Distribution of Minor Elements in Biotite Samples From Felsic Intrusive Rocks as a Tool for Correlation

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By TOM G. LOVERING

CONTRIBUTIONS TO GEOCHEMISTRY

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Differences in minor-element concentrations in biotite can be used to distinguish different intrusives of similar composition in the same area

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DISTRIBUTION OF MINOR ELEMENTS IN BIOTITE SAMPLES FROM FELSIC INTRUSIVE ROCKS AS A TOOL FOR CORRELATION

By Tom G. Lovering

ABSTRACT

Biotites separated from suites of samples from 20 bodies of felsic intrusive rocks in the Western United States were analyzed by a semiquantitative spectrographic method to investigate differences in the minor elements that might characterize the biotites from different intrusives with similar composition in the same region. The samples were taken from five regions: southern Arizona, the southern Rocky Mountains of Colorado, the Great Basin of Nevada and western Utah, the northern Rocky Mountains of Idaho and Montana, and the Cascade Range of Washington. The intrusives sampled range in composition from syenite to quartz diorite and in age from early Precambrian to Tertiary.

Different intrusives with similar composition in the same region generally exhibit characteristic differences in the concentration of one or more minor elements in their biotites. Regional differences are more subtle, but there appears to be a tendency toward high titanium in biotites from southern Arizona, high chromium in those from the southern Rocky Mountains of Colorado, high niobium in samples from the northern Rocky Mountains of Idaho and Montana, and low strontium in those from the Cascade Range of Washington. Titanium is the only minor element whose concentration in biotite appears to be related to the age of the rock from which it was taken. Biotite from the Precambrian intrusive rock samples generally contains 1 percent or less of this element; biotite from samples of Tertiary intrusives commonly contains 1.5 percent or more.

INTRODUCTION

The investigation whose results are here summarized was an extension of an earlier study on the minor-element content of biotite samples from igneous rocks (Lovering, 1969), in which it was shown that biotite may contain many minor elements that range widely in concentration. This observation led to the hypothesis that biotites crystallizing from different bodies of magma might exhibit differences in their minor-element contents that reflect differences in concentrations of these elements in the fluids present in the magma chambers at the time of biotite crystallization.

Biotite was separated from three or more samples of felsic rock from each of two or more intrusives in five regions in the Western United States (fig. 1) and analyzed by a semiquantitative spectrographic method. The rocks sampled range in composition from syenite, through granite, quartz monzonite, and granodiorite, to quartz diorite. Some of the intrusives represented by these samples are composite plutons of variable composition, some are relatively homogeneous stocks, and a few are separate small intrusives known to have had a common magmatic source.

Unfortunately, only the biotite separates were available to the author, and therefore no comparison was possible between the minor-element content of the biotite separates and that of the parent rock samples from which the biotites were derived. However, such comparisons have been published (Nockolds and Mitchell, 1946), and they indicate that the concentrations of some minor elements in biotite may be very different from those in the host rock and that some rocks in a differentiated sequence may actually show trends in the concentrations of certain minor elements that are opposite to trends in the biotite separated from them.

In primary biotite separated from representative samples of the same intrusive, the pattern of minor-element distribution varies, but certain elements are commonly present in abnormally high or abnormally low concentrations, in comparison with concentrations of the same elements in biotite from a different intrusive of similar composition in the same area. Such characteristic patterns in the minor-element content of biotite may be useful for determining the magmatic affiliations of small dikes, plugs, and sills, for estimating the probable source of float samples in areas that contain numerous intrusive bodies, and for interpreting isolated rock outcrops in covered areas.

FIGURE 1.—Locations of study regions (stippled) and intrusive rock bodies sampled. Numbers refer to localities listed in table 1.

Thanks are given to Richard Marvin, who supplied the biotite samples from the northern and southern Rocky Mountains and from the Great Basin of Nevada; to Joan Engel, who provided samples from the Cascade Range in Washington; to John Cooper and Harald Drewes, who collected the rock samples from Arizona; and to George Cone, who separated the biotite from the latter samples. I also thank Wallace Griffitts for allowing me to use analytical data on biotite samples he separated and had analyzed from rocks of the Ibapah stock in western Utah.

PREVIOUS INVESTIGATIONS

The composition of biotite separated from igneous rocks has been studied and reported in the literature by many investigators since the late 1940's. Some of these investigations concerned the variation in composition of biotite from different genetically related composite intrusives, some dealt with partition of elements between biotite and host rock or between biotite and other coexisting minerals in the rock, some compared the concentrations of certain ore metals in biotite from igneous rocks genetically related to deposits of these metals with those in biotite from petrologically similar "barren" intrusives, and others compared the composition of biotite from igneous intrusives with that of biotite from the metamorphic rocks they intrude.

Nockolds and Mitchell (1946) studied the variation of about a dozen elements in biotites separated from various facies of several composite intrusives in the Scottish Highlands. Barsukov (1957) compared the tin content of biotite from tin-bearing granites of Russia with that of biotite from granites in the same region that are not associated with tin deposits.

Several papers dealing with various aspects of the composition of biotite from igneous rocks were published in 1963. Erickson and Blade (1963) compared the concentrations of minor elements in biotites from the alkalic complex at Magnet Cove, Ark., with those in the host rocks for these biotites. Wenk, Schwander, Hunziker, and Stern (1963) determined major and minor constituents of biotite from pegmatites and various metamorphic rocks in the Tessin Alps of Switzerland. Parry and Nackowski (1963) made a statistical study of the distributions of copper, lead, and zinc in multiple samples of biotite from both mineralized and unmineralized quartz monzonite stocks of the Basin and Range province in Utah and Nevada. They made the important observation (p. 1142) that the biotite in each stock has its own characteristic base-metal population. Putman and Burnham (1963) reported the results of a systematic study of the composition of ferromagnesian mineral concentrates taken from samples of seven major plutons in northwestern and central Arizona. These concentrates consisted largely of biotite, mixed in varying proportions with chlorite, hornblende, and pyroxene. Putman and Burnham noted (p. 74) a significant difference in the pattern of minor-element distributions in the ferromagnesian mineral concentrates from the various plutons. Ishikawa, Shibata, and Negishi (1963) determined the concentrations of major constituents plus seven minor elements in biotite separates from a succession of related granitic intrusives in the Dando-San district of Japan.

Analyses of single biotite separates from several granitic intrusive rocks in various parts of Canada and of replicate separates from granodiorite and quartz monzonite facies of the White Creek batholith in British Columbia were reported by Rimsaite (1964).

Physical chemical studies on the partition of specific elements between coexisting biotite and hornblende in igneous rocks in relation to the composition of the host rock were made by Gottfried and Dinnin (1965), Greenland, Gottfried, and Tilling (1968), and Tilling, Greenland, and Gottfried (1969).

Bradshaw (1967) studied the distribution of selected elements in biotite, muscovite, and feldspar from several granitic intrusive rocks in Great Britain in relation to mineralization.

The variations in compositions of biotites from plutons in the Sierra Nevada batholith of California in relation to changes in physical and chemical conditions in the magma chambers during the time of biotite crystallization were discussed by Dodge and Moore (1968) and Dodge, Smith, and Mays (1969). A somewhat similar study of the relationship between the composition of biotite and that of its host rock, concerning both intrusive and extrusive rocks, was made by Dupuy (1968) on granodiorite samples from Elba and ignimbrite samples from Italy. Sobolev, Sitnin, and Dorokhov (1968) presented data on the variations in concentrations of selected minor elements in biotite, muscovite, and chlorite from different phases of intrusive igneous complexes in central Kazakhstan as these variations relate to the ages of the intrusives. Haack (1969) and Lovering (1969) summarized the minor-element content in biotite from igneous rocks.

SOURCE AND DESCRIPTION OF SAMPLES

One hundred and five samples of primary biotite representing 20 felsic intrusive rock bodies in five regions of the Western United States were used in this study. Splits of all but the three samples representing the Ibapah stock in Utah were examined to determine the amount and nature of mineral impurities and the characteristic color of the biotite. The locations, ages, and general compositions of the parent intrusives are given in table 1 together with the number of samples from each intrusive and a brief description of the biotite. Locations of the intrusives are indicated by latitude and longitude coordinates for a point within each intrusive.

