

DISTRIBUTION OF MINOR CHEMICAL ELEMENTS
IN TERTIARY DIKE ROCKS OF THE
FRONT RANGE, COLORADO

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ABSTRACT

Qualitative and quantitative spectrographic analyses determining the minor chemical constituents in a number of Colorado Front Range Tertiary dike rocks and their constituent minerals revealed some interesting relationships. The rocks analyzed were mainly monzonites and latites. The rock analyses (qualitative) showed some regional differences in the number and quantity of minor elements present. Slight variations with rock type also were found. Elements of special significance in the rock analyses are: Pb, Ni, Co, Sc, Cr, V, and La.

Analyses of plagioclase, biotite, groundmass, and magnetic concentrate samples (both qualitative and quantitative) showed systematic differences in the number and quantity of minor elements in each of the minerals. A few significant elements in the mineral analyses are: Sc, Y, La, Ce, Nd, Ti, V, Cr, Mn, and Co.

Comparison of analytical results obtained for the Tertiary dike rocks with those obtained for other Front Range igneous rocks of pre-Cambrian and Tertiary ages (not dikes) revealed definite points of difference. It is the author's firm belief that the spectrographic method, when properly applied, will prove a definite aid in correlation problems involving igneous rocks anywhere.

INTRODUCTION

The results here recorded represent a part of the work done in 1940 at the Massachusetts Institute of Technology as partial fulfillment of the requirements for the degree of Doctor of Philosophy in Geology. The spectroscopic distribution of minor chemical elements in the igneous rocks and rock-forming minerals of the Jamestown district, Colorado, has been taken up by the author in detail in another paper. (Bray, 1942). This paper points out that each rock body considered is characterized by its set of special minor elements, which vary with rock type, age, and province.

The Colorado Front Range offers an ideal province for the application of the spectrographic method, not only to purely petrological problems, but to those of correlation as well. The Jamestown district, with its diversity of igneous rocks, was the logical locality for the petrological study, and the surrounding sections of the Front Range, with the Tertiary sequence of dike intrusions, was equally suitable for attack upon the correlation question. In this study qualitative spectrographic analyses were made of 9 different dike rocks and 18 mineral samples, as well as quantitative analyses of 13 mineral samples. Among the rocks analyzed are: hornblende, biotite and quartz monzonites, biotite latites, and limburgite. All but the latter are somewhat similar.

The research was done in the Cabot spectrographic laboratory in the department of Geology at the Massachusetts Institute of Technology. The specimens (except those furnished by Dr. T. S. Lovering) were collected in 1939. The writer desires to express his deep appreciation to Dr. W. H. Newhouse, of the Massachusetts Institute of Technology, for his suggestions during the course of the work, to Mr. R. F. Jarrell, for his competent instruction in spectroscopy, and to Professor T. S. Lovering of the University of Michigan, for his interest and cooperation, as well as for furnishing several very interesting specimens. Mr. Albert Jehle gave painstakingly of his time and energy in assisting with the laboratory work.

GEOLOGY AND PETROLOGY

The area under consideration is located in Clear Creek and Boulder Counties, near the northeast edge of the Front Range mineral belt of Colorado. The geology of the Front Range needs no detailed repetition, as it has been ably discussed by Ball (1908), by Lovering (1929) and by Fenneman (1905). The main country rock consists of an ancient pre-Cambrian complex of gneisses and schists, intruded by a series of pre-Cambrian granite batholiths. This entire assemblage was subjected to the forces of the Laramide Revolution, which resulted in fracturing, in-

trusion of a series of Tertiary stocks and dikes, and a period of valuable metallization.

Lovering and Goddard have published a geologic map of the Front Range mineral belt under the auspices of the United States Geological Survey (1938*b* and 1939). The only rocks of any concern here are those of the Tertiary group. The physical chemistry involved in the formation of these rocks has also been considered by Lovering and Goddard (1938*a*, pp. 59-67). As for the Tertiary igneous sequence in the Boulder County area, the author follows Goddard in his report on the Gold Hill district (1940). The sequence is as follows, beginning with the first rock intruded:

- Diabase dikes (oldest)
- Hornblende granodiorite stock and dikes
- Intermediate quartz monzonite porphyry stock and dikes
- Alaskite porphyry dikes
- Sodic granite-quartz monzonite porphyry stock and dikes
- Bostonite porphyry dikes
- Biotite monzonite and latite porphyries (also biotite latite intrusion breccia)
- Limburgite (youngest of series)

From this group of rocks, the author secured and analyzed specimens of the hornblende granodiorite, intermediate quartz monzonite porphyry, sodic granite-quartz monzonite porphyry, biotite monzonite and latite porphyries, biotite latite intrusion breccia, and limburgite. The granodiorite and sodic granite stocks were considered with the Jamestown rocks (Bray, *ibid.*). The petrology of the rocks here concerned is as follows:

Intermediate Quartz Monzonite Porphyry. (Sample No. 125-A. From a dike in the Jamestown district.) Megascopically this is a gray to yellowish rock containing a large number of hexagonal black biotite plates and less numerous glassy quartz phenocrysts disseminated in a groundmass of fine-grained quartz and feldspar (oligoclase-andesine and orthoclase), which is almost completely altered to sericite mica and clay minerals, yet showing former feldspar crystal boundaries. The phenocrysts are very fresh. Apatite is also present in the groundmass.

