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Geology, mineralogy and geochemistry of the Kekem dyke swarm (Western Cameroon): Insights into Paleozoic–Mesozoic magmatism and geodynamic implications

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ABSTRACT

The broadly N70°–90°E-trending dykes swarm at Kekem cut across the Paleoproterozoic-to-Achean terranes of West Cameroon remobilized during the Pan-African orogeny. They are picrite basalts and basalts with tholeiitic/transitional affinity, as shown by mineralogical and geochemical data, with variable major and trace element contents, MgO ranges from 7.3 to 12.4 wt.%, Cr from 190 to 411 ppm, Ni from 15 to 234 ppm. All the dykes are light REE enriched with La_N/Yb_N values of 5.3–8.1, suggesting a co-magmatic origin. They originated from a 2.8% partial melting of a spinel-mantle source with no or little crustal input. The geochemical features of Kekem dykes are similar to those of Paleozoic and Mesozoic dykes recorded in North and Central Africa, suggesting multiple reactivations of pre-existing fractures that resulted in the fragmentation of western Gondwana and the opening of Central and South Atlantic Oceans.

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1. Introduction

The northern margin of the Congo craton recorded the 0.6 Ga Pan-African orogeny (also known as the Central Pan-African Fold belt; CAFB; Toteu et al., 2001). The CAFB is exposed in Cameroon, Nigeria, Chad and Central Africa Republic. It is linked to the Brasiliano orogen of northeastern Brazil in a pre-drift reconstruction (Fig. 1a). The geodynamic evolutionary models of the Cameroon segment (Fig. 1b) suggest an early extension that resulted in the formation of Early Neoproterozoic sedimentary basins followed by subduction and collision at 0.6 Ga between the São Francisco–Congo craton, the West African craton and the Saharan metacraton (Ngako and Njonfang, 2011), or between the Congo craton and the Saharan metacraton (Bouyo Houketchang et al., 2013). The post Pan-African tectonic evolution in West-Central Africa remains poorly known. During the Late Paleozoic and Mesozoic times, the regional tectonic regime of West-Central Africa was governed by tensional stresses originated from the reactivation of Central Africa Shear Zone (Guiraud and Maurin, 1991; Moreau et al., 1987; Tchouankoué et al., 2014) or St. Helena mantle plume activity (Coulon et al., 1996). In the Central Africa, this tectonic regime resulted in the formation of graben and extended intracratonic rift structures. These rifts were filled with Cretaceous sedimentary deposits, accompanied with Mesozoic to Early Cenozoic magmatism (Maluski et al., 1995). Tchouankoué et al. (2012, 2014) documented Paleozoic and Mesozoic magmatism, so far unknown within the Central Cameroon

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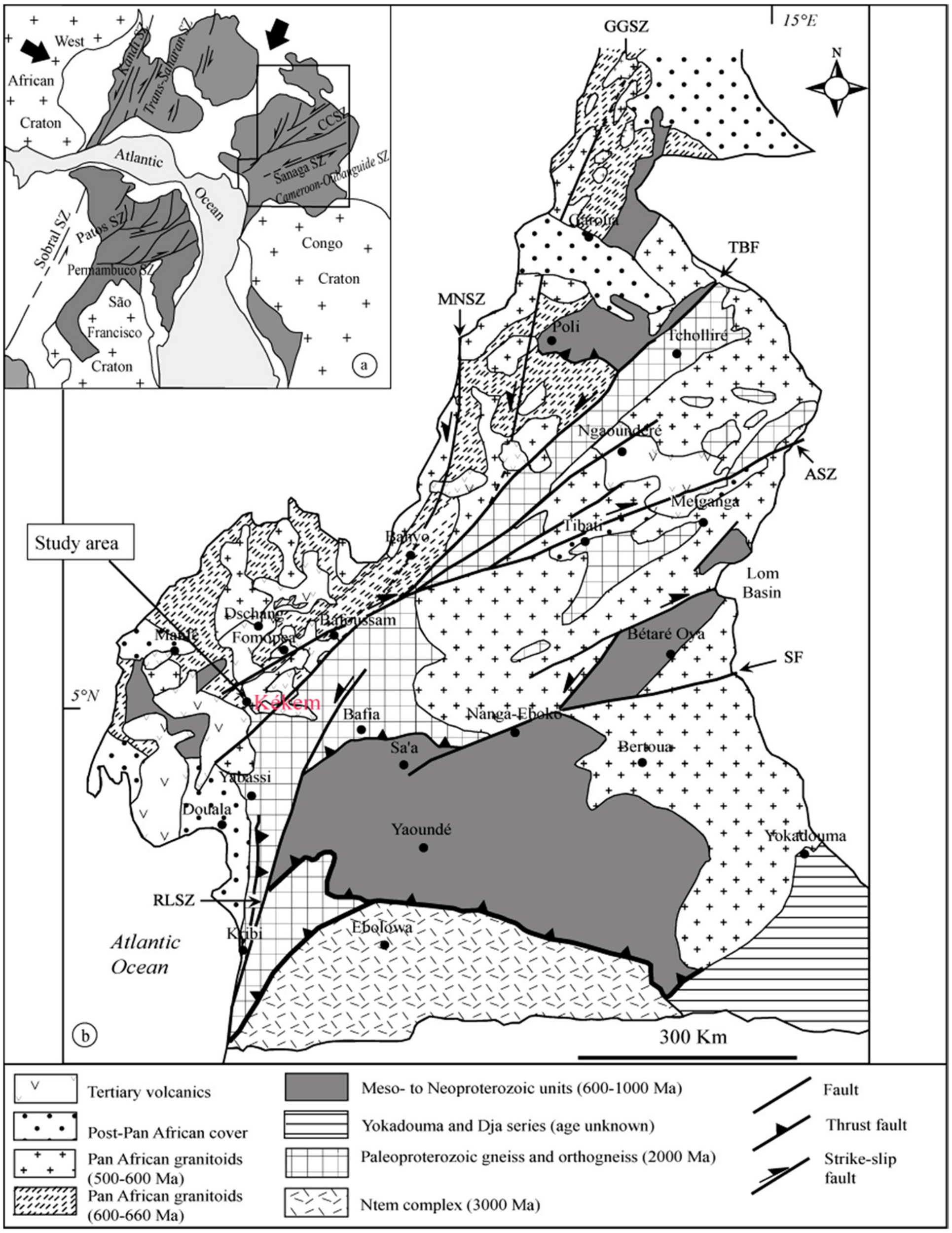

Fig. 1. a: Geological reconstruction of Africa and NE Brazil (Late Precambrian) after Caby et al. (1991). CCSZ: Central Cameroon Shear Zone; SF: Sanaga Fault; SL: São Luis Craton; Pa: Patos shear zone; Pe: Pernambuco shear zone. b: Pan-African structural map of Cameroon (Ngako et al., 2008; modified and re-interpreted by Toteu et al., 2001). Thick lines: shear zone (SZ); BSZ: Balché SZ; BNMB: Buffle Noir–Mayo Baléo; CCSZ: Central Cameroon SZ; GGSZ: Godé–Gormaya SZ; MNSZ: Mayo Nolti SZ; RLSZ: Rocher du Loup SZ; SSZ: Sanaga SZ. I: Paleoproterozoic basement and Pan-African syn-tectonic granitoids; II: Meso- to NeoProterozoic volcano sedimentary basins.

