International Journal of Geosciences, 2022, 13, 855-874
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Mapping and Petro-Structural Study of Northern Komborodougou Formations, in Korhogo Gold District: A Substantial Contribution to the Discovery of a Potential Gold Mineralization in Birimian Greenstone Belts

Houssou N'Guessan Nestor[1*], Allialy Marc Ephrem[1], Adingra Martial Pohn Koffi[1], Pria Koffi Kossonou Jean-Marie[2], Koffi N'guessan Martial Ahossi[3], Loba Gbriga Franck Cyrille[3]

[1]UFHB, University of Felix Houphouët-Boigny Abidjan, UFR Earth Sciences and Mineral Resources, Abidjan, Côte d'Ivoire
[2]UJLoG, University of Jean Lorougnon Guede, Daloa, Côte d'Ivoire
[3]CAREM Sarl, Abidjan, Côte d'Ivoire
Email: *nestor.houssou@gmail.com

How to cite this paper: Nestor, H.N., Ephrem, A.M., Koffi, A.M.P., Jean-Marie, P.K.K., Ahossi, K.N.M. and Cyrille, L.G.F. (2022) Mapping and Petro-Structural Study of Northern Komborodougou Formations, in Korhogo Gold District: A Substantial Contribution to the Discovery of a Potential Gold Mineralization in Birimian Greenstone Belts. *International Journal of Geosciences*, **13**, 855-874.
https://doi.org/10.4236/ijg.2022.1310042

Received: August 31, 2022
Accepted: October 10, 2022
Published: October 13, 2022

Abstract

The Gold District of Korhogo, in the northern region of Côte d'Ivoire, holds enormous potential for gold mineralizations, some of which are under exploration phase and others in exploitation phase (example of Tongon Gold Mine). Dormant since 1998, Mapping Services of most of the West African countries hardly provide geological maps at the scales of: 1/200,000, 1/50,000 and 1/25,000. This situation of unavailability of detailed geological maps does not help mining operators in the selection of prolific areas and also in the interpretation of in soil geochem anomies or gold mineralizations. Consequently, during the years 2020 and 2021, we have undertaken a campaign of geological mapping and petro-structural study of the northern sector of Komborodougou, located in the southern extension of Banfora Birimian Belt. This work, which allowed the realization of a geological map at 1/20,000 scale, reveals that: the mapped area includes three (3) major lithological units: 1) a volcano-sedimentary unit made up of metasediments (metaarenites, metasiltites and metaflyschs) and metavolcanites (metabasalts), which are metamorphosed and outcrop in the form of schists; 2) a metaplutonic and intrusive unit composed on the one hand of quartz-diorites and metagabbros, and on the other hand of granites and granodiorites; 3) and finally, a unit of dikes formed by micrograinites, microgabbros, aplites and quartzites. The volcano-sedimentary complex is affected by a regional fold with an axis subparallel to the regional tectonic grain and an S1 schistosity oriented NE-SW to NNE-SSW with steep dips (>60˚), except for those of the metaflyschs which are weak (<40˚); a regional NW-SE compression would be at the origin of the setting of this schistosity. The volcano-sediment and metaplutonite complex is crossed in a NNE-SSW direction by a senetral shear-zone or main shear-zone and secondary shear-zones oriented sometimes NE-SW or N-S. These shear-zones are intersected by more or less dextral or senestral strike-slip faults of NW-SE and E-W trends. N-S to NNE-SSW (N0˚ - N20˚) and NW-SE (N130˚ - N160˚) vein systems associated with the various shear-zones are the hosts of the gold mineralization in the region. These veins have been mined by orpaillors for more than two decades. The northern sector of Komborodougou is in the NNE continuity of the gold mineralization highlighted by the mining company Mako Gold Sarl on its Gogbala and Tchaga prospects, Napie project.

Keywords

Geological Mapping, Petro-Structural, Gold Mineralization, Komborodougou, Côte d'Ivoire

1. Introduction

The West African mining sector is booming. All types of minerals are coveted, from gold to diamonds, from manganese to nickel, from bauxite to coltan, not forgetting rare earths, etc. Of all these minerals, gold seems to occupy the first rank in view of the higher number of mining companies for gold, exploration and mining permits granted or in application, and their contribution to the GDP (Gross Domestic Product) of the different concerned countries. The West African gold productions come mainly from Birimian Greenstone Belts (Papon, 1973 [1]; Milesi, 1989 [2], Milesi *et al.*, 1992 [3]) to which shear-zones are associated (Hein *et al.*, 2004 [4]; Assie, 2008 [5]; Hein, 2010 [6]; Feybesse *et al.*, 2006 [7]; Tshibubudze *et al.*, 2009 [8] and 2013 [9]; Lompo, 2010 [10]; Baratoux *et al.*, 2011 [11]; Perrouty *et al.*, 2012 [12]; Houssou 2013 [13]; Sinare, 2013 [14]; Gnanzou, 2014 [15]; Ouattara, Z, 2015 [16]; Ouattara, Z *et al.*, 2015 [17] and 2020 [18]; Serigne S *et al.*, 2016 [19]; Houssou *et al.*, 2016 [20]; Siagne *et al.*, 2022 [21], etc.). Greenstones and shear-zones thus appear as major guiding elements in the choice of prospective areas. Korhogo Gold District, in the northern of Côte d'Ivoire, has potentials for gold mineralizations, some of which are under exploration and others in production (example of Tongon Gold Mine with over 4 million ounces). Dormant since years 1998, Mapping Services of most of the countries, hardly provide geological maps at 1:200,000, 1:50,000 and 1:25,000 scale. This situation of unavailability of detailed geological maps does not help mining operators in the selection of prolific zones and also in the interpretation of surface geochemical anomalies or in situ gold mineralizations. Therefore, during the years 2020 and 2021, geological mapping campaigns coupled with petro-structural study have been undertaken in the northern of Komborodougou, area located in the southern extension of Banfora Greenstone Belt. This work, which takes place on the permit PR850 of CAREM Sarl, has a double objective: to produce a 1:20,000 scale geological map and to define the metallotects that control gold mineralizations of the Komborodougou northern area.

2. Geology and Tectonic Context

Relatively large and complex in its litho-structural characteristics, the Man Dorsal, an important entity of West African Craton (WAC), is separated into two (2) distinct domains by the N-S trending Sassandra Transcurrent Fault Zone (**Figure 1**): an Archean domain occupying the western part and a Paleoproterozoic domain covering the eastern part. The Archean geological formations have undergone under catazonal type of metamorphism. They consist of grey banded gneisses of tonalitic composition with intercalations of pinkish orthopyroxene granulites and charnockites (Camil, 1984 [22]; Kouamelan *et al.*, 1997 [23]), as well as intrusive calc-alkaline granite plutons in the grey gneisses. The Paleoproterozoic domain, on the other hand, contains formations named birimian formations (Kitson, 1928 [24]; Junner, 1940 [25]; Bessoles, 1977 [26]) distributed within seventeen (17) belts that were emplaced during the Eburnian orogeny (Doumbia, 1997 [27]; Gasquet *et al.*, 2003 [28]; etc.). These greenstone belts are composed of volcano-sedimentary and plutonic rocks generally oriented NE-SW to NNE-SSW, and letely intruded by granitoids. In this domain, the metamorphism is epizonal to mesozonal, with greenschist to amphibolite facies.

