

Crustal Evolution of Southern Part of the Ferkessédougou Batholith (Côte d'Ivoire, West African Craton): Implications for Baoulé-Mossi Domain Geodynamic

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How to cite this paper: Kouassi, B.R., Kouamelan, A.N., Allialy, M.E., Boffouo, Y.C. and Digbeu, W. (2022) Crustal Evolution of Southern Part of the Ferkessédougou Batholith (Côte d'Ivoire, West African Craton): Implications for Baoulé-Mossi Domain Geodynamic. *Open Journal of Geology*, 12, 648-662.

<https://doi.org/10.4236/ojg.2022.129030>

Received: August 19, 2022

Accepted: September 20, 2022

Published: September 23, 2022

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Abstract

The southern Ferkessédougou batholith in the center-west of Côte d'Ivoire is the study area. The geology of this area includes granitoids (granodiorite, two-mica granite, biotite granite and muscovite granite) and metasediment panels. Petrographic studies were coupled with geochemical analyzes on the whole rock in order to provide new elements in the structural evolution of this portion of the West African craton. Petrographic data show that the basement of the Bonon area is partly identical to that of the northern part of the batholith. The structural data reveal three major phases of deformation that structured the study area. As for the geochemical data carried essentially on samples of granitoids, they indicated a high-k affinity the I type granite characteristics. The spectra of the REE normalized to chondrites, have moderate slopes with a fractionation highlighted by the ratios $(La/Sm)_N = 1.93 - 4.56$ and $(La/Yb)_N = 7.69 - 32.28$. The multi-element diagrams revealed negative anomalies in Ta-Nb implying the partial melting of a crust of TTG composition. Studies for the geotectonic environment have shown that the granitoids of the Bouaflé and Bonon region were emplaced in an arc environment associated with a subduction zone.

Keywords

Ferkessedougou Batholith, Granitoids, Geodynamic Context, Côte d'Ivoire

1. Introduction

The Paleoproterozoic domains of the West African Craton (COA) are mainly

characterized by NE-SW oriented volcanic belts with intermediate basins, intruded with different generations of granitoids [1] [2]. These granitoids generally outcrop in the form of very large batholiths, such as that of Ferkessedougou due to their large dimensions. The Ferkessedougou batholith, known as the Niangoloko granitic domain (in Burkina Faso), is an important Birimian structure of the Man Ridge. It is a granitic, pluri-plutonic crust, elongated from the Burkina Faso border in the northeast to the “SASCA” domain in the southwest of Côte d’Ivoire. Outcropping over 500 km long and 50 km wide, its dominant composition is that of two-mica granite with an alumino-potassic chemistry [3]. Petrographic, geochemical and geochronological studies have shown that the Ferkessedougou batholith is part of the late metaluminous to peraluminous granites dated at around 2097 Ma and emplaced within the metasedimentary series [4] [5] [6]. Here, we are interested in localities ranging from Bouaflé to Bonon, representing the southern part of this batholith. The objective of this study is the comprehension of the setting context of the granitoids forming that huge batholith.

2. Geological Setting

The West African Craton occupies the western part of Africa. It represents a vast portion of the stable Precambrian crust (4,500,000 km²), more than half of which is covered by Proterozoic and Paleozoic sedimentary basins: the Tindouf basin in the northwest, the Taoudéni basin in the center and the Volta of smaller dimensions (Figure 1) [7]. According to [8], the West African craton has three units (Figure 1). The Réguibat ridge in the north covers part of Mauritania, the Moroccan Sahara (Sahrawi) and Algeria. It is composed in its western part of gneiss, orthogneiss and Archean charnockites of around 2.7 ca and in its eastern part of granites and other volcanic and volcano-sedimentary formations from Birimian [9]. These two parts are separated by the Zednès fault; the Man or Léo ridge to the south covers a large region, Sierra-Leone, Ghana, Liberia, Guinea, Mali, Côte d’Ivoire, Burkina-Faso, Niger and Togo. This ridge is similarly divided into two parts: to the west, the Archean domain and to the east, the Paleoproterozoic or Baoulé-Mossi domain which would be the extension of the Birimian formations of Kédougou-Kéniéba under the Paleozoic formations of the SW basin of Taoudéni [10]. The two areas are separated by the Sassandra accident and the windows of Kayes and Kédougou-Kéniéba to the west outcrop in Mali and Senegal. They are formed exclusively of Proterozoic formations consisting of narrow volcanic belts and large sedimentary basins structured and intruded with Eburnean granitoids [9], the Archean having never been identified in these windows. Three major orogenic episodes mark the ancient history of the West African craton [11]: the Archean (3.4 - 3.0 Ga); the Liberian (2.9 - 2.7 Ga) and the Eburnean (2.5 - 1.8 Ga) after which it was definitively stabilized [9]. As Côte d’Ivoire is located in the Man Ridge, its geological history is part of that of the West African craton [12]. It occupies the southern fringe of the Man Ridge and its surface is covered by two distinct geological units.

