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Multi-Scale Approach for Gold Targeting in Côte d'Ivoire Paleoproterozoic Rocks

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Abstract

The aim of this study is to contribute to better targeting of gold prospecting areas using geospatial information. To this end, 3 mining sites were selected for the study. They are: the Sénoufo belt (Barrick Gold mine), the Yaouré complex (Perseus Mining mine) and the South Fetêkro belt (Bonikro, Hiré and Agbaou mines). For this study, a multi-scale approach was carried out at regional, mine and microscopic levels. At the regional scale, a comparative analysis of 1:200,000 scale geological maps revealed that 3 main lithologies are regularly repeated on and around the various mining sites. These are: undifferentiated volcanics, metagranodiorites and metasiltites dominated by meta-arenites. Most of these lithologies are affected by undifferentiated faults generally oriented NE-SW, N-S, ENE-WSW and WNW-ESE. In addition, gold and manganese occurrences are present on all the sites studied. At the mine scale, radarsat-1 images processing indicate that the main mining sites are generally located near or at the intersection of lineaments-oriented NE-SW or N-S on the one hand and E-W or ENE-WSW or WNW-ESE or again NW-SE on the other. These mines are also located at the interface between zones of high and low lineament density. At the microscopic scale, petrographic studies of undifferentiated volcanic samples from the various sites indicate that they consist of andesites, meta-andesites and tuffs.

Keywords

Gold Targeting, Undifferentiated Volcanics, Mineral Occurrences, Lineaments, Côte d'Ivoire

1. Introduction

Gold deposits in Côte d'Ivoire are generally located in the Birimian formations, which cover around 67% of the country territory. These rocks are known throughout the world to contain this type of mineralization [1] [2] [3]. Milési *et al.* (1989) [4] defined 7 types of gold mineralization typical of this geological context: 1) mineralization hosted in tourmalinized turbidites Loulo in Mali, [5]; 2) disseminated sulphide mineralization hosted in volcanic or plutonic rocks Yaouré in Côte d'Ivoire, [2], Syama in Mali [6]; 3) gold-bearing conglomerates Tarkwa district in Ghana [7]; 4) discordant arsenopyrite mineralization, Ashanti in Ghana [8] 5) discordant quartz mineralization with native gold and sulphides: polymetallic deposits (Poura in Burkina-Faso, Kalana in Mali, Sabodala in Senegal, 6) alluvial and eluvial placers and 7) lateritic deposits (Ity in Côte d'Ivoire). In addition to identifying the typology of this mineralization, several authors such as Milési *et al.* (1989) [4], Feybesse *et al.* (2006) [9], Baratoux *et al.* (2011) [10], Houssou (2013) [11], Ouattara (2015) [12], Ballo *et al.* (2016) [6] have indicated that Birimian gold mineralization is generally located in greenstone belts, more precisely at the interface between Birimian volcanics and volcaniclastics, and at the contacts between these rocks, metasediments and plutonites. These interface or contact zones are generally affected by shear corridors that act as sponges for this type of mineralization [4] [6] [10] [11] [13]. All those informations have led to the discovery of numerous deposits through the combined efforts of mining companies and the scientific research community. Despite the progress made in this area, it is clear that the ratio of mine discovery to the number of exploration campaigns remains very low. To improve this ratio, other geological indicators that play a role in gold mineralization need to be identified. It is in this context that our study takes place. The general aim of this study is to contribute to better targeting of gold prospecting areas using geospatial information from a multi-scale approach. Three main sites were chosen for the study. These are the Sénoufo belt (Barrick Gold mine), the Yaouré complex (Perseus Mining mine) and the South Fetêkro belt (Bonikro, Hiré and Agbaou mines). The specific objectives are as follows: determine the similar geological characteristics of the sites studied on a regional scale, identify the lineament signatures of the various mining sites studied by processing radarsat-1 images, and clarify the nature of the geological formations known as undifferentiated volcanics on the basis of microscopic petrography.

2. Geological Setting

The West African Craton, to which Côte d'Ivoire belongs, is a vast Precambrian geological complex covering an area of around 4,500,000 km^2. This craton is bounded to the north by the Anti-Atlas, to the west by the West African Mobile Zone and to the east by the Central African Mobile Zone. The rocks of the West African Craton essentially outcrop in three entities: the Kayes and Kedougou-Kenieba inlier, the Reguibat shield and the Man shield [14]. Côte d'Ivoire, the setting for our study, is located in the southern part of the Man shield. Two geological units stand out in this country: the Precambrian basement (97.5% of the territory) and the Mesozoic sedimentary basin (2.5%). The Precambrian basement is made up of two domains of different ages separated by the Sassandra fault (**Figure 1**): the western part of the Sassandra fault belongs to the Archean domain structured by the Leonian (3500 - 2900 Ma) and Liberian (2900 - 2600 Ma) orogenies [14] [15], while the eastern part of this domain belongs to the Paleoproterozoic (or Baoulé-Mossi) domain structured during the Eburnean orogeny (2500 - 1800 Ma). The lithology of this domain is consisted of: the granite-gneiss basement with several generations of intrusive with a wide range of compositions [16] [17] [18] [19], sedimentary and metasedimentary units [20] [21] [22] and volcanic and volcano-sedimentary rocks [10] [23] [24] [25]. The

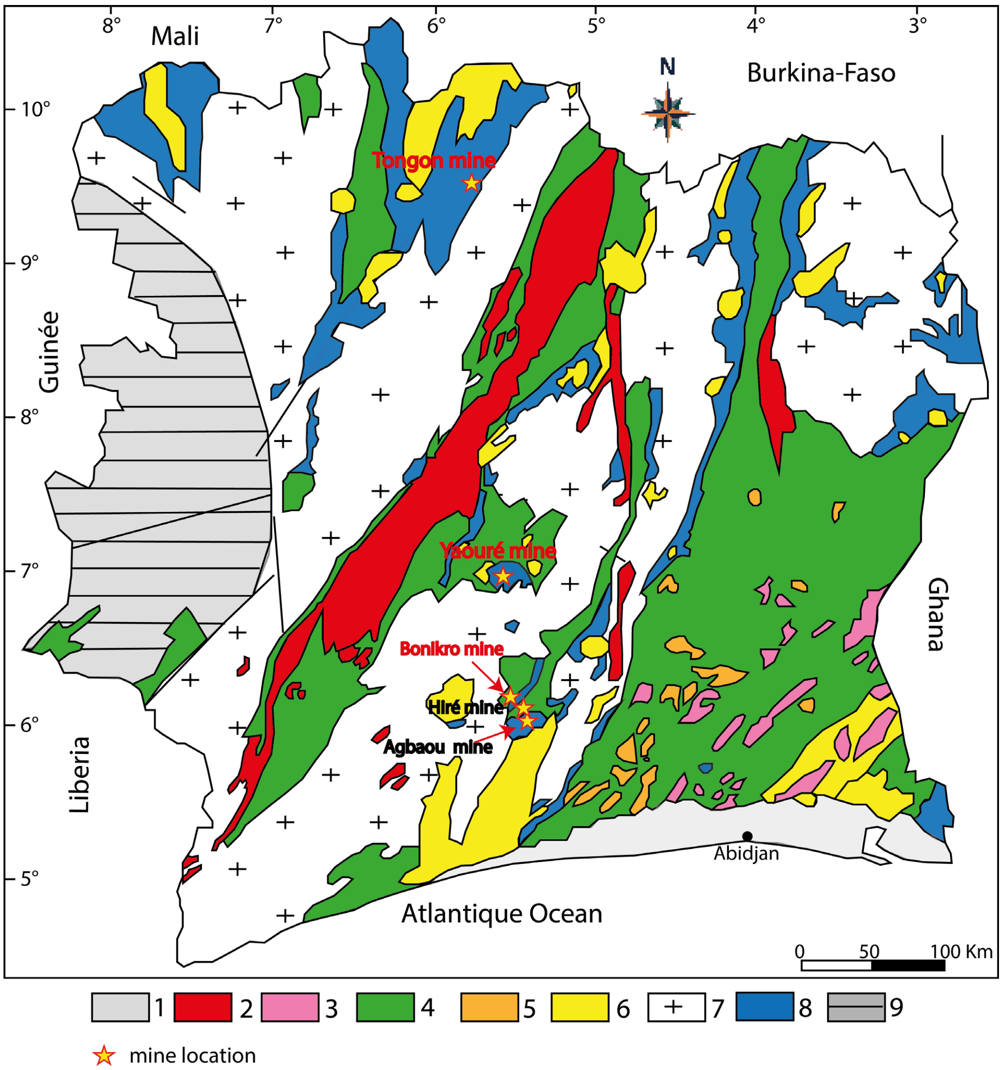

Figure 1. Geological map of Côte d'Ivoire with some mine locations [28] modified by [29]. 1 = coastal sedimentary basins; 2 = batholiths of two-mica bearing granitoids associated with meridional strike-slip structures; 3 = other two-mica bearing granites; 4 = sedimentary basins and volcano-sediments; 5 = calc-alkaline granitoids located in sedimentary basins; 6 = Calc-alkaline granitoids in greenstone belts; 7 = Undifferentiated granitoids, banded granites, gneisses and migmatites (age greater than 2.4 Ma); 8 = Undifferentiated volcanism and volcano-sedimentary rocks; 9 = Archean domain.