Shear Zone (CCSZ; Ngako et al., 1991), which underlines their geodynamic significance in the evolution of the Pan-African formation at the northern margin of the Congo craton. This magmatism is of great interest to understand the post-Pan-African crustal evolution in Cameroon and hence, the break up of the West Gondwana supercontinent.

Few mineralogical and geochemical data have been published on the Paleozoic to Mesozoic igneous rocks in Cameroon. Here, we present field, petrographic, mineral chemical and whole-rock geochemical data of the Kekem dykes swarm (Western Cameroon) and discuss the magmatic evolution, mantle source as well as their geodynamic significance in order to infer the post Pan-African tectonic evolution in Cameroon.

2. Geological setting

The Kekem area is located in the southwestern part of the CCSZ (Figs. 1b and 2a), which represents the northern limit of the Congo craton (De Plaen et al., 2014; Kwékam

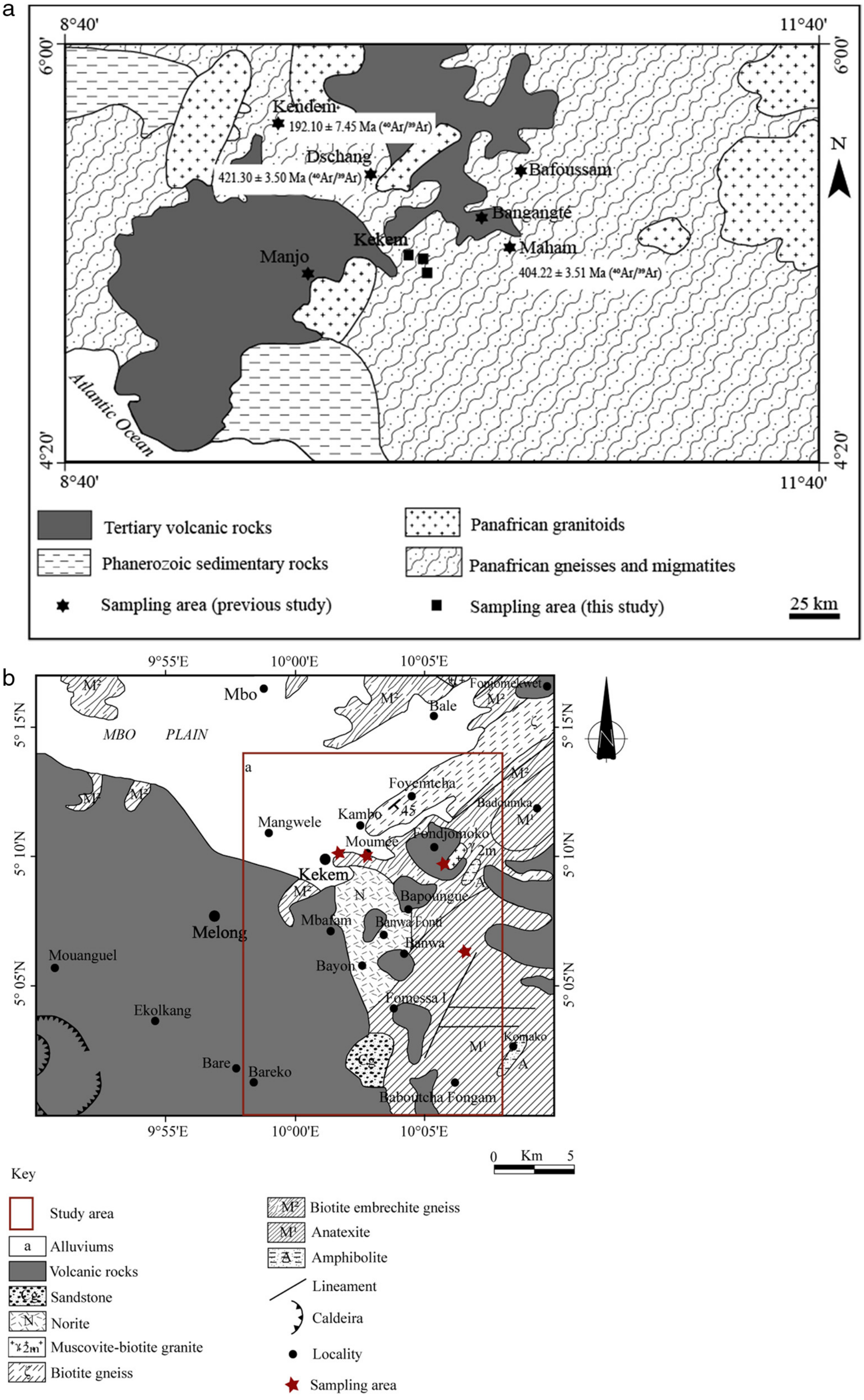

Fig. 2. Regional geological map and location of the dyke swarms: a: location of the dated dyke swarms. The coordinates of the basalt dyke in Dschang (N5°23'31''/E10°00'05''), Maham (5°02'02''N/10°41'51''E) and Kendem (5°45'36.10''N/9°42'30.04''E) are from Tchouankoué et al. (2014); b: simplified geological map of the Kekem area after Dumort (1968), with sampling area.