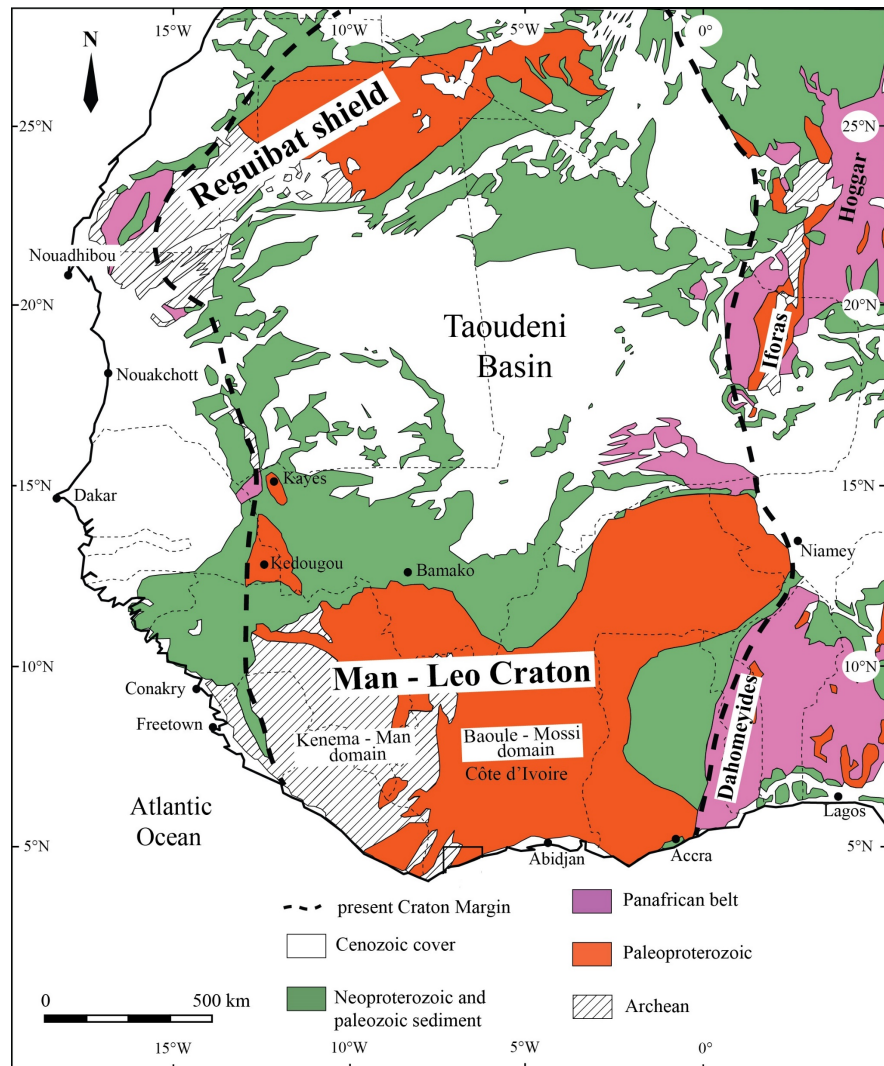


Figure 1. Simplified tectonic map of West African Craton [13].

A crystallophyllian Precambrian basement which covers 97.5% of the territory and a narrow coastal basin bordering the Gulf of Guinea which is crescent-shaped. The basement is mainly dominated by crystalline formations subdivided into three main families: 1) granitoids (granites, migmatites and granitic pegmatites); 2) crystallophyll formations (schists and micaschists) and finally 3) some rare volcanics and more or less metamorphosed sedimentary rocks are also noteworthy [14]. The emplacement of late granites developed significant contact metamorphism, currently reflected in the existence of aureoles of staurolite micaschists around these granites [14]. However, the regional metamorphism having affected the formations of region is green schist type. The granites were subject of important pegmatitic, pneumatolitic and hydrothermal processes which led to the establishment of veins and hydrothermal alteration rocks of various kinds: pegmatites, aplites, tourmalinites, quartz and greisens [15]. All the formations in the Bonon region (**Figure 2**) are substantially oriented along the Eburnean direction and constitute a structural extension of the large syn-kinematic

