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Original paper

Petrology of spinel lherzolite xenoliths and host basaltic lava from Ngao Voglar volcano, Adamawa Massif (Cameroon Volcanic Line, West Africa): equilibrium conditions and mantle characteristics

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Spinel-bearing lherzolite xenoliths have been recovered from Mio–Pliocene alkaline basalt flows of the Ngao Voglar volcano, 35 km northwest of Ngaoundere in the Adamawa volcanic Massif (Cameroon). They have been examined to characterize the petrography, mineralogical composition, and equilibrium conditions of the upper mantle beneath the Ngaoundere region. The xenoliths exhibit protogranular textures and consist of four main minerals: olivine ($Fo_{89–90}$), Mg-enstatite ($En_{89–91}Wo_1Fs_{8–10}$), Cr-diopside ($En_{49–52}Wo_{44–49}Fs_{1.5–5}$) and spinel (Mg# ~79.2, Cr# ~10.7). Thermobarometric calculations show equilibrium temperatures ranging between 850 and 950 °C and pressures of 8 to 17 kbar consistent with the spinel lherzolite stability field. These data suggest that the xenoliths come from a depth of 28–31km in the uppermost mantle situated just below a thinned crust; they are in agreement with the geophysical data previously determined in the Adamawa Massif. On the basis of these features, and considering the evidence for textural, mineralogical, and chemical equilibrium in the studied xenoliths prior to their entrainment in the host magma, we conclude that the source of these xenoliths was a chemically and petrographically homogeneous, spinel lherzolite lithospheric mantle. But the occurrence of mantle-derived xenoliths of various types (dunite, lherzolite, wehrlite, harzburgite, websterite, clinopyroxenite, and orthopyroxenite) in alkali basalts from many other localities of Cameroon (Oku Massif, Lake Nyos area and Mount Cameroon) is consistent with upper-mantle heterogeneities on a regional scale and implies that the nature of the upper mantle beneath the continental sector of the Cameroon Volcanic Line varies under its different volcanic centres.

Keywords: Cameroon Volcanic Line, Adamawa Massif, Ngaoundere region, Ngao Voglar volcano, lithospheric mantle, spinel-bearing lherzolite xenoliths
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1. Introduction

The internal structure of the Earth's mantle and its composition are classically deduced from seismic or gravity studies or from petrographic and geochemical studies, either of ultramafic orogenic massifs or of ultramafic xenoliths sampled by basaltic magmas on their way to the surface, during volcanic eruptions. The Adamawa Massif constitutes the eastern branch of the Y-shaped Cameroon Volcanic Line (Fig. 1), a N30°E tectonomagmatic structure in both oceanic and continental lithosphere, which stretches for more than 1600 km, reaching a width of up to 100 km. It extends from Pagalu Island, in the Gulf of Guinea, to Lake Chad in the interior of Africa (Fitton 1980; Déruelle et al. 2007). Only Mount Cameroon volcano, which is located at the boundary of the continental and oceanic sectors of this west African thermal structure, is still magmatically active (Fitton et al. 1983; Suh et al. 2003).

Seismic, gravity and petrological studies on the Adamawa Massif (Browne and Fairhead 1983; Girod et al. 1984; Dautria and Girod 1986; Fairhead and Okereke 1988; Poudjom Djomani et al. 1992, 1997) suggest the existence of the following features: (i) a crust uplifted by the upward migration of the lithosphere–asthenosphere boundary, (ii) an abnormally hot upwelling upper mantle located at the depth of 70–90 km (Dorbath et al. 1986), and (iii), two broad negative gravity anomalies (–80 to –100 and –120 mGal/cm), attributable to lithospheric (40 km) and crustal (20 km) thinning respectively (Poudjom Djomani et al. 1997). Upper-mantle xenoliths were found in basaltic lavas from several localities along the Cameroon Volcanic Line: São Tomé (Caldeira and Munhá 2002), Bioko and Palagu (Matsukage and Oya 2010), Biu Plateau, Lake Enep and Lake Mbarombi (Lee et al. 1996), Lake Nyos area (Temdjim et al. 2004a; Touret et al. 2010), and Mount Cameroon (Ngounouno and Déruelle 2007; Wandji et al. 2009).

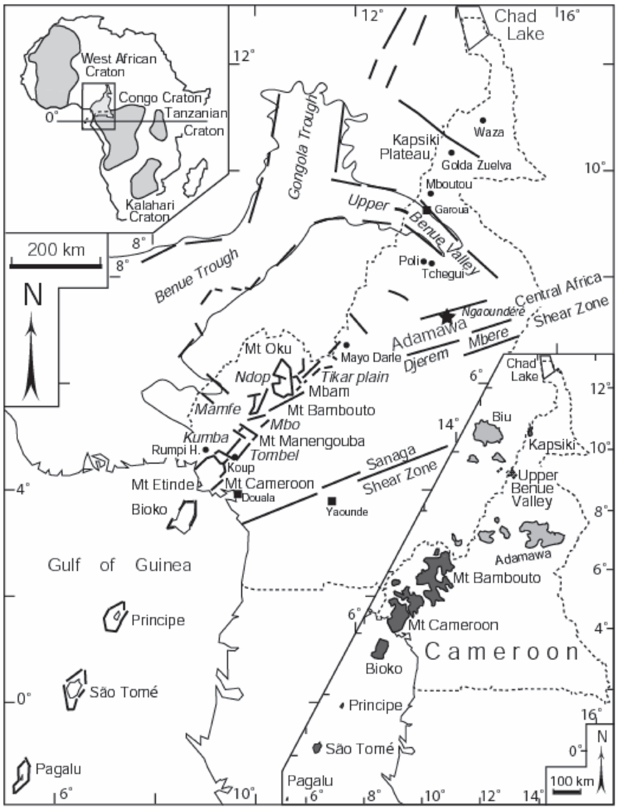

Fig. 1 Geological setting of the Cameroon Volcanic Line (after Déruelle et al. 2007, modified). *Upper inset:* relationships between the Cameroon Volcanic Line and African cratons (Kampunzu and Popoff 1991). *Lower inset:* the major Cenozoic ring-complexes and volcanic centres of the Cameroon Volcanic Line (in black) which splits into two branches in a Y-shape: one branch runs northward to the Biu Plateau while the other continues eastward through the Adamawa Massif (both in grey). *Main map:* The black dots denote anorogenic ring-complexes and the black star the location of the Ngaoundere area including the Ngao Voglar volcano, in the Adamawa volcanic Massif. Names of grabens are shown in italics.

