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Comparative Insights into Banded Iron Formations of Ivory Coast and Guinea

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Abstract

The Banded Iron Formation (BIF) is part of the Precambrian history. They are well studied in several provinces of the world: Harmesley range (Australia), Transvaal (South Africa), Krivoy Rog (Ukraine), Labrador (Canada), Lake Superior (USA), Gunflint and Biwabik (USA) and Isua (Greenland). They constitute a world-class economic reserve in Guinea and Ivory Coast, more particularly in the Nimba-Simandou-Klahoyo-Tia Mountains). The main BIF studied are located on the borders of these two countries. These BIF present close similarities in petrography, structural metallogeny and geochemistry. The metallographic study has shown that the mineralization is essentially composed of magnetite. Although they share some characteristics, they show some typical divergences in terms of metamorphism and age. The Mount Klahoyo and Tia BIF are of Archean Algoma type while those of Guinea are of Proterozoic age, characteristic of BIF of the Lake Superior type. Overall, most of the mineralization is contained in magnetite or itabirite quartzites (BIF). From this, we can deduce that the BIF of Guinea are a continuation of those identified in Ivory Coast.

Keywords: Klahoyo; Nimba; Simandou; Guinea; Ivory Coast; BIF

1. Introduction

Banded Iron Formations (BIFs) or BIFs are metamorphosed and laminated iron oxide formations in which cherts bands have been recrystallized into granular quartz, where iron is present as hematite, magnetite, and/or martite [1]. They are the most extensively studied of all iron formations, for several major reasons. Firstly, they are of great interest for their economic importance, as they are the world's largest source of iron ore [2]. Secondly, for their scientific importance, given their presumed role in the evolution of the oceans, the early atmosphere and the understanding of ancient geological systems [3]. Also iron ores (hematites, martites, goethites (≥56% Fe)) are the main source of iron for the world's steel industry. Finally, they constitute the main sulphide mineralized facies but also correspond to favourable traps for gold mineralization [4]. BIFs are the Earth's most important commercial source of iron ore, with some of the largest known deposits found around the Lake Superior region in the northern USA and Canada, in the Transvaal Basin in South Africa, in the Carajas Province in Brazil, and in the Hamersley Basin in Western Australia [5].

Sub-Saharan Africa is rich in iron deposits, with over 21 billion tonnes of iron ore in 1967. Ivory Coast contains huge reserves of iron deposits of economic interest, located in and around the Man region in the west. These iron formations are referred to as magnetite quartzites, the main ones being the Mont Klahoyo and Mont Tia deposits [6],[7],[8],[9],[10]. Similar iron formations (quartzites with magnetites) have also been identified in the Guinean part of the Nimba massif and the Simandou range [11],[12],[13],[14],[15],[16],[17]. For some researchers, these known iron formations in these

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two countries appear to be identical, as they consist of magnetite quartzite (itabirite) or ferruginous quartzite (BIF), of Archean and Paleoproterozoic age according to [13],[18],[19],[20],[21].

Furthermore, [9] suggests that they differ in terms of stratigraphic arrangement of layers as well as age, yet no study has yet been carried out between the iron deposits of Ivory Coast and Guinea. In view of this, we feel it is necessary to improve our knowledge by carrying out a comparative study between the banded iron formations (BIF) of Ivory Coast and those of Guinea, in order to understand their characteristics. The overall aim is to summarize the ribboned iron formations of Ivory Coast and Guinea.

2. Geological context of Ivory Coast and Guinea

2.1. Geology of Ivory Coast

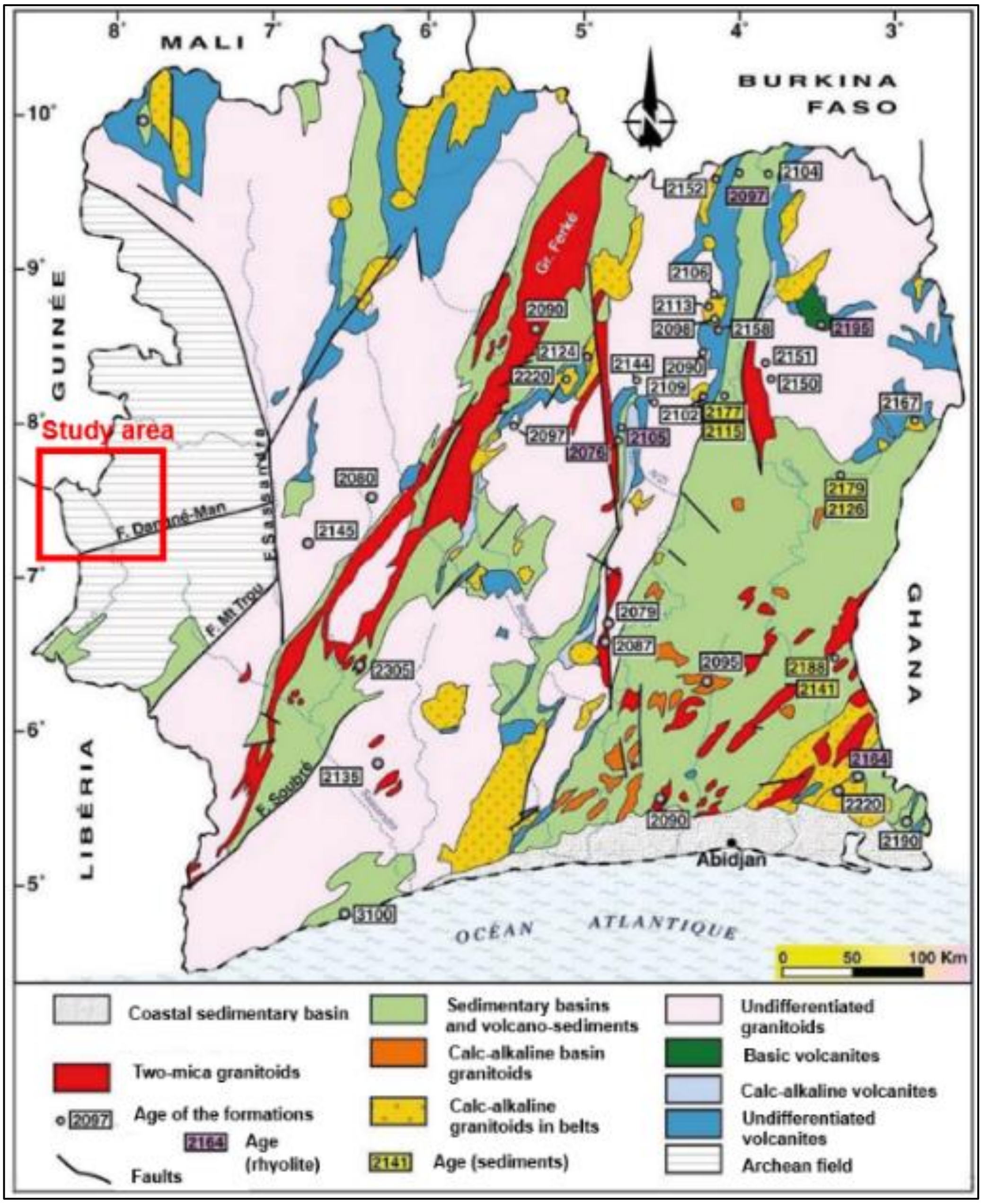

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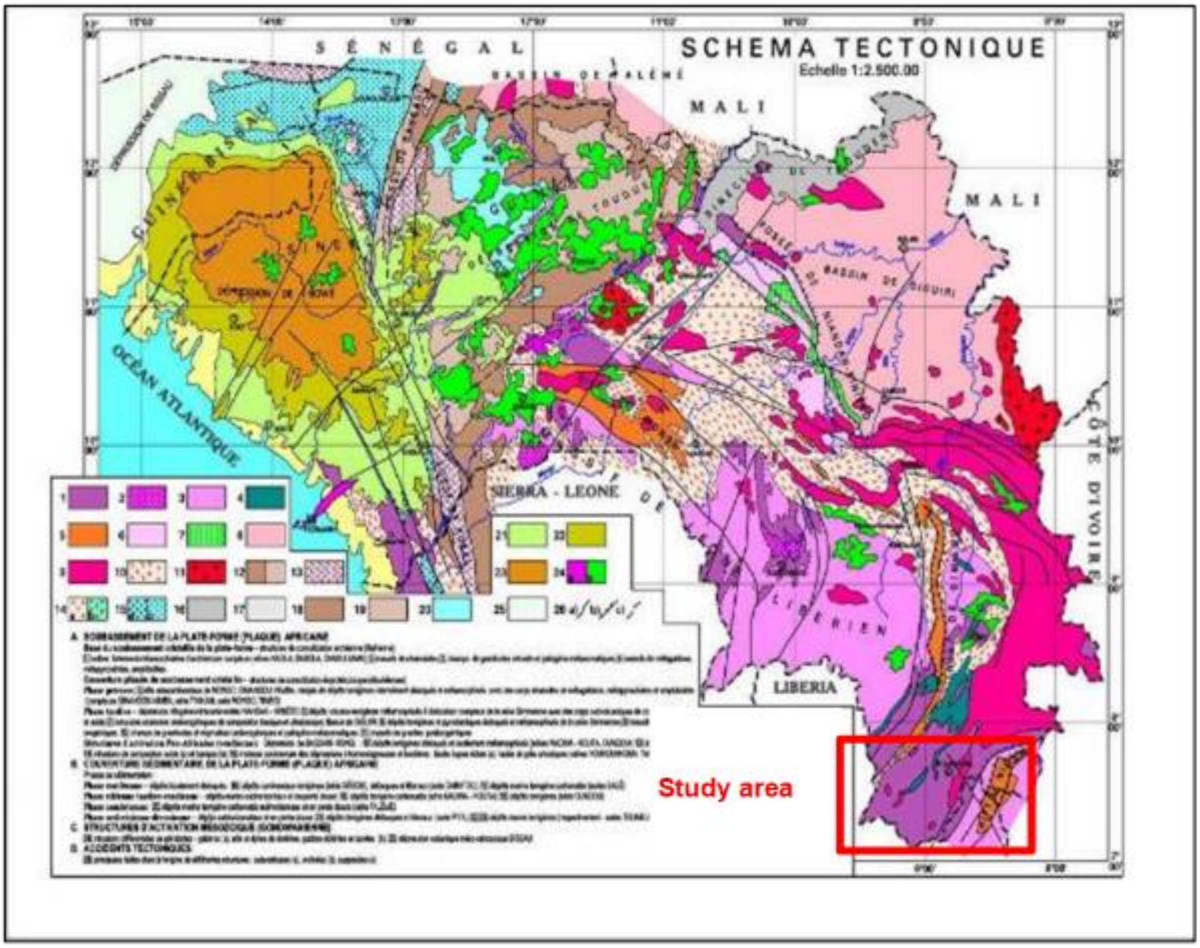
Figure 1 Simplified geological map of Ivory Coast [18] modified by [21]

Ivory Coast belongs to the West African Craton, specifically to the Man Ridge (Fig.1). Geologically, it is covered by two groups: the Precambrian basement, which accounts for around 97.5% of the surface area, and the sedimentary basin, which occupies 2.5% of the territory at the crescent-shaped southern end, stretching from Fresco to Axim (in Ghana) [22].

The Precambrian basement is made up of two major domains of different ages, separated by the Sassandra fault [23]: an Archean domain to the west, called the Kenema-Man domain, to which the study area belongs (Fig.1), and a Proterozoic domain to the east, called the Baoulé-Mossi domain. The Archean domain also covers the far west, a large part of Liberia, Guinea and the entire Serra Leone [21]. Geologically, it has been structured by two major orogenic cycles: the Leonian from 3.3 Ga to 3.0 Ga and the Liberian from 2.9 Ga to 2.7 Ga [18],[24],[25],[26],[27]. Petrographically, the Leonian domain is composed of four (4) lithological assemblages, namely magmatic grey gneisses and pink granulites, anatexites, ferriferous quartzites and intrusive charnockites. However, the Liberian domain is characterized by granulites, charnockites, migmatites, quartzites and amphibolo-pyroxenites [9].