et al., 2013). This northern margin is made up of Paleoproterozoic to Tertiary rocks (Fig. 1b). The Paleoproterozoic rocks consist of 2.1Ga granulitic gneisses (with contribution of Archean material; Ganwa et al., 2016; Toteu et al., 2001), and thermally and structurally reworked during Pan-African orogeny (Penaye et al., 1993). They occur either as septa in the Pan-African formation or as belts in Nyong series at the NW border of the Congo craton (Toteu et al., 1994), which resulted from the 2.1Ga collision between Trans-Amazonian and Congo cratons (Penaye et al., 2004; Toteu et al., 2001). These Paleoproterozoic rocks are associated with the Pan-African formation, which belongs to the CAFB in Cameroon. The high-grade metamorphic rocks of CAFB are associated with pre-, syn- to post-orogenic granitoids with high-K calc-alkaline to shoshonitic, and alkaline affinity emplaced between 630 Ma and 550 Ma (Dawaï et al., 2013; Mosoh Bambi et al., 2013; Tchaptchet Tchato, 2011; Tchouankoué et al., 2016; Toteu et al., 2001) from the crustal thickening to the uplift of the fold belt with the majority emplaced during syn- to post-collisional stages (600–580 Ma; Toteu et al., 2004). Their emplacement is controlled by N30°E or N70°E striking transpressional/transcurrent strike-slip shear zones (Kankeu et al., 2009; Ngako et al., 2003; Njanko et al., 2006; Njiekak et al., 2008; Njonfang et al., 2008; Tcheumenak Kouémo et al., 2014), which are regarded as possible prolongations of the major shear zones of NE Brazil in a pre-drift Gondwana reconstruction (Brito Neves et al., 2002; Njanko et al., 2006). This lithospheric scale shear zone, which was still active until 552 Ma (Tchaptchet Tchato et al., 2009) is associated with a network of fractures (N25–30°E, N70°E, W–E, N135°E (Mvondo Ondoa, 2009; Njome and Suh, 2005; Njonfang et al., 2008). The trend of these fractures is compatible with Riedel's model kinematic evolution (Moreau et al., 1987; Mvondo Ondoa, 2009). Some of these fractures are intruded by Paleozoic and Mesozoic tholeiitic basalts (Tchouankoué et al., 2012, 2014). This magmatism is thought to be related to the reactivation of the CCSZ in relation with the rifting process that results in the opening of the South Atlantic Ocean (Tchouankoué et al., 2014). The reactivation of CCSZ might have generated sedimentary basins exposed along the Central North Cameroon (e.g., Mbéré basin) of which the sedimentary processes span from Cretaceous to Tertiary times (Tchouatcha et al., 2010). These lithologies are associated with alkaline magmatism of the Cameroon Volcanic Line (CVL), which is a SW–NE-oriented straight line of swells and basins running from Annobon Island (in the Gulf of Guinea) to Lake Chad. The CVL, which is made up of anorogenic complexes and flood basalts and has been active since Eocene to Present (Deruelle et al., 2007; Tchuimegnie Ngongang et al., 2015).

The Kekem area (Fig. 2b) consists of inter-layered Paleoproterozoic and Neoproterozoic high-grade metamorphic rocks intruded by Kekem plutonic complex (Dumort, 1968; Kwékam et al., 2013; Ngo Belnoun et al., 2013; Tchaptchet Tchato, 2011; Tchaptchet Tchato et al., 2009). The 2.1Ga Paleoproterozoic rocks consist of amphibole-biotite gneisses and garnet-pyroxene gneisses, which were metamorphosed under granulite facies at 2050 Ma (Penaye et al., 1993; Toteu et al., 2001) and subsequently metamorphosed into amphibolite facies during the Pan-African orogeny (Penaye et al., 2004). The Neoproterozoic rocks (garnet–biotite gneiss, sillimanite-bearing garnet–biotite gneiss) were recrystallized at high temperature amphibolite facies metamorphism at 580–570 Ma (EMP dating on monazites; Tchaptchet Tchato et al., 2009) or 600 Ma (zircon U–Pb; Tchaptchet Tchato, 2011) during the continental collision (Tchaptchet Tchato et al., 2009). These metamorphic rocks were overprinted by a 560–552-Ma strike-slip shear zone, which represents the southwestern prolongation of the Foutoni shear zone (Tcheumenak Kouémo et al., 2014). The intrusive complex consists of 580–547-Ma post-collisional intermediate to basic composition rocks (granite, monzonite, monzogabbro, norite, and gabbro) with high-K calc-alkaline to shoshonitic affinity (Kwékam et al., 2013; Ngo Belnoun et al., 2013;), which is interpreted as emplaced during late D_2 to D_3 transcurrent tectonic (Tchaptchet Tchato, 2011) or D_4 dextral shearing movement along the CCSZ. These intrusive rocks originated from crustal melting (Ngo Belnoun et al., 2013; Tchaptchet Tchato, 2011) with little input from the mantle (Kwékam et al., 2013). The metamorphic and plutonic rocks were partially covered by alkali basalts dated back to 10 up until 6 Ma (Tchuimegnie Ngongang et al., 2015).

3. Field occurrence

Mafic dyke swarms are dark colored, very fine-grained rocks, exposed in the localities of Moumé and Banwa (Fig. 2b). At Moumé, they are N70°E striking, sub-vertical dykes, of 0.2–2 m in width, crosscutting or, at places, digitizing 2.1Ga locally mylonitized Paleoproterozoic gneisses (Fig. MC1a, b, c). At Banwa, located to the east of the studied area (Fig. 2), the dykes are associated with west–east striking faults and intrude granites (MC1d). There are dark-colored rocks of 20–30 cm in width, cutting across the N20°-30°E mylonitized granites (Fig. MC1).

4. Results

4.1. Analytical methods

See Appendix A (MC7).

4.2. Petrographic features and major mineral chemistry

The Kekem dykes are porphyritic with phenocrysts of olivine and rare clinopyroxene in a subophitic groundmass (Fig. MC2) of olivine, plagioclase, clinopyroxene, and opaque oxides. Olivine phenocrysts are euhedral to subeuhedral, 1 × 1.5 mm in size. Clinopyroxene with grain size between 0.2 × 0.3 mm and 0.2 × 0.1 mm mainly occurs as subhedral to anhedral grains in the groundmass. Plagioclase occurs as euhedral to subhedral lath-shaped crystals, with size varying from 0.3 to 0.1 mm. Some plagioclase crystals bear oxide inclusions. Opaque minerals are subeuhedral to anhedral crystals frequently associated with clinopyroxene and olivine or as needle-shaped crystals within plagioclase laths. Cr-bearing spinels

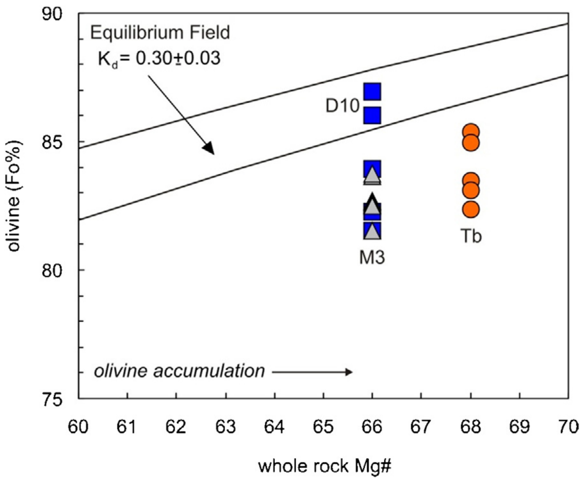

Fig. 3. Whole rock Mg# vs olivine composition (Fo%) for the Kekem dykes (only olivine core compositions are taken into account). The field represents the Fe–Mg partition coefficient between olivine and liquid ($K_d = 0.30 \pm 0.03$; Roeder and Emslie, 1970).

are enclosed in olivine phenocrysts. Alteration effects (not widespread) are shown by the presence of clay minerals, chlorite, calcite, iddingsitization of olivine.

