



(RESEARCH ARTICLE)



PETROGRAPHY OF THE GEOLOGICAL FORMATIONS OF THE NORTHERN SECTOR OF THE GUIGLO-TAÏ AREA (WESTERN CÔTE D'IVOIRE) AND ASSOCIATED MINERALIZATION

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World Journal of Advanced Research and Reviews, 2026, 32(01), 1148–1158

Publication history: Received on 07 September 2026; revised on 17 October 2026; accepted on 19 October 2026

Article DOI: <https://doi.org/10.30574/wjarr.2026.32.1.2654>

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ABSTRACT

The northern sector of the Guiglo-Taï area is located in the Cavally region in western Côte d'Ivoire. It covers the Guiglo high-technology metals research project (HTM Guiglo) and lies both to the west of the Ivorian Palaeoproterozoic domain and to the north-east of the Archaean-Palaeoproterozoic transition domain "SASCA". This study was carried out to improve the geological knowledge with a view to a better prospecting of Tin-Tungsten-Lithium mineralization. The petrographic data reveal magmatic rocks composed of pegmatites, two-mica granites (the most abundant), mica granites, garnet porphyritic granites, granodiorites and dolerites. Amphibolites (the most abundant), migmatitic gneisses and micaschists represent the metamorphic rocks. These rocks are affected by a hydrothermal alteration (pervasive and veined) marked by epidotization, chloritization, sericitization, muscovitization and sulphidation, as well as oxides. The sulphides and oxides identified are pyrite, chalcopyrite, rutile and goethite. The mineralization of high-technology metals is controlled by hydrothermal parameters.

Keywords: Côte d'Ivoire; Guiglo; Petrography; Hydrothermal parameters. Tin-Tungsten-Lithium mineralization

1 INTRODUCTION

Côte d'Ivoire is located on the crest of the Léo-Man rise, representing the southern portion of the West African craton. The national territory is geologically divided into two (2) large regions by the Sassandra fault. To the west of the fault lies the Archaean domain, and to the east, the Palaeoproterozoic domain. This geological setting displays a remarkable diversity, reflecting an ancient and complex tectono-metamorphic history, marked by several major orogenic episodes. The Guiglo-Taï region, located in the west of the country, lies entirely within the Archaean to Palaeoproterozoic zone. This region has long attracted the attention of geologists because of the complexity of its lithological and structural architecture. Thus, in a global context dominated by the energy transition and the accelerated development of green technologies, the demand for so-called high-technology metals (HTM) or "critical metals" such as lithium (Li), tungsten (W) and tin (Sn) is experiencing unprecedented growth. These metals are essential to many strategic industries,

particularly in the manufacture of batteries for electric vehicles, semiconductors, high-temperature-resistant alloys and electronic components. Ensuring a secure and sustainable supply of these resources is now a major geopolitical and economic issue on a global scale. Consequently, keen to fully develop its mining potential, which is still largely concentrated on gold mining, Côte d'Ivoire has committed to becoming a key player in the field of high-technology metals in West Africa. It is in this context that this study was initiated, to contribute to the characterization of the geological formations of the northern sector of the Guiglo-Taï area, in order to support the revival of the Ivorian mining sector.

2 GEOLOGICAL SETTING

Côte d'Ivoire is part of the West African Craton, more precisely of its southern portion known as the Man rise ([1]; Figure 1). Two large geological units crop out there: the Precambrian basement, which covers about 97.5% of the territory, and the coastal sedimentary basin, located at the southern end and representing nearly 2.5% of the national area. The northern sector of the Guiglo-Taï area, which belongs to the Guiglo high technology metals research project (HTM Guiglo), lies both to the west of the Ivorian Palaeoproterozoic domain and to the north-east of the Archaean-Palaeoproterozoic transition domain "SASCA". The geology of the region is characterized by a juxtaposition of gneissic to migmatitic units with amphibolite-facies units (micaschists) associated with granitic plutons. Indeed, the Archaean-Proterozoic transition is dominated by granito-gneissic formations, followed by volcanic, volcano-sedimentary and sedimentary units. According to [1-2], this transition is materialized by the submeridian Sassandra fault, oriented N-S to NNW-SSE. On the basis of the Sm-Nd model ages obtained on the magmatic protoliths of the grey gneisses (3207 ± 7 Ma), [3] subdivides this transition zone into three subdomains: the Boundiali domain (Northern domain), located north of the 9° parallel; the Séguéla-Vavoua domain (Central domain), comprised between the 7° and 9° parallels; and the SASCA domain (Southern domain), which extends from the 7° N parallel to the Atlantic coast.

