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RESEARCH ARTICLE

PETROGRAPHY AND HYDROTHERMAL ALTERATION OF ULTRAMAFIC BED-ROCKS OF SOUTH SIPILOU: IMPLICATION IN THE LATERITIC NICKEL MINERALIZATION (DEPARTMENT OF SIPILOU, WESTERN IVORY COAST)

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Abstract

South Sipilou is an area containing lateritic nickel mineralization that developed on ultramafic rocks in the department of Sipilou-Biankouma in western Ivory Coast. The objective of this study was to characterize the petrography and hydrothermal alterations affecting these ultramafic bed-rocks and to understand their involvement in lateritic nickel mineralization. Then to compare them to the ultramafic rocks already characterized in the department of Sipilou-Biankouma. Thus, the macroscopic characterization of these rocks was carried out in the field. Then, microscopic observations on the petrography and the hydrothermal alterations were made on these rocks after the preparation of thin sections in the laboratory. The results indicated that the lithologies of the ultramafic bed-rocks of South Sipilou consist of strongly serpentinized dunites, more or less harzburgitic lherzolites and olivine orthopyroxenites. Their petrographic characteristics showed a similarity with the ultramafic bed-rocks of the nickel-bearing lateritic mineralization of North Biankouma, North Sipilou and differences with those of Samapleu, Yepleu, in the department of Sipilou-Biankouma. Also, the main hydrothermal alterations of the ultramafic rocks of South Sipilou are composed of silicification, carbonation and serpentinization. Only serpentinization contributed to the concentration of nickel in the bed-rock and within the lateritic profile.

Introduction:-

Ivory Coast belongs to the Man ridge of the West African craton and the geology of its Precambrian basement is subdivided into two domains by the Sassandra fault with on the one hand the Archean domain in the west and on the

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other hand to the east, the Eburnean domain (Berger et al., 2013; Kouamelan, 1996; Bessoles, 1977). The department of Sipilou – Biankouma is located in the west of the Ivory Coast in the Archean domain. The rocks mainly consist of granulitic formations (the country rocks), ultramafic and mafic rocks. Some ultramafic and mafic rocks contain nickel sulfides (Ni) and others contain lateritic nickel mineralization. They form the Yacouba complex (Tiemoko, 2019; Gouedji et al., 2018; Gouedji, 2014; Baptiste, 2013). The nickel-bearing district of the Sipilou – Biankouma region is recognized for its mining potential estimated at more than 280 million tonnes of ore, as one of the main lateritic nickel deposits in the world (Freyssinetet al., 2005). Mathez (1976) highlighted four (4) main lateritic nickel deposits in the department of Sipilou – Biankouma which are the deposits of Sipilou, Foungbesso, Moyango and Viala. The Sipilou deposit is subdivided into two (2) nickel occurrences (Ouattara, 1998). The North Sipilou occurrence with ultramafic bed-rocks that are the source of nickel mineralization which are composed mainly of dunite, harzburgite, lherzolites and in places pyroxenite (Ouattara et al., 2009). And the South Sipilou occurrence, the subject of this article, whose petrography and alteration of ultramafic bed-rocks are less known.

The main objective of this article was to determine the petrographic nature of the ultramafic bed-rocks and the associated hydrothermal alterations of the South Sipilou occurrence. Thus, the petrography of these bed-rocks has been characterized through a macroscopic and microscopic description as well as the hydrothermal alterations that have affected these rocks. Then in the discussion, a correlation between the nickel concentration in the lateritic profiles and that contained in the bed-rocks has been made. Finally, these rocks were compared to other ultramafic rocks of the Yacouba complex already described in the department of Sipilou – Biankouma.

Methodology:-

Geological setting of the study area

The department of Sipilou is located in the western Ivory Coast and is bounded to the north by the town of Ouaninou, to the south by the town of Danané, to the east by the town of Biankouma and to the west by the country of Guinea Conakry (Fig. 1). Sipilou is located in the Archean domain of Man which consists of Archean fields (Fig. 2a). The Archean domain of Man was structured during two major orogenic cycles namely the Leonian (3.3 Ga to 3.0 Ga) and the Liberian (2.9 Ga to 2.7 Ga). The geological formations observed in this Archean domain in Ivory Coast are migmatitic gneisses, migmatitic biotitites, tonalitic orthopyroxene (OPX) gneisses, granodioritic gneisses, charnockites and metabasites (Fig. 2b) (Gouedji et al., 2021, 2020, 2014; Berger et al., 2013; Kouamelan, 1996; Pitra et al., 2010; Pothin and Gioan, 2000; Yacé, 1984; Kadio, 1983; Tagini, 1971). The department of Sipilou is made up of gneissic rocks which would have both sedimentary and volcanic protolith having undergone regional granulite to amphibolite metamorphism (Ouattara et al., 2009; Ouattara, 1998; Camil, 1984); anatexis products (charnockites, metadiorites, metagabbros (Kouamelan, 1996; Kouamelan et al., 1997) and mafic to ultramafic rocks. The mafic-ultramafic series with olivine and high nickel content is either in the form of veins, either in the form of sills or small stratiform massifs (Kouamelan, 1996; Kouamelan et al., 1997). It consists of olivine-bearing gabbronorites, peridotites, dunites and pyroxenites which have a cumulate texture. These are the most important of these ultramafic rocks which, under the effect of weathering in a prolonged tropical climate, gave rise to the lateritic nickel district of Sipilou-Biankouma (Ouattara et al., 2009; Ouattara, 1998; Mathez, 1976).

