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Minor and trace element contents of kimberlites of the Front Range, Colorado and Wyoming

By

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Introduction

Since 1960 about 90 separate occurrences of kimberlite have been discovered in the Front Range of northern Colorado and southern Wyoming, and in the Laramie Range, Wyoming (e.g., McCallum, Eggler, and Burns, 1975; McCallum, Eggler, Coopersmith, Smith, and Mabarak, 1977; Smith and others, 1977 and in press). All but two of the known kimberlites occur in the Colorado-Wyoming State Line district or in the Iron Mountain, Wyoming, district (fig. 1). A single kimberlite dike is located at Estes Park, Colo., and a small pipe-like body occurs immediately west of Boulder, Colo. (fig. 1). Continuous research for the purpose of locating and characterizing kimberlite in the Front Range has been conducted from 1960 to the present, primarily by M. E. McCallum, D. H. Eggler, and Colorado State University graduate students. The Boulder kimberlite specifically has been studied by Kridelbaugh and others, 1972; Kridelbaugh and Meyer, 1973; Meyer and Kridelbaugh, 1977; and Boctor and Meyer, 1977.

As part of the overall kimberlite project directed by M. E. McCallum, the U.S. Geological Survey has provided the whole-rock minor and trace element analyses reported herein. Although primarily semiquantitative, the analyses show that minor and trace element contents of kimberlites in the Front Range are similar to those of kimberlites elsewhere in the world.

Petrography of Front Range Kimberlite

Four transitional varieties of kimberlite can be distinguished; these are massive to porphyritic, carbonate-rich massive to porphyritic,

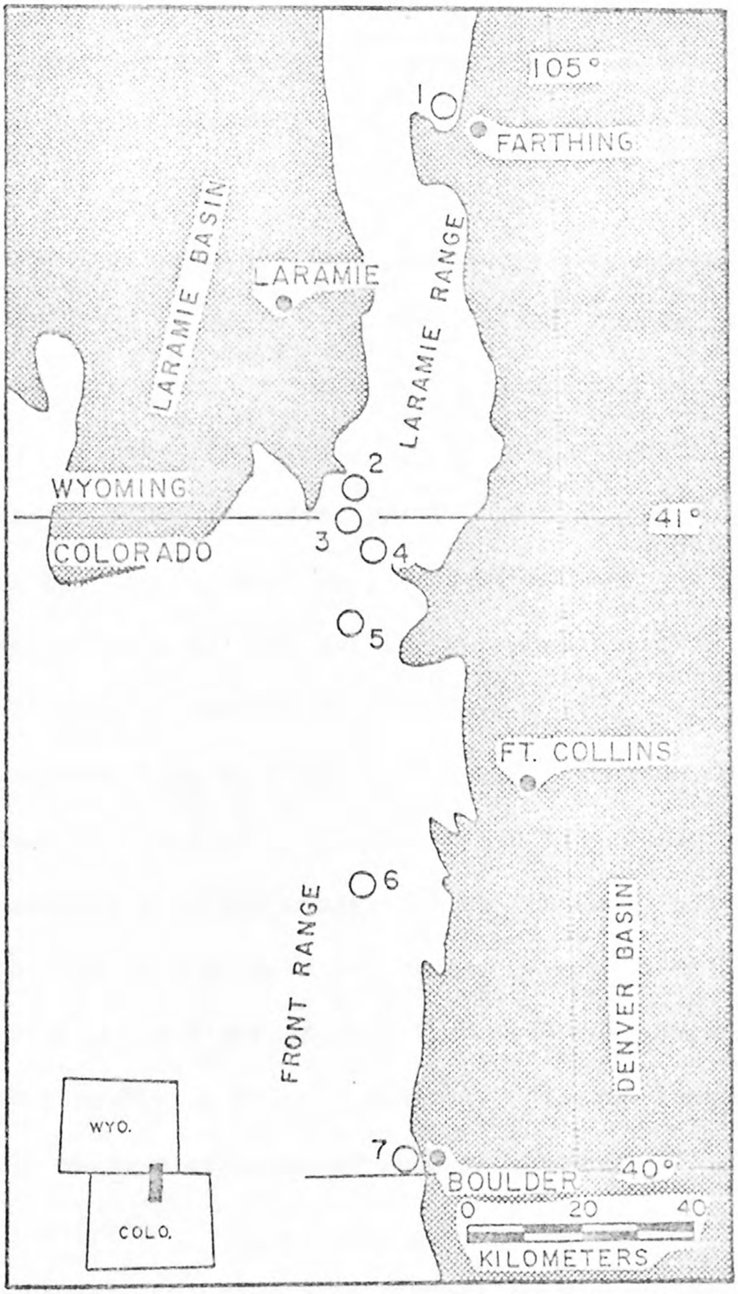

Figure 1.--Location map. 1 - Iron Mountain district; 2 - Ferris-Aultman pipes; 3 - Schaffer pipes; 4 - Nix-Moen pipes; 5 - Sloan pipes; 6 - Estes Park dike; 7 - Green Mountain pipe; 2, 3, 4, and 5 are collectively designated the State Line district. Patterned areas = post Devonian sedimentary rocks; unpatterned areas = predominantly Precambrian crystalline rocks.

intrusive breccia, and carbonate-rich intrusive breccia (Smith and others, 1977 and in press).

