Crystalline Rocks of the Strawberry Lake Area, Front Range, Colorado

A. Petrography and Geochemistry
B. Petrology

U.S. GEOLOGICAL SURVEY BULLETIN 1937

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By EDWARD J. YOUNG

A petrographic and geochemical study of the bedrock and a petrologic discussion based on felsic-mafic and silica-saturation ratios

This volume is published as chapters A and B. These chapters are not available separately

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CONTENTS

[Letters designate the chapters]

Chapter A

Petrography and Geochemistry

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A study of the petrography and geochemistry of the bedrock

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CRYSTALLINE ROCKS OF THE STRAWBERRY LAKE AREA, FRONT RANGE, COLORADO

CONTENTS

PLATE

[Plate is in pocket]

FIGURES

TABLES

Petrography and Geochemistry

By Edward J. Young

ABSTRACT

The Strawberry Lake area lies between the Continental Divide and Granby, Colorado, just north of Tabernash. It is underlain by Proterozoic rocks composed of biotite gneiss and two plutons—Boulder Creek Granodiorite of the Routt Plutonic Suite and Silver Plume Granite of the Berthoud Plutonic Suite. Relict enclaves of biotite gneiss are not uncommon in the Boulder Creek Granodiorite, in the Silver Plume Granite, and in the granitic enclaves in the biotite gneiss. Granitic and mafic enclaves in the Boulder Creek Granodiorite, granitic enclaves in the Silver Plume Granite and in the biotite gneiss, and a Tertiary andesite porphyry dike complete the rock types.

I used chemical, physical, and petrographic data to delineate properties of the rock units. The Boulder Creek Granodiorite ranges from metaluminous to peraluminous and from granodiorite to tonalite, whereas the Silver Plume Granite is peraluminous, monazite bearing, and potassium rich. The Boulder Creek Granodiorite contains less uranium and thorium and the Silver Plume Granite contains more uranium and thorium in the Strawberry Lake area than the same rocks, on average, in the entire Front Range. This finding correlates with a more mafic than average Boulder Creek Granodiorite and a more felsic than average Silver Plume Granite in the Strawberry Lake area.

Geochemical and petrologic problems are posed by the enclaves. The granitic enclaves in the two plutons and in the biotite gneiss exhibit greater enrichment in thorium and light rare-earth elements than their hosts. Small mafic enclaves in the Boulder Creek Granodiorite are enriched in mafic elements, whereas lamprophyres in the Boulder Creek Granodiorite are enriched in both felsic and mafic elements.

INTRODUCTION

The geology of the crystalline rocks of the Strawberry Lake area (northwestern flank of the central Front Range) in Colorado was not well known before completion of David A. Schroeder's (1984) thesis. Concurrent with Schroeder's investigation, and supplementary to it, my independent investigation (Young, 1984) on the chemical, petrographic, and physical properties of the crystalline bedrock resulted in additional information, which must be considered for a more complete understanding of the geology.

The geologic map of Colorado, compiled by Odgen Tweto (1979) at a scale of 1:500,000, shows that most of the area of this report is underlain by 1,700-m.y. granitic rocks. Mapping by Schroeder (1984) and myself suggests that a part of this area is underlain by the Middle Proterozoic Silver Plume Granite. A rubidium-strontium (Rb-Sr) age of 1,503 ± 100 m.y. (C.E. Hedge, written commun., 1982) confirmed this suggestion. I collected rock samples from the Strawberry Lake quadrangle and small parts of the surrounding quadrangles (fig. 1) in order to study carefully the rocks and minerals; I paid special attention to uranium and thorium, because the Front Range long has been called a "uranium and thorium province" (Phair and Gottfried, 1963). In addition, I determined foliations and other structural features in order to study the relationship between enclaves and their hosts.

Major rock units of the Strawberry Lake area include an older (Early Proterozoic) biotite-gneiss complex, Boulder Creek Granodiorite of the Routt Plutonic Suite (Tweto, 1987), and younger (Middle Proterozoic) Silver Plume Granite of the Berthoud Plutonic Suite (Tweto, 1987). All major rock units contain granitic enclaves[1] of various sizes. In addition, relict enclaves of biotite gneiss occur in the two plutons and in the granitic enclaves of the biotite gneiss. Small mafic enclaves, lamprophyres, and a Tertiary andesite porphyry dike are confined to the pluton of Boulder Creek Granodiorite.

Manuscript approved for publication, March 9, 1990.

[1]Enclave is a nongenetic term, which is useful for naming a body of rock enclosed within a host rock (Didier, 1973, p. 1).

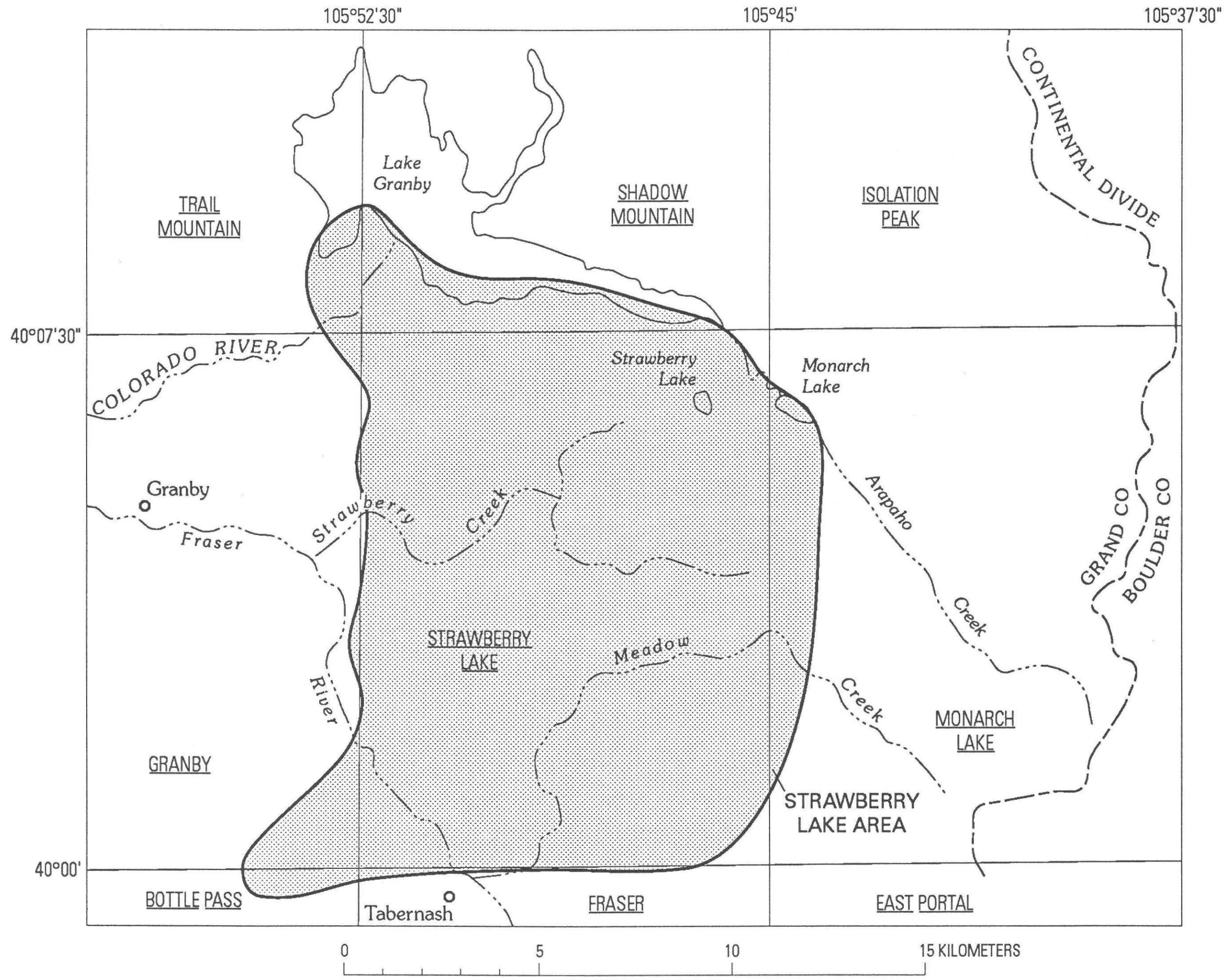


Figure 1. Index map of the Strawberry Lake area (7½-minute quadrangles are underlined).

Chapter A of this bulletin focuses on the petrography and geochemistry of the rock units. Chapter B addresses the question of origin (petrology) of the plutonic rocks and their enclaves. Chapter A has benefited from the reviews of Robert C. Pearson, Dolores J. Gable, and Alan R. Wallace. All the observations and views expressed, however, are mine.

GEOLOGIC SETTING

The 160-km^2 Strawberry Lake area lies between the Continental Divide and Granby, Colo., just north of Tabernash. Fifty percent of the area is underlain by a pluton of Boulder Creek Granodiorite of the Routt Plutonic Suite (Tweto, 1987). The Boulder Creek Granodiorite in this area has not been dated, but it is similar in all regards to Boulder Creek Granodiorite in the central Front Range, where it has been dated as 1,710 ± 70 m.y. (Hedge and others, 1967). A smaller pluton of Silver Plume Granite of the Berthoud Plutonic Suite (Tweto, 1987) underlies about 20 percent of the area and has been dated at 1,503 ± 100 m.y. (C.E. Hedge, written commun., 1982). Elsewhere in the Front Range Silver Plume Granite has been dated at 1,390–1,450 m.y. (Peterman and others, 1968). A biotite-gneiss complex (country rock) underlies about 20 percent of the area; it surrounds the two plutons and also occurs as enclaves, generally small, within the two plutons and within the granitic enclaves of the biotite gneiss. Radiometric age determinations of rocks in the biotite-gneiss complex indicate that regional metamorphism peaked between 1,700 and 1,775 m.y. ago in Colorado (Hedge and others, 1967). Numerous enclaves of fine-grained granitic rock occur in the Boulder Creek Granodiorite and in the biotite gneiss, but fewer occur in the Silver Plume Granite. These granitic enclaves aggregate about 7 percent of the total area. Small discoid, mafic enclaves, lamprophyric enclaves, and a Tertiary andesite porphyry dike occur only within the Boulder Creek Granodiorite. These last three rock units make up less than 1 percent of the map area.

Plate 1 is a generalized geologic map of the Strawberry Lake area showing sampling localities. Most of the map area is in the Strawberry Lake quadrangle, which was mapped by Schroeder (1984). Small parts of the map area are found in the Trail Mountain quadrangle (mapped by Izett, 1974), in the Granby quadrangle (mapped by Schroeder, 1984), and in the Bottle Pass quadrangle (mapped by Taylor, 1975). Portions of the map area that are in the Shadow Mountain and Monarch Lake quadrangles were mapped by me.

Regional foliations in the Boulder Creek Granodiorite and in surrounding biotite gneiss generally strike northeast and dip steeply. Foliations in biotite-gneiss enclaves within the Boulder Creek Granodiorite conform to foliations of the host. In the northeast corner of the map area, the northeast-striking regional foliation occurs in both biotite gneiss and biotite-gneiss enclaves within the Silver Plume Granite. Divergence from this northeast-striking regional foliation to a northwest-striking foliation, generally of steep dip, is chiefly found in biotite gneiss near its contact with Silver Plume Granite and in biotite-gneiss enclaves within Silver Plume Granite near its contact with biotite gneiss. This northwest-striking foliation extends from the center to the northwest corner of the map area. The zone of northwest-striking foliation near the contact of the biotite gneiss and the Silver Plume Granite indicates a structural relationship between these two rock units, but exposure is neither good enough nor continuous enough to reveal the structure. Although a fault between these two rock units would seem to be a possible inference, neither D.A. Schroeder nor I found any direct evidence for such a fault.

A small north-trending fault is found in the west-central part of the Strawberry Lake quadrangle, where normal faulting has preserved a small inlier of Mesozoic sedimentary rocks within the pluton of Boulder Creek Granodiorite. Two small faults between Mesozoic sedimentary rocks and Boulder Creek Granodiorite occur in the southwest corner of the area, and two small faults between Boulder Creek Granodiorite and biotite gneiss occur in the southeast part of the area. An inferred bifurcating fault was mapped by Izett (1974) in the southeast corner of the Trail Mountain quadrangle (northwest corner of plate 1).

PETROGRAPHY OF CRYSTALLINE ROCKS

Eight of the nine crystalline rock types described here are Proterozoic; the ninth is a Tertiary andesite porphyry dike. In general, the rocks are described in order of their volumetric importance in tables 2–17. Table 1 gives an overview of the type and number of analyses or measurements made on these rocks.

Boulder Creek Granodiorite

The Boulder Creek Granodiorite (tables 2–4) is a massive to foliated, medium-grained, light- to dark-gray, hypautomorphic granular, granitoid rock of granodioritic to tonalitic composition, similar to the Boulder Creek Granodiorite west of Boulder, Colo. (Gable, 1980). Biotite and hornblende commonly cluster, which makes the rock appear to be coarse grained. Essential minerals are quartz, plagioclase (generally andesine, locally labradorite), and biotite. The plagioclase is commonly myrmekitic and antiperthitic but is not zoned. Microcline, hornblende, muscovite/sericite, chlorite, epidote, clinozoisite, and allanite occur locally. Apatite and sphene, magnetite, hematite, and zircon are common accessory minerals and are rarely absent in a sample. Black opaque minerals in thin section present a problem to the modal analyst. Oblique reflected light aids discrimination between pyrite and the iron and titanium minerals. A strong hand magnet is useful in discriminating between magnetite-bearing and hematite-bearing rocks. Rocks designated as nonmagnetic may contain hematite or ilmenite although determinations by Isabelle Brownfield on black opaque minerals from such rocks yielded only hematite.

Because these accessory minerals are relatively abundant, they provide an opportunity for closer scrutiny of their properties and mode of occurrence. Some colorless apatite grains, which commonly occur as crystals, show radiation-damage halos in biotite (not as intense as the halos that surround zircon), but other apatite grains within the same rock specimen do not show halos. Sphene commonly surrounds biotite flakes as small noncontiguous grains and also riddles the interior of biotite flakes with trains of smaller grains. Sphene also occurs at the contact of biotite and magnetite or hematite. Radiation-damage halos do not surround sphene in biotite.

The zircons are small (less than 0.14 mm). Some zircons show syntaxial overgrowths, and all zircons invariably show radiation-damage halos in biotite.

Allanite grains tend to be relatively large (some more than 3 mm). They are yellow brown to red brown and commonly isotropic (metamict), and they show

Table 1. Parameters used in description of rocks in the Strawberry Lake area and number of analyses or measurements for each rock unit

[<, less than; < <, much less than]

Rock unit	Boulder Creek Granodiorite	Silver Plume Granite	Biotite gneiss	Granitic enclaves in biotite gneiss	Granitic enclaves in Boulder Creek Granodiorite	Biotite lamprophyre	Granitic enclaves in Silver Plume Granite	Small mafic enclaves in Boulder Creek Granodiorite	Andesite porphyre dike
				Chemical parameters					
Chemical analysis....... $K_2O:Na_2O$, A:CNK[1], F[2], S[3].	30	35	15	5	20	10	10	5	5
Spectrographic analysis La:Ni, U, Th, Th:U.	60	125	25	35	25	15	10	5	5
Rb:Sr..................	3	3	3	3	4	1	2	1	1
				Physical parameters					
Radioactivity[4], in..... counts per second.	26	33	8	8	12	4	2	0	1
Magnetic property[5]......	26	34	9	8	12	5	2	1	1
Specific gravity[6].......	25	31	7	7	12	5	2	1	1
				Petrographic parameters					
Modal analysis, color... index[7].	48	64	16	16	24	10	4	2	2
Average grain size,..... in millimeters.	26	34	9	8	12	5	2	1	1
Total number of analyses for all parameters for each rock unit.	244	359	92	90	121	55	34	16	17
Areal percentage of .... rock unit in map area.	50	20	20	5	about 1	<1	<<1	1?	<1

[1]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[2]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[3]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[4]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[5]m, rock reacts postively to a large hand magnet; nm, no reaction.

[6]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

radiation-damage halos in biotite. Locally, allanite is surrounded by yellow-green epidote. Clinozoisite commonly occurs as microcrystalline aggregates along biotite cleavages and appears almost isotropic. Table 17, which gives average volume percentages of accessory minerals in the Boulder Creek Granodiorite and other rocks, shows that sphene, apatite, and epidote each average more than 0.5 percent.

Much of the Boulder Creek Granodiorite appears homogeneous, but it contains enclaves of rock that range from felsic to mafic. The largest of these enclaves are granitic and range from less than 2 m to more than 1 km in greatest dimension. Figure 2 shows typical Boulder Creek Granodiorite in contact with a small granitic enclave. Some granitic enclaves locally contain enclaves (roughly equant) of granodiorite about 1 m in size. This "enclave within enclave" pattern indicates the complexity involved in the process of formation or transformation of the Boulder Creek Granodiorite. Wisps of biotite gneiss and larger enclaves of biotite gneiss are not uncommon. At least three enigmatic biotite-lamprophyre enclaves occur in the granodiorite, and small (1–30 cm) mafic (dioritic) enclaves are common locally (fig. 3). Large pink porphyroblasts, as much as 10 cm long, are common near contacts with the biotite-gneiss unit (fig. 4).

The Streckeisen (1976) classification is used for all rock names. Quartz–alkali feldspar–plagioclase (QAP) ratios are plotted on a QAP diagram in figure 5 for all modally analyzed rocks (24 samples) of the Boulder Creek Granodiorite. Almost one-half of these specimens are tonalite, thus placing the average composition near the granodiorite-tonalite dividing line. It is unusual for a rock of such mafic intermediate composition to be almost peraluminous. Average alumina composition [$A:CNK = Al_2O_3/(CaO + Na_2O + K_2O)$ in molecular proportions, as defined by Clarke (1981)] is 0.98. The Boulder Creek Granodiorite in the Strawberry Lake area is decidedly more mafic than the batholithic Boulder Creek Granodiorite west of Boulder, Colo. (Gable, 1980), which plots as felsic granodiorite (close to the dividing line with monzogranite).

Granitic Enclaves in Boulder Creek Granodiorite

Granitic enclaves in the Boulder Creek Granodiorite (tables 5 and 6) range from 1 m to more than 1 km in greatest dimension. The larger ones are shown on plate 1, but many are too small to be shown. Contacts between the granite and the host granodiorite are generally sharp and abrupt. The smaller enclaves are generally fine grained, and the larger enclaves are only slightly coarser. All are gray to buff and have hypautomorphic granular texture.

Essential minerals are quartz, microcline, oligoclase (rarely albite), and biotite. The plagioclase is locally antiperthitic and commonly myrmekitic. Microcline locally shows vermicular quartz and quartz blebs. Muscovite or sericite and magnetite are generally present. Hematite does not occur in the smaller enclaves and is subordinate to magnetite in the larger enclaves. Apatite and zircon occur in all the smaller enclaves and in most of the larger enclaves. The largest apatite grain is 0.15 by 0.12 mm; it contained an inclusion of zircon that, in turn, contained a core of older zircon. Many of the zircon grains show zircon cores. Chlorite, epidote, allanite, monazite, and sphene occur locally. The monazite grains are very small—the largest one is 0.02 by 0.025 mm. Some monazite grains are pale yellow and gemmy in appearance. Monazite grains included in biotite produce dark, intense radiation-damage halos.

Twelve samples of these granitic enclaves are plotted on a QAP diagram in figure 6. For comparison, eight granitic enclaves in biotite gneiss and two granitic enclaves in Silver Plume Granite are also plotted. All the granitic enclaves, regardless of host rock, contain similar amounts of quartz, but the granitic enclaves in the Boulder Creek Granodiorite are the richest in alkali feldspar. All the granitic enclaves are peraluminous.

Silver Plume Granite

The Silver Plume Granite (tables 7–9) is a generally massive, pale-gray to buff, hypautomorphic granular, medium-grained, peraluminous granite, which forms an almost homogeneous mass. Essential minerals are quartz, microcline (locally perthitic), oligoclase (unzoned, locally myrmekitic or containing quartz blebs), biotite, and muscovite. Monazite is present in every sample. Zircon, apatite, and hematite or magnetite are present in most samples; hematite is more common. Chlorite and sillimanite occur locally, and epidote and allanite are rare. Trace amounts of pyrite and fluorite, which fill fractures, occur in only one sample.

Microcline locally forms laths or is anhedral; it invariably has the largest grain size of the major minerals. Plagioclase, which is commonly sericitized, and quartz are anhedral. Biotite and muscovite occur as much smaller grains than the feldspar and quartz and locally form inclusions in the feldspars. Biotite:muscovite ratios are not at all consistent; they vary from almost 30 to less than 1.

Monazite is usually found as single, small, anhedral (less than 0.1 mm) grains, but also locally in clusters of several grains. The largest monazite grain is 0.36 by 0.2 mm. Monazite is hosted by all the major silicate minerals but is also intimately associated with magnetite or hematite. If hosted by biotite it produces an intensely dark radiation-damage halo, which is invariably 0.03 mm thick

Table 2. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of the Boulder Creek Granodiorite

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, M. Schneider, W. Stang, R. Bies, B. Keaten, and S. Lasater. Rapid rock chemical analyses of sample SL–35 by K. Coates, and sample SL–51 by N. Skinner and D. Kopilis. Chemical (X-ray spectrographic) analyses of samples SL–57, 66, 67, and 70 by J.S. Wahlberg, J. Taggart, and J. Baker. Semiquantitative spectrographic analyses of sample SL–35 by G. Kaczanowski; sample SL–51 by T. Fries; and samples SL–57, 66, 67, and 70 by N.M. Conklin. *, significant trace elements (2× crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; <, less than]

Composition	Sample No. SL–35	SL–51	SL–57	SL–66	SL–67	SL–70
	Uranium and thorium analyses, in parts per million					
U	1.67	0.81	2.32	0.84	0.87	1.24
Th	3.7	5.5	8.8	7.7	10.4	16.8
Th:U	2.2	6.8	3.8	9.2	12.0	13.5
	Chemical analyses, in weight percent					
SiO_2	60.6	58.1	60.3	61.6	64.7	66.1
Al_2O_3	16.1	16.5	16.9	16.7	15.5	15.3
Fe_2O_3	2.4	2.0	[1]6.03	[1]5.78	[1]6.05	[1]5.66
FeO	3.8	4.3	n.d.	n.d.	n.d.	n.d.
MgO	3.5	3.7	3.1	2.7	2.3	2.0
CaO	4.9	5.3	5.16	4.91	3.53	3.49
Na_2O	3.2	3.2	3.5	3.3	2.8	3.0
K_2O	3.4	3.2	2.32	2.61	3.10	2.83
H_2O+	.73	1.0	[2]2.78	[2]2.70	[2]2.80	[2]2.60
H_2O-	.33	.21				
TiO_2	.78	.84	.94	.73	.74	.70
P_2O_5	.34	.41	.40	.30	.20	.20
MnO	.08	.11	.07	.06	.07	.05
CO_2	.01	.01	n.d.	n.d.	n.d.	n.d.
Total	100	99	100	99	100	100
K_2O/Na_2O	1.1	1.0	.66	.79	1.1	.94
A:CNK[3]	.90	.90	.96	.97	1.08	1.07
F[4]	4.60	4.22	4.63	5.04	5.94	6.45
S[5]	1.62	1.52	1.63	1.71	1.94	2.05
	Spectrographic analyses, in parts per million					
B	20	<10	<10	<10	<10	<10
Ba	690	1000	300	700	700	500
Be	3.3	3.3	1.5	1.5	1.0	1.0
Ce	<100	<100	<100	<100	<100	100
Co	22	24	15	15	15	15
Cr	78	98	70	70	30	30
Cu	28	39	70	15	15	15
Ga	24	24	15	15	15	15
La	41	43	30	50	30	70*
Nb	<25	<25	<10	<10	<10	<10
Nd	n.d.	n.d.	<70	70	<70	<70
Ni	56	60	50	30	15	15
Pb	<10	<10	<10	10	10	10
Sc	20*	22*	7	20*	15	7
Sr	480	720*	700*	700*	500	500
V	140	150	70	70	70	70
Y	33	30	20	30	15	15
Yb	n.d.	n.d.	3	3	1.5	1.5
Zn	87	64	<300	<300	<300	<300
Zr	120	150	150	200	150	150
La:Ni	.73	.72	.60	1.7	2.0	4.7

Table 2. Uranium, thorium, chemical, spectrogrphic, and modal analyses and descriptive parameters of the Boulder Creek Granodiorite—Continued

Composition	Sample No. SL-35	SL-51	SL-57	SL-66	SL-67	SL-70
			Modal analyses, in volume percent			
Quartz	16.9	20.7	19.0	21.9	25.4	31.3
Microcline	10.8	9.4	-	2.6	3.3	5.5
Plagioclase[6]	42.5	37.5	59.0	55.7	52.4	37.1
Anorthite	35	43	38	36	32	32
Biotite	16.9	11.3	11.7	12.6	16.6	23.3
Muscovite/sericite	—	4.0	—	—	—	.3
Chlorite	—	—	—	.1	—	.3
Hornblende	9.4	13.7	7.5	5.4	.5	—
Magnetite	.2	.1	—	.1	.5	.9
Hematite	—	—	.4	—	—	—
Apatite*	.7	.5	.8	.7	.8	1.0
Sphene*	2.4	1.2	1.3	.9	.2	.3
Zircon	tr	tr	tr	tr	.1	tr
Epidote	.2	1.6	.3	tr	—	—
Allanite	tr	—	—	tr	.2	tr
Total	100	100	100	100	100	100
Points counted	801	826	710	684	610	690
Color index[7]	29.1	27.9	21.2	19.1	18.1	24.8
Average grain size, in millimeters.	2.5	2.5	3	3	2.5	2.5
Magnetic, m, or nonmagnetic, nm[8].	m	m	nm	m	m	m
Radioactivity,[9] in counts per second.	110	150	125	105	120	165
Specific gravity[10]	2.770	2.830	2.814	2.795	2.745	2.750
Rock name (Streckeisen, 1976).	grano-diorite.	grano-diorite.	tonalite	tonalite	tonalite	grano-diorite.

[1]Total iron reported as Fe_2O_3.

[2]LOI at 900 °C.

[3]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[4]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[5]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[6]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[8]m, rock reacts postively to a large hand magnet; nm, no reaction.

[9]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[10]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 3. Uranium, thorium, spectrographic, and modal analyses and descriptive parameters of the Boulder Creek Granodiorite

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, M. Schneider, W. Stang, R. Bies, B. Keaten, and S. Lasater. Semiquantitative spectrographic analyses of sample SL–8 by L. Castillo; samples SL–50 and 52 by T. Fries; and samples SL–53, 54, and 61 by N.M. Conklin. *, significant trace elements (2× crustal abundance, or more) and diagnostic accessory minerals. tr, trace;—, not found; n.d., not determined; n.a., not applicable]

Composition	Sample No.					
	SL–8	SL–50	SL–52	SL–53	SL–54	SL–61
Uranium and thorium analyses, in parts per million						
U	1.83	1.38	1.18	1.62	2.52	1.24
Th	6.78	14.0	8.64	18.5	11.6	9.74
Th:U	3.7	10.1	7.3	11.4	4.6	7.9
Spectrographic analyses, in parts per million						
B	<10	<10	<10	<10	<10	<10
Ba	840	890	1300*	700	1000	700
Be	3.1	4.2	2.7	1	1	1
Ce	110	<100	<100	200*	100	100
Co	23	23	15	15	15	15
Cr	55	97	58	70	70	70
Cu	21	56	9.4	30	15	30
Ga	27	25	19	15	15	15
La	68*	56	36	150*	70*	70*
Li	96*	<50	<50	<100	<100	<100
Mn	790	1100	710	700	700	500
Nb	<25	<25	<25	<10	<10	<10
Nd	n.d.	n.d.	n.d.	100*	100*	70
Ni	47	57	40	30	30	30
P	1500	2900*	1500	<2000	<2000	<2000
Pb	3.7	<10	<10	15	10	10
Sc	<10	23*	13	7	15	7
Sr	550	610	550	700*	700*	700*
Ti	6300	5400	4200	3000	3000	3000
V	150	150	92	70	70	70
Y	23	36	21	20	30	10
Yb	n.d.	n.d.	n.d.	2	3	1.5
Zn	52	71	55	<300	<300	<300
Zr	100	140	67	200	150	150
La:Ni	1.4	1.0	.9	5.0	2.3	2.3
Modal analyses, in volume percent						
Quartz	16.8		16.6	25.3	23.4	
Microcline	10.2	no	27.6	11.3	5.3	no
Plagioclase[1]	32.6		29.5	39.3	36.3	
Anorthite	30		31	38	35	
Biotite	32.2		15.3	22.4	20.9	
Muscovite/sericite	—	thin	3.8	.6	—	thin
Chlorite	.1		.3	.1	—	
Hornblende	—		3.9	—	11.6	
Magnetite	2.4		—	.1	—	
Hematite	—	section	1.0	—	.1	section
Apatite*	2.0		.7	.5	.5	
Sphene*	1.4		.7	.4	1.1	
Zircon	—		.1	tr	tr	
Epidote	—	available	.1	—	.4	available
Clinozoisite	—		—	tr	.4	
Allanite	2.3		—	—	—	
Calcite	—		.4	—	—	
Total	100.0		100.0	100.0	100.0	
Points counted	651		767	835	786	

Table 3. Uranium, thorium, spectrographic, and modal analyses and descriptive parameters of the Boulder Creek Granodiorite—Continued

Composition	Sample No. SL-8	SL-50	SL-52	SL-53	SL-54	SL-61
Color index[2]........	38.4	n.a.	21.4	23.0	34.5	n.a.
Average grain size, in millimeters.	3.5	about 3	3	2	2.5	about 3
Magnetic, m, or...... nonmagnetic, nm[3].	m	m	nm	m	nm	m
Radioactivity[4], in.. counts per second.	165	150	170	120	130	140
Specific gravity[5]...	2.720	2.812	2.759	2.807	2.789	2.850
Rock name........... (Streckeisen, 1976).	grano-diorite.	n.a.	granite	grano-diorite.	grano-diorite.	n.a.