The South Sipilou area is located northern Sipilou and belongs to the exploration permit (PR 838) of the Sama Nickel-CI company (Fig. 3). It is affected by strong weathering. Only a few rare outcrops are present. The layers of alteration are of 30 to 50 m thick or more. Thus, the petrographic assemblages observed are the gneiss and migmatitic granulites of the Archean basement which constitute the regional geological background. These rocks are intercalated in places by mafic horizons (basic granulite, jotunite) and ultramafic-mafic assemblages (peridotite, pyroxenite, gabbronorite and gabbro). Jotunite and ultramafic-mafic rocks are locally superseded by red soils. In the northern part of Figure 3, the brownish-red area which is the studied area, consists of a lateritic red-brown soil composed of pisolite, red laterite and yellow laterite (Adjaito, 2021).

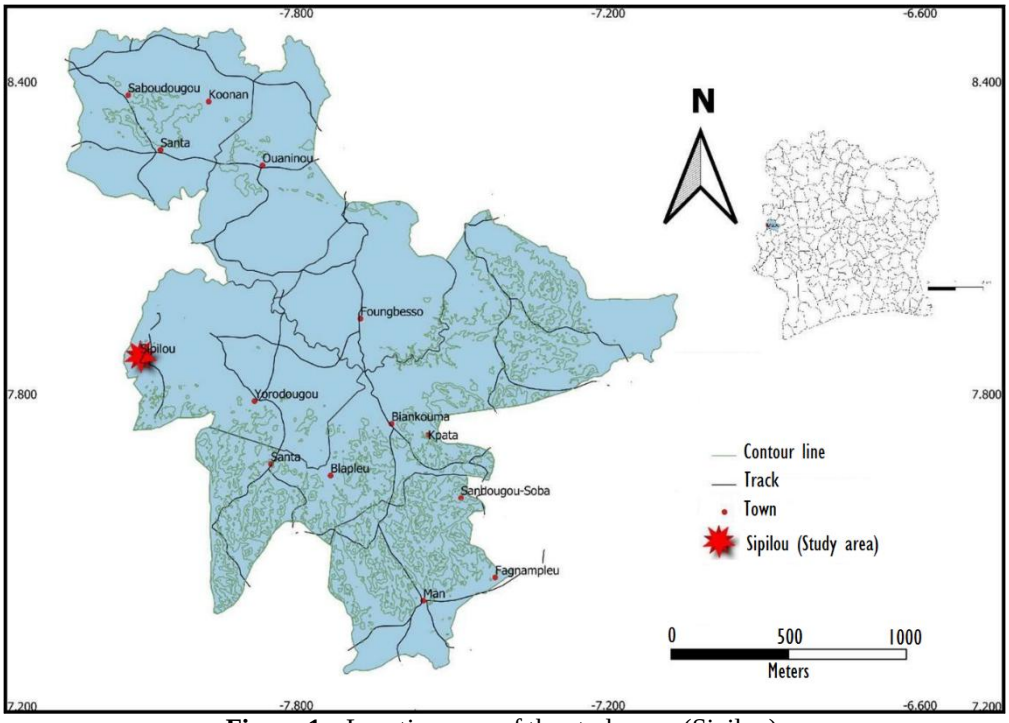

Figure 1:- Location map of the study area (Sipilou).