Paleoproterozoic rocks are generally oriented NE-SW trending volcano-sedimentary furrows (or greenstone belts) intercalated between granitoid batholiths. In Côte d'Ivoire, 17 volcano-sedimentary furrows have been identified [26]. The country's main mines are located within greenstone belts. According to the work of Leube *et al.* (1990) [27] in Ghana, Assié (2008) [13] and Houssou (2013) [11] in Côte d'Ivoire, gold mineralization is generally concentrated along corridors 10 to 15 km wide along the boundary between the volcanic belt and the sedimentary basin or between the volcano-sedimentary and the mafic volcanic rocks. The various sites studied in this work are located in these rocks. They are: the Sénoufo belt (Barrick Gold mine in the north of the Côte d'Ivoire), and the d'Ivoire), the Yaouré complex (Perseus Mining in central Côte d'Ivoire) and the Fetêkro south belt (Bonikro, Hiré and Agbaou mines in south-central Côte d'Ivoire).

3. Methodology

Methodology have been performed at 3 different scales of study: 1) at regional scale base on pre-existing geological map, 2) at mine scale with remote sensing data and 3) at the microscopic scale for the petrographic studies of undifferentiated volcanics.

3.1. Comparative Analysis of Geological Maps

For the purposes of our study, 1:200,000 scale geological maps of the Gagnoa, Bouaké and Korhogo sheets were used as basic tools. These sheets were chosen because they host the Tongon mine (in northern Côte d'Ivoire), the Yaouré mine (in central Côte d'Ivoire) and the Bonikro, Hiré and Agbaou mines (in south-central Côte d'Ivoire). The different stages of this method are as follows:

- digitization of the various portions of the geological maps: this stage was carried out using Global Mapper 24.1 software. The various maps were georeferenced and then digitized in order to extract data;
- analysis and interpretation of the maps: this stage helps us to identify the different types of data useful for our study. We focused our analysis on lithologies, structures and mineral occurrences;
- comparison of data obtains: the main data analyzed have been place in the tables for the better appreciation.

3.2. Remote Sensing Data

Radarsat-1 was developed by the Canadian Space Agency. It is equipped with a Synthetic Aperture Radar (SAR) sensor, enabling images to be acquired day and night, in the presence of clouds, smoke or fog. Synthetic Aperture Radar (SAR) data is recognised as having great potential for geological applications in general and for structural mapping in particular. The characteristics of Radarsat-1 images are given in **Table 1**.

As part of this study, various pre-processing and processing operations were carried out using ENVI 5.2 software. The pre-processing takes into account a radiometric and atmospheric correction of the raw image (**Figure 2**). Processing was carried out in three stages: speckle reduction, linear spreading and application of directional filters. Several adaptive filters have been used to reduce the speckle. These are the local sigma, Gamma, Frost, Lee and Kuan filters. The 3 × 3 Frost filter gave the best results. In fact, it helped to reduce the effects of speckle while preserving image quality. A linear spread of 2% was applied to the enhanced image resulting from the Frost filter in order to improve its contrast. Several other filters were applied to the enhanced image. These are: the Sobels

Table 1. Characteristics of Radarsat-1 raw image.

Mode	Spectral band	Polarization	Resolution
Radar SAR	Band C (5.3 Ghz)	HH	8 m < pixel < 100 m

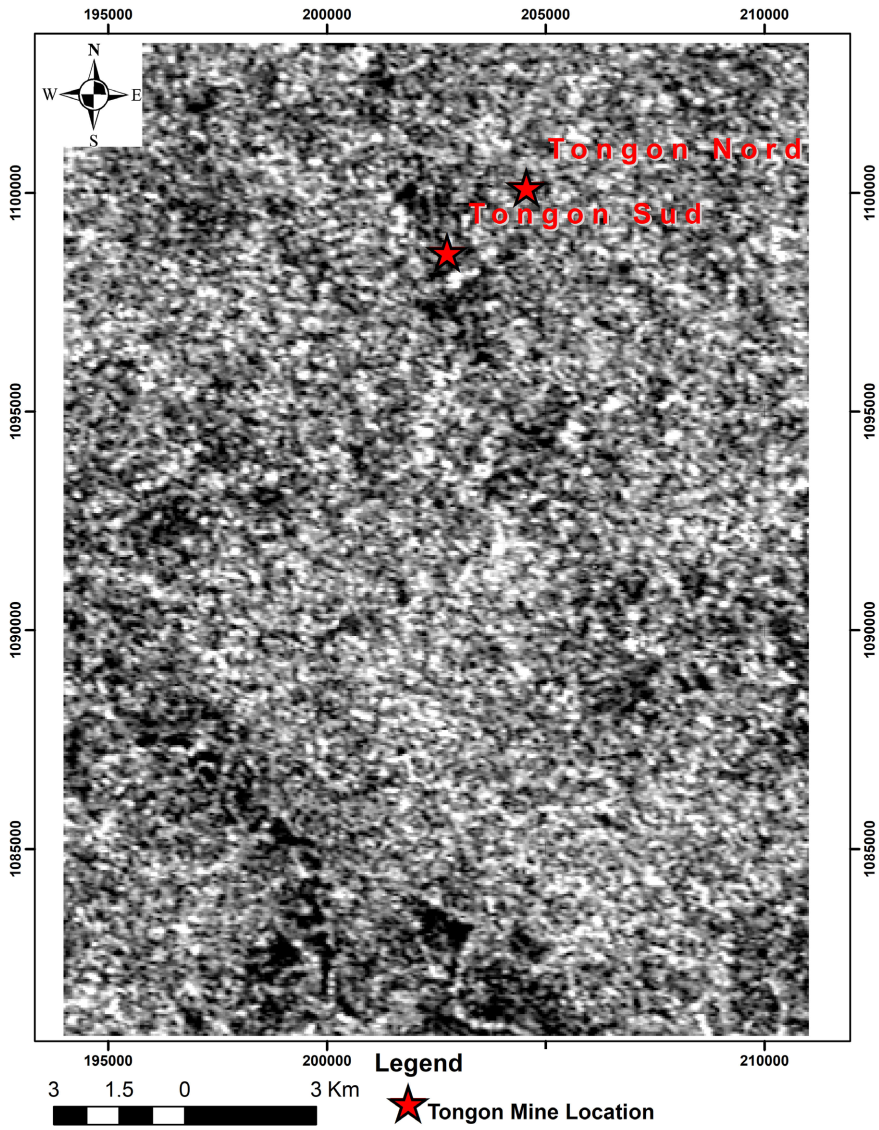

Figure 2. Tongon site radarsat-1 raw image.

directional filters (NE-SW, N-S, E-W and NW-SE), the Prewitt filter and the Yesou filter. Based on the various enhanced images obtained, several lineaments were drawn manually. The final stage of this approach was the lineament validation phase. This involved discriminating between natural and anthropogenic lineaments by superimposing the lineaments obtained on the topographical map and Google images of the study area. This phase carried out using Global Mapper 24.1 software helped us to delete all the anthropogenic lineaments (roads, farm limit, powerline…).

3.3. Microscopic Petrography Studies

This stage involved fieldwork to collect the various samples of undifferentiated volcanic rocks. We are focused on microscopic study because of the difficulties to identify properly those rocks with usual description criteria of petrography macroscopic. Four thin sections were prepared in the Geology, Mineral and Energy Resources Laboratory at the Université Félix Houphouët Boigny. The samples came from the Tongon (1 sample), Yaouré (1 sample) and Bonikro (2 samples) mines. Using an Optika polarising microscope, the thin sections were observed in order to identify texture of rock, nature, proportions and chronology of the minerals.

