COMPARATIVE GEOCHEMISTRY OF SEGUELA CRETACEOUS KIMBERLITES, SOUTH AFRICA GROUP II KIMBERLITES AND OTHER WORLDWIDE KIMBERLITES.

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Abstract

Several altered diamond-bearing kimberlites from Seguela kimberlites complex in Côte d'Ivoire (West Africa) have been investigated to determine their geochemical affinity relative to group II (micaceous) kimberlites of Southern Africa. Comparison is made with other kimberlite occurrences in West Africa and worldwide. Based on major and trace element contents, the Seguela kimberlites show a geochemical signature similar to group II (micaceous) kimberlites of southern Africa and olivine lamproites from Australia. This signature includes high Nb/U (most samples > 51), moderate Ce/Sr (0.5 - 0.6), Nb/Zr (0.2 - 0.4), P_2O_5 (22 - 37), Ba/Rb (20 - 80), U/Th* (0.1 - 0.6), Ti/K (1- 4), and Nb/La of 0.7 – 5. Compatible elements such as Ni and Cr are somewhat enriched over the average in kimberlite presumably as a result of volume decrease of the rock caused by leaching of mobile components. Incompatible elements such as Rb, Sr, Ba, La and Ce are strongly depleted relative to the least altered Seguela kimberlite. The degree of alteration varies widely for the studied samples. High La/Yb ratios and high Rb, Sr, Ba, Nb, indicate that Seguela kimberlites are formed by lower degrees of partial melting. Similarly to Yakutian kimberlites, K_2O, Na_2O and MgO contents increase while TiO_2 and CaO contents decrease as diamond grade increases in Seguela kimberlites. The strongly silica-undersatured nature, extreme enrichment in compatible elements, fractionated REE patterns and high volatile content of the Seguela kimberlites point toward a metasomatised upper mantle source.

Keywords : Seguela Kimberlite, Geochemistry, Petrogenesis, Diamond Potential, Côte d'Ivoire, West Africa

INTRODUCTION

Kimberlites were first discovered in West Africa about forty years ago (Grantham and Allen, 1960). Bardet and Vachette (1966) recognised several episodes of kimberlite emplacement in West Africa, but late-Mesozoic kimberlites are the most extensive and several fields are known in Guinea, Sierra Leone, Liberia and Mali on the West Africa Craton (Fig.1). There are however, few published petrological and geochemical investigations on West African kimberlites, and little has been published since the Bardet's (1974) work that included a compilation of geochemical data then available. Knowledge of kimberlite geochemistry and petrogenesis has been most strongly influenced by studies of fresh south African kimberlites obtained from mining operations. South African kimberlites are characterised by two isotopically and chemically distinct varieties, designated Group I and Group II (Smith 1983; Smith et al., 1985). Group I and II kimberlites essentially correspond to the "basaltic (non-micaceous or serpentine-calcite) and lamprophyric (micaceous) varieties of kimberlite, respectively, that were known from early petrographic investigations of South African kimberlites (Wagner, 1914).

Studies of kimberlite geochemistry are biased by problems inherent to the nature of kimberlite magmas and their intrusive styles (Mitchell, 1986). This includes problems of xenolith/xenocryst contamination, deuteric and hydrothermal alteration, susceptibility to weathering, volatile-loss, and crystal accumulation. Accordingly, in this study only samples from diatreme and dyke facies diamond-bearing kimberlite and lamproite have been selected for detailed geochemical characterization. An important aspect of these investigations is to compare the geochemical compositions of Seguela kimberlites with published data (including major and trace element analyses) of kimberlites from other localities on the West African Craton and where possible with kimberlites and related-rocks from central Africa, south Africa, northwest Australia, and Russia. Such comparative data can be used to place petrogenetic constraints on the origins of kimberlites as well as provide new information on diamond-bearing rocks from the West African Craton.

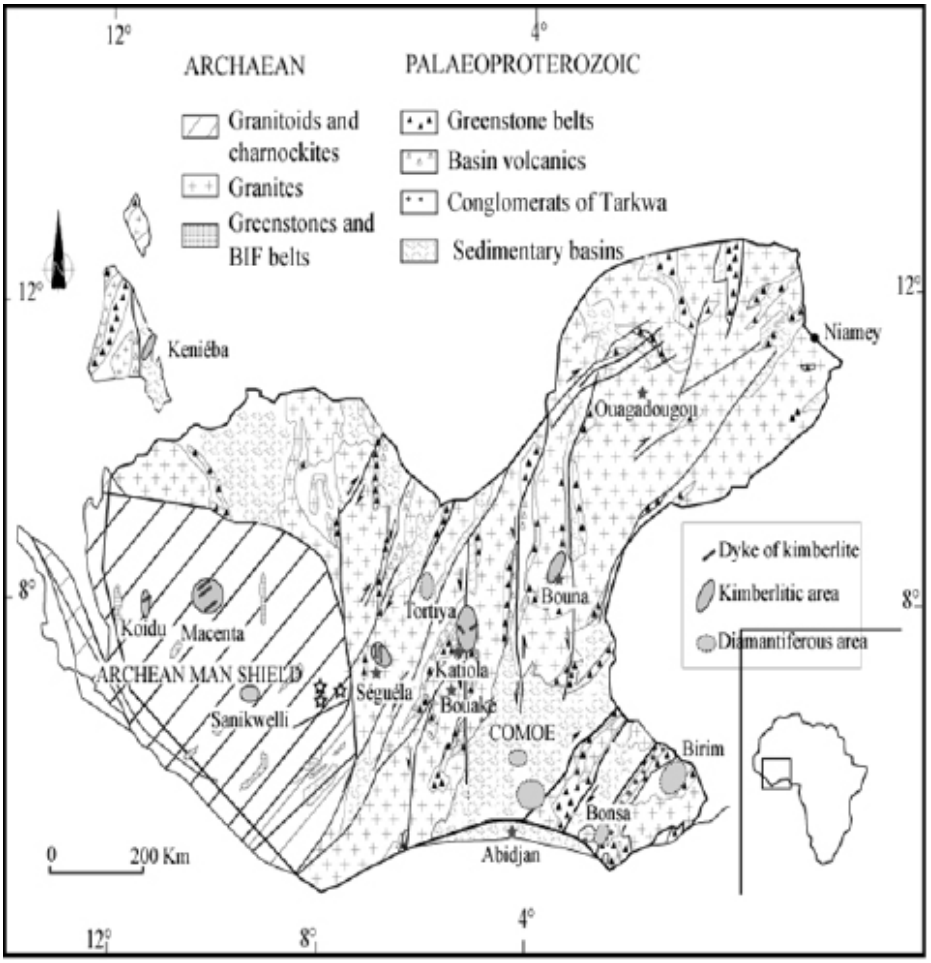


Fig.1. Simplified geological map showing tectono-stratigraphic provinces of archeans and paleoproterozoic formations of the Man Shield (West Africa craton).

Modified from Milési et al., (1989) and Olson et al., (1992).

2. GEOLOGICAL SETTING

Seguela diamond-bearing kimbelite field is located in the central-western part of Côte d'Ivoire, 30 km North of Seguela city (Fig. 2). In this region diamonds are found disseminated into eluvia, colluvia and alluvia with an average of 0.3 ct and the source of the diamonds is considered to be the two main kimberlitic dykes of Bobi and Toubabouko.

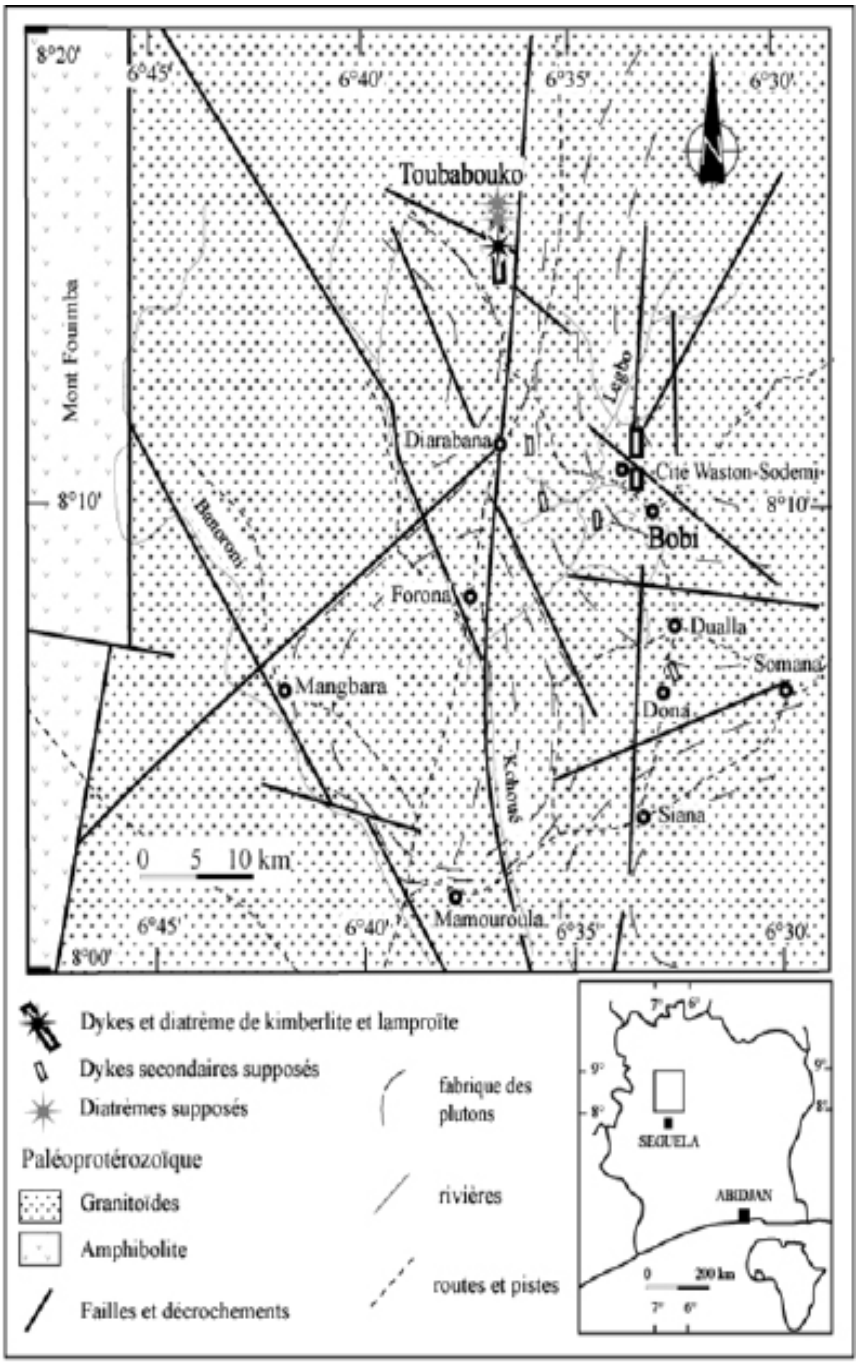


Fig.2. Geological map of Seguela area in Côte d'Ivoire (after Allialy, 2006).