Olivine is relatively homogeneous in composition apart from thin more Fe-rich rims (Supplementary Table MC3). Olivine core composition of individual samples vary from 81 to 87 Fo mol% (where Fo = 100 × Mg/[Mg + Fe]). The olivine compositions plot well below the equilibrium Kd band, implying forsterite contents too low to be in equilibrium with the whole-rock Mg# (66-68) values. Few olivine phenocrysts (sample D10) seem to be in equilibrium with their host rock (Fig. 3). NiO ranges from below detection limits to 0.5 wt.%. CaO ranges from 0.1 to 0.4 wt.% (Supplementary Table MC3). The olivines in the sample D10 are equilibrated at ~1170 °C (according to Roeder and Emslie, 1970).

The clinopyroxene of the Kekem dykes falls in the diopside/salite field or close to the diopside–augite limit, with rare Fe–augite ($Ca_{49-41}Fe_{12-38}Mg_{44-17}$; Fig. 4a; Mg# = 32-81; where Mg# = 100*Mg/[Mg + Fe]). The most Mg-rich clinopyroxenes have been found in samples Tb, M3 and D10. Ti and Al increase with decreasing Mg in the sample Tb, whereas Ti and Al decrease with decreasing Mg in the other samples (Supplementary Table MC4; Fig. 4b,c). The chemical composition of clinopyroxene (particularly the TiO_2 content, which reaches values as high as 4.4 wt.% in groundmass salite crystals of sample Mb) is strongly indicative of different magma groups and crystallization histories for the Kekem dykes. The composition of the clinopyroxenes of the Kekem dykes is similar to that of the clinopyroxenes of the basaltic dykes from Bangangte, Dschang and Manjo, and the Bangangte plateau basalts (southern continental part of the Cameroon Volcanic Line; Tchouankoué et al., 2012). The clinopyroxenes of the Kekem dykes indicate a relatively alkaline affinity of the parental magmas.

Plagioclase shows a wide range in composition from labradorite (An_{71}) to oligoclase (An_{17}) (Supplementary Table MC5; Fig. 5a). The iron content (as FeO_t) ranges from below detection limits to 1.3 wt.%.

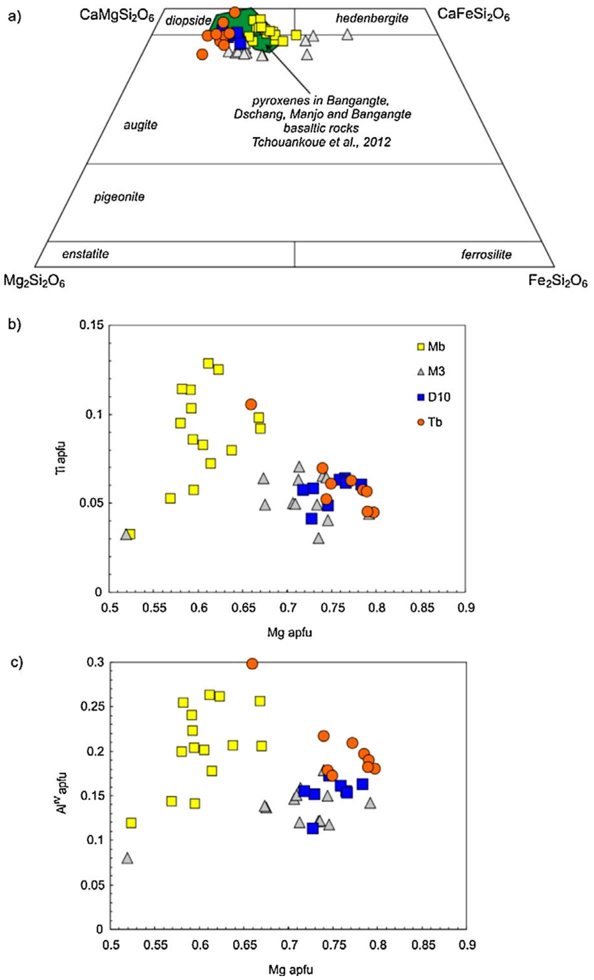

Fig. 4. a: pyroxene compositions projected in the Ca–Mg–Fe diagram for the Kekem dykes. The data of clinopyroxenes of basaltic dykes from the Bangangte, Dschang, Manjo and Bangangte plateau basalts (southern continental part of the Cameroon Volcanic Line; Tchouankoué et al., 2012) are shown for comparison; b: Ti vs. Mg (in apfu) for the Kekem clinopyroxenes; c: Al vs. Mg (in apfu) for the Kekem clinopyroxenes.

Cr-bearing spinel occurs as small inclusions in olivine phenocrysts. The compositional range observed is wide with Al_2O_3 varying from 26.2 to 42.2 wt.%, Cr_2O_3 varying from 19.7 to 33.7 wt.% (Cr# = 24–43; where Cr# = 100 × Cr/[Cr + Al]), and MgO varying from 5.5 to 15.9 wt.% (Mg# = 27–66; Supplementary Table MC6). Samples Mb, M3 and D10 have spinels that are distinctly richer in Cr than those of sample Tb (Fig. 5b). The lower Cr contents of spinels in the sample Tb clearly indicate different and unrelated parental magmas with respect to the basaltic dykes Mb, M3, and D10.

