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CHARACTERIZATION OF HYDROTHERMAL ALTERATIONS AND METALLIFEROUS GROUPS ASSOCIATED WITH NICKEL-COBALT MINERALIZATION IN THE AREAS OF GBATONGOUIN-GBONNE (MAN-BIANKOUMA), WEST OF CÔTE D'IVOIRE

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ABSTRACT

The localities of Gbatongouin and Gbonné are located between the cities of Man and Biankouman, precisely north of Man and south of Biankouman, west of Côte d'Ivoire. The objective of this study is to improve petrographic and metallogenic knowledge of geological formations in these areas in the Man region. To do this, the geological survey conducted in the study area made it possible to encounter a multitude of geological outcrops from which samples were taken for more detailed petrographic and metallographic studies. Thus, two major families of rocks have been highlighted, namely the magmatic formations (norites and charnockites) and the metamorphic formations (orthogneiss charnockitic and pink to garnet granulite). The paragenesis of some rocks has highlighted a retrograde metamorphism from granulite to greenschist facies, evidenced by the presence of low-grade minerals such as chlorite, sericite and epidote. Nickel-Cobalt (Ni-Co) mineralization in the study area is mainly disseminated and hosted in mafic rocks, as evidenced by hydrothermal alteration and soil geochemistry results. Mineralization is carried by sulfides and oxides including pyrite, chalcopyrite, ilmenite and magnetite.

Keywords: Petrography, Hydrothermal alteration, Ni-Co mineralization, Leo Ridge, Man, Côte d'Ivoire.

1 INTRODUCTION

The geological history of Côte d'Ivoire is integrated with that of the West African Craton [1]. The crystalline formations belonging to this ridge make up most of the geological landscape of Côte d'Ivoire (97.5% of the national territory). The Man region is located in the Liberian domain of the Man Ridge, which is characterized by the Liberian orogeny (2900-2500 Ma), with relics from Leonian formations where Eburnean manifestations are rare. The crystalline formations are made up of charnockites, granulites, gneisses and migmatites and are rarely overcome by catazonal metasediments [2, 3, 4, 5]. This region is divided into two large units separated by the Man-Danané fault, oriented N070: (i) a northern compartment of granulitic nature mainly composed of gray gneiss and charnockites and, (ii) a southern compartment of an anatectic nature composed of migmatites and magnetite quartzite [2, 6]. [6] identified three lithological domains, the granulitic domain in the north, the intermediate granulitic and magmatic domain and the migmatitic gneiss domain with biotite in the south. The various research projects carried out in the Man region have provided most of the current knowledge on western Côte d'Ivoire [2, 7, 3, 4]. However, his studies were carried out on large scales (1/1000,000). Consequently, these studies remain poorly detailed. Thus, to overcome this problem and contribute to the detailed geological and metallogenic knowledge of this area, a study limited to the Sycorp industries permit in the Gbatongouin-Gbonné (MAN) sectors in the west of Côte d'Ivoire was initiated with the contribution of new geological and metallogenic data. This will contribute to the improvement of knowledge on Nickel-Cobalt (Ni-Co) mineralization in the geological formations of the Gbatongouin-Gbonné area (Man-Biankouman region) as well as the associated metalliferous procession.

2 GEOLOGICAL CONTEXT

Côte d'Ivoire is located in the southern part of the West African craton, more precisely in the Man Ridge [1]. This ridge is bordered to the north by the Taoudéni basin, to the west by the Mauritanides-Rockellids chain, to the east by the mobile zone of Central Africa and to the south by the Atlantic Ocean. This cratonic domain stabilized at the end of the Eburnean cycle (1600 Ma; [8]). The geology of Côte d'Ivoire consists of two large complexes of unequal size, namely the sedimentary basin and the Precambrian basement. The Ivorian base, of Precambrian age, represents 97.5% of the territory. It has two main domains of different ages, the Archean domain and the Proterozoic domain. These are separated by the Sassandra fault, which constitutes a major accident, submeridian of the senestre type [9, 1]. This fault would be extended to the north by the Zedness fault in Mauritania and to the south by that of Guri in Venezuela in South America [10]. The Archean domain constitutes the western part, which consists of Archean rocks structured during the Leonian orogenic cycles dated from 3.4 Ga to 3 Ga and Liberian rocks dated from 2.9 Ga to 2.7 Ga. The lithostratigraphy of the Archean domain presents ferruginous quartzites, pyroxenites, amphibolites, migmatites, gneisses, leptynites, granulites, charnockites, granitoids with a granodioritic character [11, 2]. The degree of metamorphism ranges from meso to catazonal [2, 6]. This domain, like the entire Archean of the Man Ridge, is marked by the major magmatic and metamorphic event that is the Liberian [2, 4]. The Proterozoic domain is located east of the Sassandra fault. This domain consists of Birimian formations (2.1 Ga) structured during the Eburnean cycle dated from 2.5 to 1.8 Ga, [11]. In Côte d'Ivoire, this area also called Baoulé-Mossi is characterized by an alternation of volcanoplutonic and sedimentary furrows and granite areas. The volcano-plutonic assemblage consists of metabasites (basalts, dolerites, gabbro), basic epiclastites with tholeïtic characters. The detrital sedimentary ensemble associated with volcanic material is composed of sandstone, arkose, shale, pelite, greywacke and conglomerate [12]. All these formations are affected by an epizonal to mesozonal metamorphism ([8], Figure 1).