Only the samples from southern Arizona were collected for the specific purpose of studying the composition of biotite. Samples from the other four regions were taken for age determinations based on potassium-argon isotope studies of the biotite. Consequently, the

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TABLE 1.—*Description*

Loc. (fig. 1)	Name of intrusive	Number of samples	Type of rock	Location of intrusive		Geologic age
				Lat. N.	Long. W.	
	Southern Arizona					
1	Ruby Star Granodiorite	17	Granodiorite	31°55′	111°09′	Paleocene
2	Do	5	Quartz monzonite porphyry.	31°53′	111°09′	do
3	Continental Granodiorite	3	Granodiorite and quartz monzonite.	31°48′	110°47′	Precambrian
4	Madera Canyon Granodiorite.	3	Granodiorite	31°45′	110°50′	Late Cretaceous.
5	Unnamed	4	Quartz monzonite	31°54′	110°46′	Paleocene
6	Do	4	Quartz latite porphyry	31°52′	110°45′	do
	Southern Rocky Mountains, Colo.					
7	Boulder Creek Granite	7	Quartz monzonite	39°55′	105°20′	Precambrian
8	Silver Plume Granite	3	Granite to quartz monzonite.	39°40′	105°45′	do
9	St. Kevin Granite	4	do	39°20′	106°30′	do
10	Unnamed	4	Syenite	38°18′	106°56′	Early Precambrian.
11	Do	3	Mafic syenite	38°20′	105°29′	Late Precambrian.
	Great Basin, Nev. and Utah					
12	Snake Range stock	5	Quartz monzonite	38°50′	114°20′	Jurassic
13	Ibapah stock (Utah)	3	do	39°55′	113°50′	Tertiary
14	Unnamed	3	Granodiorite	40°45′	118°25′	Cretaceous
15	Climax stock	5	Quartz monzonite to granodiorite.	37°15′	116°04′	Jurassic
16	Unnamed	4	Granodiorite	40°20′	115°30′	Tertiary
	Northern Rocky Mountains, Idaho and Mont.					
17	Boulder batholith (Montana)	6	Granodiorite to quartz monzonite.	45°50′	112°20′	Cretaceous
18	Idaho batholith (Idaho)	4	Granodiorite	45°00′	115°25′	do
	Cascade Range, Wash.					
19	Chilliwack batholith	5	Quartz monzonite to granodiorite.	48°52′	121°30′	Tertiary
20	Ten Peak pluton	3	Quartz monzonite	48°00′	121°00′	Cretaceous
21	Mount Stuart batholith	6	Quartz diorite	47°30′	121°00′	do
22	Similkameen batholith	4	Syenite to quartz diorite	48°45′	119°45′	Cretaceous (?)

[1] Color terms are from Goddard and others (1948).

of biotite samples

Color of biotite [1]	Mineral impurities	
	Mineral grains in samples	Mineral inclusions in biotite
	Southern Arizona—Continued	
Dark brown (5*YR* 3/2) to medium olive brown (5*Y* 4/4).	Chlorite, hornblende, sphene ±10 percent.	Apatite, rutile, ilmenite, zircon ±5 percent.
Dark brown (5*YR* 3/2)	Chlorite, sphene ±10 percent	Apatite, ilmenite, rutile, zircon ±10 percent.
Medium olive brown (5*Y* 4/4)	None	Minor chlorite <5 percent.
Medium brown (5*YR* 3/4)	Hornblende 10 percent, chlorite 10 percent.	Ilmenite, sphene ±10 percent.
Dark yellowish brown (10*YR* 4/2).	Chlorite, sphene, plagioclase 10 percent.	Hematite, apatite, zircon ±5 percent.
Medium brown (5*YR* 4/4)	Chlorite, sphene ±10 percent	Apatite, rutile, ilmenite ±5 percent
	Southern Rocky Mountains, Colo.—Continued	
Medium olive brown (5*Y* 4/4)	Chlorite, feldspar <5 percent	None.
do	Muscovite <5 percent	Apatite, zircon <5 percent.
Medium brown (5*YR* 4/4)	None	Apatite <5 percent.
Medium olive brown (5*Y* 4/4)	Feldspar <5 percent	Apatite, rutile <5 percent.
Light brown (5*YR* 5/6)	Hornblende, feldspar, chlorite <5 percent.	Do.
	Great Basin, Nev. and Utah—Continued	
Medium yellowish brown (10*YR* 5/4).	Horblende, feldspar ±10 percent	None.
No information	No information	No information.
Medium olive brown (5*Y* 4/4)	Hornblende, chlorite ±5 percent	Rutile <5 percent.
do	Chlorite ±10 percent	Rutile, apatite, ilmenite ±5 percent.
do	None	Apatite <5 percent.
	Northern Rocky Mountains, Idaho and Mont.—Continued	
Medium brown (5*YR* 3/4)	Chlorite ±10 percent	Rutile, apatite, ilmenite ±5 percent.
do	Chlorite <5 percent	None.
	Cascade Range, Wash.—Continued	
Variable	Magnetite, hornblende <5 percent.	Apatite, chlorite <5 percent.
Light brown (5*YR* 5/6)	Hornblende, chlorite, hematite <5 percent.	Apatite, zircon, rutile <5 percent.
Medium brown (5*YR* 4/4)	Hornblende, chlorite <5 percent	None.
Medium olive brown (5*Y* 4/4)	Hornblende, chlorite ±5 percent	Apatite, sphene, hematite <5 percent.

nature and distribution of the rock bodies represented in these four regions were determined by the availability of replicate samples, and the bodies are more widely separated geographically than those in southern Arizona.

The intrusive bodies sampled are medium- to coarse-grained alkalic plutonic rocks except for the quartz latite porphyry from Arizona, which consists of three genetically related hypabyssal intrusive pipes. Most of the intrusives range in age from Jurassic to Tertiary, but one in Arizona and all in Colorado are Precambrian.

The color of the biotite ranges from olive brown through medium brown to dark brown. Grains of chlorite, hornblende, feldspar, sphene, magnetite, hematite, or muscovite are present in some of the mineral separates, and the biotite flakes commonly contain inclusions of apatite, rutile, sphene, zircon, hematite, or ilmenite; some of the biotite flakes show partial alteration to chlorite. The total amount of such mineral impurities ranges from <5 to about 20 percent.

ANALYTICAL METHODS

All the biotite samples were analyzed in the Analytical Services Laboratories of the U.S. Geological Survey in Denver, Colo., by a semiquantitative spectrographic method in which concentrations of an element are reported as the midpoints (0.1, 0.15, 0.2, 0.3, 0.5, 0.7, and 1.0, and so forth) of six geometric intervals per order of magnitude. Precision of the reported value is approximately plus or minus one interval at 68-percent confidence and plus or minus two intervals at 95-percent confidence. The method is a refinement of the three-step method described by Myers, Havens, and Dunton (1961). Sensitivity of the method varies from element to element.

ANALYTICAL DATA AND DISCUSSION

Analytical data on the biotite samples from igneous rocks in each of the five regions—southern Arizona, southern Rocky Mountains, Great Basin, northern Rocky Mountains, and Cascade Range—are presented and discussed separately to facilitate the comparison of minor-element suites in biotite from different rock bodies of similar composition in the same area. The smallest region, and also the one best represented both by number of rock bodies and by number of biotite samples, comprises the Sierrita and Santa Rita Mountains of southern Arizona.

SOUTHERN ARIZONA

Primary biotite was separated from unaltered samples of three distinct but closely related rock types of the composite Ruby Star Granodiorite pluton on the east flank of the Sierrita Mountains; biotite was also separated from samples of three unrelated intrusive plutonic rock bodies that are similar in composition to each other and to the Ruby Star Granodiorite and from samples of several hypabyssal quartz latite porphyry plugs in the Santa Rita Mountains, a larger mountain range about 15 miles east of the Sierrita Mountains across the Santa Cruz River valley. Analytical data on the biotite samples from these rocks are presented in table 2.

The Ruby Star Granodiorite in the Sierrita Mountains is a large composite southward-plunging stock of Paleocene age composed predominantly of three rock types: an equigranular border facies of granodiorite, a porphyritic core facies of granodiorite, and a quartz monzonite porphyry at the south end of the stock. The porphyry has intrusive contacts with the granodiorite in some places and gradational contacts in others. The large disseminated-copper ore bodies of the Esperanza and Sierrita mines are near the southern edge of the quartz monzonite.

Samples of biotite from these rocks provide an opportunity to investigate progressive changes in the composition of this mineral during the crystallization and differentiation of a rather large magmatic body, in which the equigranular border facies of the granodiorite is the oldest facies, the porphyritic core facies is intermediate, and the quartz monzonite porphyry is the youngest.