2.2. Geology of Guinea



1. highly metamorphosed rocks, 2. charnockites, 3. intrusive granitoids, 4. metagabbros, metapyroxenites and amphibolites. 5 metagabbros, metapyroxenites and amphibolites, 6. volcano-terrigenous deposits, 7. basite and ultrabasite intrusions, 8. dislocated and metamorphosed terrigenous and pyroclastic deposits, 9. orogenic granitoids, 10. tardiorogenic granitoids and migmatites, 11. postorogenic granitoids, 12.terrigenous deposits, 13. volcano-terrigenous deposits, 14. Acidic (a) and basic (b) intrusions, 15. continental molasse, 15. continental terrigenous deposits, 17. marine terrigenous-carbonate deposits, 19. terrigenous-carbonate deposits, 19. terrigenous deposits, 20. marine terrigenous-carbonate deposits 21. deltaic and littoral terrigenous deposits, Marine terrigenous deposits, 24. peridotite-gabbro intrusions (a), Sills and dolerite dykes, doleritic gabbros and dunites (b) , 25. main faults: subvertical (a), dipping (b) and inferred (c)

Figure 2 Geological map of Guinea [19]

Like Ivory Coast, Guinea lies on the West African Craton, more precisely at the Man ridge, in the south-western part of the craton. Its geological structure comprises three stages: i) the crystalline platform basement (craton), ii) a folded platform cover comprising two distinct units, and iii) a flat-lying sedimentary cover consisting of numerous intrusions of basic and ultrabasic composition, as well as bodies of kimberlites [19] (Fig.2). This crystalline basement comprises an Archean, early Proterozoic and Pan-African phase. According to Mamedov et al. (2010), the crystalline basement of the bedrock is composed solely of Archean consolidation structures: Early Archean (lower) and Late Archean (upper). The study area in the N'zérékoré region belongs to the Archean domain (Kenema-Man), bounded to the west by the Todi shear zone and to the east by the Sassandra-Trou shear zone, which hosts the Simandou chain and the Pic de Fon deposit. Geologically, it is composed of BIF, metagabbros and orthogneisses of granitoid composition [19] and gneissic formations including the Guélématas gneisses (~ 3.5 Ga) [28].

3. History of work on banded iron formations (BIF) in Ivory Coast and Guinea

3.1. Work carried out on banded iron formations in Ivory Coast

A number of studies have been carried out on the iron deposits in and around Man (west of Ivory Coast).

Bolgarsky was the first to explore these regions during five missions carried out between 1932 and 1945, highlighting several lithologies containing iron formations. Subsequently, [29], using samples collected by Bolgarsky in western Ivory Coast, carried out a detailed petrographic study of the Man region and surrounding area, revealing the presence of iron formations. Between 1960 and 1962, as part of a major BRGM mission, Carrive studied several massifs, including those of the Dan (Sipilou region), Toura, Baoubly-Kiriao chain and Touba region. His work revealed the most promising showings in the Baoubly-Kiriao chain (Mount Klahoyo iron deposit) and its extension towards Mount Gao. In 1962, Spindler, on the recommendation of BRGM, took up his predecessors' work in the Eburnian part of the Nimba Mountains and supplemented it with an in-depth study combining aerial magnetic prospecting, photogeological analysis and ground prospecting. He concludes that only the titaniferous magnetite lenses of the Dan Mountains massif and certain itabirites of the Nimba Mountains show significant concentrations of iron ore, while emphasizing the absence of high-grade deposits at either surface or depth in this area. [18], in his structural sketch of Ivory Coast, suggests that the ferruginous quartzites of western Ivory Coast are contemporaneous with those of the Simandou chain in Guinea. These formations, homogeneous and 150 to 400 meters thick, are interbedded, folded and recrystallized in amphibolite and sometimes granulite facies. [30] work on Mount Klahoyo identified eight stratigraphic units, of which only the oxidized-facies magnetite-quartzite units constitute the most important ores in the deposit. Finally, [9], through his petrographic and geochronological study of Archean granulite assemblages and associated formations in the Man region, showed that magnetite quartzites share similarities with those described by [1], distinguishing two main deposit types: Mount Klahoyo and Mount Tia, whose magnetite quartzites are referred to as itabirites due to their mineralogical composition.

[31] indicates that magnetite quartzites originate from fine sedimentation in a quiet environment, made possible by the reducing atmosphere of the Precambrian, which allowed the iron derived from alteration of the substratum to remain in the ferrous state and be transported in the form of soluble complexes to the sedimentary basins. According to [10], only magnetite quartzites, or itabirites, make up the bulk of the Mount Klahoyo iron deposit, these formations being associated with felsic migmatitic gneisses (FMGs) and amphibolo-pyroxenites. [32], following his study of the magnetite formations in the Danané-Biankouma region (Yepleu-Bounta sector), concludes that these formations have strong petrographic, metallographic and metamorphic similarities with the Klahoyo and Tia deposits, while differing in their mineralogical composition and the nature of their host rocks. The author suggests that these similarities testify to emplacement in the same geodynamic context and confirm the existence of a manganiferous province in western Ivory Coast, extending from the Man region to Biankouma.

3.2. Work on banded iron formations in Guinea

The Republic of Guinea has significant mineral resources, including iron, aluminum, gold and diamonds, as well as other useful minerals such as nickel, uranium, titanium, copper, platinoids, chromium, corundum, graphite, talc, monazite and topaz. These riches have attracted the interest of numerous companies who have come to explore the country's main resources. [11] distinguish two lithotectonic units at the origin of the Nimba and Simandou mountains: one plutonic and the other volcano-sedimentary, separated by tectonic contacts, and conclude that they are lithologically and geochronologically similar. In 2009, a feasibility study carried out by BSG Resources Limited on the Zogota iron deposit revealed that it results from the lateritization of subvertical itabirite units forming the backbone of the Zogota ridge, considered to be the natural extension of the Simandou chain. [19], as part of a study commissioned by the Guinean Ministry of Mines and Geology, showed that the main iron showings are concentrated on the Simandou-Nimba ranges and their southern extension, while highlighting the main useful minerals in the Archean part of the territory, where iron is associated with the magnetite quartzites of the Kasila and Kambui series. [33] indicate that the itabirites of the Nimba and Yekepa region (Tokadeh-Gangra-Yeulliton) correspond to recrystallized iron oxide formations, composed mainly of quartz, magnetite and/or hematite, probably derived from the chemical alteration of upper metavolcanic rocks. Mamadou et al (2011) identified Late Archean and Early Paleoproterozoic ribboned itabirites (magnetite quartzites) on the Nimba and Simandou mountains. Finally, [13] distinguished two groups of rocks within the iron formations of the Nimba range and its western extension: (i) magmatic and ortho-magmatic rocks (gneisses, granites, amphibolites and quartzites) of Archean age and (ii) Proterozoic rocks of metasedimentary origin.

Their petrographic and metallogenic work revealed two types of banded iron formations: silicate (SIF) and oxidized (OIF), containing minerals such as magnetite, hematite, pyrite, goethite, martite and siderite, and dating from the Proterozoic.

4. Methodology

Field petrography consisted in describing the lithological units observed on the various outcrops and drill cores. This description enabled rocks to be identified on the basis of several criteria, including texture, structure, mineralogical composition, color and lithological family. Representative samples were taken from various outcrops in Ivory Coast and Guinea. Thin sections prepared from these samples were used to determine the mineralogy of the rocks and specify their origin. The mineralogical assemblages observed complemented the macroscopic observations and helped refine the rock classification. Metallographic microscopy was also used to identify the various iron minerals present. Measurements of orientation (alpha and beta angles) and dips of primary and secondary structures were carried out on drill cores from Guinea, while in Ivory Coast, structural analysis was carried out directly on outcrops. The data obtained was then processed using Stereonet stereographic software, in order to interpret the various structures. Finally, major and trace elements were determined by X-ray fluorescence spectrometry (XRF) and inductively coupled plasma atomic emission spectrometry (ICP-AES).

5. Results

5.1. Petrographic and structural data of Ivory Coast BIFs

5.1.1. Petrographic data

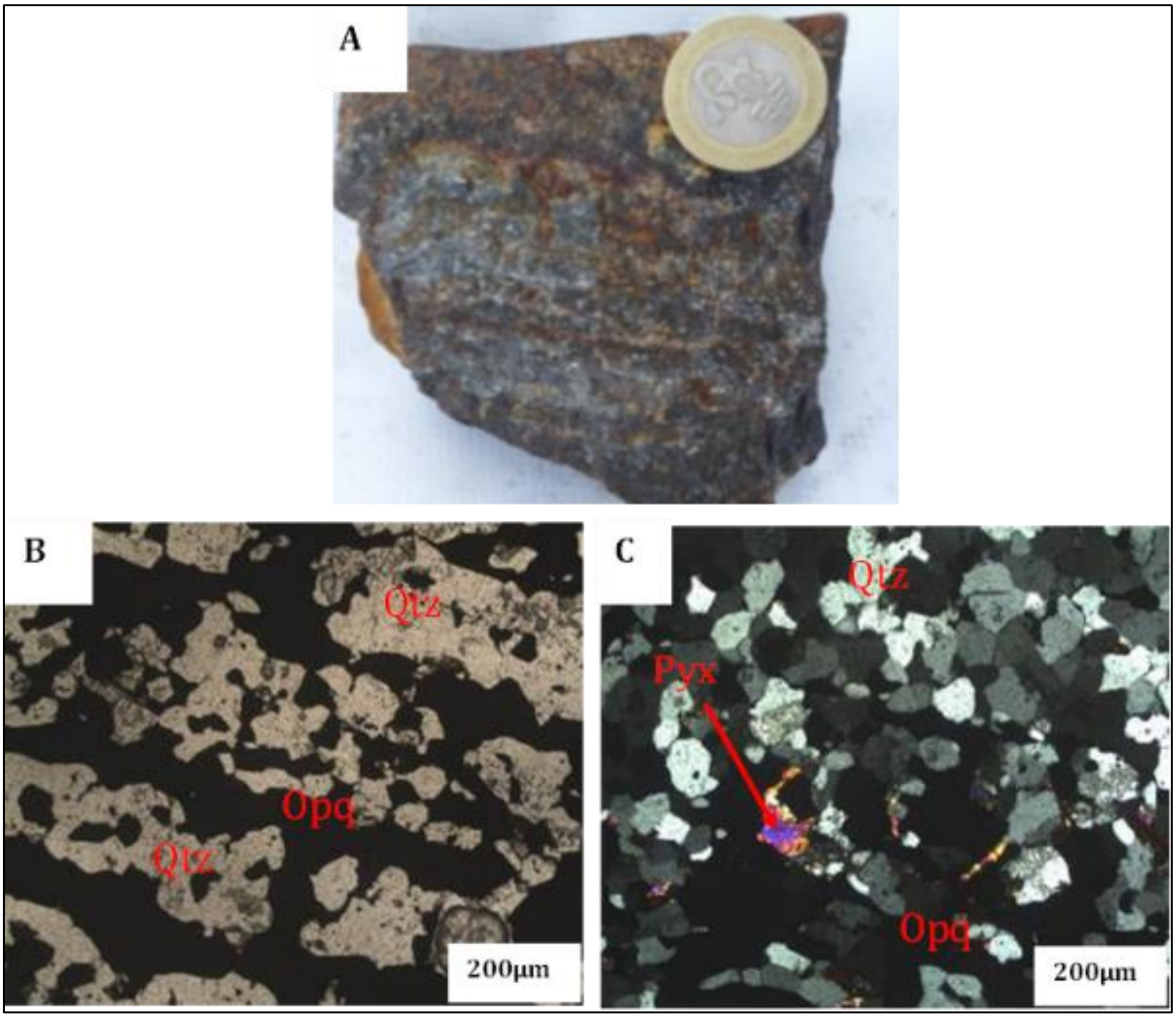
The geology of Mount Klahoyo consists of magnetite-bearing quartzite (itabirite) hosted in a band of felsic migmatitic gneiss. The deposit is Archean in age, with reserves estimated at around 700 million tonnes (Mt), for 32.72% Fe [9]. In addition to this host rock, other formations associated with the magnetite quartzites include amphibolo-pyroxenite, garnet gneisses, garnet pyroxenites, granites and garnet hypersthenites [6],[9],[10],[30]. According to [9], the Mount Klahoyo and Tia deposits are lithologically similar.

Magnetite quartzite

It is the host rock of iron ores. It has a massive, gray to whitish-gray appearance. It is characterized by alternating light bands of quartz minerals and dark bands of iron oxides (magnetite or hematite and/or goethite or limonite) (Fig.3A). Microscopically, the rock has a bedded texture (Fig.3B and C), consisting mainly of quartz, iron oxides and pyroxene [9],[10].

Amphibolo-pyroxenites

It is a massive, greenish-grey rock with an equant structure and minerals visible to the naked eye (Fig.4A). In places, it is associated bed by bed with quartzites [6],[9],[10]. Macroscopically, the minerals observed have a granoblastic texture (Fig.5B), composed in order of abundance of: amphibole, pyroxene, biotite, feldspars, orthoclase, opaque minerals and rarely quartz (Fig.4B;C and D).



Qtz: quartz, Pyx: pyroxene, Opq: opaque minerals.

Figure 3 Macroscopic and microscopic appearance of magnetite quartzites [10]. (A). Macroscopic sample of magnetite quartzites; (B). Alternating light and dark beds at LN microscopy; (C). Alternating light and dark beds at LP microscope.