These varied ultramafic xenoliths are an important source of direct information about the textural features and chemical evolution of the upper mantle beneath different regions of the Cameroon Volcanic Line. However, beneath the volcanoes of the Adamawa Massif, which is domally uplifted, there are few available data aside from peridotite nodules described from the Dibi area (Girod et al. 1984; Dautria and Girod 1986) and Youkou maar (Temdjim 2005), located 35 km SE and 5 km ESE of Ngaoundere, respectively.

This paper is focused on the petrography and mineral chemistry of spinel-bearing lherzolite xenoliths and their host basaltic lava from the Ngao Voglar volcano, a newly discovered locality of mantle-derived xenoliths located 35 km NW of Ngaoundere (Fig. 2), in the Adamawa volcanic Massif (Fig. 1). The main aims are to estimate the equilibrium pressure and temperature of the xenoliths, to improve our knowledge of the state of the sub-continental mantle beneath this segment of the Cameroon Volcanic Line, and to compare the nature of the host basaltic lava with the neighbouring ones.

2. Geological setting

The Adamawa volcanic Massif is a morphostructural unit of uplift bounded to the North and South by large N70°E strike-slip faults (Adamawa and Djerem-Mbéré faults; Moreau et al. 1987), which have been active since the Cretaceous. It belongs to the Cameroon Volcanic Line, a tectono-magmatic structure which consists of oceanic and continental sectors. The continental sector is composed of anorogenic ring-complexes and volcanoes set within a succession of horsts and grabens (Fig. 1). The Adamawa basement rocks consist of Pan-African granitoids, which were intensively deformed and metamorphosed under amphibolite-facies metamorphic conditions, with Th–U–Pb ages of 615 ± 27 Ma to 575 ± 27 Ma (Tchameni et al. 2006). These rocks are partially covered by Oligocene to Pleistocene basaltic lava flows of alkaline to peralkaline composition (Nono et al. 1994; Itiga et al. 2004; Temdjim et al. 2004b; Nkouandou et al. 2008). Low degrees of partial melting (1 to 2 %) of a FOZO-type mantle, leaving residual garnet, took place at a depth of 80 km (Nkouandou et al. 2008) and produced alkaline basalts in the Ngaoundere region (Fig. 2) during the Mio–Pliocene (7.8 ± 1.4 Ma). These lavas entrained numerous mantle xenoliths, ranging from 3 to 10 cm in size, including those of this study.

3. Analytical methods

The modal compositions of nine peridotite xenoliths (Tab. 1) and one host basaltic lava have been estimated using a Scanning Electron Microscope (SEM) in the Laboratoire de Magmatologie et de Géochimie Inorganique et Expérimentale (MAGIE), Université Pierre et Marie Curie, Paris. Electron microprobe analyses of major elements (Si, Ti, Al, Cr, Fe, Mn, Mg, Ni, Na, K and P) in minerals from two representative xenoliths and one host lava were carried out with Camebax SX50 and SX100 micro-analysers at the same laboratory. Analytic conditions were 15 kV at 10 to 40 nA and counting times of 10 to 40 s, depending on the element and mineral being analyzed. Nominal concentrations were subsequently corrected using the “PAP” data reduction method (Pouchou and Pichoir 1991). Whole-rock major-element analysis of the host basalt was performed by ICP-AES and trace elements were analysed by ICP-MS at CRPG Nancy (France), following the analytic procedures of Carignan et al. (2001).

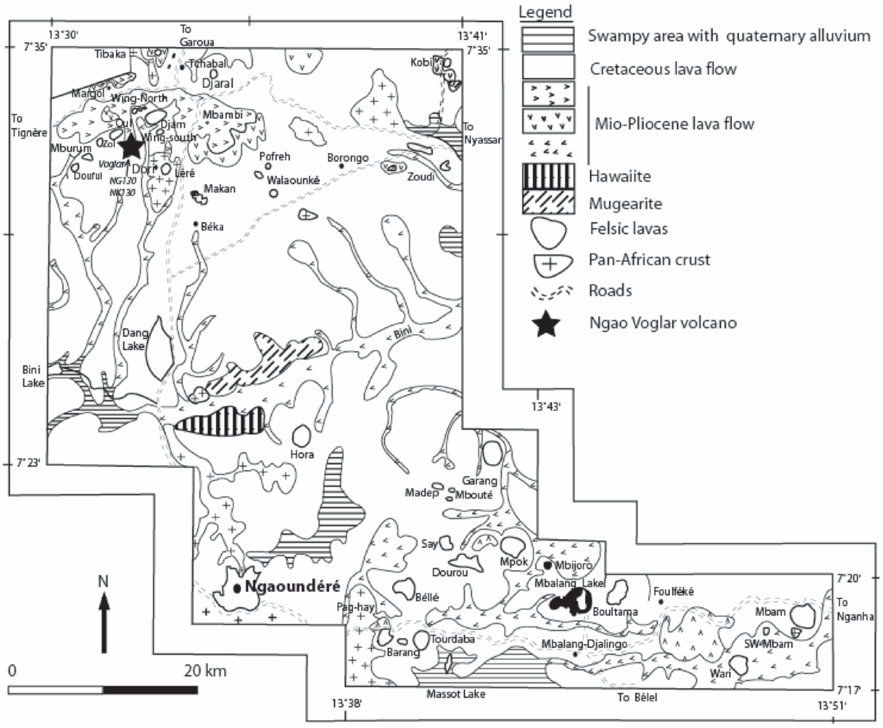

Fig. 2 Geological sketch map of the Ngaoundere area. Location of Ngao Voglar volcano is indicated by the black star (after Nkouandou et al. 2008, modified).

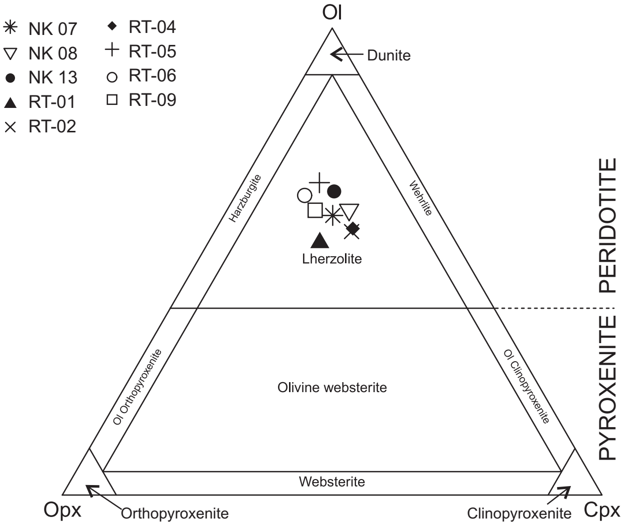

Fig. 3 Modal compositions of Ngao Voglar lherzolite xenoliths in classification diagram for ultramafic rocks after Streckeisen (1976). For underlying data, see Tab. 1.

