Research Article

Geochemistry and Geochronology of the Nlonako Alkaline Complex, Central Africa

Martin Guy ABOLO [a], Daniel LAMILEN [b], Ismaïla NGOUNOUNO [c], Dieudonné BITOM [d]

[a] Société Nationale des Hydrocarbures, BP 955 Yaoundé Cameroun

[b] Département des Sciences de la Terre, Faculté des Sciences, Université de Yaoundé 1,
BP 812 Yaoundé, Cameroun

[c] Ecole de Géologie et d'Exploitation Minière de l'Université de Ngaoundéré à Meiganga, BP 454 Meiganga, Cameroun

[d] Département des Sciences de la Terre, Faculté des Sciences, Université de Ngaoundéré, BP 454 Ngaoundéré, Cameroun

ABSTRACT

The Nlonako Anorogenic Complex (NAC) is located in the southern continental sector of the Cameroon Line (CL). It intrudes the Cretaceous sediments and the Pan-african granitogneissic basement and is characterized by an association of diversified plutonic and volcanic rocks.

Geochemical studies of major, trace and rare earth elements reveal an alkaline series which corresponds to a gabbro-diorite-monzonite-syenite-granite type. This series comprises two suites: a metaluminous suite made of basic and intermediate rocks, fayalite alkali granite and syenites; and a peralkaline suite including rhyolite and other granites. Both suites are derived from a single, hot and dry magma of basaltic composition. The evolution of the magma is dominated by fractional crystallization of mantle material and was progressively affected by crustal contamination at the end of the differentiation process. The conventional whole-rock Rb/Sr method was performed on three syenites and five granites. The ages obtained range between 44.6 and 49.7 Ma, confirming the Tertiary time of emplacement of the NAC.

Keywords: Nlonako Anorogenic Complex (NAC), alkaline series, magma, fractional crystallization, crustal contamination, tertiary age.

RESUME

Le complexe anorogénique du Nlonako (CAN) se situe dans la partie continentale sud de la ligne du Cameroun (LC). Il est intrusif dans les sédiments du Crétacé et dans le socle granito-gneissique d'âge Pan-africain et se caractérise par une association de roches plutoniques et volcaniques diversifiées.

L'étude géochimique des éléments majeurs, des éléments traces et des terres rares montre l'appartenance des roches à la série alcaline de type gabbro-diorite-monzonite-syénite-granite. Cette série alcaline a évolué en deux suites : une suite métalumineuse formée des roches basiques et intermédiaires, du granite alcalin à fayalite et de la plupart des syénites, et une suite hyperalcaline comprenant la rhyolite et les autres granites. Les deux suites proviennent d'un magma mantellique unique, chaud, sec et de composition basaltique. Celui-ci s'est différencié par cristallisation fractionnée et a été plus ou moins contaminé par la croûte en fin d'évolution. Trois échantillons de syénites et cinq échantillons de granites ont été datés par la méthode du Rb/Sr sur roche totale. Les âges obtenus sont compris entre 44.6 et 49.7 Ma et confirment la mise en place tertiaire du CAN.

Mots clés: Complexe anorogénique du Nlonako (CAN), série alcaline, magma, cristallisation fractionnée, contamination crustale, âge tertiaire.

[a] Corresponding author. E-mail: mg_abolo@yahoo.fr

INTRODUCTION

The Cameroon Line (CL) is an important tectonic line oriented N30°E which stretched more than 2000 km from Pagalu Island to Lake Chad (fig. 1). More than sixty anorogenic complexes occur along the length of the CL, among which is the Nlonako Alkaline Complex (NAC). The emplacement of anorogenic complexes and volcanoes was promoted by repeated reactivations of the structures along this line (*Moreau et al.* 1987). The NAC includes both plutonic and volcanic rocks. Plutonic rocks are dominant and are much more diversified than volcanic rocks. Together they form an alkaline series from gabbros through diorites, monzonites and syenites to granites. The existence of wide-ranging rocks types of different compositions constitutes one of the major problems of the NAC petrogenesis. *Tchoua* (1974) suggests that the

Nlonako massif was differentiated from peralkali syenitic and granitic magmas. The alkali source was confirmed by *Tempier* and *Lasserre* (1980). According to those authors, the magmatic evolution took place without any interruption. *Cantagrel et al.* (1978) utilised the whole rock K/Ar method to define ages of 45 ± 1 Ma, 43 ± 2 Ma and 35 ± 1 Ma on syenite, microgabbro and granite respectively. At the same time, *Lasserre* (1978) obtained an age of 43.3 ± 0.3 Ma on syenite, granite and rhyodacite using the whole rock Rb-Sr method.

The present paper tackles several issues, including rock relationships, the composition of the original magma and petrogenetic modelling of the NAC. In addition, the recent ages on syenites and granites are used to place the massif in context of the magmatic evolution of the CHL.
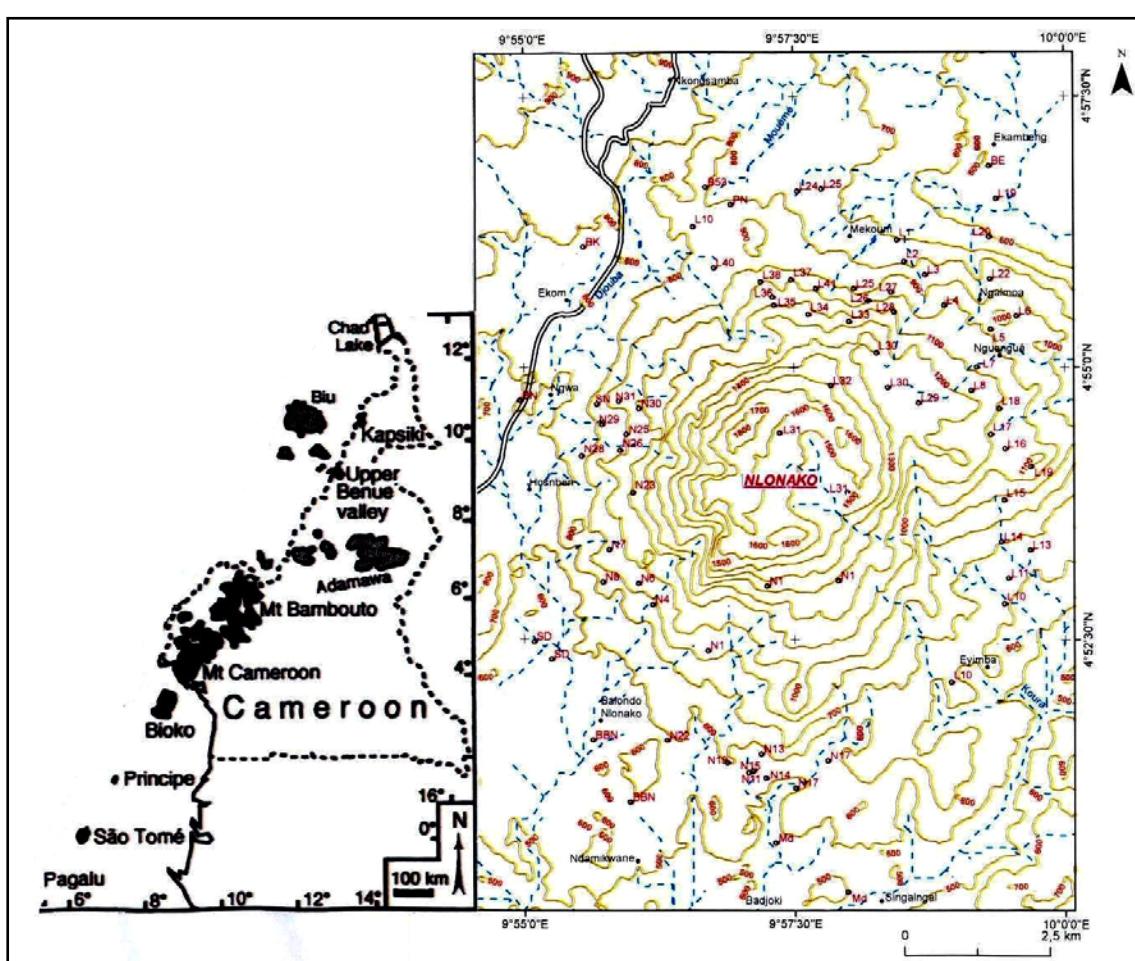

Fig. 1: Detailed map of the Nlonako Alkaline Complex including the samples location (right) and location of the Cameroon Volcanic Line (left) modified after *Déruelle et al.* 2007.