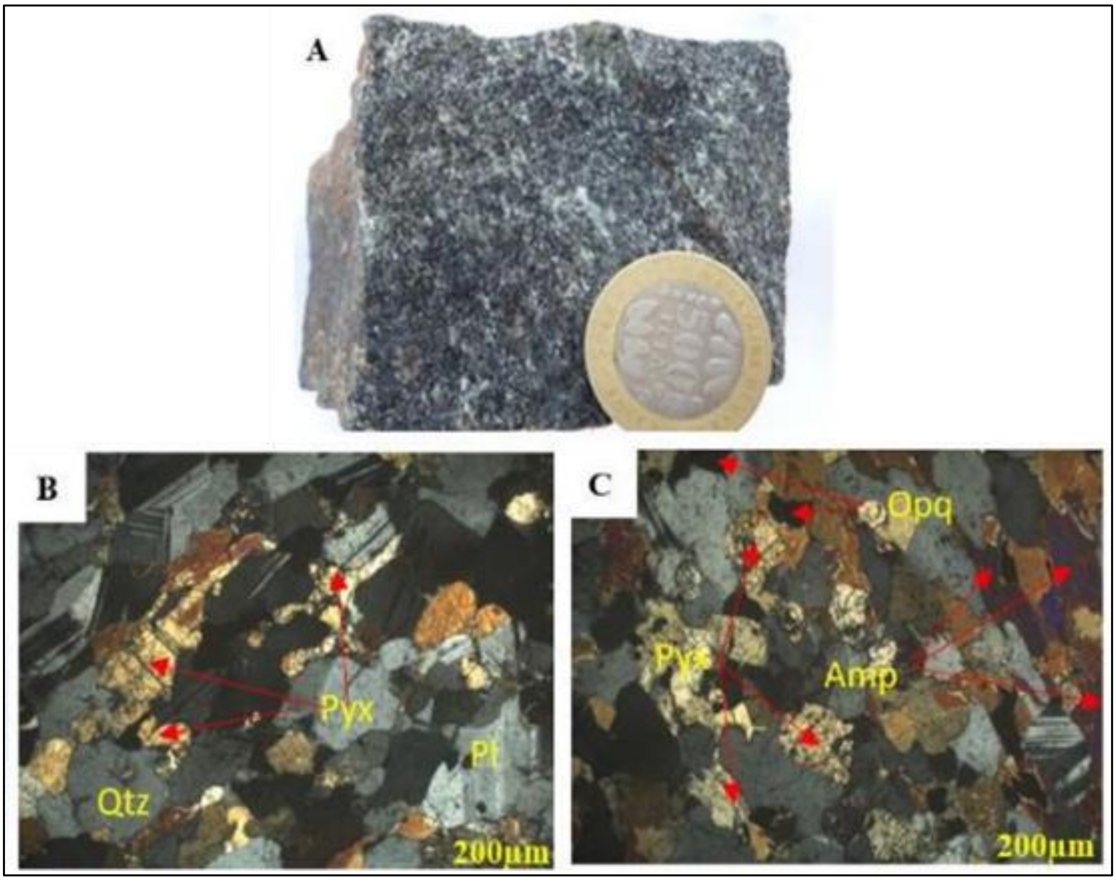


Figure 4 Macroscopic and microscopic appearance of amphibolo-pyroxenite [10]. (A). Macroscopic sample of amphibolo-pyroxenite; (B). Pyroxene in association with plagioclase and quartz and (C). Pyroxene in association with amphiboles. Qtz: quartz, Pl: plagioclase, Amp: amphibole, Pyx: pyroxene, opq: opaque minerals

Garnet gneiss

It is a massive rock with a foliated structure consisting of alternating light and dark bands (Fig.5A). The light bands are rich in felsic minerals (quartz and feldspars) and the dark bands rich in ferromagnesian minerals (biotite and amphibole) [10]. Garnet crystals are scattered throughout the rock. Microscopically, it has a granolepidoblastic texture composed of: quartz, plagioclase, biotite, microcline, garnet, sericite, chlorite and opaque minerals [10].

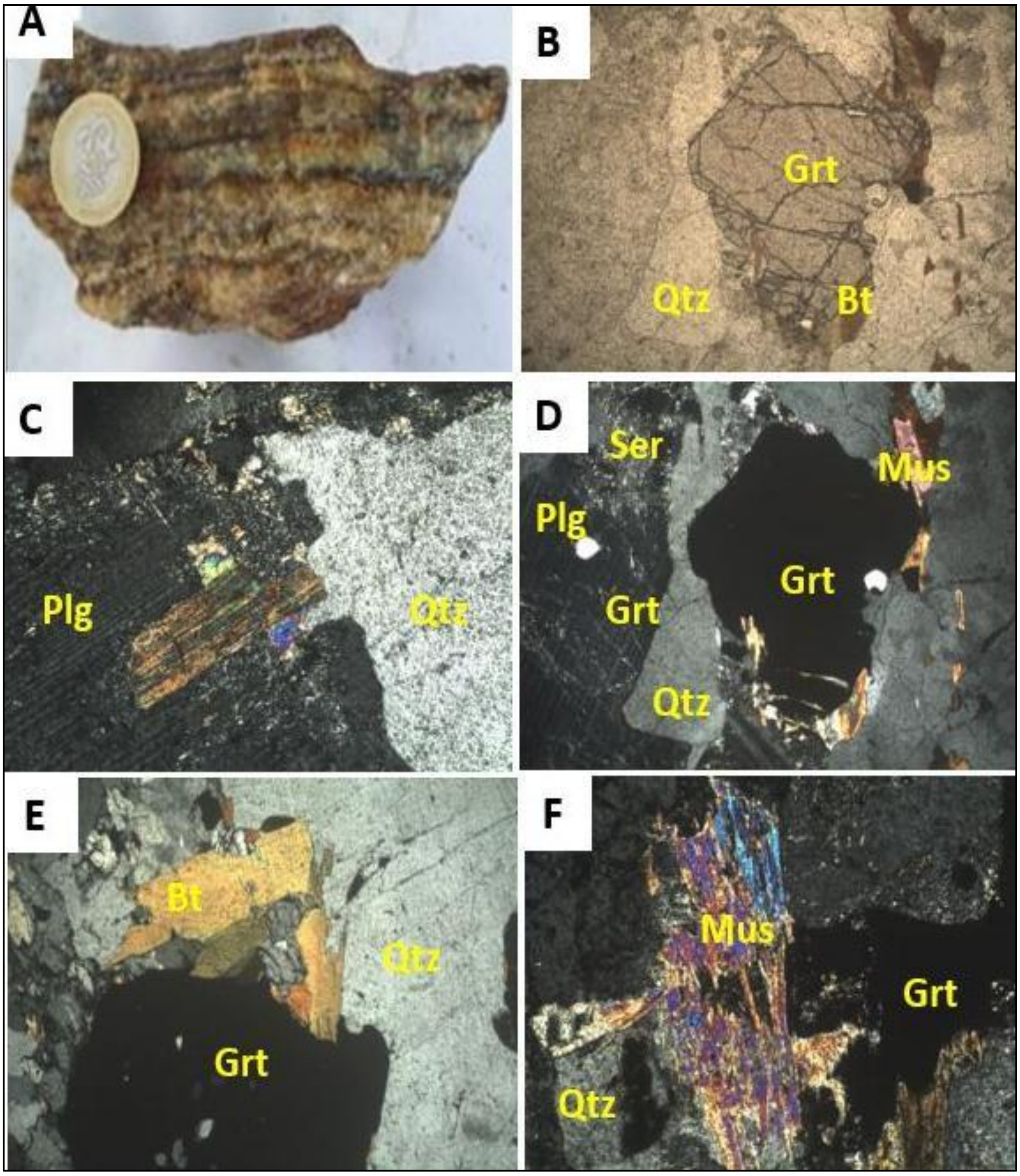


Figure 5 Macroscopic and microscopic appearance of garnet gneiss [10].. (A). Macroscopic sample, (B). Microphotograph seen in LPNA. (C). Microphotograph seen in LPA showing the association of plagioclases with quartz, (D). LPA microphotograph. (E). Microphotograph seen in LPA rich in quartzo-feldspar. (F): Microphotograph seen in LPA with a muscovite phenocrystal

Garnet granite

It is a massive, leucocratic rock with a grainy texture (Fig.6). These minerals are visible to the naked eye. Microscopically, this rock has a grainy texture. It consists of quartz, biotite, feldspar and garnet crystals scattered throughout the rock.

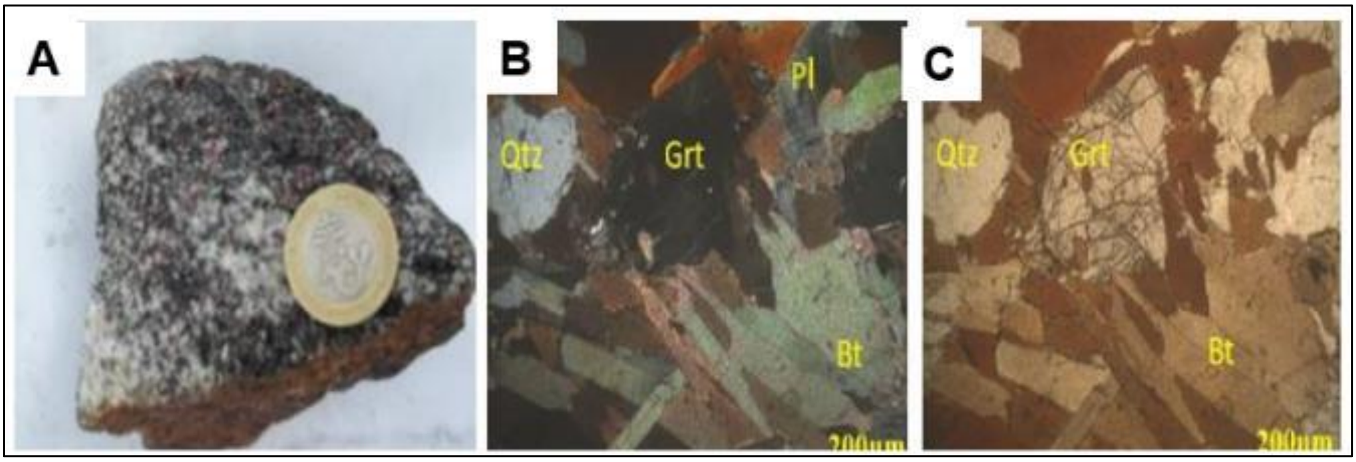


Figure 6 Macroscopic and microscopic appearance of garnet granite [10]. (A). Macroscopic appearance; (B). Microphotograph seen in LPA and (C). Microphotograph seen in LPNA. Qtz: quartz, Pl: plagioclase, Grt: garnet, Bt: biotite, Opq: opaque minerals

Garnet hypersthenite

It is a massive rock composed of quartz and hypersthene, to which garnet and traces of grünerite are added [6],[9]. It occurs within granulite gneisses and is finely associated with magnetite quartzites. Microscopically, it has a granoblastic texture.

5.1.2. Metallographic data

Metallographic analysis was carried out mainly on quartzites with magnetites. The samples were taken from [10]. Observations were made on three polished sections: KM 05, KM 22 and KM 07. Microscopically, we highlighted two facies: the oxidized facies (magnetite and hematite) and the sulfide facies (pyrite and chalcopyrite) (Fig.7).

Magnetite

Magnetite is present on two slides (MK 07 and MK 22) analyzed (Fig.7A,D and F). It is the main iron ore in the magnetite-bearing quartzites of Mount Klahoyo. It has a gray-brown hue and an automorphic form, with some subautomorphic to xenomorphic sections. It has low reflectivity. It appears on these two slides in association with hematite.

Hematite

It is mainly found on the MK 05, followed by the MK 07 blade (Fig.7D and F). It has a light gray to white hue and low reflectivity. It has an elongated shape and is always associated with magnetite. It is the second most iron-rich mineral after magnetite.

Pyrite

Pyrite is the most disseminated and abundant sulfide facies (Fig.7E). It accounts for some 80 to 85% of the sulfides present and comes in a variety of forms. It often occurs as rod and xenomorphs, disseminated or remobilized along the foliation plane in the host rock. These pyrite crystals are oriented in a well-defined direction. It has a yellowish hue.

Chalcopyrite

They are generally found in association with pyrite (Fig.7C and E). Chalcopyrite occurs as fine xenomorphic grains, sometimes elongated (Lame MK 07).

Ilmenite

Ilmenite ($FeTiO_3$) or titanium-bearing iron occurs as a grey flake with brownish tips (Lame MK 07) (Fig.7E).