4. Results

Three main results have been recorded according to the methodology and the different scales of study: comparative analysis of 1:200,000 geological maps (regional scale), lineament characteristics and density maps (mine scale) and petrography of undifferentiated volcanics (microscopic scale).

4.1. Comparative Analysis of 1:200,000 Geological Maps

Portions of the 1:200,000 geological maps including the Tongon (**Figure 3**), Yaouré (**Figure 4**), Bonikro, Hiré and Agbaou mines (**Figure 5**) were analysed and compared. The main criteria for comparative analysis were lithologies, mineral occurrences and structures. The analysis revealed that:

At the Tongon site, the lithologies observed in order of abundance are: biotite beaing granites, dominant metasiltites on meta-arenites, undifferentiated volcanics, gabbros, amphibole bearing granites, metagranodiorites, monzogranites and biotite bearing metagranites. These lithologies are generally oriented NNE-SSW. Various mineral occurrences have been identified on all the extent on the map. In this portion, we recorded: 17 gold occurrences, 9 for mercury, 7 manganese occurrences 3 for thorium, 2 for monazite, 1 for tungsten and 1 for iron. Structural aspects of this region show the presence of 11 undifferentiated faults-oriented N-S and NE-SW trending. These faults generally affect metasediments (dominant metasiltites on meta-arenites) and undifferentiated volcanics. The Tongon mine is located in the dominant metasiltites on meta-arenites close to the undifferentiated volcanics and several gold occurrences.

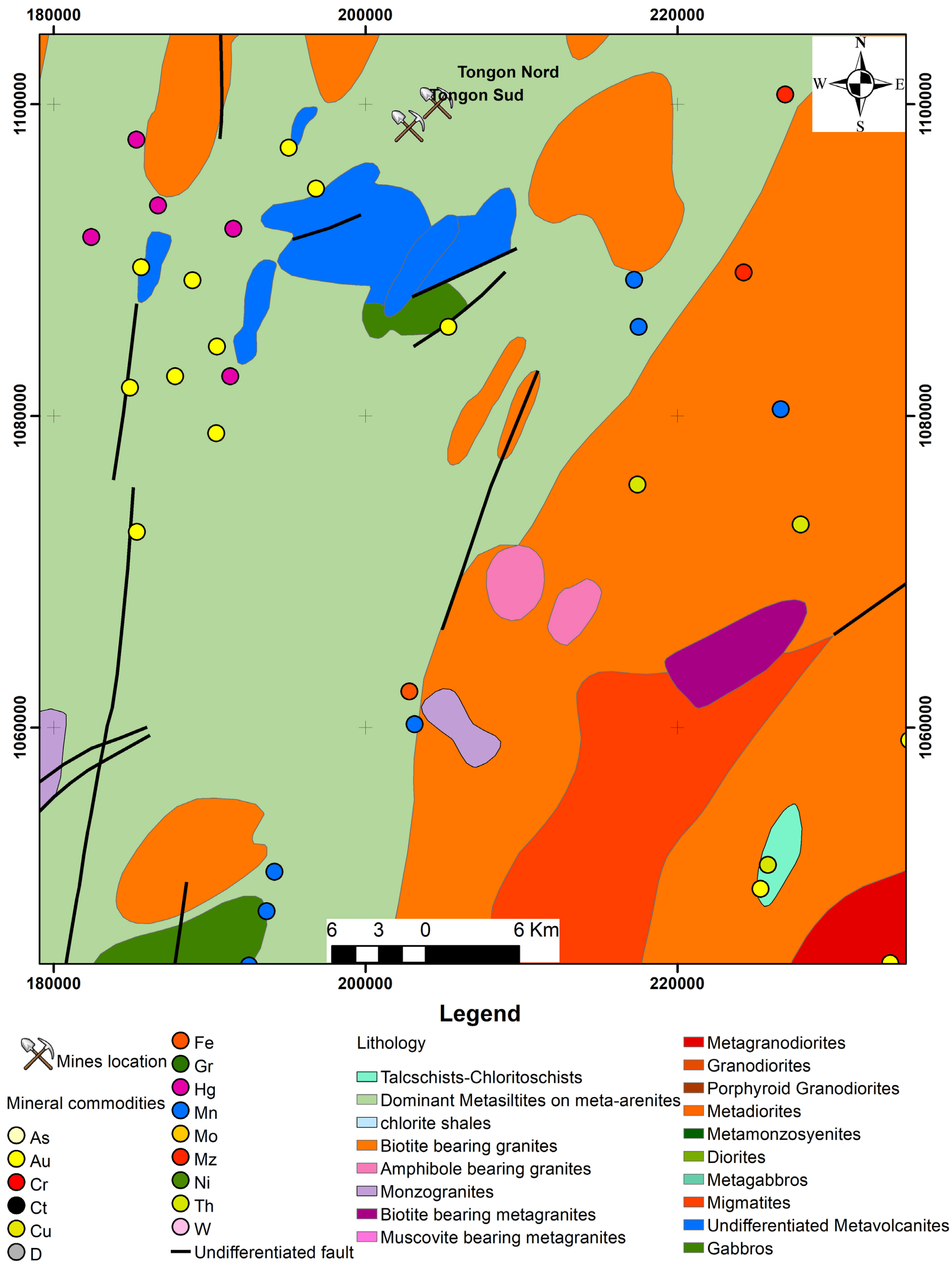

Figure 3. Geological map Portion of Korhogo sheet geological map at 1:200,000 showing the Tongon mine [30].

At the Yaouré site, the lithologies are consisted of: dominant metasiltites on meta-arenites, undifferentiated volcanics, dominant meta-arenites on metasiltites, orthogneiss, tonalites, biotite bearing granites, metagranodiorites, metagabbros and quartzites. These lithologies are generally oriented NNE-SSW and N-S. Many mineral occurrences have been identified on this portion of Yaouré

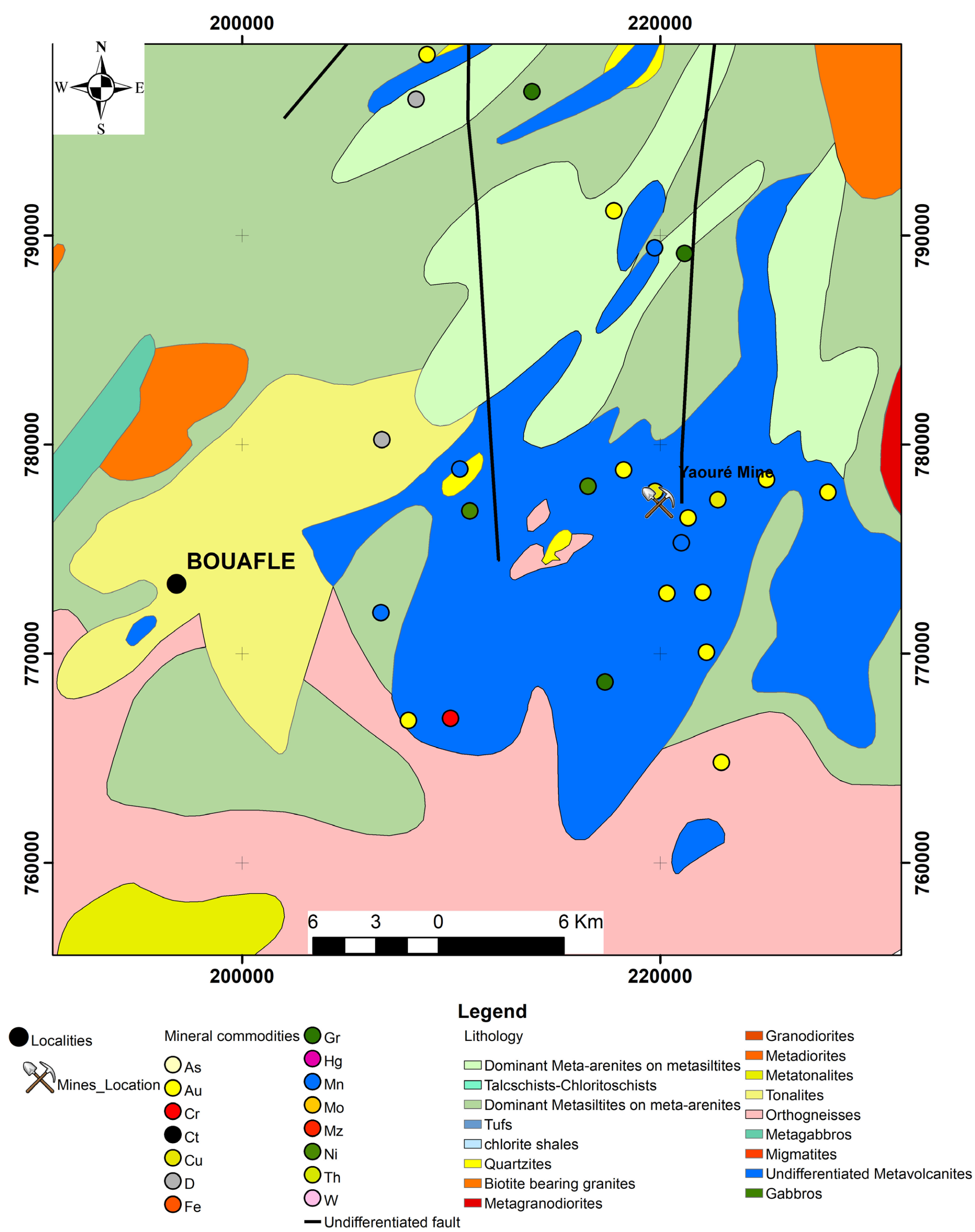

Figure 4. Geological map Portion of Gagnoa and Bouaké sheets geological map at 1:200,000 showing the Yaouré mine [31].