The study area (Gbatongouin-Gbonné) located between the departments of Man-Biankouma, is in the Archean domain. The geological formations encountered are mainly norites, peridotites, charnockites, charnockitic orthogneisses, pyroxenites, quartzites and/or ferruginous quartzites; as well as quartz gabbro-diorite and quartz pyroxenites, enriched in places with garnet, iron sulfides (pyrrhotite, pyrite) and magnetite [7, 13] (Figure 2).

3 MATERIALS AND METHODS

The methodology used includes a field phase, followed by some analytical work in the Bureau veritas laboratory, including microscopic and metallographic petrography. The petrographic study was carried out in 3 steps: first a macroscopic study, then sampling and finally a microscopic study. This work has made it possible to collect 26 samples of various lithologies. In order to better identify mineral paragenesis, 13 samples were selected for the manufacture of 11 thin sections and 2 polished sections. These thin and polished sections were made at the Laboratory of Geology, Mineral and Energy Resources of the University Félix Houphouët-Boigny (Abidjan, Côte d'Ivoire) for a petrographic and metallographic study.

4 RESULTS

4.1 Petrography of magmatic formations

4.1.1 Charnockites

This formation is the most common in the study area (Kiélé, Gbatongouin, Gbonné, Dozéré, Zagoué). It outcrops in the form of domes with more or less circular contours, mesocrates and a porphyroid grained texture (Figure 3). The grain size is variable (fine to medium), with some quartz and plagioclase phenocrysts. Its mineralogy consists mainly of quartz (30-35%), plagioclase (20-30%), microcline, pyroxene (10-15%) and biotite. Quartz minerals are abundant in the rock, very variable in size (larger sizes), and sometimes have a remarkable rolling extinction. Plagioclases are characterized by polysynthetic twins, they are sub-automorphic to automorphic and of variable sizes. They sometimes show ranges at the beginning of sericitisation. Potassium feldspars, especially microclines, are scarce and usually present as subautomorphic grains of average size. Pyroxenes, which are orthopyroxenes, are not very abundant; they occur in the form of subautomorphic to automorphic crystals that are colored. The biotites, which are rare and brown in color, are subautomorphic to automorphic with some patches showing zircon inclusions. There is also the presence of sericite minerals (from the alteration of plagioclase) as well as opaque minerals.

4.1.2 Norites

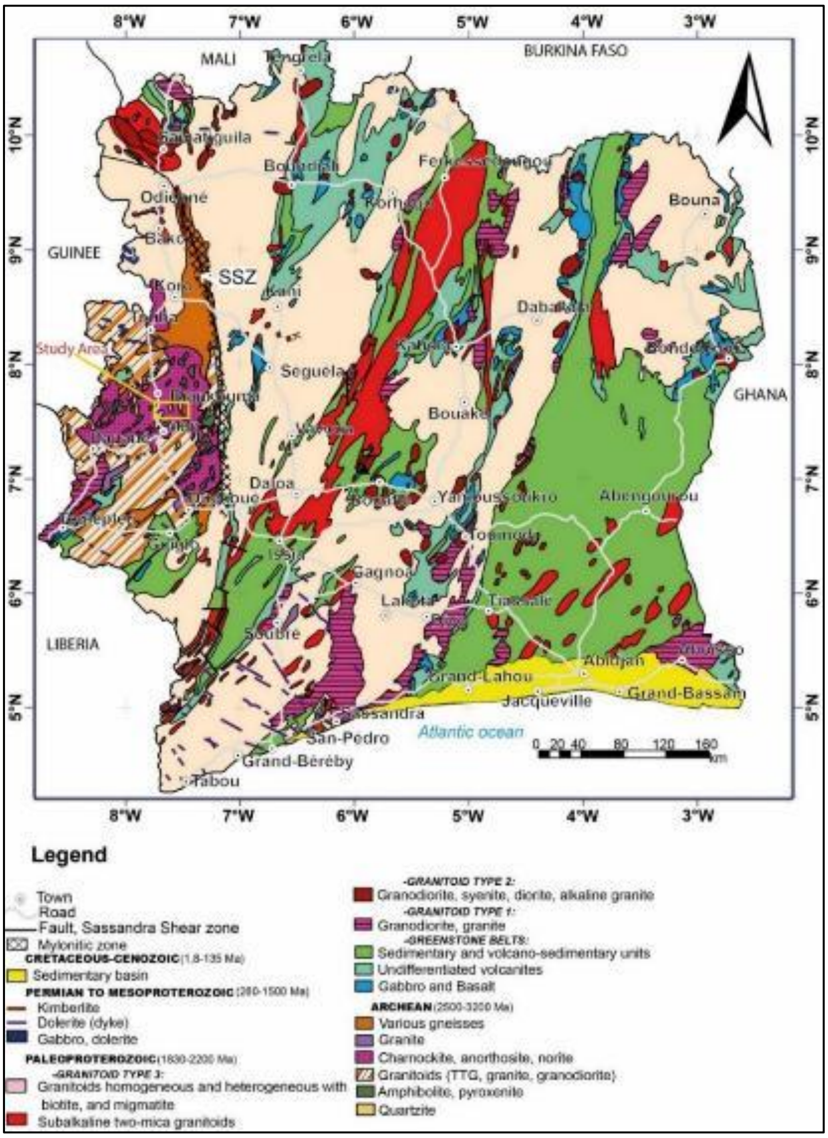

Figure 1: Simplified geological map of Côte d'Ivoire, modified, [9].