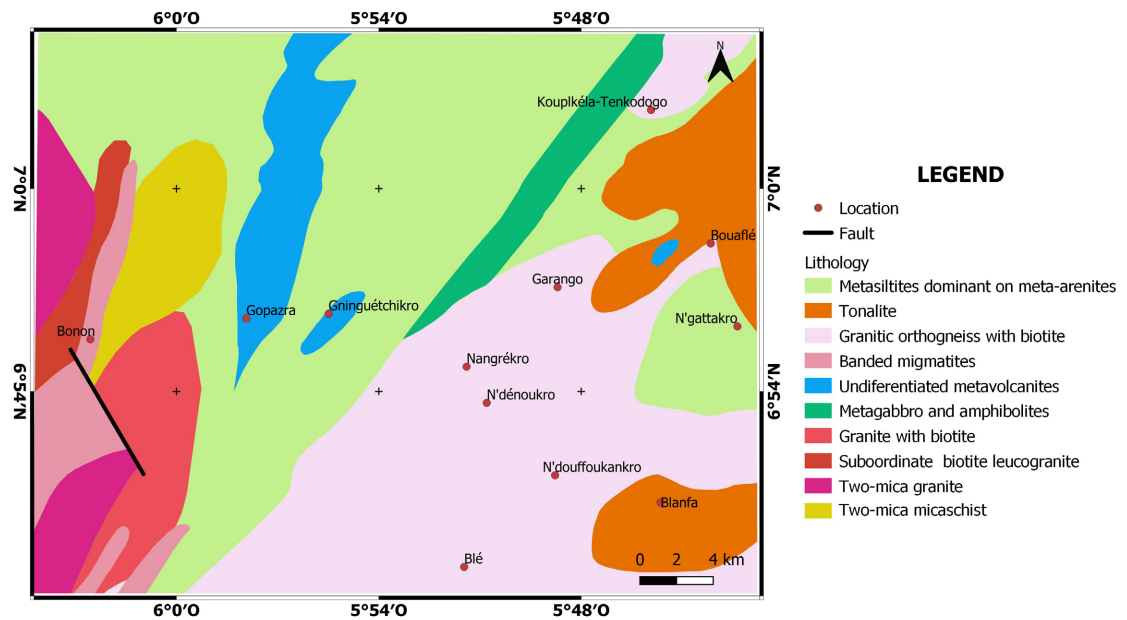


Figure 2. Geological map the Bonon area with the outcrops studied.

two-mica granite massif of Ferké [16]. The large granite outcrops are generally oriented in the following directions: N110° to 150°E, N60° to 90°E and N0° to 30°E. Metamorphic terrains generally have more or less subvertical foliations. Their directions are from N30° to 60°E in most of the region, but in the sector towards the Daloa region the directions are N10° to 25°E [17] [18].

3. Analytical Methods

To determine the different geological formations, thin sections were made at the Laboratory of Geology, Mineral and Energy Resources (LGRME) of the Félix HOUPHOUËT BOIGNY University in Cocody. Their observation was carried out with an Optical LD5500 polarizing microscope. These observations were first made in order to identify the minerals present in the rock, their proportion and their textural relationships. This guided the classification and naming of the rock. Secondly, it permitted to establish the chronology of the appearance of minerals by identifying and highlighting the phenomena of pseudomorphosis. The representative samples of the rocks observed were subjected to whole rock analysis at the Bureau Veritas mineral analysis laboratory in Vancouver, Canada, by X-ray fluorescence (XRF) for the major elements (SiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , K_2O , TiO_2 and P_2O_5) and by the inductively coupled plasma mass spectrometer (ICP MS) for trace elements (As, Ba, Be, Cd, Co, Cr, CS, Cu, Ga, Ge, Hf, In, Mo, Nb, Nd, Ni, Pb, Rb, Sb, Sn, Sr, Ta, Th, U, V, W, Y and Zn) and rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu).

4. Results

4.1. Petrography

The southern part of the Ferké batholith, located in the center west of the Ivory

Coast, is composed of different lithologies observed in the study area mainly belonging to the family of igneous rocks. These formations are composed of granodiorites, biotite granites, muscovite granites and two-mica granites. The most abundant formations are the two-mica granites as in the northern part of the batholith (**Figure 2**).

4.1.1. Biotite Granite

This rock was observed in the north of our study area near the locality of Bonon and occur in the form of slabs or small domes (**Figure 3(a)**), slightly altered and presenting medium to coarse grained (**Figure 3(a)**). The mineral paragenesis is composed of abundant quartz crystals, plagioclases and slightly altered microclines (**Figure 3(b)**). The very scarce muscovite is in the form of small isolated flakes. Biotite, the only ferromagnesian mineral in these facies, is gradually destabilized into chlorite (**Figure 3(b)**). Opaque minerals are the main accessory.

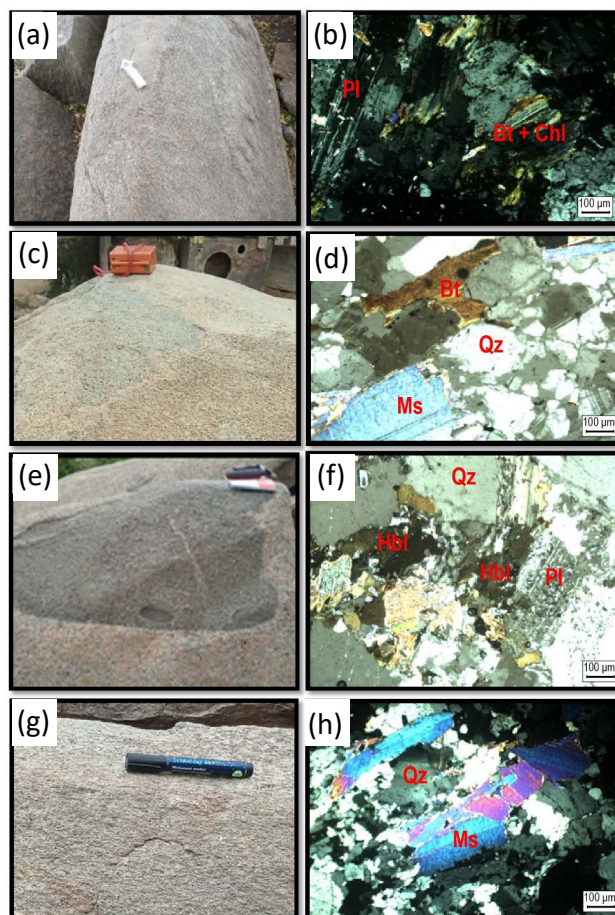


Figure 3. Field and microscopic views of granitoids from south area of Ferkessédougou batholith. (a-b) biotite granite from Bonon with phenocrystals of plagioclase and the chloritization of biotite; (c-d) muscovite and biotite granite which highlights biotite phenocrystals with zircon inclusions as well as quartz; (e-f) An enclave of granodiorite with plagioclases that gradually destabilize into sericite; (g-h) muscovite granite with huge muscovite flakes and crystals.

