



(RESEARCH ARTICLE)



LITHO-STRUCTURAL CHARACTERIZATION OF THE GEOLOGICAL FORMATIONS OF THE KOURONDOUGOU-LINGUOSSO AREA (ODIENNÉ DEPARTMENT, NORTHWEST CÔTE D'IVOIRE)

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ABSTRACT

The study area is located in the Odienné region, situated in the northwestern part of Côte d'Ivoire. This study contributes to increasing knowledge of the geology of the Kourondougou-Linguesso sector. The methodological approach began with a remote sensing study and concluded with macroscopic observations (petrography and structural analysis, with the naked eye and/or a hand lens) of outcrops in the field. Subsequently, thin sections were prepared in the laboratory for study under a polarizing and metallographic microscope. The lithologies of the study area consist of igneous rocks (granites, pink granites, granodiorites, pegmatites, microdiorites, and lapilli tuff) and metamorphic rocks (biotite metagranites, orthogneisses, and amphibolites-schists). These rocks are affected by a general metamorphism of amphibolite to green schist facies and hydrothermal alteration (both pervasive and vein-related) marked by the presence of chlorite, epidote, sericite, sulfides (pyrite, chalcopyrite, and pyrrhotite), and oxides such as magnetite. Three deformation phases (D1, D2, and D3) have been identified. The D1 phase corresponds to a N-S shortening marked by mineral stretching lineations and E-W trending foliations, with subvertical dips. The D2 phase, resulting from NNW-SSE to NW-SE shortening, is manifested by veins, dikes, faults, and fractures generally oriented NNE-SSW to NE-SW. It generates shear zones oriented NNE-SSW to NE-SW. The D3 phase is marked by fractures, veins, and late mineral veins secondarily oriented NW-SE.

Keywords: Petrography, Deformation, Kourondougou-Linguesso, Odienné, Côte d'Ivoire

1 INTRODUCTION

The Odienné region is located in the northwest of Côte d'Ivoire, straddling the Archean and Paleoproterozoic domains (**fig. 1 and 2**). This location gives it a unique character with geological features that are both complex and interesting, compared to other regions of Côte d'Ivoire. Recent work by [1] has divided this area into three domains (western, central, and eastern). The western domain is located at the far west; it is known in the Man area for Archean formations rich in iron ore [2]. The central domain corresponds to an area that is heavily sheared and faulted according to [1]. It is

therefore favorable to mineralization. The eastern domain contains the Birimian formations, defined by [3] as hosting mineralization. This immense mining potential has made it, in recent years, a coveted area for several mining companies including CENTAMIN/AMPELLA and AWALE RESOURCES, where mining exploration is thriving. However, very few scientific studies have been undertaken to help characterize these formations. Thus, this study carried out in the Kourondougou-Linguesso sector contributes, on the one hand, to improving knowledge of the lithological and structural characteristics of the geological formations, and on the other hand, to revitalizing the Ivorian mining sector.

2 GEOLOGICAL CONTEXT

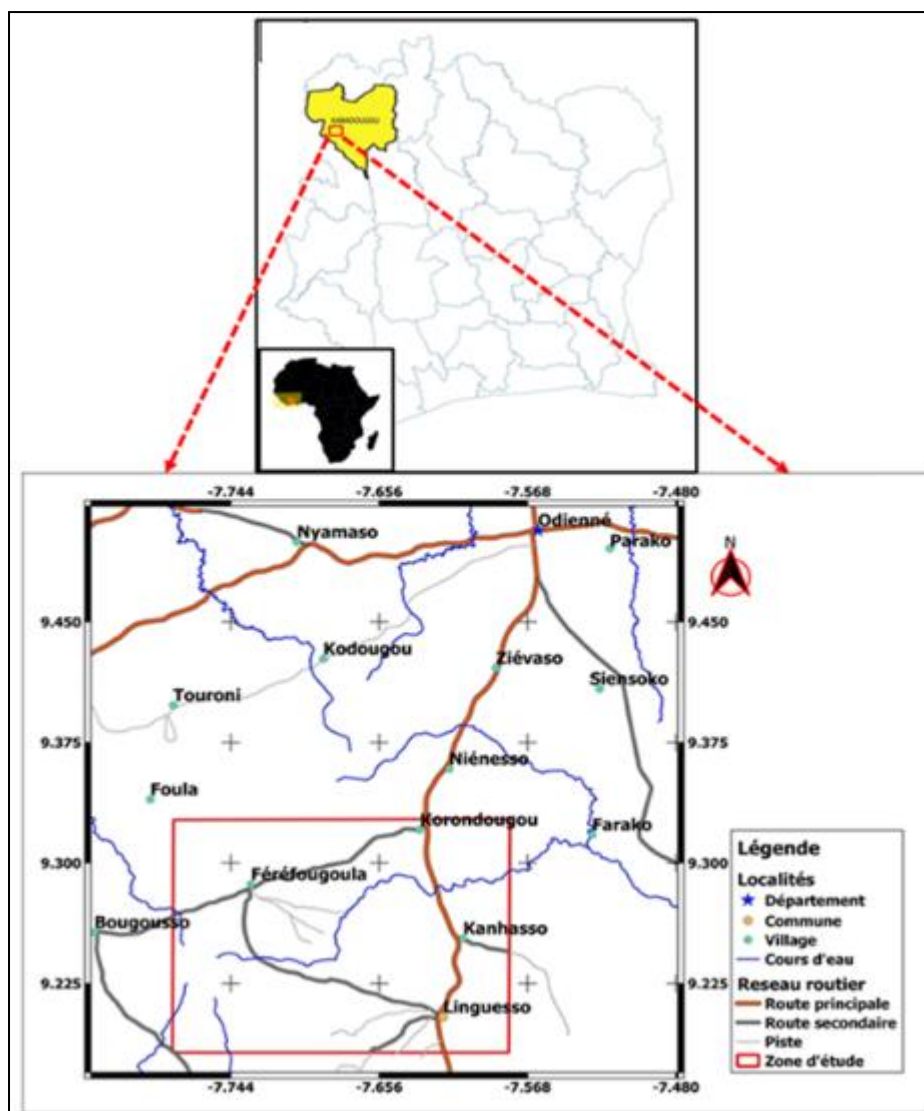


Figure 1: Location map of the study area (extracted from the administrative map of Côte d'Ivoire, 2013).