Tab. 1 Modal compositions of Ngao Voglar spinel lherzolite xenoliths (vol. %)

	Ol	Cpx	Opx	Spl
NK07	58.77	19.81	19.6	1.82
NK08	59.22	21.92	15.83	3.03
NK13	62.72	17.23	16.53	3.52
RT-01	53.89	20.65	25.22	0.24
RT-02	55.83	25.13	18.03	1.01
RT-04	56.85	25.21	17.59	0.35
RT-05	65.52	13.91	18.54	2.03
RT-06	63.33	12.66	22.75	1.26
RT-09	59.75	16.03	22.21	2.01

Modal compositions were determined from images covering the entire area of each thin section. Abbreviations of mineral names are after Kretz (1983).

4. Results

4.1. Petrography

The ultramafic xenoliths exhibit a coarse-grained, granular or protogranular texture (Mercier and Nicolas 1975). They are mainly composed of olivine, orthopyroxene and clinopyroxene, with accessory brown spinel (≤ 4 %). They are spinel-bearing lherzolites (Tab. 1 and Fig. 3), showing sharp contacts with the host basalt and occasionally thin yellow reactions rims, especially around pyroxene crystals.

Olivine crystals (3 to 4 mm, mode ~54–65.5 vol. %) show 120° grain boundaries and a few kink bands. Orthopyroxene crystals are usually elongated. They range from 1 to 3 mm in diameter, with modes of 16 to 25 vol. %. Clinopyroxene (12.6 to 25 vol. %) is often located among orthopyroxene and olivine crystals. They also show polygonal grain boundaries and are 2 to 4 mm across. All the pyroxene crystals are devoid of exsolution lamellae. Pale brown to brownish spinels (1.2 to 2.0 mm in size, < 4 vol. %) are interstitial. No other aluminous phases, such as garnet or plagioclase, or hydrous minerals, have been observed in the examined samples. The modal compositions and textural features suggest that the xenoliths were sampled in the spinel lherzolite zone of the upper mantle under the Ngao Voglar volcano.

The host lava (NG-130) of the studied xenoliths is an alkaline basalt [D.I. (Thornton and Tuttle 1960) = 29.4; Ne_n ~4.2 %] exhibiting porphyritic to glomeroporphyritic texture with a microlitic matrix. It contains large euhedral olivine (1.4 × 2 mm, 17 vol. %), clinopyroxene (2.2 × 2 mm, 15 vol. %), brown amphibole (2.0 × 1.7 mm, 1 vol. %), and Fe–Ti oxide (< 7 vol. %) phenocrysts, as well as plagioclase microlites (< 0.01 mm, 56 vol. %), titanomagnetite (< 0.01mm, 5 vol. %) and ilmenite (0.01 mm, 1 vol. %) in the matrix. Rounded xenocrysts of olivine (1.0 × 0.5 mm, 1 vol. %), orthopyroxene (~1.0 × 0.8 mm, < 1 vol. %), and K-feldspar (3.2 × 2.2 mm, 2 vol. %) are also present, suggesting disequilibrium with the host basaltic magma.

4.2. Mineral chemistry

Representative chemical analyses of mineral phases of two spinel-bearing lherzolite xenoliths (NK13 and RT-06) and one sample of host basaltic lava (NG-130) are shown in Tables 2 and 3.

Tab. 2 Representative electron microprobe analyses (wt. %) for mineral phases of spinel lherzolite xenoliths from Ngao Voglar volcano

Mineral	Olivine				Orthopyroxene			Clinopyroxene				Spinel	
Sample	NK13		RT-06		NK13	RT-06		NK13	RT-06			NK13	RT-06
Grain	Ol-1	Ol-1b	Ol-2	Ol-2b	Opx-1	Opx-2	Opx-3	Cpx-1	Cpx-2	Cpx-3	Cpx-4	Spl-1	Spl-2
SiO_2	40.06	39.99	40.85	40.84	54.79	56.02	55.01	51.68	53.16	52.62	53.25	0.02	0.04
TiO_2					0.12	0.09	0.10	0.54	0.48	0.36	0.49	0.11	0.08
Al_2O_3					3.76	3.85	3.71	6.00	6.27	5.88	6.21	56.63	57.43
Cr_2O_3					0.27	0.16	0.18	0.90	0.66	0.91	0.58	10.14	9.42
FeOt	10.64	10.46	10.06	10.29	6.54	6.62	6.67	2.71	2.85	2.75	2.94	11.53	11.50
MnO	0.2	0.07	0.12	0.09	0.14	0.13	0.09	0.08	0.07	0.03	0.04	0.16	0.13
MgO	48.37	48.5	49.33	49.03	32.95	33.46	33.79	14.94	15.18	15.23	15.32	20.49	21.05
CaO	0.05	0.08	0.03	0.05	0.51	0.48	0.48	20.68	20.80	20.82	20.46		
NiO	0.47	0.44	0.29	0.30								0.31	0.34
Na_2O					0.07	0.08	0.07	1.68	1.81	1.65	1.68		
Total	99.33	99.10	100.72	100.63	99.16	100.97	100.17	99.22	101.35	100.01	101.05	99.39	99.98
Si	0.991	0.99	0.996	0.998	1.911	1.917	1.901	1.881	1.893	1.894	1.902	0.001	0.001
Ti					0.003	0.002	0.003	0.015	0.013	0.010	0.013	0.002	0.002
Al					0.155	0.155	0.151	0.257	0.263	0.250	0.262	1.735	1.742
Cr					0.007	0.004	0.005	0.026	0.019	0.026	0.016	0.208	0.192
Fet	0.220	0.217	0.205	0.210	0.191	0.190	0.193	0.082	0.085	0.083	0.088	0.251	0.247
Mn	0.004	0.001	0.002	0.002	0.004	0.004	0.003	0.002	0.002	0.001	0.001	0.004	0.003
Mg	1.783	1.79	1.793	1.785	1.713	1.707	1.741	0.811	0.806	0.817	0.816	0.794	0.808
Ca	0.001	0.002	0.001	0.001	0.019	0.017	0.018	0.807	0.793	0.803	0.783		
Ni	0.009	0.009	0.006	0.006								0.006	0.007
Na			0.001	0.001	0.005	0.005	0.005	0.119	0.125	0.115	0.116		
Mg#	89.1	89.3	89.8	89.6	90.1	90.1	90.1	90.9	90.6	90.9	90.4	79.2	76.5
Fo	89.2	89.5	89.9	89.6									
Cr#								9.1	6.6	6.5	5.9	10.7	9.9
[Fe^{3+}]												0.024	0.029
En					91.4	89.2	89.2	49.3	51.7	51.8	51.2		
Fs					7.5	9.9	9.9	1.6	3.5	3.3	5.0		
Wo					1.0	0.9	0.9	49.1	44.8	44.9	43.8		

Star denotes recalculated values. See text for definitions of Mg#, Cr# and [Fe^{3+}]. Abbreviations of mineral names are after Kretz (1983).

