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Microstructures and magnetic fabrics of the Ngaoundéré granite pluton (Cameroon): Implications to the late-Pan-African evolution of Central Cameroon Shear Zone

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ABSTRACT

The Ngaoundéré granite pluton, in Central-North Cameroon, located near the Central Cameroon Shear zone (CCSZ), and previously studied for its petrography and geochemistry, is characterized by the absence of macroscopic markers of deformation. In this study, we report microstructures and magnetic fabrics (AMS) of this pluton and discuss the relationship with the Pan-African evolution of the CCSZ. The pluton consists of a porphyritic Hbl-Bt-monzogranite at its rim and a porphyritic biotite-granite at its core, a petrographic distribution denoting a normal zoning pattern, *i.e.* more silicic toward the centre. As expected, magnetic susceptibilities values also exhibit a zoning pattern in agreement with petrographic zonation. Thermomagnetic data indicate that this pluton is dominantly ferromagnetic in behaviour. As indicated by its microstructures, the pluton has suffered a continuum of deformation from the magmatic state to the high temperature solid-state during magma crystallization and solidification. The magnetic foliations dominantly strike NE-SW and dip moderately to steeply and the lineations mostly plunge shallowly to the NE or SW, roughly parallel to NE-to ENE-trending Central Cameroun Shear Zone (CCSZ). The foliation poles define a girdle pattern with a zone axis (52°/11°) rather close to the best line of the lineations (44°/21°). These fabrics correlate with the structures of the country rocks ascribed by several workers to a regional transpression. Toward the margins of the pluton, particularly the northern one, the lineations tend to rotate from NE to N in azimuth. This change is interpreted as due to strain partitioning, simple shearing with NE-SW extension being relayed by compression toward the northern pluton border. This new magnetic fabric study suggests that the Ngaoundéré pluton (poorly dated at *c.* 575 Ma) was emplaced during the late stages of the CCSZ dextral transpressive movement. It also provides some more constraints on the correlation between the CCSZ system and the shear zone system of NE-Brazil.

1. Introduction

The break up of West Gondwana which took place during the Mesozoic led to the disruption of the Brasiliano-Pan-African belt into Africa and South America. During the last decades, several studies were conducted for a better reconstruction of the Pre-Mesozoic correlation between these two continents (De Witt et al., 2008; Van Schmus et al., 2008; Guimaraes et al., 2009; Archanjo et al., 2013; Ganade et al., 2016). There is no consensus, however, for the adjustment between the geological domains identified on both sides of the equatorial Atlantic Ocean. This is mainly due to the limited data in central Africa, one of the most poorly understood parts of West Gondwana.

Large-scale shear zones are currently considered as key features to pre-drift reconstruction (De Witt et al., 2008). Numerous shear zones are identified in the Pan-African domain of Adamawa-Yadé (Central-North Cameroon) among which the Adamawa fault, also known as the Central Cameroon Shear Zone, or CCSZ (Ngako et al., 1991), is one of the most important. This NE-SW trending major

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lithospheric structure extends from south Sudan to Cameroon (Dumont, 1986; Ngako et al., 1991, 2003, Fig. 1) and continues into northeastern Brazil (De Witt et al., 2008; Van Schmus et al., 2008). In Cameroon, high-grade and migmatitic gneisses, and numerous granitic intrusions outcrop near the CCSZ and its branches.

From the structural point of view, due to a lack of macroscopic deformation structures recorded in the granitic intrusions that outcrop along the Central-North Cameroon shear zones, the evolution of the CCSZ is mostly known through the studies of gneissic rocks (Njonfang et al., 2006, 2008; Ganwa et al., 2011; Kankeu et al., 2012). Accordingly, the last stages of this shear zone are relatively poorly known. According to Ngako et al. (2008), the emplacement of granitic intrusions in the Pan-African domains of Cameroon was controlled by the action of the various dextral wrench faults. It is therefore inferred that such intrusions behave as “invisible” markers of the action of strike-slip faulting during the Pan-African/Braziliano orogenesis. To reveal these markers and constrain the relationship between the emplacement of granite and the regional tectonics, several studies (Archanjo et al., 2008, 2013; Majumder and Mamtani, 2009; Dawaï et al., 2013; Adissin Glodji et al., 2014; Olivier et al., 2015 amongst others) demonstrate the usefulness of combining microstructural analyses and magnetic fabrics. In this study we adopt a similar approach. The Ngaoundéré pluton being apparently isotropic and spatially closely associated with the CCSZ, the structural relationships of this pluton with the shear zones may help to understand its role during the late Pan-African orogeny, hence to contribute to a better reconstruction of West Gondwana puzzle.

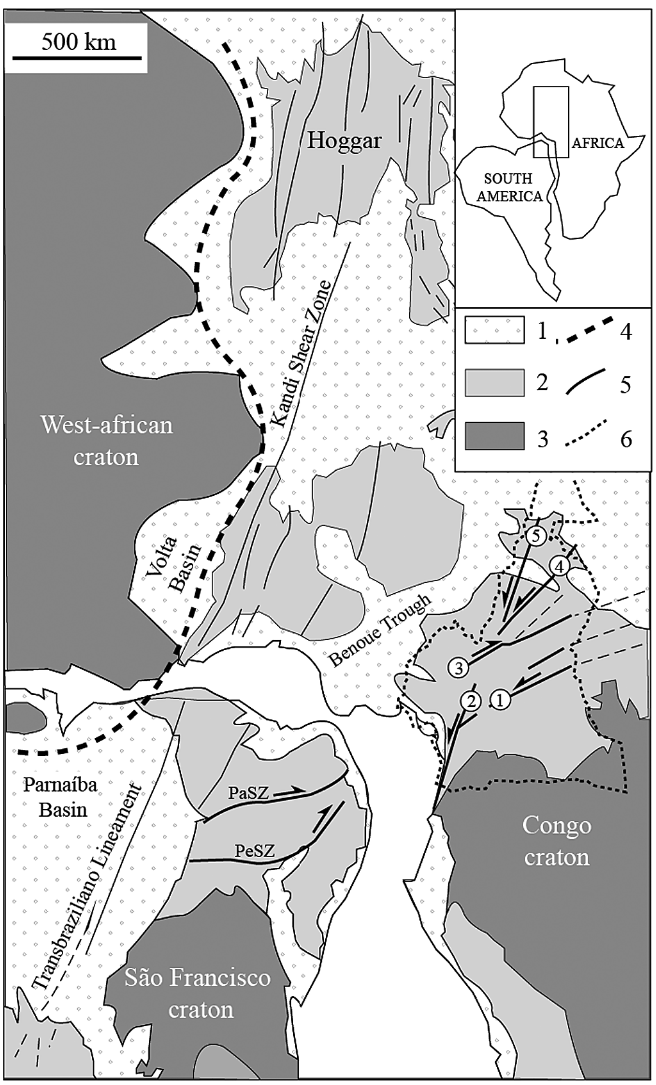

Fig. 1. West African and North-Eastern Brazil Neoproterozoic shear zones before South Atlantic Ocean opening with focus on the connection between the northern Borborema Province (NE-Brazil) and Cameroon (after Caby, 1989; modified). 1: Post-Braziliano-Pan-African sediments; 2: Braziliano-Pan-African belt; 3: Cratons; 4: Suture zone; 5: Shear zones: PaSZ: Patos; PeSZ: Pernambuco; 6: Contour of Cameroon, see Fig. 2; ①: Sanaga fault (after Ngako et al., 2008); ②: Rocher du Loup shear zone (after Toteu et al., 1994); ③: Central Cameroon shear zone (after Ngako et al., 2003); ④: Tcholliré-Banyo shear zone (after Toteu et al., 2004); ⑤: Gode Gormaya shear zone (after Ngako et al., 2008).