Norites were observed in the area of Kiélé and near Gbatongouin. The latter are massive and meso-melanocratic. These are rocks of similar depth to the gabbros; they are granular (Figure 4). The minerals that constitute it are mainly pyroxenes and plagioclases. Pyroxenes are essentially orthopyroxenes and clinopyroxenes, very abundant in the rock.

Orthopyroxenes are brown in color while clinopyroxenes are light green. Plagioclases, which are less abundant than pyroxenes, are colourless, with a low to medium relief. They are generally xenomorphic to subautomorphic. They form large beaches. Some plagioclase beaches show alterations in sericite.

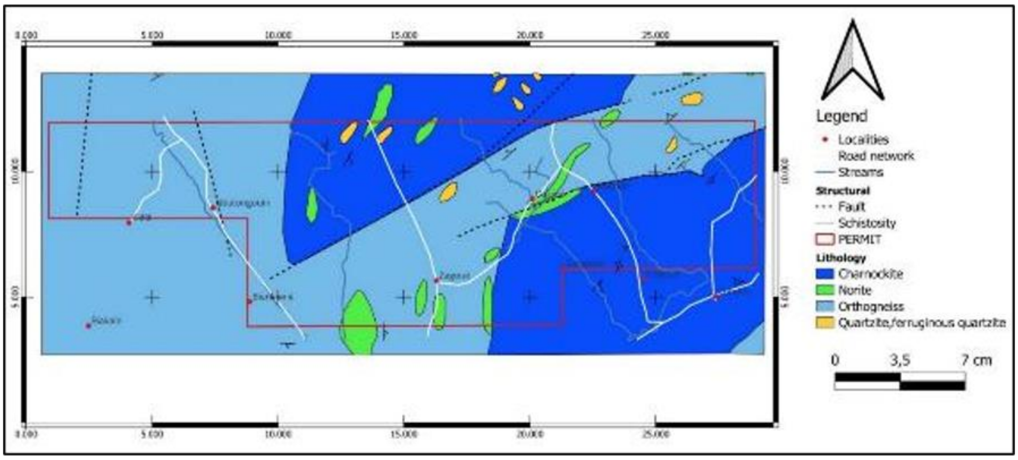

Figure 2: Geological map at 1/200,000 of the study area (excerpt from the Danané-Man sheet, modified).

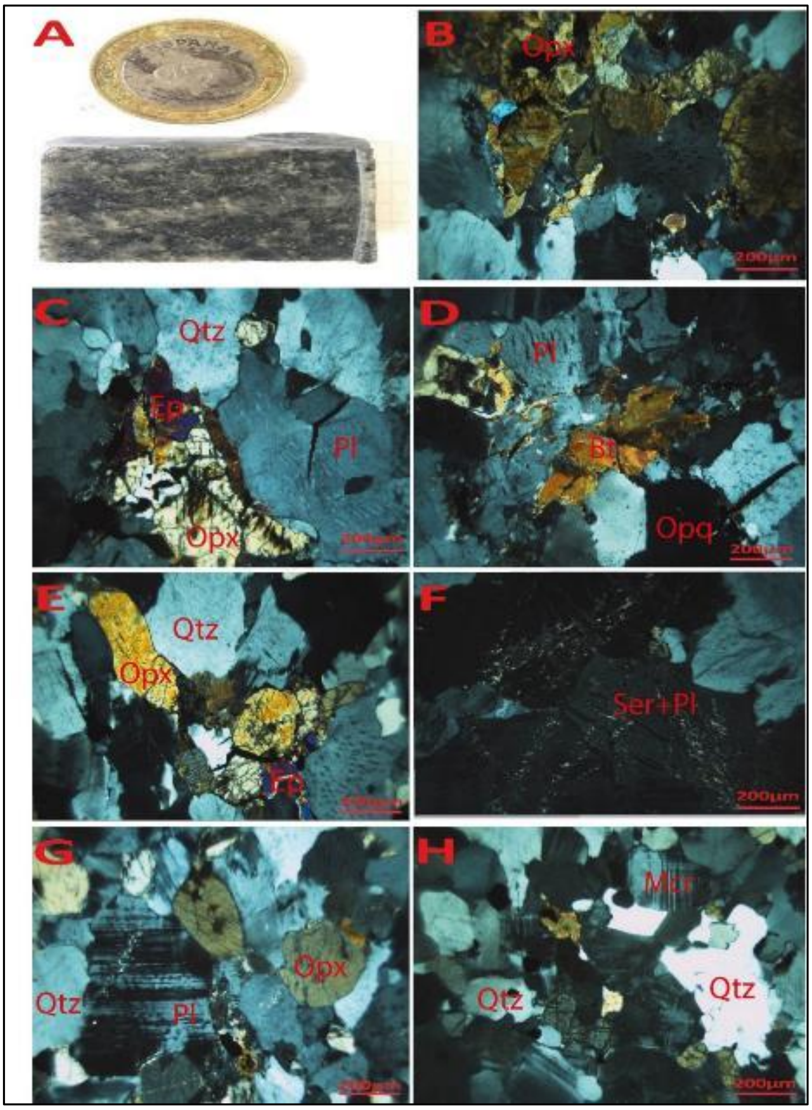

Figure 3: Macroscopic and microscopic aspects of charnockite.

