Petrogenesis of Magnesian High-K Granitoids From Bitkine (Centre Chad Massif): Major and Trace Elements Constraints

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ABSTRACT

Major and trace element data were used to constrain the nature and origin of the Bitkine gabbro-diorite magma. The gabbro-diorites of Bitkine within the Guéra Massif, and associated microgranular enclaves consist of plagioclase, k-feldspar, clinopyroxene, amphibole, biotite and quartz. Gabbro-diorites and enclaves are basic to intermediate rocks. They are high-K magnesian calc-alkaline with shoshonite affinity. Σ REE range from 132 to 436 ppm in gabbro-diorites, while they are from 134 to 207 ppm in enclaves. LREE are weakly enriched compared to HREE ($(La/Yb)_N = (12.23 - 41.40)$ and $(6.20 - 31.86)$ respectively in gabbro-diorites and enclaves. These rocks show a weak negative anomaly in europium ($Eu/Eu^* = 0.78 - 1.07$). They are rich in Ba and Sr, and show negative anomalies in Nb, Ta and Ti. The Nb/Ta, Rb/Cs and Ba/Nb ratios of the Bitkine gabbro-diorites and their enclaves indicate that they are derived from mantle magma modified by subducted fluids. This magma during its evolution by fractional crystallization was contaminated by crustal materials.

Keywords: Bitkine, Gabbro-diorite, High-k magnesian, Enriched mantle, Fractional crystallization.

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I. INTRODUCTION

The Guéra Massif is one of the smallest massifs in Chad within the Sahara Metacraton (Fig. 1), [1]-[2]. It consists of 90% granitoids [3]-[4]. These granitoids are characterised by petrographic diversity. They consist of gabbros, diorites, granodiorites, granites and charnockites [5]-[7]. These

granitoids are believed to result from intense magmatic activity during the pan-African orogeny. During this orogeny, the blocks assembled to form Gondwana. The Guéra massif is wedged between the Chad craton, the Darfur block (in the Sahara metacraton) and the Congo craton (Fig. 1). It is separated from the Chad craton by the gravity anomaly [8]. This position of the Guéra massif is very interesting for the

understanding of crustal evolution and the crustal-mantle relationship during the pan-African orogeny in central Chad. Thus, field and geochemical data of the major elements of the Bitkine gabbro-diorites and their enclaves are presented in this paper in order to determine the nature and origin of their parent magmas. These preliminary results will certainly contribute to the advancement of knowledge on the petrogenetic and geodynamic processes of the granitoids of the Central Chad Massif (Guéra Massif).

Fig. 1. Geological sketch map of west-central Africa with cratonic areas and the Pan-African-Brasiliano provinces of the Pan-Gondwana belt in a Pangea reconstruction; modified from [1], after [2].

II. GEOLOGICAL SETTING

The Precambrian formations in Chad are made up of six blocks: the Mayo-Kebbi Massif in the South-West, the Ouaddai Massif in the East, the Yadé Massif in the South, the Tibesti Massif in the North and the Guéra Massif in the Centre. These formations are largely covered by sedimentary rocks.

The Guéra Massif (Central Chad Massif) located on the southern edge of the Sahara Metacraton, is one of the least studied formations because of the scarcity of rock outcrops. It consists of magmatic rocks and metamorphic rocks (Fig. 2). These rocks were laid down during the collision between the Congo-Sao Francisco Craton and the Sahara Metacraton. The Bitkine region consists of gabbro-diorites, amphibole and biotite granites, biotite granites, charnockites and orthogneiss (Fig. 3). Recent work by [7] showed that magmatism in the Guéra Massif was active for 50 Ma in the interval 595 Ma ~545 Ma. The U-Th-Pb ages obtained on individual zircons range from 1900 Ma to 580 Ma, indicating crustal recycling during pan-African orogeny. The oldest granites (595±8 Ma, 589±6 Ma) are metaluminous to peraluminous, magnesian, alkaline to calcic-alkaline [9]. Young granites (≤570 Ma) are peraluminous, ferri-ferous, alkaline-calcic and post-collisional [10]-[14]. [15] distinguished between collisional and post-collisional granites. Post-collisional granites belong to two generations. The first generation is represented by hornblende and biotite

granites dated at 595 Ma. These are volcanic arc granites and derive from the partial melting of a mantle wedge modified by subduction [7]. The second generation consists of biotite granites dated at 590 Ma, these are post-collisional granites. The post-collisional granites are emplaced during crustal relaxation after the oblique collision between the Congo-São Francisco craton and the Sahara Metacraton ([16]-[17]). Granites dated at 560 Ma are emplaced during the second period of post-collisional magmatism after an episode of crustal thinning ([16], [17]).