Massive to porphyritic kimberlite consists of as much as 50 percent rounded olivine phenocrysts (0.2 to 3.0 cm) and microphenocrysts (less than 0.2 cm) set in a fine-grained chaotic matrix of serpentine, calcite, dolomite, perovskite, magnetite, and hematite with trace amounts of apatite. Olivine most commonly is serpentinized, and secondary groundmass minerals, including clays, hematite, Fe-Ti oxides and hydroxides, phlogopite, and several unidentified fine-grained phases, are ubiquitous. Xenocrysts of garnet, orthopyroxene, ilmenite, rutile, chromite and/or phlogopite are abundant in kimberlite soils on pipe surfaces but are rarely observed in outcrop. Textures range from massive to subporphyritic to porphyritic depending on olivine content and size. Igneous flow textures defined by alignment and size sorting of olivine, although uncommon, are present. Carbonate (primarily calcite) is a late-crystallizing magmatic product which in some samples displays emulsion-like textures indicative of liquid immiscibility during the final stages of emplacement. Matrix serpentine is distinctly finer grained than secondary serpentine in olivine, and is possibly a primary mineral. Alternatively, matrix serpentine could be an alteration product of extremely fine grained quench pyroxene and/or olivine.

Intrusive kimberlite breccia is similar to the massive to porphyritic variety, but contains more abundant xenolithic material, including Precambrian crystalline rocks and lower Paleozoic sedimentary fragments of upper crustal origin; granulite and pyroxenite of lower crustal origin;

mantle-derived garnet and spinel lherzolite, garnet websterite, garnet pyroxenite, eclogite and dunite; and earlier generation kimberlite lapillae and autoliths. Megacrysts of Cr-rich and Cr-poor garnet, clinopyroxene, ilmenite, and orthopyroxene that are possibly cognate inclusions (Eggler and others, 1977 and in press; McCallum, Eggler, and Smith, 1977) are abundant in many of the Front Range kimberlite localities.

Carbonate-rich massive to porphyritic and brecciated kimberlite has a greater carbonate content of primary and autometasomatic origin and is commonly carbonatized, as displayed petrographically by carbonatization of phenocrysts and serpentinous matrix phases.

The Colorado-Wyoming Front Range kimberlites have a large range of modal compositions, as shown in figure 2.

Massive to porphyritic kimberlite occurs in dikes and plugs and rarely in larger pipes, whereas intrusive kimberlite breccias occur in pipes or diatremes. Carbonatized kimberlite is most common in the Iron Mountain district and appears to be spatially associated with pipe structures.

Major Oxide Chemistry of Kimberlite

Except for the Sloan 1 and Nix 1, 2, and 4 diatremes in the State Line district and a few localities in the Iron Mountain district (fig. 1), kimberlite is poorly exposed and intensely weathered. However, whole-rock major oxide analyses of the least weathered samples (table 1, fig. 3) are very similar to analyses of kimberlite from southern Africa and Siberia (e.g., Dawson, 1967; Fesq and others, 1975). Except for carbonatized and

