluster of metamorphic hornblendes than do those from hornblendite. This may be due to composition, but habit of the hornblende and freshness of rock indicate that the hornblendites were intrusive at a somewhat later time and were not subjected to the brunt of the main regional metamorphism

CHEMICAL VARIATIONS IN HORNBLENDE IN RELATION TO HOST-ROCK COMPOSITION, MINERALOGY, AND METAMORPHISM

CHEMICAL VARIATIONS IN RELATION TO HOST-ROCK COMPOSITION

Compositions of Front Range hornblendes are related more to the mineral assemblage than to the bulk composition of the host rock. The

oxides in hornblendes, however, have a tendency to mimic bulk compositions of host rocks in which biotite is lacking from the assemblage. These relations are shown diagrammatically in figure 7. Figure 7 shows the modal percentage of the minerals in the hornblende assemblages and the percentage of the oxides SiO_2, FeO (total iron), MgO, CaO, and Al_2O_3 in both the hornblende and its source rock. The interrelationship of the mineral assemblage and host-rock composition is clearly evident for SiO_2, Al_2O_3, and CaO in the respective minerals quartz, plagioclase, calcite, biotite, and pyroxene. Modal quartz and hornblende reflect the fluctuations of SiO_2 very well; Al_2O_3 and CaO, however, reflect a partitioning of these oxides between mineral pairs other than pairs including hornblende. Al_2O_3 content is fairly constant in hornblende; therefore, fluctuations in Al_2O_3 in host rock are expressed generally in the mineral pair plagioclase-biotite. As the percentage of hornblende decreases, the Al_2O_3 enters biotite and some plagioclase. This is typical of the Boulder Creek Granodiorite. No relationship exists between Al_2O_3 and modal quartz or between Al_2O_3 and normative quartz in metamorphic rocks, but in Boulder Creek Granodiorite, as normative quartz increases, so does Al_2O_3. CaO is constant in hornblende, and increased amounts of CaO in the host rock produce some pyroxene; with a decrease in hornblende and plagioclase, calcite develops. Hornblende percentages drop drastically with a decrease in CaO and, at the same time, while there is an increase in plagioclase due to excess Al_2O_3, the anorthite content of plagioclase decreases. Interrelation between the iron-magnesium minerals and host rock is not easily visualized from figure 7; this is probably due to the presence of the two iron-magnesium minerals hornblende and biotite in the mineral assemblage. In figure 10 a near 1:1 relationship exists between FeO and MgO in biotite and hornblende, indicating that biotite and hornblende compositions should be considered together in relating mineral compositions to host-rock compositions.

Na/Na+Ca values in host rock and hornblende (fig. 8) also strongly indicate that the mineral assemblage determines composition of hornblende; anorthite content in plagioclase shows a straight-line relationship in figure 8*A* for hornblende which is not evident in figure 8*B* for host rock. Metamorphic hornblendes tend to reflect higher anorthite (fig. 8*A*) values except for sample 17. In this sample the biotite content is considerable, and the plagioclase has absorbed the excess Ca normally absorbed by hornblende. In figure 8*B* the Na/Na+Ca values clearly divide into two provinces: (1) granodiorite (samples 12–16) and (2) the more mafic rocks (samples 1–8, 17, 18).

ELEMENT DISTRIBUTION BETWEEN BIOTITE AND HORNBLENDE

Distributions of Mg, Fe, Mn, and V between coexisting mineral pairs, biotite (table 6), and hornblende (table 4) are fairly ordered.

