Nature, origin and significance of the Fomopéa Pan-African high-K calc-alkaline plutonic complex in the Central African fold belt (Cameroon)

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Abstract

The Fomopéa plutonic complex in West Cameroon comprises three petrographical units: a biotite–hornblende granitoid (BHG) including some diorite, a biotite monzogranite (BmG) and an edenite syenogranite (EsG). Amphibolites occur within each unit. The massif was emplaced into a Pan-African amphibolite-facies metamorphic basement. All rocks display igneous textures and are chemically calc-alkaline, the BHG being metaluminous (ASI < 1) the BmG (ASI = 0.98–1.06) and EsG (ASI = 0.94–1.1) being metaluminous to weakly peraluminous. U–Pb dates on zircon give a Pan-African age of 620 ± 3 Ma for a diorite and 613 ± 2 Ma for a quartz–monzodiorite, both belonging to the BHG. Sr–Nd isotopic data indicate the mixing between a juvenile source, probably the mantle (nearest Fomopéa pole: εNd(620 Ma) = +4 and 87Sr/86Sr(620 Ma) = 0.703) and a Palaeoproterozoic to Archaean lower continental crust (nearest Fomopéa pole: εNd(620 Ma)/C0 = 16 and 87Sr/86Sr(620 Ma) = 0.709; Nd TDM = 2.9 Ga) through a contamination process or through a bulk mixing event at the base of the crust. Evidence for both processes is provided by the coexistence of mafic enclaves and gneissic xenoliths within the granitoids. We propose a model whereby linear lithospheric delamination occurred along the Central Cameroon shear zone (CCSZ) in response to post-collisional transpression. This delamination event induced the partial melting of the mantle and old lower crust, and facilitated the ascent of the magmas. The emplacement of numerous post-collisional Neoproterozoic plutons along the CCSZ during the Pan-African orogeny indicates that this process was of paramount importance. The continental signature and geophysical data from the area indicate that the CCSZ corresponds to the northern lithospheric boundary of the Archaean Congo craton, and that the events recorded here correspond to the metacratonic evolution of the northern boundary of the Congo craton.

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1. Introduction

The Neoproterozoic Pan-African belt of Cameroon is a part of the Central Africa Pan-African belt. It connects to the west with the coeval Trans-Saharan orogenic belt; to the south it is in contact with the Archaean Congo craton, and to the north it borders the Saharan metacraton (Abdelsalam et al., 2002). This belt is connected with the northeastern Borborema Province of Brazil, which is part of the Neoproterozoic Brasiliano belt (Almeida et al., 1981; Brito et al., 2002; Lerouge et al., 2006).

Early work on the Central Africa Pan-African fold belt focused mainly on the tectonic evolution of the belt, and the general aspects of magmatic activity associated with it (e.g. Tubosum, 1983; Nédélec et al., 1986; Toteu et al., 1987, 1990; Barbey et al., 1990; Affaton et al., 1991; Ekwueme et al., 1991; Ngako et al., 1991, 1992, 2003; Penaye et al., 1993; Ferré et al., 1998, 2002). After a structural synthesis of the Eastern Nigeria and Northern Cameroon belts, Ngako (1999) suggested a continent–continent collision for the area comparable to the Himalaya collision. This model supposes the existence of one Archaean block in the Sahara which moved from NNE to SSW about 630 Ma ago forming the Central African fold belt along the Archaean Congo craton. This block is now identified as the Saharan metacraton (Abdelsalam et al., 2002).
The Pan-African belt of Cameroon includes three structural domains separated by major shear zones (Zones 1, 2, 3 in Fig. 1): (1) the southern domain comprises Pan-African metasedimentary units, whose protoliths were deposited in a passive margin environment at the northern edge of the Congo craton; (2) the central domain includes Palaeoproterozoic metasediments and orthogneiss intruded by widespread syn- to late-tectonic granitoids mainly transitional in composition and of crustal origin (Soba et al., 1991; Tchouankoué, 1992; Ganwa, 1998; Tchakounté, 1999; Toteu et al., 2001) and having high-K calc-alkaline affinities (Kwékam, 1993; Talla, 1995; Nguissi-Tchankam et al., 1997; Njonfang, 1998; Tagne-Kamga, 2003; Nzolang et al., 2003); (3) the Northern domain consists of the Poli series (Ngako, 1986; Njel, 1986; Toteu, 1990) that possesses the most oceanic character of the various Neoproterozoic basins present in Cameroon (Toteu et al., 2006a), Pan-African granitoids of mainly calc-alkaline composition emplaced between 660 and 580 Ma (Toteu et al., 1987, 2001), late alkaline granitoids and numerous basins made up of unmetamorphosed sedimentary and volcanic rocks.

Here we present the Fomopéa Pan-African magmatic complex, emplaced along the Central Cameroon Shear Zone (CCSZ) that separates the central from the northern domain (Fig. 1) as a large...
number of similar Pan-African granitoids (Fig. 2). Cameroon Pan-African granitoids are mostly post-collisional and considered to have emplaced at around 580 Ma (Kwékam, 1993; Talla, 1995; Nguissi-Tchankam et al., 1997) from a source of mixed origin (Tagne-Kamga, 2003) or made up of recycled old crustal material (Nzolang et al., 2003; Penaye et al., 2004; Nzolang, 2005; Kwékam, 2005). Based on field, petrographical, major, trace and Rb–Sr, Sm–Nd, U–Pb isotope data, this work attempts to define the nature, origin and age of the Fomopéa granitoids for constraining their geodynamic setting in the Pan-African belt of Cameroon, which knowledge is essential for deciphering West African geology, as Fomopéa is located between the West African craton, the Congo craton and the Saharan metacraton.