complex geological map. The mineral occurrences of this portion include: 13 gold occurrences, 4 for manganese, 2 for copper, 3 for graphite, 2 for nickel, 2 for diamond and 1 for chromium. On the structural aspect, only 3 undifferentiated faults trending N-S and NE-SW have been identified in this part of the map. These faults mainly affect dominant metasiltites on meta-arenites, dominant meta-arenites on metasiltites and undifferentiated volcanics. The Yaouré mine is located on the undifferentiated volcanics close to undifferentiated N-S-trending fault and Au, Mn and Cu mineral occurrences;

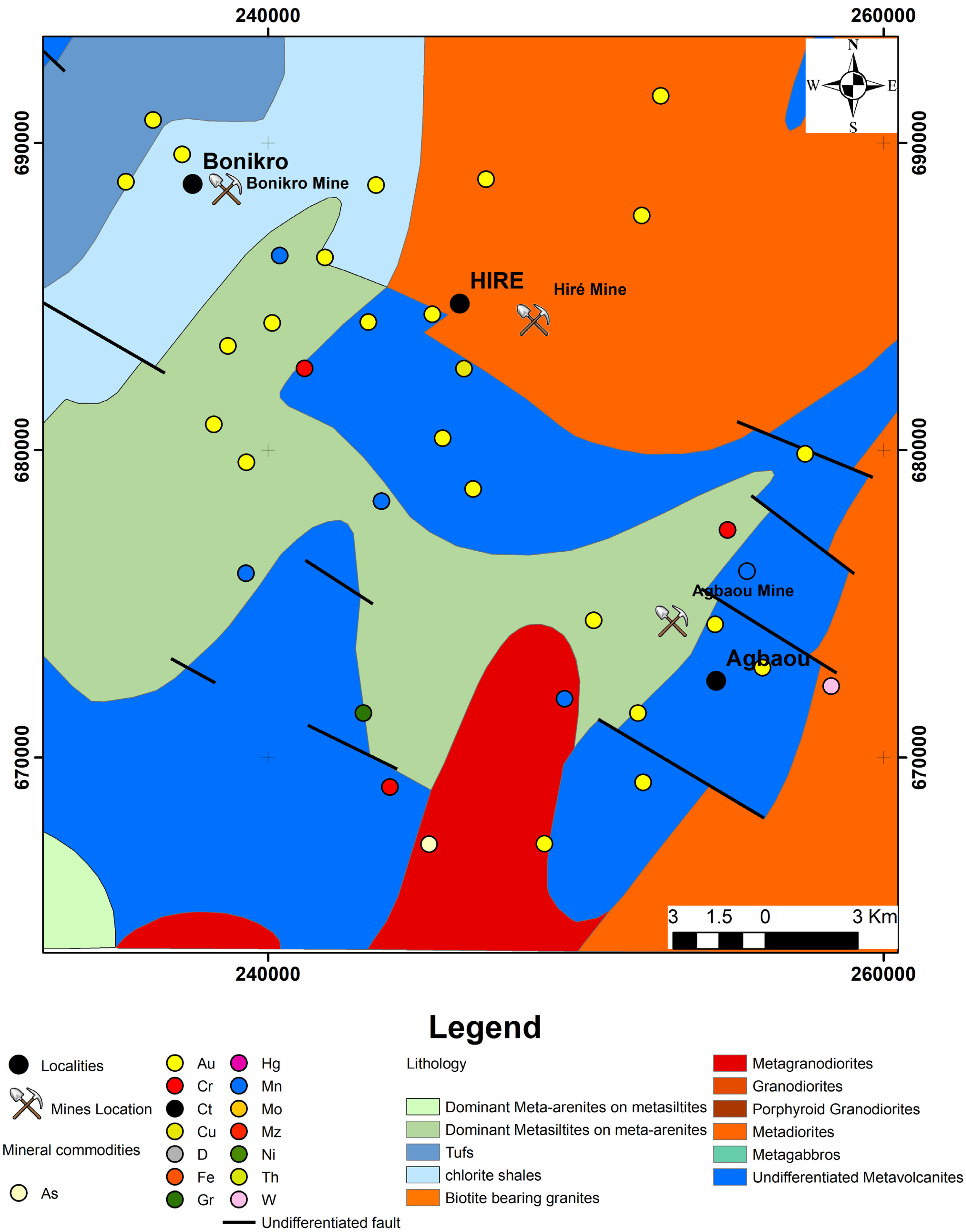

Figure 5. Geological map Portion of Gagnoa sheet geological map at 1:200,000 showing the Bonikro, Hiré and Agbaou mines [31].

At the south Fetêkro site, which covers three mines (Bonikro, Hiré and Agbaou), the lithology is consisted of a various units: undifferentiated volcanics, metadiorites, dominant metasiltites on meta-arenites, tuffs, chlorite bearing schists, metagranodiorites and dominant meta-arenites on metasiltites. These lithologies are generally oriented NE-SW and E-W. A total of 31 mineral occurrences have been listed in the vicinity of these mines: including 21 gold occurrences, 5 for manganese, 3 for chromium, 1 for copper, 1 for graphite and 1 tungsten showing. Eight undifferentiated faults trending WNW-ESE have been identified. These faults affect the following lithologies: dominant metasiltites on meta-arenites, tuffs and undifferentiated volcanics. The south Fetêkro mines are located in chlorite bearing schists (Bonikro), metadiorites (Hiré) and undifferentiated volcanics (Agbaou), close to Au and Mn mineral occurrences.

To compare the different sites studied, two summary tables were produced based on criteria such as lithology and mineral occurrences. Table 2 indicated that three main lithologies are always present on the different sites studied. These are undifferentiated volcanics, dominant metasiltites on meta-arenites and metagranodiorites. With regard to mineral occurrences, two commodities are always presents on the sites studied: gold and manganese (Table 3). In addition, undifferentiated volcanics and dominant metasiltites on meta-arenites are generally affected by undifferentiated faults, reflecting the importance of the structural aspect at the various mining sites studied.

4.2. Characteristics of Lineaments Studied

The lineaments obtained on the different mining permits and also at the scale of the mines studied were analysed and interpreted using rose diagrams and histograms. The following information was obtained:

Table 2. Summary of the different lithologies observed on the geological maps of the different sites studied.

Sites	Lithologies													
	Magmatic rocks						Metamorphic rocks							
	undifferentiated Volcanites	Tufs	gabbros	Biotite bearing granites	Tonalites	amphibole bearing granites	Meta gabbros	Méta diorites	Quartzites	Meta-siltites dominants on meta-arenites	meta-arenites dominants on metasiltites	Meta granodiorites	Ortho gneiss	biotite bearing meta granites
Tongon	++'	–'	++'	++'	–'	++'	–'	–'	–'	++'	–'	++'	–'	++'
Yaouré	++'	–'	–'	–'	++'	–'	++'	–'	++'	++'	++'	++'	++'	–'
South-Fetekro	++'	++'	–'	–'	–'	–'	–'	++'	–'	++'	–'	++'	–'	–

Table 3. Summary of mineral occurrences observed on the geological maps of the different sites studied.