Ivory Coast belongs to the West African craton, more precisely to the Man Ridge (**fig. 2**). Two geological units cover the country's surface: a Precambrian basement which occupies 97.5% of the territory, and a more recent sedimentary cover (ranging from the Mesozoic to the present) covering the remaining 2.5%. Ages obtained from this basement range between 3.45 and 1.026 Ga [4-7]. This Precambrian basement is subdivided into two domains by the Sassandra Fault: an Archean domain or Kenema-Man domain to the west of the fault, and a Proterozoic (Birimian) domain or Baoulé-Mossi domain to the east of it [8]. The Sassandra fault is generally oriented north-south; its probable continuation to the north would be the Zedness fault, which separates the Reguibat ridge into Archean and Proterozoic [9]. The work of [10] indicates the existence of a transition zone in the Paleoproterozoic between the Sassandra fault and longitude 6°W. This zone would be characterized by the contamination of Birimian juvenile formations by Archean crust (intermediate Nd model age and inherited zircons). [5] describe the existence of Archean relics within the Paleoproterozoic domain.

Indeed, the Odienné region has been the subject of several studies. The first studies carried out allowed for mapping part of the Odienné sheet, documented in a summary at 1/200,000 scale [11-13]. Three groups were distinguished:

high-temperature metamorphites, volcano-sedimentary complexes, and granitoids. [2] highlights in the Odienné region Liberian formations with petrographic and chemical characteristics identical to those of the Man region. The work of [14-15] made it possible to distinguish (i) high-temperature metamorphites with relics of rocks considered to be Liberian, (ii) a volcanic and volcano-sedimentary complex from the Bagadian of Birimian age, and (iii) orthogneisses and amphibolites. [3, 16] interpreted the contact between the Birimian formations and formations considered to be Archean as a thrust plane.

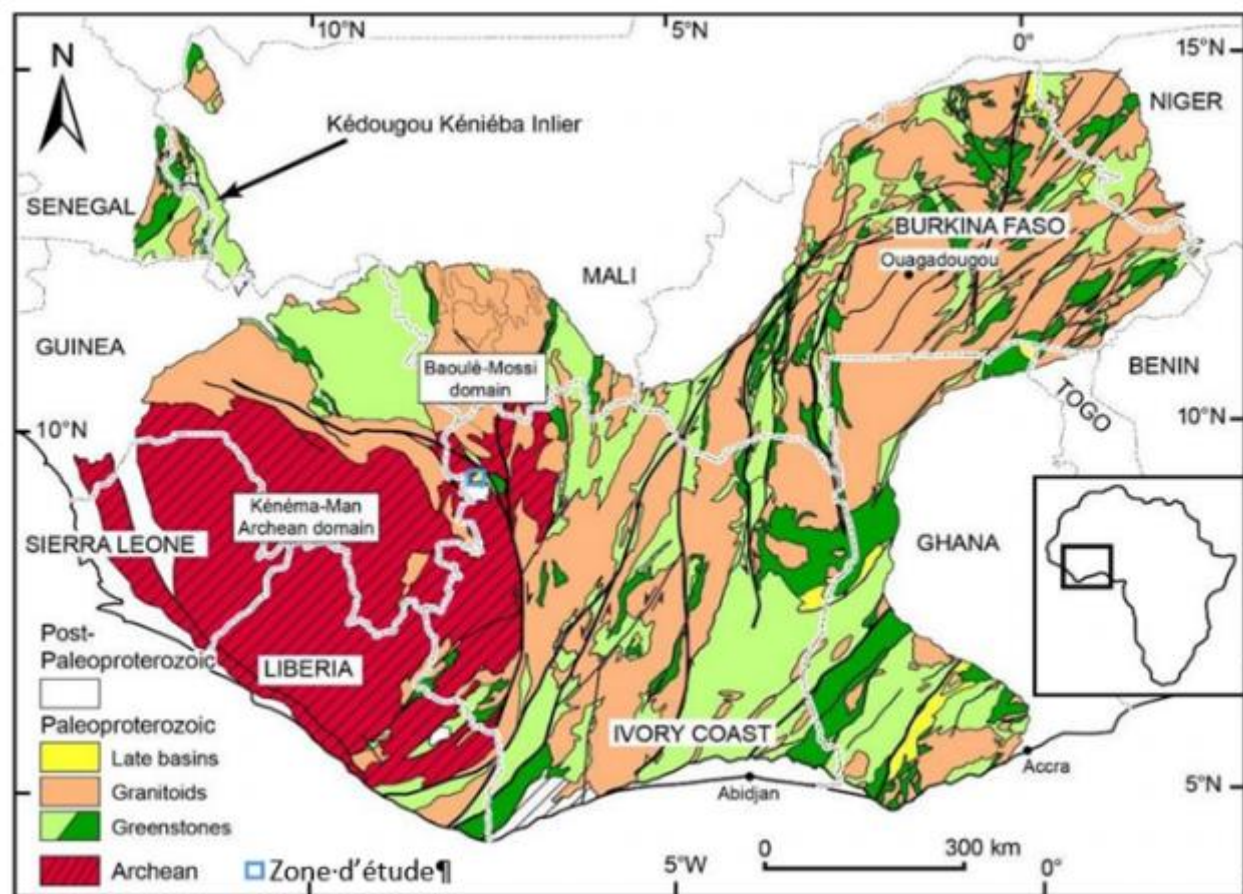


Figure 2: Simplified geological map of the West African craton ([17], modified).

The same authors identified mafic rocks with orthopyroxene in the Zébéné area, which they consider as relics of Liberian granulitic parageneses. The work of [1] allows the Odienné area to be divided into three domains. The western domain includes at its base a series of pillow tholeiitic and komatiitic metabasalts, topped by metasediments with an oceanic signature. It is followed by a volcanic complex of age Slightly older than 2.1 Ga compared to the surrounding regions which include andesites, dacites, and rhyolites. The central domain mainly consists of high-temperature paragneisses derived from pelites and semipelites. Transpressive deformation with strong N-S horizontal elongation at high temperature reflects the initial activity of the Sassandra left-lateral shear zone. The eastern domain comprises silico-clastic and volcanoclastic metasediments with an amphibolite facies, involved in the same left-lateral transpressive tectonic regime. These three domains were juxtaposed due to predominantly left-lateral horizontal movements along the Sassandra shear zone, which splits to the north of Odienné into several branches. This zone is believed to consist of syn-kinematic granitoids, undifferentiated paragneisses, lavas and undifferentiated metasediments, and tholeiitic metabasalts. The geological formations encountered in the study area consist of granodiorite, two-mica granite, undifferentiated granite, granite with migmatitic facies, migmatite enclaves, microgranite veins, and muscovite pegmatite veins (**fig. 3**).