Titaniferous magnetite and ilmenite are the main oxides found in the Kekem dykes. The Ti-magnetite has between 61 to 84 mol.% ulvöspinel and widely variable Al_2O_3 (from 1.5 to 3.3 wt.%) (Supplementary Table MC6). Ilmenites have a limited range of solid solution toward hematite and have low Al_2O_3 (< 0.5 wt.%) and MgO (< 2.7 wt%) contents (Supplementary Table MC6). Equilibrium temperatures and oxygen fugacities of coexisting

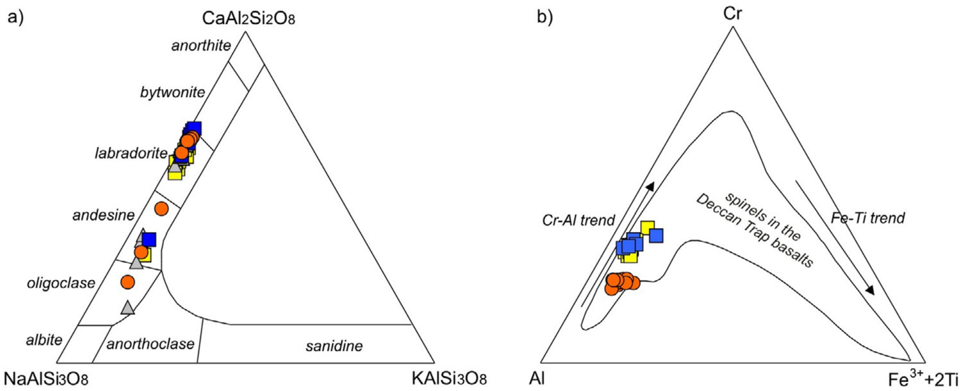

Fig. 5. a: feldspar compositions observed in the Kekem dykes; b: chemical variations of chromium-rich spinels in the Kekem dykes. The field of spinels of the Deccan Traps rocks is also shown (Cucciniello et al., 2015; Melluso and Sethna, 2011 and references therein).

magnetite and ilmenite, calculated using the ILMAT program of Lepage (2003), range from 1167 to 511 °C and from−9.4 to−27.8 log f_{O_2} units, plotting close to the synthetic quartz–fayalite–magnetite (QFM) buffer. The ilmenite-magnetite pairs that re-equilibrated in the subsolidus plot towards the wüstite–magnetite (W–M) buffer.

4.3. Whole-rock geochemistry

The Kekem dykes are tholeiitic/transitional basalts according to the total alkali–silica (TAS; LeBas et al., 1986) diagram (Fig. 6) and CIPW norms. Samples Tb, Tc, Ma, M2, M3 and D20 are olivine-hypersthene normative (hy = 0.72%–13.96%) and samples D10 and M1 are nepheline (ne = 0.65%) and quartz (2.51%) normative, respectively. Dykes characterized by high MgO contents (MgO > 12 wt.%) can be classified as picrites (they are not ferropicrites having total iron as Fe_2O_3 lower than 13 wt.%). The Kekem dykes show a loss on ignition (LOI) value between 1.6 and 3.4 wt.%, suggesting that they underwent low to moderate alteration in agreement with their petrography. We therefore use in this paper only alteration-resistant elements (Ti, Zr, Nb, Y, Th and REEs and their ratios) for geochemical modeling and interpretation. In addition, major oxide compositions are based on analyses normalized to 100 wt.% on a volatile-free basis. The Kekem dykes are characterized by low to moderate TiO_2 (1.4–2.2 wt.%), Nb (6–37 ppm) and Zr (84–381 ppm) concentrations. MgO ranges from 7.4 to 12.4 wt.% (Mg# = 57–71, where Mg# = molar $Mg^{*}100/[Mg + Fe^{2+}]$). Compatible trace elements such as Cr and Ni show considerable range (Cr from 190 to 411 ppm; Ni from 15 to 234 ppm). The most primitive basaltic dyke (M2) with Mg# = 71, Cr = 411 ppm and Ni = 234 ppm. These values are consistent with mantle-derived primitive melts. Primitive mantle-normalized multi-element patterns of Kekem basaltic dykes are variably enriched in Rb, Ba and light rare earth elements (REEs) relative to Zr, Hf, Ti and the heavy REEs (Fig. 7a). The REE patterns (Fig. 7b) show moderate light REE enrichment ($La_n/Yb_n = 5–8$). The absence of negative Europium anomalies is consistent with the complete lack of significant feldspar fractionation.

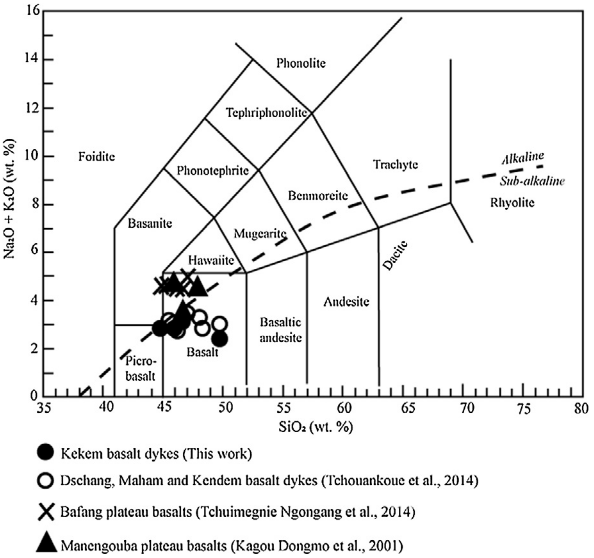

Fig. 6. TAS classification of LeBas et al. (1986). The dashed line (after Irvine and Baragar, 1971) delineates the boundary between the alkaline and subalkaline domains. Data for comparison are from Kagou Dongmo et al. (2001); Tchouankoué et al. (2014); Tchuimegnie Ngongang et al. (2015); Kagou Dongmo et al. (2001).

5. Discussion

5.1. Fractionation and magma source region of the Kekem dyke swarm

The Kekem dykes show incompatible element concentrations and ratios that can be related either to the source heterogeneity and/or to shallow level evolutionary processes. The range of MgO (7.40–12.41 wt.%), Ni (15–234 ppm) and Cr (190–410 ppm) contents indicate that olivine fractionation (+ Cr-rich spinel) played an important role in the evolution of the Kekem dykes. However, the olivine fractionation will not significantly change the incompatible element ratios of magmas. The Kekem basaltic dykes show moderate Zr/Nb ratios (9–14) and high Zr/Y ratios (4–11), Nb/Yb ratios (5–8) and Ti/V ratios (48–71), typical of magmas rich in incompatible elements,