Fig. 2. Geological map of the Guéra Massif.

III. PETROGRAPHY

The gabbro-diorite outcrops in the form of slabs (Fig. 3a), metric to decametric blocks in plains and watercourses in the NE-SW to ENE-WSW direction (Fig. 3). It also occurs in basic microgranular enclaves in granites (Fig. 3c). The microgranular enclaves are either scattered or grouped in swarms or magmatic breccias patched by granitic fluids (Fig. 3d). The size of the enclaves varies from 15 cm centimeters to 30 cm. The major axes of the enclaves are preferentially oriented in the N-S to NE-SW direction. In the field, gabbro-diorite is a dark grey to medium to coarse-grained rock. The size of the minerals varies from millimeters to centimeters. It has the same composition as the enclaves. The enclaves are medium to fine grained. They consist of plagioclase, alkaline feldspar, quartz, clinopyroxene, amphibole and biotite. Zircon, apatite and iron oxides are the accessory minerals. Plagioclase is automorphic to subautomorphic and occurs as large, often intersecting slats. It has albite polysynthetic twin. Plagioclase phenocrysts contain inclusions of small clinopyroxene crystals. Alkaline feldspar consists essentially of orthose. Orthose is present in the form of automorphic or subautomorphic phenocrysts and Carlsbad-twin. Some crystals are sometimes resorbed and appear in rounded or ovoid form. Clinopyroxene and amphibole crystals are arranged along the edges of resorbed plagioclase phenocrysts.

The amphibole is in the form of automorphic to subautomorphic phenocrysts. The size of the crystals varies from 0.3 to 0.5 mm. Clinopyroxene occurs as crystals in automorphic basal sections with two cleavages. It is automorphic to subautomorphic and less than 2 mm in size. It sometimes appears as an inclusion in plagioclase and biotite. Biotite occurs in the form of flakes and lamellae varying in size from 2 to 3mm. Biotite flakes frequently crystallize around plagioclase and clinopyroxene phenocrysts. Quartz is rare and interstitial and crystallizes as fine to medium grains around alkaline feldspar. Apatite and zircon are usually included in amphibole and biotite.

Fig. 3. Field observations, (a) Gabbro-diorite slab outcrop (GD) in contact with biotite granite (BG), (b) Gabbro-diorite dyke (GD) intersecting the amphibole-biotite granite (ABG), and taken up by a biotite granite vein (BG), (c) Elongated microgranular enclave (GD) with one extremity destabilised in swarms of small enclaves, in amphibole-biotite granite (ABG), (d) Magmatic breccia with gabbro-diorite blocks (GD) clogged by the granitic melt.

IV. ANALYTICAL TECHNIQUES

Geochemical analyses of major, trace and rare earth elements were performed at ACTLABS (Activation Laboratories) Ontario (CANADA). Major and some trace elements (Sc, V, Cr, Co, Ni, Zn, Ga, Rb, Sr, Zr, and Ba) are analyzed by ICP-AES ("inductively coupled plasma Atomic Emission"). The other trace elements are analyzed by ICP-MS ("Inductively Coupled Plasma Mass Spectrometer") using the VG-Plasma Quad STE ICP spectrometer. The uncertainties of analysis are 1% for the concentration of the major elements (with the exception of Fe and Na, which is 2%), and around 5% for the concentration of trace elements. The accuracy of analyses for rare earths, compared to the JB3 and JA2 standard, is between 15% and 20% for Nb and Ta and less than 10% for the concentrations of the other elements.

V. RESULTS

The samples analysed show a chemical composition of basic to intermediate rocks ($\text{SiO}_2 = 48.60 - 61.35\%$). They are monzogabbro, monzodiorite, diorite, monzonite and syenite in composition (Fig. 4a). They are subalkaline ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 5-10.50\%$), calc-alkaline strongly potassic to shoshonitic rocks ($\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.61-3.46$, Fig. 4b) [18]-[20]. These are

metaluminous granitoids ($\text{A}/\text{CNk} = 0.59-0.96$). They are alkali-alkaline to calcic-alkaline and magnesian ($(\text{FeOt}/\text{FeOt} + \text{MgO}) = 0.51-0.72$, in gabbro-diorites) and (0.42-0.85, in enclaves), Fig. 4c and 4d, [21]. The elements MgO, CaO, TiO_2 and P_2O_5 decrease with increasing SiO_2 content while Al_2O_3 element shows a positive correlation with SiO_2 (Fig. 5). The behavior of Al_2O_3 compared to CaO and MgO suggests that magma differentiation is controlled by the crystallization of magnesian calcareous minerals such as clinopyroxene.