Tab. 3 Representative electron microprobe analyses (wt. %) of mineral phases of the host basaltic lava and xenocrysts from Ngao Voglar volcano

Sample	Host basalt NG-130						Xenocrysts in NG-130		
Mineral	Ol	Cpx	Pl	Ti-Mt	Ilm	Amp	Kfs	Ol	Opx
SiO_2	39.04	48.65	50.50	0.09	3.91	38.87	63.66	40.15	56.29
TiO_2		2.63		22.36	46.28	5.90			
Al_2O_3		5.30	31.39	1.78	1.76	13.73	21.34		3.77
Cr_2O_3		0.62		0.54	0.04				0.19
FeOt	14.92	5.62	0.57	66.19	39.34	13.78	0.25	9.89	6.66
MnO	0.23	0.11		0.98	0.77	0.25		0.08	0.12
MgO	44.7	14.65		3.80	4.03	10.68		48.46	34.08
CaO	0.11	21.47	12.64	0.27	0.45	10.81	2.30	0.09	0.54
NiO	0.26			0.04	0.10			0.37	
Na_2O		0.54	4.17			2.82	7.93		0.08
K_2O			0.14			1.05	3.16		
BaO						0.04	0.57		
F^-						0.27			
Total	99.26	99.59	99.41	96.05	96.68	98.20	99.21	99.04	101.73
Si	0.990	1.801	9.253	0.003	0.097	5.822	11.467	0.996	1.912
Ti		0.073		0.618	0.860	0.665			
Al		0.231	6.779	0.077	0.051	2.424	4.530		0.151
Cr		0.018		0.016	0.001				0.005
Fet	0.316	0.174	0.087	2.035	0.813	1.726	0.038	0.205	0.189
Mn	0.005	0.003		0.031	0.016	0.032		0.002	0.004
Mg	1.690	0.809		0.208	0.148	2.385		1.792	1.726
Ca	0.003	0.852	2.482	0.011	0.012	1.735	0.444	0.002	0.020
Ni	0.005			0.001	0.002			0.007	
Na		0.039	1.481			0.819	2.770		0.005
K			0.033			0.201	0.726		
Ba						0.002	0.040		
Mg#	84.4	82.4				61.0		89.8	90.1
Fo	84.5							89.8	
Cr#		7.4							
Usp%				62.9					
$[Fe^{3+}]$				0.877					
An			62.0				11.2		
Ab			37.2				70.4		
Or			0.8				18.4		
En		45.8							89.2
Fs		6.0							9.8
Wo		48.2							1.0

Abbreviations of mineral names are after Kretz (1983), except for Ti-Mt (titano-magnetite).

4.2.1. Spinel-bearing lherzolite xenoliths

Olivine is relatively homogeneous, ranging in composition from Fo_{89} to Fo_{90}, with Mg# of 89.1–89.8 [Mg# = 100 × atomic $Mg/(Mg + Fe^{2+})$]. Olivine contains 0.3–0.5 wt. % NiO, less than 0.10 wt. % CaO, and 0.07–0.2 wt. % MnO.

Orthopyroxene corresponds to Mg-enstatite (Mg# = 90.1; $En_{89–91}Wo_1Fs_{8–10}$) (Fig. 4), with low TiO_2 (0.02–0.12 wt. %) and Cr_2O_3 (0.16–0.27 wt. %), as well as high Al_2O_3 (3.71–3.85 wt. %) and CaO (0.48–0.51 wt. %) contents.

Clinopyroxene compositions ($En_{49–52}Wo_{44–49}Fs_{1.5–5}$) fall within the diopside field (Fig. 4). Their TiO_2 contents are below 0.55 wt. %, and those of Al_2O_3 are 5.88–6.27 wt. % (Tab. 2). The Cr# is 5.9–9.14 [Cr# = 100 × atomic Cr/(Cr + Al)]. These compositions are typical of Cr-diopside (Morimoto et al. 1988). The clinopyroxene is characterized by Mg# values of 90.4–90.9, slightly higher than those of coexisting orthopyroxene and olivine. Its Al^{VI}/Al^{IV} ratio varies between 1.167 and 1.673.

Compositions of the silicate minerals in the Ngao Voglar xenoliths are typical of equilibrated Mg-rich

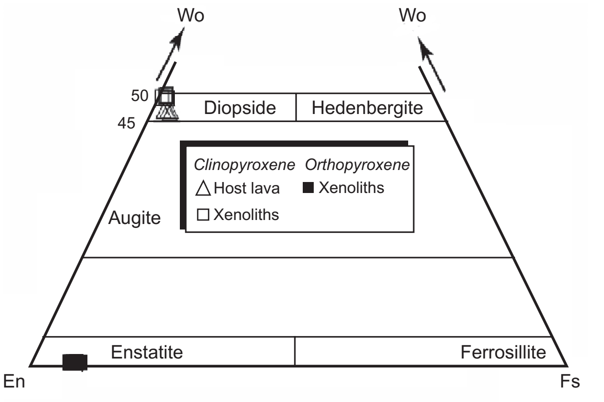

Fig. 4 Chemical compositions of pyroxenes of spinel-bearing lherzolite xenoliths and host basalt from the Ngao Voglar volcano. Diagram after Morimoto et al. (1988).

olivine, Al-rich enstatite and Cr-diopside in the upper mantle. Similar compositions have been recorded in minerals of ultramafic xenoliths from other volcanic centres of the Cameroon (Lee et al. 1996; Princivalle et al. 2000).