Two companies (Waston & SODEMI) worked in mining activities at areas with higher diamond concentration in the filed from Bobi to Toubabouko. In the present days, there is no more industrial activity and only individual diggers are working in the area. The dykes,

trending N170°E, crosscut the granitic plutons and amphibolites of the Palaeoproterozoic Birimian formations of the West-African Craton. The Seguela granite is dated at 2091 Ma (Kouamelan, 1996; Allialy, 2006). The dyke of Bobi is 2.5 km long and 25 to 50 cm wide. Length of the dyke of Toubabouko reaches 4.5 km with 80 cm to 1 m thickness. In the northern part of this dyke, a particularly enriched zone was recently discovered forming a 80-m-diameter large area and 30-m-deep pit (N 8°15' 22", W 6°37' 57") (Figs. 2, 3, 4). The age of the Seguela kimberlites is not yet constrained but they are supposed to be Cretaceous, like other occurrences inside West Africa Craton.

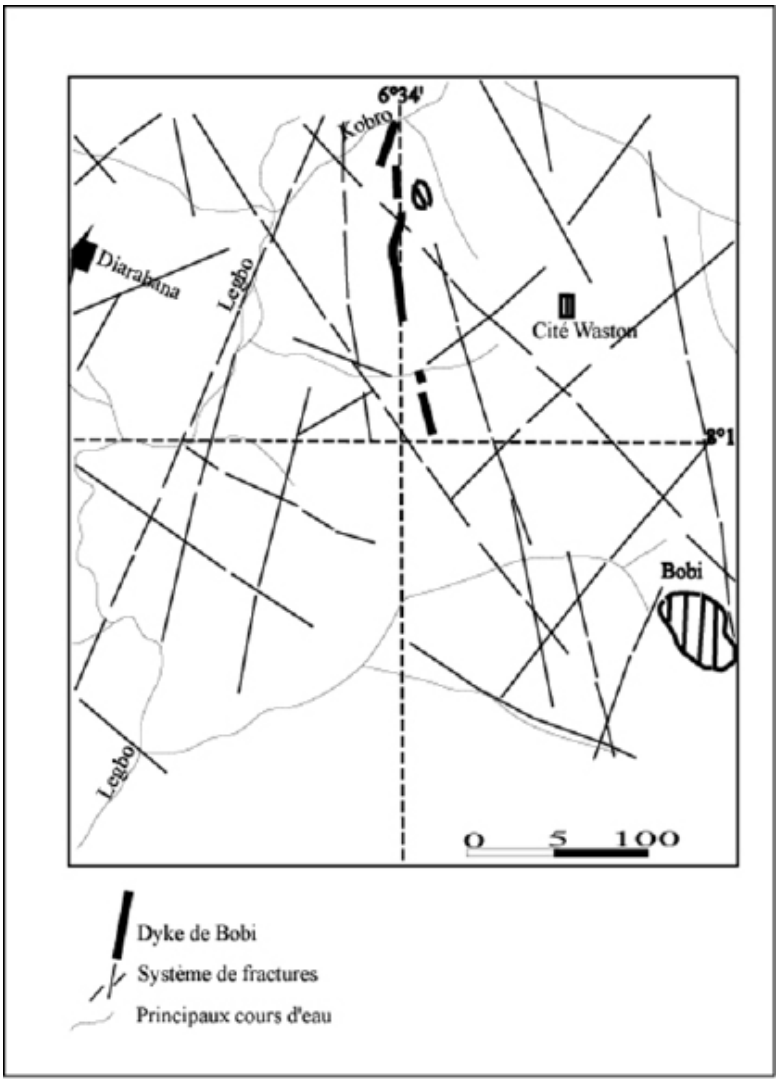


Fig.3. Map of Bobi area fracturation system (Seguela north) redraw Knopf (1970)

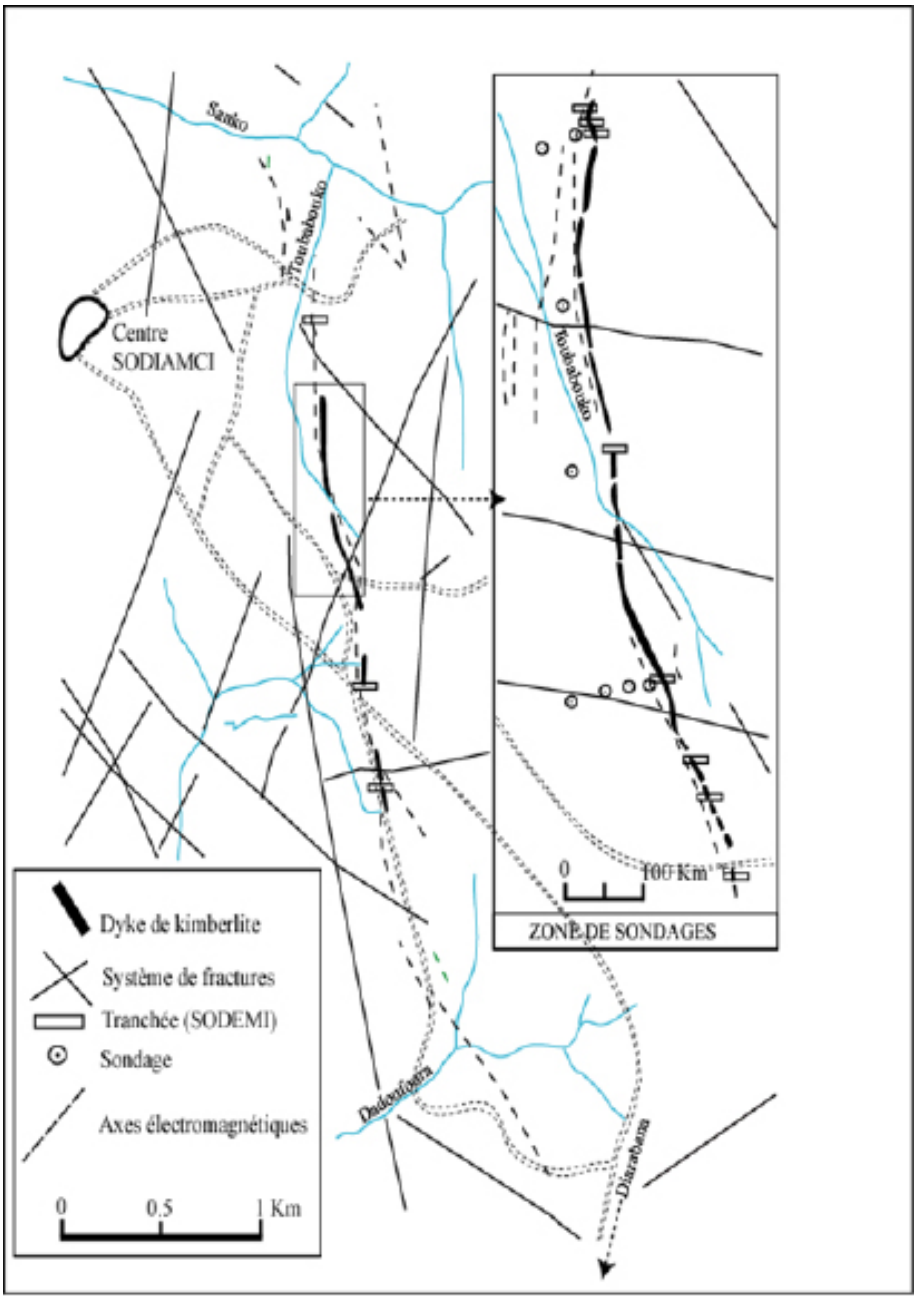


Fig.4. Map of Toubabouko area fracturation system (Seguela north) re drawn after Knopf (1970)

3. SAMPLES DESCRIPTIONS

A total of 30 samples were collected from the Seguela kimberlite field, 20 from Toubabouko dyke and 10 from Bobi dyke. Three different facies of kimberlites are known in Seguela: sensu stricto kimberlite,

kimberlite enriched with olivine nodules, and micaceous kimberlite or lamproite. The common kimberlite is a fine-grained aphyric rock occurring at the dyke margins, or moderately phyric type kimberlite inside the two main dykes and into the diatreme. Phenocrysts consist of olivine totally replaced by serpentine at depth (core samples) and by talc close to the surface. Matrix is made of tiny flakes of Ti-phlogopite (TiO_2 = 4.8– 5.5%), magnetite grains, xenomorphic Mn-ilmenite (MnO = 10.9–18.7%), and accessory magmatic minerals: apatite, titanite, zircon, baddeleyite, monazite, priderite (BaO = 2.2–3.8%), jeppeite (BaO = 17.3–19.9%) and diamonds. Abundant secondary mineralogy in the groundmass consists of Mg-chlorite (penninite), saponite, celadonite, talc, anatase, iron hydroxides, calcite and quartz. In the middle part of the Toubabouko dyke, the rock is highly enriched in 1 to 10 mm-large nodules of olivine, also replaced by serpentine or talc, and contains some xenocrysts of Mg-chromhercynite mantled by chromite and Cr-magnetite. The micaceous kimberlite is characterised by the increasing size of the phlogopite flakes, the decreasing amount of olivine, and the occurrence of Ba-rich titanates. It is defined as lamproite when showing a typical lamprophyric texture. This facies is abundant in the Bobi dyke, but is also present in the Toubabouko dyke. Petrographical features of the Seguela kimberlites are simlar to those of South Africa Group II kimberlites (Pouclet et al., 2004) (Fig. 5 & 6)

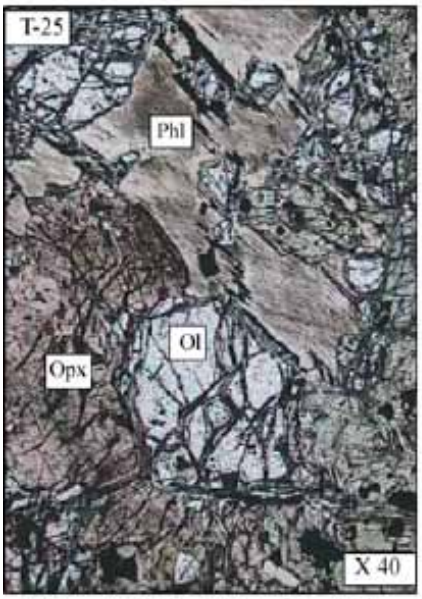
A. Sample K-12 : kimberlite

C. Sample K-11 :Olivine lamproite

B. Sample K-3B2 : kimberlite enriched in olivine nodule

D. Sample MA6B: Micaceous kimberlite

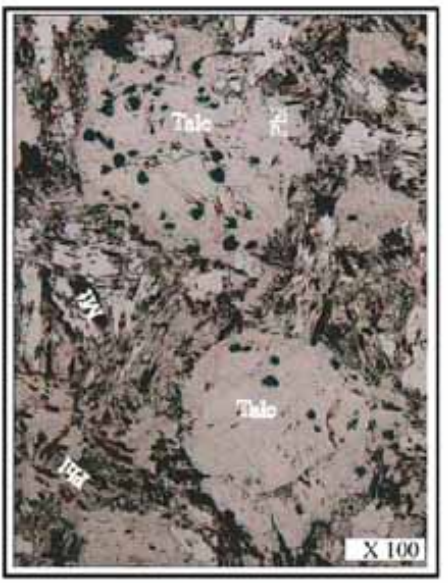
Fig.5. Samples of kimberlites and lamproites from Seguela north in Côte d'Ivoire



A. Sample K-12 : kimberlite of Seguela

C. Sample K-11 :Olivine lamproite of Seguela

B. Sample K-3B2 : kimberlite enriched in olivine nodule of Seguela



D. Sample MA6B: Micaceous kimberlite

Fig.6. Microscopic observation of Seguela kimberlites and lamproites.