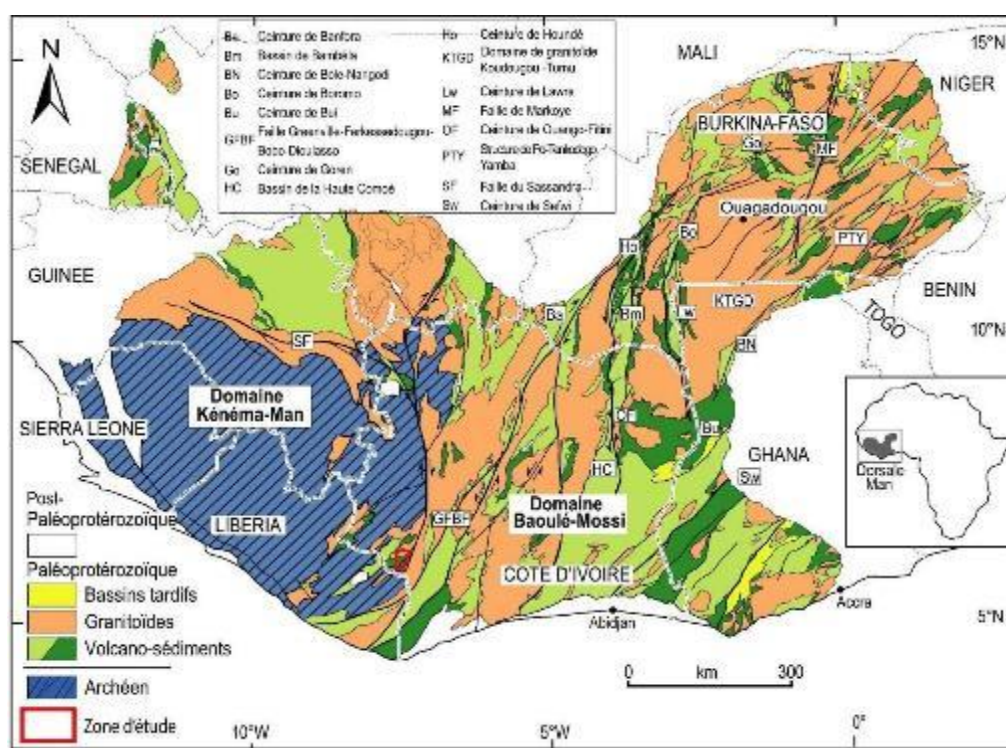


Figure 1: Synthetic regional geological map of the Man rise showing the study area ([4], modified).

The ϵ_{Hf} ages in these formations vary between -9.4 Ga and $+3.3$ Ga [5]. A potassic granite intrusion at San Pédro has been dated at 2084 ± 6 Ma. The presence of Archaean relics, combined with the negative ϵ_{Nd} values at 2100 Ma in the migmatitic grey gneisses and the ϵ_{Hf} values in the San Pédro potassic granite, suggests an interaction between Archaean rocks and juvenile magmas emplaced during the Eburnean orogeny [6, 7]. Furthermore, a garnet-cordierite-sillimanite migmatitic paragneiss from Grand-Béréby, deposited after 2069 ± 4 Ma [7], yielded Sm-Nd model ages of 2.48 and 2.47 Ga, confirming the Archaean origin of the source of the sedimentary protoliths [7-8]. According to [9], the Guiglo region displays additional lithological diversity, including in particular: muscovite-, biotite- and garnet-bearing granulites, amphibole- and biotite-bearing embrechites, embrechitic leptynites, pigeonite-bearing dolerites, muscovite-, biotite- and epidote-bearing anatexites, biotite- and muscovite-bearing paragneisses (or biotite-, muscovite-, staurolite-, sillimanite- and garnet-bearing), cordierite- and biotite-bearing quartzites, pyroxene-bearing leptynites, amphibole- and pyroxene-bearing gneisses, as well as biotite- and chlorite-bearing embrechitic leptynites. The study area is

characterized by a geology made up of formations of Archaean and Palaeoproterozoic age. The Archaean formations mainly comprise biotite- and garnet-bearing gneisses, amphibolo-pyroxenites and quartzites. As for the Palaeoproterozoic formations, they are represented by granodiorites, gabbros, diorites, basalts and intrusions of two-mica granites (muscovite and biotite) as well as undifferentiated migmatites. These data come from the provisional geological map of Côte d'Ivoire [10] (Figure 2).