4.1.2. Two-Mica Granite

The main lithology of the study area formation outcrops in the form of domes and hills (**Figure 3(c)**). The two-mica granite has a massive appearance, leucocratic in color and moderately affected by weathering. This facies contains abundant quartz phenocrysts with rolling extinction which are accompanied by sub-grains resulting from their recrystallization, oriented muscovites in sizes varying from medium to coarse (**Figure 3(d)**). Xenomorphic to subautomorphic feldspars (plagioclases and microclines) are sparsely abundant and often undergoing alteration, mainly plagioclases to sericites and epidotes. To these minerals are added more or less chloritized biotites with frequent inclusions of zircons (**Figure 3(d)**).

4.1.3. Granodiorite

This formation is located on the periphery of the two-mica granites at Bouaflé. It is a large slab that contains subcircular enclaves of diorite (**Figure 3(e)**). This granodiorite is weakly altered, mesocratic in color with a massive appearance and is made up of medium-sized grains. It is composed of plagioclase phenocrysts altered in sericite, quartz crystals with rolling extinction, a few rare more or less altered microclines (**Figure 3(f)**). As ferromagnesian we have biotite whose color varies from brown to greenish with inclusions of zircons and xenomorphic to sub automorphic green hornblende (**Figure 3(f)**). In this rock there is chlorite resulting essentially from the pseudo morphosis of biotite.

4.1.4. Muscovite Granite

Observed in Bonon, this granite has a very wide geographical distribution in the southern part. It occurs in the form of slabs or domes (**Figure 3(g)**), crossed by numerous fractures and variously oriented quartz veins. The rock has a massive appearance, leucocratic in color and is weathered. This granite is composed of quartz with rolling extinction, very large, scanty Muscovites in the form of oriented lamellae, very often altered plagioclase and microclines, chloritized biotite with zircon inclusions showing aureoles, as proof of their radioactivity (**Figure 3(h)**). As secondary minerals, we mainly noted chlorite resulting from the alteration of biotite, sericite and epidote, resulting from the destabilization of plagioclases. Accessory minerals are essentially opaques.

4.2. Geochemical Data

The geochemical analyzes of rocks in the Bonon region are presented in the **Table 1** below. These granitoids have SiO₂ contents between 72.22 wt% and 71.33 wt% and alkali contents (Na₂O + K₂O) which vary from 6.28% to 8.92%. Aluminum (Al₂O₃) ranges from 13.16 to 14.96 wt%. CaO (0.6 to 1.12 wt%) and Fe₂O₃ (1.52 to 1.74 wt%) contents are low for rocks with granitic compositions and higher for granodiorite (2.55 and 3.47 wt%, CaO and Fe₂O₃ respectively). In general, Bonon granites and granodiorite have low TiO₂ (0.16 and 0.3 wt%), MnO (0.02 to 0.05 wt%), MgO (0.3 and 0.63 wt%), and in P₂O₅ (0.06 to 0.42 wt%). Ba (260 to 582 ppm), Rb (76.1 to 408.3 ppm) and Zr (89.7 to 174.6 ppm)

Table 1. Major element and trace element composition of the Bonon granitoids.

Samples	CIS20	CIS22	CIS23	CIS24
SiO ₂	72.22	71.64	72.19	71.33
Al ₂ O ₃	13.16	14.83	14.82	14.96
Fe ₂ O ₃	3.47	1.52	1.74	1.68
CaO	2.55	1.12	0.6	0.56
MgO	0.63	0.3	0.32	0.32
Na ₂ O	3.71	4.61	3.88	3.82
K ₂ O	2.57	4.31	4.73	5.02
MnO	0.05	0.02	0.02	0.03
TiO ₂	0.3	0.19	0.17	0.16
P ₂ O ₅	0.06	0.06	0.42	0.34
LOI	0.9	0.63	0.87	1
Ba	582	893	260	296
Be	3	4	9	9
Co	5.9	2.1	1.8	1.7
Cs	0.8	18.7	37.5	16.8
Ga	14.6	22.5	22.6	20.4
Hf	4.5	3.6	3	3.4
Nb	8	4.5	7.2	6.6
Rb	76.1	202.8	408.3	390.6
Sn	2	2	6	3
Sr	144	318.6	71.1	77.4
Ta	0.8	0.6	1.4	1.7
Th	7.6	18.1	9.4	9.9
U	1.3	10.3	3.8	5.1
Zr	174.6	119.8	89.7	98.4
Y	25.7	5.7	3.8	3.5
La	29.7	14.1	16.5	13.2
Ce	59.4	51.3	38.1	33.4
Pr	6.29	3.18	4.82	4.27
Nd	22.6	11.2	18.4	17.6
Sm	3.97	2.12	4.27	4.16
Eu	0.77	0.53	0.42	0.43
Gd	4.08	1.73	2.77	2.8
Tb	0.65	0.18	0.28	0.26
Dy	4.1	0.84	1.09	0.93
Ho	0.85	0.15	0.13	0.11

