International Journal of Geosciences, 2024, 15, 180-203
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Petrographic, Geochemical and Metallogenical Context of the Geological Formations of the Goumere Region (North-East of Cote D'Ivoire): Implication to the Knowledge of Gold Mineralization

Fossou Jean-Luc Hervé Kouadio*, Alain Nicaise Kouamelan, Topka Kakeu Lionel Boya, Roger Nicaise Kanga

Laboratory of Geology, Mineral and Energy Resources (LGRME), Faculty of Earth Science and Mineral Resources, Félix Houphouët Boigny University, Abidjan, Côte d'Ivoire

Email: *fossou.kouadio95@ufhb.edu.ci

How to cite this paper: Kouadio, F.J.-L.H., Kouamelan, A.N., Boya, T.K.L. and Kanga, R.N. (2024) Petrographic, Geochemical and Metallogenical Context of the Geological Formations of the Goumere Region (North-East of Cote D'Ivoire): Implication to the Knowledge of Gold Mineralization. *International Journal of Geosciences*, **15**, 180-203.
https://doi.org/10.4236/ijg.2024.152012

Received: January 5, 2024
Accepted: February 26, 2024
Published: February 29, 2024

Abstract

The Gouméré region is located in the North-East of Côte d'Ivoire and is located in the South-West of the Bui furrow. In order to highlight the geology of the area studied, 14 samples were taken for studies using petrographic, geochemical and metallogenic methods. The study of macroscopic and microscopic petrography made it possible to highlight two major lithological units: 1) a volcano-plutonic unit, formed of gabbros, basalt, volcaniclastics and rhyodacite; 2) a sedimentary unit (microconglomerate). From a geochemical point of view, the results obtained indicate that the plutonites are gabbro and gabbro diorite while the volcanics have compositions of basaltic andesites, rhyolite and dacites. The sediments have a litharenitic to sublitharenitic character. The metallogenic study made it possible to highlight hydrothermal alterations and metalliferous paragenesis on the formations studied. Hydrothermal alteration is characterized by the presence of carbonation, silicification, sericitization, sulfidation and to a lesser degree chloritization. Metalliferous paragenesis consists of pyrite, chalcopyrite, hematite and magnetite.

Keywords

Petrography, Geochemistry, Metallogeny, Gouméré, Côte d'Ivoire

1. Introduction

West Africa is generally dominated by greenstone belts of Birimian age which are of great interest for mining research [1]. These belts contain plutono-volcanic, volcaniclastic and sedimentary sequences, metamorphosed in greenschist to amphibolite facies conditions and intruded by granitoid massifs (2.2 - 2.0 Ga), "[2]-[9]". The Paleoproterozoic domain (2.5 to 1.6 Ga) forms part of the West African craton. It consists of juvenile continental Paleoproterozoic crust that was emplaced during the Eburnean orogeny, probably due to oceanic materials "[2], [10] [11] [12]", with a legacy of older Archean crustal rocks [13]. It is made up of Birimian greenstone belts associated with granitoids "[1] [14] [15] [16]". The majority of these Birimian formations of the Dorsale de Man, approximately 35%, are found in Côte d'Ivoire and are distributed in 17 volcano-sedimentary furrows, including that of Bui. The Goumére region is located in the northeast of Côte d'Ivoire. In the southern part of this region, we encounter geological formations attributed to the Tarkwaïen and associated formations "[8] [9] [17] [18]". They are located in the Bui belt, a belt of green rocks of Paleoproterozoic age, which extends to the northwest of Ghana. Given the interest of the Tarkwaian in Ghana, both scientifically and economically, it proved necessary to look into the formations of this locality. The main objective of this study is to contribute to improving knowledge on the geological formations of the Gouméré region in order to highlight a metallotect for this area. The scarcity of fresh rock outcrops and the absence of deep works have until now prevented the pursuit of more in-depth investigations on the geological level of these Paleoproterozoic age terrains. However, the need for more in-depth studies is essential thanks to a multidisciplinary approach in order to appreciate in more detail the petrographic, geochemical and metallogenic characteristics and geological formations of the Gouméré sector.

2. Geological Context

Côte d'Ivoire belongs to the West African craton and more particularly to the Man Ridge (**Figure 1**). Two geological complexes cover the entire surface of Côte d'Ivoire. A narrow coastal sedimentary basin bordering the Gulf of Guinea occupies 2.5% of the Ivorian territory and extends from Fresco in the west to Axim in Ghana in the east and a Precambrian and crystalline basement covers the rest of the Ivorian territory, roughly 97.5%. It is made up of the Archean and Paleoproterozoic domains. The Archean domain is located to the west of the Sassandra fault (**Figure 1**) while the Paleoproterozoic domain is to the east and covers the rest of Côte d'Ivoire basement. The structuring of the latter has been the subject of several studies whose results are controversial. Indeed, according to certain authors [19] and [20], this structuring took place during the Eburnean megacycle (2.5 to 1.6 Ga) and the main tectonometamorphic phenomena occurred between 2.2 Ga and 2.0 Ga [21]. On the other hand, other authors such as [22] speak of a structure in two orogenic cycles: the Burkinian (2.4 to 2.15 Ga) and the Eburnean in the strict sense (2.15 to 1.6 Ga). Boher [10] defines the entire Paleoproterozoic domain as being of Birimian age. Birimian formations

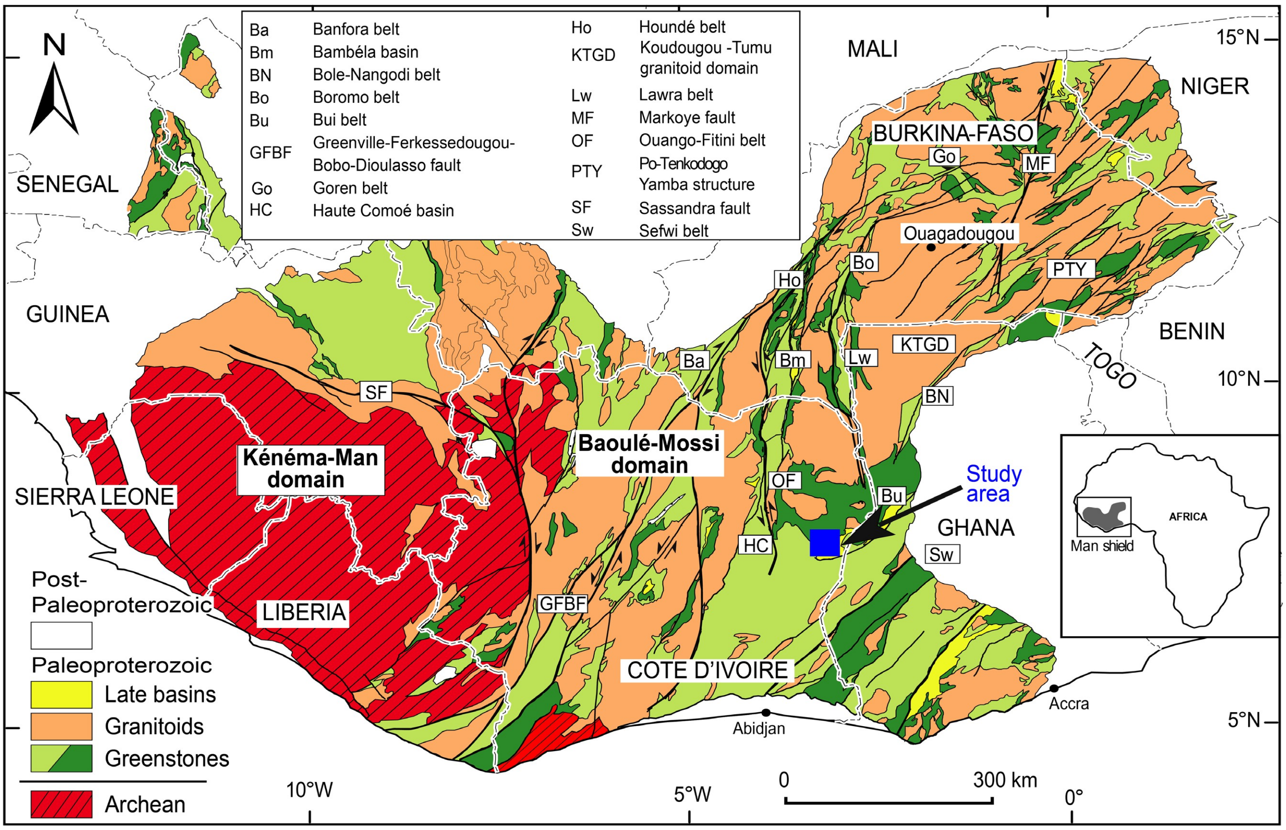

Figure 1. Simplified geological map of the Man-Leo Rise (modified after [23]).

generally form volcano-sedimentary sets-oriented NNE-SSW, bordered or containing granitoids.

Seventeen Birimian belts distributed over two fundamental reference alignments, Tehini-Dimbokro (east) and Ferké-Soubré (center), have been identified in Côte d'Ivoire [19]. These belts are composed of metavolcanites, plutonites and metasediments. The Birimian is considered to be formed by a combination of volcanic, subvolcanic and sedimentary rocks emplaced in intracratonic basins. The contents of these basins or belts are interpreted by some authors "[17] [24]" as greenstone belts or volcano-sedimentary basins. According to [25], the Birimian belts are subdivided into type I units (units which were deposited in deep basins and include various formations (Fetêkro unit, Aboisso unit) and type II units which were deposited in shallow basins composed of acidic or intermediate and volcano-sedimentary formations (Bondoukou unit, Dimbokro unit). The area studied is located in the Paleoproterozoic domain (**Figure 1**). It is covered by a complex set of Quaternary and Birimian geological formations. The Birimian occupies practically the entire surface of the study area and is subdivided into three geological units: the Tarkwaian, the volcano-sedimentary and the intrusive "[8] [9] [26]". This area belongs to the Birimian Comoé sedimentary basin. This basin is one of the largest in the Paleoproterozoic domain and outcrops in Burkina Faso and Ghana in addition to Côte d'Ivoire Ivory. The sedimentary basins are mainly siliciclastic, composed of greywackes and turbiditic claystones, the latter being occasionally carbonated [17]. The geological units of the Comoé basin form a terrigenous sedimentary series comprising sandstones with a phyllitic matrix, arkoses and pelitic layers, intruded by granitoid massifs then metamorphosed into green schist to amphibolite facies conditions "[8] [27]".

3. Methodology

Before the study of the geological formations of the Gouméré region, it initially consisted of sampling the different rocks in the field. The laboratory work combined different analytical techniques including petrography (macroscopic, microscopic and metallographic) and lithogeochemistry. Fourteen (14) representative rocks were sampled, followed by slide preparation and geochemical analyzes (**Figure 2**). The thin, polished sections were produced at the Laboratory of Geology, Mineral and Energy Resources (LGRME) at Félix Houphouët-Boigny University of Abidjan-Cocody. The geochemical analyzes on whole rock were carried out by the Bureau Veritas laboratory in Vancouver, Canada. In practice, major elements were analyzed by X-ray fluorescence using an XRF while REEs and trace elements were tested by inductively coupled plasma mass spectrometry (ICP-MS) using an Agilent 7700× mass spectrometer. These data were processed by computer programs in Excel to establish the normative compositions and the CIPW standard. Then, the GCD kit 6.0 software [28] and the Capdavilla computer program were used to establish the lithogeochemical characterization diagrams.