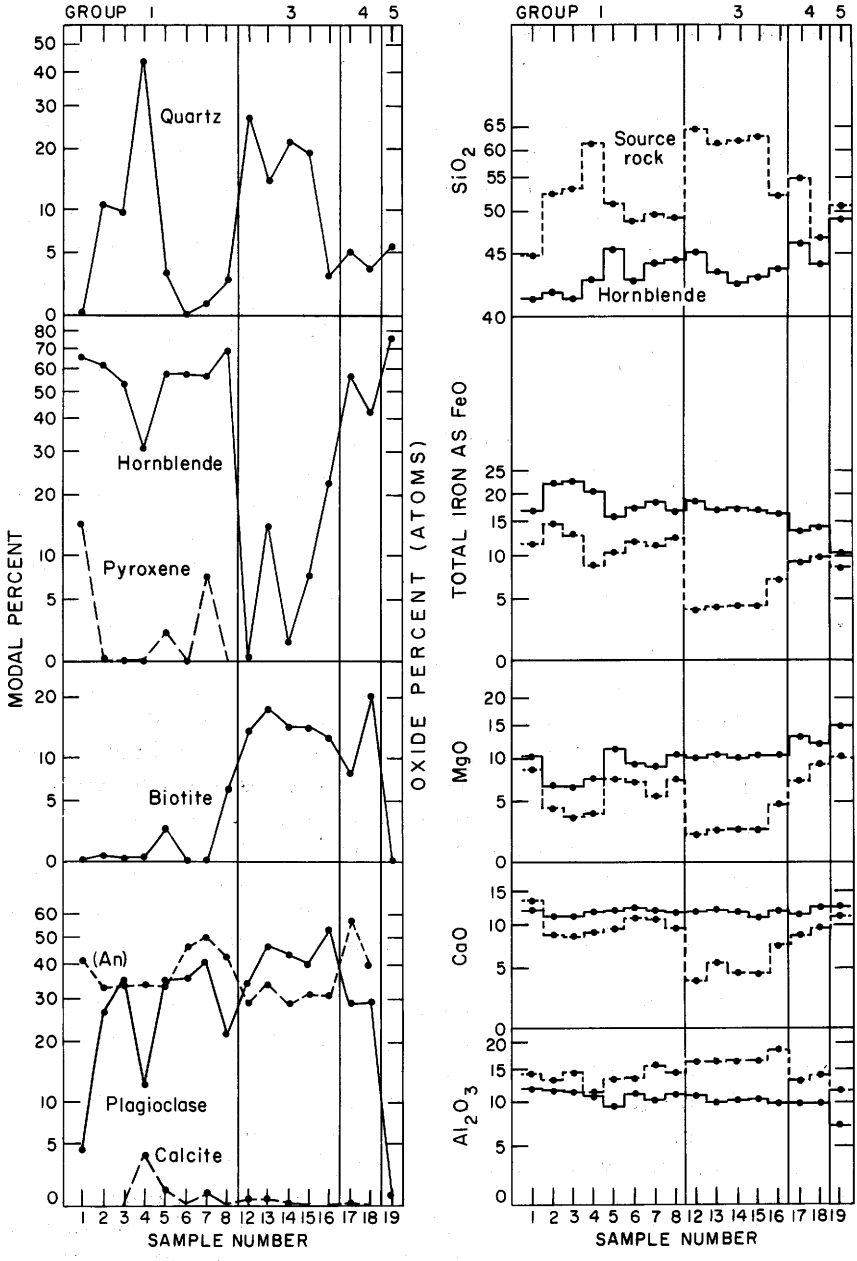


FIGURE 7. — Comparisons of modal percentage of minerals in hornblende-bearing assemblages and major oxides of source rock and hornblende. Group 1, amphibolite and hornblende-plagioclase gneiss; 3, Boulder Creek Granodiorite; 4, hornblende diorite; 5, hornblendite.