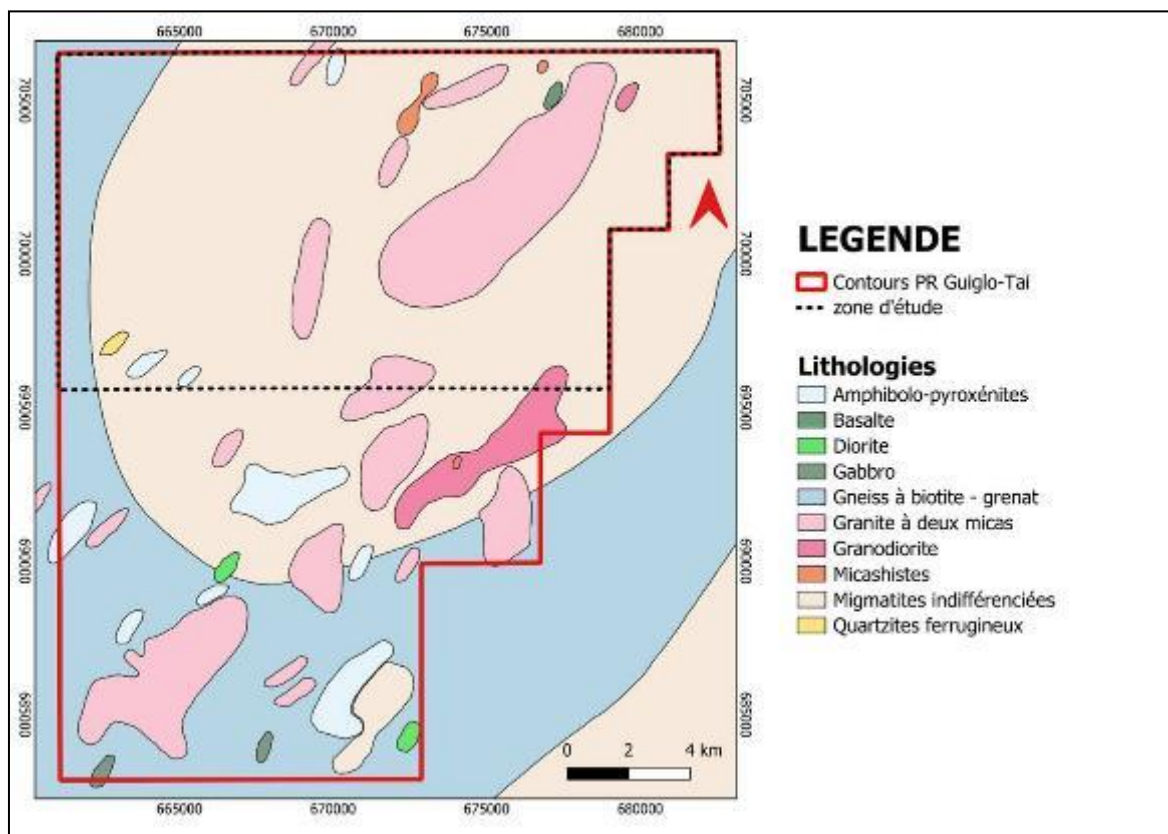


Figure 2: Geological map of the study area ([10], modified).

3 METHODOLOGY

At the end of the field work, which consisted in carrying out the macroscopic petrography, samples were carefully collected for the laboratory phase. The laboratory analyses combined microscopic petrography and metallogeny. This approach aimed to deepen the field observations, to better characterize the mineralogical assemblages, and to identify the metalliferous paragenesis. Accordingly, thin sections and polished thin sections were prepared at the litholamellage workshop of the Laboratory of Geology, Mineral and Energy Resources of the Félix HOUPOUET-BOIGNY University of Abidjan-Cocody. The thin sections were observed under a polarizing optical microscope, coupled with a digital camera connected to a computer. The metallographic analysis consisted in the study of the polished thin sections in reflected light under the metallographic microscope.

4 RESULTS

4.1 Petrography

The rocks of the northern sector of the Guiglo-Taï area are composed of magmatic rocks (plutonic and vein) and metamorphic rocks.

4.1.1 Magmatic rocks

4.1.1.1 Plutonic rocks

These rocks are essentially represented by granodiorites and granites. The granites, for their part, occur in several varieties.

4.1.1.1.1 Granodiorites

They crop out as blocks and slabs at Ditrouda Béoué (Figure 3A). These rocks are massive, granular with fine facies, mesocratic and composed mainly of quartz, feldspars, micas and amphibole. Under the microscope, quartz is abundant and of variable size (medium to coarse crystals) (Figure 3B). Plagioclase is generally subhedral and microcline occurs in low proportion and of large size. Amphibole, for its part, is observed in low proportions and is distinguished by the presence of clear cleavages and a yellowish tint. Chlorite, sericite, epidote and opaque minerals complete the mineralogy of these rocks.

