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Minor-Element and Sr-Isotope Geochemistry of Tertiary Stocks, Colorado Mineral Belt

E. Craig Simmons* and Carl E. Hedge

U.S. Geological Survey, Denver, Colorado 80225, USA

Abstract. Rocks of the northeast portion of the Colorado mineral belt form two petrographically, chemically and geographically distinct rock suites: (1) a silica oversaturated granodiorite suite; and (2) a silica saturated, high alkali monzonite suite. Rocks of the granodiorite suite generally have Sr contents less than 1000 ppm, subparallel REE patterns and initial $^{87}Sr/^{86}Sr$ ratios greater than 0.707. Rocks of the monzonite suite are restricted to the northeast part of the mineral belt, where few rocks of the granodiorite suite occur, and generally have Sr contents greater than 1000 ppm, highly variable REE patterns and $^{87}Sr/^{86}Sr$ initial ratios less than 0.706.

Despite forming simple, smooth trends on major element variation diagrams, trace element data for rocks of the granodiorite suite indicate that they were not derived from a single magma. These rocks were derived from magmas having similar REE patterns, but variable Rb and Sr contents, and Rb/Sr ratios. The preferred explanation for these rocks is that they were derived by partial melting of a mixed source, which yielded pyroxene granulite or pyroxenite residues.

The monzonite suite is chemically and petrographically more complex than the granodiorite suite. It is subdivided here into alkalic and mafic monzonites, and quartz syenites, based on the textural relations of their ferromagnesian phases and quartz. The geochemistry of these three rock types require derivation from separate and chemically distinct magma types. The preferred explanation for the alkalic monzonites is derivation from a heterogeneous mafic source, leaving a residue dominated by garnet and clinopyroxene. Early crystallization of sphene from these magmas was responsible for the severe depletion of the REE observed in the residual magmas. The lower Sr content and higher Rb/Sr ratios of the mafic monzonites requires a plagioclase-bearing source.

The Sr-isotope systematics of the majority of these rocks are interpreted to be largely primary, and not the result of crustal contamination. The positive correlation of Rb/Sr and $^{87}Sr/^{86}Sr$ ratios for the least fractionated samples indicate that the sources from which parent magmas of both the granodiorite and monzonite suites were derived are Precambrian in age.

Introduction

This report summarizes the results of a geochemical and isotope study of the igneous rocks in the northeastern half of the Colorado mineral belt. Many of these rocks are clearly related in space and time to important ore deposits. The purpose of this study was to learn something about the source materials of the magmas and to define the evolution of the magmas as they differentiated and interacted with their wall rocks.

Igneous activity began in Colorado soon after the onset of the Laramide orogeny (Tweto, 1975); but whereas the uplifts were wide-spread and had a general north-northwesterly trend, the Laramide igneous activity was confined to a narrow northeast-trending belt. This belt is known as the Colorado mineral belt because of its relatively high concentration of economic mineral deposits (Fig. 1). The Laramide igneous rocks are mostly stocks and dikes; however, large volumes of volcanic debris in upper Cretaceous and lower Tertiary sediments preserved along the flanks of the mineral belt, indicate that important volumes of lava were erupted, but most have been removed by erosion.

* Present address: Department of Chemistry and Geochemistry, Colorado School of Mines, Golden, CO 80401, USA
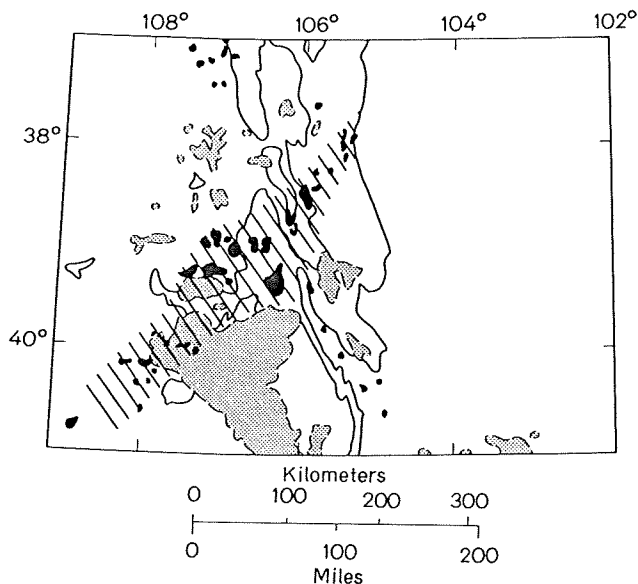
Fig. 1. Simplified geologic map of Colorado. showing the major Tertiary plutonic rocks (solid), volcanic rocks (stippled) and the extent of the Colorado mineral belt (hachured field). Heavy solid-lines show the outline of the presently exposed Precambrian

Fig. 2. A plot of total alkalies ($Na_2O + K_2O$) versus SiO_2 for representative samples of the Colorado mineral belt: granodiorites (●), mafic monzonites (◇), hornblende-pyroxene monzonites (×), quartz-bearing monzonites (□), and leucocratic monzonites (△). Analyses from Braddock (1969), Mathews (1970), Wahlstrom (1940), Van Horn (1976), Young (1972) and Phair and Jenkins (1975)

A major episode of igneous activity occurred during Oligocene time throughout much of Western U. S. and plutonism and volcanism occurred again along the Colorado mineral belt and elsewhere in Colorado. Igneous activity during the late Tertiary in Colorado was sporadic and relatively small in volume. This latest activity was concentrated in the extreme southern and northwestern parts of the state, generally outside the areas of earlier activity.

Petrology of Igneous Rocks of the Colorado Mineral Belt

Igneous rocks of the Colorado mineral belt can be divided into two petrographically, chemically and geographically distinct suites: a silica oversaturated granodiorite-quartz monzonite suite, and a silica saturated monzonite suite (Braddock, 1969).

Petrographically, monzonite rocks of the Colorado mineral belt are distinguished from rocks of the granodiorite suite by the presence of clinopyroxene and the fact that the monzonites contain less than 15% quartz. Monzonites appear to be restricted to the northeastern part of the mineral belt (Fig. 1), where few rocks of the granodiorite suite occur.

The chemical differences between the two suites are illustrated in Figure 2, a plot of total alkalies versus silica, and Figure 3, a plot of normative quartz-plagioclase-orthoclase. The locations of the igneous plutons from which the samples for this study have
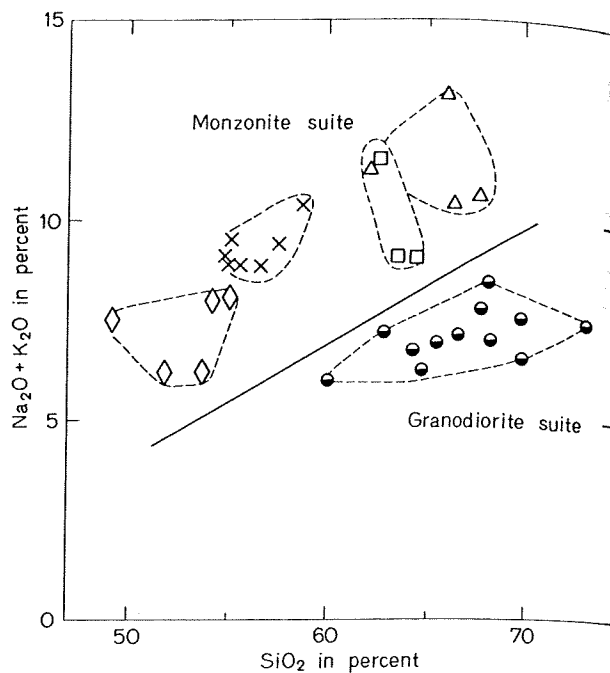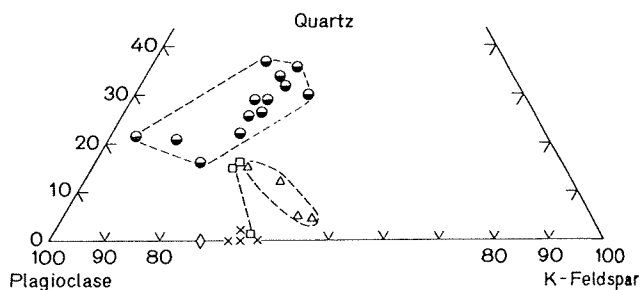

Fig. 3. A plot of normative quartz-plagioclase-K-feldspar for representative samples of the Colorado mineral belt. Symbology and references are the same as for Figure 2

been taken are illustrated on Figure 4. Table 1 gives some representative major element analyses. For a more complete compilation of chemical data including rocks of the Colorado mineral belt, see Young (1972).

Granodiorite Suite

Rocks of the granodiorite suite are volumetrically the more abundant of the two suites, occurring over almost the entire length of the Colorado mineral belt. The rocks range in composition from tonalite to quartz monzonite and contain phenocrysts of quartz, feldspar, and hornblende or biotite; hornblende predomi-
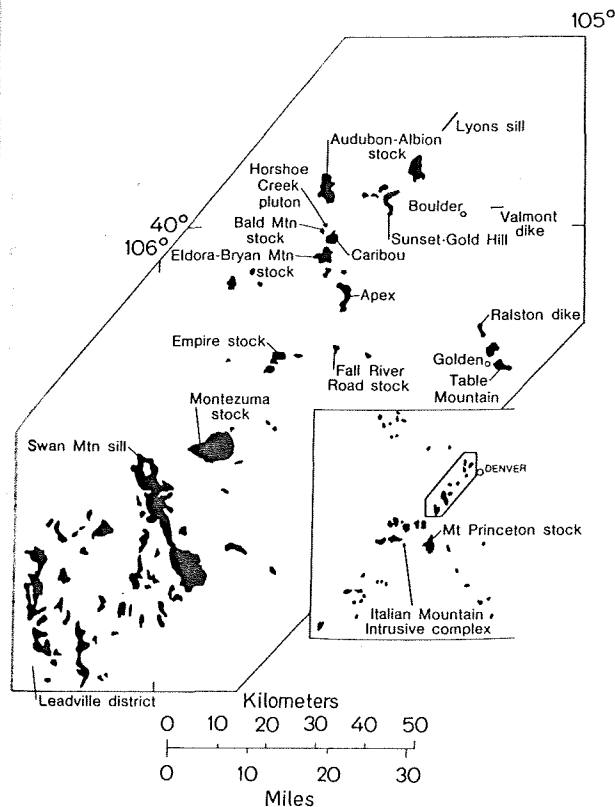
Fig. 4. Simplified map of the northeastern portion of the Colorado mineral belt, on which are shown the locations of the plutonic or volcanic units from which samples were taken for this study. Inset at lower right shows the location of Figure 4 as well as the location of the Mt. Princeton and Italien Mt. intrusions

nates in the more mafic members of the suite, biotite in the more silicic (Braddock, 1969). Rocks of the granodiorite suite generally contain more than 63% silica and have total alkali contents of about 7% (Fig. 2). On a normative quartz-plagioclase-orthoclase plot, these rocks form a field trending away from the plagioclase corner toward the middle of the diagram (Fig. 3). Almost all rocks of the granodiorite suite contain at least 20% normative or modal quartz. On major element variation diagrams (not shown), rocks of the granodiorite suite form simple, smooth trends of decreasing CaO, MgO, total Fe, and TiO_2, increasing K_2O and constant Na_2O when platted against SiO_2.