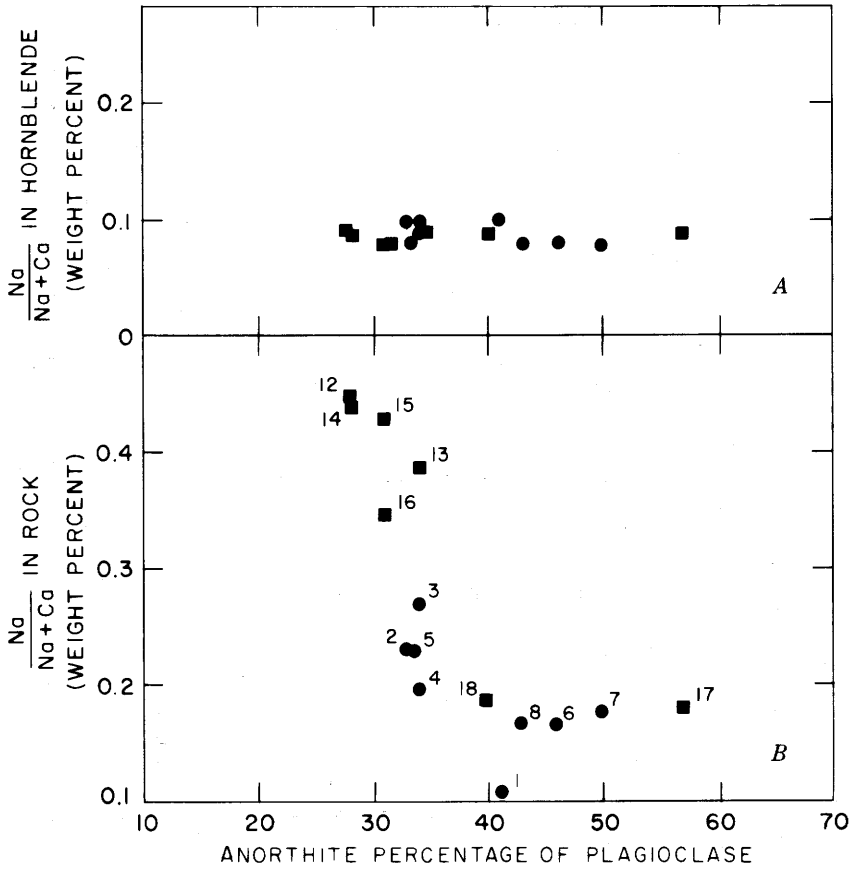


FIGURE 8. — Comparison of Na/Na+Ca in host rocks and in the hornblende in relation to anorthite percentage of plagioclase. ●, metamorphic rock and hornblende; ■, igneous rock and hornblende.

The distribution of tetrahedral aluminum in hornblende (table 4) is fairly well ordered except in hornblende samples 10–12 but these are not complete analyses and Al_2O_3 may be in error. Titanium appears to be evenly distributed in the biotite and hornblende of the Boulder Creek Granodiorite only. The concentration of calcium in hornblende is high and reasonably consistent (table 4; fig. 8) and the small variations should have no appreciable effect on the iron-magnesium distribution. Other than manganese, magnesium, and iron, which will be discussed in more detail, none of the other elements are considered here, as they show no significant trends.

In those samples for which analyses for both minerals have been made, manganese is fairly well distributed between biotite and

TABLE 6. — *Standard rock chemical and spectrographic analyses of biotite coexisting with hornblende*

[Nd, not determined; *, apatite included in weight percent of Al_2O_3; N, not detected; L, detected but below limit of determination. Sample localities are listed in table 1]

Sample No.	5	10	11	12	13	14	15	16	18
Chemical composition in weight percent Analyst: Vertie C. Smith									
SiO_2	37.43	35.96	37.02	37.67	37.50	37.88	37.34	37.43	36.97
Al_2O_3	*15.77	14.90	15.56	15.53	15.32	15.08	15.55	15.51	15.09
Fe_2O_3	2.88	3.10	1.65	3.16	2.21	2.78	2.86	3.81	3.30
FeO	14.98	21.06	17.87	14.34	15.21	14.51	14.52	13.33	12.69
MgO	12.46	8.34	11.56	13.05	13.21	12.83	12.67	13.60	14.10
CaO	1.33	.09	.20	.25	.52	1.34	.47	.98	.41
Na_2O	.34	.23	.25	.28	.29	.24	.22	.28	.13
K_2O	8.01	9.33	9.36	9.43	9.04	8.79	9.29	8.58	8.87
H_2O+	3.88	2.89	2.61	3.02	3.41	2.85	2.98	3.55	3.31
H_2O-	.22	.05	.03	.10	.11	.15	.04	.17	.23
TiO_2	2.13	2.73	2.08	1.90	1.95	2.23	2.84	1.58	3.34
P_2O_5	Nd	.03	.04	.02	.01	.05	.07	.07	.10
MnO	.20	.26	.44	.14	.26	.30	.26	.22	.17
Cl	Nd	.10	.17	.12	.14	.13	.15	.09	.15
F	.29	.80	.78	.58	.56	.81	.61	.75	.67
Subtotal	99.92	99.87	99.62	99.79	99.74	99.97	99.87	99.95	99.53
Less O	.12	.36	.37	.27	.27	.37	.29	.34	.31
Total	99.80	99.51	99.25	99.52	99.47	99.60	99.58	99.61	99.22
Density (calculated	2.92	3.04	2.99	2.94	2.93	2.95	2.95	---	---
Density (measured)	Nd	Nd	Nd	Nd	Nd	Nd	Nd	3.02	3.01
Percent biotite in rock	2.5	15	14	14.4	17.9	14.7	14.6	12.8	20.8
Number of ions on the basis of 24 oxygens (O, OH, F, Cl)									
Si	5.615	5.633	5.714	5.700	5.669	5.751	5.655	5.599	5.560
Al	2.385	2.367	2.286	2.300	2.331	2.249	2.345	2.401	2.440
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.403	0.383	0.544	0.470	0.339	0.449	0.431	.333	.235
Ti	.240	.322	.241	.216	.222	.255	.323	.178	.378
Fe^{+3}	.325	.365	.192	.360	.251	.318	.326	.429	.374