Some of the minor elements show progressive changes in concentration through the three rock types, some show distinctly different concentrations in one rock type relative to the other two, and some show little difference in concentration among the three rock types. Chromium and nickel seem to decrease and zirconium, strontium, copper, niobium, and tin seem to increase progressively in biotites from the border facies granodiorite through the core facies granodiorite to the quartz monzonite porphyry (fig. 2). Copper shows a tremendous variation in samples from the two granodiorite facies; the concentration of this element in the biotite seems to decrease systematically outward from a center of copper mineralization in the quartz monzonite porphyry, as shown previously by Lovering, Cooper, Drewes, and Cone (1970).

TABLE 2.—*Spectrographic analyses (in percent) of biotite samples from*

[Analysts, J. L. Finley and R. H. Heidel. N, looked for but not detected; D, detected but below threshold

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses) Ca (0.005)	Na (0.05)	Ti (0.0002)	Mn (0.0001)
Sierrita Mountains					
Paleocene Ruby Star Granodiorite; equigranular border facies.	T9	0.1	0.3	1.0	0.3
	T6	1.0	.3	3.0	.15
	T91	.2	.5	2.0	.1
	T165	.3	.3	3.0	.2
	T7	.7	.2	3.0	.15
	T8	1.0	.3	1.5	.15
Paleocene Ruby Star Granodiorite; porphyritic core facies.	I-3-5	.2	.3	1.0	.5
	T166	.2	.5	1.0	.5
	T452	.2	.2	1.5	.3
	T453	.2	.2	1.5	.2
	T454	.2	.3	1.5	.5
	T455	.07	.2	2.0	.3
	T92	.2	.5	3.0	.2
	T465	.2	.3	2.0	.15
	T466	.1	.3	2.0	.2
	T456	.3	.3	3.0	.1
	T457	.2	.3	2.0	.07
Paleocene Ruby Star Granodiorite; quartz monzonite porphyry at south end of pluton.	T94	.5	.7	3.0	.1
	T467	.2	.5	3.0	.07
	T468	.7	.7	1.5	.1
	T469	.2	.5	2.0	.07
	T470	.7	.5	2.0	.07
Santa Rita Mountains					
Precambrian Continental Granodiorite; granodiorite and quartz monzonite.	65D994	0.2	0.2	0.7	0.3
	66D1046	.3	.3	.7	.3
	66D1043	.7	.2	1.0	.2
Late Cretaceous Madera Canyon Granodiorite; granodiorite.	65D769	.5	.3	3.0	.1
	65D837	1.0	.3	3.0	.15
	63D316	1.0	.7	2.0	.03
Unnamed Paleocene quartz monzonite porphyry.	66D1163	.1	.3	3.0	.7
	66D1313	1.5	.7	2.0	.7
	66D1375	1.5	.7	3.0	.15
	66D1403	2.0	.5	3.0	.5
Unnamed Paleocene quartz latite porphyry.	65D921	1.5	.7	2.0	.15
	66D1098	.2	.7	2.0	.3
	66D1185	.3	1.0	2.0	.3
	66D1245	.5	.7	2.0	.3

Calcium is lower and shows less variation in biotite samples from the core facies of the granodiorite than in those from the other two rock types. This may reflect varying contamination by older, more calcic rocks near the intrusive contacts of the granodiorite and quartz monzonite, an effect from which the core facies would be well insulated. Manganese is lower in samples from the quartz monzonite than in those from either of the granodiorite facies, and both sodium and lead are higher in the quartz monzonite biotites than in the granodiorite biotites.

Titanium, barium, cobalt, lithium, scandium, vanadium, yttrium, and gallium show no significant difference in concentration in biotite *igneous rocks of the Sierrita and Santa Rita Mountains of southern Arizona*

of sensitivity; leaders (....) in figure columns, not looked for. Other element looked for but not detected: Zn]

Element (threshold of detection in parentheses)—Continued								
Ba (0.0002)	Be (0.0001)	Ce (0.015)	Co (0.0003)	Cr (0.0001)	Cu (0.0001)	Ga (0.0005)	La (0.003)	Li (0.01)
Sierrita Mountains—Continued								
0.05	N	N	0.007	0.007	0.003	0.005	N	0.05
.07	N	N	.007	.05	.001	.007	N	.03
.1	N	N	.005	.005	.0005	.005	N	.01
.15	N	N	.007	.005	.0005	.001	N	
.2	N	N	.005	.015	.002	.007	N	N
.15	N	N	.002	.01	.5	.005	N	N
.07	N	D	.007	.0015	.001	.007	N	.01
.07	N	N	.01	.002	.0015	.01	N	.05
.07	N	N	.01	.002	.002	.015	N	.015
.05	N	N	.01	.003	.002	.01	N	.05
.05	N	N	.003	.002	.015	.015	N	.05
.05	N	N	.005	.002	.1	.015	N	.03
.07	N	0.05	.003	.003	.07	.005	0.03	.02
.15	N	N	.005	.001	03	.007	N	.015
.15	N	N	.005	.001	.07	.007	N	.01
.1	N	D	.0015	.003	.5	.007	.07	.02
.1	N	N	.0015	.001	.07	.007	N	.02
.15	N	N	.005	.003	.5	.015	.007	.02
.15	N	N	.003	001	1	.007	N	.02
.15	N	.03	.005	.0005	.7	.007	.015	.01
.15	N	N	.002	.0007	.1	.007	N	.015
.3	N	D	.003	.0005	.5	.007	.003	.01
Santa Rita Mountains—Continued								
0.1	N	N	0.007	0.0015	0.003	0.007	N	N
.07	N	N	.007	.002	.007	.007	0.007	N
.15	N	N	.003	.001	.005	.005	.003	N
.3	N	N	.007	.003	.02	.007	N	N
.3	N	N	.005	.003	.01	.007	N	N
.15	N	N	.007	.003	.02	.003	.003	N
.15	0.0001	0.015	.003	.0015	.007	.007	.015	N
.07	.0002	.07	.007	.0007	.007	.007	.05	N
.15	N	N	.007	.003	.007	.007	.007	N
.15	.0001	.07	.005	.0015	.015	.007	.03	N
.3	N	.03	.005	.001	.07	.005	.015	N
.2	N	.03	.005	.0015	.1	.007	.015	N
.15	.0001	N	.003	.0015	.5	.007	N	N
.15	N	N	.005	.001	.1	.005	N	N

(Table 2 continued on next page.)

samples relative to rock type. Cerium, lanthanum, and molybdenum were detected in too few samples to provide information on their relative abundance in biotites from the different rocks of this stock.

Dodge and Moore (1968, p. B8–B9) studied the variation in minor-element content of biotite from a small pluton in the Sierra Nevada that is compositionally zoned from a porphyritic quartz monzonite core to an equigranular quartz diorite border facies. They concluded that chromium, nickel, and vanadium are more abundant in biotites from the more mafic border facies but that scandium, strontium, and zinc are more abundant in samples from the quartz monzonite core. Nockolds and Mitchell (1948, p. 566) reported the composition of biotites

TABLE 2.—*Spectrographic anlysis (in percent) of biotite samples from igneous*

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)—Continued			
		Mo (0.0003)	Nb (0.001)	Nd (0.007)	Ni (0.0003)
Sierrita Mountains—Continued					
Paleocene Ruby Star Granodiorite; equigranular border facies.	T9	N	N	----------	0.01
	T6	N	N	----------	.015
	T91	N	N	----------	.01
	T165	N	N	----------	.015
	T7	N	N	----------	.015
	T8	N	N	----------	.015
Paleocene Ruby Star Granodiorite; porphyritic core facies.	1-3-5	N	0.001	----------	.007
	T166	N	N	----------	.01
	T452	N	N	----------	.01
	T453	N	N	----------	.015
	T454	N	.001	----------	.005
	T455	N	.001	----------	.01
	T92	N	N	----------	.007
	T465	N	.002	----------	.007
	T466	N	.001	----------	.005
	T456	0.02	.001	----------	.01
	T457	N	.001	----------	.005
Paleocene Ruby Star Granodiorite; quartz monzonite porphyry at south end of pluton.	T94	.003	.007	----------	.003
	T467	N	.002	----------	.003
	T468	.0015	.0015	----------	.003
	T469	N	.0015	----------	.002
	T470	N	.0015	----------	.002
Santa Rita Mountains—Continued					
Precambrian Continental Granodiorite; granodiorite and quartz monzonite.	65D994	N	N	N	.003
	66D1046	N	N	N	.003
	66D1043	N	N	N	.002
Late Cretaceous Madera Canyon Granodiorite; granodiorite.	65D769	N	0.003	N	.01
	65D837	N	.002	N	.003
	63D316	N	.002	0.007	.015
Unnamed Paleocene quartz monzonite porphyry.	66D1163	N	.015	.015	.003
	66D1313	N	.007	.015	.0015
	66D1375	N	.005	.007	.005
	66D1403	N	.015	.03	.003
Unnamed Paleocene quartz latite porphyry.	65D921	0.0015	.002	.015	.003
	66D1098	.0015	.005	.015	.003
	66D1185	.003	.005	N	.003
	66D1245	N	.003	N	.003