Samples of the granodiorite suite analyzed in this study, selected to cover ranges in geography, age, and composition, include: (1) Four samples, ranging in composition from tonalite to quartz monzonite, from the Italian Mountain Intrusive Complex (Cunningham, 1976); fission track data for a zircon from the youngest intrusive phase yielded an age of about 33 m.y. (Oligocene) (Cunningham and Naeser, 1975); (2) Three granodiorite-quartz monzonite samples from the Mt. Princeton composite batholith, which is about 35 to 40 m.y. old (Hedge, unpublished data); (3) Samples of Johnson Gulch, Evans Gulch and Lincoln Porphyries from the Leadville district (Emmons et al., 1927), for which K/Ar data for hornblende and biotite yield ages between 64 and 67 m.y. (Late Cretaceous to Paleocene) (Pearson et al., 1962); (4) A biotite quartz monzonite sample from a sill in the vicinity of Swan Mountain, for which a Rb/Sr biotite-whole-rock age of 45 m.y. was obtained (Hedge, unpublished data); (5) Two quartz monzonites and one granite aplite from the Montezuma batholith; a Rb/Sr

biotite-whole-rock age of 39 m.y. was obtained for one of the quartz monzonites (Hedge, unpublished data); (6) One biotite quartz monzonite sample from the Empire stock, for which a Rb/Sr biotite-whole-rock age of 65 m.y. was obtained (Hedge, unpublished data); (7) One sample of a quartz monzonite sill from the vicinity of Lyons, east of the Front Range; fission track data for a zircon from this locality yielded an age of 63 m.y. (Hoblitt and Larson, 1975).

Monzonite Suite

Chemically and petrographically the monzonite suite is more complex than the granodiorite suite. We distinguish here the following igneous rocks units: (1) alkalic monzonites; (2) mafic monzonites; (3) quartz syenites; (4) ultramafic rocks; and (5) latite and bostonite dikes. These rock types are distinguished petrographically by the type, amount and textural relations of their ferromagnesian phases, along with the textural relations of quartz. These and other characteristics are summarized in Table 2.

(1) Alkalic Monzonites. Rocks which have total alkalies greater than 9%, silica contents between 53 and 65%, and contain clinopyroxene, rimmed corona-fashion by hornblende and may contain interstitial quartz, are referred to here as the alkalic monzonites. At Empire and Audubon-Albion, alkalic monzonites form plutonic complexes in which successively, more alkaline and leucocratic rocks intrude less alkaline rocks in three pulses of chemically and petrographically distinct rock types in a well developed sequence from hornblende-pyroxene monzonites, to quartz bearing monzonites and leucocratic monzonites with minor porphyritic monzonites (Wahlstrom, 1940; Braddock, 1969; Mathews, 1970).

Hornblende-pyroxene monzonites are the earliest phase and contain 10–30% ferromagnesian minerals, little or no quartz, and have silica contents of 53–58% and total alkali contents of 9–11% (Fig. 2). These rocks have previously been called hornblende-pyroxene monzonites (Braddock, 1969) or monzonites (Wahlstrom, 1940; Mathews, 1970).

Quartz-bearing monzonites are the second intrusive phase and contain less than 15% ferromagnesian minerals, 0–15% quartz, and have between 58–64% SiO_2 and 8–12% total alkalies (Fig. 2) (Wahlstrom, 1940; Braddock, 1969; Mathews, 1970).

Leucocratic monzonites are the last intrusive phase and contain less than 5–10% ferromagnesian minerals, 5–10% quartz, and have more than 64% SiO_2 and 10 to 14% total alkalies (Fig. 2). These rocks have previously been called leucocratic monzonite (Braddock, 1969) or syenite (Wahlstrom, 1940; Mathews, 1970).

Porphyritic monzonites form minor volumes of coarse grained rocks consisting dominantly of alkali feldspar, which occur as separate intrusions into, or coarse-grained, leucocratic varieties gradational into hornblende-pyroxene monzonite (Braddock, 1969).

The sequence hornblende-pyroxene monzonite to leucocratic monzonite is marked by a decrease in the amount of ferromagnesian minerals, the An content of plagioclase, an increase in SiO_2 and total alkalies, and a decrease in CaO, MgO, and TiO_2 and Mg/(Mg + Fe) ratios. For a more complete characterization of rocks of the alkalic monzonite suite see Braddock (1969) and Mathews (1970).

Analyses of representative samples of the alkalic monzonite suite from five plutonic complexes are included here: (1) Empire stock (Braddock, 1969); (2) Audubon-Albion stock (Wahlstrom, 1940; Mathews, 1970); (3) Eldora-Bryan Mountain stock (Cree, 1948); (4) a small pluton near Sunset (Breed, 1899); (5) a small pluton north of Horseshoe Creek (Gable, 1969). K/Ar and Rb/Sr ages of biotite and fission track ages an sphene and zircon suggest

Table 1. Major element compositions and CIPW norms of representative samples of the Colorado mineral belt

	Granodiorite suite				Monzonite suite								
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	64.0	64.8	67.5	72.4	49.7	54.7	59.4	62.4	65.9	60.9	64.6	36.3	52.0
Al_2O_3	16.5	16.4	15.5	14.5	18.1	18.5	18.4	16.8	17.5	17.1	16.6	10.6	15.6
TiO_2	0.59	0.50	0.49	0.29	0.85	0.89	0.57	0.64	0.30	0.50	0.42	2.1	1.1
Fe_2O_3	2.5	2.7	2.2	1.2	2.64	4.1	2.9	3.6	2.2	3.3	2.2	11.1	3.9
FeO	2.4	2.1	1.6	0.68	6.19	3.4	2.0	2.0	0.78	2.5	2.1	9.8	6.0
MgO	2.0	1.3	0.72	0.32	5.73	2.3	1.1	1.2	1.0	0.81	0.74	8.7	3.3
MnO	0.12	0.09	0.14	0.09	0.13	0.19	0.08	0.14	0.16	0.03	0.05	0.26	0.15
CaO	4.3	3.5	3.3	1.8	8.24	6.4	4.4	2.5	1.3	2.3	3.0	12.9	7.1
Na_2O	5.3	3.4	3.6	3.2	2.99	4.6	5.89	5.1	5.7	5.59	5.58	1.16	3.99
K_2O	0.67	3.4	4.1	4.2	3.90	4.2	3.84	3.8	4.7	3.68	3.09	1.55	3.16
P_2O_5	0.41	0.33	0.35	0.13	0.81	0.49	0.28	0.44	0.10	0.25	0.19	1.5	0.46
H_2O^+	1.4	1.6	0.26	0.86	0.91	0.69	0.52	0.80	0.59	1.7	0.59	2.0	1.5
H_2O^-	0.26	0.24	0.08	0.24				0.25	0.35	–	0.20	0.30	0.35	0.23
CO_2	0.02	0.08	–	0.04	–	0.01	0.08	0.11	0.02	0.51	0.02	0.48	0.95
Σ	100.5	100.4	99.8	100.0	100.2	100.5	99.7	99.9	100.2	99.4	99.5	98.8	99.4
Quartz.	19.1	23.4	23.6	34.2	–	–	0.97	12.5	10.8	10.3	12.6	–	0.59
Corundum	0.22	1.58	–	1.75	–	–	–	0.82	0.92	1.66	–	–	–
Orthoclase	4.01	20.4	24.4	25.1	23.2	24.9	23.0	22.8	27.9	21.9	18.3	8.85	18.3
Albite	45.4	29.2	30.6	27.4	19.1	36.0	50.8	43.8	48.5	46.5	48.2	4.20	33.0
Anorthite	18.9	15.4	14.1	8.18	24.6	17.5	11.8	9.66	5.82	6.51	10.5	19.6	15.9
Nepheline	–	–	–	–	3.43	1.62	–	–	–	–	–	2.76	–
Wollastonite	–	–	0.03	–	4.69	4.66	3.23	–	–	–	1.25	13.2	4.32
Enstatite	5.04	3.29	1.80	0.81	2.84	3.27	2.73	3.0	2.5	2.02	1.85	15.6	8.21
Ferrosilite	1.61	0.98	0.58	–	1.59	0.99	0.49	–	–	1.08	1.42	4.18	6.27
Forsterite	–	–	–	–	8.09	1.73	–	–	–	–	–	8.54	–
Fayalite	–	–	–	–	5.01	0.58	–	–	–	–	–	2.52	–
Magnetite	3.67	3.97	3.21	1.67	3.86	5.96	4.21	5.12	1.85	4.79	3.20	16.1	5.65
Hematite	–	–	–	0.07	–	–	–	0.12	0.94	–	–	–	–
Ilmenite	1.13	0.96	0.94	0.56	1.63	1.69	1.08	1.23	0.57	0.96	0.80	3.99	2.09
Apatite	0.98	0.79	0.83	0.31	1.93	1.16	0.67	1.06	0.24	0.61	0.44	3.56	1.08

1. Tonalite, Italian Mountain Intrusive Complex (Oligocene). Analysis from Cunningham (1976).
2. Granodiorite, Italian Mountain Intrusive Complex. Analysis from Cunningham (1976).
3. Quartz monzonite, Montezuma stock. Analysis from Young (1972).
4. Quartz monzonite, Italian Mountain Intrusive Complex. Analysis from Cunningham (1976).
5. Mafic latite, lowermost lava in the Denver Formation on Table Mountain, Jefferson County, Colorado. Analysis from Wahlstrom (1940).
6. Alkali monzonite, Empire stock, Clear Creek County, Colorado. Analysis from Braddock (1969).
7. Quartz-bearing monzonite (75CS78), Bryan Mountain stock, Boulder County, Colorado.
8. Quartz-bearing monzonite, Empire stock, Clear Creek County, Colorado. Analysis from Braddock (1969).
9. Leucocratic monzonite, Empire stock, Clear Creek County, Colorado. Analysis from Braddock (1969).
10. Quartz syenite (75CS73), small stock near Sunset, Boulder County, Colorado.
11. Quartz syenite (75CS77a), Apex stock, Gilpin County, Colorado.
12. Amphibolite (75CS72a), Caribou stock, Boulder County, Colorado.
13. Hornblende latite (75CS79), near Nederland, Boulder County, Colorado.

that these plutons are all about 60 m.y. old (Hedge, unpublished data; Naeser, oral communication).