Biotite Monzonite. (Sample No. 125. From a dike in the Jamestown district.) This is a gray porphyritic rock with many fresh andesine phenocrysts, small plates of biotite, and altered hornblende needles, set in a dense, uniform groundmass composed of equal amounts of tiny oligoclase-andesine laths and anhedral orthoclase grains. Calcite is abundant in the groundmass. Fresh magnetite is a very abundant accessory. Sphene and apatite are minor constituents.

* *Hornblende Monzonite.* (Sample No. 124TL33. From the Logan Mine, in the Gold Hill district, about 4 miles west of Boulder.) This sample was

donated by Dr. T. S. Lovering. The dike is a light gray rock containing numerous phenocrysts of clear, white, zoned oligoclase-andesine, fewer biotite plates, and a few former crystals of hornblende now completely

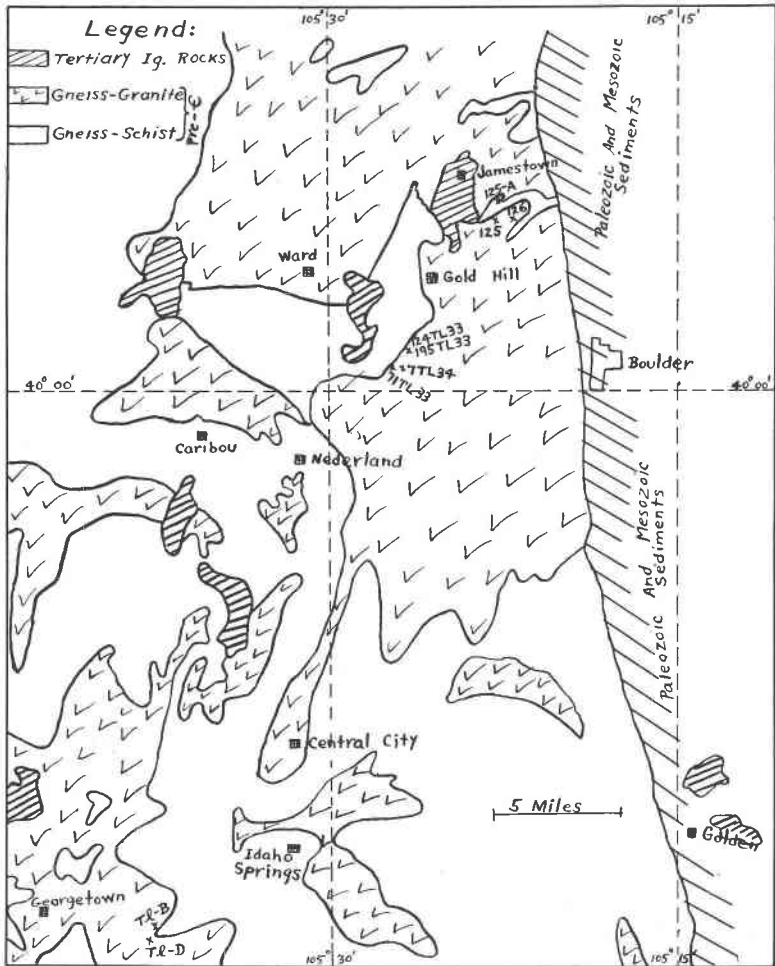


FIG. 1. Sketch Map—Location of Specimens.

altered to calcite. The groundmass is very dense and uniform, partly glassy, and composed of innumerable tiny andesine laths. Magnetite is abundant.

Biotite Latite Intrusion Breccia. (Sample 195TL33, donated by Dr. T. S. Lovering. From the Yellow Pine mine, Gold Hill district.) This sample is from the same dike as No. 124TL33. A light gray rock containing many phenocrysts of fresh, clear, quartz and altered plagioclase. Few biotite phenocrysts are present. Some potash feldspar and plagioclase crystals are unaltered. The groundmass contains small fragments of altered granite (?), is very fine-grained to glassy, and is crowded with minute shreds of quartz, feldspars, sericite, and clay minerals. Some quartz in the groundmass apparently was introduced. Abundant small grains of pyrite were apparently introduced by the tungsten-bearing solutions.