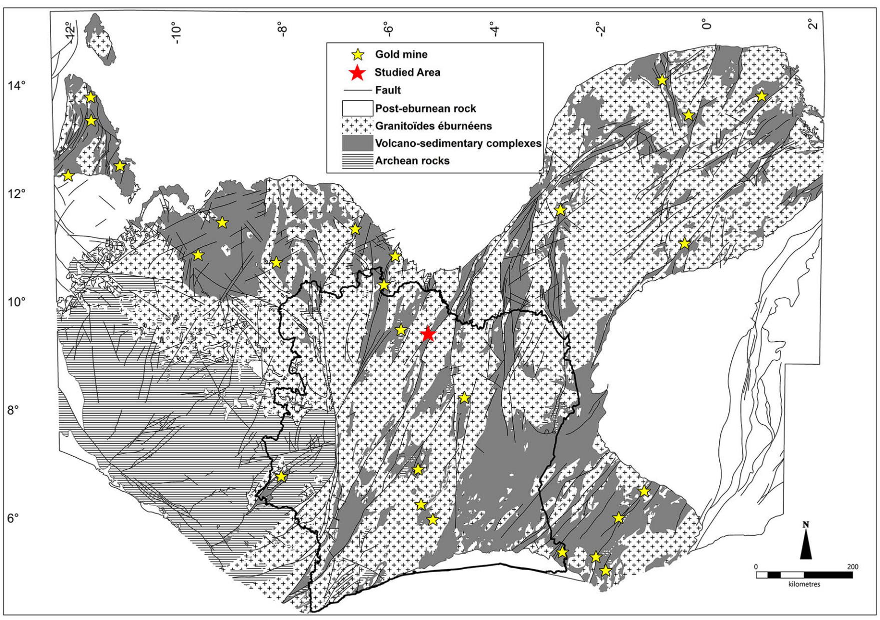

Figure 1. Simplified geological map of the West African Craton with gold mineralization and location of the Komborodougou Zone.

Komborodougou permit, in the department of Korhogo, is located in the southern extension of Banfora Greenstone Belt which extends from Burkina Faso to northern Côte d'Ivoire. This Birimian belt is crossed by the Greenville-Ferkessédougou-Bobo-Dioulasso Fault (GFBF), which is probably the source of most of the gold mineralizations (**Figure 1**). The Komborodougou area is formed by volcano-sedimentary and plutonic formations (**Figure 2**). Volcano-sedimentary rocks contain sediments (metaarenites and metasiltites) and volcanics more or less metamorphosed that sometimes outcrop as schists and quartzites. They are intruded on the one hand by metadolerites and metagabbros or amphibolites in more or less elongated shapes and on the other hand, by a metadiorite (sometimes with tonalitic character) whose shape reflects that of a senestral movement. All this whole ensemble formed by volcano-sediments and plutonites is elongated in a NE-SW to NNE-SSW direction subparallel to the regional tectonic grain. It is bounded in its western part by biotite ± amphibole granites and in the eastern by two-mica metagranites.

3. Methodology

3.1. Radarsat Data

The radar images, obtained at the University Center for Research and Application in Remote Sensing (CURAT), come from the satellite radarsat-1. This satellite, transmitted a microwave energy pulse (in C-band at 5.3 GHz frequency) is equipped of synthetic aperture radar sensor (wavelength ~ 5.6 cm). The spatial resolution of this satellite is between 1 to 100 m. The process of processing images until obtaining the lineament map is described as follows (Adingra, 2020 [30]):

Image pre-processing

This step consists of radiometric and atmospheric corrections. The radiometric correction is performed by compensating for effects of local illuminated area and incidence angle on the local backscatter. The geometric correction is needed to reduce the distortions from highly varying topography.

Image processing

The processing of these images consists of two (2) essential steps:

-*Step* 1: *speckle reduction.*

After testing several adaptive filters, Frost adaptive filter of size 3 × 3 was selected because it improves the readability of the image by preserving the structures present. After removing the speckle, a linear spread was applied to better contrast the image.

- *Step* 2: *Spatial filtering of the image using directional filters.*

Directional filters (Sobels, Yesou and Prewitt) were then used to improve the perception of lineaments, corresponding to lithological or structural discontinuities. These filters accentuate the characteristics of the image in a direction by introducing a relief effect more or less accentuated as per type.

Validation and realization of the lineament map

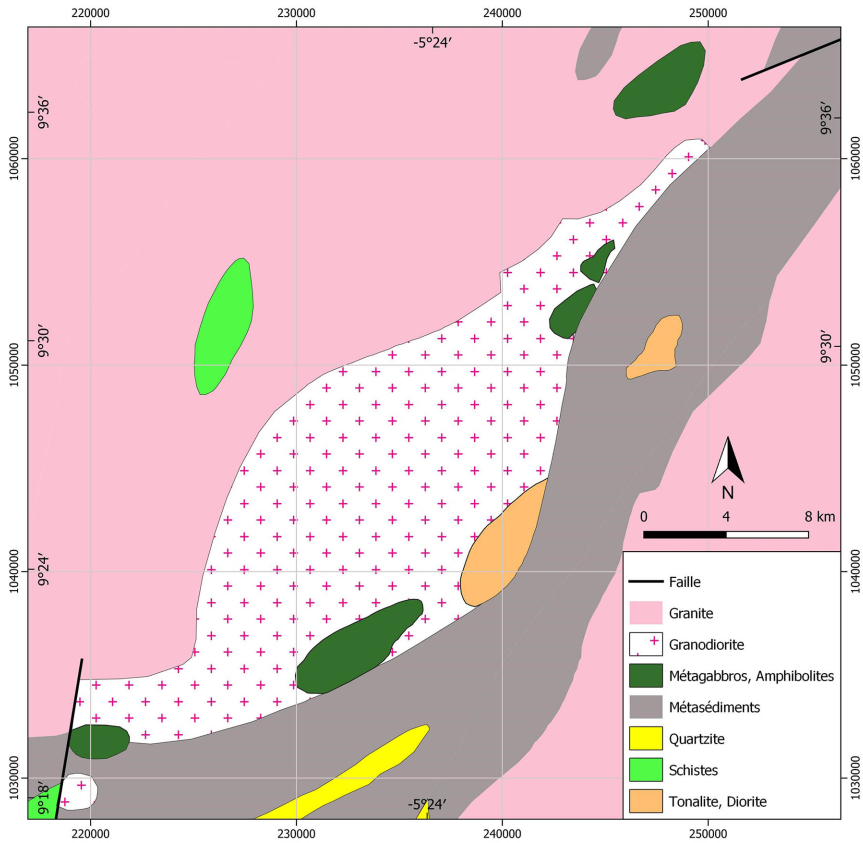

Figure 2. Geological map of the northern region of Komborodougou (Map extracted from the geological map of the Korhogo sheet at 1:200,000 (Claude DELOR and Bertin Daouda YAO, 1995 [29]).

The extraction of lineaments was manually done. Then, a first step of validation was carried out with the help of GIS software Global Mapper 19.1 and ArcGIS 10.5. The superposition of topographic and road maps, google images, OSM data and lineaments obtained allowed to distinguish the anthropic lineaments from the natural lineaments. The second step of the validation was done on the field by comparing the lineaments selected with the data collected in situ. The different maps were made with ArcGIS and the directional analyses with Georient and Excel (**Figure 3**).

3.2. Field Data

The field data are those collected during the geological mapping. The mapping consisted in going through the whole permit with the objective of discovering and describing geological formations which outcrop there. Thus, once on the ground, the rest of the work is done on foot. The roads, tracks and savannah-like vegetation facilitated the permit's route. The area was entirely covered by the geological survey at a scale of 1:20,000. Outcrops of fresh rock are quite rare; however, more than 250 outcrops including fresh to weakly weathered rocks or saprolites were described as well as about hundred orpaillage pits. A total of twenty-eight (28) fresh rock samples were collected and sent to the GRME Laboratory (Geology, Mineral and Energy Resources) of the University of Félix HOUPHOUËT-BOIGNY (UFHB) for the preparation of thin sections. These thin sections were studied in the said Laboratory.

4. Petro-Structural Caracterization

4.1. Lithological Units

Geological mapping and petrographic study revealed the existence of three (3) lithological units unevenly distributed on the geological map of Komborodougou (Figure 4): a volcano-sedimentary unit, a plutonic and intrusive unit, and finally a unit essentially made up of dike-type rocks.

4.1.1. Volcano-Sedimentary Unit

This lithological unit contains metasediments (metaarenites, metasiltites and metaflyschs) and also metavolcanites (metabasalts), which are metamorphosed and outcrop as schists.