4.1.1.1.2 Two-mica granites

These massive, leucocratic, silicified and granular rocks come from the localities of Nizahon, Béhébou and Sitakro (Figure 3C). At the outcrop, one can distinguish quartz, feldspar and mica minerals. However, the Nizahon granite contains tourmaline and the Sitakro one shows over-micaceous zones. Under the microscope, the granites show a granular to porphyritic granular texture with phenocrysts generally of quartz and feldspars (plagioclase and K-feldspar) (Figure 3D). Quartz is xenomorphic, very abundant and often affected by numerous fractures. Plagioclase is generally of medium size and subhedral. Microcline, muscovite and biotite are also observed, the latter often destabilizing into muscovite. They contain, as accessory minerals, myrmekite, chlorite, sericite, epidote and opaque minerals.

4.1.1.1.3 Garnet porphyritic granites

These granites, observed at Ladjikro, are massive, leucocratic, and contain large crystals of quartz, muscovite and feldspars, as well as biotite and garnet (Figure 3E). Observation under the microscope reveals a rock with a porphyritic granular texture containing phenocrysts of quartz, muscovite and microcline (Figure 3F). Quartz, an abundant mineral, comes in various sizes with a remarkable rolling extinction. Plagioclase is subhedral and of the medium grain size of the rock. Microcline and muscovite also occur in variable sizes ranging from coarse grain to medium grain. In addition to this are biotite and garnet, as well as chlorite, sericite and opaque minerals.

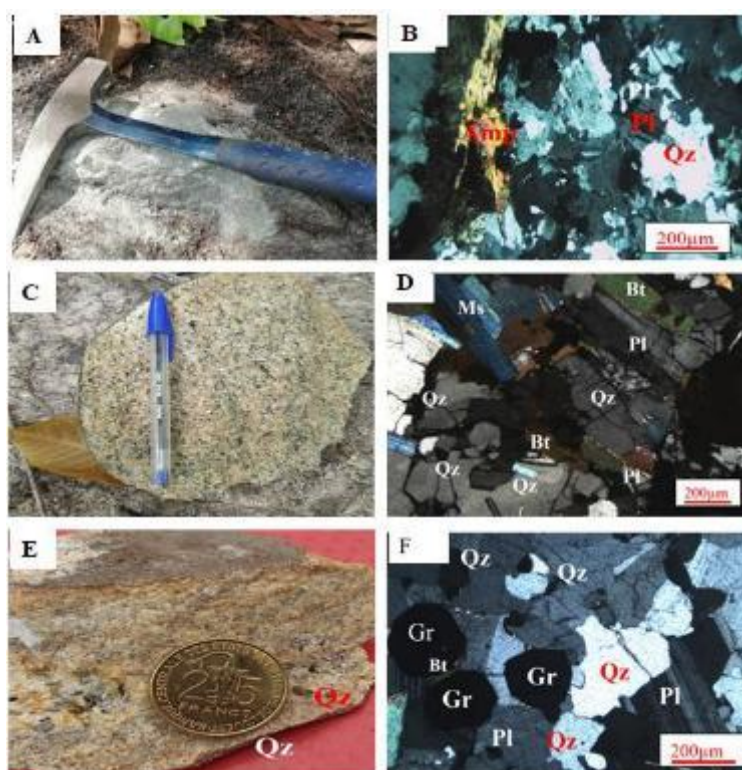


Figure 3: Macroscopic and microscopic aspects of the granodiorites (A-B), two-mica granites (C-D) and garnet porphyritic granites (E-F). Amp: Amphibole; Pl: Plagioclase; Qz: Quartz; Ms: Muscovite; Gr: Garnet.

4.1.1.1.4 Leucogranites

These rocks, encountered at Sitakro, are leucosomes that are in contact with the migmatitic gneisses (Figure 4A). They are granular, and made up of quartz, feldspars, biotite and muscovite. Under the microscope, quartz is xenomorphic and shows localized fractures (Figure 4B). Added to this are plagioclase, microcline and muscovite. Biotite is subhedral and generally alters into chlorite. Moreover, myrmekite, made up of intergrowths and quartz buds scattered in the plagioclase, develops into worm-like shapes when in contact with microcline. Chlorite, resulting from the alteration of

biotite, is also present, and epidote, of vivid tint, constitutes a mineral alteration product of feldspars and biotite. Finally, sericite, which appears in lesser proportion, results from the alteration of muscovite and feldspars. Opaque minerals of variable sizes are also present.