(2) Mafic Monzonites. Also present in the northeast part of the mineral belt are mafic monzonites, containing clinopyroxene enclosed in biotite, plagioclase (An > 40), and occasional olivine. These rocks occur at Caribou (Bastin and Hill, 1917; Smith, 1938), and Bald Mountain, and the Audubon-Albion stock (Wahlstrom, 1940; Mathews, 1970). These rocks also intrude sedimentary rocks to the east of the Front Range, forming dikes in the vicinity of Table Mountain (Van Horn, 1976) and Valmont (Emmons et al., 1896), and they occur as lavas in the Upper Cretaceous and Paleocene Denver Formation on North and South Table Mountains (Van Horn, 1976). They contain lower total alkalies than rocks of the alkalic monzonite suite (Fig. 2), and have higher MgO, total Fe, and Mg/(Mg + Fe) ratios (Table 1). These rocks are referred to as mafic monzonites and latites (e.g., Van Horn, 1976). Fission track and K/Ar data for intrusive and extrusive rocks

Table 2. Petrographic characteristics of monzonite suite rocks of the Colorado mineral belt

Rock type	Ferromagnesian phases	Quartz	Plagioclase	Other features
Alkalic Monzonites	Clinopyroxene rimmed by hornblende; no olivine	$\leqq 15\%$; always *interstitial*	An $\leqq 40$	Sphene
a) Hornblende-pyroxene monzonites	10–30%	Very minor	An 25–40	
b) Quartz-bearing monzonites	$\leqq 10$–15%	0–15%	An 15–25	
c) Leucocratic monzonites	$\leqq 5$–10%	0–10%	An 5–15	
Mafic Monzonites	Clinopyroxene rimmed by biotite; $\pm$ olivine $\pm$ quartz	Very rare, always *interstitial.*	An 40–60	
a) hornblende-free	No hornblende			No sphene
b) hornblende-bearing	Hornblende, in addition to clinopyroxene and biotite			Sphene
Quartz Syenites	Clinopyroxene, rimmed by hornblende	$\leqq 15\%$; Occurs as *phenocrysts.*	An 10–20	Sphene
Ultramafic Rocks	>70%	Very rare	Rare	
a) Pyroxenites	>70% clinopyroxene; $\pm$ biotite			Occasional sphene
b) Hornblendites	>70% hornblende; may enclose clinopyroxene			Sphene
Dikes				
a) Latite dikes	Clinopyroxene (rimmed by hornblende) in mafic compositions; biotite in silicic compositions	Minor, *interstitial* in hornblende latites; abundant in biotite latites	An 40 in hornblende latites	
b) Bostonite dikes	Very minor	0–15%; *interstitial*	Alkali feldspar only	Groundmass generally highly altered

east of the Front Range yield ages of 60–64 m.y. (Scott, 1972; Hoblitt and Larson, 1975); Rb/Sr data for biotite separates from mafic monzonites intruding the Precambrian yield ages of 57–62 m.y. (Hedge, unpublished data). Eight mafic monzonite samples were analyzed in this study. They include: samples of the three lavas from the Table Mountain Shoshonite (Paleocene), samples of the Ralston and Valmont dikes, and samples from the Caribou, Bald Mountain, and Audubon-Albion stocks. All are typical mafic monzonites, except for the Bald Mountain and Audubon-Albion samples, which contain hornblende in addition to clinopyroxene and biotite.

(3) Quartz Syenites. In addition to the two previously recognized alkaline rock types, we distinguish a third with affinities to both the granodiorite and monzonite suites. Quartz syenites contain quartz phenocrysts like rocks of the granodiorite suite, but contain hornblende-rimmed clinopyroxene like rocks of the alkalic monzonite suite. These rocks have been previously mapped as hornblende granodiorite (Wells, 1960) or leucocratic granodiorite (Gable, 1969). The quartz syenites are similar in major element chemistry to the quartz-bearing monzonite members of the alkalic monzonite suite (Table 1). However, the presence of quartz phenocrysts in the quartz syenites indicate that these two rock types experienced separate histories. Four quartz syenite samples were analyzed in this study: one from a small stock along the Fall River Road, two from the Apex stock, and one from a small body in the vicinity of Gold Hill. Fission trach data for zircon from the Apex stock yields an age of approximately 60 m.y. (Naeser, oral commu-

nication), and Rb/Sr data for a biotite separate from the Gold Hill sample yielded an age of 54 m.y. (Hedge, unpublished data).

(4) Ultramafic Rocks. Associated with both alkalic and mafic monzonites are pyroxenites and hornblendites with igneous textures. Pyroxenites contain more than 70% clinopyroxene plus apatite, opaques, and locally biotite or plagioclase and are found associated with mafic monzonites of the Caribou stock (Bastin and Hill, 1917; Smith, 1938), and alkalic monzonites in the Empire stock (Braddock, 1969; Larsen, 1968). Pyroxenites from each of the above localities were analyzed in this study. Hornblendites contain more than 70% hornblende plus clinopyroxene, opaques, sphene, and locally biotite or plagioclase, and are found associated with mafic monzonites in the Caribou and Bald Mountain plutons, and with alkalic monzonites in the Audubon-Albion stock (Wahlstrom, 1940; Mathews, 1970). Hornblendites associated with mafic monzonites from the Bald Mountain and Caribou stocks were analyzed in this study. As no ages are presently available for either type of ultramafic rock, we have assumed that they are the same age as the host alkalic or mafic monzonites.

(5) Latite and Bostonite Dikes. Latite dikes contain phenocrysts of clinopyroxene, hornblende or biotite, and feldspar and intrude Precambrian rocks in the vicinity of monzonite suite plutons. Rb/Sr data for biotite separates and fission track data for apatite from several of these dikes indicate ages in the range 56–60 m.y. (Hedge, unpublished data; Naeser, oral communication). We have analyzed three latite dikes (45, 46, and 47), all from the vicinity of Nederland (Gable, 1969).

Table 3. Selected major and trace element abundances and $^{87}Sr/^{86}Sr$ ratios for rocks of the northeastern part of the Colorado mineral belt

Sample No.	Rock[d] Type	Latitude	Longitude	Na_2O[a]	K_2O[a]	Rb[b]	Sr[b]	$\dfrac{^{87}Sr}{^{86}Sr}$	Age (m.y.)	$\left(\dfrac{^{87}Sr}{^{86}Sr}\right)_i$[c]
Granodiorite suite										
Italian Mt.[e]										
1. 1298	Ton.	−	−	5.3	0.67	16.4	941.0	0.70749	33.0	0.70747
2. 1286	Grd.	−	−	3.4	3.4	68.3	812.0	0.70682	33.0	0.70671
3. I173	QMz.	−	−	3.3	4.0	144.0	483.0	0.71114	33.0	0.71075
4. I325	QMz.	−	−	3.2	4.2	148.0	318.0	0.71033	33.0	0.70971
Mt. Princeton										
5. PT7435	Grd.	−	−	3.63	4.03	132.0	600.0	0.70738	36.0	0.70706
6. PT7438	Grd.	−	−	3.50	4.35	141.0	544.0	0.70804	35.0	0.70767
7. PT7457	Grd.	−	−	3.00	3.31	73.8	557.0	0.70873	45.0	0.70849
Leadville District										
8. 90T53	Grd.	39°15′	106°14′	3.44	4.03	126.0	801.0	0.70681	67.0	0.70639
9. 31T55	Grd.	39°15′	106°15′	3.72	3.47	104.0	802.0	0.70811	64.0	0.70778
10. 25T56	QMz.	39°21′	106°07′	3.94	2.97	65.8	591.0	0.70743	67.0	0.70713
Swan Mt.										
11. 75CS86	Grd.	39°35′28″	106°02′20″	4.74	3.61	130.0	1079.0	0.70755	44.0	0.70734
Montezuma										
12. 75CS82	QMz.	39°36′02″	105°50′07″	3.25	4.05	134.0	537.0	0.70924	39.0	0.70885
13. 75CS83	Apl.	39°36′12″	105°48′59″	0.88	6.20	258.0	93.1	0.71612	39.0	0.71178
14. 75CS84a	Grd.	39°36′18″	105°54′55″	3.40	4.11	152.0	541.0	0.70874	39.0	0.70830
Empire										
15. 75CS88	Grd.	39°45′37″	105°40′11″	3.56	3.80	85.0	925.0	0.70742	65.0	0.70718
Lyons										
16. 76CS105	QMz.	40°12′05″	105°17′46″	2.98	3.51	88.7	1209.0	0.70888	64.0	0.70870
Monzonite suite										
Empire										
17. 75CS67	HMz.	39°45′46″	105°43′08″	5.78	5.08	154.0	2829.0	0.70506	65.0	0.70490
18. 75CS76	LMz.	39°45′37″	105°38′00″	6.19	5.68	157.0	457.0	0.70641	65.0	0.70551
19. 76CS92	Pxt.	39°45′36″	105°42′50″	0.99	0.40	14.2	745.0	0.70526	65.0	0.70521
Fall River Road										
20. 75CS80	QSy.	39°46′55″	105°34′38″	5.78	3.25	70.8	1653.0	0.70523	60.0	0.70513
Apex										
21. 75CS77a	QSy.	39°52′30″	105°33′00″	5.58	3.09	63.9	1540.0	0.70556	60.0	0.70546
22. HMN-9	QSy.	39°53′45″	105°32′53″	5.51	3.45	91.3	1488.0	0.70542	60.0	0.70527
Eldora-Bryan Mt.										
23. HMN-13	MzQ.	39°57′00″	105°35′07″	3.24	5.48	212.0	494.0	0.70813	59.0	0.70711
24. 75CS78	MzQ.	39°57′14″	105°36′20″	5.89	3.84	52.9	2323.0	0.70545	59.0	0.70540
25. 76CS102	MzQ.	39°56′59″	105°35′07″	3.21	5.56	227.0	459.0	0.70879	59.0	0.70761
26. 76CS103	MzQ.	39°56′58″	105°37′01″	5.04	3.70	105.0	1510.0	0.70553	59.0	0.70537
Bald Mt.										
27. HMN-2	MMz.	39°59′16″	105°36′09″	2.71	3.40	94.6	584.0	0.70868	58.0	0.70830
28. HMN-3	Amp.	39°59′16″	105°36′09″	1.66	1.56	33.9	572.0	0.70761	58.0	0.70747
Caribou										
29. 75CS69	MMz.	39°58′58″	105°34′45″	3.49	4.99	143.0	1037.0	0.70543	60.0	0.70510
30. 75CS70a	Pxt.	39°58′57″	105°34′46″	0.23	0.10	2.52	96.5	0.70532	60.0	0.70526
31. 75CS72a	Amp.	39°58′42″	105°35′10″	1.16	1.55	27.4	607.0	0.70523	60.0	0.70512
Horseshoe Creek										
32. HMN-1	MzQ.	39°59′47″	105°35′26″	4.51	5.58	146.0	1238.0	0.70561	60.0	0.70533

Table 3 (continued)

Sample No.	Rock[d] Type	Latitude	Longitude	Na$_2$O[a]	K$_2$O[a]	Rb[b]	Sr[b]	$\frac{^{87}Sr}{^{86}Sr}$	Age (m.y.)	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_i$[c]
Monzonite suite										
Audubon-Albion										
33. 76CS96	MMz.	40°04′15″	105°36′53″	2.87	3.10	94.3	963.0	0.70746	60.0	0.70722
34. 76CS97	PMz.	40°03′11″	105°36′47″	3.86	6.60	142.0	2825.0	0.70516	60.0	0.70504
35. 76CS98	MzQ.	40°05′23″	105°35′48″	5.21	4.40	120.0	1550.0	0.70617	60.0	0.70598
36. 76CS99	MzQ.	40°04′46″	105°36′09″	6.21	4.40	112.0	1603.0	0.70615	60.0	0.70598
37. 76CS100	LMz.	40°04′46″	105°35′28″	4.52	9.08	194.0	71.8	0.71253	60.0	0.70602
Sunset-Gold Hill										
38. BC-3	LMz.	40°03′28″	105°24′26″	6.05	4.44	91.7	1990.0	0.70565	51.0	0.70556
39. 75CS73	QSy.	40°02′16″	105°26′52″	5.59	3.68	89.8	1542.0	0.70598	51.0	0.70586
Table Mt.										
40. 76CS89	MMz.	39°46′47″	105°13′29″	2.69	5.16	167.0	995.0	0.70572	64.0	0.70529
41, 76CS90	MMz.	39°46′41″	105°13′23″	3.15	4.28	135.0	893.0	0.70549	64.0	0.70510
42. 76CS91	MMz.	39°46′37″	105°13′20″	3.29	4.41	147.0	1164.0	0.70554	64.0	0.70522
Ralston dike										
43. 76CS93	MMz.	39°49′49″	105°14′32″	3.35	4.29	140.0	896.0	0.70561	64.0	0.70521
Valmont dike										
44. 76CS94	MMz.	40°01′54″	105°11′25″	3.21	4.28	110.0	941.0	0.70512	64.0	0.70482
Dike suite										
45. HMN-8	BLt.	39°57′28″	105°30′22″	3.18	3.14	85.2	980.0	0.70762	58.0	0.70742
46. HMN-10	HLt.	39°57′08″	105°33′40″	4.31	3.44	64.0	1308.0	0.70772	58.0	0.70761
47. 75CS79	HLt.	39°57′21″	105°31′00″	3.99	3.16	89.8	1040.0	0.70950	58.0	0.70930
48. 76CS101	Bst.	39°50′29″	105°35′38″	4.13	6.57	243.0	39.4	0.73023	58.0	0.71586

