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Petrochemistry and geochemistry of kimberlites from different provinces of the world

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Abstract. This paper summarizes the data available on the concentrations of major and trace elements in kimberlites from various provinces of the world. Arithmetic means were calculated for individual kimberlite pipes and dikes, for groups of bodies from individual regions, and for the whole data sample. Some of the most interesting elements and ratios between them are compared and correlation coefficients are offered. Each of the objects of study was found to have its own petrochemical and geochemical characteristics. The kimberlites of the Gondwana group were found to be rich in K, P, La, Th, Zr, and Nb and poor in Ca. Some of the patterns established for the kimberlites of Siberia appeared to be common for all kimberlites, this suggesting some common trend of the deep material evolution during the formation of kimberlite magma and its rise to the ground surface.

Introduction

Kimberlites are of great interest for geologists as the deepest igneous rocks which remove mantle rock xenoliths (nodules) to the ground surface. Most of the papers published on the topic of kimberlites are devoted to the study of these xenoliths including both the rocks as a whole and the minerals composing them. At the same time much less attention is given to kimberlites themselves. This can be accounted for, partly, by the fact that kimberlite pipes are mostly filled with breccias containing an abundant xenogenic material (fragments of intruded rocks), which is hard to remove during the preparation of specimens to be analyzed. At the same time, as mentioned by *Fresq et al.* [1975], "Particular attention was given to "immobile" incompatible elements such as Ti, P, Nb, Ta, Zr, Hf, Ba, Sr, and the REE which, due to their high abundance in kimberlites and related rocks, must have been least affected by crustal contamination." At the same time, when dealing with kimberlite breccia samples, one should try to remove foreign fragments as carefully as possible. The most confident analytical results are those that are accompanied by remarks, such as, "Great care was taken to remove all xenolithic and extensively altered material, as well as secondary veins." [*Scott Smith et al.,* 1984].

Until recently, information on the contents of macro- and microcomponents in kimberlites could be derived only from the publications dealing with kimberlites from Siberia, South Africa, India, Greenland, and some single localities in Canada and the USA. When generalizing the data available for a limited number of the objects of study, one of the authors of this paper [*Ilupin,* 1990] concluded that the kimberlites from the Southern Siberian Province were unique in terms of their low concentrations of barium, REE, thorium, zircon, and phosphorus.

In this paper we report information (collected mainly from publications of 1984–2001) about rock-forming, minor, and rare elements in the kimberlites of Canada, the USA, Greenland, Finland, the northwestern territories of Russia, Siberia, China, India, Australia, South Africa, Zaire, West Africa, and Brazil. Table 1 summarizes information on the contents of major and minor elements in kimberlites for the sites where all most important components (TiO_2, P_2O_5, Cr, Ni, Sr, Ba, La, Th, Zr, and Nb) were determined, where two or more analyses were made, and where the SiO_2/MgO ratio was found to be below 1.7.

The Si to Mg ratio is taken to be the indication of the contamination of ultrabasic kimberlite melt by the crustal material. This characteristic was offered by *Ilupin and Lutz* [1971] and used by many foreign investigators [*Fesq et al.,* 1975; *Paul et al.,* 1977]. Recently, the ratio of (SiO_2 + Al_2O_3 + Na_2O)/(MgO + $2K_2O$) has been used as the index of contamination. One can agree with the combination of Al

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Table 1. Major and Trace Elements in Kimberlites

	Canada, NWT			USA					Ontario	
	Somerset	Jeiricho	Diavik	Montana	Colorado-Wyoming	Kansas	Kentucky	Pennsylvania	Picton	"Varty Lake"
	n=5	n=7	n=6	n=5	n=4	n=2–4	n=2	n=3	n=4	n=3
	Major elements in wt.%									
SiO_2	22.89	26.89	35.58	33.34	25.54	24.03	33.50	22.94	24.12	28.60
TiO_2	1.81	0.64	0.64	2.09	1.67	1.88	2.44	2.71	1.72	3.48
Al_2O_3	212	1.49	2.66	4.13	2.12	3.38	2.89	2.46	3.19	4.49
FeO_{total}	7.35	6.18	6.89	9.77	8.26	7.93	8.82	9.41	8.18	13.91
MnO	0.148	0.156	0.145	0.192	0.188	0.20	0.18	0.203	0.16	0.23
MgO	23.56	21.99	33.44	23.55	32.21	23.70	31.69	26.33	19.72	23.87
CaO	18.00	18.66	6.40	9.52	10.37	14.88	9.50	12.77	18.95	8.93
Na_2O	0.12	0.15	0.15	0.09	0.05	0.08	0.88	0.07	0.06	0.77
K_2O	0.62	0.38	0.54	3.02	0.13	0.14	1.24	1.19	0.66	0.99
P_2O_5	0.78	0.70	0.41	1.19	0.63	1.05	0.44	0.64	0.82	1.22
CO_2	17.34	13.85	ND	4.67	ND	10.38	3.00	ND	14.70	3.50
LOI	4.01	7.42	11.32	7.08	17.77	10.56	3.98	19.52	6.72	8.16
Total	98.748	98.506	98.175	98.642	98.938	98.21	98.56	98.243	99.00	98.15
	Trace elements in ppm									
Sc	20.2	ND	ND	18.0	ND	15.9	ND	ND	22.7	32.4
V	131.6	91.1	ND	ND	ND	ND	ND	ND	140.0	123.7
Cr	1113	1629	1676	1043	1528	1006	1608	1353	954	1134
Co	60.8	ND	75.5	81.6	ND	67.8	ND	ND	108.2	110.3
Ni	720	1099	1175	967	1230	506	1304	835	448	293
Rb	39.4	25.9	66.3	132.6	14.6	14.9	80.2	69.1	24.5	34.0
Sr	1516	558	648	1211	1225	1555	530	1117	2458	1310
Ba	2090	3478	1553	2796	2169	4164	1524	1736	2327	1167
Y	14.4	10.9	7.7	ND	ND	ND	ND	ND	19.5	48.7
La	135.4	168.3	83.0	134.8	164.2	189.2	85.3	135.3	130.8	385
Th	15.7	22.8	12.2	21.1	27.5	27.4	11.2	17.1	13.0	44.3
U	3.27	ND	2.6	4.46	4.84	6.10	2.18	3.55	4.30	7.17
Zr	168.0	87.3	53.5	195.4	146.8	152.5	127.5	293.3	320	340
Hf	4.02	ND	ND	3.86	ND	ND	ND	ND	6.95	9.87
Nb	163.8	194.4	144.3	184.2	191.5	277.5	144.5	193.0	200	327
Ta	10.22	ND	ND	12.24	ND	ND	ND	ND	9.5	18.3

and Na, but the addition of K to Mg can hardly be justified. The point is that as far as the kimberlites of Siberia are concerned, the K content in the country rocks is higher than in the kimberlites. For instance, the average K_2O content in the Lower Paleozoic carbonate–terrigenous rocks from the Malo-Botuoba area (Siberian kimberlite province) is 1.89% (calculated from 214 analyses using Table 60 published in the book [*Kimberlite Petrochemistry,* 1991, p. 213], whereas the average K_2O content for the kimberlites of this region is 0.75%.

Table 2 lists data for the objects represented by single samples, for the objects where not all of the elements concerned were determined (some elements were not determined in all samples), and also for the objects where $SiO_2/MgO>1.7$. This Table also includes data for the compositions of the Japecango and Pantano bodies (Brasil). *Bizzi et al.* [1994] referred to these bodies as mica peridotites, whereas *McDonald et al.* [1995], as kimberlites.

In most cases (Tables 1 and 2) the sums of the macrocomponents are notably lower than 100%. The main cause of this is the sum deficiency in the cited publications. For instance, the sums vary from 95.73 to 98.41% in the case of four kimberlite samples from Orroroo, South Australia [*Scott Smith et al.,* 1984]. Five samples of the Nikos kimberlites (Somerset Island) showed the sums of 98.35 to 98.90% [*Schmidberger and Francis,* 2001]. Besides, we denote the total iron as FeO, whereas many authors, as $Fe_2O_{3(tot)}$ or separately as Fe_2O_3 and FeO.

Some authors neglect carbon dioxide (CO_2) including it in the loss of ignition (LOI).

Table 1. Continued

	Greenl.	Finland				Kola	Arkhangelsk region			
	Greenland	p.1	"p.2; 3"	"p.4; 5; 6"	"p.9; 10; 14"		Zolotitsa	other fields	Grib pipe	Mela sill
	n=8	n=4	n=6	n=4	n=12	n=2–3	n=11–18	n=5–10	n=6	n=2–3
	Major elements in wt.%									
SiO_2	24.21	26.80	32.94	40.72	37.28	30,39	41.55	33.71	37.16	27.83
TiO_2	2.55	1.36	2.22	1.21	2.34	1.24	0.82	2.93	0.88	1.02
Al_2O_3	1.92	3.13	5.42	4.14	4.22	5.08	3.08	3.96	2.00	3.96
FeO_{total}	10.35	9.55	10.26	7.90	8.98	8.48	6.98	9.92	7.21	10.14
MnO	0.199	0.215	0.292	0.132	0.177	0.236	0.142	0.218	0.14	0.357
MgO	26.53	27.57	21.33	26.38	26.77	25.76	29.92	28.29	33.52	22.83
CaO	14.58	14.76	11.04	4.30	5.97	10.26	3.89	4.65	1.83	13.21
Na_2O	0.12	0.115	0.16	0.14	0.51	0.23	0.96	0.31	0.20	0.18
K_2O	1.02	0.90	1.22	0.39	2.25	2.01	1.15	1.22	0.23	0.39
P_2O_5	0.83	0.52	0.67	0.24	0.38	1.64	0.42	0.91	0.17	0.96
CO_2	13.51	5.50	3.81	1.80	1.01	6.08	1.09	2.62	1.47	10.26
LOI	3.08	7.25	9.47	13.35	10.0	7.08	8.93	10.47	14.54	7.13
Total	98.899	97.670	98.832	100.702	99.857	98.486	98.932	99.208	99.35	98.267
	Trace elements in ppm									
Sc	21.0	18.5	20.4	13.6	14.8	18.8	9.1	22.5	6.3	16.0
V	153.9	123.9	184.3	80.7	132.2	99.0	71.1	196.9	75	99.3
Cr	1152	1320	1057	1416	1234	1387	978	1462	1163	1130
Co	ND	66.6	56.5	68.5	71.4	64.5	75.5	69.5	95	ND
Ni	821	898	526	1112	944	878	1192	990	1567	907
Rb	52.6	58.6	81.4	14.9	97.8	85.3	41.3	54.8	16	19.4
Sr	1283	1194	809	331	541	1380	453	576	138	938
Ba	1860	2329	1627	381	1299	1595	702	1124	261	2063
Y	14.5	8.8	14.7	9.0	10.6	14.2	12.0	15.6	4.1	15.3
La	128.2	164.0	137.2	60.0	101.9	128.1	31.2	123.3	28	99.7
Th	12.75	24.2	18.9	9.4	14.7	10.7	3.45	14.5	2.9	12.5
U	ND	3.93	3.86	1.98	2.97	ND	0.835	4.00	1.1	0.58
Zr	225.8	63.9	96.4	58.1	76.3	202.3	106.6	229.3	43	89.0
Hf	ND	1.52	2.44	1.64	2.17	ND	2.87	5.84	0.9	2.00
Nb	192.6	210.2	197.2	87.6	158.0	173.5	40.2	185.2	36	66.7
Ta	ND	12.03	10.95	5.50	10.26	ND	2.53	11.89	3.3	5.10

Kimberlites from Individual Regions (with References)

We begin our description of the Canadian kimberlites from Somerset Island, reporting an average of five samples from the NK3 Pipe of the Nikos Group [*Schmidberger and Francis,* 2001]. Apparently, the chemical composition of kimberlite from this pipe cannot be taken as representative of the kimberlite from Somerset Island as a whole. The markedly lower contents of TiO_2 (0.18%), FeO_{tot} (4.47%), and K_2O (0.08%) were reported by *Clarke and Mitchell* [1975] for a silicate groundmass sample from the Reuyuk C kimberlite body (Somerset Island).