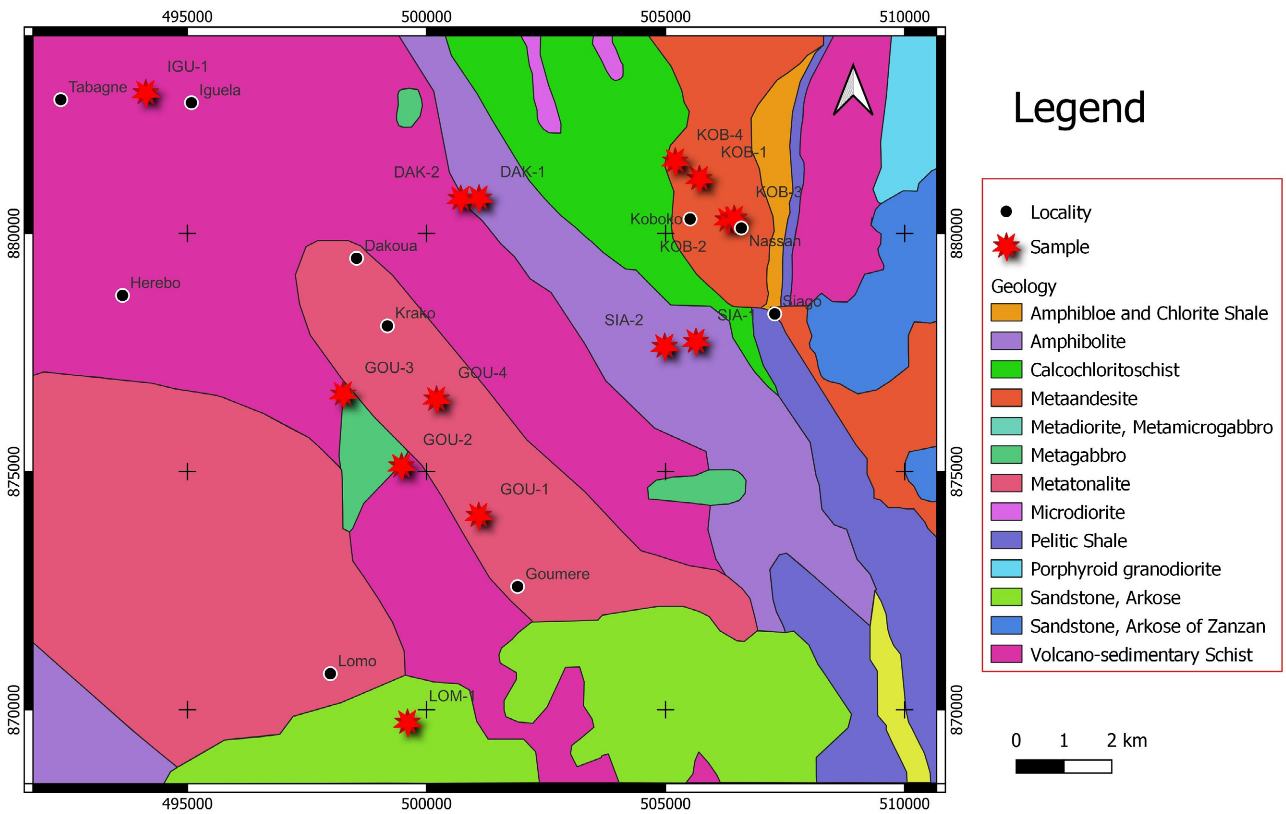

Figure 2. Geological map of Gouméré area with location of analyzed samples (modified after [27]).

4. Results

4.1. Petrography

4.1.1. Plutonic Rocks

Gabbros

Gabbros are the most dominant lithology in the study area. They are found in the localities of Gouméré, Dakoua, Siago and Koboko. They are melanocratic, massive in appearance (**Figure 3(a)**). Microscopic study of these rocks shows gritty to microgranular porphyritic textures (**Figures 3(b)-(f)**).

- Plagioclase: it represents 25% to 30% of the matrix with rarely automorphic forms. It often occurs in phenocrysts (1 to 2 mm long and 1 mm wide). It is almost unrecognizable on some sections because of alteration. It alters mainly to sericite (**Figure 3(e)**) and damourite and sometimes to epidote (**Figure 3(c)**).

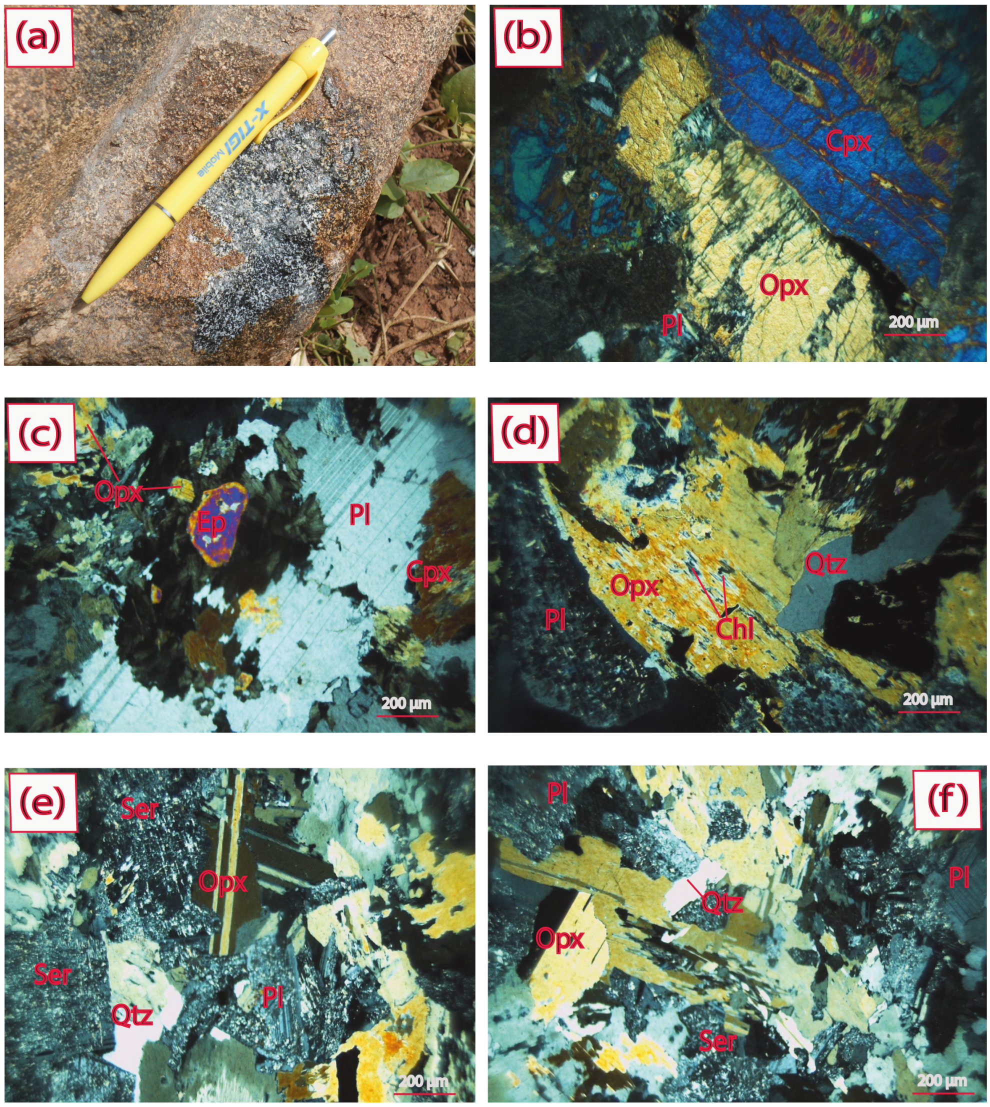

Figure 3. Macroscopic et microscopic aspects of gabbros. (a) Macroscopic aspect; (b) Crystal of Opx and Cpx; (c) Epidotization; (d) Chloritization; (e)-(f) Sericitization. (Opx: orthpyroxene, Pl: plagioclase, Chl: chlorite, Cpx: clinopyroxene, Ep: epidote, Ser: sericite; Qtz: quartz).

Plagioclase is found in places in inclusion in the green hornblendes.

- Pyroxene: abundant 35% to 40% in some thin sections and less in others where we have observed an almost total ouralitization in amphibole. Several types of pyroxenes have been described, they are augite showing a macle of albite (**Figure 3(f)**), and hypersthene.
- Green Hornblende: it represents 20%, in general automorphic. This hornblende is millimetric to centimetric, very pleochroic (dark green to light green). It is omnipresent in some parts of the thin section and comes essentially from the ouralitization of pyroxenes. It is presented in phenoblasts of more or less elongated shape (up to 2 mm long and 1 mm wide) with two sections: a basal section with two cleavage planes making 120˚ and a longitudinal section.

4.1.2. Volcanic Rocks

1) Basalt

The basalt is of massive or deformed aspect (**Figure 4(a)**). It is generally melanocratic (blackish) and sometimes traversed by veins and veinlets of quartz and calcite. This rock of basaltic composition has been observed in the Koboko and Siago localities.

Under the microscope, the basalt has a microlitic porphyry texture (**Figure 4(b)** & **Figure 4(c)**). The phenocrysts observed are generally pyroxene and amphibole.

- Green Hornblende: abundant, occurs in microliths and often alters to epidote.
- Pyroxenes: not very abundant, automorphic most often in phenocrysts with two cleavage planes at 90˚, most often augite.
- Mesostasis: composed of plagioclase and amphibole rods, is devitrified and partially recrystallized into epidote and sericite minerals.

Carbonate are also observed, most often associated with sericite, epidote, oxides and sulfides (**Figure 4(d)** & **Figure 4(e)**).

2) Volcanoclastite

These outcrops are located in the locality of Koboko. These rocks are melanocratic. Facies with dark minerals (amphiboles and pyroxenes) of millimeter to centimeter size are the most numerous. These occur locally as breccias and lapillis tuffs (**Figure 5(a)**). Microscopically, we observe a porphyritic microlithic texture.

- Mesostasis: contains glass and minerals of carbonates, amphibole, sericite and quartz. We also note the presence of quartz-carbonate veinlets. The clasts generally destabilized in carbonates and also phenocrysts of quartz, amphibole and carbonate are mainly composed of chalcedony and carbonate (**Figures 5(b)-(e)**).
- Chalcedony: subautomorphic to automorphic, consists of a quartz crown, there are two generations of quartz depending on their size and carbonates (**Figure 5(c)** & **Figure 5(d)**).
- Carbonates: mainly subautomorphic calcite, recognizable by its Carlsbad macle.