[a] Weight %
[b] Parts per million
[c] Initial $^{87}Sr/^{86}Sr$
[d] Rock type abbreviations are as follows:

Granodiorite suite	*Monzonite suite*
Apl. = aplite	HLt. = hornblende latite
Grd. = granodiorite	HMz. = hornblende-pyroxene monzonite
QMz. = quartz monzonite	LMz. = leucocratic monzonite
Ton. = tonalite	MMz. = mafic monzonite
	MzQ. = quartz bearing monzonite
Monzonite suite	PMz. = porphyritic monzonite
Amp. = Hornblendite	Pxt. = pyroxenite
BLt. = biotite latite	QSy. = quartz syenite

Bostonite dikes contain phenocrysts of alkali feldspar in a highly altered leucocratic groundmass and are commonly found within or near stocks containing alkalic monzonites. These rocks have SiO$_2$ and total alkalies of 62–70% and 10%, respectively (e.g., Braddock, 1969). Their leucocratic nature, high SiO$_2$ and total alkalies suggest affinities with late differentiates of the alkalic monzonite suite. We analyzed one bostonite sample (48) from a dike in the vicinity of the Apex stock.

Results

A general distinction between rocks of the granodiorite and monzonite suites can be made on the basis of initial $^{87}Sr/^{86}Sr$ ratios and Sr contents (Table 3). All but two samples of the granodiorite suite have less than 1000 ppm Sr and initial $^{87}Sr/^{86}Sr$ ratios greater than 0.707 and the granodiorites show a negative correlation between Sr content and initial $^{87}Sr/^{86}Sr$ (Fig. 5). Most monzonite suite samples have initial $^{87}Sr/^{86}Sr$ ratios less than 0.706 and exhibit no obvious trend with Sr content (Fig. 5); several contain more than 2000 ppm Sr.

Distinctions between rocks of the granodiorite and monzonite suites are not obvious in terms of the rare-earth elements (REE). The REE (Table 4) are more useful in determining relationship among various rocks within each suite.

Granodiorite Suite

On the basis of their Rb/Sr ratios, rocks of the granodiorite suite can be divided into two groups. Those
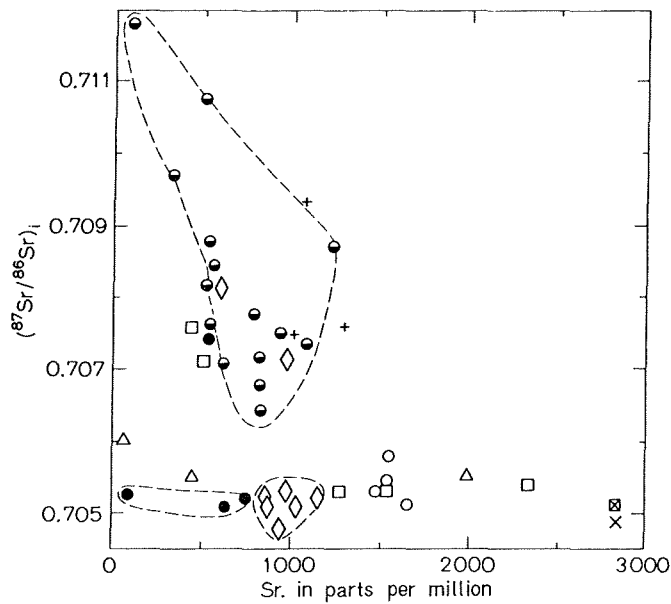
Fig. 5. A plot of initial $^{87}Sr/^{86}Sr$ ratios versus ppm Sr for samples of the Colorado mineral belt. Symbology is the same as for Figure 2, with the addition of: latite dikes (+), ultramafic rocks (●), and quartz syenites (o). Note: These are not the same samples for which major element data was given in Table 1, and Figures 2 and 3
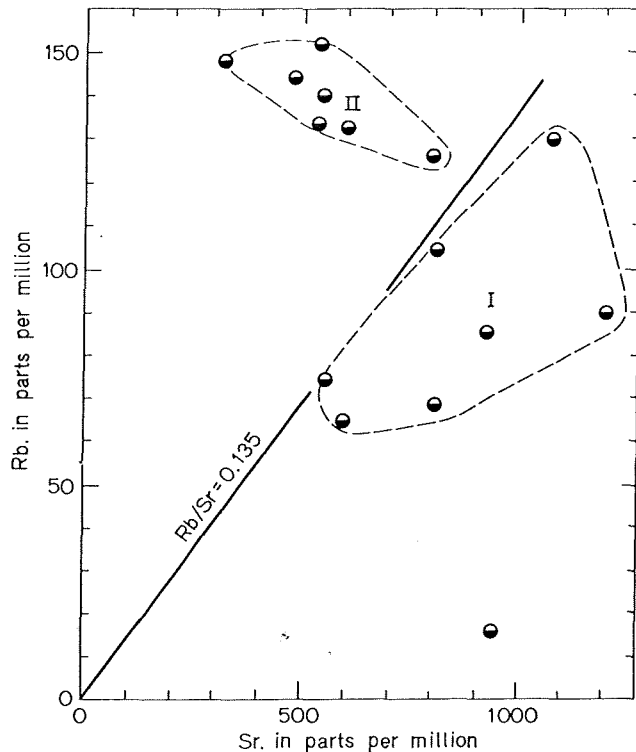

Fig. 6. A plot of Rb versus Sr for rocks of the granodiorite suite from the Colorado mineral belt. Groups I and II note granodiorites with different Rb/Sr ratios

having Rb/Sr ratios less than 0.135, hereafter referred to as "group I" granodiorites, have Sr contents greater than 500 ppm and exhibit a positive correlation between Rb and Sr (Fig. 6). Those having Rb/Sr ratios greater than 0.135, hereafter referred to as "group II" granodiorites, have Sr contents less than 600 ppm, and exhibit a slight negative correlation between Rb and Sr (Fig. 6). Sample 1, the tonalite from the Italian Mountain Intrusive Complex, does not fit this classification. Its low Rb content and Rb/Sr ratio make this sample anomalous with respect to the other granodiorites.

With the exception of samples 1 and 2, the granodiorite-quartz monzonite samples have very similar, subparallel REE patterns, which are approx. linear from Ce to Dy, concave upward for the heavy REE with a minimum at Er, and small negative Eu anomalies (Fig. 7). Samples 1 and 2, the tonalite and granodiorite from Italian Mountain, have smaller negative Eu anomalies and patterns enriched in the middle REE relative to those of the other granodiorites. While there is a slight correlation between the K content and the size of the negative Eu anomaly of the granites (Table 4), there is no apparent correlation of overall REE abundances with K content or Rb/Sr ratio. A granite aplite, sample 13, from the Montezuma pluton has a REE abundances two to three times higher (Fig. 7b).

Monzonite Suite

(1) Alkalic Monzonites. Twelve samples of the alkalic monzonite suite contain more than 9% total alkalies and, with exception of the two quartz-bearing monzonites with the lowest Sr contents, all have $^{87}Sr/^{86}Sr$ initial ratios less than 0.706. The Rb and Sr contents (Fig. 8) of these rocks are highly variable: Rb varies from 50–230 ppm, Sr from 70–2800 ppm, and the data show a good inverse correlation between Rb and Sr (Fig. 8). The REE (Fig. 9a), are highly variable, much like Rb and Sr and exhibit a good correlation between the depletion of the total REE and Sr.

(2) Mafic Monzonites. Eight mafic monzonite samples have total alkalies less than 9%, Rb contents 90–170 ppm, and Sr 500–1160 ppm. The chondrite-normalized REE patterns (Fig. 9b) are all subparallel, Ce ~100, Yb ~12 times chondrites. All have negative Eu anomalies, the size of which is inversely proportional to the overall REE abundances. The hornblende-bearing varieties (27 and 33) have lower total alkali and Rb contents, and $^{87}Sr/^{86}Sr$ ratios greater than 0.707.

Table 4. Rare Earth element abundances (in parts per million) in rocks from the northeastern part of the Colorado mineral belt