Fe^{+2}	1.879	2.759	2.307	1.815	1.923	1.842	1.839	1.667	1.596
Mn	.025	.035	.057	.044	.033	.039	.033	.028	.022
Mg	2.786	1.947	2.659	2.943	2.977	2.903	2.860	3.032	3.161
	5.66	5.81	6.00	5.85	5.81	5.81	5.81	5.67	5.77
Ca	.214	.015	.033	.041	.084	.218	.076	.157	.066
Na	.099	.070	.075	.082	.085	.071	.065	.081	.038
K	1.533	1.864	1.843	1.820	1.743	1.702	1.795	1.637	1.702
	1.85	1.95	1.95	1.94	1.91	1.99	1.94	1.88	1.81
F	.138	.396	.381	.278	.268	.389	.292	.355	.319
Cl	Nd	.027	.045	.031	.036	.033	.039	.023	.038
OH	3.662	2.967	2.656	3.048	3.328	2.734	2.970	3.542	3.320
	3.80	3.39	3.08	3.36	3.63	3.16	3.30	3.92	3.68
100Mg : Mg+Fe^{+2}+Mn	45.1	28.1	38.7	47.0	46.1	46.1	49.8	50.0	52.3

Semiquantitative spectrographic analyses, in parts per million
Analyst: Leon A. Bradley

Ba	1,500	1,000	2,000	1,000	1,000	1,000	1,000	1,000	5,000
Co	100	70	50	100	100	100	100	100	70
Cr	500	50	50	100	200	150	150	200	30
Cu	200	10	7	20	150	15	100	300	200
Ga	50	100	50	50	50	50	50	50	50
Li	N	N	N	N	N	N	N	300	N
Mo	7	7	10	5	20	5	5	7	7
Nb	N	20	N	N	N	N	10	N	20
Ni	70	15	30	100	100	100	100	300	500
Pb	N	20	N	N	N	N	N	10	N
Sc	10	20	20	20	10	30	20	10	7
Sr	20	15	20	20	15	20	20	50	70
V	300	150	300	300	300	300	300	300	300
Y	N	50	N	N	N	20	N	N	L
Yb	3	2	3	1	2	2	N	N	N
Zn	N	N	N	N	N	N	N	N	300
Zr	70	50	50	50	30	100	70	20	N

Sample No.	*Lab. No.*	*Sample No.*	*Lab. No.*	*Sample No.*	*Lab No.*
5	D102144	12	D102150	15	D102151
10	D102143	13	D102148	16	D102521
11	D102145	14	D102149	18	D102518