Next we pass to the Slave Craton. Data for aphanite kimberlite from the Jericho Pipe are reported after [*Price et al.,* 2000] and those for the Diavik Pipe, after [*I. Graham et al.,* 1999]. Table 2 lists the values averaged over 15 samples from the Slave Craton [*Pell,* 1997] and the average of three average values for the varieties of the Jericho Pipe [*Cookenboo,* 1999]. Information for the Sturgeon Lake kimberlite is given after [*Hegner et al.,* 1995].

The bulk of the information for the chemical composition of kimberlites from the USA is given after [*Alibert and Albarede,* 1988]. The same publication was used to get data for the kimberlites of Crossing Creek (British Columbia) and Bachelor Lake (Quebec). Information of the Montana kimberlites (Williams 1 and Williams 4 pipes) was borrowed from [*Hearn,* 1989]. The data reported by *Alibert and Albarede* [1988], *Brookins* [1970], and *Cullers et al.* [1982] were generalized for the kimberlites from Kansas (Riley County). The data listed in Table 2 for the George Creek dike (Col-

Table 1. Continued

	Timan	Siberia								
	Vodorazdelnaya	M. Botuobiya	Nakyn	Alakit	Daldyn	Muna	NE Sib.prov.	NW Sib.prov.	Kuoyka	Kharamay
	n=2	n=10–12	n=6	n=31–36	n=22–25	n=9-12	n=34–37	n=28	n=16–24	n=18
	Major elements in wt.%									
SiO_2	36.32	31.31	33.62	28.01	27.91	28.37	27.10	29.23	30.11	27.89
TiO_2	2.90	1.26	0.47	1.49	1.94	1.45	3.59	2.94	1.44	2.16
Al_2O_3	5.24	2.77	2.98	2.23	2.75	2.46	3.14	3.75	2.00	2.62
FeO_{total}	9.86	6.67	6.07	6.23	7.21	7.37	9.32	9.78	8.13	9.33
MnO	0.215	0.128	0.142	0.111	0.129	0.145	0.171	0.182	0.173	0.177
MgO	24.95	26.37	27.47	26.79	26.57	30.57	23.32	21.18	27.09	26.20
CaO	4.67	10.54	9.23	12.82	12.44	9.03	12.49	13.62	10.54	12.82
Na_2O	0.09	0.25	0.11	0.09	0.12	0.20	0.13	0.25	0.15	0.18
K_2O	1.10	0.75	0.58	0.38	0.50	0.76	1.53	1.70	0.66	1.34
P_2O_5	0.52	0.47	0.58	0.47	0.44	0.68	0.83	0.84	0.41	1.12
CO_2	2.56	8.18	6.91	10.27	10.05	8.05	9.28	8.36	10.26	8.02
LOI	10.84	10.47	10.82	10.36	9.49	10.11	7.64	7.16	8.25	7.02
Total	99.265	99.168	98.982	99.251	99.549	99.195	98.541	98.992	99.213	98.877
	Trace elements in ppm									
Sc	22.5	12.1	9.4	12.2	13.2	14.7	16.7	18.8	12.4	18.3
V	186.0	82.6	47.9	91.2	99.7	96.4	137.1	147.5	ND	165.4
Cr	1084	932	1028	1226	1091	1324	858	836	984	1328
Co	65	71.2	59.0	69.2	64.9	76.0	82.0	75.7	85.2	83.8
Ni	986	1150	1578	1031	884	1098	782	708	1140	1097
Rb	48.5	28.4	16.9	23.5	27.8	53.8	87.6	62.1	35.2	50.3
Sr	452	692	477	476	434	568	1002	816	794	821
Ba	834	656	498	861	612	1542	1571	1132	744	1081
Y	20.0	10.7	10.0	10.2	9.8	14.6	22.2	21.2	15.3	21.4
La	102.6	86.6	14.5	89.0	84.0	127.9	137.4	152.2	86.2	177.0
Th	12.1	9.4	1.47	9.81	9.41	14.2	16.5	15.4	11.6	21.0
U	3.05	2.02	0.58	2.14	2.05	3.01	3.67	3.95	2.45	6.41
Zr	321.0	131.4	61.6	113.8	112.9	189.9	266.0	268.4	116.7	384.6
Hf	6.75	2.93	1.54	3.04	2.97	4.57	6.53	6.65	2.91	8.86
Nb	143.5	106.0	26.3	155.5	161.4	170.4	218.6	188.1	171.8	220.8
Ta	6.0	6.17	1.46	8.04	9.58	9.51	11.0	10.14	7.01	11.04

orado) were borrowed from *Carlson and Marsh* [1986] and those for the Blue Ball kimberlite (Scott County, Arkansas), from *Salpas et al.* [1986]. The composition of the Radichal kimberlite (Iron Mountain, Wyoming) was borrowed from [*Alibert and Albarede,* 1988]. We did not combine this sample with the other Colorado–Wyoming kimberlites (see Table 1 for the average), because it is notably low in Ba, REE, Th, Nb, and Zr. Later, when we combined the sample sites into geographical groups, we added the sample from British Columbia to the US kimberlites, and the sample from Quebec, to the Ontario kimberlites.

Information for the kimberlites from the Picton and Varty Lake dikes was derived from the paper by *Arima and Kerrich* [1988]. These dikes are described separately because they differ greatly from one another (primarily in terms of the Ti and Fe contents). The compositions of kimberlites from Ontario listed in Table 2 are given after [*Meyer et al.,* 1994] for the Kirkland Lake sample, and after [*Reed and Sinclair,* 1991] for the James Bay sample. The data published for the Kirkland Lake kimberlite seem to contain a misprint: phosphorus is omitted, and the sum of the components is lower than that given in the table. We calculated the P_2O_5 content (1.18%) using a difference, therefore this value should be treated with caution.

The chemical composition of the West Greenland kimberlites is given after [*Larsen and Rex,* 1992]. When calculating the average contents, we discarded the samples where not all of the components concerned had been determined.

The evidence of the kimberlites from Finland is reported after [*O'Brian and Tyni,* 1999]. The samples described in this paper were divided into four groups: (1) Pipe 1, (2) Pipes 2 and 3, (3) Pipes 4, 5, and 6, and (4) Pipes 9, 10,

Table 1. Continued

	China				Southern Africa					
	Mengyin-1	Mengyin-2	Fuxian-3	Fuxian-4	Finsch	Bellsbank	Sover	Newlands	Star	"Kimberley area"
	n=5	n=5	n=5	n=12	n=30	n=35	n=31	n=19	n=8	n=11
	Major elements in wt.%									
SiO_2	33.74	27.38	25.60	27.93	37.53	33.02	35.09	33.52	34.01	34.03
TiO_2	1.44	1.89	1.18	1.16	0.88	0.74	1.06	0.62	1.27	1.52
Al_2O_3	2.02	2.22	3.30	2.64	3.34	1.64	2.55	1.71	2.79	3.37
FeO_{total}	7.15	6.94	7.10	6.19	7.19	6.99	7.00	6.62	7.73	7.90
MnO	0.126	0.166	0.172	0.195	0.17	0.16	0.15	0.14	0.26	0.16
MgO	32.28	21.68	18.81	19.08	28.18	31.40	29.02	34.08	25.34	25.39
CaO	6.31	17.62	18.71	18.91	6.54	6.61	6.49	6.12	7.92	9.45
Na_2O	0.03	0.02	0.04	0.02	0.21	0.12	0.18	0.11	0.17	0.48
K_2O	0.48	0.28	0.72	0.48	3.14	1.72	2.91	1.02	2.95	1.60
P_2O_5	0.83	0.98	1.39	0.59	0.61	1.41	0.68	1.13	0.82	1.12
CO_2	ND	ND	ND	ND	ND	ND	ND	ND	ND	5.08
LOI	14.18	19.57	21.12	21.48	9.90	12.99	11.76	12.42	12.89	8.25
Total	98.586	98.746	98.142	98.675	97.69	96.80	96.89	97.49	96.15	98.35
	Trace elements in ppm									
Sc	15.6	17.3	25.4	14.9	17	22	16	22	23	16.4
V	91.2	73.2	108.8	90.8	132	73	82	48	ND	98
Cr	1601	980	1229	1071	1765	1670	1852	1891	2156	1380
Co	76.6	67.0	65.5	60.2	71	96	80	71	78	87
Ni	1204	882	712	714	1214	1396	1253	1450	1207	1160
Rb	60.2	21.4	75.4	28.9	ND	ND	ND	ND	ND	58
Sr	574	542	822	516	738	1414	1127	1261	1808	632
Ba	1592	564	4381	1178	1467	3439	2442	3351	4370	808
Y	11.8	9.8	19.0	11.2	ND	ND	ND	ND	ND	13
La	168.0	188.4	360.4	126.6	62	252	168	203	192	129
Th	26.4	24.5	71.9	23.9	9	45	30	33	28	16.5
U	2.0	ND	7.64	4.17	3	7	3	5	ND	3.7
Zr	226.0	277.0	242.4	194.7	184	291	214	193	194	240
Hf	4.08	4.10	5.50	4.42	5	8	5	4	7	5.38
Nb	183.2	166.0	287.0	124.2	51	168	97	139	134	110
Ta	4.46	3.58	8.60	4.02	3	14	9	9	10	7.9

and 14. Group (2) is distinguished by the highest concentrations of Al and Fe, Group 3, by the lowest contents of P, Ba, and La. The kimberlites of Group 4 are also relatively low in P and La, though in contrast to the samples of Group 3, they are notably higher in Ti, K, and Ba.

Data for the kimberlites of the Kola Peninsula were reported by *Kalinkin et al.* [1993] and *Beard et al.* [1998]. Some analyses were made by the authors of this paper. Table 1 presents the average value derived from these three sources.

For the Arkhangelsk region we combined data from three publications [*Beard et al.,* 2000; *Bogatikov et al.,* 2001; *Mahotkin et al.,* 2000]. We calculated the average values using these values for the Zolotitskii field, for the other fields, and for the kimberlites of the Mel Sill. For the Grib pipe average data are reported by [*Verichev et al.,* 1999]. As far as the Middle Timan kimberlites are concerned, we used the data available only for the Vodorazdelnaya Pipe, because the kimberlite from the Umba Pipe contains abundant xenogenic material [*Kononova et al.,* 2000].