Biotite Latite. (Samples TL-B and TL-D, from dikes near the intersections of the 3 Chicago Creeks, about 6 miles southwest of Idaho Springs.) Gray, dense rocks, "spotted" by small black anhedral biotite plates. Flow lines are common. Small orthoclase and andesine phenocrysts are set in a very uniform groundmass of partially-devitrified glass containing numerous spherulites. The spherulites are often replaced by calcite. Accessories are magnetite, apatite, and zircon.

Limburgite. (Sample No. 7TL-34, donated by Dr. T. S. Lovering. From near Sugarloaf, about 5 miles west of Boulder.) A very dark, fine-grained dike rock composed of about 85 per cent augite and 10 per cent olivine (T. S. Lovering and E. N. Goddard, 1938a, p. 66).

Figure 1 is a sketch map of the area, showing the approximate locations of the samples analyzed.

ANALYTICAL METHODS

Space does not permit a detailed discussion of the methods used. The analyses were performed with a 21-foot, 30,000-line (per inch concave) grating spectrograph on a Wadsworth mounting. The cathode layer method of carbon-arc analysis was followed, with special techniques as outlined by the author in another paper (Bray, *ibid.*).

Great care was exercised in preparing and handling the samples. Mineral samples were carefully separated by hand. Qualitative analytical work was done by means of eye-estimation of the density of spectral lines. Quantitative analyses were performed by the internal-standard method, refined by use of iron step-sector calibrations and photometric density measurements. The results are reported in terms of oxides because oxides were used in preparing the standard mixtures. All analyses were done in duplicate, so each figure listed represents the mean of at least two separate determinations.

The symbols used to tabulate qualitative results are as follows:

VL—Very large	
L—Large	(Variations within one range are
M—Medium	expressed by means of plus
S—Small	and minus signs)
T—Trace	
VT—Very small trace	
N.D.—Not detected	
0—Not determined	

Absolute percentage figures cannot be assigned to these steps, and *symbols should be used only in comparisons involving a single element*. The spectrographic sensitivities of the various elements vary widely, so that a quantity designated as "large" for one might really be a smaller actual percentage than that for another element designated as "medium." It must also be borne in mind that when we speak of "large" amounts of the elements, we mean "large" *only in a spectroscopic sense*.

Qualitative analyses of minerals were run in a different manner from those of the rocks, so *the two sets of results are in no way to be compared*. Quantitative results are reported in percentages of oxides, except for elements that were not placed in the standard base mixtures for various reasons (unavailability, impurity, etc.). In these latter cases, the constituents are reported as " $\Delta \log. E$ " figures, strictly quantitative and accurate. A higher positive " $\Delta \log. E$ " value represents a larger percentage than a smaller positive value. Negative figures represent smaller percentages than positive figures. The " $\Delta \log. E$ " values should be used *only in comparisons involving single elements in each mineral*.

The spectral range chosen did not contain sensitive lines for all elements desirable for this study. For instance, sensitive Li and B lines were lacking. In addition, lines present in this range for a number of desirable elements (such as Nb, Ga, Rb, and Cs) were either too diffuse, too near sensitive lines of major elements (thus being masked), or concealed by cyanogen lines. Old spectrographic analyses doubtlessly at times reported the presence of certain elements that were not actually present, due to confusion with other spectral lines in the same vicinity.

The results for the magnetic concentrates are not as sensitive as could be desired, as the samples had a tendency to hop from the electrode during the excitation process.

QUALITATIVE ANALYSES

Rocks

Table 1 lists qualitative analyses of 9 dike rocks. The minor elements of most common occurrence are Sr, Ba, Sc, Y, Ce, Ti, Zr, V, Cr, Mn, and

Co. Of these, Sr and Ba seem most abundant, although Mn, V, and Cr are present in appreciable quantities. Elements not detected in any of the samples are: Sb, As, Bi, Cd, Be, Ge, Au, Os, Ir, Pd, Pt.

TABLE 1. QUALITATIVE ANALYSES OF ROCK SAMPLES

Sample No.	Sr	Ba	Sc	Y	La	Ce	Nd	Ti	Zr	V	Cr	Mn	Co	Ni	Pb
125	VL	VL	VT	T	N.D.	T	T ⁺	L	VT	VL	M	L ⁺	VT	VT?	T
126	VL	VL	T	N.D.	S	VT	T ⁺	L	T ⁺	M	S	L	VT	N.D.	VT
71TL33*	VL	VL	N.D.	N.D.	N.D.	N.D.	N.D.	S	N.D.	L	S ⁺	L	N.D.	N.D.	VT
125-A	VL	VL	T	N.D.	N.D.	VT	T ⁺	L	T ⁺	M	S	L	VT	N.D.	N.D.
124TL33*	VL	VL	T	N.D.	N.D.	N.D.	VT	L	N.D.	M ⁺	T ⁺	L	N.D.	N.D.	N.D.
195TL33*	VL	VL	T	T	N.D.	T	N.D.	L	T	L	M ⁺	S	T	S	N.D.
TL-B	VL	VL ⁺	VT	N.D.	S	T	N.D.	M ⁺	T	M ⁻	S ⁻	L	N.D.	N.D.	N.D.
TL-D	VL	VL	VT	N.D.	S	N.D.	N.D.	M	N.D.	S	T	L ⁺	N.D.	N.D.	N.D.
7TL34*	VL	VL	S	VT	VT?	N.D.	N.D.	L	VT	M ⁺	VL	L	T	S	N.D.