5.1.3. Structural data

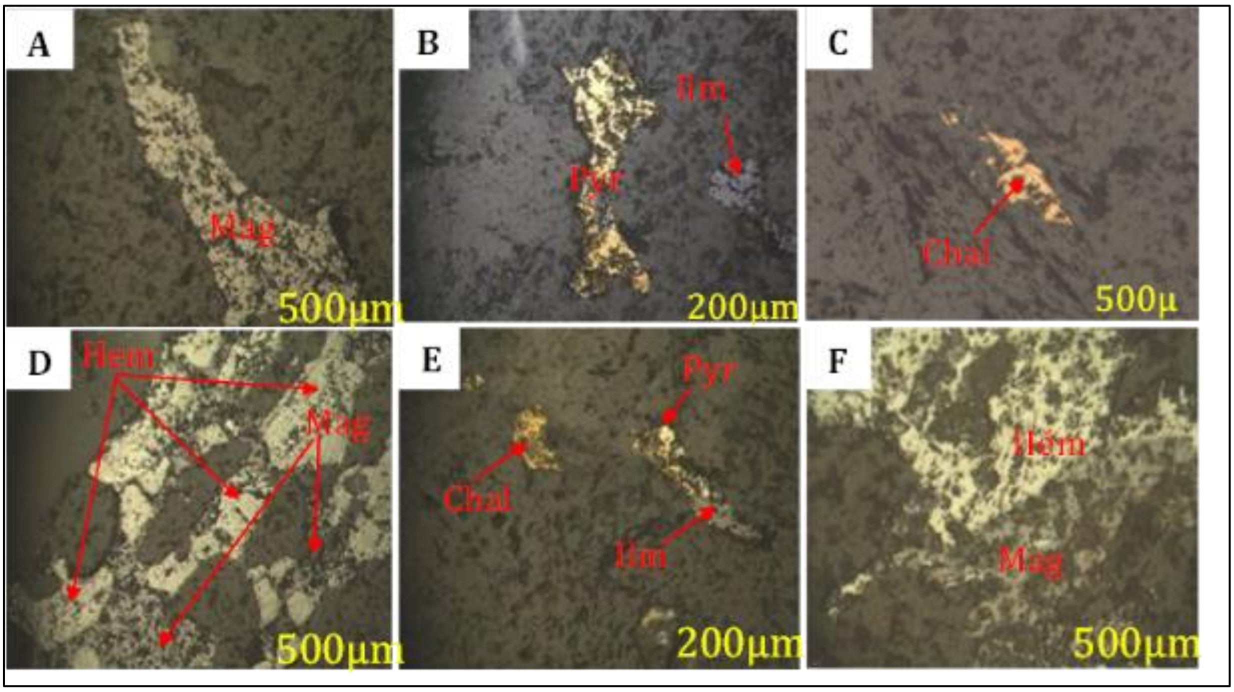


Figure 7 Metallogenic microscopic view of MK07 and MK05 magnetite quartzite thin secttions (A). Oriented magnetite, (B). Pyrite in association with ilmenite; (C). Oriented chalcopyrite;(D). Hematite in association with magnetite; (E). Xenomorphic chalcopyrite; (F). Hematite. Mgt: magnetite, Pyr: pyrite, Hem: hematite and Chal: chalcopyrite, Ilm: ilmenite

Bedding and foliation

Stratification (S0) is formed by alternating light bands of quartz and dark bands rich in magnetite-hematite-goethite-limonite ± martite in the itabirites of Mount Klahoyo [10]. These planar structures are oriented NNE-SSW. They dip subvertically or hang 60-80° to the east or southeast (Fig.8C and D). The foliation in the zone is subparallel to bedding and sometimes affected by crenulation schistosity (Fig.10B). This schistosity is the result of two successive tectonic phases: firstly, the emplacement of a first schistosity (S1), oriented NE-SW, during initial deformation and, secondly, the superimposition of a second schistosity (S2) oriented NW-SE. The crenulation schistosity in the quartzites is oriented N150° with a subvertical dip (Fig.8E and F).

Folds

Several types of folds have been observed in the area. These are similar (Fig.8A), antiformal and synformal folds with axes dipping generally to the northeast and southeast. These folds, like the foliation, are set up by a flattening mechanism [10]. Entrainment folds and chevron folds (Fig.8B) with axes dipping 10˚ to the southwest are observed. The observation of these folds testifies to ductile shearing in the area. Similar asymmetric Z-type folds (Fig.8C) are also encountered [10],[30].

Mineral stretch lineation (Lm) and intersection lineation (L1-2)

The mineral stretch lineation (Lm) is common in magnetite quartzites. It is oriented from 20 to 60°NNE and 60°SSW (Fig.10A) [10]. It is derived from ductile shearing, reflecting transcurrent movement along the sinister shear corridor. The line of intersection between S1 and S2 (L1-2) dips 67° to the SSE (Fig.10B) [10].

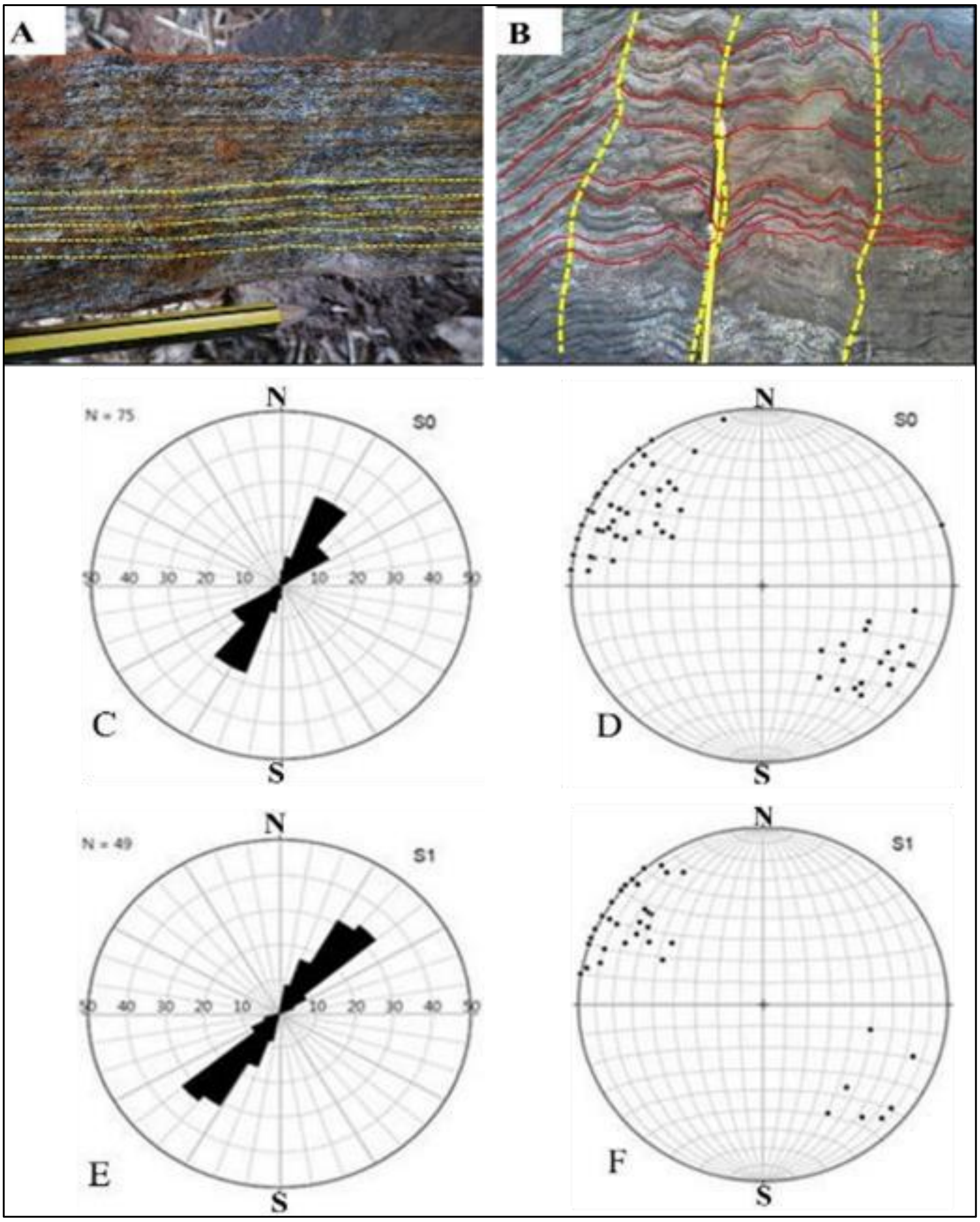


Figure 8 Photograph and stereographic projections of structures observed in magnetite quartzites [10]. (A). S0 observed in the itabirites; (B). S1 observed in crenulation schistosity; (C). Directional rosette of the S0 showing NNE-SSW orientation; (D). S0 dipping (WNW-ESE), (E). Directional rose of S1 showing NE-SW orientation, (F). Dip of S1 (NW-SE)

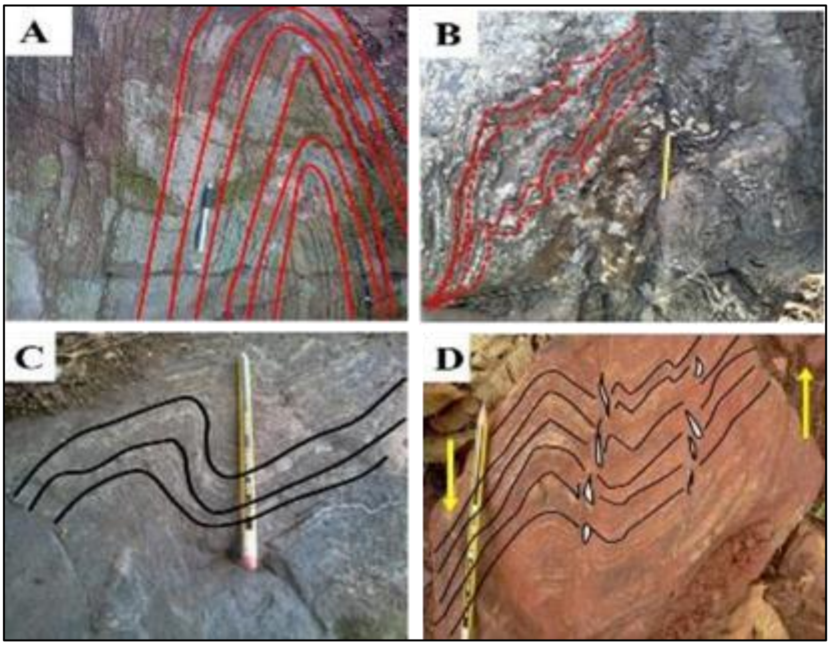


Figure 9 Different structures observed in itabirites [10]. (A). Similar folds; (B). Herringbone folds; (C). Similar asymmetrical Z-type fold; (D). Tension veins developed in a sinister crenulation schistosity

Fractures et faults

Fracturing materializes the major brittle deformation undergone by the formations in the area. In order to better identify the variations in fracture and fault directions on Mount Klahoyo, directional fracture and fault rosettes have been produced [10]. A global fracturing rosette is also produced to highlight the overall direction of the zone's fractures. At Mount Klahoyo, the main fracture direction is NNW-SSE [10]. This direction is complemented by a NNE-SSW direction. The itabirites in this sector have been affected by a sinister strike-slip fault (Fig.12). This fault is oriented N040°, 70°SE associated with a shear corridor (Fig.12). The various faults and fractures intersect and offset the formations in a NNE-trending sinister movement and NW-trending dexter movement (Fig.12C) [10].

Quartz veins and joints

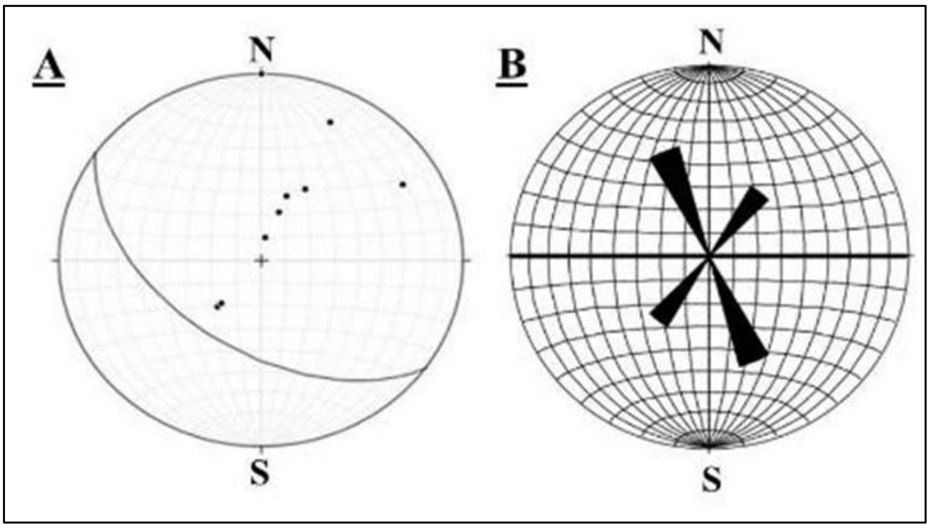


Figure 10 Stereographic projections of lineations [10](Minougou, 2017). (A). Mineral lineation of magnetite quartzites; (B). Directional rosette of the intersection lineation (L1-2) showing the NNW-SSE main orientation of the magnetite quartzites

Quartz veins are the most observable in the study area. Direction measurements obtained are NNE-SSW and NNW-SSE with dips of 70-90° (Fig.11) [10]. Three (3) categories of joints [30]: (i) vertical to subvertical joints, (ii) subhorizontal or flat joints, and (iii) slightly inclined joints. These joints are perpendicular or almost parallel to the foliation. These structures intersect and offset the formations in a sinister direction [33].