2. Geological setting

2.1. Adamawa-Yadé domain

The Central African Fold Belt (CAFB) is a major feature that resulted from the collision between the Congo craton, the West-African craton (Toteu et al., 2004) and the Saharan metacraton (Ngako et al., 2008; Liégeois et al., 2013). In Cameroon, this belt is commonly subdivided into three main domains (Toteu et al., 2004; Ngako et al., 2008; Van Schmus et al., 2008): (i) the South Cameroon domain lies south of the Sanaga fault; (ii) the Adamawa-Yadé domain, also known as Central Cameroon domain, is located between the Sanaga fault to the south and the sinistral Tcholliré-Banyo fault (TBF) to the north, and is cross-cut by the CCSZ, and (iii) the North-West Cameroon domain extending to the NW of the Tcholliré-Banyo fault (Fig. 2).

Previous geological and geochronological works (Toteu et al.,

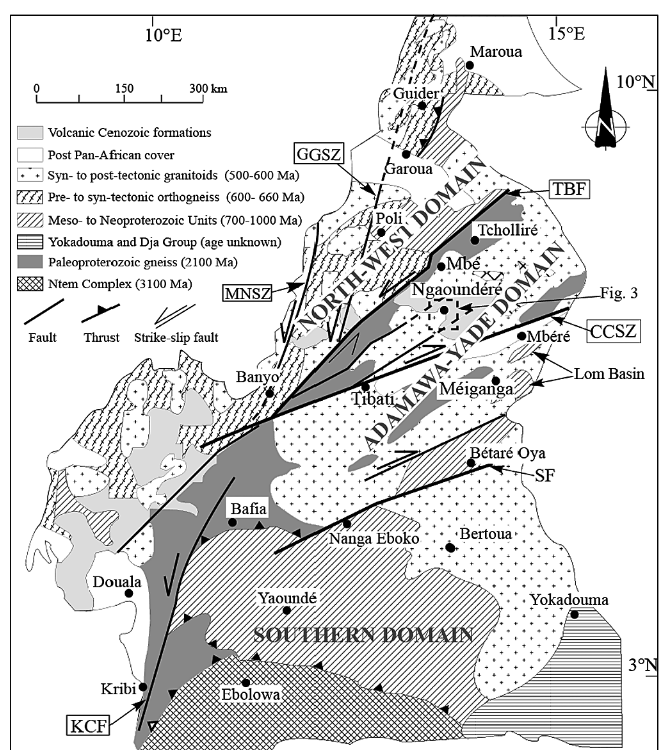

Fig. 2. Simplified geological map of Cameroon modified from Toteu et al. (2001) and Tchameni et al. (2006). CCSZ: Central Cameroon shear zone; GGSZ: Gode-Gormaya shear zone; KCF: Kribi-Campo fault; MNSZ: Mayo-Nolti shear zone; SF: Sanaga fault; TBF: Tcholliré-Banyo fault.

2001, 2004; Ganwa et al., 2016; Bouyo Houketchang et al., 2013) showed that the Adamawa-Yadé domain corresponds to a Paleoproterozoic to Archean basement complex, variably remobilized during the Pan-African orogeny by a polyphased deformation, and to the emplacement of several generations of granitoids, among which the Ngaoundéré pluton. Structural studies conducted in the Adamawa-Yadé domain showed that this domain was subjected to two phases of ductile deformation recorded in Paleoproterozoic metamorphic rocks (metasediments and orthogenesis) and in some Neoproterozoic granitoids (Toteu et al., 2004; Njanko et al., 2006; Tchameni et al., 2006; Kankeu et al., 2012). The first phase (D1), with a flat-lying foliation, was overprinted by the "main" regional event (D2) characterized by regional NE-SW trending and steeply dipping foliations, associated with shallow plunging lineations (Table 1). Kinematic markers, related to these lineations, indicate a dextral sense of shear, in accordance with the dextral motion of the CCSZ in the southern part of the domain, and a sinistral sense of shear similar to the sinistral motion of the TBF in the northern part of the domain.

Archean (2.5–2.7 Ga) and Paleoproterozoic (2.1 Ga) basement rocks were identified under the form of septa incorporated in the Pan-African granitoids (Penaye et al., 1989, 2004; Toteu et al., 2001, 2004; Ganwa et al., 2016). They mainly consist of high-grade gneiss with granulitic mineralogical assemblages more-or-less retrogressed into assemblages denoting amphibolite facies conditions (Penaye et al., 1989, 2004; Bouyo Houketchang et al., 2013). The Paleoproterozoic basement was intruded by several generations of granitic plutons exhibiting a large variability in composition and intensity of deformation at the outcrop, dated between ~630 and ~550 Ma. These intrusions are spatially close to the dextral CCSZ. According to their state of deformation, they have been classified in three groups: syn-tectonic (630-620Ma), late-tectonic (600-580Ma) and post-tectonic granitoids (~550 Ma) (Lasserre, 1961; Toteu et al., 2001). Isotopic data indicate either a Paleoproterozoic single source, or a source combining a juvenile source and a Palaeoproterozoic to Archaean lower continental crust (Toteu et al., 2001; Kwékam et al., 2010; Ganwa et al., 2011).

2.2. Central Cameroon Shear Zone

The Central Cameroon Shear Zone (CCSZ), formerly identified as the Ngaoundéré-Foumban lineament (Browne and Fairhead, 1983), is one of the major ductile shear zones in Central Africa. In Cameroon, it is mainly directed NE-to ENE (Fig. 2). This Cameroonian segment was initially considered as a dextral shear zone (Ngako et al., 1991), but the latest studies (Ngako et al., 2003, 2008; Njonfang et al., 2006, 2008) reveal that it results from a complex evolution characterized by two kinematic stages: an early sinistral motion, dated between 613 and 585 Ma, to which a dextral one, in-between 585 and 540 Ma, was superimposed in the same NE-SW direction. For the authors the change in tectonic motion is associated with a deformation regime in transpression.

3. Geology and petrography

The Ngaoundéré pluton is a part of the Adamawa-Yadé batholiths, located near the Central Cameroon shear zones system. It occurs in and around the city of Ngaoundéré. According to the geological map (1/500,000) of Lasserre (1961), the Ngaoundéré pluton is intrusive in syn-tectonic granitoids, *i.e.* mesoscopically deformed. The extensive Cenozoic basaltic cover and soil make the contact between the pluton and the host rocks hardly observable. Therefore, the limits of the Ngaoundéré pluton reported here (Fig. 3a and b) are deduced from the geological map (1/500,000), completed by our field observations.

The Ngaoundéré pluton consists of a series of subcircular outcrops that constitute NE-to ENE-alignments of hillocks. According to Tchameni et al. (2006), two main petrographic types were identified in the pluton: biotite-granite (Bt-) and hornblende-biotite-monzogranite (Hbl-Bt-). The Bt-granite is preferentially distributed in the internal zone of the pluton while the Hbl–Bt-monzogranite is located on the periphery (Fig. 3b). Both rock-types are mostly coarse-grained rocks with K-feldspar megacrysts but without visible shape preferred orientation of the main minerals. In the Hbl-Bt-monzogranite, micrugranular mafic enclaves with lobate contours occur locally. Macroscopically, the Bt-granite is

Table 1
Structural characteristics of the main regional event (D2) in the metamorphic rocks (gneiss and amphibolites) and some granitoids of the Adamawa-Yadé domain.

