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Mapping, Petrostructural Analysis and Metallogeny of the Natiemboro Geological Formations in the Tortiya Area (North-Central Côte d'Ivoire)

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Abstract

This study, which was conducted in the Natiemboro area of the Korhogo Department in north-central Côte d'Ivoire, aimed to improve our understanding of the region's petrography, structure and metallogenesis. To this end, a geological mapping campaign was carried out in combination with rock and soil sampling using satellite imagery. A total of 25 polished sections were prepared for petrographic, microstructural and metallogenic analysis. The mapping reveals four units: a metasedimentary unit consisting of sericite schists and quartzites ; a metaplutonic unit consisting of biotite metagranite, gneiss, and metamicrogranodiorite ; an intrusive unit consisting of fine- and coarse-grained granite ; and a unit consisting primarily of pegmatites. These units are primarily affected by green schist-facies metamorphism and also exhibit hydrothermal (pervasive and vein-type) and meteoric alteration. Pervasive hydrothermal alteration is exemplified by carbonation, sericitisation, chloritisation, epidotisation, silicification and sulphidation, while vein-type hydrothermal alteration is characterised by veins and dykes of quartz, carbonates and quartz-tourmaline. The metasedimentary complex exhibits S1 schistosity, which is oriented NNE-SSW or NE-SW with gentle dips of 40–46°. It is thought that regional NW-SE compression caused this schistosity. The metasedimentary and metaplutonic complexes are traversed by two main left-lateral shear zones oriented N-S and NE-SW, respectively. These shear zones are intersected by left- and right-lateral detachment faults and fractures oriented NW-SW, N-S to NNE-SSW and E-W. The NNE-SSW and N-S vein systems are associated with the shear zones and host gold mineralisation. These veins are mined by illegal gold panners.

Keywords: Geological mapping; Structural; Shear zone; Gold mineralization; Natiemboro; Côte d'Ivoire.

1. Introduction

The mining sector in West Africa is booming. All minerals are in high demand, from gold to diamonds, manganese to nickel, bauxite to coltan, not to mention rare earth elements, and so on. Of all these minerals, gold appears to take the lead, given the large number of mining companies. Gold production in West Africa comes mainly from corridors within the Birimian greenstone belts [1, 2, 3], which are associated with shear zones [4, 5, 6, 7, 8, 9, 10, 11, 12]. Shear zones appear to be major factors in the selection of potential areas. The mapping agencies of most of the countries surveyed do produce geological maps, but they provide very few at scales of 1:100,000, 1:50,000, and 1:25,000. The lack of detailed geological maps makes it difficult for mining operators to select productive areas, interpret surface geochemical anomalies and identify in-situ gold mineralisation. Consequently, geological mapping campaigns combined with a petrostructural study have been initiated in the northern part of the Tortiya zone, which is part of the Ferké-Tortiya

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Birimian Trough. This work is being carried out on SODEMI's PR500 permit with two objectives : to produce a detailed 1 :50,000 scale map and to define the metallotectonic features controlling the gold mineralisation at Natiemboro.

2. Geological Setting of the West African Craton

The Man-Léo Ridge (Figure 1), one of the major features of the West African Craton, is divided into two distinct domains by the N-S-trending Sassandra strike-slip fault zone. It is relatively extensive and complex in terms of its lithostructural characteristics. These two domains are the Archean domain and the Paleoproterozoic domain to the east, known as the Baoulé-Mossi domain [13]. The Archean domain consists of two main complexes : a basal complex composed of migmatites and granulitic gneisses overlain unconformably by a sequence of deformed and metamorphosed supracrustal rocks [14, 15]. The basal complex is cut through by various plutonic rocks, including granite, granodiorite, charnockite, as well as basic and ultrabasic rocks [16]. The supracrustal rocks reached the medium- to high-pressure granulite facies during the Liberian orogeny (~2700 Ma) [17]. The Paleoproterozoic or Baoulé-Mossi domain consists of belts of metavolcanic rocks (metarhyolite, metadacite, metandesite, metabasalts, etc.) and metasedimentary rocks (metapelite, metasandstone, metaconglomerate, quartzite, etc.) juxtaposed with granitoid batholiths [18, 19, 20, 21, 5]. The emplacement and subsequent reworking of all these lithologies occurred between 2.25 and 2.06 Ga. The structural setting of the Baoulé-Mossi domain is characterized by subvertical penetrating foliation, associated with isoclinal folds and locally affected by open folds and regional-scale shear zones. This structural setting is interpreted by many authors as the result of horizontal shortening leading to crustal thickening, followed by trans-tectonic processes. The present study area (Figure 2) is located within the Proterozoic domain in northern Côte d'Ivoire, specifically northwest of the NNE-SSW-trending Ferkessédougou Trough. Previous studies [22, 23] have identified several geological formations, such as granitoids (granites with non-oriented biotite and biotite- and hornblende-bearing metagranodiorites with a general NNE-SSW trend) and dioritoids (gabbro). This research also identified schists, metagabbros, metadolerites, amphibolo-pyroxenites, and metagranodiorites containing biotite and/or hornblende. The schists form a diverse belt trending N22° across the concession and consist of alternating grauwacke schists and arkose schists. The latter are interspersed with lenses of conglomeratic schists. This entire sequence is affected by epizonal-type metamorphism [22].

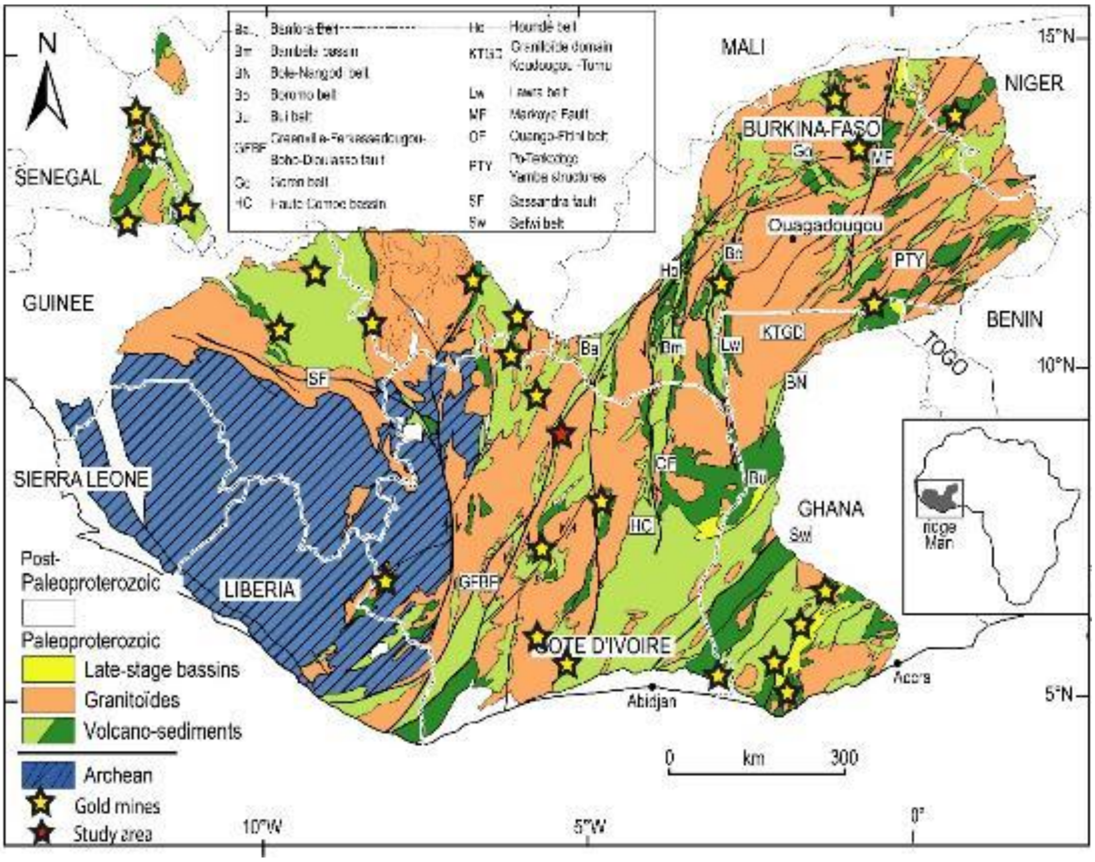


Figure 1 Simplified geological map of the Man-Léo Ridge showing gold mineralization and the location of the study area (Adapted [3]).