3. METHODS

The geochemical analyses were realized within the analytical laboratory of the CRPG (Nancy, France). Major oxide analyses were obtained using emission spectroscopy on ICP-AES whereas trace-element geochemistry were determined by mass spectroscopy on ICP-MS. Results for both major and trace elements are given in Table 1, 2, 3, 4. Samples were chipped and cleaned in acid before being crushed and powdered. Powders were mixed by coning several times to ensure homogeneity. 300 mg of the powdered sample were considered for determination of loss on ignition by living the samples in a muffle furnace at 1000°C for 12 hours. For preparation of glass fusion discs, sample was mixed with lithium tetraborate ($LiBO_3$) and the mixture was heated in a furnace to 1050°C and cast in carbon dies to form the discs. Major elements, together with V, Cr, Ni, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Pb, and Th were analysed on the prepared discs by X-Ray fluorescence (XFR) spectrometer at the Centre de Recherche Pétrographique et Géochimique de Nancy (France) using spectrometer ICP-AES Jobin Yvon JY70 for major element(Si, Al, Fe total, Mn, Mg, Ca, Na, K, P, Ti).The comparative database KIMDAT was extracted from the primitive alkaline rock database of Taylor and Rock (1991) for comparison between our data and other occurrences. This database contains ≈ 260 chemical analyses of kimberlites and ultrabasic rocks, including olivine lamproites and aillikites (central-complex kimberlite of Dawson (1971); believed to originate in the deeper mantle (e.g., Foley, 1991)). KIMDAT was screened to eliminate effect of fractionation, contamination and alteration on the samples (see Taylor and Rock, 1991) because kimberlites and olivine lamproites are susceptible to deuteritic alteration, weathering, and xenolith contamination.

Table 1. Chemical analyses of kimberlites and lamproites from Seguela

Seguela (Côte d'Ivoire)																			
	Olivine Lamp	Kimb	Kimb	Olivine Lamp	Olivine Lamp	Kimb	Kimb	Kimb	Olivine Lamp	Kimb	Kimb	Kimb	Olivine Lamp	Kimb	Kimb	Kimb	Kimb	Kimb	Kimb
Area	Bobi	TOUB	TOUB	Bobi	Bobi	TOUB	TOUB	TOUB	Bobi	TOUB	TOUB	TOUB	Bobi	TOUB	TOUB	TOUB	TOUB	TOUB	TOUB
Samples	K-11	K-12	K-3B2	K-2A1	MA-6	MA-6B	T-25	T- S4	DK-867	DK-868	DK-870	DK-871	DK-911	DK-912/3	DK-278	DK-300			
SiO2	36,95	49,75	55,60	50,76	52,33	49,76	42,30	41,84	45,80	54,80	56,30	42,66	50,11	39,12	45,60	41,70			
Al2O3	7,11	4,35	1,61	4,85	4,36	3,45	4,59	4,62	7,45	1,03	0,30	6,83	10,63	6,10	8,00	6,37			
Fe2O3	10,25	6,84	6,12	11,76	8,27	8,33	14,90	15,04	9,63	7,25	6,66	15,40	6,13	14,16	5,50	6,85			
MnO	0,14	0,11	0,05	0,13	0,10	0,08	0,20	0,19	0,06	0,11	0,06	0,16	0,17	0,07	0,20	0,23			
MgO	20,27	21,28	26,43	10,84	11,74	21,25	29,52	31,22	13,95	24,32	26,64	16,32	12,50	20,56	23,80	26,61			
CaO	8,10	5,48	1,31	3,75	4,93	2,98	3,65	3,73	3,70	2,12	0,22	0,67	7,70	3,69	5,40	5,92			
Na2O	0,72	0,24	0,10	3,80	3,50	0,14	0,54	0,72	0,13	0,09	0,09	0,60	1,50	0,05	0,40	0,28			
K2O	1,11	0,20	0,73	5,96	6,29	0,47	1,13	0,48	0,05	0,63	0,77	1,90	0,95	0,06	0,30	0,20			
TiO2	3,98	2,61	1,52	1,96	3,72	3,65	0,32	0,33	6,75	2,35	1,90	6,45	0,43	6,10	0,60	0,46			
P2O5	1,36	1,16	0,64	1,85	0,78	1,60	0,09	0,09	2,20	1,00	0,65	1,49	0,16	1,73	0,20	1,34			
Pf	9,45	8,05	6,00	4,21	3,63	8,51	2,78	1,91	10,45	6,08	6,00	7,50	9,45	8,48	10,20	9,45			
Total	99,44	100,07	100,11	99,87	99,65	100,22	100,02	100,17	100,17	99,78	99,59	99,98	99,73	100,12	100,20	99,41			
Mg#	0,66	0,76	0,81	0,48	0,59	0,72	0,66	0,67	0,59	0,77	0,80	0,51	0,67	0,59	0,81	0,80			
CI	1,99	2,51	2,05	2,61	2,47	2,40	1,49	1,47	3,80	2,19	2,01	2,49	4,32	2,19	2,21	1,79			
ilmI	0,63	0,44	0,27	0,60	0,49	0,54	0,48	0,48	1,17	0,38	0,30	1,09	0,46	0,98	0,25	0,27			
FeOt/MgO	0,51	0,32	0,23	1,08	0,70	0,39	0,50	0,48	0,69	0,30	0,25	0,94	0,49	0,69	0,23	0,26			
K2O/Na2O	1,54	0,83	7,30	1,57	1,80	3,36	2,09	0,67	0,38	7,00	8,56	3,17	0,63	1,20	0,75	0,71			
MgO/CaO	2,50	3,88	20,18	2,89	2,38	7,13	8,09	8,37	3,77	11,47	121,09	24,36	1,62	5,57	4,41	4,49			
CaO/MgO	0,40	0,26	0,05	0,35	0,42	0,14	0,12	0,12	0,27	0,09	0,01	0,04	0,62	0,18	0,23	0,22			
SiO2/Al2O3	5,20	11,44	34,53	10,47	12,00	14,42	9,22	9,06	6,15	53,20	187,67	6,25	4,71	6,41	5,70	6,55			

CI: Indice de Contamination

Mg# = MgO/(MgO+Fe2O3)

ilmI= Indice d'ilménite

TOUB = Toubabouko

Kimb = Kimberlite

Lamp = Lamproite

Table 1. Chemical analyses of kimberlites and lamproites from Seguela (suite)

Seguela (Côte d'Ivoire)																			
	Kimb	Kimb	Olivine Lamp	Kimb	Kimb	Kimb	Olivine Lamp	Kimb	Olivine Lamp	Kimb	Kimb	Kimb	Kimb	Olivine Lamp	Olivine Lamp	Olivine Lamp
Area	TOUB	TOUB	Bobi	TOUB	TOUB	TOUB	Bobi	TOUB	Bobi	TOUB	TOUB	TOUB	TOUB	Bobi	Bobi	Bobi
Samples	DK-387	DK-866	K013/3	K014/3	K015/3	K016/3	K017/3	K018/3	K019/7	K020/8	K021/8	SEG 4	SEG 5	SEG 6	SEG 7	TA
SiO2	54,32	58,08	58,35	35,47	40,22	41,35	37,25	37,21	41,77	44,85	45,00	37,49	34,06	56,28	63,58	50,53
Al2O3	4,50	3,36	6,37	8,67	6,91	6,12	7,53	11,97	3,49	7,96	3,10	7,67	11,50	15,18	5,58	11,13
Fe2O3	0,90	1,60	3,82	10,63	13,06	13,24	15,80	3,50	8,29	5,31	5,70	10,36	8,09	3,69	7,61	7,48
MnO	0,11	0,07	0,07	0,11	0,09	0,12	0,08	0,09	0,10	0,10	0,09	0,09	0,13	0,09	0,07	0,14
MgO	28,22	26,86	14,72	25,52	23,40	21,68	16,48	27,16	16,16	18,30	19,30	22,80	28,00	8,34	12,72	9,04
CaO	1,40	0,87	4,14	4,65	3,92	3,80	4,70	6,61	8,29	5,88	6,05	3,92	2,58	1,34	1,34	7,48
Na2O	0,25	0,60	0,45	0,16	0,04	0,07	0,06	0,12	1,25	0,52	0,60	0,10	0,03	1,05	0,40	0,52
K2O	0,05	0,03	0,05	0,05	0,05	0,04	0,05	0,03	2,97	1,50	1,45	0,05	0,06	3,70	0,04	1,50
TiO2	1,13	1,73	3,40	3,80	2,90	4,80	7,70	3,28	5,90	5,60	5,60	6,10	3,00	4,30	1,95	5,60
P2O5	0,09	0,13	2,01	0,48	1,63	1,76	3,23	0,31	3,59	0,58	2,25	2,84	1,73	0,18	0,65	0,58
Pf	8,96	6,50	6,57	9,55	7,16	7,12	6,62	9,66	8,35	9,41	10,75	8,38	10,87	5,90	6,26	7,11
Total	99,93	99,83	99,95	99,09	99,38	100,10	99,50	99,94	100,16	100,01	99,89	99,80	100,05	100,05	100,20	101,11
Mg#	0,97	0,94	0,79	0,71	0,64	0,62	0,51	0,89	0,66	0,78	0,77	0,69	0,78	0,69	0,63	0,55
CI	2,09	2,30	4,40	1,73	2,01	2,18	2,70	1,81	2,10	2,50	2,19	1,98	1,62	4,61	5,43	5,16
ilm1	0,07	0,12	0,49	0,56	0,68	0,83	1,42	0,25	0,64	0,51	0,51	0,72	0,39	0,51	0,75	1,09
FeOt/MgO	0,03	0,06	0,26	0,42	0,56	0,61	0,96	0,13	0,51	0,29	0,30	0,45	0,29	0,44	0,60	0,83
K20/Na2O	0,20	0,05	0,11	0,31	1,25	0,57	0,83	0,25	2,38	2,88	2,42	0,50	2,00	3,52	0,10	2,88
MgO/CaO	20,16	30,87	3,56	5,49	5,97	5,71	3,51	4,11	1,95	3,11	3,19	5,82	10,85	6,22	9,49	1,21
CaO/MgO	0,05	0,03	0,28	0,18	0,17	0,18	0,29	0,24	0,51	0,32	0,31	0,17	0,09	0,16	0,11	0,83
SiO2/Al2O3	12,07	17,29	9,16	4,09	5,82	6,76	4,95	3,11	11,97	5,63	14,52	4,89	2,96	3,71	11,39	4,54

C.I: Contamination Index

Mg# = MgO/(MgO+Fe2O3)

ilm1 = ilmenite Index

TOUB = Toubabouko

Kimb = Kimberlite

Lamp = Lamproite

Table.2. Seguela kimberlites and lamproites minor and traces elements (Allialy, 2006).