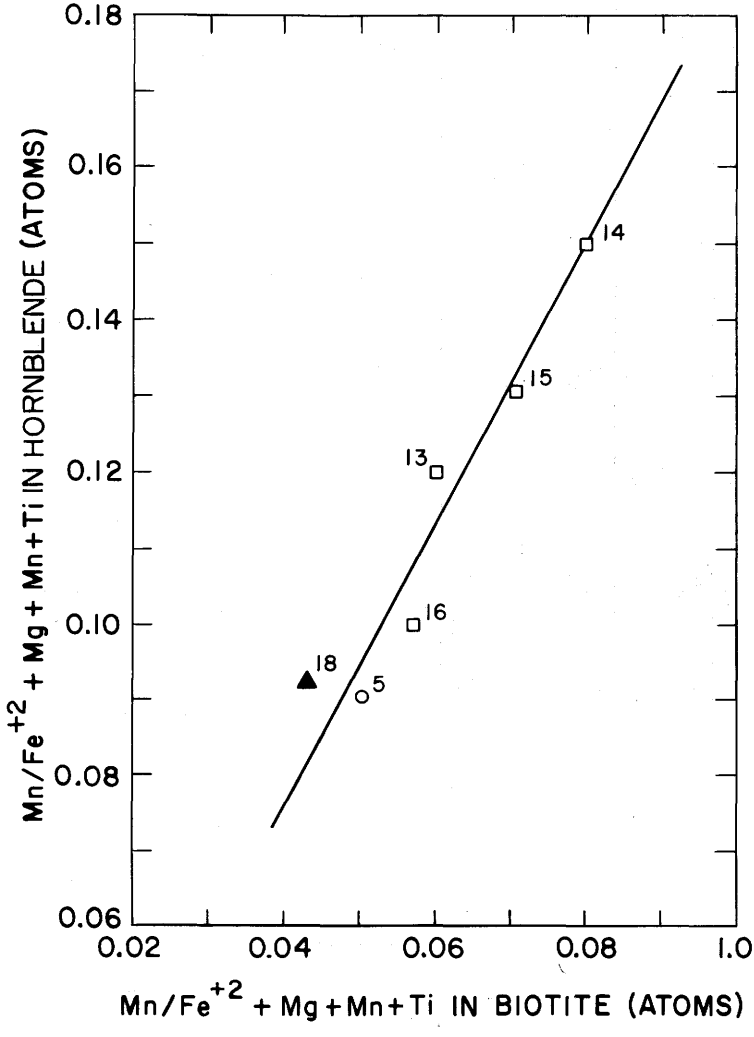


FIGURE 9. — Distribution of manganese between biotite and hornblende. ○, amphibolite and hornblende-plagioclase gneiss; □, Boulder Creek Granodiorite; ▲, hornblende diorite.

hornblende (fig. 9). Manganese, like titanium, displays a greater degree of equilibrium in the Boulder Creek Granodiorite samples.

The iron-magnesium distribution in hornblende and biotite, summarized in figure 10, shows interesting trends. The hornblendes of known igneous origin occupy the range: Mg, 2.3 to 4.0:Fe^{+2}, 0.5 to 1.5; the metamorphic hornblendes occupy the range: Mg, 1.3 to 2.5:Fe^{+2}, 1.5 to 2.4. Boulder Creek hornblendes lie midway between the above division which is probably indicative of the metamorphic imprint made on