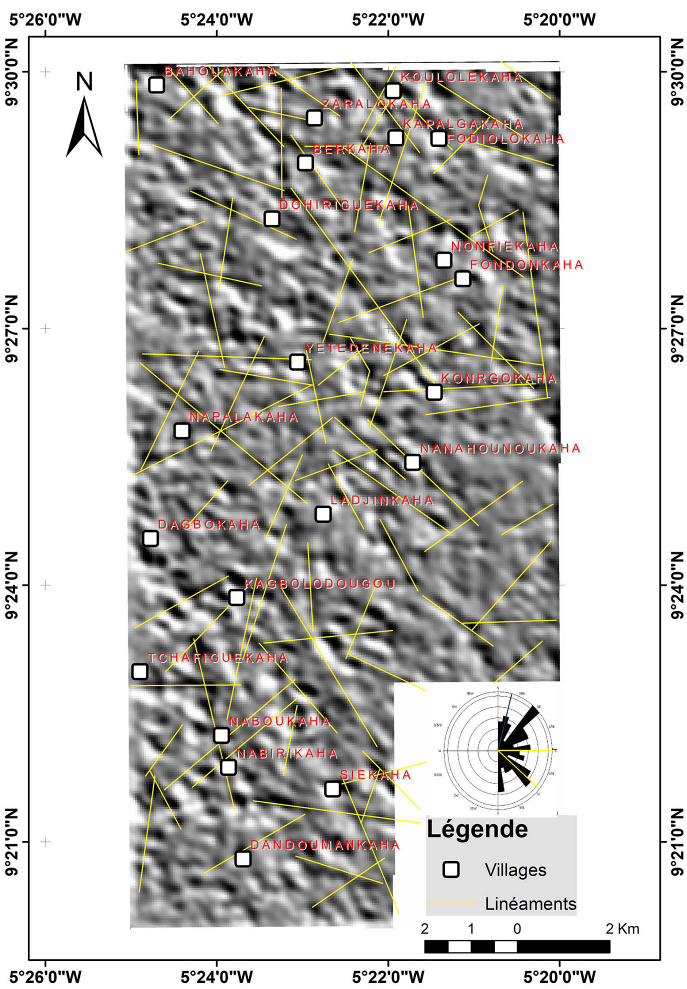

Figure 3. Sobel NW-SE enhanced radarsat-1 image of the northern region of Komborodougou.

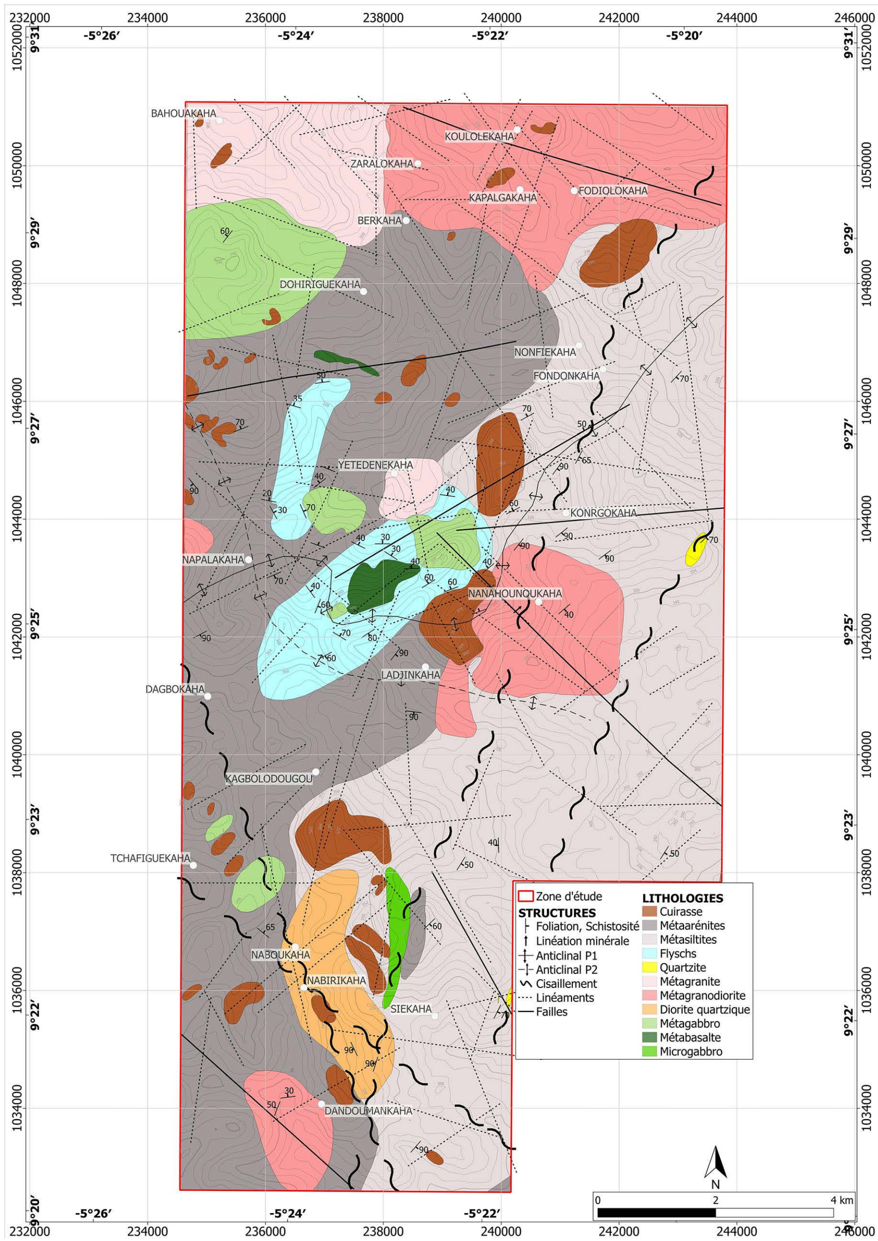

Figure 4. Geological map of permit PR850 in the Northern Komborodougou area.

- **Métasediments**

The metaarenites occur as sandstones and arkoses generally metamorphosed in greenschist facies (**Figure 5(a)**). They are heterogranular and consist of subrounded and medium to coarse grains of quartz in a feldspar-rich cement (**Figure 5(b)**). Metamorphosed, the feldspars were transformed into sericite ± muscovite minerals. However, rare feldspar relics remain (**Figure 5(c)**). Biotite minerals and often sulfides are present. In outcrop, the metaarenites occur as sericite ± quartzo-schists. The sericite-muscovite ± biotite ensemble forms a kind of subparallel schistosity with stretched quartz grains.

Metasiltites are rocks formed by fine grains of subrounded quartz in a feldspar-rich matrix completely pseudomorphosed into sericite-muscovite ± biotite

(**Figure 5(d)**, **Figure 5(e)**). The schistosity is quite well marked. Metamorphosed, they outcrop as sericite-schists. In a context of higher-grade metamorphism, these sediments are transformed into micaschists with a more intense schistosity formed by alternating mica (muscovite-biotite) and quartz minerals (**Figure 5(f)**).

Metaflyschoid rocks have been described in the area bounded by the villages of Napalakaha, Ladjinkaha and Dohiriguékaha. These metaflyschs, outcropping in the central part of the permit, consist of two types of alternating subhorizontal strata, whitish and greenish-gray in color, respectively (**Figure 6(a)**). Microscopically, the lighter part contains quartz-feldspar-mica minerals, while the darker part contains pyroxene-amphibole-plagioclase (**Figure 6(b)**, **Figure 6(c)**).

