Open Journal of Geology, 2022, 12, 767-786
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Evaluation of the Geological and Metallogenic Potential of Koffissiokaha Permit, Area of Katiola, Côte d'Ivoire

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How to cite this paper: Nestor, H.N., Koffi, A.M.P., Ephrem, A.M., Kouakou, K.K.W. and Cyrille, L.G.F. (2022) Evaluation of the Geological and Metallogenic Potential of Koffissiokaha Permit, Area of Katiola, Côte d'Ivoire. *Open Journal of Geology*, **12**, 767-786.
https://doi.org/10.4236/ojg.2022.1210037

Received: September 18, 2022
Accepted: October 24, 2022
Published: October 27, 2022

Abstract

The semi-industrial permit of Koffissiokaha, south-eastern area of Katiola, is located in the northern part of Fêtêkro Birimian Greenstone Belt (Côte d'Ivoire). This permit, applicated by the company Blue-Hill Exploration Sarl (BHEX), is in the southern continuity area of Lafigué permit (Endeavour Mining). Blue-Hill will have to work to highlight potential gold mineralization, quantify it (resource calculation) and initiate administrative procedures to obtain a Semi-Industrial Exploitation Authorization (AESI). Our recent works, including field mapping coupled with petrographic and microstructural studies, are therefore intended to contribute to the knowledge of the geology and to the evaluation of the gold potential of this permit. They suggest that Koffissiokaha permit includes four major lithologic units: 1) a sedimentary unit formed by metaarenites and metasiltites, 2) a unit of mafic pyroclastites (cinerites, tuffs and volcanic breccias) 3) a plutonic unit of metagabbro and finally, 4) a lode-type unit made up of metarhyodacites. The metamorphism that affected the volcano-sedimentary rocks is of low grade to greenschist facies. On the structural level, deformations with variable gradients are noted. The major planary structure, the schistosity, is oriented N20 - 40 with weak (<40˚), moderate (50˚ - 60˚) and steep dips (>70˚) or subvertical. The faults generally correspond to narrow dextral or senestral shear-zones (<50 m width) with subhorizontal stretching lineation. These faults strike NNE-SSW with steep dips (>75˚) towards south-east or subvertical. They are most often intersected by late strike-slip faults-oriented NW-SE, NNW-SSE and N-S. Quartz veins are associated with faults or deformation zones. They are generally oriented N20 to N40, with weak (<40˚), moderate (55˚ - 65˚) and steep dips (>75˚). Orientations of joints and fractures are mostly subparallel to the plans of schistosity, shears and most of quartz veins. However, ENE, WNW and N-S fractures are also distinguished. The sulphide paragenesis consists of pyrites (and pyrrhotites), arsenopyrites and chalcopyrites. Gold mineralization is controlled by both structural and hydrothermal parameters.

Keywords

Petro-Structural, Metallogeny, Gold Mineralization, Birimian, Koffissiokaha, Côte d'Ivoire

1. Introduction

The Koffissiokaha permit (village close to Timbe town), located at the northeast of Bouaké, city at 350 km distance from Abidjan (**Figure 1(a)**), is a semi-industrial application from Blue-Hill Exploration Sarl. It covers an area of 1 km^2 that is included in the southwestern part of Dabakala zone as described by [1] and [2]. Evidence of previous exploration works (soil geochemistry, trenches, RAB and RC drilling) has been observed on this permit. More than 60 drill holes have been counted. All these works suggest the existence of soil anomalies and gold mineralizations at depth. In order to confirm the presence of these anomalies and mineralizations and to determine their litho-structural and metallogenic characteristics, Blue-Hill Exploration Sarl has initiated a geological mapping campaign coupled with rocks sampling. The mapping program took place from April 8 to 20, 2020. Field work was completed by a petrographic study and a microstructural analysis at the GRME laboratory (Geology, Mineral and Energy Resources) of the University Félix Houphouët-Boigny (UFHB), Abidjan, Côte d'Ivoire. This work will contribute on the one hand to a better understanding and planning of subsequent research activities and exploitation and on the other hand to the improvement of geological knowledge on Fêtêkro Greenstone Belt which hosts several gold mineralizations including Agbahou ([3] [4]), Bonikro ([5] [6]), Hiré-Ouatta, Dougbafla ([7] [8]), Angovia, Lafigué ([9]), Blaffo-Guéto, Kokoumbo, etc.

2. Geological Setting

Located in the northern part of Fêtêkro greenstone belt, Koffissiokaha permit consists of a series of hills whose altitude exceeds 350 meters; the highest peak being Mount Niangbion with 600 meters of altitude. These hills and mounts are bordered by the N'Zi plain, whose altitude varies from 150 to 250 meters. The Fêtêkro Birimian Greenstone Belt belongs to Paleoproterozoic domain of Côte d'Ivoire, which was structured during Eburnian orogeny (2500 - 1600 Ma) ([10] [11]). However, some authors ([12] [13], etc.) propose that it was formed during two orogenies, the Burkinian (2400 - 2150 Ma) and the Eburnian (s.s.) (2120 - 1800 Ma). The rocks of this domain are attributed to Birimian ([14] [15]) and characterized by epi to mesozonal metamorphism. They occur as volcano-sedimentary and