(A): Macroscopic sample of the charnockite, (B, C, D, E, F, G, H): Microscopic assembly of the charnockite in polarized light and analyzed.; Qtz: Quartz, Pl: Plagioclase, Mcr: Microcline, Opx: Orthopyroxene, Ser: sericite, Ep: Epidote, Bt: Biotite, Opq: Opaque.

Figure 4: Macroscopic and microscopic aspects of norites.

(A): Macroscopic aspect of the norite, (B, C, D, E, F, G, H): Mineralogical assemblage of the norite; Pl: Plagioclase, Opx: Orthopyroxene, Cpx: Clinopyroxene, Bt: Biotite, Opq: Opaque.

4.2 Petrography of metamorphic formations

4.2.1 Charnockitic orthogneiss

These rocks outcrop in massive appearance. The texture is polygonal granoblastic with fine to medium coarse grains. They show an alternation of light beds consisting of quartz (35-45%) of the matrix, microclines, plaqioclase, opaque quartz (Figure 5 B, C, D, E), and dark beds (Figure 5 F, G, H) composed of ferromagnetic minerals (orthopyroxene, biotite, opaque) and plagioclase.

4.2.2 Pink garnet granulites

The granulites have a massive appearance, leucocratic in color with a polygonal granoblastic texture (Figure 6). The rock consists mainly of quartz and feldspar. Minerals are visible to the naked eye and vary in size. Quartz minerals, very abundant (more than 50%), they have a medium to low relief, xenomorphic, colorless and clear. Some beaches show a very remarkable rolling extinction. The feldspars, selfabundant minerals, altered, colorless and of xenomorphic forms, they present a sericization. The garnets, less abundant than the previous one, they are colorless, of strong relief and altered. Presenting a globular shape. Phenocrysts dotted with veinlets, exhibiting an accentuated serpentinization and chloritization, are also identifiable. Coronitic reactions are also observed between certain garnet phenocrysts and plagioclases (Figure 6 E, F, G, H).

4.3 Alteration associated with mineralization in Ni-Co

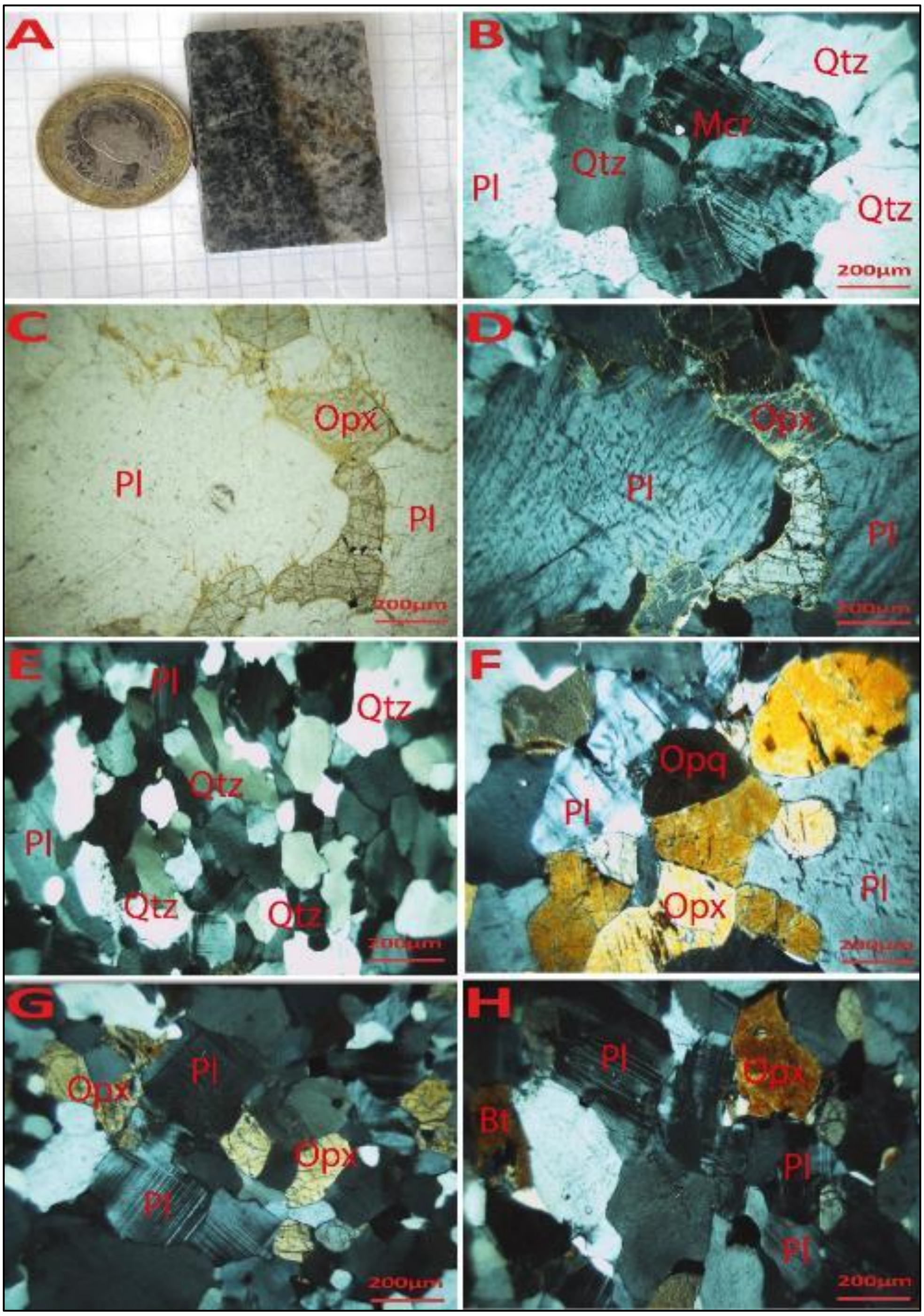

Figure 5: Macroscopic and microscopic aspect of the charnockitic orthogneiss.