from various facies of several Caledonian igneous intrusive complexes in Scotland. They found a systematic decrease in the chromium, vanadium, copper, nickel, cobalt, and strontium contents of biotite from the oldest rocks to the youngest in the Garabal Hill–Glen Fyne complex, which ranges in composition from a pyroxene-mica diorite (oldest) to a porphyritic granodiorite (youngest). However, in the Ben Nevis complex the strontium relations are reversed—strontium is markedly higher in biotite samples from the younger granite than in those from the older granodiorite. In a similar study of biotites from a series of granitic intrusive rocks from the Dando-San district in Japan, Ishikawa, Shibata, and Negishi (1963, p. 69, 74) found a decrease in contents of magnesium, manganese, chromium, vanadium, nickel, and cobalt in biotite from the older to the younger rocks.

Although these previous investigators vary somewhat in their con-

rocks of the Sierrita and Santa Rita Mountains of southern Arizona—Continued

Element (threshold of detection in parentheses)—Continued								
Pb (0.001)	Pr (0.01)	Sc (0.0005)	Sn (0.001)	Sr (0.0005)	V (0.0007)	Y (0.001)	Yb (0.0001)	Zr (0.001)
Sierrita Mountains—Continued								
N	....	0.005	N	0.0005	0.05	N	....	0.005
N	....	.003	N	.003	.05	0.002	....	.005
N	....	.003	N	D	.03	N	....	.001
N	....	.005	N	N	.05	.0015	....	.001
N	....	.003	N	.0007	.05	.0015	....	.005
N	....	.007	N	.0015	.05	.002	....	.005
D	....	.005	N	.003	.03	.001	....	.01
N	....	.005	N	.002	.05	.001	....	.007
N	....	.005	N	.001	.05	N	....	.005
N	....	.003	N	.001	.05	N	....	.001
N	....	.007	N	.0005	.015	.002	....	.005
N	....	.01	N	.0005	.02	N	....	.003
N	....	.01	N	.002	.02	.001	....	.015
N	....	.007	0.001	.001	.05	.002	....	.01
N	....	.007	N	.0005	.03	.0015	....	.005
N	....	.005	.002	.003	.05	.005	....	.01
N	....	.007	.002	.001	.05	.002	....	.005
0.005	....	.007	.001	.015	.02	.005	....	.02
D	....	.007	.003	.002	.05	.002	....	.01
.001	....	.005	.003	.015	.02	.003	....	.02
.001	....	.005	.002	.005	.05	.001	....	.007
.002	....	.005	.001	.03	.05	.003	....	.02
Santa Rita Mountains—Continued								
0.001	....	0.003	N	0.003	0.02	0.0015	0.0003	0.015
.0015	....	.007	N	.003	.02	.0015	.0003	.007
.001	N	.007	N	.003	.02	.0015	.0003	.015
.001	N	.0015	N	.003	.03	.001	.0001	.007
N	N	.002	N	.003	.03	.001	.0001	.015
.001	N	.002	N	.015	.03	.001	.0001	.02
.003	N	.007	N	.007	.02	.02	.002	.03
.005	0.01	.015	N	.015	.015	.03	.003	.05
.0015	N	.007	N	.015	.03	.01	.001	.03
.003	.015	.007	0.002	.03	.015	.03	.003	.05
.0015	.01	.007	N	.015	.03	.003	.0003	.03
.005	N	007	N	.003	.03	.007	.0007	.03
.0015	N	.007	N	.0015	.015	.007	.001	.03
.0015	N	.007	N	.005	.015	.007	.001	.03

clusions, they all concur with my observation that nickel and chromium in biotite decrease systematically with decreasing age of the rock facies in a composite intrusive complex.

The four intrusive rock bodies in the Santa Rita Mountains are of three different ages and are not closely related, although they are grossly similar in composition to each other and to the composite stock in the Sierrita Mountains. These four intrusives are represented by fewer biotite samples than the Ruby Star Granodiorite, and, therefore, apparent differences in minor-element contents of these biotite suites may not be representative of differences in composition of all the biotite in these bodies. Nevertheless, where the range of concentration of an element is small in all the samples from a given body and where this range differs appreciably from that in biotites from another body, a real difference is strongly implied.

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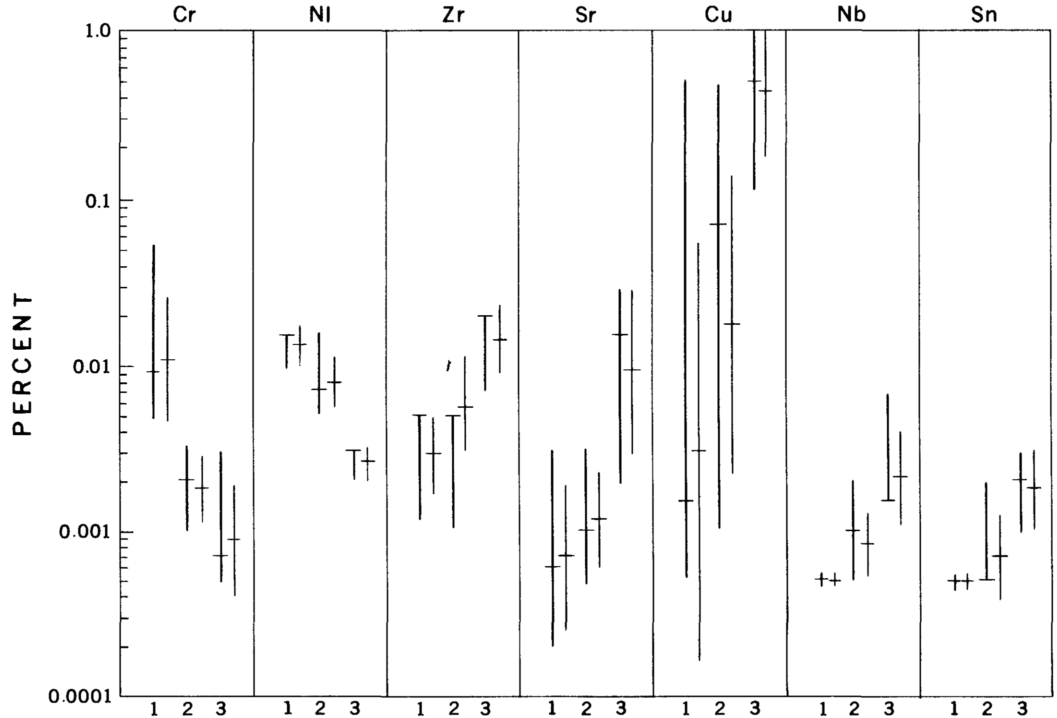

FIGURE 2.—Trends in minor-element distributions in biotite samples from composite Ruby Star Granodiorite stock. Heavy line indicates range, and tick indicates median; light line indicates geometric deviation interval, and tick indicates geometric mean. 1, Border facies granodiorite (oldest); 2, porphyritic core facies granodiorite (intermediate); 3, quartz monzonite porphyry (youngest).

As a group, the biotites from rocks of the Santa Rita Mountains appear to differ from those of the Sierrita Mountains in the absence of detectable lithium.

Biotite samples from the Precambrian Continental Granodiorite are characterized by a deficiency in sodium and titanium relative to biotite samples from the other intrusive bodies in the Santa Rita Mountains. Biotite samples from the Cretaceous Madera Canyon Granodiorite have an excess of chromium and nickel and a deficiency of manganese and scandium relative to the others. Samples from both the Paleocene rocks, the quartz monzonite porphyry and the quartz latite porphyry, are enriched in the rare-earth elements cerium, lanthanum, neodymium, praseodymium, and ytterbium, as well as in yttrium and zirconium, relative to samples from the older intrusives, and these elements appear to be somewhat higher in biotites from the quartz monzonite than in those from the quartz latite porphyry. Biotite samples from the Paleocene quartz monzonite are also enriched in beryllium and niobium relative to those from the other intrusives. Samples from the quartz latite porphyry are distinctively enriched in sodium, copper, and molybdenum as compared with samples from other intrusives in the Santa Rita Mountains.