2. Structural setting

The Neoproterozoic Pan-African belt in West Cameroon comprises granito-gneissic units intruded by mafic to felsic plutons.
Four Pan-African regional tectonic phases have been recognized in Cameroon (Toteu et al., 2004). The D1 phase created a flat-lying foliation and would correspond to early Pan-African nappe tectonics, verging east. The D2 deformation formed a foliation with steep axial planes and is associated with tight and upright folds and with syn-migmatitic conjugate shear zones; the D2 deformation is considered to be the result of an E–W regional shortening direction inducing a NE–SW transcurrent movement. Both D1 and D2 phases are associated with a N110–140°E stretching lineation. The D3 phase is related to sinistral movements along the N–S to NE–SW shear zones. The final D4 phase is characterized by N80–110°E dextral and N160–180°E sinistral shear zones. The D1–D2 phase are continued to the 635–615 Ma age range, the D3 to the 600–580 Ma age range and the D4 poorly dated, is older than 545 Ma (Toteu et al., 2004, and references therein). These four phases, associated to collisional and post-collisional evolution in the Cameroon domain, have been more recently identified as corresponding to three successive tectonic events (Ngako et al., 2008): (1) crustal thickening (ca 630–620 Ma) including the thrusting (D1) and shortening (D2) of Toteu et al. (2004); (2) the left lateral wrench movements (613–585 Ma) among which the Sanaga Shear zone, corresponding to D3 of Toteu et al. (2004); (3) the right lateral wrench movements (ca. 585–540 Ma) mainly marked by the Central Cameroon Shear Zone (CCSZ) and corresponding to D4 of Toteu et al. (2004). The CCSZ is a 70°E striking major crustal structure extending from Sudan into NE Brazil. It defines a fan-geometry in central Cameroon, due to its interaction with N40°E directed shear zone system (Ngako et al., 2003). The CCSZ seems to have been initiated earlier than the D3 phase, during the left lateral wrench movements, as indicated by sinistral shear sense indicators with the same movement direction (Ngako et al., 2003; Njonfang et al., 2006, 2008) compatible with successive shearing events, within the dextral shear zones. The tectonic evolution of the Pan-African belt in central and southern Cameroon is characterized by transpression, because of coeval shear and thrust kinematic interactions. The resulting structures include the N70°E sinistral shear zones of central Cameroon (CCSZ and Sanaga fault) and the granulitic and migmatitic thrust sheets overlying the Congo craton (Ngako et al., 2003).

In the Fomopéa area, the granite-gneiss country rocks are affected mainly by the shortening phase of crustal thickening. The schistosity and foliation planes are mainly oriented N110°E and are associated with folds and a stretching mineral lineation of the same orientation. They are often affected by N70°E dextral shear zones and are cut by N70°E migmatitic leucosomes corresponding to the second tectonic event. The magmatic fabrics (flowage) observed in the Fomopéa plutonic complex are oriented N–S to NNE–SSW (N0°–N30°E), parallel to the flow deformation found in the anatectic granite (e.g. Dschang granite) outcropping in the country-rocks. They dip towards E to ESE, in the opposite direction to that of the anatectic granite (towards NW), and are thus not parallel to the foliation of the gneissic country-rocks. However, the Fomopéa complex, like other neighbouring massifs, is elongated parallel to the regional foliation. This suggests that the geometry of the Fomopéa complex is linked to a late crustal thickening event and could be the result of the same regional stress in response to the contrasted rheological behaviour of the country rocks relatively to the moving Fomopéa magmas. The northern and northeastern edges of the massif are overlain by Cenozoic trachytic and basaltic lavas. Recent sedimentary rocks partially overlay its south-western edge, the remaining being blurred by the presence of post-magmatic dextral NE–SW faults associated with mylonite (Kwékam, 1993), probably related to the last tectonic event.

3. Field geology of the Fomopéa plutonic complex

The Fomopéa complex is made up of three main groups of plutonic rocks (Fig. 3): biotite–hornblende granitoids (BHG, including some dioritoids), a biotite monzogranite (BmG) and an edenite syenogranite (EsG). Small lens-shaped bodies, bands or masses with cumulus texture of amphibolitic rocks are often found in each group. The BHG is located around Fomopéa village. The main rock types are a porphyritic monzogranite usually grey in colour, and a dark green quartz–monzodiorite; subordinate quartz–monzonite and equigranular granodiorite are also present. Spindle-shaped enclaves of diorite and angular xenoliths of gneissic rocks are frequently observed. These enclaves are commonly elongated parallel to the magmatic foliation, defined by the alignment of amphibole, biotite, platy feldspar and schlierens. Schuppen structures present in a granitic “proto-dyke” indicate a dextral strike-slip ductile fault oriented N100°E.

The BmG forms a large homogeneous body to the NE in the Baloum area but is also cutting across dykes intruding the BHG. Monzodioritic enclaves are common, particularly along the contact with the BHG.

The EsG forms a body located to the SE, around the Fontsa-Toula and Fotoufem villages. It contains small enclaves of diorite (<5 cm in diameter). The contact with the south-western border of the BHG is progressive and often blurred by amphibolite panels whereas the contact with the gneissic country rocks is sharp. The magmatic foliation is marked by the alignment of amphibole and rare schlierens of amphibole.

The magmatic foliation in the different petrographic groups is sub-parallel to the massif elongation (NNE–SSW dipping ESE) and the regional foliation, giving it a sheet-like structure and suggesting syn-kinematic emplacement. This magmatic foliation is observed throughout the BHG unit (N0–30°E) with dips varying from 50°ESE in the margin to 85°ESE in the core, and rather lower to the margins of the BmG (N0–10°E, N50–75° ESE or E) and EsG (N10–15°E, N30–50° ESE). However, features of a syn- to late-kinematic pluton relative to the late crustal thickening event are suggested by the alignments of the minerals, and enclaves of diorite and gneissic country rocks in the presence of schuppen structures. Indeed, the Fomopéa pluton can then be considered as an early post-collisional Pan-African pluton, older than the abundant syntectonic granitic plutons (Toteu et al., 2006a) of the second to third tectonic events. The whole massif is fringed on its NE–SW edge by amphibolite bands that are mainly oriented N40°E with a dip of 60° to the SE, and on its SE edge by N50°E dextral mylonitic band, and a few late dykes of microgabbro crosscut the Fomopéa pluton.