[1]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[2]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibola, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[3]m, rock reacts positively to large hand magnet; nm, no reaction.

[4]Measured on outcrop with Mount Sopris scintillometer, Model SC-132.

[5]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 4. Modal analyses and descriptive parameters of the Boulder Creek Granodiorite

[*, diagnostic accessory minerals. tr, trace; —, not found]

Composition	Sample No. SL-84	SL-86	SL-93	SL-94	SL-96	SL-97	SL-98
Modal analyses, in volume percent							
Quartz	29.4	21.3	18.8	20.8	28.9	30.7	27.1
Microcline	18.1	.5	2.8	12.4	—	17.8	.4
Plagioclase[1]	35.1	41.1	36.7	44.4	53.5	38.1	42.2
Anorthite	32	32	28	32	32	32	30
Biotite	11.9	29.4	31.8	14.7	17.0	11.5	27.7
Muscovite/sericite	.6	—	.4	—	—	tr	—
Chlorite	tr	—	—	—	tr	1.0	—
Hornblende	1.4	1.3	5.8	6.3	—	—	—
Magnetite	—	—	—	—	—	—	.9
Hematite	tr	.3	tr	.1	tr	—	—
Apatite*	.3	.8	.4	.6	.5	.2	.3
Sphene*	.3	1.8	1.0	.6	—	.7	.9
Zircon	—	tr	tr	tr	tr	tr	tr
Epidote	2.8	2.4	2.3	.1	—	tr	.4
Allanite	—	—	tr	—	—	tr	.1
Calcite	.1	—	—	—	—	—	—
Total	100	100	100	100	100	100	100
Points counted	725	615	702	712	647	583	669
Color index[2]	16.4	36.3	40.9	21.8	17.0	13.2	30.0
Average grain size, in millimeters.	2.5	2.5	2.5	2.5	3	2.5	2.5
Magnetic, m, or nonmagnetic, nm[3].	nm	nm	nm	nm	nm	nm	m
Radioactivity,[4] in counts per second.	130	110	120	100	160	175	125
Specific gravity[5]	2.727	2.812	2.786	2.803	2.756	2.685	—
Rock name (Streckeisen, 1976).	grano-diorite.	tonalite	tonalite	grano-diorite.	tonalite	grano-diorite.	tonalite

Table 4. Modal analyses and descriptive parameters of the Boulder Creek Granodiorite—Continued

Composition	Sample No. SL-109A	SL-110	SL-111A	SL-112	SL-113	SL-114	SL-117
Quartz.............	28.0	18.7	20.1	16.5	16.8	27.6	20.3
Microcline..........	12.8	13.8	2.0	12.7	9.0	—	1.6
Plagioclase.........	35.7	43.7	59.8	48.6	46.1	44.2	47.3
Anorthite.........	33	35	35	35	32	35	32
Biotite............	18.4	20.6	17.4	15.8	13.1	23.6	25.7
Muscovite/sericite..	4.1	.1	—	—	.2	.7	.2
Chlorite...........	—	.6	—	—	.3	—	—
Hornblende..........	—	—	—	4.9	8.6	—	—
Magnetite...........	.5	.6	—	—	—	2.5	2.7
Hematite............	—	—	tr	.2	.2	—	—
Apatite*............	.5	.8	.2	.5	.7	.8	.6
Sphene*.............	—	tr	tr	.5	.7	.5	.6
Zircon..............	tr	tr	tr	tr	tr	tr	tr
Epidote.............	tr	.8	.5	.3	1.6	.1	tr
Clinozoisite........	—	.3	tr	—	1.4	—	—
Allanite............	tr	tr	tr	tr	1.3	tr	1.0
Total............	100	100	100	100	100	100	100
Points counted....	592	647	596	612	579	601	630
Color index[2]........	18.9	22.6	17.9	21.7	25.8	26.7	30.0
Average grain size, in millimeters.	1.5	2.5	2.5	2.5	2	2	2
Magnetic, m, or...... nonmagnetic, nm[3].	m	m	nm	nm	nm	m	m
Radioactivity,[4] in.. counts per second.	120	120	100	100	100	90	90
Specific gravity[5]...	2.762	2.774	2.770	2.767	2.773	2.811	2.787
Rock name.......... (Streckeisen, 1976).	grano-diorite.	grano-diorite.	tonalite	grano-diorite.	grano-diorite.	tonalite	tonalite

[1]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refactive index comparisons against quartz.

[2]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[3]m, rock reacts positively to a large hand magnet; nm, no reaction.

[4]Measured on outcrop with Mount Sopris scintillometer, Model SC-132.

[5]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with a ± 0.008 gram per cubic centimeter maximum deviation.

Figure 2. Boulder Creek Granodiorite (on right) in contact with a small fine-grained granitic enclave. Note atypical weak zoning in granitic rock parallel to contact. Specimen label is 2 centimeters long.

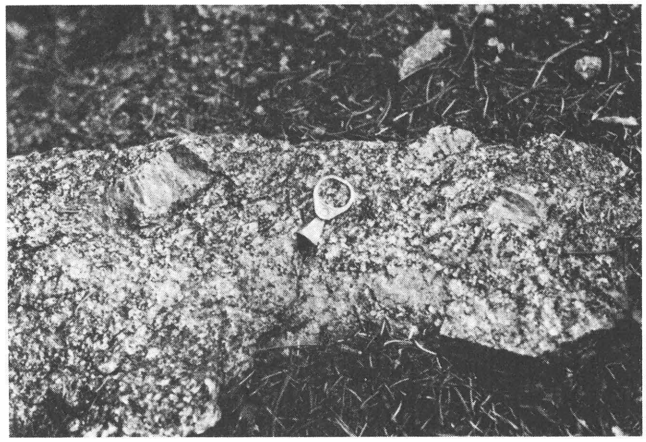


Figure 4. Pink porphyroblasts in Boulder Creek Granodiorite near contact with biotite gneiss. Poptop is 4.5 centimeters long.

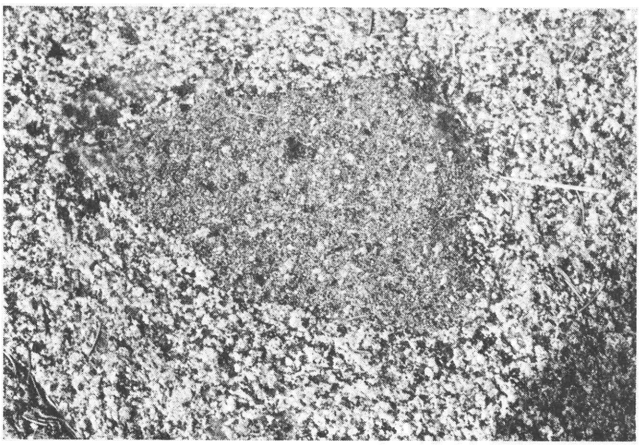


Figure 3. Small mafic enclave in Boulder Creek Granodiorite. Toothpick on right is 6 centimeters long.

(fig. 7). Locally, very small monazite grains (less than 0.02 mm) in biotite leave telltale, dark radiation-damage halos. Commonly, the peripheral contact of monazite with a feldspar or quartz host is marked by a diagnostic, dark reaction(?) or alteration ring of opaque material (fig. 8). Apatite grains are generally larger than monazite grains (the largest apatite grain is 1.8 by 0.5 mm) and are hosted by all the major silicate minerals. Radiation-damage halos caused by apatite do not occur in biotite. Most zircons are single small grains, but some have older zircon cores and syntaxial overgrowths, which are commonly zoned. Some zircons produce weak radiation-damage halos in biotite. Sillimanite occurs as single, needlelike grains or sheafs of needlelike grains in muscovite or quartz.

Foliation in the Silver Plume Granite (pl. 1) was read on enclaves of biotite gneiss or schist within the granite (fig. 9), on alignment of tabular microcline laths, or on biotite schlieren. The Silver Plume Granite is generally featureless in the Strawberry Lake area and does not show any mineral orientation, except for local biotite schlieren (fig. 10) or relicts of biotite gneiss in all stages of replacement or assimilation.

The foliation in the biotite-gneiss enclaves in the Silver Plume Granite generally conforms to the foliation in surrounding biotite gneiss. The planar orientation of the tabular microcline laths in the Silver Plume Granite, where it infrequently occurs, conforms reasonably well with the foliation in nearby enclaves of biotite gneiss. The feldspar alignment is generally attributed to magmatic flow structure (Pearson and U.S. Bureau of Mines, 1980, p. 16), but such alignment may be due to recrystallization (feldspathization) in conformity with regional foliation in this area.

Pegmatites in the Silver Plume Granite are uncommon and small. Several pegmatites, which are located along Lake Granby and are too small to show on plate 1, are notable for small amounts of tourmaline (black schorl). Granitic enclaves in the Silver Plume Granite that are more radioactive than their host are less than 100 m in greatest dimension and occur on the south shore of Lake Granby.

Whole-rock sample SM–4 was dated by C.E. Hedge (written commun., 1982) using the rubidium-strontium method. He assumed an initial $^{87}Sr/^{86}Sr$ of 0.7036, which was determined previously from suites of Silver Plume Granite, and calculated an apparent age of 1,503 ± 100 m.y. The substantial uncertainty (± 100 m.y.) results from the use of a single sample. Nevertheless, 1,503 ± 100 m.y. is closer to the 1,390–1,450-m.y. grouping of the Silver Plume Granite than to the 1,700–1,800-m.y.

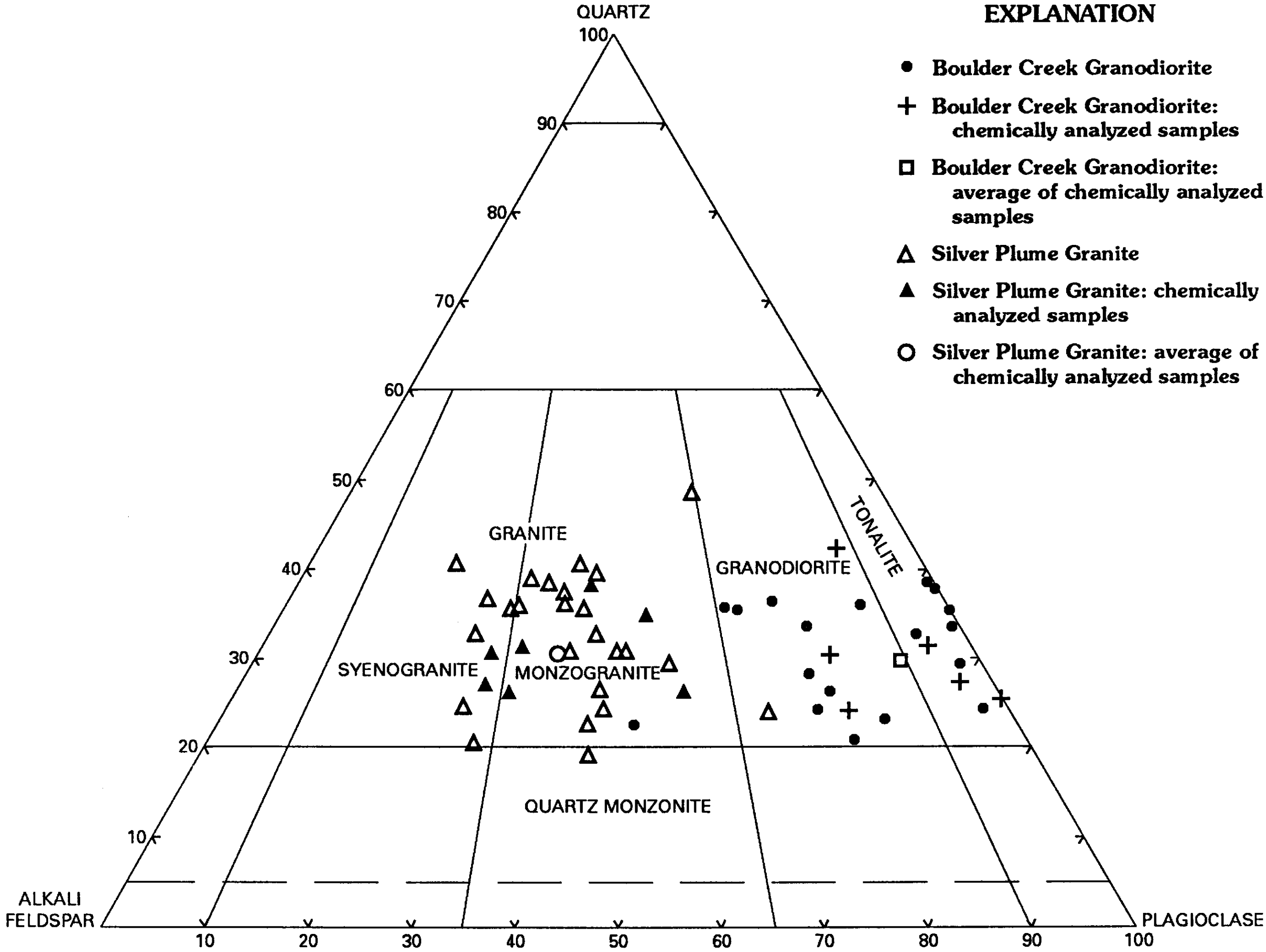


Figure 5. Quartz–alkali feldspar–plagioclase (QAP) diagram showing Boulder Creek Granodiorite and Silver Plume Granite.

grouping of the Boulder Creek Granodiorite (Peterman and others, 1968).

Quartz–alkali feldspar–plagioclase ratios are plotted on a QAP diagram in figure 5 for all modally analyzed rocks (32 samples) of the Silver Plume Granite. In the Streckeisen (1976) classification most of the rocks are monzogranites, a sizable number are syenogranites, one is a granodiorite, and one is a quartz monzonite. Potassium predominates over sodium; the average $K_2O:Na_2O$ ratio of seven samples is 1.9. Recent analyses of Silver Plume Granite by Anderson and Thomas (1985) also yield an average $K_2O:Na_2O$ ratio of 1.9 (10 samples). Another indication of how felsic the Silver Plume Granite is, in contrast to the Boulder Creek Granodiorite, is the fact that even the ranges of values for the two rock types do not overlap for color index, specific gravity, radioactivity, thorium, and $K_2O:Na_2O$ (table 17).

Granitic Enclaves in Silver Plume Granite

Granitic enclaves in the Silver Plume Granite are mappable only where exposure is very good because they are small and their megascopic appearance is similar (at first glance) to that of the Silver Plume Granite. Three sizable enclaves and two smaller ones occur in the same general area on the south shore of Lake Granby (pl. 1). The three largest bodies are about 75 m by 12 m, 45 m by 23 m, and 30 m by 8 m. The latter two are close to water's edge, and they are susceptible to seasonal flooding. The longest enclave, which is confined to a small ravine, is high enough above lake level for exposure preservation (pl. 1).

The rock that composes these enclaves is approximately twice as radioactive, more melanocratic,

Table 5. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of granitic enclaves in the Boulder Creek Granodiorite.

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, R. Bies, B. Keaten, S. Lasater, J. Storey, and S. Danahey. Rapid rock chemical analyses of sample SL–11 by V. Smith and J. Reid, and sample SL–20 by K. Coates. Chemical (X-ray spectrographic) analyses of sample SL–147 by A. Bartel; and sample SL–58 by J.S. Wahlberg, J. Taggart, and J. Baker. Semiquantitative spectrographic analyses of sample SL–58 by N.M. Conklin; samples SL–3, 11, and 20 by G. Kaczanowski; and sample SL–147 by L. Bradley. *, significant elements (2 × crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; <, less than; >, greater than]

	Size of enclave				
	Small: 1–5 m		Large: 0.5 km or more		
	Sample No.				
Composition	SL-11	SL-20	SL-58	SL-59	SL-147
Uranium and thorium analyses, in parts per million					
U	1.96	1.77	1.55	2.08	1.87
Th	86.2*	33.9*	55.1*	23.7	8.65
Th:U	44.0	19.2	35.5	11.4	4.63
Chemical analyses, in weight percent					
SiO_2	69.3	71.2	71.8	n.d.	63.8
Al_2O_3	14.7	13.4	15.4	n.d.	14.7
Fe_2O_3	2.0	1.9	[1]1.86	n.d.	[1]6.94
FeO	1.0	.96	n.d.	n.d.	n.d.
MgO	.64	.78	.68	n.d.	1.09
CaO	.98	1.1	2.19	n.d.	2.51
Na_2O	2.4	1.9	3.4	n.d.	3.20
K_2O	7.5*	7.4*	3.75	n.d.	4.41
H_2O^+	.42	.64	} [2].70	n.d.	[2].51
H_2O^-	.21	.32			
TiO_2	.55	.51	.28	n.d.	1.02
P_2O_5	.23	.09	<.1	n.d.	.50*
MnO	.02	.04	<.02	n.d.	.07
CO_2	.03	.02	n.d.	n.d.	n.d.
Total	100	100	100	n.d.	99
$K_2O:Na_2O$	3.13	3.90	1.10	n.d.	1.38
A:CNK[3]	1.16	1.05	1.02	n.d.	1.13
F[4]	17.1	17.0	16.7	n.d.	6.78
S[5]	2.37	2.59	2.63	n.d.	1.94
Spectrographic analyses, in parts per million					
B	<10	<10	<10	<10	<10
Ba	2400*	1500*	700	700	3000*
Be	1.1	1.1	<1	<1	1.5
Ce	420*	<100	150*	150*	300*
Co	5.3	6.0	3	3	7
Cr	<10	<10	7	15	5
Cu	7	12	1	2	10
Ga	20	14	15	15	30
La	230*	67*	150*	100*	150*
Nb	<25	<25	<10	<10	15
Nd	n.d.	n.d.	70	70	150*
Ni	5.3	8.4	3	3	<10
Pb	38*	38*	30	30	30
Sc	<10	<10	7	7	15
Sr	270	240	700*	700*	1000*
V	42	33	15	30	70
Y	15	12	10	15	50
Yb	n.d.	n.d.	1	7	3
Zn	57	<50	<300	<300	<300
Zr	340*	380*	150	150	200
La:Ni	43	8.0	50	33	>15

Table 5. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of granitic enclaves in the Boulder Creek Granodiorite—Continued

	Size of enclave				
	Small: 1-5 m		Large: 0.5 km or more		
	Sample No.				
Composition	SL-11	SL-20	SL-58	SL-59	SL-147
	Modal analyses, in volume percent				
Quartz	23.2	27.9	32.9	28.5	22.6
Microcline	54.3	41.8	30.5	13.3	27.8
Plagioclase[6]	11.6	17.6	29.1	50.7	35.3
Anorthite	14	05	12	15	24
Biotite	8.5	8.4	3.4	5.0	8.4
Muscovite	.5	—	2.7	2.1	—
Sericite	—	.2	tr	.1	2.5
Chlorite	—	.5	.3	.3	tr
Magnetite	1.0	2.1	—	—	1.9
Hematite	—	—	.9	—	—
Apatite	.7*	.3*	tr*	tr*	1.4*
Monazite	—	—	tr	tr	—
Sphene	—	.8	tr	—	.1
Zircon	.2	.3	tr	—	tr
Epidote	—	tr	.2	—	—
Allanite	—	.1	—	—	—
Total	100	100	100	100	100
Points counted	801	1803	584	701	806
Color index[7]	9.7	12.2	4.8	5.4	10.4
Average grain size, in millimeters.	<1	<1	1.5	2.5	<1
Magnetic, m, or nonmagnetic, nm[8].	m	m	nm	nm	m
Radioactivity[9], in counts per second.	490	525	220	200	150
Specific gravity[10]	2.650	2.630	2.677	2.689	2.758
Rock name (Streckeisen, 1976).	granite (syenogranite).	granite (syenogranite).	granite (monzogranite).	granodiorite	granite (monzogranite).

[1]Total iron reported as Fe_2O_3.

[2]LOI at 900 °C.

[3]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[4]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[5]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[6]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[8]m, rock reacts postively to a large hand magnet; nm, no reaction.

[9]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[10]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 6. Modal analyses and descriptive parameters of granitic enclaves in the Boulder Creek Granodiorite

[*, diagnostic accessory minerals. tr, trace; —, not found; <, less than]

Composition	Size of enclave: Small: 1-5 m				Large: 100-400 m		
	Sample No.						
	SL-95	SL-109B	SL-111B	SL-85	SL-99	SL-115	SL-116
	Modal analyses, in volume percent						
Quartz	31.8	33.0	35.5	33.0	25.3	24.3	25.2
Microcline	41.8	32.6	36.2	55.8	45.4	48.8	44.2
Plagioclase[1]	19.5	21.6	18.8	7.4	20.2	15.1	18.9
Anorthite	28	20	26	13	13	27	25
Biotite	5.0	5.7	6.4	1.6	5.1	7.1	4.6
Muscovite	—	6.1	tr	2.1	2.0	2.1	4.1
Chlorite	0.5	tr	0.7	—	tr	0.1	0.8
Magnetite	0.5	1.0	1.2	—	1.0	1.8	1.0
Hematite	—	—	—	—	—	—	—
Apatite	tr*	tr*	0.5*	0.1*	0.5*	0.3*	0.5*
Monazite	—	tr	—	tr	—	tr	—
Sphene	0.2	—	tr	—	0.5	—	—
Zircon	tr*	tr*	tr*	—	tr	0.4	0.1
Epidote	0.7	tr	0.7	—	—	—	0.3
Allanite	—	tr	—	—	tr	—	0.3
Total	100	100	100	100	100	100	100
Points counted	559	592	563	578	605	708	608
Color index[2]	6.9	6.7	9.0	1.6	6.6	9.4	7.4
Average grain size, in millimeters	1	<1	1.5	1	1	<1	<1
Magnetic, m, or nonmagnetic, nm[3].	m	m	m	nm	m	m	m
Radioactivity[4], in counts per second.	180	480	365	165	270	470	400
Specific gravity[5]	2.666	2.666	2.665	2.625	2.670	2.674	2.675
Rock name (Streckeisen, 1976).	granite (syenogranite).	granite (monzogranite).	granite (syenogranite).	granite (syenogranite).	granite (syenogranite).	granite (syenogranite).	granite (syenogranite).

[1]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[2]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[3]m, rock reacts postively to a large hand magnet; nm, no reaction.

[4]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[5]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

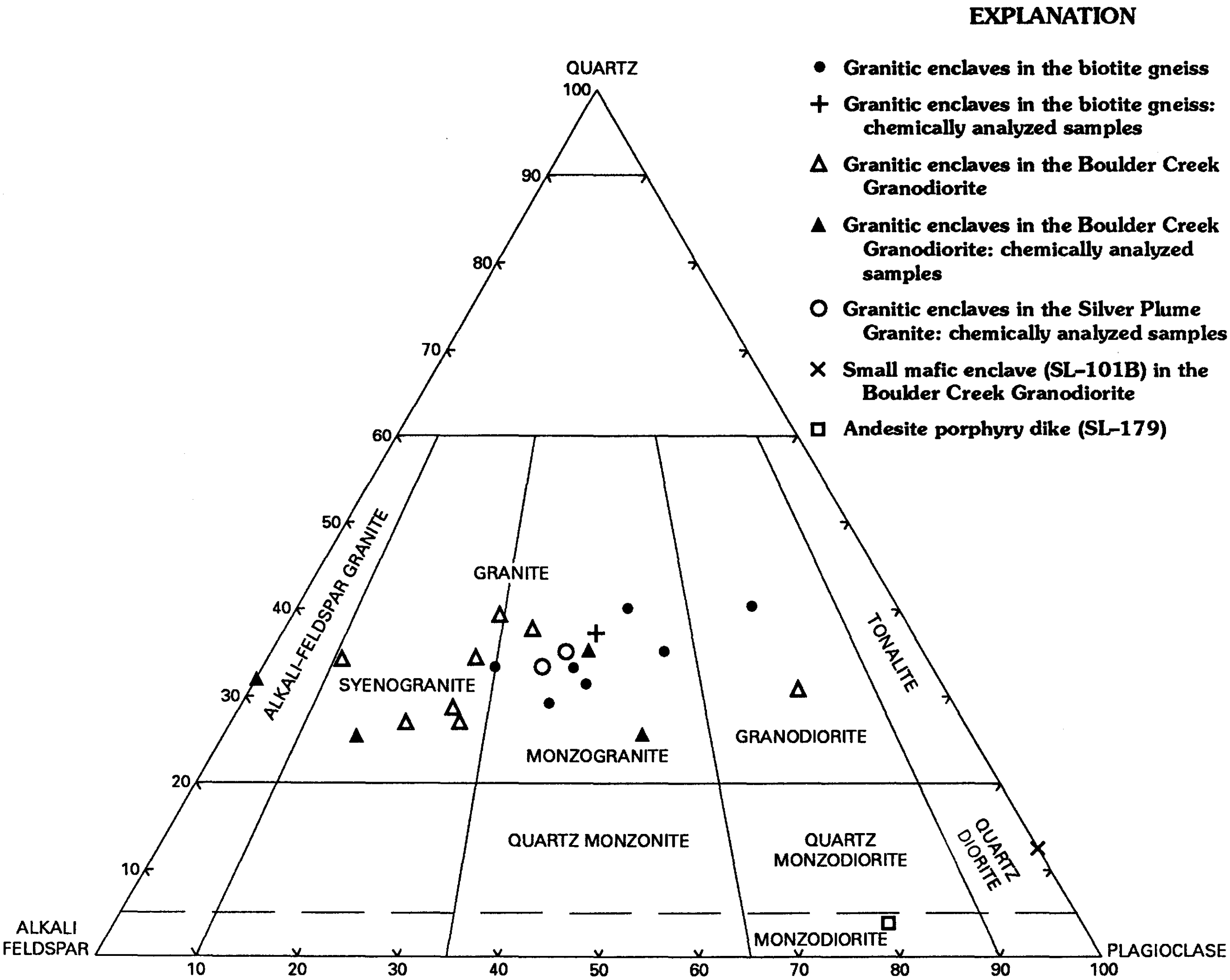


Figure 6. Quartz–alkali feldspar–plagioclase (QAP) diagram showing granitic enclaves and mafic rocks.

and slightly finer grained than the Silver Plume Granite, and it shows a subtle crystalloblastic texture (fig. 11). Contact relations between the granitic enclaves and the Silver Plume Granite are generally sharp, but there is no semblance of a chilled border in the enclaves.

Quartz, microcline (locally perthitic), oligoclase (locally antiperthitic), biotite, and muscovite are essential minerals. Chlorite is secondary after biotite, and magnetite, monazite, apatite, zircon, and sillimanite (occurring as elongate prisms) are common accessory minerals (table 10). Monazite is definitely more abundant than zircon or apatite. Monazite occurs as small inclusions in all the essential minerals; the largest monazite grain is 0.09 by 0.06 mm. Dark, intense radiation-damage halos in biotite that were produced by monazite are invariably 0.03 mm thick. Halos that were produced by zircon are less intense and no more than 0.01 mm thick.

The granitic enclaves are plotted on a QAP diagram in figure 6, where they appear as monzogranites. In contrast to the host Silver Plume Granite, the granitic enclaves are more peraluminous (tables 10 and 17), show higher K_2O:Na_2O ratios, higher color indices and specific gravities (primarily due to more biotite), and contain one and one-half times as much radioactivity and twice as much thorium.

Biotite Gneiss

The biotite-gneiss unit is predominantly a fine- to medium-grained biotite gneiss (tables 11 and 12) but includes minor granite gneiss, amphibolite, quartzite, pegmatite, and cordierite-garnet-sillimanite-biotite gneiss and schist. The biotite-gneiss unit is host to fine-grained granitic enclaves of variable size as described below.