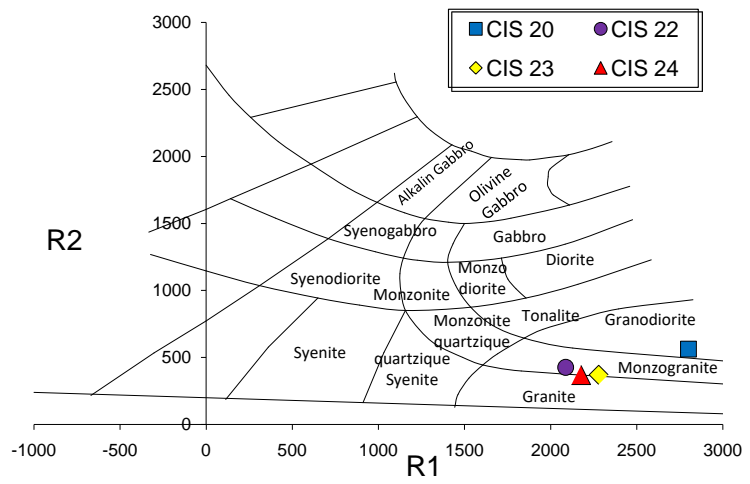
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Er	2.54	0.36	0.3	0.28
Tm	0.39	0.04	0.04	0.04
Yb	2.55	0.27	0.25	0.27
Lu	0.42	0.03	0.04	0.03
Mo	0.8	0.1	0.4	0.3
Cu	19.9	15.4	4.2	9.1
Pb	4	23	5.5	15.6
Zn	36	32	26	46
Ni	6.5	3	2.1	3
As	1.2	<0.5	<0.5	<0.5
Au	0.9	0.7	0.7	0.7
Tl	0.2	0.1	0.3	0.4

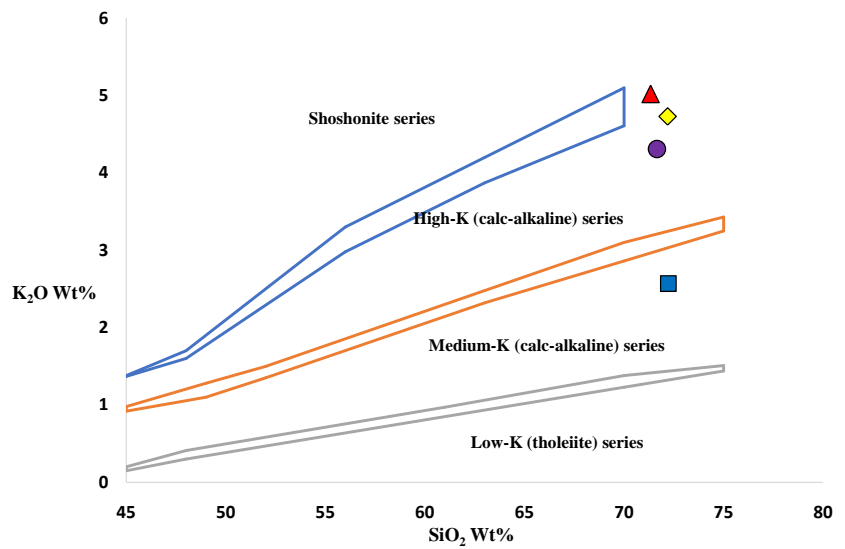
represent the highest proportions of trace elements. In the R1 vs R2 diagram (**Figure 4(a)**) the samples are distributed in the fields of granodiorites, monzogranites and granites. Thus, projected in the Hughes diagram (**Figure 4(d)**), the samples are all located in the field of igneous rocks. In other words, the samples analyzed are very weakly altered and reliable for the Petro-genetic characterization of the southern part of the Ferkessédougou batholith. The insertion of the rocks CIS 20, CIS 22, CIS 23 and CIS 24 in the binary K₂O versus SiO₂ diagram of [19] confirms the calc-alkaline character of the samples. Thus, the CIS 20 granodiorite of Bouaflé corresponds to moderately potassium calc-alkaline granitoids while the other facies are identified calc-alkaline rocks highly rich in potassium (**Figure 4(b)**). The use of the A/NK diagram according to A/CNK of [20] (**Figure 4(c)**), made it possible to better appreciate the alkalinity of the granitoids of the southern part of the batholith of Ferkessédougou.

According to this classification, the CIS 20 granodiorite from Bouaflé corresponds to a metaluminous rock, whereas the CIS 22, CIS 23 and CIS 24 granites are weakly peraluminous. The granitoids of the Bonon zone have Rare Earth (Σ REE) contents which vary between 135 and 171 ppm and are characterized by more or less parallel spectra similar to those of the Archean TTG (**Figure 5(a)**).