Seguela											
Samples	K-11	K-12	K-3B2	K-2-A1	MA-6	MA-6B	T-25	T- S4	MA-9	MA-12	MA-7
Minor and REE (ppm)											
As	0,78	0,58	0	0	0	0	0	0	0	0	0
Ba	934	117	462	274	364	542	148	119	17,7	1353	503
Be	7,47	5,03	2,67	14,2	9,37	3,3	0	0	0	0	3,89
Bi	0	0	0	0	0	0		0,11	0	0	0
Cd	0,52	0,44	0	0,32	1,09	0,61	0	0	0	0	0
Co	61,2	58	72,4	39,2	32,9	71,8	138	138	52,59	2,97	21,5
Cr	1323	1399	525	954	782	988	3146	3184	260	23,9	203
Cs	0,29	0	0,26	0	0	0,24	1,67	0,95	0	0,74	1,72
Cu	66,3	15,5	13,5	7,1	20,3	61,5	43,9	54	109	7	78,4
Ga	18,8	15	5,51	17,3	13,9	17,4	7,24	6,62	16,5	18	40,8
Ge	1,82	1,49	0,91	11,7	2,17	1,75	1,36	1,19	1,66	0,86	1,79
Hf	20,7	15,6	9,47	11,5	40,4	22,4	1	0,94	1,46	5,38	5,24
Mo	0,7	0,58	0	0	0	0,44	2,35	1,54	1,56	0,6	0,68
Nb	282	199	86,89	87,3	372	242	1,85	6,09	2,55	4,2	23,8
Ni	679	1229	1338	488	319	1355	1079	994	160	11,9	92,1
Pb	19,3	6,73	21,5	5,85	4,78	4,04	1,12	1,16	0	19	17,1
Rb	36,2	4,48	5,85	76	58,5	26,1	30,4	15,4	0	165	90,2
Sb	0	0	0	0	0	0	0	0,61	0,53	0	0
Sn	33,44	2,39	1,21	5,05	5,07	3,35	0	0,68	0,89	0,62	4,41
Sr	1218	883	407	1410	963	1001	133	158	181	291	151
Ta	16,3	11,6	5,13	4,79	15,7	12,9	0,13	1,76	0,19	0,21	1,51
Th	24,7	16,1	10,2	18,7	9,85	16,9	0,69	0,82	0,45	14,2	15,2
U	2,72	2,89	1,68	0,89	5,42	4,34	0,28	0,21	0	0,62	3,79
V	111	91,5	32,2	142	105	90,5	89,8	86,2	272	20,5	114
W	3,34	1,49	0,17	0,2	0,13	1,21	0,18	0,38	0,25	0,1	0,66
Y	20,3	12,9	9,71	16,6	13,4	20,1	6	7,52	20,2	3,64	32,8
Zn	192	240	86,4	121	88,1	119	113	115	87,3	32,5	125
Zr	933	719	356	256	2010	923	39	33,4	60,7	224	209
Li	0	0	0	0	0	0	0	0	0	0	0
Ti	15600	23880	5988	7682	14581	14307	1920	1293	3567	980	4490
REE (ppm)											
La	340	259	79,8	304	72,5	227	7,52	6,31	3,26	71,6	92,3
Ce	597	481	183	583	210	495	17	15,9	9,03	133	158
Pr	69,5	55,4	23,7	67,4	31,9	54	2,14	2,09	1,27	12,5	19,1
Nd	236	186	85	238	127	190	9,15	8,97	6,67	36,3	67,3
Sm	25,8	19,4	10,4	26,1	16,1	25,1	2,02	2	2,09	3,73	10,7
Eu	6,24	4,32	2,48	5,79	3,71	6,28	0,558	0,54	0,795	1,07	2,19
Gd	12,9	8,89	4,5	11,7	8,74	12,8	1,61	1,6	2,76	2,07	8,17
Tb	1,67	1,17	0,732	1,57	1,01	1,37	0,197	0,224	0,464	0,251	1,12
Dy	6,47	4,72	2,86	6,34	4,31	5,36	1,08	1,33	3,16	1,06	5,94
Ho	0,813	0,522	0,364	0,716	0,5	0,716	0,23	0,253	0,704	0,127	1,08
Er	2,32	1,56	1,08	2,01	1,27	1,65	0,545	0,71	1,94	0,337	2,7
Tm	0,18	0,121	0,109	0,141	0,186	0,174	0,081	0,112	0,305	0,05	0,413
Yb	1,1	0,801	0,667	0,829	1,46	1,02	0,537	0,726	2,02	0,328	2,54
Lu	0,175	0,101	0,071	0,111	0,239	0,138	0,087	0,116	0,32	0,058	0,346

Table.3. Comparision between Seguela kimberlites, lamproites and world wide kimberlites, minor and REE elements (after Mitchell, 1986).

	Seguela kimberlites and lamproites										worldwide kimberlites		
	K-11	K-12	K-3B2	K-2-A1	MA-6	MA-6B	T-25	T- S4	MA-9	MA-12	MA-7	Z1-2-1	Z1-2-2	Mura 83	P-1	P-2
Ni/Cr	0,51	0,88	2,55	0,51	0,41	1,37	0,34	0,31	0,62	0,50	0,45	0,89	1,20	1,08	0,57	0,56
La/Nb	1,21	1,30	0,06	3,48	0,19	0,94	4,06	1,04	1,28	17,05	3,88	0,98	0,73	1,06	0,32	0,35
La/Ba	0,88	0,39	0,14	1,19	0,66	0,37	0,02	0,02	0,06	11,18	1,72	0,05	0,04	0,21	0,59	0,63
(La/Yb)n	309,09	323,35	119,64	366,71	49,66	222,55	14,00	8,69	1,61	218,29	36,34	101,67	75,83	125,00	145,00	186,25
Th/Yb	22,45	20,10	15,29	22,56	6,75	16,57	1,28	1,13	0,22	43,29	5,98	4,44	1,88	14,17	21,00	28,75
Ta/Yb	14,82	14,48	7,69	5,78	10,75	12,65	0,24	2,42	0,09	0,64	0,59	5,65	6,25	9,17	9,40	12,50
Ce/Y	20,30	12,90	9,71	16,60	13,40	20,10	6,00	7,52	20,20	3,64	32,80	8,30	8,60	22,00	25,00	21,00
Ti/Y	768,47	1851,16	616,68	462,77	1088,13	711,79	320,00	171,94	176,58	269,23	136,89	500,48	428,37	536,36	0,00	0,00
Ta/Hf	0,79	0,74	0,54	0,42	0,39	0,58	0,13	1,87	0,13	0,04	0,29	1,53	1,07	1,96	1,47	2,33
Th/La	0,07	0,06	0,13	0,06	0,14	0,07	0,09	0,13	0,14	0,20	0,16	0,04	0,02	0,11	0,14	0,15
Ti/K	1,79	6,53	1,04	0,16	0,30	3,88	0,14	0,34	4,55	0,02	0,42	0,38	0,28			
Ba/Sr	0,77	0,13	1,14	0,19	0,38	0,54	1,11	0,75	0,10	4,65	3,33	1,17	2,43	1,29	2,77	1,27
Ce/Pb	30,93	71,47	8,51	99,66	43,93	122,52	15,18	13,71		7,00	9,24			13,07		
Ba/Nb	3,31	0,59	5,32	3,14	0,98	2,24	80,00	19,54	6,94	322,14	21,13	7,48	15,56	7,80	7,59	3,60
Zr/Hf	45,07	46,09	37,59	22,26	49,75	41,21	39,00	35,53	41,58	41,64	39,89	44,00	43,21	32,86	47,81	46,98
Zr/Nb	3,31	3,61	4,10	2,93	5,40	3,81	21,08	5,48	23,80	53,33	8,78	1,57	2,42	1,30	0,68	0,47
Th/Pb	1,28	2,39	0,47	3,20	2,06	4,18	0,62	0,71		0,75	0,89			1,11		
La/Lu	1942,86	2564,36	1123,94	2738,74	303,35	1644,93	86,44	54,40				610,00	520,00	937,50		
P2O5/Ce*	22,78	24,12	34,97	31,73	37,14	32,32	52,94	56,60	121,82	6,77	7,59	86,68	68,86	0,00	0,00	0,00
Nb/Zr	0,30	0,28	0,24	0,34	0,19	0,26	0,05	0,18	0,04	0,02	0,11	0,64	0,41	0,77	1,48	2,12
Nb/U*	103,68	68,86	51,72	98,09	68,63	55,76	6,61	29,00		6,77	6,28	101,82	416,67	45,48	181,20	138,39
Ba/Rb	25,80	26,12	78,97	3,61	6,22	20,77	4,87	7,73		8,20	5,58	7,19	16,52	15,07	13,02	5,08
Nb/La	0,83	0,77	1,09	0,29	5,13	1,07	0,25	0,97	0,78	0,06	0,26	1,02	1,37	0,94	3,12	2,88
U/Th*	0,11	0,18	0,16	0,05	0,55	0,26	0,41	0,26	0,00	0,04	0,25	0,23	0,13	0,18	0,12	0,13
Ce/Sr	0,49	0,54	0,45	0,41	0,22	0,49	0,13	0,10	0,05	0,46	1,05	0,22	0,21	0,24	0,20	0,21
Ni/MgO	33,50	57,75	50,62	45,02	27,17	63,76	36,55	31,84	21,95	25,87	63,08	47,28	48,98	0,00		

Table.4. Seguela kimberlites elements ratios compared to worldwide kim berlites, olivine lamproites and lamprophyres (after Mitchell, 1986).

