Abstract — This study concerns five regions of Côte d’Ivoire where fracturing is developed. It is about Northern, Northeastern, Centre, Western and Southwestern regions. The principal objective is to understand the organization of fracture networks on Precambrian basement of Côte d’Ivoire. Statistical and geostatistical methods were used in this study for fracturing characterization. Fracture lengths are spread at least on 2 orders of magnitude putting in evidence heterogeneousness of the medium. These fractures reached an advanced development stage according to characteristic parameters of power law (\(\alpha\)). The distribution of fractures spacing is variable from an area to another one. This parameter is described by many laws according to area and stage of fracture networks development: gamma, log normal and power laws; underlining the various development stages of fracture networks. The most developed fracture networks are met at western and northeastern areas. The less developed ones are met at Southwestern. These fractures networks developed on Precambrian basement are spatially structured. This structuring depends on organization of the various fractures networks. Variograms of Bondoukou (North-east), Korhogo (North) and Oumé (Centre) are characterized by a multi-regionalization which is highlighting the complexity of fracturing. The practical range of these variograms oscillates between 44 and 91 km and from 11 to 56 km respectively for global fracturing and fracture families. Behavior of fracturing in various directions of the space is not same on studied areas. Fracture networks from Precambrian basement of Côte d’Ivoire are well organized. These results contribute to better knowledge of fracture networks organization of Côte d’Ivoire.

Keywords — Remote sensing, fracturing, basement, statistical, geostatistical, Côte d’Ivoire.

I. INTRODUCTION

The basement of Côte d’Ivoire is mainly constituted by pre cambrian crystalline and metamorphic rocks; they occupy 97.5% of the territory.

Several tectonic events occurred on this basement which led to set fracturing more or less developed according to type, intensity of deformation and geological context ([1], [2] and [3]). The main part of groundwater is contained inside the fractured reservoirs of basement. These reservoirs are formed by weathered materials, fractures and faults ([3], [4], [5], [6], [7], [8], [9], [10] and [11]). The groundwater flows depend on geometrical properties of fracturing and connectivity of fracture networks. A fine knowledge of discontinuous media is necessary to get a better exploitation, protection and effective management of their resources. This knowledge proceeds from characterization of reservoirs by statistical, geostatistical, hydrodynamic, hydrochemical and isotopic approaches.

Several hydrogeological studies was carried out during two last decades: in the north ([12], [13], [14] and [15]); in the East ([16] and [17]); in the West ([18], [3], [19], [20] and [21]), in the Centre ([22], [10] and [23]) and in the South-west ([24], [25], [11] and [26]). The various results obtained are interesting and extremely encouraging. They will lead to undertake the simulation of groundwater flows and understand functioning of aquifers from basement areas. The aim of this study consists to understand the organization of various fractures networks developed on the Precambrian basement of Côte d’Ivoire.

This study concerns 5 regions where fracturing is developed (Northern, Northeastern, Centre, West and Southwestern). It will highlight differences and similarities in the behavior of fracturing on national scale. It constitutes a contribution to a better knowledge of geometry and organization of fractures networks from Precambrian rocks of Côte d’Ivoire.
II. STUDIED AREAS AND GEOLOGICAL CONTEXT

The sector of study is constituted by 5 areas: the West (Man-Danané), South-west (San Pedro, Soubré), North (Korhogo), the North-East (Bondoukou) and the Centre (Oumé, Katiola) (figure 1). These areas spread on two principals fields of the Precambrian basement: Archaean field at western and southwestern areas and paleoproterozoic field at other areas. On geological view, these areas are dominated by crystalline and metamorphic rocks (Figure 1).

Figure 1: Location of studied areas with there rock formations.

They were affected by several significant tectonic events. Archaean domain was affected by Leonian (3500-2900 My) and Libérian orogenesis (2900-2500 My). Paleoproterozoic domain was affected by Eburnean orogenesis (1500-2500 My). These various events led to developed fracturing. In addition to tectonics events, other processes such as weathering, unloading and seismic events can develop fracturing ([4], [7], [9] and [11]). On hydrogeologic view, there are three principals aquifers in these areas: unconsolidated alterite (saprolite or weathered materials), fissured layer and faults of fresh basement ([9], [10], [11] and [26]). The two first can constitute a composite aquifer superimposed and narrowly linked by a phenomenon of drainance ([11], [3] and [7]). Weathered materials aquifers have primarily capacitive function when fissured and deep fractured aquifers have conducting function. Aquifers of weathered materials and faults are exploited respectively with wells and drillings.

