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Revised petrology and new chronological data on the peralkaline felsic lavas of Ngaoundéré volcanism (Adamawa plateau, Cameroon, Central Africa): evidence of open-system magmatic processes

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Abstract

The petrology of the peralkaline felsic lavas from the Ngaoundéré region was re-examined, together with new chronological data obtained on them, in order to determine their petrogenesis and investigate their peralkaline features. The results showed that all lavas have a microlitic porphyritic texture. They are composed of more than 70% phenocrysts and microlites of alkali feldspar, with diopside, hedembergite, augite, aegirine-augite for trachytes, and nosean, nepheline, kaersutite, titanite, apatite and oxides¸ set in a matrix of the same minerals, in phonolite. All lavas, Miocene in age, are the result of the fractional crystallization processes undergone by the surrounding basaltic lavas. The titanite crystallization phase is responsible for the concave downward appearance of the REE pattern of peralkaline phonolite, as well as the slight depletion of Nb and Ta. AFC modeling using Pan-African basement rock as contaminant was also intended. The genesis of peralkaline trachytes from less-evolved lavas requires a Ma/Mc ratio of 0.1, and a fractionation process ($F \approx 0.9$) involving only feldspar so as to comply with the ($^{87}Sr/^{86}Sr$) 9Ma values of ≈ 0.710. Additionally, hydrothermal fluid effects are suspected. The peralkalinity of the lavas is the result of a pronounced fractionation of the Al_2O_3 component by aluminous-enriched phases, in combination with alkali- and volatile-enriched metasomatized fluids, which have acted through the network of Pan-African cracks.

Keywords: petrology, geochronology, peralkaline felsic lavas, crustal contamination, Adamawa-Cameroon, Central Africa.

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Introduction

More than thirty plugs and domes of trachyte, phonolite and peralkaline trachyte and phonolite, surrounded by numerous basaltic lava flows, occur in the north of the Ngaoundéré region, in the Adamawa plateau (Cameroon, Central Africa, Fig. 1). Petrological, geochemical (Nkouandou et al., 2008) and field work data suggest that the felsic lavas are the final products of the differentiation of basaltic lavas through fractional crystallization processes, in spite of the compositional gap between basaltic and felsic lavas. The occurrence of such a gap in alkali volcanism suites has been largely discussed (Thompson et al., 2001) and arose the problem of the origin of the associated felsic lavas. The petrological data on the peralkaline felsic lavas of the Adamawa plateau is not sufficiently detailed. On the other hand, the origin of the peralkaline feature of these lavas is still debated. The following hypotheses have been advanced in this respect: peralkalinity in igneous rocks is attributed to (1) subsolidus reactions with metasomatic fluids (Taylor et al., 1980) or (2) an alkali-enriched source region (Bailey, 1987). It is also suggested that (3) the peralkalinity of felsic magmas may result from the partial melting of different lithospheric mantle or lower continental crustal sources (Bailey and McDonald, 1987). Avanzinelli et al. (2004) have suggested that simple fractional crystallization by itself cannot explain the generation of peralkaline magmas when starting from parental basalts, and that other processes, such as partial melting of gabbroic cumulates, are more viable and have to be considered when it comes to the genesis of peralkaline magmas.

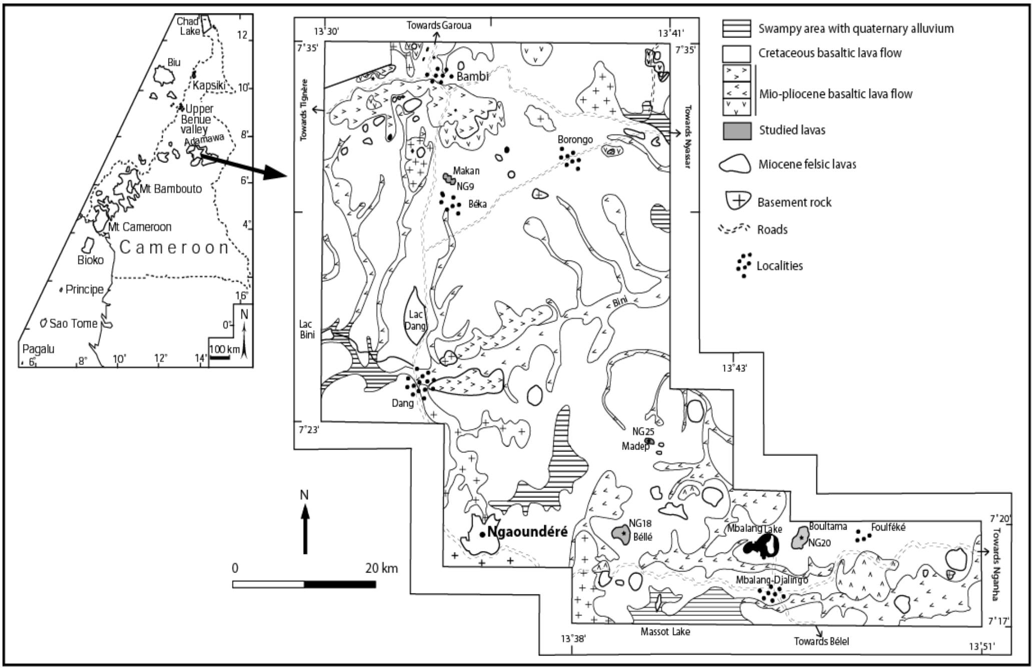


Fig. 1 Geological map of Ngaoundéré region after Nkouandou et al. (2008), modified. Rigth inset shows the mains volcanic zones of Cameroon: Cameroon Volcanic Line and Adamawa plateau.

As a result, the detailed petrology of the peralkaline felsic lavas from the Ngaoundéré region provides an opportunity of highlighting their peralkaline character and the magmatic processes involved in their petrogenesis, using mineral and whole-rock chemistry, as well as Sr-Nd-Pb isotopes. The new chronological data are integrated so as to document the petrogenetic history of the peralkaline felsic lavas from the Adamawa plateau.