	Kimberlite	micaceous Kimberlite	Olivine	Kimberlite	Kimberlite	Kimberlite	Lamprophyre	Kimberlite	Kimberlites
	Group 1A & 1B	group 2	Lamproite	Koidu	Kundelungu	Aries	Bow Hill	Tres Ranchos	Seguela
	South Africa	South Africa	Australie	Sierra Leone	RD. Congo	Aurtralie			Côte d'Ivoire
P2O5/Ce*	58,00	33,00	34,00	18,00	27,00	9,00	13,00	18,00	22-37
Nb/Zr	1,10	0,48	0,20	1,70	1,80	4,20	0,90	1,00	0,19-0,34
Nb/U*	42,00	25,00	95,00	62,00	64,00	100,00	83,00		51-103
Ba/Rb	26,00	19,00	20,00	24,00	31,00	12,00	9,00	35,00	20-79
Nb/La	1,80	0,70	0,80	1,40	1,80	1,70	1,30	0,80	0,77-1,09
U/Th*	0,21	0,17	0,11	0,16	0,20	0,10	0,16		0,11-0,26
Ce/Sr	0,24	0,32	0,31	0,57	0,45	0,74	0,35	0,38	0,22-0,49
Ni/MgO	40,00	49,00	42,00	42,00	37,00	61,00	48,00	49,00	33,5-63,76
Sc/Al2O3	7,20	6,00	5	6,70	5,70	6,20	3,10	6,20	

The contamination index (C.I.) of Clement (1982) was used to characterize our samples. This index which is expressed as a ratio of oxides: (SiO_2 + Al_2O_3+Na_2O)/(2K_2O + MgO), uses the oxides because they are characteristically elevated in weathered and granite-contaminated kimberlite (Fairban and Robertson, 1966). Clement (1982) found that uncontaminated kimberlites have generally C.I. near 1, however some apparently fresh and contamination-free kimberlites, particularly the micaceous kimberlites, may have C.I. up to 1.5 or more. Only Olivine lamproites and micaceous kimberlites with C.I. ratio varing from 1.5 to1.7 were accepted. Rocks lying outside these ranges were considered likely to be contaminated by crustal materials.

In West Africa an important problem for some kimberlites, particulary, those from Liberia, is the presence of abundant ilmenite xenocryts which may prove difficult to fully remove from samples. To identify kimberlites potentially contaminated by accumulated xenocrystal or megacristal ilmenite an Ilmenite Index (Ilm.I.)-(FeOt+TiO_2)/(2K_2O + MgO) has been used. In addition to C.I. and Ilm.I., a bivariate CaO vs. Al_2O_3 oxide plot was found to be useful in discriminating some altered and/or highly carbonated kimberlites that otherwise do not show significant elevation of their C.I. values.

4. GEOCHEMISTRY OF MAJOR ELEMENT

Geochemical analyses of Seguela kimberlites are listed in Table 1. The major contents are strongly modified by talcification process and alteration. The Seguela dikes and pipe samples have TiO_2 and K_2O contents similar to those of nonmicaceous kimberlites (Figs. 9, 10) although two K_2O-rich samples plot within the micaceous kimberlites field. In contrast P_2O_5 contents in the Seguela kimberlites are generally higher than southern African, Sierra Leone and RDC kimberlites. Al_2O_3 and TiO_2 contents are similar to the South Africa micaceous kimberlite.

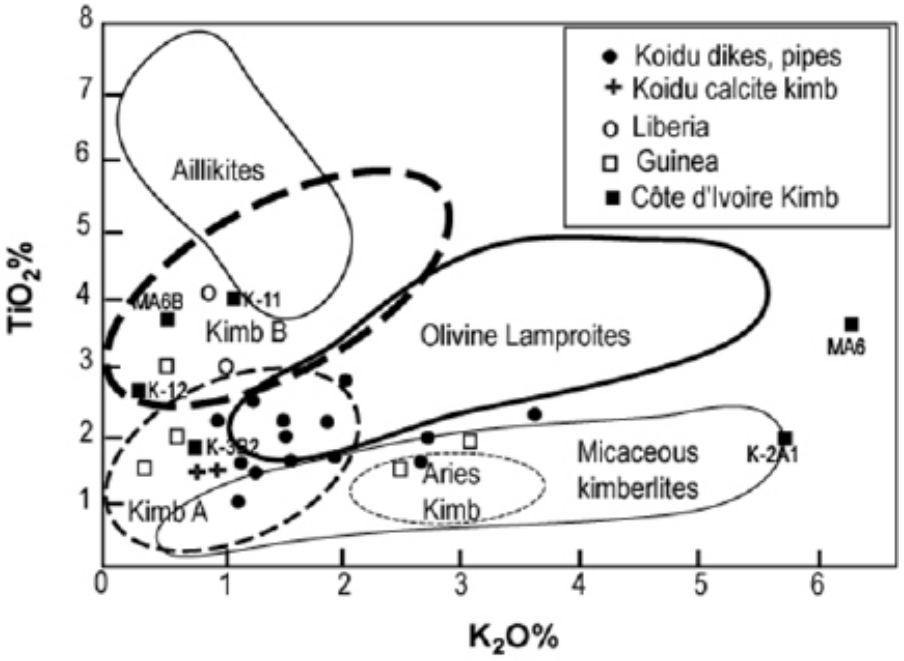


Fig.9. West African kimberlites data exclusive of altered and contaminated compositions, plotted on a TiO_2 vs K_2O (wt.%) diagram.

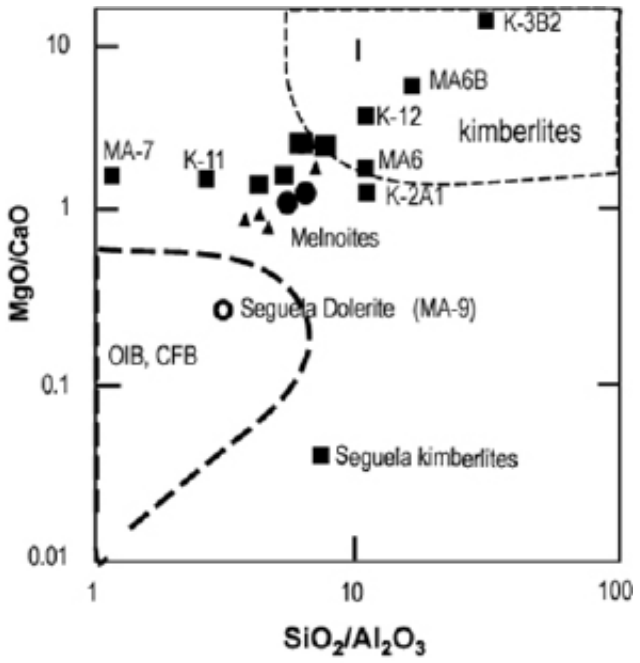


Fig.10. Seguela kimberlites samples compositions plotted on a MgO/CaO vs SiO_2/Al_2O_3 diagram.

Calculated C.I. of samples of Seguela diamond-bearing kimberlites (K011, K12, K03B2, K2A1, MA6 and MA6B) range from 1.99 to 2.62 (Table 1) indicating that the Seguela kimberlites are contaminated by crustal materials. In Fig.7, C.I. is plotted against Ilm.I. with fields delineated for the various kimberlite sub-groups, and the olivine lamproites and aillikites in KIMDAT. The shapes of fields show dominant control by modal olivine abundance for kimberlite and lamproite compositions. It is clear that Ilm.I. should not exceed 0.52 for type A non-micaceous kimberlites, and 0.47 for olivine lamproites and micaceous kimberlites. Seguela kimberlites Ilm.I. values (0.27-0.63) are equivalent to those of olivine lamproites and micaceous kimberlite (Table 1). In Fig 7, the Seguela kimberlite samples plot outside kimberlite and lamproite fields. The extent of any ilmenite contamination is difficult to judge in type B non-micaceous kimberlites and in aillikites due to their relatively high bulk-rock TiO_2 contents.

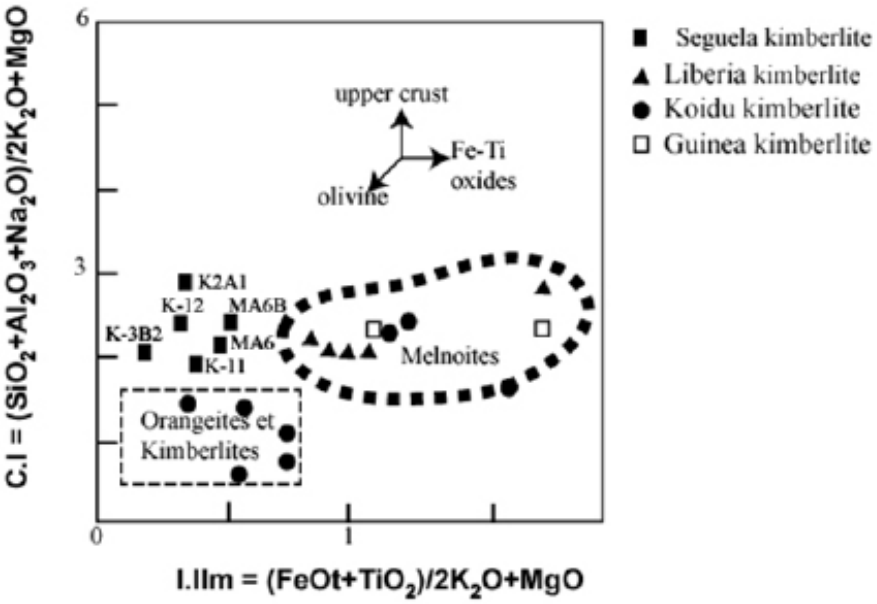


Fig.7. Contamination index (C.I.) vs (I.Ilm) ilmenite index

In Fig.8, data from KIMDAT show that all kimberlite and lamproite fields are confined to bulk Al_2O_3 contents of 0.7- 5.2 wt%, and CaO contents of 2.8-20 wt%. Compositions outside these limits can be considered as product of modification by secondary processes. Seguela kimberlites have Al_2O_3 contents of 1.61-4.85 wt% and CaO contents of 2.98-8.10 wt%. These compositions reflect those of olivine lamproites and micaceous kimberlites. Seguela samples plot inside the olivine

lamproites and micaceous kimberlites fields. Samples K011 and K03B2 compositions are outside these limits suggesting that they may have undergone modification by secondary processes.