3 METHODOLOGY

The methodology began with remote sensing, which involved processing Landsat 8 OLI optical images in order to identify the different lineaments, which were subsequently validated in the field. The lineaments were obtained from teleanalytic data derived from synthetic aperture radar (SAR) images, processed using the QGIS 3.10 GIS software. The images used in this study were sourced from the USGS platform (<http://earthexplorer.usgs.gov/>). The validation step was carried out in the field to compare the selected lineaments with the data collected. Subsequently, we described the

various lithologies encountered and interpreted the structural elements that affected them. Eleven (11) samples were selected for the preparation of thin sections, of which four (04) were polished at the lithothin section workshop of the Geology, Mineral and Energy Resources (GRME) laboratory of the Faculty of Earth Sciences and Mining Resources at Félix HOUPOUT-BOIGNY University in Abidjan. The obtained thin sections were observed under a polarizing light optical microscope and a transmitted light metallographic microscope in order to highlight the mineral and metallographic parageneses.

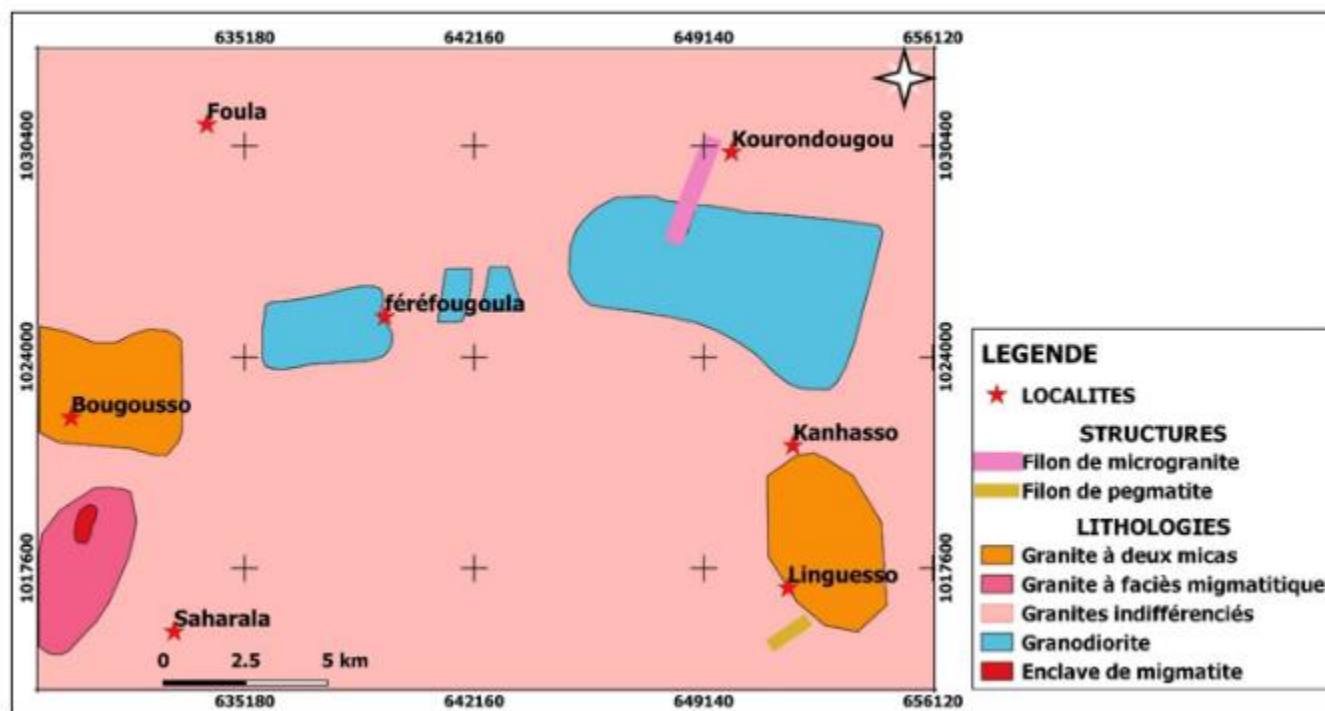


Figure 3: Geological map of the study area (extracted from the geological map of Odienné at a scale of 1/500000 by [11]).

4 RESULTS

4.1 Petrography

The lithologies encountered in the study area consist of igneous rocks (lapilli tuffs, granites, granodiorites, pegmatites, and microdiorites) and metamorphic rocks (orthogneisses, ortholeptynites, and amphibolites).

4.1.1 Igneous rocks

4.1.1.1 Lapilli tuff

These massive melanocratic rocks were observed in Korondougou. At outcrop, they are slightly deformed, and phenocrysts of pyroxenes and amphiboles can be observed (**fig. 4A**). Under the microscope, these rocks show a porphyritic microlitic texture with phenocrysts of pyroxenes (Opx and Cpx) and brown hornblende (**fig. 4B**). Amphiboles are generally subhedral to euhedral, sometimes with simple twinning. The mesostasis consists of fine rods of plagioclase and ferromagnesian minerals. Rare quartz minerals are also observed as inclusions in the veinlets.

4.1.1.2 Granodiorites

The granodiorites, mainly found in Kanhasso, Korondougou, and Féréfougoula, are mesocratic and outcrop in the form of moderately deformed slabs and domes. They range from medium- to very coarse-grained, often showing migmatitic tendencies (**fig. 4C**). In thin section, they generally exhibit a granular to porphyroclastic texture and are composed of plagioclase in subhedral to euhedral phenocrysts, quartz, and microcline (**fig. 4D**). Plagioclases are sometimes zoned and heavily sericitized. Biotite minerals occur as subhedral to euhedral phenocrysts and are locally stretched, with zircon inclusions. Green hornblende is subhedral to euhedral and often exhibits simple twinning. Additionally, there are a few rare orthoclase minerals. These rocks also contain minerals of epidote, chlorite, sericite, titanite, and myrmekite. The majority of sulfides and oxides encountered are disseminated in the rock, generally associated with

amphibole, biotite, titanite, and within plagioclases. These include mainly pyrite, which is more abundant, chalcopyrite, pyrrhotite, and magnetite (**fig. 4 E-F-G-H**).