Geological setting

The Adamawa Plateau (Fig. 1) is one of the African uplift domes, bordered in the north and in the south by large N70°E striking-slip faults (the Adamawa and Djerem-Mbéré faults respectively), active since the Cretaceous (Moreau et al., 1987). The Adamawa Plateau basement rocks are composed of granitoids facies of Th-U-Pb age – 615 to 575 ± 27 Ma (Tchameni et al., 2006; Ganwa et al., 2008). These rocks are partially covered by Cretaceous-to-recent basaltic lava flows (Lasserre et al., 1961; Temdjim et al., 2004) of typical alkali composition (Nkouandou el al., 2008). The plateau is intruded along the N70E, N65E and N135E Pan-African directions by more than thirty plugs and domes of trachyte and phonolite of peralkaline composition (Fig. 1). Similar alkali lavas series are still studied at the Tchabal Mbabo volcano (Fagny, in preparation), 250 km, western Ngaoundéré. The low partial melting (1 to 2%) of the FOZO-type component mantle source with residual garnet took place at a depth of 80 km (Nkouandou et al., 2010). Numerous basaltic lava flows containing various mantle peridotites (Nkouandou and Temdjim, 2011) are easily distinguished, based on their stratigraphic and surface-weathering characteristics, as the (1) low flow unit (LFU), (2) middle flow unit (MFU) and (3) upper flow unit (UFU), as established for the basaltic lavas in the nearby Ngaoundéré region (Nono et al., 1994). The felsic lavas sometimes contain fragments (5 to 25 cm in diameter) of basaltic glasses and granitoid basement rock. The origin of these felsic lavas has been discussed previously (Nkouandou et al., 2008; Legendre et al., 2005). However, it remained difficult to establish, as there is a large compositional gap between the two poles of local volcanism suites. On the other hand, their peralkaline features have never been tackled and they may result from numerous petrogenetic processes, as proven worldwide. The present study deals with the petrology and geochemistry of one peralkaline phonolite plug (Ngao Mokon) and three peralkaline trachyte domes (Ngao Belle, Ngao Madep and Ngao Mboultama), in order to highlight the origin of their peralkaline character and to document their geochronological history.

Analytical methods

Microprobe chemical analyses of the elements (Si, Ti, Al, Cr, Fe, Mn, Mg, Ni, Na, K and P) of representative minerals were carried out using a SX50 and SX100 Camebax microprobe at the “Pierre et Marie Curie” University, Paris 6. The analytical conditions were the following: for clinopyroxene : 15k V and 40 nA, 20s, except Ti (30 s); plagioclase, K-feldspar, nepheline and noseane: 15k V, 10 nA, 10 s; Fe–Ti oxides: 20 kV and 40 nA; Si, Ca, Ni:10 s; Mn: 25 s ; Cr: 15 s; Al: 30 s; Ti, Fe, Mg: 40 s; kaersutite (analyses not shown): 15 kV, 21 nA; Si, Al, Mg, Na, K, and Ba: 15 s; Ti, Ca: 20 s; Fe, Mn: 25 s; F, Cl: 30 s. The “PAP” correction program used is defined by Pouchou and Pichoir (1991). The analyses of the major elements of all the lavas have been performed through ICP-AES, and those of trace elements – through ICP–MS, at the “Centre de Recherche Pétrographique et Géochimique” of Nancy, France, following the analytical procedure of Carignan et al. (2001). The samples for the isotopic analyses of Rb–Sr and Sm–Nd were dissolved in a mixture of HF–HNO_3 (10:1), and chemical separation was carried out through cation-exchange chromatography; blanks were < 1 ng. Sr and Nd isotopic ratios were measured on a VG Sector 54 multicollector thermal ionization mass spectrometer. Replicate analyses of the MERCK Nd standard yielded an average ^{143}Nd/^{144}Nd value of 0.512742 ± 8 (normalized to ^{146}Nd/^{144}Nd = 0.7219), and measurements of NBS 987 Sr led to an average ^{87}Sr/^{86}Sr value of 0.710247 ± 7 (normalized to ^{86}Sr/^{88}Sr = 0.1194). Epsilon Nd values were calculated assuming ^{147}Sm/^{144}Nd = 0.1967 and ^{143}Nd/^{144}Nd = 0.512638 for CHUR (after Ashwal et al., 2002). The differentiation index (D.I., Thornton and Tuttle, 1960) is deduced from the CIPW norms, which were calculated assuming a FeO/Fe_2O_3 ratio of 0.3.

Table 1 New chronological data of the Mio-Pliocene alkali lavas series from Ngaoundéré (Adamawa Plateau, Cameroon)

Sample	Rock type	K_2O (wt %)	100×rad.^{40}Ar/total^{40}Ar	rad.^{40}Ar (10^{-11} mol g^{-1})	Age (±2Ò) (Ma)
NG130	basalt	2.51	7.6	2.82	7.8 ± 1.4
NG1T	phonolite	5.18	53.1	8.13	10.9 ± 0.4
NG9	peralkaline phonolite	5.38	57.9	7.55	9.7 ± 0.4
NG13	trachyte	5.40	28.1	6.96	8.9 ± 0.4
NG20	peralkaline trachyte	4.80	27.7	5.75	8.3 ± 0.5

Results

Geochronology

The results of the K–Ar dating of the volcanic rocks of the northern and eastern regions of Ngaoundéré are presented in Table 1. All lavas are of Pliocene age, between 7.8 ± 1.4 and 10.9 ± 0.4 Ma, thus within the range of previous K–Ar data (7.0 to 9.8 ± 0.2 Ma; Gouhier et al., 1974) and ^{40}Ar–^{39}Ar data (9.28 to 11.39 ± 0.03 Ma; Marzoli et al., 1999). Among the dated lavas, the felsic are older than the basaltic ones. This proves that the basaltic lavas sampled around the felsic domes cannot be regarded as their parental magma, as they are more recent in age. These observations suggest that all the lavas are from the Miocene eruption period, confirming the occurrence of numerous volcanic episodes.

Field work

One plug of peralkaline phonolite occurs in the northern part of the Ngaoundéré region, while four domes of peralkaline trachyte occur in the eastern part of the region (Fig. 1). The plug and domes occasionally display a strong parallel orientation to the N70E Pan-African direction. They range between 40 to 200 m in diameter, and they crop out between 20 and 250 m above the surrounding basement rocks. A systematic sampling of the lavas has been carried out through painstaking field work. The relative chronology of different rocks is assessed and mostly based upon the xenolith (1 to 20 cm) occurrence of metamorphic, granitic basement rocks or basaltic lava in all lavas. The contact points between plug or domes and granitoid basement rocks are obscured by talus. The plug and domes are always divided into subvertical columns of 1 to 3 meters in diameter, and cut horizontally into units of 2 to 5 meters high. Some display fountains or onion-bulb-like structures with peculiar surfaces on which scattered translucid feldspar phenocrysts (0.5 to 1.0 cm) stand out from the groundmass. The hand specimens display a matrix of greenish or greyish-white colour in trachytic lavas, while phonolite is light green, sometimes bluish when dominated by glassy materials.

Lavas have been named according to their mineralogy (the occurrence of minerals belonging to the nepheline or sodalite groups within phonolite) and their differentiation index (D.I.) after Thornton and Tutle (1960): 93.1 for phonolite, 87.9, 90.1, and 90.7 for peralkaline NG18, NG25 and NG20, respectively. The peralkaline index [P.I. = (Na_2O + K_2O)/Al_2O_3] of the lavas is around 1.0 (Table 5), and all the lavas are nepheline normative. SI (diorite) was sampled from well-exposed basement rock of dioritic composition, analysed and added to the present study so as to easily assess the contamination process.