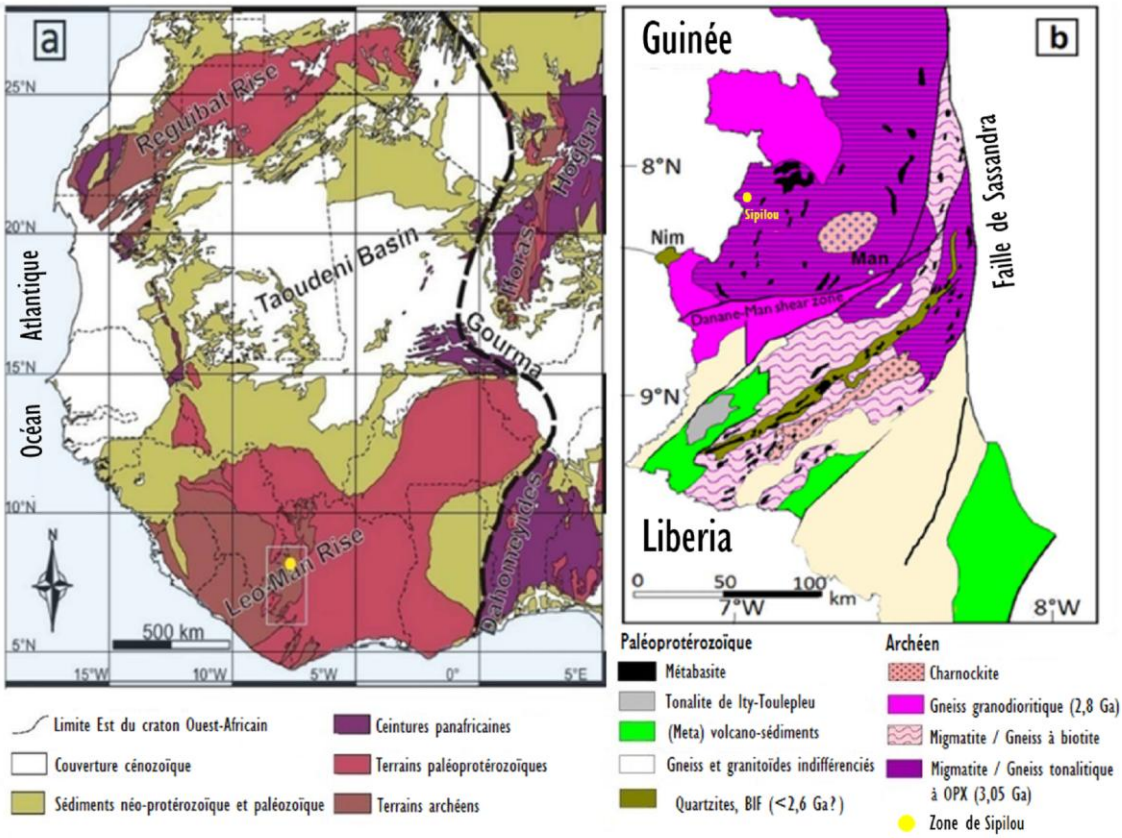

Figure 2:- Schematic geological map of the study area. **(a)** West African shield (adapted from figure 1a in Berger et al., 2013). **(b)** Man craton in western Ivory Coast (adapted from figure 2 in Pitra et al., 2010); the inset shows the Sipilou area (in Gouedji et al., 2021).

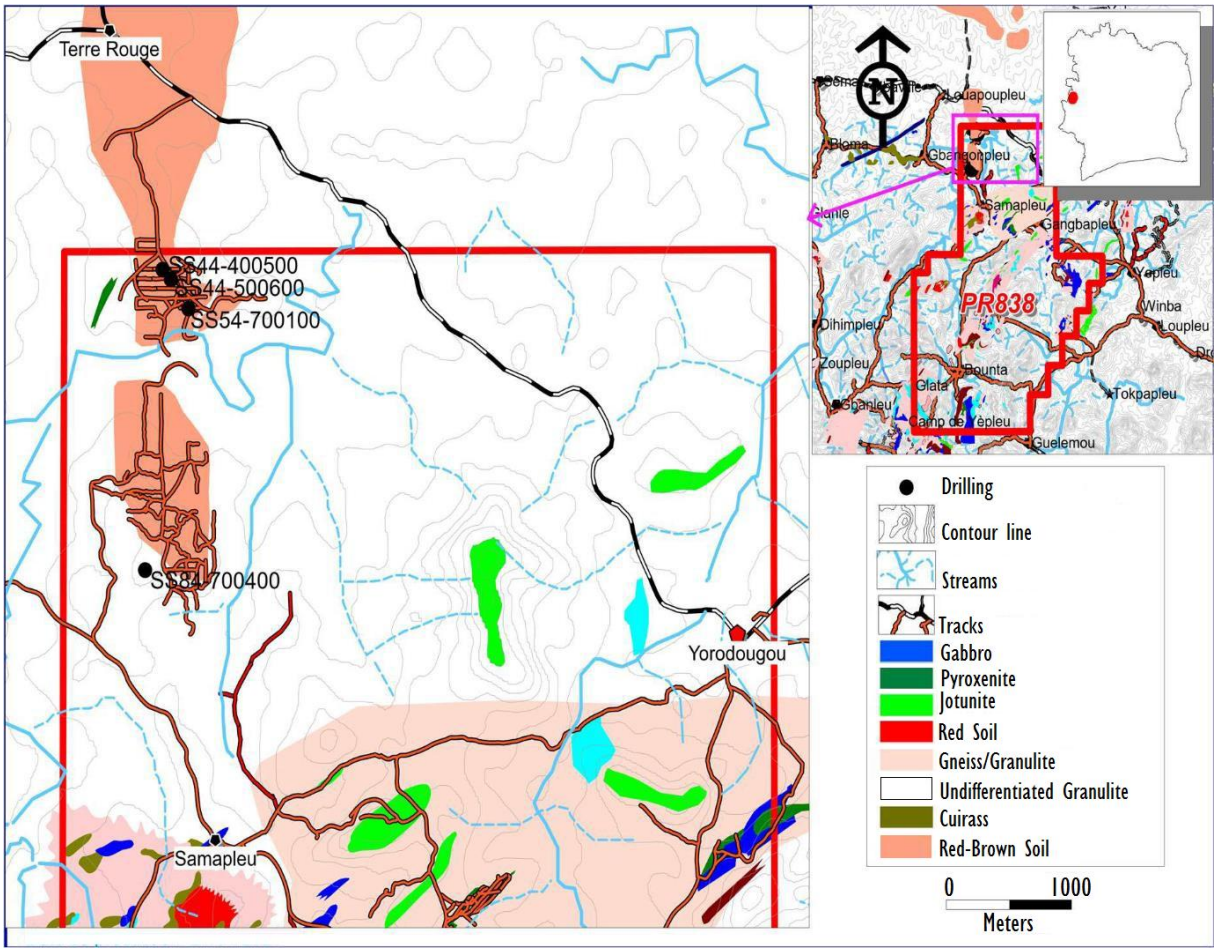

Figure 3:- Geological map of the study area (Exploration permit 838; Adjaito, 2021).