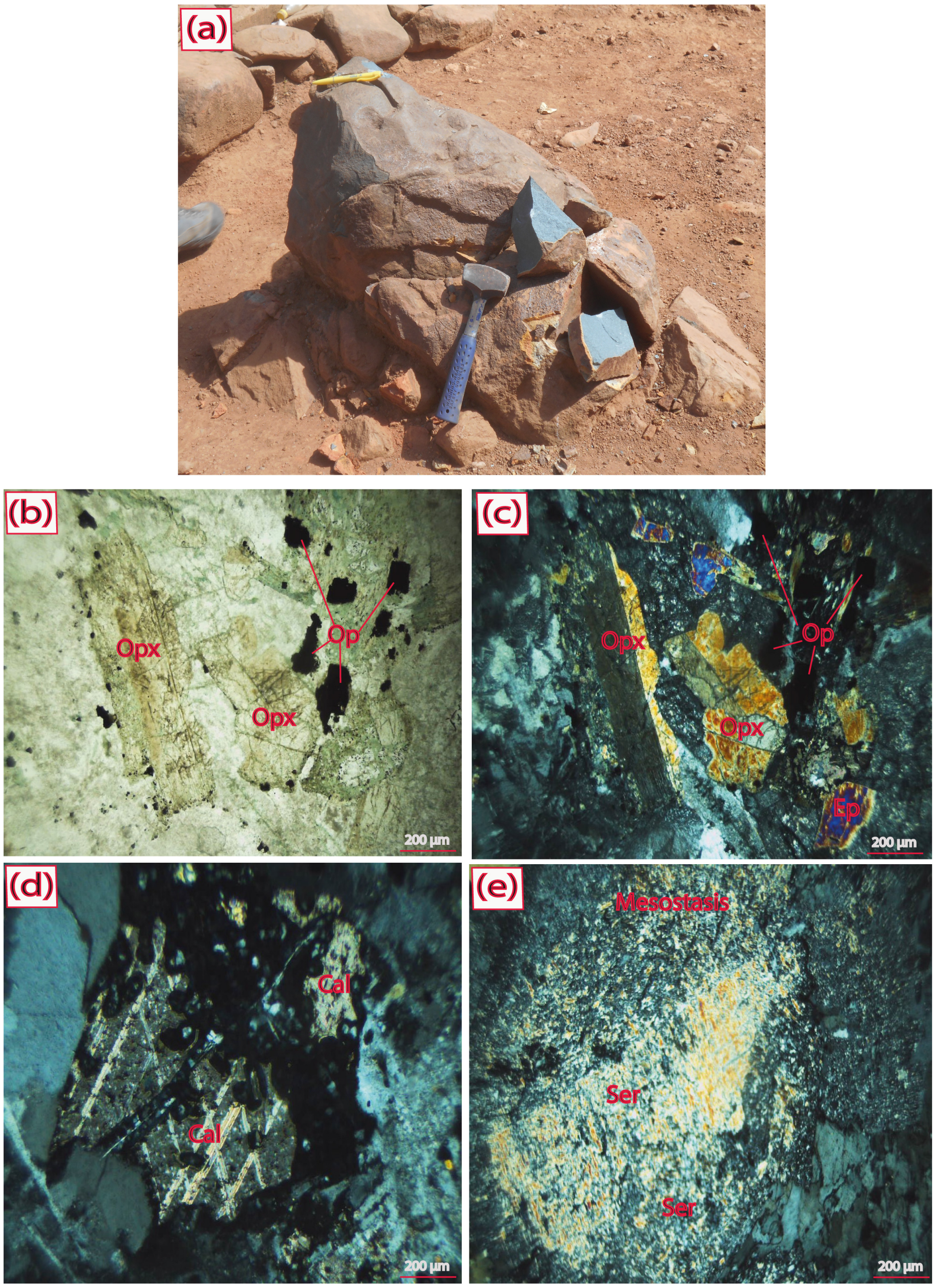

Figure 4. Macroscopic et microscopic aspects of basalt. (a) Macroscopic aspect; (b)-(c) Pyroxene phenocrystal in thin section; (d) Calcite and silica in thin section; (e) Sericitization. (Opx: orthopyroxene, Op: opaque, Cal: calcite, Ep: epidote, Ser: sericite).

3) Rhyodacite

These outcrops are located in the Siago and Koboko localities. These rocks are mesocratic (brownish) with dark minerals (amphiboles) of millimeter to centimeter size being the most numerous. Quartz phenocrysts are also present (**Figure 6(a)**). The microscopic mineralogy of the rhyodacites shows a porphyritic microlithic texture, composed of plagioclase, amphibole and quartz in a plagioclase matrix.

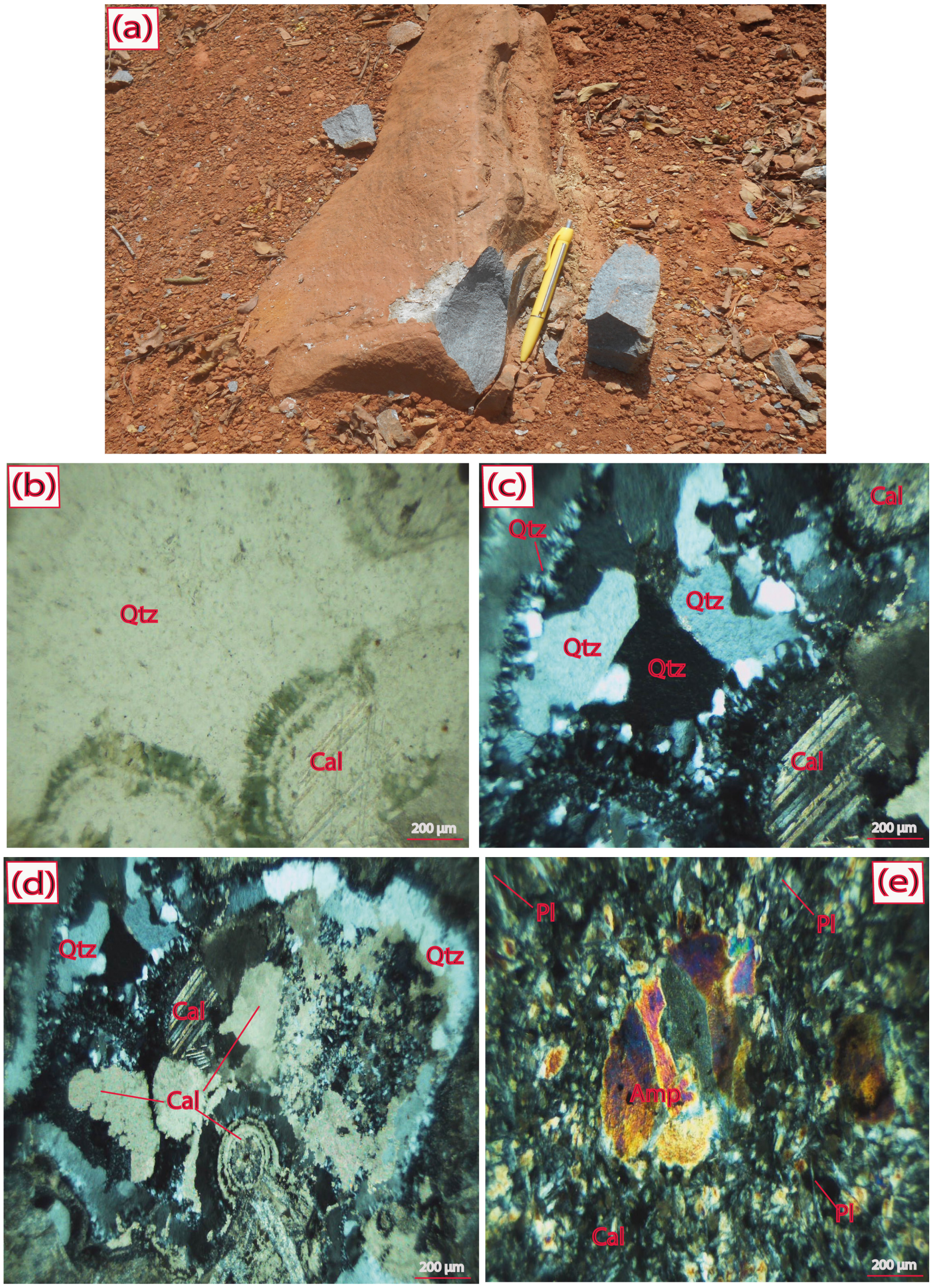

Figure 5. Macroscopic et microscopic aspects of volcanoclastite. (a) Macroscopic aspect; (b)-(d) Chalcedony. (e) Phenocrystal of amphibole. (Pl: plagioclase, Cal: calcite, Amp: amphibole, Qtz: quartz).

- Plagioclase: abundant and automorphic (rectangular), sometimes in phenocrysts up to 1.5 mm long and 1 mm wide. It may exist as a micrograin associated with the matrix. It is frequently altered to sericite and sometimes shows zonation (**Figures 6(d)-(f)**).
- Hornblende: automorphic (rhombic) phenocrysts of about 1.5 mm long and 1 mm wide. It has two cleavage planes at 120˚ in basal section. It also exists in

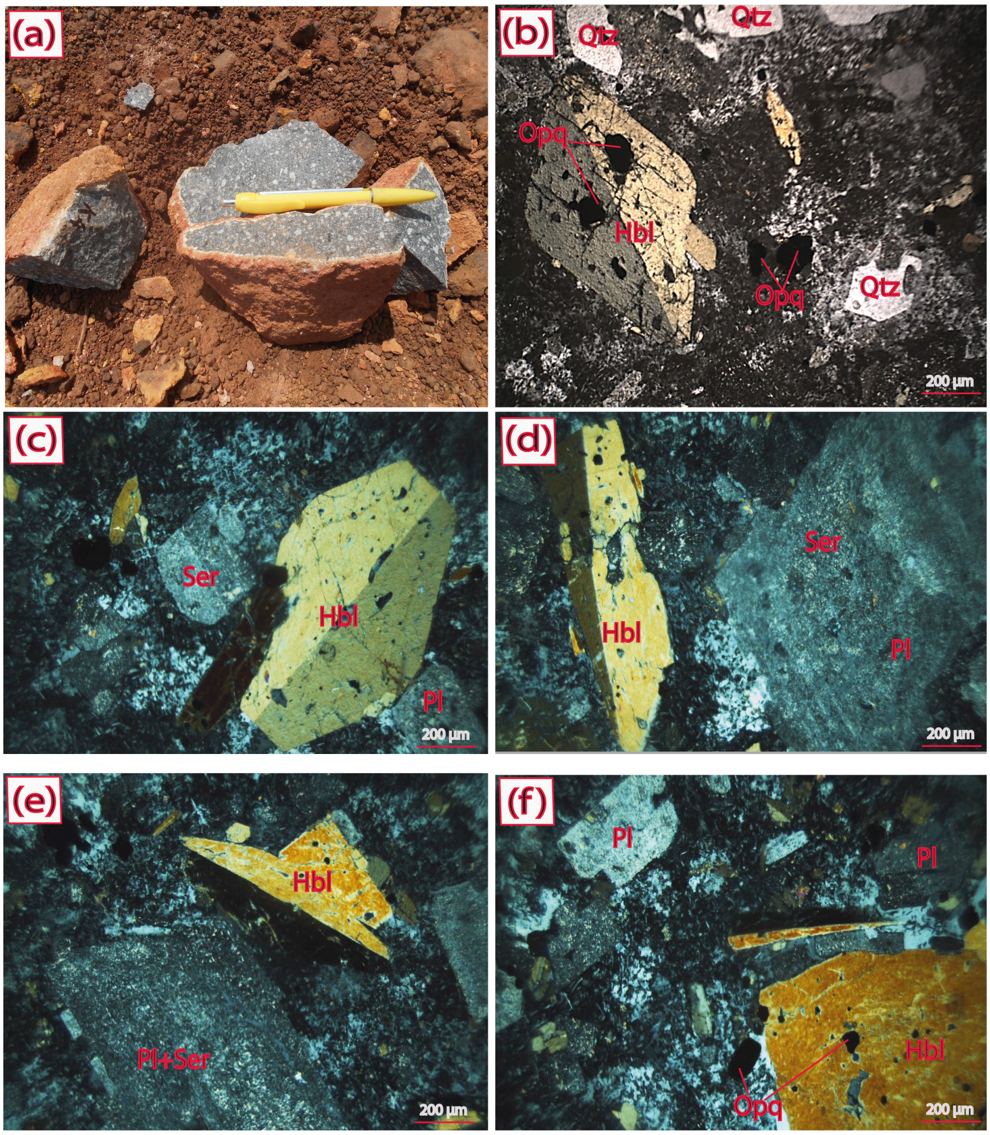

Figure 6. Macroscopic et microscopic aspects of rhyodacite. (a) Macroscopic aspect; (b)-(f) Microscopic aspect. (Pl: plagioclase, Ser: sericite, Hbl: hornblende, Qtz: quartz, Opq: opaque).

automorphic micrograin (Figures 6(b)-6(f)).

- Quartz: less abundant, corroded and showing rolling extinction (Figure 6(b)).
- Mesostasis is essentially composed of plagioclase microliths, showing a sericitization.

4.1.3. Microconglomerate

These rocks were collected in the localities of Lomo and Iguéla, of brown color, they are characterized by grains of quartz taken in a clayey cement (Figure 7(a), Figure 7(b)). Microscopy reveals quartz and muscovite minerals organized in a granular texture (Figures 7(c)-(f)).