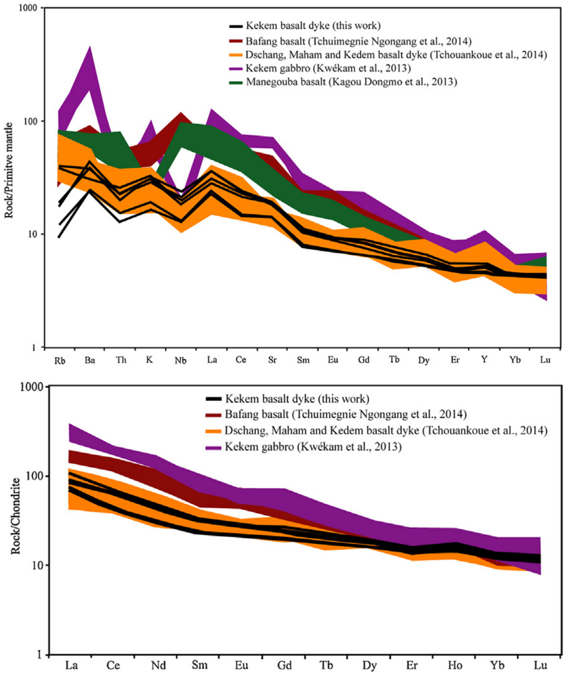

Fig. 7. a: Primitive mantle-normalized incompatible trace elements for the Kekem dykes; b: chondrite-normalized REE for the Kekem dykes. The data for the basaltic dykes (Dschang, Maham and Kendem) are from Tchouankoué et al. (2014), Kekem Gabbro from Kwékam et al. (2013), flood basalts of Bafang from Tchuimegnie Ngongang et al. (2015) and Manengouba from Kagou Dongmo et al. (2001). The normalization values are from Sun and McDonough (1989).

such as ocean island basalts (OIB) (e.g., Sun and McDonough, 1989).

Trace element ratios such as Nb/U, Th/Nb and La/Nb are commonly used to assess the role of crustal contamination in basaltic rocks because they are not strongly modified from their source material by partial melting or fractional crystallization processes. The continental crust has low Nb/U (4.4–25) and high La/Nb (1.6–2.6) and Th/Nb (0.24–0.88) ratios (e.g., Rudnick and Gao, 2003). The Kekem dykes have Nb/U (29–32), Th/Nb (0.12–0.14) and La/Nb (1.5–1.8) ratios suggesting small crustal input. Furthermore, they show small negative Nb anomalies on the primitive mantle-normalized multi-element patterns (Fig. 7a), reflecting small crustal contamination. However, the Nb anomalies could be interpreted as source characteristics (Bensalah et al., 2013). In the Nb/Zr vs. Nb/La diagram (Fig. 8; Dadd et al., 2015), the data of Kekem dykes plot close to subcontinental lithospheric source. Therefore, the large range of geochemical compositions of the studied dykes is probably due to the heterogeneity of their mantle source region. Bensalah et al. (2013) distinguishes lithospheric from asthenospheric magma sources based on La/Ta and La/Nb ratios. The lithospheric sources are characterized by La/Ta > 22 and La/Nb > 1.5 whereas the asthenospheric sources have La/Ta < 22 and La/Nb < 1.5. The studied rocks display La/Ta (47–262) and La/Nb (1.5–1.8) suggesting a lithospheric origin.

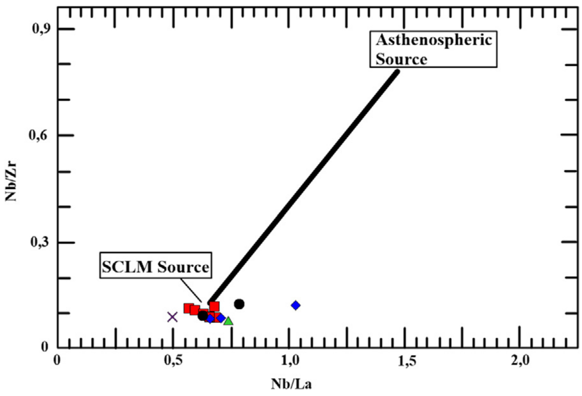

Fig. 8. The data of basaltic rocks from Dschang, Maham, Kendem and Bangoua are also shown (Tchouankoué et al., 2012, 2014).

In summary, the geochemical signatures and particularly the immobile incompatible element ratios of the Kekem dykes closely correspond to magmatic compositions. Fractional crystallization and crustal contamination have not notably overprinted the geochemical signature of Kekem dykes. The Kekem dykes with high MgO, Ni and Cr contents record geochemical characteristic of primary melts, and can be regarded as geochemical tracers of mantle source regions. The Visual Basic Excel spreadsheet of Lee et al. (2009) was used to constrain the major element compositions, temperature and depth of primary melts. This program is only valid for basaltic rocks that have fractionated along olivine-control line and reverse-fractionates the olivine crystallization (or accumulation for picrites). In addition, the average pressures and temperatures calculated are reliable only for primary mantle-derived magmas that came from a peridotitic (ol + opx + cpx) source (see Lee et al., 2009 for further details). The Kekem dykes have only fractionated olivine and so are suitable for modeling considering magmas with > 9.0 wt.% MgO and assume $Fe^{3+}/Fe = 0.1$ and forsterite of the mantle source of 0.9. The temperatures and pressures of the primary magmas are respectively of 1392–1435 °C and 1.8–2.1 GPa (~60–75 km), falling above the dry lherzolite solidus and the spinel–garnet transition (e.g., 80–100 km; Robinson and Wood, 1998). The Kekem data yield mantle potential temperatures around ~1415 °C, which is slightly hotter than the average ambient mantle ~1350 °C (e.g., Lee et al., 2009 and references therein).

To evaluate the melting processes involved in the formation of the Kekem dykes, we used the non-modal fractional melting mode (Shaw, 1970). The estimated composition of the primitive mantle (PM; Lyubetskaya and Korenaga, 2007) has been chosen as the potential mantle source, considering, as extreme cases, a spinel and a garnet facies. The source modal composition range is 53–60% olivine, 27–20% orthopyroxene, 17–10% clinopyroxene, and 3% spinel or 10% garnet. The amounts of minerals participating in the melt used in the model are as follows: spinel-bearing lherzolite source–6% olivine, 28% orthopyroxene, 67% clinopyroxene and 11% spinel; garnet-bearing lherzolite source 3% olivine,–16% orthopyroxene, 88% clinopyroxene, and 9% garnet. Mineral/melt distribution coefficients are from Niu et al. (1996). The results indicate that the Kekem dykes could be produced by 2–8% melting of a primitive source in the spinel stability field (Fig. 9). Our modeling implies that the Kekem magmas were generated at shallow depth (~80–100 km; Robinson and Wood, 1998) in a within plate environment.