4. Petrography

The biotite–hornblende granitoids (BHG) include diorite, quartz–monzodiorite, quartz–monzonite, granodiorite and monzogranite. The rocks are medium- to coarse-grained, with biotite, hornblende, plagioclase, K-feldspar and quartz as the major mineral phases and magnetite, zircon, apatite, titanite and allanite as common accessory phases. The rocks display well-defined magnetic textures. Plagioclase is often zoned and has andesine composition (An80–35). Green, brownish to reddish biotite (X_Mg = 0.45–55) is common. Hornblende, the main amphibole, occurs both as euhedral prisms and as anhedral crystals often surrounding euhedral flakes of biotite. Its chemical composition vary from tschermakitic hornblende (X_Mg = 0.50–0.60) in diorite to magnesio–hornblende (X_Mg = 0.54–0.56) in the BHG. Titanite, the most abundant accessory mineral, may reach more than 4% volume in some samples. Secondary minerals, chlorite, actinolite and epidote occur as sub-solidus alteration products of biotite, hornblende and plagioclase.
The biotite–monzogranite (BmG) is fine- to medium-grained and heterogranular. The main mineral phases are brownish to reddish biotite (X_Mg = 0.45–0.50), zoned plagioclase (An25–30), K-feldspar (microcline) and quartz whereas the accessory minerals remain the same as in the BHG except allanite which was not found. Secondary minerals are sericite and chlorite, resulting from the alteration of feldspar and biotite, respectively, while muscovite occurs as a hydrothermal mineral. Late magmatic to subsolidus deformation imprints such as undulose extinction in quartz grains, minor sub-grain development along quartz–quartz boundaries, mechanical twinning in feldspars and herringbone cleavage (kink-band) in biotite are common in this monzogranite.

The edenite–syenogranite (EsG) is leucocratic, medium-grained and heterogranular. It differs from the BmG mainly by the absence of biotite and the occurrence of amphibole. As a whole, it contains larger quartz crystals, K-feldspar, plagioclase (An5–25, dominantly albite) and green sub-euhedral to euhedral hornblende (X_Mg = 0.50–0.70). Accessory minerals include titanite, apatite and Fe–Ti oxides. As in the BmG, undulose extinction in quartz grains and mechanical twinning in feldspars are observed.

The chemical compositions of biotite from the Fomopéa rocks plot in the calc-alkaline field of Nachit et al. (1985) in Kwékam (2005). The amphibole geothermobarometer of Johnson and Ruth erford (1989) calculated for magmatic hornblende gives a temperature range of 710–760 °C with pressure varying from 2.2 to 4.8 kbar. Higher grade conditions are obtained in the diorite and lower ones in the edenite syenogranite.

5. U–Pb on zircon and Rb–Sr on whole-rock geochronology and Sr–Nd isotopes

5.1. Analytical techniques

U–Pb analytical data were obtained at the Isotopic Geochemistry Laboratory (IGL), University of Kansas, following the procedures described by Toteu et al. (1994). All zircons analyzed were air-abraded for 2–4 h to remove as much of the altered outermost part as possible (Krogh, 1982). All U–Pb analyses were performed on single grains; all our samples were spiked with 205Pb–235U tracer solution before dissolution. Results are given in Table 1.

Sr isotopes on whole rocks were measured at the Royal Museum for Central Africa, Tervuren (Belgium). After dissolution in an HF/HClO4 mixture, Sr was separated on Dowex 50/150 ion exchange resin. Total chemical blanks range between 10 and 15 ng Sr. Measurements were carried out on a GV Sector 54 TIMS. An error of 4% on Rb/Sr ratios is estimated on standard and sample replicates. The external reproducibility on NBS987 standard solution was 0.710255 ± 0.000015 during the course of this study. Sr compositions were corrected to a value of 0.710250 for NBS987 and frac-
tionation corrected to $^{86}$Sr/$^{88}$Sr = 0.1194. Ages were calculated following Ludwig (2003). Results are given in Table 2.

Nd isotopes on whole rocks were measured at the Geowissenschaftliches Zentrum Göttingen-Isotopengeologie. Samples were spiked with a mixed $^{150}$Nd/$^{149}$Nd Sm spike prior to dissolution. The separation was performed in two steps: cation exchange columns with HCl chemistry preceded a separation of Sm and Nd on Teflon columns coated with HDPE. The analyses were performed on a Finnigan MAT 262 TIMS operating in static mode. The total reproducibility on a La Jolla standard solution was 0.12 for the source prior to the intrusion age, using the evolving mantle curve of Nelson and DePaolo (1985). Results are given in Table 2.

Table 1
<table>
<thead>
<tr>
<th>Sample</th>
<th>Isoplot data</th>
<th>Calculated ages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fraction</td>
<td>Size (mg)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(obs.)</td>
</tr>
<tr>
<td>Diorite</td>
<td>K204</td>
<td>Zr-1</td>
</tr>
<tr>
<td></td>
<td>K204</td>
<td>Zr-2</td>
</tr>
<tr>
<td></td>
<td>K204</td>
<td>Zr-3</td>
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</table>

Table 2
<table>
<thead>
<tr>
<th>Sample</th>
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</thead>
<tbody>
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<td></td>
<td>Rb (ppm)</td>
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<tr>
<td>BHG</td>
<td>Fk12</td>
</tr>
<tr>
<td>BHG</td>
<td>K34</td>
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<tr>
<td>BHG</td>
<td>K35</td>
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<tr>
<td>BHG</td>
<td>K70</td>
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<td>BHG</td>
<td>K75</td>
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<tr>
<td>BHG</td>
<td>K56</td>
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<tr>
<td>BmG</td>
<td>K61</td>
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<tr>
<td>BmG</td>
<td>K68</td>
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<tr>
<td>BmG</td>
<td>K72</td>
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<tr>
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</tr>
<tr>
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<td>K51</td>
</tr>
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</tr>
<tr>
<td>Amphibolites</td>
<td>AM2</td>
</tr>
<tr>
<td>Amphibolites</td>
<td>K71</td>
</tr>
</tbody>
</table>