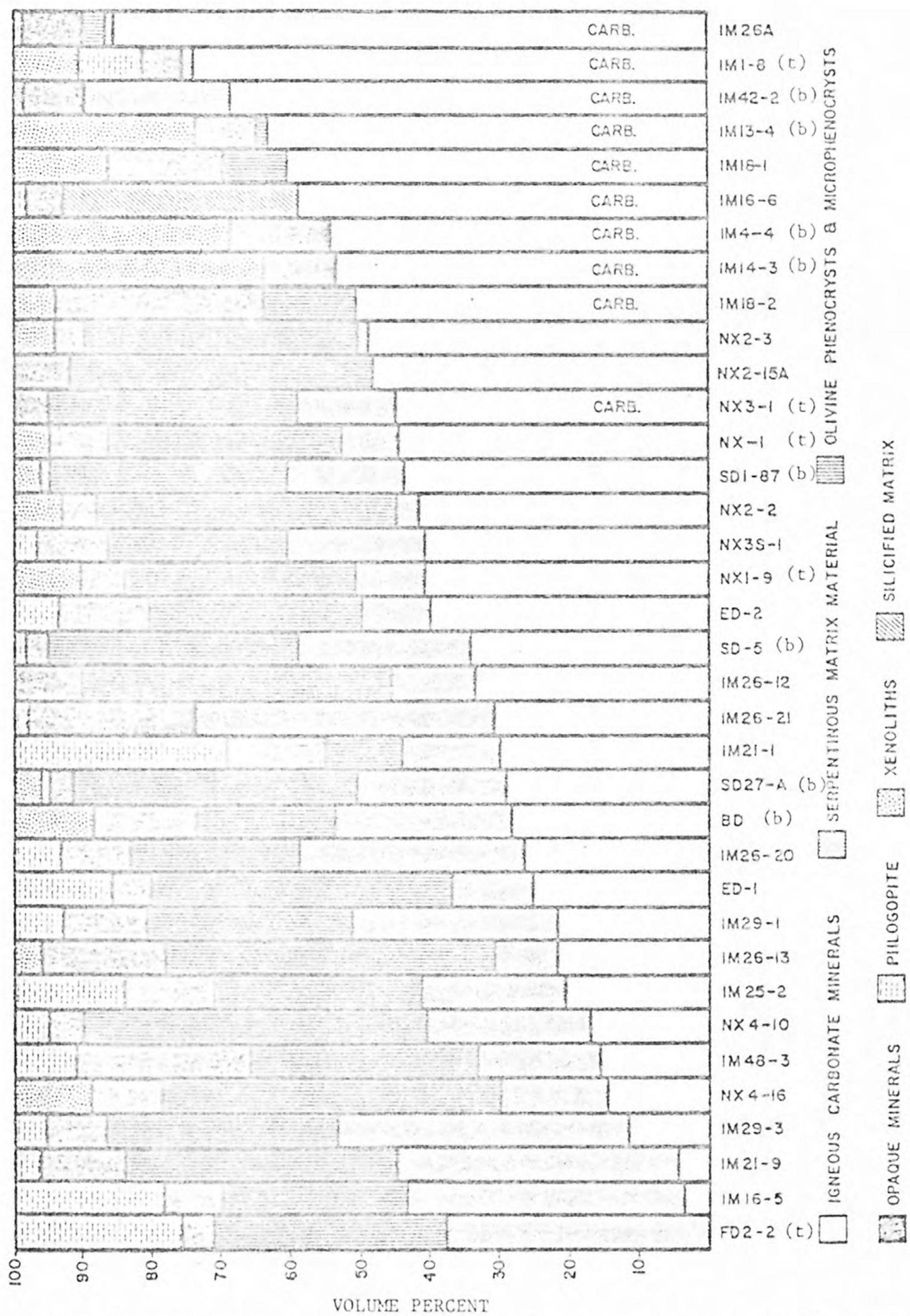

Figure 2.--Modal analyses. Carb. = carbonatized. The relative scarcity of olivine and serpentinous matrix in carbonatized samples is due to replacement by carbonate. Sample classified as intrusive breccias are identified by (b). Samples transitional between breccia and massive to porphyritic are identified by (t). All other samples are massive to porphyritic kimberlite. Opaque minerals are predominantly magnetite, hematite, and perovskite.

Table 1.--Chemical analyses of Colorado-Wyoming kimberlite

[Analyses by Skyline Labs, Inc., Wheat Ridge, Colo., under NSF Grant EAR74-13098 A01]

Oxide	ED1-1	FD2-2	IM21-1	IM16-5	NX4-16	NX1-18	SD1-86	NX3S-1	IM1-8	IM53-1
SiO_2	29.6	36.3	29.6	33.6	34.2	28.0	30.4	24.8	25.7	27.8
Al_2O_3	2.7	2.9	4.0	2.8	2.7	3.2	1.9	3.1	2.1	2.8
Fe_2O_3	5.6	9.0	10.3	7.7	6.4	6.3	4.0	7.0	8.7	7.5
FeO	5.0	0.85	1.8	3.8	1.5	0.78	2.0	1.3	0.87	2.8
MgO	23.1	32.7	22.9	28.4	30.7	26.0	25.9	22.2	12.6	12.3
CaO	10.2	0.67	13.1	5.1	6.8	11.8	14.8	16.2	19.9	11.8
Na_2O	0.03	0.07	0.07	0.05	0.09	0.03	0.04	0.07	0.05	0.07
K_2O	0.94	0.23	1.8	1.4	0.42	0.18	0.29	0.16	1.0	1.7
CO_2	5.8	0.00	1.3	1.7	2.2	8.9	8.9	10.5	21.0	21.5
TiO_2	5.2	1.9	4.0	3.0	0.95	1.4	0.90	1.4	2.6	2.5
P_2O_5	0.09	0.07	0.30	0.35	0.30	0.30	0.35	1.4	0.35	0.55
MnO	0.25	0.16	0.19	0.18	0.14	0.15	0.13	0.15	0.16	0.21
L.O.I.	8.9	12.8	8.9	9.2	14.1	10.3	9.7	10.0	4.4	8.5
Total	97.41	97.65	98.26	97.28	100.5	97.34	99.31	98.28	99.43	100.03