- Quartz: very abundant, 70% to 80% of minerals. It is subrounded and angular with a diameter of up to 1 mm. It is often in the form of cracked porphyroclasts

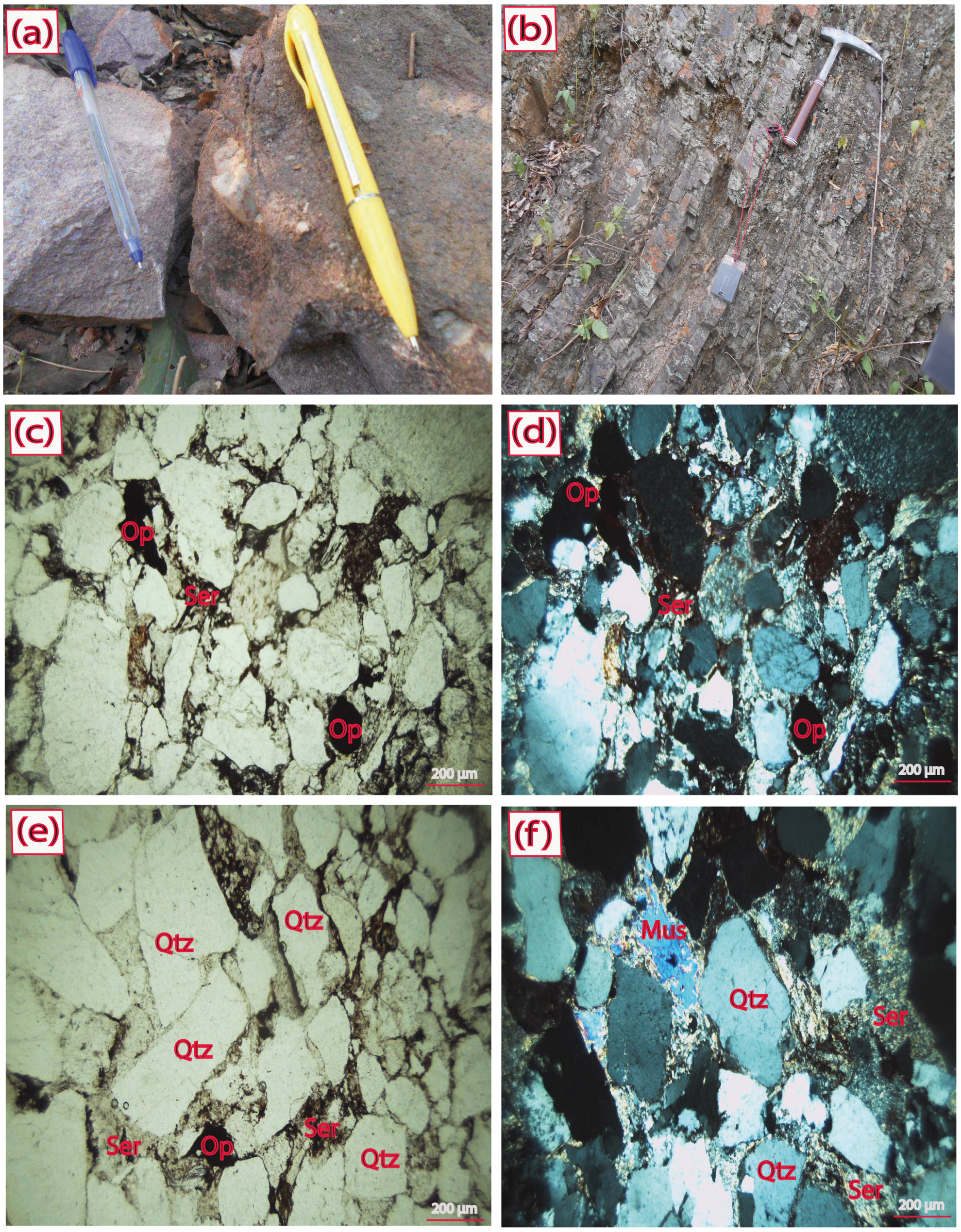

Figure 7. Macroscopic et microscopic aspects of microconglomerate. (a), (b) Macroscopic aspect; (c)-(f) Microscopic aspect. (Mus: muscovite, Qtz: quartz, Op: opaque, Ser: sericite).

showing a direction of deformation and also in micro grains (**Figure 7(f)**). These grains have a preferential orientation.

- Muscovite: rare, showing a wavy extinction and a bright hue. It is found only in the matrix (**Figure 7(f)**).
- Matrix: less than 20%, it is made of ferro-titanium clay with an important sericitization.

4.2. Geochemistry

These Major element (wt%) chemical analyses (**Table 1**) of the samples are

Table 1. Major element composition (%) of the samples collected.

Sample	GOU 1 Plutonic	GOU 2 Plutonic	GOU 3 Plutonic	GOU 4 Plutonic	KOB 1 Volcanic	KOB 2 Plutonic	KOB 3 Volcano-clastic	KOB 4 Volcanic
SiO_2	49.8	54.2	52.27	48.72	52.57	49.86	50.14	67.02
TiO_2	0.85	0.93	0.75	0.8	1.01	1.37	0.81	0.42
Al_2O_3	16.66	15.31	14.75	13.75	14.57	14.08	12.85	15.02
Fe_2O_3	9.72	11.19	9.79	14.22	11.69	14.59	8.84	4.63
MnO	0.14	0.15	0.16	0.22	0.21	0.22	0.16	0.07
MgO	6.31	5.29	9.07	7.36	6.41	5.61	3.61	1.51
CaO	10.39	8.08	9.03	11.3	7.85	9.07	10,01	3.3
Na_2O	3.11	3.29	2.25	1.95	4.09	2.76	2.32	5.28
K_2O	0.74	0.45	0.8	0.18	0.21	0.4	0.38	1.06
P_2O_5	0.11	0.14	0.11	0.06	0.11	0.07	0.09	0.11
Cr_2O_3	0.04	0.03	0.07	0.03	0.04	0.01	0.05	0.02
LOI	1.42	1.08	1.58	2	2.04	2.8	10.98	0.79

Sample	DAK 1 Plutonic	DAK 2 Plutonic	SIA 1 Volcanic	SIA 2 Plutonic	LOM 1 Micro-conglomerate	IGU 1 Micro-conglomerate
SiO_2	49.11	50.75	78.38	52.03	80.32	86.14
TiO_2	1.9	0.78	0.25	1.25	0.46	0.22
Al_2O_3	14.87	16.06	10.39	13.11	8.99	6.23
Fe_2O_3	15.15	10.21	3.03	14.19	5.63	3.62
MnO	0.16	0.15	0.22	0.23	0.03	0.02
MgO	5.27	7.29	2.54	5.69	0.39	0.29
CaO	9.04	10.52	0.26	9.76	0.09	0.07
Na_2O	2.53	2.66	1.92	2.65	0.12	0.12
K_2O	0.38	0.4	0.44	0.22	2.63	1.82
P_2O_5	0.07	0.05	0.13	0.08	0.04	0.03
Cr_2O_3	0.03	0.07	0.01	0.01	0.02	0.01
LOI	1.6	2.12	2.53	1.74	1.34	0.64

projected onto discriminant diagrams to establish the classification and nomenclature of all the rocks. The rocks reported in the discriminating diagram of [29], (**Figure 8**), allows to distinguish two sets of geological formations namely magmatic and sedimentary rocks.

4.2.1. Magmatic Rocks

1) Plutonic rocks

These rocks (GOU, DAK, KOB 2, SIA 2) are characterized by SiO_2 contents of

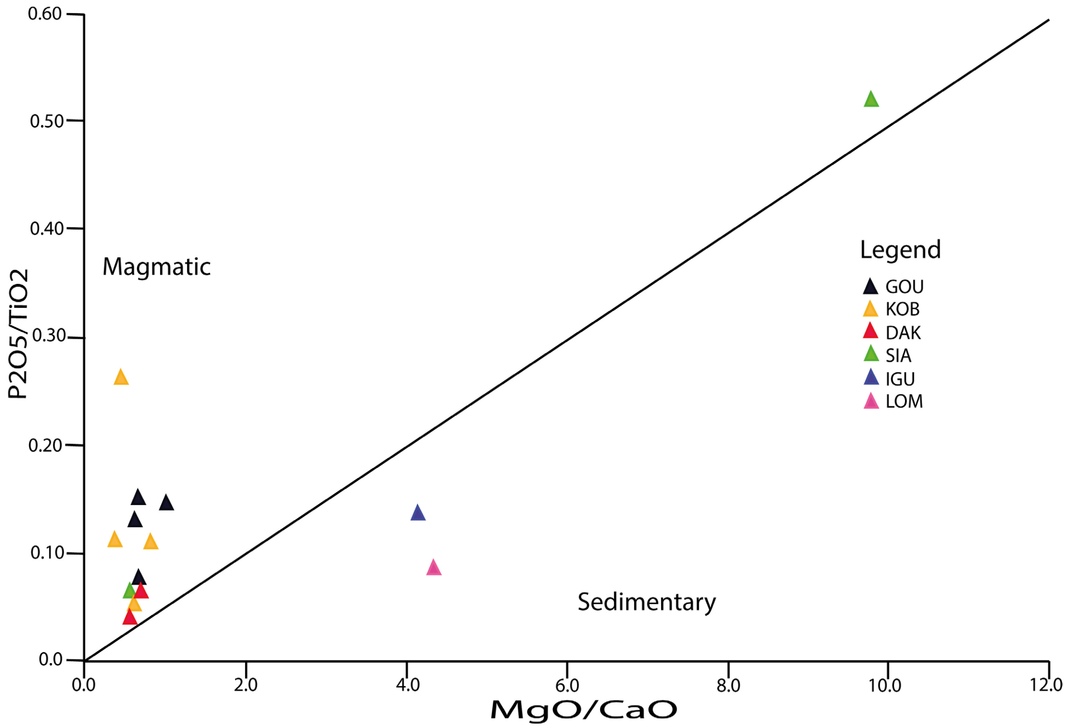

Figure 8. P_2O_5/TiO_2 versus MgO/CaO diagram of [29] applied to Gouméré rocks.

48.72% to 54.2% and alkalis (Na_2O + K_2O) of 2.85% to 3.87%, which give them a gabbro and gabbroic diorite composition on the classification diagram of [30] (**Figure 9**). Al_2O_3 contents vary between 13.11% and 16.66%; MgO between 5.29% and 9.07%; Fe_2O_3 between 9.72% and 15.15%. CaO contents vary from 8.08% to 11.3%, Na_2O from 1.95% to 3.29% and K_2O from 0.18% to 0.8%. MnO contents are between 0.14% and 0.23%. The TiO_2 values are lower than 2% (**Table 1**).

2) Volcanic rocks

The basalt (KOB 1), (**Figure 10**) has SiO_2 contents of 52.57% (**Table 1**); MgO of 6.47%; Fe_2O_3 is 11.69%; Al_2O_3 of 14.57% and CaO of 9.07%. Na_2O and K_2O contents are 4.09% and 0.21% respectively. The low TiO_2 content of 1.37% of the analyzed basalt resembles those of plutonic rocks of magmatic arcs [31], but are different from intraplate basalts, which often possess high TiO_2 contents (>2%). This mafic volcanoclastite (KOB 3) is characterized by SiO_2 contents of 50.14% (**Table 1**); MgO of 3.61%; Fe_2O_3 of 8.84%; Al_2O_3 of 12.85% and CaO of 10.01%. Na_2O and K_2O contents vary respectively by 2.32% and 0.38%; MnO by 0.16%. Low levels of TiO_2 (0.81%) are also observed. This rock corresponds to basaltic andesites as shown in the diagram of [30], (**Figure 10**).