Table 7. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of the Silver Plume Granite

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, M. Schneider, W. Stang, R. Bies, B. Keaton, S. Lasater, J. Storey, and S. Danahey. Rapid rock chemical analyses of samples SM–3 and SL–34 by K. Coates, and sample SL–40 by N. Skinner and D. Kobilis. Chemical (X-ray spectrographic) analyses of samples SM–4 and 43A by A.J. Bartel; and samples SL–64 and 65 by J.S. Wahlberg, J. Taggart, and J. Baker. Semiquantitative spectrographic analyses of samples SM–3 and SL–34 by G. Kaczanowski; sample SM–4 by L. Bradley; sample SL–40 by T. Fries; and sample SM–43A and SL–64 and 65 by N.M. Conklin. *, significant elements (2 × crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; <, less than]

Composition	Sample No. SM-3	SM-4	SM-43A	SL-34	SL-40	SL-64	SL-65
			Uranium and thorium analyses, in parts per million				
U	8.79*	3.65	6.8*	6.77*	7.44*	6.57*	8.27*
Th	37.0*	30.0*	41.0*	48.0*	27.1*	38.2*	52.8*
Th:U	4.2	8.5	6.0	7.1	3.6	5.8	6.4
			Chemical analyses, in weight percent				
SiO_2	72.8	71.0	71.0	71.4	72.0	73.0	71.8
Al_2O_3	14.5	14.7	14.8	14.5	14.3	14.7	14.7
Fe_2O_3	1.2	[1]2.36	[1]1.82	1.4	0.83	[1]1.38	[1]1.37
FeO	0.68	n.d.	n.d.	1.0	.68	n.d.	n.d.
MgO	.36	0.67	0.48	0.65	.34	0.40	0.40
CaO	1.0	.99	1.27	1.80	.96	.92	1.05
Na_2O	3.0	2.74	2.82	2.80	3.30	2.80	3.1
K_2O	6.0*	5.49	5.63	6.00*	5.00	5.66	5.49
H_2O^+	.59	} [2].94	[2].76	.51	.53	} [2].71	[2].58
H_2O^-	.24			.26	.23		
TiO_2	.27	.32	.28	.33	.17	.19	.23
P_2O_5	.13	.15	.14	.18	.14	<.10	.10
MnO	.02	<.02	<.02	.04	.04	<.02	<.02
CO_2	.03	n.d.	n.d.	.01	.01	n.d.	n.d.
Total	101	99	99	101	99	100	99
$K_2O:Na_2O$	2.0	2.0	2.0	2.1	1.5	2.0	1.8
A:CNK[3]	1.09	1.20	1.13	1.01	1.14	1.19	1.13
F[4]	25.2	19.7	22.3	16.5	28.6	30.2	24.2
S[5]	2.72	2.63	2.65	2.54	2.83	2.82	2.75
			Spectrographic analyses, in parts per million				
B	<10	<10	<20	<10	<10	<10	<10
Ba	850	500	700	610	430	300	500
Be	1.6	<1.5	<1	1.3	1.7	<1.0	<1
Ce	<100	<100	150*	170*	<100	150*	200*
Co	2.4	<5	<3	1.5	1.4	<3	<3
Cr	<10	5	3	<10	<10	1.5	7
Cu	6.2	15	30	23	12	7	30
Ga	17	30	30	20	21	15	15
La	54	70*	70*	100*	31	70*	150*
Nb	<25	10	15	<25	<25	<10	<10
Nd	n.d.	150*	n.d.	n.d.	n.d.	70	150*
Ni	4.9	<5	<3	4.4	2.7	<2	2
Pb	53*	50*	30	36*	21	30	30
Sc	<10	<10	5	<10	<10	<10	<10
Sr	200	200	200	120	81	150	150
V	17	30	30	21	11	15	30
Y	13	<10	10	18	<10	10	15
Yb	n.d.	<1	n.d.	n.d.	n.d.	1	1
Zn	<50	<300	<300	61	<50	<50	<50
Zr	160	70	150	120	62	70	150
La:Ni	11	>14	>23	23	12	>35	75

Table 7. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of the Silver Plume Granite—Continued

Composition	SM-3	SM-4	SM-43A	SL-34	SL-40	SL-64	SL-65
				Sample No.			
				Modal analyses, in volume percent			
Quartz	23.6	28.6	28.1	23.5	35.1	32.3	24.7
Microcline	43.1	39.0	43.2	43.0	31.3	28.1	28.3
Plagioclase[6]	20.7	22.8	20.7	23.5	26.5	33.3	40.0
Anorthite	12	15	15	25	12	13	15
Biotite	7.1	.9	3.3	4.5	2.8	4.1	4.9
Muscovite	3.6	3.7	3.5	3.1	3.2	1.3	1.3
Chlorite	—	3.1	.6	.8	.3	—	tr
Magnetite	—	.9	.1	.9	—	—	—
Hematite	1.5	—	—	—	tr	.1	.6
Apatite	.2	.6	.4	.3	tr	—	.1
Monazite*	.2	tr	tr	.4	tr	tr	tr
Zircon*	tr	tr	tr	tr	tr	tr	tr
Sphene	—	.3	—	—	—	—	—
Epidote	—	tr	—	—	—	—	—
Sillimanite	—	—	—	tr	.8	.8	.1
Allanite	—	—	—	—	—	tr	—
Fluorite	—	tr	—	—	—	—	—
Pyrite	—	tr	—	—	—	—	—
Calcite	—	.1	.1	—	—	—	—
Total	100	100	100	100	100	100	100
Points counted	813	703	691	800	713	716	750
Color index[7]	8.8	5.2	4.0	6.6	3.1	4.2	5.5
Average grain size, in millimeters.	1.5	3.0	2.5	2.5	1.5	2.5	3.5
Magnetic, m, or nonmagnetic, nm[8].	nm	m	m	m	nm	nm	nm
Radioactivity,[9] in counts per second.	350	460	335	450	390	320	360
Specific gravity[10]	2.630	2.668	2.662	2.660	2.643	2.647	2.664
Rock name (Streckeisen, 1976).	granite (syeno-granite).	granite (monzo-granite).	granite (syeno-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).

[1]Total iron reported as Fe_2O_3.

[2]LOI at 900 °C.

[3]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[4]F = $\frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[5]S = $\frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[6]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[8]m, rock reacts postively to a large hand magnet; nm, no reaction.

[9]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[10]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 8. Uranium, thorium, spectrographic, and modal analyses and descriptive parameters of the Silver Plume Granite

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, M. Schneider, W. Stang, R. Bies, B. Keaten, and S. Lasater. Semiquantitative spectrographic analyses of samples ML–1, 2, and 4, and samples SL–29, 30, and 31 by G. Kaczanowski; samples SL–37, 39, 41, 42, 44, 45, 46, 47, 48, and 49 by T. Fries; and samples SL–62 and 63 by N.M. Conklin. *, significant trace elements (2 × crustal abundance, or more), and diagnostic accessory minerals, tr, trace; —, not found; n.d., not determined; n.a., not applicable; <, less than]

Composition	Sample No.																	
	ML-1	ML-2	ML-4	SL-29	SL-30	SL-31	SL-37	SL-39	SL-41	SL-42	SL-44	SL-45	SL-46	SL-47	SL-48	SL-49	SL-62	SL-63
Uranium and thorium analyses, in parts per million																		
U	2.23	2.78	5.80*	3.33	5.00*	4.42	4.39	6.08*	5.59*	9.03*	3.36	5.83*	3.04	5.42*	5.91*	7.35*	5.60*	5.76*
Th	71.5*	71.2*	45.2*	70.7*	33.8*	38.7*	21.6	33.6*	31.9*	61.7*	41.1*	60.0*	32.8*	64.0*	50.1*	71.2*	31.9*	26.4*
Th:U	32.1	25.3	7.8	21.2	6.8	8.8	4.9	5.5	5.8	6.8	12.2	10.3	10.8	11.8	8.5	9.7	5.7	4.6
Spectrographic analyses, in parts per million																		
B	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ba	1300*	1500*	700	720	470	590	470	620	580	720	890	1000	1200	830	810	730	500	300
Be	1.2	1.4	2.4	<1	2.1	2	3.6	2.9	1.8	1.8	1.6	2.2	1.9	1.6	1.4	<1	<1	<1
Ce	200*	280*	200*	270*	<100	140*	140*	150*	150*	190*	140*	190*	130	230*	200*	280*	100	200*
Co	3.4	3.9	3.0	4.7	1.1	2.8	2.3	2.3	2.2	4.1	2.6	6.0	4.9	3.1	3.1	4.6	<3	<3
Cr	11	11	<10	<10	<10	<10	<10	<10	<10	<10	11	<15	13	<10	<10	11	3	1
Cu	24	19	14	22	5.8	18	11	25	6.6	51	17	9.9	5.1	24	19	9.6	7	15
Ga	21	22	26	20	20	23	23	24	18	22	20	24	20	16	22	19	15	15
La	85*	170*	120*	150*	45	80*	60*	75*	69*	100*	72*	130*	58*	140*	120*	160*	70*	150*
Mn	<200	<200	230	290	<200	260	230	<200	<200	<230	<200	270	250	<200	210	<200	100	70
Nb	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<10	<10
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	70	150*
Ni	7.6	7.0	5.5	8.5	2.5	3.7	3.2	3.5	3.0	5.1	4.8	7.7	6.6	4.1	4.0	5.9	2	<2
P	900	1000	900	900	1100	900	1600	1500	1000	2100*	1400	1600	1400	1100	1500	900	<2000	<2000
Pb	31	61*	46*	46*	34*	35*	23	26	20	49*	52*	25	25	41*	31	32*	30	30
Sc	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<7	<7
Sr	160	210	130	180	82	120	100	120	140	120	170	180	210	160	160	150	150	150
Ti	2200	2300	1300	2100	1200	1700	1200	1400	1000	1900	1800	3000	2100	2400	1900	2100	1500	700
V	39	41	38	23	<10	23	14	19	16	30	21	48	37	27	26	32	15	15
Y	16	21	14	33	12	21	16	13	12	21	11	12	16	15	15	24	10	15
Yb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1	1
Zn	68	89	57	<50	<50	<50	<50	<50	<50	84	61	86	50	<54	66	63	<300	<300
Zr	150	130	170	230	64	91	33	96	98	210	170	280	170	130	110	160	100	70
La:Ni	11	24	22	18	18	22	19	21	23	20	15	17	9	34	30	27	35	>75

Composition	Sample No. ML-1	ML-2	ML-4	SL-29	SL-30	SL-31	SL-37	SL-39	SL-41	SL-42	SL-44	SL-45	SL-46	SL-47	SL-48	SL-49	SL-62	SL-63
Modal analyses, in volume percent																		
Quartz................	23.7	31.7	46.6	33.7	29.6	26.2	35.7	29.1	33.3	19.8	34.0	21.0	17.2	22.4	18.6		22.4	
Microcline...........	35.1	38.0	17.7	41.1	42.8	26.7	34.8	31.3	33.1	37.0	33.4	20.5	38.8	47.8	48.3	No	36.2	No
Plagioclase[1].........	31.8	19.7	32.5	17.7	18.1	35.7	22.9	28.0	27.0	31.6	24.3	46.1	34.0	20.4	23.0		33.7	
Anorthite..........	15	15	15	12	14	15	13	23	25	18	20	17	15	15	17		12	
Biotite..............	3.8	4.1	.2	2.7	2.8	.9	3.2	4.1	4.2	4.0	3.7	10.0	.8	4.1	4.6		2.9	
Muscovite............	4.7	4.1	1.7	2.3	6.2	6.3	3.4	6.6	1.1	4.4	1.1	1.3	1.8	3.9	2.5	thin	3.8	thin
Chlorite.............	tr	1.5	.6	1.0	—	3.4	—	—	—	.5	—	.2	6.3	—	1.2		—	
Magnetite............	—	.3	—	—	—	—	—	—	—	—	—	—	1.1	—	—		—	
Hematite.............	.7	—	.6	1.4	.5	.3	tr	.1	[1].8	[1]2.3	[1]3.4	.6	—	1.2	1.2		.6	
Apatite..............	tr	.3	tr	—	—	.5	tr	.1	—	tr	.1	.3	tr	tr	tr	section	.3	section
Monazite*............	tr	.2	tr	.1	tr	tr	tr	tr	tr	.2	tr	tr	tr	.2	tr		tr	
Zircon*..............	tr	tr	.1	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr		tr	
Epidote..............	.2	.1	—	—	—	—	—	—	—	—	—	—	—	—	—	available	—	available
Sillimanite..........	tr	tr	tr	—	—	—	tr	.7	.5	.2	tr	—	—	—	.6		.1	
Allanite.............	—	—	tr	—	—	—	—	—	—	—	—	—	tr	—	—		—	
Calcite..............	—	tr	—	—	—	—	—	—	—	—	—	—	—	—	—		—	
Total..............	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100		100	
Points counted.....	553	604	661	824	794	587	682	740	644	1210	618	629	652	608	679		662	
Color index[3]..........	4.7	6.2	1.5	5.2	3.2	4.6	3.2	4.2	5.0	7.0	7.1	10.8	8.2	5.5	7.0	n.a.	3.5	n.a.
Average grain size,... in millimeters.	1.5	1.5	5	<1	1.5	3	1.5	3	2.5	3	2	1.5	1.5	2	2.5	2	3	3
Magnetic, m, or...... nonmagnetic, nm[4].	nm	m	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	m	nm	nm	nm	nm	nm
Radioactivity[5], in.... counts per second.	420	410	280	240	300	330	255	350	390	505	380	390	360	350	430	300	330	305
Specific gravity[6].....	2.660	2.650	2.630	2.640	2.630	2.670	—	2.655	2.651	2.659	2.655	2.683	2.641	2.679	2.664	—	2.660	—
Rock name (Streckeisen, 1976).	granite (monzo-granite).	granite (syeno-granite).	granite (monzo-granite).	granite (syeno-granite).	granite (syeno-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	grano-diorite	quartz monzo-nite.	granite (syeno-granite).	granite (syeno-granite).	n.a.	granite (monzo-granite).	n.a.

[1]About one-half of the opaque mineral is secondary in grain interstices.

[2]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[3]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[4]m, rock reacts postively to a large hand magnet; nm, no reaction.

[5]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[6]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 9. Modal analyses and descriptive parameters of the Silver Plume Granite

[*, diagnostic accessory minerals. tr, trace; —, not found]

Composition	Sample No. SL-75	SL-81	SL-91	SL-92	SM-35	SM-52	SM-55	SM-72	SM-73
					Modal analyses, in volume percent				
Quartz	36.1	29.8	36.7	36.0	27.3	28.4	34.0	33.7	32.2
Microcline	30.1	37.8	40.9	36.2	30.7	30.6	39.6	27.6	33.1
Plagioclase[1]	23.5	29.0	12.7	20.7	30.4	32.7	21.8	24.6	24.2
Anorthite	18	17	25	15	15	15	13	12	13
Biotite	3.2	2.2	8.6	4.7	5.2	6.1	1.8	2.0	4.8
Muscovite	5.7	.9	.3	1.9	2.4	1.2	2.7	11.2	3.8
Chlorite	.5	—	—	.5	2.0	—	—	—	.6
Magnetite	.5	—	—	—	1.5	.6	—	—	.3
Hematite	—	.3	.3	—	—	—	.1	.1	—
Apatite	.2	tr	tr	—	.4	.4	tr	.1	.1
Monazite*	tr	tr	.5	tr	tr	tr	tr	tr	.1
Zircon*	tr	tr	—	tr	tr	tr	tr	tr	.1
Epidote	—	—	—	—	—	—	—	—	—
Sillimanite	.2	—	—	tr	—	—	—	.7	.7
Allanite	—	—	—	tr	tr	—	—	—	—
Pyrite	—	—	—	—	tr	—	—	—	—
Calcite	—	—	—	—	—	—	—	—	—
Total	100	100	100	100	100	100	100	100	100
Points counted	631	1273	640	580	735	668	670	802	715
Color index[2]	4.2	2.5	9.4	5.2	8.8	6.7	1.9	2.1	5.9
Average grain size, in millimeters.	2.5	3	3	1	2	1.5	2	2.5	2.5
Magnetic, m, or nonmagnetic, nm[3].	m	nm	nm	nm	m	m	nm	nm	m
Radioactivity,[4] in counts per second.	450	400	370	260	—	280	380	290	300
Specific gravity[5]	2.660	2.642	2.635	2.643	2.668	2.668	2.652	2.654	2.662
Rock name (Streckeisen, 1976).	granite (monzogranite).	granite (monzogranite).	granite (syenogranite).	granite (monzogranite).	granite (monzogranite).	granite (monzogranite).	granite (monzogranite).	granite (monzogranite).	granite (monzogranite).

[1]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[2]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[3]m, rock reacts postively to a large hand magnet; nm, no reaction.

[4]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[5]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

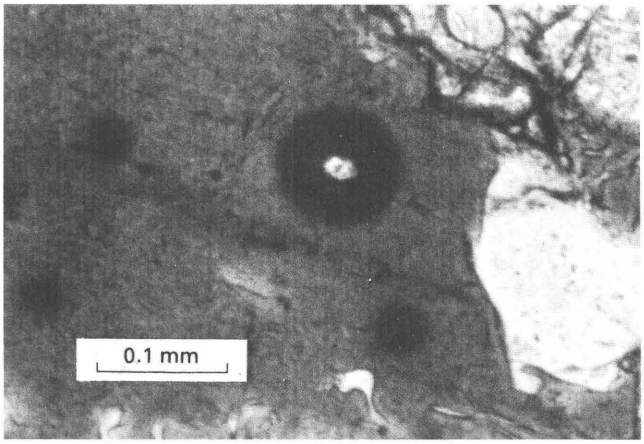


Figure 7. Monazite in biotite shows intense, dark, radiation-damage halo. Although thin section is from biotite gneiss, similar monazite and halos are common in biotite of the Silver Plume Granite. Note garnet in upper right, quartz in lower right, vermicular quartz in biotite at bottom, and three small radiation-damage halos interpreted to be the result of thin section cutting above or below a monazite grain, thereby slicing through the halo only. Plane-polarized light.

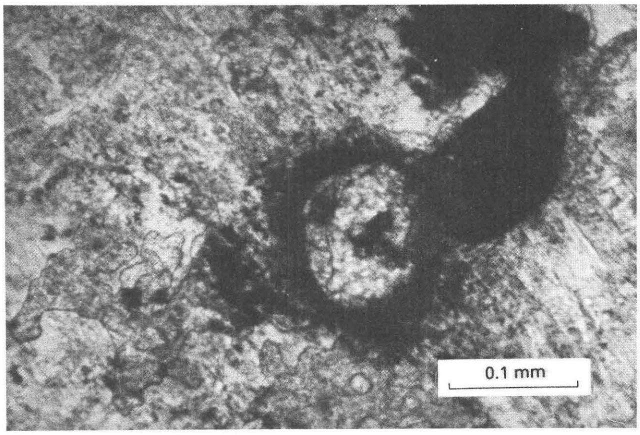


Figure 8. Monazite in plagioclase with typical alteration ring of opaque material. Dark grain to right of monazite is radiation-darkened biotite. Plane-polarized light.

Grain size of the biotite gneiss is variable, from less than 1 mm to 10 mm, but much, if not most, of the unit is fine grained. Foliation is ubiquitous, and the rock becomes schistose as biotite and muscovite increase. Essential minerals are quartz and biotite (locally altered to chlorite). Muscovite (both primary and secondary), microcline, and plagioclase (oligoclase, andesine, and rarely labradorite) are generally present; locally the plagioclase is antiperthitic. Hornblende, garnet, sillimanite, and cordierite occur locally. Commonly, garnet has biotite inclusions, and brown biotite fills fractures in garnet. Cordierite has poikilitic inclusions of sillimanite

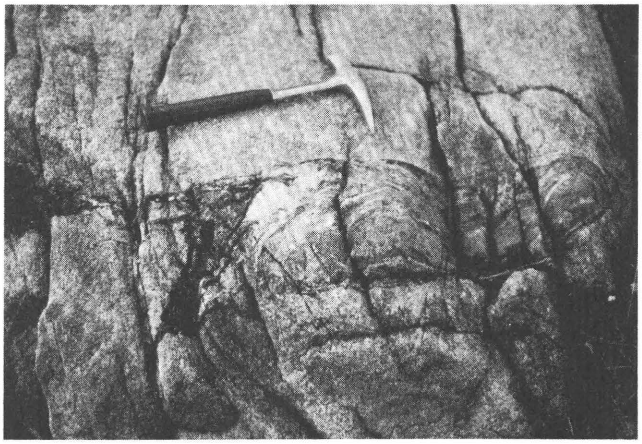


Figure 9. Small enclave of biotite gneiss in Silver Plume Granite. Rock hammer is 33 centimeters long.

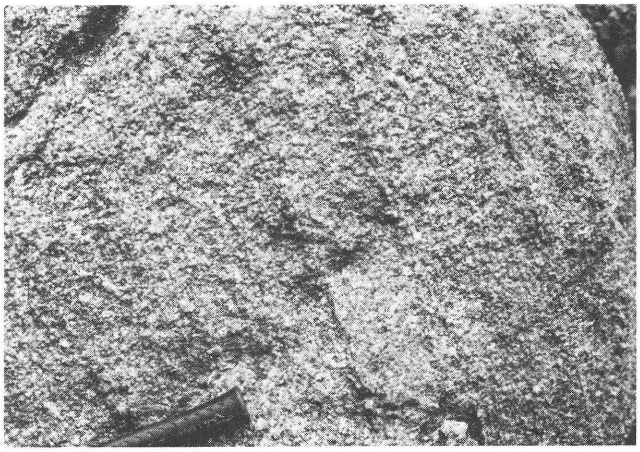


Figure 10. Thin, parallel biotite schlieren shown here are probably relicts of biotite gneiss in Silver Plume Granite. Hammer handle is 3 centimeters in diameter.

Figure 11. Crystalloblastic texture of granitic enclave in Silver Plume Granite. Coin is 19 millimeters in diameter.

Table 10. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of granitic enclaves in the Silver Plume Granite

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, R. Bies, B. Keaten, S. Lasater, J. Storey, and S. Danahey. Chemical (X-ray spectrographic) analyses of samples SM–43B and SM–48 by A. Bartel. Semiquantiative spectrographic analyses of samples SM–43B and SM–48 by N.M. Conklin. *, significant elements (2× crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; <, less than]

	Size of enclave	
	Small: <100 m	
	Sample No.	
Composition	SM–43B	SM–48
Uranium and thorium analyses, in parts per million		
U	3.4	5.0*
Th	75.9*	123.0*
Th:U	22.3	24.6
Chemical analyses, in weight percent		
SiO_2	70.2	70.7
Al_2O_3	14.6	14.4
Fe_2O_3	[1]3.24	[1]2.84
FeO	n.d.	n.d.
MgO	.86	.69
CaO	1.14	.85
Na_2O	2.33	2.23
K_2O	5.33	5.83
H_2O^+ / H_2O^-	[2].91	[2].79
TiO_2	.44	.41
P_2O_5	.12	.16
MnO	<.02	<.02
CO_2	n.d.	n.d.
Total	99	99
$K_2O:Na_2O$	2.29	2.61
A:CNK[3]	1.25	1.25
F[4]	14.9	18.0
S[5]	2.55	2.63
Spectrographic analyses, in parts per million		
B	<20	<20
Ba	1000	700
Be	<1	<1
Ce	200*	300*
Co	<3	7
Cr	15	15
Cu	30	7
Ga	30	30
La	150*	150*
Nb	10	10
Nd	150*	150*
Ni	7	7
Pb	30	30
Sc	7	5
Sr	300	150
V	30	30
Y	15	15
Yb	1.5	1.5
Zn	<300	<300
Zr	150	150
La:Ni	21	21

	Size of enclave	
	Small: <100 m	
	Sample No.	
Composition	SM–43B	SM–48
Modal analyses, in volume percent		
Quartz	29.9	29.7
Microcline	29.8	34.3
Plagioclase[6]	25.2	24.2
Anorthite	27	27
Biotite	9.6	5.9
Muscovite	3.0	4.3
Sericite	—	—
Chlorite	1.0	.1
Magnetite	1.1	.9
Apatite	tr*	tr*
Monazite	.1*	.1*
Sphene	—	—
Zircon	tr*	tr*
Epidote	—	—
Allanite	—	—
Sillimanite	.3	.5
Total	100	100
Points counted	1769	1036
Color index[7]	11.8	7.0
Average grain size, in millimeters.	1.5	1.5
Magnetic, m, or nonmagnetic, nm[8].	m	m
Radioactivity[9], in counts per second.	500	550
Specific gravity[10]	2.673	2.675
Rock name (Streckeisen, 1976).	granite (monzo-granite).	granite (monzo-granite).

[1]Total iron reported as Fe_2O_3.

[2]Loss on ignition at 900 °C.

[3]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[4]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight perecent).

[5]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[6]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[8]m, rock reacts postively to a large hand magnet; nm, no reaction.

[9]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[10]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 11. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of the biotite gneiss

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., B.A. Keaten, F.M. Luman, J. Storey, S. Danahey, B. Vaughn, and M. Coughlin. Chemical (X-ray spectrographic) analysis of sample SM–152 by A. Bartel, and samples SL–69 and 71 by J.S. Wahlberg, J. Taggart, and J. Baker. Semiquantitative spectrographic analyses of samples SL–69 and 71 by H.M. Conklin, and sample SM–152 by L. Bradley. *, significant elements (2× crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; n.a., not applicable; <, less than]

Composition	Sample No. SL-69	SL-71	SM-152
Uranium and thorium analyses, in parts per million			
U	2.02	2.69	5.33*
Th	24.7	23.4	22.2
Th:U	12.2	8.7	4.2
Chemical analyses, in weight percent			
SiO_2	52.4	66.5	62.0
Al_2O_3	26.5	17.0	21.5
Fe_2O_3	[1]12.4	[1]7.15	[1]8.89
FeO	n.d.	n.d.	n.d.
MgO	2.6	2.6	2.23
CaO	.27	.82	.38
Na_2O	.6	1.0	.58
K_2O	3.84	2.47	2.59
H_2O^+ / H_2O^+	[2].94	[2]1.20	[2].45
TiO_2	1.07	.76	1.09
P_2O_5	<.1	<.1	.08
MnO	.1	.08	.11
CO_2	n.d.	n.d.	n.d.
Total	101	100	100
K_2O:Na_2O	6.40	2.47	4.47
A:CNK[3]	4.64	2.95	4.81
F[4]	3.72	6.62	5.67
S[5]	1.13	2.14	1.71
Spectrographic analyses, in parts per million			
B	<10	<10	<10
Ba	700	500	300
Be	1	<1	<1
Ce	100	100	<100
Co	30	15	20
Cr	150	70	100
Cu	3	70	10
Ga	30	15	30
La	70*	70*	50
Nb	<10	10	10
Nd	70	70	70
Ni	70	20	30
Pb	15	10	15
Sc	30*	15	20*
Sr	150	150	50
V	70	70	150
Y	50	70*	15
Yb	7*	7*	n.d.
Zn	<300	<300	<300
Zr	150	300	150
La:Ni	1.0	3.5	1.7

Composition	Sample No. SL-69	SL-71	SM-152
Modal analyses, in volume percent			
Quartz	12.0	31.1	
Microcline	7.5	4.4	
Plagioclase[6]	—	16.5	No
Anorthite	—	35	
Biotite	21.5	16.5	
Chlorite	2.5	1.8	
Garnet	42.1	6.2	thin
Cordierite	6.8	12.8	
Sillimanite	6.2	10.1	
Hematite	1.3	.6	
Apatite	—	—	section
Sphene	—	—	
Monazite	.1*	tr*	
Zircon	tr	tr	
Epidote	.1	—	available
Allanite	—	—	
Total	100	100	
Points Counted	601	662	
Color index[7]	67.4	25.1	n.a.
Average grain size, in millimeters.	3	2.5	2
Magnetic, m, or nonmagnetic, nm[8].	nm	nm	m
Radioactivity[9], in counts per second.	210	155	—
Specific gravity[10]	2.920	2.872	—
Rock name (Streckeisen, 1976).	n.a.	n.a.	n.a.

[1]Total iron reported as Fe_2O_3.

[2]Loss on ignition at 900 °C.

[3]$\text{A:CNK} = \text{alumina saturation} = \frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[4]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[5]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[6]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[8]m, rock reacts postively to a large hand magnet; nm, no reaction.