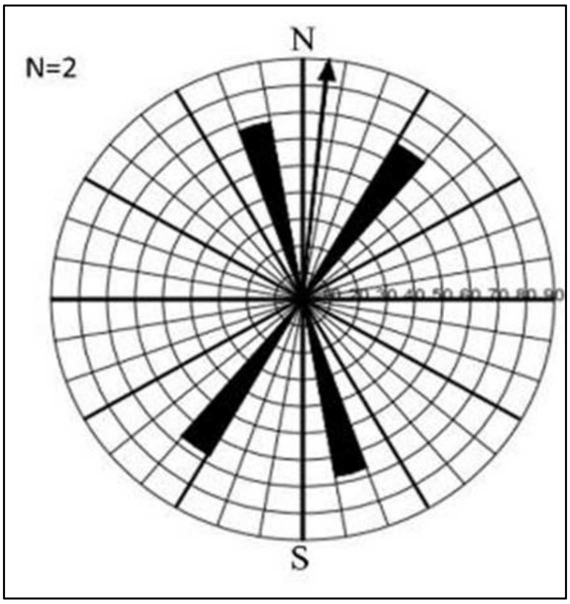


Figure 11 Stereographic projections of veins [10]

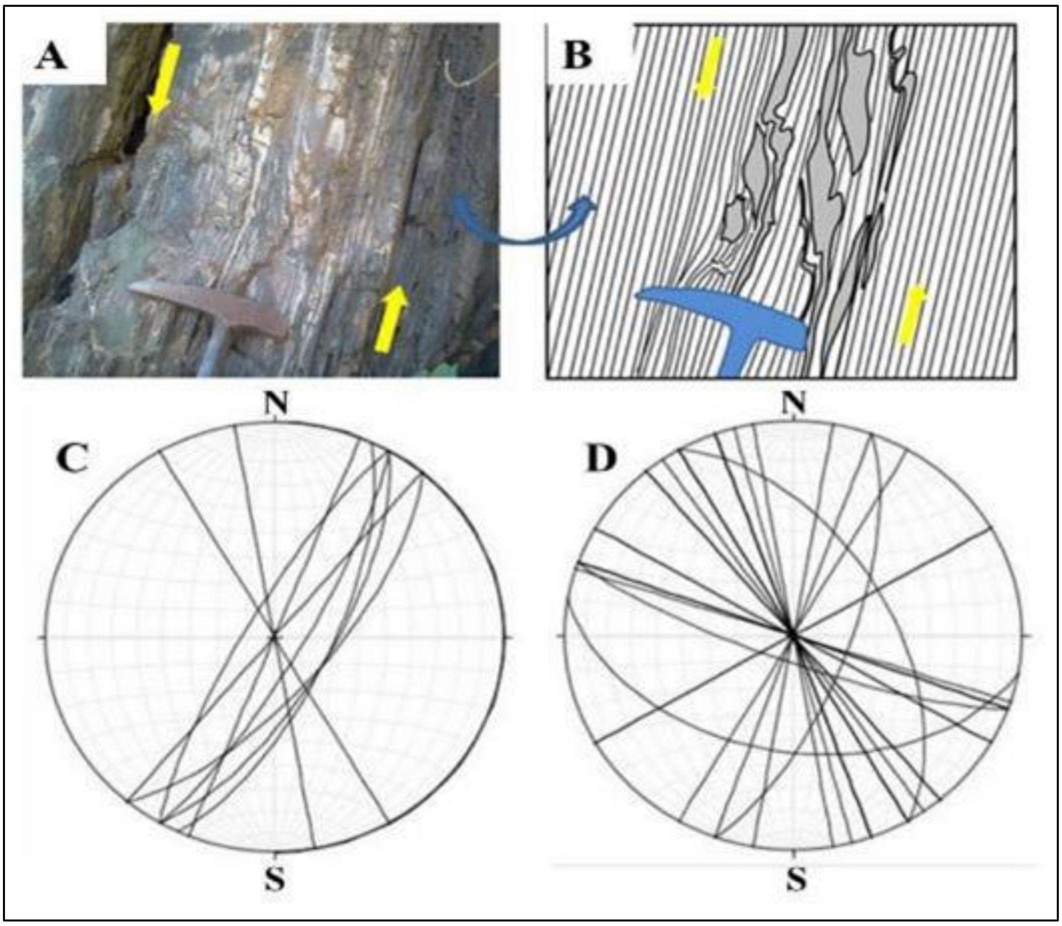


Figure 12 Photograph and stereographic projections of the structure observed in the magnetite quartzites with a sinister set. (A) orientation sinister set fault (N040, 70°SE); (B) fault drawing, (C) stereographic projection of shear zones, (D) stereographic projection of faults and fractures [10]

5.2. Petrographic and structural data for Guinea's BIFs

5.2.1. Petrographic data

Itabirites

These are the rocks themselves that contain the iron ores in this area of Guinea. According to [13], the itabirites of the Nimba Range correspond to those defined by [1],[34]. These itabirites are metamorphosed and laminated iron oxide formations in which, on the one hand, cherts or jasper bands have been recrystallized into granular quartz and, on the other hand, in which iron is present in the form of hematite, magnetite, and/or martite. In addition, microscopic studies carried out by [13] have identified several types of itabirites: garnet itabirites, garnet-granite itabirites, transition zone itabirites and chloritic itabirites (Fig.13). Under a polarizing microscope, they consist of quartz, magnetite, pyrite, hematite, brown amphibole, grünerite, biotite (chlorite) and pyroxene (hypersthene) [13].

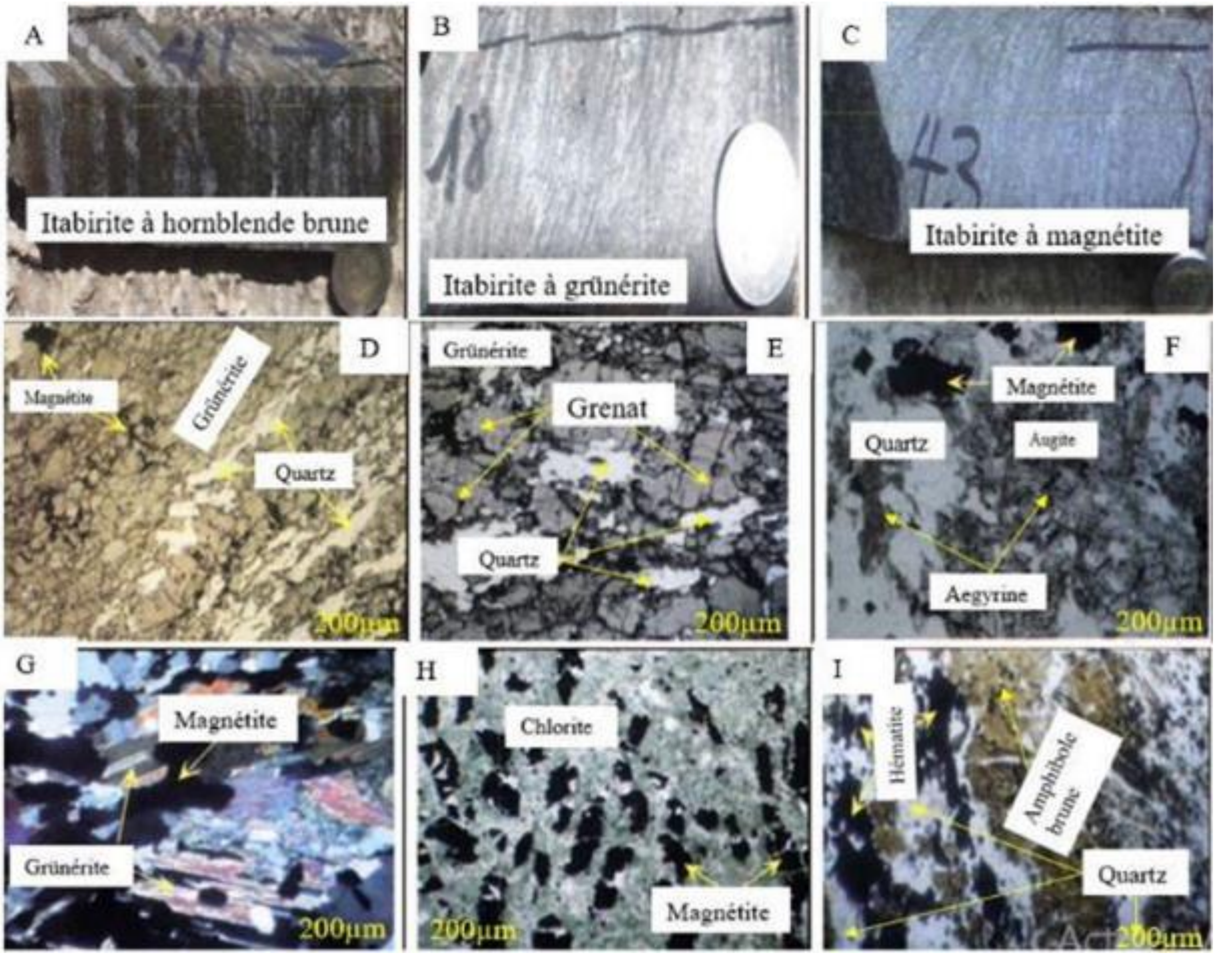


Figure 13 Microscopic appearance of different itabirites from Mount Tokadeh (western extension of Mount Nimba). (A). Brown hornblende itabirite; (B). Itabirite with grünerite and magnetite; (C). Alignment of grünerite, garnet, quartz and magnetite crystals in grünerite itabirite;(D). Xenomorphic garnet crystals surrounded by fine to medium grünerite grains in grünerite itabirite; (E). Grünerite itabirite showing frequent macular crystals (LPA);(F,H). Chlorite itabirite showing fine to medium magnetite grains in a chlorite matrix (LPNA);(G,I). Brown hornblende itabirite showing an alignment of quartz brown hornblende and magnetite (LPNA)

The itabirites of the Simandou chain are the product of metamorphism of ferruginous quartz sands accumulated with clayey sediments in the shallow rift basin [35]. According to [35] known deposits and showings in this chain are polygenetic in nature and are characterized by the presence of two main ore types: primary (magnetite) and secondary (hematite, goethite and sometimes limonite). Microscopically, these rocks are composed of cryptocrystalline quartz and magnetite.

- **Chlorite schists**

Chlorite schists consist mainly of chlorite crystals, associated with quartz, zircon, apatite and uraninite (Fig.14A). These chlorites are subautomorphic showing pleochroism, green, blue and purple, with medium to coarse grains [13]. The source rock is a pelitic sedimentary rock.

- **Micaschists**

Micaschists occur in three facies: chlorite micaschists (Fig.24B), biotite and garnet micaschists (Fig.14C) and biotite, garnet and sillimanite micaschists (Fig.14D).

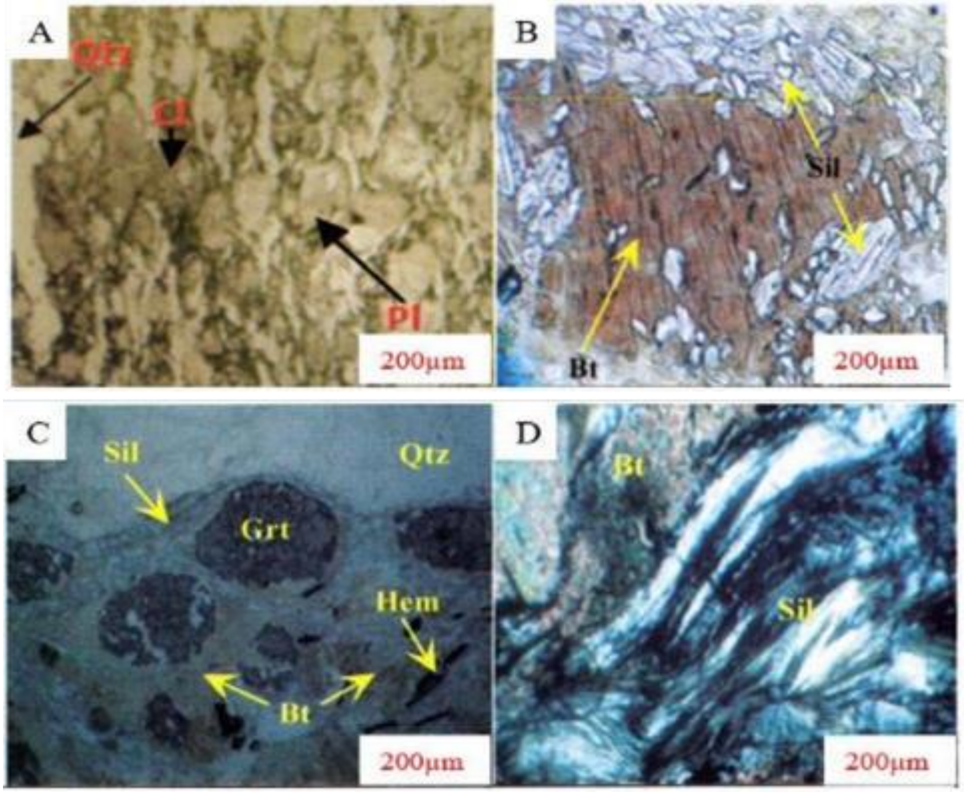


Figure 14 Microscopic appearance of schists and micaschists. (A). Chlorite schist (Chl); (B). Biotite (Bt) and sillimanite (Sil) micaschist; (C). Garnet micaschist (Grt); (D). Micaschist with biotite and fibrous sillimanite

Microscopically, these rocks are composed mainly of biotite, garnet, sillimanite and quartz. Biotite is subautomorphic, usually embedded in large chlorite and quartz crystals. Some biotite crystals show symplectite figures with quartz, which may mark the onset of partial melting or anatexis (Fig.14A). Sillimanite is very abundant in most of the thin sections analyzed. It appears as colorless fibrous rods contrasting with colored biotite crystals (Fig.14B and D).