Analytical procedures

Major and trace elements of thirty one (31) samples were determined by X-Ray fluorescence techniques at the Laboratory of the "Bundesanstaalt für Geowissenchaften und Rohstoffe" (B.G.R) in Hanover, Germany, using a Philips P.W 1480/20 Sequential X-Ray Spectrometer System. REE analyses including Y were performed on twenty one (21) samples using inductivity coupled plasma-mass spectrometry (ICP/MS). Three (3) and five (5) whole rock samples of syenites and granites respectively were dated by the conventional Rb/Sr method. In some samples, Sr was determined using the X-Ray Spectrometer. In other samples, Sr including Nd was determined by isotopic dilution using the Mass Spectrometer. $^{143}Nd/^{144}Nd$ ratios were corrected by isotopic fractionation to $^{146}Nd/^{144}Nd$ = 0.7219 and $^{87}Sr/^{86}Sr$ to $^{88}Sr/^{86}Sr$ = 8.37521. $^{87}Sr/^{86}Sro$ values for each rock were calculated by giving the rocks an average emplacement age of 50 Ma.

Geochemistry

Major and trace element compositions of selected rock samples are presented in table 1 whereas REE analyses are shown in table 2. Because of their limited numbers (2), volcanites are plotted on the same diagrams as the plutonites. The NAC includes acid, intermediate and basic components (41%<SiO_2<71%). Normative quartz is absent from the gabbros, diorites, microdiorites, micromonzodiorites and hawaiites, but appears in the remainder of the rocks in the proportions of 0.01 to 30%. The Nlonako rocks belong to the alkaline series. The alkalinity was most influenced by Na_2O in comparison with K_2O. The presence of ægirine and arfvedsonite in the granites and rhyolites reveals the peralkalinity, as confirmed in figure 2 where two suites are defined: - *(i)* a metaluminous suite represented by basic and intermediate rocks, fayalite alkali granite and most of the syenites; - *(ii)* a peralkaline suite made of rhyolite and the rest of the granites. According to the coefficient of agpaicity (Na+K)/Al), most of the rocks are miaskitic types except one quartz syenite, some alkali granites and alkali rhyolite. The behavior of major elements during the magma evolution is represented in figure 3. The silica has been used as differentiation index. Broadly, the distribution of these elements is homogeneous despites the scatter of points which is observed in some oxides such as Al_2O_3, MnO and P_2O_5. The overall trend with differentiation is an increase of Na_2O and K_2O, and a decrease of Al_2O_3, CaO, Fe_2O_3, MgO and TiO_2. MnO firstly increases slightly then becomes scattered especially in the syenite. P_2O_5 is very scattered in mafic and intermediate rocks but decreases with differentiation to some extent in felsic rocks.
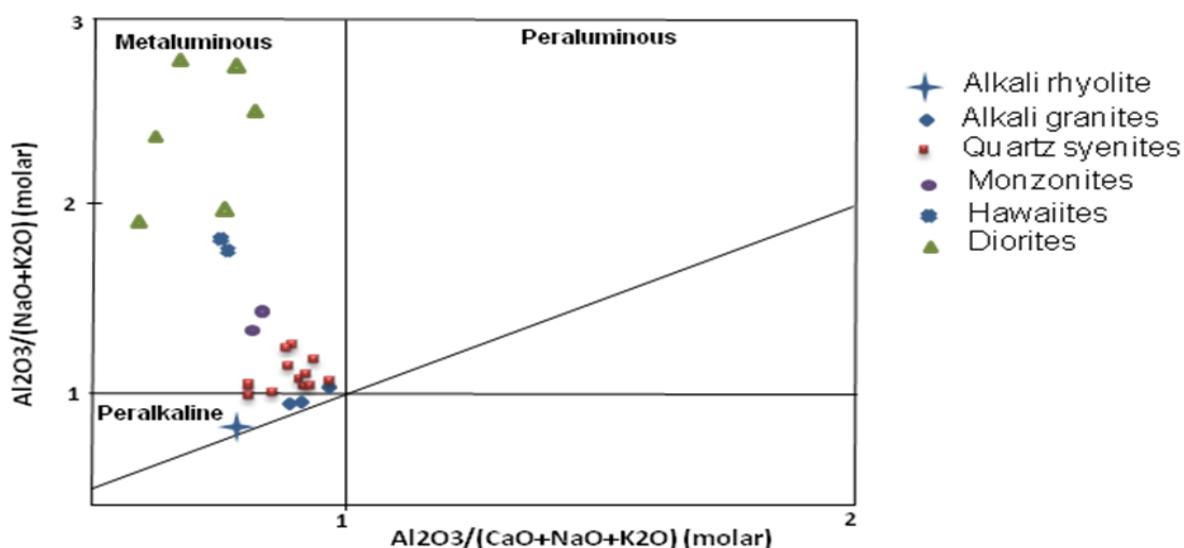
Fig. 2: Diagram to show $Al_2O_3/(Na_2O+K_2O)$ in relation to $Al_2O_3/(CaO+Na_2O+K_2O)$.

As for trace elements, in general Sc, Sr and Co decrease with the differentiation whereas Ga increases. Zn, Zr, Rb and Nb have no particular t d