Rhyodacite (KOB 4) shows SiO_2 contents of 67.02%; MgO of 1.51%; Fe_2O_3 of 4.63%. Al_2O_3 varies by 15.02%; CaO by 3.3%; Na_2O by 5.28%; K_2O by 1.06% and MnO by 0.07%. TiO_2 values are less than 2% (0.42%).

4.2.2. Sedimentary Rocks

Reference [29], allows us to discriminate magmatic to sedimentary rocks. We

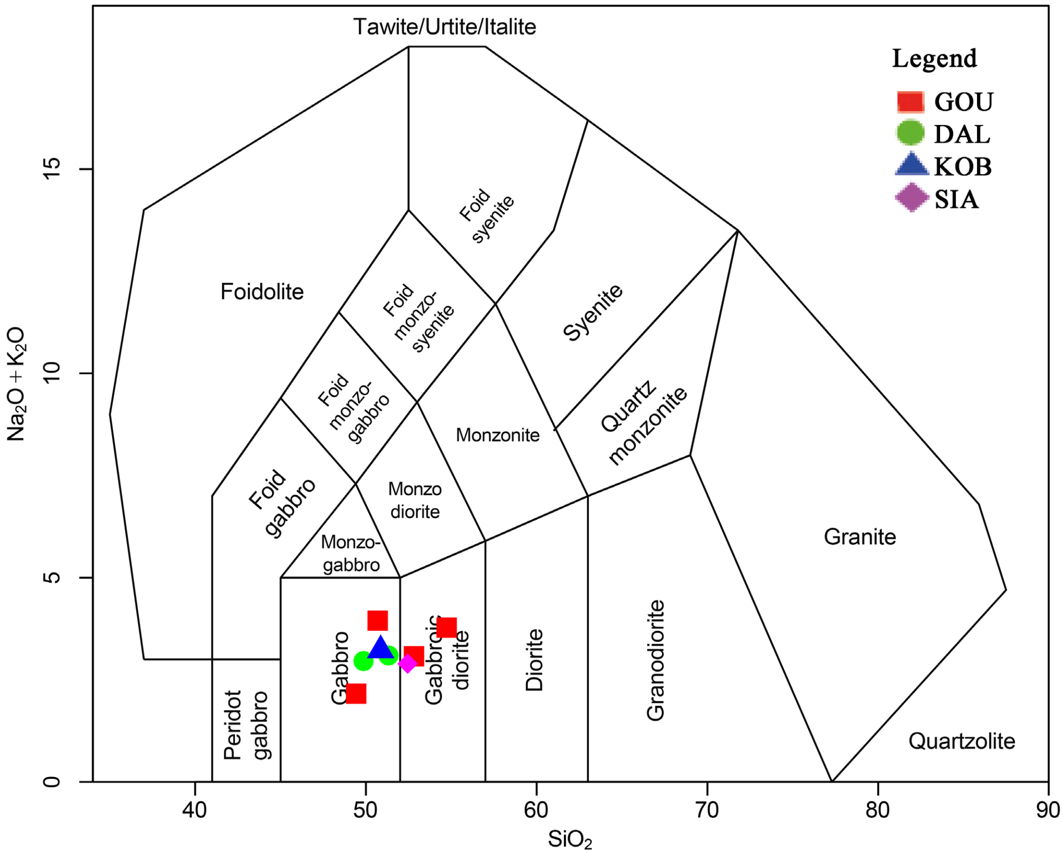

Figure 9. TAS diagram after [30] applied to analyzed plutonic samples.

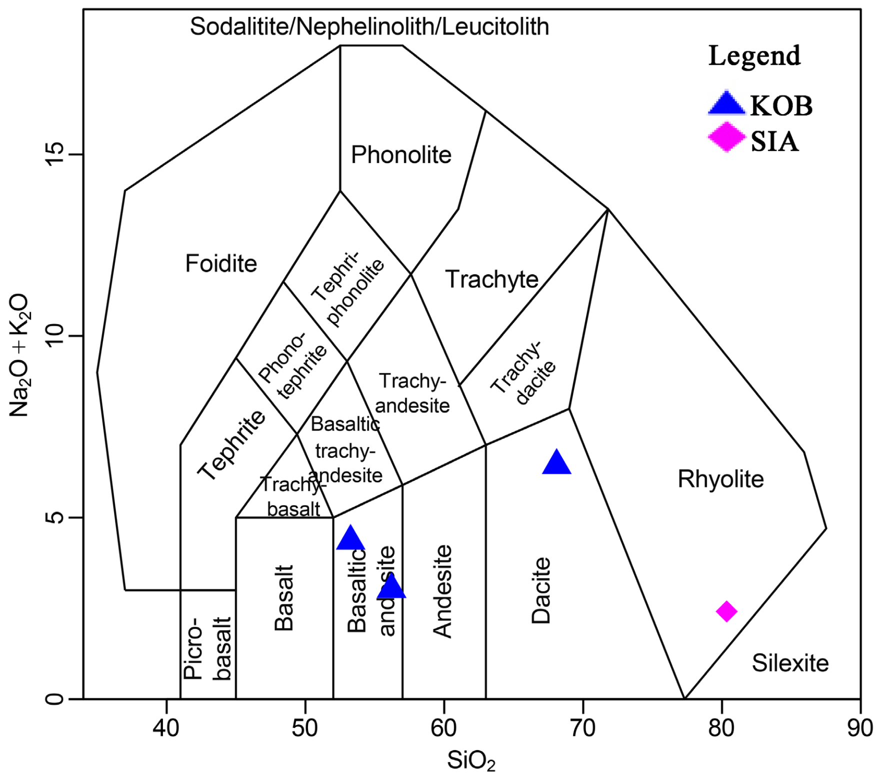

Figure 10. TAS diagram after [30] applied to analyzed volcanic samples.

have highlighted two samples of sedimentary origin: IGU 1 and LOM 1 (**Figure 8**). This diagram is based on P_2O_5/TiO_2 ratios versus MgO/CaO. These ratios give values for sandstones (metasediments) between 0.09 - 0.14 for P_2O_5/TiO_2 and 4.14 - 4.33 for MgO/CaO.

Reference [32] diagram based on the log (SiO_2/Al_2O_3) and log (Fe_2O_3/K_2O) ratios, shows a litharenite and sublitharenite composition respectively for the samples of IGU 1 and LOM 1 (**Figure 11**).

4.3. Metallogeny

4.3.1. Hydrothermal Alteration

Gold mineralization in the Gouméré area occurs in mafic volcanics and in microconglomerates. The processes that affected these formations result in the formation of quartz veinlets and are accompanied by hydrothermal alterations.

Carbonation, silicification, sericitization and sulfidation are the most important alterations in the study area. Carbonation leads to the impregnation of the surrounding rocks by carbonates. The commonly encountered carbonates are calcites and to a lesser degree, dolomites and/or ankerites. They are found pervasively in rocks (**Figure 12(d)**, **Figure 12(f)**). Carbonation is greatest in mafic lava where all calcic plagioclase and other minerals are destroyed and replaced by calcite, dolomite or ankerite.

Silicification indeed appears as the process of impregnation of the surrounding rocks by silica (quartz, chalcedony). It includes at least two phases: one being a quartz-feldspar vein (**Figure 12(a)**, **Figure 12(b)**, **Figure 12(e)**) and the other being related to sulphides and carbonates (**Figure 12(a)**, **Figure 12(d)**, **Figure 12(f)**). The first phase would correspond to vein alteration; these are phenomena of clogging of fractures by hydrothermal fluids highly enriched in metals. The second phase is manifested by the abundance of fine quartz and chalcedony

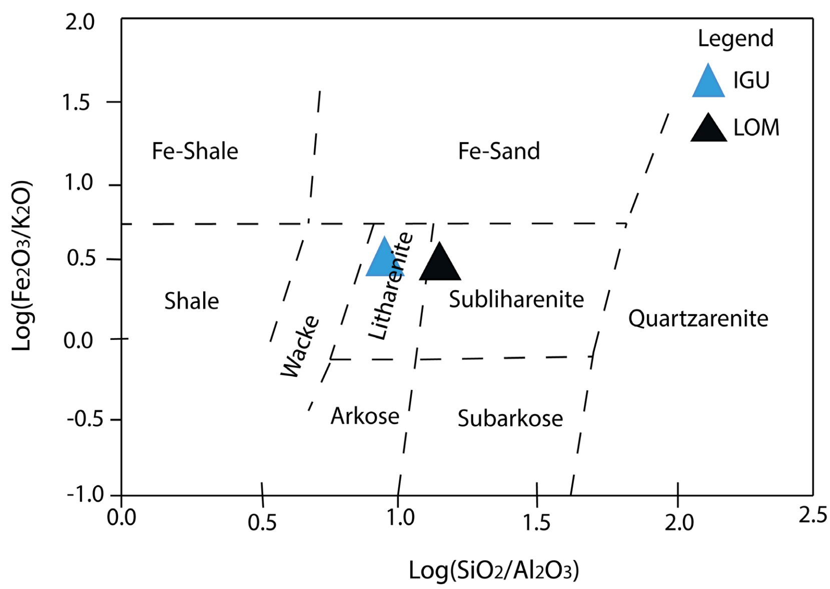

Figure 11. Diagram of [32] applied to microconglomerate.

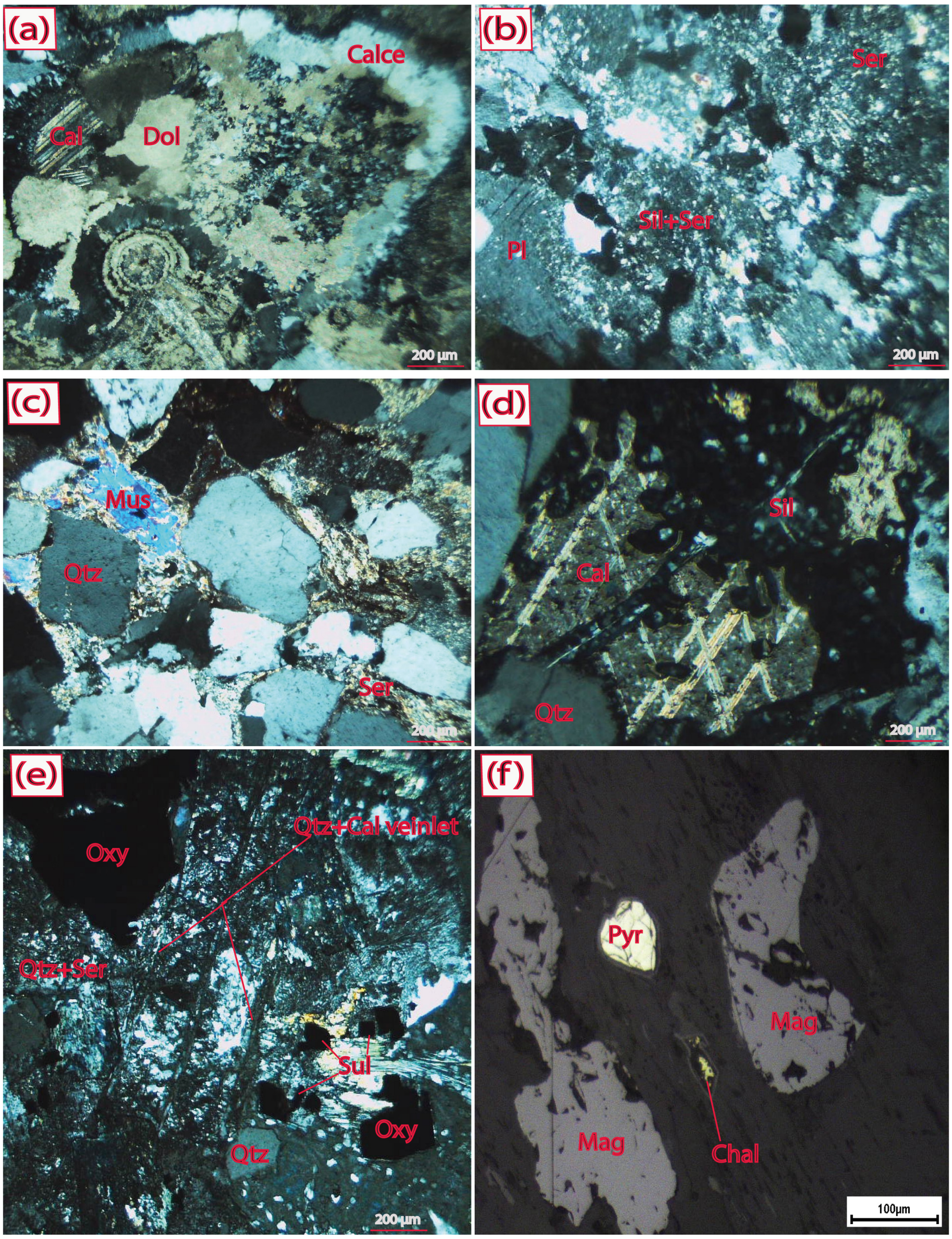

Figure 12. Hydrothermal alteration of the geological formations of Gouméré. (Mus: muscovite, Qtz: quartz, Oxy: oxyde, Ser: sericite, Cal: calcite, Dol: dolomite, Calce: chalcedony, Sul: sulfide, Mag: magnetite, Chal: chalcopyrite, Pyr: pyrite, Pl: plagioclase, Sil: silica).