The compositions of the Siberian kimberlites are reported here using mainly our own data. Data for the Nakyn field (Botuoba Pipe) were the courtesy of Yu. Yu. Golubeva. We discuss separately five kimberlite fields in the Southern (diamondiferous) part of the Siberian Province. The Malo-Botuoba and Nakyn fields are markedly distant from each other and from the other fields. The neighboring Alakit and Daldyn fields are different markedly in terms of their average Ti, Al, and Fe contents. Compared to the kimberlites from the other southern fields of the province, the kimberlites of the Upper Mun field are enriched in P, La, Th, and Zr. In the northern (poorly diamondiferous) part of the province, we

Table 1. Continued

	Southern Africa			Sierra Leone		Liberia	Brazil		
	IA+IB	Benfontein	Venetia	dikes	pipes	"Sample Creek"	Tr.Ranch., Limeira	Alto Paranaiba	Paranatinga
	n=17	n=4	n=13	n=13	n=2–5	n=14	n=2	n=5	n=11
	Major elements in wt.%								
SiO_2	29.10	21.81	31.61	30.87	31.69	30.42	32.10	30.06	41.32
TiO_2	2.71	3.81	1.10	2.02	1.59	5.32	1.83	2.21	2.03
Al_2O_3	2.40	3.23	2.73	2.08	2.39	1.24	2.21	2.99	3.36
FeO_{total}	9.70	13.44	7.47	10.14	9.28	14.04	10.40	9.30	9.09
MnO	0.198	0.27	0.197	0.182	0.158	0.221	0.23	0.190	0.154
MgO	28.44	24.38	28.34	29.48	28.50	30.38	30.75	27.57	28.13
CaO	9.52	15.03	9.60	7.06	8.21	0.90	7.74	8.71	3.69
Na_2O	0.10	0.43	0.43	0.03	0.29	0.10	0.06	0.74	0.07
K_2O	1.06	0.18	1.11	1.37	1.36	0.10	0.99	1.97	0.22
P_2O_5	1.18	2.64	0.86	0.42	0.73	0.31	1.89	1.09	0.15
CO_2	6.04	ND	ND	4.97	4.44	0.94	ND	ND	ND
LOI	8.66	12.52	15.01	9.41	9.06	13.55	11.22	14.23	10.81
Total	99.108	97.74	98.457	98.032	97.698	97.521	99.42	99.06	99.024
	Trace elements in ppm								
Sc	18.3	25.2	12.6	14.3	14.0	ND	21.4	ND	12.0
V	115.8	220.2	79.2	74.2	69.8	163.7	79.4	111.0	142.7
Cr	1202	1019	1532	1479	1252	1803	1536	860	938
Co	90.8	ND	64.1	ND	ND	ND	97.0	ND	77.9
Ni	1170	549	1321	1251	1209	1694	1568	1055	1238
Rb	56.7	16.5	69.2	68.9	66.4	5.8	87.0	97.3	13.6
Sr	858	1594	985	548	653	75.0	2328	1825	154
Ba	1024	2746	1784	1477	1912	356	2978	2716	374
Y	19.4	27.0	6.8	8.7	11.6	3.9	28.0	24.5	8.0
La	129.2	282.2	151.6	162	205	50.1	276.0	152.8	20.85
Th	27.8	50.7	34.1	25.8	25.7	20.1	32.5	23.8*	4.18
U	5.68	10.5	12.6	3.76	4.75	ND	5.40	ND	0.92
Zr	283	661	102.6	143	208	340	457.5	511.6	55.5
Hf	ND	14.68	ND	5.42	7.6	ND	ND	6.70	1.41
Nb	218	300	209.2	219	270	342	256.0	186.8	63.2
Ta	ND	29.9	ND	16.0	18.8	ND	ND	ND	5.44

Note: ND – No data (here and in other tables).

distinguished the Kuoi field as an independent site, where the kimberlites resemble, in terms of several factors, the kimberlites from the southern part of the province [*Ilupin,* 1990]. We describe separately the data for the northeastern and northwestern groups of the fields [*Ilupin and Genshaft,* 1994]. The kimberlites of the Kharamai field differ from the kimberlites of the other fields of the Siberian Province by their enrichment in P, Zr, and Hf [*Ilupin,* 1999].

The kimberlites of China are described here after [*Tompkins et al.,* 1999]. We classified them into four groups: Group 1 comprising pipe 701 (1) and Group 2 with pipes 6 and 28 (2) in the Mengyin area; Group 3 including pipe 1 and dikes 2, 3, 10, and 11; Group 4 including pipes 30, 42, 50, 51, and 110 and dikes 52, 75, and 104 in the Fuxian area. Groups 1 and 2 differ in the contents of Ti, K, Cr, Ni, Ba, and Zr. The samples of Group 3 are distinguished by their high Ba, La, Th, and Nb concentrations. Their Th contents are higher than in any other sites described in this paper. Note that the contents of the trace elements are high in all five samples included in Group 3: 262 to 401 ppm La, 53.7 to 82.9 ppm Th, and 216 to 347 ppm Nb. Table 2 lists data of kimberlites from North China reported by [*Zhang and Liu,* 1983].

The data for the kimberlites of India and Australia are listed in Table 2. The average data for the kimberlites of Southern India are given after [*Middlemost and Paul,* 1984]. The value averaged over 5 kimberlite samples from the Wajrakarur area was calculated using the data reported by [*Nagabhushanam and Venkatanarayana,* 1985]. The composition of the Chelima micaceous kimberlite dike is given

Table 2. Single Samples, Kimberlites with SiO_2/MgO>1.7 and Samles with Incomplete Set of Elements in Question

	NWT		Saskat.	Br.Col.	USA			Quebec	Ontario	
	Slave craton	Jericho	Sturgeon Lake	Crossing Creek	"Wyom., Radichal"	"Col., George Cr."	Ark., Blue Ball	Bachelor Lake	Kirkland Lake	James Bay
	n=15	n=3 av.	n=1	n=1	n=1	n=1	n=2	n=1	n=1	n=25
	Major elements in wt.%									
SiO_2	38.13	33.93	28.72	32.47	29.93	21.70	ND	20.91	35.15	32.37
TiO_2	0.52	0.84	0.52	1.46	2.56	2.43	ND	2.6	3.13	1.44
Al_2O_3	3.97	2.14	0.79	2.07	2.88	2.45	ND	3.8	3.03	3.31
FeO_{total}	6.75	7.17	6.63	6.28	9.85	9.50	8.86	11.01	9.14	8.73
MnO	0.147	0.143	0.14	0.14	0.18	0.24	ND	0.3	0.15	0.21
MgO	28.03	33.87	27.29	23.82	27.67	15.73	ND	14.58	27.64	27.11
CaO	5.57	6.63	17.00	12.51	9.12	23.65	12.05	22.49	6.54	9.28
Na_2O	0.26	0.13	0.09	0.08	0.07	0.03	0.04	0.12	0.32	0.20
K_2O	1.17	0.32	0.20	1.37	1.05	0.51	3.27	2.22	2.16	1.39
P_2O_5	0.41	0.32	0.14	0.87	0.43	0.72	ND	1.7	1.18*	0.65
CO_2	ND	ND	ND	9.05	4.86	ND	ND	ND	1.77	ND
LOI	13.16	12.82	17.20	8.02	9.20	20.38	ND	19.12	6.96	12.96
Total	98.117	98.313	98.72	98.14	97.80	97.34	24.22	98.85	95.99	97.65
	Trace elements in ppm									
Sc	ND	ND	ND	ND	ND	ND	19.9	ND	ND	ND
V	ND	ND	27	ND	ND	ND	ND	ND	ND	131
Cr	1213	1847	944	1411	1369	583	1411	585	1916	1302
Co	61.5	ND	ND	ND	ND	57	69.05	ND	64	ND
Ni	1142	1395	1472	1142	1209	711	665	220	1100	931
Rb	70.7	40.7	10.2	68.6	66.7	24	157.5	111	105	ND
Sr	613	424	281	975	516	759	915	1685	360	631
Ba	1299	1235	332	2200	992	921	1860	2232	1164	1376
Y	8.5	7.3	3	ND	ND	18	ND	ND	ND	ND
La	ND	ND	ND	134*	88*	144	64.8	236*	47	129
Th	ND	ND	11.7	20.8	11.2	14	5.37	28.3	5	ND
U	ND	ND	1.24	4.1	2.21	ND	0.86	6.27	ND	ND
Zr	100.7	58.3	33	257	98	234	87.5	329	145	220
Hf	ND	ND	ND	ND	ND	ND	2.13	ND	ND	ND
Nb	140.7	116.0	61	152	132	205	ND	240	140	137
Ta	ND	ND	ND	ND	ND	17	7.25	ND	20	ND

after [*Rao,* 1976], and the content of thorium in this dike, after [*Paul et al.,* 1977].

The data for Australia were collected from the kimberlites of the Northern Territory (Timber and Merlin), South Australia (Orroroo), and Western Australia (the remaining sites). Data for the Timber Creek kimberlites are given after [*Berryman et al.,* 1999] for the least altered kimberlite. Data for the macrocomponents were obtained by way of a reverse calculation for the water-bearing material (because the authors of the cited paper carried out their calculations for the anhydrous material). The Merlin kimberlites are described here after [*Lee et al.,* 1997]. Cited here is the average for two samples. Analyses for Sc, Co, and Th had been made using one sample, and the ratios including these elements had been calculated only for this sample. The composition of the kimberlite from the Aries Pipe is given here after [*Edwards et al.,* 1992], and the compositions of kimberlites from the Earaheedy Basin are given here after [*S. Graham et al.,* 1999]. The Skerring and Bow Hill kimberlites are reported here after [*Atkinson et al.,* 1984], and the composition of the Orroroo kimberlites, after [*Scott Smith et al.,* 1984].