Spinel crystals are chemically homogenous, with low TiO_2 (0.08–0.11 wt. %) and high Al_2O_3 (up to 57 wt. %). Their Cr_2O_3 contents vary between 9.42 and 10.14 wt. %, with low Cr# values ranging from 9.9 to 10.7 (Tab. 2; Fig. 6). As calculated by stoichiometry, spinel has very low ratios of [Fe^{3+}], less than 0.03, where [Fe^{3+}] = atomic $Fe^{3+}/(Fe^{3+} + Cr + Al)$. The Mg# values of spinel are high, from 76.5 to 79.2. As Al > Cr and Mg > Fe^{2+}, it is $MgAl_2O_4$-rich spinel (Fig. 6). The distribution of Cr between pyroxene and spinel complies with the relation ($Cr\#_{Spl} > Cr\#_{Cpx} > Cr\#_{Opx}$). The same is true for Al.

4.2.2. Host basalt

Olivine crystals in the host basaltic lava NG-130 have homogenous MgO contents (Fo ~$Mg\#^{Ol}$ = 84.35). NiO (0.26 wt. %) and CaO (0.11 wt. %) concentrations (Tab. 3) are lower and higher, respectively, than those in olivine in the xenoliths (Tab. 2). *Clinopyroxene* phenocrysts are diopside ($Wo_{48}En_{45}Fs_{07}$; Fig. 4), with high TiO_2 (2.63 wt. %) and Al_2O_3 (5.30 wt. %) contents, and with lower Mg# values (Mg# = 82.43; Tab. 3) than in xenolith clinopyroxene ($Mg\#^{Cpx}$ = 90.4–90.9). *Plagioclase* is labradorite ($Or_{0.8}Ab_{37.2}An_{62.0}$). The Fe–Ti oxides are *titanomagnetite* (22.36 wt. % TiO_2 and 66.19 wt. % FeO) or *ilmenite* (46.28 wt. % TiO_2 and 39.34 wt. % FeO), with relatively high MgO (3.8–4.03 wt. %) contents (Tab. 3). Brown *amphibole* (5.9 wt. % TiO_2) corresponds to kaersutite (Leake et al. 1997), with Mg# value (= 61) close to that (~64) of the host basalt.

4.2.3. Xenocrysts

Olivine xenocrysts are Mg-enriched, and show Fo contents (Fo ~ Mg# = 89.81; Tab. 3) similar to those in olivine from xenoliths (Fo = 89–90; Tab. 2). Resorbed xenocrysts of orthopyroxene are magnesian enstatite. Their compositions ($En_{89.20}Wo_{1.03}Fs_{9.77}$, Mg# ~90; Tab. 3) fall within the range of those registered in orthopyroxene from mantle xenoliths. Therefore, the rounded xenocrysts of olivine and orthopyroxene may be considered as isolated crystals resulting from disintegration of mantle xenoliths during their transport in the host magma. Alkali feldspar xenocrysts correspond to sodium-rich K-feldspar ($Or_{18.4}Ab_{70.4}An_{11.2}$), probably derived from the granitic basement rocks.

4.3. *Host lava geochemistry*

Whole-rock composition of the basaltic host lava (NG-130) is shown in Tab. 4. Other more

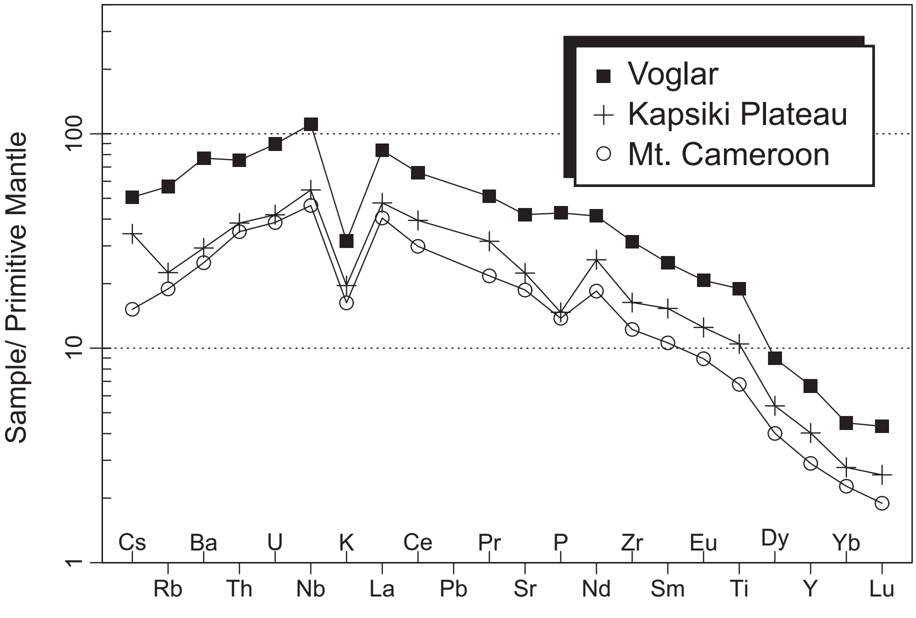

Fig. 5 Primitive mantle-normalized (Sun and McDonough 1989) multi-element diagrams of Ngao Voglar host basaltic lava, Mt Cameroon and Kapsiki Plateau. Samples are the same as in Tab. 4.

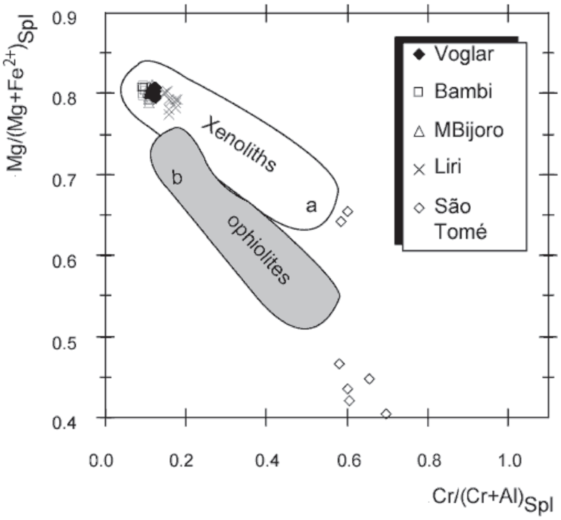

Fig. 6 Mg# vs. Cr# diagram for spinels from Voglar (this study), Bambi, Mbijoro, Liri and São Tomé. a: domain of mantle xenoliths (lherzolites and harzburgites) in basaltic lavas, after Conticelli and Peccerillo (1990). b: domain of mantle rocks in ophiolites, after Cabanes and Mercier (1988b). Data (not published) of Bambi and Mbijoro are available from the authors. Data of Liri (Kapsiki) are from Nguihdama (2007) and those of São Tomé from Caldeira and Munhá (2002).