- 125—Biotite monzonite (Jamestown)
- 126—Hornblende monzonite (Jamestown)
- 71TL33—Hornblende monzonite (Sugarloaf Mt.)
- 125-A—Quartz monzonite (Jamestown)
- 124TL33—Biotite latite (Logan Mine, Gold Hill)
- 195TL33—Biotite latite intrusion breccia (Gold Hill)
- TL-B—Biotite latite (intersection of Chicago Creeks)
- TL-D—Biotite latite (intersection of Chicago Creeks)
- 7TL34—Limburgite (near Sugarloaf, Boulder County)

* Samples donated by T. S. Lovering.

- Not detected in any samples:
Sb, As, Bi, Cd, Be, Ge, Au, Os, Pd, Pt, Ag, Zn.
- Explanation of Symbols:
N.D.—not detected
VT—very small trace
T—trace
S—small
M—medium
L—large
VL—very large
0—not determined

Several features of the analyses deserve special mention. First, Ag and Zn were not detected in any samples, and Pb is confined to the hornblende and biotite monzonites. The element Co is quite generally present, except in the biotite latite dike rocks. Ni, where present, occurs in those rocks where Co is most abundant. Sr and Ba are high in all of the rocks. Sc seems to be lowest in the "biotite rocks" (that is, the biotite monzonites and latites). The rare earth elements occur sporadically, with Ce most generally present. V is rather abundant in all samples, but tends to be lowest in the biotite latite dike rocks, and highest in the limburgite and intrusion breccia. An exactly similar relative distribution is shown by Cr. It is interesting to note several "pairs" of chemically-similar elements that seem to be distributed in parallel fashion in these rocks. Three such pairs are Sr-Ba, Ni-Co, and V-Cr. The same was found true for the pre-Cambrian and Tertiary granitic stocks of the Jamestown district (Bray, *ibid.*).

One point brought forcibly to attention by Table 1 is that the limburgite and intrusion breccia are so different from the other rocks concerned, especially as regards Ni, Co, and Cr, while being similar to each

other. Both rocks contain very many of the minor elements, some in quite large amounts. A significant fact brought out by Lovering and Goddard (1938, p. 66) is that both these rocks seem to be genetically related to the tungsten ores of this district, the limburgite being formed by remelting of basic crystal settlings as a consequence of explosive release of pressure exerted on the magma chamber. The released volatiles apparently deposited the tungsten ores (Lovering, 1940, pp. 142-143). A small trace of tungsten was found in the intrusion breccia.

Definite *regional* differences occur as well as the general differences in distribution of the minor elements already pointed out. For instance, Pb is confined to the Jamestown rocks, and (if we exclude the limburgite and intrusion breccia) V, Co, Cr, and Sc all tend to be highest in these same rocks. La, on the other hand, is highest in the Chicago Creek rocks. So there are definite regional differences as well as differences based on rock type. Important "index elements" (those which show these variations) are Pb, V, Co, Cr, Sc, and La. If these results are compared with qualitative analyses of the Jamestown stocks, it can be seen that the Tertiary group differs materially in a number of respects from the pre-Cambrian group (Bray, *ibid.*).

Minerals

The minerals analyzed qualitatively included plagioclases, biotites, magnetic concentrates, groundmasses and one hornblende. Results are tabulated in Tables 2 to 6. Each number in the tables indicates the rock sample from which each mineral was separated.

TABLE 2. QUALITATIVE ANALYSES OF PLAGIOCLASES

Sample No.	Sr	Ba	Nd	Ti	V	Cr	Mn	Ag
TL-B	M	L	VT	T	N.D.	VT	VT	N.D.
124TL33	VL	L	?	S ⁺	M	VT?	M ⁻	VT

Not detected in any samples: Sb, As, Be, Bi, B, Cd, Ce, Cs, Co, Ge, Au, Hf, In, Ir, La, Pb, Mo, Ni, Os, Pd, Pt, Sc, Sn, W, Y, Zn, Zr.