[9]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[10]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 12. Uranium, thorium, spectrographic, and modal analyses and descriptive parameters of the biotite gneiss

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, M. Schneider, and W. Stang. Semiquantitative spectrographic analyses of sample SL–1 by L. Castillo, and sample SL–36 by T. Fries. *, significant elements (2× crustal abundance, or more) and diagnostic accessory minerals. tr, trace; —, not found; n.d., not determined; n.a., not applicable; <, less than]

Composition	Sample No. SL-1	SL-36	SL-76	SL-79	SL-80	SL-89
Uranium and thorium in parts per million						
U	3.04	2.65	n.d.	n.d.	n.d.	n.d.
Th	12.6	7.6	n.d.	n.d.	n.d.	n.d.
Th:U	3.7	2.9	n.d.	n.d.	n.d.	n.d.
Spectrographic analyses, in parts per million						
B	15	15	n.d.	n.d.	n.d.	n.d.
Ba	890	1300	n.d.	n.d.	n.d.	n.d.
Be	3	3.1	n.d.	n.d.	n.d.	n.d.
Ce	<100	<100	n.d.	n.d.	n.d.	n.d.
Co	16	9.9	n.d.	n.d.	n.d.	n.d.
Cr	84	<10	n.d.	n.d.	n.d.	n.d.
Cu	8.9	4.5	n.d.	n.d.	n.d.	n.d.
Ga	24	22	n.d.	n.d.	n.d.	n.d.
La	54	39	n.d.	n.d.	n.d.	n.d.
Li	170*	<50	n.d	n.d.	n.d.	n.d.
Mn	600	1200	n.d.	n.d.	n.d.	n.d.
Nb	<25	<25	n.d.	n.d.	n.d.	n.d.
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	34	6.5	n.d.	n.d.	n.d.	n.d.
P	600	2000*	n.d	n.d.	n.d.	n.d.
Pb	<10	<10	n.d.	n.d.	n.d.	n.d.
Sc	17	21	n.d.	n.d.	n.d.	n.d.
Sr	130	180	n.d.	n.d.	n.d.	n.d.
Ti	5200	4100	n.d.	n.d.	n.d.	n.d.
V	92	52	n.d.	n.d.	n.d.	n.d.
Y	43	59*	n.d.	n.d.	n.d.	n.d.
Yb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	91	90	n.d.	n.d.	n.d.	n.d.
Zr	190	240	n.d.	n.d.	n.d.	n.d.
La:Ni	1.6	6.0	n.d.	n.d.	n.d.	n.d.
Modal analyses, in volume percent						
Quartz	51.9	41.6	58.8	47.3	33.3	25.5
Microcline	—	.6	4.2	.3	13.2	4.5
Plagioclase[1]	13.3	23.2	24.6	32.2	36.9	20.0
Anorthite	28	68	15	17	28	28
Biotite	16.4	27.8	9.9	18.9	14.7	36.9
Muscovite	17.9	3.1	1.7	.5	.3	.8
Chlorite	—	.1	.1	.2	—	—
Hornblende	—	.9	—	—	—	—
Garnet	—	—	—	—	.2	1.8
Sillimanite	—	.1	.1	—	.2	10.3
Magnetite	—	—	.6	—	.7	—
Hematite	.5	—	—	.5	—	.2
Apatite	—	.4	—	—	.5	tr
Sphene	tr	—	—	—	tr	—
Monazite	tr*	tr*	tr*	.1*	—	tr*
Zircon	tr	—	tr	tr	tr	—
Epidote	—	2.2	—	—	—	—
Allanite	—	—	tr	tr	—	—
Total	100	100	100	100	100	100
Points counted	801	681	710	640	1314	514

Composition	Sample No. SL-1	SL-36	SL-76	SL-79	SL-80	SL-89
Color index[2]	16.9	31.0	10.6	19.7	15.6	38.9
Average grain size, in millimeters.	<1	<1	<1	1	1	1
Magnetic, m, or nonmagnetic, nm[3].	nm	nm	m	nm	m	nm
Radioactivity[4], in counts per second.	180	170	230	240	185	165
Specific gravity[5]	2.760	2.807	2.719	2.718	2.749	—
Rock name (Streckeisen, 1976).	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

[1]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[2]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[3]m, rock reacts postively to a large hand magnet; nm, no reaction.

[4]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[5]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

and quartz and displays twinning that is similar to, but diagnostically different from, that of plagioclase. Monazite and zircon are common; apatite is less so. Monazite produces intense, dark, radiation-damage halos in biotite (fig. 7) and lighter ones in cordierite. The largest monazite grain is 0.14 by 0.08 mm. Zircons commonly contain older zircon cores. Hematite or magnetite are normally present, epidote and allanite are uncommon, and sphene is rare.

Three chemical analyses (table 11) of biotite gneiss indicate that it is very peraluminous, has high K_2O:Na_2O ratios, and is poor in calcium.

Granitic Enclaves in Biotite Gneiss

Granitic enclaves in the biotite gneiss range from 1 m to about 7 km in greatest dimension. The long, narrow enclave in the northwest part of the area was mapped as Silver Plume Granite by Schroeder (1984) and as quartz monzonite by Izett (1974). My interpretation of this elongate body as being different from the Silver Plume Granite is based on its finer grain size and lower uranium content. Moreover, the area bounded by this elongate body is poorly exposed and contains considerable amounts of biotite gneiss. These generally fine grained granitic rocks are gray to buff and have hypautomorphic granular texture.

Essential minerals are quartz, microcline, oligoclase (rarely andesine), and biotite (locally altered to chlorite). Muscovite is generally present, zircon is very common, and apatite and monazite are less common (tables 13 and 14). Monazite is conspicuous by its production of intense, dark, radiation-damage halos in biotite. The largest monazite grain is 0.04 by 0.08 mm. Monazite commonly shows an alteration ring and locally produces small fractures in quartz. The largest apatite grain is 0.5 by 1.2 mm. Hematite is generally present (magnetite occurs in only one sample); garnet, epidote, allanite, sillimanite, and tourmaline are rarely present. The tourmaline is dichroic from almost colorless to dark gray blue.

One chemical analysis of a typical sample (sample SL–3, table 13) from a large granitic enclave in the biotite gneiss indicates that the rock is a peraluminous and very potassic monzogranite. Eight samples (including the chemically analyzed one) of the granitic enclaves in the biotite gneiss are plotted on a QAP diagram in figure 6; six are monzogranites, one is a syenogranite, and one is a granodiorite. On figure 6 the trends of all the granitic enclaves (those in Boulder Creek Granodiorite, those in the Silver Plume Granite, and those in biotite gneiss) are similar; in other words, plagioclase content increases with increasing quartz content, or conversely, alkali feldspar content increases with decreasing quartz content. Furthermore, granitic enclaves in the biotite gneiss contain considerably more plagioclase than do granitic enclaves in the Boulder Creek Granodiorite. Granitic enclaves in the Silver Plume Granite contain more plagioclase than do granitic enclaves in the Boulder Creek Granodiorite but less than granitic enclaves in the biotite gneiss.

Biotite Lamprophyre Enclaves in Boulder Creek Granodiorite

Enclaves of biotite lamprophyre are tens of meters in length and cluster in the south-central portion of the area (pl. 1, table 15). Individual pods (broken blocks of a dike?) show sharp contact with their host. A single enclave, which is 30 m in length, is 3.5 km to the west-southwest of the cluster. Another enclave was mapped 3 km to the north-northeast of the cluster by Schroeder (1984). The biotite lamprophyre is dark gray, fine grained, and holocrystalline; some parts of the lamprophyre show irregular, delicate veining by pink feldspar (fig. 12). Most specimens are massive, but sample SL–10 (table 15) showed a pronounced foliation. I use the name "enclaves," rather than "dikes," in order to emphasize that their origin is open to question.

Biotite and hornblende are essential minerals, which are set in a matrix of microcline and microcline microperthite that invariably is heterogeneously light brown (fig. 13). Biotite is commonly intergrown with hornblende, which implies simultaneous crystallization. Monoclinic pyroxene occurs in sample SL–142 (table 15) as very small phenocrysts. Quartz occurs in sample SL–82 (table 15). Sphene and apatite are very abundant. Hematite, epidote, and triangular inclusions of rutile in biotite occur in all samples; the hematite is locally bordered with granular sphene. Zircon and allanite occur locally. Allanite, where included in biotite, produces dark, intense radiation-damage halos.

The narrow range of specific gravities for these five samples (2.903; maximum deviation does not exceed ± 0.029) (table 15) indicates the relative homogeneity of the rock. According to the Streckeisen (1979) classification for lamprophyres, all five samples are minette-vogesites, and they are metaluminous.

Small Mafic Enclaves in Boulder Creek Granodiorite

Small (generally 1–20 cm), fine-grained, generally discoid enclaves in the Boulder Creek Granodiorite are abundant locally (fig. 3). I would not call them xenoliths because no country rock fits their description. One could assume that they come from a source at depth, but that may be an unwarranted assumption.

Essential minerals (table 15) are andesine, biotite, and hornblende. Small amounts of quartz and muscovite (secondary?) are present in some samples. Accessory minerals are epidote, sphene, apatite, magnetite, zircon, and allanite. Some apatite grains show weak radiation-damage halos in biotite; others do not. Zircons, some with older zircon cores, show moderate radiation-damage halos in biotite, whereas sphene does not produce halos. A few, very small, unidentified nonopaque grains show dark, intense radiation-damage halos in biotite; these grains may be monazite.

Sample SL–101B, which is a metaluminous representative of this rock type, is plotted on a QAP diagram in figure 6. It is classified as a quartz diorite according to the Streckeisen (1976) system. The mafic composition (rich in Fe, Mg, Ca, Cr, V, and Sc) of the small mafic enclaves (table 15) matches that of the biotite lamprophyres, although the latter are also enriched in K and other felsic trace elements.

Andesite Porphyry Dike

The Tertiary(?) andesite porphyry dike (table 15) in the southwest part of the area is about 9 m wide and at least 150 m long, and it intrudes Boulder Creek Granodiorite. The andesite porphyry is dark and fine grained.

Table 13. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of a granitic enclave in the biotite gneiss

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, R. Bies, B. Keaten, S. Lasater, J. Storey, and S. Danahey. Rapid rock chemical analysis by V. Smith and J. Reid. Semiquantitative spectrographic analysis by G. Kaczanowski. *, significant elements (2× crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; <, less than]

Composition	Size of enclave Large: 0.5 km or more Sample No. SL-3
Uranium and thorium analyses, in parts per million	
U	4.50
Th	53.1*
Th:U	11.8
Chemical analyses, in weight percent	
SiO_2	72.4
Al_2O_3	14.5
Fe_2O_3	1.6
FeO	.52
MgO	.29
CaO	.66
Na_2O	2.7
K_2O	6.3*
H_2O^+	} [1].03
H_2O^-	
TiO_2	.29
P_2O_5	.12
MnO	.00
CO_2	.08
Total	100
$K_2O:Na_2O$	2.33
A:CNK[2]	1.16
F[3]	26.5
S[4]	2.72
Spectrographic analyses, in parts per million	
B	<10
Ba	1100
Be	2.4
Ce	210*
Co	1.8
Cr	<10
Cu	27
Ga	19
La	130*
Nb	<25
Nd	n.d.
Ni	4
Pb	23
Sc	<10
Sr	120
V	14
Y	17
Yb	n.d.
Zn	<50
Zr	170
La:Ni	33

Composition	Size of enclave Large: 0.5 km or more Sample No. SL-3
Modal analyses, in volume percent	
Quartz	32.7
Microcline	27.6
Plagioclase[5]	27.2
Anorthite	14
Biotite	4.8
Muscovite	6.5
Chlorite	—
Hematite	.6
Apatite	.1*
Monazite	.5*
Zircon	tr*
Epidote	—
Allanite	—
Sillimanite	—
Total	100
Points counted	805
Color index[6]	5.9
Average grain size, in millimeters.	1.5
Magnetic, m, or nonmagnetic, nm[7].	nm
Radioactivity[8], in counts per second.	345
Specific gravity[9]	2.650
Rock name (Streckeisen, 1976).	granite (monzogranite).

[1]Loss on ignition at 900 °C.

[2]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[3]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[4]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[5]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[6]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[7]m, rock reacts postively to a large hand magnet; nm, no reaction.

[8]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[9]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Essential minerals are plagioclase (An_{30}), biotite, hornblende, monoclinic pyroxene, potassium feldspar, and minor quartz. Most of the plagioclase occurs as microlites; some of the larger plagioclase phenocrysts are zoned. Potassium feldspar and quartz are largely interstitial. Magnetite, apatite, sphene, and epidote are accessory minerals. An unusual mineral in the dike is scapolite, which occurs as phenocrysts as much as 2.5 by 3.5 mm in size and aggregates about 2 percent of the dike. This is the first reported occurrence of meionite (calcium scapolite) from Colorado (Eckel, 1961). All the scapolite phenocrysts have a light-colored reaction rim, which may be microcrystalline epidote. The scapolite phenocrysts have a lustrous, black, glassy appearance in hand specimen, break conchoidally, and show no cleavage. Under the polarizing microscope the scapolite phenocrysts are light brown, slightly dichroic, and uniaxial negative. Cleavage is not evident, but many fractures (some curved) are filled with an unidentified mineral that is probably identical to that of the light-colored reaction rim. Refractive indices of the scapolite are $\omega = 1.600$ and $\epsilon = 1.565$.

Data shown below are from the studies of the scapolite by Isabelle Brownfield utilizing an X-ray diffraction-powder camera and a microprobe.

X-ray diffraction-powder camera study

d, in angstroms	2θ–CuKα, in degrees	Intensity[1]	*hkl*[2]
9.509	9.3	ms	--
3.867	23.0	s	--
3.493	25.5	vs	112
3.100	28.8	vs	400
2.814	31.8	w	--
2.739	32.7	vs	--
2.344	38.4	s	--
2.181	41.4	w	--
2.113	42.8	s	--
2.045	44.3	s	--
1.949	46.6	vs	--
1.903	47.8	vw	--
1.787	51.1	vvw	--
1.755	52.1	vw	--
1.598	57.7	w	--
1.5465	59.8	vw	--
1.5033	61.7	w	--
1.4568	63.9	w	--
1.4041	66.6	s	--
1.3507	69.6	vw	--

[1]vs, very strong; s, strong; ms, medium strong; w, weak; vw, very weak; vvw, very very weak.
[2]--, not determined.

Microprobe study

Composition[1]	Average of eight determinations on first phenocryst	Average of three determinations on second phenocryst
SiO_2	42.65	43.27
Al_2O_3	26.30	26.72
FeO	.76	.80
MgO	.33	.38
CaO	16.44	16.00
Na_2O	3.68	3.85
K_2O	.26	.29
TiO_2	.09	.11
MnO	.03	.02
F	.02	.03
Cl	.08	.08
Total	90.64	91.55

[1]No analyses for H_2O^+, CO_2, and SO_3.

$CaO:Na_2O$ ratios range from 4.1 to 4.7 and suggest that this scapolite could be considered meionite (Me) $[Ca_4Al_6O_{24}(CO_3,SO_4)]$, which is the Ca-rich end member of the marialite-meionite series (Fleischer, 1983). However, comparison of the 2,813 gram-atoms of Ca of this scapolite with the gram-atoms of Ca of other analyzed scapolites (Shaw, 1960) indicates that this scapolite is about 73 percent Me. Therefore, on the basis of $CaO:Na_2O$ ratios, this scapolite is a mizzonite (Me_{50}–Me_{80}).

If the refractive indices are used as a gauge of composition, the use of Shaw's (1960) equation $\frac{\epsilon+\omega}{2} = 1.5346 + 0.000507$ (Me percent) yields 94.5 percent 2 Me, which indicates this scapolite is a meionite.

I also utilized the X-ray method of Burley and others (1961), which uses the difference in 2θ–CuKα spacings between the (112) and (400) hkl planes; it was necessary to extrapolate their curve. The result obtained for the scapolite of this report was about 87 percent Me. The average of the three methods is 85 percent Me, which would justify the name meionite.

Sample SL–139, which is a metaluminous representative of the andesite porphyry dike, is plotted on a QAP diagram in figure 6, which indicates that it is a monzodiorite in the Streckeisen (1976) classification. Of all the rock units, this rock alone can unequivocally be called igneous, because of its dikelike structure and two types of plagioclase phenocrysts: larger zoned ones and microlites.

Table 14. Uranium, thorium, spectrographic, and modal analyses and descriptive parameters of granitic enclaves in the biotite gneiss

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., M. Solt, M. Coughlin, B. Vaughn, M. Schneider, W. Stang, B. Keaten, and F. Luman. Semiquantitative spectrographic analyses of samples SL–4 and SL–17 by L. Castillo, samples TM–2 and SL–25 by G. Kaczanowski, and samples SL–38 and SL–43 by T. Fries. *, significant elements (2× crustal abundance, or more) and diagnostic accessory minerals. tr, trace; —, not found; n.d., not determined <, less than; >, greater than]

	Size of enclave						
	Small: 1-5 m	Small: <50 m			Large: 0.5 km or more		
	Sample No.						
Composition	SL-103	SL-25	SL-38	SL-43	SL-4	SL-17	TM-2
Uranium and thorium analses, in parts per million							
U	n.d.	6.97*	2.73	1.36	2.78	3.89	3.99
Th	n.d	26.4*	29.9*	30.4*	75.2*	75.6*	26.2*
Th:U	n.d.	3.8	11.0	22.0	27.1	19.4	6.6
Spectrographic analyses, in parts per million							
B	n.d.	<10	<10	17	<10	<10	<10
Ba	n.d.	340	220	1700*	2000*	1100	370
Be	n.d.	1.9	2.8	3.6	1.4	1.5	3.2
Ce	n.d.	<100	<100	310*	390*	320*	110
Co	n.d.	1.1	1.5	10	4.3	4.2	1.8
Cr	n.d.	<10	<10	13	<10	<10	<10
Cu	n.d.	<1	8.7	30	11	6.5	12
Ga	n.d.	18	18	25	25	21	22
La	n.d.	44	<20	190*	230*	160*	54
Li	n.d.	<50	<50	<50	<50	<50	55
Mn	n.d.	<200	260	860	<200	230	<200
Nb	n.d.	<25	<25	<25	<25	<25	<25
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	n.d.	2.4	4.3	11	6.2	4.7	2.3
P	n.d.	600	1000	>4500*	700	500	900
Pb	n.d.	51*	14	<10	43*	50*	31
Sc	n.d.	<10	<10	11	<10	<10	<10
Sr	n.d.	170	73	290	190	150	61
Ti	n.d.	900	900	6300	3100	2200	1300
V	n.d.	<10	<10	77	41	27	<10
Y	n.d.	<10	17	43	17	16	20
Yb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	n.d.	<50	<50	170*	54	55	<50
Zr	n.d.	<20	43	420*	280	220	130
La:Ni	n.d.	18	<5	17	37	34	23
Modal analyses, in volume percent							
Quartz	32.2	31.1	28.3	28.7	29.2	30.1	35.3
Microcline	11.7	34.1	38.6	20.8	30.8	39.5	23.9
Plagioclase[1]	36.2	32.8	29.1	32.3	27.0	20.8	29.1
Anorthite	33	13	12	32	13	12	16
Biotite	15.1	2.0	3.2	13.8	7.3	7.1	1.7
Muscovite	3.6	—	0.8	1.1	2.8	2.5	8.8
Chlorite	—	tr	—	0.1	0.6	—	—
Magnetite	—	—	—	2.5	—	—	—
Hematite	0.3	tr	—	—	1.5	tr	0.8
Apatite	.7*	—	tr	.6	.4*	tr*	.4*
Monazite	tr*	0.1	tr	—	.4*	tr*	tr*
Zircon	tr*	tr*	tr*	.1*	tr*	tr*	tr*
Allanite	tr	—	—	tr	—	—	—
Sillimanite	—	tr	—	—	—	tr	—
Tourmaline	—	—	tr	—	—	—	—
Epidote	tr	—	—	—	—	—	—
Garnet	.2	—	—	—	—	—	—
Total	100	100	100	100	100	100	100
Points counted	583	549	622	832	800	552	809

Table 14. Uranium, thorium, spectrographic, and modal analyses and descriptive parameters of granitic enclaves in the biotite gneiss—Continued

	Size of enclave						
	Small: 1-5 m	Small: <50 m			Large: 0.5 km or more		
	Sample No.						
Composition	SL-103	SL-25	SL-38	SL-43	SL-4	SL-17	TM-2
Color index[2]............	15.6	2.1	3.2	16.5	9.8	7.1	2.5
Average grain size,..... in millimeters.	<1	1	1.5	2	<1	<1	1
Magnetic, m, or......... nonmagnetic, nm[3].	nm	nm	nm	m	nm	nm	nm
Radioactivity[4], in...... counts per second.	50	330	165	325	385	325	280
Specific gravity[5].......	—	2.620	2.649	2.776	2.630	2.640	2.640
Rock name (Streckeisen, 1976).	grano-diorite.	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (monzo-granite).	granite (syeno-granite).	granite (monzo-granite).

[1]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[2]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[3]m, rock reacts postively to a large hand magnet; nm, no reaction.

[4]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[5]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Table 15. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of the biotite lamprophyre enclaves, a small mafic enclave in the Boulder Creek Granodiorite, and an andesite porphyry dike

[Delayed neutron activation analyses for U and Th by H.T. Millard, Jr., B.A. Keaten, F.M. Luman, J. Storey, S. Danahey, B. Vaughn, and M. Coughlin. Chemical (X-ray spectrographic) analyses of samples SL–88, 101B, 139, and 142 by A. Bartel. Semiquantitative spectrographic analyses of sample SL–10 by L. Castillo; and samples SL–88, 101B, 139, and 142 by L. Bradley. *, significant elements (2 × crustal abundance, or more) and diagnostic accessory minerals. n.d., not determined; tr, trace; —, not found; <, less than]

	Biotite lamprophyre enclaves					Small mafic enclave	Andesite prophyry dike
	Sample No.						
Composition	SL-88	SL-142	SL-10	SL-82	SL-83	SL-101B	SL-139
Uranium and thorium analyses, in parts per million							
U	8.31*	9.52*	7.68*	n.d.	n.d.	2.15	3.38
Th	51.6*	62.6*	43.9*	n.d.	n.d.	<2.7	22.9
Th:U	6.2	6.6	5.7	n.d.	n.d.	<1.3	6.8
SiO_2	50.0	47.7	n.d.	n.d.	n.d.	46.8	52.2
Al_2O_3	11.2	11.7	n.d.	n.d.	n.d.	16.5	15.0
Fe_2O_3	[1]7.77	[1]7.84	n.d.	n.d.	n.d.	[1]13.4*	[1]8.51
FeO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	9.20*	9.04*	n.d.	n.d.	n.d.	6.07	6.01
CaO	7.01	7.43	n.d.	n.d.	n.d.	8.54	6.41
Na_2O	.71	.78	n.d.	n.d.	n.d.	2.76	2.80
K_2O	7.67*	7.84*	n.d.	n.d.	n.d.	2.38	3.51
H_2O^+ } H_2O^-	[2].57	[2].75	n.d.	n.d.	n.d.	[2]1.21	[2]1.29
TiO_2	1.39	1.12	n.d.	n.d.	n.d.	1.25	1.02
P_2O_5	1.53*	1.79*	n.d.	n.d.	n.d.	.42*	1.06*
MnO	.13	.11	n.d.	n.d.	n.d.	n.d.	.12
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	97	96	n.d.	n.d.	n.d.	100	98
$K_2O:Na_2O$	10.8	10.1	n.d.	n.d.	n.d.	.86	1.25
A:CNK[3]	.50	.50	n.d.	n.d.	n.d.	.73	.75
F[4]	2.44	2.32	n.d.	n.d.	n.d.	1.85	2.80
S[5]	1.15	1.07	n.d.	n.d.	n.d.	0.94	1.24
Spectrographic analyses, in parts per million							
B	<10	<10	<10	n.d.	n.d.	<10	<10
Ba	5000*	15000*	4100*	n.d.	n.d.	300*	5000*
Be	3	5	11*	n.d.	n.d.	2	1.5
Ce	500*	700*	440*	n.d.	n.d.	<100	300*
Co	20	20	38*	n.d.	n.d.	20	20
Cr	500*	300*	420*	n.d.	n.d.	300*	300*
Cu	15	50	36	n.d.	n.d.	30	30
Ga	20	20	25	n.d.	n.d.	30	20
La	300*	300*	230*	n.d.	n.d.	<50	200*
Nb	<10	<10	<25	n.d.	n.d.	<10	<10
Nd	300*	700*	n.d.	n.d.	n.d.	100*	200*
Ni	150*	150*	220*	n.d.	n.d.	30	70
Pb	30	50*	<10	n.d.	n.d.	15	50*
Sc	30*	20*	29*	n.d.	n.d.	50*	15
Sr	1500*	3000*	1700*	n.d.	n.d.	500	3000*
V	200*	150	240*	n.d.	n.d.	200*	150
Y	50	70*	64*	n.d.	n.d.	70*	30
Yb	3	3	n.d	n.d.	n.d.	5	3
Zn	<300	<300	<50	n.d.	n.d.	<300	<300
Zr	150	150	510*	n.d.	n.d.	70	100
La:Ni	2.0	2.0	1.0	n.d.	n.d.	<1.7	2.9

Table 15. Uranium, thorium, chemical, spectrographic, and modal analyses and descriptive parameters of the biotite lamprophyre enclaves, a small mafic enclave in the Boulder Creek Granodiorite, and an andesite porphyry dike—Continued

	Biotite lamprophyre enclaves					Small mafic enclave	Andesite prophyry dike
	Sample No.						
Composition	SL-88	SL-142	SL-10	SL-82	SL-83	SL-101B	SL-139
	Modal analyses, in volume percent						
Quartz	—	—	—	0.4	—	5.7	1.9
Microcline	45.8	24.9	37.6	37.4	37.7	tr	10.4
Plagioclase[6]	1.6	—	0.5	12.3	2.8	37.9	39.1
Anorthite	5	—	8	20	8	32	30
Biotite	23.6	38.1	20.7	12.1	20.5	28.0	20.7
Hornblende	20.8	15.6	34.2	30.5	29.3	20.7	17.3
Monocline pyroxene	—	5.7	—	—	—	—	2.9
Scapolite (meionite)	—	—	—	—	—	—	2.1
Magnetite	—	—	—	—	—	.9	2.7
Hematite	1.3*	.5*	.5*	1.9*	.1*	—	—
Apatite	2.3*	4.2*	2.1*	.8*	3.7*	1.0	1.9
Sphene	2.6*	4.8*	4.3*	4.4*	5.8*	1.0	.3
Zircon	—	—	—	—	.1	tr	—
Epidote	2.0*	5.9*	.1*	.2*	tr*	4.8	.7
Allanite	tr	.3	—	—	tr	tr	—
Rutile	tr*	tr*	tr*	tr*	tr*	—	—
Calcite	—	—	—	tr	—	—	—
Total	100	100	100	100	100	100	100
Points counted	696	598	807	571	711	690	701
Color index[7]	50.3	70.9	59.8	49.1	55.8	55.4	46.7
Average grain size, in millimeters.	<1	<1	<1	<1	1	<1	<1
Magnetic, m, or nonmagnetic, nm[8].	nm	nm	nm	nm	nm	m	m
Radioactivity,[9] in counts per second.	295	—	250	380	210	—	160
Specific gravity[10]	2.899	2.932	2.890	2.896	2.899	—	2.852
Rock name (Streckeisen, 1976).	minette-vogesite.	minette-vogesite.	minette-vogesite.	minette-vogesite.	minette-vogesite.	quartz-diorite.	monzo-gabbro.

[1]Total iron reported as Fe_2O_3.

[2]Loss on ignition at 900 °C.

[3]A:CNK = alumina saturation = $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$ (in molecular proportions).

[4]$F = \frac{SiO_2+Na_2O+K_2O}{FeO+Fe_2O_3+MgO+CaO}$ (oxides in weight percent).

[5]$S = \frac{SiO_2}{Al_2O_3+Na_2O+K_2O+MgO+CaO+FeO+Fe_2O_3}$ (oxides in weight percent).

[6]Plagioclase determinations were made by a combination of maximum extinction angles to the 010 trace, optic sign, and refractive index comparisons against quartz.

[7]Color index is the sum of the colored (melanocratic) minerals expressed in percent. Colored minerals are: biotite, amphibole, pyroxene, chlorite, scapolite, all opaque minerals, garnet, allanite, zircon, sphene, tourmaline, epidote, and monazite. Light (leucocratic) minerals are: quartz, feldspar, muscovite, cordierite, calcite, fluorite, apatite, sillimanite, and clinozoisite.

[8]m, rock reacts postively to a large hand magnet; nm, no reaction.

[9]Measured on the outcrop with a Mount Sopris scintillometer, Model SC-132.

[10]Determined with an air pycnometer, described by McIntyre and others (1965). An average of three determinations for each rock specimen yields a specific gravity with ± 0.008 gram per cubic centimeter maximum deviation.

Figure 12. Block of biotite lamprophyre (minette-vogesite) showing irregular veining by aligned pink potassium feldspar (raised, lighter veinlets near coin). Coin is 19 millimeters in diameter.