Sample No.	Rock[c] Type	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu	$(Ce/Yb)_N$[a]	$(Eu/Eu*)$[b]
Granodiorite suite												
Italian Mt.												
1. I298	Ton.	88.7	32.0	5.36	1.43	4.28	3.44	1.88	1.74	0.259	13.1	0.86
2. I286	Grd.	91.2	54.6	9.07	2.18	6.44	4.35	2.05	1.89	0.294	12.3	0.84
3. I173	QMz.	120.0	35.5	6.49	1.47	5.11	4.18	2.39	2.46	0.395	12.5	0.76
4. I325	QMz.	74.3	28.2	4.68	0.913	3.29	2.48	1.37	1.59	0.273	12.0	0.68
Swan Mt.												
11. 75CS86	Grd	131.0	50.0	7.93	1.82	5.35	4.06	2.27	2.39	0.375	14.0	0.81
Montezuma												
13. 75CS83	Apl.	267.0	92.5	12.50	3.24	9.44	7.47	4.57	4.52	0.671	15.1	0.89
14. 75CS84a	Grd.	119.0	45.4	7.80	1.69	5.69	4.64	2.65	2.85	0.434	10.7	0.75
Empire												
15. 75CS88	Grd.	76.1	31.4	5.34	1.28	3.87	2.98	1.62	1.77	0.276	11.0	0.83
Lyons												
16. 76CS105	QMz.	41.8	16.4	3.74	1.14	3.29	2.65	1.45	1.49	0.239	7.2	0.98
Monzonite suite												
Empire												
17. 75CS67	HMz.	230.0	86.3	13.7	3.23	8.51	4.47	2.24	2.00	0.307	29.4	0.86
18. 75CS76	LMz.	107.0	27.1	3.36	0.895	2.28	1.68	1.16	1.61	0.311	16.9	0.94
Fall River Road												
20. 75CS80	QSy.	141.0	53.7	8.54	2.28	6.12	4.34	2.48	2.74	0.438	13.2	0.93
Apex												
21. 75CS77a	QSy.	159.0	57.6	9.27	2.30	6.37	4.28	2.43	2.49	0.386	16.3	0.88
Eldora-Bryan Mt.												
23. HMN-13	MzQ.	30.0	6.63	0.927	0.228	0.755	0.664	0.464	0.765	–	10.0	0.82
24. 75CS78	HMz.	218.0	83.1	13.1	3.37	8.68	5.71	3.01	2.84	0.423	19.6	0.92
Caribou												
29. 75CS69	MMz.	78.2	34.0	6.39	1.50	5.14	3.76	2.24	2.15	0.356	9.34	0.78
30. 75CS70a	Pxt.	18.3	16.0	4.32	1.01	4.19	3.17	1.80	1.50	0.222	3.12	0.72
31. 75CS72a	Amp.	131.0	82.4	17.8	4.54	15.1	10.7	6.07	4.86	0.710	6.88	0.83
Audubon-Albion												
33. 76CS96	MMz.	76.0	39.4	7.01	1.64	5.65	4.32	2.28	2.11	0.335	9.17	0.78
34. 76CS97	PMz.	110.0	48.2	9.11	2.35	6.72	4.68	2.15	1.70	0.237	16.5	0.89
35. 76CS98	MzQ.	69.6	20.5	3.52	0.771	2.49	1.70	0.860	0.900	0.158	19.8	0.77
Sunset-Gold Hill												
39. 75CS73	QSy.	149.0	60.0	9.46	2.47	6.59	4.64	2.54	2.52	0.428	15.1	0.92
Table Mt.												
40. 76C	MMz.	83.5	42.9	8.40	2.33	7.19	5.53	3.08	2.79	0.421	7.69	0.90
41. 76CS90	MMz.	89.4	42.4	8.05	2.05	6.55	5.22	2.96	2.83	0.429	8.09	0.84
42. 76CS91	MMz.	92.3	40.5	7.50	1.80	6.17	4.86	2.82	2.69	0.442	8.84	0.79
Dike suite												
47. 75CS79	HLt.	84.2	30.0	5.75	0.999	4.50	4.34	2.89	3.28	–	6.58	0.58
48. 76CS101	Bst.	89.1	23.5	3.56	0.689	2.71	2.64	2.31	3.57	–	6.43	0.66

[a] $(Ce/Yb)_N = [(Ce\ in\ rock)/(Ce\ in\ chondrites)]/[(Yb\ in\ rock)/(Yb\ in\ chondrites)]$

[b] $(Eu/Eu*) = [(Eu\ in\ rock)/(Eu\ in\ chondrites)]/[(Eu*\ in\ rock)/(Eu*\ in\ chondrites)]$ where Eu* is given by linear extrapolation between Sm/chondrites and Gd/chondrites

[c] For rock type abbreviations, see footnote [d] from Table 2

Fig. 8. A plot of Rb versus Sr for rocks of the monzonite suite from the Colorado mineral belt. Symbology is the same as for previous figures, with the addition of the bostonite dike (⊕)
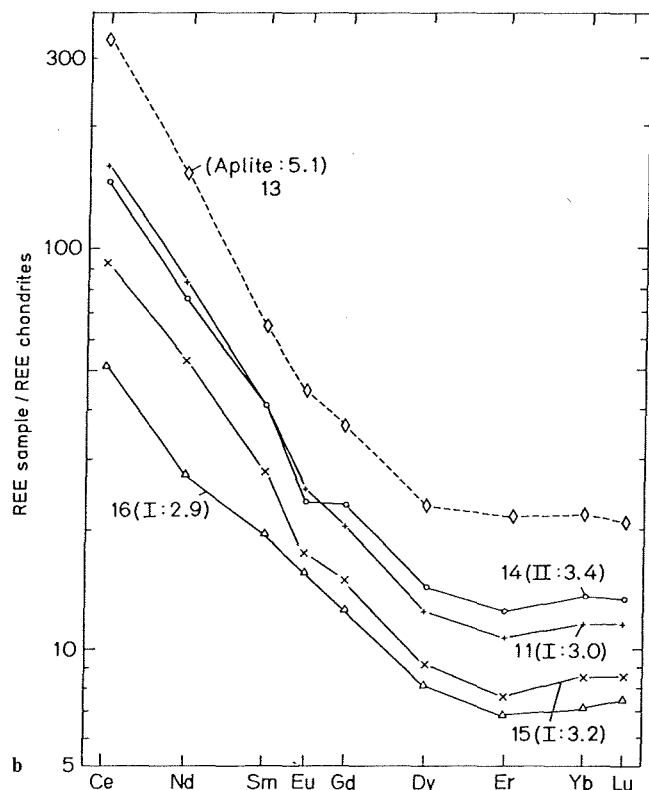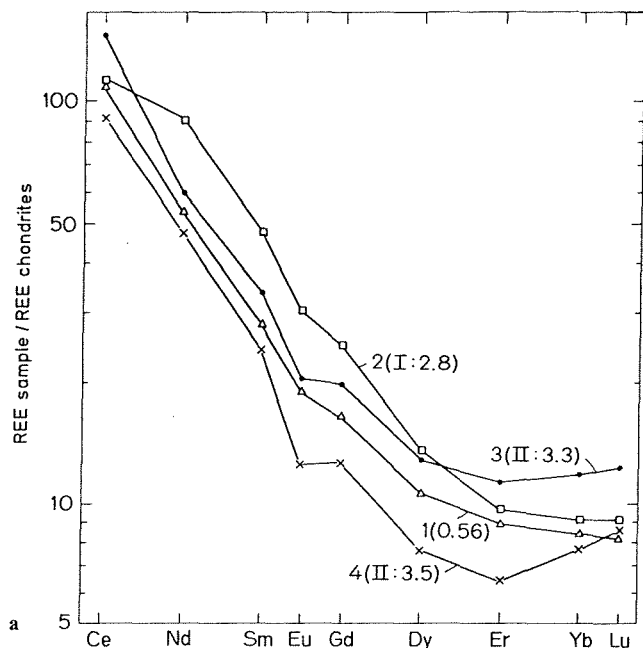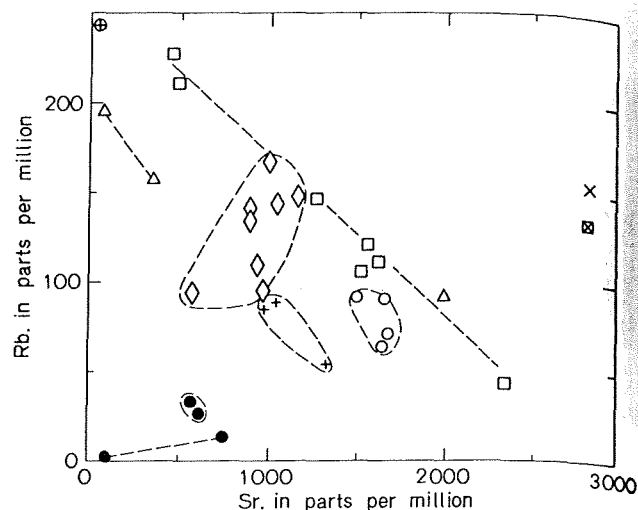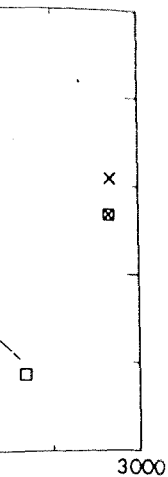

Fig. 7a and b. Chondrite-normalized REE data for rocks of the granodiorite suite from the Colorado mineral belt. Numbers in parenthesis (next to sample numbers from Tables 2 and 3) refer to weight % K from Table 2 and I and II note different Rb/Sr ratios. a Four samples from the Italian Mountain Intrusive Complex. b Five additional samples of the granodiorite suite

(3) Quartz Syenites. Four quartz syenite samples have very similar K_2O, Na_2O, Rb and Sr contents, and have $^{87}Sr/^{86}Sr$ initial ratios less than 0.706 (Table 3). Chondrite-normalized REE data for three of the samples (Fig. 9c) are nearly identical, with Ce $\sim$175–200 and Yb $\sim$12–13 times chondrites, and small negative Eu anomalies.

(4) Ultramafic Rocks. Two pyroxenite samples have low alkalies and Rb. Their Sr contents reflect those of their host monzonites: sample 19, associated with alkalic monzonites in the Empire stock has more than 700 ppm Sr, while sample 30, associated with mafic monzonites in the Caribou stock, has less than 100 ppm Sr. Their initial $^{87}Sr/^{86}Sr$ ratios are low, and close to the values obtained from their host rocks. The two hornblendites are both associated with mafic monzonites, and have very similar alkali, Rb and Sr contents, but different Sr isotope compositions. The $^{87}Sr/^{86}Sr$ ratio of the Caribou sample (31) is close to that for the associated monzonite, but the initial ratio for the Bald Mountain sample (28) is distinct, outside of analytical uncertainty, from that of the associated mafic monzonite (27) (Table 3). The chondrite-normalized REE patterns of the pyroxenite (30) and hornblendite (31) from the Caribou stock are shown in Figure 12d.