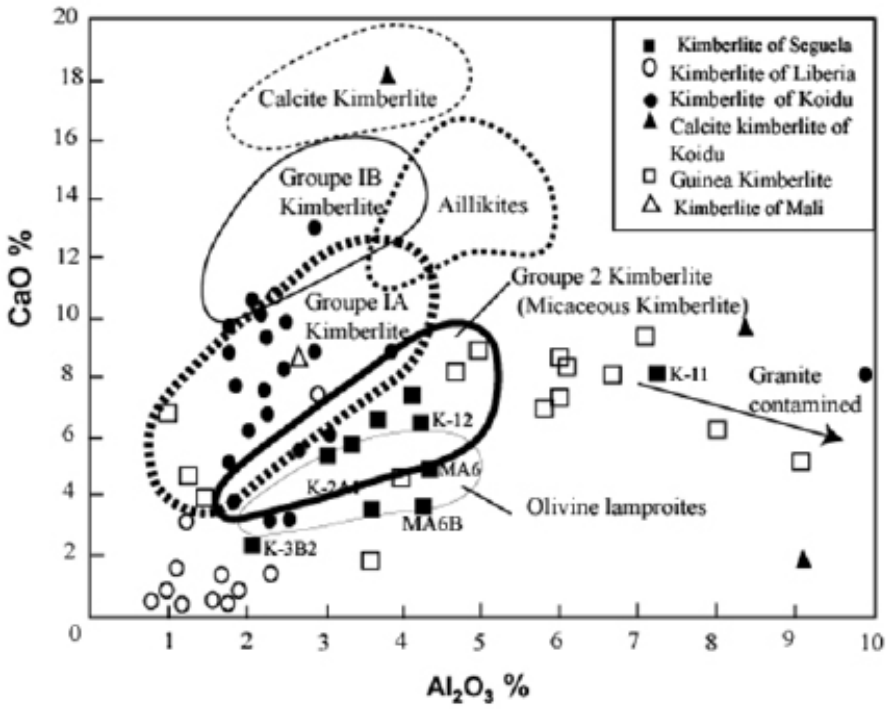


Fig.8. West African kimberlites data plotted on a CaO vs Al_2O_3 (wt.%) diagram showing fields for different kimberlites and related rocks.

5. TRACE ELEMENT GEOCHEMISTRY

Trace element data including rare earth elements (REE) and high-field-strength elements (HFSE) are listed in Table 2 for the Seguela kimberlites. Few trace element data for West African kimberlites exist in the literature. In the following discussion trace element comparisons are made with Southern African group I and II kimberlites, olivine lamproites, and non-DUPAL and DUPAL Atlantic Ocean Island Basalts (OIB) including those from the Ascension and Gough Island hotspots (Weaver et al., 1987). Where availability of data permits, comparison is made with the Kundelungu and Mbuji Mayi kimberlites in the D.R. Congo (Fieremans et al., 1984). The distribution of trace elements in the Seguela kimberlites essentially reflects major element abundance patterns. Incompatible elements such as Rb, Sr, Ba, and La, are strongly depleted relative to the least altered Seguela kimberlites. Compatible elements such as Ni

and Cr are somewhat enriched over average kimberlite abundances presumably as a result of volume decrease of the rock caused by leaching of mobile components. These characteristics are typical of altered kimberlites (Fairbairn and Robertson, 1966)

Seguela kimberlites are characterized by high Ni (679-1355 ppm) and Cr (525-1399 ppm) contents and high Ni/MgO ratios (Tables 2, 3) which are similar to average Group II kimberlites (Mitchell, 1986). Correlation between Ni and bulk rock Mg# indicate control by modal olivine abundance (e.g. Scott, 1979). The overall variation of other compatible elements also reflect mineralogical control, e.g., Rb abundance is controlled by modal phlogopite content as shown by positive correlations between Rb and K_2O and Al_2O_3.

The Seguela kimberlites have 300-1400 times chondritic values for La (Fig. 11) which is generally higher than most of Group I but similar to Group II kimberlites (Allialy, 2006). The Seguela kimberlites have steep REE patterns (Fig.12) with (La/Yb)n = 119- 366, which is typical of kimberlites and high Ni/MgO ratios (Table 3) which are similar to average Group II kimberlites (Mitchell, 1986). One feature of the REE patterns for the Seguela rocks is the apparent depletion of middle REE (Eu-Ho) that gives the patterns a downward concave shape. This feature does not correlate with abundances of other elements such as P_2O_5, as might be expected for apatite control, so the feature may be source-related. Comparative element abundance plots normalized against primitive mantle values (Fig. 12) show marked large-ion lithophile element (LILE) and LREE enrichments (> 100 times primitive mantle abundance) with pronounced positive Nb, Nd, and Sm anomalies, and negative K, Sr, P, Hf, and Zr anomalies. These are all features previously documented for kimberlites (Smith et al. 1985; Sun and McDonough, 1989).

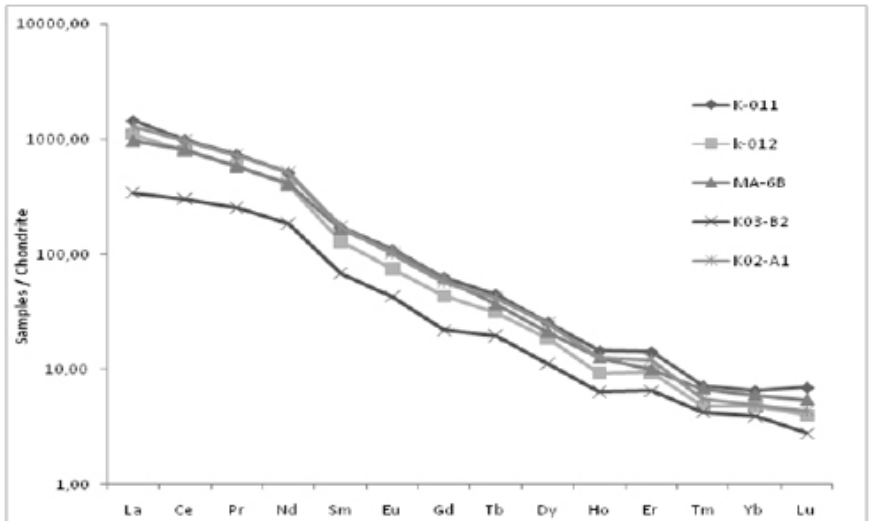


Fig.11. Selected chondrite normalised REE patterns for Seguela dike and pipe kimberlite samples (Sun & McDonough, 1989).

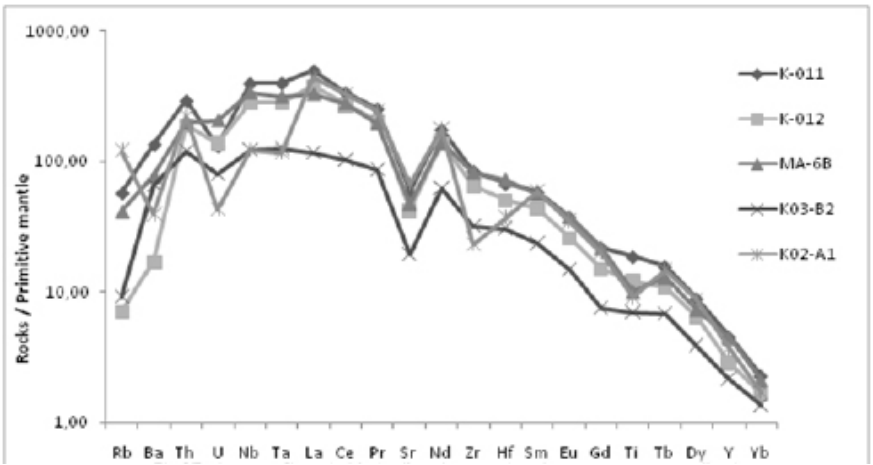


Fig.12. Average Seguela kimerlite element abundance patterns normalized against primitive mantle (Sun & McDonough, 1989).

These elemental abundance patterns indicate that Seguela kimberlites have close affinity with southern Africa Group II kimberlites and olivine lamproites (Australia), although in the latter case all elements are offset to lower values perhaps due to dilution by macrocrystal olivine. Seguela kimberlites have on average higher abundances of LILE and LREE but lower Sr and P abundances compared with Group II kimberlites (Figs. 13, 14). The Seguela kimberlite incompatible element contents are different to those of

intraplate basaltic rocks (e.g., non-DUPAL OIBs) and most of other kimberlites, with the exception to the Kundelungu kimberlites (Fieremans et al. 1984; Batumike et al. 2009). They do have elevated Nb/Zr ratios which is similar to Group II and olivine lamproites.

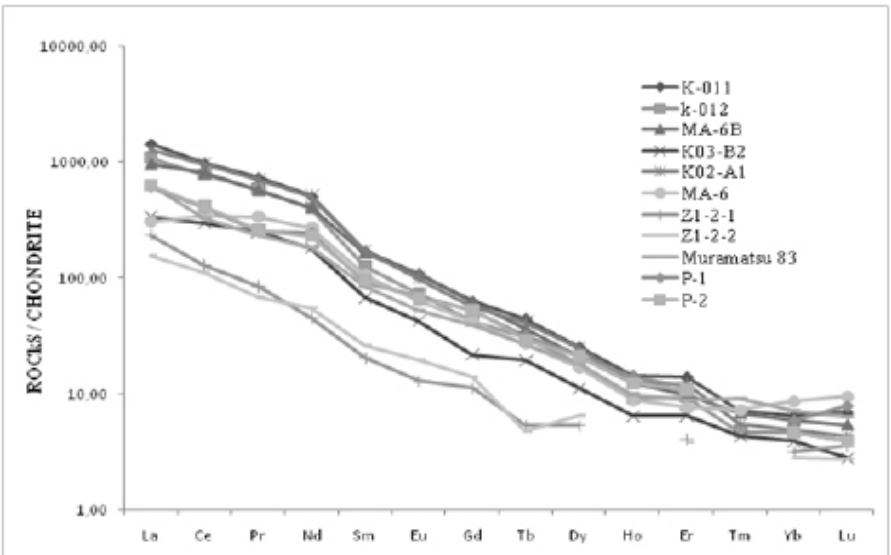


Fig.13. Selected chondrite normalised REE patterns for Seguela compare with South Africa, Russia and India kimberlites samples stippled patterns after Mitchell (1986).

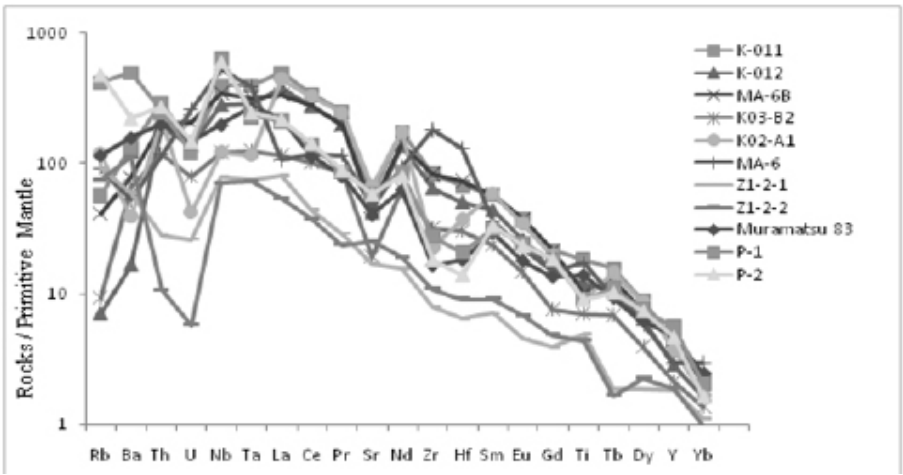


Fig.14. Average Seguela kimerlite element abundance patterns normalized against primitive mantle compare with South Africa, Russia and India kimberlites samples stippled patterns after Mitchell (1986).