Petrography

Peralkaline phonolites have a microlitic porphyritic texture. They are characterized by the occurrence of abundant needlelike green aegirine crystals, always lying around the phenocrysts and microphenocrysts of minerals belonging to the nepheline and haüyne groups. They also contain abundant titanite (15 vol.%) microphenocrysts in a glassy matrix of microcrystalline aegirine, alkali feldspar, rare haüyne group minerals, nepheline and interstitial oxides, and apatite. Nepheline microphenocrysts occur as euhedral hexagonal crystals commonly containing acicular deep-green aegirine. Amphibole phenocrysts of the kaersutite type (analyses not shown), rounded by a thin layer of Fe–Ti oxides, sometimes contain apatite or titanite. Alkali feldspar phenocrysts dominate the mineral assemblage. Two types of haüyne group mineral phenocrysts, up to 2 mm in size occur: thin light rime with a dark-greyish core, and dark rime (containing numerous pyrite microcrysts) with a white-greyish core. Phenocrysts always form a glomeroporphyritic texture within the glassy matrix. Zeolite veins (1–2 mm wide) are common.

Peralkaline trachytes exhibit a microlitic porphyritic texture, characterized by the occurrence of abundant (> 70 wt%) K-feldspar phenocrysts and microphenocrysts, set in the groundmass made up of the same phases, plus Fe–Ti oxides. K-feldspar crystals are rounded by numerous fibrous deep-green aegirine microlites. Both euhedral diopside and rare dark-green skeleton aegirine-augite phenocrysts (0.5 mm) occur within the interstitial matrix of K-feldspar phenocrysts. Titanite, Fe–Ti oxides and apatite phenocrysts are also present in some lavas. Microlites of the same minerals constitute the matrix of all the lavas, except peralkaline trachyte NG20, which is only composed of K-feldspar, aegirine-augite and rare Fe–Ti oxides (< 1 wt%).

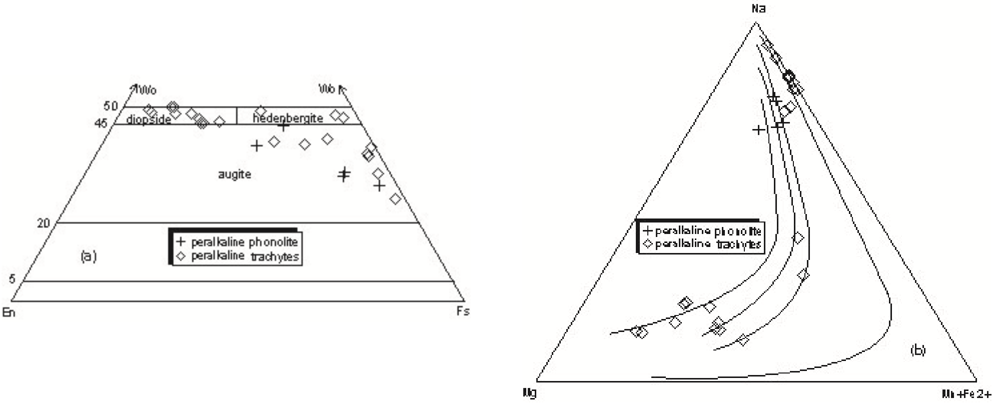


Fig. 2 Evolutionary trends of clinopyroxene compositions of peralkaline felsic lavas from Ngaoundéré plotted in terms of : (a) Na–Mg– (Mn + Fe^{2+}) and (b) Wo–En–FS.

Mineralogy

The clinopyroxene analyses conducted on all the lavas are presented in Table 2 and represented in Figs. 2a and 2b. Their compositions (nomenclature after Morimoto et al., 1988) vary (Fig. 2a) from diopside ($Wo_{46.0–48.2}En_{34.8–36.1}$)

to hedenbergite ($Wo_{46.3–47.7}Fs_{23.0–47.7}$) in peralkaline trachyte, while augite ($Wo_{39.7–32.0}En_{26.1–10.9}$), aegirine-augite ($Wo_{33.1–39.7}Fs_{66.4–34.2}$) and aegirine ($Wo_{29.4}Fs_{66.4}$) occur in peralkaline phonolite and trachyte. All compositions define a regular evolutionary trend, as shown in Fig. 2b. Aegirine-augite in peralkaline phonolite are rich in TiO_2 (up to 6.1 wt% TiO_2 in microlites), while high contents of Fe_2O_3* (up to 33.0 wt%) and Na_2O (12.3 wt%) are found in peralkaline trachyte microlites with a high value of acmite (Ac_{83}). Prior to interpretation, high TiO_2 contents (6.1 wt%) in aegirine microlites (with $Al_{VI}/Al_{IV} < 0.25$) indicate a low crystallization temperature (< 600°C; Ferguson, 1977), and the occurrence of Fe–NAT ($NaTi_{0.5}Fe^{2+}_{0.5}Si_2O_6$) in microlites suggests low oxygen fugacity during crystallization (Nielsen, 1979; Duggan, 1988).

Table 2 Representative chemical analyses of clinopyroxene of peralkaline felsic lavas from Ngaoundéré; ph, c: phenocryst core; ph, r: phenocryst rime; ml: microlite