a continuous evolution with a great affinity of quartz syenites towards Ba while mafic rocks and other felsic rocks occupy respectively Sr and Rb
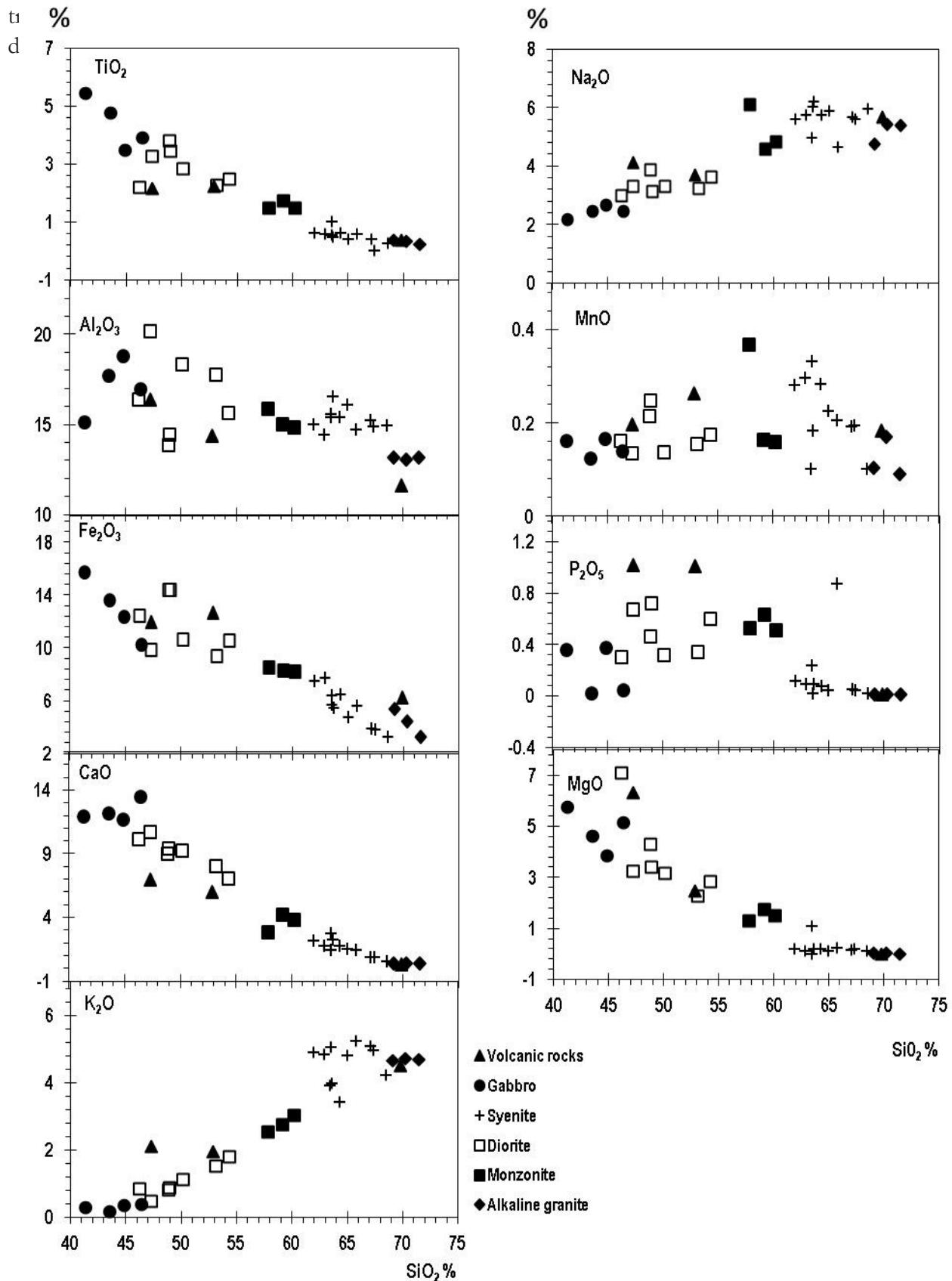
Fig. 3: Major element distribution diagrams vs SiO_2 for Nlonako rocks.

Table 1: Chemical compositions (major and trace elements) of the Nlonako Massif

Major and normative compositions

| Rocks	Alkali granites			Monzonites			Diorites						Quartz syenites							Qz microsyenite				Microgabbro	Gabbros		Alkali
Sample N°	L37	L34	L38	N23	L3	L1	N30	L30	L33	L8	L7	L39	N19	N29	N13	L31	N1	N4	N31	L10	L24	L35	N28	N7	L15	L16	L5
SiO2	71,46	69,13	70,26	57,9	60,22	46,23	53,18	54,33	50,15	48,99	48,88	61,97	64,98	63,65	62,93	63,51	68,55	64,33	63,48	67,09	67,38	65,77		41,33	44,87	46,43	43,57
TiO2	0,243	0,381	0,336	1,48	1,741	2,223	2,284	2,866	3,46	3,824	3,46	0,625	0,402	0,501	0,582	0,572	0,288	0,65	0,429	0,04	0,584			5,471	3,487	3,907	4,761
Al2O3	13,15	13,14	13,06	15,9	14,96	14,86	14,77	15,62	10,64	14,39	13,84	14,97	16,1	16,53	14,41	15,36	15,54	15,37	15,54	15,21	14,9			18,76	16,94	17,68	
Fe2O3	3,23	5,36	4,42	8,49	8,28	8,16	12,46	10,53	18,33	14,39	14,39	7,46	4,71	5,47	6,36	6,47	3,26	5,7	3,89	5,63	15,75	10,22	13,58				
MnO	0,091	0,103	0,17	0,37	0,164	0,16	0,164	0,155	0,174	0,138	0,249	0,214	0,281	0,183	0,225	0,333	0,102	0,283	0,101	0,193	0,161	0,166	0,125				
MgO	0,03	0,06	0,04	1,31	1,76	1,5	2,3	2,86	3,16	3,41	4,32	0,2	0,12	0,21	1,53	1,74	0,57	1,74	0,23	0,19	5,76	12,35	13,58				
CaO	0,34	0,39	0,35	2,81	4,15	3,79	9,42	9,25	8,95	9,2	9,42	2,13	1,53	2,23	1,74	0,57	1,74	0,88	1,44	11,87	11,66	13,42	12,14				
Na2O	5,41	4,78	5,42	6,12	4,57	4,83	3	3,23	3,62	3,3	3,88	3,13	4,82	4,86	4,84	5,06	5,75	5,67	4,99	5,62	4,64	2,17	2,68	2,45			
K2O	4,7	4,67	4,71	2,55	2,75	3,02	0,86	1,53	1,81	1,14	0,88	4,9	5,06	5,1	4,97	3,44	3,91	4,24	2,7	0,85	1,44	0,31	0,38	0,16			
P2O5	0,01	0,01	0,01	0,53	0,86	0,63	0,51	0,3	0,34	0,6	0,32	0,46	0,04	0,09	0,12	0,02	0,08	0,05	0,24	0,05	0,87	0,36	0,37	0,02			
P.F	0,92	1,53	0,93	0,81	1	0,73	1,41	0,49	0,45	0,51	0,1	1,1	0,85	0,59	1,05	0,78	1,4	0,71	0,87	1,05	1,16	1,07	0,62	0,52			
Total	99,58	99,55	99,71	98,2	99,22	99,51	99,56	99,66	99,53	99,74	99,47	99,35	99,66	99,54	99,13	99,57	99,44	99,57	98,01	99,44	99,44	99,64	99,7	99,65			
Qz	21,42	20,01	21,21	2,19	9,9	9,37						17,8	8,99	6,73	6,91	1,89	3,05	4,18	7,23	14,79	10,88	12,34	5,63				
Or	27,75	27,54	27,79	15,1	16,21	17,8	5,03	8,99	6,69	5,14	4,73	28,81	29,74	30,13	29,07	20,29	23,1	25,05	29,34	5	8,99	1,81	2,1	0,94	2,23		
Ab	41,28	40,22	40,69	51,9	38,36	40,55	22,55	27,83	27,63	26,1	32,35	47,08	49,73	52,43	46,7	50,48	50,37	48,47	42	47,8	39,07	16,69	22,4	20,52			
An		0,56		8,25	12,05	9,66	28,22	28,78	31,49	22,34	17,69	3,18	5,36			1,41	5,93	8,36	42	47,8	30,06	37,63	33,76	36,28			
Ne						1,37											2,66						2,68	0,75	0,13		
Di (Wo, En, Fs)	1,46	1,17	1,49	4,38	3,85	5,06	16,13	7,13	16,16	19,27	16,59	3,92	4,94	6,1	1,24	7,27	6,08	3,1	3,1	2,81	5,14	21,1	14,33	25,9	19,03		
Hy (En, Fs)	3,3	5,22	4,88	9,1	9,34	8,35	9,1	11,2	10,59	11,52	7,9	3,41	3,73	3,76	6,24			3,07				3,16	1,3				
Ac	1,86	3,3	2,55																								
Ms	0,52		0,48							0,11	1,41																
OL (Fa, Fo)						14,94		9,41			2,75											9,6	5,89	3,23	7,34		
Ap	0,02	0,02	0,02	1,25	1,47	1,19	0,7	4,3	1,4	1,67	0,45	0,28	0,09	0,21	0,05	0,21	0,09	0,05	0,56	0,12		0,84	0,86	0,09	0,05		
Il	0,46	0,72	0,64	2,81	3,28	2,81	4,17	4,3	4,69	5,39	6,48	7,16	0,76	0,95	1,08	0,55	1,23	1,91	0,81	0,75	1,1	10,23	6,54	7,35	8,92		
Py											0,06																
Cm	0,04	0,06		0,01	0,04	0,06	0,06	0,03	0,04	0,03	0,03	0,01	0,01	0,03	0,03	0,05	0,04	0,06	0,04	0,04	0,03	0,02	0,03				
Mt		1,55		2,47	2,38	2,35	3,57	2,7	3,02	4,11	4,11	2,15	1,36	1,58	1,77	1,51	1,87	1,64	1,12		1,62	4,5	3,54	3,89			
Z	0,06		0,08	0,08	0,07		0,03	0,04	0,05		0,06	0,07	0,06		0,05	0,14	0,14	0,09	0,08		0,07	0,02	0,02	0,01			
Total	98,18	97,22	98,07	97,4	96,95	97,24	96,75	96,73	97,32	97,04	96,63	97,12	97,18	97,57	97,69	97,31	97,75	97,69	98,01	98,16	97,79	96,48	97,36	96,81			
C.1	7,73	8,89	10,16	20	20,44	19,86	24,39	28,69	29,83	40,01	42,34	15,89	12,96	13,61	16,92	12,18	12,34?		13,61	8,09	10,84	34,36	40,85	39,26	21,27		
D.1	90,45	87,77	87,77	69,2	64,46	67,72	64,55	47,84	36,21	34,28	37,09	80,08	85,39	81,58	80,39	84,61	76,64	76,04	89,01	89,12	83,18	19,25	24,5	22,75	21,27		