Gneiss

Two types of gneiss have been identified in the study area, specifically in the Tokadeh Range [13] paragneiss and orthogneiss. Paragneisses are derived from the metamorphic transformation of schists, giving the rock the name schiste gneissique. They are rich in feldspars (orthoclase and microcline), with a reddish color known as red or potassic gneiss. Orthogneiss, on the other hand, comes from the metamorphic transformation of pre-existing granitoids in the basement. In fact, they have the same petrographic and mineralogical characteristics as granites (felsic or white gneiss). Microscopically, orthogneisses are essentially composed of quartz, plagioclase, microcline, biotite, chlorite, muscovite, epidote, anthophyllite and garnet, with accessory opaque minerals.

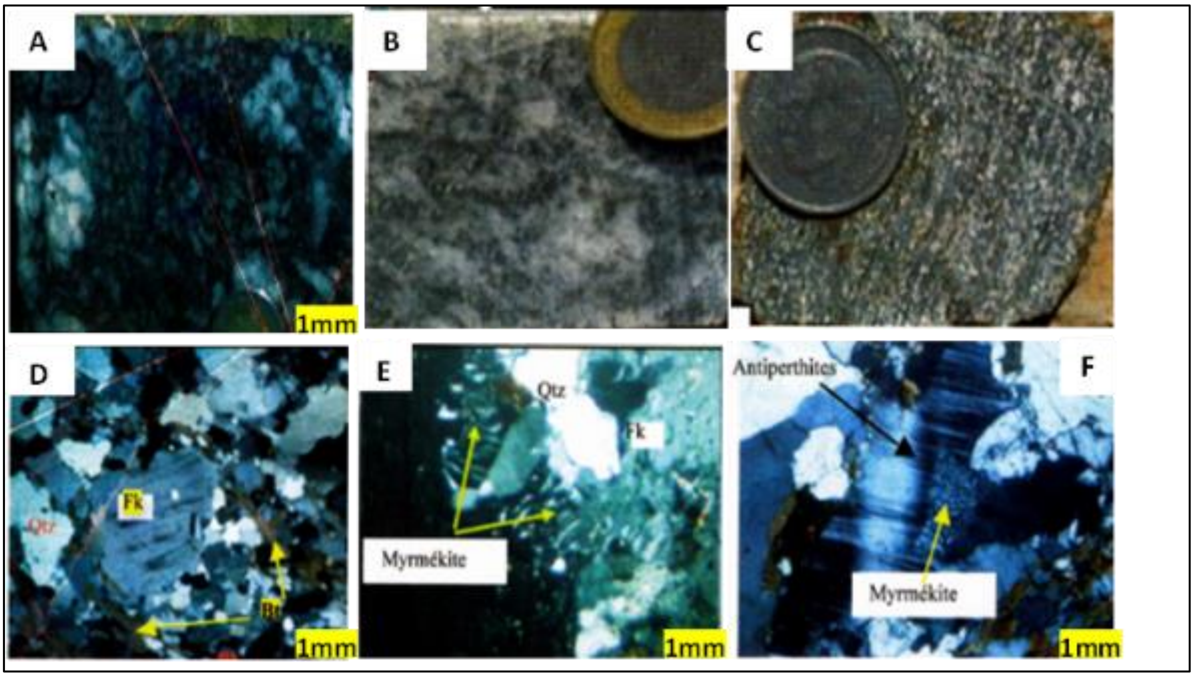


Figure 15 Microscopic appearance of Tokadeh orthogneiss and metagneiss. (A). Gneissic schist; (B). Gneissified granite (Orthogneiss); (C). Orthoamphibolite; (D). Reorientation of biotites, potassium feldspars, quartz recrystallization; (E). Symplectic or myrmekite association of orthogneiss; (F). Plagioclase in fine orthoclase flecks (antiperthites) and potassium feldspars in streaks

In these gneisses, quartz is found in symplectic or myrmekite association (Fig.15E and F). It occurs in the form of fine vermicules, localized at the edges of large feldspar crystals (orthoclase, microcline, but often plagioclase). Microscopically, the plagioclase is rich in fine orthoclase flecks (antiperthites) and the potassium feldspars in albite streaks. Myrmekites are also present (Fig.15E).

Phyllites

According to stratigraphic data from this area, phyllites are rocks underlying itabirite. They can be observed at three levels. First, basal phyllites are represented by very fine-grained, dark greenish-grey pelites, with minor intercalations of quartzite and itabirite. This is followed by very fine-grained, medium to pale greenish-gray phyllites with locally deformed quartz bands/veins. Finally, there are iron oxide-banded phyllites, with a medium to dark brownish-red color and fine iron oxide bands.

Quartzites and cherts

The quartzites and cherts of Mount Simandou are the basic formations on which the itabirites abut. These formations are closely associated with the basal phyllites. Microscopically, the quartzites have a granoblastic texture, consisting of quartz, garnet, pyroxene and opaque minerals. Similarly, cherts are composed of silica or microcrystalline quartz.

Amphibolites and pegmatites

These formations are less abundant in the Tokadeh-Beeton-GangraYeulliton chain. They are intercalated in the gneissic basement.

The amphibolites in this area derive from the regional metamorphic transformation of basic gabbro-type rocks (orthoamphibolite) in the Nimba region. They occur as dykes (Fig.16A). Microscopically (Fig.16B and 16C), these amphibolites consist of amphibole, plagioclase, biotite, chlorite, hypersthene, diopside, epidote, quartz, sericite, apatite, muscovite and opaque minerals. Amphiboles account for over 50% of this rock.

The pegmatitic facies takes the form of a vein or dyke (Fig.16D) that is genetically related to the granitic pluton. It is formed of residual water-rich liquid from the final crystallization of granitic magma. The presence of water facilitates the diffusion of chemical elements, enabling the growth of large crystals. Microscopically (Fig.16), pegmatite from a

320m-deep core hole on Mount Tokadeh is composed of large minerals: quartz, plagioclase, microcline, muscovite, biotite and opaque minerals [13].

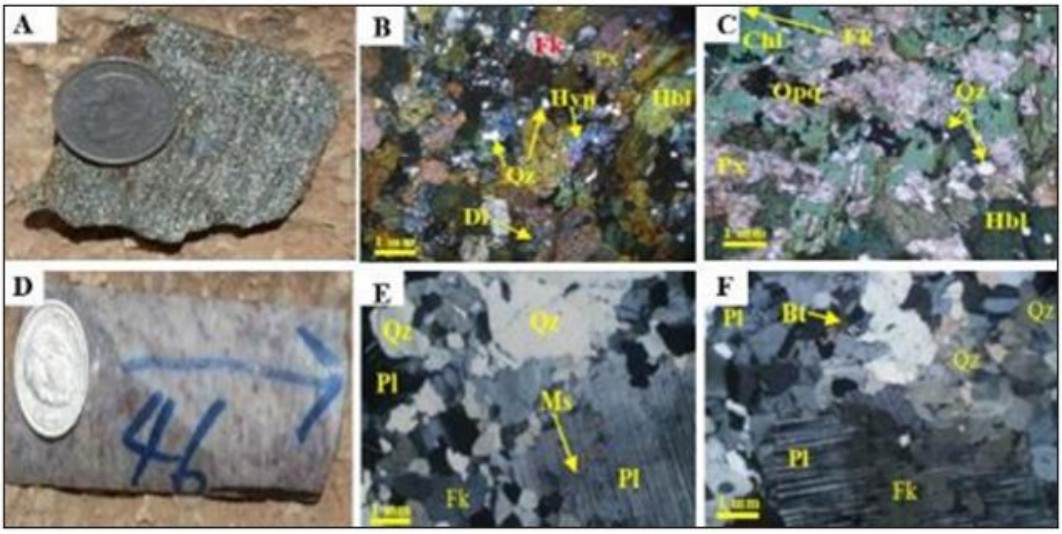


Figure 16 Macroscopic and microscopic aspects of amphibolites (A) and pegmatites (D). (A). Macroscopic aspect of an amphibolite dyke; (B) and (C). LPA microphotograph of the amphibolitic dyke. (D) Macroscopic aspect of a pegmatite dyke; (E) and (F) LPA microphotograph of the pegmatitic dyke

Granites

They are abundant in the Nimba region (sub-prefectures of Tounkarata, N'Zoo and Bossou, on the Guinean side). Among these different granites, the most characteristic are the pale pink granites. Microscopically, they consist of: quartz, orthoclase, muscovite, biotite, plagioclase and microcline (Fig.17) [13]

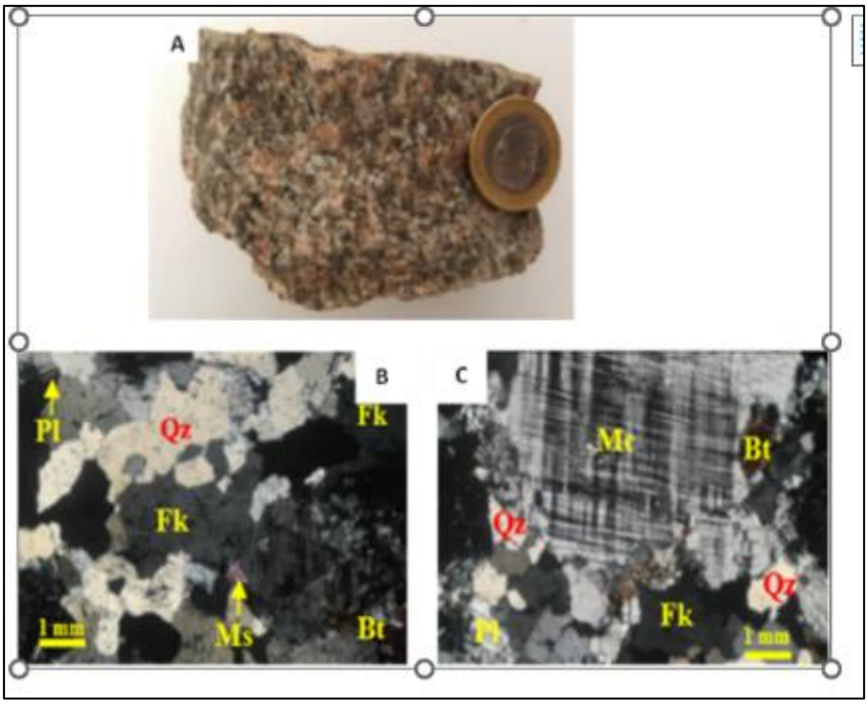


Figure 17 Macroscopic and microscopic appearance of pink granite [13]. (A). Granite sample; (B). Inclusion of muscovite microcrystals in potassium feldspars in PAL; (C). Microcline phenocrysts surrounded by microcrystals of biotite, quartz and potassium feldspar (Fk). Pl: plagioclase; Fk: potassic feldspar; Bt: biotite; Qz: quartz; Mc: microcline; Ms: muscovite

5.2.2. Metallographic data

From a metallogenic point of view, all the known iron deposits and showings on Mount Nimba and its western extension, as well as the Mount Simandou deposit (Pic de fon), display a diversity of iron-bearing minerals. Among these minerals, two primary iron ore minerals have been identified: magnetite and pyrite [13]. Magnetite (Fig.18C) has equidimensional grains, while pyrite grains (Fig.18B and D) are automorphic, fine to medium. Magnetite has a grey-brown hue, while pyrite has a light yellow hue. Hematite also occurs occasionally as martite. It arises from the oxidation of magnetite and can also be observed along the cleavage planes in magnetite crystals. Martite appears thanks to secondary transformations caused by surface alteration agents (pseudomorphosis of magnetite into hematite) and/or goethite (Fig.18).