4.1.1.2 Vein rocks

4.1.1.2.1 Dolerites

They outcrop at Konankro, and are melanocratic, weakly to moderately magnetic, and made up of ferromagnesian minerals (amphibole and pyroxene) and plagioclases (Figure 4C). Under the microscope, pyroxene is distinguished by euhedral crystals (Figure 4D). The brown hornblende observed results for the most part from the destabilization of pyroxene. Plagioclase occupies about 40% of the assemblage and occurs as subhedral crystals, showing characteristic polysynthetic twinning. Moreover, sericite, resulting from the destabilization of plagioclases, is frequently encountered at the junctions and interstices between the minerals. Olivine, in small quantity, is recognizable by its rounded crystals of vivid tint, often filled with fractures.

4.1.1.2.2 Muscovite pegmatites

The pegmatites, located at Ditrouda Béoué, occur in various forms including slabs, blocks and veins (Figure 4E). They are massive, leucocratic, and made up of feldspars, quartz and muscovite. Under the microscope, the pegmatites are characterized by a mineralogical composition dominated by feldspars (plagioclase and microcline), which occupy almost the entire mineralogical field (Figure 4F). Indeed, the feldspars, in association with quartz and muscovite, constitute the essential part of the mineralogical composition. Orthoclase, for its part, appears in very small proportions. Perthite veinlets are identifiable within the microcline patches, as well as oxides and opaque minerals.



Figure 4: Macroscopic and microscopic aspects of the leucogranites (A-B), dolerites (C-D) and muscovite pegmatites (E-F). Mc: Microcline; Chl: Chlorite; Ep: Epidote; Px: Pyroxene; Prt: Perthite.

4.1.1.2.3 Two-mica and garnet pegmatites

These massive, leucocratic rocks containing quartz, feldspars, micas and garnet were observed at Béhébou (Figure 5A). Under the microscope, quartz shows numerous fractures (Figure 5B). Its growth also takes place at the expense of the other minerals through the interstices, cleavages and fractures that testify to a significant silicification. The plagioclases occur in subhedral form, and the potassic feldspars, for their part, are made up mainly of microcline and rare orthoclase. Muscovite is the most abundant mica, and is often contained inside the biotites. Sericite occurs as small flakes of mica, resulting from the alteration of feldspars and micas. These rocks also contain garnet.

4.1.2 Metamorphic rocks

4.1.2.1 Amphibolites

They are massive, greenish-grey in color, deformed, crop out as slabs at Béoué Ditrouda and contain amphibole, quartz and feldspar minerals (Figure 5C). Under the microscope, the texture is nematogranoblastic, with a remarkable abundance of amphibole, most often altered into chlorite (Figure 5D). A more or less clear orientation of the minerals is observed, due to the deformation. Brown hornblende is very abundant and often twinned, while green hornblende is less frequent. Quartz and plagioclase are also present.

4.1.2.2 Micaschists

At the outcrop, these rocks observed at Béhébou are grey, massive and made up of quartz and micas (Figure 5E). Under the microscope, the micaschists show a granolepidoblastic texture and contain quartz, very abundant with a remarkable undulose extinction (Figure 5F). Biotite is present, and often destabilizes into chlorite. Muscovite, plagioclase and microcline are also observed.

4.1.2.3 Migmatitic gneisses

These rocks crop out at Sitakro and are made up of light quartzo-feldspathic bands and dark biotite-bearing bands (Figure 5G). Under the microscope, the migmatitic gneisses show a nematoblastic texture, with quartz minerals in dominant proportion and locally cracked (Figure 5H). Plagioclase is subhedral and of medium size, forming the light bands together with quartz and muscovite. Biotite, for its part, is arranged as oriented minerals and generally alters into chlorite.

4.2 Alterations

4.2.1 Supergene alteration

The weather conditions in the study area favor pronounced supergene weathering. The weathered surface part thus displays a well-developed regolithic profile, composed of lateritic gravels or duricrust, a clayey-mottled transition zone, and a saprolite that extends from the hills to the prospecting pits.

4.2.2 Hydrothermal alteration

The data collected in the study area indicate that the mineral modifications of this zone result mainly from a hydrothermal alteration. This alteration arises from the circulation of hot fluids that infiltrate the pores and fractures of the rocks, often created by tectonic deformation. In the study area, it is expressed by the formation of quartzo-feldspathic veins and veinlets, whose thicknesses and lengths vary from the millimeter to the meter. These veins are observed in all the formations and are generally made up of an association of quartz crystals and fine flakes of micas (Figure 6). This hydrothermal alteration induced a pervasive mode in the host rocks, resulting in: (i) a silicification observed in all the rocks; (ii) an epidotization of the feldspars and ferromagnesian minerals; (iii) a muscovitization of the biotites; (iv) a sericitization of the plagioclases and muscovites; (v) an important chloritization of the biotites and amphiboles in all the lithologies; and (vi) a sulphidation visible for the most part in the granitoids. The metalliferous paragenesis identified consists of pyrite (the main sulphide), chalcopyrite, and rutile (Figure 7). Pyrite occurs in various forms (cubic, disseminated or remobilized). Two generations can be defined. A primary generation, characterized by the preferential orientation of the crystals, thus formed before the deformation but also during the deformation (ante- or synkinematic); and the secondary subhedral generation, probably post-tectonic. Chalcopyrite, for its part, occurs as medium to coarse and subhedral grains. In addition to these metals is goethite, which results from the alteration of pyrite or chalcopyrite.