Lava	Peralk. trachyte								Peralk. phonolite	
Sample	NG20		NG25		NG18				NG9	
Type	ph.c			ph.r	ph.c			ml	ph.c	ml
Oxides (wt%)										
SiO_2	52.35	53.23	53.21	51.60	51.62	52.37	51.35	53.54	53.33	53.24
TiO_2	0.37	1.82	1.39	0.55	0.53	0.49	0.88	6.07	5.13	4.79
Al_2O_3	0.64	1.14	0.75	2.20	2.22	0.70	1.72	0.79	0.55	0.83
FeO	33.12	31.20	32.04	12.54	12.61	13.52	13.05	21.90	24.39	25.24
MnO	0.89	0.95	1.14	1.88	1.63	2.07	2.21	0.96	1.16	1.33
MgO	0.11	0.10	0.10	9.47	9.56	8.94	8.91	3.07	1.67	1.40
CaO	2.55	2.23	2.94	19.43	19.41	20.12	18.88	4.91	3.26	2.64
Na_2O	12.19	12.33	12.04	1.98	2.03	1.63	2.80	11.25	11.62	12.32
ZrO_2	0.39		0.06							
Sum	102.61	102.99	103.68	99.65	99.61	99.84	99.80	102.49	101.11	101.79
Cations (apuf)										
Si	1.976	1.989	1.984	1.962	1.962	2.004	1.950	1.975	2.008	1.989
Ti	0.010	0.051	0.039	0.016	0.015	0.014	0.025	0.168	0.145	0.135
Al_{VI}	0.005	0.040	0.017	0.061	0.061	0.032	0.027	0.034	0.024	0.037
Al_{IV}	0.024	0.011	0.016	0.038	0.038		0.050			
Fe^{3+}_{VI}	0.882	0.762	0.789	0.092	0.097	0.053	0.176	0.481	0.516	0.608
Fe^{2+}	0.065	0.129	0.123	0.297	0.293	0.374	0.219	0.141	0.194	0.113
Mn	0.029	0.030	0.036	0.061	0.052	0.067	0.071	0.030	0.037	0.042
Mg	0.006	0.006	0.006	0.537	0.542	0.510	0.504	0.169	0.094	0.078
Ca	0.103	0.089	0.118	0.792	0.790	0.825	0.768	0.194	0.131	0.106
Na	0.892	0.894	0.871	0.146	0.150	0.121	0.206	0.805	0.848	0.893
Zr	0.007		0.001							
Minerals (%)										
Wo	47.7	33.1	39.8	46.0	46.1	46.3	48.2	39.7	29.4	32.0
En	4.6	2.4	0.3	34.8	35.0	30.7	36.1	26.1	4.2	10.9
Fs	47.7	64.5	59.9	19.2	18.9	23.0	15.7	34.2	66.4	57.1

Table 3 Representative chemical analyses on feldspar and feldspatoids from the peralkaline felsic lavas of Ngaoundéré; l.r.: light rime; l.c.: light core; d.r.: dark rime; d.c.: dark core; ph.c: phenocryst core; mph: microphenocryst

Lavas	Peralkaline trachyte									Peralkaline phonolite							
Samples	NG25				NG20		NG18			NG9							
Minerals	K-feldspar									Nepheline			Noseane				
Description	ph.c									ph.c.	mph			d.c.	l.r.	l.c.	d.r.
SiO_2 (wt%)	67.03	66.56	67.23	67.38	69.00	69.32	68.73	69.16	68.94	46.96	47.65	49.51	36.84	36.36	37.13	36.71	33.37
Al_2O_3	18.97	19.04	19.23	18.97	19.35	19.56	19.69	19.77	19.47	32.53	31.51	29.83	30.22	29.97	28.79	27.95	26.97
FeO*	0.30	0.18	0.24	0.14	0.38	0.31	0.18	0.32	0.34	0.84	0.70	1.88	0.96	0.25	0.23	2.16	4.50
CaO	0.15	0.13	0.18	0.18	0.07	0.15	0.10	0.12	0.09	0.25	0.28	0.08	0.48	0.14	0.98	0.68	0.36
Na_2O	7.01	5.65	6.71	7.39	8.49	8.79	9.01	8.91	8.95	16.84	16.24	16.54	18.17	21.33	20.01	16.72	14.02
K_2O	6.43	8.27	6.56	6.04	5.49	4.61	4.85	4.57	4.87	3.56	3.58	2.96	2.01	1.86	3.51	7.93	11.24
SO_3													10.11	9.76	8.20	7.27	9.71
Cl													0.57	0.79	0.80	0.35	0.07
Sum	99.89	99.83	100.15	100.1	102.78	102.74	102.56	102.85	102.66	100.98	99.95	100.80	99.36	100.46	99.65	99.77	100.24
Si (apuf)	2.996	2.993	2.995	3.001	2.990	2.993	2.980	2.982	2.986	8.773	8.781	9.182	6.040	6.070	6.260	6.180	5.840
Al	0.999	1.009	1.010	0.996	0.988	0.995	1.006	1.005	0.994	7.163	7.145	6.521	5.840	5.900	5.720	5.550	5.570
Fe^{++}	0.011	0.007	0.009	0.005	0.014	0.011	0.007	0.011	0.012	0.126	0.107	0.265	0.120	0.030	0.030	0.270	0.590
Ca	0.007	0.006	0.009	0.009	0.003	0.007	0.005	0.006	0.004	0.050	0.057	0.016	0.080	0.020	0.180	0.120	0.070
Na	0.609	0.494	0.581	0.640	0.715	0.738	0.760	0.747	0.754	6.118	6.075	5.964	5.780	6.910	6.530	5.460	4.760
K	0.367	0.474	0.373	0.343	0.304	0.254	0.268	0.251	0.269	0.847	0.878	0.701	0.420	0.400	0.750	1.700	2.510
S													1.240	1.220	1.040	0.920	1.280
Cl													0.160	0.230	0.230	0.100	0.020
Or (%)	37.3	48.7	38.7	34.4	29.7	25.4	25.9	25	26.2								
Ab	62	50.7	60.4	64.2	70	73.8	73.5	74.4	73.3								
An	0.7	0.6	0.9	1.4	0.3	0.8	0.6	0.6	0.5								
Ne										79.1	78.9	66.7					
Ks										14.8	15	22.3					
Q										6.1	6.1	11					

Table 4 Representative chemical composition of titanite, Ti-magnetite and apatite of Ngaoundéré peralkaline felsic lavas; ph.c.: phenocryst core; mic: microcryst

Lavas	Peralk phonolite	Peralk. trachyte						Peralk. phonolite		
Minerals	Titanite					Ti-magnetite				
Samples	NG9	NG20		NG18	NG25	NG18	NG25	NG9		
Description	ph.c		ph.c		mic	ph.c		ph.c		
					(wt%)					
SiO_2	30.00	29.44	29.75	29.58	29.86					
TiO_2	33.57	33.26	33.26	32.26	33.22	12.83	13.16	16.38	14.29	14.53
ZrO_2	0.69	0.82	0.76	1.14	0.68					
Nb_2O5	1.12	1.58	1.83	1.81	1.75					
La_2O_3	0.37	0.51	0.60	0.61	0.47					
Ce_2O_3	0.69	0.88	0.83	0.79	0.83					
Nd_2O_3	0.62	0.73	0.71	0.48	0.61					
Y_2O_3	0.24	0.39	0.36	0.22	0.29					
Al_2O_3	1.65	1.87	1.58	1.75	1.78	0.19	0.60	0.13	1.02	0.31
Fe_2O_3	2.42	2.59	2.39	2.50	2.43	81.30	80.91	76.89	78.18	79.96
MnO						3.69	4.33	3.38	3.41	3.35
CaO	26.42	25.95	25.85	25.82	25.67	0.02	0.15	0.00	0.03	0.03
Na_2O	0.06	0.07	0.09	0.07						
Sum	97.85	98.08	98.02	97.03	97.57	98.03	99.14	96.78	96.93	98.19
					(apfu)					
Si	4.168	4.124	4.162	4.179	4.180					
Ti	3.507	3.504	3.499	3.428	3.497	0.161	0.165	0.205	0.179	0.182
Zr	0.047	0.056	0.052	0.079	0.046					
Nb	0.035	0.050	0.058	0.058	0.055					
Y	0.009	0.015	0.013	0.008	0.011					
La	0.009	0.013	0.015	0.016	0.012					
Ce	0.018	0.023	0.021	0.020	0.021					
Nd	0.015	0.018	0.018	0.012	0.015					
Al	0.135	0.154	0.130	0.146	0.147	0.004	0.012	0.003	0.020	0.006
Fe^{3+}	0.253	0.273	0.252	0.266	0.256	1.070	1.065	1.019	1.037	1.056
Mn						0.052	0.061	0.048	0.048	0.047
Mg						0.001	0.004	0.000	0.001	0.001
Ca	3.932	3.895	3.874	3.909	3.850					
Na	0.008	0.009	0.013	0.009						
X'Usp						0.36	0.36	0.47	0.44	0.41