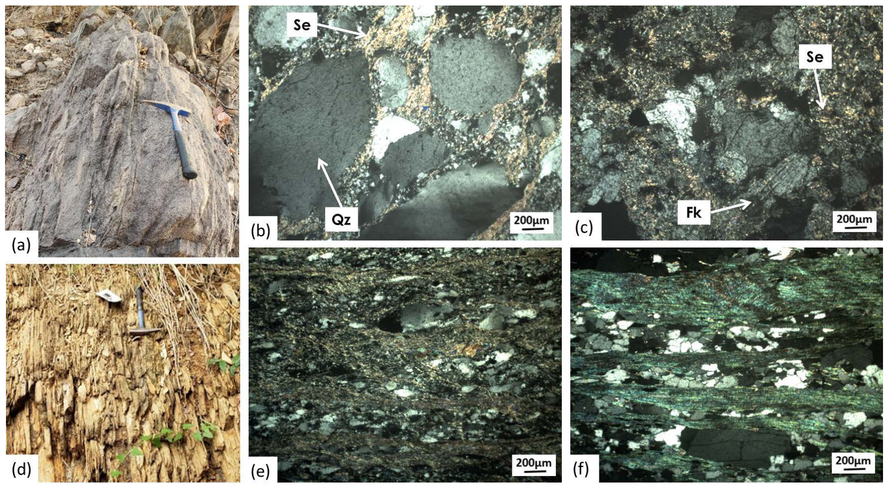

Figure 5. Macroscopic and microscopic aspects of metasediments. (a) Metaarenite mostly sandstone, (b) Coarse subrounded quartz grains in a sericite-rich matrix, (c) Feldspar relic partially pseudomorphosed into sericite, (d) Metasiltite, (e) Fine subrounded quartz grains in a sericite matrix, (f) Alternating bands of micas and quartz in a micaschist.

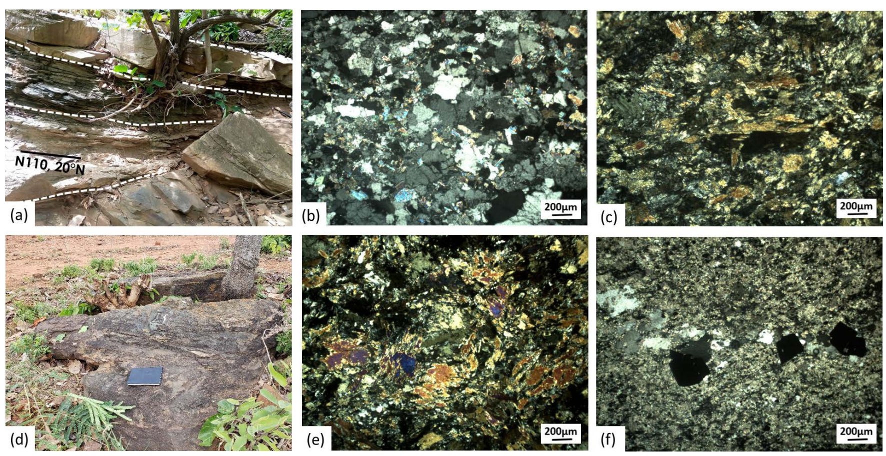

Figure 6. Macroscopic and microscopic aspects of metaflyschs and metabasalts. (a) Outcrop of metaflysch with alternating light and dark strata, (b) Light stratum formed by quartz-feldspars-micas, (c) Dark or greenish stratum formed by ferromagnesians (pyroxenes-amphiboles) and plagioclases, (d) Outcrop of metabasalt, (e) Microlitic texture formed by pyroxenes-amphiboles-plagioclases, (f) Sulphides in metabasalts.

- **Metavolcanites**

These are metabasalts forming small elongated hills in a NE-SW direction. They are located in the central part of the permit in the heart of the metaflyschs. They are also found as enclaves within the Ladjinkaha granodiorite. They are melanocratic and microlitic or microlitic porphyry in texture (Figure 6(d)). These rocks are composed of pyroxenes (relict), amphiboles, plagioclases, very little quartz and sulfides (Figure 6(e), Figure 6(f)). In general, they are metamorphosed and outcrop as chloritoschists. The metabasalts are often cut by quartz ± carbonate veins or veinlets.

4.1.2. Plutonic and Intrusive Unit

This unit contains on the one hand metaplutonites (metadiorites and metagabbros) and on the other hand granitoid intrusives (granites and granodiorites).

- **Metaplutonites**

Metadiorites are rarely observed in outcrop (Figure 7(a)). They are observed in the form of quartz diorites in the gold pits around the village of Dandoumankaha. These rocks are sometimes intensely deformed and transformed into mylonitic rocks; the deformation having led to a reduction in the size of the mineral grains. Its elongated and sinusoidal shape undoubtedly testifies to this more or less shearing deformation. These mesocratic rocks are formed of amphiboles, plagioclases, biotites and very little quartz. Due to important alteration phenomena, some minerals (amphiboles, plagioclases and biotites) have destabilized and transformed into chlorite, sericite and epidote minerals (Figure 7(b), Figure 7(c)).

Metagabbros, however, outcrop as subcircular hills (Figure 7(d)). They are melanocratic rocks, which are generally composed of pyroxenes (sometimes in the form of relics), amphiboles, plagioclases (partially altered to epidotes) and rare quartz minerals (Figure 7(e), Figure 7(f)). Except for Dohiriguekaha, the other metagabbros appear to be deformed, the deformation having resulted in a reduction in the size of their constituent minerals.

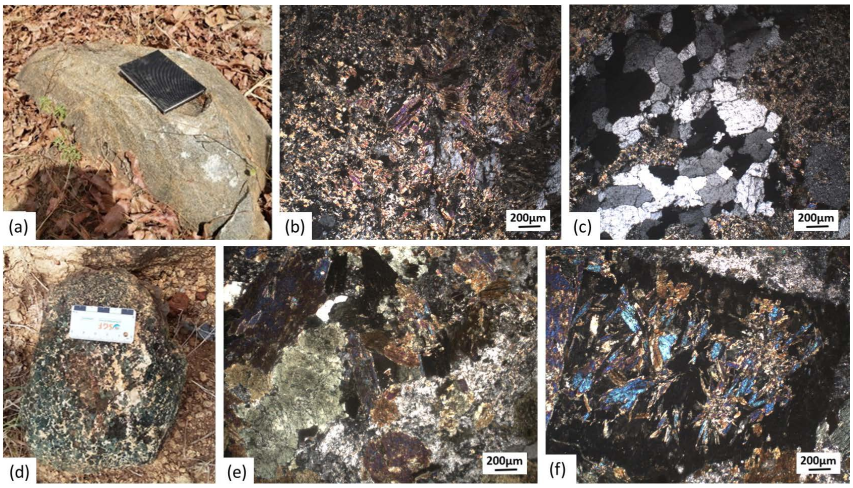

Figure 7. Macroscopic and microscopic aspects of quartz diorites and metagabbros. (a) Quartz diorite outcrop, (b) (c) Microscopic aspect of quartz diorite, (d) Metagabbro outcrop, (e) (f) Microscopic aspect of metagabbro.

▪ **Granitoid intrusives**

Formed by granites and granodiorites, this unit also outcrops in the form of domes or subcircular hills. Granites occupy only the northwestern part of the permit, while granodiorites outcrop in the southwestern, central and northeastern parts respectively.

The granites are leucocratic and composed of quartz, feldspars (often partially altered to sericite), and micas (biotite and muscovite) (Figures 8(a)-(c)). They are usually very deformed in some places due to local deformation (faults).

The granodiorites are generally mesocratic and grenue in texture (Figure 8(d)) except for Nonzorikaha which has a porphyritic grenue texture. At Dandumankaha, the granodiorite is similar to a deformed quartz diorite marked by a more pronounced alteration phenomenon. Granodiorites are composed of quartz, feldspars, amphiboles and biotite. However, feldspars and ferromagnesians (biotite and amphibole) are partially altered to sericite-epidote-carbonates and chlorites (Figure 8(e), Figure 8(f)). Within the granodiorites, mafic enclaves, microgranite and aplite veins are observed.

4.1.3. Mainly Dike-Type Unit

The dike-type unit is composed of microgranite, aplite, microgabbro and quartzite; microgranite and aplite being generally associated with granitoid intrusives.

The microgranite is of micrograined texture formed of quartz, feldspars (partially pseudomorphosed into sericite) and biotite minerals.

The microgabbro forms an important dike at the East of the villages of Naboukaha and Nabirikaha. It extends over hundreds of meters and is elongated in a North-South direction. It is very deformed in its contact zones with the metasediments, where most of quartz veins are sometimes found. Rare fragments of rocks like dolerite were sometimes observed in the Western area, close to the village of Nonzorikaha.