Fig. 4. Geochemical characterization of Bitkine's gabbro-diorites, (a) $\text{K}_2\text{O}+\text{Na}_2\text{O}$ vs SiO_2 de (b) K_2O vs SiO_2 diagram, field boundaries ([18]-[19]), fields of andesite and tonalite melts are from [20], (c) Mali diagram and (d) $\text{FeO}/(\text{FeO}+\text{MgO})$ diagram from [21].

Some selected trace elements, Sr, Zr, Co, V and Cr decrease with increasing SiO_2 content. The elements TiO_2 , P_2O_5 , Sr, Zr and Cr show two trends which converge towards the most acidic terms (Fig. 5). Gabbro-diorite has high Sr (572-1146 ppm), Ba (927-2147 ppm) and medium to low Rb (75-145 ppm) values. It has average to high Cr (50-640 ppm), Ni (40-190 ppm) and average Co (8-46 ppm) contents. The Zr values (146-466 ppm) are high. Sr/Y (32-62.23), La/Yb (9.15-61.07) and Nb/Ta (11.67-15.45) ratios are high. Basic enclaves have high Sr (574-706 ppm) and Ba (873-6333 ppm) concentrations. They have low levels of Rb (72-125 ppm). They are richer in Cr (430-1040 ppm), Ni (170-330 ppm) and Co (33-48 ppm) compared to gabbro-diorites and granites. Enclaves have high Zr contents (155-925 ppm). The Sr/Y (21.55-39.22), La/Yb (9.15-47) and Nb/Ta (12.50-20) ratios are close to those of gabbro-diorites which are well above the crustal average.

The REE patterns normalized to the values of the primitive mantle are parallel to each other (Fig. 6) [22]-[23]. Gabbro-diorites are enriched more in REE ($\Sigma\text{REE} = 132-436$) than enclaves ($\Sigma\text{REE} = 134-207$). The REE patterns are LREE enriched in gabbro-diorites ($(\text{La}/\text{Sm})_N = 2.54-4.16$) than the enclaves ($(\text{La}/\text{Sm})_N = 1.76-3.06$). The HREE are little differentiated in the two types ($(\text{Yb}/\text{Dy})_N = 1.3 - 2.3$ in the gabbro-diorites and (1.1-1.7 in the enclaves). The REE patterns show weak negative europium anomalies ($\text{Eu}/\text{Eu}^* = 0.78-1.00$). The multi-element normalized to the primitive mantle values diagrams (Fig. 5b and 5d) show strong positive Ba and K anomalies in both rocks, whereas the enclaves show strong positive Hf-Zr anomalies, and gabbro-diorites show negative Hf-Zr anomalies in both elements. Negative U, Th,

Nb, Ta and Ti anomalies are observed in the gabbro-diorites and enclaves.

Fig. 5. Harker diagrams of some selected major and trace elements, sometimes showing two converging lines of evolution, indication of two sources and their mixture.

VI. DISCUSSION

A. Nature

The gabbro-diorites of Bitkine and their associated enclaves are magnesian high-K calc-alkaline granitoids with shoshonite affinity. Their petrographic (rich amphibole + pyroxene + biotite) and geochemical ($(\text{FeO}^t/(\text{FeO}^t+\text{MgO})) = 0.51-0.85$) characteristics are comparable to the ACG (Amphibole-rich Calc-alkaline Granitoids) type granitoids of [24]. The relatively high Sr (> 300 ppm), Ba (> 500 ppm) and relatively low Rb (110-219 ppm) contents indicate that they are high-Ba-Sr granitoids (high-Ba-Sr granitoids) of [25]. Some samples of gabbro-diorites and enclaves have Sr/Y ratios greater than 40 suggesting an adakite characteristic. The Sr/Y vs Y diagram (Fig. 7) [26] shows that the Bitkine gabbro-diorites are typical calc-alkaline granitoids of active continental margins (Fig. 7b,c and d) [27]-[29], which is confirmed by the Th/Ta vs Yb, Ce/P₂O₅ vs Zr/TiO₂ and La/Yb vs Th/Yb diagrams (Fig.8) [27]-[30].