ED = Estes Park dike
FD = Ferris groups, State Line district
IM = Iron Mountain district
NX = Nix group, State Line district
SD = Sloan group, State Line district
L.O.I. = Loss on ignition at 1000°C

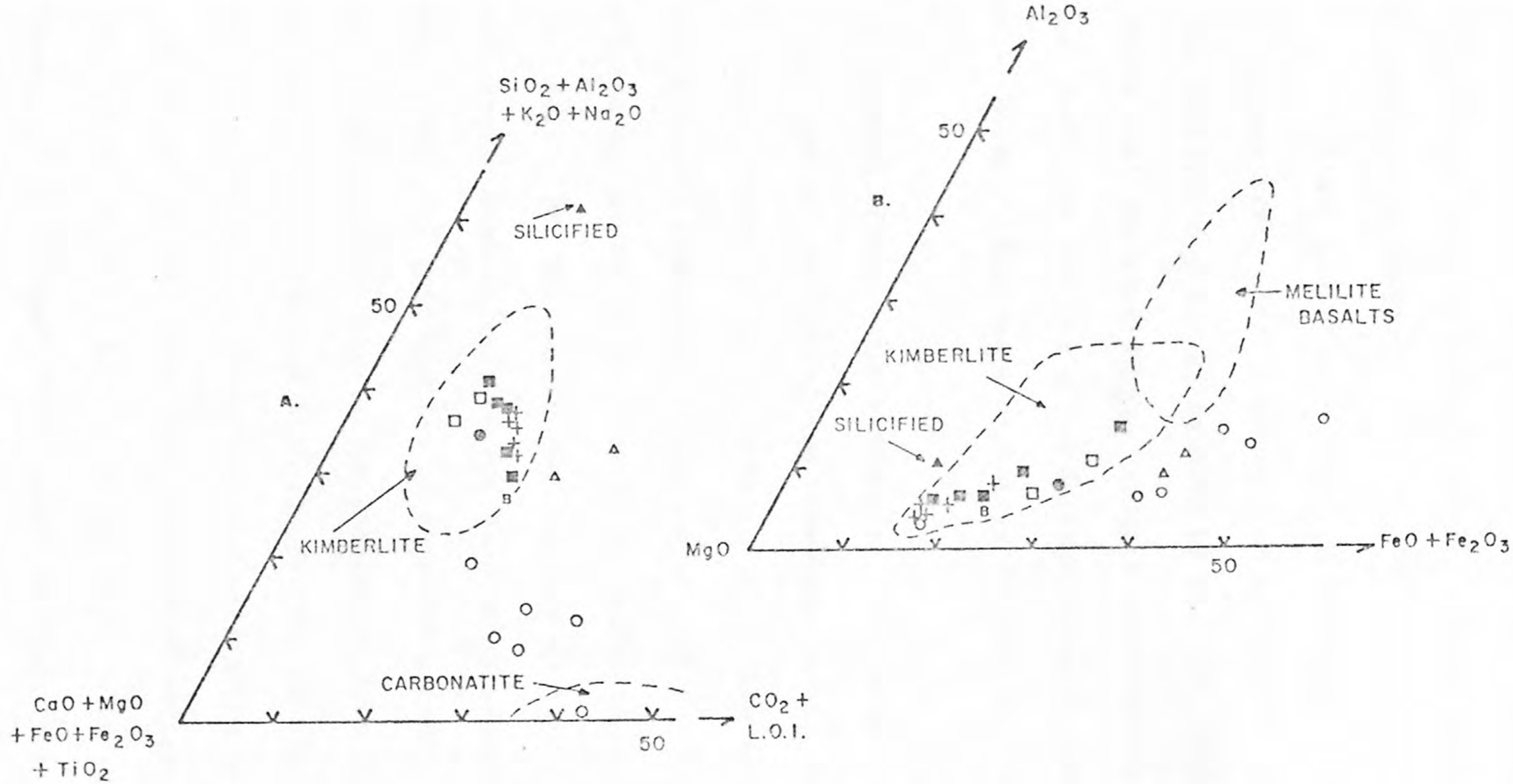

Figure 3.--Chemical compositions of Colorado-Wyoming kimberlite compared to ranges of Dawson (1967) and Cornelissen and Verwoerd (1975) (dashed fields). Open circles are carbonatitic kimberlite from Quebec (Gittens and others, 1975) and Benfontein sill (Dawson and Hawthorne, 1973). Open triangles = Iron Mountain carbonatized kimberlite; solid triangle = State Line carbonatized and silicified breccia; crosses = Sloan 1 breccias (State Line district); open squares = Iron Mountain massive to porphyritic kimberlite; solid squares = State Line massive to porphyritic kimberlite; solid circle = Estes Park, Colorado, dike; B = Green Mountain diatreme, Boulder, Colorado. L.O.I. = loss on ignition at 1000°C.

silicified kimberlite, and one phlogopite-rich sample from Iron Mountain (IM21-1), Front Range kimberlite has "basaltic" rather than micaceous affinities (Dawson, 1967).