5.2. Age results

Three zircons from one diorite (K204) and five zircons from one quartz–monzodiorite (K104), both from the BHG, were analyzed. The results are presented in Table 1 and Fig. 4. Two diorite zircons are concordant and one is discordant towards 0 Ma. The two concordant zircons give, respectively, 648 ± 5 Ma and 621 ± 3 Ma. This suggests an intrusion age for the diorite at 621 ± 3 Ma and an inherited zircon at 648 ± 5 Ma. Four zircons from the quartz–monzodiorite are concordant and one is discordant towards 0 Ma. Two zircons are discordant at 623 ± 2 Ma and the two others at 613 ± 2 Ma. This suggests an intrusion age for the quartz–monzodiorite at 613 ± 2 Ma with inherited zircons at 623 ± 2, possibly coming from the diorite: combining the magmatic zircon from the diorite with those zircons gives an age of 622 ± 4 Ma with an acceptable MSWD of 1.3. This suggests that the Fomopéa complex was emplaced within about 10 m.y. These U–Pb results on zircon indicate that the Fomopéa complex was emplaced at the end of the crustal thickening and represents an early generation of high-K calc-alkaline plutons emplaced in Cameroon, being older than most of the Pan-African plutons that intruded at ca. 580 Ma, during the second tectonic event. It is contemporaneous to the onset of the Yaoundé nappe tectonics towards the south (616–610 Ma; Toteu et al., 2006b).

Sixteen whole-rock Sr isotopes analyses were carried out and the results are presented in Table 2 and Fig. 5. The six samples from the biotite–hornblende granodiorite define an isochron with an age of 572 ± 48 Ma (Sr initial ratio = 0.705520 ± 0.00053, MSWD = 1.15); the diorite is strongly below. The three samples from the biotite–monzogranite and the three from the edenite–syenogranite determine an isochron of 561 ± 34 Ma (Sr initial ratio = 0.70926 ± 0.00095, MSWD = 3.9). These ages are affected by large errors and partly based on mixed groups, which weaken
the information. However, some conclusions can be given: (1) the Rb–Sr ages of the Fomopéa pluton are centred on the age of the right lateral wrench movements at 580 Ma that affected the complex and then also probably this isotopic system; (2) whatever this reactivation, different initial ratios are recorded following the facies considered with increasing Sr initial ratios.

5.3. Nd–Sr isotopic characteristics

The $^{87}$Sr/$^{86}$Sr initial ratios calculated at 620 Ma do not vary significantly within a given petrographical type: diorite (0.703), amphibolites (0.704), biotite–hornblende granitoid (0.704–0.705), biotite–monzogranite (0.704–0.708) and edenite–syenogranite (0.708–0.709). As for the Sr isotopes, the Nd isotopes are grouped when considering one petrographical type but show a large variation when the whole Fomopéa complex is considered: the diorite (K19) displays the most juvenile characteristics with moderately positive $\varepsilon_{\text{Nd}}$ value (+4) and young $T_{\text{DM1}}$ ($T_{\text{DM1}}$ = 0.90/0.92 Ga and $T_{\text{DM2}}$ = 0.89 Ga). The BHG (Fk12, K34, K70, K75, and K56) have $\varepsilon_{\text{Nd}}$ around 0 (between +0.9 and −1.5) with $T_{\text{DM1}}$ between 1.03 and 1.34 Ga. The biotite monzogranite (K61, K68, and K72) have negative $\varepsilon_{\text{Nd}}$ (between −0.9 and −1.2) with $T_{\text{DM1}}$ between 1.23 and 1.34 Ga. The edenite–syenogranite has more crustal Nd signature. The two samples analyzed (K51 and K52) have more negative $\varepsilon_{\text{Nd}}$ (between −5.7 and −15.6) with older model ages $T_{\text{DM1}}$ of 1.15 and 2.98 Ga and $T_{\text{DM2}}$ of 1.28 and 3.29 Ga.

Palaeoproterozoic crust (2.1–1.66 Ga, U–Pb on zircon) is known in SW Cameroon (Penaye et al., 2004; Lerouge et al., 2006) and in Bafia region (Tchakounte et al., 2007) and Archaean crust (2.9 Ga, Rb–Sr isochron) in the nearby Congo craton (Lassere and Soba, 1976; Shang et al., 2004, 2007).

6. Geochemistry

6.1. Analytical procedures

Major and some trace elements were measured at the "Institut für Geowissenschaften, Christian-Albrechts-Universität zu Kiel, Kiel, Germany".
Table 4

Major (wt.%, recalculated to 100% on an anhydrous basis) and trace elements data for Fomopéa plutonic complex, n.m. and blank = not measured, b.d.l. = below detection limit.

<table>
<thead>
<tr>
<th>Amphibolites</th>
<th>Diorites</th>
<th>Biotite–hornblende granitoids (BHG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K22 AM2 AM1 K71 K19 SO1 FK6 FK5</td>
<td>K1 K35 K45 K54 K75 FK12 K4 K34 K40 K56 K70</td>
<td></td>
</tr>
</tbody>
</table>

Major elements (recalculated for 100%)

- SiO$_2$ 51.55 50.12 56.79 50.37 51.78 52.55 51.78 49.06 63.39 64.39 61.35 65.63 62.85 63.35 66.65 69.42 72.99 68.96 66.57
- TiO$_2$ 0.80 2.11 1.11 1.05 1.52 1.70 1.63 1.38 0.71 0.65 0.90 0.63 0.75 0.69 0.66 0.40 0.20 0.59 0.49
- Fe$_2$O$_3$ 10.08 13.97 7.91 11.85 8.64 10.45 8.77 11.49 5.72 5.36 6.50 4.71 5.89 4.88 6.01 5.89 4.98 4.27 5.92
- MnO 0.16 0.20 0.16 0.22 0.12 0.14 0.10 0.19 0.10 0.11 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10

Trace elements (ppm)