The chemical compositions of kimberlites from several areas in South Africa, namely, from Finsch, Bellshank, Sover, Newlands, Star (Table 1), and Swartruggens (Table 2), are given here after [*Mitchell,* 1995]. The mean values for the Finsch Pipe reported by this author are close to the means calculated for 16 samples by [*Fraser and Hawkesworth,* 1992], namely: 0.88 and 0.92% TiO_2, 3.14 and 3.20% K_2O, and 0.61 and 0.64% P_2O_5, respectively. The kimberlites from the Kimberley area are known from the data reported by [*Muramatsu,* 1983] and [*Muramatsu and Wedepohl,* 1985]. The arithmetic means for kimberlites of groups IA and IB

Table 2. Continued

	China	India			Australia						
	North China	South India	Wajrak. area	Chelima	Timber Creek	Merlin	Aries	Earaheedy	Skerring	Bow Hill	Orroroo
	n=1–4	average	n=5	n=4	n=1	n=1–2	n=2	n=3	n=1	n=1	n=4
	Major elements in wt.%										
SiO_2	29.32	35.57	36.27	32.85	15.87	29.05	40.58	43.92	54.3	32.4	30.36
TiO_2	1.21	1.75	2.57	4.65	3.19	0.48	1.21	3.00	2.9	1.2	1.33
Al_2O_3	1.93	5.25	5.84	4.15	6.83	3.97	4.26	6.50	2.2	5.7	2.88
FeO_{total}	7.37	8.48	8.90	9.18	5.94	7.98	9.90	7.65	9.53	9.17	8.03
MnO	0.165	0.17	0.178	0.26	0.10	0.125	0.17	0.107	ND	ND	0.152
MgO	30.59	23.23	23.27	18.13	23.28	18.43	22.26	23.24	19.3	26.0	25.34
CaO	9.84	13.25	10.95	9.78	19.61	17.16	6.76	3.68	1.8	9.0	10.59
Na_2O	0.12	0.25	0.81	0.105	<0.02	0.12	0.66	0.52	0.40	0.04	0.07
K_2O	0.42	0.99	1.39	2.44	0.11	2.38	2.39	2.11	0.15	0.10	1.40
P_2O_5	0.53	0.71	0.73	1.65	1.74	0.50	0.28	0.99	0.39	0.13	0.66
CO_2	ND	1.95	ND	ND	ND	ND	4.19	ND	ND	ND	7.27
LOI	17.68	7.86	8.79	15.49	22.66	18.78	9.25	6.77	ND	ND	8.12
Total	99.175	99.46	99.698	98.685	99.33	98.975	101.91	98.487	90.97	83.74	96.202
	Trace elements in ppm										
Sc	14.2	ND	ND	ND	ND	12*	24.5	12.6	ND	ND	ND
V	90.2	ND	ND	60.0	196.1	69.5	86.5	187.7	ND	ND	112.8
Cr	1395	ND	889	632	1552	1069	2106	910	1600	870	1411
Co	94.2	ND	70.6	95	24?	66	ND	51.0	75	90	93.2
Ni	1247	ND	834	548	394	743	1292	546	835	765	1366
Rb	27*	123	148.0	105.0	7.3	242.0	171.5	110.0	ND	ND	100.5
Sr	564	766	873	1280	345	1175	428	368	260	220	828
Ba	1175	3158	1657	2050	3008	2805	1914	1466	430	120	ND
Y	9.5	ND	ND	45.0	67.7?	10.5	15.5	19.0	ND	10	14.0
La	165.2	98	ND	360	222	220.5	251	135.3	ND	ND	ND
Th	ND	21.8	ND	38.2*	22.3	51*	51.9	39.3	ND	ND	ND
U	ND	2.93	ND	3.93*	4.9	ND	3.9	6.84	ND	ND	ND
Zr	198	404	ND	560	553	59.5	96.0	399	340	140	167.0
Hf	ND	3.9	ND	ND	ND	ND	1.85	10.2	ND	ND	ND
Nb	180*	ND	ND	315	286	214.0	436	135.7	120	150	195.5
Ta	17*	11.0	ND	ND	ND	ND	27.8	7.81	ND	ND	ND

have been calculated using the data reported by [*Smith et al.,* 1985]. The average of four samples from the Benfontein Sill is used here after [*Pearson and Taylor,* 1996]. The average value was calculated using 13 samples from the Venetia kimberlite cluster by [*Seggie et al.,* 1999]. The compositions of the other kimberlites from South Africa are listed in Table 2. The average compositions of the kimberlites from the Premier Mine are given after [*Fesq et al.,* 1975] and [*Kable et al.,* 1975]. Data for the compositions of kimberlites from the Kuruman Province are given after [*Shee et al.,* 1989]. Average values were calculated separately for the Bathlaros and Elston 01 kimberlites differing distinctly in terms of Ti, P, and other elements. The composition of the kimberlites from East Griqualand are given after [*Nixon et al.,* 1983], who found Co and Nb only in three samples (out of the total eight), V in five samples, Y in six samples, and Zr in seven samples. Data for kimberlites from the Prieska area are given after [*Skinner et al.,* 1994].

The composition of kimberlites from Zaire was computed using data from [*Fieremans et al.,* 1984]. When calculating the average values, we discarded the samples for which no carbon dioxide had been calculated, and also the Mbuji–Mayi samples in which SiO_2 predominated over MgO ($SiO_2 > 60\%$; $SiO_2/MgO > 9.0$). As to the most interesting components, no Ni, Zr, and Nb had been determined. Unfortunately, it was difficult to estimate the Zr content after Hf and the Nb content after Ta, because, judging by the data from the literature, the ratios of these elements varied rather widely: 26.4 to 103.6 for Zr/Hf and 7.0 to 46.4 for Nb/Ta. Naturally, it cannot be ruled out that the extreme values of the ratios between the elements had been caused by analytical errors.

Table 2. Continued

	Southern Africa					
	Swartruggens	Premier	Bathlaros	Elston 01	East Griqualand	Prieska area
	n=15–21	n=15	n=8	n=2	n=3–8	n=17
	Major elements in wt.%					
SiO_2	36.44	44.33	31.94	30.65	25.74	34.59
TiO_2	1.58	1.82	2.63	0.70	2.61	2.04
Al_2O_3	4.02	3.95	2.50	1.10	3.42	4.05
FeO_{total}	7.34	7.91	9.31	6.12	11.26	8.94
MnO	0.16	0.143	0.213	ND	0.21	0.182
MgO	21.25	23.97	30.00	35.90	22.55	25.04
CaO	8.39	6.10	6.91	7.07	15.76	7.87
Na_2O	0.24	0.68	0.29	0.14	0.18	0.19
K_2O	4.65	1.24	1.39	0.46	0.53	2.66
P_2O_5	1.34	0.26	0.56	1.94	0.79	1.21
CO_2	ND	0.47	3.82	4.68	9.46	ND
LOI	10.45	7.70	8.83	9.92	7.36	12.07
Total	95.86	98.573	98.393	98.68	99.87	98.842
	Trace elements in ppm					
Sc	20	10.2	ND	ND	ND	ND
V	131	ND	ND	14.0	186	157.1
Cr	1207	1020	1060	1180	1172	1382
Co	73	75.9	138.8	117.5	52	90.6
Ni	1034	969	1069	1700	752	1034
Rb	ND	103.0	72.5	10	ND	119.8
Sr	1139	367	771	1140	970	1158
Ba	5183	565	2926	775	698	2297
Y	ND	8.1	14.2	14.0	30.3	22.9
La	218	33.7	ND	ND	105.8	ND
Th	26	6.17	ND	ND	ND	ND
U	7	1.07	ND	ND	ND	ND
Zr	401	106.7	323.1	317.5	350	268.8
Hf	10	2.52	ND	ND	ND	ND
Nb	143	68.2	452.8	203.5	144	138.3
Ta	8	9.52	ND	ND	ND	ND

Evidence for the kimberlites of West Africa (Sierra Leone and Liberia) was derived from [*Taylor et al.,* 1994] and used in Tables 1 and 2. As far as the kimberlites of Sierra Leone (Koidu kimberlites) are concerned, the cited authors had calculated separately the average data for the dikes and pipes and also discarded several samples, because they believed them to have been altered or contaminated. They also discarded the samples in which not all elements of interest had been determined. In the case of the cited average value for the Sierra Leone pipes, Sc, U, Hf, and Ta had been determined in two cases out of five. Calcite kimberlites are reported separately. In the case of Liberia, these authors calculated an average value using 14 samples having the "Sample Creek" index, whereas listed in Table 2 are data for three samples, the L-4 and BJC samples being characterized as relatively unaltered and uncontaminated. The geochemical features of the Sample Creek kimberlites are classified as typical of the first phase of kimberlite alteration [*Taylor et al.,* 1994]. This statement is not quite clear. Using the results of studying the kimberlites of Siberia, it was found that the alteration of kimberlites leads to the growth of the Si/Mg ratio and to the removal of Mg and Ni. At the same time, compared to the unaltered L-4 and BJC samples, the Sample Creek samples showed the lower SiO_2/MgO ratio (1.00 against 1.19 and 1.15), the higher Ni content (1694 against 970 and 858 ppm), and even the higher Ni(ppm)/MgO(wt.%) ratio (55.8 against 39.1 and 34.2, respectively).

The compositions of the Brazilan kimberlites (Tables 1 and 2) were borrowed from [*Araujo et al.,* 2001; *Bizzi et al.,* 1994; *Greenwood et al.,* 1999]. Because Th was not reported from the Alto Paranaiba kimberlites, we derived its

Table 2. Continued

	Zaire		Sierra-Leone	Liberia			Brazil	
	Mbuji-Mayi	Kundelungu	Calcite kimb.	"B.R.G.M. L-4"	Bomojaha BJC	Wusea WSA	Batovi	Japecanga, Pantano
	n=6	n=4	n=2	n=1	n=1	n=1	n=1	n=3
	Major elements in wt.%							
SiO_2	35.61	30.68	14.97	29.45	28.76	49.49	32.06	33.24
TiO_2	1.46	2.26	1.46	3.06	4.21	2.71	2.69	3.29
Al_2O_3	4.24	2.64	2.86	2.20	2.87	2.86	3.20	1.33
FeO_{total}	6.96	9.91	4.65	10.22	13.39	9.34	10.10	13.58
MnO	0.138	0.215	0.34	0.14	0.42	0.12	0.17	0.203
MgO	14.27	32.56	7.40	24.80	25.08	23.74	31.54	29.06
CaO	13.93	7.00	36.22	10.55	7.46	2.78	4.31	5.40
Na_2O	0.156	0.14	<0.05	0.30	0.08	0.14	0.71	0.05
K_2O	0.58	0.20	0.80	1.00	0.73	0.36	0.27	0.94
P_2O_5	1.13	0.55	1.26	0.72	0.65	0.99	0.62	0.43
CO_2	10.98	2.72	26.74	7.15	3.08	0.17	ND	ND
LOI	9.46	10.11	2.19	8.80	10.45	6.23	14.63	12.04
Total	98.914	98.985	98.89	98.39	97.18	98.93	100.30	99.563
	Trace elements in ppm							
Sc	12.3	14.2	13.4	ND	ND	ND	15.8	18.0
V	ND	ND	74.5	227	111	128	254	152.7
Cr	1703	1540	1605	1070	1225	2083	1175	1031
Co	56.3	92.0	ND	ND	ND	ND	91	116.7
Ni	ND	ND	1023	970	858	1936	1076	1890
Rb	33.2	20.0	43.5	ND	43	17	26.3	69.0
Sr	747	421	2165	735	566	132	433	924
Ba	578	912	1728	885	916	1063	2308	1212
Y	ND	ND	32.0	34	23	13	12.9	13.4
La	79.0	113.8	188.0	ND	173	93	113	89.3
Th	16.9	15.95	25.8	ND	18	25	16.2	16.2
U	2.43	4.05	6.35	ND	ND	ND	2.91	6.67
Zr	ND	ND	238.0	ND	273	244	119	709.7
Hf	4.65	2.93	7.05	ND	ND	ND	2.67	ND
Nb	ND	ND	306.5	ND	305	307	179	215.7
Ta	15.5	13.9	16.3	ND	ND	ND	10.9	ND

concentration from the data available for the contents of La, Ni, and P and the ratios of these elements with Th in some other areas of Brazil (proceeding from the strong positive Th-La, Th-Nb, and Th-P correlations). The Paranatinga kimberlites are classified as altered and contaminated with crustal material: the SiO_2/MgO ratio is 1.47 for the average of eleven samples, the contamination index varying from 1.25 to 1.97 for some samples. As mentioned by *Greenwood et al.* [1999], "neither this contamination, nor the degree of alteration of the samples (estimated visually) appears to have a major effect on the ratios of incompatible trace-elements." Like in the case of the Liberian kimberlites, we would note that the Paranatinga kimberlites are richer in nickel than the Batovi kimberlites, discussed in the same paper: 1238 against 1076 ppm, the Ni/MgO ratio being higher, too, 44.0 against 34.1.