Minor and Trace Element Chemistry of Kimberlite

Minor and trace element abundances were determined by whole-rock emission spectroscopy for 25 samples by the U.S. Geological Survey (table 2). These analyses should be considered semiquantitative only, as the standard deviation for any given determination is +50 percent and -33 percent. However, the range of values defines realistic compositional limits.

In general, Front Range kimberlites have minor and trace element abundances typical of kimberlites elsewhere in the world (table 2) (e.g., Dawson, 1967; Kable and others, 1975; Fesq and others, 1975). Although discrete kimberlite varieties are not easily distinguished by their trace and minor element contents, carbonate-enriched samples have high Zr, Zn, Y, Sr, Nb, Be, La, Ce, Nd, and Pb relative to carbonate-poor, serpentine-rich kimberlite. Co and Ni display negative correlations with carbonate content. Four samples of serpentine-rich, carbonate-poor, massive to porphyritic dike facies kimberlite from Iron Mountain (IM16-5, IM21-1, IM29-3, IM29-4) have high Zr, Sr, Nb, La, Ce, Nd, and Gd relative to State Line district kimberlite. One silicified sample (NX3A-1, fig. 3) does not differ notably from other kimberlite in trace and minor element chemistry except that it is anomalously high in Cu (table 2).

There are no distinct differences in trace or minor element chemistry between massive to porphyritic kimberlite (dike facies) and brecciated

Table 2.--Minor and trace elements in Front Range kimberlite

Sample Rock Type	BD-4 KIMB	ED1-1 KIMB	FD2-2 KIMB	FD2-5 KIMB	IM1-8 KIMB	IM16-5 KIMB	IM18-1 KIMB	IM21-3 KIMB	IM29-3 KIMB	IM-29-4 KIMB	NX1-18 KIMB	NX2-15A KIMB	NX3A-1 KIMB
B	40	14	58	91	10	130	20	25	140	140	43	80	5.3
Ba	180	600	450	650	650	720	1900	580	1400	1000	390	1400	570
Be	0	0	0	1.50	3.6	1.1	8.5	.71	3.8	1.9	0	1.4	1.6
Ce	100	220	84	210	290	220	660	390	390	480	150	440	220
Co	52	59	54	76	37	69	28	56	80	79	50	81	18
Cr	780	1300	930	1000	660	970	610	1000	930	850	1100	1100	1100
Cu	90	150	10	19	21	85	22	54	97	71	33	9.8	820
Eu	0	0	0	0	2	2	4.1	2.5	2.8	3.5	0	0	2.6
Ga	2.5	9.7	6.8	12	5.5	8.4	8.5	11	12	11	4	5.8	2.5
Gd	0	7.7	0	0	11	8.5	21	10	17	21	0	12	7.9
La	37	98	35	82	120	98	380	190	220	270	72	200	150
Li	0	0	0	0	0	0	0	0	0	0	78	0	0
Mn	1100	2700	1300	2200	1100	1800	2000	2200	2200	2200	1100	2000	840
Mo	2.3	0	3.2	5.9	4.2	2.6	7.6	0	6.8	7.5	3.3	7	0
Nb	53	97	62	130	110	100	310	150	220	290	73	230	210
Nd	0	88	0	63	150	80	190	180	61	120	88	0	180
Ni	720	640	760	1200	530	820	500	500	1100	940	760	1300	200
Pb	19	12	37	59	23	13	72	13	21	32	54	12	24

Table 2.--Minor and trace elements in Front Range kimberlite--cont.

Sample Rock Type	ED-4 KIMB	ED1-1 KIMB	FD2-2 KIMB	FD2-5 KIMB	IM1-8 KIMB	IM16-5 KIMB	IM18-1 KIMB	IM21-3 KIMB	IM29-3 KIMB	IM-29-4 KIMB	NX1-18 KIMB	NX2-15A KIMB	NX3A-1 KIMB
Sc	4.8	10	5	11	8.4	10	23	14	20	22	5	12	13
Sn	0	0	0	9.1	0	0	14	0	16	18	0	18	0
Sr	100	310	21	300	330	320	1300	600	910	800	310	820	420
Th	0	0	0	24	0	0	56	0	36	42	0	54	0
V	45	64	43	140	60	62	120	70	130	120	41	81	170
Y	5.1	9.2	5.7	9.1	13	9.7	26	15	23	31	5.1	11	6.5
Yb	.77	1.2	1.2	1.1	1.3	1.3	2.2	1.9	2.2	3	.73	.53	.83
Zn	26	74	80	120	140	75	190	110	130	120	74	120	26
Zr	53	44	52	98	68	81	280	110	250	290	42	170	86

Table 2.--Minor and trace elements in Front Range kimberlite--cont.