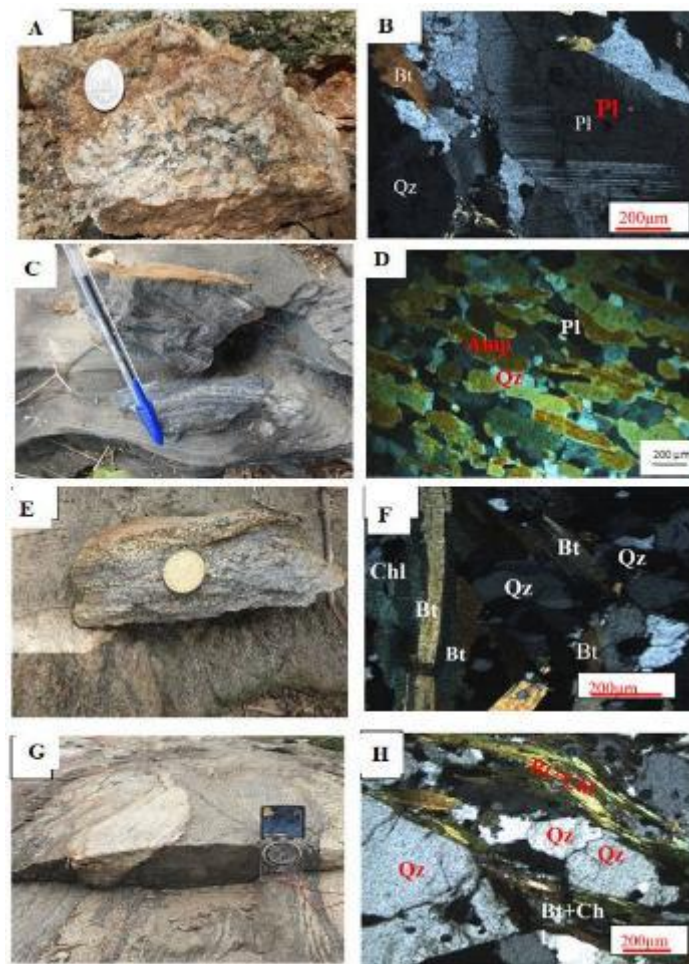


Figure 5: Macroscopic and microscopic aspects of the garnet pegmatites (A-B), amphibolites (C-D), micaschists (E-F) and migmatitic gneisses (G-H).

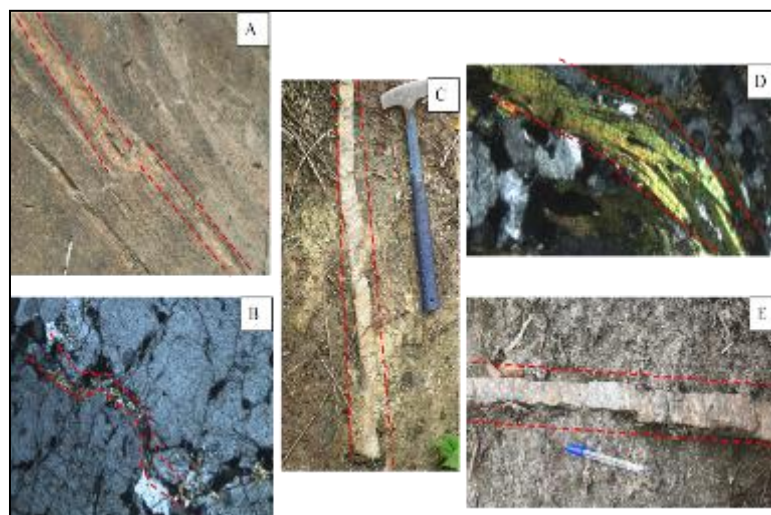


Figure 6: Veined alterations at the macroscopic and microscopic scale. A-C-E: Quartz veins; B: Sericite veinlet; D: Chlorite veinlet.