Analytical methods

The petrographic characterization of the bed-rocks of the nickel mineralization of the South Sipilou occurrence and their associated hydrothermal alterations was carried out using sampling methods and analytical techniques. Thus, rock sampling in the field was carried out on the cores of three (3) boreholes (SS44500600, SS84700400 and SS44700100). This step allowed the macroscopic identification of twenty-nine (29) samples, from the saprolite rock to the bed-rock, through the determination of the lithology parameters (color, texture, mineralogical composition, alteration and structure).Among the samples that were taken for the macroscopic descriptions, fifteen (15) were chosen for the fabrication of polished thin sections in order to refine the petrographic characterization of different rocks and types of hydrthermal alterations to the microscope. These polished thin sections were produced at the Laboratory of the Geology of the Basement and Metallogeny (LGSM, UFR- STRM) of the Félix Houphouët Boigny University (UFHB) from Abidjan (Ivory Coast). The minerals of these rocks were studied in transmitted light using an Optika Jeulin type microscope at the Geology Laboratory of the University of Man (Ivory Coast). In addition, the chemical data, the nickel (Ni) contents of the samples were obtained from a HORIBA MESA-50 type X-ray fluorescence spectrometer used at the geology laboratory of the University of Man.

Results:-

Petrography of ultramafic bed-rocks

The bed-rocks below the lateritic nickel profiles of the South Sipilou area consist of dunites, harzburgitic lherzolites and olivine-bearing orthopyroxenites.

Dunite

Dunite was macroscopically green to dark green in color with a fine grained texture. It was magnetic in places and affected by networks of white serpentine vein (Fig. 4a). To the microscope, dunite has a mesh-like pseudomorphic

texture. It was strongly serpentinized and was composed of olivine, serpentine, magnetite, orthopyroxene (Opx), amphibole and accessory talc (Fig. 4b and c). The olivine (more than 80% of the rock), euhedral, with a size between 200 µm and 0.1 mm in diameter, was to greenish-blue to yellowish-green polarization tint in analyzed polarized light. Olivine crystals were strongly serpentinized. The serpentine (17% of the rock) had a polarization hue ranging from light gray to purple and has developed following a dendritic network around the olivine. The anhedral magnetite (5% of the rock), was elongated in the networks formed by the serpentine and completely opaque in transmitted light. The orthopyroxene (less than 5% of the rock) had perfect cleavage and an orange tint. The amphibole formed around the serpentine. The talc was observed incidentally in clusters of small crystals generally interstitial between the crystals of orthopyroxene and olivine.

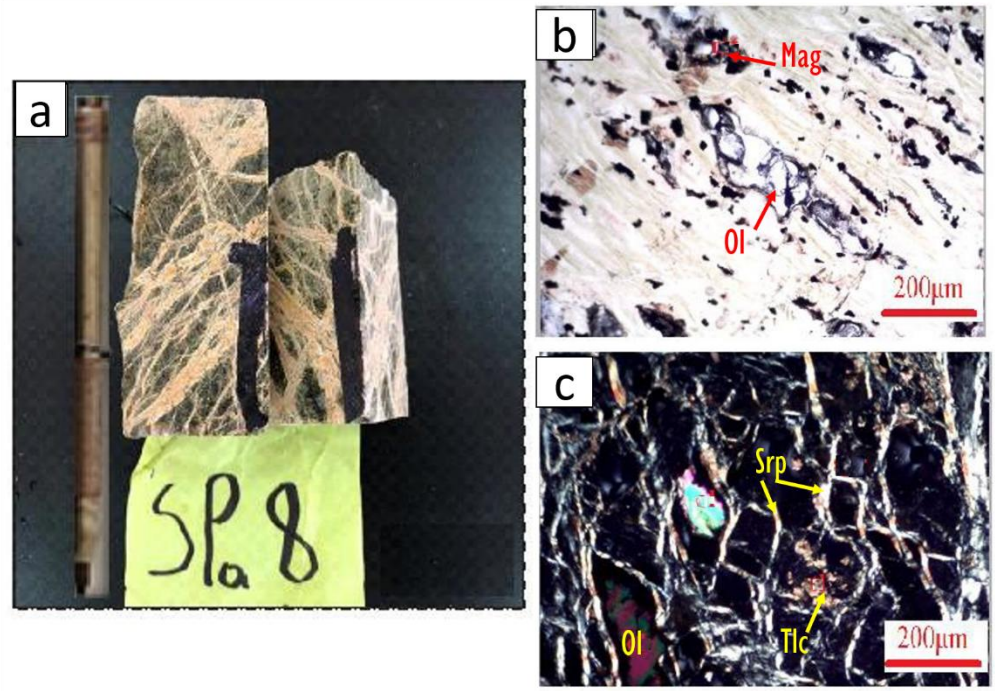

Figure 4:- Photomacrograph and photomicrographs of a strongly serpentinized dunite. **a.** Serpentinized dunite core; **b.** Serpentinized dunite with small olivine crystals in unanalyzed polarized light; **c.** Serpentinized dunite with serpentine network in analyzed polarized light.
Ol = Olivine; Mag =Magnetite; Tlc =Talc; Srp = Serpentine