Sites	Mineral Commodities										
	Au	Mn	Cu	Cr	W	Ni	Fe	Gr	Hg	Mz	Th
Tongon	+	+	–	–	+	–	+	+	+	+	+
Yaouré	+	+	+	+	–	+	–	–	–	–	–
South-Fetekro	+	+	+	+	+	–	–	–	–	–	–

On Barrick Gold's Tongon mining licence, 248 lineaments were identified (Figure 6(A)). The general directional on rose diagram of this part of the birimian indicates that the main direction is ESE-WNW, the secondary directions NE-SW and NW-SE and the tertiary direction ENE-WSW to E-W (Figure 6(B)). In detail, the histogram showing the number of lineaments as a function of direction classes (Figure 7(A)) confirms the observations on rose diagram and indicates that 30.64% of the lineaments belonging to the [101˚ - 140˚] class. The histograms of the cumulative lengths of the lineaments and the number of lineaments per direction class show a correlation between the parameters (number of lineaments and cumulative lengths of lineaments) (Figure 7(B)). The peak in cumulative lengths is in the [101˚ - 110˚] class. The rose diagram of the lineaments located within 2 km of the mine (Figure 6(C)) is almost identical to the general rose diagram (predominance of ESE-WNW lineaments, followed by NE-SW and ENE-WSW lineaments). The difference between these two rose diagrams is marked by the low representation of NW-SE lineaments in the mine radius. This feature shows the low contribution of NW-SE lineaments in structuring this part of the study area. The two pits are located close to the intersection between the NE-SW and ESE-WNW or ENE-WSW lineaments;

On the Perseus Yaouré licence 163 lineaments have been identified (Figure 6(D)).

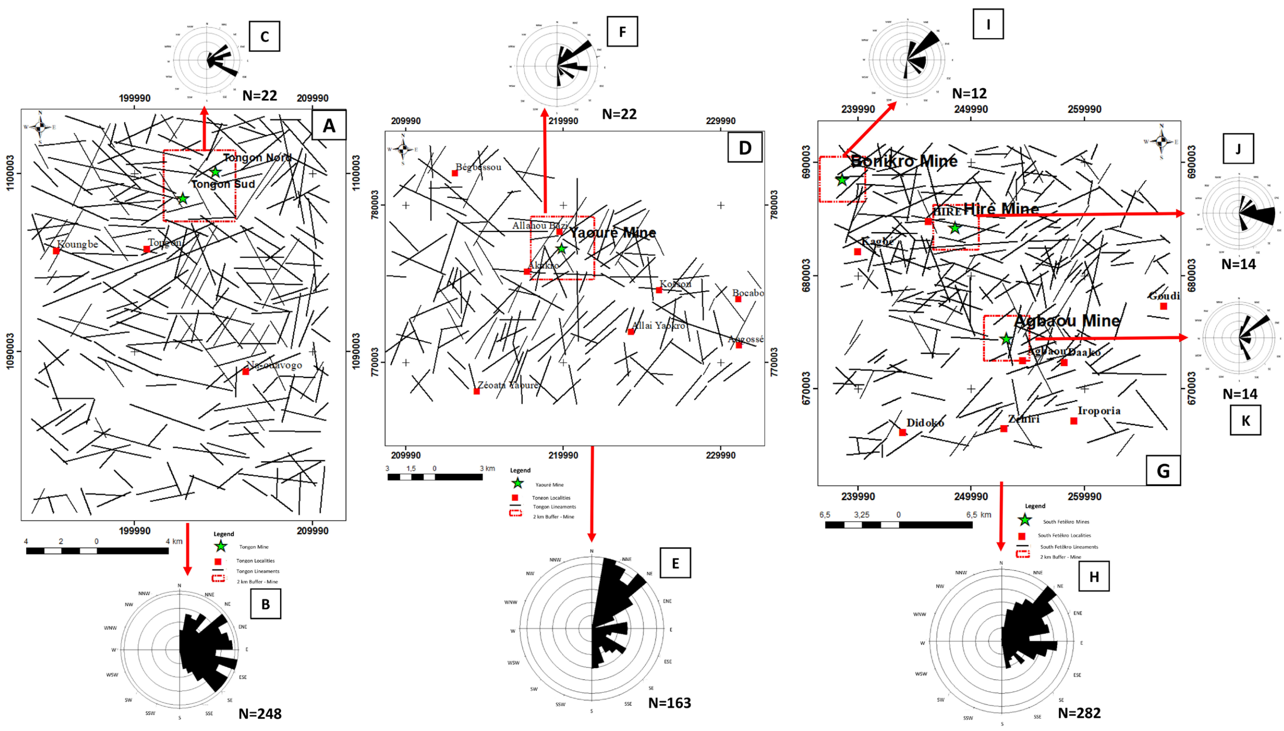

Figure 6. Lineament maps and rose diagrams of the different sites studied. (A) lineament map of the Tongon permit; (B) Rose diagram of Tongon permit lineaments; (C) Rose diagram for lineaments at 2km around of Tongon mine; (D) lineament map of the Yaouré permit; (E) Rose diagram of Yaouré permit lineaments; (F) Rose diagram for lineaments at 2 km around of Yaouré mine; (G) lineament map of the mines area in the southern part of the Fetêkro furrow; (H) Rose diagram of southern part of the Fetêkro furrow; (I) Rose diagram for lineaments at 2 km around of Bonikro mine; (J) Rose diagram for lineaments at 2 km around of Hiré mine; (K) Rose diagram for lineaments at 2 km around of Agbaou mine.

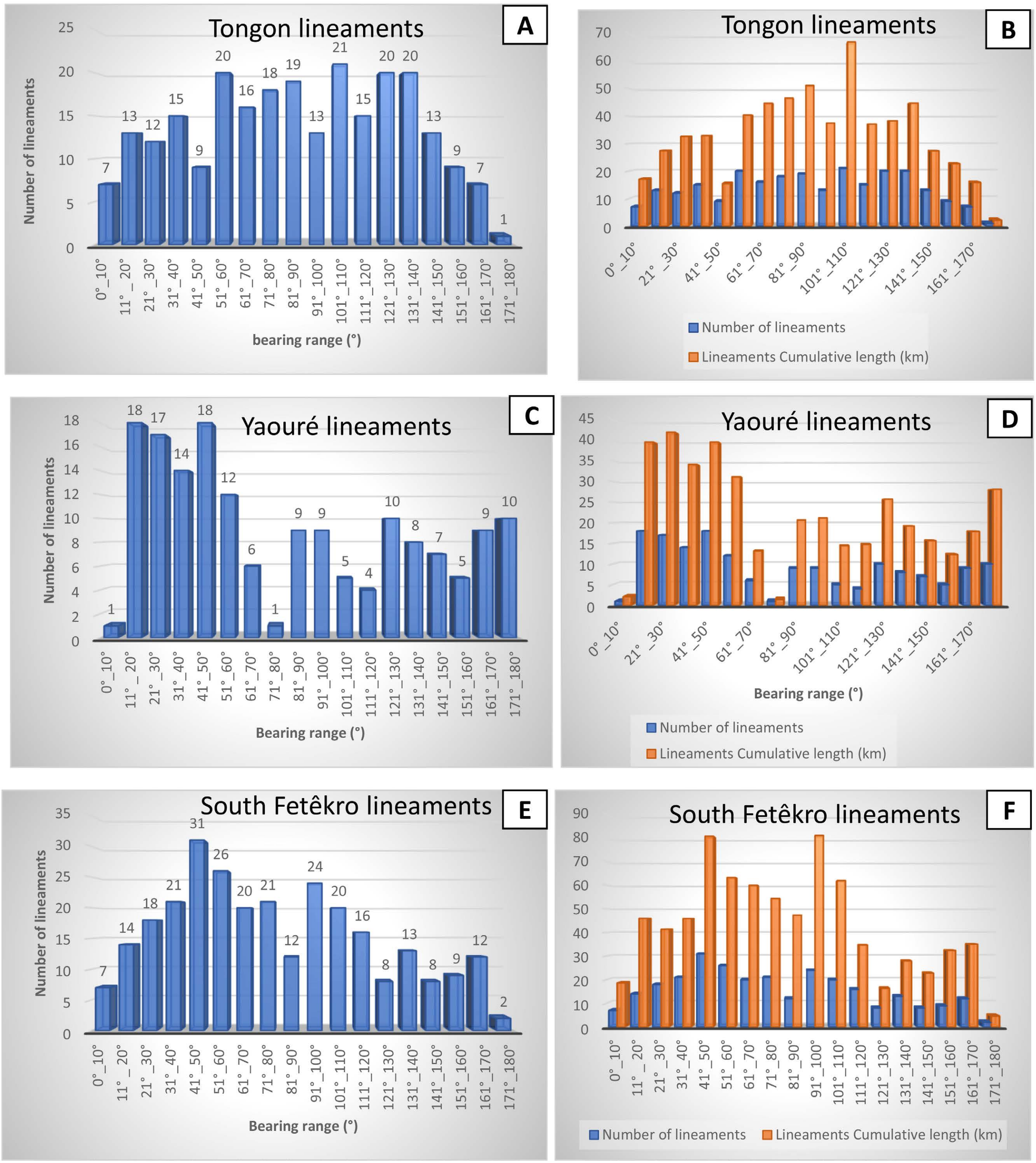

Figure 7. Histograms of the number of lineaments and cumulative lineaments by directional class. (A) and (B) Tongon site; (C) & (D) Yaouré site; (E) & (F) South Fetêkro site.