(5) Latite and Bostonite Dikes. Three latite samples (45, 46, and 47) have 6.3–7.8% total alkalies and 60–80 ppm Rb and 1000–1300 ppm Sr. All three have $^{87}Sr/^{86}Sr$ initial ratios greater than 0.7074. The chondrite-normalized REE pattern for sample 47, a horn-
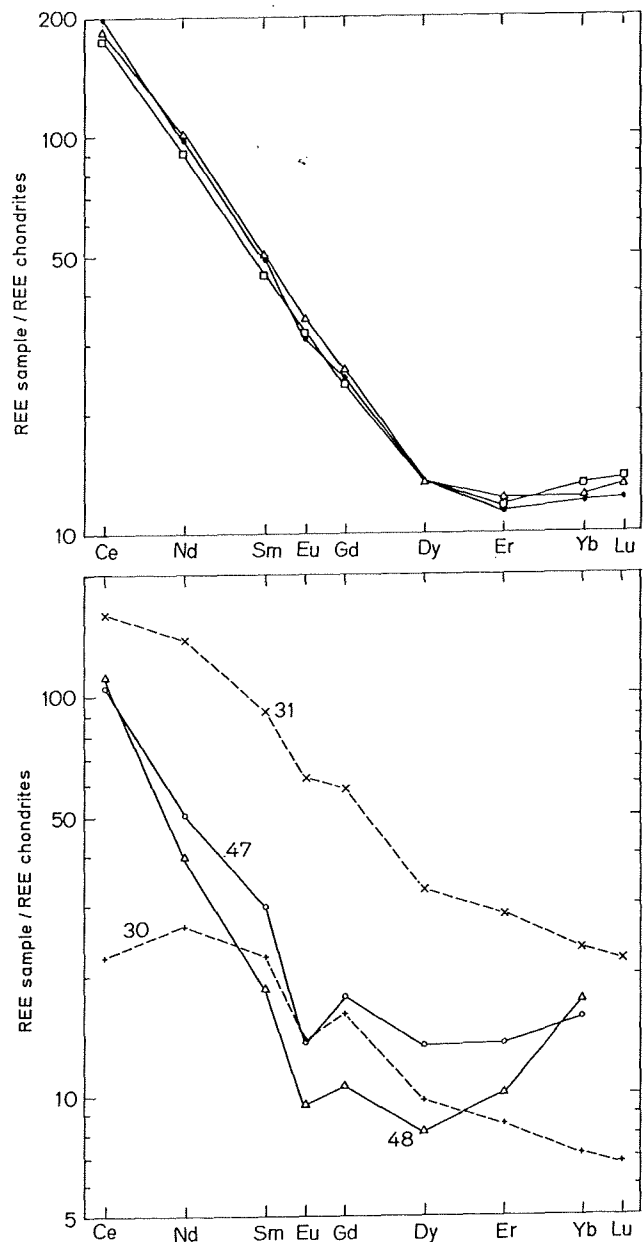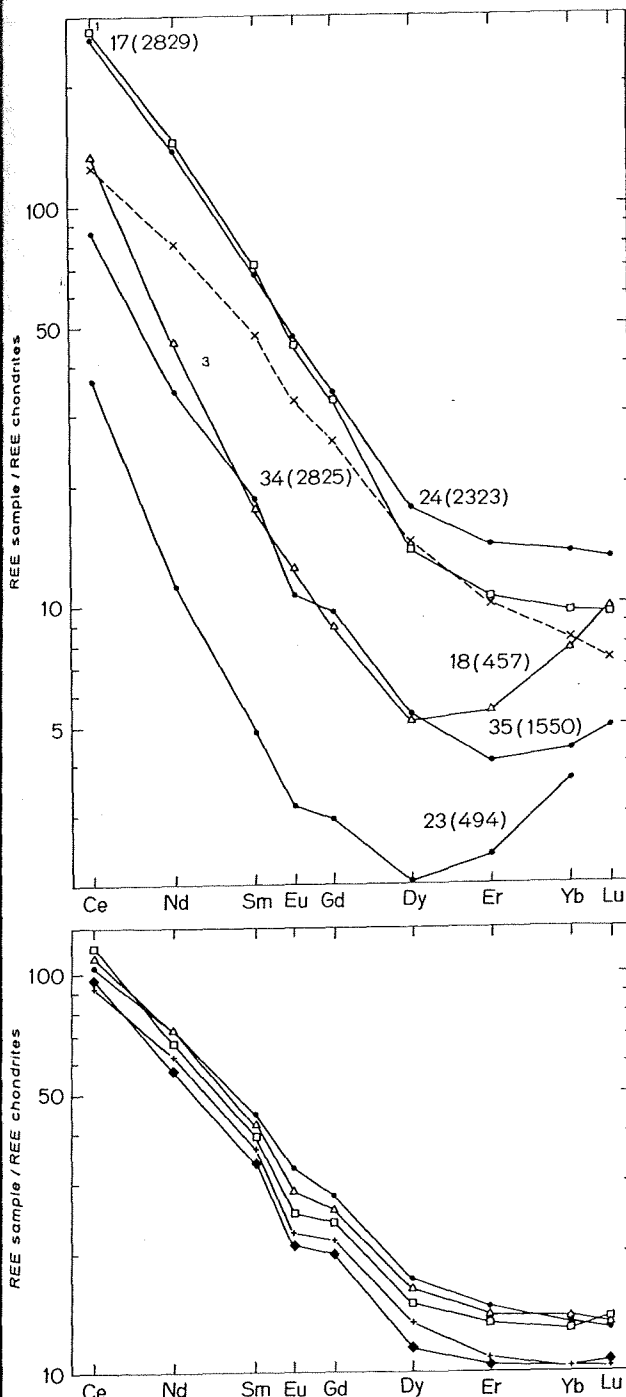
Fig. 9a–d. Chondrite normalized REE data for samples of the monzonite suite from the Colorado mineral belt: **a** Six samples of the alkalic monzonite suite; numbers in parenthesis are ppm Sr, from Table 2; **b** Mafic monzonite samples: three samples from the Table Mountain Shoshonite – lowermost lava (40:○), middle lava (41:△), upper lava (42:□); hornblende-bearing mafic monzonite from the Audubon-Albion pluton (33:+) and Caribou stock (29:◆); **c** three quartz syenite samples, including: Fall River Road pluton (20:□), Apex stock (21:●) and Gold Hill pluton (39:△); **d** two ultramafic samples, including: hornblendite (31) and pyroxenite (30), along with a hornblende latite dike (47) and bostonite dike (48). Numbers outside parenthesis are sample numbers

blende latite, has Ce 100 and Yb 16 times chondrites and a significant negative Eu anomaly (Fig. 9d). The overall pattern is concave upward, depleted in the middle REE and enriched in the heavy REE, and exhibits a significant begative Eu anomaly. A bosto-

nite sample (48) has the highest Rb (234 ppm) and lowest Sr (39 ppm) of any of the alkalic rocks (Table 3). Its $^{87}Sr/^{86}Sr$ initial ratio is anomalously high (0.7159), suggesting that this magma probably assimilated some radiogenic Sr from its Precambrian wall

rocks. Its chondrite-normalized REE pattern (Fig. 9d) is very similar to that of the latite dike, but is more depleted in the middle REE.

Discussion

This study is aimed at answering four basic questions. First, how many parent magmas are needed to explain the igneous rocks of the Colorado mineral belt? Second, what limits can be placed on the composition and modes of origin of these magmas? Third, how were these magmas modified by fractional crystallization or assimilation processes? Fourth, what limits can be placed on the composition and age of the source materials from which these magmas were derived?

Trace Elements Modelling
and Possible Cumulate Effects

Many previous trace element studies of granitic rocks have used models and equations which are based on the assumption that samples of granitic plutons can be treated as liquid compositions (see Arth, 1976, for a summary of the models and equations). We feel that this premise is not necessarily valid and that the possibility of the samples being partially or totally cumulate in origin must be considered. These considerations are particularly important because, in the rocks we studied, trace minerals such as sphene and apatite occur in amounts up to 1–2 vol.%, and crystallized early, on the basis of textural evidence. Apatite is known (Nagasawa, 1970) to have a large affinity for REE and we have demonstrated (Table 5) that sphene does even more so. Early crystallization of these minerals (even to the extent of a few tenths of a percent) can strongly influence the REE patterns of the residual magmas.

The viscosities of granitic magmas are commonly assumed to be too high to permit effective crystal setting. However, separation of the liquid from the solid phases can be accomplished by flow differentiation or filter pressing, as well as crystal settling. The important point is that the rock contains a disproportionate amount of early crystallizing minerals. Wilshire (1969) interpreted textures in a pluton of the Colorado mineral belt, as having been the result of mechanisms such as flow differentiation. Minor element data for rocks such as these, could not be correctly modelled assuming that they represent a liquid composition; and erroneous results might thereby be obtained if the sample contained a disproportionate amount of an early crystallizing mineral such as sphene.

Field and petrographic observations can provide evidence as to the possible cumulate character of

Table 5. Trace element abundances for sphene and groundmass samples

	RS-2[c]			75CS80	
	Sphene	Grdms.	Sphene / Grdms.	Sphene	Sphene[a] / W.R.
Ce	6143.0	115.2	53.3	3514.0	24.9
Nd	3513.0	39.8	88.3	4180.0	77.8
Sm	705.0	6.94	102.0	912.7	107.0
Eu	206.0	2.04	101.0	213.4	93.6
Gd	570.0[b]	5.58	102.0	691.0	113.0
Dy	370.0	4.59	80.6	480.0	111.0
Er	158.0	2.69	58.7	265.0	107.0
Yb	98.3	2.63[b]	37.4	227.0	82.8
Lu	11.0	0.409	26.9	27.1	62.0
Sr	2162.0	2475.0	0.874		

[a] Whole-rock data given in Table 3
[b] By interpolation
[c] Nepheline Phonolite — Rattles nake Hills, Wyoming

various samples and can say something about the sequence of mineral crystallization. These observations must be incorporated into any modelling of trace element data from plutonic rocks.

Petrogenesis of the Granodiorite Suite

The consistently higher $^{87}Sr/^{86}Sr$ ratios, along with the more silicic and less alkaline character of the granodiorite suite suggest that these rocks cannot be derived from the monzonite suite. For example, to derive rocks of the granodiorite suite from an alkalic monzonite parent, would require removal of a high alkaline, low silica phase (Fig. 2). Therefore, in agreement with Braddock (1969), we suggest that the rocks of the granodiorite suite have an origin independent of the monzonite suite.

The distinction between the group I and II granodiorites could be interpreted in two ways. First, the rocks with the lowest Rb/Sr ratios (group I) could approximate the compositions of the original parent magmas, and the higher Rb/Sr samples (Group II) could represent differentiates. In this case, the strong positive correlation between Rb and Sr for the group I samples (Fig. 6), suggests that both Rb and Sr were incompatible, and there could have been little feldspar in the residues of partial melting. Second, the high Rb/Sr samples approximate compositions of the original parent magmas, and the low Rb/Sr samples could represent partial or total cumulates involving phases with low Rb/Sr (i.e., feldspar). In this case, the lower Sr contents and limited range of Rb and Sr exhibited by the group II samples would suggest that considerable residual plagioclase feldspar was involved. However, neither possibility would appear to satisfactorily explain the data. Assuming that the higher Rb/Sr

Colorado

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rocks are the parents, and that the lower Rb/Sr rocks are cumulates would not explain sample 16 (group I), a Sr-rich sill emplaced at shallow depth and containing less than 10% phenocrysts. The high Sr content of this sample precludes significant plagioclase fractionation. Assuming that the high Rb/Sr rocks are differentiates of magmas with low Rb/Sr ratios like rocks of group I also presents problems. Relative to the group I samples, some of the group II rocks have Rb/Sr ratio more than a factor of three higher. To increase the Rb/Sr ratio by a factor of three would require removal of at least 25% plagioclase. However, petrographic evidence from these samples indicated that the crystallization of plagioclase would have been preceded or accompanied by apatite, sphene, and hornblende, requiring even larger amounts of solidification. Removal of these phases in sufficient quantity to prevent development of a large negative Eu anomaly in the differentiates would not result in the subparallel REE patterns observed. Therefore, at least some of the differences between the group I and II granodiorites appear to be primary.

The most likely explanation for the data is that the granodiorites reflect the end products of similar partial melting or fractional crystallization processes, and that group I and II grandiorites represent compositional variants of two distinct primary magma types. These two magma types were very similar in major and trace element chemistry, except for their Rb/Sr ratios, which is best explained by differences in the amount of feldspar left in the residue of partial melting. That even the high Rb/Sr samples have only small negative Eu anomalies indicates that a significant amount of ferromagnesian phases must have been involved. However, the fact that all the granodiorites have REE patterns which are subparallel and do not cross, rules out involvement of significant amounts of phases with high K_d's for the REE, such as hornblende, sphene, garnet or apatite. This suggests that the ferromagnesian phases in the residue were dominated by pyroxene. The K_d's for the REE in pyroxene would dominate the bulk distribution coefficients for the REE even if a significant amount of feldspar was involved, explaining why the REE patterns for all the granodiorites are subparallel. However, the fact that there exists no correlation between the REE abundances and the K contents of these rocks suggest that no combination of differentiation or partial melting processes involving a homogeneous parent can account for these samples.