Harzburgitic lherzolite

This rock had a variable mineralogical composition. In places, it resembles harzburgite with the proportion of Opx tending to increase compared to that of clinopyroxene (Cpx). This rock was macroscopically massive, dark gray in color with a grainy texture (Fig. 5a). To the microscope, it has a cumulative grainy texture and is composed of olivine, Cpx, Opx, magnetite, spinels, serpentine, amphibole and talc. The olivine (about 70% of the rock) which is euhedral and partially serpentinized had a size between 0.8 and 5 mm. The serpentine formed mesh cracks, filled by the magnetite, within the olivine crystals. The Cpx (15-20% of the rock) was subhedral, ranging in size from 1 to 3 mm, in tint from gray to yellow-orange with undulating extinction and deformation kinks in places. Its crystals were generally intercumulus between olivine crystals (Fig. 5b). The Opx (5 to 10% of the rock), less than 2 mm in size, was subhedral with a light gray tint (Fig. 5c). The amphibole (less than 5% of the rock), with a size between 500µm and 2 mm, was brown in analyzed polarized light. It was subhedral, green-blue in tint. Spinel (less than 1% of the rock), brown in color, anhedral was of micrometric size (< 1 mm), disseminated and accessory within the rock. The talc was in the form of a micrometric cluster, interstitial between the crystals of Cpx and olivine.

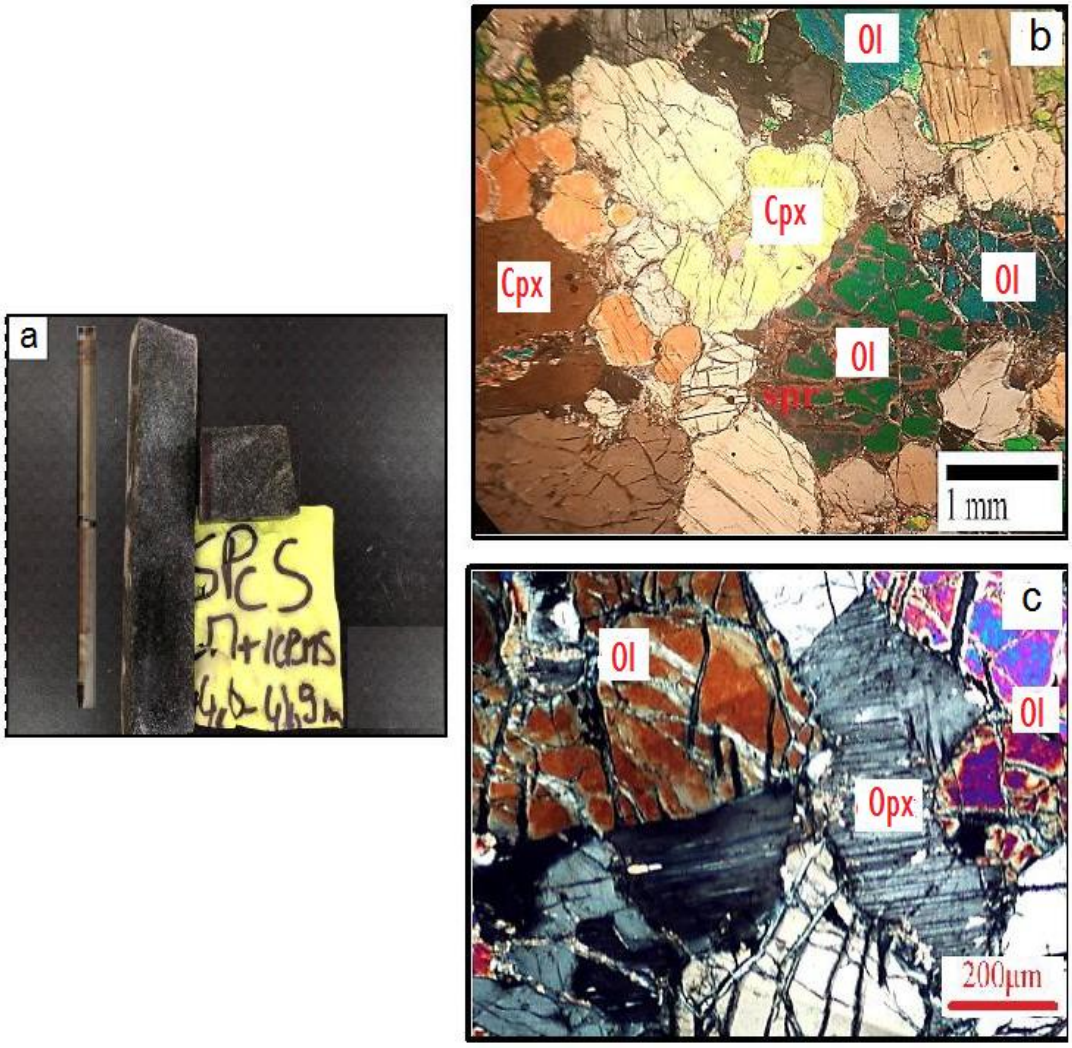

Figure 5:- Photomacrograph and photomicrographs of lherzolite. **a.** Lherzolite core; **b. and c.** Olivine cumulus lherzolite with Opx and Cpx intercumulus in analyzed polarized light.
Ol = Olivine; Cpx = Clinopyroxene; Opx = Orthopyroxene