Trace elements

Rocks	Quartz syenites							Qz microsyenite				Alkali granites			Monzonites			Diorites						Microgabbro	Gabbros		Alkali
Sample N°	N19	N29	N13	L31	N1	N4	N31	L10	L24	L35	N28	L37	L34	L38	N23	L3	L1	N30	L30	L39	L33	L8	L7	N7	L15	L16	L5
Ba	1166	1387	2321	1067	82	561	3868	822	549	530	1182	113	111	14208	703	762	175	455	514	417	226	400	400	344	155	113	77
Co	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	14	10	20	28	9	20	21	26	28	27	22	25	61	29	34	46
Ga	32	29	32	39	29	32	32	25	33	32	27	38	40	26	21	57	30	32	37	28	27	22	25	20	20	18	21
Nb	45	65	54	43	49	43	47	42	64	65	44	90	57	40	43	19	43	12	30	28	21	22	25	11	20	17	<5
Ni	<7	7	<7	7	8	<7	7	13	<7	<7	9	10	35	57	10	9	<7	32	11	32	21	11	44	17	21	16	12
Rb	61	65	50	43	46	103	52	168	119	116	137	121	137	19	22	130	143	21	53	25	58	30	10	56	20	21	12
Sc	17	6	10	15	3	4	8	8	8	42	10	5	5	7	5	14	14	17	17	18	21	30	16	12	<5	7	5
Sr	24	125	259	15	5	286	323	48	42	35	43	43	15	63	485	422	589	514	505	529	583	528	617	47	30	46	34
V	<10	<10	<10	<10	63	10	<10	<10	<10	<10	15	63	42	<10	9	9	7	17	29	18	21	26	30	344	204	300	423
Zn	121	109	169	162	92	217	127	110	116	102	88	102	143	70	254	155	149	336	155	149	230	228	141	403	91	80	73
Zr	292	289	289	348	261	750	715	402	410	417	349	689	341	84	443	88	126	196	245	166	203	94	141	94	70	70	28
Ba/Sr	48,5	11,1	8,9	71,1	16,4	8,9	13,5	11,4	12,6	12,5	7	2,5	13,5	12,3	10,7	11,4	12,6	1,4	1,8	2,94	2,81	3,07	0,71	14,33	25,9	19,03	0,13
Ba/Sr	48,5	11,1	8,9	71,1	16,4	8,9	13,5	11,4	12,6	12,5	7	2,5	13,5	12,3	10,7	11,4	12,6	1,4	1,8	0,7	0,3	0,7	0,8	0,5	0,2	0,2	0,1
K/Rb	666	615	662	937	913	341	548	193	355	390	7	330,4	282,4	322,3	959	175	338	240	268	309	203	294	294	80	70	70	28
K/Rb	666	615	662	937	913	341	548	193	355	390	7	12,5	12,3	10,7	1,4	1,8	0,3	0,3	0,3	0,7	0,3	0,3	0,7	0,5	0,2	0,2	0,1
Rb/Sr	2,54	0,52	0,19	2,86	9,2	1,63	0,18	2,47	2,76	0,51	1	11,11	15,22	17,28	0,51	175	0,33	0,04	0,05	0,1	0,05	0,1	0,03	0,02	0,01	0,01	0,01

Table 2: Chemical analyses of rare earth elements of the Nlonako Massif.