The analyses conducted on representative alkali feldspar in all the lavas reveal sanidine ($Or_{37.3–48.7}Ab_{62.0–50.7}$) and anorthose ($Or_{25.0–34.4}Ab_{74.4–64.2}$) in composition, as shown in Figure 3 and presented in Table 3. Albite phenocrysts (analyses not shown) also occur in some peralkaline phonolites. The Al_2O_3 content is around 20 wt% in all the feldspar crystals analysed. The mean of $Na_2O + K_2O$ content is 13.0 wt%.

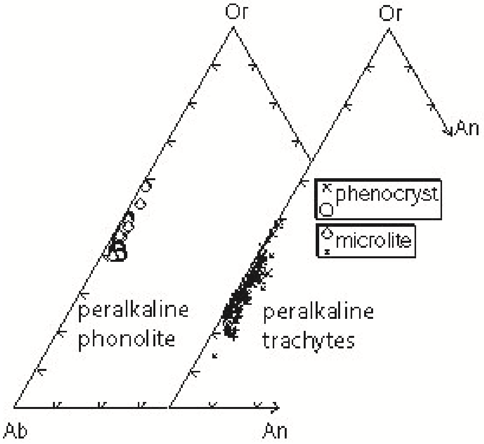


Fig. 3 Feldspar chemical composition ploted in Or–Ab–An diagram of peralkaline felsic Miocene lavas from Ngaoundéré.

The nepheline composition (Table 3) ranges between $Ne_{66.7–79.1}$ $Ks_{22.3–14.8}$ $Qz_{6.1–11.0}$. The average Na_2O content is 16.5 wt%, while SiO_2, K_2O and recalculated Fe_2O_3 contents are high (up to 50.0, 3.6 and 1.9 wt%, respec-tively). The Al_2O_3 content is up to 33 wt%. The crystallization temperature of nepheline is higher than 700°C (estimated in agreement with Hamilton, 1961). Petrographic observa-tions indicate that nepheline crystallized as a primary phase.

The minerals of the Haüyne group are markedly heterogeneously nosean in composition, with SO_3 contents between 7.0 and 10.1wt %, the lowest value being recorded in light cores and rims (Table 3). The Al_2O_3 and $Na_2O + K_2O$ contents range between 27.0–30.2 wt% and 20.2–25.2 wt%, respectively. In anticipation, more phenocrysts are euhedral, indicating their crystallization as primary phase (Wooley and Platt, 1988). Dark-grey crystals with a light rim are distinguished from light-grey ones with a dark-grey rim. Dark rims contain numerous pyrite microcrystals.

In advance, the noseane + nepheline + sanidine association indicates low crystallization pressures (0.16 < P GPa < 0.28, estimated according with Wellman, 1970).

Titanite (Table 4) phenocrysts, micro-phenocrysts and microlites occur in all the lavas (TiO_2: 32.0–33.3, and CaO: 25.0–26.4 wt %), and are sometimes as abundant as 10 % of the total volume in peralkaline phonolite. Zr (4928.6–8143.0 ppm) and Nb (4223.0–6824.6 ppm) contents are high at Ngao Makan (NG9). Zr/Nb ratios are lower than 2.0.

Ti-magnetite (TiO_2: 12.0–16.4 wt%, recalculated Fe_2O_3 between 78.0 and 81.3 wt%; Table 4) is present as microcrysts in all the lavas. MnO contents are up to 4.3 wt%.

Apatite is present in peralkaline phonolite as fluoroapatite (CaO: 53.45-53.50 wt%, and P_2O_5: 39.44-39.74 wt%), with F contents of up to 3.5 wt%.

Geochemistry

Whole-rock chemistry and isotopic analyses of all the lavas with surrounding dioritic basement rock are presented in Table 5. Four main oxides constitute more than 90 wt% of the major elements: SiO_2 (56.0–62.6 wt%), Al_2O_3 (16.8–22.4 wt%), with ($Na_2O + K_2O$) between 12.7 and 15.7 wt% (the higher value being recorded in peralkaline phonolite). Apart from Fe_2O_3, which is up to 4.4 wt%, early fractionated oxides remain low (< 2.0 wt%).

Transition element contents (Ni, Cr, V and Co) are usually below the analytical detection limit. Rb and Cs are very high in peralkaline trachytes (Rb = 350 ppm; Cs = 4.55 ppm). Sr and Ba contents are low in all the lavas, while contents of Be and incompatible elements (Th, U, Nb, Ta, Pb, Hf, Zr) are high in peralkaline trachytes. The highest Zr (2004 ppm) and Nb (725 ppm) contents are found in peralkaline trachytes. Zr/Hf ratios vary widely between 38.3 and 57.4, while the Nb/Ta ratio ranges between 13.7 and 25.1, as indicated by their patterns.

As a typical feature of the alkaline lavas series worldwide, REE normalized patterns (Fig. 4a, normalization values after McDonough and Sun, 1995) exhibit a regular decrease from La to Lu, with significant enrichment of LREE (100 to 300 times the chondritic normalized values) and tend towards flat heavy REE. Lavas are characterized by concave-downward REE patterns, particularly for peralkaline phonolite NG9, which is also characterized by the lack of elementary anomalies and lower REE abundances, as depicted in Figure 4a. In addition, this lava is characterized by an increasing depletion in MREE. Peralkaline trachytes (particularly NG20) have high REE contents and a noteworthy Eu anomaly (Eu/Eu* as low as 0.6). $(La/Yb)_N$ ratios vary between 13.6 and 22.5.