Biotites from each of the seven intrusive bodies (including three forming a composite body) sampled in southern Arizona seem to have certain characteristics in their minor-element contents that distinguish them from biotites from all other intrusives in the region. These characteristics are summarized in table 3.

A systematic screening based on the criteria provided by table 3 will allocate any biotite sample to the correct igneous intrusive on the basis of the concentrations of not more than four elements in the sample. If chromium is $\geqq$0.005 percent, the sample is from the border facies of the Ruby Star Granodiorite stock. If chromium is <0.005

TABLE 3.—*Distinguishing features of minor-element contents of biotite from igneous intrusives of southern Arizona*

Intrusive rock	Distinctive minor elements in biotite
Ruby Star Granodiorite stock:	
Border facies	Chromium $\geq$0.005 percent.
Core facies	Chromium <0.005 percent, nickel $\geq$0.005 percent, lithium $\geq$0.01 percent.
Quartz monzonite porphyry	Chromium <0.005 percent, nickel <0.005 percent, lithium $\geq$0.01 percent, tin $\geq$0.001 percent.
Continental Granodiorite	Lithium not detected, yttrium <0.003 percent, titanium <1.5 percent, scandium $\geq$0.003 percent.
Madera Canyon Granodiorite	Lithium not detected, yttrium <0.003 percent, titanium $\geq$2 percent, scandium <0.003 percent.
Paleocene quartz monzonite porphyry	Lithium not detected, yttrium $\geq$0.003 percent, copper <0.03 percent.
Paleocene quartz latite porphyry	Lithium not detected, yttrium $\geq$0.003 percent, copper $\geq$0.03 percent.

percent and lithium is $\geqq 0.01$ percent, the sample is from one of the other two facies of this stock; if, in addition, nickel is $\geqq 0.005$ percent, the sample is from the core facies; if nickel is <0.005 percent, the sample is from the quartz monzonite porphyry. If chromium is <0.005 percent and lithium is <0.01 percent (not detected), the sample is from one of the intrusives in the Santa Rita Mountains. If, in addition, yttrium is <0.003 percent, the sample is from one of the two older intrusives; scandium $\geqq 0.003$ percent indicates the Continental Granodiorite, and scandium <0.003 percent indicates the Madera Canyon Granodiorite. Chromium <0.005, lithium <0.01, and yttrium $\geqq 0.003$ percent allocate the sample to one of the two types of Paleocene intrusive. If, in addition copper is <0.03 percent the sample represents the quartz monzonite porphyry; if copper is $\geqq 0.03$ percent, the sample is from the quartz latite porphyry.

SOUTHERN ROCKY MOUNTAINS, COLO.

Biotite separates from five different intrusive bodies, all of Precambrian age, in the southern Rocky Mountains of Colorado were analyzed for this study. The Boulder Creek Granite and the Silver Plume Granite intrude the Front Range of the Rocky Mountains west and northwest of Denver, east of the Continental Divide. The St. Kevin Granite is in the northern Sawatch Range in Eagle County, west of Denver and west of the Continental Divide. The unnamed lower Precambrian syenite is in southeastern Gunnison County, Colo., about 100 miles south of the St. Kevin Granite locality. The unnamed upper Precambrian mafic syenite forms small intrusive bodies in the Wet Mountains of southern Fremont County, about 100 miles east of the Gunnison County syenite locality.

The Boulder Creek, Silver Plume, and St. Kevin Granites range in composition from granite to granodiorite but are largely quartz monzonite. The syenite in Gunnison County is a true syenite, but the syenite in Fremont County is variable in composition from a silica-deficient mafic nepheline syenite to a true syenite.

Analytical data on the biotites separated from samples of these rocks are presented in table 4.

Minor elements in the biotites of the Silver Plume and St. Kevin Granite samples show a marked similarity in concentration. Although these two bodies are about 50 miles apart, they are nearly the same age and are also similar in appearance and composition. The Boulder Creek Granite, on the other hand, is at least 300 million years older than the Silver Plume and St. Kevin Granites, and the concentrations of several minor elements in the Boulder Creek Granite are distinctly different from those in the Silver Plume and St. Kevin Granites.

Niobium, tin, and yttrium and the rare-earth elements cerium, lanthanum, neodymium, and ytterbium are higher and nickel and vanadium are lower in biotite from the Silver Plume and St. Kevin rock samples than they are in biotite from the Boulder Creek rock samples.

A comparison of the minor-element concentrations in biotite from the older Precambrian syenite samples from Gunnison County with those in biotite from the younger Precambrian syenitic rock of the Wet Mountains also shows some distinguishing patterns. Sodium, titanium, manganese, and niobium are distinctly lower in the Gunnison County biotites, and beryllium, vanadium, and zirconium are higher.

Similarly, certain characteristics distinguish biotite of each intrusive from that of any other intrusive, with the exception of the Silver Plume and St. Kevin bodies. Although the overall patterns of biotite content of the Boulder Creek Granite and of the syenites from Gunnison County are similar, there are noticeable differences in sodium, manganese, and barium concentrations. The high rare-earth content of the Silver Plume and St. Kevin biotites distinguishes them from biotites of both of the syenites as well as those of the Boulder Creek Granite, and the Boulder Creek biotites differ from biotites of the syenite from the Wet Mountains in their lower titanium and higher vanadium contents.

GREAT BASIN, NEV. AND UTAH

The five intrusive bodies in the Great Basin that are represented in this study range in composition from quartz monzonite to granodiorite. They range in age from Jurassic to Tertiary and are widely separated geographically; therefore each is related to a magmatic source entirely separate from any of the others. The Snake Range stock is in southeastern White Pine County, Nev.; the Ibapah stock is in northwestern Juab County, Utah, about 80 miles north-northeast of the Snake Range stock; and the Climax stock is near the east edge of the southern part of Nye County, Nev., nearly 150 miles southwest of the Snake Range stock. One of the unnamed granodiorite stocks is in southern Elko County, Nev., about 100 miles west of the Ibapah stock; the other is nearly 150 miles farther west, in northern Pershing County, Nev.

Analyses of biotite separated from samples of these intrusives (table 5) suggest distinctive differences in the minor-element contents of biotite samples from each of the intrusives. The presence of detectable zinc ($\geqq$0.02 percent) distinguishes Ibapah stock biotite samples from all the others. Lithium was detected only in samples from the Snake Range and Ibapah stocks and the granodiorite of Pershing

TABLE 4.—*Spectrographic analyses (in percent) of biotite samples from igneous rocks of the southern Rocky Mountains, Colo.*

[Analysts, A. L. Sutton, Jr., Barbara Tobin, and Harriet Neiman. N, looked for but not detected; D, detected but below threshold of sensitivity; leaders (....) in figure columns, not looked for. Other elements looked for but not detected: Mo and Zn]

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)											
		Ca (0.005)	Na (0.05)	Ti (0.0002)	Mn (0.001)	Ba (0.0002)	Be (0.0001)	Ce (0.015)	Co (0.0003)	Cr (0.0001)	Cu (0.0001)	Ga (0.0005)	La (0.003)
Precambrian Boulder Creek Granite; granite to granodiorite, largely quartz monzonite.	ST3	0.7	1.5	0.5	0.2	0.3	N	N	0.003	0.005	0.0015	0.002	N
	ST8	.3	1	.7	.15	.15	N	N	.002	.007	.015	.003	N
	432	.5	.3	1.5	.2	.3	N	N	.01	.015	.0007	.005	N
	434	.15	.5	1.0	.2	.3	N	N	.007	.03	.01	.005	N
	435	1.5	.3	1.0	.15	.2	N	N	.01	.03	.0015	.005	N
	324B	.3	.3	1.0	.5	.05	0.0001	N	.01	.015	.0007	.007	N
	433B	.3	.7	1.0	.2	.07	.0001	N	.007	.02	N	.007	N
Precambrian Silver Plume Granite; granite to quartz monzonite.	220B	.07	.2	1.0	.15	.15	N	N	.005	.007	.0005	.01	0.007
	431	.2	.3	1.0	.1	.03	N	0.02	.003	.007	.005	.007	.01
	ST11	.07	.5	1.0	.1	.07	N	.02	.003	.003	.002	.01	.01
Precambrian St. Kevin Granite; granite to quartz monzonite.	C2	.07	1.5	1.5	.1	.15	N	.015	.003	.01	.001	.007	.01
	C3	.05	1.5	1.0	.15	.03	N	N	.005	.005	.0007	.007	.003
	C21	.3	1	1.5	.2	.3	N	N	.005	.007	.0007	.005	N
	C25	.15	.15	1.0	.15	.15	N	.015	.005	.007	.0015	.007	.01
Unnamed lower Precambrian syenite from Gunnison County.	2G3200	.3	.2	1.0	.1	.5	.001	N	.007	.02	.015	.005	N
	G3730N	.3	.3	1.0	.1	.7	.0002	N	.005	.03	.01	.005	N
	BSJ139	.2	.2	1.5	.07	.3	.0001	N	.007	1	.005	.003	N
	BSJ140	.5	.3	1.5	.1	.3	.0001	N	.007	.1	.005	.005	N
Unnamed upper Precambrian mafic syenite from Fremont County (Wet Mountains).	WM62-115	.5	.7	2.0	.15	1	N	N	.01	.005	.015	.003	N
	WM66-116C	.1	.5	2.0	.3	1	N	N	.01	.07	.005	.005	N
	WM62-143	.3	.5	2.0	.5	.15	N	N	.002	.0005	.001	.005	N