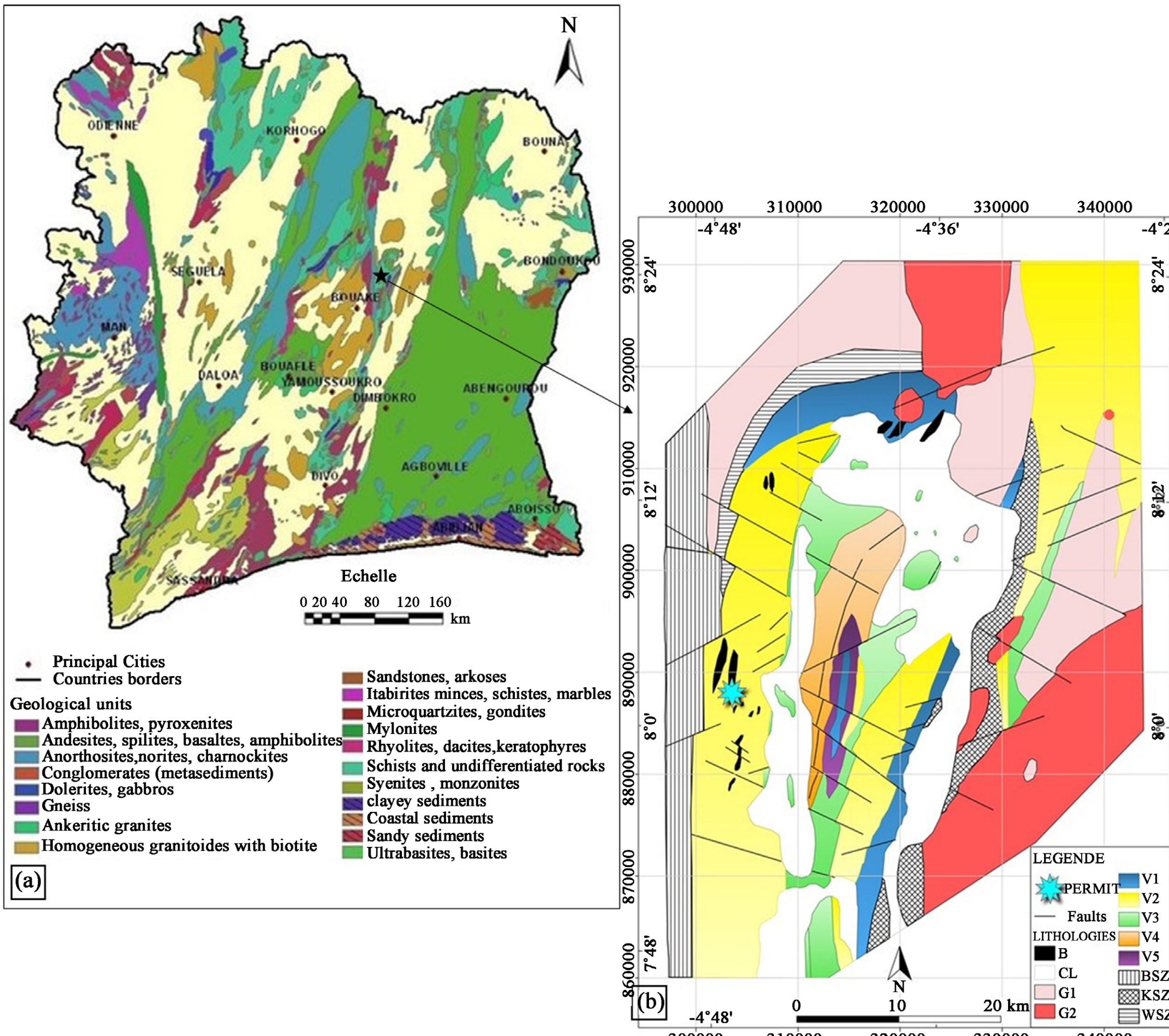

Figure 1. (a) Simplified geological map of Côte d'Ivoire at 1:4,000,000 scale with the location of Koffissiokaha permit. (b) Geological map of the northern part of Fêtêkro Greenstone Belt ([1]): KSZ: Katidougou Shear-Zone; BSZ: Brobo Shear-Zone; WSZ: Waléguéra Shear-Zone; G1: Syntectonic Granites; G2: Post-tectonic Granites; V1: Mbé Group; V2: Timbéguélé Group; V3: Gboli Group; V4: Ko Komba Group; V5: Sandérékro Group; B: Gabbros; CL: Lateritic Cuirasse.

plutonic units generally oriented NNE-SSW to NE-SW, and intruded by granitoids. Geology of Fêtêkro Birimian Belt is now better known through the works of [1]-[6] [12] [16]-[21], etc. However, in this northern part of Fêtêkro Greenstone Belt, the works of [1] and [2] suggest a lithostratigraphy divided into eight (8) units (**Figure 1(b)**):

1) Mbé unit (V1): it is made up of Sepia formations (paragneiss, amphibolites and pillow basalts) and Londo Koffi formations (rhyolitic tuffs and breccias). This unit probably corresponds to the basement rocks known as Dabakalian of [12];

2) Timbéguélé unit (V2): separated from the previous group by a tectonized contact. Unit (V2) consists of N'Dénou volcanoclastic formations (rhyolitic tuffs and pillow basalts) and Namouénou volcanoclastic formations (epiclastites and

tuffs); the Koffissiokaha permit, object of our study, belongs to this unit;

3) Gboli unit (V3): this unit includes Kouroudia bedded iron formations (or BIF) at the base, the Digbé formations (grauwackes, siltstones, tuffs and andesites) and the Totou formations (basaltic lavas and some intrusions);

4) Ko Komba unit (V4): it is made up of Nangbion basaltic formations and the tuffs of Tigitamé;

5) Sandérékro unit (V5): separated from the unit (V4) by an unconformity, this unit (V5) consists of rhyolitic tuffs of Yangadougou, conglomerates and ignimbrites of Adoumanté.

The units (V), generally of regional N-S tectonic grain and in synclinal or anticlinal position, are intruded by syntectonic granites (G1) and post-tectonic granites (G2), as well as north-south trending dikes of gabbro (B). Three (3) important shear-zones dominate the area: the N-S oriented Brobo Shear-Zone (BSZ) the western border, the NNE-SSW trending Katidougou Shear-Zone (KSZ) located in the east and finally, located further north, the Waléguéra Shear-Zone (WSZ) which with a particular sinusoidal shape evolves from a N-S to E-W direction via NNE-SSW and NE-SW. In the central part, there is a less important shear-zone than the other three, the Windéné Shear-Zone, which evolves from N-S to NE-SW direction via NNE-SSW. This entire litho-structural sequence is crosscut and sometimes displaced by late faults: ENE-WSW faults and NW-SE faults respectively dextral and senestral. An important lateritic cuirasse covers and hides different lithologies and structures, especially in the central part of the area.

3. Methodology

In Koffissiokaha permit, there is a large hill where several outcrops are visible. In order to well cover the entire permit, 1000 m × 100 m grids (square permit with 1 km edge) have been made and traveled. Thus, details geological mapping method allowed to locate and describe almost all of rock outcrops, and to determine and mark their contours and extensions. Trenches and drill holes previously completed on the permit by the mining company Equigold SA were also a great help. During the geological mapping, rock samples and cuttings from drill holes were collected for the preparation of twenty-three (23) thin sections for microscopic petrography and microstructural analysis, and three (3) polished sections for metallogenic study. These studies and analysis were carried out at GRME laboratory (Geology, Mineral and Energy Resources) of the University Félix Houphouët-Boigny (UFHB), Abidjan, Côte d'Ivoire.

4. Petro-Structural and Metallogenic Characterization

4.1. Petrographic Study

4.1.1. Metasedimentary Rocks

These are the most dominant rocks, occupying more than 70% of the permit area. Metaarenites (above all metagrauwackes) and metasiltites are distinguished, but metaarenites are dominant over metasiltites. They are generally deformed and metamorphosed under greenschist facies.

-Metagrauwackes

The metagrauwackes encountered are generally schistosed, altered or fresh (Figure 2(a) and Figure 2(b)), with greenish-gray color. They contain porphyroblasts of calcite, plagioclase and quartz, mostly in polycrystalline aggregates, within a fine intergranular matrix of quartz and calcite (Figure 2(c)). Calcite is very abundant in the rock (~40%), has anhedral to subhedral shape and is derived from the alteration of plagioclase. Secondary minerals of sericite and chlorite, resulting from the pseudomorphosis of plagioclase, are also present. The matrix minerals and porphyroblasts all appear to be stretched and arranged in the schistosity planes.

Two other metagrauwackes facies are also distinguished:

- a dark grey, very stiff and oxide-rich facies (Figure 2(d)). It contains quartz, plagioclase, calcite, some alkali feldspar minerals and opaque minerals in a chlorite, sericite, carbonates and ferro-titanium oxides-rich matrix (Figure 2(e)