- Li 7.7 n.m n.m 35.9 35.4 39.6 58.4 39.5 14.4 26.8 33.5
- Sc 42.5 n.m n.m 80.2 66.2 55.6 40.5 35.3
- Co 38.9 n.m n.m 48.5 42.7 26.9 34.6 27.7
- Ni 153.2 n.m n.m 133 69.2 47.1 32.8 27.7
- Cu 115.7 n.m n.m 273 188 117 49.9 39.9
- Zn 124.7 n.m n.m 313 188 117 49.9 39.9
- Cd 328 355 498 1013 794 448 620 401
- Sr 328 355 498 1013 794 448 620 401
- Y 37.2 16.9 18.3 22.9 18.3 22.9 18.3 22.9
- Zr 174 173 110 153 85 178 181 173
- Nb 8.5 12.3 8.2 12.7 9.9 16.0 14.8 13.0
- Mo n.m n.m n.m 4.2 2.5 2.4 2.0 1.5
- Cs n.m n.m n.m 4.2 2.5 2.4 2.0 1.5
- Ba 208 577 265 466 671 635 867 443 889
- La 22.2 38.8 18.2 23.4 29.7 39.5 44.4 29.3 35.9 45.8 45.8
- Ce 38.8 82.6 41.9 47.0 64.6 73.8 69.9 54.4 77.7 90 91.6
- Pr 5.3 10.0 5.3 6.0 8.4 8.2 8.2 6.0 9.0 6.2 6.2
- Nd 22.9 38.6 24.0 25.8 39.4 31.9 29.5 25.3 30.5
- Sm 6.1 6.7 5.6 7.9 8.9 8 5.8 6.2 6.8 5.9 3.9
- Eu 1.9 1.8 1.5 1.9 2.0 1.7 1.2 1.5 1.0 1.1 0.8
- Gd 6.6 5.9 5.4 5.1 8.1 5.7 5.6 5.3 5.7 4.3 4.3
- Tb 1.1 b.d.l. b.d.l. 0.8 1.4 0.7 0.6 0.9 0.8 0.8 0.5
- Dy 7.3 4.0 4.2 5.4 7.4 4.7 3.8 4.8 4.1 3.3 2.4
- Ho 1.7 0.8 0.9 1.2 1.5 1.0 0.8 0.8 1.0 0.7 0.5
- Er 4.4 2.2 2.3 3.0 3.6 2.0 1.3 2.6 2.6 3.0 1.4
- Tm 0.6 b.d.l. b.d.l. 0.6 0.7 0.4 0.3 0.4 0.3 0.4
- Yb 3.8 1.8 2.0 4.0 3.3 2.3 2.0 2.5 3.1 1.8 1.7
- Lu 0.6 0.3 0.3 0.5 0.6 0.5 0.3 0.4 0.5 0.4 0.3
- Hf 4.2 3.8 2.9 3.9 3.4 4.8 5.5 3.4 5.2 4.7
- Ta 0.4 0.7 0.4 1.0 0.8 1.3 0.8 1.3 1.9 2.2 0.8
- Th 2.0 4.6 5.5 4.1 2.9 11.2 18.1 45.6 38.6 30.4
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<tr>
<th>Major elements (recalculated for 100%)</th>
<th>Biotite monzogranites (BMG)</th>
<th>Edenite syenogranites (ESG)</th>
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<tr>
<td><strong>SiO₂</strong></td>
<td>69.04 70.44 69.45 74.38</td>
<td>74.73 74.95 74.63</td>
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<tr>
<td><strong>TiO₂</strong></td>
<td>0.56 0.34 0.48 0.15</td>
<td>0.09 0.07 0.11</td>
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<td><strong>Fe₂O₃</strong></td>
<td>3.00 2.58 2.91 1.21</td>
<td>0.98 0.91 0.94</td>
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<td><strong>MnO</strong></td>
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<tr>
<td><strong>MgO</strong></td>
<td>1.22 0.61 0.78 0.19</td>
<td>0.03 0.03 0.38</td>
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<tr>
<td><strong>CaO</strong></td>
<td>2.61 1.59 1.92 1.32</td>
<td>0.87 0.89 1.31</td>
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<tr>
<td><strong>Na₂O</strong></td>
<td>3.59 2.94 2.89 3.32</td>
<td>4.21 4.85 4.88</td>
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<tr>
<td><strong>K₂O</strong></td>
<td>4.64 6.15 6.30 5.33</td>
<td>4.32 4.18 3.80</td>
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<tr>
<td><strong>Na₂O + K₂O</strong></td>
<td>8.23 9.09 9.20 8.65</td>
<td>8.53 9.03 8.68</td>
</tr>
<tr>
<td><strong>CaO + Na₂O</strong></td>
<td>10.00 100 100 100</td>
<td>10.00 100 100</td>
</tr>
<tr>
<td><strong>LOI</strong></td>
<td>0.53 0.53 0.37 0.42</td>
<td>0.19 0.18 0.16</td>
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<td>8.53 9.03 8.68</td>
</tr>
<tr>
<td><strong>Mg/Mg + Fe</strong></td>
<td>0.45 0.32 0.35 0.24</td>
<td>0.06 0.06 0.44</td>
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<tr>
<td><strong>A/CNK</strong></td>
<td>0.93 1.03 0.99 1.00</td>
<td>1.10 0.98 0.94</td>
</tr>
<tr>
<td><strong>K₂O/CaO + Na₂O (molar)</strong></td>
<td>0.61 1.06 1.05 0.87</td>
<td>0.60 0.51 0.45</td>
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<td><strong>Li</strong></td>
<td>17.0 49.5 36.7</td>
<td>n.m.</td>
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<tr>
<td><strong>Sc</strong></td>
<td>23.9 26.5 13.8</td>
<td>10</td>
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<tr>
<td><strong>Co</strong></td>
<td>7.4 6.8 4.9</td>
<td>7</td>
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<tr>
<td><strong>Ni</strong></td>
<td>13.6 17.2 9.6</td>
<td>n.m. 38</td>
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<tr>
<td><strong>Cu</strong></td>
<td>27.7 30.9 15.3</td>
<td>30</td>
</tr>
<tr>
<td><strong>Zn</strong></td>
<td>39.8 43.7 64.9</td>
<td>60</td>
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<tr>
<td><strong>Ga</strong></td>
<td>28.0 31.6 30.5</td>
<td>13</td>
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<tr>
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<tr>
<td><strong>Sr</strong></td>
<td>211 173 395</td>
<td>1134</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>12.1 11.3 7.4</td>
<td>32</td>
</tr>
<tr>
<td><strong>Zr</strong></td>
<td>146 121 202</td>
<td>207</td>
</tr>
<tr>
<td><strong>Nb</strong></td>
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<td>12</td>
</tr>
<tr>
<td><strong>Mo</strong></td>
<td>0.8 1.1 0.4</td>
<td>n.m. 1.0</td>
</tr>
<tr>
<td><strong>Cs</strong></td>
<td>6.5 9.9 6.5</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Ba</strong></td>
<td>439 376 901</td>
<td>6721</td>
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<tr>
<td><strong>La</strong></td>
<td>55.8 41.5 69.3</td>
<td>73.2</td>
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<tr>
<td><strong>Ce</strong></td>
<td>93.5 66.4 120</td>
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<td><strong>Pr</strong></td>
<td>5.1 6.8 11.1</td>
<td>127</td>
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<tr>
<td><strong>Nd</strong></td>
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<td>51.2</td>
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<tr>
<td><strong>Sm</strong></td>
<td>4.3 3.7 4.4</td>
<td>9.7</td>
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<tr>
<td><strong>Eu</strong></td>
<td>0.5 0.5 0.8</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Gd</strong></td>
<td>3.5 2.3 3.0</td>
<td>7.8</td>
</tr>
<tr>
<td><strong>Tb</strong></td>
<td>0.5 0.4 0.4</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Dy</strong></td>
<td>2.1 1.9 1.4</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Ho</strong></td>
<td>0.4 0.3 0.2</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Er</strong></td>
<td>1.3 1.2 0.7</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Tm</strong></td>
<td>0.2 0.2 0.1</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Yb</strong></td>
<td>1.3 1.1 0.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>