Olivine-bearing orthopyroxenite

Olivine-bearing orthopyroxenite was macroscopically massive, dark gray in color, grainy in texture and weakly magnetic (Fig. 6a). It was composed of orthopyroxene, olivine, serpentine, clinopyroxene and accessory spinel and magnetite. To the microscope, the rock had a cumulative grainy texture and orthopyroxene is the cumulus mineral. The Opx (about 60% of the rock) was subhedral, millimetric in size and light gray to yellow-orange in tint (Fig. 6b). Its crystals were in places affected by kinks of deformation and recrystallization texture (small Opx crystals associated with large crystals of Opx and Cpx). Opx crystals were locally weakly serpentinized. The olivine (20 to 30% of the rock) had sizes ranging from 1 to 5 mm. It was generally subhedral, cracked and partially serpentinized. The Cpx (less than 10% of the rock), brown in unanalyzed polarized light, subhedral, of variable size (500 µm to 4 mm) was altered in places with a yellow-orange tint. Accessory subhedral minerals (< 2% of the rock) composed of dark brown spinel in unanalyzed polarized light and round-shaped magnetite were globally small (less than 500 µm).

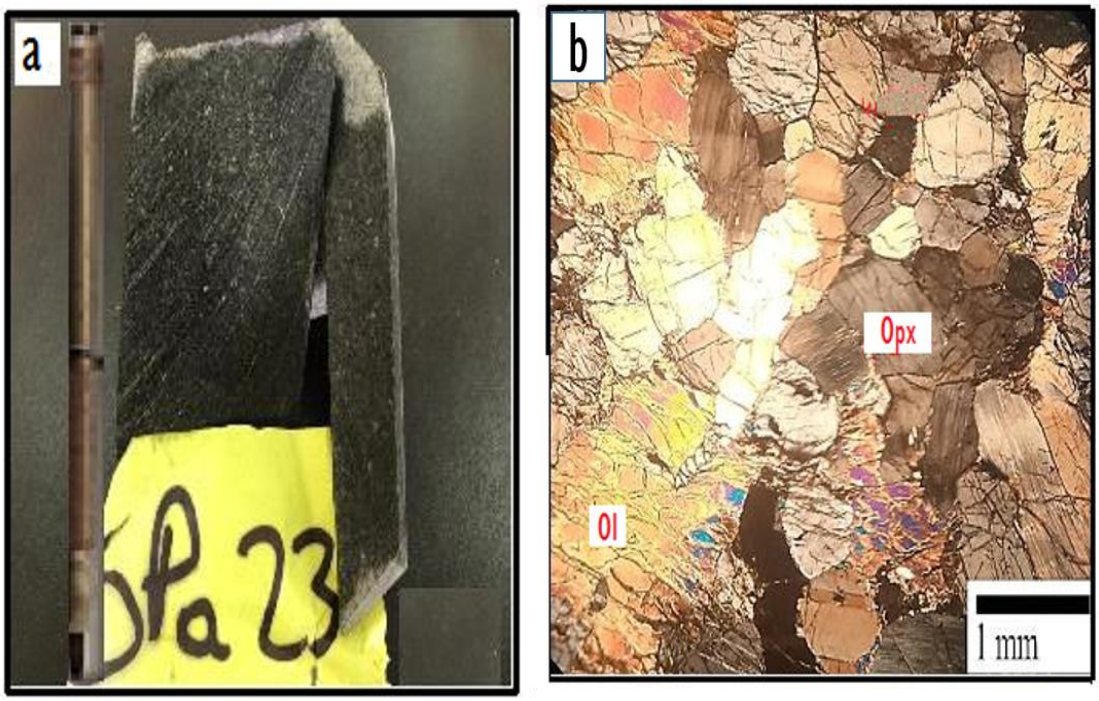

Figure 6:- Photomacrograph and photomicrograph of olivine-bearing orthopyroxenite. **a.** Olivine-bearing orthopyroxenitecore; **b.** Orthopyroxenite with olivine and orthopyroxene crystals in analyzed polarized light. Ol = Olivine; Opx=Orthopyroxene

Bed-rock alterations

The alterations that affected the bed-rocks of the lateritic nickel mineralization of South Sipilou are subdivided into supergene and hydrothermal alterations. The alterations related to hydrothermal fluids, objects of this study consisted of serpentinization, carbonation and silicification.

Serpentinization

This alteration affected dunite at about 90%, harzburgitic lherzolite at 10-20% and olivine-bearing orthopyroxenite at less than 10%. It generally attacked olivine and to a lesser extent Opx through the fracture networks of these silicate minerals. Serpentinization was characterized by the development of new mineral phases (serpentines, magnetites, talc, amphiboles and brucite). Newly formed serpentine was generally associated with magnetite. These two minerals have crystallized as veins within the olivine. Some crystals of orthopyroxene due to high degrees of serpentinization transformed into brucite and talc (Fig. 7a and b).

Carbonation

Carbonation can be defined as the process by which bed-rocks of lateritic nickel mineralization have been impregnated by carbonates (Fig. 7a). The effervescence observed during the hydrochloric acid test carried out on some of these altered rocks indicates the presence of carbonate in certain rock samples. The carbonation developed in the fractures and in the vicinity of the amphiboles. These carbonates formed at the end of this process were very friable and would be dolomites.