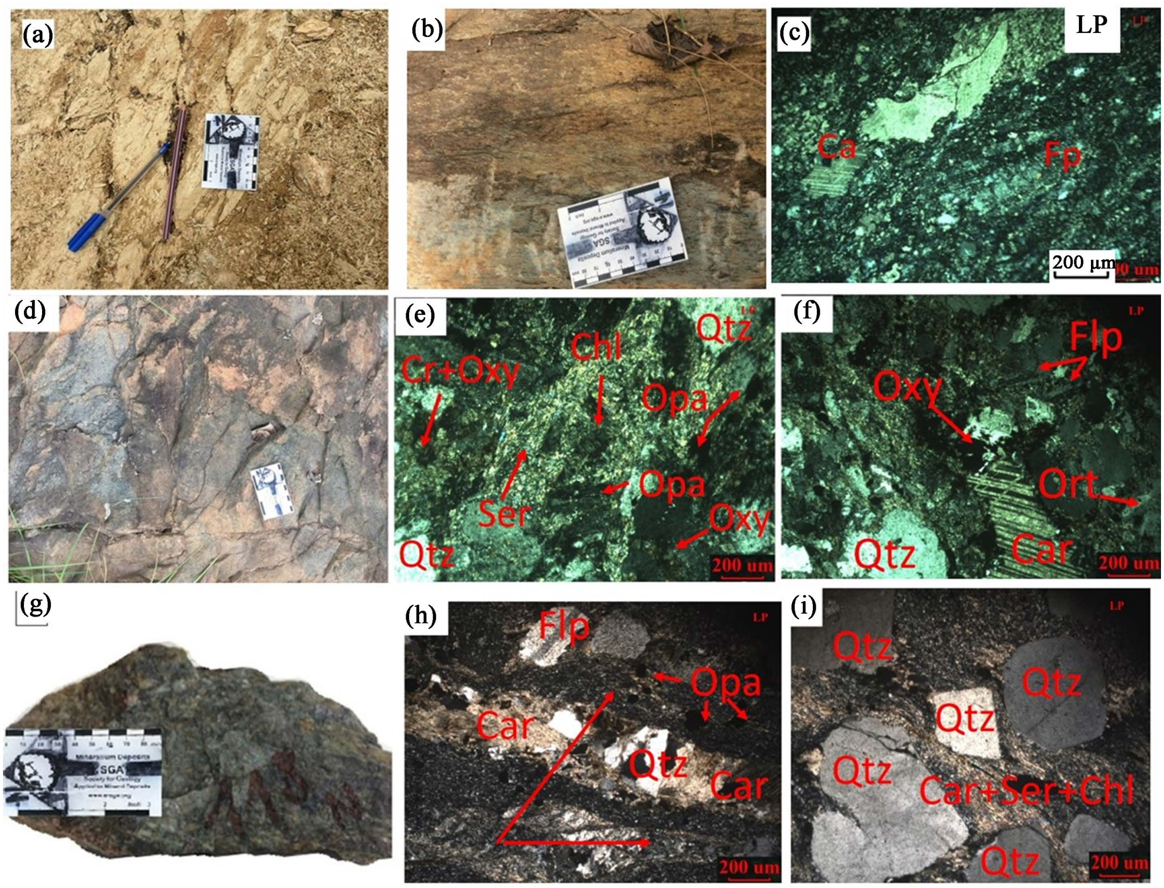

Figure 2. Macroscopic and microscopic aspect of metagrauwackes. (a) Schistosed grauwacke slightly weathered, (b) fresh green-gray schistosed grauwacke, (c) microscopic aspect of green-gray schistosed grauwacke, (d) dark-gray grauwacke, (e) and (f) microscopic aspect of dark-gray grauwacke, (g) light-gray grauwacke, (h) and (i) microscopic aspect of light-gray grauwacke. Qtz: quartz, Car: carbonate, Cal: calcite, Flp: feldspath plagioclase, Ort: Orthose, Ser: séricite, Chl: chlorite, Oxy: oxyde ferro-titané et Opa: minéral opaque.

and Figure 2(f)); the quartz (~45%) being in angular or subangular grains, often with deformation breaks.

- a light grey facies (Figure 2(g)), also very rigid, rich in quartz porphyries (rounded, angular or subangular) and some relictual plagioclases (Figure 2(h) and Figure 2(i)); the plagioclases are generally pseudomorphosed by damouritization. Their matrix consists of fine crystals of chlorite and sericite associated with carbonates and clusters of opaque minerals.

-Metasiltites

The metasiltites are located in the northeast part of the permit. In outcrop, they are light grey and more or less schistosed (Figure 3(a)). Under microscope, they appear very altered and the minerals are difficult to recognize. However, quartz, relict feldspars, calcite, sericite, ferro-titanium oxides and opaque minerals can be distinguished. Carbonates, deriving from plagioclases alteration, are the more abundant minerals (Figure 3(b)); quartz is generally aggregated with calcite phenocrysts (Figure 3(c)). Opaque minerals and ferro-titanium oxides are very present and associated with the sericite matrix (Figure 3(d)).

4.1.2. Pyroclastites

Pyroclastic rocks consist of cinerites, tuffs and volcanic breccias. They are found throughout the permit area in various locations.

-Cinerites

They outcrop in boulders to the east and southeast. These are very fine-grained

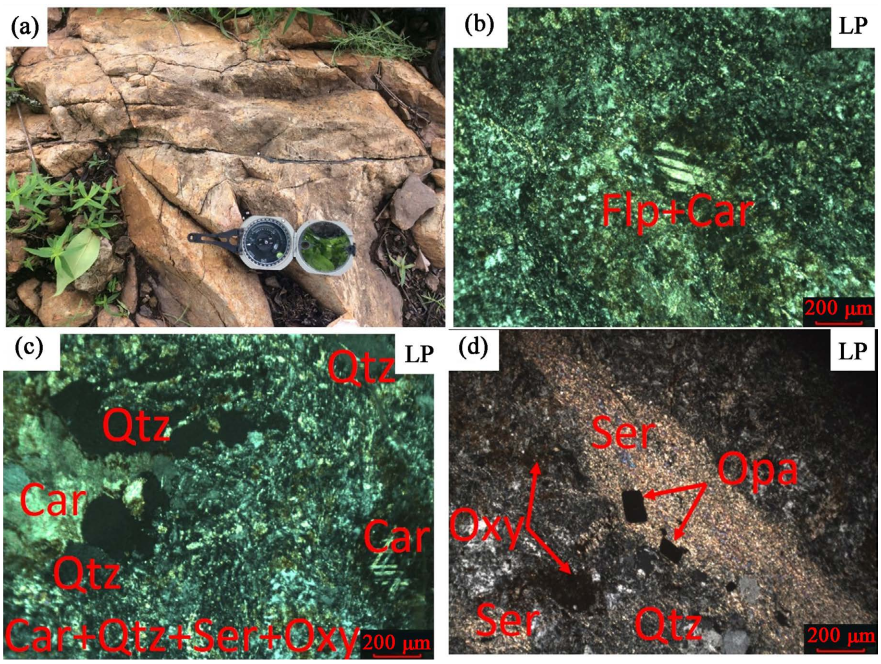

Figure 3. Macroscopic and microscopic aspect of metasiltites. (a) Outcrop of metasiltites, (b) relict plagioclase and calcite, (c) aggregates of quartz and calcite phenocrysts and (d) ferrotitanium oxides and opaque minerals associated with a sericite matrix. Flp: plagioclasic feldspar, Qtz: quartz, Cal: calcite, Ser: sericite, Oy: ferrotitanium oxides and Opa: opaque mineral.

rocks, whose minerals are difficult to identify with naked eye (**Figure 4(a)**). The bedding is not well marked. The Microscopy studies allowed us to identify a fine-grained rock composed of quartz crystals, small and large fragments of feldspars, relict pyroxenes and secondary minerals of chlorite, epidote and sericite as well as opaque minerals (**Figure 4(b)** and **Figure 4(c)**). Plagioclases represent around 45% of the minerals and occur as large subhedral crystals with weak alteration in sericite and epidote. Alkali feldspars (20%) also occur as medium-sized anhedral grains. Pyroxenes, generally augite, are euhedral and occur like prisms with breaks, truncated or altered prisms. They are frequently altered into ouralite (ouralitization).

-Tuffs and volcanic breccias

Tuffs outcrop in the northern and western parts of the permit. Greenish-gray color, they are formed of lapillis with amphibole minerals (green hornblende) (**Figure 4(d)**). A lineation of lapillis stretching along the schistosity planes is observed. Microscopic study suggests that the tuffs are composed of plagioclase in rods with porphyroblasts of amphibole, plagioclase and alkaline feldspars. euhedral and stretched amphibole relics are almost no visible, they have been altered to chlorite. Feldspar porphyroblasts are also stretched but less altered than amphiboles (**Figure 4(e)**). Chlorite and epidote, alteration products, constitute the secondary minerals. Volcanic breccias (**Figure 4(f)**) are observed on the slope of hill at the northwest of the permit in the contact with metagabbros. They consist of enclaves of cinerites set in lapilli tuffs matrix rich in fine and large crystals of amphibole and carbonates. Massive beds, poorly classified and showing in