Kimberlite Peculiarity

When examining the data listed in Tables 1 and 2, one notes the peculiarity of the chemical composition of kimberlites from each region concerned. The idea that the compositions of all known kimberlite bodies are unique was offered by *Kryuchkov and Khar'kiv* [1989]: "Each body of these rocks is a unique geologic object having no complete analog in nature in terms of its mineralogy, petrochemistry, texture, and structure."

We calculated the arithmetic means for the contents of major and trace elements in kimberlites using the data listed in Tables 1 and 2. The number of source data for each element varied from 71 to 84. The mean values thus obtained are generally close to the values cited in [*Muramatsu,* 1983]; notably higher were only our mean values for Ba (1665 against 1000 ppm), Th (21.1 against 16 ppm), and Nb (183 against 110 ppm); slightly higher was the mean value for Cr (1286 against 1100 ppm).

We combined these objects into larger groups: the Slave Craton kimberlites in the northwest of Canada; the USA kimberlites, this group including a kimberlite sample from British Columbia, Canada; kimberlites from Ontario and Quebec (Southeast Canada); kimberlites from Finland; kimberlites from the Northeast of Russia (Arkhangelsk Province, Kola Peninsula, and Middle Timan); kimberlites from the southern (diamondiferous) part of the Siberian Province; kimberlites from the northern (poorly diamondiferous) part of the Siberian Province; kimberlites from China, India, Australia, South Africa, Zaire, West Africa, and Brazil. For each of these groups we computed the arithmetic means of the components (using data from Tables 1 and 2). These arithmetic means, as well as the data for the Nikos kimberlite (Somerset Island), for the Western Greenland kimberlite (Table 1), and for the Sturgeon Lake (Saskatchewan) kimberlite (Table 2) are listed in Table 3. Each value is supplemented with an "accumulation factor" obtained as a result of the division of this value by the average content of this component in kimberlites. The coefficients higher than 1.2 are given in bold, the values lower than 0.8, in italics. Table 3 lists also the mean values of the components we computed in the kimberlites and the mean values for ultrabasic rocks borrowed from [*Wedepohl and Muramatsu,* 1979].

The individual kimberlite bodies or their groups, listed in Table 3 as "objects", may differ notably from one another. At the same time each object (as a whole) shows its own undoubtful peculiarity. Described below are the peculiarities of the chemical compositions of some kimberlite pipes and dikes, groups of pipes, and kimberlite provinces.

One of the most unique pipes is the Aries Pipe in West Australia. The unique character of its kimberlites was demonstrated, for example, by [*Taylor et al.,* 1994]. Compared to the other well known pipes, Aries stands out because of its high ratios of La(ppm)/P_2O_5 (wt.%) (896) and Th(ppm)/P_2O_5 (wt.%) (185.4). As to the other objects of study, high values were shown by the Merlin kimberlites (Australia): 441 and 104.1, respectively.

With the great diversity of kimberlites in Australia, we would note insignificant Sr contents at five sites out of the seven discussed: 220 to 428 ppm. The exceptions are 828 ppm in the Orroroo kimberlite and 1175 ppm in the Merlin kimberlite. The Zr(ppm)/TiO_2(%) ratio varies from 116.7 to 133 over a limited range (again in 5 cases out of 7), the exceptions being Aries (79.3) and Timber (173.4). Thorium was found only at four sites, its values ranging from 22.3 to 51.9 ppm, the maximum average value being 41.1 ppm (shown in Table 3). Rubidium was determined in four areas, the K/Rb ratio being almost equal (116–125) in three areas (Timber, Aries, and Orroroo), 82 in the Merlin kimberlite, and 159 in the Earaheedy kimberlite.

Very low contents of Sr, Ba, REE, Zr, and Nb were found in the kimberlites of Sturgeon Lake (Saskatchewan), in the Grib pipe (Arkhangelsk Province), and in the Nakyn Field (Siberia). Although this analogy is not complete beginning with the contents of TiO_2 (0.52, 0.88, and 0.47%), Al_2O_3 (0.79, 2.00. 2.98%), and P_2O_5 (0.14, 0.17, and 0.58%).

The kimberlites of Sierra-Leone differ from those of Liberia in their TiO_2 contents (1.46–2.02 against 2.71–5.32%) and in the Ba contents (1477–1912 against 356–1063 ppm), both showing the high concentrations of niobium (219–342 ppm) and the similar ratios of Zr/Nb (0.65–0.99) and K/Rb (141–176). The kimberlites of Sierra-Leone (dikes and pipes) showed very low Zr/Hf ratios: 26.4 and 27.4, respectively. A roughly similar value (27.7) was found for the Star Pipe (South Africa). This value was found to be not lower than 33 in the other kimberlites.

The kimberlites of Liberia are most rich in titanium. The average TiO_2 content in the Sample Creek specimens was found to be 5.32% with variations of 1.57 to 11.40%. Similarly high Ti concentrations were found in the Mayeng kimberlite sill complex (South Africa) [*Apter et al.,* 1984]. This author reported the values of 4.7, 5.12, and 5.42% TiO_2 for three samples. Because he reported only the macrocomponents, we did not include the Mayeng samples in our review. Among the other areas concerned, the highest TiO_2 content was found in the Chelima dike, India (4.65%), this being followed by the value of 4.21% in the BJC sample (Liberia). The kimberlites of the Benfontein Sill (South Africa), known for their abundance of metallic minerals, are slightly lower in titanium: the value of 3.81%, included in our Table 1, is an average of 4 samples. The value of 4.08% TiO_2 was reported by [*Yoshida and Aoki,* 1986] as an average of two samples.

The highest Zr/Hf value (103.6) was found for the kimberlites of India [*Middlemost and Paul,* 1984]. As far as the other objects are concerned, the highest ratio (76.4) was found in the kimberlites of the Alto Paranaiba area (Brazil).

As follows from [*Tompkins et al.,* 1999], the kimberlites of China show high Nb/Ta values: 31–33 ppm for the Fuxian area and 41–46 for Mengyin. The high values for the other kimberlites discussed are 23.9 (Middle Timan, NW Russia) and 23.8 (Kuoika, Siberia). It should be emphasized that the extreme values of some factors (component contents and, especially, ratios between elements) may be associated with analytical errors. Note that the Nb/Ta value of 10.6 for North China was found to be most common [*Zhang and Liu,* 1983]. The lowest Nb/Ta values were found for the Kirkland Lake kimberlite, Ontario (7.0), and for the Premier kimberlite, South Africa (7.2).

The Slave Craton kimberlites are distinguished by the fairly narrow variation ranges of TiO_2 (0.52–0.84%), Zr (53.5–100.7 ppm), Sr (424–648 ppm), and Zr/Nb ratio (0.37–0.72). The P_2O_5 content is slightly higher in the aphanite kimberlite of the Jericho Pipe (0.70%). The three other areas concerned showed this ratio to be rather low: 0.32 to 0.41%. The hypabyssal kimberlite of the Leslie Pipe from the same region (two samples) [*Berg et al.,* 1998] showed similar values for Ti and P: 0.52 and 0.66% TiO_2 and 0.26 and 0.40% P_2O_5. Because merely main components are reported for the Leslie pipe, it was not included in our review, similar to the Mayeng Complex.

In terms of their low Zr contents (58.1–96.4 ppm) the kimberlites of Finland are similar to those of the Slave Craton. Also similar are the average values of P, La, Th, and Nb. Yet, the kimberlites of Finland are more enriched in TiO_2, (av-

Table 3. Average Concentration, and Enrichment Coefficients

Objects	TiO_2	FeO_{tot}	MnO	Al_2O_3	K_2O	CaO	P_2O_5	Cr	Ni	Sr	Ba	La	Th	Zr	Nb
kimb. (n=71–84)	1.94	8.63	0.184	3.12	1.14	10.39	0.81	1286	1037	842	1665	152.2	21.1	223.6	183
ultrabasites, av.	0.13	8.34	0.134	2.70	0.05	3.81	0.05	3090	1450	22	20	0.92	0.07	16	1.3
Somerset Island	1.81	7.35	0.148	2.12	0.62	18.00	0.78	1113	720	1516	2090	135.4	15.7	168	163.8
coeff	0.93	0.85	0.80	*0.68*	*0.54*	**1.73**	0.96	0.87	*0.69*	**1.80**	**1.26**	0.89	*0.74*	*0.75*	0.90
Slave craton	0.66	6.75	0.148	2.56	0.60	9.32	0.46	1591	1203	561	1891	125.6	17.5	75.0	148.8
coeff.	*0.34*	*0.78*	0.80	0.82	*0.53*	0.90	*0.57*	**1.24**	1.16	*0.67*	1.14	0.82	0.83	*0.34*	0.81
Sturgeon Lake	0.52	6.63	0.14	0.79	0.20	17.00	0.14	944	1472	281	332	ND	11.7	33	61
coeff.	*0.27*	*0.77*	*0.76*	*0.25*	*0.18*	**1.64**	*0.17*	*0.73*	**1.42**	*0.33*	*0.20*		*0.55*	*0.15*	0.33
USA	2.16	8.74	0.190	2.80	1.32	12.71	0.75	1257	952	978	2040	131.1	17.3	176.9	185.0
coeff.	1.11	1.01	1.03	0.90	1.16	**1.22**	0.93	0.98	0.92	1.16	**1.23**	0.86	0.82	*0.79*	1.01
Ontario + Quebec	2.47	10.19	0.210	3.56	1.48	13.24	1.11	1178	598	1289	1653	185.6	22.6	270.8	208.8
coeff.	**1.27**	1.18	1.14	1.14	**1.30**	**1.27**	**1.37**	0.92	*0.58*	**1.53**	0.99	**1.22**	1.07	**1.21**	1.14
E.Greenland	2.55	10.35	0.199	1.92	1.02	14.58	0.83	1152	821	1283	1860	128.2	12.8	225.8	192.6
coeff.	**1.31**	1.20	1.08	*0.62*	0.89	**1.40**	1.02	0.90	*0.79*	**1.52**	1.12	0.84	*0.61*	1.01	1.05
Finland	1.78	9.17	0.204	4.23	1.19	9.02	0.45	1257	870	719	1409	115.8	16.8	73.7	163.2
coeff.	0.92	1.06	1.11	**1.36**	1.04	0.87	*0.56*	0.98	0.84	0.85	0.85	*0.76*	*0.80*	*0.33*	0.89
Arkh.+Kola+Timan	1.63	8.76	0.218	3.89	1.02	6.42	0.77	1201	1087	656	1096	85.5	9.4	165.2	107.5
coeff.	0.84	1.02	1.18	**1.25**	0.89	*0.62*	0.95	0.93	1.05	*0.78*	*0.66*	*0.56*	*0.44*	*0.74*	0.59
Siberia-south	1.32	6.71	0.131	2.64	0.59	10.81	0.53	1120	1148	529	834	80.4	8.9	121.9	123.9
coeff.	*0.68*	*0.78*	*0.71*	0.85	*0.52*	1.04	*0.65*	0.87	1.11	*0.63*	*0.50*	*0.53*	*0.42*	*0.54*	*0.68*
Siberia-north	2.53	9.14	0.176	2.88	1.31	12.37	0.80	1002	932	858	1132	138.2	16.1	259.0	199.9
coeff.	**1.30**	1.06	0.96	0.92	1.15	1.19	0.99	*0.78*	0.90	1.02	0.68	0.91	*0.76*	1.16	1.09
China	1.38	6.95	0.165	2.42	0.48	14.28	0.86	1255	952	604	1778	201.7	36.7	227.6	188.1
coeff.	*0.71*	0.80	0.90	*0.78*	*0.42*	**1.37**	1.06	0.98	0.92	*0.72*	1.07	**1.32**	**1.74**	1.02	1.03
India	2.99	8.85	0.203	5.08	1.61	11.33	1.03	760	691	973	2288	229.0	30.0	482.0	315
coeff.	**1.54**	1.02	1.10	**1.63**	**1.41**	1.09	**1.27**	*0.59*	*0.67*	1.16	**1.37**	**1.50**	**1.42**	**2.16**	**1.72**
Australia	1.90	8.31	0.131	4.62	1.23	9.80	0.67	1360	849	518	1624	207.2	41.1	250.6	219.6
coeff.	0.98	0.96	*0.71*	**1.48**	1.08	0.94	0.83	1.06	0.82	*0.62*	0.98	**1.36**	**1.95**	1.12	1.20
Southern Africa	1.67	8.33	0.187	2.85	1.77	8.63	1.10	1432	1152	1064	2258	160.5	27.8	275.3	171.7
coeff.	0.86	0.96	1.02	0.91	**1.55**	0.83	**1.36**	1.11	1.11	**1.26**	**1.36**	1.05	**1.32**	**1.23**	0.94
Zaire	1.86	8.44	0.176	3.44	0.39	10.46	0.84	1622	ND	584	745	96.4	16.4	ND	ND
coeff.	0.96	0.98	0,96	1.10	*0.34*	1.01	1.04	**1.26**		*0.69*	*0.45*	*0.63*	0.78		
West Africa	2.91	10.15	0.226	2.36	0.82	10.45	0.73	1502	1277	696	1191	145.2	23.4	241.0	291.6
coeff.	**1.50**	1.18	**1.23**	*0.76*	*0.72*	1.01	0.90	1.17	**1.23**	0.83	*0.72*	0.95	1.11	1.08	**1.59**
Brazil	2.41	10.49	0.189	2.62	0.88	5.97	0.84	1108	1365	1133	1918	245.4	18.6	370.7	180.1
coeff.	**1.24**	**1.21**	1.03	0.84	*0.77*	*0.57*	1.04	0.86	**1.32**	**1.35**	1.15	**1.61**	0.88	**1.66**	0.98