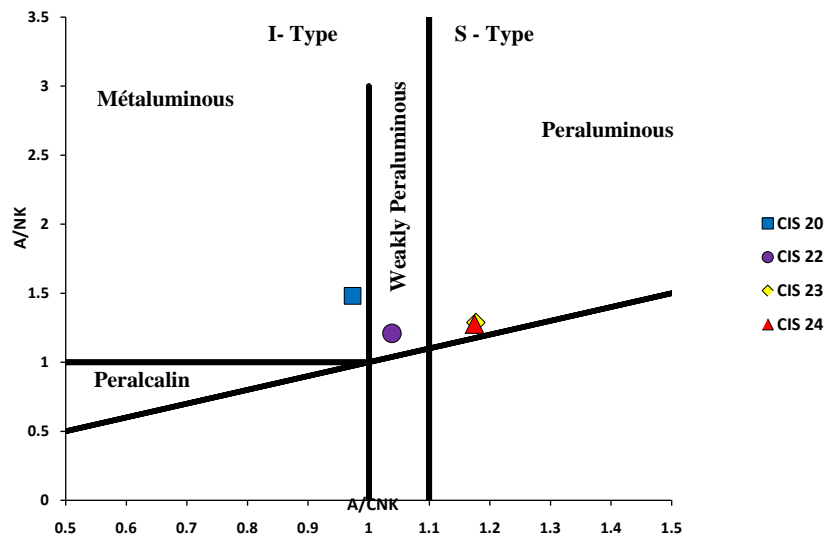
In general, these spectra are very highly fractionated and highly enriched in light rare earths with ratios (La/Sm)_N = 1.93 - 4.56. At the level of heavy rare earths (HREE), the granodiorite sample seems moderately depleted compared to granites whose (La/Yb)_N ratios vary between 7.69 and 32.28. The Bonon granitoids are marked by a very negative europium anomaly expressed by Eu/Eu* = 0.38 - 0.85. There is also at the level of the CIS 22 granite, a positive anomaly in Ce, a high concentration of zircon in the source of the magma. Mantle-normalized multi-element spectra (**Figure 5(b)**) of the granitoids show variable (sawtooth) anomalies. At the level of the Ba and Ti elements, negative anomalies are observed. There are also negative anomalies at the level of the Ta-Nb.



(a)



(b)



(c)

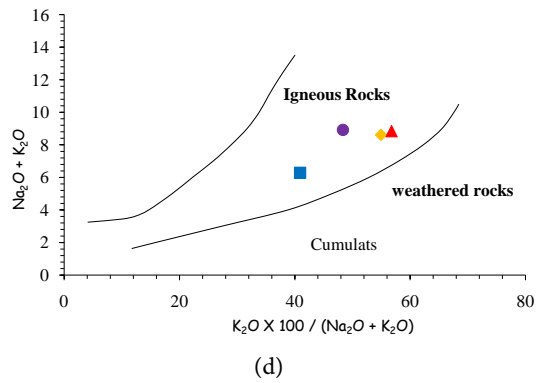


Figure 4. (a) Nomenclature of the granitoids of the Bonon region through the R1 vs R2 diagram of Roche *et al.* (1980); (b) K₂O vs SiO₂ diagram of [19] applied to granitoids in the Bonon area; (c) A/NK vs A/CNK diagram from [20] applied to granitoids in the Bonon area. (d) Diagram of Hugues (1973) applied to the granitoids of the Bonon region;

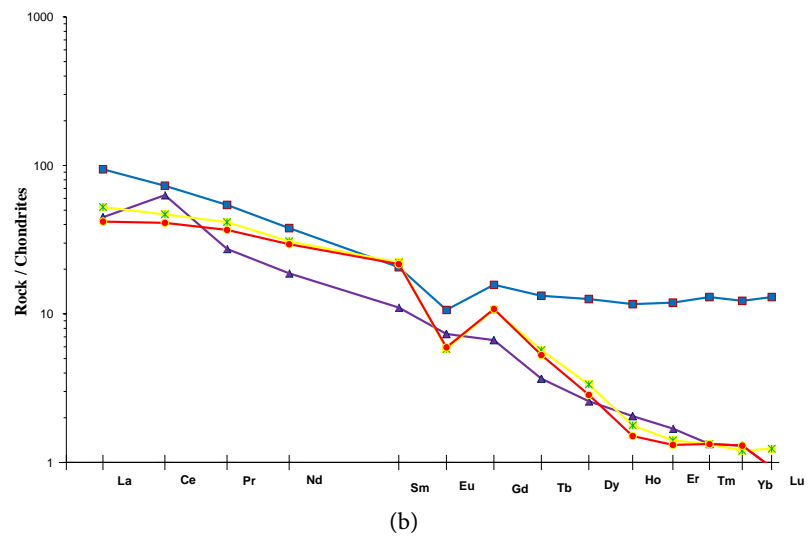
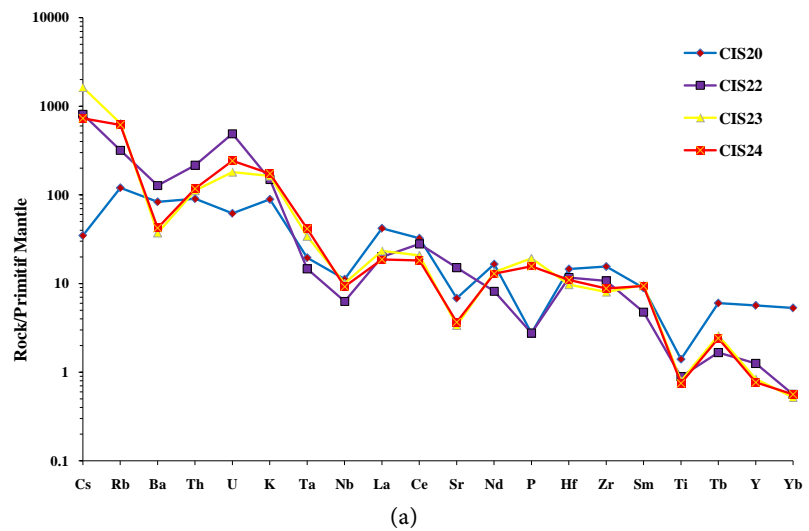