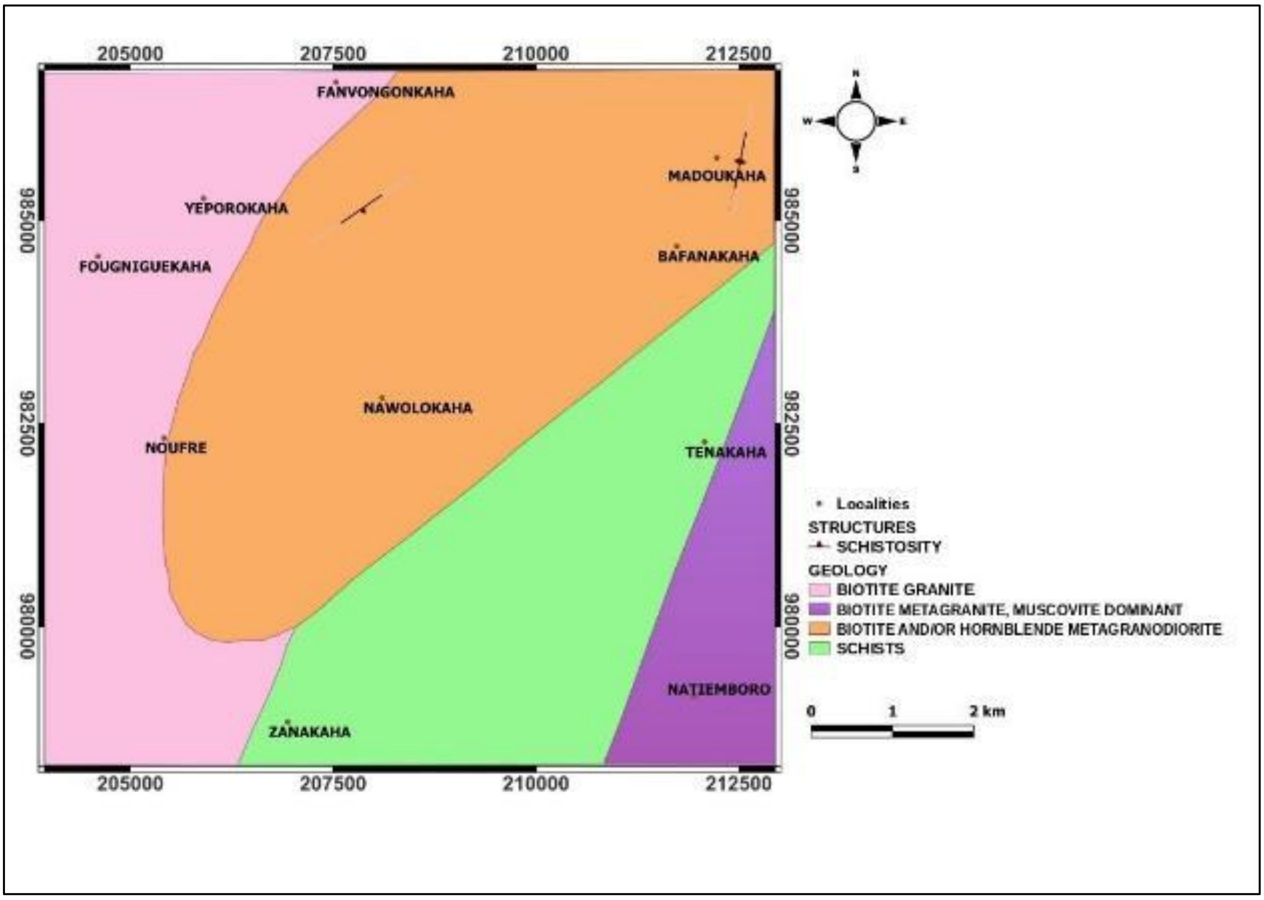


Figure 2 1:200,000 geological map of the study area (excerpt from the 1:200,000 geological map of the Katiola square degree, [24])

3. Methodology

Geological mapping involves a variety of activities in the field and laboratory, including petrography and structural analysis. During fieldwork, rocks are described and sampled in order to prepare thin sections for microscopic examination and polished sections for metallogenic studies. At an outcrop, a map is created by plotting the various lithologies and structures on graph paper bearing the coordinates of the mining concession, following macroscopic description and structural measurements. Several rock outcrops were surveyed, described and sampled to this end. A total of 25 rocks samples were collected, with at least one thin section or polished section prepared per sample for petrological, metallogenic and microstructural analysis. These 25 thin and polished sections were prepared at the GRME (Geology, Minerals and Energy Resources) laboratory at Félix Houphouët-Boigny University (UFHB).

4. Results

4.1. Lithological Units

Geological mapping and petrographic studies have identified two lithological units, the metamorphic unit and the plutonic unit, which are unevenly distributed across the geological map of Natiemboro.

4.1.1. Metasedimentary units

Quartzite has been identified in the Zanakaha area, which is located at the southernmost tip of the study area. It is a friable rock with a well-defined schistose structure. It is grey in colour and composed of quartz (Figure 3A). Under a microscope, it is mainly quartz, which varies in size and occasionally exhibits recrystallisation into subgrains (Figures 3B and C). The quartz grains are arranged in bands, indicating deformation. We also observed biotite microlites that follow a preferred orientation within the rock. The biotite is sometimes altered to epidote, which exhibits blue-violet hues.

Sericite schists were collected from a well at a depth of around 10 metres in the Bafanakaha and Madoukaha regions. This deformed brown rock has a very tight schistose structure (see Figures 3D and E). It often has a black colour reminiscent of black shales. The rock has undergone episodes of hydrothermal alteration, including silicification, as evidenced by quartz veinlets, and in some cases, recrystallisation (Figure 3F). Furthermore, microscopic observation reveals an abundance of sericite, followed by quartz in the form of small, closely packed, xenomorphic crystals forming veinlets. This observation confirms the very tight schistose structure, which is likely to be flow schistosity. The presence of these two elements indicates a lepidogranoblastic texture. Recrystallisation of subgrain quartz (Figure 3F) and numerous sericite crystals present as very fine grains with a fibrous appearance were observed. Finally, opaque minerals develop along the schistosity planes.

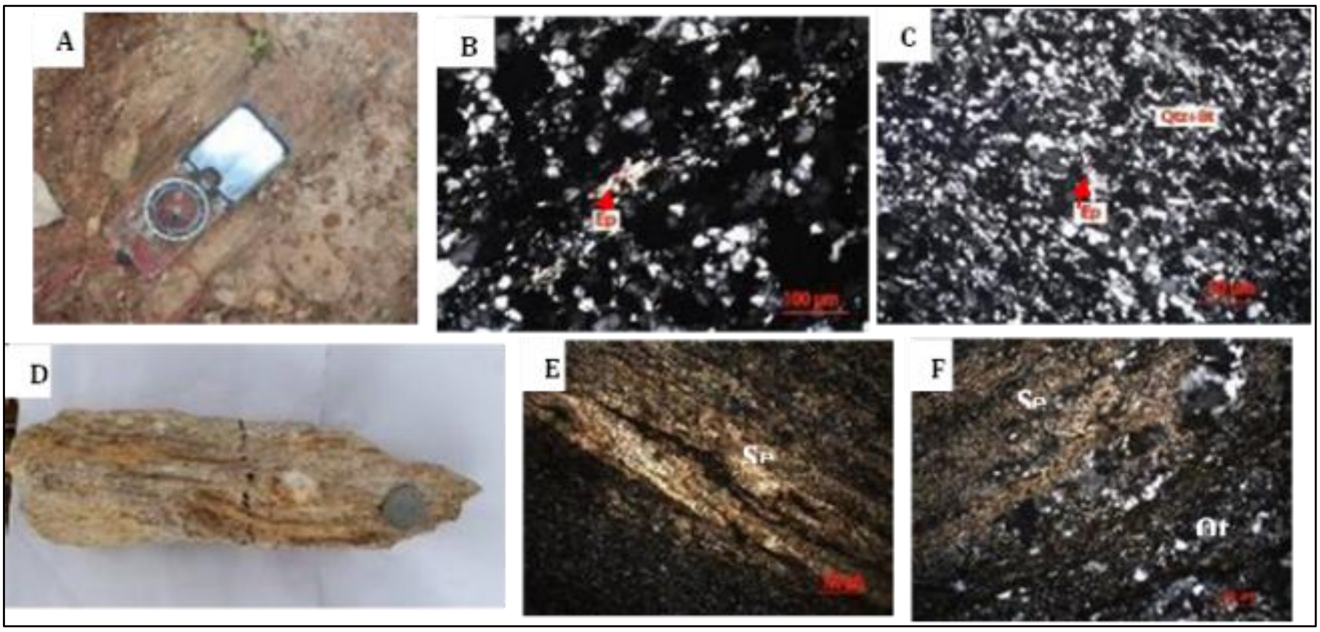


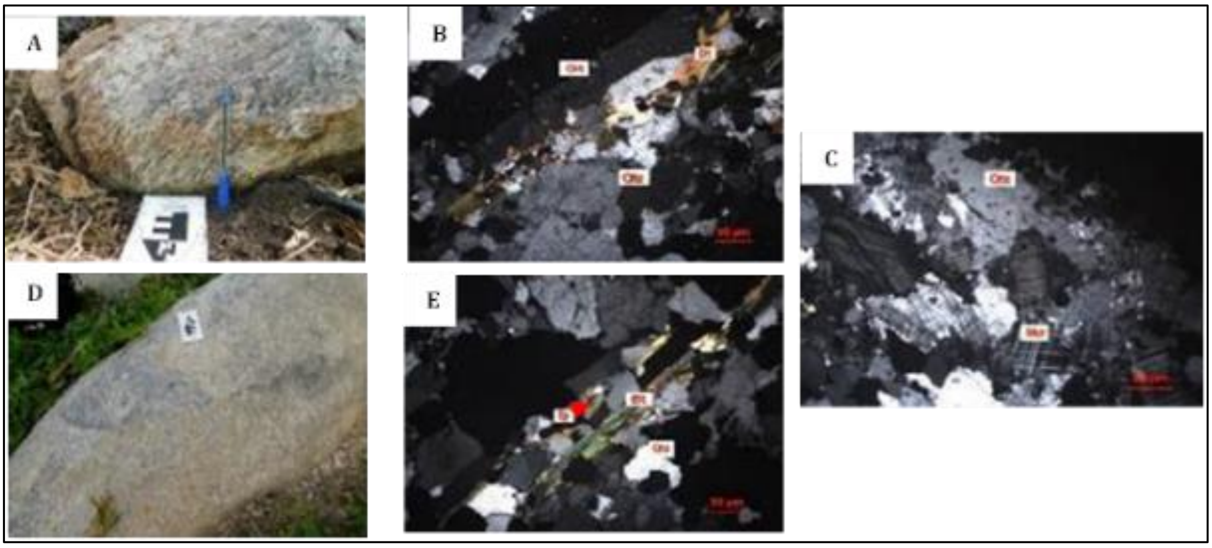
Figure 3 Macroscopic and microscopic appearance of metasediments

A: Macroscopic appearance of quartzite ; B and C: Schistosity in quartzite ; D: Macroscopic appearance of sericite schist ; E: Flow schistosity in sericite schist ; F: Hydrothermal features in sericite schist (sausage-shaped quartz veins) ; Qtz: quartz; Bt: biotite; Ser: sericite; Ep: epidote.