Note: Bold font means coefficient > 1.2. Italic font means coefficient < 0.8.

eragely 1.78 against 0.66%), in FeO_{tot} (9.17 against 6.75%), and in Al_2O_3 (4.23 against 2.56%) compared to the samples of the Slave Craton.

The kimberlites of South Africa show high variations in all petrochemical and geochemical data. Four objects (Benfontein, Bellsbank, Venetia Cluster, and Newlands) showed high Th contents (33 to 50.7 ppm). Extremely high Zr(ppm)/TiO_2(%) values were found for Newlands (311),

Table 4. Selected components in Kurkhan diatreme and in kimberlites, poor in lithophile rare elements (from pipes of Siberia, Canada and Arkhangel'sk region)

Object	TiO_2 %	Al_2O_3 %	P_2O_5 %	Sr ppm	Ba ppm	La ppm	Th ppm	Zr ppm	Nb ppm	Ta ppm
Kurkhan diatreme	0.04	0.42	0.16	3.41	7.73	0.69	0.29	4.83	1.24	0.01—0.02
Ruslovaya pipe	0.12	1.55	0.23	630	100	45	4.6	28	ND	1.2
Muza pipe	0.065	0.78	0.18	490	150	42	4.2	49	ND	1.8
Sturgeon Lake	0.52	0.79	0.14	281	332	ND	11.7	33	61	ND
Grib pipe	0.88	2.00	0.17	138	261	28	2.9	43	36	3.3
Botuobinskaya	0.47	2.98	0.58	477	498	14.5	1.47	61.6	26.3	1.46

Bellsbank (393), and Elston 01 (454). As to the remaining study areas, the maximum values of this ratio were found to be 254 (Swartruggens, South Africa) and 250 (Tres Ranchos–Limeria Group in Brazil).

The kimberlites of Zaire are (averagely) low in Ba (745 ppm, the lower value (332 ppm) having been found only in the Sturgeon Lake sample) and are rich in Cr (1622 ppm) which is similar to the value of 1591 found in the kimberlite of the Slave Craton.

The kimberlites from the southern part of the Siberian Province are averagely low in La and Th (80.4 and 8.9 ppm). Very similar values were found for the kimberlites from the northwestern province of Russia (85.5 and 9.4 ppm). Yet, the latter are notably richer in Ti, Fe, Mn, K, and P, compared to the south of the Siberian Province. Judging by the contents of Nb and Sm, the lowest concentration of La (about 30 ppm) was found in a Sturgeon Lake sample (Saskatchewan).

Kimberlites from different bodies vary in the absolute MnO content. The maximum values were found in the kimberlite of the Mell Sill (Arkhangelsk Province) (0.357%) and in the calcite kimberlites of Sierra Leone (0.34%). Varying widely is the $100\times MnO/FeO_{tot}$ value: from 1.28 and 1.37 in WSA and L-4 samples (Liberia) to 7.31 in calcite kimberlite (Sierra Leone). Relatively low $100\times MnO/FeO$ values were found in the kimberlites of Australia (1.40–1.89), in the samples of the Paranatinga–Batovi Group (Brazil) (1.68–1.69), and in the kimberlites from most of the studied fragments in the Siberian Province (1.78–1.97), except for the Kuoi Field (2.13) and the Nakyn Field (2.34). This ratio is somewhat higher in the kimberlites of the Slave Craton (1.99–2.18) and in the Jericho aphanite kimberlite (2.52). Most of the South African kimberlites (10 out of 14) showed this value to be 2.01 to 2.36. Lower values were found in the Premier (1.81) and East Griqualand (1.86) kimberlites; the highest – in the Venetia Cluster (2.64) and in the Star Pipe (3.36).

The fairly high $100\times MnO/FeO_{tot}$ value (2.76) was found in the kimberlites of the Kola Peninsula with a fairly good agreement between the values obtained from the results of three laboratories (2.48, 2.78, and 3.09). In this connection it is pertinent to mention the conclusion of *Shcherbina et al.* [1971] about the varying Mn content of the rocks from different regions. They mentioned, in particular, that "...the Lovozero alkaline massif shows a higher Mn content compared to SW Greenland." It cannot be ruled out that the Mn-rich region includes the fragment of the Kola Peninsula, where kimberlites have been found. This ratio is markedly lower (1.92) in the kimberlites of Western Greenland.

Bogatikov et al. [2001] emphasized differences between the kimberlites and lamproites from the Northern continents (Laurasia Group) and those from the southern continents (Gondwana Group), this reflecting the global geochemical heterogeneity of the mantle. The data we collected in this study illustrate these differences. The kimberlites of the southern continents are averagely enriched in P, La, Th, Zr, Nb, and less distinctly in Ti, being low in Ca (Table 3).

Mentioning the wide variations of trace and rare elements in kimberlites, it should be emphasized that even the minimum concentrations reported in literature are notably higher than the average values known for common ultrabasic rocks [*Wedepohl and Muramatsu,* 1979]. In this connection the rocks of the Kurkhan diatreme (Far East, Russia) can hardly be classified as kimberlites. Reporting the very low content of Ti in the studied samples of this diatreme, *Sakhno et al.* [1997, 2001] compared their samples with the kimberlite of the Ruslovaya Pipe. Indeed, the Ruslovaya Pipe, like the Muza Pipe (both located in the Kuoi Field, Siberian Province), is very low in Ti and low in Al and P. Table 4 compares the contents of these components, and also of some minor and trace elements, in the Kurkhan diatreme, in the Ruslovaya and Muza pipes, and also in the pipes reported here, which are the poorest in lithophile trace elements: Sturgeon Lake Pipe (Saskatchewan), Grib Pipe (Arkhangelsk Province), and Botuoba Pipe (Nakyn Field). As far as the Kurkhan diatreme is concerned, *Sakhno et al.* [1997] calculated its Ti, Al, and P contents as averages for 8 samples; they also calculated trace and rare earth elements as averages of three samples [*Sakhno et al.,* 2001]. This showed that the contents of Sr, Ba, La, Th, Zr, Nb, and Ta were one to two orders of magnitude lower in the samples from the Kurkhan diatreme than in our pipes.

The peculiarity (uniqueness) of the chemical compositions of kimberlites from individual provinces, fields, and groups of pipes agrees with the data on the compositions of trace elements in diamonds. *Watling et al.* [1995] reported the results of studying diamonds in Russia, China, Australia, South Africa, and Zaire, unfortunately without mentioning