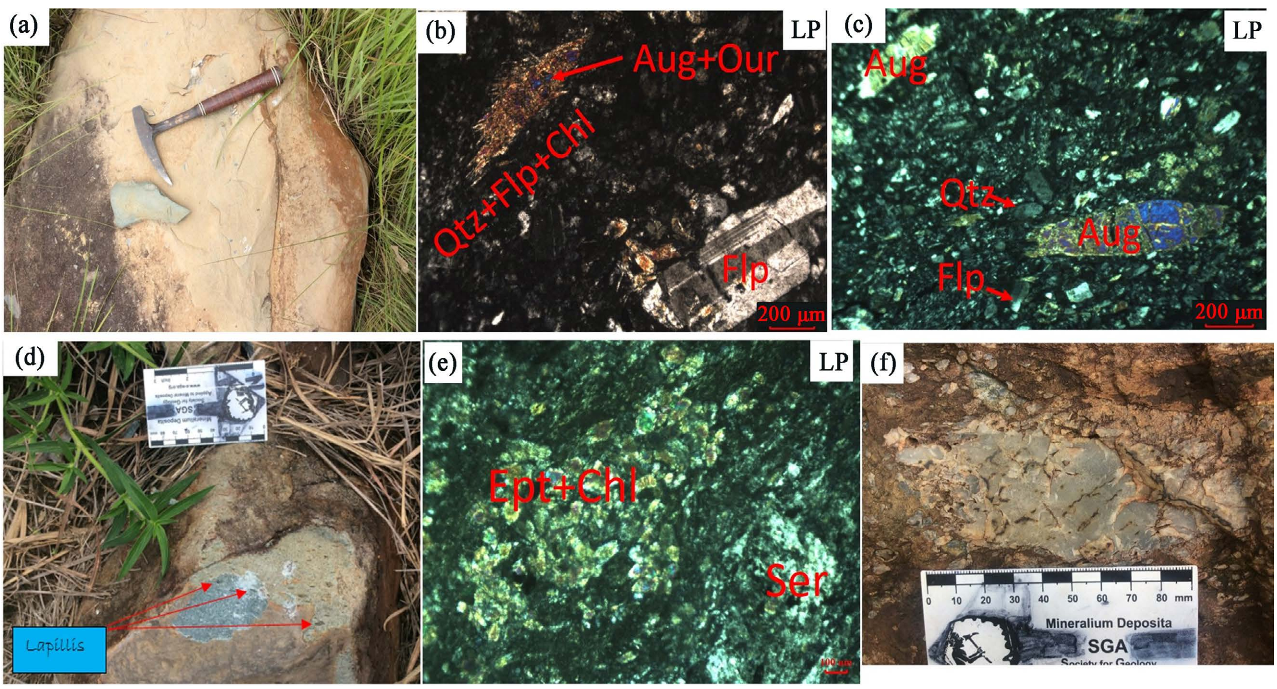

Figure 4. Macroscopic and microscopic aspect of pyroclastites. (a) Cinerite, (b) and (c) phenocrysts of plagioclase and augite in a matrix of chlorite, feldspar and quartz, (d) Lapilli tuff, (e) Alkali feldspar minerals in a matrix of chlorite and epidote, (f) Volcanic breccia. Qtz: quartz, Flp: plagioclase feldspar, Aug: augite, Chl: chlorite, Ept: epidote, Our: ouralite, Ser: sericite.

places a slight normal or inverse bedding.

4.1.3. Plutonic Rocks

The plutons described on the permit are mainly metagabbros. They occupy the entire top of the largest hill in the northwest. They also outcrop like some sub-circular intrusives in the north and center of the permit. At outcrop, the rock has melanocratic color with a green background and a grainy texture (Figure 5(a)). Microscopy studies reveal that metagabbros contain amphibole (60% - 70%), plagioclase, quartz, alkali feldspars and myrmekites, some pyroxenes and also secondary minerals from primary minerals alteration: chlorite, epidote, carbonates and serpentine (Figure 5(b) and Figure 5(c)). Chloritization of amphiboles and pseudomorphosis of plagioclases into epidotes and carbonates are noted. Metagabbros are intensely deformed, mylonitized and contain sulphides (pyrites), quartz ± carbonate veins and veinlets.

4.1.4. Lode Rocks

The lode volcanic rocks are metarhyodacites. They are located in the central part of the permit and outcrop in NNE-SSW trending lodes along shear zones (Figure 5(d)). They are whitish with quartz and feldspar porphyroblasts that are generally altered and transformed into sericite (Figure 5(e) and Figure 5(f)). Feldspars (40% - 45%) are subhedral and plagioclases often have polysynthetic zoned macles. Quartz porphyroblasts are highly deformed, crushed or broken with appearance of subgrains.

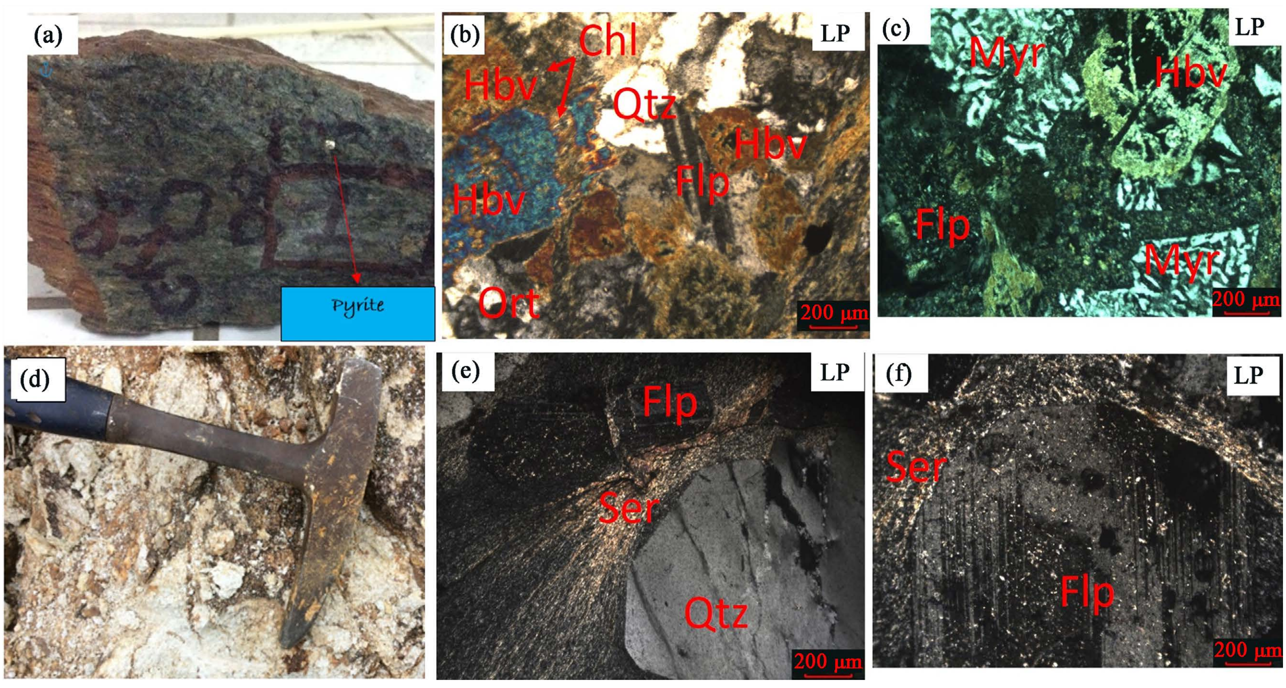

Figure 5. Macroscopic and microscopic aspects of metagabbros and metarhyodacites. (a) Metagabbro, (b) Amphibole (green hornblende) minerals, plagioclase, quartz and chlorite, (c) myrmekites, (d) metarhyodacite, (e) and (f) quartz and feldspar pseudomorphosed into sericite. Qtz: quartz, Hbv: green hornblende, Flp: plagioclase feldspar, Ort: orthose, Myr: myrmekite, Chl: chlorite, Ser: sericite.

4.1.5. Metamorphism and Hydrothermalism

-Metamorphism

The petrographic study indicates that a metamorphism has affected all the lithologies of the permit. This resulted in the disruption of the stability conditions of the original minerals and in mineralogical and structural transformations. The mineralogical transformation shows substitution of ferromagnesian minerals (amphibole and pyroxene) by chlorite and epidote, as well as feldspars by sericite, epidote and carbonate. This metamorphic paragenesis reflects a low grade greenschist facies metamorphism. The structural transformation shows presence of schistosities or stretching lineations, with lepidoblastic and nematoblastic textures; this suggesting a context of regional metamorphism.

-Hydrothermalism

Hydrothermalism is very marked over a large part of the permit, mainly in the shear zones. Following implementation process, two types of hydrothermal alteration can be distinguished: pervasive alteration and fissural alteration. The Pervasive alteration includes chloritization, sericitization, epidotization, silicification, carbonation, sulfidation, etc. However, the fissural alteration is at the origin of the setting of quartz ± carbonates veins and veinlets.

4.2. Structural Analysis

Most of formations encountered on Koffissiokaha permit are deformed with variable gradients (weak to strong). The structures include schistosities, lineations, shear zones and faults, quartz veins and veinlets, joints and fractures.