Rock	Quartz syenites					Quartz microsyenite	Alkali granites			Gabbros					Diorites					Alkali rhy
Sample number	N29	N1	N4	L24	L35	N28	L37	L34	L38	N7	L15	L16	L5	L17	L30	L33	L8	L7	L39	
La	62	24	112	27	32	46	53	69	67	10	16	8	3	20	36	47	28	48	36	
Ce	112	46	177	58	66	90	100	128	55	24	12	18	8	44	77	98	57	100	75	
Pr	14,4	6,8	22	7,6	8,1	10,4	11,4	16,5	13,2	3,2	29	2,3	1	5,7	8,8	11,6	7	12,5	9,3	
Nd	57	28	94	32	33	41	46	64	46	15	3,9	10	5	22	35	42	26	47	35	
Sm	11,2	6,5	20,4	7,9	7,3	8,5	9,1	13,8	8,4	4	18	2,7	1,4	5,2	7,8	9,7	6,1	11,3	8,5	
Eu	3,4	1,4	2,6	1,4	1,2	2,6	1,1	1,4	1	2,1	4,5	1,2	0,77	2	1,9	2,6	1,8	3,2	2,6	
Gd	11	5,7	20	7,1	7	8,2	8,5	14	8,2	3,6	2,1	2,5	1,3	4,8	7,8	9,4	5,9	11	8	
Tb	1,38	0,85	2,88	1,05	0,97	1,06	1,02	1,84	1,04	0,49	4,2	0,38	0,2	0,63	1	1,24	0,77	1,47	1,1	
Dy	6,4	4,4	15	6,1	5,3	5,5	4,6	9,8	5,2	2,6	3,1	0,4	0,2	3,3	5,6	6,5	4,2	7,9	5,9	
Ho	1,2	0,78	2,64	1,05	0,95	1	0,77	1,79	0,92	0,44	3,1	0,4	0,2	0,54	1,01	1,14	0,74	1,4	1,07	
Er	3,4	2,2	7	2,8	2,6	2,9	2,2	5,1	2,8	1,1	0,53	1,1	0,5	1,5	2,8	3,1	2,1	3,8	2,9	
Yb	3,1	2,3	6,1	2,6	2,5	2,9	2,1	4,5	2,9	0,95	0,16	0,98	0,45	1,2	2,4	2,9	1,9	3,6	2,6	
Lu	0,49	0,39	0,83	0,38	0,36	0,43	0,33	0,68	0,47	0,14	1,2	0,13	0,06	0,18	0,34	0,4	0,27	0,49	0,36	
REE	320	155	563	184	197	250,87	261	385	237,5	80,8	96,8	62	29,1	129	222,8	273	165	296,1	222	143
Eu/Eu*	0,92	0,68	0,38	0,56	0,5	0,94	0,37	0,3	0,36	1,66	1,45	1,39	1,71	1,2	0,73	0,82	0,9	0,86	0,94	
La/Yb	20	1	18,3	10,3	12,8	15,8	25,2	15,3	23,1	10,5	10	8,1	6,6	16,6	15	16,2	14,7	13,3	13,8	
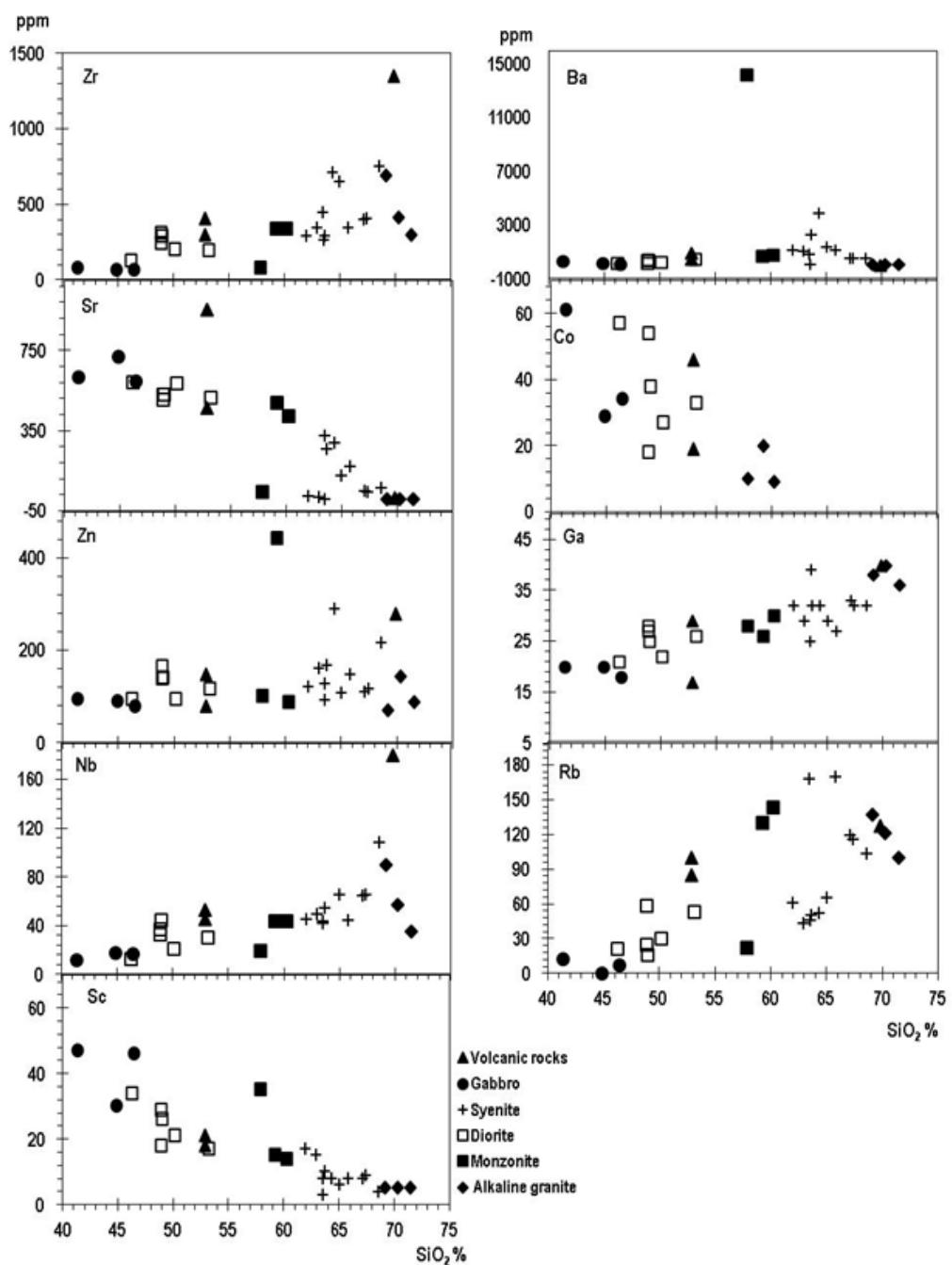
Fig. 4: Trace element distribution diagrams vs SiO$_2$ for Nlonako rocks.
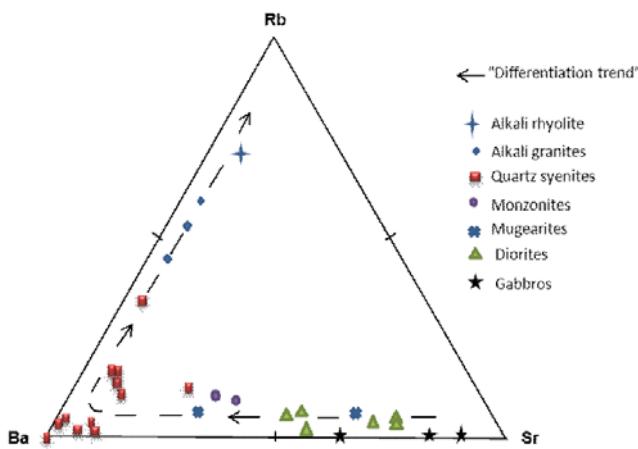
Fig. 5: Ba-Rb-Sr diagram for Nlonako rocks.

A primitive mantle-normalised REE diagram for the Nlonako rocks is shown in figure 6. REE concentrations in gabbros (samples N7, L16 and L17) vary between close limits and are less enriched in comparison with other rocks. La/Yb ratio comprises between 6.6 and 16.6 whereas "REE varies between 29.14 and 129.22 respectively in microgabbro and gabbro. Normalised patterns indicate positive europium anomalies (Eu/Eu*=1.20 to 1.71). The diorites (samples L30, L33, L8, L7 and L39) are more enriched in light REEs than heavy REEs with La/Yb ratios ranging between 13.3 and 16.2: the Europium anomaly is negative (0.73 <Eu/Eu*< 0.94). REE concentration seems not be related to the differentiation as its value ranges from 165.04 in one quartz microdiorite (sample L8) to 296.13 in another quartz microdiorite (sample L7). Normalised patterns are subparallel except for europium, indicating a REE fractionation in relatively constant proportions as it is the case in the Adirondack Highlands (*Olson* 1992). REE concentrations in quartz syenites and microsyenites (samples N29, N1, N4, L24, L35 and N28) are slightly more enriched and more fractionated than those in diorites. La/Yb ratio varies from 1 to 20. Normalised patterns are different and intersect at some points. The Europium anomaly is slightly negative (Eu/Eu*=0.38 to 0.94). Alkali granites (samples L37, L34 and L38) yield normalised patterns close to those of quartz syenites and microsyenites apart from Ce which indicates a slight negative anomaly (sample L38). " REE in alkali rhyolite (sample L14) and hawaiite (sample L26) are equal to 1430.95 and 393.76 ppm respectively. As

in the plutonic rocks, these volcanic rocks are more enriched in light REEs than in heavy REEs.
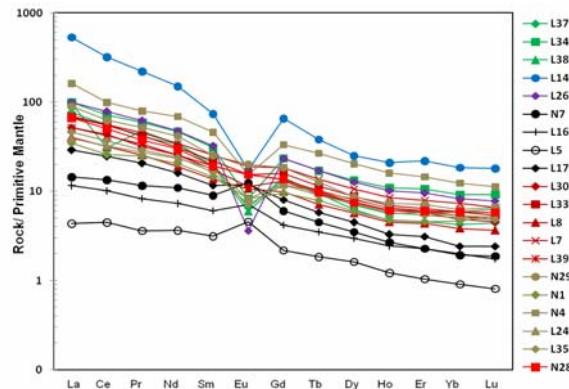
Fig. 6: Primitive mantle-normalized REE diagrams for the Nlonako rocks.