(continued on next page)
Germany" on fused discs by XRF technique. The 2σ-error for major elements is <1%, for trace elements <5%. All other trace elements were determined by ICP-MS, with errors 2σ < 20% for Nb and Ta, <10% for Cs, Cu, Hf, Li, Ni, Sc, Y, Pb, Th, and U, and ≈5% for Rb, Sr, and the REE. Major elements have been recalculated to 100% without the loss of ignition (LOI) before use in the geochemical study. Representative data from 37 rock samples of three main groups from Fomopéa plutonic complex are given in Table 4.

6.2. Major elements

The SiO2 contents range from 49 to 52.6 wt.% in diorites to 61.4% to 69.4 wt.% in the BHG and are higher and similar in the BmG (69.4–75.6 wt.%) and the EsG (71.9–75.0 wt.%). Harker diagrams (Fig. 6) show a general linear decrease in Al2O3, TiO2, Fe2O3, CaO, and MgO with increasing SiO2 at least for SiO2 > 60%. The diorites and the BHG belong to a calc-alkalic series while the BmG and the EsG belong to an alkali-calcic series (MALI diagram, Frost et al., 2001; Fig 7). This difference can be seen in the Na2O vs. SiO2 diagram (Fig. 6) where, with increasing SiO2, Na2O decreases in the BHG group and increases in the BmG group with opposite trends for K2O (Fig. 8). In the total alkali–silica diagram (Na2O + K2O vs. SiO2), the three groups display a subalkaline affinity (Fig. 9a) whereas in the A/NK vs. A/CNK (Fig. 9b), BHG is metaluminous (A/CNK < 1), both EsG and BmG are metaluminous or weakly peraluminous (A/CNK = 0.94–1.1 with 2 samples > 1) except sample K52 from the EsG which is peralkaline (A/CNK: 0.67; NK/A: 1.22) due to a very low Al2O3 content. There is a silica gap (52–62%) between the diorites and the BHG and BmG, partly filled by an amphibolite. This rises to the relation existing between the granitoids. As we will see, the trace elements are similar all over the silica range, pointing to a common origin and a likely link trough a crystal fractionation process. Such a modelization would require more samples and is out of the scope of this study.

6.3. Trace and rare earth elements

The sliding normalization (each rock is normalized to the virtual rock from the reference series that has the same silica content) proposed by Liégeois et al. (1998) for distinguishing the potassic from the alkaline-peralkaline series confirms that no alkaline rocks are present in Fomopéa (Fig. 10). The Fomopéa rocks follow a potassic trend, parallel to the Y axis, implying a strong enrichment in LILE compared to HFSE. This diagram show that the EsG is not very rich in LILE if its silica content is taken into account, in agreement with the decrease in K2O with SiO2, due to the crystallization of K-rich minerals such as K-feldspar.

As a whole, trace elements (Fig. 11) are distributed non-uniformly in the three groups of rocks. The BHG group contains the highest content of Nb (20.9 ppm, lowest value – 6 ppm – in EsG), Y (36.3 ppm, lowest value – 7.4 ppm – in BmG), Hf (5.72 ppm, lowest value – 2.1 ppm – in EsG) and Ni (133 ppm, lowest value – 9.5 ppm – in BmG). The BmG group contains the highest contents of Rb (366 ppm, lowest value – 34 ppm – in BHG), Th (59 ppm, lowest value – 1 ppm – in EsG) and U (14.8 ppm, lowest value – 0.3 ppm – in EsG). The EsG group shows the highest content of Sr (1134 ppm, lowest value – 173 ppm – in BmG) and Zr (207 ppm, lowest value – 85 ppm – in BHG) and the highest and lowest content of Ba (6721 and 344 ppm); here, the samples with the highest Ba (K47) and lowest Ba (K51) also have the highest and lowest Sr and Zr contents of the group (Table 4). With the exception of those samples in the corresponding diagrams, rocks in the Harker diagrams behave differently from the group to another and sometimes within the same group with increasing SiO2 (Fig. 11). Rb is incompatible in the BHG, dispersed in the BmG and shows a convex down profile in the EsG with a maximum (on-
set of orthoclase crystallization) at 73.4 wt.% SiO$_2$. Ba, although dispersed, increases in the BHG and becomes compatible in the BmG and the EsG with steeper slope in the BmG. Sr decreases in the BHG in a dispersed way and remains compatible in the BmG and the EsG with similar slopes as for Ba. Zr is also compatible in the BmG and EsG, with a steeper slope in the BmG, whereas Nb displays three trends, each being incompatible, with steeper and parallel slopes in the BmG and EsG. The similar behaviour of Zr, Sr and Ba in the three remaining samples of EsG is also attested by their constant ratios (Sr/Zr = 5.93–6.18; Ba/Sr = 2.67–2.77; Ba/Zr = 16.45–16.61). Th is incompatible in BHG and EsG with more regular and steeper slope in BHG, and compatible in BmG. All these characteristics are compatible with a calc-alkalic source and a crystal fractionation process, low values of elements such as Nb or Th in the most evolved EsG facies being explained by the crystallization of late minerals uneasy to determine in the absence of the cumulates, generally formed in that case through filter-pressing (Hadj Kaddour et al., 1998).