III. MATERIAL AND METHODS

The satellite images (Landsat and Radar) and air-photography were used to make structural cartography of fracture networks in the Precambrian basement of Côte d'Ivoire by various authors ([3], [14], [16], [24], [10], [26] and [23]). These images were treated by using various software (Easi-pace of NCV, Idrisi, Envi, etc.). Lineaments were identified manually through screen visualization. On air-photography, they were mapped by stereoscopic visions. The lineaments which didn’t result from tectonic events have been removed during the validation process. Thus, the selected ones can be considered as fracturing. Statistical and geostatistical treatments were executed with selected fractures to make their characterizations. Geostatistical analysis was carried out by using software Variowin and GS+; when software Statistica is used for the statistical analysis.

Linwin program from the Hydrogeology Laboratory of UMR 6532-HydrASA of the University of Poitiers is used to digitize processes of fracture networks. The results obtained from various works were compared and analyzed. The statistical analysis mainly consisted to study distribution-laws of some geometrical parameters of fracturing such as lengths and spacing of fractures. Number and size of fractures, fracture length magnitude, fracture density, power law parameter were analyzed. Geostatistical analysis consisted to realize variographic analysis of the fracturing, i.e. the determination of regionalization parameters: nugget effect, range and sill on the variogram. Structures of variogram were analyzed and compared.

The space organization of various fracture networks of the Precambrian basement of Côte d'Ivoire is studied and related to statistical and geostatistical results.

IV. RESULTS

A. Fracturing at Northern area: Korhogo

The fracturing-map highlights 8,000 fractures with variously directions and sizes. Major and secondary fractures are respectively N-S and E-W, SE-NW, ENE-WSW. Fracturing of this area is not homogeneous. The lengths of fractures are distributed according to a power law (figure 2).
The α value is equal to 2.73 in this area. This characterization concerns lengths of fractures between 1,487 and 4,412 m. Spacing distribution of azimuth fractures is described by gamma law. Variogram of azimuth fractures is structured and presented nugget effect equal 38% of total dispersion. This variogram presents a particular behavior characterized by double regionalization i.e. two elementary variogram combined ($a_1 = 36$ km and $a_2 = 90.8$ km) (figure 3).

Variograms of fractures families N-S, NE-SW, E-W and NW-SE were structured with a significant nugget effect. Behavior of the fracturing on these various directions is not same.

This distribution law is valid for fractures which lengths are superior than 2.23 km. According to lengths lower than 2.23 km, one moves away the theoretical line that highlights the limits of image resolution by break of slope. Fracture spacing oscillates between 5 and 7,580 m with an average of 1,000 m. These spacings spread over 3 orders of magnitude. More than 80% of fractures spacing are lower than 1,500 m and they are distributed following the gamma law.

2) Geostatistical analysis of fracture networks:

Variograms of fracturing (azimuth) and fractures families NE-SW and NW-SE were spatially structured. They were characterized by nugget effect ($C_0$), sill ($C_1$) and range ($a$). Existence of these parameters indicates that deployment of fracturing on basement area of Bondoukou is not made randomly. Variogram of fracturing is characterized by six sills whose last one is unfinished ($a_1 = 8.52$ km, $a_2 = 16$ km, $a_3 = 32.5$ km, $a_4 = 48.3$ km and $a_5 = 56$ km) (figure 5).
Figure 5: Variogram of fracturing density in Bondoukou area.

The maximum range of variogram is equal to 56 km.

\[
\gamma_c(h) = 9.75 \times 2.85 \left[1 - \exp\left(-\frac{h}{8.52}\right)\right] + 3.09 \times \left[1 - \exp\left(-\frac{h}{16}\right)\right] + 4.10 \times \left[1 - \exp\left(-\frac{h}{32.5}\right)\right] \\
5.11 \times \left[1 - \exp\left(-\frac{h}{48.3}\right)\right] + 6.42 \times \left[1 - \exp\left(-\frac{h}{56}\right)\right]
\]

(2)

\[
\gamma_{NE-SW}(h) = 6.84 + 2.91 \times \left[1 - \exp\left(-\frac{h}{11.1}\right)\right]
\]

(3)

\[
\gamma_{NW-SE}(h) = 4.12 + 2.11 \times \left[1 - \exp\left(-\frac{h}{14.92}\right)\right]
\]

(4)

Parts of nugget effect on total dispersion are 77.38, 66.13 and 70.15% respectively at fracturing, families of fractures NW-SE and NE-SW. The range of structuring of families fractures NE-SW and NW-SE are respectively equals to 11.1 and 14.92 km. These various results testify the fracture networks complexity of Bondoukou area.