Table 5 Whole rock geochemistry of peralkline felsic lavas and basement rock from Ngaoundéré

Lavas	Peralkaline phonolite	Peralkaline trachyte			Diorite
Samples	NG9	NG18	NG20	NG25	SI
		Oxides (wt%)			
SiO_2	56.01	60.63	62.58	61.70	53.47
TiO_2	0.30	0.29	0.19	0.23	1.01
Al_2O_3	22.43	18.19	16.75	18.07	17.87
Fe_2O_3	2.13	3.86	4.43	3.74	7.98
MnO	0.18	0.42	0.57	0.37	0.13
MgO	0.09	0.22	0.03	0.18	3.83
CaO	0.72	1.17	1.02	0.92	7.09
Na_2O	10.16	7.38	7.71	8.04	4.17
K_2O	5.66	5.25	4.76	4.95	2.15
P_2O_5	0.08	0.05	0.05	0.05	0.35
LOI	1.39	1.62	1.48	1.28	1.22
Sum	99.14	99.08	99.57	99.53	99.25
D.I.	93.1	87.9	90.1	90.7	48.0
P. I.	1.0	1.0	1.1	1.0	0.5
		Cations (ppm)			
Be	7.0	9.3	19.0	11.6	2.9
Rb	240	210	350	240	64
Sr	201	45	31	28	755
Cs	2.25	1.57	4.45	1.51	2.19
Ba	140	133	15	20	747
V	11				161
Cr	< L.D.				41.6
Co	0.4	0.3	0.2	0.2	21.7
Ni	< L.D.				22.8
Cu	< L.D.				17
Zn	141	245	406	253	97
Y	17.6	75.1	137.5	69.7	20.3
Zr	1,244	1,307	2,004	1,358	175
Nb	172	347	725	419	10
Hf	21.7	32.1	52.4	33.9	4.4
Ta	6.88	25.16	50.51	30.47	0.59
Th	28.19	34.66	85.86	42.09	1.77
U	11.57	9.27	21.29	11.50	0.83

Lavas	Peralkaline phonolite	Peralkaline trachyte			Diorite
Samples	NG9	NG18	NG20	NG25	SI
La	57.4	239.7	249.8	201.2	27.7
Ce	88	426	524	371	61
Pr	7.7	39.6	53.5	34.6	8.0
Nd	22	133	189	115	33
Sm	3.3	19.8	32.1	17.7	6.5
Eu	0.94	3.01	3.38	2.19	1.71
Gd	2.63	14.20	23.49	13.03	4.99
Tb	0.436	2.239	3.851	2.089	0.705
Dy	2.79	12.64	22.37	12.01	3.86
Ho	0.58	2.44	4.29	2.29	0.70
Er	1.85	7.02	12.29	6.72	1.92
Tm	0.33	1.07	1.89	1.05	0.28
Yb	2.56	7.24	12.46	7.14	1.82
Lu	0.44	1.10	1.82	1.09	0.29
$^{87}Sr/^{86}Sr$	0.703614	0.706072	0.710526		0.706886
$^{143}Nd/^{144}Nd$	0.512826	0.512742	0.512754		0.512312
$^{206}Pb/^{204}Pb$	20.2353	19.038	19.2958		17.8948

In spider diagrams (Fig. 4b), patterns are similar to typical OIB, with positive Nb–Ta and negative Ba, K, Sr, and Ti anomalies. They are also characterized by positive anomalies in the case of Zr and Hf. Peralkaline phonolite is marked by slightly negative Nb and Ta anomalies.

Strontium, Nd and Pb isotopic ratios have been measured for the selected lavas (peralkaline phonolite and trachyte) and in the Ngaoundéré basement rock (Tab. 5). Initial isotopic compositions (Sr_i) have been recalculated for 9 Ma. The isotopic ratios of peralkaline phonolite are within the 0.703390 (± 0.000009) range. Peralkaline trachytes NG18 and NG20 have distinct highest values: 0.706072 (± 0.000009) and 0.710526 (± 0.000008), respectively.

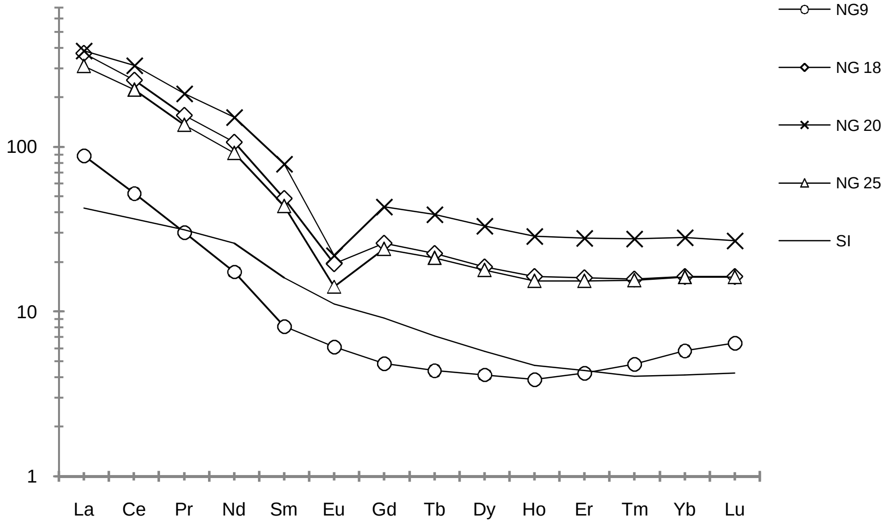
The peralkaline felsic lavas of Ngaoundéré exhibit a slight difference in the case of Pb and Nd isotopes, compared to those erupted along the Cameroon Line (Halliday et al., 1988). Peralkaline phonolite with a low $^{87}Sr/^{86}Sr$ isotope value has the highest $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ values, compared to peralkaline trachytes NG18 and NG20 (see Table 3), which are more radiogenic in the $^{87}Sr/^{86}Sr$ isotope, close to diorite sample S1 from the neighbouring Pan-African basement.

The comparison of regional variations (Halliday et al., 1990; Lee et al., 1994; Yokoyama et al., 2006) shows that the isotopic compositions of the Ngaoundéré peralkaline felsic lavas display slightly different values. For example, Pb ratios ($^{206}Pb/^{204}Pb$: 19.04–20.24) are intermediate between those from volcanoes located near the continent-ocean boundary (Bioko, Mt. Etinde and Mt. Cameroon: $^{206}Pb/^{204}Pb$= 20.52) and that of continental volcanoes (e.g. Pagalù, the southernmost island: $^{206}Pb/^{204}Pb$= 19.01).