primitive volcanic rocks are also shown for comparison, namely the basalts S5 from Mount Cameroon volcano (Ngounouno and Déruelle 2007) and C10J from Kapsiki Plateau (Ngounouno et al. 2000), both belonging to the Cameroon Volcanic Line. The chemistry of NG-130 is not significantly affected by the occurrence of xenocrysts, because the modal abundance of these accidental crystals is very low, less than 0.4 %. NG-130 is a sodic alkali basalt (D.I. = 29.4; $Na_2O + K_2O$ = 4.71 wt. %; Ne_n ~ 4.2 % – CIPW norm), with concentrations of MgO (7 wt. %), Ni (50.5 ppm), Cr (79.1 ppm), V (290 ppm) and Co (44.5 ppm) lower than in the two primitive basalts S5 and C10J. Trace-element compositions of these lavas normalized to primitive mantle (Sun and McDonough 1989) are shown in Fig. 5. The Ngao Voglar lava NG-130 also differs from the others by being somewhat more enriched in all trace elements, and all three patterns are subparallel (Fig. 5). It has higher LREE contents than HREE as attested by its normalized ratio $(Ce/Yb)_n$ of ~ 17. As is typical of alkaline lava series worldwide, multi-element patterns in Fig. 5 depict increasing values from Cs to Nb (and Ta) and continuously decreasing values towards Yb and Lu.

Tab. 4 Whole-rock chemical composition of the host basalt (NG-130) compared to other representative data from the continental sector of the Cameroon Volcanic Line

Location	Ngao Voglar	Mt. Cameroon	Kapsiki
Sample	Host lava NG-130	S5	C10J
(wt. %)			
SiO_2	42.21	42.53	45.00
TiO_2	4.11	1.47	2.27
Al_2O_3	14.24	7.09	8.43
Fe_2O_3	14.37	13.48	11.07
MnO	0.20	0.18	0.18
MgO	7.04	25.63	14.46
CaO	10.22	7.66	14.57
Na_2O	3.76	1.41	1.26
K_2O	0.95	0.49	0.59
P_2O_5	0.93	0.30	0.32
LOI	1.93	–0.64	1.87
Total	99.95	99.60	100.02
D.I.	29.4	11.6	11.7
(ppm)			
Rb	36	12	14.3
Sr	885	394	473
Cs	0.40	0.12	0.27
Ba	538	175	205
Be	1.9	0.0	
V	290	184	235
Cr	79.1	1883.0	1304.0
Co	44.5	93.0	57.0
Ni	50.5	784.0	279.0
Cu	32	0	55
Zn	152	0	88
Y	30.4	13.2	18.3
Zr	352	137	183
Nb	79	33	39
Hf	7.7	3.1	4.5
Ta	5.89	2.45	2.88
Th	6.40	2.97	3.26
U	1.88	0.81	0.88
La	57.4	27.8	32.7
Ce	117	53	70
Pr	14.1	6.0	8.7
Nd	56	25	35
Sm	11.1	4.7	6.8
Eu	3.48	1.50	2.10
Gd	9.12	3.21	5.51
Tb	1.244	0.530	0.76
Dy	6.60	2.95	3.97
Ho	1.10	0.51	0.66
Er	2.72	1.07	1.66
Tm	0.36		0.23
Yb	2.21	1.12	1.37
Lu	0.32	0.14	0.19

Data sources: NG-130 (Ngao Voglar volcano – this work), lavas from Mt. Cameroon (S5, Ngounouno and Déruelle 2007) and Kapsiki Plateau (C10J, Ngounouno et al. 2000). LOI: loss on ignition.

4.4. Estimation of equilibrium conditions

The spinel lherzolite xenoliths from Ngao Voglar are in textural equilibrium, and their pyroxenes have not experienced compositional modification, as indicated by the

Tab. 5 Geothermometric estimates of lherzolite xenoliths from Ngao Voglar volcano

Sample	NK13	RT-06
T °C (2-px) BK	907	930
T °C (2-px) BM	852	874
T °C (2-px) T	834	862
T °C (AlCr-in-Opx) WS	896	858
T °C (Ol–Opx–Spl) WS	855	866
T °C (Opx–Spl) SS	905	919
T °C (Ol–Spl) OW	905	919
P_{max} kbar (O81)	17.4 at 850 ºC	17.6 at 900 ºC

References: BK (Brey and Köhler 1990), BM (Bertrand and Mercier 1985), T (Taylor 1998), WS (Witt-Eickschen and Seck 1991), SS (Sachtleben and Seck 1981), OW (O'Neill and Wall 1987), O81 (O'Neill 1981). 2-px: clinopyroxene–orthopyroxene thermometer.

lack of exsolution lamellae (Brearley et al. 1984). The two studied peridotites (NK13 and RT-06) consist of compositionally homogeneous minerals, reflecting their chemical equilibrium. Therefore, crystal core compositions have been used for geothermobarometric calculations. Temperatures and maximum pressures of xenolith equilibration have been determined by applying several currently available and appropriate geothermometers, based on different exchange mechanisms.

4.4.1. Equilibrium temperatures

Equilibrium temperatures for the Ngao Voglar xenoliths were estimated from six geothermometers, including the two-pyroxene geothermometers of Bertrand and Mercier (1985), Brey and Köhler (1990), and Taylor (1998), the orthopyroxene–spinel geothermometer of Sachtleben and Seck (1981), the olivine–spinel geothermometer of O'Neill and Wall (1987), and the Al-in-orthopyroxene geothermometer (Witt-Eickschen and Seek 1991). The results, calculated at a pressure of 15 kbar, are listed in Tab. 5.

(i) The two-pyroxene geothermometers yield temperatures of 834–907 °C for xenolith NK13, and 862–930 °C for xenolith RT-06 (Tab. 5). In general, there is good agreement among the three geothermometers, with the Brey and Köhler method yielding temperatures about 50 ºC higher than the other two methods.