Sample Rock Type	NX3S-1 KIMB	NX4-5 KIMB	NX4-10 KIMB	NX4-16 KIMB	SD1-86 KIMB	SD1-87 KIMB	SD1-88 KIMB	SH13-2 KIMB	SD1-56 CARB	SD2-LC36 GRAN	SH3-E4 EC	SH3-E5 EC
B	34	59	59	33	30	31	15	110	36	14	0	14
Ba	760	620	670	740	300	430	100	1800	4400	650	450	380
Be	.89	.99	0	0	0	0	0	6.4	2.4	1.6	0	0
Ce	470	210	130	170	100	93	73	400	360	70	130	0
Co	47	54	60	56	49	45	45	58	21	37	50	47
Cr	720	950	920	1100	970	930	660	730	21	280	280	300
Cu	17	190	4.5	11	26	120	16	21	17	52	19	140
Eu	2.2	0	0	0	0	0	0	3.1	0	0	1.9	0
Ga	4	2.9	2.9	3.9	3.7	2.6	2.4	10	0	19	21	18
Gd	8.7	0	0	0	0	0	0	16	22	11	16	9.1
La	250	100	58	74	46	42	27	260	190	33	48	11
Li	0	0	0	0	0	0	0	73	0	0	0	0
Mn	1500	1100	1100	1200	1100	930	580	1500	2100	1600	2000	690
Mo	2.7	19	4.7	3.9	2.4	2.4	2.5	8.1	4.8	3.4	6	4.3
Nb	220	71	49	55	45	38	18	290	35	12	20	6.8
Nd	160	0	0	50	0	0	0	80	0	0	0	0
Ni	580	1200	1100	1000	890	830	810	430	170	120	270	690
Pb	42	23	15	0	16	17	16	87	14	0	23	11

Table 2.--Minor and trace elements in Front Range kimberlite--cont.

Sample Rock Type	NX3S-1 KIMB	NX4-5 KIMB	NX4-10 KIMB	NX4-16 KIMB	SD1-86 KIMB	SD1-87 KIMB	SD1-88 KIMB	SH13-2 KIMB	SD1-56 CARB	SD2-LC36 GRAN	SH3-E4 EC	SH3-E5 EC
Sc	12	5.4	3.6	4.3	4.5	4	2.6	18	10	37	50	6
Sn	0	0	0	0	0	0	0	9.7	0	0	7.7	0
Sr	700	290	240	270	200	210	43	820	2900	660	230	280
Th	24	0	0	0	0	0	0	45	160	0	0	0
V	60	60	25	30	37	34	23	180	27	190	310	17
Y	9.1	4.6	3.6	5.2	4.4	4.6	3.5	22	59	28	25	2.9
Yb	1.4	.72	.62	.62	.65	.62	.47	2.4	6.9	3.6	3.7	0
Zn	73	37	53	28	40	30	46	100	79	120	120	71
Zr	160	39	35	36	37	43	21	420	950	130	100	9.5

Concentration in parts per million
0 = below detection limit of analytical method
CARB = carbonatite; KIMB = kimberlite; EC = eclogite; GRAN = granulite
Eu determinations may be in error.
Sample index (see fig. 1):
SD = Sloan diatremes; IM = Iron Mountain district; FD = Ferris diatremes;
SH = Schaffer diatremes; NX - Nix diatremes; BD = Boulder diatreme (Green Mountain diatreme);
ED = Estes Park dike.
Samples SH13-2, IM1-8, and IM18 are carbonatized.
Sample NX3A-1 is silicified.
Analytical method = emission spectroscopy (whole rock)
Analyst - L. Mei
Standard deviation of any single answer = +500/0 and -330/0.
Elements not detected (Lower limit of detection in brackets):

Ag (0.1)	As (150)	Au (10)	Bi (22)	Cd (32)	Dy (32)	Er (10)	Ge (4.6)
Hf (100)	Ho (6.8)	Lu (22)	Os (10)	Pd (1.5)	Pr (68)	Pt (6.8)	Re (10)
Rh (1.0)	Ru (3.2)	Sb (100)	Sm (46)	Ta (320)	Tb (32)	Tl (10)	Tm (4.6)
U (320)	W (10)						

Descriptions of samples in Tables 2 and 3

Kimberlite

Many of the samples listed here do not appear in table 1 or figure 2. In these cases, the descriptions note similar samples that do appear and that have nearly identical major oxide analyses and modal analyses.