Figure 5. (a) Chondrite-normalized rare-earth spectra applied to granitoids from the Bonon region and (b) Mantle-normalized rare-earth spectra applied to granitoids from the Bonon region.

5. Discussion

The Bouaflé-Bonon area, located in the center-west of Côte d'Ivoire, belongs to the southern part of the Ferkessédougou batholith. This exclusively Paleoproterozoic domain presents a wide variety of geological formations whose genesis and structural evolution continue to be subjected to misunderstandings. From the petrographic and structural analyses, the present study tries to bring new elements in the comprehension of the geology of this locality. Petrographic work has revealed a predominance of igneous rocks in the study area. The two-mica granite, which is the most widespread geological formation, is made up of quartz minerals, alkaline feldspars, plagioclase, biotite and a procession of accessory minerals (sericite, chlorite and epidote). The observed results are consistent with those of [3] and [21] which describe two-mica granites as the main constituents of the northern part of the large elliptical batholiths of Ferkessedougou. All the geological formations of the study area have undergone various phenomena of alteration. These are highlighted by the data collected and are generally related to either hydrothermal fluids and/or meteoric agents. They come from the pseudo morphosis of primary minerals, and generally affect all rocks. Pervasive alteration of the hydrothermal type, vein alteration and meteoric alteration are also present (**Figure 6**). The geochemical study reveals that the batholith of Ferké is of granitic and granodioritic composition. These rocks have a subalkaline to calc-alkaline affinity. Granodiorite has a metaluminous character; this character is described by [22] as implying that the granodiorite originated from the mantle. As for the other rocks, they have a peraluminous character; a character which would prove according to [22].

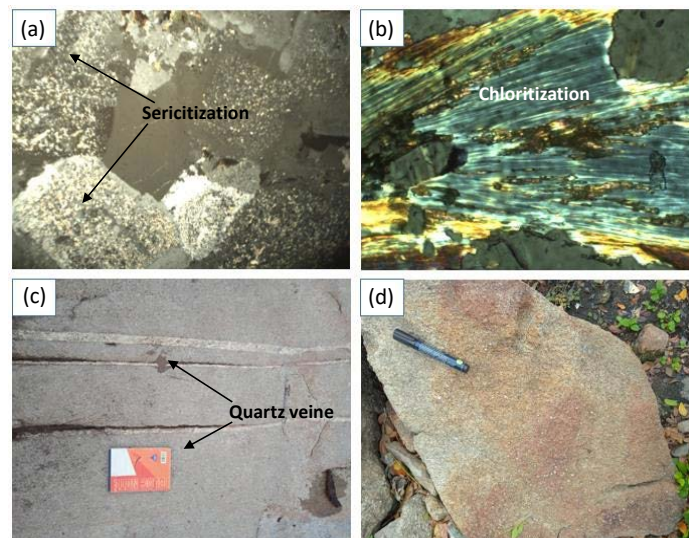
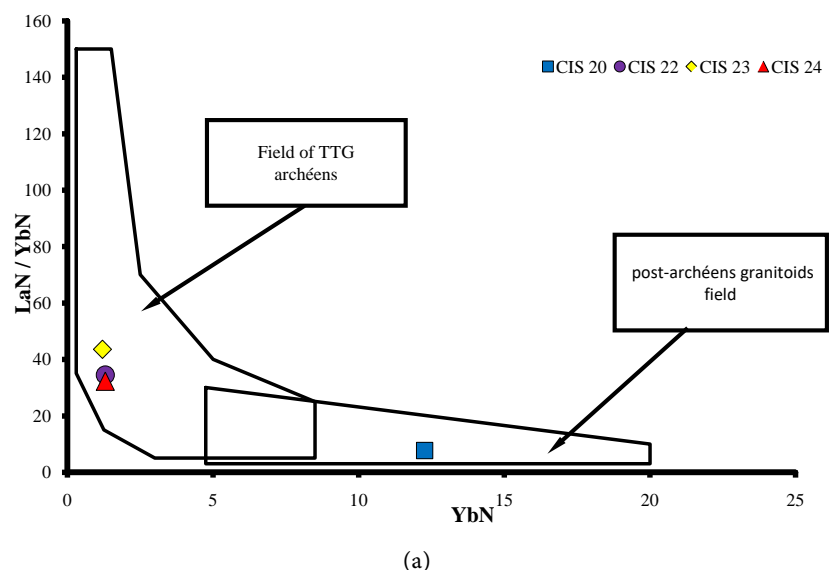