Silicification

The silicification was marked by the presence of silica veinlets which most come from the arrival of late silica fluids often soaks the fractures of the rocks which host them. Also, these silica veinlets would mark the release of silica during the onset of supergene alteration of ultramafic bed-rocks. The silica veinlets observed in the bed-rocks were marked by the presence of fine quartz minerals in the veins. (Fig. 7b).

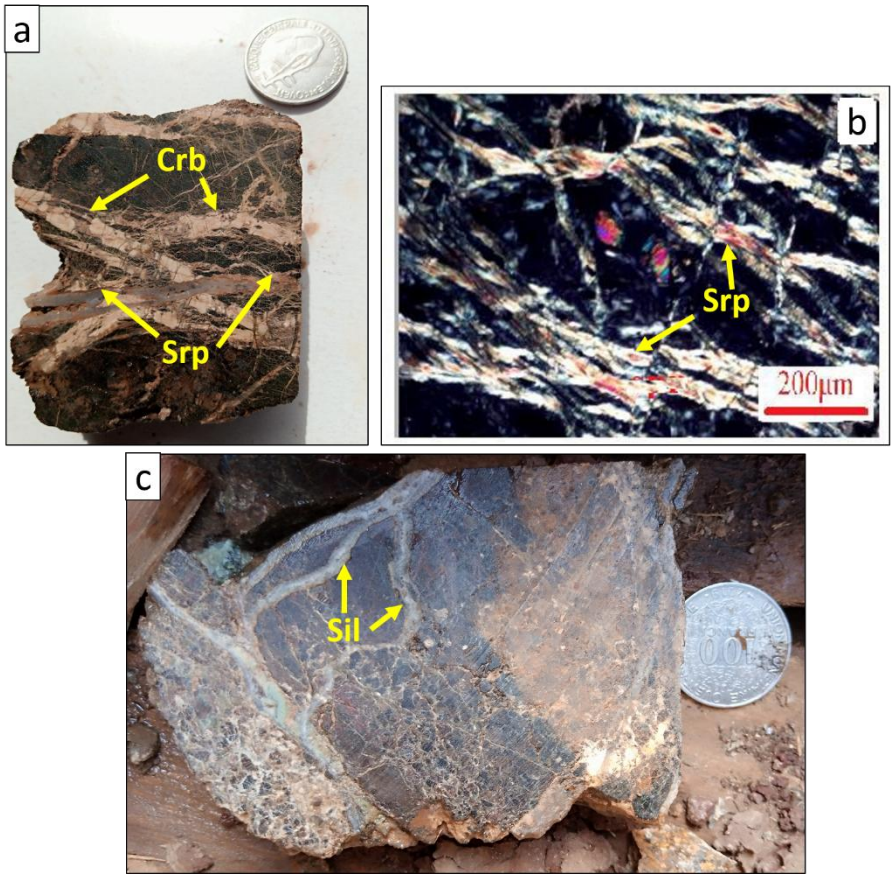

Figure 7:- Photomacrographs and photomicrograph of hydrothermal alterations. **a.** Core of a dunite with serpentinization and carbonation ; **b.** Photomicrograph of olivine crystals affected by serpentinization in analyzed polarized light ; **c.** Core of a dunite crossed by silica veinlets obtained by silicification.
Srp = Serpentine; Crb = Carbonate; Sil = Silice

Nickel (Ni) contents of ultramafic bed-rocks

The geochemical data presented in Table 1 indicate the variation of the Ni contents within the bed-rocks of South Sipilou depending on their nature. The Ni contents obtained in the dunites varied from 0.247 to 0.304% and those observed in the olivine-bearing orthopyroxenites varied from 0.162 to 0.224%. The high contents in the dunites would be explained by the fact that nickel is found in the crystalline structure of the olivine. However the dunite is a rock which contains more olivine than the olivine-bearing orthopyroxenite.

Table 1:- Nickel contents of ultramafic bed-rocks from boreholes studied in the South Sipilou area.

boreholesnames	Lithologies	Depth(m)	Ni (%)
SS44 400500	Olivine-bearing orthopyroxenite	24	0.162
SS44 500600	Olivine-bearing orthopyroxenite	40.5	0.168
SS44 500600	Olivine-bearing orthopyroxenite	42	0.176
SS44 500600	Olivine-bearing orthopyroxenite	43.5	0.199
SS44 500600	Olivine-bearing orthopyroxenite	45	0.224
SS44 500600	Dunite	46.5	0.247
SS44 500600	Dunite	48	0.294
SS44 500600	Dunite	49.5	0.304
SS84 700400	Olivine-bearing orthopyroxenite	39	0.193

Discussion:-

Petrographic features

The Ultramafic bed-rocks of the lateritic nickel mineralization of the South Sipilou area consisted of dunites, harzburgitic lherzolites and olivine-bearing orthopyroxenites. These rocks had a cumulative texture and did not contain sulfide. They are composed in varying proportions of olivine, serpentine, magnetite, Opx, Cpx and accessory spinel. Within these rocks, some olivine and pyroxene crystals had undulating extinctions and deformation kinks. These lithologies have mineralogical and textural compositions almost similar to those of the ultramafic bed-rocks identified in the nickeliferous district of North Biankouma and North Sipilou (Ouattara et al., 2009; Ouattara, 1998). However, the ultramafic rocks of South Sipilou are different from the mafic-ultramafic rocks of Samapleu (department of Sipilou) and Yepleu (department of Biankouma). According to the authors Ouattara (1998), Gouedji (2014) and Fofana (2021), these mafic-ultramafic rocks of Samapleu and Yepleu are composed of ultramafic unit (peridotite, pyroxenite, chromitite) and mafic unit (gabbro, gabbronorite, norite and anorthosite) which have a cumulative texture and contain nickel sulfide mineralization.