Thus, the data indicate the parent magmas for the granodiorite suite were originally derived by partial melting of a source which left a residual assemblage dominated by pyroxene $\pm$ feldspar. In a study of nodules in diatremes near the Colorado-Wyoming border, Eggler and McCallum (1974) concluded that the lower crust in this area is made up of a mixture of pyroxene granulite and pyroxenite. Partial melting of a plagioclase-pyroxene granulite assemblage leaving significant plagioclase in the residue would yield granitic magmas with the Rb/Sr characteristics of the group II granodiorites. Partial melting of a more pyroxene-rich rock, leaving a pyroxenitic residue, would yield the strong positive correlation between Rb and Sr noted for the group I granodiorites, and REE patterns similar to those of the group II granodiorites. Testing of this hypothesis must await the trace element characterization of these granulite nodules.

Samples 1 and 2, both from the Italian Mountain Intrusive Complex, have anomalous trace element chemistry relative to other members of the granodiorite suite. The tonalite, sample 1, has anomalously low Rb and K abundances relative to other samples. Based on this, the calcic plagioclase composition of these rocks (Cunningham, 1976), and the more mafic character of this sample, we propose that the tonalite is actually a partial cumulate. Sample 2 has a REE pattern enriched in the light and middle REE, and has an anomalously low Ce/Nd ratio relative to the other granodiorite samples (Fig. 7a). These features could also be the result of cumulate processes, if the sample contained a disproportionate amount of early-crystallized sphene and/or apatite. Alternatively, the anamalous geochemistry of these rocks could be real, and reflect heterogeneties in the source regions.

Petrogenesis of the Monzonite Suite

Rocks of the monzonite suite divide, on the basis of mineralogy and major and minor element geochemical data, into the following groups: alkalic monzonites, mafic monzonites, quartz syenites, ultramafic rocks, and latite and bostonite dikes. The alkalic monzonite group can be further subdivided into hornblende-pyroxene monzonites, quartz-bearing monzonites, and leucocratic monzonites.

(1) Alkalic Monzonites. Relative to SiO$_2$, rocks of the alkalic monzonite group exhibit consistent trends of increasing alkalies, and decreasing Mg/(Mg+Fe), feldspar An content of plagioclase, Sr, and total REE contents (Fig. 10; Larsen, 1968; Mathews, 1970). The chemical trends for these rocks can be modelled by the removal of plagioclase and Ree-rich minerals. Sphene (Table 5) and apatite appear to be the most likely candidates for the latter based on their ubiquitous occurrence and the observation that they are early crystallizing minerals in these rocks.
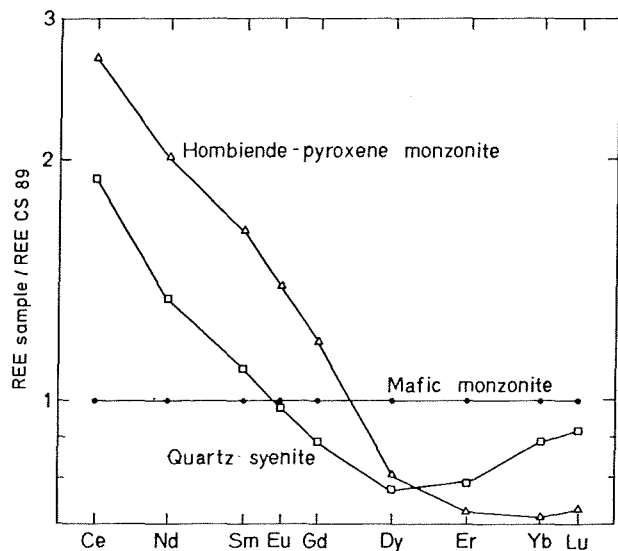
Fig. 10. REE data for the hornblende-pyroxene monzonite (17), quartz syenite from the Apex stock (21) and the lowermost mafic latite of Table Mountain Shoshonite on Table Mt. (40), normalized to the mafic monzonite. Sample numbers from Table 2

The most complete data are presently available for the quartz-bearing monzonite members of the alkalic monzonite group. The data exhibit an excellent negative correlation of Sr and Rb (Fig. 8), and strong depletion of REE (Fig. 9a; samples 24, 35 and 23). The data are best explained by removal of plagioclase-rich (>90%) cumulates, along with sphene, apatite, hornblende, and pyroxene. Removal of only 2% sphene easily accounts for the depletion of the REE and concave-upward REE patterns of the most depleted rocks (Fig. 9a). The large K_d's for the REE in sphene prevent the development of a large negative Eu anomaly, despite the high percentage of feldspar in the crystallizing solids. The small amounts of ferromagnesian phases required, make it unlikely that the quartz-bearing monzonites can be derived from the same magma which gave rise to hornblende-pyroxene monzonites.

The REE pattern of the leucocratic monzonite with the lowest Sr content (18), is, like those of the Sr-poor quartz-bearing monzonites, depleted in the middle and light REE relative to the hornblende-pyroxene monzonite. However, while this rock contains less than 400 ppm Sr (Table 3), it has Yb abundances higher than that of the quartz-bearing monzonite with more than 1500 ppm Sr. This relationship implies that fewer ferromagnesian phases were involved in the differentiation process that produced this rock, than were involved in the production of the quartz-bearing monzonites. That is, the original magma from which this leucocratic monzonite was derived was more leucocratic than the magma which produced the quartz-bearing monzonites, which, in

turn, was more leucocratic than the magma which gave rise to the hornblende-pyroxene monzonites.

The plagioclase-rich composition of the porphyritic monzonite from the Audubon-Albion stock (34), combined with its high Sr content relative to other alkalic monzonites and coarse grain size suggests to us that it is probably a plagioclase-rich cumulate. This interpretation is supported by the fact that, in the vicinity of where this sample was collected, alignment of feldspar phenocrysts suggests that flow differentiation was occurring. Such a process could result in a rock containing a disporportionate amount of the early crystallizing phases. Textural evidence suggests that this sample formed by crystallization of sphene + apatite + opaque oxide, followed by crystallization of plagioclase, pyroxene, hornblende, and alkali feldspar. Model calculations were made to set limits on the trace element composition of the parent magma from which sample 34 might have been derived and the results were similar to the leucocratic monzonite (18) from the Empire stock or the quartz-bearing monzonite from the Audubon-Albion stock (35).

Several lines of arguments indicate the hornblende-pyroxene monzonites, quartz-bearing monzonites and leucocratic monzonites could not have been derived from the same magmas. First, where a later phase intrudes an earlier one, evidence such as brecciated contact zones clearly indicate that the first had completely solidified before the second had intruded. Second, rocks of the three groups exhibit a similar range of Sr contents, up to 2000 ppm. Third, even those samples with high Sr contents are petrographically distinct from one another. Fourth, REE and other evidence indicate that the magmas which produced these three rock types were successively more leucocratic. Thus the rocks of the alkalic monzonite suite were apparently derived from slightly different magmas; these magmas had high (>2000 ppm) Sr contents, 100 ppm Rb, and light-enriched REE patterns having Ce up to 300 and Yb 9–13 times chondrites with small Eu anomalies, based, on the least differentiated samples (17 and 24).

This information allow limits to be set on the composition of the source of these magmas. This source must have been fairly alkaline to produce the high (4–5%)K$_2$O observed. That primary magma compositions for the alkalic monzonites lie close to the join plagioclase-K-feldspar, a low pressure thermal divide, have high Sr contents, and only small Eu anomalies, all indicate that feldspar did not play a significant role in the genesis of these magmas. The presence of clinopyroxene, preserved within coronas of hornblende, suggests that clinopyroxene may have been a high pressure liquidus phase. The highly fraction-

ated REE pattern of the least differentiated (i.e., high Sr rocks) samples suggest that garnet, which has a high affinity for the heavy REE relative to the light REE, played a significant role in the production of these magmas. Based on these lines of argument, we propose that the rocks of the alkalic monzonite suite were produced by partial melting of a moderately alkaline mafic rock, leaving a residue dominated by pyroxene and garnet.

(2) Mafic Monzonites. The REE data for five mafic monzonites (Fig. 9b) shows a good inverse correlation between REE abundances and the size of the negative Eu anomaly. While this could be explained by fractional crystallization of plagioclase + apatite, both phenocryst phases, the fact that there does not exist a correlation between the size of the Eu anomaly and the Sr abundances (Tables 2 and 3) argues that the geochemical differences between these samples cannot be explained by removal of any combination of the phenocryst assemblage (Olivine + apatite + oxide + clinopyroxene + plagioclase). These differences more likely reflect heterogeneties in the sources of these magmas. The most puzzling feature of the mafic monzonites is their high Rb/Sr ratio, almost three times higher than that of the hornblende-pyroxene monzonite. The low $^{87}Sr/^{86}Sr$ ratios of the hornblende-free samples indicates that this high Rb/Sr ratio is a recent phenomena, and not a long-lived feature of the source of these magmas. The most likely explanation for the high Rb/Sr ratios of these rocks would appear to be partial melting of a plagioclase-bearing source. Small ($<5\%$) degrees of partial melting of a source containing only 20–30% plagioclase could explain the high Rb/Sr ratios and small negative Eu anomalies. A plagioclase-bearing residue would also explain why the mafic monzonites contain less than half the Sr of the least differentiated alkalic monzonites. However, the relative Ce and Rb contents of the most primitive (i.e., high Sr) alkalic monzonites rule out derivation from the same source by different degrees of partial melting, or melting of the same material under different conditions. While the mafic monzonites have similar Rb concentrations as the alkalic monzonite, the Ce contents of the mafic monzonites is a factor of three lower. This suggests that the source of the mafic monzonites had light REE abundances lower than the source of the alkalic monzonites.

The high initial $^{87}Sr/^{86}Sr$ of the hornblende-bearing mafic monzonites clearly set these rocks apart from the other mafic monzonites. Their high Sr contents would necessitate unreasonably large amounts of crustal contamination to raise the initial $^{87}Sr/^{86}Sr$ ratio to more than 0.707. We therefore interpret the high $^{87}Sr/^{86}Sr$ ratios as a primary feature of the source of the hornblende-bearing mafic monzonites.

(3) Quartz Syenites. The presence of quartz phenocrysts and lower alkali contents of the four quartz syenite samples make them anomalous with respect to other members of the monzonite suite. The low initial $^{87}Sr/^{86}Sr$ ratios of the quartz syenites (<0.705), however, clearly indicate that these rocks were not derived from the same source as the granodiorites. While the quartz syenites are similar to the quartz-bearing monzonite members of the alkalic monzonite suite in major element composition (Table 1), Sr contents and initial $^{87}Sr/^{86}Sr$ ratios (Table 2), the presence of quartz phenocrysts in the quartz syenites and the fact that the quartz syenites (20, 21, and 39) and the quartz-bearing monzonite (35) have different REE patterns clearly indicate that these rocks have experienced different histories. All four samples have remarkably similar Na_2O, K_2O, Rb, and Sr abundances (Table 3), and three have essentially identical REE patterns (Fig. 9c). This uniformity is probably not the result of fractional crystallization of the early crystallizing phases, such as plagioclase, clinopyroxene, but particularly not sphene or apatite. We suggest therefore, that these rocks approximate the composition of primary magmas, relatively unmodified by high level differentiation.