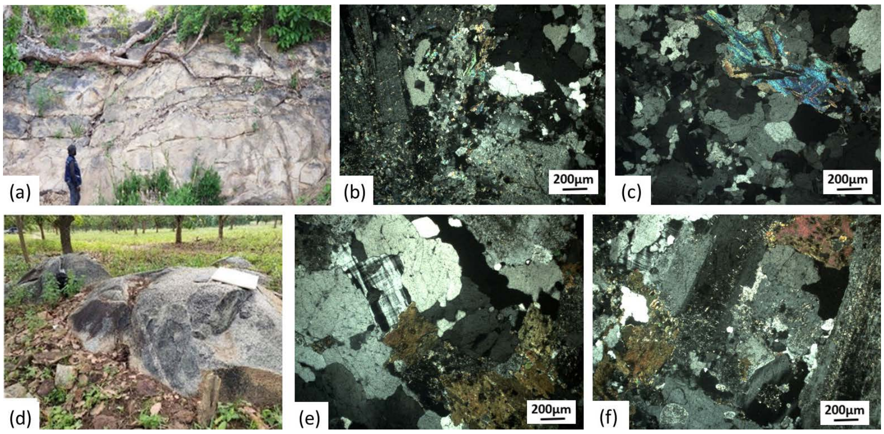

Figure 8. Macroscopic and microscopic aspects of granites and granodiorites. (a) Granite outcrop, (b) (c) Microscopic aspect of granite, (d) Granodiorite outcrop, (e) (f) Microscopic aspect of granodiorite.

The quartzites are smoky and outcrop as veins of up to 10 - 20 meters in the Eastern sectors of Siekaha and Konrgokaha. They form small elongated hills in the NNE-SSW direction. They contain sulphides arranged in the fractures and microfractures planes that cross them.

4.2. Structures

4.2.1. Bedding and Regional Folds

Beddings S0 are associated with metaarenites-metasiltites and flyschoids. They show orientations of which the major ones being NE-SW and NW-SE. The distribution of the beddings as well as their orientations (directions, dips) suggest the existence of two (2) antiformal folds: the first (F1) with an axial plane subparallel to the NE-SW to NNE-SSW birimian direction and steep dips, and the second (F2) with an axial plane NW-SE and weaker dips (**Figure 4**).

4.2.2. Schistosity et Crenulation

The S1 schistosity mainly affects the volcano-sedimentary rocks and is characterized by NE-SW or N30˚ - 50˚ orientations. Sometimes subparallel to the S0 bedding, S1 schistosity is marked by steep dips (>60˚) (**Figure 9(a)**). However, syn-sedimentary schistosity is present in the flyschoids. These are oriented NW-SE (N110˚ - 120˚) and characterized by very shallow dips (>40˚) (**Figure 9(b)**). This is an early schistosity that is subparallel to the S0 bedding. It shows no signs of penetrative deformation. This shallowly dipping S0-S1 schistosity is characteristic of thrust deformation. The other schistosities or foliations of NNE-SSW (N25˚), NE-SW (N50˚), NW-SE (N130˚ - N150˚), E-W (N80˚ - N90˚) and N-S (N170˚ - N180˚) directions with generally subvertical dips are related to faults. The schistosity evolves from simple mineral orientations to well-marked penetrative schistosities, sometimes followed by S2 crenulations (**Figures 9(c)-(e)**). Microscopically,

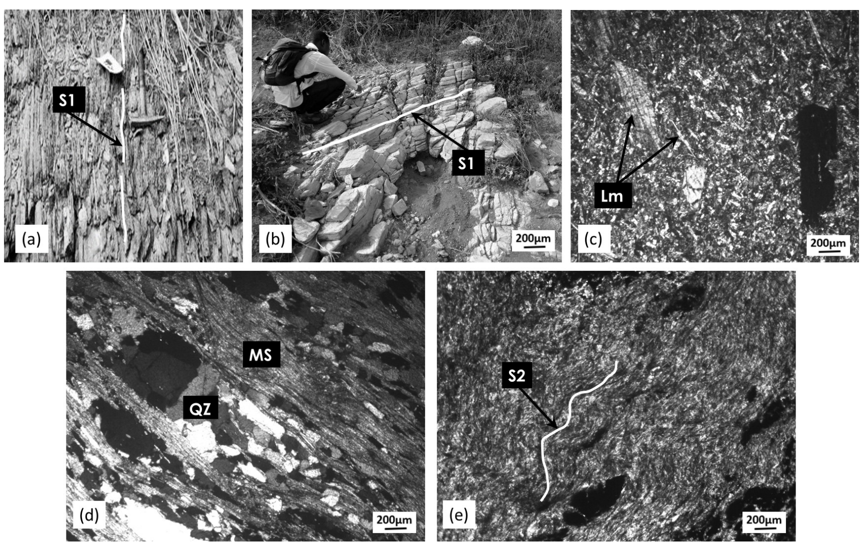

Figure 9. Deformation meso and microstructures. (a) Schistosity (N50, 85˚SE) in metasiltites, (b) Schistosity (N45, 20˚NW) in metaflyschs, (c) Oriented pyroxene minerals in metabasalts, (d) Penetrative schistosity in micaschists, (e) Microfolded schistosity in metaarenites.

S1 schistosity is supported by micas minerals arranged parallel to the stretched quartz grains, especially in the schistose metasediments. These micas are highly deformed and often crenulated or distorted in cases of shear deformation. In granitoids, schistosity or foliation corresponds to mineral lineations or submagmatic foliations.

4.2.3. Shears and Faults

The North Komborodougou permit is crossed by shear-zones and multiple dextral or senestral strike-slip faults (**Figure 10(a)**). The shear-zones show a ductile-brittle character in the volcano-sediments and essentially brittle in the granitoids. Four (4) shear-zones were distinguished and named Komboro Shear-Zones (KSZ): KSZ01 and KSZ02 of NNE-SSW (N20˚ - 25˚) orientation, KSZ03 and KSZ04 respectively of NW-SE (N130˚) and NNW-SSE (N160˚) directions. The intersection of the KSZ02, KSZ03 and KSZ04 shear-zones makes Dandumakaha one of the most deformed areas. Both in outcrop and microscopy, the shear-zones are marked by schistosity or foliation deflections, shear bands (**Figure 10(b)**), C/S fabrics (**Figure 10(c)**), intra-foliar folds (**Figure 10(d)**, **Figure 10(e)**), parasitic folds (**Figure 10(f)**), pink-and-swells, shear direction indicators (**Figure 10(g)**, **Figure 10(h)**), mineral lineations, etc. The NNE-SSW trending shear-zone KSZ02 is marked by both two (2) shear senses: a senestral sense with a subhorizontal mineral lineation (10˚NNE) and a dextral sense with a steeply dipping lineation (45˚SSW). The shear-zones are generally intersected and sometimes displaced by senestral or dextral strike-slip faults or microfaults (**Figures 11(a)-(c)**). We also suggest a possible thrusting of metaflyschs on the birimian units; these are marked by a very shallowly dipping S0-S1 syn-sedimentary schistosity.

4.2.4. Diaclases, Fractures and Veins

The brittle deformation is materialized by joints or diaclases and fractures. They affect all lithologies but appear more developed in the granitoids. Diaclases and fractures are mostly oriented E-W to NW-SE, followed by those of NNE-SSW to NE-SW direction (**Figure 10(d)**). These fractures are sometimes filled to form veins. Aplite, microgranite, microgabbro and quartzite veins (oriented NNE-SSW) are distinguished (**Figure 11(e)**). Quartz veins are centimetric to metric (**Figure 11(f)**). Generally associated with shear-zones, they are smoky, translucent or saccharoid in saprolites. Quartz veins follow the main directions NE-SW (N30˚ - 50˚) and NW-SE (N110˚ - 130˚), and by N-S to NNE-SSW (N0˚ - 20˚) and E-W directions. The dips of quartz veins are relatively steep (>50˚). The dominant veins are those related to shear-zones. Some veins, however, are subparallel or contemporaneous with the regional schistosity.