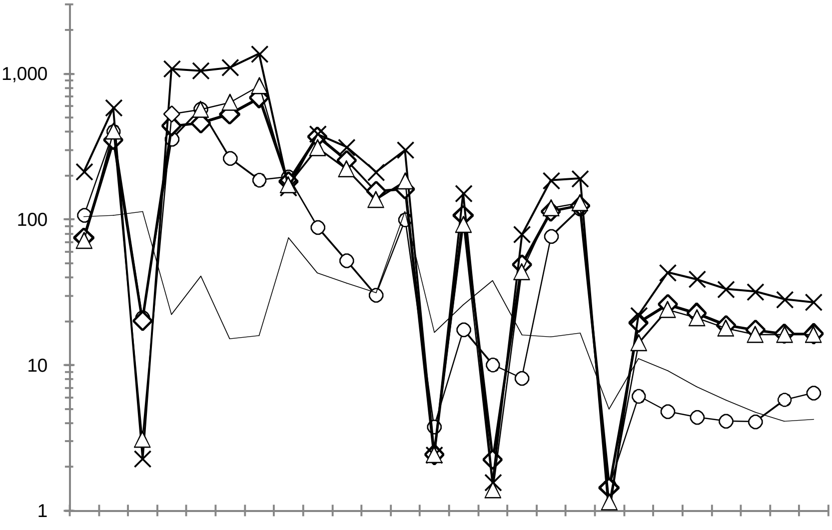
Discussions

Petrogenesis and geochronology of the felsic lavas from Ngaoundéré

There is no doubt that the occurrence of basaltic and felsic lavas side by side in the area, as well as the presence of fragments of basaltic glasses in the felsic lavas, are solid field arguments, which clearly suggest a genetic relationship between the lavas.



(a)



(b)

Fig. 4 Normalized REE (a) and multi-element patterns (b) to primitive mantle (after McDonough and Sun, 1995) of peralkaline phonolite (NG9), trachytes (NG20, NG25 and NG18) and diorite basement rock (SI).

This plausible genetic relationship has previously been modelled by Nkouandou et al. (2008) when discussing the petrogenesis of the Mio-Pliocene lava series of the Adamawa region. It was, thus, suggested that the felsic lavas derived from basaltic ones through fractional crystallization processes, in spite of the compositional gap between felsic and basaltic lavas. New K–Ar dating of volcanic rocks of the North and East of Ngaoundéré challenge this assumption, as the former are older (8.3 to 11.0 Ma) than the latter (7.8 Ma). Regarding the petrographic study, the modal mineralogical composition is mainly dominated by alkali feldspar (up to more than 70% of the total volume), nosean and nepheline (in phonolite), augite, aegirine-augite and aegirine phases, which are believed to occur in the late differentiated lavas of the alkaline magmatic series, as indicated by the temperature and pressure present during the crystallization of these minerals.

Geochronological data, as well as the existing compositional gap between basaltic and felsic lavas, raise the question of the origin of the peralkaline felsic lavas from Ngaoundéré volcanism. Three main hypotheses may be suggested in this respect: (1) Ngaoundéré peralkaline felsic lavas may represent the primary melt of the local basement rock or the (2) end-product of the fractional crystallization process of the primitive mantle melt, as previously believed. As alternative hypothesis, the peralkaline felsic lavas of the Adamawa volcanic province may be the result of the (3) late combination of the complexing and transport of the volatile fluids phase with fractional crystallization. The petrogenetic implication of crustal anatexis (first proposal) encounters difficulties in explaining the process of generation of peralkaline melts from the crustal lithologies of the Ngaoundéré basement rocks, which are metaluminous or peraluminous (Tchameni et al., 2006; Ganwa et al., 2008); it also lacks experimental verification. In addition, the high $(La/Yb)_N$ values suggest the low-degree partial melting of the mantle source, situated at more than 80 km, as suggested by the low content of heavy REE, indicating the presence of residual garnet in the parental mantle source. Positive Nb and Ta anomalies in the pattern of trace elements point against crustal source melting. Thus, the peralkaline felsic lavas of Ngaoundéré may be regarded as the products of the differentiation process of the surrounding basaltic lavas, generated within the spinel-peridotite stability field of the FOZO type component, at depths below 90 km, in the lithospheric mantle source, as previously suggested by Nkouandou et al. (2010). The very low contents of early fractionated transional elements (Ni, Co and Cr), the high contents of incompatible elements (Zr, Nb, LREE etc.), together with the continuous chemical variation of the clinopyroxene phases, strongly support this hypothesis. However, the contamination effect of peralkaline trachyte (NG20 and NG18) is relevant, as proven below. From a geochronological point of view, we simply suggest that the analysed basalt has probably been sampled from the basaltic lavas of the upper flow unit, which certainly erupted after the construction of the felsic lava domes.

Taking into consideration the isotopic data available on the lavas, peralkaline phonolite NG9, with a (Sr_i) value of approximately 0.703, is of mantle origin, as this value is isotopically similar to those of the basaltic and felsic lavas from the Cameroon Volcanic Line (Lee et al., 1996; Marzoli et al., 2000; Wandji et al., 2008; Kamgan et al., 2010; Déruelle et al., 2007) and the Adamawa plateau (Nkouandou et al., 2010), which are already regarded as mantle products. Among the Sr, Nd and Pb isotopes, only Sr isotopes suggest a possible contamination of peralkaline trachytes by crustal materials or fluid (Macdonald, 1987; Cousens et al., 1993). Peralkaline trachyte NG18, with a Sr_i value of 0.706, close to that of Ngaoundéré basement rock (represented here by sample SI), might suggest a crustal contamination/assimilation process involving SI as the protolith. Peralkaline trachyte NG20, with a higher Sr_i value (0.710), might have undergone a complex petrogenetic process, with (1) the involvement of other crustal contaminating materials, different in composition from SI, or even (2) a primary melt of the crustal region with such a Sr_i composition. These suggestions are strongly supported by the occurrence of fragments of country rocks of different compositions (granulites and gneiss), which are potential protoliths for partial melting. An alternative hypothesis for the genesis of peralkaline trachyte NG20 is an addition to crustal contamination materials of a volatile fluids phase, through complexing and transport, as previously suggested by Ren et al. (2006) for the peralkaline trachytes and pantellerites of the Eburru volcanic complex. This suggestion is the potential solution when trying to explain the high Sr_i value of peralkaline trachytes, particularly NG20, as only the Sr_i isotopes suggest the contamination process undergone by those lavas. Thus, peralkaline felsic lavas, particularly peralkaline trachyte NG20, have been generated through the differentiation process of the associated basaltic lavas, by fractional crystallization, and have been contaminated by the country basement rock, coupled with the effect of Sr (?)-enriched fluid, as indicated by their high LREE content (more than 300 times the chondritic normalized values), HFSE (e.g. Zr, Nb, Hf.), and alkali contents (Leat and McDonald, 1984; Bohrson and Reid, 1997; Balcone-Boissard et al., 2009).