The rose diagram of the lineaments indicates that the main directions are NNE-SSW and NE-SW, the secondary direction N-S and the tertiary directions E-W and NW-SE (Figure 6(E)). The histogram showing the number of lineaments according to direction classes confirms the observations of the rose diagram, specifying that 30% belong to the [11˚ - 40˚] class (Figure 7(B)). The histograms (**Figure 7(C)** & **Figure 7(D)**) show a correlation between the number of lineaments and cumulative length by class direction; the peak of cumulative lengths is in the [21˚ - 30˚] class. The rose diagram of the lineaments located in vicinity of the mine (**Figure 6(F)**) shows many similarities with the general rose diagram (main direction: NE-SW lineaments, secondary direction: E-W lineaments, and tertiary direction: N-S). In detail, it should be noted that the mine is located near the intersection between two lineaments trending E-W on the one hand and two lineaments trending N-S and NE-SW on the other;

A total of 282 lineaments were counted to the south of the Fetêkro furrow (**Figure 6(G)**). The general rose diagram indicates that the main direction is NE-SW, the secondary direction E-W and the tertiary direction ENE-WSW (**Figure 6(H)**). The histogram showing the number of lineaments according to directional classes confirms the observations of the rose diagram. In other words, approximately 27.65% of the lineaments belong to the [31˚ - 60˚] class (**Figure 7(E)**). The histograms (**Figure 7(F)**) show a certain correlation between the number of lineaments and the cumulative length per direction class, except for the [91˚ - 100˚] class. Although this class has an average number of lineaments, it represents one of the peaks in cumulative lengths. This could indicate the importance of regional lineaments within this class. On a local scale, the rose diagram of the lineaments within a 2-km radius of the mines shows the following results: at the Bonikro mine (main direction is oriented NE-SW and secondary directions E-W and NNE-SW) (**Figure 6(I)**), at the Hiré mine (main direction is E-W and secondary direction N-S) (**Figure 6(J)**) and at the Agbaou mine (main direction is NE-SW and secondary directions NNE-SW and NW-SE) (**Figure 6(K)**). The main direction of the Bonikro and Agbaou mines is NE-SW, while the main direction for the Hiré mine is E-W. These two mines are also close to the intersection between the NE-SW and E-W lineaments.

Based on the detailed study carried out using rose diagram, three main lineament directions emerge within the 2 km radius around the mine sites. These are: NE-SW, N-S and E-W. The main mining sites are generally located near the intersection of lineaments-oriented NE-SW, N-S on the one hand and lineaments-oriented E-W or ESE-WNW or NW-SE on the other hand.

4.3. Lineament Density Maps

Three lineament density maps were produced for the various sites studied. Across all the sites studied, the distribution of lineament density is fairly variable:

At the Tongon site, areas of high lineament density are generally located in the northern and central parts of the study area (**Figure 8**). The Tongon mine (2 pits) is located in the northern part of permit licence, precisely at the interface between a zone of high and low lineament density.

In the Yaouré permit licence, the zones of high lineament density are located in the central, south-western and north-western parts of the study area (**Figure 9**). Located in the central part of the study area, the Yaouré mine lies between the high-density zones and a zone of low lineament density.

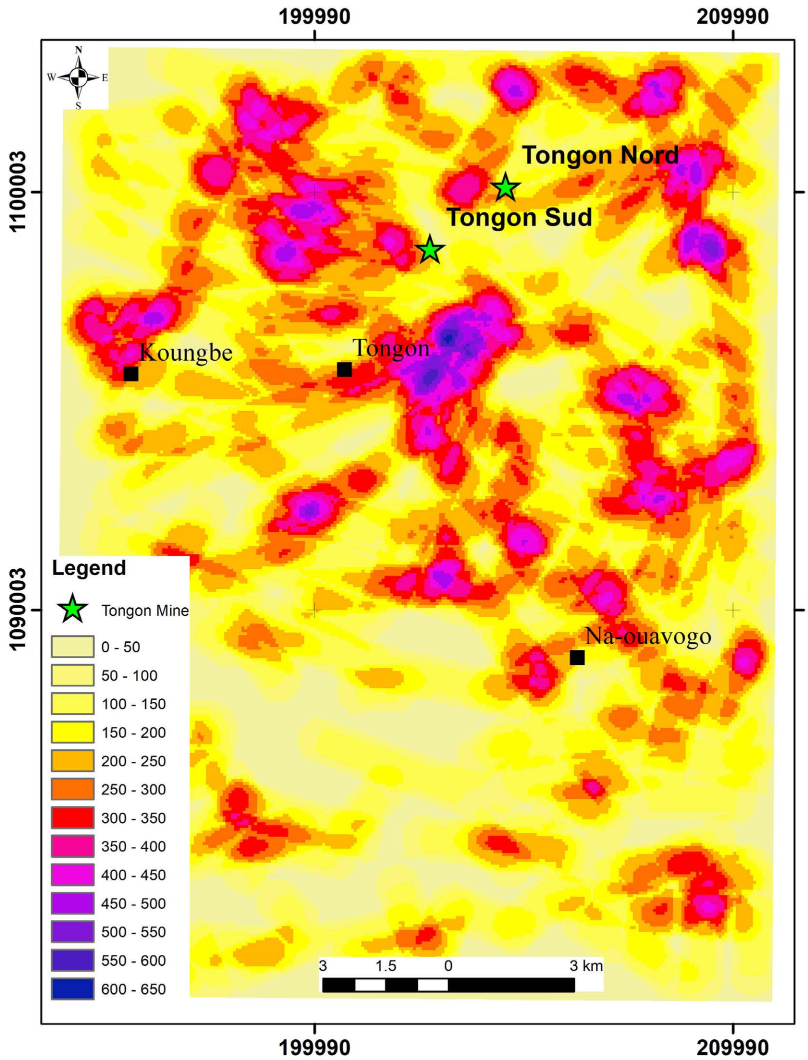

Figure 8. Lineament density map of Barrick Gold Tongon permit.

In the southern part of the Fetêkro furrow, the areas of high-density lineament are more important in the central, central-southern, northern, western and north-western parts. The Agbaou, Hiré and Bonikro mines are also located at the interface between a zone of high and low lineament density (Figure 10).

All the mines in the different study areas are therefore located at the interface between areas of high and low lineament density.

4.4. Petrography of Undifferentiated Volcanics

These rocks are varied and have been described according to the different areas studied.