Initial isotopic compositions (^{87}Sr/^{86}Sr) of the Nlonako rocks range between 0.70381 and 0.74221 (table 3). In mafic rocks, these isotopic values are low (0.70381-0.70588). In quartz syenites and microsyenites, they vary between 0.70482 and 0.72509 whereas alkali granites and rhyolite yield values between 0.71074 and 0.74221. Initial ^{143}Nd/^{144}Nd ratios for all the investigated rocks are very close (0.512817-0.512929) apart from one quartz syenite (0.512454) and quartz microsyenite (0.512485) which indicate quite low values (table 4).

Table 3: Representative Rb/Sr analyses of the Nlonako rocks.

Sample Number	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr (1s = ± 1%)	^{87}Sr/^{86}Sr (1s = ± 0.03%)
Quartz syenites				
N29	61.4	123.8	1.436	0.70482
N1	41.5	3.58	33.58	0.72509
N4	99.2	62.4	4.608	0.70661
Alkali granites				
L41	116	46.9	7.162	0.71074
L36	112.6	42	7.776	0.71094
L34	137.2	12.54	31.76	0.72808
L37	97.3	9.1	31.02	0.72736
L38	115.8	6.49	51.92	0.74221
Alkali rhyolite				
L14	125.4	10.1	36.01	0.72981
Quartz microsyenite				
N28	164.2	167.6	2.839	0.71463
Gabbros				
L15	5.31	711	0.02161	0.70402
L5	5*	763	0.01897	0.70499
Diorites				
L39	21.1	511	0.1196	0.70588
L17	4.4	794	0.01606	0.70415
L7	16*	536	0.08643	0.70407
L8	30*	590	0.1473	0.70381

(*Rb concentrations were determined with X-Ray Spectrometer).

Table 4: Sm-Nd compositions of some rocks from Nlonako Massif.

Sample number	Sm (ppm)	Nd (ppm)	^{148}Sm/^{144}Nd (1s = ± 0.7%)	^{143}Nd/^{144}Nd (1s = ± 0.007%)	εNd (t)	(^{87}Sr/^{86}Sr)t (à t = 50 Ma)
Gabbros						
L17	5.524	24.2	0.1374	0.512885	5.2	0.7041
L15	4.636	18.43	0.1515	0.512883	5.1	0.704
L5	1.255	4.31	0.1753	0.512852	4.3	0.705
Diorites						
L39	8.683	37.65	0.1389	0.512929	6.1	0.7058
L7	11.498	50.96	0.1359	0.512817	3.9	0.704
L8	4.737	21.19	0.1346	0.51291	5.7	0.7037
Quartz microsyenite						
N28	10.231	51.67	0.1192	0.512485	-2.5	0.7126
Quartz syenites						
N29	13.549	64.92	0.1206	0.51286	4.8	0.7038
L10	10.964	55.67	0.1186	0.512454	-3.1	0.709
Alkali granites						
L34	17.38	79.09	0.1323	0.51283	4.2	0.7056
L38	12.754	70.42	0.1091	0.512856	4.8	0.7056

Geochronology

Conventional Rb/Sr measurements on whole rock were performed on five alkali granites, three quartz syenites, one quartz microsyenite and one alkali rhyolite. The results are reported in table 3 and plotted on a ^{87}Sr/^{86}Sr – ^{87}Rr/^{86}Sr diagram (fig. 7). A good isochron was obtained from quartz syenites indicating an age of 44.6 ± 1.6 Ma, an initial ^{87}Sr/^{86}Sr of 0.7038 ± 0.0003 and a Mean Square of Weighted Deviation (MSWD) of 0.53. Alkali granites define an age of 49.7 ±1.2 Ma, an initial ^{87}Sr/^{86}Sr of 0.7056 ± 0.0004 and a MSWD equal to 0.25. Quartz microsyenite and alkali rhyolite do not lie on these isochrons. The ^{87}Rb/^{86}Sr ratios of the gabbros and diorites (ranged between 0.01606 and 0.1473) are too close to allow precise isochrons to be constructed.
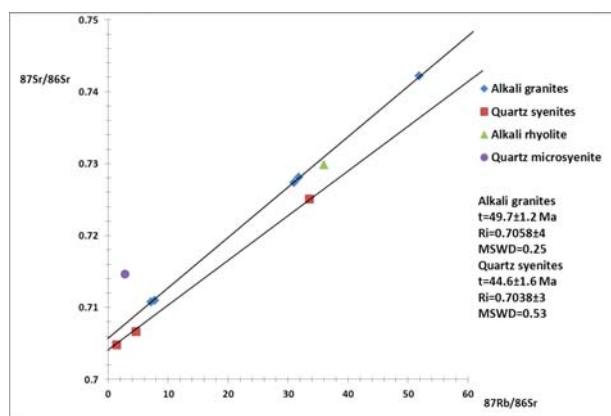
Fig. 7: ^{87}Sr/^{86}Sr – ^{87}Rr/^{86}Sr whole rock isochrons for alkali granites and quartz syenites.

Interpretation and Discussion

Co-magmatism and differentiation process

The co-magmatism of the Nlonako rocks is attested by major-and trace-element distributions vs silica where good linear correlations are broadly observed (figs. 3, 4). Despite the differences noted between acid rock REE patterns, which could be related to the heterogeneity of the source, the comparable evolution of all the REE patterns implies a cogenetic origin (fig. 6). The distribution and the fractionation of REE from the Nlonako Massif differ from one suite to another. Within plutonic rocks, "REE increases progressively with differentiation from gabbros (samples N7, L16, L17) to alkali granites (samples L37, L34, L38) through diorites (samples L30, L33, L8, L7, L39) and syenites (samples N29, N1, N4, L24). Apart from Eu, overall normalised patterns are quite uniform with abundant light REEs compared to heavy REEs. Europium behavior is also dependent on the degree of evolution. The gabbro positive europium anomaly is related to the fractionation of plagioclase as this mineral concentrates more europium than other REE (*Treuil* and *Joron* 1975, *Steinberg et al.* 1979, *Eby* 1989). A slight negative europium anomaly is observed in diorites and is due to the absence of cumulates in Nlonako rocks as reported elsewhere (*Cocherie* 1984). In the quartz syenites and alkali granites, the europium anomaly is related to peralkalinity (*Bowden* and *Whitney* 1974). Normalised patterns of volcanic rocks are similar

to those of acid rocks although REE are more concentrated. The Rb-Sr-Ba diagram takes into account the evolution of magmatic rocks (fig. 5). In the present case, quartz syenites are concentrated at the Ba pole whereas mafic and other felsic rocks occupy respectively Sr and Rb areas. The magmatic differentiation is continuous from Sr-Ba and Ba-Rb lines. It is mainly controlled by the K-feldspar/plagioclase ratio. In fact, the chemical trend suggests that K-feldspar becomes more important than plagioclase with magmatic evolution. Regarding what precedes, the predominance of felsic rocks over mafic rocks in the NAC can be explained by the variable level of erosion that has followed the emplacement of the massif. Alternatively, the density difference between acid and basic liquids has favoured emplacement of more acid rocks at present exposure levels.