The P_2O_5/Ce ratios of the Seguela kimberlites are low (31-37) compared with Atlantic Ocean OIBs (≈ 60-100), Group I kimberlite and Koidu calcite kimberlite but these values together with Nb/La ratios are similar to those of Group II kimberlites and olivine lamproites (Table 3,4). The Nb/La of Seguela kimberlites is also similar to that of DUPAL OIB. The Seguela Kimberlites have elevated Ce/Sr ratios (0.22-054) similar to values from Aries, Kundelungu, Tres Ranchos, some Group II kimberlites and olivine lamproites. The low Nb/La coupled with elevated Ce/Sr (Fig. 15) is similar to that observed in Group II kimberlites and olivine lamproites that was interpreted as consistent with presence of recycled sediment component in mantle source region (e.g. Sun and McDonough, 1989).

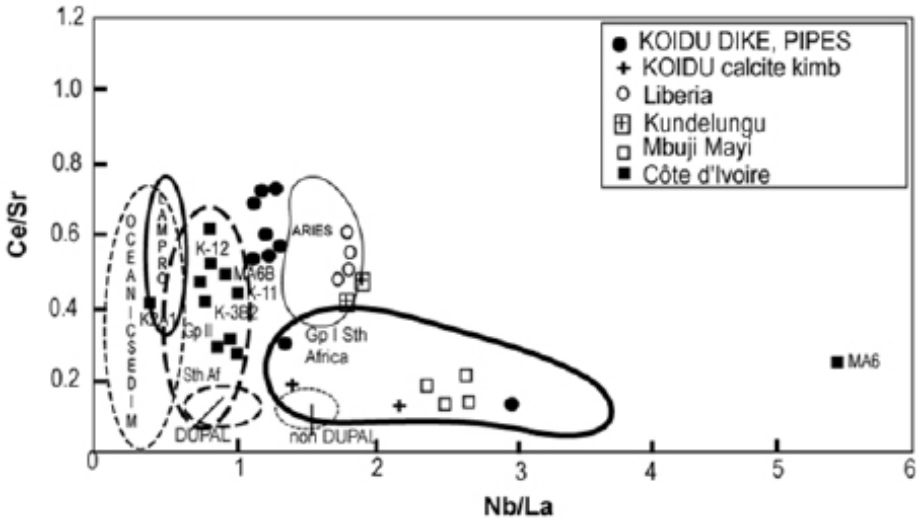


Fig.15. Plot of Ce/Sr vs Nb/La ratio showing geochemical signature of Seguela and worldwide kimberlites (Mitchell, 1986)

The only significant geochemical difference between the dyke of Toubabouko and Bobi dyke is slight depletions in Ti, Y, Yb, U, Nb and Ta, which may be a consequence of the dilution acquired during the accumulation of country rock or leaching, while the enrichment in Rb, Ba, K, La Ce, and Pb, may have resulted from alteration processes.

6. DISCUSSION

In general, high Ni and Cr concentrations are correlated with the amount of xenocrystic olivine in the kimberlite (e.g. Tainton, 1992; McDonald et al., 1995; Graham, 1999) while low Ni and Cr are consistent with low xenocryst mineral abundance (Graham, 1999). It

is accepted that the disaggregation of lithospheric mantle peridotite within individual intrusions does not affect incompatible element ratios such as La/Nb, Sr/Nb, La/Yb or Sm/Nd (Tainton, 1992; Carlson et al., 1996; Graham, 1999; Graham et al., 2001a). Hence the trace element budget of an alkaline ultramafic rock (kimberlites) is a mixture between two distinct components: refractory lithospheric mantle peridotite (xenocrysts-MgO, Ni, Cr) and incompatible element-enriched (presumably) metasomatised source (incompatible elements). The lithophile element isotope systematics of Group II kimberlites and lamproites, on the other hand, is very evolved, providing evidence that source for these rocks resided within the lithospheric mantle (Smith, 1983; Nelson et al., 1989; Tainton, 1992; Lambert et al., 1995; Carlson et al., 1996; Graham et al., 1999a; Nowell et al., 1999).

The sensitivity of incompatible element ratios to kimberlite alteration, including trace element ratios such as Zr/Nb and Nb/La, which have petrogenetic significance (e.g. Weaver, 1991), can be evaluated from the Seguela kimberlites data. However, it should be stressed that the Seguela kimberlites are substantially more altered than any of the analysed Southern African material. The Seguela kimberlites show, on average, significant increase in the ratios P_2O_5/Ce* (22-37), Ce/Sr (0.49-0.54), Ba/Rb (20-80), and Nb/La (0.7-5.13) that can be attributed to chemical alteration. Zr/Nb ratio shows no discernable alteration-related trend. Ratios such as Ce/Sr and Ba/Rb, which both increase sharply during the early stages of alteration, indicate that there is a distinctive pattern of alteration-related coupling between trace element ratios. These data together with overall abundances indicate that differential mobilisation of incompatible elements occurs during alterations. Seguela kimberlites exhibit geochemical characteristics intermediate between southern African Group II kimberlites and olivine lamproites of northern Australia.

It is generally accepted that kimberlites represent low-degree partial melts of incompatible-element-enriched (metasomatized) mantle peridotite (Mitchell, 1986). The characteristic incompatible element ratios reflect both the characteristics of the metasomatised source region and fractionation effects arising from the presence of residual phases during partial melting (Weaver et al., 1987). South African Group II kimberlites and Australian olivine lamproites have isotopic characteristics that indicate their source regions contained an incompatible element enriched component that has been isolated from general mantle convection for at least 500 Ma and probably longer (Smith, 1983; Mc Culloch et al., 1983). The source region candidate for this component includes the deep subcratonic lithosphere, which may be most suitable for the Group II kimberlites.

Because the spatial distribution of the DUPAL anomaly in the southern-hemisphere (Hart, 1984) can be linked with the Mesozoic rifting and redistribution of Gondwanaland continental fragments (Hawkesworth et al., 1986). Although the mechanisms of kimberlite melting are not well understood, volatile induced melting of upwelling source materials in a fO_2-zoned mantle is likely to be a possibility. Recent study the mantle oxygen fugacity structure (O'Neill et al., 1993), indicate that the Transitional Zone will be a strongly reduced region where CH_4-dominant fluids can coexist with Fe^{3+}-bearing silicate components from the Upper-Lower Mantle boundary through the transition zone will be a strongly reduced region. The diatrem features and the absence of diagenetic process in the maar deposit attest the youngest geological age of the kimberlite activity. In West Africa there are some cretaceous kimberlite dikes and pipes in Sierra Leone according to Rb-Sr and paleogenetic data (Taylor et al., 1994). The cretaceous age seems to be the more accurate and could be that of the Seguela kimberlites (Pouclet et al., 2004). New U-Pb and Sm-Nd analyses from Guinea and Mauritania kimberlites propose a mid-Jurassic age (154-155 Ma) for the kimberlite event (Delor et al., 2004).

The strongly silica-undersaturated nature, fractionated REE-patterns and high volatile content of the kimberlites point a metasomatised upper mantle source. The experiments of Lloyd et al., (1985) and Foley et al. (2000) and the observations of Lorand (1989) and Lloyd et al., (1985) show that the refractory melt-depleted lithospheric mantle will play only a marginal influence on the geochemistry of the vein melts. The high Ni and Cr concentration of kimberlites may therefore be explained by the contamination of vein melts by lithospheric mantle peridotite to produce an incompatible element-enriched melt. The average values of CaO/MgO ratio of Seguela kimberlites exhibit a regular trend from 0.05 to 0.42. This trend reflects decreasing temperature, as evidence from experimental data (Dalton and Presnall, 1998; Wyllie and Lee, 1998). In the case of Seguela kimberlites,High Ni and Cr contents can also be explained by kimberlites magmas melts produced by lithospheric mantle (Allialy, 2006; 2008).

Based on experiments on the CaO-(Na_2O + K_2O)-(MgO+FeO)-(SiO_2 + Al_2O_3)-CO_2 system, Wyllie and Lee (1998) showed that carbonatite magmas correspond to low-temperature part of continuous set of low-capacity partial melts, including kimberlites. At 70 kbar, even a slight temperature rise usually results in a change of partial melt compositions from carbonatite to kimberlite (Dalton and Presnall, 1998). The study of diamond potential of Yakutian kimberlites in the petrochemical model (Vasilenko et al., 1997) showed that kimberlite varities with CaO/MgO ratio < 6 contain small amounts

or lack diamonds. As the CaO/MgO ratio decreases, diamond grade increases, reaching maximal values in the kimberlites varieties with CaO/MgO ratios between 0.5 and 0.35. Similary to yakutian kimberlites, Seguela kimberlites CaO/MgO ratio lower than 0.83 can be explained by the presence of important diamond potential shown by increasing of diamond grade.

The kimberlites varieties with CaO/MgO ratios of < 0.35 are characterized again by decreasing diamond grade. Oxides of K, Na, Ti, Ca and Mg are of major importance for the estimation of diamond potential. Comparison of the average compositions of Yakutian kimberlite suggests that the contents of K_2O, Na_2O and MgO increase and the contents of TiO_2 and CaO decrease with increasing diamond grade (Vasilenko et al., 2002). Similary to Yakutian kimberlite, Seguela Kimberlites contents of K_2O, Na_2O and MgO increase and the contents of TiO_2 and CaO decrease. In view of all this we can conclude that Seguela kimberiltes diamond grade also increase.

The coupling of low Nb/La with elevated Ce/Sr observed in the Seguela kimberlites indicates important sediment recycling. In this case kimberlite alteration has caused high Ce/Sr. The Ce vs P_2O_5 and Nb/La vs Ce/Sr plots show that the Seguela kimberlites also occupy the kimberlite fields (Figs.15, 16,17). The presence of higher content of Zr (< 719 ppm), and MgO contents in spinel (< 15) and Lower Zr/Nb ratio (Table 2) varying from 2 to 4, support their kimberlite nature. A small amount of partial melting of a phlogopite-garnet-lherzolite source can produce high La/Yb ratios of 100-200 (Mitchell, 1986). Higher La/Yb and significantly high Rb, Ba, and Nb represent lower degrees of partial melting. The Seguela kimberlites show relatively high Rb, Ba, Nb and La/Yb ratios compared with South African kimberlites, indicating that Seguela kimberlites derived from relatively low degrees of partial melting.