	Mbé[a] (~60 km at N of Ngaoundéré)	Meiganga area[b] (~120 km at SE of Ngaoundéré)	Goumbela[c] (~60 km at NW of Meiganga)	Around Douar[c] (~80 km at WNW of Meiganga)	Along the CCSZ or Adamawa Shear zone near Tibati town[d] (~140 km at SW of Ngaoundéré)			
					Tongo village	Southern Part	Central Part	Northern Part
Foliation	Strike: dominantly NNE-SSW to ESE-WNW Dip: sub-vertical	Strike : NE-SW to E-W Dip: between 30° and 90° towards NW to N or S to SE	Strike: dominantly NE-SW Dip: intermediate to steep (30°80°)	Strike: dominantly ENE-WSW Dip: steep to vertical	Strike: dominantly NE-SW Dip: steep to intermediate Best pole: 141/14)	Strike: dominantly NE-SW Dip: steep to intermediate Best pole: 144/34	Strike: dominantly NE-SW Dip: steep to intermediate Best pole: 319/10	Strike: dominantly ENE-WSW Dip: Steep to intermediate Best pole: 155/6
Lineation	Trend: dominantly NE-SW to ENE-WSW Plunge: gentle	Trend : NE-SW Plunge: up to 40°			Trend: Dominantly NE-SW Plunge: subhorizontal to gentle Best line: 218/3	Trend: Dominantly WNW-ESE Plunge: gentle Best line: 291/5		Trend: Dominantly ENE-WSW Plunge: gentle Best line: 67/17
Folds axis	Trend: NE-SW Plunge: subhorizontal	Up to 10° to the NE			Trend: NE-SW Best axis: 219/4 Plunge: gentle to medium (20° to 35) to the SW			

[a] Ngako et al. (2008).
[b] Ganwa et al. (2011).
[c] Kankeu et al. (2012).
[d] Njanko et al. (2006).

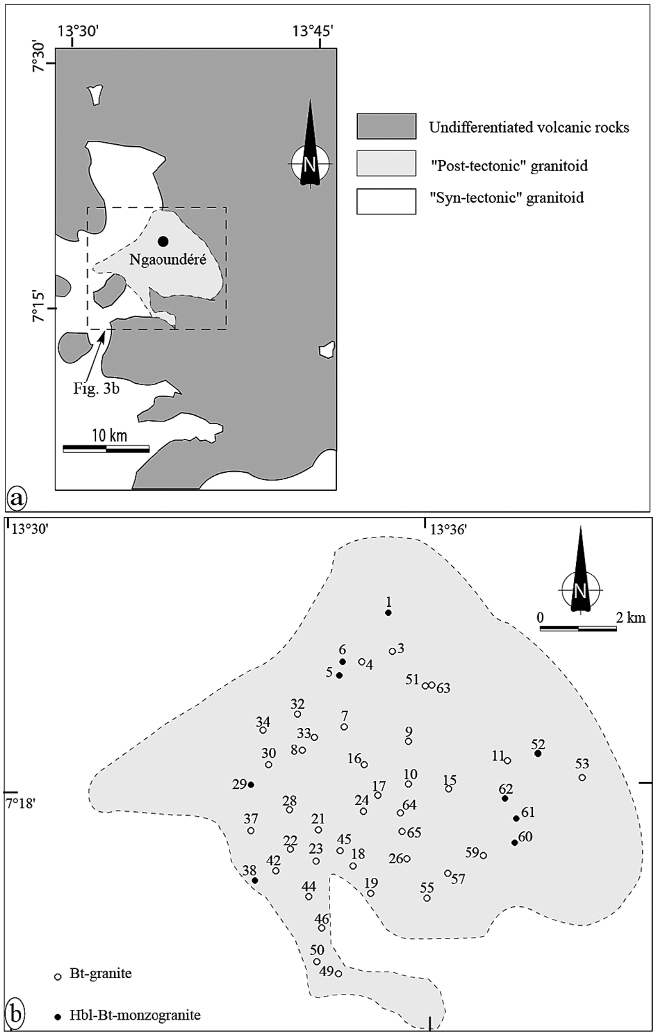

Fig. 3. Simplified geological map of the studied area: (a): Ngaoundéré pluton and its country rocks (modified after Lasserre, 1961; Tchameni et al., 2006). (b): Sampling map of the pluton. The limits of the pluton are modified from the geological map of Adamawa after Lasserre (1961) and from field observations.

relatively lighter in color than the monzogranite which is enriched in Fe-bearing minerals. In thin section, the Bt-granite displays a porphyritic texture, with K-feldspar megacrysts reaching 2 cm and large quartz grains (Fig. 4a). In addition to K-feldspar, the Bt-granite is constituted by plagioclase, quartz, biotite and in some places primary muscovite (Fig. 4b). Zircon, apatite, monazite, fluorite, xenotime and opaque minerals are common accessory phases. In some samples, secondary muscovite occurs as small flakes resulting from transformation of plagioclase or biotite. The Hbl-Bt-monzogranite has a porphyritic to granular texture (Fig. 4c) and, in addition to the presence of hornblende, its mineral composition differs from that of the Bi-granite mainly by the absence of muscovite and the abundance of titanite and opaque minerals. Opaque minerals occur as euhedral to subhedral grains corroborating their magmatic origin (Ferré et al., 2012), and form two generations: (i) an early one, often included in hornblende, biotite and titanite, appears as small grains (Fig. 4d); and (ii) a late generation, generally forming clusters of coarse grains (up to 200 μm; Fig. 4d) around ferromagnesian minerals or titanite. From the chemical point of view, both rock-types are high-K calc-alkaline, metaluminous to weakly peraluminous and I-type granitoids. Petrological data (Tchameni et al., 2006) indicate that this pluton may have resulted from the melting of middle Neoproterozoic continental crust and was emplaced in a post-orogenic setting. Finally, on the basis of the Th–U–Pb data on monazite and data for a single zircon, Tchameni et al. (2006) have estimated the emplacement age of the Ngaoundéré pluton at ~575 Ma.

4. Microstructures

Microstructural study is an essential aspect preceding the analysis of AMS fabric. For this purpose, oriented thin-sections obtained from 19 sampling stations (13 samples for the Bt-granite and 6 samples for the Hbl-Bt-monzogranite) were realized.

In the Bt-granite, two types of microstructures were distinguished: (1) magmatic and (2) with incipient solid-state deformation at high temperature. (1) The magmatic microstructures are more abundant, characterized by mineral phases showing imbricate structures with random orientations (Fig. 5a), large interstitial quartz grains with slight undulose extinctions and euhedral plagioclase grains (Fig. 5b). These microstructures characterize magmatic flow, *i.e.* acquired by displacement of melt partially crystallized without sufficient interference between crystals to cause crystal plastic deformation (Paterson et al., 1989; Smith, 2002). (2) Microstructures indicating an incipient solid-state deformation at high temperature are also observed in some section of the Bt-granite. They are mostly marked by chess-board subgrains patterns in quartz (Fig. 5c), pointing to intracrystalline deformation at around 700 °C (Blumenfeld et al., 1986; Mainprice et al., 1986), and by deformation twins in feldspars (Fig. 5d). According to Nédélec and Bouchez (2015), these microstructures suggest that this incipient deformation overprints the early magmatic microstructures during temperature decrease under the effect of increasing the crystalline load.

In the Hbl-Bt-monzogranite, the most common microstructure is “submagmatic” (Bouchez et al., 1992), marked by melt-present crystal deformation, corresponding to the pre-full crystallization fabric of Hutton (1988). These microstructures are accompanied by ubiquitous chessboard patterns in quartz grains, presence of myrmekites along the feldspar grain boundaries (Fig. 5e) and presence of microfractures in feldspars filled-up by quartz and/or plagioclase proving the presence of a small melt fraction. Several authors confirm that these patterns point to some deformation above 700 °C (Rutter and Neumann, 1995; Kruhl, 1996; Passchier and Trouw, 2005). In most of the thin sections the latter microstructure coexists with recrystallization features indicating grain boundary migration, as marked by quartz-quartz or quartz-feldspar lobate contacts (Fig. 4a). In addition, the observations of small recrystallized grains along with the presence of myrmekites on the edges of K-feldspars (Fig. 5f) also suggest that the deformation took place around 600 °C (Passchier and Trouw, 2005). The coexistence of such microstructures at different grades in the same section strongly suggests that the deformation started in the presence of a residual melt and ended after the full crystallization of the rock at high temperature.