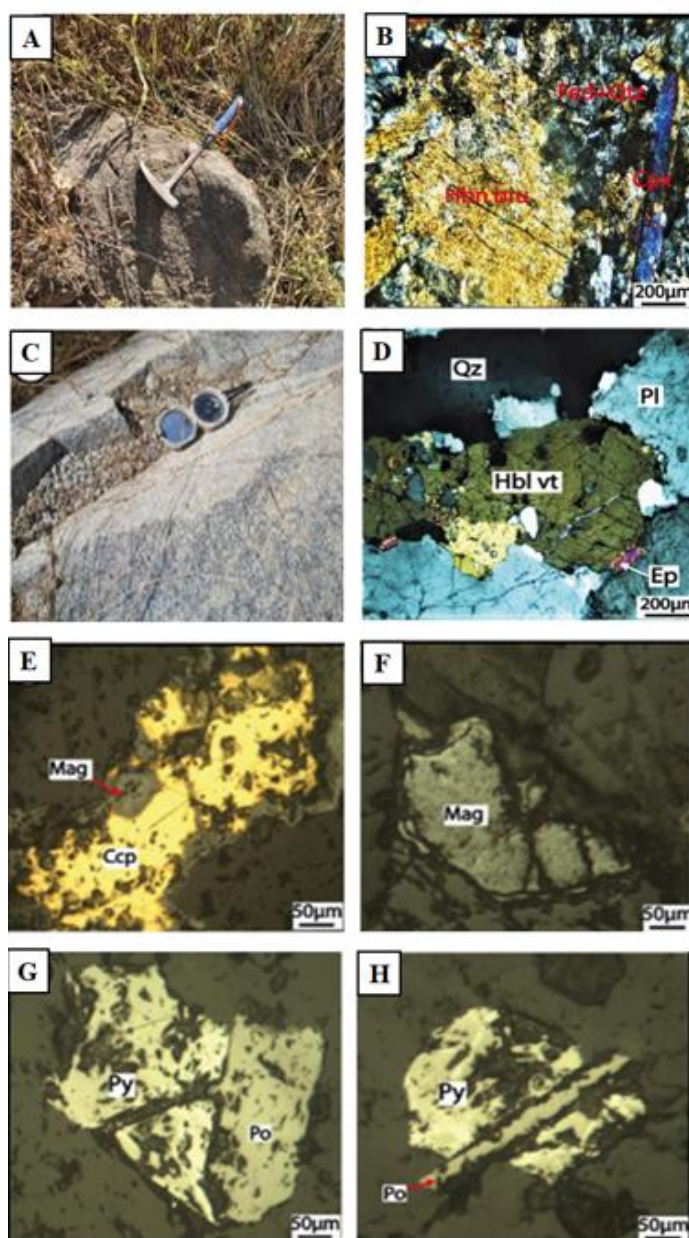


Figure 4: Macroscopic and microscopic aspects of tuffs, granodiorites, granites, and metalliferous paragenesis
A-B: Tuff, C-D: Granodiorite, E: chalcopyrite and magnetite, F: magnetite, G-H: pyrite and pyrrhotite.
Qz : quartz, Bt : biotite, Pl : plagioclase, Bru : brown hornblende, Cpx : clinopyroxene, Fed : feldspars, Hbl vt : opaque green hornblende, Ep : epidote, Mag : magnetite, Ccp : chalcopyrite, Py : pyrite, Po : pyrrhotite.

4.1.1.3 Granites

4.1.1.3.1 Granites ss

The granites are massive, coarse-grained to coarse-porphyritic, weakly deformed and outcrop as domes, blocks, and slabs (**fig. 5A**) in most of the localities visited. At outcrop, relic enclaves of migmatites (melanosome) can be observed in the coarse-grained facies, along with quartz, feldspar, and often oriented biotite minerals. These lithologies are often traversed by quartz-feldspar veins. Under the microscope, phenocrysts of quartz and plagioclase, biotite, microcline, and rare muscovite are observed (**fig. 5B**). Occasionally, sphene, chlorite, epidote, sericite, myrmekite, and opaque minerals are also observed.

4.1.1.3.2 Pink granite

These rocks observed in Kanhasso and near Bougoussou are granular and have a high proportion of orthoclase and microcline (**fig. 5 C**). At outcrops, magnetite streaks and microdiorite enclaves can be seen in places. Under the microscope, their mineralogy consists of orthoclase, microcline, plagioclase, quartz, biotite, and muscovite (**fig. 5 D**). The accessory minerals observed are sericite, perthite, titanite, and chlorite.

4.1.1.4 Quartz Microdiorites

They are massive, melanocratic, fine-grained, and generally outcrop as blocks at Korondougou (**fig. 5E**). Under the microscope, these rocks exhibit a fine-grained porphyritic texture with phenocrysts. Their mineralogy consists of green hornblendes, subhedral to euhedral, often displaying simple twinning (**fig. 5F**), plagioclase, biotite, and a few quartz minerals.

4.1.1.5 Pegmatites

These massive, leucocratic, and slightly deformed lithologies outcrop at Féréfougoula and Korondougou (**fig. 5G**). These rocks, containing centimeter-sized minerals, generally cut through the granites. Under the microscope, these rocks consist of plagioclase and potassium feldspars partially destabilized into sericite on certain sections (**fig. 5H**). Minerals of quartz, biotite partially altered to chlorite, and muscovite are also present.