TABLE 3. QUALITATIVE ANALYSES OF GROUNDMASS SAMPLES

Sample No.	Sr	Ba	Sc	Y	La	Ce	Nd	Ti	V	Cr	Mn	Fe	Co	Yb
125	VL	VL	T	T	T	VT	T	L	L ⁻	T ⁺	M	L	N.D.	VT
71TL33	VL	VL	N.D.	?	N.D.	N.D.	N.D.	M	M	T	M	L	N.D.	VT
124TL33	VL	VL	T	T	N.D.	VT	T	L	L	S ⁺	M	L	VT	VT ⁺
TL-B	VL	VVL	VT	VT	T	T	VT	L	T	N.D.	L	L	N.D.	VT
TL-D	VL	VL	?	T	N.D.	VT	N.D.	M	T	N.D.	M	L	N.D.	VT ⁺

Not detected in any samples: Sb, As, Be, Bi, B, Cd, Cs, Ge, Au, In, Ir, Pb, Mo, Ni, Os, Pt, Ag, Sn, W, Zn, Zr

TABLE 4. QUALITATIVE ANALYSES OF BIOTITE

Sample No.	Sr	Ba	Sc	Nd	Ti	Zr	V	Cr	Mn
TL-D	T	VL ⁺	N.D.	VT	M	N.D.	N.D.	N.D.	M ⁺
71TL33	VL	VVL	VT	N.D.	L	N.D.	M	M ⁻	M ⁺
125-A	T	VL	T	VT?	L	T ⁺	M	S ⁺	M ⁺

Not detected in any samples: As, Sb, Be, Bi, B, Cd, Cs, Ge, Au, In, Ir, Mo, Os, Pd, Pt, Ag, Sn, W, Y, La, Ce, Co, Ni.

TABLE 5. QUALITATIVE ANALYSES OF MAGNETIC CONCENTRATES

Sample No.	Na	K	Mg	Ca	Sr	Ba	Al	Ti	V	Cr	Mn	Zn	Ni	Co	Sc	Ce	Nd	Er
125	N.D.	N.D.	VT	L	N.D.	S	M ⁺	S ⁺	S	T	S	VT	N.D.	N.D.	S	0	0	0
126	S	VT	S	L	N.D.	S	L	M	M	S	L ⁻	T	N.D.	N.D.	S	0	0	0
71TL33	T	T	S	L	N.D.	S ⁺	L	M	M	S	L ⁻	S	N.D.	N.D.	T	0	0	0
124TL33	N.D.	VT	T	L	S	S	L	M ⁻	M	S	VT	S	N.D.	N.D.	T	N.D.	L	0
195TL33	T	M	S	L	L	L ⁺	VL	L	L	M ⁺	M	VT	S	T	S	N.D.	VT	VT
TL-D	N.D.	T	T	L	N.D.	T	L	S	M	M ⁺	L ⁻	VT	N.D.	N.D.	S	0	0	0
7TL34	0	S	VL	VL	L	L ⁺	VL	M ⁺	L ⁻	L	L	N.D.	S	T	S	N.D.	VT	?

Not detected in any samples: Sb, As, Be, Bi, B, Cd, Cs, Ge, Au, In, Ir, Os, Pd, Pt, Sn, Y.
 Detected only in 195TL33: Zr (VT), Ag (T), Pb (VT), W (VT), Mo (VT), and La (VT).

TABLE 6. QUALITATIVE ANALYSIS OF HORNBLLENDE

Sample No.	Na	K	Sr	Ba	Sc	Y	La	Ce	Nd	Ti	Zr	V	Cr	Mn	Co
126	S	S	L ⁺	VL	M	N.D.	N.D.	N.D.	T	L ⁺	T	L	L ⁻	M	VT

Not detected: Sb, As, Be, Bi, Cd, Cs, Ge, Au, In, Ir, Pb, Mo, Ni, Os, Pt, Ag, Sn, W, Zn.

Differences Among Mineral Species. Na, K, Mg, Fe, Ca, Si, and Al can be considered as major elements and will not be discussed.

Sr, present in all samples, is highest in the plagioclases and groundmasses, probably because the Sr ion (valence 2; ionic radius 1.27 Å) substitutes readily for the bivalent Ca ion (ionic radius 1.06 Å) in the plagioclase crystal structure. Ba is also present in all samples, most abundantly in the biotites and groundmasses, both rather rich in potash. The bivalent Ba ion (ionic radius 1.43 Å) substitutes readily for the univalent K ion (radius 1.33 Å) where the latter is abundant. The plagioclases contain less Ba. The Sr:Ba ratios are highest for the plagioclases and groundmasses, as would be expected for high-Ca minerals. Al is an important minor constituent in the magnetic concentrates (ionic radii: trivalent Fe, 0.67 Å; trivalent Al, 0.57 Å). Sc is most abundant in the hornblende and magnetic concentrates, in both cases probably as a substitute for bivalent Mg and Fe (ionic radii: Mg, 0.78 Å; trivalent Sc, 0.83 Å; bivalent Fe, 0.83 Å).

Y and Ce occur only in the groundmasses. La shows a tendency toward a similar behavior. Yb is present in all groundmasses, but was not determined for other samples. Nd is present more or less generally. The rare earth elements are thought to substitute most readily for Ca (Tröger 1935).