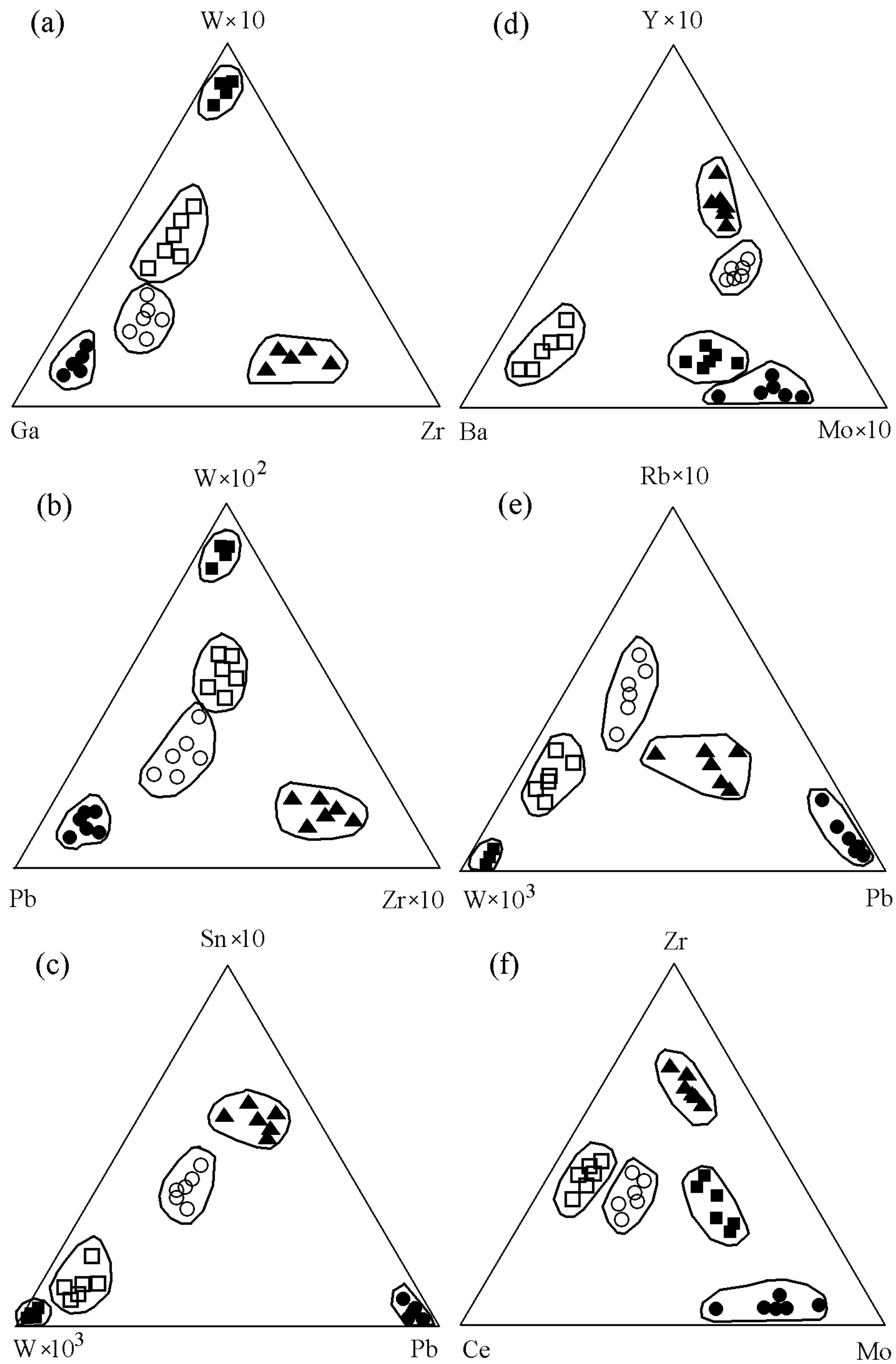

Figure 1. Selected ternary distribution diagrams for element associations in diamonds from five deposits: solid square – Russia; open square – China; triangle – Australia; solid circle – South Africa; open circle – Zaire.

their more exact locations. Their triangular diagrams showing relationships among Ga, Rb, Y, Zr, Mo, Sn, Ba, Ce, W, and Pb, show that the data points for the samples from different regions are grouped to independent, not overlapping fields (Figure 1). Diamonds from Russia are relatively enriched in tungsten, those from South Africa, in lead, and those from Australia, in zirconium.

Classification of Kimberlites into Groups

Smith et al. [1985] suggested that kimberlites can be classified into Group 1 (basaltic) and Group 2 (micaceous). The attributes distinguishing these varieties include a $^{87}Sr/^{86}Sr$ ratio of 0.703–0.705 for Group 1 and of 0.7075–0.710 for

Group 2. They also mentioned some mineralogical differences, although with the reservation that "these are generalized trends only," and also some mineralogical differences, namely: the kimberlites of Group 1 are poor in phlogopite and contain zircon and ilmenite, while those of Group 2 are rich in phlogopite with zircon and ilmenite being absent. It should be emphasized that the first paragraph of this paper includes an important reservation: "Isotopic studies have provided unambiguous evidence that the source rocks of these two varieties of kimberlite must be distinctive, *at least in southern Africa"* (italics ours – I.I. and I.R.). We will also remind that in his well-known monograph, ?.?. *Mitchell* [1986] repeated (pp. 125, 235, 394) that the regularities found for kimberlites of some region cannot be applied to kimberlites as a whole. For instance, in Section 5.3 (Tectonic controls on the distribution of kimberlites), he states: "...it is inappropriate to apply hypotheses developed for any given province to another region."

Nevertheless, the authors of many recent publications dealing with kimberlite compositions often compare their study objects with kimberlites of Groups 1 and 2 after C. B. Smith. It should be recognized that this kimberlite classification cannot always be used unconditionally.

Taylor et al. [1994] emphasized the peculiarity of the Koidu kimberlite (Sierra-Leone). As follows from a number of their geochemical characteristics, these kimberlites differ from the kimberlites of Groups 1 and 2 and show some similarity with the peculiar kimberlites of the Aries Pipe (Australia).

Beard et al. [2000] stated that the kimberlites from the Arkhangelsk region occupy the intermediate position between the kimberlites of Group 1, the kimberlites of Group 2, and lamproites. The term "transitional kimberlite magma types" was used in the heading of this paper.

Kornilova and Safronov [1995] advanced their view against the subdivision of the Yakutian kimberlites into Groups 1 and 2: "No division into Groups 1 and 2, like in South Africa, can be made. Yakutian kimberlites show wide variations of their geochemical and chemical compositions, without any distinct grouping. The initial $^{87}Sr/^{86}Sr$ ratio of the Yakutian kimberlites varies from 0.7034 to 0.7127, being the highest in micaceous–carbonate kimberlites and kimberlite breccias with both high and low TiO_2 concentrations."

The classification of the Siberian kimberlites into Groups 1 and 2 is doubtful also because the Siberian Province is known to include kimberlite bodies containing abundant macrocrysts of both phlogopite and ilmenite (in contrast to the criteria suggested by C. B. Smith). Examples are the well known Iskorka Pipe in the Alakit Field, the micaceous variety of the Druzhba Pipe in the Chomurdakh Field, the "Anomaly 62n" Pipe in the West-Ulukit Field, the Sister-1 Pipe in the Upper-Motorchun Field, Kubanskaya Pipe in the East-Ulukit Field, the Flogopite Pipe in the Merchimden Field, and the Slyudyanka and Pyatnitsa pipes in the Kuoi Field.

It is advisable to classify kimberlites into types (varieties) using the classifications developed by many authors, which are based on their textures, structures, and mineralogy. In particular, the following varieties are known: massive kimberlites, kimberlite breccias, tuff breccias, and tuffs; kimberlites containing abundant and scarce autoliths; kimberlites rich and poor in mica; kimberlites containing and devoid of pyrope ("picrite porphyry" after V. A. Milashev); and, finally, kimberlites differing in the predominant size of magmatic minerals. The classification of kimberlites using these bases (applicable in the field) will be more important, both in terms of theory and practice, than the attempts of the artificial classification into Groups 1 and 2.

Carbonate Matter in Kimberlites

Of particular importance is the information on the content of carbonate matter in kimberlites. Because until recently the best known kimberlites (as indicated by the number foreign publications) were those from South Africa, the comparison of the Siberian kimberlites with them has revealed the unusual enrichment of the Siberian kimberlites in CaO and CO_2. The common view was to associate these features with the composition of the host rocks. The Lower Paleozoic substantially carbonate rocks intruded by kimberlite pipes and dikes in the Siberian Province are found as xenoliths in the kimberlite breccias. While preparing specimens for analyses, these fragments were not always removed carefully enough. Very small fragments measuring fractions of a millimeter can hardly be removed at all. Moreover, some amounts of carbonate matter might have been removed by solutions from the host rocks in the course of the secondary transformations of kimberlites. At the same time, a positive correlation between the CaO and CO_2 contents, on the one hand, and between the contents of P and REE, on the other, was discovered for the kimberlites of Siberia. Using the kimberlites of Siberia as an example, *Ilupin* [1970] proved that the addition of carbonate material from the country rocks caused the growth of the CaO/P_2O_5 ratio.

The average CaO contents in the kimberlites of the southern and northern Siberian Provinces are 10.81 and 12.37%, respectively (Table 3). Some kimberlites from our list showed higher CaO contents (%): 18.00 (Somerset I.), 17.00 (Sturgeon Lake, Saskatchewan), 14.58 (Greenland), 14.28 (China), 13.24 (Ontario + Quebec), and 12.71 (USA). The high contents of calcium and carbon dioxide in the kimberlites are believed by the authors of the cited papers to have been associated with mantle material. For instance, *Schmidberger and Francis* [2001] wrote in their paper devoted to the Nikos kimberlite (Somerset I.): "The kimberlite whole-rock analyses are extremely high in $CaCO_3$ (27–39 wt.%), indicating liquid compositions intermediate between kimberlite and carbonatite..."

The attitude toward carbonate matter (and water) in kimberlite composition was clearly formulated by *Smith et al.* [1985]: "Kimberlite analyses have not been normalized to volatile-free composition simply because the H_2O^+ and CO_2 contents are unquestionably an integral part of the rock."

Table 5. Inter-element Correlation of Elements in Kimberlites

Correlation	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	K_2O	P_2O_5	Si/Mg	Mg/Fe	Fe/Ti
TiO_2	1	0.144	0.832	0.346	−0.159	−0.059	−0.065	0.164	−0.147	−0.709	−0.778
Al_2O_3	0.157	1	0.269	0.431	−0.429	−0.050	0.282	0.109	0.616	−0.467	−0.153
FeO	0.862	0.222	1	0.627	−0.082	−0.149	−0.003	0,324	−0.133	−0.776	−0.497
MnO	0.522	0.304	0.687	1	−0.309	0.113	0.100	0.411	0.056	−0.660	−0.119
MgO	−0.173	−0.370	−0.037	−0.207	1	−0.729	−0.005	−0.206	−0.475	0.656	0.287
CaO	−0.049	−0.085	−0.169	0.065	−0.736	1	−0.222	0.303	−0.114	−0.329	−0.148
K_2O	−0.083	0.324	0.010	0.214	−0.020	−0.214	1	0.120	0.296	−0.046	−0.001
P_2O_5	0.174	0.130	0.331	0.529	−0.216	0.302	0.129	1	−0.221	−0.327	−0.067
Si/Mg	−0.167	0.570	−0.190	−0.100	−0.441	−0.134	0.311	−0.221	1	−0.192	0.065
Mg/Fe	−0.755	−0.409	−0.768	−0.668	0.629	−0.319	−0.067	−0.343	−0.132	1	0.610
Fe/Ti	−0.779	−0.198	−0.552	−0.336	0.340	−0.180	0.036	−0.086	0.077	0.698	1
Cr	−0.220	−0.317	−0.101	0.109	0.498	−0.363	0.287	−0,017	−0.179	0.383	0.351
Ni	−0.277	−0.462	−0.213	−0.252	0.743	−0.661	0.057	−0.290	−0.084	0.592	0.458
Sr	0.007	0.036	0.175	0.446	−0.190	0.356	0.252	0.622	−0.289	−0.264	−0.053
Ba	−0.199	−0.121	−0.073	0.315	−0.155	0.338	0.254	0.512	−0.190	−0.048	0.169
La	0.127	0.014	0.304	0.417	−0.269	0.362	0.066	0.713	−0.197	−0.354	−0.124
Th	0.101	−0.105	0.238	0.381	−0.193	0.280	0.021	0.651	−0.178	−0.257	−0.052
Zr	0.554	0.048	0.587	0.544	−0.207	0.156	0.096	0.747	−0.221	−0.544	−0.419
Nb	0.609	−0.069	0.659	0.530	−0.232	0.302	−0.177	0.498	−0.420	−0.632	−0.477
Zr/Nb	−0.032	0.130	−0.021	0.082	−0.024	−0.141	0.399	0,271	0.206	0.036	0.122
K/Ba	−0.031	0.492	−0.029	−0.095	0.004	−0.383	0.609	−0.199	0.520	−0.006	0.014
Mn/Fe	−0.413	0.052	−0.390	0.385	−0.259	0.307	0.224	0.203	0.158	0.117	0.303