(A): Macroscopic aspect; (B, C, D, E): Mineralogical assemblage of the light band, (F, G, H): Mineralogical assemblage of the dark band.; Pl: Plagioclase, Opx: Orthopyroxene, Qtz: Quartz, MCR: Microcline, Bt: Biotite, Opq: Opaque.

All the geological formations of the study area have undergone various phenomena of alteration. These alterations have indeed been highlighted by the petrographic data collected and are generally linked either to hydrothermal fluids and/or meteoric agents. They come from the pseudomorphosis of primary minerals, and generally affect all rocks. Two main types of alteration.

Pervasive hydrothermal alteration (Figure 3E and Figure 3 F) occurs in various types:

- Sericitization: the most dominant alteration. It is observed practically in all the lithologies of the area and mainly affects feldspar crystals;
- Chloritization: also important in the rocks of the study area, it develops at the expense of the biotites;

- Epidotization: it affects basic lithologies. There is observed destabilization of pyroxene and plagioclase crystals, with development of epidote;
- Sulfuration: it is most often visible in mafic and intermediate rocks.

The filonial hydrothermal alteration is observed by the presence of chlorite veinlets and quartz stringers. They have varying thicknesses and lengths (Figure 6 D and Figure 6 F).

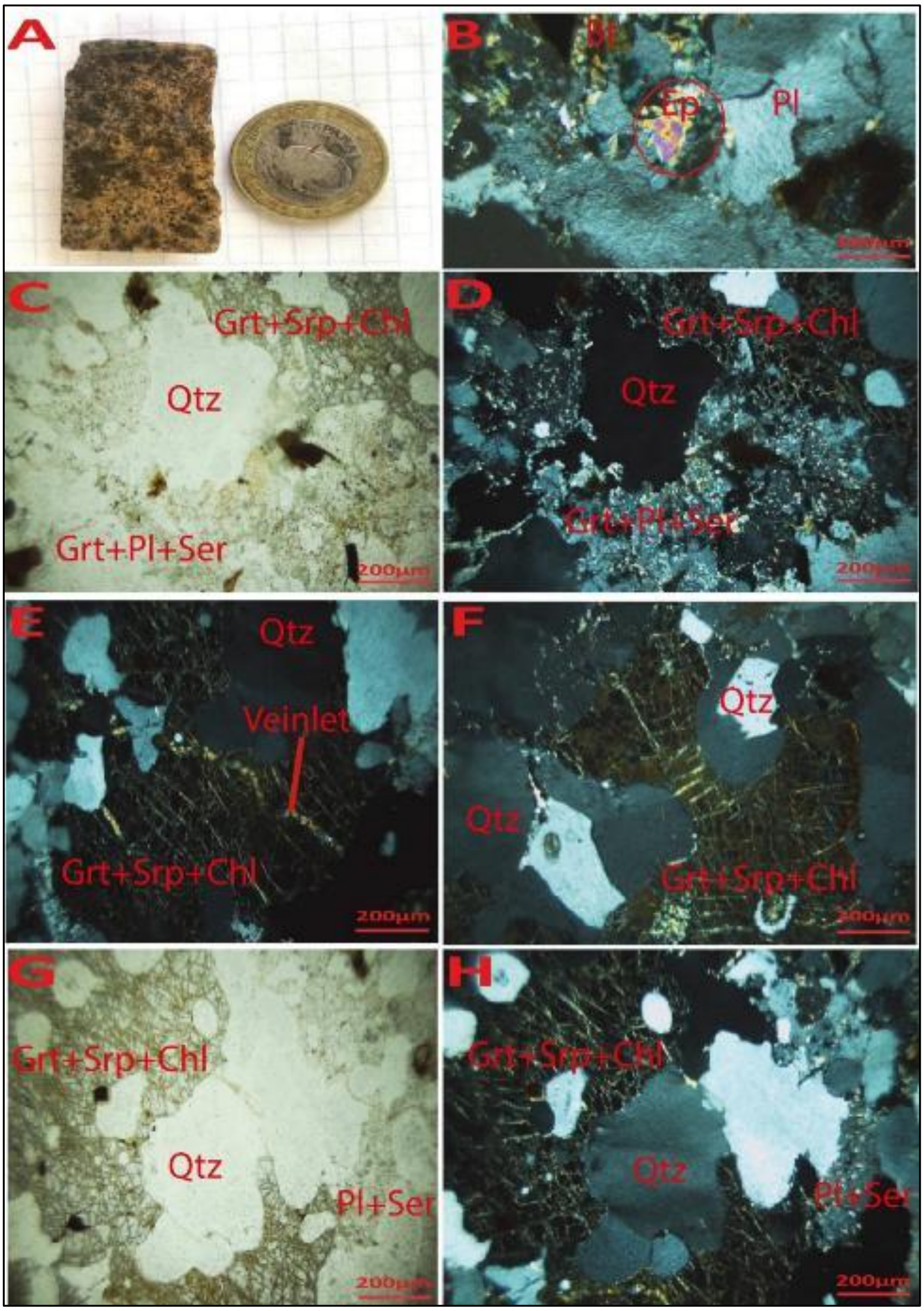

Figure 6: Macroscopic and microscopic aspects of pink to garnet granulite.