4.4.1. Tuffs (Tongon)

The undifferentiated volcanics of the Senoufo belt have a microlithic porphyry texture marked by a fine matrix and minerals of varying sizes (small to large). The mineralogical composition is as follows:

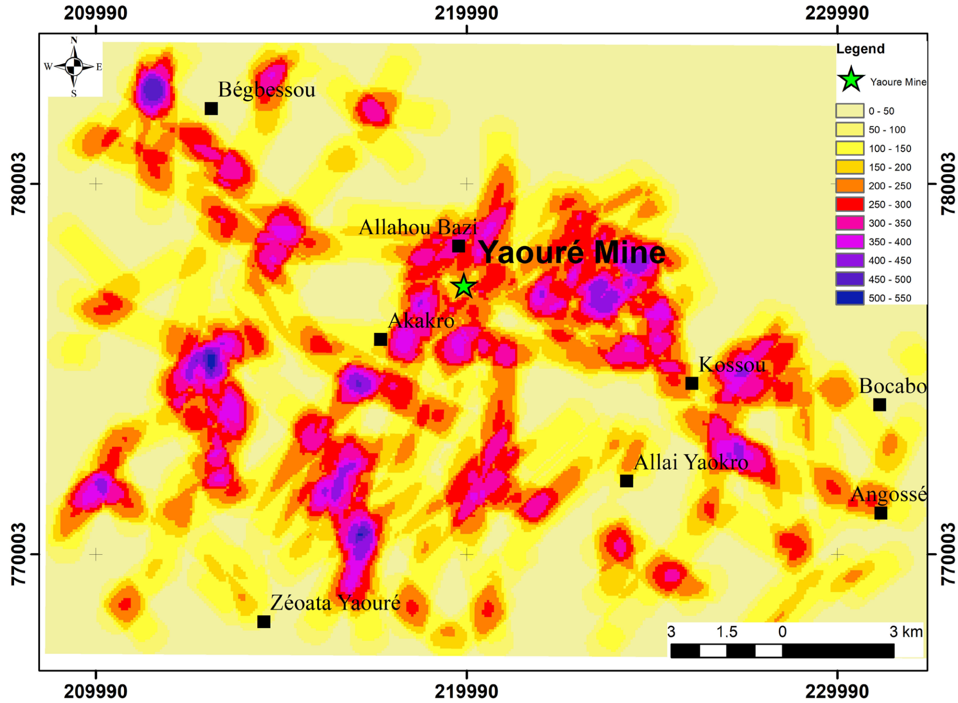

Figure 9. Lineament density map of the Perseus Yaouré permit.

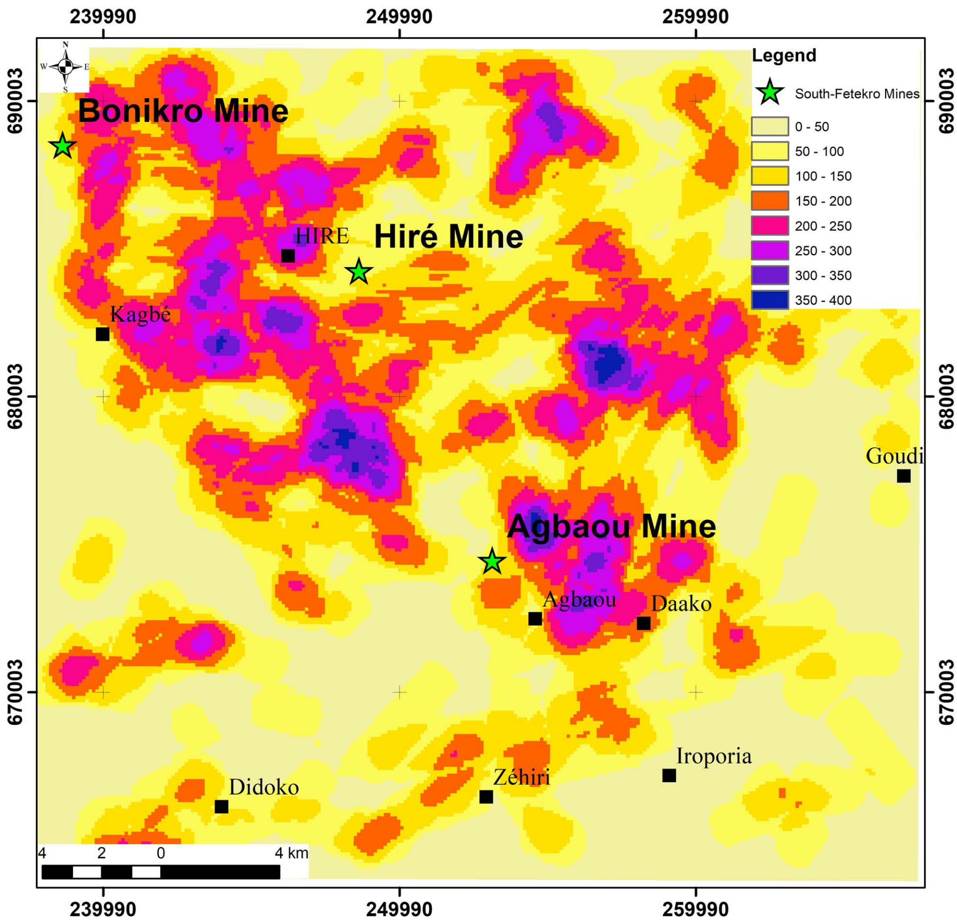

Figure 10. Lineament density map of south Fetêkro.

Amphiboles (hornblendes): about 35% of the rock, make up most of the phenocrysts in the rock, with a few small crystals. They are subeuhedral, sometimes with a few rounded crystals indicating the volcano-sedimentary character of the rock (Figure 11(A)). Most of the amphiboles have been altered into epidotes or chlorites. Some minerals show simple macles (Figure 11(B)).

Plagioclases: generally, subeuhedral, they appear in the form of rods between 100 µm and 300 µm, with a few individuals in the form of phenocrysts. They are abundant in the rock (around 30%) and some crystals are marked by epidotization.

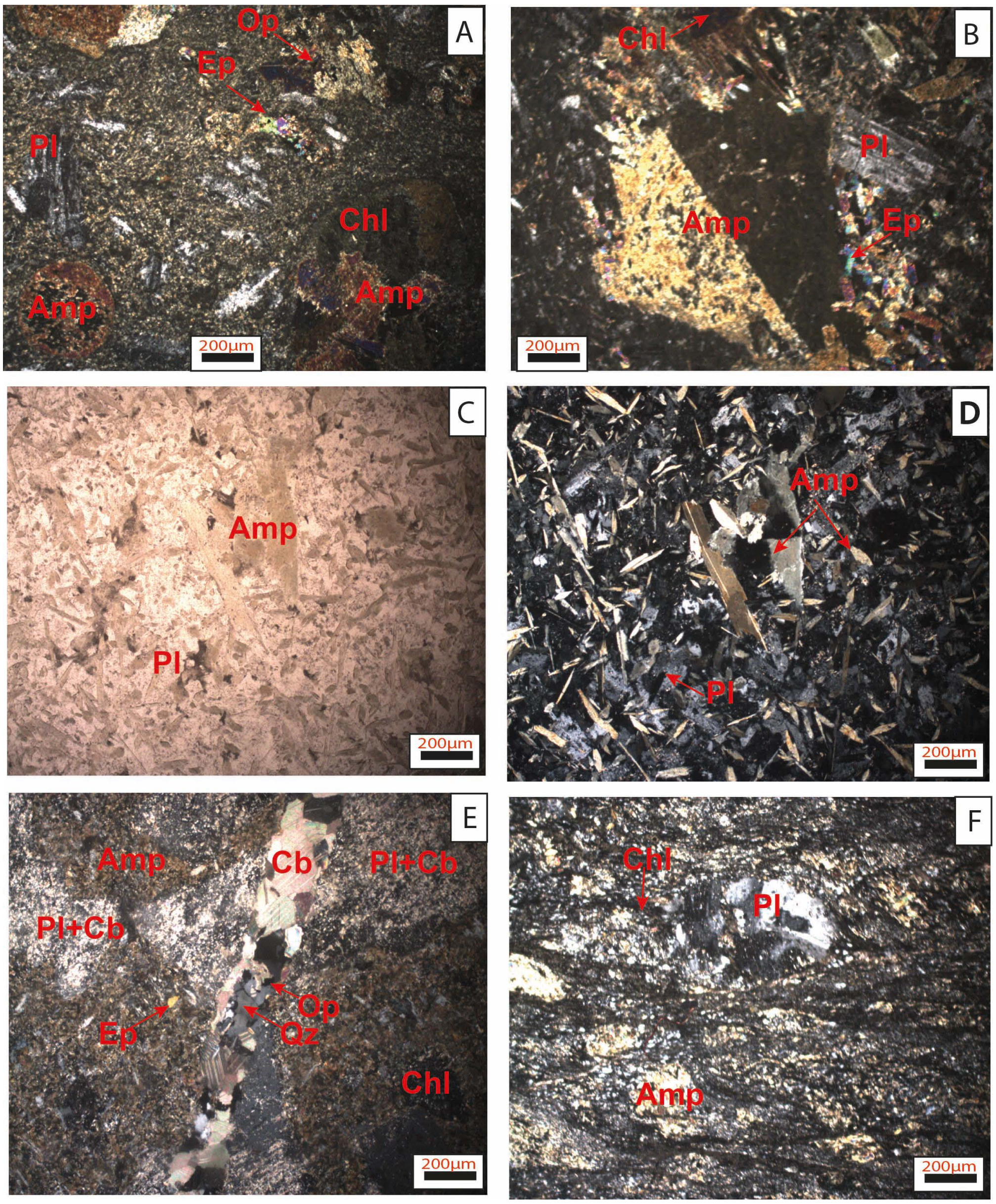

Figure 11. Microscopic aspects of undifferentiated volcanic rocks at the various sites studied. (A) Rounded and subeuhedral amphiboles in LPA in tuff (Tongon mine); (B) Single macle of an amphibole in LPA in tuff (Tongon mine); (C) & (D) Microlithic texture marked by plagioclases and amphiboles respectively in LPNA and LPA in andesites (Yaouré mine); (E) carbonation of a porphyritic andesite (Bonikro mine); (F) meta-andesite showing S/C planes (Bonikro mine).