minerals in mafic volcanic rocks, associated with calcite (Figure 12(a)). Sericite minerals are generally common in feldspar-rich volcanic and sedimentary rocks. Indeed, the strongly sericite zone developed around gold-bearing quartz veins or in mineralized zones is of hydrothermal origin. Sericitization accompanies the establishment of gold mineralization (Figure 12(e)). The process of forming sulfides is called sulfidation. In Gouméré, sulphides are mainly formed of pyrite and chalcopyrite (Figure 12(f)). The oxidation of these sulfides gives titanium iron oxides in occurrences magnetite and hematite (Figure 12(f)). In the area studied, sulfidation is more significant in highly deformed zones. Sulfides are generally concentrated in mineralized zones invaded by numerous quartzcarbonate veins and/or veinlets.

4.3.2. Chemical Characterization of Alteration

The mineralized zones are intensely deformed and have undergone pervasive alteration. There is a gradual reduction in the intensity of the alteration as one moves away from the mineralized zones. The formulas of [33] and [34] made it possible to make a quantitative evaluation of the alteration minerals. These two parameters were plotted on the same diagram to evaluate the enrichment of the surrounding rocks in alteration minerals (**Figure 13**). All rock samples were plotted on the IA-ICCP diagram. It appears that most of the samples are affected by hydrothermal alteration. They are all generally grouped in the ankerite-sericite-chlorite triangle and converge more towards the ankerite-dolomite poles. The microconglomerates, on the other hand, are richer in sericite (Muscovite).

4.3.3. Metalliferous Paragenesis

Metalliferous paragenesis is mainly formed of pyrite, followed by chalcopyrite. The sulphides occur either in the form of veinlets parallel to the schistosity or in the interstices of the minerals, or in the form of automorphic phenocrysts. The

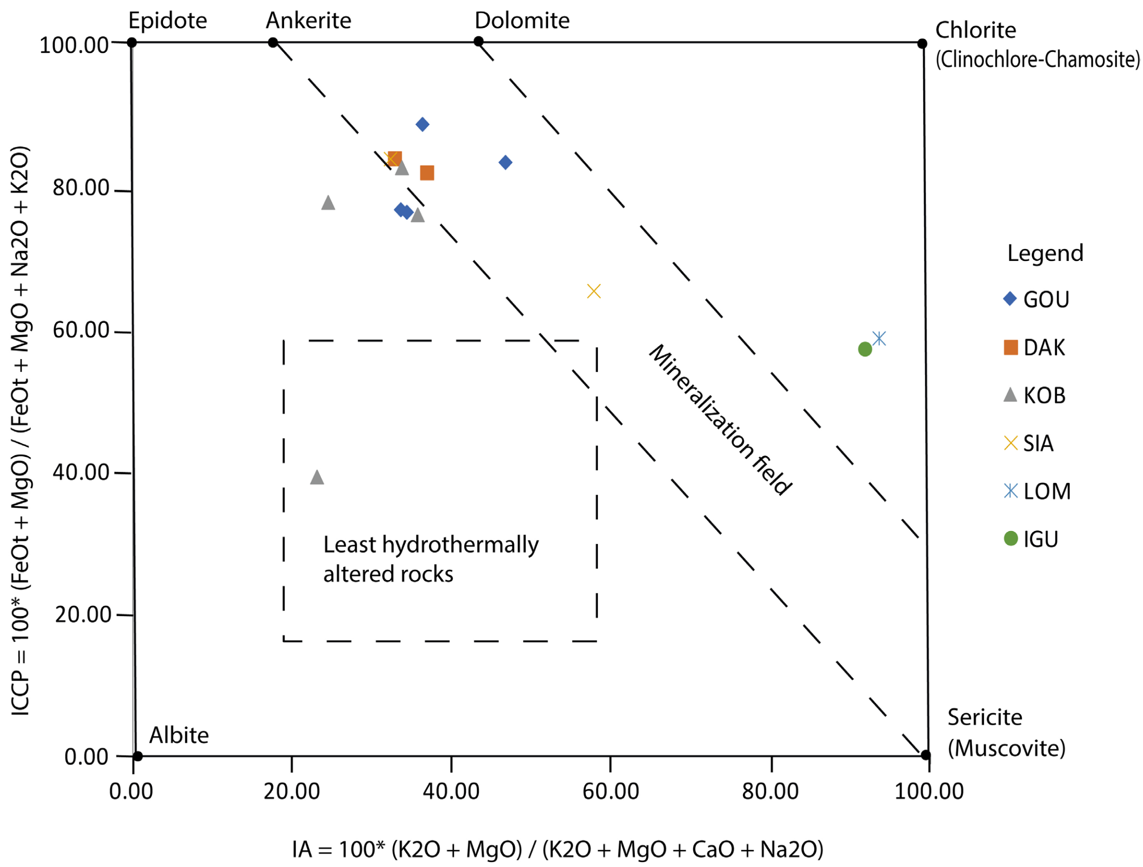

Figure 13. IA-ICCP variation diagram applied to mineralized rocks and alteration minerals of the geological formations of Gouméré.

former are anteschistose while the latter demonstrate post to late tectonic recrystallization. Gold mineralization appears to have a close relationship with sulphides. The grains of pyrite are either disseminated in the host rocks or either in filling of the microfractures in the host (Figure 14(a), Figure 14(f)). Pyrite occurs in the form of fine xenomorphic crystals, elongated rods, aggregates or subautomorphic porphyroblasts (Figures 14(b)-(d)). There are two generations of pyrite: early pyrite in fine grains aligned along the S1 schistosity and late pyrite in the form of randomly oriented aggregates. The preferential orientation of the pyrite crystals suggests that they formed before or during deformation (Figure 14(b), Figure 14(c)). Some pyrites are interpreted as replacement minerals (Figure 14(d)). They often show flowing or distorted movements

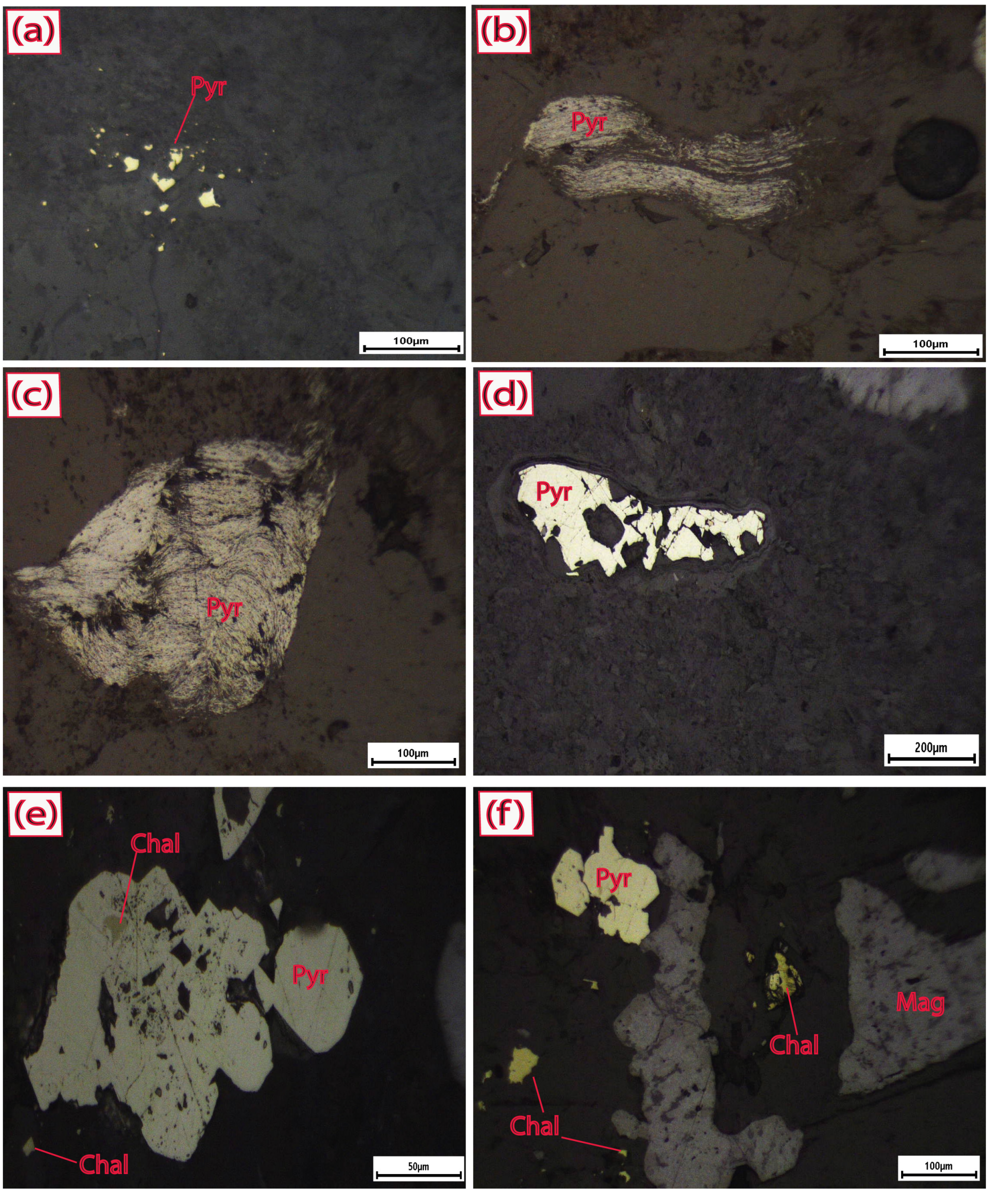

Figure 14. Metalliferous minerals of the geological formations of Gouméré, (Pyr: pyrite, Chal: chalcopyrite, Mag: magnetite).

(**Figure 14(b)**, **Figure 14(d)**).

Chalcopyrite appears in the form of fine xenomorph to automorph grains or phenocrysts. They are isolated or often associated with pyrite, hematite and magnetite (**Figure 14(f)**). They are often inclusions in pyrite (**Figure 14(e)**). Chalcopyrite also occurs in the form of fine, disseminated xenomorphic crystals and in aggregates (**Figure 14(f)**).