4.3. Metamorphism and Alteration

The petrographic study shows that Komborodougou rocks have undergone metamorphic and alteration processes. These phenomena have resulted in the disruption of the stability conditions of some of the original minerals and in the

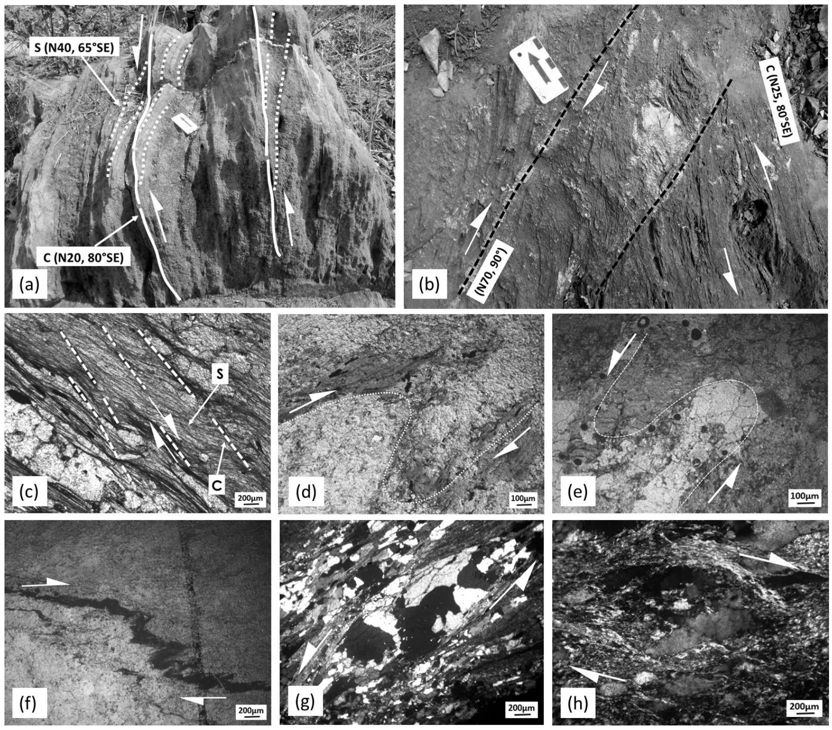

Figure 10. Deformation meso and microstructures. (a) Senestral shear (N20, 65˚SE) displacing schistosity in metaarenites, (b) Senestral shear (N25, 80˚SE) with dextral shear bands (N70, 90˚), (c) C/S fabric indicating dextral shear, (d) Intrafoliar "Z" fold, (e) Intrafoliar "S" fold, (f) Parasitic microfold, (g) Indicator object of senestial shear, and (h) Indicator object of dextral shear.

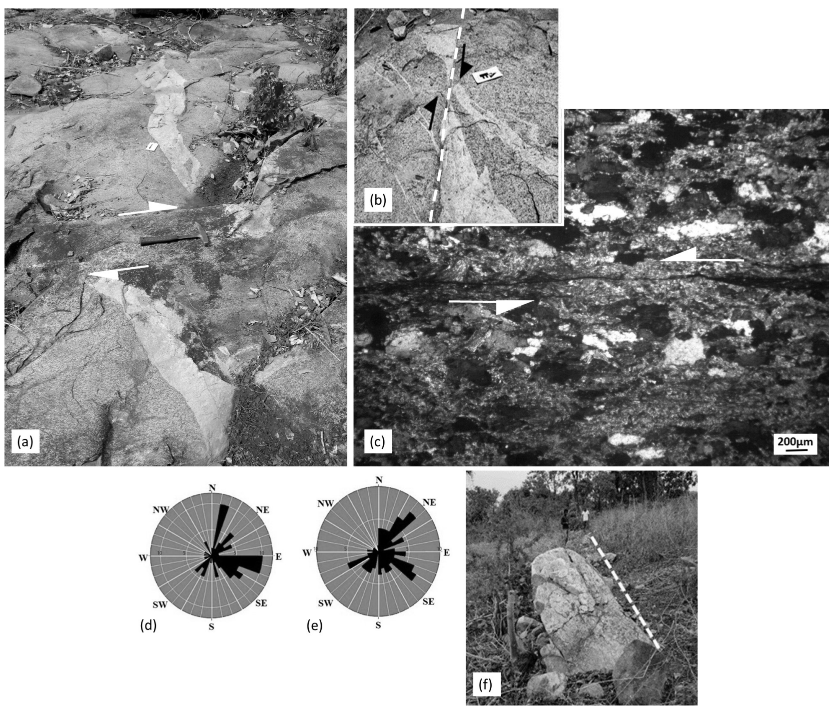

Figure 11. Deformation meso and microstructures. (a) (b) Dextral strike-slip faults displacing microgranite veins, (c) Senestral strike-slip microfault, (d) Metric quartz vein, (e) Directional rosette of fractures and (f) Directional rosette of veins.

circulation of fluids causing mineralogical and structural transformations. The ferromagnesian minerals (pyroxenes, amphiboles and biotites) commonly present in metabasites have almost disappeared and have been transformed into chlorites, carbonates and epidotes. Feldspars however are generally destabilized into carbonates, epidotes and/or sericites. The presence of all these minerals suggests a low grade regional greenschist metamorphism. Moreover, the structural study, having indicated the presence of stretched minerals in the metabasites, micaschists, granodiorites, metasiltites and metaarenites, justifies that there was a structural transformation marked by more or less constricted schistosity planes and lineations.

The alterations that have affected the rocks concern the meteoric and hydrothermal alteration:

- Hydrothermal alteration: it is due to the crossing of the different lithological facies of the area by a huge amount of hydrothermal fluids, especially when these have a considerable permeability in the form of fractures or interconnected pore spaces. This activity consists of a distribution of chemical elements between the fluids and the country rocks. This is materialized by mineralogical, chemical and textural changes in the country rocks. Two types of hydrothermal alteration can be defined basing on the process of setting up: pervasive alteration and vein alteration. Pervasive alteration is indeed very pronounced in the volcano-sedimentary rocks. Sericitization, chloritization, carbonation, silicification, epidotization and sulfidation have been distinguished. Sericitization is more present in metaarenites, métasiltites and metaflyschs, while chloritization, carbonation and epidotization are more developed in metabasites and sometimes in oriented diorites or granodiorites. Silicification and sulfidation are associated with all lithologies. The vein alteration is indeed due to the filling of the various fractures by hydrothermal fluids, thus generating the setting up of a system of quartz veins. These veins, generally associated with shear-zones, are the carriers of gold mineralization.

- Meteoric alteration: this has affected all the formations in the region. However, due to the weaknesses created by the schistosity or foliation, meteoric alteration appears more intense and deeper in the volcano-sediments (except for the sandstones) than in the granitoids; the alteration profile reaches a depth of 20 - 60 m depending on the area.