REE contents are generally low in the Fomopéa rocks (45–290 ppm). The BmG has higher concentrations (148–243 ppm) followed by the BHG (132–201 ppm); the EsG have <123 ppm total REE with one sample (K47) at 290 ppm. The light rare earth elements are more enriched in the BmG (LREE/HREE: 18.6–38.5) than in the BHG (5.5–13.3) and the EsG (5.1–12.5). All rocks show moderate negative europium anomalies excepted in amphibolites and diorites (Fig. 12): the negative Eu anomaly (Eu/Eu*) is higher in the BmG (0.40–0.64) than in the EsG (0.80–0.89, with one sample at 0.35) and more variable in the BHG (0.60–0.91). The general patterns show LREE enrichment and almost flat HREE except in diorites. The Fomopéa REE patterns are similar to the Pan-African

Fig. 6. Harker diagrams of selected major elements.

Fig. 7. MALI diagram from Frost et al. (2001). Plot of Na$_2$O + K$_2$O – CaO vs. SiO$_2$ showing the ranges for the alkalic, alkali calcic, calc-alkalic, and calcic rock series. Fomopéa granitoids are calc-alkalic (diorites and BHG) and alkali-calcic (BmG and EsG).

Fig. 8. Classification of the Fomopéa plutonic complex in the K$_2$O vs. SiO$_2$ diagram. The diagram shows the subdivisions of Le Maitre et al. (2004) (broken lines) and of Rickwood (1989) (nomenclature in parentheses). The shaded bands are the fields in which the boundary lines of Peccerillo and Taylor (1976) are located.
syn-shear granitic group from Aïr (Niger), sharing a similar geotectonic setting (Liégeois et al., 1998; Fig. 13). In spidergrams (Fig. 13), negative Nb, Ta and Ti anomalies are common and higher in the BmG and EsG than in the BHG. In addition, Th, Ce and P negative anomalies are common in the EsG, except in K47 for the Ce and in K51 for P which rather shows slight positive anomalies; Sr negative anomalies occur in the BmG; weak P negative anomalies are observed in the BHG and Zr negative anomalies occur in diorites and some BHG samples. HREE enrichment relative to chondrite (Thompson, 1982) is higher in the BHG group than in the others. Globally, Fomopéa shows an enrichment of LILE over HFSE and Nb–Ta negative anomalies occurs in diorites and some BHG samples. This is shown with the similar patterns of the Aïr Pan-African syn-shear granitic group (Liégeois et al., 1998; Fig. 13).

Fig. 9. Sliding normalization diagram comparing the Fomopéa plutonic complex to the reference syn-shear HKCA of the Yenchichi–Telabit series (Liégeois et al., 1998). The Fomopéa plutonic complex displays a strong potassic trend.
7. Discussion

7.1. Nature and origin of the Fomopéa magmatism

The petrography, mineral chemistry and whole-rock geochemistry of the Fomopéa pluton are those of I-type calc-alkaline granitoids. More precisely, the calc-alkalic BHG rocks are similar to amphibole-rich calc-alkaline granitoids (ACG) and the alkali-calcic BmG and EsG rocks are comparable to K-rich and K-feldspar porphyritic calc-alkaline granitoids (KCG) of Barbarin (1999). Following the terminology of Sha and Chappell (1999), the BHG with its biotite and hornblende, SiO₂ contents between 60 and 69 wt.%, and ASI < 1, correspond to the mafic I-types, whereas the others, because of their higher SiO₂ contents and their metaluminous to weakly peraluminous compositions correspond to the felsic I-types.

According to Barbarin (1999), both the ACG and KCG are derived from mixing of mantle-derived basaltic magmas and crustal melts with varying proportions. The coexistence of mafic enclaves and gneissic country rocks in the Fomopéa plutonic complex indicates magma mixing on the one hand and interaction with the country rocks on the other hand, because of their higher SiO₂ contents and their metaluminous to weakly peraluminous compositions correspond to the felsic I-types.

Assessing the interaction between mantle and continental crust requires the use of Nd and Sr isotopes, recalculated to the age of intrusion (620 Ma). In the area of Fomopéa, the continental basement is represented by Eburnian (ca. 2 Ga) and Archaean rocks of the Congo craton and within the Yaoundé nappes. Part of this basement consists of Rb-depleted granulitic rocks. The Nd–Sr signature (Fig. 15) at 620 Ma of this basement is then in strong contrast with the mantle and there is no evidence for a juvenile continental crust at depth. The Fomopéa pluton displays a trend from a preponderantly mantle-derived signature represented by the diorites ($^{87}$Sr/$^{86}$Sr): 0.703, $\varepsilon_{Nd} = +4$, Nd $T_{DM}$: 0.9 Ga), towards the edenite syenogranite (EsG) displaying $^{87}$Sr/$^{86}$Sr up to 0.7085, $\varepsilon_{Nd}$ down to −15.8 and a Nd $T_{DM}$ close to 3 Ga. The other samples lie between these two extremes (Fig. 14). This indicates a source combining an old felsic granulitic crust and a mafic mantle-derived magma (Fig. 15) probably at the origin of the heat needed for the crustal melting (Bonin, 2004). At 620 Ma, the most depleted mantle has $^{87}$Sr/$^{86}$Sr = 0.70219 and $\varepsilon_{Nd} = +8.6$. The diorites have a more enriched signature that can correspond either to such a depleted mantle with crust participation or to a more enriched mantle. The distinction between these two possibilities cannot be resolved here but whatever, the mantle signature in these rocks is largely preponderant. The felsic continental crust must include an Archaean segment for generating Archaean $T_{DM}$. A Palaeoproterozoic segment can have also participated as most of the $T_{DM}$ ages are between 1 and 2 Ga. The close association of Archaean and Palaeoproterozoic rocks in the area supports such an interaction (Penaye et al., 2004; Tchakounte et al., 2007). This evidence thus links the Fomopéa magmatism with the continental crust melting generally evoked for other granitoids in the West Cameroon part of the Central Africa Pan-African fold belt, on the basis of their strong negative $\varepsilon_{Nd}$ (e.g. the Ngondo complex, Tagné-Kamga, 2003; the Batoum granitoids, Nzolang et al., 2003 and Nzolang, 2005).
7.2. The Fomopéa plutonic complex and the evolution of the Cameroon Pan-African fold belt