5. Discussion

5.1. Lithologically

The petrographic study of geological formations shows a variety of rocks in the area studied: plutonites, volcanics and microconglomerates. Gabbros, basalts, volcanoclastites and rhyodacites constitute the main volcano-plutonite formations encountered. These formations were also described by "[35] [36]" in Ghana in the Bui furrow and "[8] [9] [27]" in the study area. We also note the presence of microconglomerate with a quartz character. This rock is similar to the quartzite described by [36] in the Ghanaian Tarkwaian. The microconglomeratic level with quartz and phyllite minerals, observed at Iguela and Lomo, is similar to the Banket series described by [37] and [36] in the Ghanaian Tarkwaian. These results were obtained by [8] in Koun Fao and [9] in the same area. Reference [38] also assert that the Tarkwaian in Burkina-Faso is made up of sandstone, quartzite, arkose, phyllite and conglomerates (with pebbles from the adjacent greenstone belt: quartz, rhyolite, schist) weakly metamorphosed [39]. The petrographic study showed that the surrounding rocks of the Gouméré region have undergone metamorphic and hydrothermal alteration processes. Commonly observed alteration minerals are: sericite, epidote, chlorite and hornblende ± actinolite. All these minerals are only low pressure minerals; there are no high pressure minerals. The presence of chlorite, epidote, sericite and actinolite in the rocks indicates that the region was affected by greenschist facies metamorphism. These metamorphism conditions were described by [6] [38] [40] and [41]. The rocks studied indicate that the lithostratigraphy of the south of the Bui furrow is similar to that of most of the volcano-sedimentary furrows of the Baoulé-Mossi domain, except for the presence of granitoids in our analyzed samples "[6] [19] [38] [41] [42] [43]".

5.2. Geochemically

Geochemical data reveal two major geological groups [29], namely igneous rocks and sedimentary rocks. The TAS Diagram applied to plutonites allowed us to highlight gabbros and gabbros-diorites. The volcanics have compositions of basalt, rhyodacite and volcaniclastics with a background of basaltic andesite. These geochemical characters are similar to those described by [6] [40] and [44] in the gabbros and basalts of the Agbahou and Bobosso gold deposits, located respectively to the south and north of the Fettêkro furrow. These same characters were highlighted on the green rocks of the Séguéla region on the Fouimba and Goma mountains [45]. Concerning the sediments (litharenites and sublitharenites), they were highlighted by the diagram of [32] and are similar to those of the Comoé basin described by [8]. All these formations have very low TiO_2 contents which are between 0.22% - 1.9%. This suggests that these are similar to the rocks of the magmatic arcs [31] described by several authors in the Toumodi Fettêkro furrow "[6] [41] [46]". The alteration minerals of the Gouméré formations according to the IA-ICCP diagram are carbonates (ankerite and dolomite), sericites and chlorites. These hydrothermal alteration minerals are identical to those described by [6] in the Agbahou deposit.

5.3. On the Metallogenic Level

The Gouméré formations show vein type mineralization of quartz-carbonate with sulphides and disseminated sulphide mineralization in the surrounding areas. This bimodal distribution of gold has also been demonstrated in the deposits of the Ashanti belt in Ghana [47], Agbahou in Côte d'Ivoire [6] and in several deposits regionally and globally known gold mines. However, if in the Ashanti belt, vein type mineralization and disseminated sulphide mineralization are of equal importance, at Gouméré disseminated sulphide vein mineralization is predominant. According to several authors including "[47] [48] [49]", there is a more or less close genetic relationship between these two types of mineralization. They are interpreted as manifestations of several episodes of hydrothermal fluid infiltration and mineral deposition along the shear zones. This suggests the contemporaneity of quartz vein type mineralization and disseminated sulphide mineralization in the surrounding areas. For [47], they are products of mesothermal fluids (pressure = 2 - 5 Kbars and temperature = 400˚C ± 50˚C) and the gold mineralization is largely syn-metamorphic and syn to post-tectonic.

In Gouméré, quartz-carbonate-sulphide vein type ores are characterized by gold contents and an abundance of sulphides (pyrite in higher proportions, followed by chalcopyrite, magnetite and hematite). The sulphide ores disseminated in the surrounding areas, on the other hand, seem to be dominated by pyrite and chalcopyrite minerals. In terms of metalliferous paragenesis, Gouméré appears on the one hand similar to the deposits of Aféma, Agbahou (in Côte d'Ivoire; [6] [50] [51]), Bogosu and Prestea (in Ghana, [47]) where the proportions of pyrite are higher compared to arsenopyrite, and on the other hand different from the Ashanti and Konongo deposits (in Ghana, [52]) and Passagem (in Brazil, [53]) having arsenopyrite as the dominant mineral.

Hydrothermal alteration is marked by silicification, carbonation and sulfidation, and to a lesser degree sericitization and chloritization. Geochemical and petrographic data further revealed the probable existence of carbonation, sulfidation, silicification, sericitization and chloritization phenomena. In the Sabodala gold deposit (in Senegal), the hydrothermalism which affected the surrounding rocks is marked by strong albitization [54].

6. Conclusion

This present study highlights the geology of Gouméré thanks to a petrographic, geochemical and metallogenic study. The geological formations of the Gouméré region are made up of basalts, gabbros, rhyodacites, volcaniclastics and micro-conglomerates (litharenite and sublitharenite). These rocks were highlighted thanks to macroscopic, microscopic petrography and geochemistry studies. These lithologies were generally affected by hydrothermal alteration processes (pervasive and veins). The pervasive alterations observed are silicification, chloritization, carbonation, sericitization and sulfidation. The vein alteration consists of quartz-feldspar-carbonate veins and veinlets. This hydrothermal alteration is highlighted thanks to microscopic and geochemical studies of the rocks in the study area. Metalliferous paragenesis is mainly formed of pyrite and chalcopyrite, which are often associated with hematite and magnetite. This paragenesis is either filling in microfractures or in the form of veinlets, or in association with minerals disseminated throughout the rock. The data from this study also show that gold mineralization would be linked to hydrothermal alteration characterized, among other things, by the presence of carbonates and sulphides. In fact, these are iron-bearing carbonates (ankerite) and pyrite-type sulphides, and chalcopyrite with a common denominator which is iron. We know that iron Fe^{2+} is a chemical factor favorable to the precipitation of gold. They also show a syn-kinematic, post-peak metamorphic character and could belong to the family of epigenetic gold deposits.

Acknowledgements

This work is part of the projects financed by TROPIC MINING GROUP.

Conflicts of Interest

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

References

[1] Milesi, J.P., Feybesse, J.L., Ledru, P., Dommanget, A., Ouedraogo, M.F., Marcoux, E., Prost, A., Vinchon, C., Sylvain, J.P., Johan, V., Tegyey, M., Calvez, J.Y. and Lagny, P. (1989) Minéralisations aurifères de l'Afrique de l'Ouest, leurs relations avec l'évolution lithostructurale au Protérozoïque inférieur. Carte au 1/2000000ème. *Chronique de la Recherche Minière*, **497**, 3-98.

[2] Abouchami, W., Boher, M., Michard, A. and Albarede, F. (1990) A Major 2.1 Ga Event of Mafic Magmatism in West Africa: An Early Stage of Crustal Accretion. *Journal of Geophysical Research*: *Solid Earth*, **95**, 17605-17629. https://doi.org/10.1029/JB095iB11p17605

[3] Boher, M. (1991) Croissance crustale en Afrique de l'Ouest à 2.1 Ga. Apport de la Géochimie isotopique. Doctorat, University of Nancy-I, Nancy, 180 p.

[4] Hirdes, D., Davis, D.W., Lüdtke, G. and Konan, G. (1996) Two Generations of Birimian (Paleoproterozoïc) Volcanic Belts in Northeastern Côte d'Ivoire (West Afri-

ca): Consequences for the Birimian Controversy. *Precambrian Research*, **80**, 173-191. https://doi.org/10.1016/S0301-9268(96)00011-3

[5] Lompo, M. (2010) Paleoproterozoic Structural Evolution of the Man-Leo Shield (West Africa) Key Structures for Vertical to Transcurrent Tectonics. *Journal of African Earth Sciences*, **58**, 19-36. https://doi.org/10.1016/j.jafrearsci.2010.01.005

[6] Houssou, N.N. (2013) Etude pétrologique, structurale et métallogénique du gisement aurifère d'Agbahou, Divo, Côte d'Ivoire. Doctorat, Université Félix Houphouët-Boigny, Boigny, 177 p.

[7] Houssou, N.N., Allialy, M.E., Fossou, J.-L.H.K. and Gnanzou, A. (2017) Structural Control of Auriferous Mineralization in the Birimian: Case of the Agbahou Deposit in the Region of Divo, Côte d'Ivoire. *International Journal of Geosciences*, **8**, 189-204. https://doi.org/10.4236/ijg.2017.82008

[8] Boya, T.K.L.-D., Kouadio, F.J.-L.H., Adingra, M.P.K., N'gatta, K.G.-L. and Kouamelan, A.N. (2022) Les métasédiments de Kouassi Bilékro, S/P de Kouassi Datèkro, Est de la Côte d'Ivoire: Un exemple de pétrogénèse complexe au sein du bassin de la Comoé. *Afrique Science*, **20**, 57-71. http://www.afriquescience.net

[9] Kouadio, F.J.-L.H., Boya, T.K.L.-D., Houssou, N.N., Kanga, R.N. and Kouamelan, A.N. (2022) Petrogenetic Characterization of the Geological Formations of the Localities of Goumere-Iguela in the South West of the Bui Belt (North-East of Cote d'Ivoire). *Open Journal of Geology*, **12**, 947-972. https://doi.org/10.4236/ojg.2022.1211045

[10] Boher, M., Abouchami, W., Michard, A., Albarede, F. and Arndt, N.T. (1992) Crustal Growth in West Africa at 2.1 Ga. *Journal of Geophysical Research*: *Solid Earth*, **97**, 345-369. https://doi.org/10.1029/91JB01640

[11] Dia, A., Van Schmus, W.R. and Kröner, A. (1997) Isotopic Constraints on the Age and Formation of a Palaeoproterozoic Volcanic Arc Complex in the Kedougou Inlier, Eastern Senegal, West Africa. *Journal of African Earth Sciences*, **24**, 197-213. https://doi.org/10.1016/S0899-5362(97)00038-9

[12] Pouclet, A., Doumbia, S. and Vidal, M. (2006) Geodynamic Setting of the Birimian Volcanism in Central Ivory Coast (Western Africa) and Its Place in the Palaeoproterozoic Evolution of the Man Shield. *Bulletin de la Société Géologique de France*, **177**, 105-121. https://doi.org/10.2113/gssgfbull.177.2.105

[13] Kouamelan, A.N., Peucat, J.J. and Delor, C. (1997) Reliques archéennes (3.15 Ga) au sein du magmatisme birimien (2.1 Ga) de Côte d'Ivoire, craton ouest-africain. *Comptes rendus de l'Académie des Sciences*, **324**, 719-727.

[14] Yacé, I. (1972) Le Birrimien de la région de Toumodi (Côte d'Ivoire). *Annales de l'Université d'Abidjan*: *Sciences*. *Série C*, **8**, 27-31.

[15] Feybesse, J.L., Billa, M., Guerrot, C., Duguey, E., Lescuyer, J.L., Milesi, J.P. and Bouchot, V. (2006) The Paleoproterozoic of Ghanaian Province: Geodynamic Model and Ore Controls, Including Regional Stress Modeling. *Precambrian Research*, **149**, 149-196. https://doi.org/10.1016/j.precamres.2006.06.003

[16] Coulibaly, Y., Boiron, M.C., Cathelineau, M. and Kouamelan, A.N. (2008) Fluid Immiscibility and Gold Deposition in the Birimian Quartz Veins of the Angovia Deposit (Yaouré, Ivory Coast). *Journal of African Earth Sciences*, **50**, 234-254. https://doi.org/10.1016/j.jafrearsci.2007.09.014

[17] Soule-de-Lafont, D. (1956) Le précambrien moyen supérieur de Bondoukou (Côte d'Ivoire). Bulletin du Service des mines (Dakar), Dakar, 163 p.