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)—Continued												
		Li (0.01)	Nb (0.001)	Nd (0.007)	Ni (0.0003)	Pb (0.001)	Pr (0.01)	Sc (0.0005)	Sn (0.001)	Sr (0.0005)	V (0.0007)	Y (0.001)	Yb (0.0001)	Zr (0.001)
Precambrian Boulder Creek Granite; granite to granodiorite, largely quartz monzonite.	ST3	N	N	N	0.005	N	--------	0.002	N	0.02	0.03	N	N	N
	ST8	N	0.003	N	.007	N	--------	.003	N	.015	.03	0.002	N	0.02
	432	N	N	N	.02	N	--------	.005	N	.005	.07	N	----------	.007
	434	N	N	N	.03	N	--------	.002	N	.002	.07	N	----------	.005
	435	N	N	N	.05	N	N	.0007	N	.015	.05	N	N	.002
	324B	D	N	N	.02	N	N	.002	0.0015	.003	.05	N	N	.002
	433B	D	N	N	.02	N	N	.007	N	.007	.05	N	N	.003
Precambrian Silver Plume Granite; granite to quartz monzonite.	220B	D	.007	0.01	.007	N	N	.003	.0015	.002	.03	N	N	.01
	431	D	.007	.02	.007	0.002	N	.003	.003	.003	.02	.003	0.0007	.02
	ST11	D	.005	.007	.005	.002	N	.003	.001	.003	.02	.002	.0005	.03
Precambrian St. Kevin Granite; granite to quartz monzonite.	C2	D	.007	.015	.005	N	N	.003	.005	.0015	.03	.0015	.0005	.02
	C3	D	.007	.007	.005	N	N	.005	.002	.0015	.015	.001	.0003	.015
	C21	N	.005	.02	.002	N	N	.001	N	.007	.015	.001	.0002	.007
	C25	D	.007	.03	.003	N	N	.0015	.0015	.0015	.015	.0015	.0003	.02
Unnamed lower Precambrian syenite from Gunnison County.	2G3200	N	N	--------	.015	D	--------	.005	N	.02	.05	.001	----------	.003
	G3730N	N	.001	--------	.015	.001	--------	.007	N	.01	.05	.001	----------	.003
	BSJ139	N	.001	--------	.05	N	--------	.0007	N	.003	.03	N	----------	.003
	BSJ140	N	N	--------	.05	N	--------	.001	N	.01	.05	.001	----------	.01
Unnamed upper Precambrian mafic syenite from Fremont County (Wet Mountains).	WM62-115	N	.002	--------	.007	N	--------	.0005	N	.05	.03	N	----------	N
	WM66-116C	N	.002	--------	.03	N	--------	N	N	.015	.03	N	----------	N
	WM62-143	N	.002	--------	.0007	N	--------	.0015	N	.003	.01	.001	----------	.003

TABLE 5.—*Spectrographic analyses (in percent) of biotite samples from igneous rocks of the Great Basin, Nev. and Utah*

[Analysts, A. L. Sutton, Jr., G. W. Sears, and Harriet Neiman. N, looked for but not detected; D, detected but below threshold of sensitivity; leaders (--) in figure columns, not looked for; +, detected by qualitative analysis only. Other element looked for but not detected: Mo]

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)												
		Ca (0.005)	Na (0.05)	Ti (0.0002)	Mn (0.0001)	Ba (0.0002)	Be (0.0001)	Ce (0.015)	Co (0.0003)	Cr (0.0001)	Cu (0.0001)	Ga (0.0005)	La (0.003)	Li (0.01)
Jurassic Snake Range stock; quartz monzonite.	40AMW60	0.5	0.5	1.5	0.3	0.3	0.0002	N	0.005	0.002	0.0015	0.007	N	0.015
	16MW60	.5	3.0	1.0	.15	.15	.00015	N	.005	.02	.02	.003	N	+
	57W51	.5	.7	1.5	.7	.3	.00015	0.015	.005	.005	.0007	.01	0.01	+
	71MW60	.3	.1	1.5	.3	.2	.00015	N	.005	.007	.0007	.007	N	+
Tertiary Ibapah stock; quartz monzonite.	D110828	.1	.3	1.0	.3	.1	--------	N	.003	.01	.002	.007	N	D
	D110829	.2	.2	1.5	.5	.2	--------	.05	.002	.005	.0005	.01	.03	.03
	D110830	.15	.2	1.5	.5	.07	--------	N	.002	.01	.005	.01	N	D
Jurassic Climax stock; quartz monzonite to granodiorite.	110	.5	3.0	1.0	.2	.15	N	N	.003	.002	.0015	.01	N	N
	111	.2	3.0	1.0	.3	.15	N	N	.003	.002	.0007	.01	N	N
	132	.2	2.0	1.0	.3	.15	N	N	.005	.002	.002	.01	N	N
	130	.5	.3	2.0	.7	.2	N	N	.003	.0015	.01	.01	N	N
	133	.7	.7	1.0	.3	.1	N	N	.003	.0015	.0015	.01	N	N
Unnamed Tertiary granodiorite from Elko County, Nev.	473	1	.3	1.5	.2	.3	N	N	.003	.001	.001	.01	N	N
	474	.7	.3	1.0	.7	.3	N	N	.003	.001	.0007	.015	N	N
	475	1	.5	1.0	.3	.3	N	N	.005	.005	.002	.01	N	N
	476	.7	.5	1.0	.15	.7	N	N	.005	.003	.002	.007	N	N
Unnamed Cretaceous granodiorite from Pershing County, Nev.	63T961	1	.3	1.5	.3	.2	N	N	.007	.002	.01	.007	N	.01
	63T975	.15	.2	1.0	.3	.15	N	N	.007	.002	.002	.007	N	.01
	63T1010	.3	.3	1.5	.15	.3	N	N	.007	.01	.002	.007	N	.01

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)—Continued												
		Nb (0.001)	Nd (0.007)	Ni (0.0003)	Pb (0.001)	Pr (0.01)	Sc (0.0005)	Sn (0.001)	Sr (0.0005)	V (0.0007)	Y (0.001)	Yb (0.0001)	Zn (0.02)	Zr (0.001)
Jurassic Snake Range stock; quartz monzonite.	40AWM60	.005	----------	0.001	0.002	----------	0.002	N	0.007	0.03	0.002	----------	N	0.007
	16MW60	N	N	.01	N	----------	.0005	N	.015	.03	N	N	N	.007
	57W51	.01	0.01	.005	.002	----------	.007	0.003	.007	.02	.005	0.0005	N	.02
	71MW60	.01	N	.003	.003	----------	.003	.0015	.015	.03	.002	.0003	N	.01
Tertiary Ibapah stock; quartz monzonite.	D110828	.0015	N	.01	N	N	.005	N	.002	.05	N	----------	0.05	.003
	D110829	.007	.03	.005	.007	N	.007	.005	.003	.02	.002	----------	.05	.007
	D110830	.003	N	.01	N	N	.003	N	.0015	.05	.0015	----------	.05	.007
Jurassic Climax stock; quartz monzonite to granodiorite.	110	.005	----------	.0015	N	----------	.002	N	.003	.03	N	N	N	.02
	111	.003	----------	.0015	N	----------	.003	N	.005	.03	N	N	N	.01
	132	.002	----------	.002	N	----------	.0015	N	.0015	.03	N	N	N	.007
	130	N	----------	.001	N	----------	.003	N	.003	.07	N	N	N	.005
	133	.005	----------	.001	N	----------	.002	N	.01	.03	N	N	N	.007
Unnamed Tertiary granodiorite from Elko County, Nev.	473	.015	----------	N	N	----------	.005	.01	.01	.02	.005	----------	N	.03
	474	.02	----------	N	N	----------	.007	.015	.003	.015	.005	----------	N	.02
	475	.005	----------	.002	N	----------	.003	N	.005	.03	N	----------	N	.03
	476	N	----------	.002	N	----------	.002	N	.003	.05	N	----------	N	.02
Unnamed Cretaceous granodiorite from Pershing County, Nev.	63T961	N	----------	.003	N	----------	.002	N	.007	.03	N	----------	N	.003
	63T975	N	----------	.003	N	----------	.0015	N	.001	.05	N	----------	N	.002
	63T1010	N	----------	.007	N	----------	.0015	N	.0015	.07	N	----------	N	.001