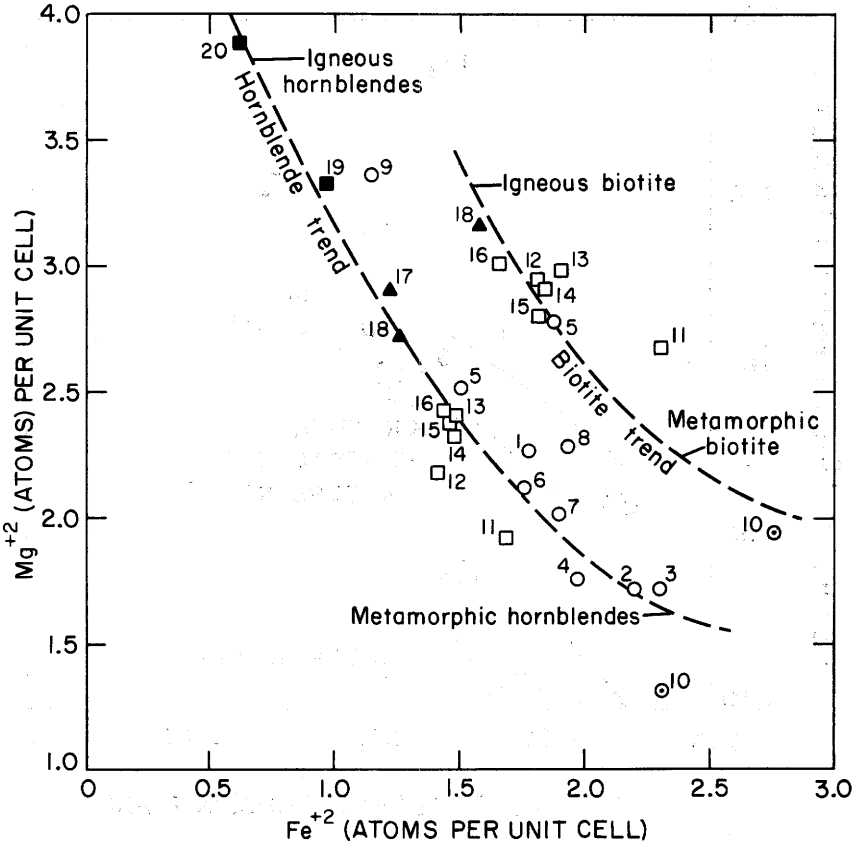


FIGURE 10. — Distribution of Fe^{+2} versus Mg^{+2} between hornblende and biotite. Sample-10 hornblende, Fe^{+2} estimated. ○, amphibolite and hornblende-plagioclase gneiss; ⊙, microcline gneiss; □, Boulder Creek Granodiorite; ▲, hornblende diorite; ■, hornblendite.

the rocks. Biotites associated with the above hornblendes mimic hornblende trends (fig. 10).

FRONT RANGE AMPHIBOLES AS INDICATORS OF OXIDATION DURING METAMORPHISM

The thermal environment in which hornblende developed is in general characteristic of the sillimanitic-potassic feldspar grade of regional metamorphism. This metamorphism is related principally to the major deformation, and because emplacement of the Boulder Creek Granodiorite occurred late in the major regional metamorphic event, hornblendes from the granodiorite were modified in part by the metamorphism. Hornblendes least affected by metamorphism are those from some of the diorites and hornblendites. In some outcrops,

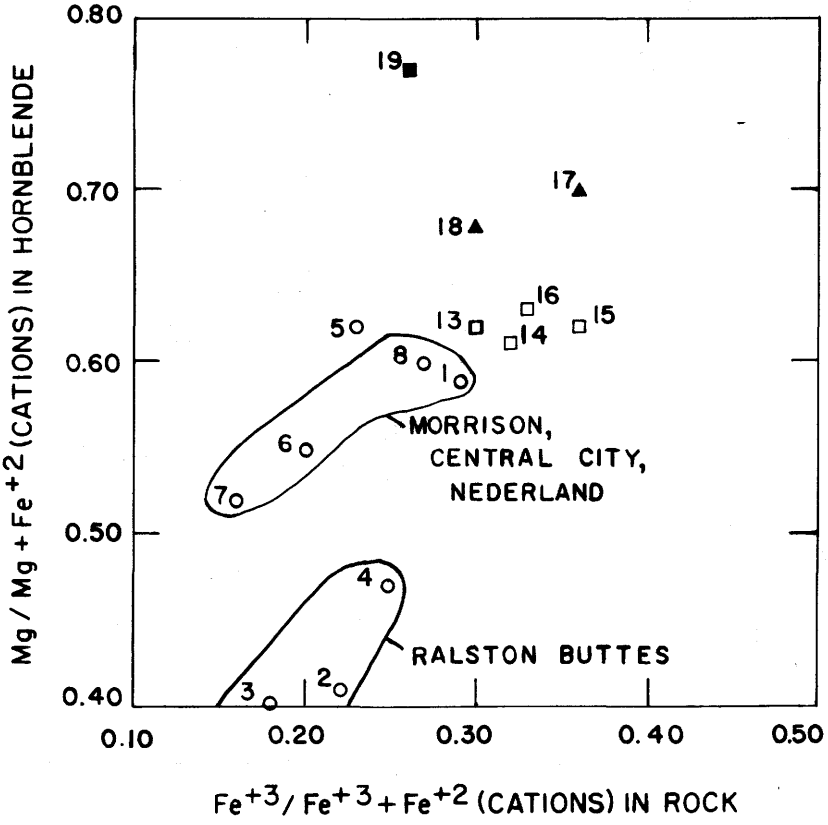


FIGURE 11. — Magnesium ($Mg/Mg+Fe^{+2}$) in hornblende versus degree of oxidation ($Fe^{+3}/Fe^{+3} + Fe^{+2}$) in host rock. ○, amphibolite and hornblende-plagioclase gneiss; □, Boulder Creek Granodiorite; ▲, hornblende diorite; ■, hornblendite.

diorite and hornblendite bodies exhibit few metamorphic structures, though in others they are clearly evident, perhaps indicating their emplacement at different times; certainly, some are younger than the major metamorphism.