4.1.2. Metaplutonite units

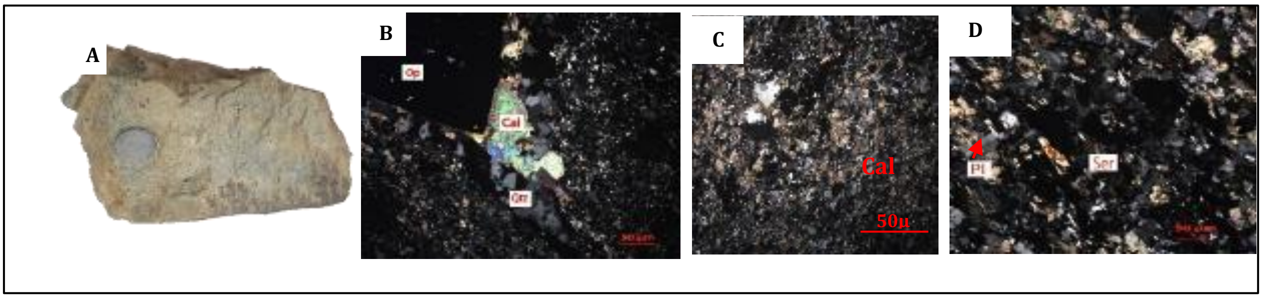
Biotite metagranite occurs in the form of blocks and domes at Bafanakaha. These are cut by fractures of various orientations, which are sometimes filled with quartz veins. The rock has a massive appearance and a medium- to coarse-grained, granoblastic texture, and it reacts to a magnetic stylus. It consists primarily of light-coloured minerals, including quartz and feldspar, as well as dark-coloured minerals such as biotite, which are present in smaller proportions (see Figures 4A and 4B). Due to significant weathering, certain minerals (such as plagioclase and biotite) have been destabilised and transformed into chlorite, epidote and myrmekite.

Metamicrogranodiorite has been found in placer gold mining waste dumps in the Bafanakaha area, which are approximately 10 m deep. It is a grey, massive rock whose mineral arrangement reveals a granoblastic texture (Figure 5A). This rock has undergone episodes of pervasive and vein-type alteration, including carbonation, which is marked by the presence of calcite veinlets; chloritization, which gives the rock a greenish appearance; and sulfidation, which is marked by the presence of pyrite porphyries. Under the microscope, it consists primarily of calcite, plagioclase and quartz, with minor amounts of chlorite and opaque minerals.



A and D: Macroscopic appearance; B and E: Biotite stretching ; C: Twin in microcline. ; Mcr: microcline ; Qtz: quartz; Bt: biotite; Ort: orthoclase; Ep: epidote

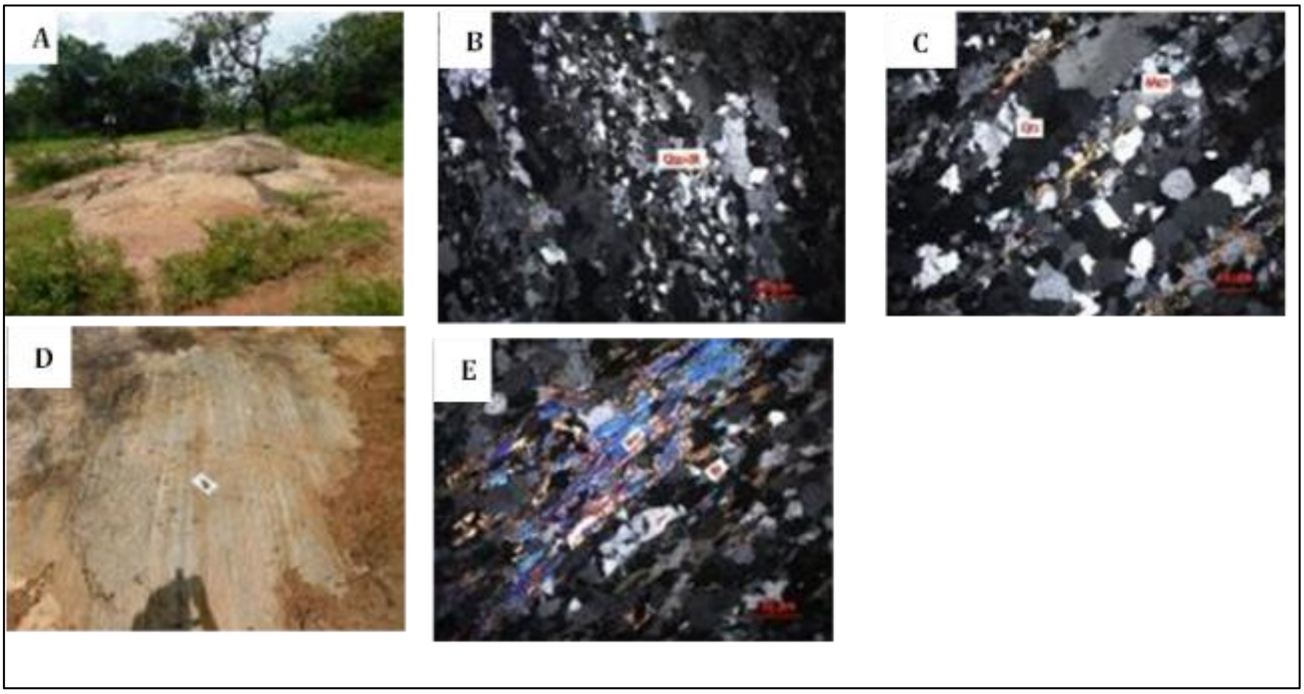
Figure 4 Macroscopic and microscopic appearance of biotite metagranite



A: Macroscopique appearance ; B: quartz-calcite-sulfide vein; C: carbonation in the metamicrogranodiorite; D: sericitis in the metamicrogranodiorite. ; Qtz: quartz ; Op: opaque ; Pl: plagioclase ; Cal: calcite ; Ser: sericite

Figure 5 Macroscopic and microscopic appearance of the metamicrogranodiorite

Orthogneiss can be found in the Natiemboro area. At the outcrop, it occurs as a large slab with a predominantly planar texture. This texture defines a metamorphic unit known as a paleosome, which consists of distinct foliated zones. This is the gneissic zone, where the characteristics of gneiss persist (see Figures 6A and 6D). This zone is characterised by alternating layers of lighter quartz and feldspar and darker layers rich in biotite, which are sometimes altered to epidote. Microscopic examination of the orthogneiss reveals a paragenesis consisting of quartz, biotite, muscovite, plagioclase, microcline and epidote. The rock exhibits a granolepidoblastic texture with significant quartz recrystallisation in the form of polygonal bands.



B: Recrystallization of quartz ; A, C, D, and E: Dark and light bands in the gneiss. ; Mcr: microcline ; Qtz: quartz ; Bt: biotite ; Pl: plagioclase ; Mus: muscovite ; Ep: epidote

Figure 6 Macroscopic and microscopic appearance of orthogneiss

4.1.3. Plutonic units

Intrusive granitoids primarily consist of granite, which is classified as either fine- or coarse-grained based on grain size. In the Natiemboro area, fine-grained granites outcrop in a dome-shaped formation and exhibit a fine-grained texture. Microscopic analysis reveals a dominant grain size range of between 50 and 200 µm. This leucocratic rock contains varying proportions of quartz, feldspar, microcline, orthoclase and muscovite. These minerals are associated with biotite, the most abundant ferromagnesian mineral (see Figure 7B). Numerous microfractures within the quartz and plagioclase minerals indicate submagmatic deformation.

The coarse-grained granite in the Natiemboro area exhibits preferential mineral orientation and visible alteration, such as chloritisation, which manifests as green colouring. Minerals that can be seen with the naked eye include quartz, feldspar and biotite, the latter of which sometimes transforms into epidote. Microscopic examination reveals some phenocrysts among minerals of uniform size, giving the rock a porphyritic texture. These large plagioclase crystals range in size from 400 µm to 800 µm (see Figures 7F and G).

The dykes are primarily composed of leucocratic pegmatite with a pinkish hue. They cut across almost all of the geological formations on the eastern side of the study area (see Figures 7H and I). This rock typically outcrops within the gneisses. At Natiemboro, we have identified two generations of pegmatite based on their respective orientations. The very coarse texture of the pegmatite enables the rock's mineralogy to be determined. Thus, we observed large quartz crystals and centimetre-sized patches of plagioclase and biotite flakes, some of which had been altered to chlorite. Note the presence of garnet, which gives the rock a reddish-brown mottled appearance.