County. Biotite from the Snake Range intrusive contains detectable beryllium, whereas that from the granodiorite of Pershing County does not. Biotite samples lacking detectable zinc or lithium characterize the Climax stock and the granodiorite of Elko County; samples from the Climax stock contain <0.3 percent barium, and those from the granodiorite of Elko County contain ≧0.3 percent barium.

NORTHERN ROCKY MOUNTAINS, IDAHO AND MONT.

Only two rock bodies in the northern Rocky Mountains are represented by suites of analyzed biotite samples: the Idaho batholith in Idaho and the Boulder batholith in Montana, both of Cretaceous age. Both these batholiths are large, and they range in composition from granite to granodiorite. Only six biotite samples are available from the Boulder batholith, and only four from the Idaho batholith—far too few to adequately represent such vast and complex bodies. The analytical data on these 10 samples are presented in table 6, but until more data are acquired, apparent differences in the minor-element contents of the two analyzed suites must be regarded as merely suggestive of possible differences in the biotite of the two batholiths.

TABLE 6.—*Spectrographic analyses (in percent) of biotite samples from igneous rocks of the northern Rocky Mountains, Idaho and Mont.*

[Analysts, A. L. Sutton, Jr., and Barbara Tobin. N, looked for but not detected; leaders (--) in figure columns, not looked for. Other elements looked for but not detected: Be, Ce, Pb, Sn, and Zn]

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)								
		Ca (0.005)	Na (0.05)	Ti (0.0002)	Mn (0.0001)	Ba (0.0002)	Co (0.0003)	Cr (0.0001)	Cu (0.0001)	Ga (0.0005)
Cretaceous Boulder batholith; granodiorite to quartz monzonite.	280	0.7	0.7	3.0	1.5	0.3	0.005	0.001	0.0015	0.005
	247B	.15	.3	1.5	.2	.05	.003	.002	.003	.007
	273B	1.	.7	1.5	.5	.1	.007	.003	.015	.007
	274B	.2	.5	1.5	.3	.15	.01	.003	.002	.007
	275B	.7	.5	1.5	.3	.1	.007	.003	.015	.007
	276B	.1	.3	1.5	.7	.2	.007	.001	.001	.007
Cretaceous Idaho batholith; granodiorite.	308	.03	.3	1.5	.3	.2	.0015	.0015	N	.01
	134	.3	.2	2.0	.15	.3	.003	.003	.0007	.01
	135	.7	.3	2.0	.2	.2	.002	.003	.0005	.015
	137	.2	.3	2.0	.3	.1	.002	.005	.0005	.01

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)—Continued								
		La (0.003)	Nb (0.002)	Ni (0.0003)	Sc (0.0005)	Sr (0.0005)	V (0.0007)	Y (0.001)	Yb (0.0001)	Zr (0.001)
Cretaceous Boulder batholith; granodiorite to quartz monzonite.	280	N	0.005	0.003	0.003	0.01	0.03	N	--------	0.01
	247B	N	.01	.005	.007	.002	.03	0.002	0.0003	.03
	273B	N	.005	.007	.003	.003	.05	.001	N	.015
	274B	N	.002	.007	.001	.002	.05	N	N	N
	275B	N	.002	.007	.0015	.003	.05	.001	N	.007
	276B	N	.003	.002	.002	.001	.02	N	N	N
Cretaceous Idaho batholith; granodiorite.	308	0.003	.003	N	.003	.0015	.02	N	.0003	.01
	134	N	.007	.0015	.005	.003	.007	N	--------	.01
	135	N	.01	.0015	.0015	.005	.003	N	--------	.01
	137	N	.015	.002	.002	.003	.015	N	--------	.01

The biotite samples from the Boulder batholith contain appreciably more copper, and most of the samples also contain more cobalt, nickel, and vanadium, than do the biotite samples from the Idaho batholith. On the other hand, the analyzed samples from the Idaho batholith are richer in gallium than are the samples from the Boulder batholith. It is highly probable, however, that different rock facies within each batholith differ in the minor-element content of their biotites. More data are needed to determine whether these differences are characteristic of biotites from the entire batholiths or merely of biotite from certain facies within them.

CASCADE RANGE, WASH.

Suites of biotite samples from four intrusives in the Cascade Range of northern Washington represent a region slightly smaller than the southern Rocky Mountains in Colorado and range in age from cretaceous(?) to Tertiary. The Chilliwack batholith in Whatcom County near the Canadian line is a composite intrusive of Tertiary age composed of quartz monzonite and granodiorite. The Ten Peak pluton, about 100 miles to the southeast, in northwestern Chelan County, is Cretaceous and is composed largely of quartz monzonite. The Mount Stuart batholith, about 50 miles farther south, is also Cretaceous and is largely quartz diorite. The Similkameen batholith, in northern Okanogan County, about 100 miles east of the Chilliwack batholith, is also composite and ranges in composition from syenite to quartz diorite. The age of the Similkameen batholith is in doubt, but it is no younger than Cretaceous. Analyses of biotite samples from these four intrusive bodies are presented in table 7.

The biotite suites representing the four intrusives in the Cascade Range can be most readily distinguished by their titanium, strontium, and scandium contents. Biotites from the rocks of the Chilliwack batholith consistently contain 2 percent titanium, and none of the other biotites contain more than 1.5 percent. If a sample contains <2 percent titanium and $\geqq 0.002$ percent strontium, it represents the Similkameen batholith; samples from both the Mount Stuart batholith and the Ten Peak pluton contain $\leqq 0.0015$ percent strontium. Samples from the Ten Peak pluton can be distinguished from those of the Mount Stuart batholith on the basis of scandium content. Mount Stuart samples generally contain $\geqq 0.001$ percent scandium, whereas those from Ten Peak contain <0.001 percent.

TABLE 7.—*Spectrographic analyses (in percent) of biotite samples from igneous rocks of the Cascade Range, Wash.*

[Analyst: Harriet Neiman. N, looked for but not detected; D, detected but below threshold of sensitivity; leaders (..) in figure columns, not looked for. Other elements looked for but not detected: Ce, La, and Mo]

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)										
		Ca (0.005)	Na (0.05)	Ti (0.0002)	Mn (0.0001)	Ba (0.0002)	Be (0.0001)	Co (0.0003)	Cr (0.0001)	Cu (0.0001)	Ga (0.0005)	Li (0.01)
Tertiary Chilliwack batholith; quartz monzonite to granodiorite.	RWT474-67	0.15	0.2	2.0	0.1	0.2	N	0.007	0.005	0.005	0.005	N
	RWT475-67	.2	.2	2.0	.15	.2	N	0.1	.0015	.01	.007	N
	RWT476-67	.15	.3	2.0	.5	.3	N	.005	.0007	.002	.01	0.02
	RWT480-67	.15	.5	2.0	.1	.07	N	.007	.001	.001	.005	N
	75R-66	.05	.3	2.0	.07	.2	N	.01	.0015	.002	.003	N
Cretaceous Ten Peak pluton; quartz monzonite.....	60-62	.1	.3	1.0	.1	.5	N	.005	.007	.0007	.005	N
	JE-15-67	.1	.3	.7	.1	.3	N	.007	.03	.001	.005	N
	JE-16-67	.15	.3	1.0	.15	.5	N	.003	.005	.0005	.005	N
Cretaceous Mount Stuart batholith; quartz diorite..	JE-12A-67	.15	.2	1.0	.15	.3	N	.005	.02	.002	.007	N
	JE-13-67	.1	.3	1.5	.2	.5	N	.007	.02	.002	.007	N
	JE-14-67	.15	.2	1.0	.1	.1	N	.005	.05	.0015	.007	.015
	JE-20-67	.15	.5	1.0	.15	.3	N	.007	.05	.01	.005	N
	JE-21-67	.2	.5	1.5	.05	.5	N	.007	.05	.0005	.003	N
	JE-22-67	.1	.2	1.5	.07	.3	N	.005	.02	.002	.003	N
Cretaceous(?) Similkameen batholith; syenite to quartz diorite.	L277Z	.1	.2	1.0	.07	.3	N	.01	.0002	.001	.002	N
	L301	.15	.3	.7	.1	.03	N	.007	.03	.02	.005	N
	L589	.5	.3	.7	.3	.05	0.0001	.005	.005	.002	.007	.015
	L618	.2	.7	.7	.5	.02	.0001	.005	.001	.005	.005	.01