One control of metamorphism is the degree of oxidation that has occurred in a host rock and its contained amphibole (table 7; figs. 11, 12). Plots of Mg ($Mg/Mg+Fe^{+2}$) in hornblende versus degree of oxidation ($Fe^{+3}/Fe^{+3}+Fe^{+2}$) in rock indicate that, with increasing Mg in hornblende from metamorphic rocks, the Fe^{+3}, or the oxidation degree, in host rock increases (Bard, 1970, p. 127), but Front Range metamorphic hornblendes separate into two areas, possibly due to different degrees of metamorphism. In figure 11, a break at 0.60 cations of $Mg/Mg+Fe^{+2}$ places all the metamorphic hornblendes except sample 5 below 0.60 cations and all igneous hornblendes above this value. With

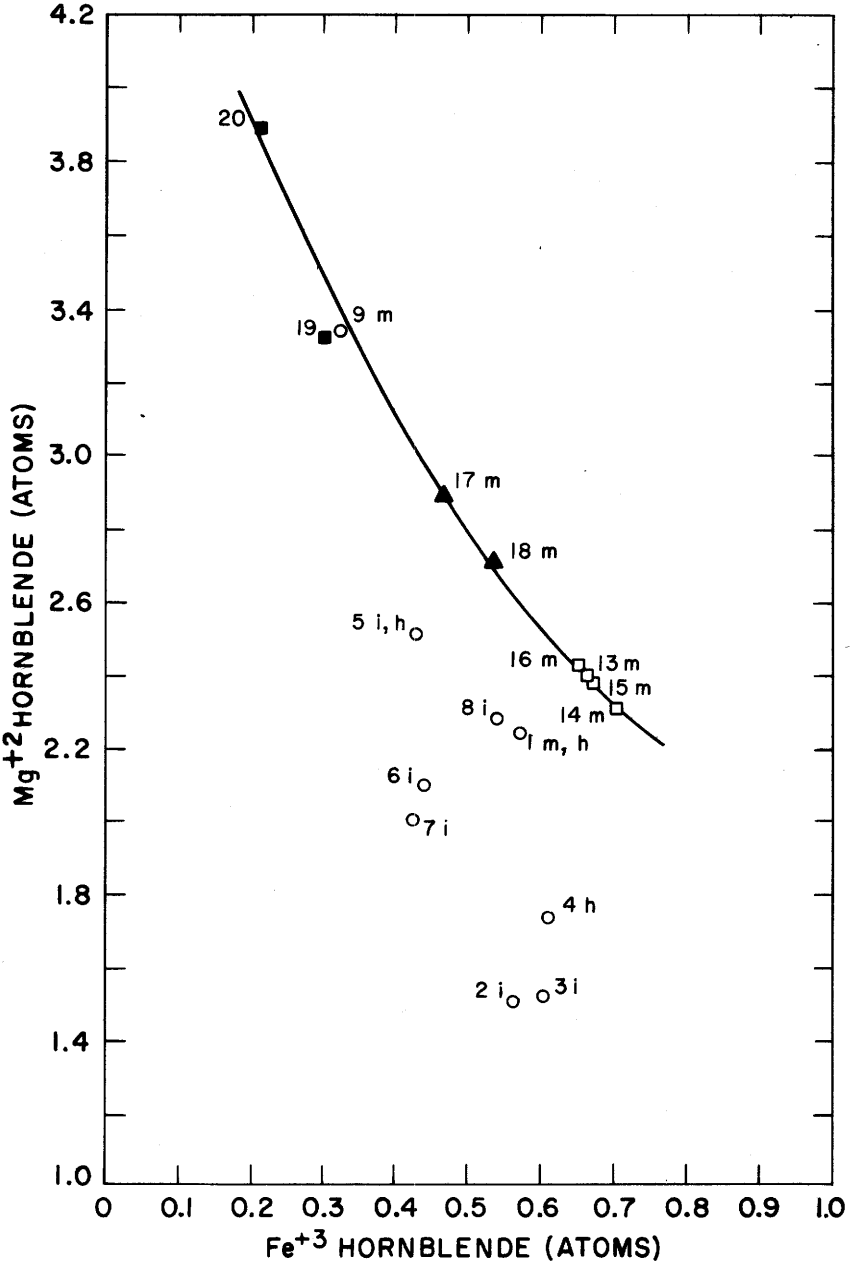


FIGURE 12. — Plot of magnesium versus ferric iron showing degree of oxidation in some hornblendes. ○, amphibolite and hornblende-plagioclase gneiss; □, Boulder Creek Granodiorite; ▲, hornblende diorite; ■, hornblendite. **m**, magnetite; **h**, hematite; **i**, ilmenite.

increasing Mg in igneous hornblendes, there is erratic distribution of Fe^{+3} in host rock, indicating Mg in hornblende is not completely controlled by the Fe^{+3} content of host rock, but there is a closer correlation between Fe^{+3} and Mg in hornblende and host rock within igneous rock types.