4.2.1. Schistosity and Lineations

Schistosity is the dominant planar structure of the permit. It can be observed on outcrop as well as in thin sections. It is well marked in the metasiltites, metagrauwackes and pyroclastites (**Figures 6(a)-(c)**). At outcrop, it is not very expressed in metarhyodacites. However, in thin sections it is well defined by the alignment of sericite minerals. Schistosity is generally oriented N30 - N40 with variable dips: low (<40˚), moderate (50˚ - 60˚) and steep (>70˚) to the southeast (**Figure 6(d)**); low dips obtained could be related to the subsidence of schistosity due to the influence of the weight of overlying materials and the steep slope of the hills. Mineral stretching lineation is observed in metagabbros, lapilli tuffs and metagrauwackes (**Figure 6(e)**). It is expressed in the form of stretched minerals of carbonates in the metagrauwackes and of amphiboles in the metagabbros and metatufs. This lineation is oriented N20 to N35 and globally subhorizontal. Schistosity and lineation are more or less contemporaneous structures.

4.2.2. Shear-Zones et Faults

Shear-zones of Koffissiokaha crosscut all the lithologies (metasediments, pyroclastites, metarhyodacites and metagabbros) and some structures (schistosity and lineations). These shears are more or less narrow (<50m), dextral or senestral and generally marked by a subhorizontal stretching lineation (**Figure 7(a)** and **Figure 7(b)**). They are NNE-SSW trending with steep dips (>75˚) or

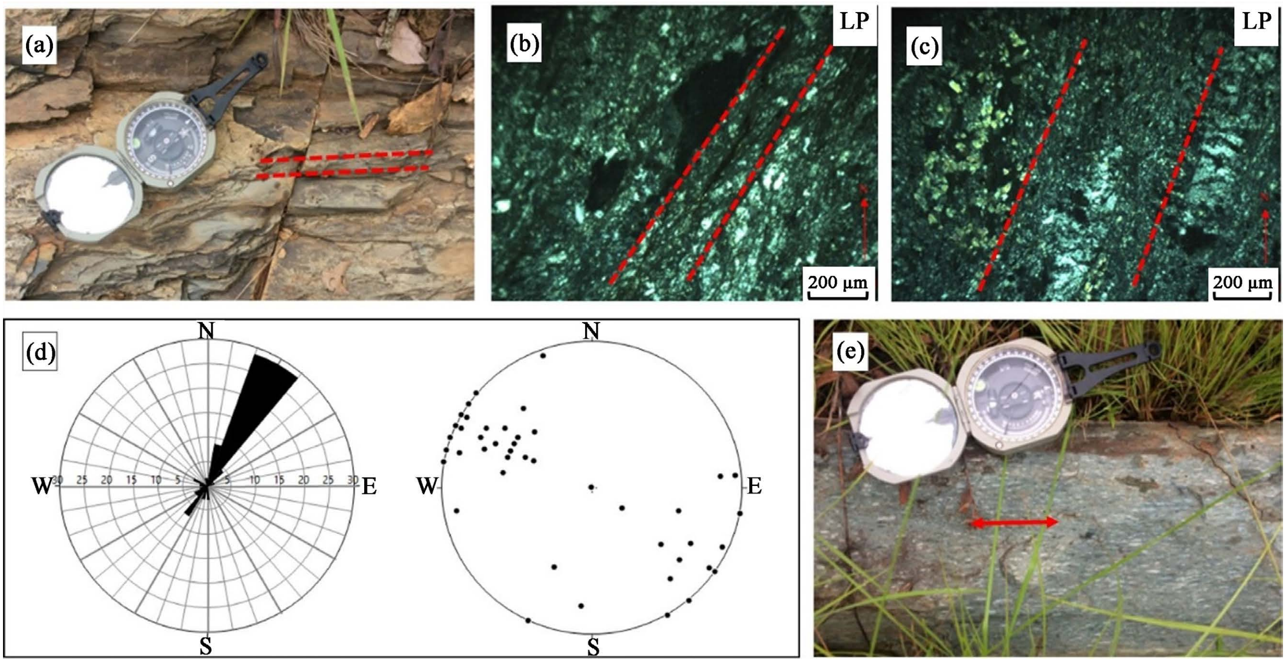

Figure 6. Macroscopic and microscopic aspects of schistosity and mineral lineation. (a) Schistosity in metasiltites, (b) schistosity in metagrauwackes, (c) schistosity in pyroclastites, (d) stereographs of schistosity, and (e) mineral stretching lineation in metagrauwackes.

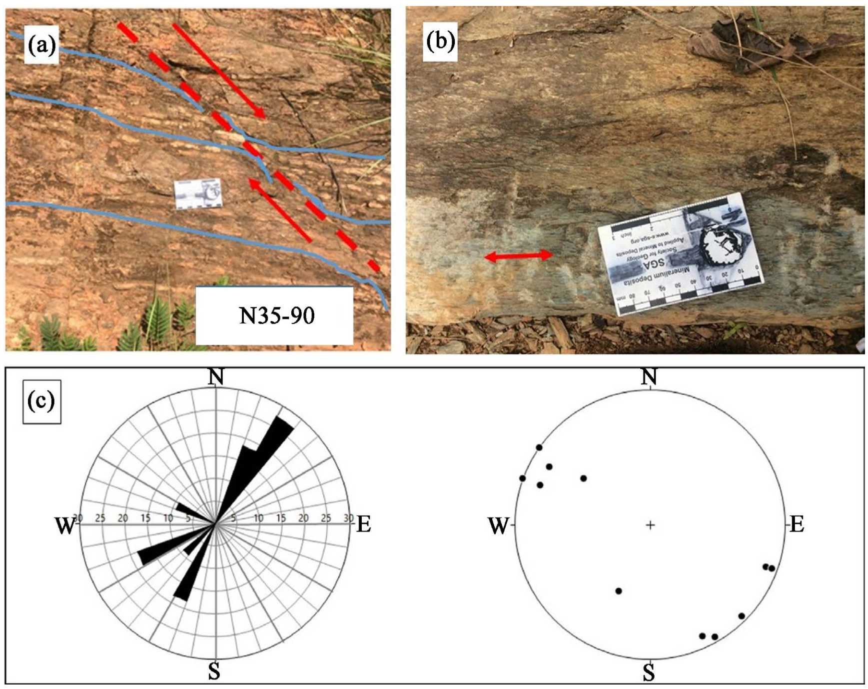

Figure 7. Illustration of faults and associated directional rosettes. (a) Senestral shear affecting a metagrauwacke, (b) shear with subhorizontal lineation, and (c) directional rosette of faults and shears.

subvertical (**Figure 7(c)**) and dominated by mylonites or cataclasites. Their emplacement is accompanied by important hydrothermal alteration phenomena at the origin of the formation of quartz veins. They constitute the most intense deformations listed on the permit and are the potential structures that host the gold mineralization. These shear-zones are cut by faults striking NW-SE, NNW-SSE, N-S and NE-SW. Microstructures that indicate dextral or senestral shear movements were distinguished in microscopy. The shape and movement along the fracture planes in some minerals as well as the characteristics of certain minerals such as quartz confirm the presence of deformation. Asymetric and symetric pressure-shadows developped around porphyroblasts and dynamic recrystallization of fine-grained quartz within dislocations, are observed (Figure 8(a)). Sigmoidal or sometimes dislocated porphyroblasts of quartz, carbonates and feldspars indicate the presence of dextral and senestral faults (Figures 8(b)-(d)). These microstructures are consistent with the existence of mega and mesostructures described during the field mapping.

4.2.3. Quartz Veins and Veinlets

Quartz veins of Koffissiokaha area are generally associated with shear zones or faults. They are observed in outcrops or in orpaillage pits with variable sizes and orientations (Figures 9(a)-(c)). Millimeter to metric sizes, quartz veins are oriented N20 - N40 (Figure 9(d)), with gentle (<40˚), moderate (55˚ - 65˚) and rarely steep (>75˚) dips. Some veins are developed within the interface between two lithologies. Syn-schistose veins or veins subparallel to NE-SW schistosity (ante-tectonic veins), sheared or laminated veins and extensional or tension veins associated to NNE-SSW shear corridors (syn-tectonic veins), and finally,