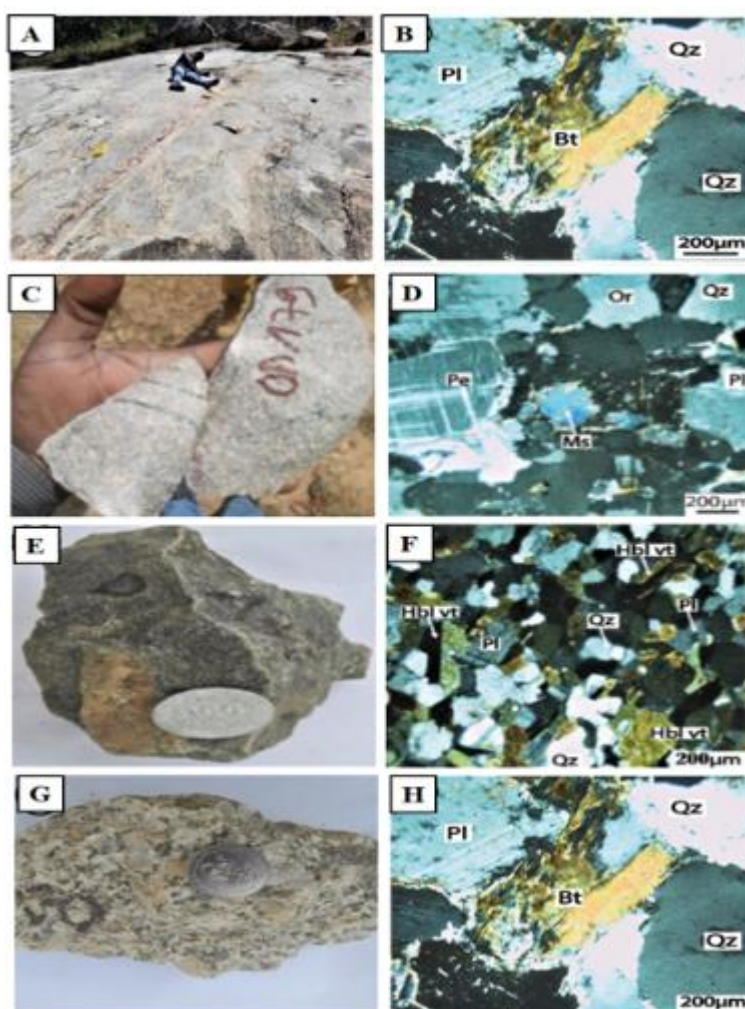


Figure 5: Macroscopic and microscopic aspects of granites, pink granites, quartz microdiorites, and pegmatites.

A-B: Pink granite, **C-D:** Pink granite, **E-F:** Quartz microdiorite, **G-H:** Pegmatite. **Bt:** Biotite, **Pe:** Perthite, **Ms:** Muscovite.

4.1.2 Metamorphic Rocks

4.1.2.1 Biotite Metagranites

They are massive, leucocratic, and generally outcrop in the form of domes and blocks at Kanhasso and Féréfougoula (**fig. 6A**). At the outcrop, an orientation of biotite minerals as well as quartz-feldspar minerals can be observed. In thin section, these granites display a granolepidoblastic texture (**fig. 6B**). Quartz is abundant in the rock and is especially distributed in a very heterogeneous manner. These quartz minerals are crushed in places and, for the most part, associated with plagioclase minerals and potassium feldspars. The biotite is oriented and destabilizes in some sections into chlorite. The feldspars (plagioclase and potassium feldspar) also destabilize into sericite.

4.1.2.2 Orthogneiss

These highly deformed rocks were primarily observed south of Féréfougoula (**fig. 6C**). The light bands are quartzofeldspathic, and the dark bands are composed of ferromagnesian minerals. Under the microscope, the rock exhibits a granolepidoblastic texture with a paragenesis consisting of quartz and plagioclase in the light bands, and amphibole and biotite in the dark bands (**fig. 6D**). The minerals vary in size overall.

4.1.2.3 Amphibole Schists

These formations have been observed mainly south of Féréfougoula. They are highly deformed and generally consist of amphibole (**fig. 6E**). In thin section, the texture is lepidonematoblastic with a mineral paragenesis composed of amphibole, very abundant, in euhedral to subhedral phenocrysts, destabilizing into epidote and chlorite (**fig. 6F**). The quartz-feldspar assemblage appears in places along schistosity planes. Rare euhedral clinopyroxenes are present.

4.2 Structural

4.2.1 Remote analysis study

Processing of the Landsat 8 satellite image revealed 31 lineaments of varying orientations and lengths (**fig. 7A**). Most of these lineaments correspond to different structures (fractures, veins, faults, lineations, foliations, etc.). Statistical analysis reveals that these lineaments are mainly oriented WNW-ESE (**Fig. 7B**). The second most important direction is E-W, followed by NE-SW.

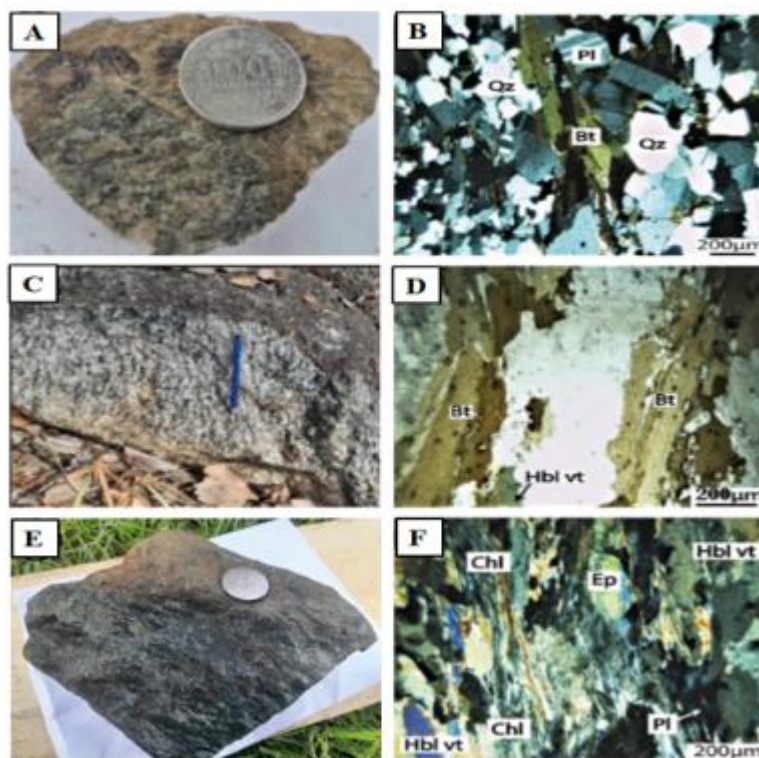


Figure 6: Macroscopic and microscopic aspects of biotite metagranites, orthogneisses, and amphibole schists.

A-B: Biotite metagranite, **C-D:** Orthogneiss, **E-F:** Amphibole schist; **Chl:** Chlorite.

4.2.2 Structures Observed in the Field

4.2.2.1 Brittle Deformations

These are the most commonly represented deformations (**fig. 8**). They consist of fractures, which are very abundant in the study area, primarily oriented NE-SW, N-S, and NW-SE. The veins and dikes observed can be classified into three major generations (F1, F2, and F3). The first generation (F1), oriented $N070^{\circ}$ to $N110^{\circ}$, is generally synchronous with foliation and mineral stretching. The quartz-feldspathic veins and some pegmatite dikes oriented $N015^{\circ}$ to $N060^{\circ}$, representing F2, are subsequent to F1. The microgranite dikes and some pegmatite dikes oriented $N145^{\circ}$ to $N195^{\circ}$, representing F3, are subsequent to both F1 and F2. These generations of dikes highlight the deformation events that occurred in the study area. The area was affected by a system of right-lateral and left-lateral strike-slip faults oriented mainly NNE-SSW and NW-SE. These different structures are evidence of the occurrence of simple shear.