Major elements display good linear, regular and progressive correlations with SiO2 (except MnO and P_2O_3); precisely, as previously stated, NaO and K_2O increase whilst MgO, CaO, Al_2O_3, Fe_2O_3 and TiO_2 decrease (fig. 3). The concentration of transition elements in mafic rocks is followed by their diminution in differentiated liquids. In addition to this observation, trace elements indicate regular evolution and a gradual increase of the Rb/Sr ratio with differentiation. On the basis of these arguments as well as the high K/Rb ratios (*Duschesne* and *Demaiffe* 1978), Rb/Sr, and Rb/Ba ratio variations (*Whalen et al.* 1987), it appears that fractional crystallization has played a major role in the differentiation of the Nlonako rocks.

Magma source and Evidence of crustal contamination
Magmatic rocks are believed to generate within either the mantle or the crust. One of the major issues concerning the petrogenesis of the NAC is the occurrence of different rock types of various compositions. These rocks form a continuous series from gabbros to granites through diorites, monzonites and syenites. As indicated above, the series defines two suites: a metaluminous suite ($Na_2O+K_2O<Al_2O_3$) and a peralkaline suite

($Na_2O+K_2O>Al_2O_3$). Sodium in the melt was high enough to allow arfvedsonite and aegirine to crystallize in peralkaline rocks under both reduced and oxidized conditions (*Markl et al.* 2010, *Marks et al.* 2011). The TiO_2 percentage in the mafic and intermediate rocks is higher than 1, suggesting a mantle source. Similarly, the high Fe_2O_3 and MgO contents (respectively 13 and 4.8% in mean) in the mafic rocks indicate the role of the mantle during the magmatic evolution. Moreover, the quite low contents of the transition element observed in these rocks assign to them a more or less differentiated source as in some Tertiary massifs along the CHL (*Jacquemin* 1981, *Kamgang* 1986, *Lamilen* 1989). The alkaline character is consistent with the uniform abundance of LREE in comparison with HREE except for Eu. The negative correlation of Sr vs Rb observed here was also mentioned by *Bonin* and *Lameyre* (1978) and *Ghogomu* (1984). According to *Arth* (1976), *Bonin* (1982), and *El-nisr* and *Saleh* (2001) this negative correlation is due to Rb enrichment coupled with Sr impoverishment and indicates the important role of feldspar fractionation during the evolution of the Nlonako Complex.

Isotopic data of Sr-Nd clearly demonstrate that the Nlonako rocks are mantle-derived magma. In fact, most of the samples are positioned close to the "mantle array" (fig. 8).
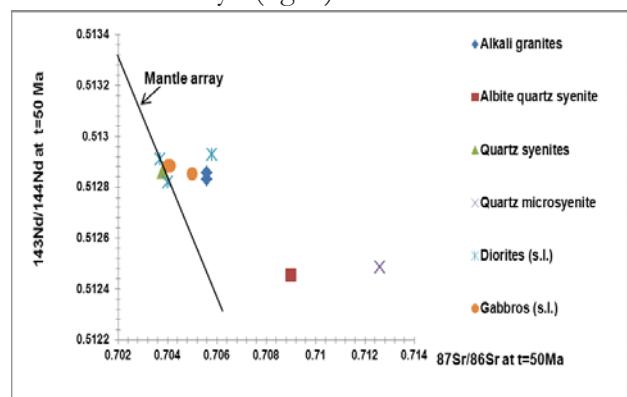

Fig. 8: $^{143}Nd/^{144}Nd$ vs $^{87}Sr/^{86}Sr$ diagram for Nlonako rocks

Albite quartz syenite and quartz microsyenite with low $^{143}Nd/^{144}Nd$ ratios and high $^{87}Sr/^{86}Sr$ ratios deviate slightly from this array as a result of crustal contamination. The crustal contamination of the quartz microsyenite is also confirmed by the Sr isotope data (fig. 7): its $^{87}Sr/^{86}Sr$ ratio is

higher than that of other samples. The relationship between the quartz microsyenite and other analyzed rocks is not clear. Nevertheless, if we attribute it a similar age to that of the granites (49.7 ±1.2 Ma), its initial Sr isotopic composition will be more or less equal to 0.713, confirming crustal contamination by Sr enrichment from country rock, in keeping with its location close to the margin of the complex. Finally, alkali granites were also slightly contaminated at depth by crustal material as its initial Sr isotopic (0.7056) is slightly high compared to recent upper mantle value (0.704) (*Gunter* 1986). In addition, the fact that mean K/Rb ratios are higher in felsic and intermediate rocks than in the mafic rocks in comparison with the mean crust composition simply indicates the crustal contamination of the magma during its last stage of evolution, as confirmed above by isotopic geochemistry. Crustal contamination is common along the CHL (*Cantagrel et al.* 1978, *Lasserre* 1978, *Jacquemin et al* 1982, *Njonfang* and *Moreau* 1996).

Age of emplacement of the NAC
The age of 49.7± 1.2 Ma obtained from the alkali granites can be interpreted as the age for the emplacement of these rocks. The representative point of the alkali rhyolite is situated beneath the alkali granites isochron (fig. 7). In the absence of a whole-rock isochron, the significance of this point is unclear. However, if this volcanic rock is assigned the same initial Sro as that of the alkali granites, the alkali rhyolite will be about 2 Ma younger than the alkali granites. *Cantagrel et al.* (1978) used the whole-rock K/Ar method on the granites to define an age of 35.5±1 Ma. This contrasts with the age obtained here and that determined by *Lasserre* (1978) on granite and rhyodacite (43.3± 0.3 Ma). All of the dated granites are from the same locality (northern border of the massif). Perhaps this young age can be related to a complete or partial argon loss as a result of a very localized alteration event (*Goll et al.* 1995) or tectonic event leading to the temperature increase. This inconsistency clearly shows the disadvantage of using the K/Ar method especially when dealing with the rain forest environment where faults are usually hidden by vegetation and soil. In order to avoid such discrepancies and to increase the reliability of the geochronological results, it is advised to use the laser incremental heating $^{40}Ar/^{39}Ar$ method which permits identification of samples subjected to loss or excess of Ar, or detecting effects of other alteration that cannot be determined by the conventional K/Ar method (*Perlingeiroa et al.* 2012).

The age of 44.6 ± 1.6 Ma represents the timing of emplacement of quartz syenites. It is similar to the ages of 45 ±1 Ma and 43.3 ± 0.3 Ma found respectively by *Cantagrel et al.* (1978) and *Lasserre* (1978) in similar rocks.

The older age of the granites (49.7 Ma) in comparison with the syenites (44.6 Ma) is at variance with fractional crystallization which has been proposed to explain the differentiation process of the Nlonako rocks. Taking into account the fact that these rocks are co-magmatic and the ages defined here are reliable, it is presumed that syenites have spent more time than granites in the secondary magmatic chambers (*Baker et al.* 1977, *Gamble et al.* 1992), due to the difference of viscosities of the parental magma (*Poitrasson et al.* 1995). The low viscosities have allowed a faster ascent of the granites in the crust compared to the syenites. This hypothesis should be confirmed by the variations in U-Th-Ra isotope compositions of bulk rocks reflecting different degrees of magma differentiation (*Hawkesworth et al.* 2000).

Conclusions
Geochemical study of the NAC defines a complete alkaline series from gabbros to granites through trough diorites, monzonites and syenites. This series comprises two suites: a metaluminous suite made of basic and intermediate rocks, fayalite alkali granite and most of the syenites; and a peralkaline suite including rhyolite and other granites. Peralkalinity is expressed by the presence of ægirine and arfvedsonite in the granites and rhyolites. The magma in both suites was developed by fractional crystallization from single basaltic

mantle material and was progressively affected by crustal contamination at the end of the differentiation process. The role of the continental crust is implicated by elevated initial $^{87}Sr/^{86}Sr$ ratios and by Sr-Nd isotopic data. In addition, fractional crystallization was mainly controlled by feldspar.