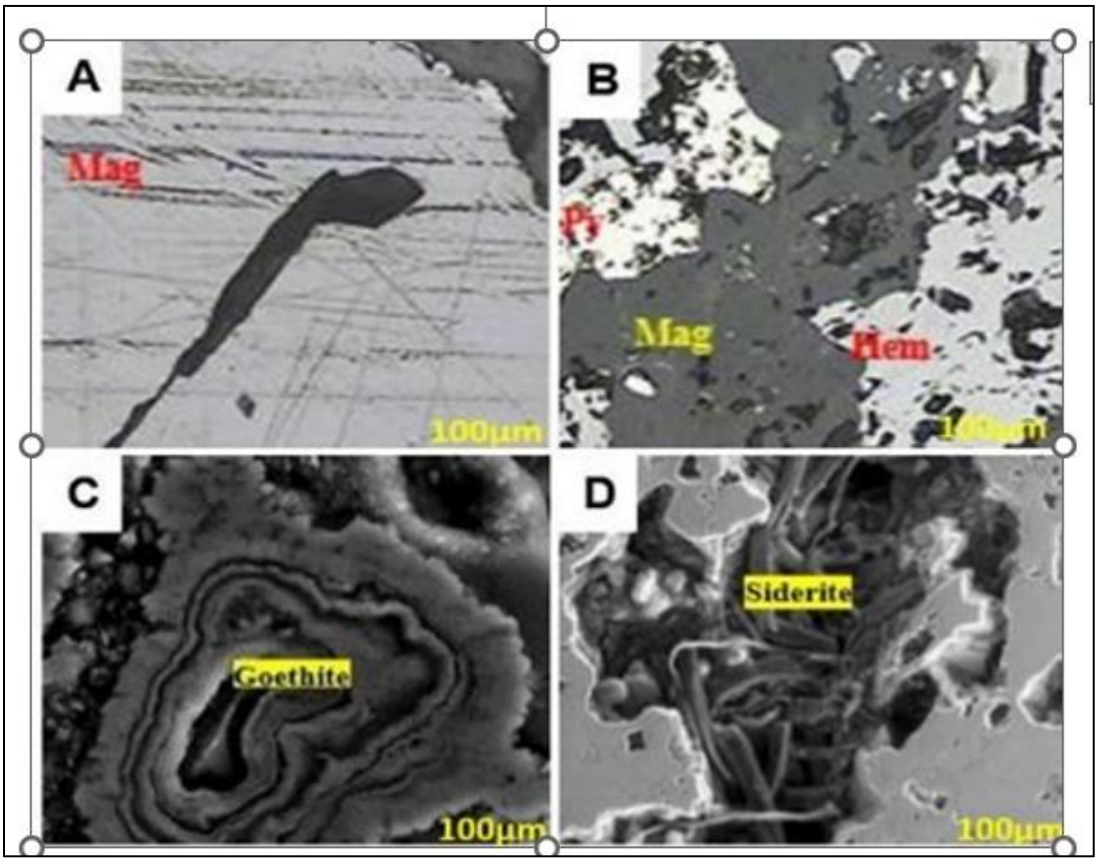


Figure 18 Microscopic appearance of magnetite quartzite slides viewed under a metallogenic microscope [13]. (A). Magnetite with striking structures (seen in polished section); (B). Xenomorphic magnetite with automorphic to subautomorphic pyrite; (C). SEM image of an itabirite matrix showing abundant goethite; (D). SEM image of an itabirite matrix showing abundant siderite

Mag: magnetite, Py: pyrite, Hem: hematite

5.2.3. Structural data

The data we have on the structural analysis of iron formations (BIF) are derived from various previous works [11],[13],[33],[35]. Our synthesis consists of noting the various structural features associated with the previously described rocks and their associated deformation mechanisms. The iron formations of Monts Nimba and Mont Simandou have been affected by two types of deformation (D1 and D2), both belonging to the Paleoproterozoic domain [36],[37].

The D1 deformation is typical of tangential tectonics, characterized by an S1 foliation, developed throughout the tectonic stack. This foliation (S1) carries a stretching lineation L1, oriented NNW-SSE to NNE-SSW in the Simandou and NW-SE to NNW-SSE in the Nimba Mountains. The stretching lineation (L1) is marked in ductile shear zones developed through various levels of the lithotectonic pile. The overall shear direction is southward in these zones, according to tectonic analyses. Indeed, the metamorphic conditions of deformation (D1) vary according to the lithotectonic units, from low degree, medium degree to high degree. In addition, deformation (D2) is characterized by regional-scale P2 folds [36]. These folds are synchronous with an S2 crenulation schistosity, and associated with ductile, brittle, generally senestial detachments. Indeed, D2 structures are characteristic of low-grade or low-intensity metamorphic conditions (Chl, Ser or actinote) [36].

5.3. Metamorphism

The magnetite-bearing quartzites of Mont Klahoyo and Tia, as well as their gneiss counterparts, have been affected by granulite facies metamorphism [9]. This metamorphism is expressed by a number of mineralogical equilibria that differ from one lithology to the next and can be observed in both types of deposit: i) in garnet amphibolo-pyroxenite : orthopyroxene + clinopyroxene + brown hornblende + plagioclase (1), ii) in magnetite quartzite (Itabirite): hypersthene + magnetite + garnet + clinopyroxene + quartz (2) and iii) in hypersthenites: hypersthene + garnet + magnetite (3) , hypersthene + garnet + grünerite (4). Paragraphs (1), (2), (3) and (4) confirm that these rocks are typically granulite facies. In addition, the presence of grünerite is evidence of hypersthene retromorphosis. This retromorphosis is manifested in parageneses (1) and (2) by the transformation of clinopyroxenes and actinolitization of brown hornblende, sometimes accompanied by traces of chlorites and calcites. The magnetite-bearing quartzites of Mount Nimba and Simandou, and the various lithologies associated with them, have been affected by prograde metamorphism. This metamorphism varies from greenschist facies to granulite facies to amphibolite facies [13],[33]. These metamorphisms have made it possible to highlight three metamorphic zones (the low-grade zone, the medium-grade zone and the high-grade zone of metamorphism) as a function of depth, temperature and pressure [13]. Indeed, they are characterized by a number of mineralogical equilibria (Table 5). In general, the intensity of metamorphism in these regions increases from east to west [13].

5.4. Geochemistry of BIFs Ivory Coast and Guinea

5.4.1. Geochemistry of Ivory Coast BIFs

According to the results of chemical analyses of BIFs carried out by [9], BIFs are rich in Fe_2O_3, FeO and SiO_2. These BIFs are rich in Fe_2O_3, FeO and SiO_2. On the other hand, BIFs are poor in TiO_2, CaO, MgO, K_2O, MnO, Na_2O, Al_2O_3 and P_2O_5. Geochemical analyses carried out on itabirite samples collected by [9] at Mont Tia, were not assayed for trace elements. Since [9], no geochemical work has been carried out on the BIFs of western Ivory Coast.

5.4.2. Geochemistry of Guinea's BIFs

According to the results of chemical analyses carried out by Mohamed et al. (2019), BIFs are rich in Fe_2O_3, FeO and SiO_2. On the other hand, we note that the BIFs are poor in TiO_2, CaO, MgO, K_2O, MnO, Na_2O, Al_2O_3, and P_2O_5 as the percentages of these elements are low (Fig.19 and 20).

Trace elements in itabirites from the Nimba region have been normalized to chondrites [38]in [13]. Indeed, the magnetite itabirite (SIF.1) shows enrichment in Al, Zn, Pb, Co and depletion in Mg, Ti, V and Ni. On the other hand, itabirite with magnetite (SIF. 2) shows enrichment in Mg, Ti, Zn, Cu and depletion in Mn, Al, V, Ni and Co (Fig.19A). Chlorite itabirites (SIF. 8) and garnet-granite itabirites (SIF. 19) show enrichment in Mg, Zn, Pb, but depletion in Al, Ti, V, Ni and Co (Fig.19B). Garnet (SIF. 33), transition zone (SIF.Tz. 41), garnet-grünerite (SIF. 43 and 45) and brown hornblende (OIF. 24) itabirites show enrichment in Mg, Ti, Zn, Pb and depletion in Mn, Al, V, Ni, Co (Fig.19C). All itabirites from the Nimba region show a significant Pb peak.

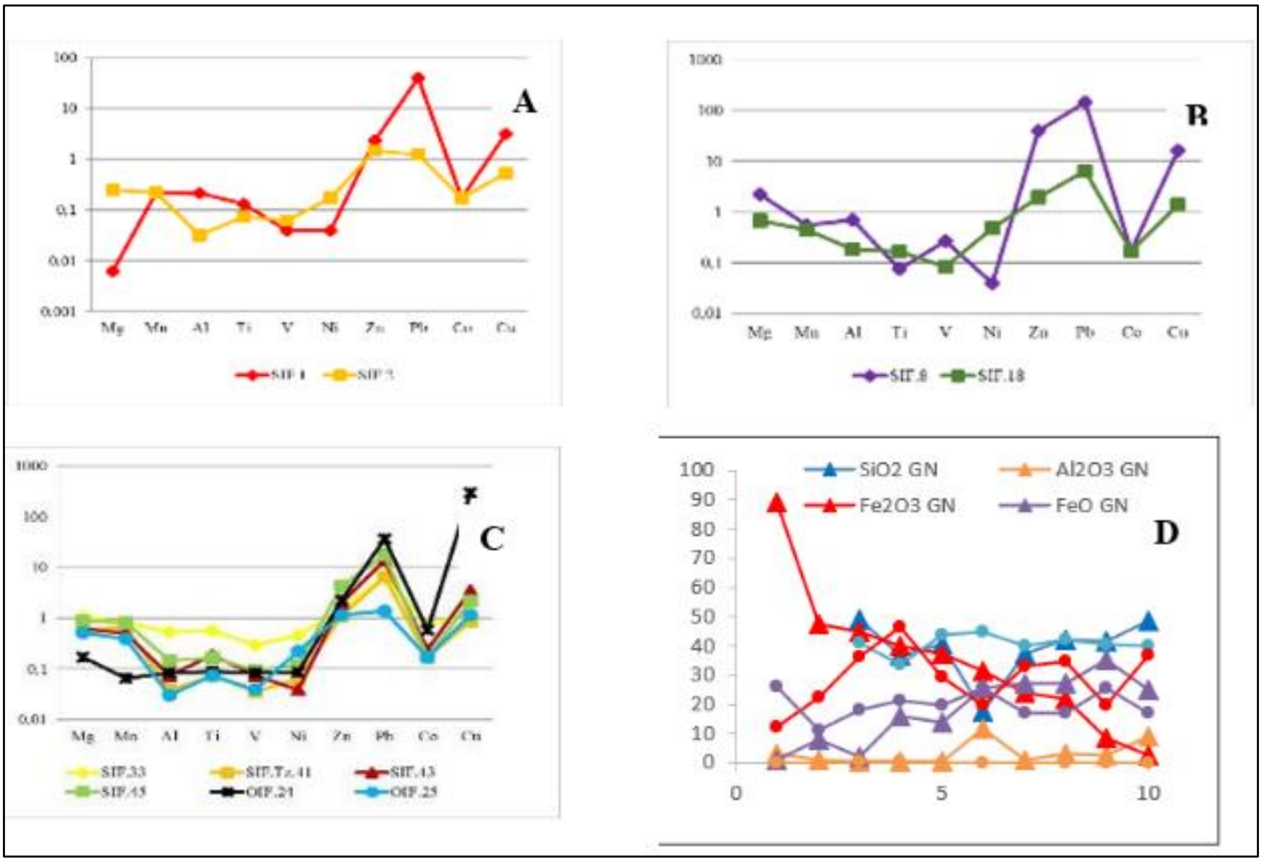
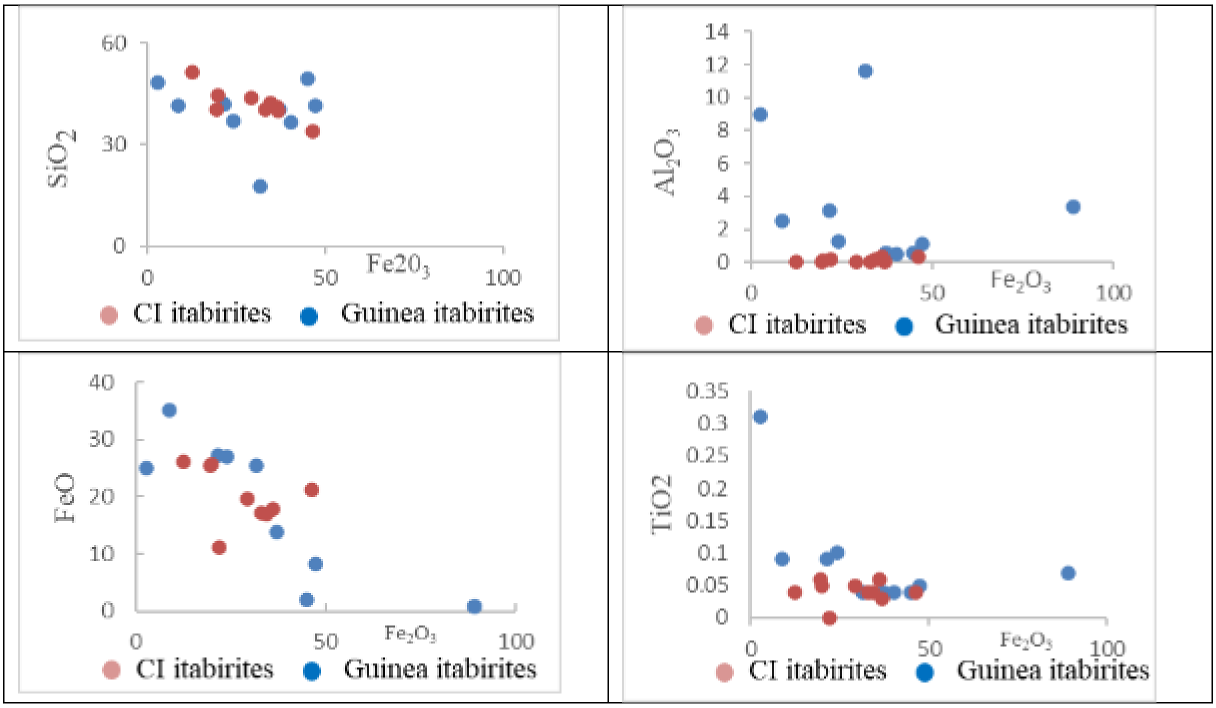