CHEMICAL, PHYSICAL, AND PETROGRAPHIC COMPARISON OF ROCK UNITS

Table 16 gives Rb:Sr ratios for each of the rock units. Although limited data indicate variability within a rock unit, the Rb:Sr averages are in direct proportion (loosely) to the felsic nature of the rock.

Table 17 summarizes significant data for each of the rock units by listing ranges and averages of chemical, physical, and petrographic properties; enrichment factors of significant elements; and average contents of accessory minerals. Table 17 also clearly points out how different the Boulder Creek Granodiorite is from the Silver Plume Granite by showing that their ranges of values for K_2O:Na_2O, Th, La:Ni, radioactivity, specific gravity, and color index are mutually exclusive. A glance at the significantly enriched elements of all the rock types shows that the three mafic rocks (biotite lamprophyre, small mafic enclaves in the Boulder Creek Granodiorite, and the andesite porphyry dike) are the most enriched (discussed in detail in the geochemistry section of this report). Table 17 also shows significant differences in accessory-mineral composition of the rock types; for example, the zircon content of the biotite gneiss is about one-half that of either the Boulder Creek Granodiorite or the Silver Plume Granite.

GEOCHEMISTRY

Uranium and thorium analyses of the Boulder Creek Granodiorite and the Silver Plume Granite of the Strawberry Lake area, which are summarized in figure 14, differ but slightly from previous analyses of the same rock types by Phair and Gottfried (1963) and Hills and Dickinson (1982). In the Strawberry Lake area these two plutonic rocks show slightly less uranium and thorium for the Boulder Creek Granodiorite and slightly more uranium and thorium for the Silver Plume Granite than these rocks do elsewhere in the Front Range. This difference is probably explained by the fact that the Boulder Creek Granodiorite in the Strawberry Lake area is more mafic than Boulder Creek Granodiorite in the central and eastern parts of the Front Range and that the Silver Plume Granite in the Strawberry Lake area is more felsic than Silver Plume Granite in the eastern part of the Front Range. The following averages for silica illustrate this point:

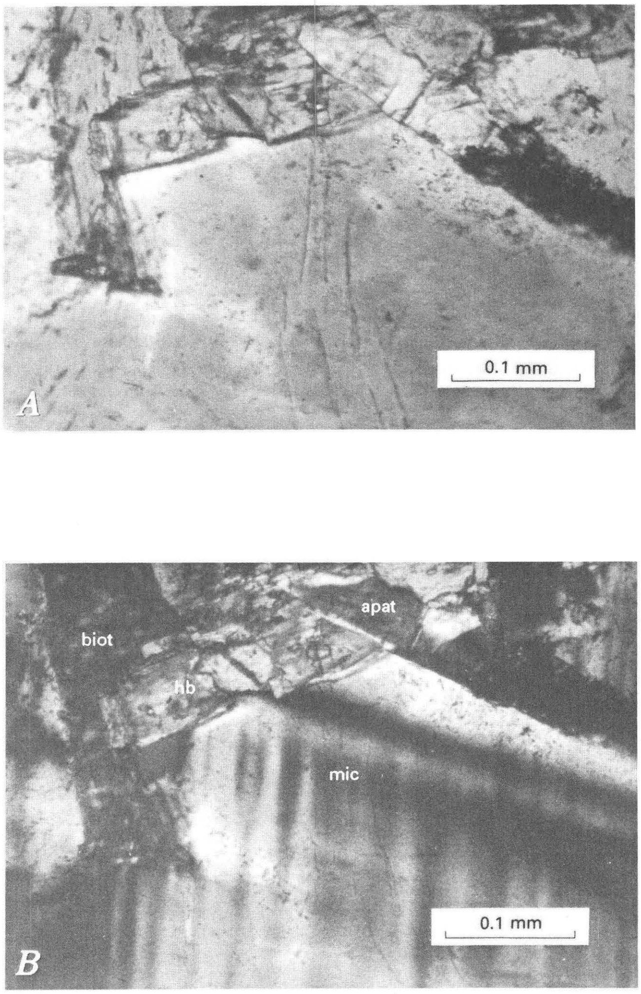


Figure 13. Photomicrograph of biotite lamprophyre (minette-vogesite); microcline shows inhomogeneous brown color under the microscope. A, Plane-polarized light; B, Crossed nicols. Minerals: apat, apatite; biot, biotite; hb, hornblende; mic, microcline.

Samples	Silica, in percent
Average of 35 samples of Boulder Creek Granodiorite from the Boulder Creek batholith (Gable, 1980, p. 61).	65.4
Average of 6 samples of Boulder Creek Granodiorite from the Strawberry Lake area (this report, table 2).	61.9
Average of 10 samples of Silver Plume Granite from the Silver Plume batholith (Anderson and Thomas, 1985).	69.9
Average of 7 samples of Silver Plume Granite from the Strawberry Lake area (this report, table 7).	71.9

Uranium and thorium contents of the rock units of the Strawberry Lake area are compared in figure 15. Notable are the high thorium content of the small granitic enclaves in the Silver Plume Granite and the very low thorium content of the small mafic enclaves in the Boulder Creek Granodiorite. More importantly, however, the thorium content in 9 of the 11 rock units is above crustal abundance. The rock unit richest in uranium is the biotite lamprophyre, and the uranium content in 7 of the 11 rock units is above crustal abundance (fig. 15). Altogether, the rock units of the Strawberry Lake area support the appellation "uranium and thorium province" that Phair and Gottfried (1963) gave to rocks of the Front Range.

I used the method of Shaw (1961) to compare the trace-element contents of different rocks. Shaw proposed the term "coefficient of trace element accumulation" (R), which is defined as $R=1/n\sum_{i=1}^{n} k_i/k_i$ where k_i equals the concentration of element i in a rock or mineral, K_i equals the crustal abundance of element i, and n equals the number of trace elements determined. In figure 16, R is shown for each rock unit in the Strawberry Lake area for 21 elements: Ba, Be, Ce, Co, Cr, Cu, Ga, La, Mn, Nd, Ni, P, Pb, Sc, Sr, Th, Ti, U, V, Y, and Zr. For those few spectrographic analyses near a detection limit that are reported as a "less than" value, a conservative estimate of one-half that value was chosen for calculation. The coefficient of accumulation for the crust, or lithosphere, is 1.00, by definition.

All the rock units accumulated more trace elements than crustal abundance. As figure 16 shows, two of the rock units, the biotite lamprophyre and the andesite porphyry dike, are accumulators of trace elements far in excess of crustal abundance. Most of the granitic enclaves and the small mafic enclaves have accumulated slightly more trace elements than did their much larger hosts, the Boulder Creek Granodiorite, the Silver Plume Granite, and the biotite gneiss.

Table 16. Rubidium:strontium ratios of rocks in the Strawberry Lake area

[X-ray fluorescence analysis of sample SM–4 by C.E. Hedge; samples SM–43A, 43B, and 48, and SL–76, 84, and 89 by Z.E. Peterman; and samples SL–3, 10, 11, 20, 25, 72, 96, 100, 116, 139, 147, 152, and 155, and TM–2 by G.N. Green]

Ratio	Boulder Creek granodiorite	Silver Plume granite	Biotite gneiss	Granitic enclaves in biotite gneiss	Granitic enclaves in Boulder Creek granodiorite	Biotite lamprophyre	Granitic enclaves in Silver Plume granite	Small mafic enclaves in Boulder Creek granodiorite	Andesite porphyry dike
Rb:Sr...	SL–84 0.095 SL–96 .41 SL–100 .13	SM–4 2.47 SM–43A 1.94 SL–72 3.98	SL–76 0.49 SL–89 .27 SL–152 1.30	SL–3 1.92 SL–25 .80 TM–2 5.02	SL–11 0.72 SL–20 .61 SL–116 1.03 SL–147 .08	SL–10 0.18	SM–43B 1.57 SM–48 2.51	SL–155 0.02	SL–139 0.03
Average Rb:Sr.	0.21	2.80	0.69	2.58	0.61	0.18	2.04	0.02	0.03

Table 17. Averages and ranges of chemical, physical, and petrographic parameters of rock units in the Strawberry Lake area

[Key to system of averages and ranges: 25 ———Number of samples contributing to average.

7 ———————Average.

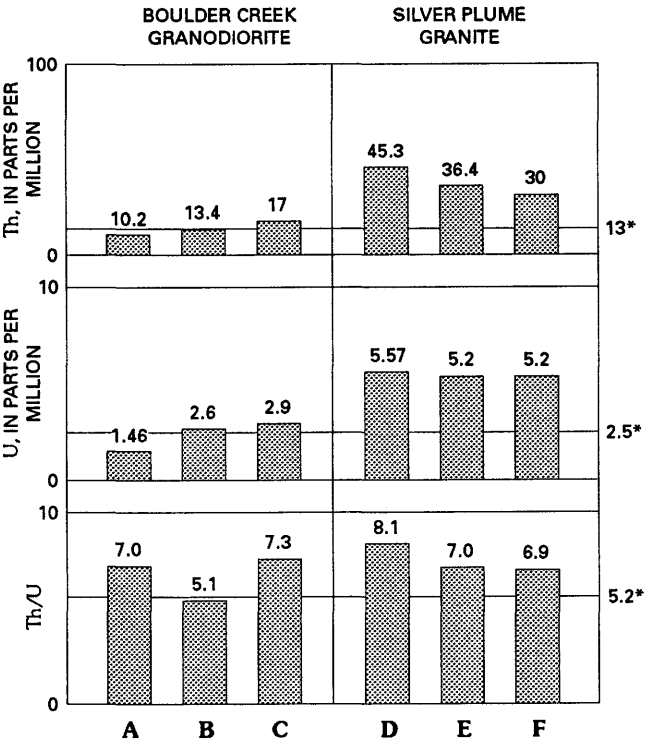
(3 to 10) ————Range.

Key to system of significant elements: 618 (1.8) ——Enrichment factor = Average/crustal abundance (Average).

—, no data; <, less than; n.d., no determination; ~, approximately. Accessory minerals: computed as averages (volume percentage), trace counted as 0.01 percent]

	Boulder Creek Granodiorite	Silver Plume Granite	Biotite gneiss	Granitic enclaves in biotite gneiss. Small: <50 m	Granitic enclaves in biotite gneiss. Large: >0.5 km	Granitic enclaves in Boulder Creek Granodiorite. Small: 1–5 m	Granitic enclaves in Boulder Creek Granodiorite. Large: 100 m to >0.5 km	Biotite lamprophyre	Granitic enclaves in Silver Plume Granite. Small: <80 m	Mafic enclaves in Boulder Creek Granodiorite. Small	Andesite porphyry dike
						Averages and ranges					
K_2O/Na_2O	6 0.93 (0.66 to 1.10)	7 1.9 (1.5 to 2.1)	3 4.45 (2.47 to 6.40)	—	1 2.33	2 3.52 (3.13 to 3.90)	2 1.24 (1.10 to 1.38)	2 10.5 (10.1 to 10.8)	2 2.45 (2.29 to 2.61)	1 0.86	1 1.25
A:CNK	6 0.98 (0.90 to 1.08)	7 1.13 (1.01 to 1.20)	3 4.13 (2.95 to 4.81)	—	1 1.16	2 1.11 (1.05 to 1.16)	2 1.08 (1.02 to 1.13)	2 0.50 (0.5 to 0.5)	2 1.25 (1.25 to 1.25)	1 0.73	1 0.75
F	6 5.15 (4.22 to 6.45)	7 23.8 (16.5 to 30.2)	3 5.34 (3.72 to 6.62)	—	2 2.65	2 17.1 (17.0 to 17.1)	2 11.7 (6.78 to 16.7)	2 2.38 (2.32 to 2.44)	2 16.5 (14.9 to 18.0)	1 1.85	1 2.80
S	6 1.75 (1.52 to 2.05)	7 2.71 (2.54 to 2.83)	3 1.66 (1.13 to 2.14)	—	1 2.72	2 2.48 (2.37 to 2.59)	2 2.29 (1.94 to 2.63)	2 1.11 (1.07 to 1.15)	2 2.59 (2.55 to 2.63)	1 0.94	1 1.24
U, in parts per million.	12 1.46 (0.81 to 2.52)	25 5.57 (2.23 to 9.03)	5 3.15 (2.02 to 5.33)	3 3.89 (1.36 to 6.97)	4 3.79 (2.78 to 4.50)	2 1.87 (1.77 to 1.96)	3 1.83 (1.55 to 2.08)	3 8.50 (7.68 to 9.52)	2 4.2 (3.4 to 5.0)	1 2.15	1 3.38
Th, in parts per million.	12 10.2 (3.7 to 18.5)	25 45.3 (21.6 to 70.5)	5 18.1 (7.6 to 24.7)	3 28.9 (26.4 to 30.4)	4 57.5 (26.2 to 75.6)	2 60.1 (33.9 to 86.2)	3 29.2 (8.65 to 55.1)	3 52.7 (43.9 to 62.6)	2 99.5 (75.9 to 123)	1 <2.7	1 22.9
Th:U	12 7.0 (2.2 to 12.0)	25 8.13 (3.6 to 32.1)	5 5.75 (2.9 to 12.2)	3 7.4 (3.8 to 22.0)	4 15.2 (6.6 to 27.1)	2 32.1 (19.2 to 44.0)	3 16.0 (4.6 to 35.5)	3 6.2 (5.7 to 6.6)	2 23.7 (22.3 to 24.6)	1 <1.3	1 6.8
La:Ni	12 1.9 (0.6 to 5.0)	25 25 (9 to >75)	5 2.8 (1 to 6)	3 13 (<5 to 18)	4 32 (23 to 37)	2 26 (8 to 43)	3 >33 (>15 to 50)	3 1.7 (1 to 2)	2 21 (21 to 21)	1 <1.7	1 2.9
Radioactivity, in counts per second.	26 127 (90 to 175)	33 355 (240 to 505)	8 192 (155 to 240)	4 218 (50 to 330)	4 334 (280 to 385)	5 408 (180 to 525)	7 268 (150 to 470)	4 284 (250 to 310)	2 525 (500 to 550)	—	1 160
Magnetic, m, or nonmagnetic, nm.	26 (14m, 12nm)	34 (9m, 25nm)	9 (3m, 6nm)	4 (1m, 3nm)	4 (0m, 4nm)	5 (5m, 0nm)	7 (4m, 3nm)	5 (0m, 5nm)	2 (2m, 0nm)	2 (2m, 0nm)	1 (1m)
Specific gravity	25 2.778 (2.685 to 2.850)	31 2.654 (2.630 to 2.683)	7 2.792 (2.718 to 2.920)	3 2.682 (2.620 to 2.776)	4 2.640 (2.630 to 2.650)	5 2.655 (2.630 to 2.666)	7 2.681 (2.625 to 2.758)	5 2.903 (2.890 to 2.932)	2 2.674 (2.673 to 2.674)	—	1 2.852

Color index	24.9 (13.2 to 40.9) 24	5.0 (1.5 to 10.8) 32	28.2 (10.6 to 67.4) 8	9.4 (2.1 to 16.5) 4	6.3 (2.5 to 9.8) 4	8.9 (6.7 to 12.2) 5	6.5 (1.6 to 10.4) 7	57.2 (49.1 to 70.9) 5	9.4 (7.0 to 11.8) 2	55.4 1	46.7 1
Average grain size, in millimeters.	2.5 (1.5 to 3.0) 26	2.3 (<1 to 5.0) 34	<1.5 (<1 to 3) 9	~1.2 (<1 to 2) 4	1 (<1 to 1.5) 4	<1 (<1 to 1.5) 5	1 (<1 to 2.5) 7	<1 (<1 to 1) 5	1.5 (1.5 to 1.5) 2	<1 2	<1 1
Crustal abundance	Significant element [average, in weight percent (enrichment factor)]										
Fe (4.65)	—	—	6.64 (1.4)	—	—	—	—	—	—	9.38 (2)	—
Ti (0.45)	—	—	—	—	—	—	—	0.76 (1.7)	—	0.75 (1.7)	0.61 (1.4)
Mg (1.87)	—	—	—	—	—	—	—	5.47 (2.9)	—	3.64 (1.9)	3.61 (1.9)
Ca (2.96)	—	—	—	—	—	—	—	5.16 (1.7)	—	6.10 (2.1)	4.58 (1.5)
K (2.5)	—	4.66 (1.9)	—	—	5.23 (2.1)	6.18 (2.5)	—	6.44 (2.6)	4.63 (1.9)	—	—
P (0.093)	—	—	—	~0.22 (2.4)	—	—	—	0.72 (7.7)	—	0.18 (1.9)	0.46 (4.9)
Crustal abundance	Significant element (in parts per million)										
U (2.5)	—	5.57 (2.2)	—	3.89 (1.6)	3.79 (1.5)	—	—	8.50 (3.4)	4.2 (1.7)	—	3.38 (1.4)
Th (13)	—	45.3 (3.5)	18.1 (1.4)	28.9 (2.2)	57.5 (4.4)	60.1 (4.6)	29.2 (2.2)	52.7 (4.1)	99.5 (7.7)	—	22.9 (1.8)
La (29)	60 (2.1)	96 (3.3)	57 (2)	~ 80 (2.8)	144 (5)	149 (5.1)	133 (4.6)	277 (9.6)	150 (5.2)	—	200 (6.9)
Ce (70)	—	166 (2.4)	—	~150 (2.1)	258 (3.7)	245 (3.5)	200 (2.9)	547 (7.8)	250 (3.6)	—	300 (4.3)
Nd (37)	—	118 (3.2)	70 (1.9)	n.d.	n.d.	n.d.	97 (2.6)	500 (13.5)	150 (4.1)	100 (2.7)	200 (5.4)
Y (29)	—	—	47 (1.6)	—	—	—	—	61 (2.1)	—	70 (2.4)	—
Yb (3)	—	—	7 (2.3)	n.d.	n.d.	n.d.	—	—	—	5 (1.7)	—
Ba (650)	—	—	—	—	1143 (1.8)	1950 (3)	1467 (2.3)	8033 (12.4)	—	—	5000 (7.7)
Sr (340)	618 (1.8)	—	—	—	—	—	800 (2.4)	2067 (6.1)	—	500 (1.5)	3000 (8.8)
Zr (170)	—	—	—	—	—	360 (2.1)	—	270 (1.6)	—	—	—
Be (3.8)	—	—	—	—	—	—	—	6.3 (1.7)	—	—	—
Pb (16)	—	35 (2.2)	—	—	37 (2.3)	38 (2.4)	30 (1.9)	28 (1.8)	30 (1.9)	—	50 (3.1)
Sc (10)	—	—	21 (2.1)	—	—	—	—	26 (2.6)	—	50 (5)	—
Cr (83)	—	—	—	—	—	—	—	407 (4.9)	—	300 (3.6)	300 (3.6)
Ni (58)	—	—	—	—	—	—	—	173 (3)	—	—	—
V (90)	—	—	—	—	—	—	—	197 (2.2)	—	200 (2.2)	150 (1.7)
Co (18)	—	—	—	—	—	—	—	26 (1.4)	—	—	—
	Accessory mineral (average, in volume percent)										
Magnetite	0.48	0.19	0.16	0.63	0	1.16	0.81	0	1.0	0.9	2.7
Hematite	0.10	0.52	0.39	0.08	0.73	0	0.17	0.86	0	0	0
Pyrite	0	0.0006	0	0	0	0	0	0	0	0	0
Sphene	0.73	0.009	0.0025	0	0	0.20	0.09	4.4	0	1.0	0.3
Apatite	0.64	0.14	0.11	0.33	0.23	0.30	0.40	2.6	0.01	1.0	1.9
Monazite	0	0.067	0.03	0.008	0.23	0.002	0.006	0	0.1	0	0
Zircon	0.017	0.015	0.0075	0.033	0.01	0.11	0.08	0.02	0.01	0.01	0
Rutile	0	0	0	0	0	0	0	0.01	0	0	0
Epidote	0.58	0.01	0.29	0.003	0	0.28	0.07	1.6	0	4.8	0.7
Clinozoisite	0.09	0	0	0	0	0	0	0	0	0	0
Allanite	0.21	0.0016	0.0025	0.005	0	0.02	0.04	0.06	0	0.01	0
Fluorite	0	0.0003	0	0	0	0	0	0	0	0	0
Tourmaline	0	0	0	0.003	0	0	0	0	0	0	0
Garnet	0	0	6.0	0.05	0	0	0	0	0	0	0
Cordierite	0	0	2.5	0	0	0	0	0	0	0	0
Sillimanite	0	0.17	3.4	0.003	0.003	0	0	0	0.4	0	0



EXPLANATION

A Averages of 12 samples of Boulder Creek Granodiorite, Strawberry Lake area, this report.

B Averages weighted for areal abundance in Boulder Creek-type intrusives, Front Range, Colorado (Phair and Gottfried, 1963).

C Averages of 69 samples of Boulder Creek Granodiorite from the Tallahassee Creek area, Colorado (Hills and Dickinson, 1982).

D Averages of 25 samples of Silver Plume Granite, Strawberry Lake area, this report.

E Averages weighted for areal abundance in Silver Plume-type intrusives, Front Range, Colorado (Phair and Gottfried, 1963).

F Averages of 50 samples of Silver Plume Granite from the Tallahassee Creek area, Colorado (Hills and Dickinson, 1962).

Figure 14. Uranium and thorium in the Boulder Creek Granodiorite and in Silver Plume Granite in the Front Range, Colorado. Crustal abundances (*) from Vinogradov (1962).

The ratio La:Ni is useful to distinguish felsic rocks from mafic and intermediate rocks. As shown in table 17 La:Ni averages about 25 for the felsic rocks and about 2 for the mafic to intermediate rocks in the Strawberry Lake area.

Figure 17 shows the significant elemental enrichment (1.4 times crustal abundance or greater) in the rock units of the Strawberry Lake area. From this figure, several conclusions can be drawn:

1. The biotite lamprophyre shows the greatest number of enriched elements (22) and the greatest enrichment above crustal abundance of the 11 rock units, primarily due to the enrichment of K and Mg, which are incompatible major elements. Elements associated with K enrichment, the felsic suite, are: Nd, Ba, La, Ce, Th, U, Pb, Be, and Zr. Elements associated with Mg enrichment, the mafic suite, are: P, Sr, Cr, Ni, Sc, V, Y, Ti, Ca, Co, and Mn.
2. The andesite porphyry dike is the rock unit next most enriched in elements. Because of the mafic composition of the andesite porphyry, Sr, P, Cr, Mg, V, Sc, Ca, and Ti are enriched elements, but in the process of intrusion through relatively felsic country rock, the dike also may have become enriched with a felsic suite of Ba, La, Nd, Ce, Pb, Th, and U.
3. The most consistent enrichment of any element or coherent element group in all the rock units is that of the light rare-earth elements (LREE). Enrichment in heavy rare-earth elements (HREE), which is represented by Y and Yb, occurs only in the small mafic enclaves in the Boulder Creek Granodiorite, although there is some enrichment of Y in the biotite gneiss and the biotite lamprophyre.
4. Thorium is the next most enriched element in all the rock units, except in the Boulder Creek Granodiorite and in the small mafic enclaves in the Boulder Creek Granodiorite.
5. All the granitic enclaves in the major host rocks consistently show enrichment in LREE, Th, and Pb.

CONCLUSIONS

The Boulder Creek Granodiorite in the Strawberry Lake area contains slightly less uranium and thorium than the average of the Boulder Creek Granodiorite in the Front Range, whereas the Silver Plume Granite in the Strawberry Lake area contains slightly more uranium and thorium than the average of the Silver Plume Granite in the Front Range. Such divergence from the mean correlates with the more mafic nature of the Boulder Creek Granodiorite and the more felsic nature of the Silver Plume Granite in the Strawberry Lake area.

The granitic enclaves in the Boulder Creek Granodiorite, in the Silver Plume granite, and in the biotite gneiss are notable for their relatively high thorium and LREE contents compared to their hosts. The biotite lamprophyres are equally enriched in felsic elements (K, U, Th, La, Ce, Nd, Ba, Zr, Be, and Pb) and mafic elements (Mg, Ca, Ti, P, Y, Sr, Sc, Cr, Ni, V, and Co), whereas the small mafic enclaves in the same host are only enriched in mafic elements. The Tertiary(?) andesite dike is enriched in mafic elements, LREE, and thorium. The selective enrichment that occurred in all the enclaves and the dike is related to their origin and that of their hosts; this topic is discussed in chapter B of this bulletin.

Three problems that stand out involve the enclaves. Petrographically, their constitution is known, but

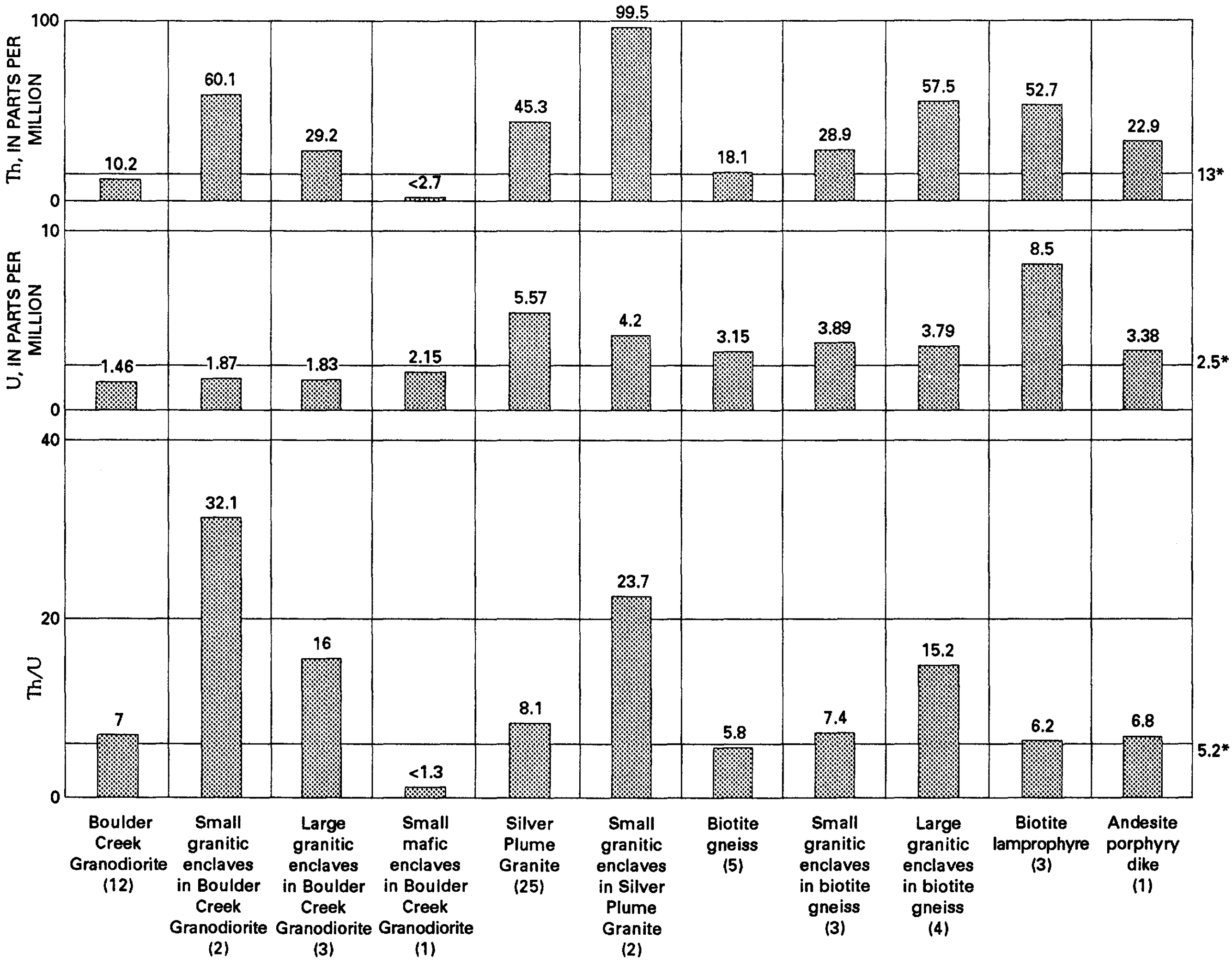


Figure 15. Uranium and thorium contents of rock units in the Strawberry Lake area. Number in parentheses represents number of samples that contributed to average. Crustal abundances (*) from Vinogradov (1962).

petrologically they are enigmatic. The granitic enclaves in the Boulder Creek Granodiorite and in the Silver Plume Granite are notable for their relatively high thorium and high rare-earth-element contents compared to their hosts. How and why is such enrichment achieved? An inquiry into the process of formation of these enclaves is necessary to an understanding of this geochemical behavior.