5. Magnetic susceptibility and magnetic fabrics

5.1. Sampling and measurement

In the present study, 101 samples have been collected in 46 different sites in the Ngaoundéré pluton (Fig. 3b), ~0.2 km to ~1.2 km apart from each other. Two to four cores were extracted from each site with a portable drilling machine and non-magnetic drills and were oriented in the field using a magnetic compass. Each core was then cut into 2.2 × 2.5 cm cylindrical specimens, using a non-magnetic dual-blade saw, giving a total of 205 oriented

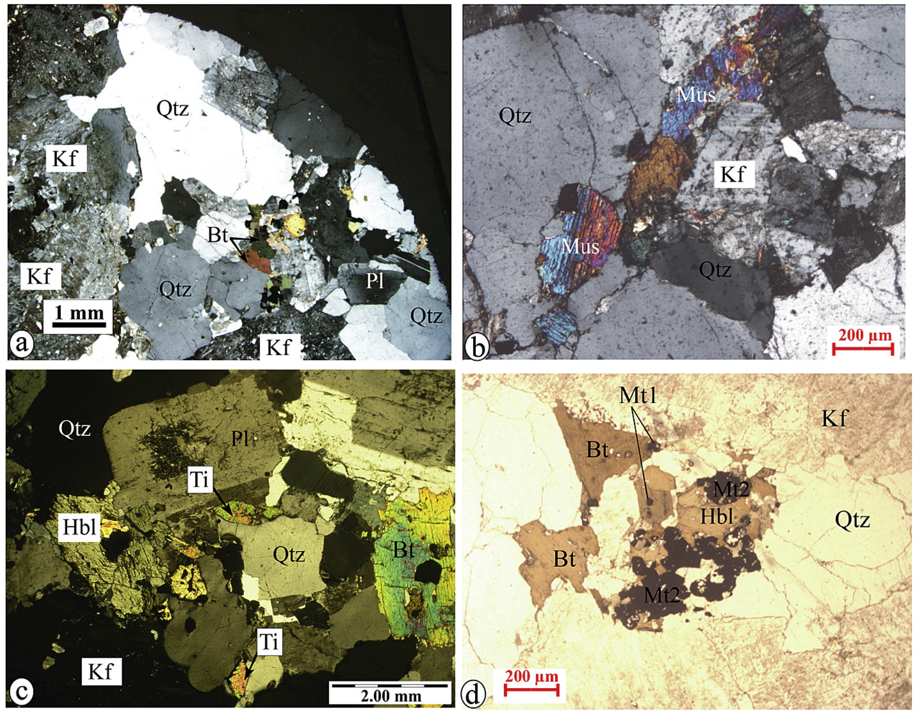

Fig. 4. Photomicrographs of representative specimens from the Ngaoundéré pluton. (a) porphyritic coarse-grained of the Bt-granite with large K-feldspars and quartz grains, (b) primary muscovite in the Bt-granite, (c) coarse-grained texture of the Hbl-Bt monzogranite, (d) magnetite grains from the Hbl-Bt-monzogranite: Mt1: an early generation of small magnetites included in biotite; Mt2 magnetites forming coarse-grained clusters around the ferromagnesian crystals; Qtz: quartz; Kf: K-feldspar; Pl: plagioclase; Bt: biotite; Hbl: hornblende; Mus: muscovite; Ti: titanite.

specimens used for magnetic fabric measurements. The anisotropy of magnetic susceptibility (AMS) measurements were carried out at "Geosciences Environment Toulouse" (GET) laboratory of the University of Toulouse (France), and "Laboratoire Magmas & Volcans" of the Jean-Monnet University (Saint-Etienne, France) using Kappabridge instruments (AGICO). Thermomagnetic K(T) measurements, aimed at specifying the magnetic mineralogy, were carried out between −194 °C and 700 °C using both a low temperature cryostat (CS-L) and a furnace (CS4) of the LMV laboratory. Measurements between 20 °C and 700 °C were performed in argon environment to prevent sample oxidation. The AMS data were statistically evaluated following the approach of Jelínek (1978) using both the ANISOFT software (www.agico.com) of the LMV laboratory and the software developed by the GET laboratory.

The data obtained from the Ngaoundéré pluton are presented in terms of magnitude and orientation of the main axes ($K_1 \geq K_2 \geq K_3$) of the AMS ellipsoid (Table 2). The bulk susceptibility (Km) represents the average magnitude of the three susceptibility axes ($Km = 1/3(K_1+K_2+K_3)$). K_1 is the maximum susceptibility, parallel to the maximum elongation direction of the AMS ellipsoid. It is commonly named the magnetic lineation. K_3 is the axis of minimum susceptibility and corresponds to the pole of magnetic foliation. P% expresses the anisotropy percentage ($P\% = 100 \times [(K_1/K_3) - 1]$). T, the shape parameter of Jelínek (1978) ($T = (2 \ln (K_2/K_3)/\ln (K_1/K_3)) - 1$), indicates the symmetry of the AMS ellipsoid. It varies from −1 to +1. When $1 < T < 0$ the AMS ellipsoid is prolate (or linear) and when $0 < T < +1$ it is oblate (or planar).

5.2. Magnetic mineralogy and scalar magnetic data

The bulk susceptibility values range from 0.2 to 39.4 x 10^{-3} SI (average Km = 9.6 x 10^{-3} SI). Except for two sites of the Bt-granite (stations 19 and 21) located to the south of the pluton, all the stations have susceptibilities higher than 0.5 x 10^{-3} SI. Such values point to a ferromagnetic behavior and suggest that magnetite, the main ferromagnetic mineral species in the granite, dominates the magnetic fabric (Rochette, 1987; Bouchez, 1997). One sample of Hbl-Bt-monzogranite (station 5; Km = 39.4 x 10^{-3} SI) and one sample of Bt-granite (station 64; Km = 5.9 x 10^{-3} SI) were used for K(T) measurements in order to confirm the dominant contribution of magnetite grains to the K values. The K(T) curves of both specimens (Fig. 6) display a well defined Verwey transition at ~150 °C and a sharp Km decrease at around 580 °C (Curie point), confirming the presence of magnetite.

Expectedly, the susceptibility values of the Hbl-Bt-monzogranite are higher than those of the Bt-granite, corroborating our thin section observations of large opaque minerals (magnetite) in the Hbl-Bt-monzogranite. In map view (Fig. 7), three susceptibility domains can be traced from the centre to the periphery of pluton: lower than 5 x 10^{-3} SI, between 5 and 13 x 10^{-3} SI, and higher than 20 x 10^{-3} SI. The lowest and intermediate susceptibility domains correspond to areas where the Bt-granite outcrops whereas the highest susceptibilities correspond to the area occupied by the Hbl-Bt-monzogranite. This repartition is in agreement with our petrographic observations and confirms the normal zonation of the pluton.