Bard (1970) indicated that with Mg enrichment and Fe^{+2} impoverishment in hornblende there is a rise in Fe^{+3} which holds true for Front Range metamorphic hornblendes but is not true for known igneous hornblendes (table 7); in fact, the reverse is true, with increasing Mg and decreasing Fe^{+2}, Fe^{+3} decreases (fig. 11). This reversal in Fe^{+3} for the igneous hornblendes no doubt is an indication of their igneous origin.

TABLE 7. — Mg, Fe^{+2}, Fe^{+3} *ions for analyzed hornblendes, table 4*

[Arrow indicates direction of enrichment]

Sample No.	Mg^{+2}	Fe^{+2}	Fe^{+3}	Fe total/Fe total+Mg oxidation-reduction ratios
IGNEOUS HORNBLENDES				
20	3.897	0.632	0.212	0.319
19	3.326	.988	.319	.418
17	2.900	1.225	.447	.514
18	2.722	1.265	.538	548
16	2.431	1.450	.652	.620
13	2.406	1.476	.668	.622
15	2.389	1.461	.678	.623
14	2.329	1.456	.702	.633
METAMORPHIC HORNBLENDES Ralston Buttes Area				
4	1.757	1.972	0.612	0.728
3	1.528	2.200	.608	.774
2	1.523	2.308	.565	.770
Morrison and Nederland-Central City Area				
8	2.285	1.548	0.540	0.626
6	2.115	1.755	.440	.654
7	2.024	1.899	.421	.676

In figure 12, igneous hornblendes have a definite trend while metamorphic hornblendes cluster as to areas (fig. 11); samples 1, 6–8, Morrison, Central City, Nederland; and 2–4, the Ralston Buttes area. The orderly relationship along the igneous trend (fig 12) is not displayed by the metamorphic hornblendes; with increasing Fe^{+3} in igneous hornblendes, there is a regular decrease in Mg, and the ratios $Fe^{total}/Fe^{total}+Mg$ for these hornblendes decrease. The trend is somewhat similar to that observed by Czamanske and Wones (1970) for hornblende Fe/Fe+Mg ratios to monitor oxidation-reduction reactions in monzonite, granodiorite, and granite during magmatic processes. This trend in the Boulder Creek hornblendes appears relic and is indicative of their igneous origin. This trend also indicates that under regional metamorphic conditions the Boulder Creek Granodiorite and

associated rocks reacted as a single unit to the partial pressures of oxygen. Hornblende gneiss and amphibolite, because of varying Fe^{+3} (fig. 12), seem to have behaved as much more narrowly defined units closed to oxygen. Relationships between Fe^{+3} and Mg or $Fe^{total}/Fe^{total}+Mg$ in biotite are not nearly as well defined and probably reflect the partitioning of iron, not used by the hornblendes, between biotite and the iron oxides.

Iron oxides, as observed in polished sections and as shown in figure 12, are predominantly ilmenite below 2.5 atoms of Mg^{+2} and 0.60 atoms of Fe^{+3}, followed by lesser amounts of hematite and some magnetite. Above 2.2 atoms of Mg^{+2} and above 0.60 atoms of Fe^{+3}, the iron oxides are dominantly magnetite. In table 7, samples 14–20, the lower oxidation-reduction ratios belong to samples that are dominantly magnetite-bearing.

CONCLUSIONS

Regional metamorphism has left a definite and orderly imprint on the hornblendes in the Boulder Creek Granodiorite. Decided trends indicate that hornblende composition is dependent primarily on mineral assemblage and secondarily on host rock composition in a potassic feldspar-sillimanite grade of regional metamorphism. Regional metamorphism is responsible for some element variation in hornblende, principally due to the activity of oxygen fugacity. Fe^{+3} appears to regulate the iron-magnesium content in hornblende and, where it coexists with biotite, in biotite as well.

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