5 DISCUSSION

5.1 Petrography

The petrographic study of the northern sector of the Guiglo-Taï area revealed that it contains plutonic magmatic rocks (granodiorite, two-mica granites, garnet porphyritic granites, and leucogranite) and vein magmatic rocks (dolerites,

muscovite pegmatites, and two-mica and garnet pegmatites). The metamorphic rocks are represented by amphibolites, micaschists and migmatitic gneisses. It should nonetheless be noted that there is a strong predominance of granitic formations. This diversity confirms the observations of [10] as well as those of [9], who already reported a complex succession of granitoids and metamorphic series in the region. It also reflects a complex magmatic and metamorphic evolution, in connection with the major Leonian and Liberian orogenic events, such as described by [3, 11-12]. The pegmatites encountered in the study area, notably at Ditrouta Béoué and Béhéhou, occur as slabs, dykes and veins, with a composition dominated by quartz, feldspars (microcline, plagioclase) and muscovite, sometimes accompanied by biotite and garnet. Indeed, the

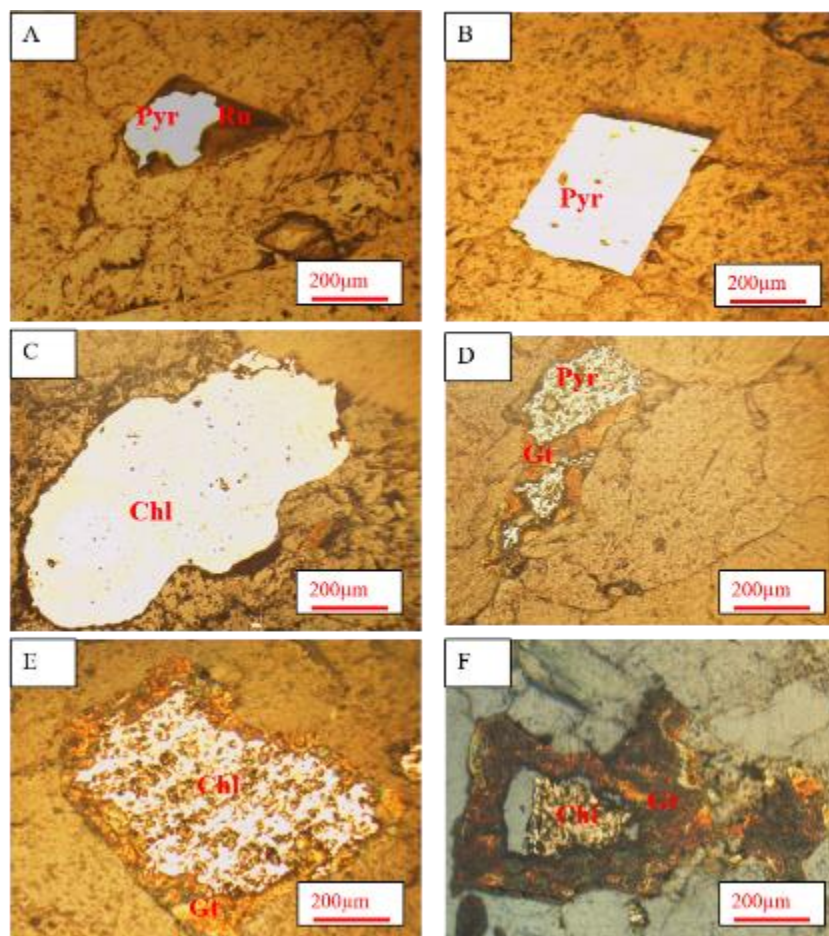


Figure 7: Microscopic aspects of the sulphides and oxides. A: Rutile; B: Pyrite; C: Chalcopyrite; D: Pyrite and goethite; E-F: Chalcopyrite and goethite. (Pyr: Pyrite; Chl: Chalcopyrite; Ru: Rutile; Gt: Goethite).

muscovite pegmatite described by [13] in the Issia region, known for its columbo-tantalite mineralization, displays mineralogical parameters similar to the Ditrouta Béoué pegmatite. Our work made it possible to highlight several types of granites, contrary to the observations of [10] on the Guiglo sheet. However, these authors mention the predominance of two-mica granites in the study area, as mentioned in our work. This strong presence of two-mica granites, to which are added the garnet porphyritic granites and the leucogranites, is part of a context of advanced differentiation of the magmas, a phenomenon widely documented in the Man rise [3, 11]. The mineralogical assemblages observed (quartz, feldspar, micas, garnet, etc.) confirm an evolved crustal magmatism, often intrusive into the older metamorphic series. The two-mica granites studied here are identical to those described by [14] in the Alépé area at the mineralogical level, but with a difference concerning the size of the muscovites, which he describes as phenocrysts in his area. They also match the oriented granites described by [13] in central-western Côte d'Ivoire at the mineral level. The garnet porphyritic granite identified at Ladjikro had already been reported by [9] in the Guiglo region as a rock typical of the Birimian domain. Indeed, this contrast between acidic and basic rocks reflects the existence of multiple intrusions, a phenomenon observed by [15] Dago (2020) in the Daloa region. The metamorphic rocks identified, in particular the amphibolites and the migmatitic gneisses, testify to a medium- to high-pressure metamorphism. Their nematoblastic texture and their banding are comparable to the observations made in other Archaean segments of the Man rise [16-17]. The presence of the index minerals (hornblende, biotite, garnet) in the amphibolites reflects metamorphic conditions typical of the amphibolite facies, which were reported by [9, 18] in the Man rise. The micaschists, rich in quartz, biotite, muscovite, with a marked schistosity, are reminiscent of the Birimian formations described by [10].