The anisotropy percentage, P%, varies from 1.1 to 17.6 (average: 5.3%). In map view, we observe two defined zones (Fig. 8a) fitting more-or-less precisely with the susceptibility zonation, *i.e.* with the petrographic types: (i) an inner zone with P% ≤ 4.6%, mainly located in the core of pluton, and (ii) an outer and peripheral zone with P% ≥ 5.9%. When reported in a P% *vs.* Km plot (Fig. 9a), the data points clearly define two distinct clusters corresponding to the Bt-granite, with low P% (average = 3.7%) and low Km, except for station 53, and to the Hbl-Bt-monzogranite, with high P% (average P% = 11.8%) and high Km. The increase of P% as a function of Km

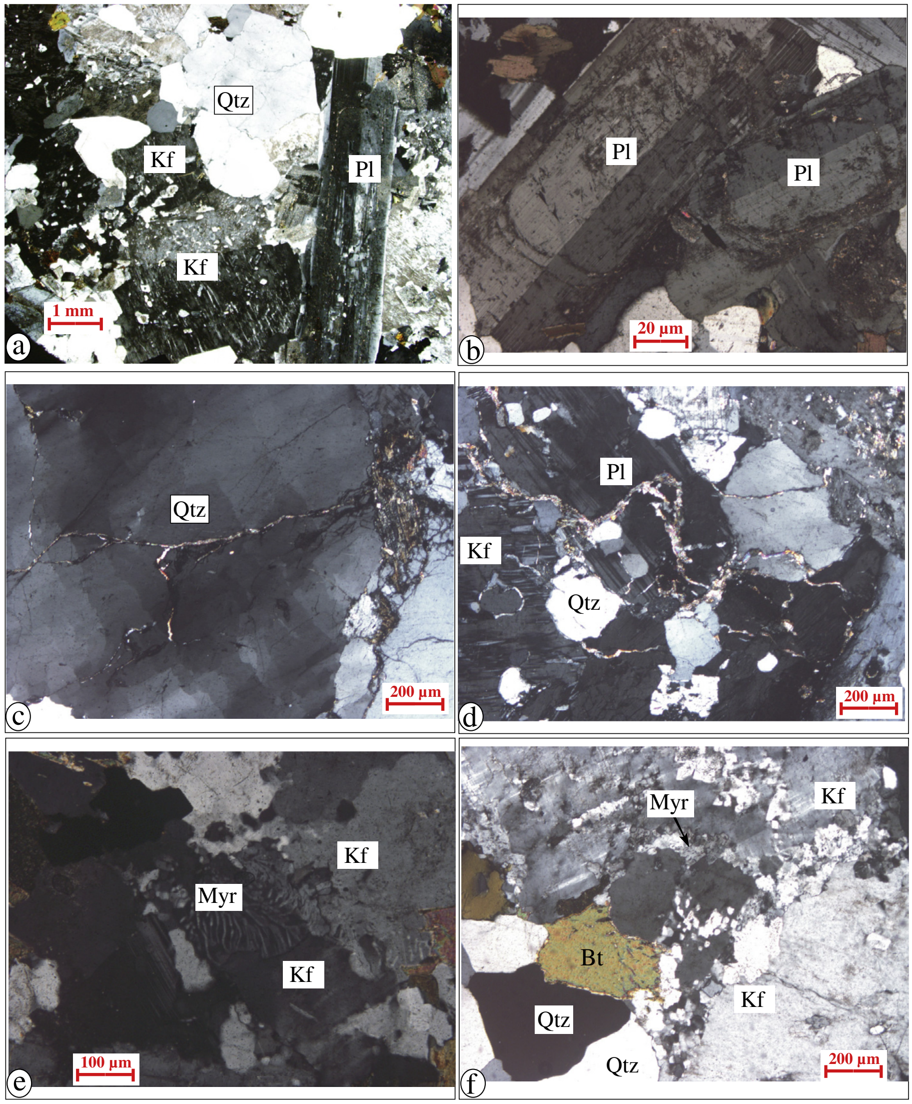

Fig. 5. Magmatic to incipient solid-state microstructures of the Ngaoundéré pluton (crossed polars). (a) Mineral phases showing imbricate structures with random orientations (Bt-granite: station 08). (b) Zoned plagioclase grains (Bt-granite: station 51). (c) Chess-board pattern in quartz (Bt-granite: station 42). (d) Deformation twins in feldspars indicating incipient solid-state deformation at high temperature (Bt-granite: station 49). (e) Myrmekites along a feldspar grain-boundary (Hbl-Bt-monzogranite: station 6). (f) Recrystallization along K-feldspar boundaries (Hbl-Bt-monzogranite: station #60). Myr: myrmekite. For the other abbreviations, see Fig. 4.

could be related to the effect of the magnetite grains on the anisotropy with a stronger shape magnetic anisotropy in rock samples that are richer in magnetite. However, the stronger increase of P% *vs.* Km of the Hbl-Bt-monzogranite may be partially also due to the magnetic interactions (Grégoire et al., 1998; Bouchez, 2000; Cañón-Tapia, 2001) between magnetite grains that are more closely packed in the Hbl-Bt-monzogranite than in the Bt-granite, as supported by observations under the microscope (Fig. 4d). In addition, on the map view (Fig. 8), we observe that the values of P% are not really consistent with microstructures. In conclusion these P% values cannot be used as quantitative or qualitative indicators of the degree of deformation in the Ngaoundéré pluton.

The shape parameter T, with values ranging from −0.92 to 0.83 and an average of 0.093 (Table 2), indicates ellipsoid shapes varying from strongly prolate to oblate (Fig. 9b). In addition, we note that most stations (63%) have positive T values (oblate), which tend to be more abundant toward pluton margins, particularly the northern one, than in its interior (Fig. 10).

5.3. Directional magnetic data

The quality of magnetic directional data is given by the confidence angles E13, E12, E23 (Table 2) for the three principal axes (K1, K2, K3) of each station. According to several study (*e.g.* Archanjo and Fetter, 2004; Pueyo et al., 2004; Salazar et al., 2013), magnetic fabrics are acceptable if the confidence angles E12 and E23 are less than 30°, for higher confidence angles the magnetic fabrics must be interpreted with caution. For the Ngaoundéré pluton 37% of the stations have simultaneous E12 and E23 angles lower than 30°; 41% and 29% of stations have, respectively, high E12 and E23 angles. These high confidence angles, indicating unreliable measures, may originate from interaction between magnetic grains, particularly for Hbl-Bt-monzogranite, or from the approximate orientation of the magnetite grains because of the dominant magmatic deformation of the pluton or even may be due to its porphyritic texture with K-feldspar megacrysts sometimes occupying a large part of the AMS specimens. However, except the magnetic lineations of three stations (9, 55, 59), the rest of the data

Table 2
Anisotropy of magnetic susceptibility (AMS) data for the pluton and its country rock. n: number of specimens analyzed in each site; long: longitude coordinate (degrees); lat: latitude coordinate (degrees); Km: mean magnetic susceptibility; K1D°, K3D°: declination of K1 and K3, respectively; K1I°, K3I°: inclination of K1 and K3, respectively; E12, E23, E31: 95% confidence angles for the long (1), intermediate (2) and short (3) axes of the magnetic susceptibility ellipsoid; P%: anisotropy percentage of the magnetic susceptibility; T: shape parameter.