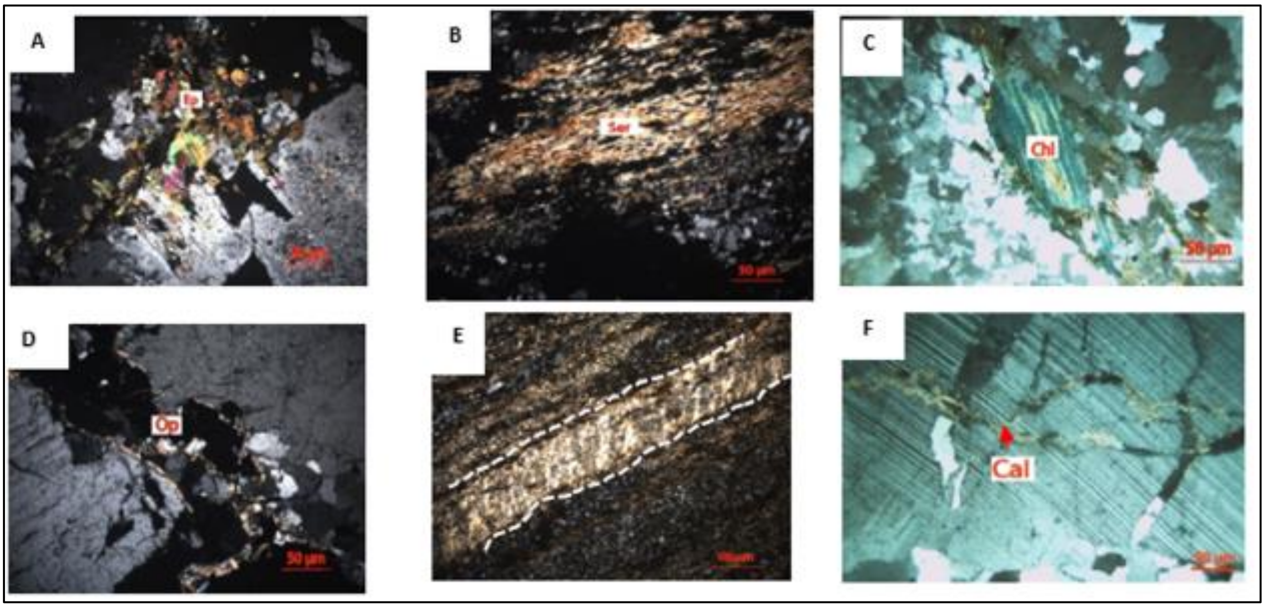
A: Macroscopic appearance of fine-grained granite ;B, C and D: Microscopic appearance of fine-grained granite. ; E: Coarse-grained granite at the outcrop ; F and G: Microscopic appearance of coarse-grained granite. ; H and I: Macroscopic appearance of the dyke unit. ; Qtz : quartz ; Bt : biotite ; Pl : plagioclase ; Mus : muscovite ; Ep : epidote ; Ort : Orthose

Figure 7 Macroscopic and microscopic appearance of the intrusive and dyke units.

4.2. Alterations

Macroscopic petrography reveals that the rocks in the Natiemboro area have undergone mineralogical and textural changes due to hydrothermal activity. This is due to the rocks' considerable permeability, which takes the form of interconnected fractures or pore spaces. Two types of alteration can be identified: supergene and hydrothermal. As Natiemboro has a tropical, sub-Saharan climate, its outcrop rocks have undergone extensive supergene weathering. The resulting regolith generally consists of reddish to dark brown lateritic gravel composed of hematite and quartz in the upper part, followed by a brown-ochre clayey transition zone and then a violet to greenish saprolitic horizon containing a small proportion of fragments. Beneath this sequence lies the saprock: a greenish, semi-consolidated layer containing a high proportion of granodiorite and gneiss fragments. The last three horizons are intersected by quartz veins containing gold mineralization. Depending on the mechanism by which hydrothermal alteration occurs, two types of alteration are defined: pervasive and vein-type.

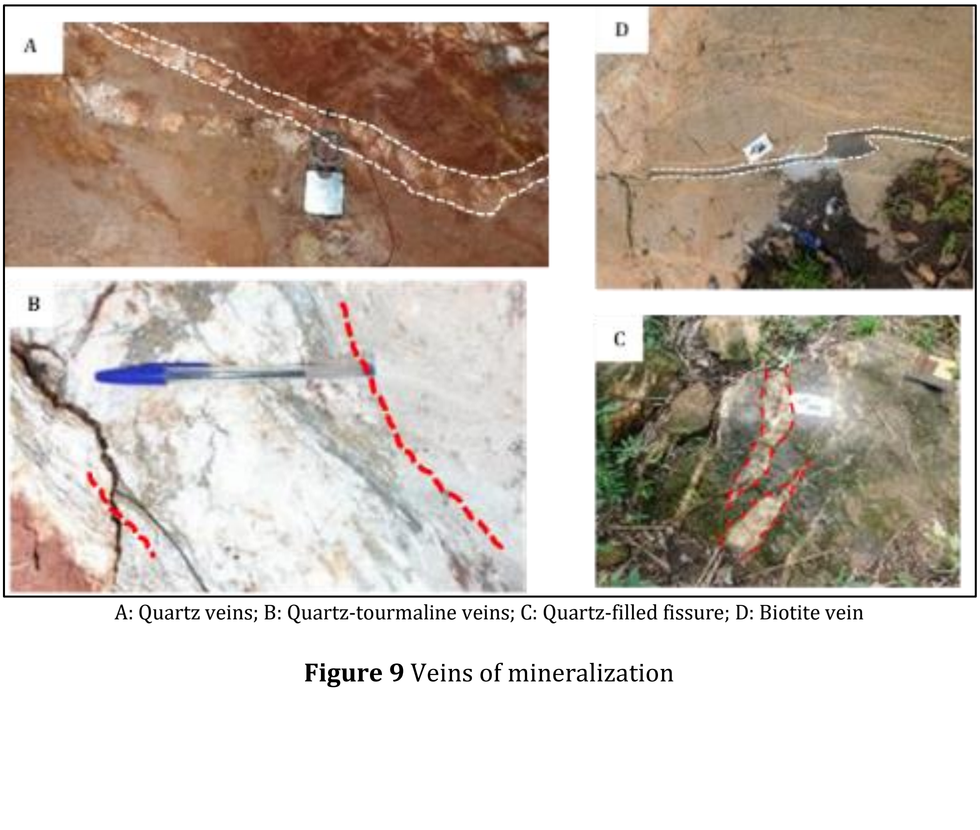
Pervasive alteration is characterised by silicification, carbonation, chloritisation, epidotisation, sericitisation and sulphidation (see Figure 8). The most commonly observed type of alteration is silicification, which involves the impregnation of rocks such as sericite schist, gneiss and biotite metagranite by the late-stage introduction of silica in the form of fine quartz crystals (Figure 8E). Carbonation, on the other hand, involves carbonate impregnation of the same rocks and replacement of plagioclase by calcite (Figure 9F). Calcite is also present in the pegmatite. Epidotization involves the destabilisation of feldspar and biotite crystals, resulting in the formation of epidote (Figure 8A). Chloritisation, on the other hand, is characterised by the transformation of biotite and amphibole into chlorite (Figure 8C). Chlorite is a ubiquitous mineral in the Natiemboro area's rocks. Sericitization is marked by the replacement of feldspar crystals with sericite (Figure 8B). Sulphidation, which is the most significant alteration process in highly deformed zones, corresponds to the formation of sulfides and accompanies gold mineralization in the study area (Figure 8D).



A: Epidotization; B: Sericitization; C: Chloritization; D: Sulphidation; E: Quartz veinlet; F: Calcite veinlet. Op: Opaque; Ep: Epidote; Chl: Chlorite; Cal: Calcite

Figure 8 Pervasive alterations observed under a microscope

Veining refers to the formation of veins and veinlets of various thicknesses, which are composed of quartz, calcite and biotite. Occasionally, they also contain quartz-tourmaline or quartz-calcite. This results from silicification and carbonation processes in the rocks of the study area (Figure 9). Two generations of quartz veins and veinlets are present in the Natiemboro area. One generation, termed 'shear zone veins', follows the direction of the general foliation of the geological formations. These veins are rich in sulfides and contain visible gold within the quartz and the gangue in places. The other vein is nearly perpendicular to the foliation, is generally younger than the first vein, and is less rich in sulphides. Calcite veinlets, whether associated with quartz or not, generally cut through the gneiss and biotite-bearing metagranite.