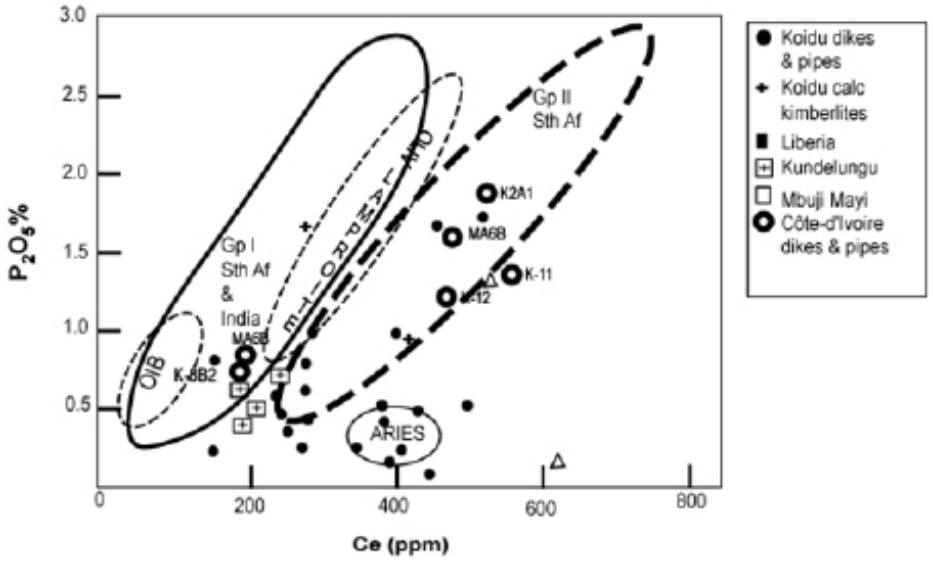


Fig.16. P_2O_5-Ce covariation with two unusual micaceous group I kimberlites (Smith et al., 1985)

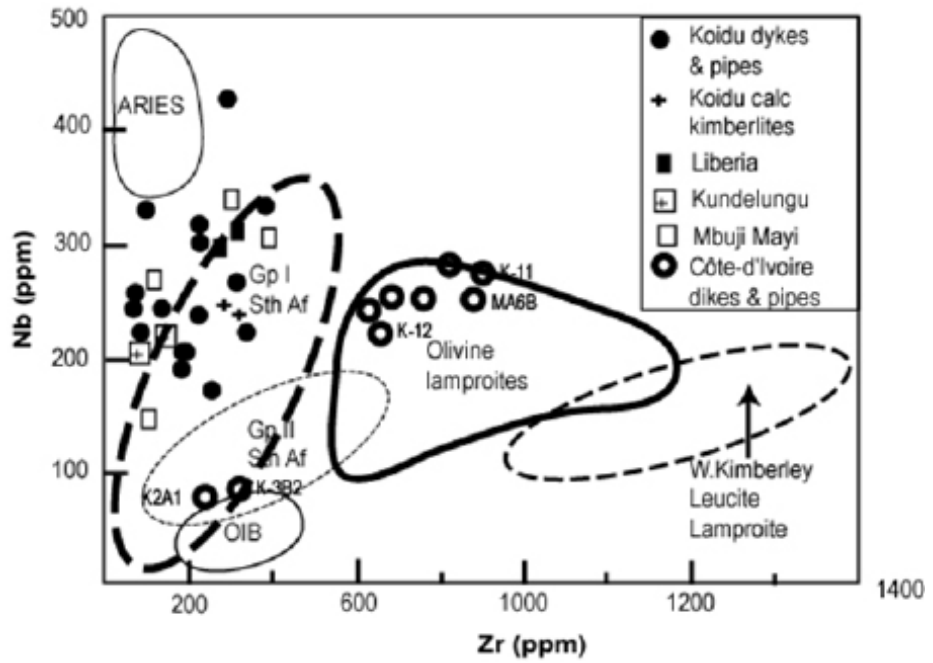


Fig.17. Nb-Zr covariation showing low Nb/Zr of Seguela kimberlite relative to other kimberlites (Smith et al., 1985)

The Seguela kimberlites have lower Zr/Nb ratio and high La/ Yb ratio (Figs. 18, 19). The conventional interpretation indicates that increasing La/Yb ratios represent decreasing amount of partial melting (Mitchell, 1995).Thus it is evident that the Seguela kimberlites are formed by lower degrees of partial melting of the mantle source relative to Group II kimberlites of South Africa. The Ce/Y vs Zr/Nb ratios are commonly used to infer the degrees of melting involved in the production of basaltic rocks from a peridotitic source (Tainton, 1992). Rocks that derive from a similar source tend to show a decrease on Ce/Y with increasing Zr/Nb. The Seguela kimberlites show that Ce/Y increases with decreasing Zr/Nb indicating that they derived from a difference source (Fig.18, 19). The La/Yb ratios (119 to 366) of Seguela kimberlites are typical of kimberlite worldwide (Mitchell, 1986). However, the higher concentrations of Rb, Ba and K in Seguela rocks may be indicative of the residual phlogopite in the source (e.g. Rogers et al., 1992), or simply, a modal abundance of phlogopite.

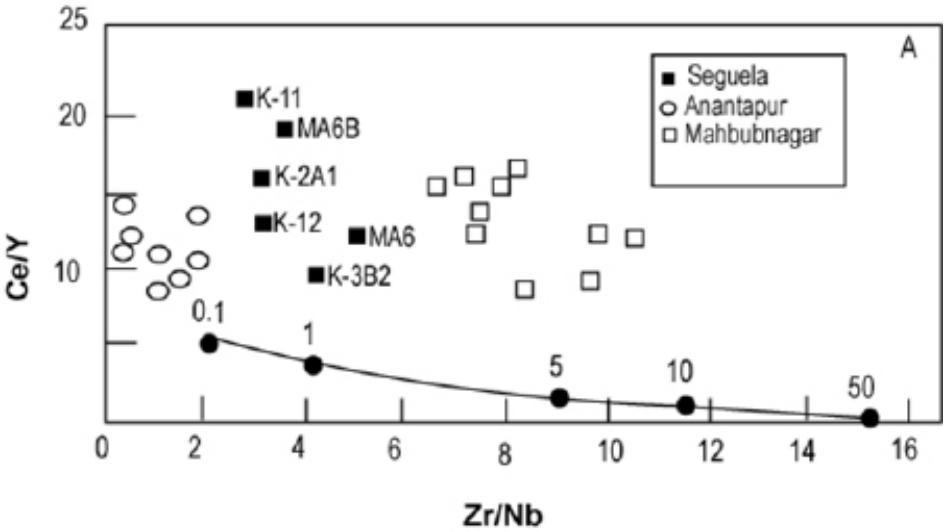


Fig.18. Seguela kimberlites data Plotted on a Ce/Y vs Zr/Nb diagram

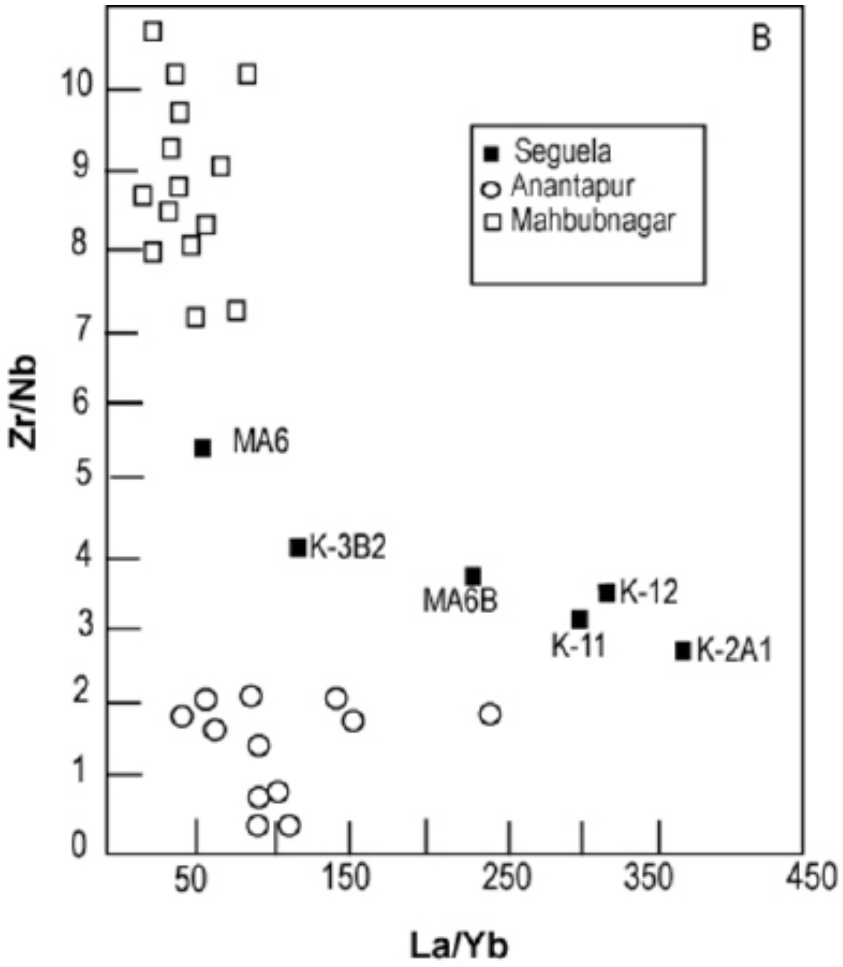


Fig.19. Seguela kimberlites data Plotted on a Zr/Nb vs La/Yb diagram.

CONCLUSION

Petrogaphic characteristics of Seguela kimberlites dykes and pipes suggest that they were crystallised from melting. The strongly silica undersaturated nature, extreme enrichment in incompatible elements fractionated REE patterns and high volatile content of the Seguela kimberlites point toward a metasomatised upper mantle source. Seguela kimberlites geochemical signatures are characterized by Nb/la, Nb/Zr, Ce/Sr and P_2O_5 ratios are similary to Southern African group II kimberlite. Zr/Hf and Nb/Ta from Seguela kimberlites ratios reflect mantle magmatic source. Seguela Kimberlites have on average higher abundances of LILE and LREE but lower Sr compared with group II kimberlite.

In comparison to other African kimberlites and Australia olivine lamproite, these kimberlites have a distinctive element enrichment pattern with much greater average enrichements in Rb, Th, Ta, Nb and La. They have strongly leached of mobile elements components. High Nb shows that they might be derived from phlogopite-bearing peridotites that represent residues, recycled into the mantle, following extraction of subduction-related melts. If the source materials of these kimberlites like group II kimberlites are related to those of ocean-island basalts, (Le Roex, 1986), then the genesis of kimberlite at high pressures and OIB at lower pressures will depend on the extent to which deep mantle material can upwell beneath lithosphere of different thickness and on the existence to the appropriate source materials at depth. Creataceous inferior Seguela kimberlites dikes, pipes and diatrems on the West Africa craton are mostly phlogopite-diamond-bearing kimberlites with geochemical characteristics intermediate between southern Africa Group II kimberlites and Australia olivine lamproites.

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