5. Discussion

The Komborodougou permit is located in the extreme south of Banfora Birimian greenstone belt, close to Korhogo in northern Côte d'Ivoire. This Birimian belt and others (Dabakala, Fêtêkro, Goren, Hounde, etc.), crossed by the famous Greenville-Ferkessedougou-Bobo-Dioulasso (GFBF) Shear-Zone, are prolific targets for mining research. Several gold mineralizations (Agbaou, Angovia, Bonikro, Dougbafla, Hire-Ouatta, Hounde, Yaho, Lafigue, Seguela, Morondo, Bobosso, etc.) have been discovered within. These greenstone belts have similar geological contexts with some slight variations in litho-structural features as revealed by mining exploration and by some authors who have studied the associated gold mineralizations (Papon, 1973; Sinare, 2013; Houssou 2013 and 2017; Gnanzou 2014; Ouattara Z. 2015, 2018a [31] and 2020; Ouattara S. 2021 [32], etc.). Our recent works suggest that the Komborodougou permit contains volcano-sedimentary (metasiltites, metaarenites, metaflyschs and metabasalts) and plutonic (quartz diorite, metadiorite and metagabbro) units, granitoid intrusives (granodiorite and granite) and finally, mafic and felsic dikes (microgabbro and microgranite). However, the metaflyschs found at Komborodougou have been rarely observed elsewhere. Milesi *et al.* (1992) described them in the Dalema supergroup at Loulo in the Lower Birimian or Birimian B1; the Upper Birimian or Birimian B2 being formed essentially of volcanics and volcanosediments. The Birimian B1 at Loulo includes from the base to the top by a large flyschoid formation, followed by a stratum of sandstone and tourmaline conglomerates that hosts the gold mineralization. In contrast to Loulo, the lower Birimian B1 at Komborodougou contains a large detrital formation (metarenites and métasiltites) underlain by a shallow level of metaflyschs; the upper Birimian B2 being mostly volcanic. The volcano-sedimentary roks of Komborodougou are generally metamorphosed in greenschist facies and sometimes amphibolites around granitoid intrusives or in zones of intense deformation; the metasediments being sometimes observed in the form of micaschists. This metamorphic phenomenon is quite identical to those described in the Birimian greenstones by many authors. The volcano-sediments form a NE-SW to NNE-SSW belt due to regional NW-SE to WNW-ESE birimian compression. The distribution of S0 beddings suggests the existence of F1 and F2 antiformal folds whose axial planes are oriented NE-SW to NNE-SSW and NW-SE, respectively. The S1 schistosity, in the metasediments (metaarenites-metasiltites) and metabasalts, with a NE-SW direction and steep dips (>60˚), overprints S0 bedding. However, in the metaflyschs, the schistosity S1 appears to be synsedimentary and shallowly dipping, and thus subparallel to the bedding. These metaflyschs are probably thrusting on the metasediments. Except the volcano-sedimentary rocks, the other formations show clear signs of sometimes intense deformation. The quartz diorite, by its overall sinusoidal shape, shows signs of more or less senestral shear deformation, while the metagabbros are subcircular or elongated outcropping as small hills.

The granodiorites cover the permit from north to south and outcrop in different zones which trend NNE-SSW. They sometimes show signs of intense deformation in some places and outcroping as mylonites. Quartzites (derived from the metamorphism of quartzo-feldspathic veins) are also aligned as small hills in NNE-SSW to NE-SW direction with above all sulphide-filled fractures. The Komborodougou lithological sequences are crossed by shear-zones of variable extensions and orientations. Four major shear-zones have been distinguished and named Komboro Shear-Zones (KSZ): KSZ01 and KSZ02 are oriented N-S to NNE-SSW, KSZ03 and KSZ04 are NW-SE and NNW-SSE respectively. Quartzites, outcropping in the east of the permit, occur along KSZ01, while KSZ02, the most important shear zone, occupies the central part of the permit. Most of the orpaillage sites have been identified in the south along KSZ02, KSZ03 and KSZ04, orpaillage activity being prohibited in the northern part of the permit. Subsequent faults intersect and sometimes displace all the lithologies and structures in senestral or dextral sense. They are generally NW-SE, NNW-SSE and E-W trending. Several families of joints or fractures with variable orientations are associated with the different shear-zones and faults. Filled with quartz and/or carbonates ± sulphides, fractures and joints form an important veins system. These veins are oriented NNE-SSW, NE-SW, E-W, NW-SE, NNE-SSE and rarely N-S. Some veins, already mined or are mining, indicate that they are the hosts of gold mineralizations in Komborodougou area.

Our recent works suggest that the geological history of Komborodougou permit can be summarized in three major deformation phases, a context similar to that distinguished of most of the authors in West African Greenstone Belts:

- D1 Deformation phase: The distribution of S0 bedding in metasediments (metasiltites-metaarenites) reveals a regional D1-folding that appears to form a steeply dipping and NE-SW to NNE-SSW-trending axial plane F1 antiform. However, we suggest the probable presence of an F2 antiform, which affected the metaflyschs and whose axial plane is oriented NW-SE and dips relatively low. These narrow detrital flyschoids were emplaced in a late phase of D1 deformation. They appear less deformed and marked by a rather synsedimentary schistosity subparallel to S0 bedding. A regional axial plane schistosity oriented NE-SW to NNE-SSW was emplaced during regional NW-SE to WNW-ESE birimian compression, followed by a magmatism that is at the origin of the emplacement of granitoid plutons. This D1 phase is also marked by a regional metamorphism of low grade and greenschist facies, which can locally reach amphibolite facies in the vicinity of granitoid plutons.

- D2 Deformation phase: the structuring of the birimian volcano-sedimentary units and the granitoid plutons, is controlled by N-S to NNE-SSW trending main transcurrent D2 shear and zones of intense deformation. We note the presence of two other transcurrent D2 shears, less important than the first one, oriented NW-SE and NNW-SSE respectively. These shear-zones cut through the volcano-sediments and granitoids (granodiorite and quartz diorite), then intersect and displace D1 structures and metamorphic schistosities. However, the determination of the overall direction of these shears remains more or less ambiguous because on a same shear the indicators sometimes show both a dextral and senestral senses. The different shear-zones are characterized by mylonitic corridors hosting the Komborodougou gold mineralizations. In the south of the permit, gold mineralization may be developed in both quartz diorite and metasediments, while in the north, it is more likely to be developed in the granodiorite-metasediment interface.

-D3 Deformation phase: E-W, NNW-SSE and NW-SE faults as well as late joints and fractures intersecting all lithologies and structures D1 and D2 constitute structures D3. Among these structures, we also suggest crenulation schistosities with NW-SE oriented axial planes.

6. Conclusions

Korhogo district, after the important discovery of Tongon gold mine by Rangold Resources, is currently a prolific area for mining companies. A permit has been granted to CAREM Sarl since November, 6th 2019. The permit covering the northern part of Komborodougou is also considered to be an area of scientific interest, where a details litho-structural map and study can contribute to the improvement of geological knowledge of the Birimian and to the orientation of CAREM Sarl's exploration works.

Geological mapping, petrographic studies and structural analyses have resulted in the development of a lithostructural map of Komborodougou permit at a scale of 1:20,000. This map includes existing information as well as new field data. Our works have thus highlighted:

- Petrographically, four lithological units: a volcano-sedimentary unit (including metasiltites, metaarenites, metaflyschs and metabasalts), a plutonic unit (quartz diorite, metadiorite and metagabbro), intrusive unit (granodiorite and granite) and finally, a unit essentially formed of dikes (microgabbro and microgranite).

- Structurally, three phases of deformation D1, D2 and D3: the D1 phase being marked by antiformal folds F1 and F2 with axial planes of respective orientations NNE-SSW to NE-SW and NW-SE; the D2 being transcurrent and at the origin of the setting of Komborodougou shear-zones, KSZ01 and KSZ02 with orientation NNE-SSW, KSZ03 and KSZ04 respectively NW-SE and NNW-SSE; and finally, the D3 phase marked by late faults (with E-W, NNW-SSE and NW-SE orientations) and crenulation schistosity with NW-SE axial planes. N-S to NNE-SSW (N0˚ - 20˚) and NW-SE (N130˚ - 160˚) trending quartz vein systems associated with the shear-zones are the hosts of gold mineralization. These quartz veins have been mined by orpaillage miners for more than two decades.

- Metallogenically, several gold mineralization corridors related to the different shear-zones and associated with mylonites developed in metasediments, quartz diorites or in granodiorite-metasediment interfaces. The existence of these mineralizations has been attested by several orpaillage pits mapped along the shear-zones; the quartz and their eponts containing gold and sulphides (pyrite).

Acknowledgements

This article was possible by the contribution of Adingra M.P.K (for remote sensing), Pria K. K. J-M., Kouman A. and Koffi N. M. A. (for geological field mapping), Allialy M. E. (for petrography) and Loba G. F. C. (for the digitalization of the maps). This work is greatly supported by CAREM Sarl and GoldRidge Resources Pty whose respective Directors Mr. Famie Akattia Félix and Mr. Yao N'kanza, 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.