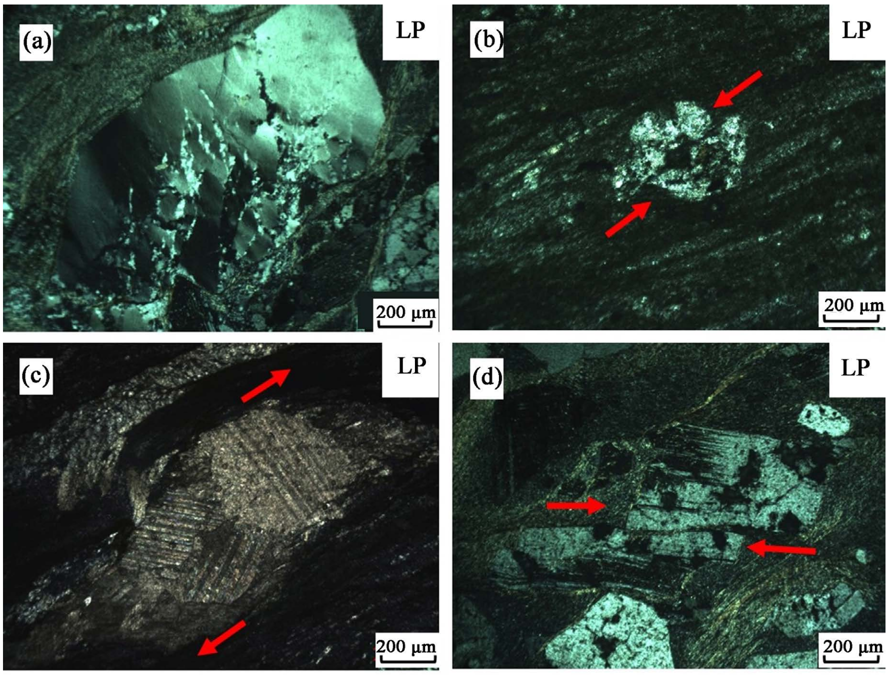

Figure 8. Microstructures indicating deformation and direction of fault movement. (a) Schistosity by pressure-dissolution around quartz porphyroblasts and dynamic recrystallization of fine-grained quartz in dislocations, (b) dislocated phenocrystal indicating senestral movement, (c) carbonate phenocrystals indicating dextral movement, (d) dislocated feldspar porphyroblasts indicating dextral movement.

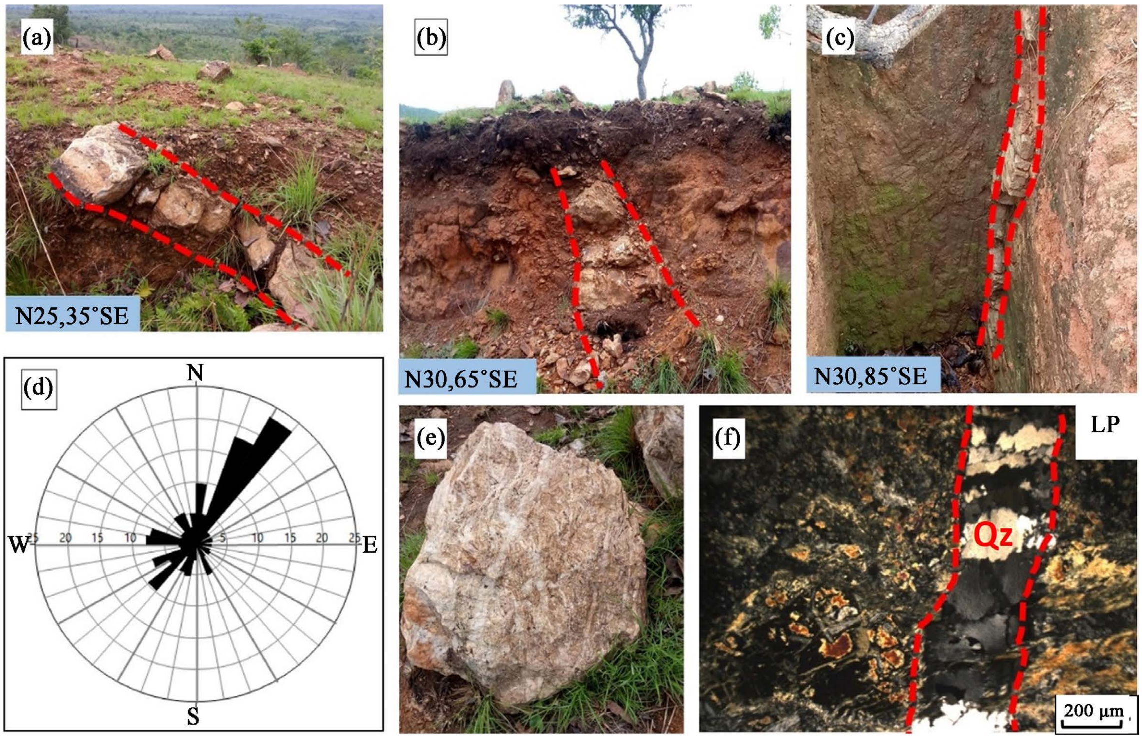

Figure 9. Illustrations of quartz veins and directional rosettes. (a) Laminated quartz vein (N25, 35˚SE), (b) brecciated quartz vein (N30, 65˚SE), (c) quartz vein (N30, 85˚ - 90˚) seen in an orpaillage pit, (d) directional rosette of veins, (e) sheared and brecciated vein with fractures filled with quartz, carbonates, and sulfides, (f) quartz veinlet seen under a microscopic observation.

rare veins related to late faults (post-tectonic veins) are distinguished; sheared veins being those that carry numerous fractures filled with quartz, carbonates, sulphides and gold, and thus mineralized (Figure 9(e)). Structural microscopy also revealed quartz and/or calcite and epidote veinlets (Figure 9(f)).

4.2.4. Joints et Fractures

Joints or fractures are multiple and present as much in rocks as in quartz veins. These fractures show sometimes slight dextral or senestral movements. Filled with minerals, they form quartz ± carbonates or epidote veins and veinlets. Joints and fractures are oriented N20 to N40 and generally subparallel to the schistosity, shears and most of quartz veins. However, some fractures of ENE-WSW, WNW-ESE and N-S orientations, intersect them.

4.3. Final Geological Map

The geological field mapping, coupled with petrographic study and structural analysis, has allowed to realize the geological map of Koffissiokaha (Figure 10). Among the different described formations, métasédiments (metaarenites-metasiltites) appear as the dominant lithologies, followed by pyroclastites (lapilli tuffs, cinerites and vocanic breccias); pyroclastites being elongated following the NNE-SSW to NE-SW trending regional tectonic grain. This volcano-sedimentary sequence is crossed by syn-tectonic metarhyodacite lodes and intruded by metagabbro plutons.