Rock body and rock type	Sample No.	Element (threshold of detection in parentheses)—Continued										
		Nb (0.001)	Ni (0.0003)	Pb (0.001)	Sc (0.0005)	Sn (0.001)	Sr (0.0005)	V (0.0007)	Y (0.001)	Yb (0.0001)	Zn (0.02)	Zr (0.001)
Tertiary Chilliwack batholith; quartz monzonite to granodiorite.	RWT474-67	0.002	0.005	N	0.002	N	0.001	0.07	N	----------	N	N
	RWT475-67	N	.003	N	.002	N	.0007	.07	N	----------	N	N
	RWT476-67	N	.002	N	.01	0.002	.001	.02	0.01	0.001	N	0.02
	RWT480-67	.005	.003	N	.0015	N	.0015	.03	.001	----------	N	N
	75R-66	.002	.01	N	.005	N	.001	.05	N	----------	N	N
Cretaceous Ten Peak pluton; quartz monzonite	60-62	.001	.002	0.002	D	N	.0015	.02	N	----------	N	.0015
	JE-15-67	N	.01	N	N	N	.001	.03	N	----------	0.03	.005
	JE-16-67	N	.0015	N	.0007	N	.001	.02	N	----------	.03	.003
Cretaceous Mount Stuart batholith; quartz diorite	JE-12A-67	N	.007	N	.005	N	.0007	.05	N	----------	.05	.007
	JE-13-67	.002	.01	N	.0015	N	.0005	.05	N	----------	.05	N
	JE-14-67	N	.01	N	.003	N	.001	.05	N	----------	.03	.002
	JE-20-67	N	.02	N	.0007	N	.001	.03	N	----------	N	N
	JE-21-67	N	.03	N	.001	N	.0015	.05	N	----------	N	N
	JE-22-67	N	.01	N	.001	N	.0005	.05	N	----------	N	N
Cretaceous(?) Similkameen batholith; syenite to quartz diorite.	L277Z	N	.01	N	.0015	N	.002	.03	N	----------	N	N
	L301	N	.02	N	N	N	.003	.03	N	----------	.03	N
	L589	N	.002	N	.001	N	.002	.05	N	----------	.05	.005
	L618	N	.001	N	.002	N	.005	.03	N	----------	.05	.007

REGIONAL VARIATIONS AND VARIATION WITH AGE OF INTRUSIVE

When all the biotite analyses are grouped by region, the concentration ranges of the elements overlap to such an extent that no element is distinctively higher or lower in the biotite of any one region compared with the biotite in any other. However, there are differences in the regional median values for certain elements that may reflect regional tendencies toward concentration or impoverishment of these elements in the biotite. The median concentration of titanium in the biotite samples from southern Arizona is twice as much as it is in the samples from any other region except the northern Rocky Mountains; chromium has its highest median in samples from the southern Rocky Mountains; niobium has its highest median value in samples from the northern Rocky Mountains; and the median for strontium is distinctly lower in samples from the Cascade Range than in those from any other region. None of the other minor elements show any appreciable differences on a regional basis.

If the samples are classified broadly by age into Precambrian, Mesozoic, and Cenozoic, only two elements, titanium and chromium, show consistent trends relative to the age of the samples. Titanium has a rather narrow concentration range and increases progressively from Precambrian to Cenozoic (fig. 3). The median values for chromium in the samples trend in the opposite direction; they are 0.01 percent for the Precambrian, 0.003 percent for the Mesozoic, and 0.002 percent for the Cenozoic. The range in concentration of chromium in these samples is so great, spanning two orders of magnitude, that a far larger and more representative suite of samples would be needed to adequately test the hypothesis of a relationship between the age of a biotite and its chromium content. Although there is considerable overlap in the titanium values for biotite of various ages, titanium covers a much narrower range and is more consistent in its distribution than chromium. All the biotite samples that contain >1.5 percent titanium are from Mesozoic or younger rocks, and all those that contain <1 percent titanium are from rocks older than Cenozoic (fig. 3).

CONCLUSIONS

Rock samples from unrelated felsic igneous intrusive bodies of similar composition in the same area can commonly be distinguished by the patterns of minor-element distributions in their biotites. Such patterns provide evidence for the parent affiliation of small satellite bodies—such as dikes, sills, and plugs—in an area characterized by

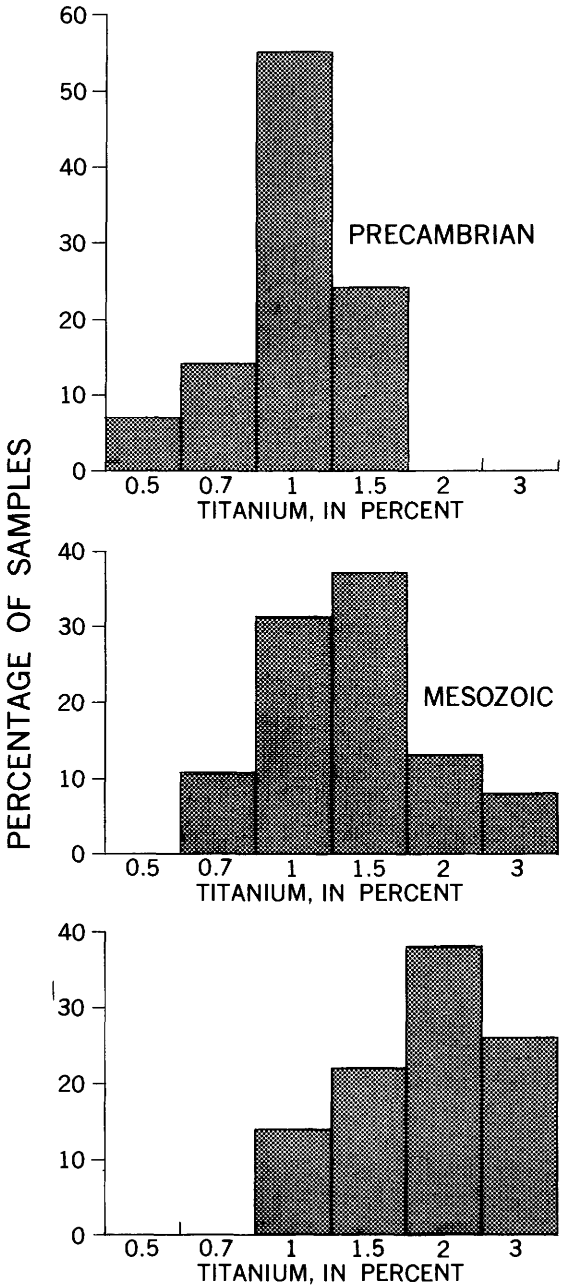

FIGURE 3.—Titanium content of biotite from felsic intrusive rocks of various ages.

multiple intrusives of different ages. They may also indicate the probable source rock for float samples or detrital cobbles, and they may aid the correlation of isolated outcrops in a covered area.

Biotite separates from different facies of a composite intrusive may show consistent trends in the concentrations of certain minor elements relative to the ages of these facies. Such trends can be useful in helping to establish the intrusive sequence from a common center in areas where the observable field relations are not diagnostic.

Although the data of this paper are insufficient to establish regional differences in the composition of biotite from igneous intrusives, they do suggest the possibility that such differences may exist. A possible trend toward enrichment of titanium in Tertiary biotite as contrasted with Precambrian biotite is worthy of more systematic investigation.

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