Correlation	Cr	Ni	Sr	Ba	La	Th	Zr	Nb	Zr/Nb	K/Ba	Mn/Fe
TiO_2	−0.213	−0.272	0.004	−0.204	0.134	0.110	0.549	0.618	−0.042	−0.010	−0.390
Al_2O_3	−0.340	−0.511	0.023	−0.108	−0.004	−0.118	−0.027	−0.077	0.054	0.413	0.210
FeO	−0.122	−0.244	0.169	−0.068	0.287	0.220	0.534	0.612	−0.041	−0.049	−0.233
MnO	0.001	−0.308	0.332	0.259	0.268	0.232	0.286	0.292	0.007	−0.165	0.594
MgO	0.511	0.755	−0.179	−0.154	−0.244	−0.168	−0.149	−0.196	0.011	0.031	−0.335
CaO	−0.368	−0.650	0.353	0.340	0.351	0.268	0.135	0.273	−0.142	−0.392	0.312
K_2O	0.289	0.056	0.248	0.245	0.075	0.031	0.108	−0.143	0.384	0.617	0.133
P_2O_5	−0.015	−0.272	0.622	0.513	0.706	0.644	0.731	0.473	0.275	−0.204	0.182
Si/Mg	−0.205	−0.153	−0.284	−0.183	−0.194	−0.179	−0.252	−0.387	0.145	0.480	0.223
Mg/Fe	0.402	0.614	−0.249	−0.052	−0.322	−0.226	−0.462	−0.564	0.068	0.026	−0.043
Fe/Ti	0.321	0.423	−0.047	0.175	−0.140	−0.072	−0.425	−0.508	0.128	−0.031	0.358
Cr	1	0.527	0.032	0.326	0.122	0.219	−0.086	−0.001	−0.022	−0.077	0.176
Ni	0.516	1	−0.319	−0.173	−0.377	−0.207	−0.205	−0.350	0.138	0.126	−0.126
Sr	0.030	−0.337	1	0.668	0.534	0.389	0.508	0.342	0.176	−0.302	0.233
Ba	0.331	−0.179	0.668	1	0.631	0.654	0.237	0.349	−0.048	−0.470	0.412
La	0.116	−0.399	0.536	0.638	1	0.902	0.546	0.678	−0.054	−0.360	0.085
Th	0.213	−0.226	0.391	0.661	0.901	1	0.489	0.641	−0.061	−0.419	0.127
Zr	−0.113	−0.259	0.514	0.246	0.545	0.485	1	0.552	0.487	−0.106	−0.158
Nb	−0.012	−0.373	0.353	0.368	0.679	0.641	0.552	1	−0.342	−0.430	−0.206
Zr/Nb	−0.040	0.102	0.174	−0.051	−0.056	−0.065	0.482	−0.346	1	0.448	0.063
K/Ba	−0.093	0.119	−0.305	−0.470	−0.380	−0.443	−0.134	−0.484	0.461	1	−0.173
Mn/Fe	0.286	−0.041	0.281	0.467	0.150	0.208	−0.074	−0.141	0.121	−0.111	1

Note: Figures above diagonal represent the inter-element correlation in all objects from Table 1 "Figures below diagonal represent the inter-element correlation in the same collection without two objects (Finland – p. 2–3; Arkhangel'sk – Mela sill)".

General Reqularities in the Chemical Compositions of Kimberlites

Some regularities discovered in the compositions of the Siberian kimberlites [*Ilupin,* 1997, 1999, 2000; *Ilupin et al.,* 1978] turned out to be common for the kimberlites of all regions discussed.

Pair correlation coefficients were calculated for all regions listed in Table 1. The coefficients for the most interesting components are listed in Table 5, separately for the whole data array and for the array without two regions (Group 2 for Finland and the Mell Sill from the Arkhangelsk Province), which showed anomalous relationships of manganese with trace elements.

A direct correlation was found between the Al_2O_3 contents and the SiO_2/MgO ratio (0.616); this relationship for the kimberlites of Siberia is shown graphically in the book by [*Ilupin et al.,* 1978, p. 85]. Closely related are Ti with Fe (0.832) and Mg with Ni (0.755). A distinct negative correlation exists between Mg and Ca (−0.729), reflecting a variable relationship between the "silicate" and "carbonate" constituents of the kimberlites.

A direct relationship (r=0.610) was found between the MgO/FeO_{tot} and FeO_{tot}/TiO_2 ratios. Using the Siberian Province as an example, it was shown that the elevated values of both ratios were typical of diamond-bearing kimberlite bodies. The Fe/Ti ratio is the most important constituent of a "potential diamond content factor (PDCF)" offered by *Milashev* [1965].

The trace and rare elements concerned (Sr, Ba, La, Th, Zr, and Nb) were found to correlate with one another. The strongest correlation exists between Th and La (0.902). Only one (Ba-Zr) correlation (0.237) was found to be below the critical value. Also poorly correlated are Sr-Th (0.389), Sr-Nb (0.342), and Ba-Nb (0.349). All of these six elements have a positive correlation with P, the correlation coefficients varying from 0.473 (Nb) to 0.731 (Zr). Zr and Nb also correlate with Ti and Fe, the respective coefficients varying from 0.534 to 0.618.

Information on the CO_2 content in the samples is not reported by all researchers. We examined the relations of CaO with the other components (keeping in mind that kimberlites contain Ca not only in the form of carbonate, but also in the forms of perovskite, apatite, and other minerals). We found that Ca showed a low (yet significant) correlation with P (0.303), Sr (0.353), Ba (0.340), and La (0.351).

We found a positive correlation (r=0.461) between the K/Ba and Zr/Nb ratios.

A week but significant correlation (0.307) was found between the Ca content and the Mn/Fe ratio. In the case of Siberian kimberlites this correlation is shown graphically by [*Ilupin et al.,* 1978, p. 202] and [*Ilupin,* 1997] and is explained by the high Mn/Fe ratio in the carbonate matter. For instance, the kimberlite veins (dikes) of the Malo-Botuoba Field (Siberian Province), most rich in carbonate (30.30–36.06% CO_2 and 38.60–46.25% CaO [*Ilupin et al.,* 1978, p. 21] showed a MnO/FeO_{tot} ratio of 2.85 to 9.01, this ratio being 2.13 for the average kimberlite contents obtained in our study.

A direct relationship was found between the concentrations of manganese and LREE [*Ilupin,* 1997]. In our case, having discarded two "anomalous" areas, we got a significant correlation of manganese with Ti, P, Sr, Ba, La, Th, Zr, and Nb, the correlation of Mn with P_2O_5, Sr, Ba, La, and Th being stronger than the correlation of these elements with Fe (see Table 5, values below the diagonal).

The comparison of kimberlites from different fields (and groups of pipes) in the Siberian province revealed a direct relationship between the Co(ppm)/MgO(wt%) ratio and the contents of Ti, P, and lithophile trace elements [*Ilupin,* 1999].

Table 6. Pair correlation coefficients of components with values Co/MgO and Ni/Co (for 45 objects, critical value $r_{0.05}$ = 0.292)

	MgO	Co/MgO	Co	Ni/Co	Ni
TiO_2	−0.369	0.517	0.309	−0.638	−0.467
P_2O_5	−0.210	0.392	0.257	−0.326	−0.202
Sr	−0.159	0.480	0.392	−0.322	−0.147
Ba	−0.106	0.135	0.042	−0.131	−0.078
La	−0.289	0.479	0.281	−0.510	−0.393
Th	−0.180	0.247	0.132	−0.353	−0.284
Zr	−0.219	0.575	0.509	−0.362	−0.064
Nb	−0.306	0.510	0.325	−0.649	−0.483
MgO/FeO_t	0.707	−0.649	−0.190	0.696	0.590

To verify this relationship we used samples listed in Table 1 (those found to contain Co) and samples from Table 2, found to contain all components of interest. We calculated correlation coefficients (Table 6) for our data array of 45 objects. We found significant correlations between Co/MgO and TiO_2 (0.517), P_2O_5 (0.392), Sr (0.480), La (0.479), Zr (0.575), and Nb (0.510). Like in the case of the Siberian kimberlites, the correlation coefficient (absolute value) of all listed components with Co/MgO is higher than in the case of the correlation separately with Co and Mg.

A significant inverse correlation was found between the Ni/Co ratio and TiO_2 (−0.638), P_2O_5 (−0.326), Sr (−0.322), La (−0.510), Th (−0.353), Zr (−0.362), and Nb (−0.649). The absolute values of the coefficients were again found to be higher than in the case of the correlation separately with Ni and Mg. As would be expected, a direct correlation was found between MgO/FeO_{tot} and Ni/Co (0.696).

In the overwhelming majority of cases our correlation coefficients for the kimberlite of the whole world are lower (in absolute value) than the coefficients calculated earlier for the Siberian Province. To some extent, this might have been caused by analytical errors. Yet, the main cause seems to be the peculiarity of individual kimberlite provinces, fields, and pipe groups. The ratios between elements can vary notably from region to region. This can be illustrated by the Th(ppm)/P_2O_5(wt.%) ratio varying from 28.2 to 46.5 for the groups of samples from Finland, from 6.5 to 17.1 for the samples from the neighboring region of the Arkhangelsk Province (including the Kola Peninsula), and being 23.3 in the Vodorazdelnaya Pipe (Middle Timan). The Zr/Nb ratio was found to vary from 0.65 to 0.99. As far as the South African kimberlites are concerned, a similar value (0.71) was found only for the Bathlaros kimberlite, whereas in other 11 cases it varies from 1.30 to 2.21, being even higher in Swartruggens (2.80) and in Finsch (3.61). These differences are bound to impair correlation.

Conclusions

1. In terms of their petro- and geochemical characteristics, kimberlites from all regions (provinces, groups of bodies, and

individual bodies) are peculiar, differing from other objects in some attributes or their combinations (because some attributes may happen to be identical). This peculiarity of all kimberlite occurrences (like the peculiarity of diamonds transported by them) can be explained by the heterogeneity of the upper mantle. The most exact information of the chemical compositions of kimberlites can be obtained if all foreign (epigenetic) materials are removed thoroughly.

2. Compared to the kimberlites of the northern continents (Laurasia group), the kimberlites of the southern continents (Gondwana Group) are more enriched in P, La, Th, Zr, Nb, and Ti and are poor in Ca.

3. The subdivision of kimberlites into Groups 1 and 2, specified for the kimberlites of South Africa, can hardly be used for the kimberlites of all other provinces, keeping in mind a remark offered by [*Smith et al.,* 1985] concerning the applicability of this subdivision "at least in southern Africa."

4. Similar to water, carbon dioxide is a natural constituent of kimberlite.

5. The common regularities, proved for all known provinces, seem to attest the existence of some common trends in the evolution of a deep-seated material during the generation of kimberlite magma and its movement toward the Earth's surface.

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