[18] Lüdtke, G. (1999) Géologie de la région de la Haute Comoé sud. Bulletin No. 2, Direction de la Géologie, Abidjan, 164 p.

[19] Tagini, B. (1971) Esquisse structurale de la Côte d'Ivoire; Essai de géotectonique régionale. Doctorat, Univ. Lausanne, Lausanne, Côte d'Ivoire (SODEMI), Bulletin No. 5, 302 p.

[20] Yacé, I. (1993) Les complexes volcano-sédimentaires précambriens en Afrique de l'Ouest. Symposium sur le protérozoïque inférieur, CIFEG, 1993/23.

[21] Feybesse, J.L., Milesi, J.P., Johan, V., Dommanget, A., Calvez, J.Y., Boher, M. and Abouchami, W. (1989) La limite Archéen-Protérozoïque inférieur de l'Afrique de l'Ouest: Une zone de chevauchement majeur antérieure à l'accident de Sanssandra: L'exemple des régions d'Odienné et de Touba (Côte d'Ivoire). *Comptes rendus de l'Académie des Sciences*, **309**, 1847-1853.

[22] Tempier, P. (1986) Le Burkinien: Cycle orogénique majeur du protérozoïque inférieur en Afrique de l'Ouest. *Journée Scientifique du C.I.F.E.G*, **10**, 17-23.

[23] Milesi, J.P., Ledru, P., Feybesse, J.L., Dommanget, A. and Marcoux, E. (1992) Early Proterozoic Ore Deposits and Tectonics of Birimian Orogenic Belt, West Africa. *Precambrian Research*, **58**, 305-344. https://doi.org/10.1016/0301-9268(92)90123-6

[24] Doumbia, S. (1997) Géochimie, géochronologie et géologie structurale des formations Birrimiennes de Katiola-Marabadiassa (Centre-Nord de la Côte d'Ivoire) Evolution magmatique et contexte géodynamique du Paléoprotérozoïque. Thèse de doctorat, Univ. Orléans, Orléans, Éd. BRGM, No. 276, 207 p.

[25] Papon, A. (1973) Géologie et minéralisations du Sud-Ouest de la Côte d'Ivoire. Vol. 80, Mémoire du BRGM, Paris, 284 p.

[26] Toure, S. (2007) Pétrologie et géochronologie du massif granitoïde de Bondoukou. Nord-Est de la Côte d'Ivoire. Évolution magmatique et contexte géodynamique au Protérozoïque inférieur. Relations avec le volcano-détritique du Zanzan, Koun, Tanda attribué au Tarkwaïen du Ghana. Implications paléogéographiques. Université d'Abobo-Adjamé, Abidjan, 224 p.

[27] Simeon, Y., Delor, C., Zeade, Z., Kone, Y., Yao, B., Vidal, M., Diaby, I., Konan, G., Dje, B.I., N'da, D., Dommanget, A., Cautru, J.P., Guerrot, C. and Chiron, J.-C. (1995) Notice explicative de la carte géologique de la Côte d'Ivoire à 1/200000, feuille Agnibilékro. Mémoire de la Direction des Mines et de la Géologie de la Côte d'Ivoire, Abidjan, 5-8, 13.

[28] Janousek, V., Farrow, C.M. and Erban, V. (2006) Interpretation of Whole-Rock Geo-Chemical Data in Igneous Geochemistry: Introducing Geochemical Data Toolkit (GCDkit). *Journal of Petrology*, **47**, 1255-1259. https://doi.org/10.1093/petrology/egl013

[29] Werner, C.D. (1987) Saxonian Granulites: A Contribution to the Geochemical Diagnosis of Original Rocks in High-Metamorphic Complexes. *ZfS-Mitteilungen*, **133**, 221-250.

[30] Middlemost, E.A.K. (1994) Naming Materials in the Magma/Igneous Rock System. *Earth-Science Reviews*, **37**, 215-224. https://doi.org/10.1016/0012-8252(94)90029-9

[31] Pearce, J.A. and Cann, J.R. (1973) Tectonic Setting of Basic Volcanic Rocks Determined Using Trace Element Analyses. *Earth and Planetary Science Letters*, **19**, 290-300. https://doi.org/10.1016/0012-821X(73)90129-5

[32] Herron, M.M. (1988) Geochemical Classification of Terrigenous Sands and Shales from Core or Log Data. *Journal of Sedimentary Petrology*, **58**, 820-829. https://doi.org/10.1306/212F8E77-2B24-11D7-8648000102C1865D

[33] Ishikawa, Y., Sawaguchi, T., Iwaya, S. and Horiuchi, M. (1976) Delineation of Prospecting Targets for Kuroko Deposits Based on Modes of Volcanism of Underlying Dacite and Alteration Haloes. *Mining Geology*, **26**, 105-117.

[34] Large, R.R., Gemmell, J.B., Paulick, H. and Huston, D.L. (2001) The Alteration Box Plot: A Simple Approach to Understanding the Relationship between Alteration Mineralogy and Lithogeochemistry Associated with Volcanic-Hosted Massive Sulfide Deposits. *Economic Geology*, **96**, 957-971. https://doi.org/10.2113/96.5.957

[35] Leube, A., Hirdes, W., Mauer, R. and Kesse, G.O. (1990) The Early Proterozoic Birimian Supergroup of Ghana and Some Aspects of Its Associated Gold Mineralization. *Precambrian Research*, **46**, 139-165. https://doi.org/10.1016/0301-9268(90)90070-7

[36] Perrouty, S. (2012) Evolution structurale de la ceinture minéralisée d'Ashanti, SO du Ghana. Université de Toulouse, Toulouse, 233 p.

[37] Junner, N.R. (1940) Geology of the Gold Coast and Western Togoland. Gold Coast Geological Survey, Accra, Bulletin n°11, 40 p.

[38] Baratoux, L., Metelka, V., Naba, S., Jessell, M.W., Gregoire, M. and Ganne, J. (2011) Juvenile Paleoproterozoic Crust Evolution during the Eburnean Orogeny (~2.2-2.0 Ga), Western Burkina Faso. *Precambrian Research*, **191**, 18-45. https://doi.org/10.1016/j.precamres.2011.08.010

[39] Bossiere, G., Bonkoungou, I., Peucat, J.-J. and Pupin, J.-P. (1996) Origin and Age of Paleoproterozoic Conglomerates and Sandstones of the Tarkwaian Group in Burkina Faso, West Africa. *Precambrian Research*, **80**, 153-172. https://doi.org/10.1016/S0301-9268(96)00014-9

[40] Gnanzou, A. (2014) Study of Volcanosedimentary Series of Dabakala Region (Northeast of Côte d'Ivoire): Genesis and Magmatic Evolution. Contribution to the Knowledge of Bobosso Gold Mineralization Located in the Haute-Comoe Serie. Thesis Unique, Université de Paris-Sud Paris XI, Faculté des Sciences d'Orsay, Bures-sur-Yvette, Memory, 258 p.

[41] Coulibaly, I. (2018) Pétrographie des volcanites et plutonites de la partie Sud dusillon volcanosédimentaire de Toumodi-Fétèkro. Thèse Univ. Felix Houphouët Boigny d'Abidjan, Abidjan, 221 p.

[42] Pouclet, A., Vidal, M., Delor, C., Simeo, Y. and Alric, G. (1996) Le volcanisme birimien du nord-est de la Côte d'Ivoire, mise en évidence de deux phases volcanotectoniques distinctes dans l'évolution géodynamique du Paléoprotérozoïque. *Bulletin de la Société Géologique de France*, **167**, 529-541.

[43] Vidal, M., Delor, C., Pouclet, A., Simeon, Y. and Alric, G. (1996) Evolution géodynamique de l'Afrique de l'Ouest entre 2.2 et 2 Ga: Le style archéen des ceintures vertes et des ensembles sédimentaires birimiens du nord-est de la Côte d'Ivoire. *Bulletin de la Société Géologique de France*, **167**, 307-319.

[44] Houssou, N.N., Kouadio, F.J.-L.H., Allialy, M.E., Kouassi, B.R. and Adingra, M.P.K. (2022) Geochemistry of Volcano-Sedimentary and Plutonic Formations of the Agbaou Gold Deposit, Ivory Coast. *Earth Science Research*, **11**, 76-97. https://doi.org/10.5539/esr.v11n1p76

[45] Ephrem, A.M., Bedel, S.D., Kouadio Fossou, J.L., Nestor, H.N., Rolland, K.B., Oufouet, K.F. and Sekou, D. (2023) Petrochemical Studies of Fouimba and Goma Mounts, Central-West of Cote d'Ivoire: Implication on Petrogenesis Tectonic Setting. *Open Journal of Geology*, **13**, 91-106. https://doi.org/10.4236/ojg.2023.132005

[46] Ouattara, Z. (2015) Caractères lithostratigraphiques, structural, géochimique et métallogénique du gisement d'or de Bonikro, sillon birimien de Fettèkro, Centre-Sud de la Côte d'Ivoire. Université Félix Houphouët-Boigny, Abidjan, 275 p.

[47] Oberthür, T., Schmidt, M.A., Vetter, U., Simon, K. and Amanor, J.A. (1996) Gold Mineralization in the Ashanti Belt of Ghana: Genetic Constraints of the Stable Iso-

tope Geochemistry. *Economic Geology*, **91**, 289-301.
https://doi.org/10.2113/gsecongeo.91.2.289

[48] Sibson, R.H., Robert, F. and Poulsen, K.H. (1989) High-Angle Reverse Faults, Fluid Pressure Cycling, and Mesothermal Gold-Quartz Deposits. *Geology*, **16**, 551-555.
https://doi.org/10.1130/0091-7613(1988)016<0551:HARFFP>2.3.CO;2

[49] Oberthür, T., Vetter, U., Schmidt Mumm, A., Weiser, T., Amanor, J.A., Gyapong, W.A., Kumi, R. and Blenkinsop, T.G. (1994) The Ashanti Gold Mine at Obuasi in Ghana: Mineralogical, Geochemical, Stable Isotope and Fluid Inclusion Studies on the Metallogenesis of the Deposit. *Geologisches Jahrbuch D*, **100**, 31-129.

[50] Kramo, K.B., Coulibaly, Y., Pothin, K.B.K. and Kadio, E. (2008) Mineralogical and Chemical Characters of the Aféma Shear Zone Gold Mineralization, South-East of Ivory Coast: Example of the Hermann Mine. *European Journal of Scientific Research*, **21**, 154-163.

[51] Assié, K.E. (2008) Lode Gold Mineralization in the Paleoproterozoic (Birimian) Volcanosedimentary Sequence of Afema Gold District, Southeastern Côte d'Ivoire. Thesis, Faculty of Energy and Economic Sciences, Technical University of Clausthal, Clausthal-Zellerfeld, 180-210.

[52] Oberthür, T., Weiser, T. and Amanor, J.A. (1997) Mineralogical Siting and Distribution of in Quartz Veins and Sulphide Ores of the Ashanti Mine and Other Deposits in the Ashanti Belt of Ghana: Genetic Implications. *Mineralium Deposita*, **32**, 2-15. https://doi.org/10.1007/s001260050068

[53] Vial, D.S., Duarte, B.P., Fuzikawa, K. and Vieira, M.B.H. (2007) An Epigenetic Origin for the Passagem de Mariana Gold Deposit, Quadrilátero Ferrífero, Minas Gerais, Brazil. *Ore Geology Reviews*, **32**, 596-613.
https://doi.org/10.1016/j.oregeorev.2005.03.017

[54] Sylla, M. and Ngom, P.M. (1997) Le gisement d'or de Sabodala (Sénégal Oriental): Une minéralisation filonienne d'origine hydrothermale remobilisée par une tectonique cisaillante. *Journal of African Earth Sciences*, **25**, 183-192.
https://doi.org/10.1016/S0899-5362(97)00097-3