Epidotes, with sizes ranging from 50 to 200 µm, with harlequin bright color, they generally come from the alteration of amphiboles and plagioclases.

Chlorites: with bright interference colours, they derived from the alteration of hornblendes.

Opaque minerals: in the form of rods with a size of less than 30 µm, they are generally present as inclusions in hornblendes.

4.4.2. Andesites (Yaouré Complex)

In this part of Côte d'Ivoire, the undifferentiated volcanics have a microlithic texture marked by plagioclase and amphibole rods (**Figure 11(C)** & **Figure 11(D)**). The mineralogical composition consists of:

- ✓ Plagioclases: representing about 35% of the rock, they are in the form of rods between 100 and 300 µm in size. Some crystals are altered in sericites.
- ✓ Amphiboles: subeuhedral to euhedral, elongate form, with sizes ranging from 50 to 300 µm, they make up around 30% of the rock.
- ✓ Sericites, secondary minerals, in the form of flakes, they generally come from the alteration of plagioclases.
- ✓ Carbonates: with pink color, in form of veinlet, they are the later mineral in the rock.

4.4.3. Porphyritic Andesites and Meta-Andesites (Bonikro)

The undifferentiated volcanics from southern Fetêkro described come from the Bonikro mine. Two samples have been described: porphyritic andesite and meta-andesite.

- *Porphyritic andesites*

They have a porphyritic microlithic texture with plagioclase phenocrysts. The mineralogy of this rock is consisted of:

- ✓ Plagioclases: subeuhedral to euhedral, are found in two forms: as small crystal flakes and as phenocrysts in the rock. They represent approximately 35% of the rock. Phenocrysts are generally altered into carbonates, sericites and epidotes.
- ✓ Amphiboles: with green in colour, they are abundant in the matrix (around 30% of the rock). They generally undergo chloritization and/or epidotization.
- ✓ Carbonates: they appear sometimes in the form of veinlets cross-cutting the others minerals in the rock, sometimes as the product of alteration of plagioclases (**Figure 11(E)**). With pink colour, they show regular cleavages and are often associated with quartz and opaque minerals in veinlets.
- ✓ Opaque minerals: not very abundant, they are subeuhedral to euhedral with small sizes crystals (less than 100 µm). These crystals are often present in the matrix and associated with amphiboles.

In addition to carbonates, other secondary minerals are present in the rock. These include chlorites, epidotes and secondary quartz.

- *Meta-andesites*

They have the same mineralogy as the andesites, but with a nematoblastic texture marked by the orientation of the amphibole minerals and chlorites. Some plagioclase and amphibole porphyroclasts are sheared in a sinistral movement. S/C microstructures confirm the shear deformation undergone by this rock (**Figure 11(F)**). The importance of hydrothermal alteration such as chloritization, epidotization and carbonation within this highly deformed rock should also be noted.

The undifferentiated volcanics studied are generally mafic volcanic or volcano-sedimentary rocks that have undergone significant hydrothermal alteration and are sometimes derived from effusive volcanism, sometimes from explosive volcanism. Some units are deeply deformed.

5. Discussion

Three main aspects will be discussed in this part of our study. These are: regional mapping, remote analytical data and the petrography of undifferentiated volcanics. In terms of regional mapping, the comparative study of pre-existing 1:200,000 geological maps carried out in this study highlighted three main lithologies that are repeated in the vicinity of the various mining sites selected. These are: undifferentiated volcanics, dominant metasiltites on meta-arenites and metagranodiorites. These different lithologies have more or less been listed in the work of authors such as Houssou (2013) [11] on the Agbaou mine and Ouattara (2015) [12] on the Bonikro mine. In addition, this comparative analysis revealed the simultaneous presence of gold and manganese mineral occurrences on all the mine sites. This suggests that there is a close link between gold mineralisation and the coupled presence of these both mineral occurrences. The work of Milési *et al.* (1989) [4] indicates that Mn levels are widespread in West Africa (the Zn-Ag sulphide cluster at Perkoa in Burkina-Faso, the Falémé iron lenses in Senegal and the tourmalinised sandstones at Loulo in Mali). Authors such as Leube and Hirdes (1988) [32] have recorded that the association of graphite and manganese in metasediments could favour the precipitation of gold in birimian formations. According to Milési *et al.* (1989) [4], there is a spatial link between manganese and gold in Ghana and throughout the West African Craton. This study seems to confirm the existence of this spatial link in Côte d'Ivoire.

Tele-analytical data from radarsat-1 image processing indicates that the main direction of the lineaments is NE-SW. This orientation is typical for Birimian formations and structures. The main mine sites studied are generally located near the intersection of lineaments-oriented NE-SW or N-S and lineaments-oriented E-W or ESE-WNW or even ENE-WSW. The rose diagram of the lineaments around the Tongon mine indicates that the main direction is ESE-WNW and the secondary directions are NE-SW and ENE-WSW. These different directions corroborate the work of Lawrence *et al.* (2017) [33], which shows that the Tongon gold mineralisation is carried along a corridor of faults-oriented ENE-WSW. The lineament map shows that the two pits mined on behalf of Barrick Gold are located near the intersection between the NE-SW and ESE-WNW or ENE-WSW lineaments. At the Bonikro mine, the main shear zone occupying the interface between the mineralised lithologies is oriented N-S to NE [34]. These directions were confirmed by the results of the lineament study carried out in the vicinity of the mine. The lineament density maps show that the mines at the various sites studied are located at the interface between zones of high and low lineament density. According to the work of Adingra (2020) [35] in the south-eastern part of the Comoé basin, these interfaces could suggest the presence of major structures such as shear corridors in certain regions. Houssou (2013) [11] work on the Agbaou gold deposit highlights that gold mineralisation is controlled by a major NE-trending shear zone straddling the contact between mafic volcanics and volcanosedimentary rocks.

According to Milési *et al.* (1989) [4] these undifferentiated volcanics are geological formations for which petrographic and chemical data are often insufficient or fragmentary. Microscopic petrographic work on a few samples of undifferentiated volcanics indicates that they are consisted of tuffs, andesites and meta-andesites. These formations are sometimes deeply altered and/or sometimes deformed. These phenomena would have contributed to making their identification particularly difficult. Undifferentiated volcanics have been identified in several volcano-sedimentary furrows in Côte d'Ivoire: Aboisso, Fetêkro, Bondoukou, Bouaflé, Boundiali-korhogo, etc. [28] [36].

6. Conclusions

This study on the gold targeting in paleoproterozoic rocks of Côte d'Ivoire has been led at three main scales:

- On a regional scale, data compiled from pre-existing geological 1:200,000 maps have highlighted some precious information such as the presence of same three lithologies on the different sites studied (undifferentiated volcanics, granodiorites, dominant metasiltites on meta-arenites), the simultaneous presence of gold and manganese mineral occurrences and undifferentiated faults-oriented N-S, NE-SW and WNW-ESE. There is a spatial link between these different lithologies, manganese and gold mineral occurrences and undifferentiated faults. All those criteria are important for targeting an excellent prospect for gold exploration.
- At mine scale, radar image processing indicates that the main mine sites are generally located near the intersection of lineaments-oriented NE-SW, N-S on the one hand and E-W or ESE-WNW or ENE-WSW or ESE-WNW or NW-SE on the other. These mines are also located at the interface between zones of high and low lineament density.
- On a microscopic scale, the petrographic study of the undifferentiated volcanics studied reveals that they are generally volcanic rocks (andesites) or mafic volcanic-sedimentary rocks (tuffs) that have undergone significant hydrothermal alteration. The different types of alteration observed are: chloritization, carbonation, sericitization and epidotization. They are the product

of both effusive and explosive volcanism. Some units are highly deformed (meta-andesites).

The multi-scale targeting approach used on the basis of accessible data is a valuable tool to help mining companies for targeting prospects. It complements other approaches to help discover new deposits.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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