The mineralogical composition and the cumulative texture of the ultramafic rocks of South Sipilou, of the zones of Samapleu and Yepleu, of North Sipilou, of North Biankouma would imply a mantle magmatic origin with a formation of these rocks by fractional crystallization (Woods and Cowan, 2009; Pupier, 2006). Also, the undulating extinctions and deformation kinks observed within certain minerals (olivine, pyroxene) of these rocks would imply an emplacement of these rocks at high temperature (HT) and medium to high pressure (MP/HP) (Gouedji et al, 2014).

Gouedji (2014) and Gouedji et al. (2014) indicated that these characteristics (undulating extinctions and deformation kinks) that were observed within the mafic-ultramafic rocks of Samapleu would be the result of a placement of these rocks in the lower crust at the Eburnean (2.09 Ga). As for the ultramafic rocks of South Sipilou, North Sipilou, North Biankouma which have not been dated, they could have been affected by the Archean granulite metamorphism (2.8 Ga) described in the region (Kouamelan, 1996, Gouedji, 2014) which induced these same characteristics to the rocks affected by this metamorphism. Thus, the ultramafic bed-rocks of South Sipilou could be of Archean age like certain intrusions described in West Africa in the Archean domain (layered intrusion of Guelb el Azib in Mauritania; Berger et al., 2013).

Alteration

The supergene ore formation process developed on ultramafic rocks within lateritic profiles (Freyssinet et al., 2005) is subsequent to hydrothermal alteration which is likely to facilitate the degradation of ultramafic rocks. The bed-rocks below the lateritic horizons of the South Sipilou zone showed marks of silicification, carbonation and serpentinization, as the main hydrothermal alterations.

Silicification is common in lateritic nickel profiles and most often associated with garnierite ore (Quesnel, 2015). The quartz resulting from silicification and observed in the bed-rock, would reflect low temperature hydrothermal conditions (40°C and 80°C) associated with their formation. The origin of silicification would be either due to the circulation of convective-type fluid at depth (Fyfe, 1974) or due to meteoric water involved in the laterization process (Guillou-Frottier et al., 2015).

Carbonation generally corresponds to late alteration stages and is not directly linked to the formation of serpentine (Mével, 2003). It would be linked to the precipitation of carbonates by the alteration of the serpentine (Abu-Jaber and Kimberley, 1992).

The nickel contents of the South Sipilou bed-rocks were between 0.1642% and 0.304% and are lower than those indicated by Golightly (1981) as primary nickel content (0.3%). Nickel contents in borehole SS44500600 evolved from depth to surface from 0.304% to 0.247% in serpentinized dunites and from 0.224% to 0.162% in serpentinized olivine-bearing orthopyroxenites (Table 1). This decrease in nickel content in these bed-rocks could be justified by the alteration of olivine into serpentine. Indeed, serpentinization involves physical and chemical changes due to hydration when ultramafic rocks are exposed to circulating aqueous fluids at a temperature below 400°C. This leads to the formation of serpentine (Lamadrid et al., 2017). Additionally, Irfanet al. (2021) showed that the serpentinization of olivine and pyroxene would cause a redistribution of nickel and other mobile elements within the bed-rock. Nickel having a semi-mobile character cannot be reduced spontaneously from bed-rock and combines with serpentine. Therefore, the degree of serpentinization and the characteristics of the bed-rock are at the origin of

the development of nickel, from the bed-rock to the laterite. The lateritic nickel profile would show a nickel enrichment of about ten (10) times more than that of the nickel contained in the bed-rock. This process was highlighted at South Sipilou by Adjaito (2021) through the evolution of nickel contents in laterite profiles developed on ultramafic bed-rocks. Thus, serpentinization is a hydrothermal alteration that contributes to lateritic nickel mineralization in contrast to silicification and carbonation.

Conclusion:-

The lithologies of the bed-rocks of the lateritic nickel mineralization of South Sipilou (western Ivory Coast) consisted of strongly serpentinized dunite, harzburgitic lherzolite and olivine-bearing orthopyroxenite. These rocks were composed in varying proportions of olivine, serpentine, magnetite, Opx, Cpx and accessory spinel.These ultramafic rocks which belong to the Yacouba complex showed petrographic and textural similarities with the lateritic nickel-bearing ultramafic rocks of North Sipilou and North Biankouma in the region. However, the bed-rocks of lateritic nickel mineralization at South Sipilou differed from the mafic-ultramafic nickel sulfide-bearing rocks of the Samapleu and Yepleu zones in their mineralogical and metallogenic characteristics, indicating a likely different origin.

All the lithologies of the bed-rocks of South Sipilou have been affected by hydrothermal alteration to varying degrees through serpentinization, silicification and carbonation. Serpentinization, which mainly affected olivine and to a lesser extent orthopyroxene, contributed to the reconcentration of nickel from the bed-rock to the laterite, favoring the formation of lateritic nickel mineralization. On the other hand, silicification and carbonation, although affecting the bed-rocks, did not contribute to the nickel enrichment of these rocks.

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