Finally, the migmatitic gneisses, whose mineralogy confirms the intense migmatization described by [3] as a major process in the evolution of the Ivorian Archaean basement.

The hydrothermal alteration phenomena (sericitization, chloritization, muscovitization, epidotization, silicification and sulphidation) observed in most of the lithologies reflect a late reworking of the rocks by fluid circulation. These alterations are frequent in regions that have undergone several tectono-metamorphic episodes, and they underline the reactivity of the rocks with respect to these processes.

5.2 Metallogeny

The metallogenic study of the Guiglo-Taï study area, more precisely in the northern zone of the PR0972 permit, made it possible to highlight the metalliferous paragenesis composed of pyrite, chalcopyrite, rutile and goethite, the latter being an alteration product of the identified sulphides. This metallographic assemblage was observed mainly in a granodiorite and a granite. Like many high-technology metal mineralizations known worldwide, felsic intrusives (pegmatite, two-mica granite, sometimes diorite, etc.) are generally known as being carriers of mineralization. This is notably the case in Australia, where the Greenbushes lithium deposit is linked to pegmatitic and granitic intrusions and in Zimbabwe at the Bikita deposit, where the mineralization developed within the pegmatites [19].

In the West African context, similar sulphide assemblages have been described in the Birimian provinces of Ghana, Burkina Faso and Mali, in association with differentiated granitic plutons [20-21]. The occurrence of primary pyrite with preferential orientation in the granodiorites is particularly significant. Indeed, ante- to synkinematic pyrite is often a precursor of hydrothermal base-metal and critical-metal mineralization, because it traps the trace elements during its crystallization in a deformation context [22]. The presence of two generations of pyrite, one oriented and the other post-tectonic subhedral, reflects a polyphase metallogenic evolution consistent with the three deformation phases identified in this study.

The presence of rutile is significant because it constitutes a geochemical indicator of systems enriched in high-field-strength elements, often correlated with Sn-W mineralization and in certain cases with the lithium pegmatites associated with differentiated acidic rocks [23-24]. Goethite, widely developed, corresponds to the supergene oxidation of the primary sulphides, mainly pyrite and chalcopyrite. Its formation marks a late post-hydrothermal phase linked to the infiltration of meteoric fluids. This supergene alteration indicates that the mineralization is ancient and has undergone a multiphase evolution. The whole of this paragenesis is consistent with a granodioritic and granitic system capable of concentrating critical elements such as tungsten and tin in late hydrothermal stages [25-26]. Pyrite-chalcopyrite-bornite associations are frequent in the Sn-W environments of the Birimian provinces. Although the oxide phases associated with Sn and W were not directly observed in the studied samples, the nature of the identified paragenesis, the hydrothermal inheritance, and the presence of rutile reinforce the metallogenic potential of the zone for high-technology metals.

6 CONCLUSION

At the petrographic level, two (2) large groups of rocks were studied. These are the magmatic rocks and the metamorphic rocks. The magmatic rocks are represented by pegmatites, granites, granodiorites and dolerites. Several types of granites were also observed, namely the garnet porphyritic granites, the two-mica granites, and the leucogranites. The metamorphic rocks are represented by amphibolites, micaschists and migmatitic gneisses, with a predominance of amphibolites. All these rocks were affected by a hydrothermal alteration, whose veined mode is characterized by quartzo-feldspathic veins and veinlets, and by veins. The pervasive mode is materialized by chloritization, epidotization, sericitization, silicification, muscovitization and sulphidation. It should also be mentioned that a supergene alteration occurred, represented by oxidations and caused by meteoric agents. The sulphides and oxides identified are pyrite, chalcopyrite, rutile and goethite. These metals are products of the hydrothermal alteration, but some oxides come from the alteration of pre-existing sulphides.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

We thank SODEMI (Société pour le Développement Minier de la Côte d'Ivoire) for its significant involvement in academic and mining research in Côte d'Ivoire.

Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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