Site	n*	long (°)	lat (°)	Km (10^{-3} SI)	K1D°	K1I°	K3D°	K3I°	E12	E23	E31	P%	L%	F%	T
Biotite-granite															
3	6	13.5917	7.3322	5.7	46	20	150	34	49	32	22.1	5.9	2	3.8	0.31
4	6	13.5843	7.3299	5.7	18	38	141	35	28.1	26.8	14.5	2.2	1.1	1.1	0.03
7	6	13.5800	7.3143	8.2	71	29	310	43	13.2	63.8	63.8	4.1	3.6	0.5	−0.76
8	6	13.5699	7.3088	3.6	254	22	141	44	47.5	36	23.6	2.1	0.8	1.3	0.21
9	4	13.5954	7.3108	7.2	229	63	52	27	49.6	30.8	21.6	1.1	0.4	0.7	0.33
10	6	13.5952	7.3006	8.7	70	25	282	62	15.4	23.6	24.5	3.6	2.7	0.9	−0.49
11	7	13.6191	7.3060	7.4	152	42	351	46	35.8	24.7	36.2	1.8	0.6	1.2	0.31
15	8	13.6047	7.2994	6.8	63	5	329	37	9.3	13.6	13.1	3.9	1.5	2.3	0.21
16	4	13.5846	7.3054	3.0	86	5	182	50	40.3	29.6	18.8	2.8	1.1	1.7	0.21
17	4	13.5878	7.2981	2.4	64	30	220	57	15.1	11	6.4	4.2	1.7	2.5	0.17
18	4	13.5818	7.2813	0.6	234	3	324	9	26.1	26.1	13.8	2.6	1.3	1.3	0.00
19	4	13.5859	7.2746	0.3	79	6	171	23	62.5	27	22	3.4	0.7	2.7	0.59
21	4	13.5736	7.2900	0.2	201	3	292	3	34.4	14.6	10.7	3.7	1	2.7	0.46
22	4	13.5667	7.2853	3.3	26	38	135	23	22.8	22.8	13.7	3.7	2.1	1.5	−0.15
23	4	13.5729	7.2824	2.6	24	11	278	56	31.7	19.9	12.8	3.4	1.2	2.1	0.27
24	4	13.5844	7.2942	2.7	193	20	31	70	25.5	25.5	17	2.3	1.5	0.8	−0.27
26	3	13.5946	7.2829	1.8	43	7	149	67	39.3	21.8	15.1	1.8	0.6	1.2	0.35
28	4	13.5668	7.2948	2.7	209	12	117	7	35.8	13.6	10.3	3.2	0.8	2.4	0.50
30	4	13.5619	7.3055	8.7	4	23	116	42	54.1	38.6	26.8	9.5	3.3	6	0.29
32	4	13.5688	7.3175	7.4	1	33	119	35	78.9	25.7	23.8	2.4	0.2	2.2	0.83
33	4	13.5728	7.3120	4.4	344	41	134	45	66.4	26.8	22.5	4.5	0.8	3.7	0.65
34	4	13.5606	7.3138	8.7	37	33	137	16	42.4	32	20.4	3.5	1.4	2.1	0.20
37	4	13.5574	7.2899	12.9	112	9	215	54	29.8	23.2	13.8	6.8	2.8	3.9	0.16
42	4	13.5632	7.2803	5.8	45	32	313	4	27	27	26	2.7	2.6	0.1	−0.92
44	4	13.5711	7.2740	5.6	52	16	321	1	34.6	34.6	24.5	2.8	1.9	1	−0.32
45	4	13.5787	7.2849	1.5	62	2	154	37	44.5	22	16	2.9	0.8	2.1	0.42
46	4	13.5740	7.2664	6.2	49	39	196	46	39.8	39.8	23.5	3.1	1.6	1.5	−0.04
49	4	13.5780	7.2556	8.4	243	16	119	63	16.9	11.8	7	6.7	2.6	4	0.20
50	5	13.5729	7.2584	7.4	51	0	320	77	43.7	31.7	20.5	4.6	1.7	2.8	0.23
51	4	13.5999	7.3240	5.4	241	9	5	75	21.5	21.5	13.7	3.6	2.2	1.4	−0.23
53	4	13.6370	7.3018	3.4	296	57	167	22	27	27	15.7	11	5.8	4.9	−0.08
55	4	13.5993	7.2734	8.7	6	14	225	72	47.8	30	20.8	2.4	0.8	1.6	0.32
57	4	13.6044	7.2793	8.4	256	22	115	64	18.9	18.9	14.9	3.3	2.6	0.7	−0.55
59	4	13.6132	7.2833	4.2	309	12	46	32	32.3	30.2	16.9	2.8	1.3	1.5	0.05
63	6	13.6011	7.3241	5.4	239	1	329	14	22	29.4	31.6	3.6	2.9	0.6	−0.66
64	6	13.5933	7.2937	5.9	55	25	209	62	20.4	51.8	51.6	2.9	2.1	0.8	−0.44
65	6	13.5934	7.2893	5.6	57	43	324	3	60	36.4	60.6	1.8	0.6	1.2	0.31
Hornblende-biotite-monzogranite															
1	4	13.5909	7.3416	25.0	323	33	195	44	55.4	15	12.7	7.3	1.1	6.2	0.70
5	5	13.5790	7.3267	39.4	339	47	172	43	38.5	14.9	11.2	12.4	2.8	9.3	0.52
6	4	13.5797	7.3299	29.7	5	33	194	57	37.4	16.9	12.2	9.7	2.6	7	0.45
29	4	13.5575	7.3008	25.6	296	25	189	33	37.3	22.8	15.2	10	3.3	6.4	0.31
38	4	13.5583	7.2780	26.0	337	42	205	36	32.9	32.9	19.1	12.4	6.3	5.7	−0.05
52	4	13.6263	7.3075	24.8	351	29	91	16	19.7	19.7	15.9	11.2	8.6	2.3	−0.57
60	4	13.6206	7.2863	24.2	196	15	84	54	40.9	15.4	11.8	17.6	3.7	13.3	0.55
61	4	13.6211	7.2922	31.2	267	80	165	1	26.1	24.9	13.4	14.8	6.7	7.6	0.06
62	4	13.6184	7.2969	20.4	35	20	190	68	11.9	11.9	10.1	10.6	8.8	1.6	−0.68

was considered from our structural analysis because of their coherence with the better defined fabrics of the neighboring sites.

51% of the AMS sites (22/43) have NE-SW to ENE-WSW magnetic lineation trends with predominant low plunges (<30° in 65% of the stations) to the NE or SW. To the north of pluton (Fig. 11a), the lineations trend dominantly to the north with moderate plunges to the north. The magnetic foliations (Fig. 11b) have mostly moderate to steep dips (30% of the stations have dips > 60°). Although more scattered, both in strikes and dips, than the lineations, a large fraction of magnetic foliations (37%) has NE-to ENE-directed strikes (mean strike/dip: 57°/50°SSE), sub-parallel to the CCSZ. Some moderate to shallow dipping foliations in the core of intrusion are also observed in-between two "belts" of NW–SE foliations strikes with moderate to steep dips (Fig. 11b). We note that, in the equal-area lower hemisphere projections of Fig. 10, the foliation poles are distributed on a great circle whose zone axis (52°/11°) is close to the average lineation (44°/21°).

6. Discussions

6.1. Significance of microstructures

Based on the isotropic appearance and geochemical data, the Ngaoundéré pluton was considered as a post-tectonic intrusion (Tchameni et al., 2006). The present microstructural study strongly suggests that the pluton has undergone a continuous deformation from the magmatic state to the solid state at high temperature during magma emplacement. The magmatic origin of the magnetite grains, as proved by their (sub)euhedral shapes, implies that the main carriers of the ASM signal have crystallized before the full crystallization of the magma. As a consequence, the preferred orientation of the magnetite grains, that results mostly from their alignment with the extension direction of the melt fraction, is at the origin of the magnetic fabric (Bouchez, 2000). As such, analogue modeling (Arbaret et al., 1996, 1997; Ildefonse et al., 1997) and

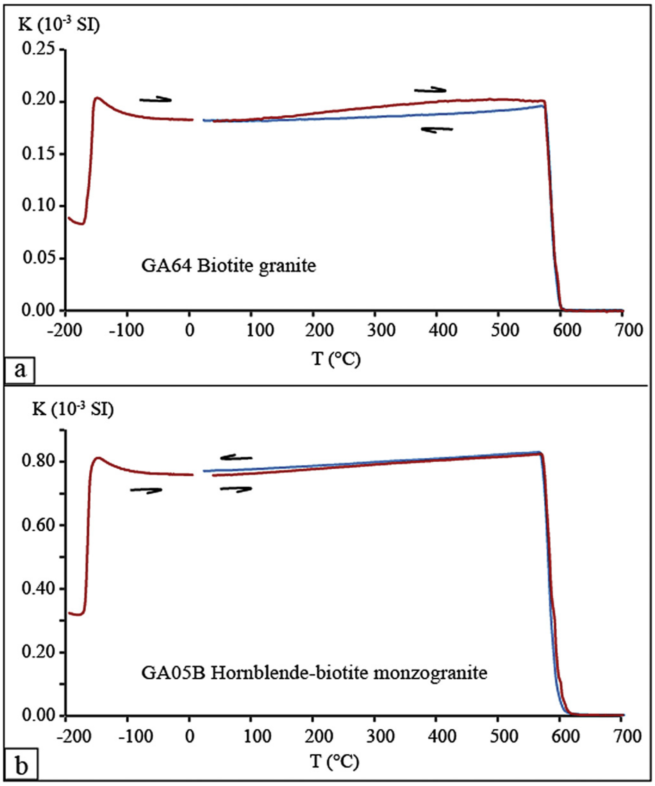

Fig. 6. Thermomagnetic curves illustrating the presence of magnetite for representative samples of (a) Bt-granite, and (b) Hbl-Bt-monzogranite of the pluton.

microstructures, from the chess-board patterns to the submagmatic microfractures in feldspars and undulose extinctions in quartz, indicate that a continuous deformation took place from the magmatic state to the solid state at high temperature. Finally, the absence of macroscopic deformation feature demonstrates that no deformation event took place after the emplacement of the pluton. The magnetic fabric of this intrusion is concluded to be a reliable marker of the latest increments of its magmatic deformation.