The high Sr contents of these rocks indicate that little, if any feldspar could have been involved in the genesis of these magmas; these rocks were therefore derived from a mafic source. The residue of partial melting could not have been dominated by hornblende, as hornblende would have produced a REE pattern more depleted in the middle and heavy REE; the presence of clinopyroxene within coronas of hornblende suggest that these magmas may have been in equilibrium with clinopyroxene at high pressure. Thus the data suggest that the quartz syenites were derived from a quartz-bearing mafic source, which had an initial $^{87}Sr/^{86}Sr$ ratio less than 0.706, and which, on partial melting, yielded a pyroxene-dominated residue.

(4) Ultramafic Rocks. The occurrence of pyroxenitic rocks with both the mafic and alkalic monzonites, combined with textural evidence that pyroxene is one of the earliest phases to crystallize in both these rock types, suggests that these rocks could represent cumulates from either. The high Sr content (>700 ppm) of the pyroxenite associated with the alkalic monzonites of the Empire stock (18) indicate a parent magma having more than 2000 ppm Sr, clearly indicating that this rock was derived form an alkalic, not a mafic parent magma. The low Sr content of

the pyroxenite associated with the mafic monzonites of the Caribou stock (30), suggest that the magma from which this rock crystallized contained less than 1000 ppm Sr. A plot of the REE content of this pyroxenite, normalized to the abundances of the host monzonite (29), yields a light-depleted REE pattern, very similar to clinopyroxene mineral-melt distribution coefficient patterns for clinopyroxene. This, along with the low Sr content of the inferred parent and the nearly identical initial $^{87}Sr/^{86}Sr$ ratios of these two rocks, is consistent with derivation of the pyroxenite as a pyroxene-rich cumulate from a mafic monzonite parent like 29. However, Smith (1938) failed to observe any field evidence for a cumulate origin for the pyroxenites of the Caribou stock, and Larsen (1968) noted that the pyroxenites of the Empire stock contain inclusions of the associated monzonite. Thus a simple cumulate origin for these rocks does not explain the field relations.

Despite their association with the mafic monzonites of the Caribou and Bald Mountain plutons, the high Sr (> 500 ppm) content of the hornblendites indicate that they were derived from magmas having >1500 ppm Sr, based on mineral-melt distribution coefficient data for hornblende. This conclusion is consistent with the fact that hornblende, if present, is not an early crystallizing phase in the mafic monzonites. Using textural evidence and the mineral-melt distribution coefficient data from the literature, we have made calculations to set limits on the trace element composition of the magma from which the hornblendite from the Caribou stock crystallized. Textural evidence suggests that this sample formed by crystallization of apatite + opaques, followed by crystallization of hirnblende + sphene + clinopyroxene + plagioclase. The calculated REE pattern and Sr abundances (1474 ppm) of the parent magma are similar to those of the quartz-bearing monzonite (35) from the Audubon-Albion stock.

(5) Latite and Bostonite Dikes. The fine-grained nature of the groundmass and the lack of major element data preclude an exact characterization of the latites (45, 46, 47), but the presence of clinopyroxene and high Sr contents (1000–1300 ppm) suggest that these rocks have strong affinities to the monzonite suite. The depletion of the middle REE, significant negative Eu anomaly (Fig. 9d) for the hornblende latite (47) suggest that the REE abundances of the magma from which this rock was derived were controlled by removal of plagioclase + minor amounts of sphene + hornblende. The high Sr contents of these rocks would require unreasonably large ($>30\%$) amounts of assimilation to explain the high initial $^{87}Sr/^{86}Sr$ ratios, if the parent magmas had initial ratios less

than 0.706. We therefore conclude that the high initial $^{87}Sr/^{86}Sr$ ratios of these rocks are primary, and reflect those of the source from which the magmas were derived.

The high alkali content, leucocratic character, and low Sr content of the bostonite dike (48), suggest that this is a highly differentiated rock with affinities to derivatives of the leucocratic monzonites. The low Sr, significant negative Eu anomaly, and depletion of the middle REE (Fig. 9d, suggest that bostonitic magmas formed under conditions requiring dominated by plagioclase and a phase with high distribution coefficients for the middle and light REE, such as sphene or apatite. However, the high Yb abundances (almost 20 times chondrites) indicate that very few ferromagnesian phases were removed, and that the original magma from which the bostonite was derived was itself very leucocratic.

Possible Relationships Among Rocks of the Monzonite Suite

Figure 10 shows REE data for alkalic monzonite (17) and quartz syenite (21) samples, normalized to one of the mafic monzonites (40). Relative to the mafic monzonite, the quartz syenite has a light-enriched REE pattern which is depleted in the heavy REE, with a minimum at Dy. This pattern could be explained by 50% solidification of mineral assemblages dominated by clinopyroxene from the mafic monzonite; however such a mechanism would require a concomitent three-fold reduction of the Rb/Sr ratio. This would require at least 30% fractional crystallization of a phase with a high affinity for Rb relative to Sr (i.e., biotite); it could not have been accompanied by any plagioclase, which has a high affinity for Sr relative to Rb. Biotite occurs only as a late crystallizing phase in the mafic monzonites, which combined with the unreasonably large amounts of biotite required, indicate that the mafic monzonites could not have been the parent magmas for the quartz syenites. The REE pattern of the alkalic monzonite relative to the mafic monzonite, is strongly enriched in the light REE and depleted in the heavy REE. The fractionation of the REE pattern of the alkalic monzonite can only be explained by at least 50% solidification of the mafic monzonite as garnet. However, removal of this much garnet would result in at least a 50% increase in the SiO_2 content of the derivative magmas; this is inconsistent with the observation that the mafic and alkalic monzonites have very similar SiO_2 contents (Table 1). These relationships serve to emphasize that the alkalic monzonites, quartz syenites and mafic monzonites cannot be related by fractional crystallization from a common parent.
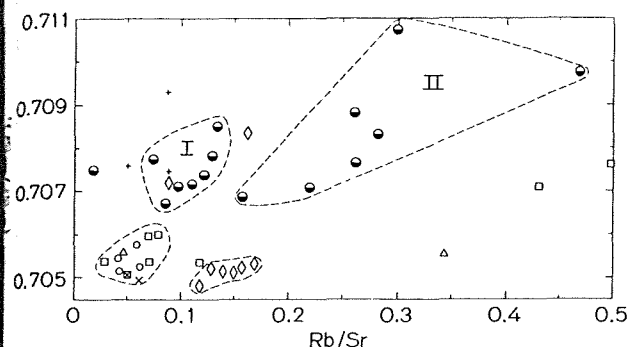
Fig. 11. A plot of initial $^{87}Sr/^{86}Sr$ ratios versus Rb/Sr ratios for rocks of the Colorado mineral belt. Symbology is the same as for previous figures; ultramafic rocks have been omitted for clarity. Groups I and II note granodiorites with different Rb/Sr ratios

Age of the Source of the Magmas

The data for the hornblende-pyroxene monzonite, quartz syenites, hornblende-bearing mafic monzonites and latite dikes, for which we have concluded that the differences in initial ratio reflect primary heterogeneities in the source, show a positive correlation between Rb/Sr and $^{87}Sr/^{86}Sr$ ratios (Fig. 11). A best fit line through this array has a slope corresponding to an age of approx. 1350 m.y., which we interpret as a minimum age for the source of these rocks. The data for the group I granodiorites lie close to the array for the selected monzonite suite of rocks. The positive correlation of Rb and Sr for these rocks (Fig. 6) suggest that, if primary magmas, both Rb and Sr were incompatible elements and the Rb/Sr ratio was not significantly fractionated during partial melting. This suggests a Precambrian age for the source of these granodiorites. As pyroxene will retain some Sr, any calculated age is probably 10 to 20 percent low. Group II granodiorites also exhibit a positive correlation between Rb/Sr and $^{87}Sr/^{86}Sr$ (Fig. 11). The slope of a line through these data points is much shallower, yielding a calculated age of approximately 500 m.y. These rocks have been interpreted to be either primary magmas, derived by partial melting of a plagioclase-bearing source and/or the product of a fractional crystallization involving plagioclase. In either case the effect of equilibration with plagioclase would be to lower the Sr content and markedly increase the Rb/Sr ratio, requiring that the true age of the source is greatly in excess of 500 m.y. Thus both the monzonite and granodiorite suites were apparently derived from Precambrian sources, whose ages are approximately the same as the age of crustal formation in Colorado.

Conclusions

It has frequently been suggested that the stocks of the Colorado mineral belt are high-level expressions of an underlying batholith or string of batholiths (Lovering and Goddard, 1938; and Tweto, 1975). The geochemical data presented here, would be consistent with such an interpretation for some of the larger plutons such as Montezuma and Mt. Princeton. Rocks from these plutons have the geochemical characteristics of fractionated magmas that might be expected to form near the top of large magma bodies. Many of the rocks of the smaller plutons (for example: Italian Mountain, Caribou, and Empire), however, have been shown, on the basis of minor-element geochemistry, mineralogy and texture to be partially cumulate. Other samples appear to represent primary or only sightly fractionated magmas. Primary magmas and crystal cumulates would not be expected to be high-level expressions of batholiths, and we conclude that stocks which exhibit these features are probably not underlain by large volumes of comagmatic igneous rocks.

The chemical and isotopic differences between the monzonitic and granodioritic suites of rocks in the Colorado mineral belt are the results of their derivation from different types of source materials. The granodioritic suite was generated from pyroxene granulites in the lower crust. The source material for the alkalic monzonites was a alkaline, mafic rock; and, upon melting left an eclogitic residual assemblage. This source material was not completely uniform in composition, mineralogy, or $^{87}Sr/^{86}Sr$ ratios. The mafic monzonites apparently formed in equilibrium with a plagioclase-bearing residue. The depth of the sources for the monzonitic rocks is not certain, but the conclusion that garnet was residual to the alkalic monzonites might be interpreted as indicating that they were generated deeper than the granodiorites. In any case, the source rocks, for both the granodioritic and monzonitic suites, were formed at essentially the same Precambrian time as the upper-crustal rocks in this region.

We can not explain the fundamental causes of the magmatism, which we have studied. We can only say that an important increase in the geothermal gradient seems necessary to initiate partial melting of rocks within the lower crust.

Appendix 1: Analytical Methods

Rubidium and strontium were analyzed by isotope dilution, and the values reported in Table 2 have uncertainties of approx. 0.5% of the amount present. $^{87}Sr/^{86}Sr$ ratios for these samples were measured on a 6″ radius of curvature mass spectrometer; seven analyses of the E. & A. standard yielded a value of 0.70799 ± 0.00002 (2σ) and five analyses of the SRM 987 standard yielded a value of 0.71014 ± 0.00002 (2σ). On the basis of these standard analyses and duplicate analyses of unknowns, we believe the uncertainty of the $^{87}Sr/^{86}Sr$ ratios reported in Table 2 to be less than ± 0.00004 (2σ), except for samples 25 and 48, for which the uncertainty is less than 0.00020.

The rare-earth elements (REE) were analyzed by isotope dilution, using a 12″ radius of curvature mass spectrometer. The uncertainty of the data listed in Table 3 is believed to be less than 3% of the amount present for all the REE elements except lutetium, for which the uncertainty is approximately 10% of the amount present.

Values for K_2O and Na_2O listed in Table 2 were determined by flame photometry (Violet Merritt analyst), and have uncertainties of approx. 2% of the amount present. Five samples of this study were analyzed for major elements (L. Artis, analyst), using the method described as "single solution" in Shapiro (1975); the values for Na_2O and K_2O are those given in Table 2.

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