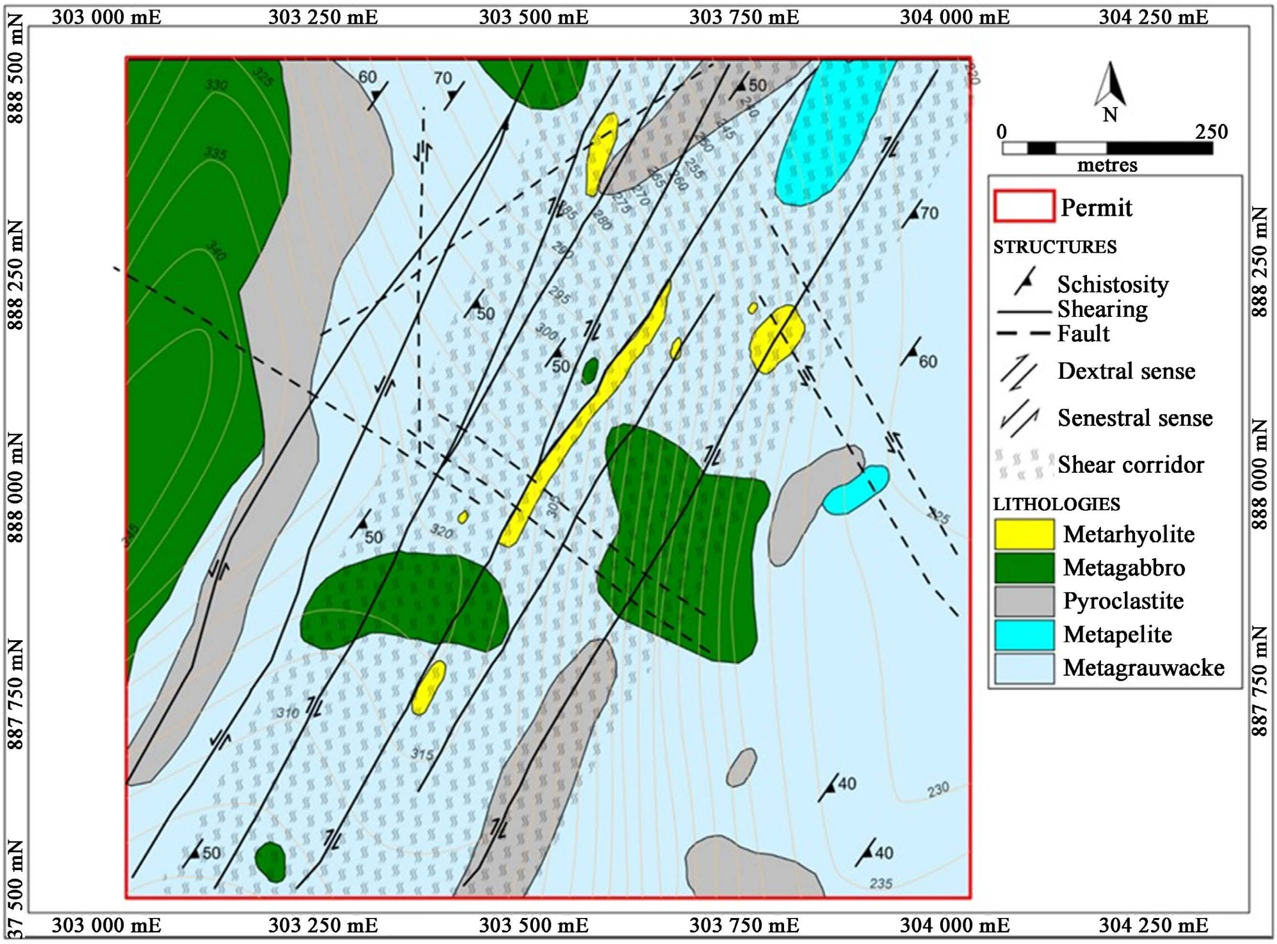

Figure 10. Final geological map of Koffissiokaha permit.

Regional schistosity is the dominant planar structure on the permit. Several NNE-SSW trending shear zones and late NW-SE, NNW-SSE, N-S and NE-SW faults, overprinted the regional schistosity.

4.4. Metallogenic Study

This study highlighted the metalliferous paragenesis based on the microscopic description of sulphides contained in the fragments or cuttings from RAB and RC drillings. The different rocks of the permit are affected by hydrothermalism and the remarkable alterations are: chloritization, sericitization, carbonation, silicification, epidotization and sulfidation. They are generally very clear in microscopy. Mineral associations are distinguished: quartz + chlorite + carbonate + pyrite (Figure 11(a) and Figure 11(b)) and quartz + sericite + carbonate + pyrite (pyrite with hexagonal prism habit similar to pyrrhotite) (Figure 11(c) and Figure 11(d)). These mineral associations highlight propylitic alteration and phyllic or sericite alteration, respectively. In phyllic alteration, porphyroblasts of magnetic pyrite or pyrrhotite, with associated pressure shadows, indicate very high pressure and temperature conditions. This reflects a phase of intense deformation. Both mineral associations are in fact intimately associated with the

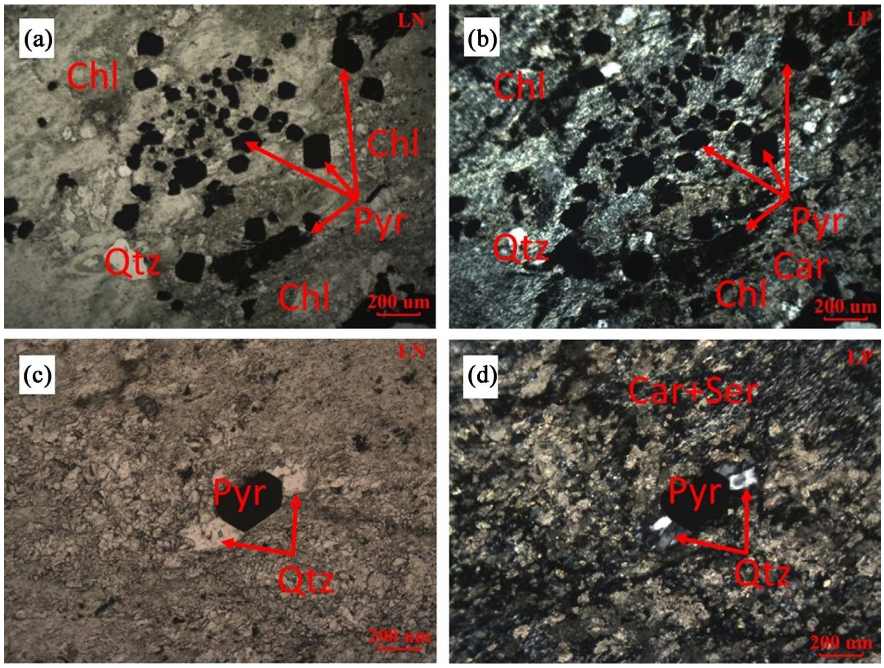

Figure 11. Hydrothermal alteration related to mineralization. (a) and (b) Propylitic alteration, (c) and (d) Phyllic alteration. Pyr: pyrite; Pyo: pyrrhotite; Chl: chlorite; Ser: sericite; Car: carbonate; Qtz: quartz.

shear corridors and their corollary of mineralized quartz veins. The post-magmatic tectonic events that affected the formations are accompanied by the circulation of hydrothermal fluids with silica and carbonate cristallization, as well as the development of a sulphide mineral paragenesis and gold. Sulphides described are mostly pyrite (and pyrrhotite), arsenopyrite and chalcopyrite. Pyrite represents 80% to 85% of the sulphides and occurs in cubic form and in disseminated or remobilized clusters within the schistosity planes of host-rocks. It presents a rather euhedral to subhedral habitus (**Figure 12(a)** and **Figure 12(b)**), sometimes fractured. Arsenopyrite, on the other hand, is present in the form of elongated acicular prisms following a direction (**Figure 12(a)** and **Figure 12(c)**). Arsenopyrite and pyrite observed as pyrrhotite suggest emplacement in a high temperature hydrothermal environment. Chalcopyrite, a mineral almost similar to pyrite, occurs under fine grains with an euhedral to subhedral habitus and shows corrosions; this well reflects the fact that these two minerals are intimately associated (**Figure 12(d)**).

5. Discussion

Our recent work has ensured the petrographic, structural and metallogenic characterization of the Koffissiokaha permit. The results obtained suggest the existence of metallotects controlling the emplacement of gold mineralizations. Petrographic study revealed that metasediments (metagrauwackes and metasiltites) are the dominant rocks, followed by pyroclastites (cinerites and tuffs), then finaly plutonic (metagabbros) and volcanic rocks (metarhyodacites); volcanic

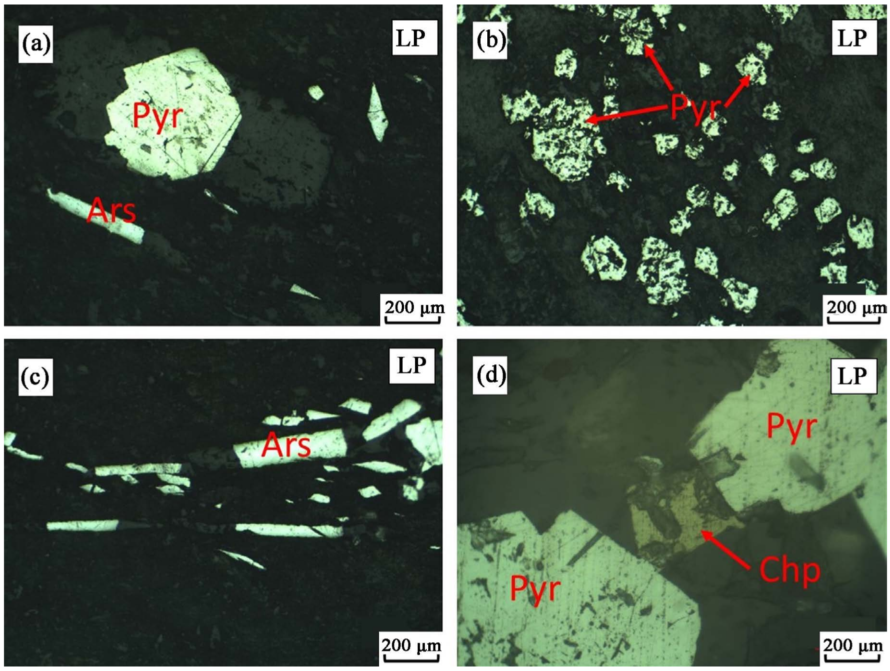

Figure 12. Microscopic aspect of metalliferous paragenesis: (a) Pyrite and Arsenopyrite, (b) disseminated or aggregates of pyrites, (c) arsenopyrite in rods, (d) chalcopyrite associated with pyrite minerals. Pyr: pyrite, Ars: arsenopyrite, Chp: chalcopyrite.