A: Quartz veins; B: Quartz-tourmaline veins; C: Quartz-filled fissure; D: Biotite vein

Figure 9 Veins of mineralization

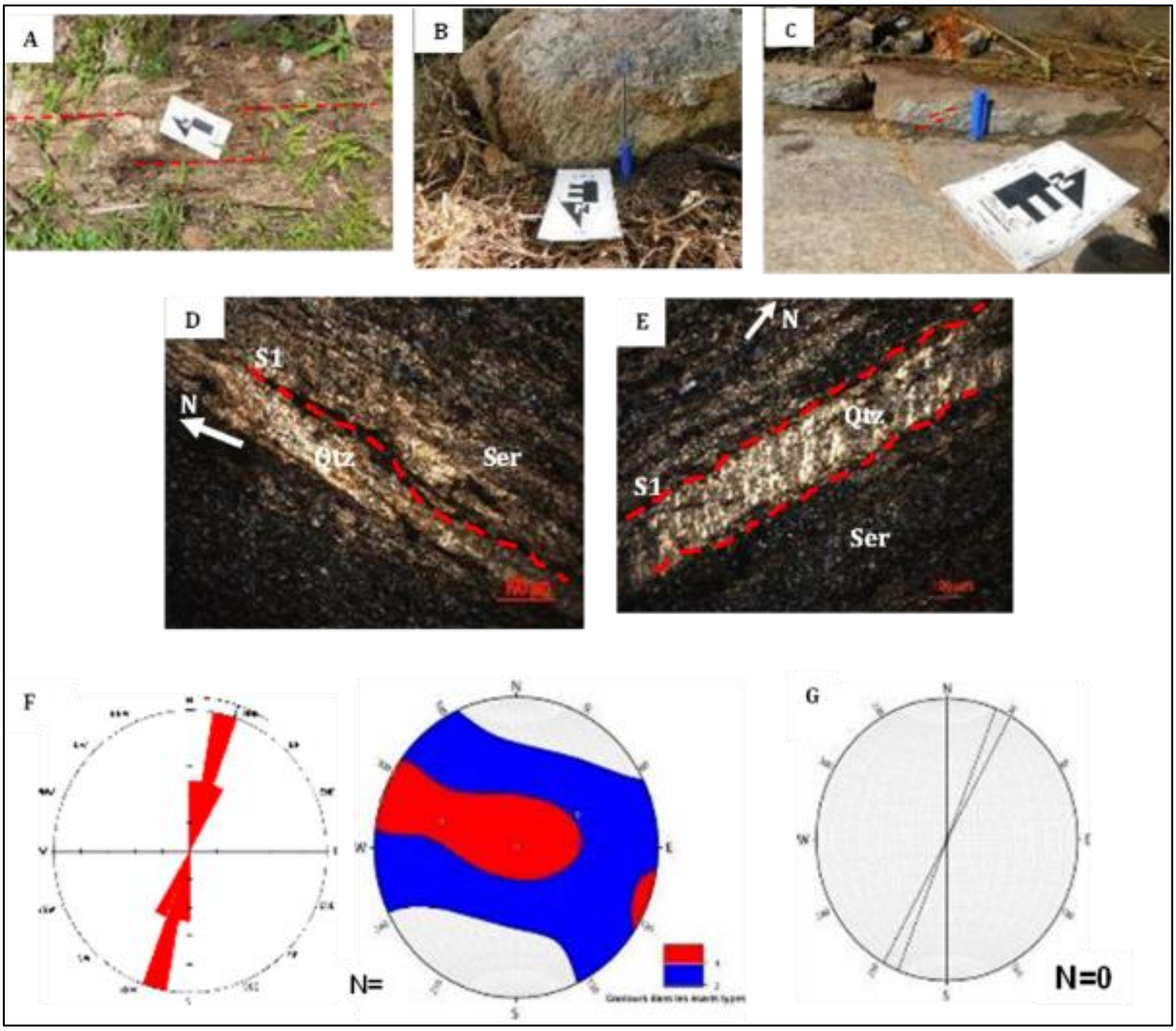
4.3. Structures

4.3.1. Schistosity and Lineation

Schistosity can be observed at outcrops and in thin sections. It has been observed in the Bafanakaha, Madoukaha and Zanakaha areas. In the Zanakaha and Madoukaha areas, schistosity is visible in schistose formations with strike directions of N22° and N52°–60° SE, respectively. In the Bafanakaha area, schistosity is visible in schistose formations with strike directions of N10° and N18°, with dips ranging from 40° to 46° towards the SE. Schistosity is also visible in biotite metagranite and is associated with mineral lineation trending N22°.

It is visible under a microscope in sericite schists. However, it is not clearly visible in biotite metagranite. To better understand these measurements, a directional rose diagram of the various schistosity measurements was created. The predominant schistosity direction in the study area is NNE-SSW, also known as the Birimian direction.

Mineral lineations are common in the formations of the study area, particularly in the biotite metagranite. The ferromagnesian minerals (biotite) have primarily been stretched and reoriented in preferential directions. In the Natiemboro sector, this lineation dips 20° towards the SW, with its bearing plane oriented N 22° and subvertical (Figure 10B). In the Bafanakaha sector, the preferred orientation of these minerals (light and dark minerals) indicates stretching lineation, specifically S/L tectonite. Measurement of these orientations revealed a direction of N 22°.



S1: schistosity; Ser: sericite; Qtz: quartz

Figure 10 Meso- and microstructural deformation; A: Schistosity N 30° in metasediments; B: Tectonic S/L in biotite metagranite; C: Mineral lineation; D and E: Flow schistosity N 22° in sericite schist; F: Directional rosette and stereogram of schistosities; G: Stereogram of lineations.

4.3.2. Foliations

This is one of the major structures encountered in the gneiss of the Natiemboro area. These foliations exhibit two distinct characteristics in terms of their configurations, particularly with regard to strike and dip:

- Foliation (S1), oriented N22°; N30°; N40°; N46°, with a dip of 60° toward the NW. It is characterized by alternating dark and light bands (Figures 11A and B). Specific structures are also observed within this foliation, notably symmetric and asymmetric sills, as well as associated dextral and sinistral intrafoliar folds. Taken together, these structures indicate a second NW-SE flattening, accompanied by shearing parallel to the foliation.
- The foliation (S2) is oriented N70°; N84°; N90°. It is characterized by alternating dark and light bands, which are often thin pegmatite veins that are sometimes sausage-shaped (Figure 11C). This foliation results from a N-S to NNW-SSE-oriented flattening.