A more complex problem is the multielemental enrichment of the biotite lamprophyre (minette-vogesite), which profits from the best of two worlds: the felsic world (enrichment in K, Nd, Ba, La, Ce, Th, U, Pb, Be, and Zr) and the mafic world (enrichment in Mg, P, Sr, Cr, Ni, Sc, V, Y, Ti, Ca, Co, and Mn). A conventional explanation of lamprophyres invokes metasomatic alteration of diabase dikes, but this is far from being proven.

Constrained in size, the small mafic enclaves in the Boulder Creek Granodiorite may figure prominently in the genesis of the host, but how? Thus, knowledge of the origin of these felsic and mafic enclaves is mandatory to a full understanding of the formation of their host plutons.

A discussion of the origin of the enclaves and their host rocks is deferred to chapter B of this bulletin, which covers the petrology of the crystalline rocks of the Strawberry Lake area. Because the isolated enclaves have no connection with an igneous source they cannot be considered intrusive. The following options for formation of these enclaves might be considered:

1. As the plutons were being emplaced they transported their enclaves as accompanying different magmas.

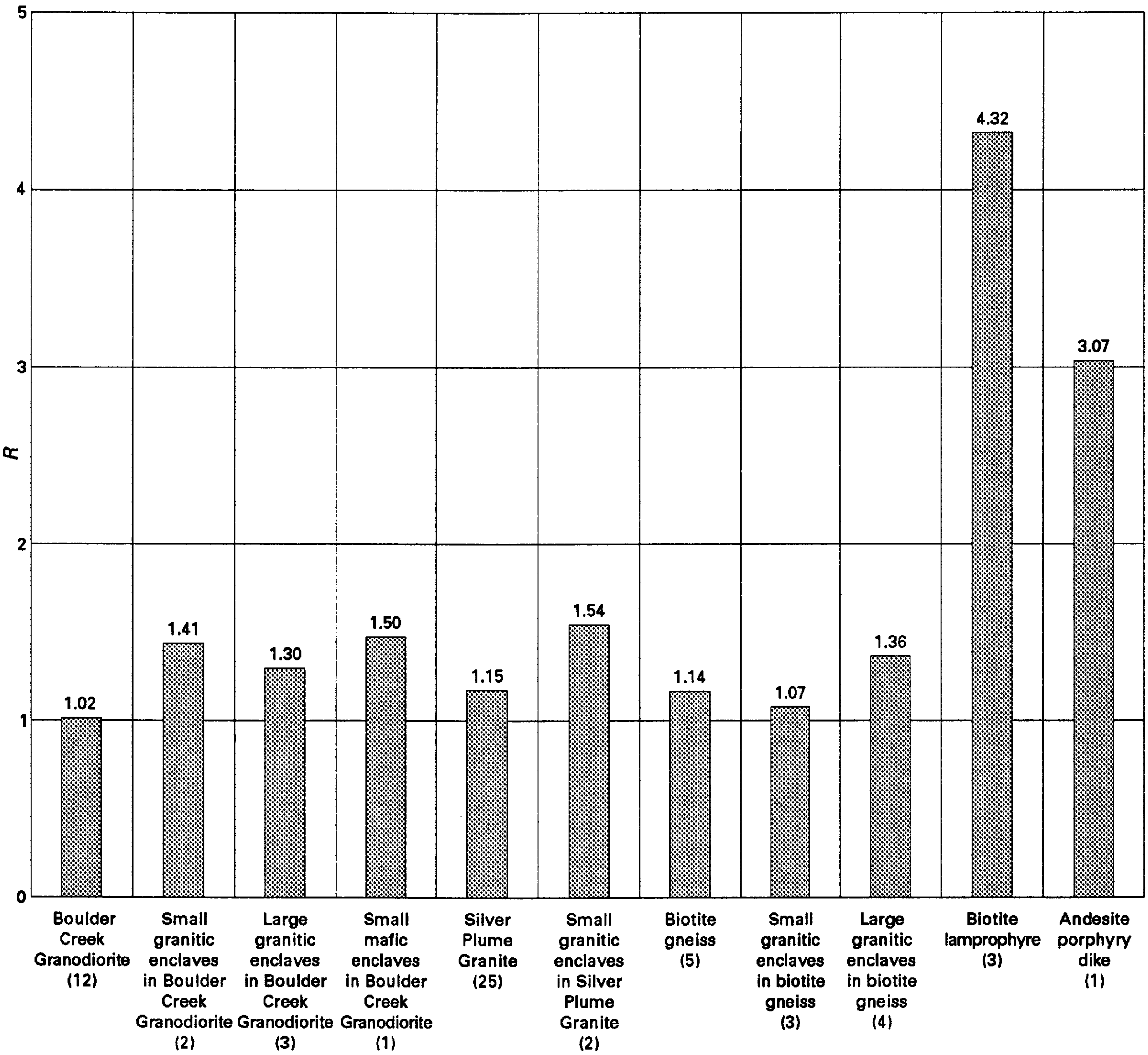


Figure 16. Coefficient of trace element accumulation, *R*, in rock units in the Strawberry Lake area. Number in parentheses represents number of samples that contributed to average.

2. The enclaves are xenoliths (country rock not completely assimilated by magma).
3. The host plutons represent largely granitized or ultrametamorphic rock (does not exclude local melting), and the enclaves are relicts of country rock that resisted granitization or ultrametamorphism.
4. The process of enclave formation (metamorphic differentiation) is an outgrowth of the metamorphic-metasomatic processes that were involved in formation of the host. Local melting is not excluded.

Options 1 and 2 would represent a relatively short time of formation (10 million years or less), whereas options 3 and 4 would entail a long time of formation (100 million years or more). Whichever option is more likely, it must account for the relatively high LREE and Th contents of the granitic enclaves, the HREE enrichment in the small mafic enclaves, and the felsic and mafic elemental enrichment of the biotite lamprophyre.

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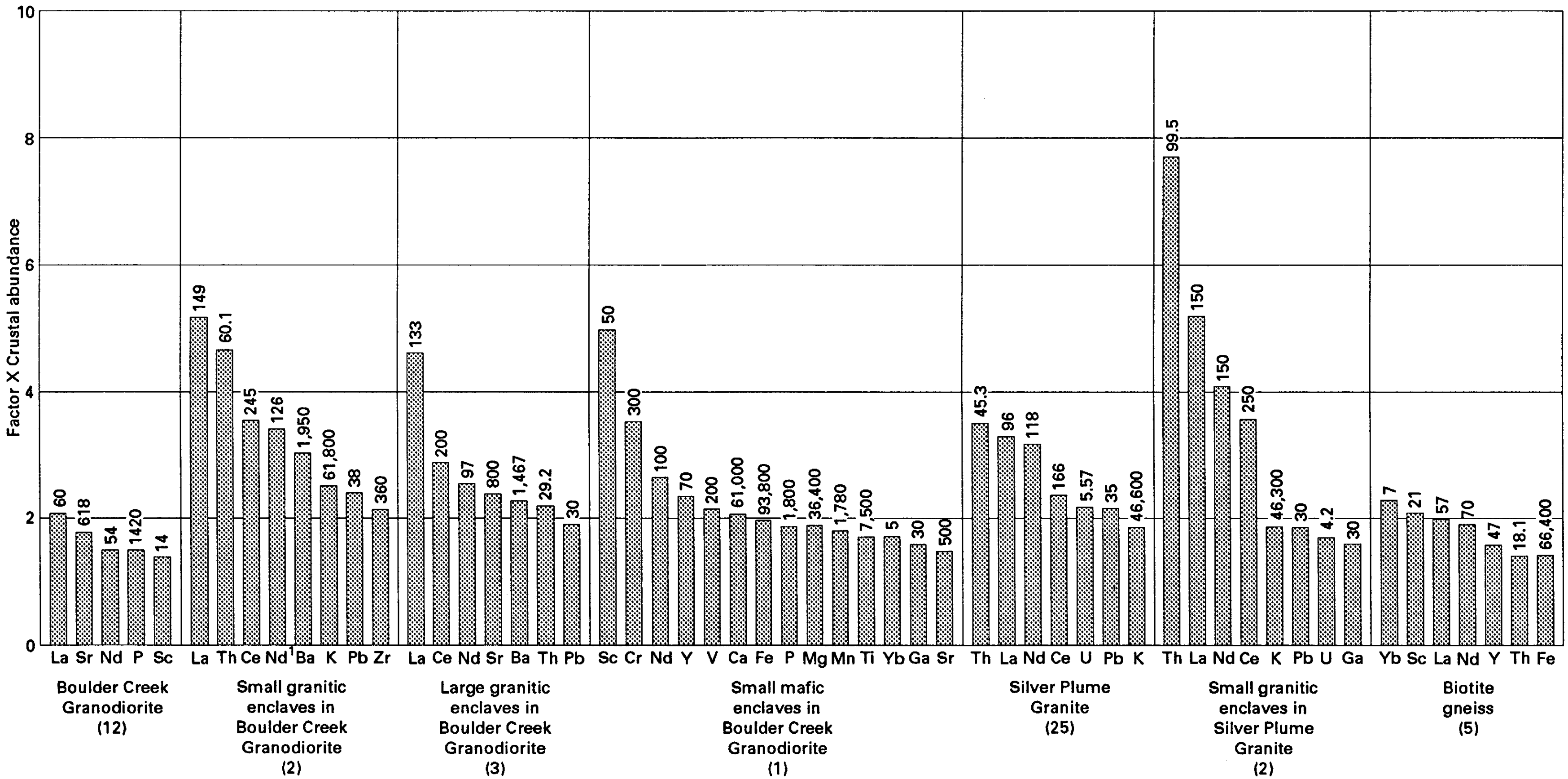

Factor X Crustal abundance
0
2
4
6
8
10
60 618 54 1420 14
La Sr Nd P Sc
Boulder Creek Granodiorite (12)
149 60.1 245 126 1,950 61,800 38 360
La Th Ce Nd[1] Ba K Pb Zr
Small granitic enclaves in Boulder Creek Granodiorite (2)
133 200 97 800 1,467 29.2 30
La Ce Nd Sr Ba Th Pb
Large granitic enclaves in Boulder Creek Granodiorite (3)
50 300 100 70 200 61,000 93,800 1,800 36,400 1,780 7,500 5 30 500
Sc Cr Nd Y V Ca Fe P Mg Mn Ti Yb Ga Sr
Small mafic enclaves in Boulder Creek Granodiorite (1)
45.3 96 118 166 5.57 35 46,600
Th La Nd Ce U Pb K
Silver Plume Granite (25)
99.5 150 150 250 46,300 30 4.2 30
Th La Nd Ce K Pb U Ga
Small granitic enclaves in Silver Plume Granite (2)
7 21 57 70 47 18.1 66,400
Yb Sc La Nd Y Th Fe
Biotite gneiss (5)

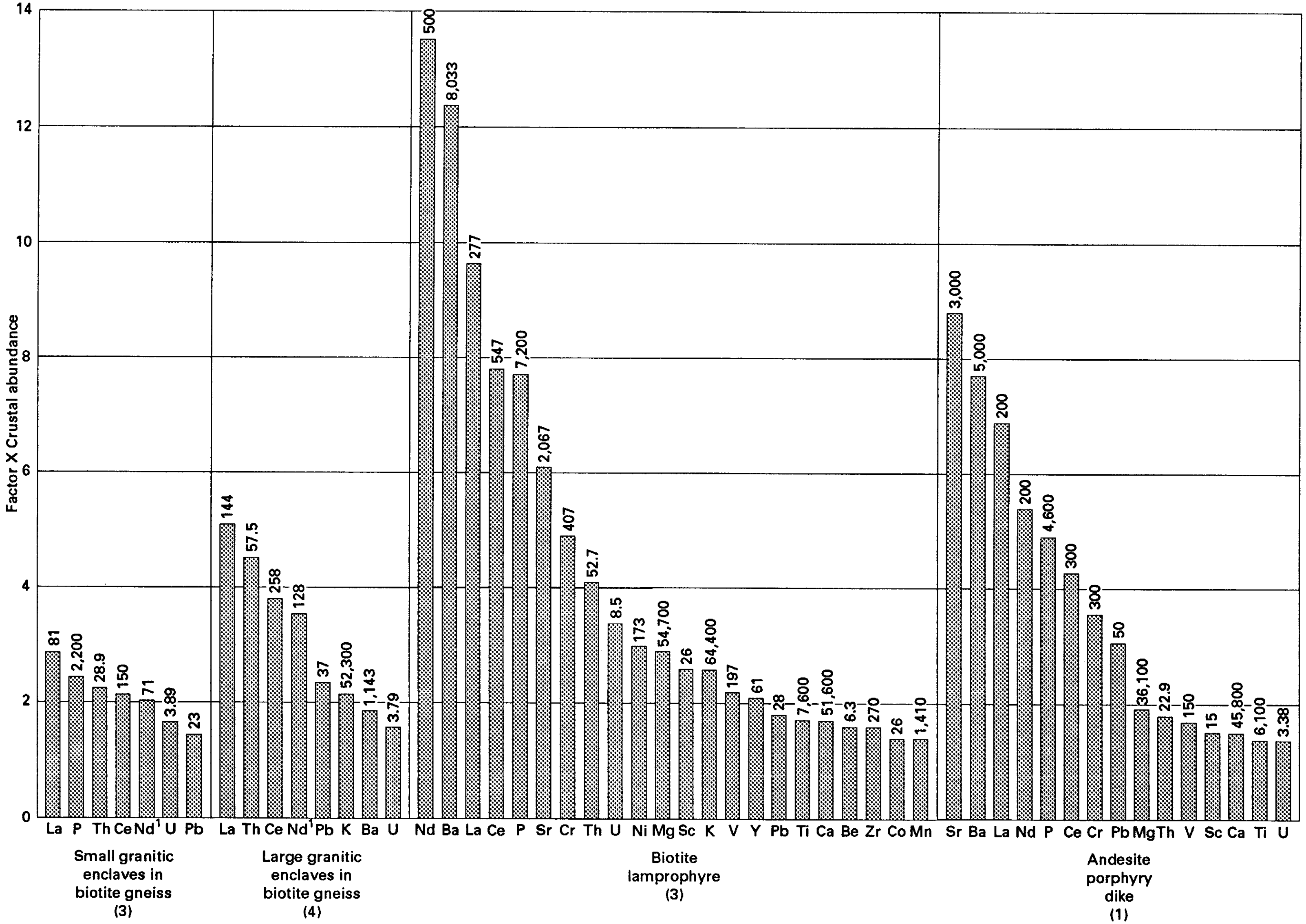


Figure 17 (above and facing page). Significant elemental enrichment (1.4 x crustal abundance or greater) in rock units of the Strawberry Lake area. Number in parentheses represents number of samples that contributed to average. Number at top of distribution bar is average in parts per million. Crustal abundances from Vinogradov (1962), except for Yb (Taylor, 1964). Nd[1] identifies samples where Nd content was estimated from Nd/Ce+La = ~0.32.

Chapter B

Petrology

By EDWARD J. YOUNG

A discussion of the petrology and felsic-mafic and silica-saturation ratios

U.S. GEOLOGICAL SURVEY BULLETIN 1937

CRYSTALLINE ROCKS OF THE STRAWBERRY LAKE AREA, FRONT RANGE, COLORADO

CONTENTS

FIGURES

TABLES

Petrology

By Edward J. Young

Abstract

Felsic-mafic ratios and silica-saturation ratios (F–S method) lead to inferences concerning the origin of crystalline rocks. Corroboration of the validity of the inferences is supported by two different methods, which involve biotite analysis and the $\Sigma Al_2O_3+Na_2O+K_2O$ in the rock.

The Boulder Creek Granodiorite, which is tonalitic in composition, in the Strawberry Lake area of northern Colorado is part of a large Early Proterozoic plutonic complex. Evidence from the F–S method, from the $\Sigma Al_2O_3+Na_2O+K_2O$ method, and from a few biotite analyses favors a metamorphic-metasomatic origin for most of the Boulder Creek Granodiorite in the study area. Other evidence for a metamorphic-metasomatic, rather than a totally intrusive, origin is:

1. Enclaves of biotite gneiss within the Boulder Creek Granodiorite show foliation attitudes similar to foliation attitudes in surrounding country rock of biotite gneiss.
2. The average composition of the Boulder Creek Granodiorite is approximately the same as that of the biotite-gneiss country rock.
3. Many, if not most, zircons in the Boulder Creek Granodiorite were inherited from the biotite gneiss as evidenced by zircon overgrowths on older zircon cores.
4. Dissimilarities in uranium content of apatites favor a metamorphic-metasomatic origin.

Granitic enclaves within the Boulder Creek Granodiorite probably represent an outgrowth of metamorphic-metasomatic processes during formation of the host. Attributes of the granitic enclaves compared to their host are: increased $K_2O:Na_2O$, Ba, Th:U, and light rare-earth elements; a tendency toward lower silica saturation; and accessory apatite and sphene, which represent a reflection of the same chemistry that produced apatite and sphene in the host.

The Middle Proterozoic Silver Plume Granite from the Strawberry Lake area is more felsic than Silver Plume Granite from the Front Range as a whole. Evidence from the F–S method, from the $\Sigma Al_2O_3+Na_2O+K_2O$ method, and from a few biotite analyses generally favors a metamorphic-metasomatic origin for the Silver Plume Granite. Local partial melting is possible. Foliation of biotite-gneiss enclaves within the Silver Plume Granite and planar orientation of feldspar laths in the Silver Plume Granite generally conform to foliation in surrounding biotite gneiss. Biotite:muscovite ratios are highly variable. Some zircon was inherited from older precursor rock.

Granitic enclaves in the Silver Plume Granite may represent zones of partial melting. The enclaves are more mafic, more radioactive, and finer grained than their host.

Granitic enclaves in the biotite-gneiss country rock are compositionally and mineralogically similar to Silver Plume Granite, but they are finer grained. They may be Silver Plume Granite precursor rock that has been subjected to the same metamorphic-metasomatic conditions that produced the Silver Plume Granite in this area.

Textural evidence and low $\Sigma Al_2O_3+Na_2O+K_2O$ values suggest that the biotite lamprophyres had attained a magmatic state. The small mafic enclaves in the Boulder Creek Granodiorite are interpreted to be restites, which are geochemically immobile segregations. The Tertiary(?) andesite porphyry dike is unequivocally igneous as shown by structure, two types of plagioclase phenocrysts and low $\Sigma Al_2O_3+Na_2O+K_2O$ values.

INTRODUCTION

This report uses an entirely new method of classifying crystalline rocks, the F–S method, which is based on felsic-mafic and silica-saturation ratios (Young, 1989). The petrologic inferences that are suggested by the F–S method have been corroborated by two other, completely different methods, which use biotite analysis and the $\Sigma Al_2O_3+Na_2O+K_2O$ in the rock (Young, 1989).

In particular, my work strongly suggests that most, if not all, of the Proterozoic plutonic rocks in the Strawberry Lake area are metamorphic-metasomatic, rather than magmatic, in origin. These inferences may be disturbing to many geologists. If the inferences are invalid, no change need be made in the opinion of most "magmatists." However if the inferences are valid, or even partially valid, further inquiry along similar lines needs to be undertaken by other curious investigators. It is appropriate to keep in mind the following words of Roddick (1982):

> We can conclude safely that the logic applied to granitic rocks has not been rigorous. In spite of the inconclusiveness of the evidence, the view that most plutonic bodies were emplaced in a magmatic state is held by the overwhelming majority of geologists. Why this should be is almost as complex as the granite problem itself. Geologists, by and large, have no corner on perverse logic, and if at times they lean too heavily on the collective wisdom of individual ignorance, it is probably because the demands of their specialites force them, in peripheral fields, to rely more on the judgment of others than on the evidence. For some specialties, however, the origin of granite is not merely a peripheral aspect but a square-one assumption that must be correct if the subsequent edifice is not to collapse. Theories of ore deposition, geochronology and some geochemical arguments are peculiarly sensitive to any erosion of this assumption.
>
> Until the origin of granite is truly understood a large part of geological science has no reliable foundation.

If the results of this study were the only suggestion that the plutonic rocks of this area are largely metamorphic-metasomatic, rather than magmatic, perhaps the evidence would not be strong enough to justify a reappraisal of the origin of these rocks. However, I believe that many other geologic and petrographic observations of these rocks are more compatible with a metamorphic-metasomatic, rather than a magmatic, origin, and consequently that this reappraisal is not only justified but necessary.

The terms "metamorphic-metasomatic" and "magmatic" are from Gokhale (1968). "Magmatic" means the involvement of fully molten rock with no or variable amounts of phenocrysts. "Metamorphic-metasomatic" describes processes that range from solid-state reactions to in-situ partial melting (anatexis), in short, granitization. As Krauskopf (1967) pointed out,

> The important geological question, however, is not whether partial melting is possible—no one would seriously deny this—but on what sort of a scale the process operates in nature. Is partial melting a rare and local phenomenon to be found occasionally in areas of high-grade metamorphism, or is it a general process responsible for the origin of most granite plutons? Field observations should be the best approach to an answer, but unfortunately their interpretation is not wholly unambiguous. Relations at some granite contacts demonstrate beyond question that high-grade metamorphic rocks are locally transitional into igneous-appearing materials, but the great bulk of most large plutons shows no structures that give conclusive evidence as to origin. From field evidence alone most plutons may apparently have moved into their present positions as molten material from far below, or they may consist chiefly of material already present and made over into granitic rock by extreme metamorphism, or they may contain materials of both kinds. The question as to which process is the more important—the old argument between the 'granitizers' and the 'magmatists'—must wait for an ultimate solution on evidence other than field criteria.
>
> The current status of this controversy we have reviewed in an earlier discussion (Sec. 14–6). Here we need only emphasize that, from a purely chemical standpoint, a metamorphic origin of all granite out of crustal materials seems entirely possible. Some granite bodies may have remained practically static during the process of extreme metamorphism, while others may have moved as a liquid or partly liquid mass from deep levels into cooler parts of the crust and hence may show all the familiar phenomena of intrusion. Chemical support for the orthodox magmatic hypothesis, envisioning differentiation of granitic liquid out of primordial subcrustal material, is currently more difficult to muster because of experimentally demonstrated changes in the differentiation process at high pressures. But evidence is by no means all on the one side, so that characterization of granites in general as a product of extreme metamorphism is hardly warranted.

Metamorphic-metasomatic processes include ultrametamorphism and metamorphic differentiation. Metamorphic-metasomatic processes require relatively long periods of time and elevated temperatures and pressures; such conditions can not be duplicated in the laboratory. By contrast, magmatic processes, which usually produce textures that are unambiguous, are relatively short lived.

Chapter B has benefited from the reviews of Robert C. Pearson, Thomas P. Frost, and James E. Elliott. All the observations and views expressed, however, are mine.

THE F–S METHOD

The F–S method of classifying crystalline rocks is based on a felsic-mafic ratio,

$$F = \frac{SiO_2 + Na_2O + K_2O}{FeO + Fe_2O_3 + MgO + CaO}$$

and a silica-saturation ratio,

$$S = \frac{SiO_2}{Al_2O_3 + Na_2O + K_2O + MgO + CaO + FeO + Fe_2O_3} .$$

A full explanation of the rationale, validity, and use of the F–S method is contained in Young (1989). Because the F–S method is used extensively in this report, I will briefly describe its main features here. Figure 1 illustrates how the method is applied. If F and S of any crystalline rock are known, a compositional-equivalent name may be obtained as well as information about the degree of silica saturation of the rock. The compositional-equivalent names are derived from comparison with Nockolds' (1954) average rocks (Young, 1989).

From consideration of a test set of five metamorphic-metasomatic and seven magmatic (igneous) rocks (Young, 1989), I found that metamorphic-metasomatic rocks tend to show lower silica saturation(s) than magmatic rocks; in other words, metamorphic-metasomatic rocks plot left of the oversaturation trendline, whereas magmatic rocks plot right of the trendline. Therefore, inferences about the origin of quartz-bearing crystalline rocks should be obtainable with the F–S method. Several examples presented in Young (1989) demonstrate that the petrologic inferences are consistent with field data.

Two independent methods support and corroborate the F–S method (Young, 1989). One method involves biotite in the rock; Gokhale (1968) has shown that biotite from magmatic (igneous) rocks tends to contain less Mg than biotite from metamorphic-metasomatic rocks. The other method demonstrates that the $\Sigma Al_2O_3+Na_2O+K_2O$ tends to be less than 22 percent in granitic magmatic rocks and greater than 23 percent in granitic metamorphic-metasomatic rocks; values between 22 and 23 percent are generally equivocal.

PETROLOGY

The petrology of the crystalline rocks of the Strawberry Lake area is discussed in the same order as in Chapter A of this bulletin, which described the petrography and geochemistry of these rocks. First, comparisons of the results of classifying these rocks using the Johannsen (1939) and Streckeisen (1976, 1979) classifications and the F–S method are made. Then, inferences about the origin of these rocks based on the F–S method and $\Sigma Al_2O_3+Na_2O+K_2O$ are discussed. Finally, geologic and petrographic observations bearing on the origin are covered.

Boulder Creek Granodiorite

Table 1 compares the classification of the Boulder Creek Granodiorite in the Strawberry Lake area using the Johannsen (1939) and Streckeisen (1976) classifications and the F–S method. The F–S method suggests that the Boulder Creek Granodiorite in the Strawberry Lake area would be more accurately classified as a tonalite than a granodiorite.

The six chemically analyzed samples of Boulder Creek Granodiorite are plotted on an F–S diagram in figure 2. For comparison, the average of 42 chemically analyzed samples of Boulder Creek Granodiorite in the Boulder Creek batholith (Gable, 1980) is also plotted. This comparison shows that Boulder Creek Granodiorite in the Strawberry Lake area is considerably more mafic than Boulder Creek Granodiorite in the batholith—even the most felsic sample of Boulder Creek Granodiorite in the Strawberry Lake area is not as felsic as the average Boulder Creek Granodiorite in the batholith. The two most felsic samples from the Strawberry Lake area (fig. 2) plot on the high-S side of the oversaturation trendline—this position is indicative of magmatic conditions.

More support for this inference is shown by figure 3, where Boulder Creek Granodiorite is plotted on the $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram. Both figures 2 and 3 suggest that more magmatic conditions were attained by more felsic portions of the precursor Boulder Creek Granodiorite. This is a reasonable suggestion because the felsic part of the precursor (biotite gneiss) would achieve partial melting before the mafic part, when and if higher pressure-temperature conditions were attained. The two most felsic (highest SiO_2) samples plot on the magmatic side of figure 3. These two samples are the only samples of peraluminous Boulder Creek Granodiorite. The more mafic samples and the average of 35 samples of Boulder Creek Granodiorite in the batholith fall in the equivocal part of the diagram (22–23 percent).

Biotite in the Boulder Creek Granodiorite may be helpful as an indicator of the mode of origin of the host rock. Gable (1980) presented seven chemical analyses of biotites from the Boulder Creek batholith and chemical analyses of the rocks from which the biotite was separated. Using the method of Gokhale (1968), all seven biotites plot in the metamorphic-metasomatic field. Furthermore, all seven rocks from which the biotites were removed plot as metamorphic-metasomatic in both the F–S method and the $\Sigma Al_2O_3+Na_2O+K_2O$ method.

Where the Boulder Creek Granodiorite is foliated (pl. 1 of Chapter A of this bulletin), the foliation attitude conforms to that of the surrounding biotite-gneiss country rock. Even more indicative of metamorphic-metasomatic conditions are the relict enclaves of biotite gneiss within the pluton of Boulder Creek Granodiorite. The foliations in the these enclaves are conformable with that of host Boulder Creek Granodiorite or nearby biotite-gneiss country rock. If the Boulder Creek Granodiorite had been emplaced as a gross intrusion, it would be difficult to account for not only the foliation pattern but also the necessary space.