(A): Macroscopic sample of pink to garnet granulite, (B, C, D, E, F, G, H): Microscopic assembly of the pink granulite with mineralogical reaction.; Qtz: Quartz, PL: Plagioclase, Chl: chlorite, Ser: sericite, Srp: serpentine, Bt: biotite, Grt: Garnet, Ep: Epidote.

4.4 Sulfides and oxides associated with Ni-Co mineralization

The opaque mineral composition of different rocks varies according to the samples studied. These minerals are essentially made up of sulfides and oxides. In addition to this, there are the results of analyses of soil geochemistry samples in % nickel and cobalt. These results reveal very good concentrations, particularly for nickel which varies between 80 ppm and 4520 ppm in the studied area. Cobalt has relatively very low levels (Table I).

4.5 Sulfides

Sulfides are generally in the form of subautomorphic grains with disseminated xenomorphs or as veinlets. They are almost always associated with ferromagnetic minerals.

Pyrite is an iron sulfide with the chemical formula FeS_2, which generally crystallizes in the cubic system and has a pale brass yellow color. It can contain quite large amounts of nickel and cobalt. Under the metallographic microscope, pyrite crystals are subautomorphic while others are deformed (Figure 7 A, B, C, E and Figure 8 B, F). They are observed in the rock in disseminated form or as veinlets and present weak cleavages and irregular breaks. Its grains have very variable sizes ranging from micrometre to centimetre and its reflectivity is medium to strong. They are commonly associated with pyroxenes, specifically orthopyroxenes. It is the most abundant mineral among all sulfides.

Chalcopyrite is a double copper-iron sulfide with the chemical formula $CuFeS_2$ that crystallizes in the quadratic system. Under the microscope, it is sub-automorphic, yellow in color, and can be seen in disseminated form in the rock. The grain size is very varied from micrometric to millimetric with a lower reflectivity compared to that of pyrite (Figure 7 D and Figure 8 C, D, F). Chalcopyrite is often associated with pyrite and magnetite.

4.6 Oxides

Oxides are generally subautomorphic to xenomorphic with very variable sizes and scattered in the rock. Magnetite with the chemical formula Fe_3O_4 is a very important iron mineral that crystallizes in the cubic system. Under the microscope, the magnetite shows a gray-brown hue, a subautomorphic shape with some xenomorphic sections. Having no cleavages and deformed, it presents irregular breaks. It has a low reflectivity. It is scattered in the rock in very varied sizes ranging from micron to millimeters (Figure 7 E and Figure 8 A, E).

Ilmenite is a titanated iron mineral crystallizing in the rhombohedral system with chemical formula FeTiO3. The ilmenite appears under the microscope in the form of lamellae, black gray characterized by brownish points. The reflectivity is lower than that of magnetite because ilmenite is an accessory mineral to magnetite and others. The grains are very small to small stretched and scattered in the rock (Figure 8 A, B, E, F).

5 DISCUSSION

5.1 Magmatism and metamorphism in the study area

Investigations conducted in the study area have identified a lithological assemblage mainly comprising igneous rocks (charnockites and norites) and metamorphic rocks (charnockite orthogneiss and pink garnet granulites). These formations present similarities with those described in western Côte d'Ivoire, sharing common petrographic and mineralogical characteristics [2, 6, 7, 14, 13, 3]. Charnockites, rich in orthopyroxene, correspond to the descriptions made by [2] and [6]. Norites, distinct from gabbros by their higher orthopyroxene content, show affinities with the observations of [7]. Pink-garnet granulites have similarities with those documented by several authors, although local variations are noted ([2, 6]. In addition, the petrographic study reveals that the different lithological facies of the study area were mainly affected by metamorphic processes. These are manifested by significant mineralogical transformations, indicating a disruption of the stability conditions of the initial mineral assemblages. Microscopic analysis confirms the almost systematic substitution of ferromagnesium minerals (pyroxene, biotite), characteristic of the granulite facies, by assemblages typical of the greenschist facies, such as chlorites and epidotes. At the same time, feldspars are frequently altered in epidote or sericite, minerals indicative of low-grade metamorphism. The presence of coronitic reactions between garnet and quartz (Figure 6 F & H) also corroborates these metamorphic conditions. All of these mineralogical observations could suggest a change in pressure-temperature conditions, marked by a transition from high degree to low degree metamorphism. This trajectory would probably reflect a phenomenon of retromorphosis, attesting to a retrograde metamorphism that has affected the area.

Table 1: Analysis results for samples in % of Nickel and Cobalt.