Several dyke swarms crop out in the central domain of the Cameroon Pan-African fold belt (also referred to as the South Continental part of the Cameroon Volcanic Line; Tchouankoué et al., 2014). Fig. 7a shows that the Kekem dykes have incompatible element patterns similar to those of the Dschang, Maham and Kendem basaltic dykes (Tchouankoué et al., 2014), suggesting a common mantle source. The basalt dykes of the southern continental part of the CVL were emplaced in the same geological environment, characterized by Paleoproterozoic to Archean crust remobilized during Pan-African orogenesis (Ganwa et al., 2016; Toteu et al., 2001).

5.2. Comparison with other regional igneous events

The differences between the basaltic dykes of CCSZ and Cenozoic alkali basalts of the Cameroon Volcanic Line (Mt Manengouba; Kagou Dongmo et al., 2001; Bafang region; Tchuimegnie Ngongang et al., 2015) and the post-collisional Kekem Neoproterozoic Gabbro (Kwékam et al., 2013) are highlighted in Fig. 7. The Kekem dykes are different from those of the Bafang and Manengouba basalts, which have higher LREE, MREE contents and no Nb anomalies in the primitive mantle-normalized diagram (Fig. 7a). The alkali basalt of the Cameroon Volcanic Line appears to have been derived from a distinctly more enriched mantle source, with no crustal contamination. The Kekem gabbros have higher incompatible element contents than Kekem dykes and negative Nb anomalies in the primitive mantle-normalized multi-element patterns (Fig. 7). Kwékam et al. (2013) argued that the Kekem gabbros were derived from the partial melting of a garnet-spinel lherzolite mantle source. The negative Nb anomalies indicate that this mantle source was modified by the contribution of a subduction-related material (Kwékam et al., 2013).

As discussed above, the Kekem dykes and the other dyke swarms of CCSZ originated from a source area different from those of post Pan-African collision gabbros and CVL basalts in the studied area. This fact precludes any relationship between CCSZ dyke swarms and alkali basalts of the Cameroon Volcanic Line, and reinforces the hypotheses of Tchouankoué et al., 2012, 2014) that the dyke swarms represent magmatic events different from those of the Cenozoic Cameroon Volcanic Line.

5.3. Geodynamic implications of the Kekem as well as the other dykes swarm of the CCSZ

Trace elements ratios are currently used to constrain the tectonic setting of dyke swarms (Bensalah et al., 2013). In Fig. 10 most of the Kekem dykes as well as those of the CCSZ plotted in within plate basalts field. These dykes swarm are associated with a network of post-pan-African fractures whose arrangement is compatible with Riedel's fracture model (Moreau et al., 1987; Mvondo Ondoa, 2009).

The N70–90°E oriented dykes swarm yielded an age of 421.3 ± 3.5 Ma (^{40}Ar/^{39}Ar) in Dschang (Tchouankoué et al., 2014), 404.2 ± 3.2 (^{40}Ar/^{39}Ar) and 417 ± 8.1 (^{40}K/^{39}Ar) in Maham (Tchouankoué, 2005; Tchouankoué et al., 2014). The ^{40}Ar/^{39}Ar age interval overlaps with the less imprecise age of K/Ar obtained in Maham, which suggests that they might belong to a same magmatic event. The field study, the geochemical features as well as the mineralogy data are similar to those of the Dschang and Maham areas, whose emplacement age is bracketed between 420 and 404 Ma (^{40}Ar/^{39}Ar age). Therefore, such a time interval can be constrained to the Kekem dyke swarm. Such a magmatic event is not widespread in Cameroon. However, a 428 ± 5.2 Ma magmatic event is reported in Senegal at the eastern border of the West African craton (Fullgraf et al., 2013). These magmatic events display a similar magma source region. Furthermore, both regions occupied the central Gondwana in the pre-drift reconstruction. These similarities suggest that the syn-rift magmatism as well as the opening of the Rheic Ocean ascribed to the Senegal Paleozoic can be envisaged for Cameroon dyke, and therefore the latter belongs to the same event.

The N25°–35°E oriented fractures in Bangoua and Kendem yielded ages of 214 ± 6.6 Ma (^{40}K/^{39}Ar) and 192.1 ± 7.5 Ma (^{40}Ar/^{39}Ar), respectively (Tchouankoué,

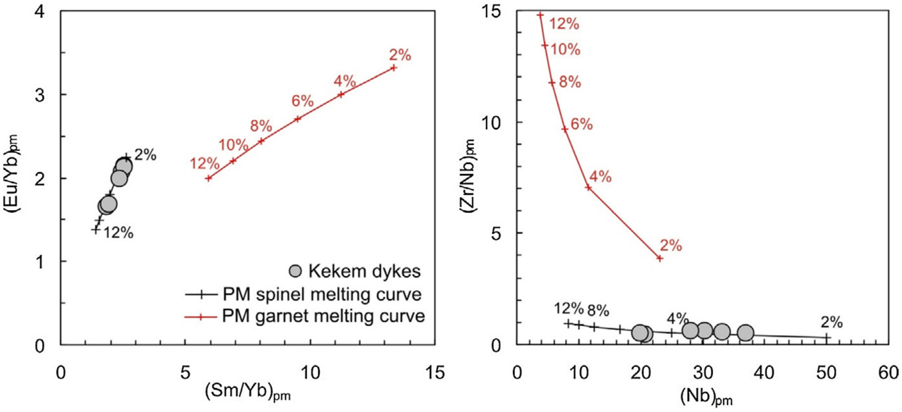

Fig. 9. (Eu/Yb)pm vs (Sm/Yb)pm and (Zr/Nb)pm vs (Nb)pm diagrams illustrating non-modal fractional melting models for the Kekem dykes. The values along curves are the degrees of partial melting. The Kekem dykes correspond to a 2–8% melting in the spinel lherzolite field.

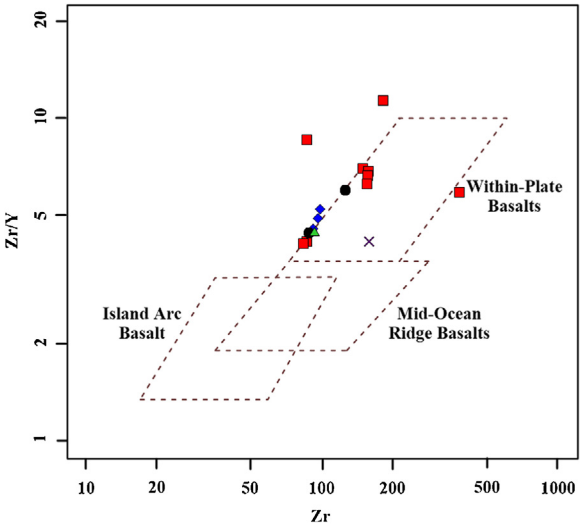

Fig. 10. Zr/Y vs Zr diagram (Pearce and Norry, 1979) for the Kekem dykes. ■ Kekem (this study), ● Dschang, × Maham, ▲ Kendem and ◆ Bangoua (Tchouankoué et al., 2012, 2014).