Fig. 6. REE normalized to primitive mantle diagram after [22]: (a) Enclaves pattern, (b) spider diagram of Enclaves, (c) Gabbro-diorites pattern, (d) Spider diagram of gabbro-diorites, values of Bulk crust (BC) and MORB are from [23].

B. Origin

The gabbro-diorites and enclaves are magnesian and shoshonite and occupy the domain of andesitic rocks in the K₂O vs SiO₂ diagram (Fig. 4b) [20].

Fig. 7. (a) Sr/Y vs Sr discrimination diagram [26] of studied samples, distribution of the samples in the geotectonic trace-element discrimination diagrams of [27] (b), [28](c) and [29](d).

They are characterized by relatively high contents of MgO (6-11%), Ni (40-330ppm) and Cr (50-1040ppm), similar to those of rocks of mantle origin [30]. Their Nb/Ta (12-20) and Rb/Cs (11.31-126) ratios are closer to mantle values [22]-[30]. The negative Hf-Zr anomaly also underlines the mantle origin of the Bitkine gabbro-diorites (Fig. 6d). Indeed, in the diagrams Nb/Ta vs Th/Yb, Rb/Cs vs Rb and Th/Yb vs Nb/Yb (Fig. 8) [23]-[32], the gabbro-diorites and their enclaves are plotted between the MORB and the upper crust.

This intermediate position suggests that the gabbro-diorites and their enclaves are the result of a mixture of two magmas, one of mantle origin and the other of crustal origin, or of a mantle magma enriched by the material of the crust. Moreover, their position in the Th/Yb vs. Nb/Yb diagram (Fig. 8c) indicates that the evolution of this mantle magma was influenced by a component of the subduction zone. If the vector of fractional crystallization is significant (Fig. 9) [33]-[34], it remains that other phenomena have also impacted the differentiation of the original magma. Generally, the Eu/Eu* value decreases when the SiO₂ content increases in a mantle magma that is differentiated by simple fractional crystallization. In gabbro-diorites and their enclaves, Eu/Eu* seems to be constant despite the fact that some samples cluster around two to three oblique lines underlining a differentiation by fractional crystallization (Fig. 8d).

Fig. 8. Nb/Ta vs Th/Yb (a), Rb/Cs vs Rb (b) and Th/Yb vs Nb/Yb (c) diagrams showing the position of the studied samples in relation to the MORB and upper crust, MORB, OIB primitive mantle (PM), lower crust (LC), upper crust (UC) values are from [27] and [30]. Eu/Eu* vs SiO₂ (d) diagram showing the complexity of the differentiation of magma.

The behavior of Eu/Eu* values in the diagram Eu/Eu* vs SiO₂ (Fig. 8d) indicates that fractional crystallization is not the only process of differentiation of the magma of these rocks. Indeed, in the Ba/Nb vs Nb diagram (Fig. 9a), the enclaves and some gabbro-diorite samples are arranged vertically and parallel to the Ba/Nb axis, indicating the slab fluids enrichment of the magma [33]–[35].

Fig. 9. Nb versus Ba/Nb diagram [33] with sample distribution displaying a trend consistent with the fractional crystallization (FC) and slab fluid input process (a) and Dy/Yb vs Dy diagram [34] showing two parallel trends of fractional crystallization (b).

The fractional crystallization process is further highlighted in the Dy/Yb vs Dy diagram (Fig. 9b) [34] in which the samples are zoned around two horizontal lines. This arrangement confirms that the Bitkine rocks are derived from two magmas from different sources, a mantle source enriched by subduction zone fluids and a crustal source. Field data as well as geochemical data indicate that the two magmas evolved by fractional crystallization and subsequently underwent incomplete mixing as highlighted by the presence of swarms of microgranular enclaves (Fig. 3c and 3d).

VII. CONCLUSION

The Bitkine gabbro-diorites and their enclaves have the composition of monzogabbro, monzodiorite, diorite, monzonite and syenite. They are high-K calc-alkaline, magnesian granitoids with shoshonite affinity. Their Nb/Ta, Rb/Cs and Th/Yb ratios suggest that they result from the crystallization of a magma of hybrid origin. The swarms of enclaves and magmatic breccias, as well as the development of two straight lines of evolution by certain major and trace elements, clearly show the existence of two magmas that have mixed together. These magmas occurred in an environment of active continental margin. The most probable source is a

mantle enriched by the fluids of the subduction zone, whose partial melting produced a magma that initially evolved by fractional crystallization and during its ascent was contaminated by crustal material.

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