ash and metarhyodacites being related to explosive and effusive volcanic activities respectively. However, the magmatic activity at the origin of metagabbro plutons emplacement appears to be a recent event. Consequently, they intrude all the volcano-sedimentary sequence. Metagabbros have a grenue to microgrenue texture similar to those described by [22] in the Junction deposit of Aféma Gold District, by [23] and [9] in Lafigué and Gogo prospects respectively. Different lithologies of Koffissiokaha permit are similar to those known to characterize the birimian formations ([14] and [15]). They have been described by [16] and [18] in Toumodi area, [3] and [5] respectively on Agbaou and Bonikro gold deposits of the southern part of Fêtêkro Greenstone Belt, as well as by [1] and [2] in areas marking the northern termination of Fêtêkro Belt (Dabakala area). Furthermore, mafic pyroclastites described at Koffissiokaha are similar to those observed by [3] at Agbaou, [5] in Bonikro deposit, [24] in Toumodi area and [25] at Nanglé-koffikro in Djékanou region. Metasediments were described by [2] in Bobosso area under the term of arenites (for sandstones) and lutites (for metasiltites). Metarhyodacites have also been observed by several authors including [26] in Tondabo prospect where they probably carry gold mineralizations. The metamorphism at Koffissiokaha is of low grade and greenschist facies as in most of West African gold deposits; this metamorphism is overprinted by hydrothermalism marked by formation of quartz veins and silico-carbonate emanations rich in sulfides and gold. Hydrothermal alteration is manifested on the one hand by a pervasive alteration and on the other hand, by a fissural alteration at the origin of the setting of quartz and/or carbonates veins and veinlets; the pervasive alteration having led to the appearance of secondary minerals such as quartz, carbonates, sericites, epidotes and chlorites in the mineralogy of rocks. Similar alteration phenomena have been described in different gold districts in West Africa. On the structural aspect, the regional schistosity that affected volcano-sediments appears to be the dominant planar structure of Koffissiokaha permit. With NE-SW trending and dips 40˚ - 60˚ to southeast or subvertical, the schistosity is intersected and sometimes displaced by dextral or senestral NNE-SSW trending shear-zones with generally subvertical dips. Mineral stretch lineations affecting in particular metagrauwackes, lapilli tuffs and metagabbros, are arranged along schistosity planes; some lineations being typically associated with shear planes. Several families of fractures and joints in which minerals have crystallized to form quartz ± calcite veins and veinlets, are associated with shear-zones. However, late faults of NNW-SSE, NW-SE, N-S and NE-SW directions with subvertical dips (>80˚) have also been observed. These faults intersect all the lithologies and structures of the permit. The structural setting of Koffissiokaha permit can thus be summarized in three deformation phases D1, D2 and D3:

- D1 phase: the D1 deformation is dominated by a S1 schistosity of NE-SW orientation and a low-grade metamorphism of greenschist facies whose emplacement is related to the regional NW-SE birimian compression. This compression was followed by magmatism which is at the origin of the setting of metagabbro plutons. Koffissiokaha metagabbros appear to be post to tardi-tectonic basing on their subcircular or slightly elongated NE-SW shape.
- Phase D2: the dextral or senestral shear-zones of NNE-SSW orientation and subvertical dips, as well as their corollary of fractures of which some are filled by minerals and forming quartz ± carbonates veins and veinlets, constitute the essential structures of the D2 deformation. These shear corridors, generally narrow and marked by mylonitic formations and quartz veins, host the gold mineralizations of Koffissiokaha.
- Phase D3: Late faults, sometimes strike-slip with NNW-SSE, NW-SE, N-S and NE-SW orientations and associated fractures, crosscuting all the lithologies and structures, constitute the features of the D3 deformation.

Koffissiokaha gold mineralization is associated to different shear-zones that provide structural control, thus suggesting a geological setting similar to that of some West African gold mineralizations (Agbaou, Bonikro, Dougbafla, Aféma, Tongon, Bobosso, Kalana, Houndé, Konongo, etc.). This mineralization is vein-type and hosted in schistosed metasediments. It is associated with sulphides in hydrothermalism zones. The metalliferous paragenesis consists of pyrite (more abundant), arsenopyrite and chalcopyrite (less abundant and generally associated with pyrites). [22] and [19] also describe gold mineralization hosted in metasediments with structural control respectively at Afema and Kalana gold projects. The gold paragenesis is identical to that of Bobosso ([2]), Aféma ([22] [27]) and Tondabo ([26]) in Côte d'Ivoire, Kalana ([19]) in Mali, Bogosu and Prestea

([28] [29]) in Ghana where the proportions of pyrite are higher compared to arsenopyrite. However, this paragenesis is different from that of Ashanti and Konongo gold deposits in Ghana and Passagem in Brazil ([30]) where the dominant mineral is arsenopyrite. The gold mineralization of Koffissiokaha is associated with NNE-SSW shear-zones such as in Konongo mine, Ghana ([31]) and therefore, related to structural control. This form has also been described within several West African gold deposits. Pervasive and fissural or vein-type hydrothermal alteration accompanies the emplacement of gold mineralizations. One of the most important pervasive alterations is carbonation expressed by the presence of calcite minerals; carbonation is probably the precursor event of gold mineralization as suggested by [32]. Carbonation related to gold mineralization has been demonstrated by various authors in several West African gold deposits.

6. Conclusions

Blue-Hill Exploration Sarl, having applied for the Koffissiokaha semi-industrial permit, had one major concern, that of proving the existence of exploitable gold mineralization, before committing costly expenses for obtaining the Semi-Industrial Exploitation Permit (AESI). Mapping and petro-structural and metallogenic study carried out of this permit has improved our knowledge of the geology of the area and assessed the presence of gold mineralizations. The geology of Koffissiokaha area is dominated by metaarenites (metagrauwackes) and metasiltites, pyroclastites (cinerites, tuffs and volcanic breccias), metarhyodacites and metagabbros. The relationships between the different rocks suggest that volcano-sediments (metaarenites, metasiltites and pyroclastites) are the oldest rocks of the area, then intruded by metarhyodacite veins and metagabbro plutons. All the rocks are affected by a low-grade metamorphism with greenschist facies characterized by an association of chlorite-epidote-sericite. Quartz and/or calcite veins on the one hand and carbonation, chloritization, sericitization, epidotization and sulfidation on the other hand, characteristic elements of an important hydrothermal activity, are noted. The structural context is dominated by a regional schistosity of Birimian age trending NE-SW, which is cut by dextral or senestral shear-zones trending NNE-SSW; these shear-zones are crosscut by late faults striking NNW-SSE, NW-SE, N-S and NE-SW. Koffissiokaha gold mineralization is hosted in sheared volcano-sediments with associated quartz veins. The metalliferous paragenesis is composed of pyrite (the most abundant), arsenopyrite and chalcopyrite. The study conducted on Koffissiokaha permit contributes to geological knowledge and, at the same time, to help orient the exploration and/or exploitation of the gold deposits. Consequently, it would be advantageous for the mining operator:

- to seek and dispose of data from previous exploration work (soil geochemistry, RAB or RC drilling);
- to carry out additional drilling to better understand the geometric characteristics of gold mineralizations and to ensure the calculation of resources, be-

fore starting the semi-industrial exploitation phase.

Acknowledgements

This article was possible by the contribution of Kra Wilfried K. (for the field mapping), Adingra M.P.K and Allialy M. E. (for petrography study) and Loba G. F. C. (for the maps digitalization). This work is greatly supported by Blue-Hill Exploration Sarl staff whose Director Mr. Kouame A. I wish to thank for their kind support and consideration.

Conflicts of Interest

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

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