BD-4	Intrusive kimberlite breccia (equivalent to sample BD, Fig. 2).
ED1-1	Porphyritic kimberlite (equivalent to sample ED-1, Table 1, Fig. 2).
FD2-2	Massive to porphyritic kimberlite gradational into intrusive breccia (equivalent to FD-2, Table 1).
FD2-5	Massive to porphyritic kimberlite gradational into intrusive breccia (equivalent to sample FD-2, Table 1 and sample FD2-2, Fig. 2).
IM1-8	Carbonatized porphyritic kimberlite gradational into intrusive breccia.
IM16-5	Porphyritic kimberlite.
IM18-1	Carbonatized massive kimberlite (similar to sample IM53-1, Table 1).
IM21-1	Massive to porphyritic micaceous kimberlite.
IM29-3	Porphyritic kimberlite (similar to sample IM16-5, Table 1).
IM29-4	Porphyritic kimberlite (similar to sample IM29-3, Fig. 2 and sample IM16-5, Table 1).
NX1-18	Carbonate-rich intrusive kimberlite breccia gradational in porphyritic kimberlite (similar to samples NX-1 and NX1-9, Fig. 2).
NX2-15A	Carbonate-rich porphyritic kimberlite (not equivalent to any analyses included in Table 1).
NX3A-1	Silicified intrusive kimberlite breccia (not equivalent to any analyses included in Table 1 or Fig. 2).
NX3S-1	Carbonate-rich intrusive kimberlite breccia gradational into porphyritic kimberlite.

NX4-5	Porphyritic kimberlite (equivalent to samples NX4-10 and NX4-16, Fig. 2 and sample NX4-16, Table 1).
NX4-10	Porphyritic kimberlite (equivalent sample NX4-16, Table 1).
NX4-16	Porphyritic kimberlite.
SD1-86	Intrusive kimberlite breccia (equivalent to sample SD1-87, Fig. 2).
SD1-87	Intrusive kimberlite breccia (equivalent to sample SD1-86, Table 1).
SD1-88	Intrusive kimberlite breccia (equivalent to sample SD1-86, Table 1, and sample SD1-87, Fig. 2).
SH13-2	Carbonatized porphyritic kimberlite gradational into intrusive breccia (similar samples not included in Table 1 or Fig. 2).

Xenoliths

SD1-56	Calcite-barite-biotite carbonatite.
SD2-LC36	Granoblastic plagioclase-clinopyroxene-orthopyroxene-magnetite-orthoclase(?) granulite.
SH3-E4	Granoblastic garnet-clinopyroxene-quartz-rutile eclogite.
SH3-E5	Foliated granoblastic kyanite-garnet-clinopyroxene eclogite.

kimberlite (diatreme facies).

Rare earth element (REE) chondrite-normalized patterns (fig. 4) show variable fractionation toward the light REE's and have La/Yb ratios ranging from 29 to 377. Carbonatized kimberlite has generally higher light-REE contents than noncarbonatized kimberlite (fig. 4). These patterns are similar to those of kimberlites elsewhere in the world (e.g., Mitchell and Brunfelt, 1975; Paul and others, 1975).

Seven kimberlite samples were analyzed by atomic absorption for Na_2O, K_2O, Li, Rb and Sr; by the specific ion electrode method for F; and by flame spectrophotometer for Ba and Cs. The results are given in table 3, and are considered quantitative.

Minor and Trace Element Chemistry of Xenoliths in Kimberlite

Minor and trace elements were analyzed in four xenoliths from State Line district kimberlite (SH3-E4, SH3-E5, SD2-LC36, and SD1-56), and these results are included in tables 2 and 3. The two eclogites (SH3-E4 and SH3-E5) are mantle derived, the granulite (SD2-LC36) is of lower crustal origin, and the carbonatite nodule (SD1-56) may be a cognate inclusion.