Figure 19 (A). Trace element spectra normalized to itabirite chondrite (SIF.1 and SIF.2) from the Nimba region; (B). Trace element spectra normalized to itabirite chondrite (SIF.8 and SIF.18) from the Nimba region; (C). Chondrite-normalized trace element spectra of itabirites (SIF.33, SIF.41, SIF.43 and 45, OIF.24 and OIF.25) from the Nimba region; (D). Evolutionary spectra of major elements (SiO2, Al2O3, Fe2O3 and FeO) in itabirites from Ivory Coast and Guinea [38] in [13]



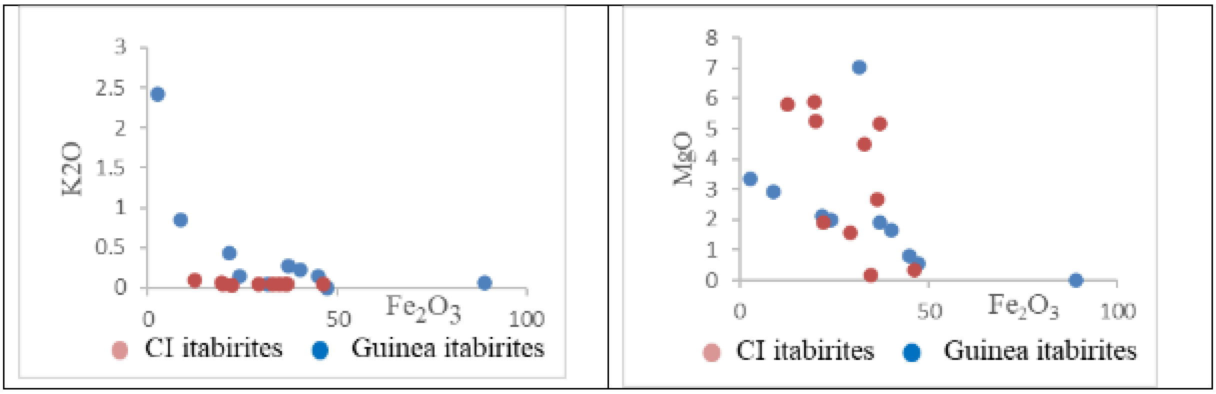


Figure 20 Major element differentiation diagrams based on Fe2O3 for BIFs from Mont Tia (Ivory Coast and Mont Nimba (Guinea)

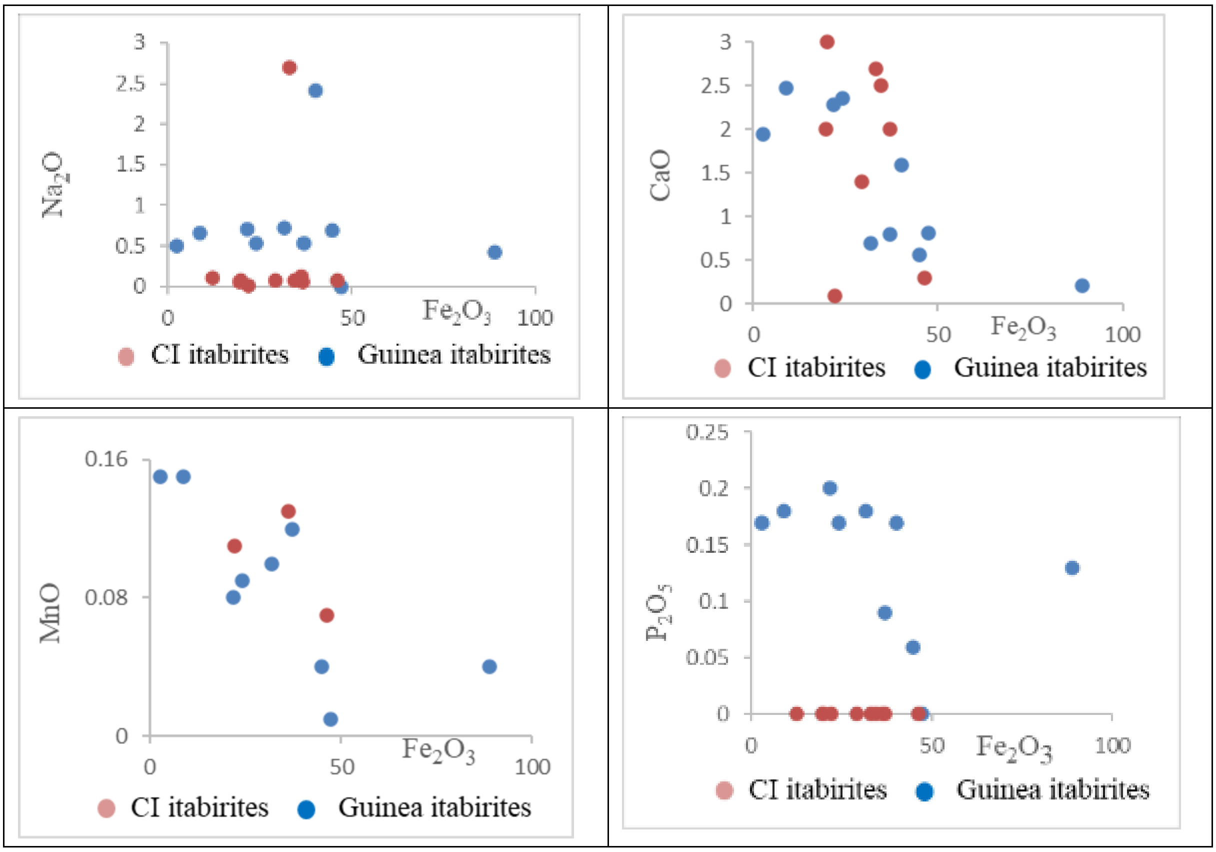


Figure 20 (continued) Diagrams of major element differentiation as a function of Fe2O3 in the BIFs of Mont Tia (Ivory Coast) and Mont Nimba (Guinea)

6. Discussion

6.1. Petrography

Magnetite quartzites, garnet gneisses, granites, amphibolo-pyroxenites and hypersthenites are found in the Mount Klahoyo and Tia area. Of these different formations, only the magnetite quartzites are host to iron mineralization. These formations are encased in a band of migmatitic gneiss [9],[10]. These same itabirites were previously described in the Yepleu-Bounta area by [25],[32]. They were also recorded in the southwestern part of Guiglo by [6],[7] affected by magnesian rocks and to the northwest in the Odienné department by [18].

According to [9] and [10], the BIF or itabirite of Mount Klahoyo and Tia are rocks of sedimentary origin belonging to the Archean and the other formations observed are of metamorphic and magmatic origin.
Similarly, itabirite-type formations similar to those described in western Ivory Coast have been highlighted in Guinea at Mount Nimba by [11],[13],[33]. These same itabirites have been recorded at Mount Simandou (Guinea) in the Pic de Fon deposit by [35]. These itabirites are sedimentary rocks of Proterozoic age [13],[33]. They are associated with magmatic, metamorphic formations of Archean age (gneisses, granites, amphibolites, quartzites, schists, phyllites, cherts and micaschists) [13],[33]. They are locally associated with volcanosedimentary rocks according to [11].

Indeed, the magnetite-bearing quartzites described above are similar to those found in various parts of the West African craton. For example, [4] highlights the itabirites of Guelb El Rhein in northern Mauritania, which rest on a host rock composed of gneiss, quartzite, amphibolite, leptynite and pegmatite. These itabirites are of Archean (the western extension of Tiris) and Proterozoic (Koedia Idjil) age and sedimentary origin, but the rocks associated with them are of volcanic origin. In Brazil, [39] found itabirites in sedimentary and volcanic rocks hosted in gneisses. In Ukraine, [40] identified itabirites in the Krivoy Rog basin. These itabirites are described as Proterozoic taconite. The same type of formation has also been described in Canada, in the Grenville province of Quebec [10].

6.2. Metallography

The metalliferous paragenesis found at Mount Klahoyo consists of iron oxides (magnetite and hematite) and sulfides (pyrite, chalcopyrite and ilmenite). According to [9],[10], magnetite represents the main iron ore in the BIFs of western Ivory Coast. [32] has identified a quasi-identical paragenesis in the Yepleu-Bounta area consisting solely of iron oxide (magnetite and hematite). He also deduced that only magnetite represents the main iron ore in the Yepleu-Bounta BIFs. However, this same paragenesis has been identified in Guinea, more specifically at Mount Nimba and Simandou, consisting of iron oxide (magnetite and hematite), sulfides (pyrite), carbonates (siderite) and goethite. According to [13], magnetite and pyrite represent the main iron ores in the Mount Nimba BIFs. [4] identifies a similar paragenesis consisting of iron oxide (magnetite and hematite) and sulfide (pyrite).

6.3. Structural

In the study area, particularly at Mount Klahoyo, the structural markers of deformation are: folds (similar folds, sometimes isoclinal, antiformal, synformal with NE to SE plunging axis, intrafolial S-type and Z-type folds, entrainment folds, and chevron folds), stratifications, foliations, crenulation schistosities, stretching lineations and the intersection lineation between S1 and S2 (L1-2). These folds and foliations were highlighted by the flattening mechanism. There are also NNW-SSE to NNE-SSW oriented fractures and faults affecting the Itabirites. In fact, these various faults and fractures intersect and offset the ductile formations in a NNE-trending sinister movement, testifying to polyphase tectonics (D1 and D2). The main direction of these faults and structures is NE-SW, which according to [18] is characteristic of Birrimian formations. All these structures reveal the existence of a shear corridor.

Furthermore, the work at Mount Klahoyo is similar to that in Guinea, particularly at Mount Nimba and Mount Simandou, according to [34]. The NE-SW-trending foliations observed at Mount Klahoyo are identical to those identified at the NE-SW to NNE-SSE-trending Nimba and the NNE-SSW-trending Mount Simandou [34].

According to [4], the iron deposits of Mauritania (Guelb El Rhein deposit) have also undergone large-scale ductile deformation composed of two phases linked to a compressive regime. This compressive mechanism generated an isoclinal fold and a second one at the origin of the synformal fold.

7. Conclusion

Banded iron formations (BIFs) are the most important source of iron ore in the world, particularly in Ivory Coast and Guinea, where they are deposits of high economic value. Most BIFs were formed in the Precambrian, Archean and Proterozoic eras. They are distinguished into two types: Algoma and Lake Superior. The Algoma type is the oldest, more than 2.6 Ga old, typical of Archean formations. The banded iron formations of Mount Klahoyo and Tia (Ivory Coast) belong to this type. The Upper Lake type, on the other hand, is specific to Proterozoic formations. In fact, the itabirites of Guinea are of the Lac Supérieur type, formed in the Proterozoic.

The BIFs of Ivory Coast and Guinea were subjected to two types of tectonic events (ductile deformation or D1 and brittle deformation or D2), generating several types of structures. Indeed, ductile deformation or D1 has led to the development of various structures (folds, foliations and lineations) in these two countries. In Ivory Coast, brittle deformation or D2 also led to the formation of faults, fractures, veins and joints, while in Guinea, it led to the formation of folds (P2) [36]. The magnetite quartzites of Guinea, like those of Ivory Coast, are rocks of sedimentary origin. They have a granoblastic or bedded texture.

Geochemical data revealed similar scattered and negative correlations in both countries' BIFs with SiO_2, TiO_2, CaO, MgO, K_2O, MnO and P_2O_5, in addition to the correlations observed only with Al_2O_3 and FeO in Guinea's BIFs. The metallogenic data reveals that the BIFs from these two countries are similar. This is since magnetite represents the main iron ore in the BIFs of both countries, in addition to pyrite, which is the second ore in Guinea, and hematite, which is the second ore in Ivory Coast. Both deposits are of sedimentary origin.

Indeed, this study shows on the one hand that the BIFs of these two countries are lithologically, structurally and metallogenically similar. Thus, we confirm the hypotheses of the players [11],[13] who suggested a similarity of the BIFs of these two countries. On the other hand, the BIFs of these two countries show divergent features at the geochemical, metamorphic, geochronological and typological levels.

Compliance with ethical standards

Disclosure of conflict of interest

conflict of interest to be disclosed. Yes, there is no conflict of interest between the different authors.

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