(ii) Witt-Eickschen and Seck (1991) established an empirical geothermometer based on the composition of orthopyroxene in equilibrium with spinel and olivine, for which two formulations were given, one expressed in terms of the Al and Cr contents of orthopyroxene alone (AlCr-in-Opx), and another including the compositions of all three phases (Ol–Opx–Spl). The AlCr-in-Opx formulation yields 896 ºC for sample NK13 and 858 ºC for RT-06, and the Ol–Opx–Spl version yields 855 and 866 ºC (Tab. 5). The two variations of the Witt-Eickschen and Seck (1991) method give similar results, indicating that orthopyroxene, spinel, and olivine were in equilibrium within the upper mantle, shortly before the transport of xenoliths to the Earth's surface.

(iii) An earlier version of the Al-in-orthopyroxene geothermometer, based on the composition of orthopyroxene in equilibrium with spinel and olivine, was formulated by Sachtleben and Seck (1981). For xenoliths NK13 and RT-06, the calculated temperatures are 905 °C and 919 °C, respectively.

(iv) The O'Neill and Wall (1987) geothermometer, which is based on the compositions of coexisting olivine and spinel, yields 905 °C for xenolith NK13 and 919 °C for RT-06. Interestingly, the results obtained from this calibration are exactly the same as those from the orthopyroxene-spinel calibration of Sachtleben and Seck (1981). The results from both calibrations (Sachtleben and Seck 1981; O'Neill and Wall 1987) are also in excellent correspondence with those calculated with the Brey and Köhler (1990) two-pyroxene thermometer (907–932 °C, Tab. 5).

In general, the various geothermometers yield similar results for both Ngao Voglar xenoliths, with sample RT-06 exhibiting slightly higher temperatures than NK13 (Tab. 5). The correspondence among results from the different geothermometers indicates that the coexisting mineral phases were in chemical equilibrium prior to entrainment of the xenoliths in their host magma, and the estimated temperatures can be considered as those prevailing in the source mantle when the xenoliths were sampled. The slight difference in temperatures for samples NK13 and RT-06, 834–907 ºC and 858–930 ºC, respectively, suggests that the two xenoliths were extracted from a narrow range of depth.

Temperatures for the Ngao Voglar xenoliths are within the range of those (700–1200 °C) recorded in mantle xenoliths from other volcanic centres along the Cameroon Volcanic Line (Lee et al. 1996; Caldeira and Munhá 2002; Ngounouno and Déruelle 2007; Wandji et al. 2009; Matsukage and Oya 2010). These equilibrium estimates also fall within the temperature range for other spinel-bearing peridotite xenoliths localities (Brey and Köhler 1990; Glaser et al. 1999; Medaris et al. 1999; Foley et al. 2006). The estimated crystallization temperatures from titanomagnetite–ilmenite pairs (Stormer 1983) of the host basalt (NG-130) are 910 ± 50 °C, which is within the range of temperature (850–930 °C) for the Ngao Voglar spinel lherzolite xenoliths.

4.4.2. Equilibration pressures

At present, there is no direct method for determining pressure in spinel lherzolite xenoliths. Despite use of the Ca-in-olivine barometer (Köhler and Brey 1990) in some investigations, it has been demonstrated that this geobarometer is incorrect, and its application produces spurious results (O'Reilly et al. 1997; Medaris et al. 1999; Christensen et al. 2001).

Ngao Voglar mantle xenoliths are spinel peridotite, containing neither plagioclase nor garnet, and were derived from the spinel stability field in the mantle, which lies in a pressure range of ~8 to ~20 kbar (O'Neill 1981; Gasparik 1987). Although there is no direct method for determining specific pressure in spinel lherzolites at present, a maximum possible pressure can be calculated from the composition of spinel (O'Neill 1981). Such upper pressure constraints for the Ngao Voglar xenoliths are 17.4 kbar at 850 °C for sample NK13 and 17.6 kbar at 900 °C for RT-06. These maximum pressures can be used to determine the depth limit, above which the studied xenoliths could have originated. Accordingly, maximum depths of origin of the Ngao Voglar xenoliths are. 57–58 km, if one uses a conversion factor of 33 km × GPa^{-1}. Such estimated maximum depths are consistent with geophysical (Dorbath et al. 1984; Stuart et al. 1985; Dorbath et al. 1986; Poudjom Djomani et al. 1997) and petrological (Girod et al. 1984; Dautria and Girod 1986) data, indicating that the Moho is situated at a depth of ~23–30 km (7–9 kbar) under the Adamawa volcanic Massif. The position of the Moho and calculated maximum pressures constrain the Ngao Voglar xenoliths to have been derived from depths between ~30 and 58 km (pressures of ~8 and 17 kbar), which lies within the range suggested (8–20 kbar) for other spinel lherzolite xenoliths reported throughout the world (O'Reilly and Griffin 1985; O'Reilly et al. 1997; Xu et al. 1998, Glaser et al. 1999; Medaris et al. 1999; Christensen et al. 2001; Foley et al. 2006).

The estimated pressures and depths are consistent with the existence of a thinned crust (thickness < 30 km) beneath the Ngaoundere Rift situated within the Adamawa region (Browne and Fairhead 1983; Poudjom Djomani et al. 1997). Gravimetric studies have revealed that the thinning of this crust is associated with the well-known Adamawa uplift, which has been related to an anomalously hot body within the uppermost mantle (Gass et al. 1978; Dorbath at al. 1984; Stuart et al. 1985). The inferred hot body has been interpreted as asthenopheric material at shallow depth beneath a lithosphere which has been thinned by the upward migration of the lithosphere–asthenosphere boundary during Tertiary to Recent times (Browne and Fairhead 1983; Noutchogwé-Tatchum 2004). Thus, ultramafic xenoliths from Ngao Voglar represent peridotites sampled from thinned lithospheric mantle, at levels (30–58 km) shallower than those (50–70 km) of xenoliths from other volcanic centres along the Cameroon Volcanic Line (Lee et al. 1996; Caldeira and Munhá 2002; Matsukage and Oya 2010).

5. Discussion and conclusions

Considering the mineral chemistry, the olivine of Ngao Voglar xenoliths has high Fo and NiO concentrations [Fo = $Mg\#^{Ol}$ = 89–90, NiO (0.3–0.5 wt. %)] and low MnO contents (0.07–0.2 wt. %), which are characteristic of olivine of upper mantle origin. Similar compositions for Mg-rich olivine (Fo_{89-90}) have been described at São Tomé Island (Caldeira and Munhá 2002) and other regions of the continental sector of the Cameroon Volcanic Line (Matsukage and Oya 2010). Also, all the resorbed olivine xenocrysts studied in the host lava reflect disequilibrium between melt and xenocrysts. Their Fo, Ni, Ca and Mn contents [~Fo_{90}, NiO = 0.37 wt. %, CaO = 0.09 wt. % and MnO = 0.08 wt. % (Tab. 3)] are similar to those of mantle olivine found in the Ngao Voglar xenoliths (Tab. 2). Therefore, these olivine xenocrysts are interpreted as crystals detached from mantle xenoliths, probably during the magma ascent to the surface.