No order	Samples references	Mass percentage of the elements measured /dry Samples.	
		Ni (%)	Co (%)
1	ECH000001	0,016	0,004
2	ECH000002	0,011	0,003
3	ECH000003	0,011	0,003
4	ECH000004	0,014	0,005
5	ECH000005	0,046	0,003
6	ECH000004	0,012	0,005
7	ECH000006	0,008	0,002
8	ECH000007	0,008	0,002
9	ECH000008	0,012	0,004
10	ECH000009	0,012	0,005
Duplicate	ECH000009a	0,01	0,004
11	ECH000010	0,012	0,005
12	ECH000011	0,009	0,004
13	ECH000012	0,013	0,007
14	ECH000013	0,013	0,006
15	ECH000014	0,01	0,005
16	ECH000015	0,02	0,004
17	ECH000016	0,02	0,004
18	ECH000017	0,015	0,006
19	ECH000018	0,013	0,006
20	ECH000019	0,014	0,007
21	ECH000020	0,013	0,005
22	ECH000020	0,021	0,005
23	ECH000021	0,012	0,002
24	ECH000022	0,014	0,004
25	ECH000023	0,01	0,003
26	ECH000024	0,015	0,003
27	ECH000025	0,011	0,001
28	ECH000026	0,013	0,002
29	ECH000027	0,013	0,006
30	ECH000028	0,011	0,001
31	ECH000029	0,01	0,001
Duplicate	ECH000029a	0,009	0,002
32	ECH000030	0,012	0,002

33	ECH000031	0,014	0,003
34	ECH000032	0,011	0,003
35	ECH000033	0,01	0,002
36	ECH000034	0,016	0,003
37	ECH000035	0,014	0,002
38	ECH000036	0,012	0,003
39	ECH000037	0,452	0,019
40	ECH000038	0,026	0,012
Duplicate	ECH000038a	0,028	0,011
41	ECH000039	0,01	0,004
42	ECH000040	0,014	0,005
43	ECH000041	0,009	0,003
44	ECH000042	0,096	0,01
45	ECH000043	0,021	0,007
46	ECH000044	0,014	0,009
Duplicate	ECH000044a	0,015	0,008

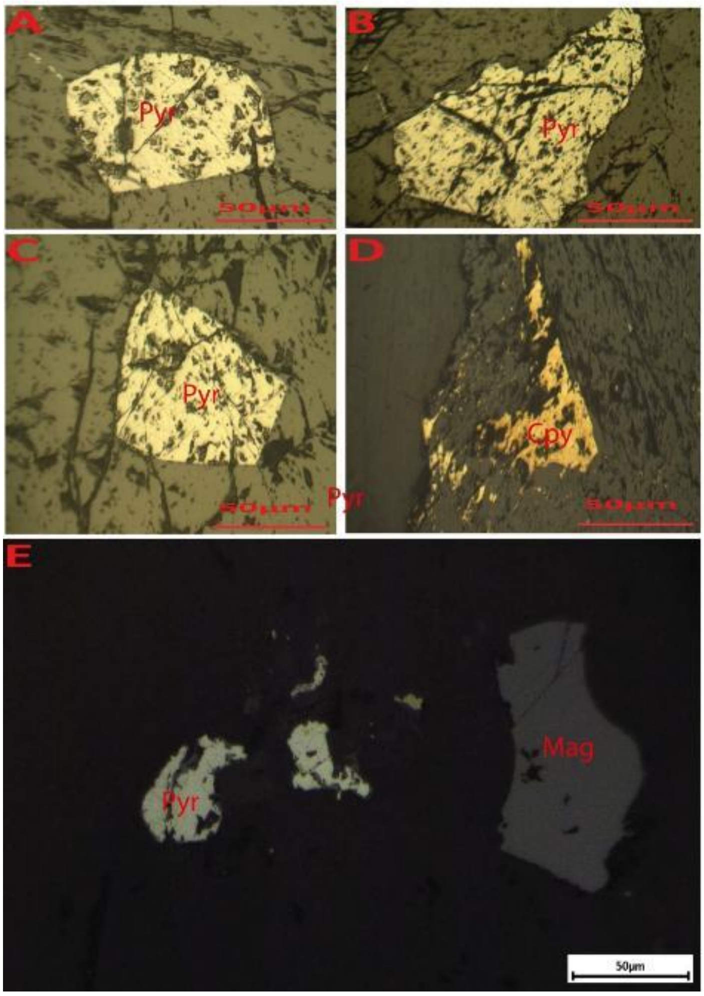

Figure 7: Microphotographs of sulfides and oxides in metallographic microscopy.

Pyr: Pyrite, Cpy: Chalcopyrite, Mag: magnetite.