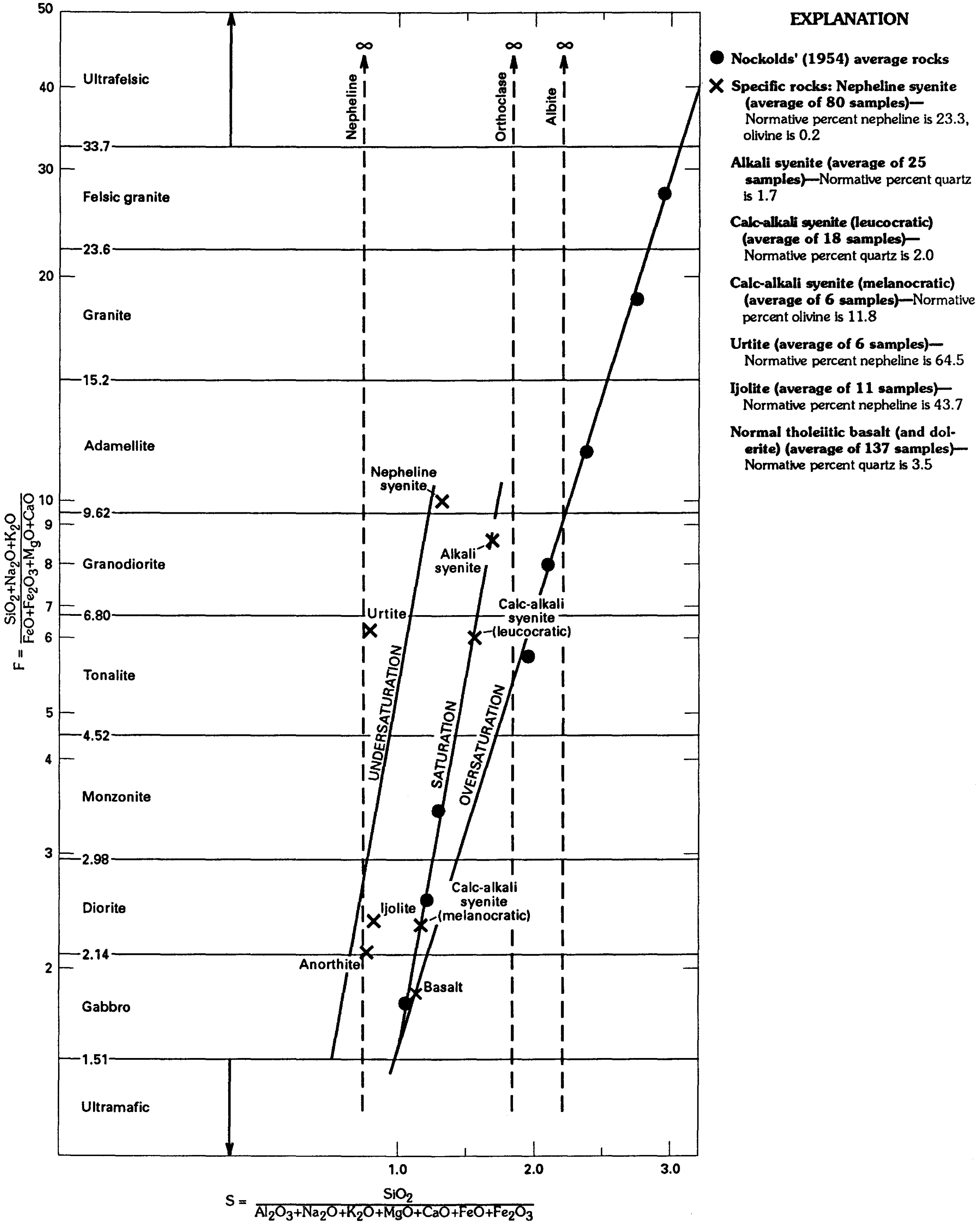


Figure 1. F–S diagram of crystalline rocks. F, felsic-mafic ratio; S, silica-saturation ratio. All oxide values are in weight percent. Data from Nockolds (1954) for average rocks (dots) and other rocks (described below).

Table 1. Classification of rock types of the Boulder Creek Granodiorite, Strawberry Lake area

[=, equals]

Johannsen (1939) method	Streckeisen (1976) method	F-S method[1] (Combined F's from specific gravity and modal analysis)	F-S method[1] (Chemically analyzed samples)
15 granodiorite 8 tonalite 1 adamellite	13 granodiorite 10 tonalite 1 monzogranite	15 tonalite 6 monzonite 2 granodiorite 1 adamellite	5 tonalite 1 monzonite
		Average F = 5.75 (tonalite).	Average F = 5.15, average S = 1.75 (tonalite).

[1]Rock names are compositional-equivalent names.

Additional compelling evidence for a metamorphic-metasomatic origin for the Boulder Creek Granodiorite is the similarity in composition of the biotite gneiss (F=5.34) and the Boulder Creek Granodiorite (F=5.15), both of which are tonalitic in composition (Chapter A of this bulletin). The F–S classification points explicitly to this similarity. The composition of an intruding magma would probably not match that of the host rock unless the intruding magma originated by the melting of identical host rock.

Petrographic evidence favors a metamorphic-metasomatic origin for the Boulder Creek Granodiorite in the Strawberry Lake area. Many, if not most, zircons in the Boulder Creek Granodiorite contain older zircon cores that are surrounded by recrystallized zoned or unzoned overgrowths of zircon. Stern and others (1971) called these zircons noneuhedral and considered them to have been inherited by assimilation, in contrast with euhedral, magmatic zircons. Both types of zircon are found in the Boulder Creek Granodiorite of the Strawberry Lake area. Thus, zircon morphology is consistent with a metamorphic-metasomatic history of the Boulder Creek Granodiorite; that is, many zircons were inherited from the country rock (biotite gneiss), and some crystallized as a result of partial melting.

Some apatite in the Boulder Creek Granodiorite shows weak radiation-damage halos in biotite, but other grains of apatite do not; the difference is evidently due to variation in uranium content among the apatite population. This is not a likely circumstance for a magma, but instead, suggests the heterogeneous environment of a metamorphic-metasomatic origin.

Biotite in the Boulder Creek Granodiorite locally contains many small grains of sphene, and some biotite shows borders of small grains of sphene. These occurrences of sphene suggest that temperatures were not high enough for biotite to keep Ti in solid solution during crystallization.

Thus, geologic relations, similar composition of host rock (biotite gneiss) and the Boulder Creek Granodiorite, petrographic observations, and, most of all, evidence from included biotite, the F–S method, and the method of $\Sigma Al_2O_3 + Na_2O + K_2O$ in the rock suggest that a metamorphic-metasomatic origin for the Boulder Creek Granodiorite in the Strawberry Lake area is reasonable.

Granitic Enclaves in Boulder Creek Granodiorite

Granitic enclaves in the Boulder Creek Granodiorite range from 1 m to greater than 1 km in greatest dimension. The range in rock type of these enclaves is shown in table 2, which describes them according to three classifications. For rocks of this composition (granite to adamellite), the three methods are in reasonable agreement. These rocks fit the description of the Twin Spruce Quartz Monzonite of Gable (1980) in their fine grain size, chemical composition, and petrography. Gable (1980, p. 27) noted that the Twin Spruce Quartz Monzonite forms not only mappable bodies but also local thin lenses that are commonly intermixed with the granodiorite or are gradational into it. Gable (1980, p. 27) also stated that the Twin Spruce Quartz Monzonite is in part the same age as upper Boulder Creek Granodiorite and in part younger than Boulder Creek Granodiorite. From these two observations of Gable (1980), it is clear that the Boulder Creek Granodiorite and the Twin Spruce Quartz Monzonite demonstrate an intimate and genetic interdependency.

Gable (1980) presented chemical analyses of nine biotites from the Twin Spruce Quartz Monzonite. Again, using the method of Gokhale (1968), every biotite plots in the metamorphic-metasomatic field. Complications arise, however, because six of the biotites come from

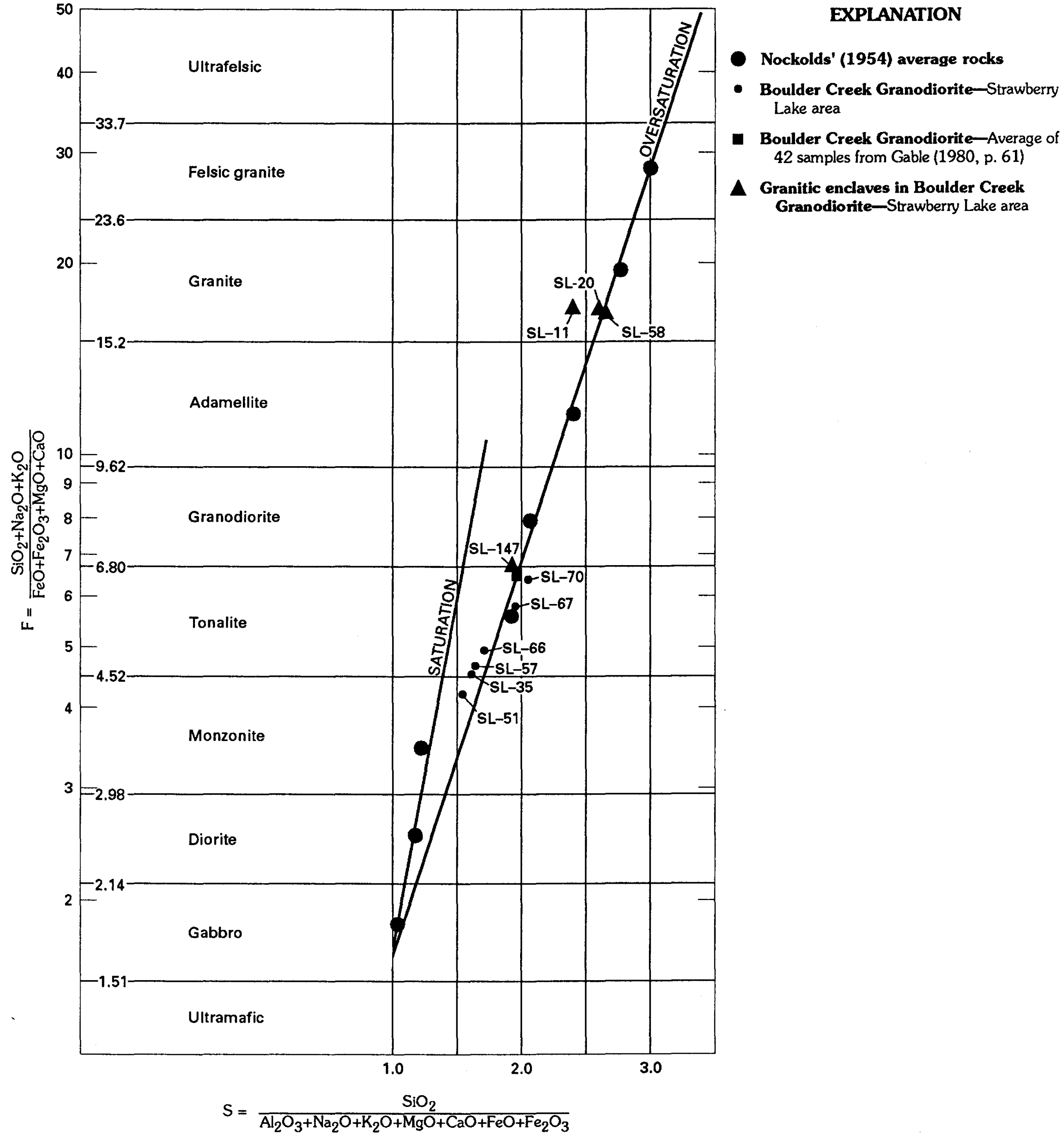
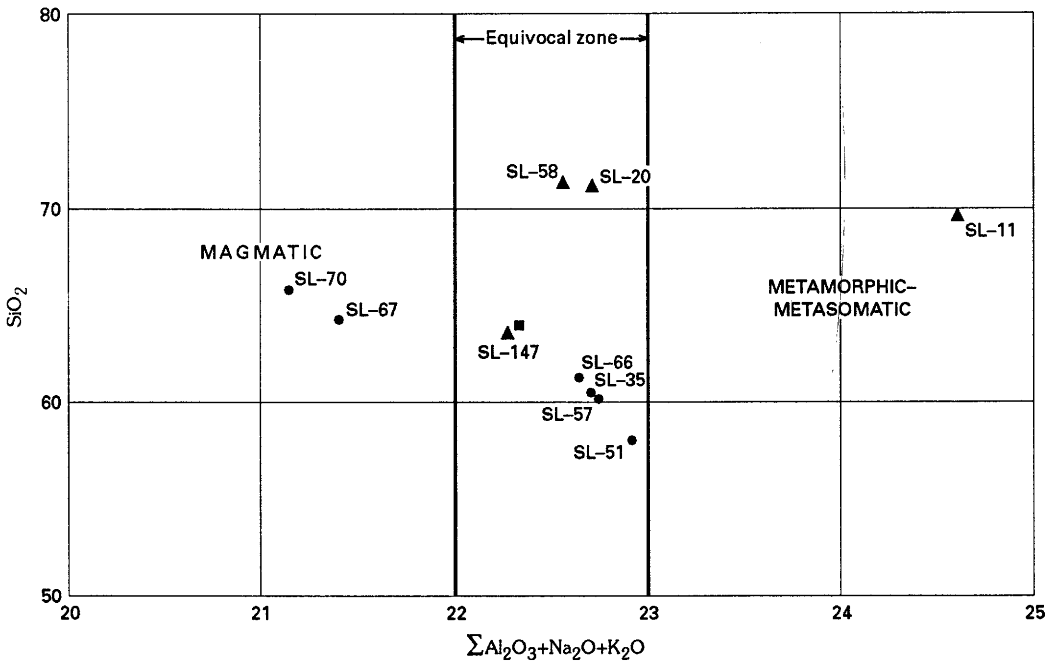


Figure 2. F–S diagram of Boulder Creek Granodiorite and its granitic enclaves. F, felsic-mafic ratio; S, silica-saturation ratio.

Twin Spruce Quartz Monzonite (average 39.5 percent modal quartz) enclaves in metasedimentary rock and three of the biotites come from Twin Spruce Quartz Monzonite (average 21.1 percent modal quartz) enclaves in Boulder Creek Granodiorite. The reason for bringing modal quartz into the picture is that four of the six samples of the Twin Spruce Quartz Monzonite enclaves in metasedimentary rock plot as igneous in both the F–S and $\Sigma Al_2O_3+Na_2O+K_2O$ methods, which, I believe, is due to the excess quartz. On the other hand, all three samples of the Twin Spruce Quartz Monzonite enclaves in Boulder Creek Granodiorite plot as metamorphic-metasomatic using the F–S and $\Sigma Al_2O_3+Na_2O+K_2O$ methods.



EXPLANATION

- ● **Boulder Creek Granodiorite**—Strawberry Lake area
- ■ **Boulder Creek Granodiorite**—Average of 42 samples from Gable (1980, p. 61)
- ▲ **Granitic enclaves in Boulder Creek Granodiorite**—Strawberry Lake area

Figure 3. $\Sigma Al_2O_3 + Na_2O + K_2O$ versus SiO_2 diagram of Boulder Creek Granodiorite and its granitic enclaves.

The four chemically analyzed samples in this report are plotted on an F–S diagram in figure 2, which shows that three are very similar in composition (granite) and the fourth is close to the line between tonalite and granodiorite. All four samples are peraluminous. Sample SL–11 contains 54 percent modal microcline and shows the least oversaturation of any sample on the diagram. Sample SL–11 shows the highest $\Sigma Al_2O_3 + Na_2O + K_2O$ in figure 3 and demonstrates a tendency toward saturation, which is indicative of a process similar to the formation of small pegmatites by replacement (notable enrichment in alkali feldspar). The other three samples are more equivocal.

The granitic enclaves in the Boulder Creek Granodiorite appear to be completely surrounded by their host. Of course their contacts with their host at depth cannot be seen, but many enclaves are so small that pipelike extensions at depth can be discounted, which means that they are enclaves and not intrusions into the Boulder Creek Granodiorite. Some possible explanations for the presence of these enclaves are the following:

1. The enclaves were carried along as immiscible magmas within the host magma of Boulder Creek Granodiorite as the pluton of Boulder Creek Granodiorite was being intruded into the country rock of biotite gneiss:
   (a) I have not seen any evidence of wholesale intrusion of Boulder Creek Granodiorite into the biotite gneiss.
   (b) Other data, which I discussed previously, do not support a full magmatic history for the Boulder Creek Granodiorite.
   (c) The physical process implied by this explanation should attenuate and distort the "carried along" immiscible magmas.
   (d) For the granitic enclaves to be magmatic differentiates requires a fully magmatic system, which necessitates high temperatures for which there is no evidence.

2. The enclaves are xenoliths (country rock not completely assimilated by magma):
   (a) Objections (a) and (b) for explanation 1 apply here also.
   (b) No evidence for any assimilation of these granitic enclaves has been found.

Table 2. Classification of rock types of the granitic enclaves in the Boulder Creek Granodiorite, Strawberry Lake area

[=, equals; >, greater than]

Johannsen (1939) method	Streckeisen (1976) method	F-S method[1] (From modal analysis)	F-S method[1] (Chemically analysed samples)
6 granite	7 syenogranite	5 adamellite	3 granite
2 adamellite	3 monzogranite	3 granite	1 tonalite
2 leucoadamellite	1 alkalifeldspar granite.	3 granodiorite	
1 kaligranite		1 ultrafelsic granite	
1 granodiorite	1 granodiorite		
		Average F > 14.7 (adamellite or more felsic).	Average F = 14.4, average S = 2.38 (adamellite).

[1]Rocks names are compositional-equivalent names.

(c) No country rock matches the granitic enclaves.

3. The host pluton represents largely granitized or ultrametamorphic rock (does not exclude local melting), and the enclaves are relicts of country rock that resisted granitization or ultrametamorphism.

(a) Objections (b) and (c) of explanation 2 apply here also.

4. The process of enclave formation (metamorphic differentiation?) is an outgrowth of the metamorphic-metasomatic processes during formation of the host. Local or partial melting is not excluded.

(a) The enclaves are genetically related to their host by the following:

(1) The enclaves have relatively high apatite and sphene contents as does their host (table 17 of Chapter A of this bulletin).

(2) Rb:Sr ratios of the enclaves are more similar to Rb:Sr ratios of the host than to Rb:Sr ratios of other granitic rocks in the area (table 16 of Chapter A of this bulletin).

(b) Other than by metamorphic differentiation, it is difficult to explain why the enclaves

(1) show high K_2O:Na_2O ratios and enrichment in Ba and

(2) show high Th:U ratios and enrichment in LREE (light rare-earth elements).

Explanation 4 fits the data the best.

Silver Plume Granite

The Silver Plume Granite in the Strawberry Lake area is an acid or felsic type granite as is made clear in table 3. To further illustrate how felsic the Silver Plume Granite in the Strawberry Lake area is, the seven chemically analyzed samples are plotted on figure 4. For comparison, data on Silver Plume Granite from other areas are also plotted on the same diagram: GSP–1, Flanagan (1976); average of five samples, Lovering and Tweto (1953); and average of ten samples, Anderson and Thomas (1985). The Silver Plume Granite in the Strawberry Lake area is the most felsic of all.

Without exception all plots of the Silver Plume Granite fall on the low-S side of the oversaturation trendline, which may be an indication of metamorphic-metasomatic origin. Further support for that inference may be seen in figure 5, which shows that all the Silver Plume Granite data points have high or equivocal $\Sigma Al_2O_3 + Na_2O + K_2O$ (an indication of metamorphic-metasomatic conditions or derivation from pelitic metasediments or both). The three data points from chemically analyzed biotite from Silver Plume Granite in Young (1989) all fall in the metamorphic-metasomatic field also. Thus, three different chemical methods are in agreement on the metamorphic-metasomatic origin of the Silver Plume Granite, small though the number of samples may be.

Certain structural features in the Silver Plume Granite are more simply explained by a metamorphic-metasomatic history than by a magmatic history. For example, the foliation in the biotite-gneiss enclaves in the Silver Plume Granite generally conforms to the foliation in surrounding biotite gneiss (pl. 1 of Chapter A of this bulletin). These relicts of biotite gneiss would not show foliation conformity if they were xenoliths that had been carried along in an invading magma. Similarly, planar

Table 3. Classification of rock types of the Silver Plume Granite, Strawberry Lake area

[=, equals; >, greater than]

Johannsen (1939) method	Streckeisen (1976) method	F-S method[1] (From modal analysis)	F-S method[1] (Chemically analyzed samples)
12 leucoadamellite	22 monzogranite	12 adamellite	4 felsic granite
11 adamellite	8 syenogranite	10 ultrafelsic granite	3 granite
6 granite	1 quartz monzonite	9 granite	
2 leucogranite	1 granodiorite	1 granodiorite	
1 granodiorite			
		Average F > 20.8 (granite or more felsic).	Average F = 23.8, average S = 2.71 (felsic granite).

[1]Rocks names are compositional-equivalent names.

orientation of tabular microcline laths in the Silver Plume Granite (pl. 1 of Chapter A of this bulletin) conforms reasonably well with foliation in nearby enclaves of biotite gneiss. I think that this orientation is probably due to feldspathization in conformity with regional foliation rather than to flow structure in a magma.

Mineralogical features in the Silver Plume Granite favor a metamorphic-metasomatic origin rather than a magmatic origin. For example, biotite:muscovite ratios are highly variable from much greater than 1 to much less than 1. Such variability is more reasonably explained by heterogeneity of metasedimentary source material than by exotic magmatic (more or less homogeneous) intrusion. Zircons are of two types in the Silver Plume Granite; most are single, small euhedral crystals, but some show zoned or unzoned, recrystallized overgrowths on older zircon cores. The single, euhedral zircons may represent crystallization from an ultrametamorphic condition; the recrystallized zircons obviously inherited cores from older, precursor material. Zircon content of the Silver Plume Granite is about twice that of the surrounding biotite gneiss (table 17 of Chapter A of this bulletin; Schroeder, 1984). This fact is consistent with new crystallization and recrystallization of zircon in the Silver Plume Granite, which added zircon mass to the inherited portion.

Koschmann (1960) was one of the first geologists to point out that the Silver Plume Granite in the Tenmile Range, Colo., and in the Montezuma area of the Front Range, gave evidence of having originated from local centers of fusion or recrystallization. This perception especially applied to small, ductless, isolated bodies that are surrounded by metamorphic rocks.

Much later, Anderson and Thomas (1985) concluded that the Silver Plume and St. Vrain batholiths were derived from largely metasedimentary crust. Their scenario, however, involved generation of a magma from an oxidized, peraluminous quartzofeldspathic source at a depth of 36 km or more (pressure of at least 10 kbar) and emplacement at a depth as shallow as 8–9 km (pressure of 2.3 kbar) at a P_{H_2O} of 487–560 bar and a temperature of 740–760 °C. I do not accept Anderson and Thomas' (1985) hypothesis of emplacement or intrusion of a body of magma of batholithic size with all its attendant space problems, especially in an area of compressed metamorphic rocks. Moreover, such a hypothesis does nothing to explain the small isolated bodies of Silver Plume Granite mentioned by Koschmann (1960).

DePaolo (1981) concluded from a study of Nd-Sm characteristics that the Silver Plume-type magmas of the Colorado Front Range were crustally derived. Fountain and others (1983) also suggested a crustal source for the Silver Plume and Sherman Granites and the granite of the Log Cabin batholith.

Thus there seems to be general agreement on the source rocks of the Silver Plume Granite. The point of contention, however, is whether the Silver Plume Granite represents emplacement (intrusion) of a magma or whether most, if not all, of the granite is actually transformed pelitic metasediments with a small metavolcanic component as a result of metamorphic-metasomatic processes. Partial or minor melting is not excluded from these metamorphic-metasomatic processes.

Granitic Enclaves in Silver Plume Granite

The five granitic enclaves in the Silver Plume Granite are small (largest dimension is about 75 m) and generally elongate (pl. 1 of Chapter A of this bulletin). Compared to their host they are twice as thoriferous, more melanocratic, and slightly finer grained. The enclaves show a subtle crystalloblastic texture. According to the Johannsen (1939) classification they are adamellites, and according to the Streckeisen (1976)

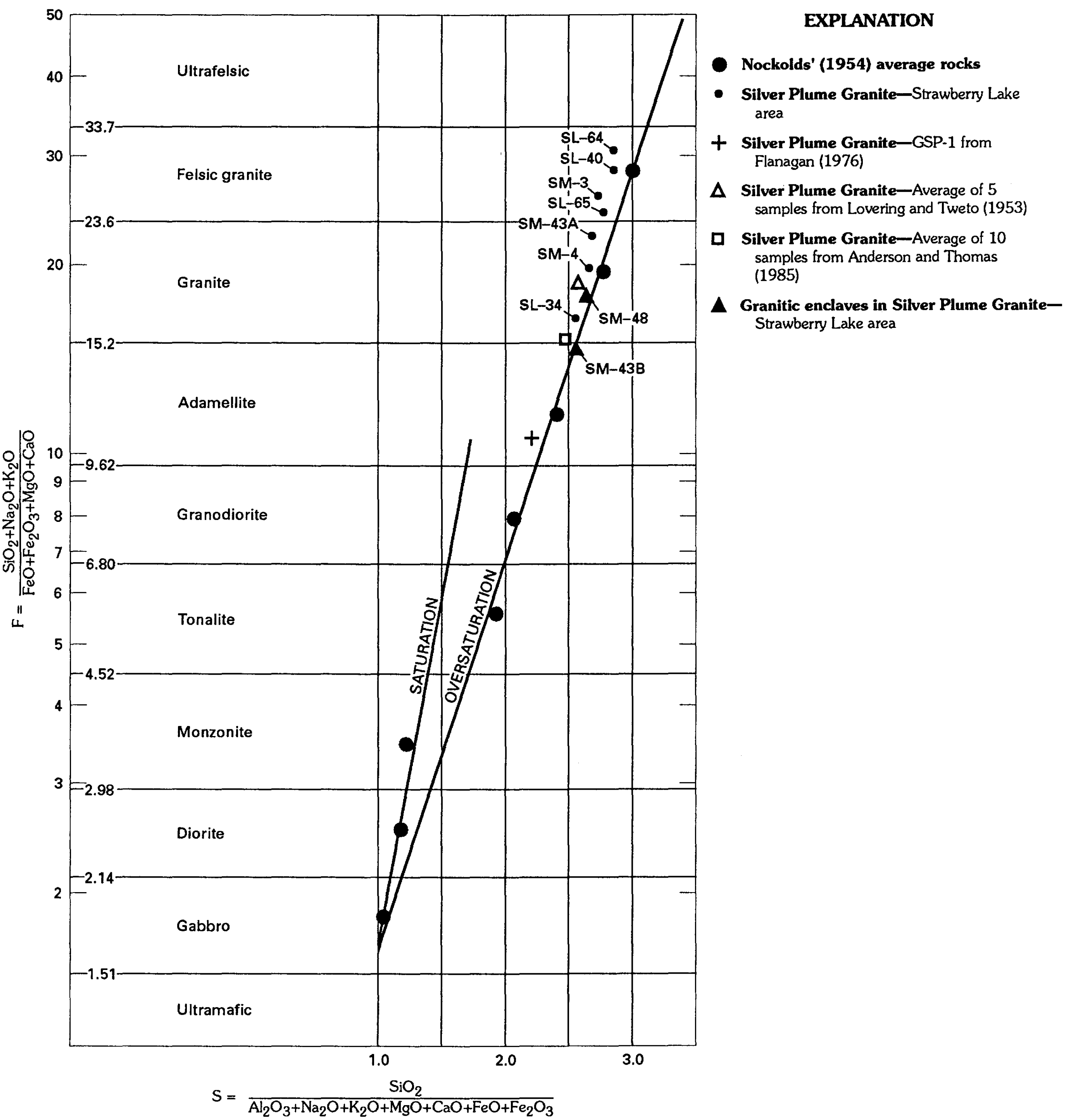
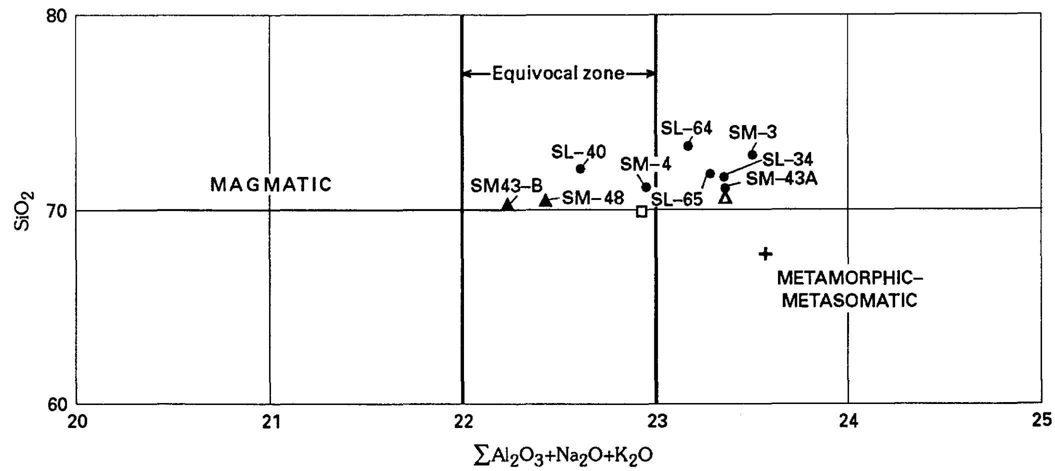


Figure 4. F–S diagram of Silver Plume Granite and its granitic enclaves. F, felsic-mafic ratio; S, silica-saturation ratio.

classification they are monzogranites. According to the F–S method one is a granite and one is an adamellite (close to granite). On figure 4 they appear somewhat more mafic than their host.