6.2. *Late tectonic transpressive emplacement of the Ngaoundéré pluton*

The dominant NE-SW trending and subhorizontal magnetic lineations, parallel to the overall lineations and fold axes of the host rocks, strongly suggest that the emplacement of the Ngaoundéré pluton is controlled by the regional tectonics, as represented in particular by the CCSZ which are mapped on northwestern side of the pluton. The core and axial parts of the pluton, with moderate to shallow dipping magnetic foliations, seem to point to the proximity of a roof above the pluton. The poles of the magnetic foliation, organized in a zone around the mean NE-SW lineation (Fig. 11), appear like if they were disposed around a fold axis.

For comparison, Table 1 reports the structural patterns (lineations, foliations, folds axes) observed on the metamorphic rocks (gneiss, amphibolites) and some granitoids on sides of the CCSZ. We note that the foliations also have NE-to ENE-strikes and moderate to steep dips and that the lineations also have sub-horizontal NE-to ENE-trends, almost parallel to the fold axes. These structures are interpreted as due to a regional folding associated with a NW- to NNW-directed and sub-horizontal shortening, along with a sub-

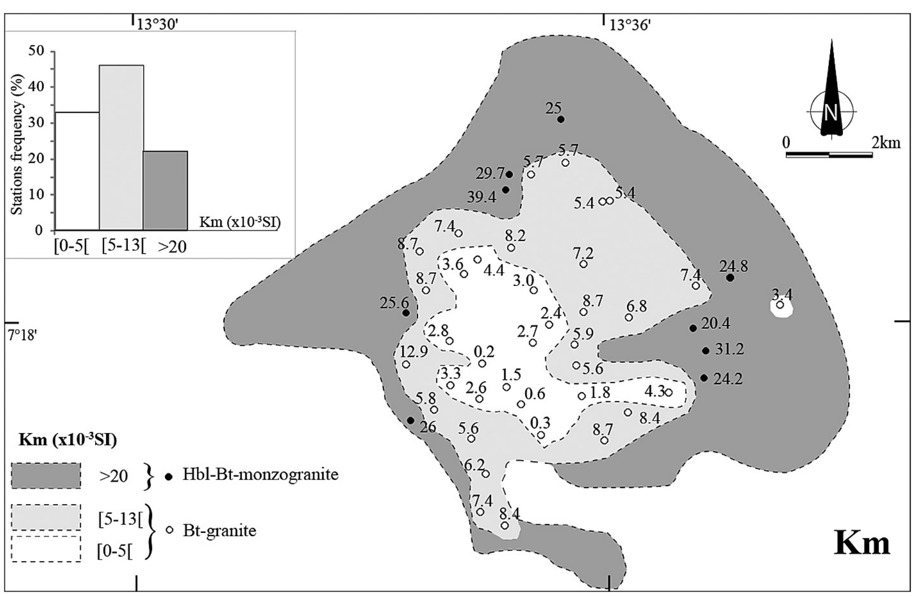

Fig. 7. Contours map of the magnetic susceptibility magnitudes (10^{-3} SI) in the pluton and corresponding petrographic types.

many other fabric studies of granitic rocks (*e.g.*, Bouchez, 1997; Majumder and Mamtani, 2009; Olivier et al., 2015; among others) have established that the planar and linear fabrics can be equated with the flattening plane and stretching direction to which the magma was subjected before its full crystallization, and likely during the ultimate stage of its emplacement (Benn, 1994; Sen and Collins, 2013).

Whatever the precise time of the fabric record in a granite, the

horizontal NE-to ENE-stretching direction parallel to the lineations (*e.g.* Ngako, 1999; Njonfang et al., 2008; Ganwa et al., 2011; Kankeu et al., 2012).

Given these similarities between the regional structures and our magnetic fabrics in the Ngaoundéré pluton, we suggest that the pluton emplacement is coeval with the folding event and has accommodated the strain related to this folding. As also illustrated by the models of Tikoff and Peterson (1998), parallelism between

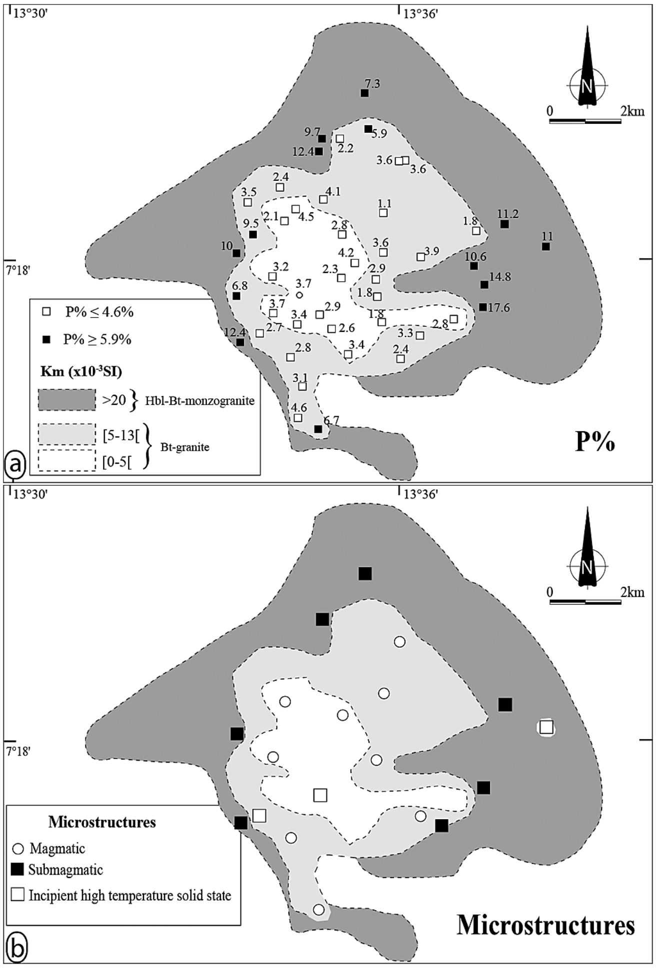

Fig. 8. Distribution map of the anisotropy percentage P% (a) and the microstructures (b).