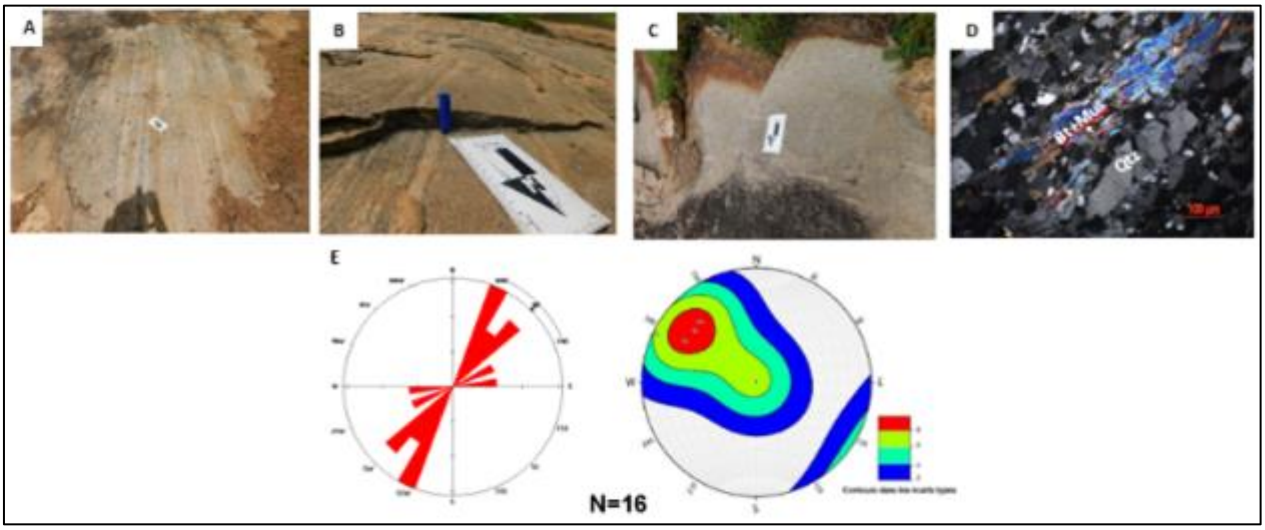


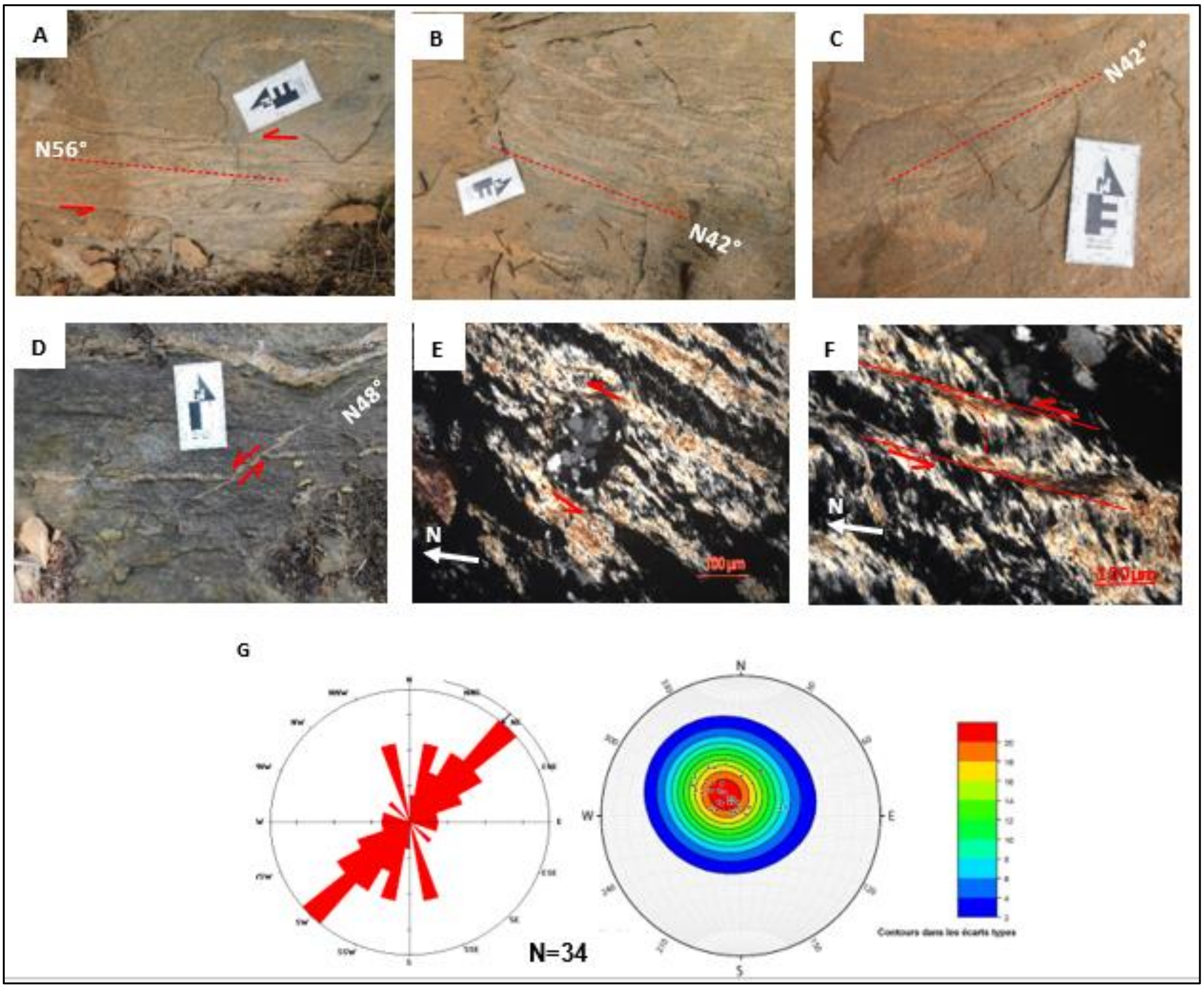
Figure 11 Meso- and microstructural deformation; A: Foliation N 46°; B: Foliation N 40°–60° NW; C: Foliation N 90°; D: Foliation marked by a dark band and a light band; E: Directional rosette and stereogram of the foliations.

4.3.3. Shear zone (SZ) and folds

The Natiemboro area is crossed by several shear zones and a number of left- and right-lateral detachment faults. The shear zones exhibit a ductile-brittle character in the metasediments and are predominantly brittle in the granitoids. Two shear zones have been identified.

SZ 1, located in the Bafanakaha sector, affects schist and biotite metagranite, exhibiting a generally north-south oriented left-lateral shear zone. A schistosity oriented N 10° is associated with this shear zone, resulting in C/S fabric patterns. Left-lateral N-S movement is also evidenced by sigma figures, as shown by sheared quartz in the sericite schists (Figures 12E and F). This shear zone lies at the interface between the schists and the granodiorite.

The SZ 2 was observed in the Natiemboro area. Its characteristics include isolated hinge folds (N42°), which are the result of transposition; ptygmatic folds (N45°); asymmetric senestre folds (N56°); S-type intrafoliar folds (in foliations ranging from N22° to N46°); and anisopaque folds. NE-trending senestre-component detachments formed by shear zones were also observed. This is further evidenced by shear-band schistosity, or a C/S structure, within the gneissic slab. This structure comprises an 'S' schistosity plane trending N45° and a 'C' shear plane trending N62° and being dextral. The presence of these C/S planes along the foliation and vein directions highlights the existence of an NE-trending shear corridor in the Natiemboro area (Figure 12A–D).



A: Left-lateral asymmetric fold; B: Transposition manifested by isolated hinge folds; C: Anisopaque fold; D: Left-lateral detachment; E: Left-lateral sigma figure; F: Left-lateral C/S fabric; G: Directional rosette and stereogram of the axial planes of the folds.

Figure 12 Mesostructural and microstructural deformations

4.3.4. Fractures, veins and cracks

Brittle deformation is manifested by fractures and veins. These affect all lithologies but are more developed in granitoids (Figure 13A–F). The fractures are primarily oriented NNW–SSE (N162° to N174°), followed by WNW–ESE and NNE–SSW directions. These fractures are sometimes filled to form veins. The veins include quartz veins, sometimes quartz±calcite and quartz±tormaline, as well as pegmatite and aplite veins (N-S to ENE-WSW). Quartz veins are generally associated with shear zones and exhibit a smoky, translucent, and saccharoid appearance in saprolites. Quartz veins follow the main N-S and NNE (N20–30°) directions, followed by the ENE–WSW (N60–80°) direction. As for tension cracks, they have been observed in the gneiss with directions of N90° and N74°.

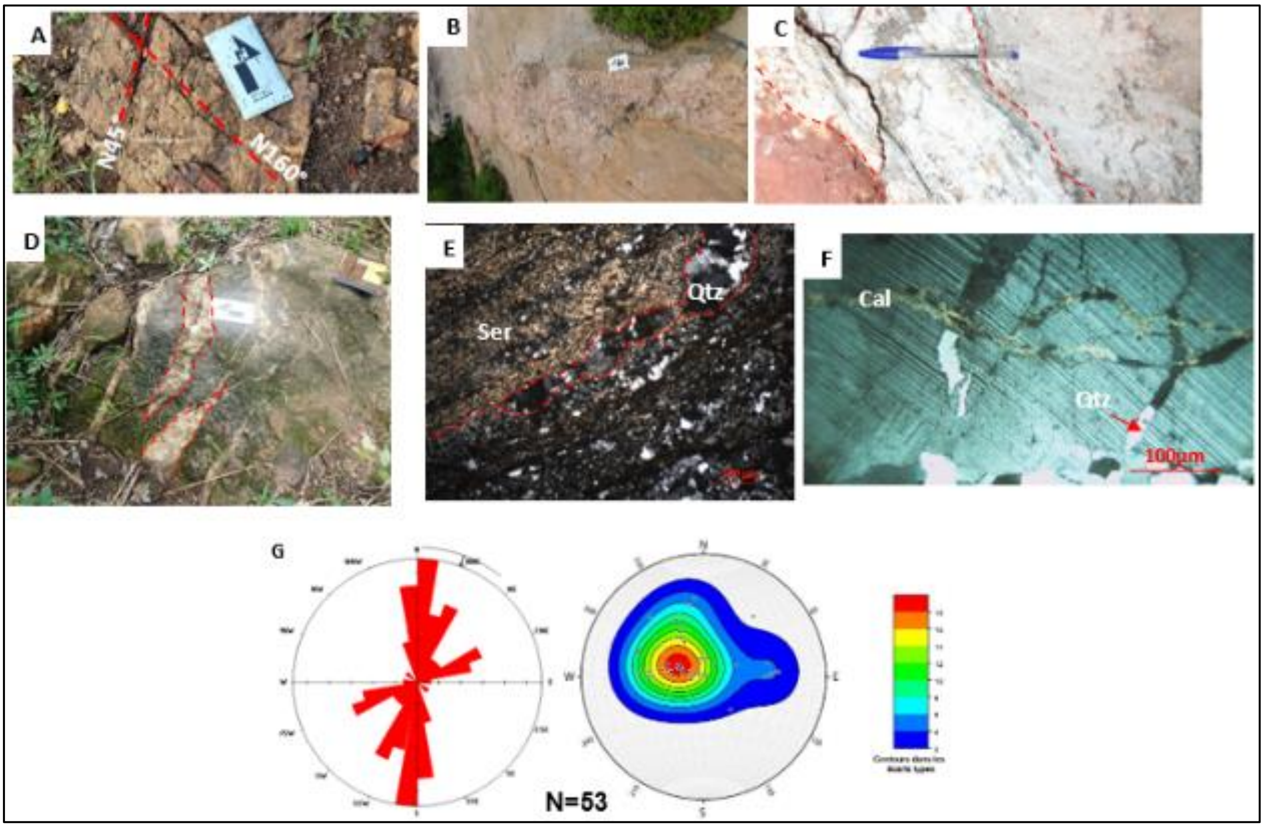


Figure 13 Meso- and microscopic fractures, veins, and fissures; A: Fracture network; B: N-S-trending pegmatite vein; C: Quartz-tourmaline vein; D: Tensile fissure at 80° to the north; E: Sausage-shaped quartz vein in sericite schist; F: Calcite and quartz veinlets in the pegmatite; G: Directional rosette and stereogram of the veins and dykes.