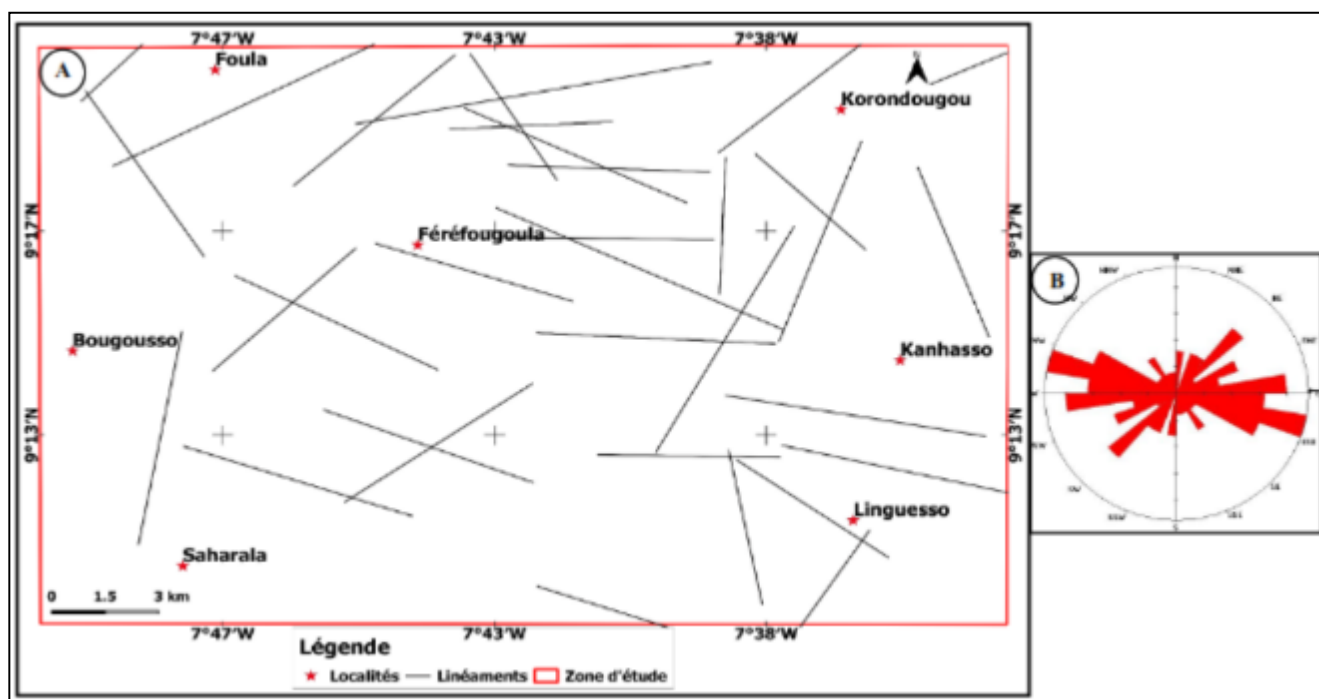


Figure 7: Lineament map and associated directional rose.

A: lineament map, B: directional rose associated with the lineament map.

4.2.2.2 Ductile Deformations

These structures are shown in **fig. 9**. They consist of anisotropic and asymmetric folds with axial planes P1 and P2 respectively oriented $N040^{\circ}$ and $N170^{\circ}$, with in some places Z-type anisotropic folds having an axial plane oriented $N050^{\circ}$. The axial planes of the concentric anisotropic folds are oriented $N015^{\circ}$. The presence of dextral intrafolial folds affecting the foliation is noted. Indeed, the Z-type anisotropic folds and the intrafolial folds indicate a dextral simple shear. The boudins are asymmetric and generally parallel to the foliation plane or to the mineral stretching marked by the E-W orientation of biotite, chlorite, and rarely amphibole minerals. The boudins and mineral stretching indicate the presence of compressive stresses, reflecting a simple shear. The observed foliation is mainly oriented E-W with subvertical dips. However, a 10° rotating foliation toward $N00$ has been identified, indicating the presence of two episodes of shearing.

Indeed, there is a pure shear that, due to compressive stress, generated the foliation, and a simple shear that later rotated it. The observed C/S fabric is represented by an 'S' foliation plane oriented $N050^{\circ}$ and a dextral 'C' shear in the $N090^{\circ}$ direction. These C/S planes highlight the existence of an E-W trending shear zone in the Kanhasso area. The observed microstructures are characterized by quartz-feldspar veins formed along fractures and in the cleavage planes of amphibole minerals, fresh fractures, and both dextral and sinistral shears.