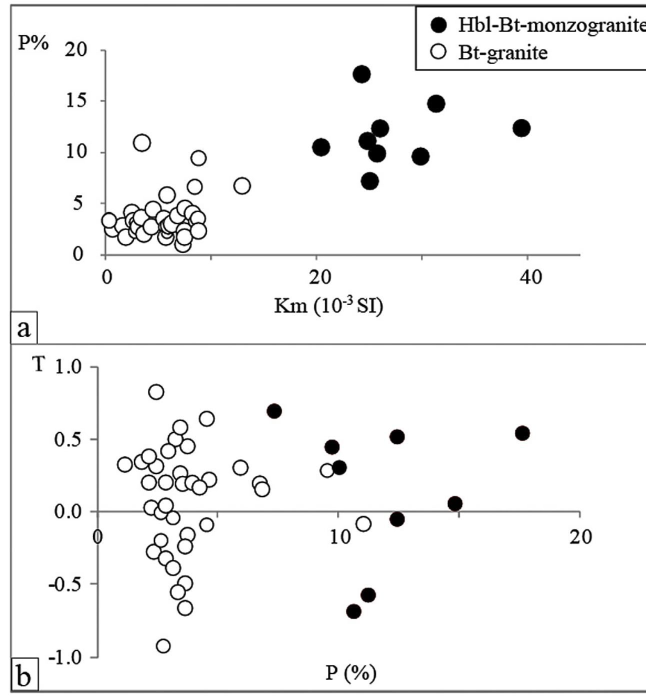

Fig. 9. Relationships between AMS parameters. (a) Anisotropy percentage *versus* magnetic susceptibility. (b) Shape parameter *versus* susceptibility.

the stretching direction and the fold axes points to a deformation in which a component of shear is active at a low angle to the folds axes. Such features call for a transpressive event that took place between the two branches of the CCSZ.

Transpression is a regime commonly defined as a combination of strike-slip and coeval contraction at a high angle to the strike-slip fault (Sanderson and Marchini, 1984; Dewey et al., 1998). The stretching lineations are steeply plunging in transpressive zones in which pure-shear is dominant, while they are gentle in zones where simple-shear dominates. According to Fossen and Tikof (1993) and Tikoff and Teyssier (1994), if the angle between the extension direction and strike of the shear zone is larger than 20°, the transpression is dominated by pure shear. In the Ngaoundéré pluton the main NE-to ENE-orientation of the magnetic lineations sub-parallel to CCSZ, tends to rotate toward N-S on its northern margin, *i.e*, at a very high angle with the CCSZ trend. This rotation could point to a partition of strain that took place between the two, NE-directed, branches of the CCSZ during the emplacement of the pluton. We suggest that a dominant pure shear component may have affected the northern border of the pluton while the rest of the pluton was affected by a dominant simple shear component. Note that a similar partitioning is also reported by Kankeu et al. (2012) in the region of Meiganga (southern side of the CCSZ), ~120 km at the south-east of the study area (Fig. 2).

6.3. Correlation with NE-Brazil

In a pre-drift reconstruction of West Gondwana, recent studies equate the Cameroon Pan-African shield with the Nordeste domain of Brazil, and the CCSZ with the Patos shear zone (Caby, 1989; De Witt et al., 2008; Aslanian et al., 2009; Archanjo et al., 2013). The previous study of Tchameni et al. (2006) has shown that the age (~575 Ma) and the metaluminous to weakly peraluminous high-K calc-alkaline nature of the Ngaoundéré pluton, were points of similarity with the Ediacaran granitoids described in the Nordeste (Nascimento et al., 2000; Guimaraes et al., 2009). In the Brazilian side the emplacement of the high-K calc-alkaline granitoids was controlled by the dextral transpressive shear zone of Patos striking E–W to NE–SW (Vauchez et al., 1995, 1997; Archanjo and Fetter, 2004). Magmatic and tectonic similarities between the Ngaoundéré pluton and coeval plutons along the Patos shear zone support the previous pre-drift reconstruction that equates the CCSZ and the Patos shear zone. However, a more precise dating of the Ngaoundéré pluton remains important for a better understanding of the CCSZ evolution and Pre-Mesozoic reconstruction of Gondwana.

7. Conclusion

This study demonstrates the importance of magnetic fabric and microstructural analyses for decrypting the internal structures of plutons devoid of macroscopic markers of deformation. This new investigation applied to the Ngaoundéré pluton indicates that this calc-alkaline and high-K pluton is not post-tectonic but rather late-tectonic. Its emplacement was influenced by the dextral transpressive tectonics related to the NE-to ENE directed Central Cameroon Shear Zone which remained active until the emplacement of the pluton. Our results strongly suggest that the emplacement of this pluton along the CCSZ was tectonically controlled in a way very similar to numerous Ediacaran high-K calc-

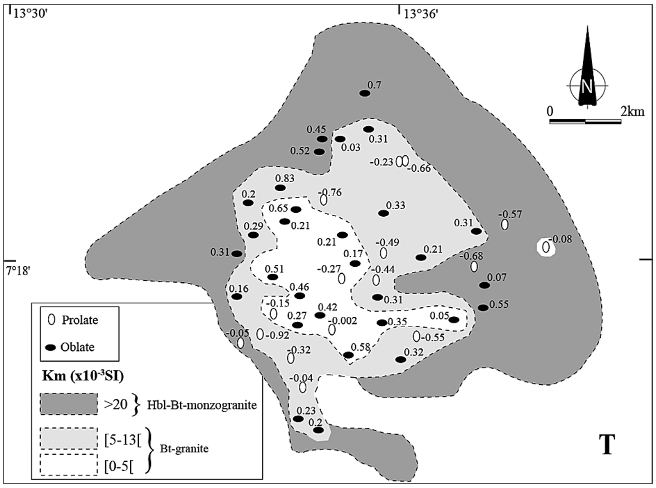

Fig. 10. Distribution map of the AMS shape parameter (T) in the Ngaoundéré pluton.

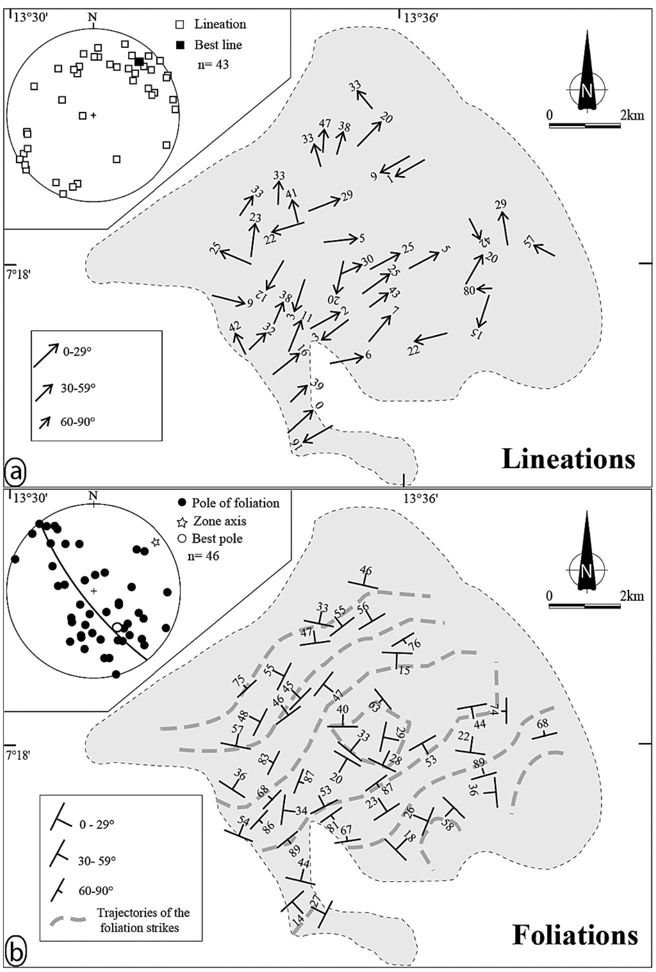

Fig. 11. Magnetic structures of the pluton. (a) Magnetic lineations and corresponding orientation diagram (n = number of measurements, best line -azimuth/plunge-: 44°/21°). (b) Magnetic foliations and orientation diagram of their poles (Schmidt lower hemisphere; n: number of measurement, zone axis: 52°/11°).

alkaline granitoids that outcrop along the Patos shear zone (NE-Brazil). These results reinforce the hypothesis of Pre-Mesozoic reconstruction of West Gondwana proposing that the Patos SZ connects with the Central Cameroon SZ.

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