4.4. Metamorphism

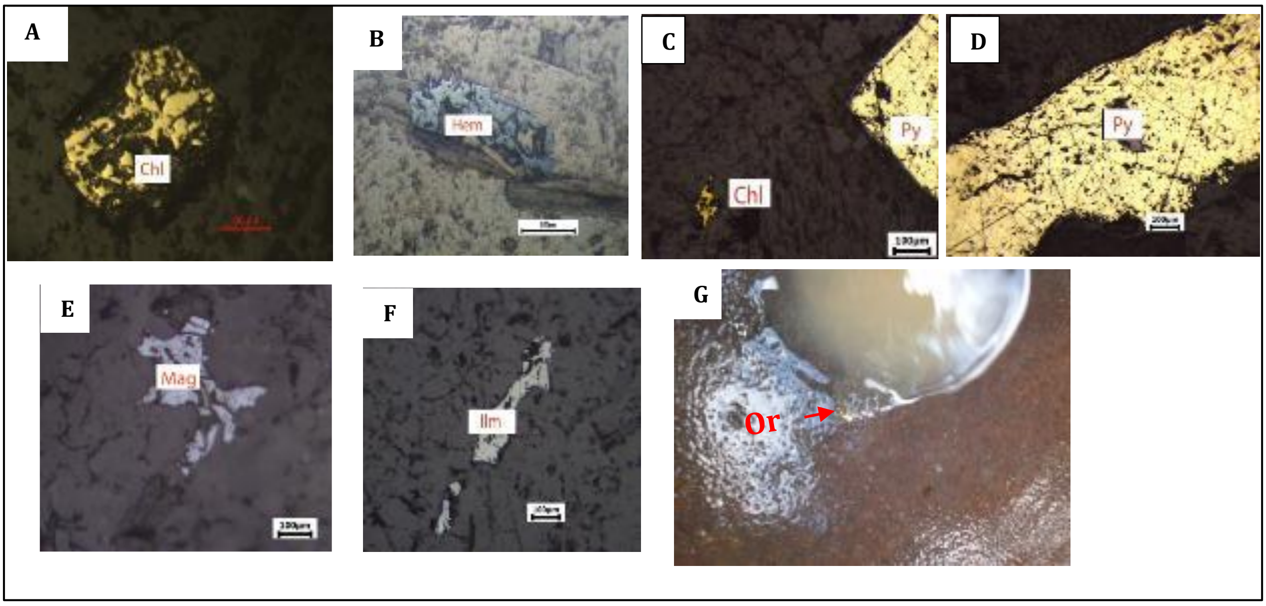
Table 1 The various mineral phases observed in the rocks of the study area.

Lithologies	Primary minerals	Hydrothermal Alteration	Metamorphism
Biotite metagranite	Quartz+Biotite+Microcline+Othose+Plagioclase+Pyrite	Magnetite+Hematite	Epidote+Chlorite
Gneiss	Quartz+Biotite+Plagioclase+Muscovite+Microcline	Hematite+Pyrite+Chalcopyrite	Chlorite+Epidote+Sericite
Sericite schist		Quartz+Pyrite+Arsenopyrite	Sericite
Metamicrogranodiorite	Quartz+Plagioclase	Calcite+Magnetite	Sericite+Chlorite

A petrographic study of the different lithological facies revealed that most of the rocks in the study area have undergone various metamorphic processes. Evidence of these processes can be seen in the mineralogical and structural transformations of the rock, which are the result of disturbances to the stability conditions of the original minerals and the circulation of hydrothermal fluids (Table 1). Microscopic analysis of the rocks shows that certain ferromagnesian minerals, specifically biotite which is usually abundant in these rocks, have largely been replaced by other metamorphic minerals such as chlorites, epidotes and sericite. Furthermore, the feldspars are generally destabilised into epidote or sericite, which also indicates low-grade metamorphism. Microstructural analysis revealed minerals stretched along preferred directions and schistosity in virtually all formations within the study area, reflecting a context of regional metamorphism. The biotite + chlorite + epidote metamorphic assemblage in the metamorphic rocks is associated with discrete transcurrent ductile deformation. The confirmed metamorphic paragenesis consisting of biotite, epidote, chlorite and sericite reflects low-grade metamorphic conditions and thus green schist facies in the metamorphic rocks.

4.5. Gold Mineralization

The gold mineralization in the study area is of the sulphide type and is disseminated in moderately deformed and altered granitoids, as well as in quartz veins. The metal-bearing paragenesis (Figure 14) consists mainly of pyrite, which is sometimes found alongside chalcopyrite, magnetite, hematite and ilmenite. Gold grains are found within quartz, quartz-calcite-sulfide and quartz-tourmaline veins, as well as being associated with sulfides. Bright yellow native gold occurs as microscopic grains within quartz veins and their stopes. Pyrite, which is generally cubic in shape, accounts for 80–85% of the sulfides. It is either disseminated primarily or remobilised secondarily along the foliation plane in the host rock. Chalcopyrite is generally found alongside pyrite, albeit only locally (see Figures 14C and D). The presence of pyrite appears to indicate the presence of gold. Ilmenite, which occurs in lamellar forms and is grey in colour with brownish tips, is also present in the mineralized zone.



A: Chalcopyrite; B: Hematite; C: Chalcopyrite and Pyrite; D: Pyrite; E: Magnetite; F: Hematite; G: Gold in a pan tailings.; Py: Pyrite; Chl: Chalcopyrite; Prt: Pyrrhotite; Mag: Magnetite; Hm: Hematite; Ilm: Ilmenite

Figure 14 Microscopic appearance of the metal-bearing paragenesis

4.6. Geological sketch

Compiling the results of field studies has made it possible to create a lithostructural sketch of the study area (Figure 15). In this lithostructural sketch, the formations generally trend NNE-SSW. The most significant formations are the plutonic formations (granitoids), which outcrop to the west and southeast of the study area, alongside the metasediments (sericite schist, quartzite, etc.). In this sketch, we have refined the boundary between the schistose formations and the granitoids, and confirmed the extent of the schists. Two zones of generally left-lateral shear were also identified: one in the Bafanakaha sector with a general NS trend showing signs of gold, and the other in the Natiemboro sector with a general NNE to NE trend.

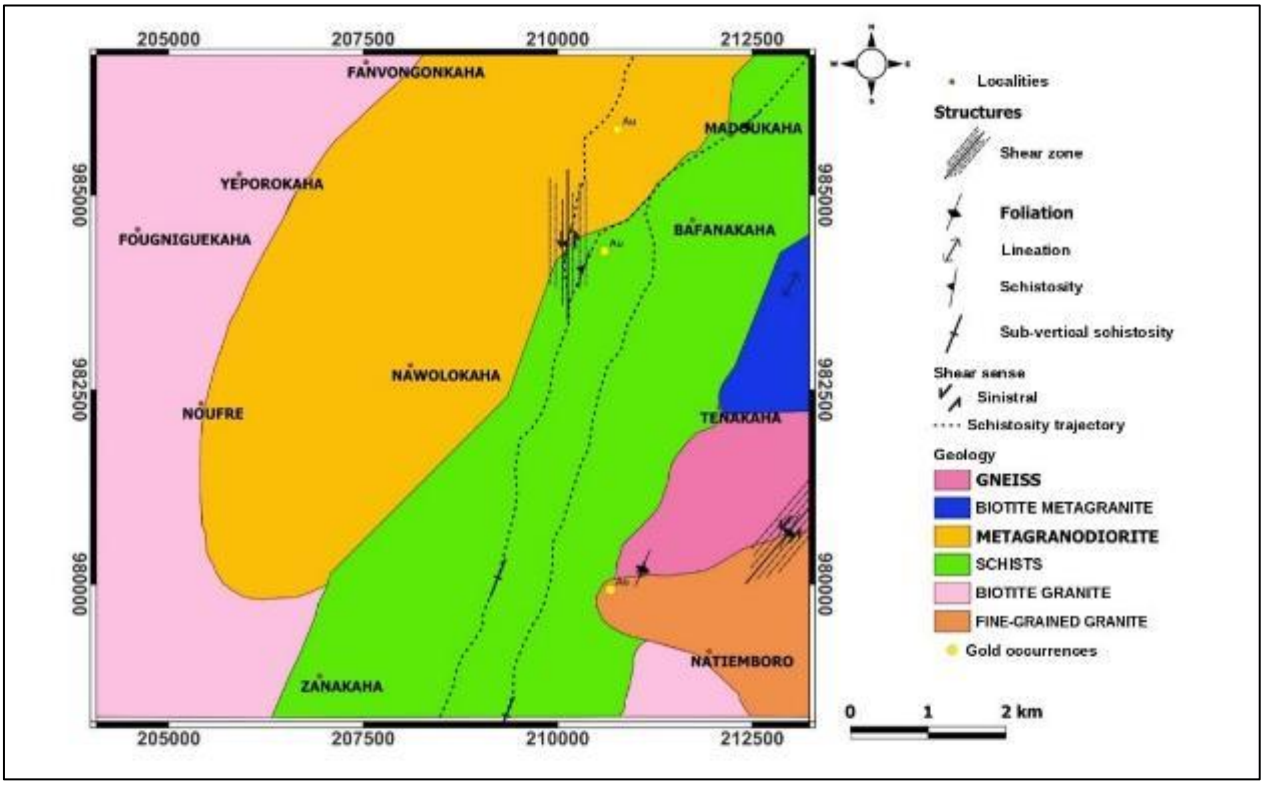


Figure 15 Geological sketch of the Natiemboro prospect

5. Discussion

Mapping data from the Natiemboro area indicates that it consists of metamorphic formations, such as gneiss, biotite metagranite, metamicrogranodiorite, quartzite and sericite schist, as well as plutonic igneous formations, such as fine- and coarse-grained granite, which are mineralised with gold-bearing sulphides. There are also vein-type igneous formations, such as pegmatite, which cut through the aforementioned rock units.