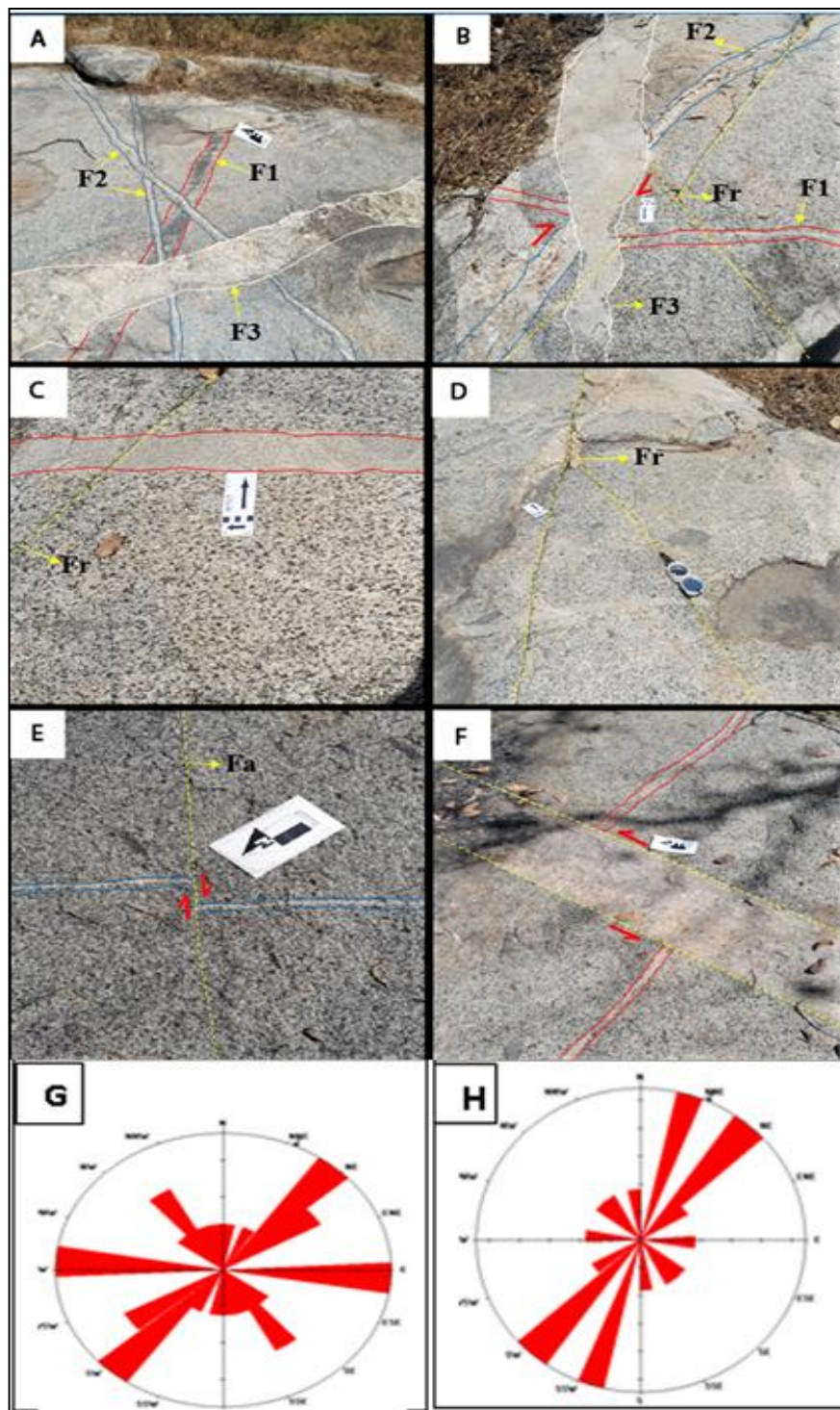


Figure 8: Structures related to brittle deformation

A-B : Fractures and vein generations ; C-D : Fracture and aplite vein ; E : Strike-slip fault with right-lateral component ; F : Left-lateral strike-slip fault ; G : Directional rose of veins and veinlets ; H : Directional rose of fractures and faults. F : Vein ; Fr : Fracture ; Fa : Fault

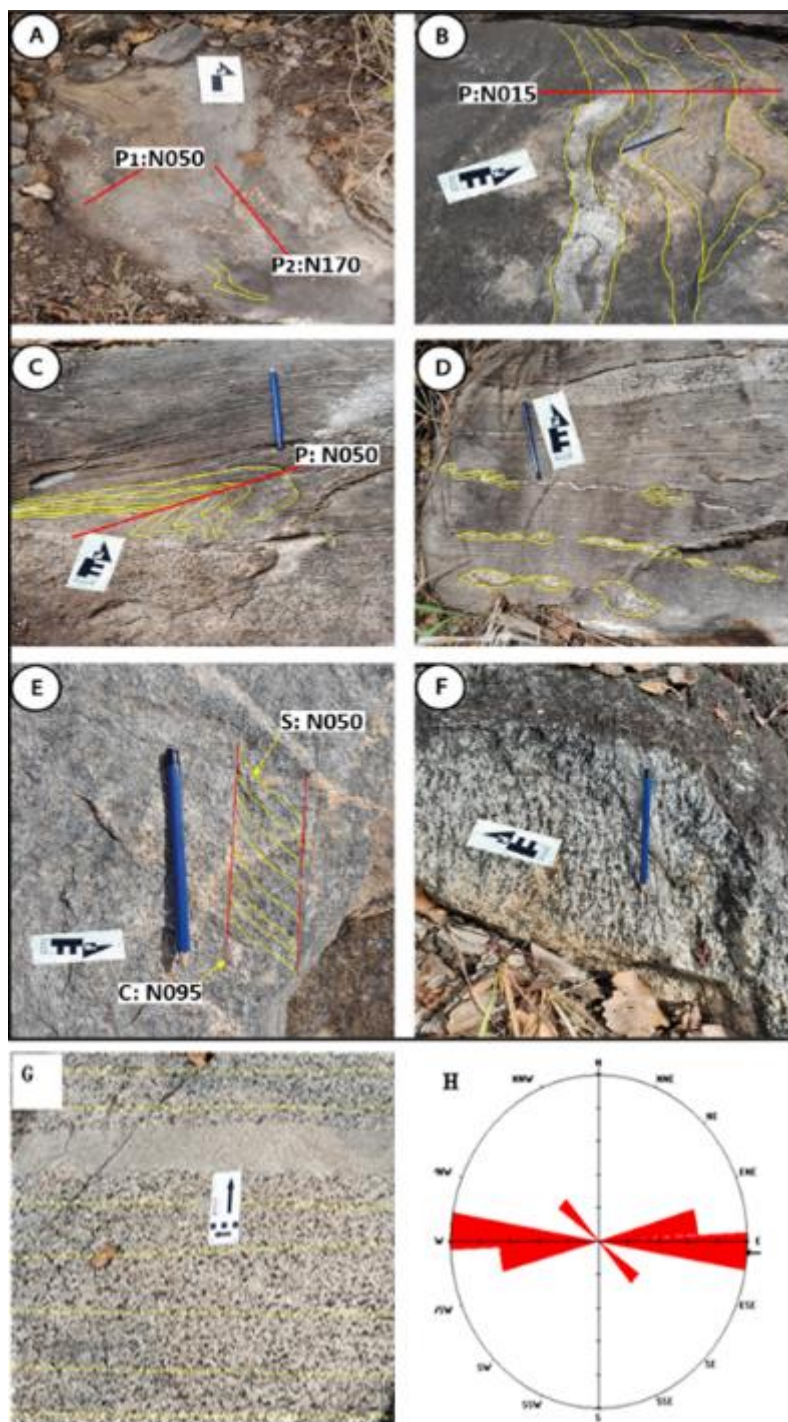


Figure 9: Structures related to ductile deformation

A : re-folded drag folds ; B : anisopaqued concentric folds ; C : asymmetric folds ; D : folds, boudins, and intra-folial folds ; E : C/S fabric ; F : foliation ; G : mineral stretching lineation ; H : directional rosette of mineral stretching lineaments.