Orthopyroxene is Mg-enstatite (En_{89-91} with $Mg\#^{Opx}$ ~90) typical of mantle origin (Dick and Bullen 1984). The high ratios of Al^{VI}/Al^{IV} (=1.167–1.673) of coexisting clinopyroxene also provide evidence for a high-pressure mantle environment (Wass 1979; Preß et al. 1986). In other respects, the high values of mg-numbers of clinopyroxenes ($Mg\#^{Cpx}$ = 90.4–90.9) and those of coexisting orthopyroxenes ($Mg\#^{Opx}$ ~90) and olivines ($Mg\#^{Ol}$ ~90) are characteristic of mantle lherzolites (Reid and Woods 1978). The high Mg# values of the coarse spinels ($Mg\#^{Sp}$ = 76.5–79.2) imply that they are in equilibrium with coexisting olivines (Fo_{89-90}), which is supported by the calculated temperatures of 880–966 °C for the two xenoliths.

Spinel crystals exhibit another feature typical of mantle origin with their low TiO_2 contents (0.08–0.11 wt. %) (Sigurdsson and Schilling 1976; Miller and Mogk 1987; Cabanes and Mercier 1988b). The relatively low contents of Fe_2O_3 ($[Fe^{3+}] = (Fe^{3+}/(Fe^{3+} + Cr + Al)] < 0.03$) and Cr_2O_3 ($Cr\#^{Sp}$ = 9.9–10.73) in this spinel are common in lherzolite xenoliths of mantle origin (Witt-Eickschen and Seck 1991; Webb and Wood 1986; Preß et al. 1986), or in slightly depleted mantle rocks considered as the source of basaltic lavas (Reid and Woods 1978). Although the number of investigated Ngao Voglar xenoliths is small, all the above arguments suggest that these xenoliths were extracted from a homogeneous part of the upper mantle, as also indicated by their microtexture, modal compositions and mineral chemistry.

Spinel in xenoliths from other localities along the Cameroon Line, except for São Tomé Island, is similar in composition to that from Ngao Voglar, having Mg# of

77–82 and Cr# of 8–19 (Fig. 6; Lee et al. 1966; Wandji et al. 2009). In contrast, spinel from São Tomé Island, which is located in the oceanic sector of the Cameroon Volcanic Line, has Mg# as low as 40–47 and Cr# as high as 58–70 (Fig. 6; Caldeira and Munhá 2002). The low Cr# (~10) and high Al_2O_3 contents (56.63–57.43 wt. %) of spinel from the Ngao Voglar xenoliths imply a relatively small degree of depletion in the lithospheric mantle in this area.

The small amounts of Fe^{3+} ($[Fe^{3+}] = 0.024–0.029$; Tab. 2) in spinel reflect a relatively low oxidation state of the xenolith source region, i.e. an oxygen fugacity at or ~1/2 log unit below that of the fayalite–magnetite–quartz buffer, and suggest that the xenolith source was little affected by infiltrating melts (or fluids) (Halliday et al. 1990). Elsewhere along the Cameroon Volcanic Line, heating of lithospheric mantle by the emplacement of an upwelling hot plume of deep origin has been recorded in some ultramafic xenoliths (Lee et al. 1996; Caldeira and Munhá 2002). Such a plume may be responsible for the petrological variability and chemical heterogeneity of the upper mantle under much of the Y-shaped Cameroon hot line (Lee et al. 1996; Caldeira and Munhá 2002; Temdjim 2004a, 2005). The emplacement of that hot mantle plume beneath the previous continent–continent boundary between Africa and South America has been related to the opening of the Atlantic Ocean in Mesozoic time (Halliday et al. 1990; Matsukage and Oya 2010).

The Ngao Voglar spinel lherzolite xenoliths were entrained by an alkaline basaltic magma. Their modal compositions, mineral chemistries, and equilibrium conditions suggest that they were derived from a mantle characterized by relative chemical homogeneity. The Ngao Voglar spinel lherzolite xenoliths are devoid of hydrous phases, and their mantle source could have been similar to that under the Kapsiki Plateau (Tamen 1998; Nguihdama 2007) or beneath the Kumba Plain (Teitchou et al. 2007), where ultramafic xenoliths also consist only of anhydrous spinel lherzolites. In contrast, mantle-derived xenoliths from other localities along the Cameroon Volcanic Line provide evidence of mantle heterogeneities, due to a wide variation in petrography, mineral chemistries, and thermobarometric estimates. Petrographically, the xenoliths vary from peridotites to pyroxenites (Streckeisen 1976). Xenoliths of olivine websterite, spinel lherzolite and spinel harzburgite occur in phreatomagmatic deposits from Lake Nyos Maar (Temdjim 2004a, in print); websterite, orthopyroxenite, and lherzolite xenoliths occur in basaltic lava flows from the Oku Massif (Matsukage and Oya 2010). Moreover, nodules of dunite, wehrlite and clinopyroxenite have been collected in basanites from Mount Cameroon (Ngounouno and Déruelle 2007; Wandji et al. 2009), accompanied by a subordinate number of composite samples, which consist of 1-cm-thick pyroxenite layers in peridotite (Temdjim 2005; Matsukage and Oya 2010). In other cases, ultramafic xenoliths provide evidence for mantle metasomatism by enriched fluids (or melts), or give evidence of LREE depletions resulting from mantle partial melting (Lee et al. 1996; Temdjim 2005, in print; Matsukage and Oya 2010). All these features demonstrate the diverse characteristics of the upper mantle beneath the main volcanic centres in the continental segment of the Cameroon Volcanic Line.

In summary, the Ngao Voglar spinel lherzolite xenoliths represent samples of relatively homogeneous, slightly depleted lithospheric mantle. Petrochemical and geophysical data indicate that the xenoliths were extracted from a depth between 30 and 58 km at temperatures of 850–950 °C, beneath the domally uplifted and thinned crust (~ 30 km) of the Adamawa Massif (Browne and Fairhead 1983; Noutchogwé-Tatchum 2004). The Ngao Voglar mantle xenolith suite shows less diversity and was derived from shallower depths than most xenoliths in other volcanic areas along the continental sector of the Cameroon Volcanic Line.

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