Sample SM–43B, the adamellite, plots on the high-S side of the oversaturated trendline in figure 4; sample SM–48, the granite, plots slightly on the low-S side of the oversaturated trendline. From this tendency toward higher S, more so than any of the samples of Silver Plume Granite, one might infer that these granitic enclaves represent sites of partial melting. Indeed, in figure 5, which shows $\Sigma Al_2O_3 + Na_2O + K_2O$, the position of SM–43B appears possibly more magmatic than that of SM–48. Of course, both positions are in the equivocal zone of 22–23 percent, but it is significant that their plots are to the left of the Silver Plume Granite plots.



EXPLANATION

- ● **Silver Plume Granite**—Strawberry Lake area
- + **Silver Plume Granite**—GSP-1 from Flanagan (1976)
- △ **Silver Plume Granite**—Average of 5 samples from Lovering and Tweto (1953)
- □ **Silver Plume Granite**—Average of 10 samples from Anderson and Thomas (1985)
- ▲ **Granitic enclaves in Silver Plume**—Strawberry Lake area

Figure 5. $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram of Silver Plume Granite and its granitic enclaves.

There are more similarities than differences between the granitic enclaves in the Silver Plume Granite and the granitic enclaves in the Boulder Creek Granodiorite. The similarities common to both enclaves, compared to their hosts, are higher Th:U and K_2O:Na_2O ratios and enrichment in Th and LREE. The main difference is that the granitic enclaves in the Silver Plume Granite are more mafic than their host and the granitic enclaves in the Boulder Creek Granodiorite are more felsic than their host.

Biotite Gneiss

It is not surprising that a highly variable rock unit such as biotite gneiss should show such diversity on the F–S diagram (fig. 6). The three chemically analyzed samples range from the compositional equivalent of monzonite (between saturated and undersaturated) to very oversaturated tonalite (close to granodiorite). This range in composition includes all the compositional varieties of Boulder Creek Granodiorite. Similar compositions were reported for an average of ten samples of sillimanitic biotite gneiss and schist associated with the Boulder Creek Granodiorite batholith (Gable, 1980, p. 61). This average is also plotted on figure 6 along with the average of six samples of Boulder Creek Granodiorite from the Strawberry Lake area to show the prevalence of tonalitic composition. Therefore, the derivation of the Boulder Creek Granodiorite from the biotite gneiss is not only plausible, it is almost mandatory. It is highly unlikely that the Boulder Creek Granodiorite in the Strawberry Lake area intruded its way, as a single pluton, into its present position—the space problem is a formidable barrier. Transformation by metamorphic-metasomatic processes of biotite gneiss into Boulder Creek Granodiorite with local, partial melting solves the space problem, and the compositional similarity of the two rock types obviates the need to add other material.

Plotting the points of the three analyzed samples of biotite gneiss on the $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram (fig. 7) also shows the heterogeneous nature of the raw materials from which the Boulder Creek Granodiorite may have been produced. In fact, one sample (SL–71) of the biotite gneiss plots on the magmatic side of figure 7, whereas averages of this rock type, both from the Strawberry Lake area and the Boulder Creek batholith, plot on the metamorphic-metasomatic side. Figure 7 may indicate that the source of the biotite gneiss varied from metamorphosed, oversaturated igneous materials (volcanic ash, tuff) to metamorphosed, undersaturated pelitic materials.

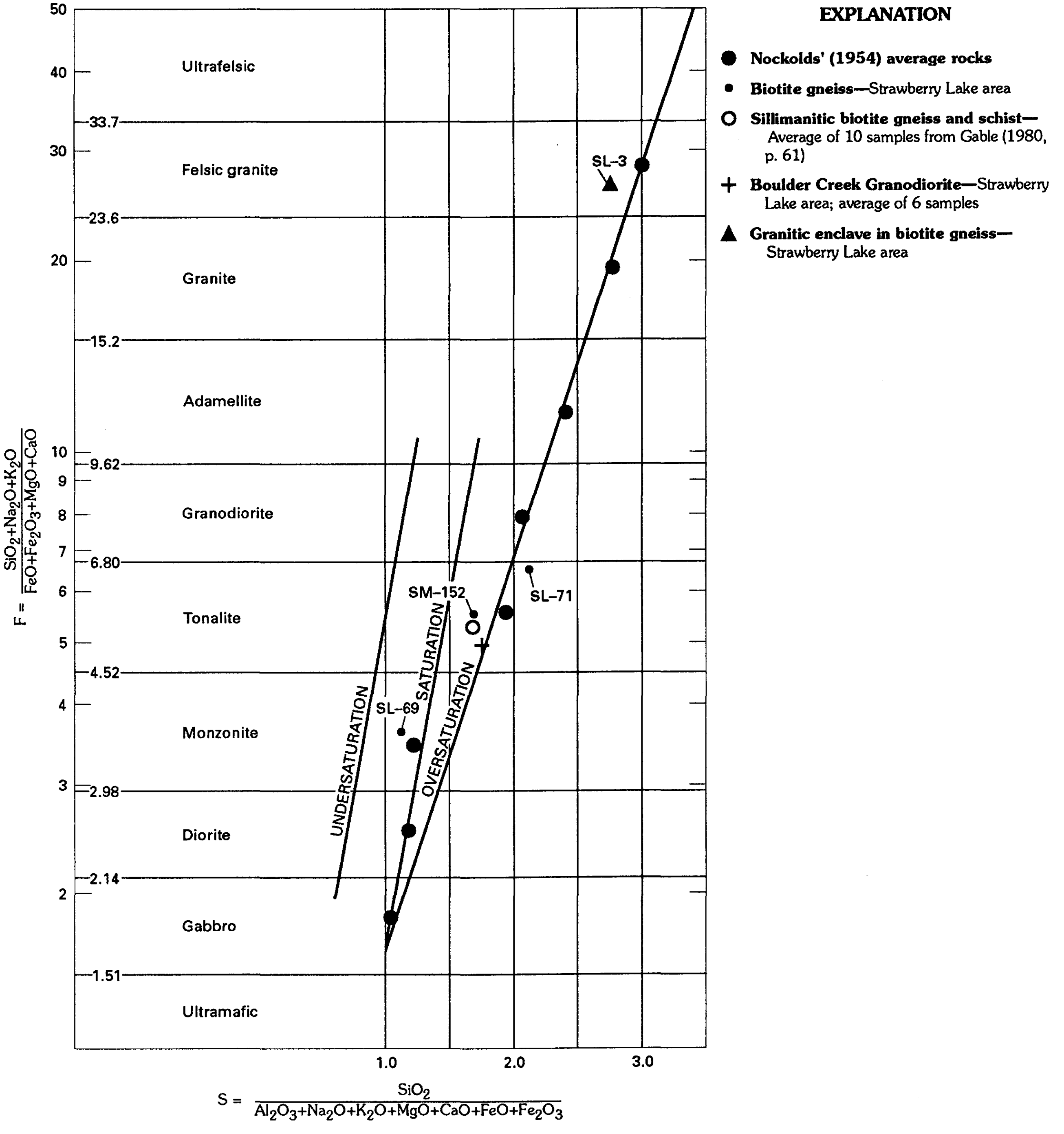


Figure 6. F–S diagram of biotite gneiss and a granitic enclave. F, felsic-mafic ratio; S, silica-saturation ratio.

Granitic Enclaves in Biotite Gneiss

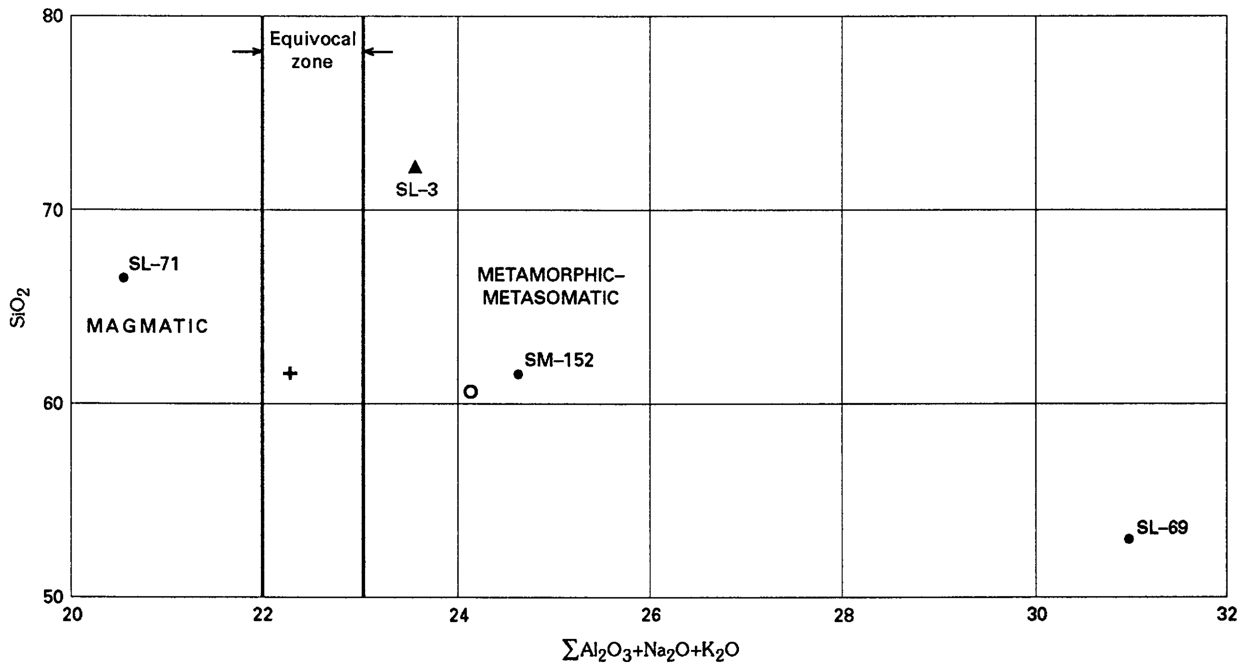
Granitic enclaves in the biotite gneiss vary in size from small (about 1 m) to large (several kilometers). The larger granitic enclaves themselves contain enclaves or bodies of biotite gneiss, hence they are not homogeneous bodies of granite. The range in rock type of the granitic enclaves is shown in table 4. The plot of the one chemically analyzed sample of a granitic enclave in biotite gneiss on the F–S diagram (fig. 6) and on the $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram (fig. 7) suggests that it is metamorphic-metasomatic in origin. What is more revealing is that its position on both

Table 4. Classification of rock types of the granitic enclaves in the biotite gneiss, Strawberry Lake area

[=, equals; >, greater than]

Johannsen (1939) method	Streckeisen (1976) method	F-S method[1] (From modal analysis)	F-S method[1] (Chemically analyzed sample)
3 leucoadamellite	6 monzogranite	3 ultrafelsic	F = 26.5, S = 2.72 (felsic granite).
3 adamellite	1 syenogranite	2 adamellite	
1 granite	1 granodiorite	2 granodiorite	
1 granodiorite		1 tonalite	
		Average F > 18.6 (granite or more felsic).	

[1]Rocks names are compositional-equivalent names.



EXPLANATION

- ● **Biotite gneiss**—Strawberry Lake area
- O **Sillimanitic biotite gneiss and schist**—Average of 10 samples from Gable (1980, p. 61)
- + **Boulder Creek Granodiorite**—Strawberry Lake area; average of 6 samples
- ▲ **Granitic enclave in biotite gneiss**—Strawberry Lake area

Figure 7. $\Sigma Al_2O_3 + Na_2O + K_2O$ versus SiO_2 diagram of biotite gneiss and a granitic enclave.

diagrams is very close to that of Silver Plume Granite. In addition, both composition and mineralogy of the granitic enclaves are similar to those of the Silver Plume Granite. A notable difference, however, is that the granitic enclaves are finer grained.

The granitic enclaves may be precursor Silver Plume Granite that has been subjected to the same metamorphic-metasomatic conditions that produced the pluton of Silver Plume Granite, but the smaller size of the enclaves limited grain-size development.

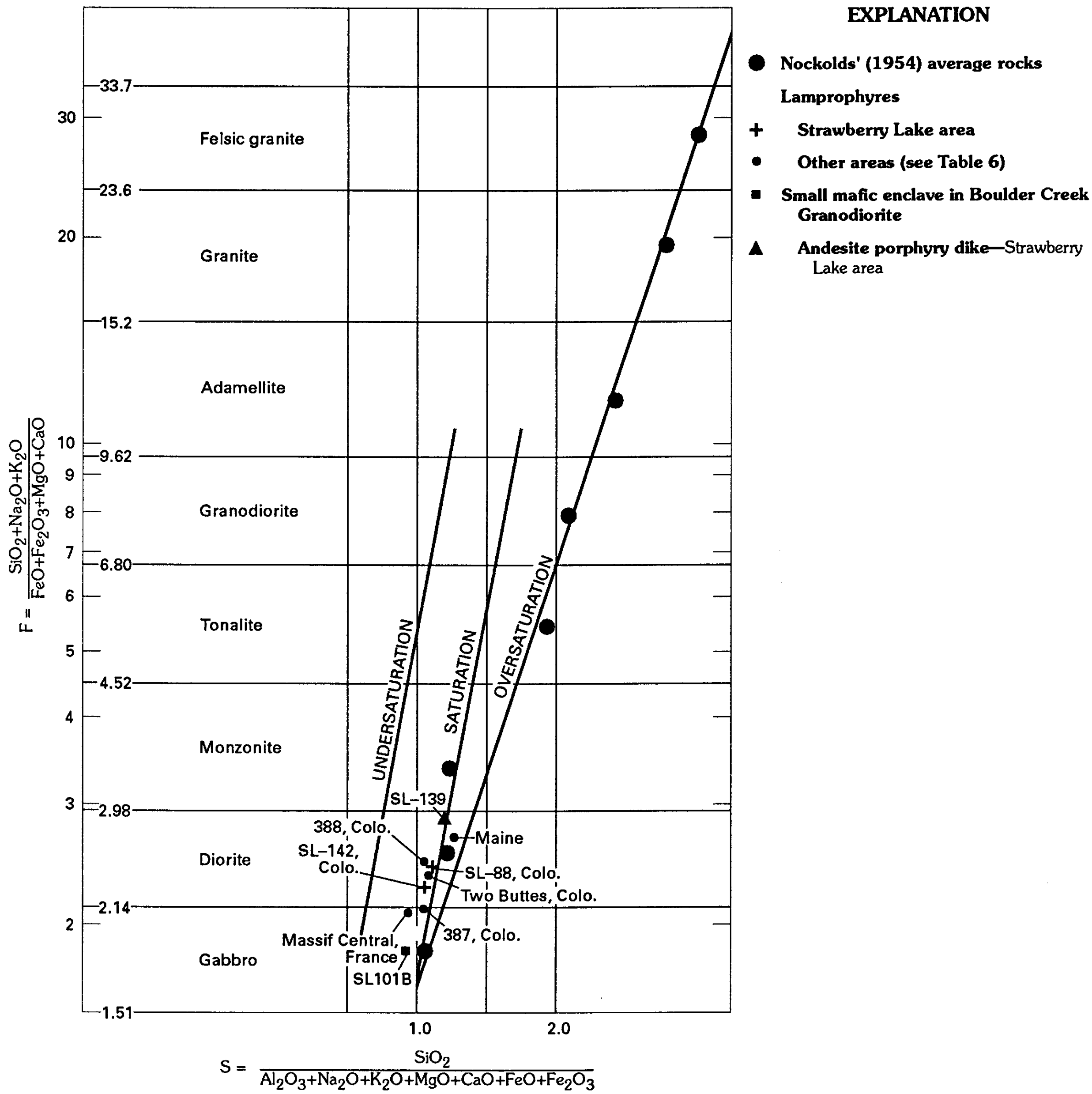


Figure 8. F–S diagram of biotite lamprophyres and other mafic rocks. F, felsic-mafic ratio; S, silica-saturation ratio.

Biotite Lamprophyre Enclaves in Boulder Creek Granodiorite

Enclaves of biotite lamprophyre, which are tens of meters in length, occur only in the Boulder Creek Granodiorite, hence it is reasonable to suspect a genetic connection between the two rock types. The biotite lamprophyre is compared by using three classifications in table 5. The plot of the two chemically analyzed samples of biotite lamprophyre on an F–S diagram (fig. 8) shows that both are saturated and compositionally equivalent to diorite; sample SL–142 has a tendency toward undersaturation. Several other lamprophyres from Colorado and elsewhere are plotted on figure 8; the ones from Colorado cluster fairly closely. Chemical analyses are given in table 6. The samples (SL–88 and SL–142) from the Strawberry Lake area are the most enriched in K_2O, P_2O_5, and BaO.

Figure 9 shows that all the lamprophyres plot on the magmatic side of the $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram except the vaugnerite from France. The position of the vaugnerite, however, does not mean that it is not magmatic, but rather that it has a strong tendency toward undersaturation (evidenced by the lowest

Table 5. Classification of rock types of the biotite lamprophyre, Strawberry Lake area

[=, equals]

Johannsen (1939) method	Streckeisen (1979) method	F-S method[1] (From modal analysis)	F-S method[1] (Chemically analyzed samples)
3 mela-kalisyenite 2 mela-sodaclase syenite.	5 minette-vogesite	4 diorite 1 gabbro	2 diorite
		Average F = 2.14 (between diorite and gabbro).	Average F = 2.38, average S = 1.11 (diorite).

[1]Rocks names are compositional-equivalent names.

$SiO_2$and highest Al_2O_3 values of these lamprophyres). Figure 8 shows that the vaugnerite has the strongest degree of undersaturation of the compared lamprophyres.

The interstice-filling, allotriomorphic microcline and microcline microperthite indicates that the lamprophyres of the Strawberry Lake area attained a magmatic state. Grain size remained small (generally less than 1 mm), perhaps due to relatively rapid crystallization.

It is not necessary to call upon an intrusion of foreign magma to form the dikelike bodies of biotite lamprophyre in the Boulder Creek Granodiorite. All components of the biotite lamprophyres could have been obtained from its host. This is convincingly shown by the similarity in accessory minerals between the biotite lamprophyre and its host (table 17 of Chapter A of this bulletin), except for the greater enrichment of sphene, apatite, and epidote in the lamprophyre. The most outstanding characteristic of the biotite lamprophyre, at least in the Strawberry Lake area, is its propensity for unusual enrichment of many elements. A quantitative measure of this propensity, called coefficient of trace element accumulation (Shaw, 1961), indicates that the biotite lamprophyre is enriched in 21 elements four times more than its host, Boulder Creek Granodiorite (see Geochemistry section in Chapter A of this bulletin). Potassium enrichment in the biotite lamprophyre may have been in two stages: most of the enrichment occurred as anhedral microcline and microcline microperthite, and the remainder of the enrichment occurred as delicate veins of the same minerals throughout some parts of the lamprophyre.

Potassium enrichment may represent endstage ultrametamorphism in the Boulder Creek Granodiorite. The granitic enclaves in the Boulder Creek Granodiorite also show pronounced potassium enrichment.

Small Mafic Enclaves in Boulder Creek Granodiorite

The small (generally 1–20 cm) mafic enclaves in the Boulder Creek Granodiorite are roundish to discoid, fine grained, and notably similar in appearance. They are abundant locally but are not omnipresent. Sample SL–101B, which is a chemically analyzed representative of the small mafic enclaves, is classified as a melatonolite or vaugnerite in the Johannsen (1939) classification and as a quartz diorite in the Streckeisen (1976) classification. The thin section of vaugnerite that Johannsen (1939) had at his disposal contained only 1–2 percent of orthoclase, whereas the vaugnerite described by Sabatier (1980) contained 5–10 percent perthitic orthoclase (table 6). The biotite lamprophyres (minette-vogesite) of this report contain 25–46 percent potash feldspar. In the F–S classification sample SL–101B appears as a compositional equivalent of gabbro, which is somewhat undersaturated ($F=1.85$, $S=0.94$; fig. 8). Sample SL–101B plots on the magmatic side of the $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram (fig. 9).

The small mafic enclaves are too homogenous to be xenoliths in the Boulder Creek Granodiorite, and moreover, no rocks that fit their description occur in the country rock (biotite gneiss). This last point was also made by Vernon (1984), who, in discussing the origin of these small mafic enclaves in intermediate plutonic rocks, believed them to be mainly trapped globules of hybrid magma.

The following facts and interpretations (in parentheses) indicate to me that the small mafic enclaves in the Boulder Creek Granodiorite are restites, that is, they were geochemically immobile parts of a rock during partial mobilization (anatexis) of rock components:

Table 6. Comparative chemical analyses of lamprophyres

Component	Sample A	B	C	D	E	F	G
SiO_2	50.0	47.7	50.41	48.8	50.7	52.26	46.73
Al_2O_3	11.2	11.7	12.27	12.5	13.3	10.63	17.38
Fe_2O_3	[1]7.77	[1]7.84	5.71	2.7	3.0	2.47	0.90
FeO	n.d.	n.d.	3.06	5.2	5.7	5.45	6.36
MgO	9.20	9.04	8.69	8.4	7.9	9.32	9.25
CaO	7.01	7.43	7.08	9.6	7.8	5.62	8.42
Na_2O	0.71	0.78	0.97	1.5	1.7	1.60	1.28
K_2O	7.67	7.84	7.53	5.9	6.6	5.99	4.51
H_2O^+	[2].57	[2].75	1.80	1.3	0.40	1.97	n.d.
H_2O^-	n.d.	n.d.	.46	.14	.15	0.98	n.d.
TiO_2	1.39	1.12	1.47	1.7	1.3	1.92	1.74
P_2O_5	1.53	1.79	.46	1.2	1.2	.98	.94
MnO	.13	.11	.15	.04	.16	.12	.10
CO_2	n.d.	n.d.	n.d.	<.05	<.05	.75	n.d.
F	n.d.	n.d.	n.d.	.62	.59	n.d.	n.d.
Cl	n.d.	n.d.	n.d.	.04	.04	n.d.	n.d.
V_2O_3	[3].03	[3].02	.03	[3].02	[3].02	n.d.	n.d.
NiO	[3].02	[3].02	.04	[3].04	[3].03	n.d.	n.d.
BaO	[3].56	[3]1.67	.23	[3].11	[3].11	n.d.	n.d.
SrO	[3].18	[3].35	.06	[3].24	[3].24	n.d.	n.d.
Total	98	98	100.42	100	101	100.06	98
K_2O/Na_2O	10.8	10.1	7.76	3.93	3.88	3.74	3.52
F[4]	2.44	2.32	2.40	2.17	2.42	2.62	2.11
S[5]	1.15	1.07	1.11	1.07	1.10	1.27	0.97

[1]Total iron reported as Fe_2O_3.

[2]Loss on ignition at 900 °C.

[3]Oxide value calculated from semiquantitative spectrographic analysis.

[4]F = felsic-mafic ratio (in weight percent) $= \dfrac{SiO_2 + Na_2O + K_2O}{FeO + Fe_2O_3 + MgO + CaO}$.

[5]S = silica saturation ratio (in weight percent) $= \dfrac{SiO_2}{Al_2O_3 + Na_2O + K_2O + MgO + CaO + FeO + Fe_2O_3}$.

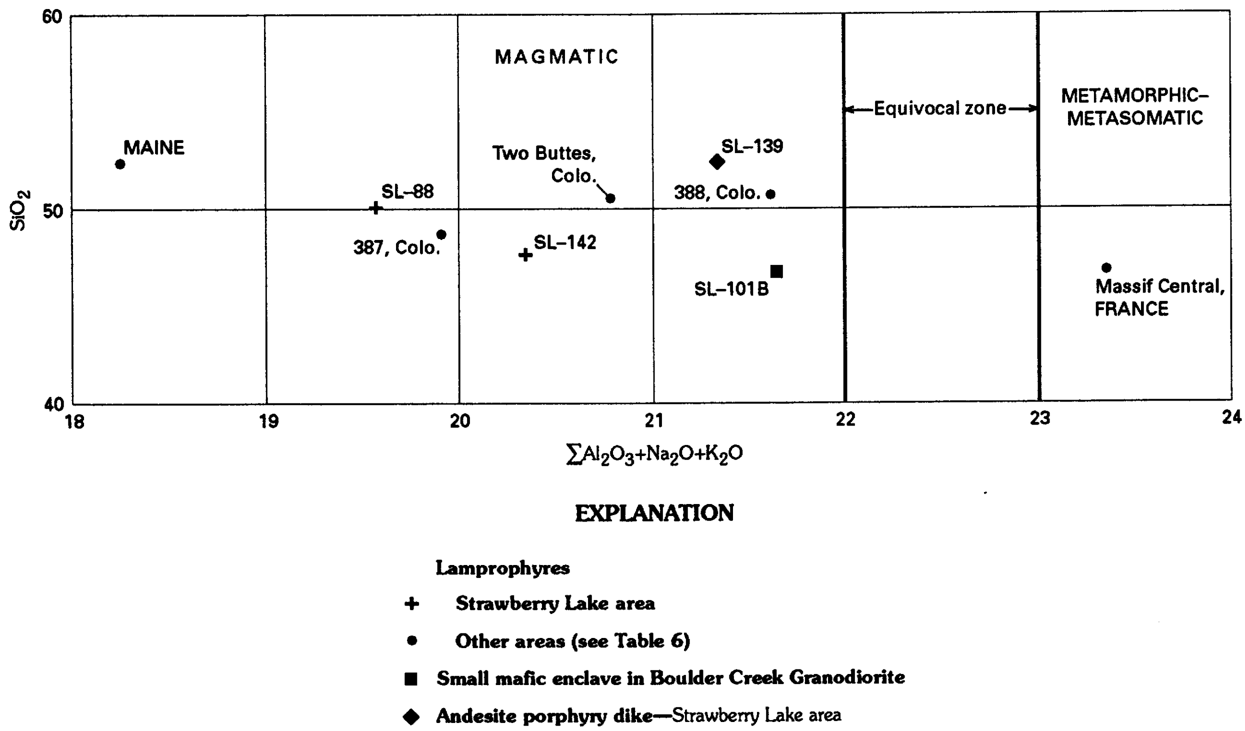


Figure 9. $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram of biotite lamprophyres and other mafic rocks.

(1) Small mafic enclaves are abundant locally but are not omnipresent. (Some portions of the biotite-gneiss precursor contain more mafic components than others—such local volumes produce restites as more felsic parts of the biotite gneiss are mobilized to form Boulder Creek Granodiorite.)

(2) About nine-tenths of the small mafic enclaves consist of andesine, biotite, and hornblende. (This is the mafic residue of excess immobile components.)

(3) Thorium is severely depleted in the small mafic enclaves with respect to their host. (Thorium was mobilized away from restite to its more felsic host under ultrametamorphic conditions.)

Speculation on the possible genetic relationship between the small mafic enclaves and the biotite lamprophyres is supported by the dual classification of the small mafic enclaves as melatonalites or vaugnerites in the Johannsen (1939) classification. Figure 8 shows that the small mafic enclaves and the biotite lamprophyres are not very far apart in composition, which would be brought even closer with an infusion of potassium. Table 17 of Chapter A of this bulletin shows that the accessory minerals of the two rock types are virtually identical. Locally, swarms of the small mafic enclaves are abundant enough to provide the mafic component of the biotite lamprophyres. Thus, local or partial melting and (or) metamorphic differentiation processes could produce the biotite lamprophyres from in-situ sources.

Andesite Porphyry Dike

The Tertiary(?) andesite porphyry dike is about 9 m wide and at least 150 m long; it intrudes Boulder Creek Granodiorite. Sample SL–139, which is representative of the andesite porphyry dike, is classified as a syenodiorite porphyry in the Johannsen (1939) classification and as a monzodiorite in the Streckeisen (1976) classification. In the F–S classification it is the compositional equivalent of a felsic andesite (F = 2.80, S = 1.24; fig. 8), which is saturated in silica. Sample SL–139 plots on the magmatic side of $\Sigma Al_2O_3+Na_2O+K_2O$ versus SiO_2 diagram (fig. 9).

Of all the rock units in the Strawberry Lake area, this one alone can unequivocally be called igneous, because of its dikelike structure and two types of plagioclase phenocrysts: large zoned crystals and small microlites. The source of the magma that formed the andesite porphyry dike probably was the same that produced the biotite lamprophyres—namely, crustal material—but the degree and length of time of heating may have been different. A general similarity in composition and accessory minerals supports this supposition.

CONCLUSIONS

Chemical, structural, and mineralogic evidence favors a metamorphic-metasomatic origin for the Boulder Creek Granodiorite and the Silver Plume Granite in the Strawberry Lake area. Partial melting occurred, but no evidence has been found for gross intrusion. Granitic enclaves in the Boulder Creek Granodiorite and in the Silver Plume Granite probably represent end phases of metamorphic-metasomatic processes in these two plutons, but the granitic enclaves in the Silver Plume Granite may have undergone partial melting. Granitic enclaves in the biotite-gneiss country rock may be synchronous with the Silver Plume Granite.

The small mafic enclaves in the Boulder Creek Granodiorite are restites, and the biotite lamprophyres in the same host probably represent end-stage ultrametamorphism.

The Tertiary(?) andesite porphyry dike is unequivocally igneous.

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