Crustal contamination model and peralkalinity of felsic lavas

AFC modelling (after De Paolo, 1981), using partition coefficients from Mahood and Stimac (1990) and a Pan-African gneiss country rock (sample SI: Sr = 112 ppm; $(^{87}Sr/^{86}Sr)_{9Ma} = 0.749$) as a contaminant, was also intended. The differentiation of peralkaline trachyte NG18 (0.706072 ± 0.000009) and peralkaline trachyte NG20 (0.710526 ± 0.000008) from the less-evolved lavas requires a Ma/Mc ratio of 0.1 and a fractionation process ($F \approx 0.9$), involving only feldspar so as to comply with the $(^{87}Sr/^{86}Sr)_{9Ma}$ values ($\approx$ 0.710) of the considered lavas. Nkouandou et al. (2008) show that major and trace elements of felsic lavas point to their origin as results of fractional crystallization processes, in spite of the occurrence of a compositional gap, which may be explained by the lack of eruption of lavas of intermediate composition (Bonnefois et al., 1995) or by the high viscosity of the crystal-rich intermediate magmas (Mungall and Martin, 1995). The pronounced Eu anomalies of peralkaline trachytes suggest the strong implication of alkali feldspar in the petrogenetic processes of those lavas, as do the Ba, Sr and Zr contents. The implication of feldspar is also supported by petrographic evidence, as more than 70% of the volume of these lavas consists of sanidine and anorthose. The contamination of lavas by crustal material is difficult to establish using data related to trace elements, as Nb and Ta, which are compatible in crustal rocks, display positive anomalies. Thus, contamination remains selective.

The modal abundance of alkali feldspar (70% of the volume of trachyte lavas) is required to assess the peralkalinity of lavas. As the peralkalinity of lavas is expressed by the ratio (> 1) of $(Na_2O + K_2O)/ Al_2O_3$, the continued crystallization of alkali feldspars, which fractionate more than 20 %wt of Al_2O_3, remains the best explanation for the peralkaline character of those lavas. This model assumes that increased fractionation of Al_2O_3, coupled with increasing $(Na_2O + K_2O)$ during differentiation, leads to strongly peralkaline residual liquids, as previously proven (Markl et al., 2001; Macdonald and Scaillet, 2006; Ren et al., 2006). Thus, the peralkaline character of Ngaoundéré felsic lavas is linked to the strong fractionation of alkali feldspar and feldspatoid (in peralkaline phonolite), which are highly aluminous and the most abundant phenocryst fractionating phase of all the lavas. However, the lack of an Eu anomaly in the REE patterns (Fig. 4) of peralkaline phonolite NG9, as well as their high Sr (201), Ba (140) and alkali ($Na_2O + K_2O$ = 16 wt%) contents, compared to peralkaline trachyte lavas (see Table 4), contradicts the idea of only metaluminous minerals (alkali feldspar, nosean and nepheline) being involved in the lava genesis processes, as those phases might have played only a minor role. These Sr, Ba and alkali contents of Ngaoundéré felsic lavas may be the evidence of the major role played by hydrothermal fluids (White and Patchett, 1984; McCulloch and Gamble, 1990). As previously noted, the plug and domes occasionally display a strong parallel orientation to the N70E Pan-African direction. Those faults are the possible pathways for alkali metasomatized hydrothermal fluids, which may have contributed significantly to the alkali enrichment of Ngaoundéré felsic lavas. Such hydrothermal event have been noticed in at the Kitongo region, northern Cameroon (Kouske et al., 2012). However, the rapid crystallization of those minerals, and the additional fluid effect, as previously noticed at Mt. Vulture (Italy), where dark rims of minerals from the sodalite group (as nosean in peralkaline phonolite NG9), containing numerous pyrite microcrysts, have been interpreted as the result of a rapid crystallization driven by the exsolution of an S-scavenging fluid phase (Di Muro et al., 2004), may have limited the Eu, Sr and Ba fractionation in this phonolite. Therefore, the peralkalinity of phonolite NG9 is the result of the rapid crystallization of alkali feldspar, sodalite and nepheline, with the additional effect of alkali-enriched fluids. In this respect, the crystallization of Na-clinopyroxene, nepheline and nosean is the result of a continuous alkali enrichment of residual liquid, after more fractionation of the Al_2O_3 component over (Na_2O + K_2O) and volatile fluid (SO_3 up to 10 wt%, Cl up to 0.8 wt% in nosean and F up to 3.5 wt% in apatite). In addition, peralkaline phonolite NG9 is characterized by Sr, Nd and Pb isotopes which exclude any crustal contamination. Among the felsic lavas of the Ngaoundéré series, this lava is particularly depleted in MREE, resulting in a spectacular spoon-shaped pattern (Fig. 4). It contains kaersutite, apatite and particularly abundant titanite phenocrysts (11 % of the volume) which are characterized by high partition distribution coefficients for MREE (Green, 1994; Worner et al., 1983). Slightly depleted Nb and Ta in the spider-like NG9 pattern may be due particularly to titanite crystallization, as this phase is characterized by high Kd values for these elements (Kd_{Nb}= 5, 7 and KD_{Ta}= 15, 5; Green and Pearson, 1987), instead of crustal contamination. Thus, we conclude that the crystallization of those phases is responsible for the slightly depleted Nb and Ta in the multi-element NG9 pattern and its downward MREE patterns. Such spoon-shape patterns also characterize the felsic lavas of the Tchabal Nganha volcano in the Adamawa plateau (Nono et al., 1994; John et al., 2011), northern Cameroon Line (Ngounouno et al., 2003), as well as those on the Fernando de Noronha Island in South Atlantic Ocean (Weaver, 1990).

Conclusions

Field studies, in combination with petrology and geochronology, show that the peralkaline felsic lavas from the Ngaoundéré region represent the final products of the differentiation of the surrounding basaltic lavas through fractional crystallization. Peralkaline trachytes have been contaminated by the basement rock of dioritic composition, coupled with the additional effects of a Sr(?)-enriched fluid phase. Peralkaline phonolite, which is characterized by a low Sr (0.703) isotope, is, however, an exception. The contamination effects remain selective, as it is only evidenced by Sr isotopes. The peralkalinity of felsic Ngaoundéré lavas is clearly due to the pronounced crystallization of aluminous phases (e.g. alkali feldspar in trachyte and alkali feldspar, plus nepheline and nosean, in phonolite), with additional alkali-enriched hydrothermal fluid phases, which have acted through the Pan-African network faults, cutting the basement rocks of the Adamaoua plateau. Thus, the crystallization of enriched Na-phases (aegirine-augite, augite and feldspathoïd) is the result of a continuous enrichment in alkali of residual liquid after the increased fractionation of the Al_2O_3 component over (Na_2O + K_2O), in addition to fluid phase effects. The spoon-shaped patterns of the lavas, particularly phonolite NG9, are due to the crystallization of titanite and amphibole, which preferentially incorporate MREE with Nb and Ta (in titanite).

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