Ti is highest in the hornblende, groundmasses and biotites. Zr is distributed sporadically, but where found occurs exclusively in the dark minerals, probably as a substitute for ferrous Fe (ionic radii: ferrous Fe, 0.83 Å; tetravalent Zr, 0.87 Å). V is most abundant in the hornblende, magnetic concentrates and biotites, where it probably substitutes for the ferrous or ferric ions (radii: ferrous Fe, 0.83 Å; V, 0.75 Å; ferric Fe, 0.67 Å). Cr is also highest in the hornblende, magnetic concentrates, and biotites, where it proxies for the ferric Fe ion (radii: ferric Fe, 0.67 Å; Cr, 0.65 Å). Mn is highest in the magnetic concentrates and groundmasses. A very apparent and important fact is that Ti, Zr, V, Cr, and Mn are abundant minor elements in the dark minerals. Co and Ni are rather restricted in occurrence. Zn was detected only in the magnetic concentrates, where it undoubtedly proxies for the ferrous Fe ion (ionic radii: ferrous Fe, 0.83 Å; bivalent Zn, 0.83 Å).

A startling fact is revealed when the analysis of the magnetic concentrate from the intrusion breccia (195TL33) is examined. It is the only sample that contains W, Mo, Pb and Er, and contains more Ni, Al, and Co than any other, as well as being one of two samples bearing Ag. These results show that certain minerals are characterized by certain minor elements. The minor constituents probably occur in solid solution in the crystals of the various minerals.

Differences in Content of Minor Elements in Single Minerals. Aside from the variations already noted, each single mineral species shows differences worthy of note. First, consider the plagioclases (see Table 2). The two plagioclases are characterized particularly by a special abundance of Sr and Ba. Both samples are relatively "pure," since they bear few minor constituents. Differences between the two analyses exist for Ti, Mn, Sr, and Ag. These differences are regional, since the samples came from widely separated localities.

The groundmasses as a group (see Table 3) are characterized by abundant Sr, Ba, Mg, Ti, and Mn. All are quite "impure," as they contain numerous minor elements. The presence of Ce, Nd, and Yb is notable. The elements Nd, Ce, La, Ti, Y, and Sc are more abundant in the groundmasses of biotite-rich rocks as against that of the hornblende-rich rock (71TL33). The greatest number of minor constituents is present in the groundmasses of samples 125 and 124TL33. Cr, V, and Mg are lower and Mn tends to be higher in the Chicago Creek samples (TL-B and TL-D) than in those from the districts farther north. Sc, Y, La, Ce, Nd, and Ti also tend to show some regional variation. An interesting sidelight is the difference between the two Chicago Creek samples, especially in Y, La, Ce, Nd, and Ti.

The biotites (see Table 4) are characterized by an abundance of Ba, Mn, and Ti. The Chicago Creek sample (TL-D) bears fewest minor constituents, and is thus the "purest" of the group. There are pronounced regional differences between the Chicago Creek biotite latite sample (TL-D) on the one hand and those of the Jamestown-Sugarloaf monzonite samples on the other, especially in regard to Sc, Ti, V, and Cr.

The magnetic concentrates (Table 5) bear abundant Ca, Al, Ti, V, Mn, and Cr, as well as Zn. The most notable feature of Table 5 is the pronounced difference between the intrusion breccia sample and all others. Those from the Jamestown-Sugarloaf-Gold Hill and Chicago Creek rocks are relatively "pure." As for regional variations, the intrusion breccia sample is unique. The limburgite sample also differs from most of the others. The elements Ba, Sr, Mg, K, Al, Ti, V, Cr, Mn, and Zn all show regional differences. Ti, V, Mn, and Zn are more abundant in magnetic concentrates from the Tertiary rocks than in those of the pre-Cambrian rocks in the Jamestown district (Bray, *ibid.*).

Only one hornblende was analyzed. It bears abundant Sr, Ba, Ti, V, and Cr.

As a summary of this section, the obvious conclusion is that on the basis of qualitative spectrographic analyses of individual minerals from the various rocks, a definite distinction between each rock body is possible.

This fact is important from the standpoint of correlation. Each mineral is characterized by specific minor elements.

QUANTITATIVE ANALYSES

These analyses (Tables 7, 9, 10, and 11) show the same general and relative distributions as the qualitative analyses, but give actual percentages of certain important constituents. Elements not included in the tables are not necessarily absent.

TABLE 7. QUANTITATIVE ANALYSES OF PLAGIOCLASE

Sample No.	$\Delta \text{Log. } E$ Mg	% SrO	% BaO	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	% MnO	$\Delta \text{Log. } E$ Fe	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
125	0.51	0.185	0.0305	0.0124	0.0012	N.D.	0.019	0.61	6.1	I
126	0.39	0.230	0.0370	0.0150	0.0031	0.0003	0.0105	0.44	6.2	10
71TL33	0.52	0.300	0.0630	0.0690	0.0035	N.D.	0.0285	0.57	4.8	I
124TL33	0.83	0.360	0.0690	0.0500	0.0038	N.D.	0.0360	1.01	5.2	I

I—Infinite.