The geochemical and mineralogical characteristics of granitoids are related to the nature of their protolith, as well as to the geodynamical environment under which their source magma formed and evolved (Roberts et al., 2000). The post-collisional environment is particularly rich in calc-alkalic and alkali-calcic granitoids originating from the remobilization of an older continental crust (Liégeois et al., 1998). The field relationships of the Fomopéa complex define its syn- to late kinematic emplacement relatively to the D2 deformation. It is NE–SW elongated and has an emplacement age between 621 and 613 Ma (U–Pb ages) which corresponds to the end of crustal thickening in the area. The Fomopéa pluton has been affected by the right lateral wrench movements as shown by the Fomopéa Rb–Sr isochron reset to ca. 572 Ma. This tectonic event coincides with the emplacement of most of the post-collisional high-K calc-alkaline granitoids in the central domain of the Central Africa Pan-African fold belt (Nguessi-Tchankam et al., 1997; Tagne-Kamga, 2003; Toteu et al., 2004, 2006a).

All these granites are intruded along the Central Cameroon Shear Zone (CCSZ; Fig. 1) and the parallel Sanaga Fault (SF; Fig. 1). To the south of the latter, the Pan-African Yaoundé nappes were thrust towards the Archaean craton. The Fomopéa pluton and its associated granitoids are located just to the north of an area characterized by a thick lithosphere as indicated by seismic tomography (Fig. 16). We can then suggest that the CCSZ and the SF mark the northern lithospheric boundary of the Congo craton and that the intrusion of these post-collisional granitoids is due to the post-collisional movements that occurred along this boundary. Such movements could occur during the start of a metacratonic evolution of the cratonic boundary, i.e. its fracturing by shear movements.

Fig. 13. Chondrite-normalized spidergrams using the normalization factors of Thompson (1982). Fomopéa complex rocks are compared to Adma and Iforas granitoids from syn-shear HKCA granitoids from the Tuareg shield (Liégeois et al., 1998).

Fig. 14. $\text{Th vs. Th/La}$ diagram from Plank (2005) showing the link between the different groups of Fomopéa rocks. Diorite sample occupies the array of mantle mafic rocks.
**Fig. 15.** $^{87}\text{Sr}/^{86}\text{Sr}_{620\text{Ma}}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}_{620\text{Ma}}$ showing the evolution of the rocks from the Fomopéa plutonic complex, compared to the Batoum granitoids (Nzolang et al., 2003) and the Ngondo plutonic complex (Tagne-Kamga, 2003), which are mainly generated by crustal reworking. The Fomopéa plutonic complex defines a trend from the mantle array (diorites) towards an Archaean/Palaeoproterozoic continental crust, represented by both a Rb-depleted granulitic lower crust and a Rb-undepleted amphibolite upper crust.

**Fig. 16.** Horizontal tomographical cross section of Africa showing the shear-wave velocity variation (in %) at 200 km depth (Pasyanos and Nyblade, 2007). This shows that the Fomopéa pluton is located along the northern boundary of the thick lithosphere of the Congo craton.
8. Conclusions

The Fomopéa plutonic complex is located at the south-western edge of the Central Cameroon mega Shear Zone (CCSZ). It comprises biotite–hornblende granitoids (BHG) associated with diorites and amphibolites, a biotite monzogranite (BMG) and an edenite syenogranite (ESg). The first rock types belong to a calc-alkalic series and the last two to an alkal-calcic series, all being I-type high-K calc-alkaline and metaluminous to weakly peraluminous.

The Fomopéa protolith corresponds to the Archaean and Palaeoproterozoic granulitic lower crust most probably that of the Congo craton melted by mantle-derived magmas, with mixed isotope ratios ($^{206}$Pb/$^{238}$U = 0.7030–0.7085 and $^{143}$Nd/$^{144}$Nd = $^{16}$ to +4 with $^{87}$Sr/$^{86}$Sr model ages from 3 Ga to 0.9 Ga). Some relics of dismembered Palaeo-proterozoic crust (2.1 Ga) are observed to the south of the Fomopéa area (Kékm granulites; Penaye et al., 2004).

We associate the origin of the Fomopéa pluton to the Pan-African convergence between the Congo craton and the Saharan metacraton that initiated the metacratonization of the northern boundary of the Congo craton. Post-collisional transpressive movements (strike-slip partitioned; Tagné-Kamga, 2003; Ngako et al., 2003) along the CCSZ (sinistral stage) and the SF induced linear lithospheric delamination allowing the uprise of mantle magmas (Black and Liégeois, 1993), triggering the partial melting of the old lower continental crust of the Congo craton's northern boundary. Mixing of the two types of magmas generated the Fomopéa pluton and the other Cameroon post-collisional granitoids. The Fomopéa pluton (621–613 Ma) corresponds to the initiation of the process (transition between crustal thickening and left lateral wrench movements), the climax being dated at ca. 580 Ma (late left lateral wrench movements to early right lateral wrench movements) during which most of the Cameroon granitoids intruded.

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References