Acknowledgements

References

Arth, J. G. 1976. Behaviour of trace elements during magmatic processes. A summary of theoretical models and their applications. Journ. Res. U.S. Geol. Surv., 4: 41-47.

Baker, B. H., Goles, G. G., Leeman, W. P. and Lindstrom, M. M. 1977. Geochemistry and petrogenesis of basalt -benmoreite-trachyte suite from the Southern part of the Gregory Rift, Kenya. Contrib.Mineral Petrol., 64: 303-332.

Bonin, B. 1982. Les granites des complexes annulaires. B.R.G.M. éd. coll. manuels et méthodes 4. 183 p.

Bonin, B. et Lameyre, J. 1978. Réflexions sur la position et l'origine des complexes magmatiques anorogéniques. Bull. Soc. Geol. France. 7, XX, 45-59.

Bowden, P. and Whitley, J. E. 1974. Rare earth patterns in peralkaline and associated granites. Lithos 7: 15-21.

Cantagrel, J.M., Jamond, C. et Lasserre, M. 1978. Le magmatisme alcalin de la ligne du Cameroun au Tertiaire inférieur : données géochronologiques K/Ar. C.R. Soc. Géol. Fr, Fasc. 6: 300-303.

Cocherie, A. 1984. The variscan calc-alkalic plutonism of Western Corsica: mineralogy and trace elements geochemistry. Phys. Earth Planet. Inter. 35: 145-178.

Déruelle, B., Ngounouno, I., Demaiffe, D. 1987. The 'Cameroon Hot Line' (CHL): A unique example of active alkaline intraplaque structure in both oceanic and continental lithospheres. C.R. Geoscience 339: 589-600.

Duchesne, J. C. and Demaiffe, D. 1978. Trace elements and anorthosite genesis. Earth. Planet. Sci. Lett 38: 249-272.

Eby, N. G. 1989. Petrology and geochemistry of Mount Yamaska; Quebec, Canada: a mafic representative of the Monteregian Hills igneous province in Memoirs Geol. Soc. India 15: 63-82.

El-nisr, S. A. and Saleh, G. M. 2001. Geochemistry and Petrogenesis of the Late Jurassic-Early Cretaceous Mansouri Ring Complex, Southeastern Desert, Egypt. Journ. Afr. Earth. Sci. 32 (1): 87-102.

Gamble, J. A., Meighan, I. G. and Cornick, A. G. 1992. The petrogenesis of Tertiary microgranite and granophyres from Slieve Gullion Central complex, N.E Irland. Journ. Geol. Soc. London 149: 93-106.

Ghogomu, T. R. 1984. Geology, geochemistry and petrology of the Ntumbaw anorogenic complex, Cameroon : an example of a ring complex of intermediate composition. Doct. Degree Univ. of Nancy I, Univ. of Yaounde, 146 p.

Goll, M., Lippolt, H. J., Hess, J. C. und Hoefs, J. 1995. Isotopische Hinweise auf spat-und postvariscische Alterationen von Thüringer-Wald-Vulkaniten. Beihefte zum European Mineralogy 7, 86.

Gunter, F. 1986. Principles of isotope geology. 2nd Ed. John. Wiley and Sons 589 p.

Hawkesworth, C. J., Blake, S., Evans, P., Hughes, R., MacDonald, R., Thomas, L. E., Turner, S. P. and Zellmer, G. 2000. Time Scales of Crystal Fractionation in Magma Chambers-Integrating Physical, Isotopic and Geochemical Perspectives. Journ. Petrol. 41 (7): 991-1006.

Jacquemin, H. 1981. Contribution à l'étude géochimique des éléments en traces à la pétrogenèse des complexes anorogéniques. Exemples des massifs de M'boutou et de Golda Zuelva Nord Cameroun. Thèse 3ième cycle. Univer. nancy I, France, 251 p.

Jacquemin, H., Sheppard, S. M. F. and Vidal, P. 1982. Isotopic Geochemistry (O, Sr, Pb) of the Golda Zuelva and Mboutou anorogenic complexes. North Cameroun: mantle origin with evidence for crustal contamination. Earth. Planet. Sci. Lett. 61: 97-111.

Kamgang, P. 1986. Contribution à l'étude pétrologique du massif du Nkogam (Pays Bamoun : Ouest Cameroun). Thèse 3ième cycle Univ. Yaoundé. 250 p.

Lamilen, B. D. 1989. Contribution à l'étude du complexe anorogénique du mont Koupé: un exemple de série alcaline incomplète. Pétrologie et géochimie. Thèse 3ième Univ. Yaoundé 169 p.

Lasserre, M. 1978. Mise au point sur les granitoïdes dits "ultimes" du Cameroun: gisements, pétrographie et géochronologie. Bull. B.R.G.M. sect. IV, 2: 143-156.

Markl, G., Marks, M. A. W. and Frost, B. R. 2010. On the Controls of Oxygen Fugacity in the Generation and Crystallization of Peralkaline Melts. Journ. Petrol. 51 (9): 1831-1847.

Marks, M. A. W., Hettmann, K., Schilling, J., Frost, B. R. and Markl, G. 2011. The mineralogical Diversity of Alkaline Igneous Rocks: Critical Factors for the Transition from Miaskitic ti Agpaitic Phase Assemblages. Journ. Petrol. 52 (3): 439-455.

Moreau, C. Regnoult, J. M., Deruelle, B. and Robineau, B. 1987. A new tectonic model for the Cameroon line, central Africa. Tectonophysics. 139: 317-334.

Njonfang, E. and Moreau, C. 1996. The mineralogy and geochemistry of a subvolcanic alkaline complex from the Cameroon Line: The Nda Ali massif, southwest Cameroon. Journ. Afr. Earth. Sci. 22 (2): 113-132.

Olson, K. E. 1992. The petrology and geochemistry of mafic igneous rocks in the anorthosite-bearing Adirondack Highlands, New YorK. Journ Petrol. 33 (2): 471-502.

Perlingeiroa, G., Vasconcelosa, P. M., Knesela, K. M., Thiedea, D. S. and Cordanid, U. G. 2012. $^{40}Ar/^{39}Ar$ geochronology of the Fernando de Noronha Archipelago and implications for the origin of alkaline volcanism in the NE Brazil. J. Volcanol. Geotherm. Res. 249: 140-154.

Poitrasson, F., Duthou, J. L. and Pin, C. 1995. The relationship between Petrology and Nd Isotopes as Evidence for Contrasting Anorogenic Granite Genesis: Example of the Corsican Province (SE France). Journ. Petrol. 36 (5): 1251-1274.

Steinberg, M., Touray, J. C., Treuil, M. et Massard, P. 1979. Géochimie principes et méthodes. II. Cristallochimie et éléments en traces. Doin ed. Paris 599 p.

Tchoua, F. M. 1974. Contribution à l'étude géologique et pétrologique de quelques volcans de la ligne du Cameroun (Monts Manengouba et Bamboutos) Thèse doct. d'Etat Univ. Clermont-Ferrand 347p.

Tempier, P. et Lasserre, M. 1980. Géochimie des massifs "ultimes" du Cameroun : rapports entre l'évolution magmatique, l'âge et la position géographique. Comparaison avec les "Younger granites" du Nigeria. Bull. Soc. Géol. Fr., 7, t. xx II (2) : 203-211.

Treuil, M. et Joron, J. L. 1975. Utilisation des éléments hygromagmatophiles pour la simplification de la modélisation quantitative des processus magmatiques Exemple de l'Afar et de la dorsale médio atlantique. Soc. Ital. Minéral. Pétrol. Milano. XXXI (1): 125-174.

Whalen, J. B., Currie, K. L. and Chappell, B. W. 1987. A-type granites geochemical characteristics, discrimination and petrogenesis. Contrib.Mineral.Petro. 95: 407-419.