The Plagioclases. Table 7 gives quantitative analyses of 4 plagioclases. Table 8 gives their compositions as determined from refractive indices. The most abundant constituent is SrO, a fact to be expected from what has already been said. BaO is next to SrO in the list of abundances. The

TABLE 8. COMPOSITIONS OF THE PLAGIOCLASE FELDSPARS

Sample No.	Rock	Composition
125	Biotite monzonite (Jamestown)	Ab ₅₈ An ₄₂
126	Hornblende monzonite (Jamestown)	Ab ₅₈ An ₄₂
71TL33	Hornblende monzonite (Sugarloaf Mt.)	Ab ₆₂ An ₃₈
124TL33	Biotite latite (Logan Mine, Gold Hill)	Ab ₆₂ An ₃₈
T1-B	Biotite latite (Chicago Creeks)	Ab ₅₈ An ₄₂
T1-D	Biotite latite (Chicago Creeks)	Ab ₅₈ An ₄₂

plagioclase from the Gold Hill biotite latite (124TL33) is definitely the most "impure" of the group. The Jamestown biotite monzonite sample (125) is definitely the "purest." The universal presence of V₂O₅ is noteworthy, as is the fact that this constituent is always much more abundant than Cr₂O₃, as the V₂O₅:Cr₂O₃ ratios reveal. The SrO:BaO ratios gen-

TABLE 9. QUANTITATIVE ANALYSES OF GROUNDMASS SAMPLES

Sample No.	Δ Log. E Mg	% SrO	% BaO	% Sc ₂ O ₃	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	% MnO	Δ Log. E Fe	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
125	0.86	0.083	0.093	0.0049	0.33	0.0064	0.0001	0.075	1.70	0.9	64
126	0.50	0.124	0.054	0.0020	0.18	0.0080	0.0002	0.028	1.15	2.3	40
71TL33	0.63	0.185	0.046	N.D.	0.10	0.0061	0.0002	0.040	1.05	4.0	30
124TL33	0.63	0.076	0.044	0.0025	0.20	0.0084	0.0007	0.052	1.30	1.7	12
TL-D	0.49	0.150	0.060	0.0022	0.105	0.0023	0.00014	0.045	0.70	2.5	20

TABLE 10. QUANTITATIVE ANALYSES OF BIOTITE

Sample No.	% SrO	% BaO	% Sc ₂ O ₃	Δ Log. E La	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	Δ Log. E Mn	% NiO	% ZnO	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
125	0.037	>0.1	0.0022	-1.17	5.6*	0.12	0.046	-0.46	0.0064	0.092	<0.3	2.5
124TL33	0.054	>0.1	0.0028	-0.90	10.0*	0.14	0.0108	-0.60	0.0073	0.140	<0.5	10.0
TL-D	0.016	>0.1	0.0045	N.D.	3.7*	0.03	0.0054	-0.66	N.D.	0.140	<0.2	6.0

* Really means greater than 1.3%

TABLE 11. QUANTITATIVE ANALYSIS OF HORNBLLENDE

Sample No.	% SrO	% BaO	% Sc ₂ O ₃	Δ Log. E La	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	Δ Log. E Mn	% Co	Δ Log. E Co	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
71TL33	0.083	0.012	0.015	-1.06	2.3*	0.06	0.035	-0.68	-1.04	-0.68	6.9	1.6

* Really means greater than 1.3%

erally exceed a magnitude of 5, far greater than the same ratios for potash feldspars (Bray, *ibid.*). This is because Sr has a special tendency to substitute for Ca, and Ba for K.

Notable in Table 7 is the fact that the Jamestown plagioclases (125 and 126) are quite similar in their analyses, as is the case for the Gold Hill Sugarloaf samples (71TL33 and 124TL33). These two major groups differ from each other for practically every minor constituent. The Jamestown SrO:BaO ratios are in the neighborhood of 6, whereas those for the other group are about 5. The plagioclase from these Tertiary dike rocks contains more SrO, BaO, TiO₂, V₂O₅, FeO and MnO than any other plagioclases (some from pre-Cambrian rocks and some from Tertiary stocks) analyzed by the author. To make desired comparisons see the paper by Bray (*ibid.*).