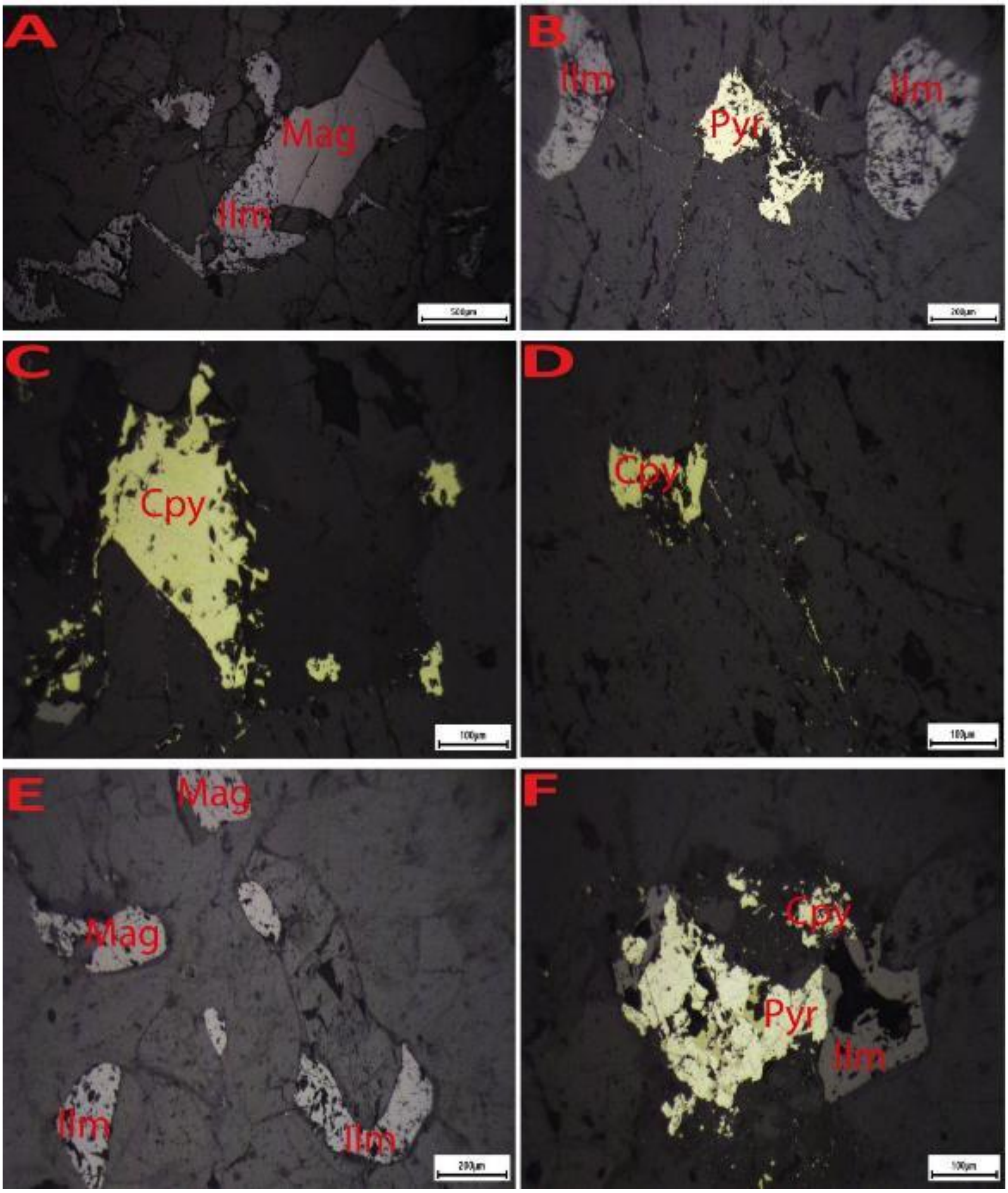

Figure 8. Microphotographs of sulfides and oxides in metallographic microscopy.

Mag: magnetite, Ilm: ilmenite, Pyr: pyrite, Cpy: chalcopyrite.

5.2 Metallogenic characteristics of Ni-Co mineralization

Nickel mineralization in the study area is disseminated within mafic formations. It is characterized by a combination of sulfides (pyrite with variable particle size and small to medium sized chalcopyrite) and oxides (magnetite and ilmenite). This mineralization presents similarities with several known nickel-bearing systems. Locally, it is comparable to the mineralization of the company Sama Nickel-CI, although the latter has a more diversified sulfur assemblage (with pyrrhotite and pentlandite) and an absence of oxides [7]. Regionally within the West African craton, analogies exist with the Bounta deposit for sulphide and oxide types, but the latter is hosted in ultramafic rocks [13]. The encaissement model in mafiques, however, is consistent with observations made by [15] in the Sipilou sector, highlighting the role of mafic and sometimes ultramafic formations as hosts for nickel mineralization. This regional context is consistent with recent models of nickel mineralization in the West African craton, which highlight the control of mafic-ultramafic complexes within the Archean and Paleoproterozoic greenstone belts [16, 17, 18]. The presence of oxides such as magnetite, observed in our study and in the district of Bou-Azzer in Morocco [19, 20], may be an indicator of magmatic and hydrothermal processes affecting these systems. Thus, the mineralization of the study area is part of the broader metallogenic framework of the West African craton, sharing common characteristics with other occurrences, while presenting a specific mineral association and type of host.

6 CONCLUSION

The geology of the study area is marked by the presence of two major lithological complexes: magmatic rocks such as charnockites and norites, and metamorphic formations such as charnockite orthogneiss and pink garnet granulites. These geological formations have undergone various processes of alteration, including pervasive hydrothermal alteration, highlighted by sericization, chloritization, epidotization and sulfuration and the filonial alteration materialized by veinlets and stringers. This area has been affected by a retrograde metamorphism from the granulite to the greenschist facies. Ni-Co mineralization is carried by sulfides (pyrite and chalcopyrite) and oxides (magnetite and ilmenite) that are disseminated in the rock. The results of analysis of samples in percent nickel and cobalt indicate a nickel mineralization with a good grade (0.096% Ni).

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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