5 DISCUSSION

5.1 Petrography

The work of [1] made it possible to divide the Odienné area into three domains (western, central, and eastern). The eastern domain includes siliciclastic and volcanoclastic metasediments of amphibolite facies and the large Tiémé batholith. Indeed, our work conducted in the eastern part allowed us to identify magmatic rocks (granites, pink granites, granodiorites, pegmatites, microdiorites, and lapilli tuffs) and metamorphic rocks (biotite metagranites, orthogneisses, and amphibolites-schists). Volcanic activity, both effusive and explosive, is noted, similar to observations made in the Odienné region [15], in the Toumodi-Fètêkro trough [18, 19], and in the eastern branch of the Boundiali-Korhogo trough

[20]. The granitoids in the study area contain microcline, just like those from the Korhogo trenches [21] and Toumodi-Fètêkro [19], as well as those from the Bonikro deposit [18]. Indeed, according to [22], this microclinalization indicates a late water influx, even occurring after the emplacement of the rocks, which took place at temperatures between 400 and 500°C. The biotite metagranites described correspond to those described by Pothin (1988) in the Odienné area and to those described in the central-west of the country in the Doropo permit [23] (Siagné, 2022). The identified orthogneisses consist of plagioclase, quartz, biotite, chlorite, and amphibole. This paragenesis is identical to that observed by [14] in the biotite and amphibole facies orthogneisses in the same Odienné area and also corresponds to those in the Grand Béréby area [24]. The studied granites are identical to those described by [14], but differ from those described by [25] in the northern part of the Alépé area, in terms of relative's proportions as well as the presence of significant muscovite phenocrysts. The observed pink granites correspond to intrusive granite massifs composed of feldspar megacrysts, as described by [10] in the Boundiali region, or the northern domain of the Archean-Paleoproterozoic transition zone. The set of lithologies observed in the study area is generally affected by pegmatite veins, sometimes refilled. Such observations have been highlighted in the Monoho, Monogaga, and Kounoukou areas in the San-Pédro region [24, 26]. These lithologies have been affected by metamorphism of green schist to amphibolite facies. These metamorphic conditions are similar to those observed by some authors in the Ivorian Birimian belts [19-20, 27] and elsewhere in the West African craton [27-30]. The granodiorites, generally deformed, are affected by intense pervasive and fissural alteration. The minerals in these rocks typically alter into carbonates, chlorite, sericite, and epidote, associated with silicification, oxidation, and sulfuration. Hydrothermalism is marked by the formation of quartz-feldspar veins associated with sulfides. These sulfides are mainly represented by pyrite, accompanied by chalcopyrite and pyrrhotite. Similar alterations and parageneses have been observed in West African gold deposits: Dougbafla [31], Bonikro [18], Agbahou [27], Bobosso [32], Tongon [33], Angovia [34], and Taparko [30].

5.2 Structural

The various structures observed in the study area indicate a polyphase tectonics and ductile-brittle deformation, with structures mostly oriented NNE-SSW to NE-SW. This corroborates observations already made in the West African Birimian [20, 35-37]. Three phases of deformation D1, D2, and D3 have been identified. The D1 phase corresponds to a marked N-S shortening characterized by mineral stretching lineations and E-W trending foliations with subvertical dips. It corresponds to the deformation phase identified by [16] in the Odienné region as the phase controlling the emplacement of granitoids. Recent studies also highlight in the Doropo region a D1 phase corresponding to N-S compression that produced a local main E-W foliation, conjugate dextral and sinistral shears, and folding [23]. This corroborates the observations of [20] in the Korhogo trough. Indeed, this author highlights a D1 deformation phase oriented E-W to WNW-ESE, corresponding to a compressive phase responsible for the flattening that created the S1 schistosity. This shortening phase is interpreted by some authors, such as [38], as slightly compressive. Indeed, they describe the D1 phase as a N-S to NNE-SSW elongation of the massifs, suggesting the appearance of initial extensional phases, followed by slight compressive phases along an E-W to WNW-ESE direction. The mineral stretch lineations, very abundant and affecting almost all encountered lithologies, mostly oriented E-W, also align with the foliation direction. This parallelism and the predominance of mineral stretch lineations in most encountered lithologies demonstrate a syntectonic emplacement in the study area. This direction is in perfect agreement with that of the foliation and lineations, with high plunge values (50-90°) highlighted by [1] at Foula to the west of the study area. These authors define the orientation of mineral lineations in the Foula pluton as the direction of magmatic flow and highlight plunging lineations that characterize the predominance of vertical movements. Thus, these authors lean towards an architecture acquired through diapiric-type evolution. Our observations made on certain plutons encountered in the study area also favor an evolution through diapirism. The D2 deformation phase results from NNW-SSE to NW-SE shortening. It manifests through veins, dikes, faults, and fractures generally oriented NNE-SSW to NE-SW. It generates shear zones with directions NNE-SSW to NE-SW. D2 corresponds to a phase of NW-SE compression, described as a transpressional phase [39]. This deformation mechanism, characterized by shortening followed by strike-slip tectonics generating shears, has already been identified in the West African craton [26, 36-37, 40-43]. The D3 phase is manifested by fractures, late-stage veins, and dykes secondarily oriented NW-SE. This NW-SE direction was mentioned by [1, 14], respectively at Ziévasso and Ziéougoula in the Odienné area, as the northern extension of the left-lateral Sassandra shear zone. Furthermore, [1] highlighted a NW-SE oriented mylonitic zone to the north of the study area. Indeed, the NW-SE oriented structures are interpreted as channels exerting control over the distribution of gold mineralizations in the Ashanti belt [40]. They transported and trapped hydrothermal fluids. These structures have also been identified in the West African Craton [20, 36-38, 44-46]. This D3 phase would correspond to a late Eburnean compression phase, which has also been highlighted.

6 CONCLUSION

This study, conducted in the northwest of Ivory Coast, in the Odienné region, specifically in the Kourondougou-Linguesso area, has helped to improve knowledge about the geology of Odienné. Our investigations highlighted a variety of lithologies, including igneous rocks (granites, pink granites, granodiorites, pegmatites, microdiorites, and lapilli tuff) and metamorphic rocks (biotite metagranites, orthogneisses, and amphibolites schists). These rocks are affected by a

general amphibolite to green schist facies metamorphism and hydrothermal alteration (both pervasive and vein-type), marked by the presence of chlorite, epidote, sericite, sulfides (pyrite, chalcopyrite, and pyrrhotite), and oxides such as magnetite. The different structures observed in the study area indicate polyphase tectonics and deformation of a ductile-brittle nature. Three deformation phases (D1, D2, and D3) have been identified. Phase D1 corresponds to a N-S shortening marked by mineral stretching lineations and E-W trending foliations with subvertical dips. Phase D2, resulting from NNW to NW shortening, is manifested by veins, dikes, faults, and fractures generally oriented NNE to NE. It generates shear zones trending NNE to NE. Phase D3 is represented by late fractures, dikes, and veins secondarily oriented NW-SE.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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