The Groundmasses. Quantitative analyses of groundmasses are listed in Table 9. Obvious facts are as follows: TiO₂ is the most abundant minor constituent given in per cent. SrO is next. The Jamestown biotite monzonite sample (125) is "purest," and the Chicago Creek sample the most "impure." Cr₂O₃ and V₂O₅ are universal, the latter in all cases more abundant than the former (see ratios), as was the case for plagioclase. The SrO:BaO ratios are generally less than 2.5, much smaller than those for the plagioclases. As far as regional differences are concerned, the Chicago Creek sample (TL-D) differs materially from all the others. The Jamestown and Gold Hill-Sugarloaf groups are not as well defined as was the case for the plagioclases.

The Biotites. Quantitative analyses of the biotites appear in Table 10. TiO₂, BaO, and ZnO are the most abundant minor constituents. (Zn was detected in the quantitative and not in the qualitative analyses because of differences in method.) Sc₂O₃, V₂O₅, Cr₂O₃, Co and NiO are also characteristic. The SrO:BaO ratios are all less than 0.5, indicating that BaO is more abundant than SrO in all cases, a condition greatly different from that pertaining to the plagioclases and groundmasses. The V₂O₅:Cr₂O₃ ratios are rather large.

As for regional differences, the T1-D sample differs distinctly from the others. Recognizable regional variations exist for SrO, La, TiO₂, and Cr₂O₃. These Tertiary biotites bear more BaO than those from the pre-Cambrian and Tertiary stocks of the Jamestown district. Their SrO:BaO ratios are less than those for the biotites of the other rocks mentioned. Sc₂O₃, La, and Mn are present in smaller quantities in the Tertiary than in the Jamestown pre-Cambrian biotites (Bray, *ibid.*).

Hornblende. Only one hornblende was analyzed. It is rich in TiO₂, SrO,

and V_2O_5 , and has the highest SrO:BaO and V_2O_5 : Cr_2O_3 ratios of any of the minerals analyzed.

SUMMARY AND CONCLUSIONS

Special "geochemical affinities" are noticeable in the analyses. That is, certain minor elements are most abundant in those minerals rich in particular major (or "essential") elements. Typical examples of this condition are the tendencies of Ba to substitute for K, Sr for Ca, V and Cr for Fe, Zn for ferrous Fe, and Sc for ferrous Fe and Mg. These "geochemical affinities" depend upon the ionic properties of the various elements concerned. "Geochemical pairs," or pairs of minor elements distributed in an exactly similar manner, are also notable. Examples are V and Cr, Ni and Co.

Ratios between similar minor constituents, such as SrO:BaO and V_2O_5 : Cr_2O_3 , are useful for indexing the relative abundance of these constituents. The ratios mentioned showed systematic differences from mineral to mineral, and from district to district.

Analyses of minerals from Tertiary dikes showed distinct differences from those of the same minerals in Tertiary and pre-Cambrian stocks. The rock analyses show similar behavior.

Important "index elements," or those that appear in different rocks and minerals in systematically different quantities, are as follows: Pb, Ni, Co, Sc, Cr, V, La, Y, Ce, Nd, Ti, and Mn. Use of these elements permits a grouping or correlation of the various rock types as well as a rough regional classification. Both qualitative and quantitative analyses, especially those of minerals, are useful in this respect. Each mineral species is characterized by particular minor constituents.

The data here presented seem to indicate that the spectrograph is destined to become an important geological tool, not only for purely petrological investigations, but for practical commercial purposes as well.

REFERENCES

- BALL, S. H., Geology of the Georgetown Quadrangle, Colorado: *U. S. Geol. Survey*, Prof. Paper 63, 29-96 (1908).
- BRAY, J. M., Spectroscopic distribution of minor elements in igneous rocks from Jamestown, Colorado: *Geol. Soc. Am. Bull.*, 53 (No. 5), 765-814 (1942).
- FENNEMAN, N. M., Geology of the Boulder District, Colorado: *U. S. Geol. Survey, Bull.* 265 (1905).
- GODDARD, E. N., Preliminary report on the Gold Hill Mining District, Boulder County, Colorado: *Colo. Sci. Soc. Proc.*, 14, No. 4, 103-139 (1940).
- LOVERING, T. S., Geological history of the Front Range, Colorado: *Colo. Sci. Soc. Proc.*, 12, No. 4 (1929).

- , Tungsten deposits of Boulder County, Colorado: *U. S. Geol. Survey, Bull.* **922F** (1940).
- , and GODDARD, E. N., Laramide igneous sequence and differentiation in the Front Range, Colorado: *Geol. Soc. Am. Bull.*, **49**, 35-68 (1938a).
- , and GODDARD, E. N., Geologic map of the Front Range Mineral Belt, Colorado (Explanatory Text): *Colo. Sci. Soc. Proc.*, **14**, No. 1, 3-48 (1938b).
- , and GODDARD, E. N., Geologic map of the Front Range Mineral Belt, Colorado: *U. S. Geol. Survey Publication* (1939).
- TRÖGER, E., Der Gehalt an selteneren Elementen bei Eruptivgesteinen: *Chemie der Erde*, **9** (3), 286-310 (1935).