The plutonic and metamorphic formations consist of primary minerals (amphibole, plagioclase, quartz and biotite), though in varying proportions, as well as secondary minerals (chlorite, sericite, epidote and calcite). Accessory minerals, such as alkali feldspars, complete the mineralogy of these rocks. Pegmatite, on the other hand, consists of phenocrysts of quartz, alkali feldspar, sodium plagioclase, chlorite and, to a lesser extent, garnet. Their primary porphyroid texture is superseded by secondary textures ranging from lepidogranoblastic to nematogranoblastic. The Natiemboro formations generally run in an NNE-SSW direction (Eburnaian orientation) and have been affected by ductile deformation in the same direction, resulting in foliation and mineral lineations. These formations are intersected by faults and fractures trending NW-SE and N-S, some of which have been filled by either late-stage mineralised hydrothermal fluids forming sulphide-bearing quartz-calcite veins or unmineralised fluids forming pegmatites trending generally N-S. The geological formations at Natiemboro that host gold mineralisation are, from a petrographic standpoint, broadly similar to certain formations containing gold occurrences in the Birimian of Côte d'Ivoire and Africa. In Côte d'Ivoire, these include the Bonikro [9], Agbahou [7], Lafigué [25], Souwa [26] and Bobosso [8] deposits; in West Africa, the Boulgou-Kodisare deposit [27], the Ayanfuri deposit in Ghana [28] and the Morila deposit in Mali [29]. According to [30], the lithologies observed at Natiemboro are part of the characteristic Birimian formations.

At Natiemboro, the rocks have been affected by intense weathering processes. Supergene weathering has led to the formation of a regolith profile reaching depths of more than 15 m in some places. Intense hydrothermal weathering, manifested as pervasive and fissure-related weathering, has been accompanied by the formation of secondary minerals such as chlorite, epidote, quartz, carbonates, tourmaline, and sericite. The formation of these minerals, which gave rise to secondary textures, indicates that the formations in the area were affected by low- to medium-grade regional metamorphism of the green schist facies. These regional metamorphic characteristics have also been documented in several Birimian gold prospects and deposits in Côte d'Ivoire and West Africa [26, 7, 31, 8, 27,10, 5]. The Natiemboro area owes its structure to three phases of deformation (D1, D2, D3), a context similar to that identified by most authors in the Birimian greenstone belts. All of these deformation phases are characterized by having occurred in typically granitoid terrain.

Phase D1 gave rise to the following: (i) E-W-trending veins, (ii) isopachal folds with N-S-trending axial planes, (iii) NNE-trending schistosity associated with NNE-trending stretch lineations, and (iv) ENE-trending dexter C/S fabric. This phase is the result of E-W to WNW-ESE compression, which is less pronounced in the region and is likely due to Phase D2 partially masking it. This phase has been reported in other regions of the Man Ridge. However, there are variations in its manifestation (lithological competence) and the resulting structures. Thus, in addition to schistosity, it underlies (i) N-S foliations and (ii) isoclinal folds [32]. Some authors, such as [36], interpret this shortening phase as slightly compressive. They describe phase D1 as N-S to NNE-SSW elongation of the massifs, implying the occurrence of initial distensive phases followed by slightly compressive phases in an E-W to WNW-ESE direction. In southeastern Côte d'Ivoire, [33] interprets this E-W shortening as the cause of crustal thickening that led to migmatization.

Phase D2 is a well-defined, NW-SE transpressional phase in the study area. The compressional phase resulted in: (i) well-defined NE-SW foliation, (ii) anisotropic folds with axial planes parallel to the foliation and (iii). In addition to the aforementioned structures, it generates bands of conjugate dextral and sinistral shear zones, as described by Siagné [12] in north-eastern Côte d'Ivoire. The second phase is transpressive and generates: (iv) well-defined NE-trending S-type intrafoliation folds; (v) N-S left-lateral offsets affecting the E-W veins of D1; (vi) NNE left-lateral shear zones; (vii) asymmetric folds reflecting NE-trending left-lateral movement; (viii) ptygmatic folds; (ix) lineations dipping 20° towards N209° and 5° towards the south; and (x) transposition affecting isopachal folds and creating isolated hinge folds. As this transposition is localised, left-lateral coiling structures are generated near the intrafoliation folds. Deformation D2 is also accompanied by a shear zone oriented from north-south to north-east-south-west with left-lateral movement, exhibiting C/S planes and significant recrystallisation.

The small angle (10–20°) between the S and C planes, coupled with left-lateral shear, suggests substantial non-coaxial deformation. This could explain the striking absence of mineral lineation in certain regions. This D2 phase is recognised as one of the major phases across the West African Craton: (i) northwest and southwest Ghana [6, 34, 35], (ii) northeast Côte d'Ivoire [36], (iii) Burkina Faso [5], and (iv) southwest Côte d'Ivoire [32].

Phase D3 is responsible for right-lateral ductile-brittle shearing, with a strike ranging from north-west to south-east, ending in north-south flattening. This shear is manifested by the following: (i) asymmetric north-south right-lateral buckling; (ii) symmetric north-northwest buckling; (iii) north-northwest stretching lineations; (iv) north-south right-lateral offsets; (v) north-south fractures that are sometimes filled; and (vi) buckling bands observable in the Natiemboro area. Mineral lineations have been observed. The N-S flattening phase establishes the following: (i) E-W foliations, (ii) N-S fractures and (iii) N-S veins that cut into those of D1. This phase was identified in north-eastern Côte d'Ivoire by [12], who also identified conjugate fractures oriented NE and NW.

Gold mineralisation at Natiemboro is primarily found in moderately deformed, metamorphosed and hydrothermally altered granodiorite, and to a lesser extent in gneiss and granite. It also occurs abundantly in quartz-calcite-tourmaline veins. This mineralisation consists mainly of pyrite, which is sometimes associated with chalcopyrite, magnetite, haematite, ilmenite and native gold. The primary (syngenetic) mineralisation consists of disseminated sulfides within plutonic rocks. Secondary (epigenetic) mineralisation is found within quartz veins, quartz-calcite-sulfide veins and quartz-tourmaline veins. Post-magmatic tectonic events (both brittle and ductile) affected the plutonites, particularly the granodiorites, forming triple junctions that allowed mineralising hydrothermal fluids to easily flow and cool within fractures. This led to the deposition of silica and carbonate, as well as the development of sulphide parageneses and gold. Furthermore, the interface between highly and moderately deformed zones created heterogeneous and inhomogeneous areas that favoured fluid circulation and consequently the deposition and formation of gold-bearing sulphide parageneses.

The gold mineralisation observed in the plutonic intrusions at Natiemboro is typical of many other known Birimian gold mineralisations. Examples of this can be found in Côte d'Ivoire at Bonikro in granodiorites [9], at Souwa in granodiorites [26], at Bobosso in quartz diorites [8], and in West Africa at Ayanfuri in Ghana within granitoid plutons [28] and at Morila in Mali in quartz diorites, granodiorites and leucogranites [29].

These two types of mineralisation (disseminated syngenetic and vein-type epigenetic) are more or less closely genetically related at Natiemboro. They are interpreted as resulting from several episodes of hydrothermal fluid infiltration and mineral deposition along shear zones. This type of bimodal mineralisation has been identified in several Birimian gold deposits in Côte d'Ivoire and across Africa [4, 7, 10, 26, 8, 27].

6. Conlusion

Thanks to geological mapping, petrographic studies and structural analyses, it has been possible to develop a lithostructural outline of the Natiemboro prospect. This incorporates both existing and new data. Four lithological units, as determined by petrography: the metasedimentary unit (sericite schists and quartzites); the plutonic unit (biotite metagranite, gneiss, and metamicrogranodiorite); the intrusive unit (fine- and coarse-grained granite); and a unit consisting primarily of dikes (pegmatites). These units are mostly affected by green schist-facies metamorphism and also exhibit hydrothermal (pervasive and vein-type) and meteoric alteration. Pervasive hydrothermal alteration is exemplified by carbonation, sericitis, chloritisation, epidotisation, silicification and sulphidation, while vein-type hydrothermal alteration is characterised by veins and filons of quartz, carbonates and quartz-tourmaline. A structural analysis revealed that the tectonic history can be divided into three deformation phases. Initial E-W to WNW-ESE compressive deformation (D1) produced E-W veins, isopachal folds with N-S axial planes and NNE schistosity. This was followed by regional NW-SE transpression (D2), the major phase on a regional scale, which produced NE-SW foliation, right-lateral ENE shearing (C/S fabric), stretch lineation, left-lateral N-S faults and isopac, anisopac and isoclinal folds with NE-trending axial planes. The D2 phase ended with N-S flattening, establishing a local E-W foliation and N-S veins. Added to the D2 phase was a NE-SW shear (D3), which generated S-type intrafoliation folds indicating a left-lateral sense, as well as isolated hinge folds with NE axial planes and SE symmetric buckling. The gold mineralisation at Natiemboro is primary (syngenetic) in the form of disseminated sulphide within moderately deformed, metamorphosed and hydrothermally altered plutonites, and secondary (epigenetic) in quartz, quartz-calcite-sulphide and quartz-tourmaline veins. It is believed that this mineralisation formed as a result of post-magmatic tectonic events (both brittle and ductile), occurring at the interface between high- and moderate-deformation zones. These zones were created by the deformation of the rocks and favoured fluid circulation and the deposition of gold-bearing sulfides. The mineralisation consists primarily of pyrite and, to a lesser extent, chalcopyrite, pyrrhotite and native gold. Finally, the Natiemboro gold deposit is similar to many other Birimian deposits in Côte d'Ivoire and across Africa within the Éburnaian domain.

Compliance with ethical standards

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Disclosure of conflict of interest

All the authors declare no conflicts of interest.

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