Figure 6. (a) sericitization-like pervasive weathering observable in feldspars of all lithologies; (b) pervasive chloritization-type weathering from hornblendes and biotites; (c) dyke hydrothermal alteration characterized by the presence of quartz, pegmatite, aplite and carbonate veins and veinlets of varying thicknesses; (d) meteoric alteration materialized in the rock by vacuoles and traces of oxidation from iron oxides and hydroxides.

The samples studied from the Bonon sector confirm the results of [5] and [23] who assert that the granitoids of Côte d'Ivoire have a double origin. The negative europium anomaly indicates plagioclase fractionation or genesis of melting in the plagioclase stability field. Besides, spectra reflect the fractionation of feldspars, and the HREE fractionation of said granites would indicate the presence of garnet and, to a lesser extent, of zircon, in the melting residue of the source [4]. The diagrams of [24] indicate that granitoids are Archean granites conforming to the geochemical characteristics of type S granites generated by the partial melting of metasedimentary rocks [25] except for granodiorite which falls within the domain common to granitoids post-Archean and would have taken place in a context of arc magmatism typical of Birimian formations (**Figure 7(a)**). These granites come from the partial melting at shallow depth of crustal rocks associated with sediments as defended by [26] for the Birimian formations of Comoé and [5] [27] and for the granitoids of the Bandama basin. However, the position of the granites in the diagram of [28] indicates that the protoliths of these granites are TTG (tonalite, trondhjemite, granodiorite). So, these granites with a TTG character would be the result of the contamination of the Archean crust from juvenile formations according to [29]; that is to say the presence of the Archean in the Birimian.

It is therefore possible that the extension of the southern part of the Ferké batholith located in the center-west of Côte d'Ivoire contains Archean relics. The discrimination diagrams of [30] were used to determine the geotectonic environment which conditioned the emplacement of granitoids in the localities of Bonon. In the Nb vs Y diagram, (**Figure 7(c)**) all of the granitoids analyzed indicate volcanic arc environments associated with collisional tectonics. This distribution is confirmed by the Rb vs Y+Nb diagram, in which the CIS 20 granodiorite sample falls within the field of volcanic arc formations, while the CIS 22, CIS 23 and CIS 24 granites plot in the syn-collisional field (**Figure 7(b)**).



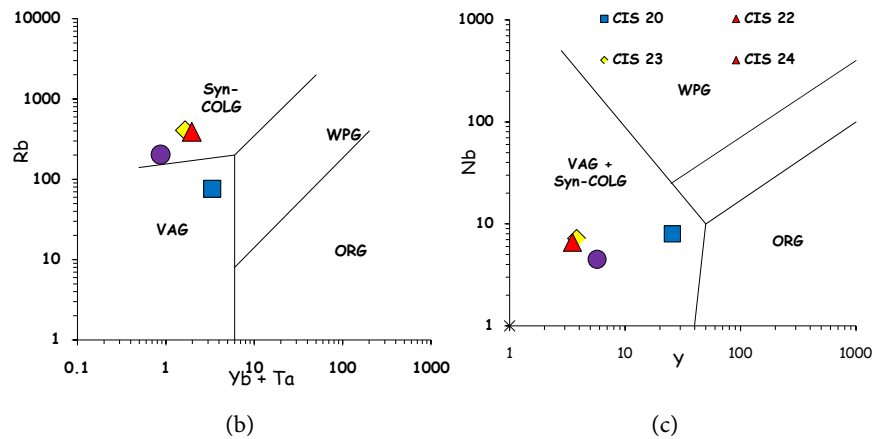


Figure 7. (a): LaN / YbN versus YbN diagram from [28] applied to granitoids in the Bonon region; (b) and (c): position of the granitoids of the Bonon sector in the diagram of [30]. VAG = volcanic arc granites; WPG = Within Plate Granite; ORG = oceanic ridge granites; Syn-COLG = syn-collisional Granite.

6. Conclusion

The southern part of the Ferké batholith consists essentially of granitoid, namely granodiorites, two-mica granites, biotite granites and muscovite granites. Geochemical data indicate that the granitoids of the southern part of the Ferké Batholith have granodiorite-monzogranite-granite compositions. They have a strongly potassic calc-alkaline affinity and correspond to granites of igneous origin (Type I). The trace element distribution shows spectra with LREE enrichments and HREE depletions. The negative anomalies in Ta-Nb as well as in Eu would imply that the studied rocks are generated by partial melting of a crust of TTG composition. All samples have a composition of arc and collision granites and would be generated in a subduction zone.

Acknowledgements

This work was done as part of a collaboration between Félix Houphouët Boigny University and West African Exploration Initiative. The analyses and fieldwork were financially supported by PRESED-CI T2GEM research grant “Geophysical and Geochemical Techniques for Mining Exploration”.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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