2005; Tchouankoué et al., 2014). Both ages might belong to a same magmatic event and the slight difference should be due to the imprecision of K/Ar method (Maluski et al., 1995). Given that ^{40}Ar/^{39}Ar age is more reliable that ^{40}K/^{39}Ar age, the age of 192.1 Ma recorded in Kendem fall within the interval of Triassic–Jurassic magmatism constrained at 200–190 Ma (^{40}Ar/^{39}Ar; Vérati et al., 2007) that affected America, Africa and the European continent. However, its geodynamic significance is diversely interpreted. It is considered as the early stage of the opening of the South Atlantic Ocean in South America (Thomaz-Filho et al., 2000) or of the lithospheric extension that results in central Africa rift (Youbi et al., 2003). This magmatic event displays similarities with the Kendem dyke swarm that yielded an age of 192 Ma (^{40}Ar/^{39}Ar, Tchouankoué et al., 2014), which falls in the interval between 200 and 190 Ma. These features suggest that the Kendem dyke in Cameroon is likely the manifestation of this magmatism in Cameroon. However, the lithospheric extension can be envisaged for Kendem dykes during the Triassic–Jurassic rift in the Central Africa rift, as the Kendem fracture trend (N25°E) is consistent with an ENE–WSW extensional direction suggested for the Benue Trough dyke swarm dated back to 148 Ma (Maluski et al., 1995), interpreted as the forerunners of the opening of the South Atlantic ocean (Maluski et al., 1995), which suggests that the latter have previously experienced an extension. This argument precludes any correlation with an early opening of the South Atlantic Ocean, as reported by Tchouankoué et al. (2014).

The age of 148 ± 38 Ma (obtained with K/Ar method) in Bangoua (Tchouankoué, 2005) is close to the dyke swarm ages (146–106 Ma, obtained with Ar/Ar method) of tholeiitic affinity, well documented in the northern area of the Benue Through in Nigeria (Maluski et al., 1995), and to the 145–127.5 Ma ages of the alkaline igneous rocks from the Parana–Etendeka large igneous province in the South American continent (Gibson et al., 2006). Both events were previously interpreted as forerunners of the extension of the South Atlantic Ocean (Maluski et al., 1995). However, Gibson et al. (2006) considered them as resulted from a plume–lithosphere interaction. In Cameroon, in the stage of knowledge, no data about large igneous province associated with a dyke swarm of such an age was reported. Rather, magmas generally consisting of high Mg and Ni contents suggest plume activity related magmatism (Gibson et al., 2006) and tholeiitic affinity is indicative of a lithospheric extension (Gibson et al., 2006; Kuepouo et al., 2006; Maluski et al., 1995; Youbi et al., 2003). Therefore, the role played by the lithospheric extension should not be excluded and the interplay between both phenomena should be taken in account. This implies that a plume–lithosphere interaction is the most plausible explanation, as suggested by Gibson et al. (2006). From a regional point of view, the northern Benue trough and the Bangoua area are located in central Africa, which suggests that both dyke swarms might belong to a same magmatic episode. Accordingly, the hypothesis of forerunners of the extension of the South Atlantic Ocean applied in Northern Benue can be envisaged in the Bangoua dyke swarm in Cameroon. This interpretation is consistent with structural studies that suggest an ENE–WSW extensional direction that reactivated pre-existing Pan-African fractures, leading to the formation of intracontinental NNE–SSW- and east–west-oriented graben systems transferred along N60°E sinistral faults (Maluski et al., 1995), as the N25–35°E oriented dyke swarm in Kekem matches well with one of the two directions.

The field relation (this study) and geochronological data (^{40}Ar/^{39}Ar and ^{40}K/^{39}Ar ages) on the mafic dyke swarm show that they post-date the pan-African deformation (Tchouankoué et al., 2014). N20 and N70 °E striking tholeiitic dyke swarms were reported in NE Nigeria, especially in the Benue Through (Maluski et al., 1995). The orientation of dyke swarms in Cameroon and NE Nigeria is consistent with Riedel's fractures kinematic model (Moreau et al., 1987; Mvondo Ondoa, 2009), suggesting that they resulted from a same tectonic event. In fact, both areas are located within the Central Africa Pan-African Shear Zone, and it has been demonstrated that the activity of such a large-scale shear zone is capable to originate similar structural associations (Moreau et al., 1987). Therefore, the late dextral shearing movement dated at 552 Ma (EMP dating on monazite; Tchaptchet Tchato et al., 2009) along the CCSZ, which served as pathways for the ascent into the surface of tholeiitic magma, is consistent with the geometric arrangement of this Pan-African fracture network and the hypothesis of a reactivation of Pan-African structures that originated from the Cretaceous sedimentary basins with which the dyke swarms are associated (Noutchogwe et al., 2010). These within-plate basalts derived from lithospheric extension (Kuepouo et al., 2006; Maluski et al., 1995; Youbi et al., 2003), which is consistent with the geophysical data of Tokam et al. (2010), in which the crustal thickness in Cameroon is significantly thinned under Cretaceous sedimentary basins.

6. Conclusion

The Kekem dyke swarm occurrence is associated with N70–90°E-striking vertical fractures, which belong to the network of post Pan-African fractures cross cutting the Precambrian terranes. They are within-plate tholeiitic/transitional basalts originating from partial melting of a spinel lherzolite lithospheric mantle source in contrast to Cenozoic Cameroon Volcanic Line and Late Neoproterozoic magmatism, which are rather deeper mantle-source-derived magmas (garnet-bearing lherzolite).

The Kekem dykes swarm shows mineralogical, geochemical features and mantle source similar to those of Kendem, Maham and Dschang. In addition, the similar occurrence with Maham and Dschang dyke swarms, which yielded respectively an age of 420 Ma and 404 Ma, points to an age constrained between 420 and 404 Ma for Kekem dyke swarms. The Paleozoic basaltic magmatism documented in the Central Africa Fold Belt, which is part of West Gondwana in the pre-drift reconstruction, likely represents the northwest fragmentation.

The post pan-African crustal evolution in Cameroon is characterized by three successive extensional tectonic episodes, which result in the fragmentation of northwestern Gondwana, the Central Atlantic rift and the opening of the South Atlantic Ocean during the Paleozoic, the Triassic-Jurassic and the Early Cretaceous, respectively. These above-mentioned extensional events were controlled by the pre-existing fractures in the Precambrian lithosphere.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crte.2017.02.005.

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