Acknowledgment

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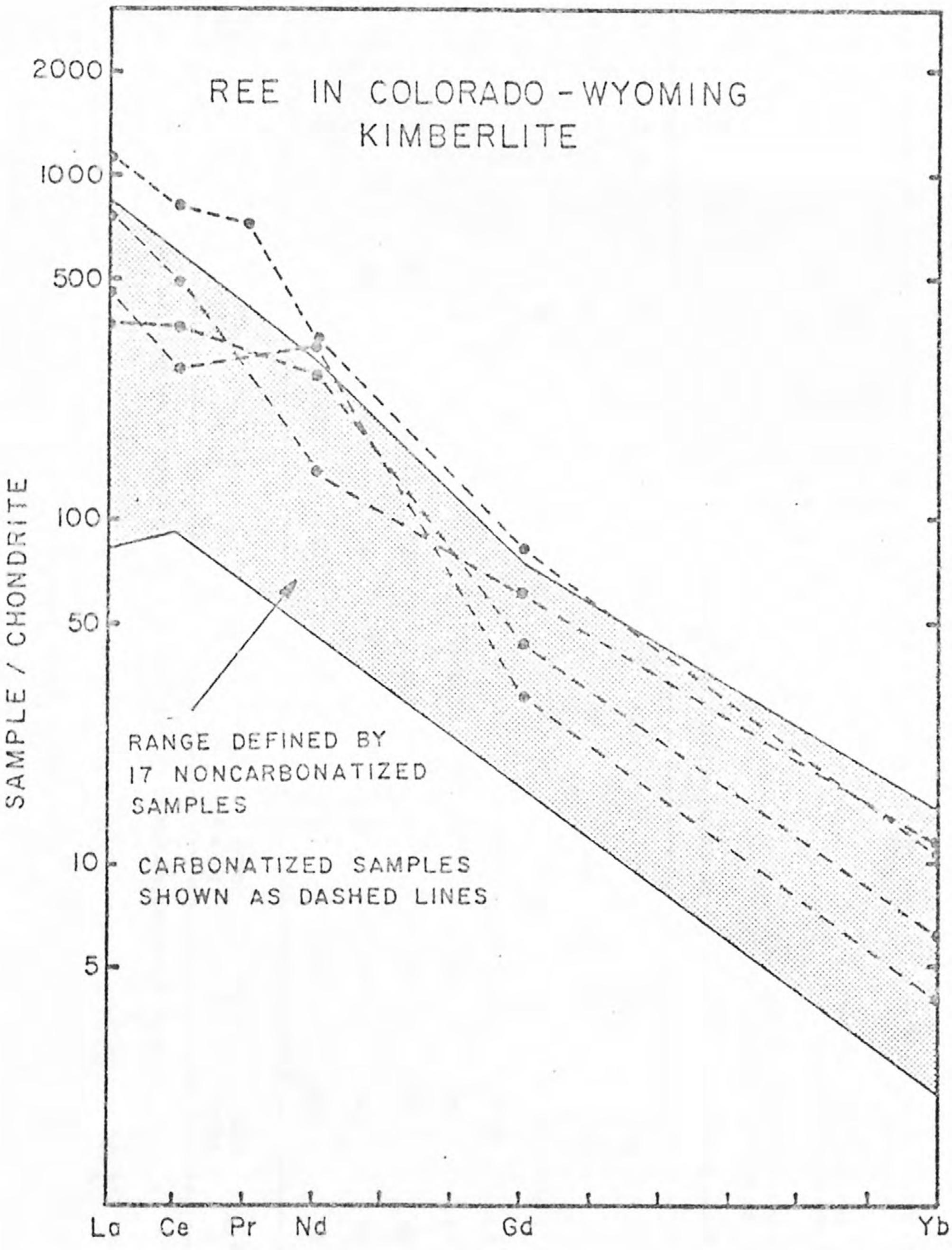

Figure 4.--Chondrite-normalized rare earth element abundances in Colorado-Wyoming Front Range kimberlite.

Table 3.--Quantitative minor and trace element abundances of selected samples.

Sample Rock Type	FD2-5 KIMB	IM18-1 KIMB	IM29-3 KIMB	IM29-4 KIMB	NX2-15A KIMB	NX4-5 KIMB	SH13-2 KIMB	SD1-56 CARB	SD2-LC36 GRAN	SH3-E4 EC	SH3-E5 EC
Na_2O	.10	.07	.06	.05	.04	.05	.05	.04	2.55	1.46	1.59
K_2O	.48	1.91	.09	1.78	.21	.60	1.53	.04	.76	.86	.34
F	.26	.56	.05	.30	.30	.14	.86	.04	.04	.05	0
Ba	.13	.48	.31	.22	.28	.15	.48	11.5	.09	0	0
Cs	2.5	24.5	2.5	2.5	0	0	2.5	0	0	0	18
Li	35	35	15	10	5	4	90	10	9	45	30
Rb	55	145	125	105	35	60	130	10	45	25	15
Sr	475	920	1035	845	1225	715	855	50	740	215	225

Na_2O, K_2O, F, Ba given in percent. Cs, Li, Rb, Sr given in parts per million.

Na_2O, K_2O, Li, Rb, Sr by atomic absorption;
Analysts - V. Merritt and H. Neiman.

F by specific ion electrode method;
Analysts - J. Gardner and P. Guest.

Ba and Cs by flame photometer;
Analysts - W. Mountjoy and C. Gent.

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