References

[1] Papon, A. (1973) Geology and Mineralization of Southwestern Côte d'Ivoire. Memory of the BRGM, Paris, n˚80, 284 p.

[2] Milesi, J.P. (1989) West Africa Gold Deposits in Their Lower Proterozoïc Lithostructural Setting. *Chronique Recherche Minière,* **497**, 3-98.

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

[4] Hein, K.A.A., Morel, V., Kagone, O., Kiemde, F. and Mayes, K. (2004) Birimian Lithological Succession and Structural Evolution in the Goren Segment of the Boromo-Goren Greenstone Belt, Burkina Faso. *Journal of African Earth Sciences,* **39**, 1-23. https://doi.org/10.1016/j.jafrearsci.2004.05.003

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

[6] Hein, K.A.A. (2010) Succession of Structural Events in the Goren Greenstone Belt (Burkina Faso): Implications for West African Tectonics. *The Journal of African Earth Sciences,* **56**, 83-94. https://doi.org/10.1016/j.jafrearsci.2009.06.002

[7] Feybesse, J.L., Billa, M., Guerrot, C., Duguey, E., Lescuyer, J.L., Milesi, J.P. and Bouchot, V. (2006) The Paleoproterozoïc 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

[8] Tshibubudze, A., Hein, K.A.A. and Marquis, P. (2009) The Markoye Shear Zone in NE Burkina Faso. *Journal of African Earth Sciences,* **55**, 245-256. https://doi.org/10.1016/j.jafrearsci.2009.04.009

[9] Tshibubudze, A. and Hein, K.A.A. (2013) Structural Setting of Gold Deposits in the Oudalan-Gorouol Volcano-Sedimentary Belt East of the Markoye Shear Zone, West African Craton. *Journal of African Earth Sciences*, **80**, 31-47. https://doi.org/10.1016/j.jafrearsci.2012.11.010

[10] Lompo, M. (2010) Structural Evolution of Paleoproterozoïc Belts (Eburnean Event) in the Man-Leo Shield, West African Craton. 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

[11] 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

[12] Perrouty, S., Aillères, L., Jessell, M.W., Baratoux, L., Bourassa, Y. and Crawford, B. (2012) Revised Eburnean Geodynamic Evolution of the Gold-Rich Southern Ashanti Belt, Ghana, with New Field and Geophysical Evidence of Pre-Tarkwaian Deformations. *Precambrian Research,* **204-205**, 12-39. https://doi.org/10.1016/j.precamres.2012.01.003

[13] Houssou, N.N. (2013) Petrological, Structural, Geochem and Metallogenic Study of the Agbahou Gold Deposit, Divo, Côte d'Ivoire. Thesis Unique, Univ. Felix Hou-

phouet Boigny-UFR STRM, Abidjan, 257 p.

[14] Sinare, M. (2013) Metallogeny of the Yaho Gold Deposit, Houndé Birimian Belt, Burkina Faso. Univ. du Québec à Chicoutimi, Québec, 285 p.

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

[16] Ouattara, Z. (2015) Lithostratigraphic, Structural, Geochem and Metallogenic Characters of Bonikro Gold Deposit, Fettekro Birimian Belt, Centre-South of Côte d'Ivoire. Thesis Unique, Univ. Felix Houphouet Boigny-UFR STRM, Abidjan, 330 p.

[17] Ouattara, Z., Coulibaly, Y. and Lieben, F. (2015) Petrography of Bonikro Gold Deposit, Oume-Fettekro Greenstone Belt, Côte d'Ivoire. *European Scientific Journal*, **11**, 119-132.

[18] Ouattara, Z., Coulibaly, Y. and Boiron, M.C. (2020) Shear-Hosted Gold Mineralization in the Oumé-Fettèkro Greenstone Belt, Côte d'Ivoire: The Bonikro Deposit. Geological Society, London, Special Publications, 502. https://doi.org/10.1144/SP502-2019-103

[19] Serigne, S., Mamadou, G. and Papa, M.N. (2016) New Approach of Structural Setting of Gold Deposits in Birimian Volcanic Belt in West African Craton: The Example of the Sabodala Gold Deposit, SE Senegal. *International Journal of Geosciences*, **7**, 440-458. http://www.scirp.org/journal/ijg https://doi.org/10.4236/ijg.2016.73034

[20] Houssou, N., Allialy, M., Kouadio, F. 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

[21] Ziandjêdé, H.S., Tahar, A., Kouamelan, A.N., Houssou, N.N., Digbeu, W., Kakou Bi, K.F. and Pierrick, G. (2022) New Lithostructural Map of the Doropo Region, Northeast Côte d'Ivoire: Insight from Structural and Aeromagnetic Data. *Journal of African Earth Sciences,* **196**, Article ID: 104680. https://www.elsevier.com/locate/jafrearsci https://doi.org/10.1016/j.jafrearsci.2022.104680

[22] Camil, J. (1984) Pétrographie, chronologie des ensembles archéens et formations associées de la region de Man (Côte d'Ivoire) Implications pour l'histoire géologique du craton ouestafricain. Thèse de Doctorat ès Sci. Univ. D'Abidjan, Côte d'Ivoire, Abidjan, 306 p.

[23] Kouamelan, A.N., Delor, C. and Peucat, J.J. (1997) Geochronological Evidence for Reworking of Archaean Terrains during the Early Proterozoic (2.1 Ga) in the Western Côte d'Ivoire (Man Rise-West African Craton). *Precambrian Research*, **86**, 177-199. https://doi.org/10.1016/S0301-9268(97)00043-0

[24] Kitson, A.E. (1928) Provisional Geological Map of the Gold Coast and Western Togoland, with Brief Descriptive Notes Thereon. Gold Coast Geological Survey, Accra, Bulletin No. 2, 13 p.

[25] Junner, N.R. (1940) Geology of the Gold Coast and Western Togoland. Gold Coast Geological Survey, Accra, Bulletin No. 11, 40 p.

[26] Bessoles, B. (1977) Geology of Africa. The West African Craton. Memory in B.R.G.M., No. 88, 402 p.

[27] Doumbia, S. (1997) Geochemistry, Geochronology and Structural Geology of the Birimian Formations of the Katiola-Marabadiassa Region (North-Central Côte

d'Ivoire). Thesis Doc., Univ. Orleans, Orléans, 214 p.

[28] Gasquet, D., Barbey, P., Adou, M. and Paquette, J.L. (2003) Structure, Sr-Nd Isotope Geochemistry and Zircon U-Pb Geochronology of the Granitoids of the Dabakala Area (Côte d'Ivoire): Evidence for a 2.3 Ga Crustal Growth Event in the Paleoproterozoic of West Africa? *Precambrian Research,* **127**, 329-354. https://doi.org/10.1016/S0301-9268(03)00209-2

[29] Delor, C. and Daouda, Y.B. (1995) Geological Mapping of the Korhogo Sheet at 1/200.000. Map Published by the Direction des Mines et de la Géologie with the Technical Support of BRGM, 1995.

[30] Adingra, M.P.K. (2020) Petro-Structural and Geochemical Characterization of the Birimian Formations of the South-Eastern Part of the Comoé Basin (North of Alépé, South-East of Côte d'Ivoire): Implication on the Geodynamic Evolution. Thesis Unique, Univ. Felix Houphouet Boigny-UFR STRM, Abidjan, 271 p.

[31] Ouattara, Z., Coulibaly, Y. and Boiron, M.C. (2018) Lithostratigraphy of the Bonikro Gold Deposit: Contribution to the Setting of the Birimian Units in the Fettèkro Greenstone Belt, Côte d'Ivoire. *RAMRES*, **6**, 6-14.

[32] Ouattara, A.S., Coulibaly, I., Kouamé, L.N., Coulibaly, Y. and Goné, D.L. (2021) Aero-Geophysical Mapping Applied to the South of the Fêtêkro Greenstone Belt, Centre-West Côte d'Ivoire: Case of Oumé Mining Permit. *Afrique Science*, **19**, 149-166. https://doi.org/10.51202/0043-7131-2021-4-166-1