C. Fracturing at Western area: Man-Danané

The fracturing map showed 10 071 fractures which size varies from 91 to 21 154 m with average of 1 500 m. These lengths of fractures spread over 4 orders of magnitude. On the circular histogram, fractures NS constitute the major family. The other fractures families do not exceed 10% in frequency. Fractures NNE-SSW, NE-SW and E-W constitute the secondary directions of fracturing of this area. Fracturing in Man-Danané area is heterogeneous. Fractures lengths are described by power law with characteristic parameter (\(\alpha\)) equals 2.91. This power law satisfied lengths longer than 1.58 km (figure 6). For the small fractures (lengths lower than 1.58 km), there is a sampling problem which does not characterized the behavior of these fractures.

Figure 6: Distribution of fractures length of Man-Danané area in bi-logarithmic diagram.

The geostatistical analysis indicates that fracturing can be considered as a regionalized variable. The variogram of fracturing highlights a nugget effect that represents 21.61% of total dispersion (figure 7).

Figure 7: Variogram of fracturing density in Man-Danané area.

The practical range is equal to 44 km. The equation of modeling is given by the following expression:

\[
\gamma(h) = 97.2 \times \left[1 - \exp\left(-\frac{h}{44.25}\right)\right] + 26.79
\]

(5)

On the families fractures, the practical range oscillates between 14.4 and 18.68 km. The nugget effect on these variograms represents 49 to 58.6% of the total dispersion. The structural equations modeling are represented by the expressions 6 to 9:

\[
\gamma_{NS}(h) = 8.61 \times \left[1 - \exp\left(-\frac{h}{17.60}\right)\right] + 12.18
\]

(6)

\[
\gamma_{NE-SW}(h) = 8.07 \times \left[1 - \exp\left(-\frac{h}{25.79}\right)\right] + 8.67
\]

(7)

\[
\gamma_{NW-SE}(h) = 5.10 \times \left[1 - \exp\left(-\frac{h}{14.40}\right)\right] + 4.9
\]

(8)
The values of practical range indicates that the behavior of fracturing on the Man-Danané area is not identical everywhere in the space.

### D. Fracturing at South-western area: San-Pedro and Soubre

1) Fracturing of San Pedro:

The fracturing map of this area highlights 4,181 fractures which sizes vary from 0.4 to 29.6 km with an average equal to 2.5 km. These lengths spread over 3 orders of magnitude. More than 95% lengths are lower than 4 km. The small fractures are more numerous than the large ones. Major families of fracturing are N-S and ESE-WNW. This fracturing is heterogeneous with a variable density from a sector to another. The lengths of fracture are distributed following power law with an exponent characteristic $\alpha = 2.65$. This law characterizes the fractures length ranged between 1,908 to 16,908 m (figure 8).

Fracture spacing varies from 3.25 to 12,500 m with an average of 1,328 m and statistical distribution described by exponential law. These values spread over 4 orders of magnitude.

2) Fracturing of Soubre:

Fracturing map contains 2,565 fractures which lengths are between 319 and 56,040 m, spreading over 4 orders of magnitude. On the circular histogram, fractures ENE-WSW, E-W and N-S dissociated from the other, however there is no family fractures that exceeds 10% in frequency. Fracturing of Soubre area is homogeneous. Spacing oscillates between 6 and 6,600 m. These values spread over 4 orders of magnitude. More than 80% of these spacings are lower than 1,500 m.

Length and spacing of fractures are distributed following power law whose exponent characteristic ($\alpha$) is respectively equal to 2.37 and 2.18 (figures 10 and 11). The power law characterizes the lengths of fractures ranging between 2,155 and 20,680 km. About spacing of fractures this law characterize spacings between 0.79 and 4.8 km.

\[
\gamma_{NW-SE}(h) = 5.5 \times \left[ 1 - \exp\left( -\frac{h}{18.68} \right) \right] + 5.97 \quad (9)
\]

Nugget effect of this variogram represents 86% of total dispersion.

\[
\gamma(h) = 4.68 \left( \frac{h}{47} \right)^{\alpha} + 28.8 \quad \text{for} \ h \leq 47 \text{ km} \quad (10)
\]

\[
\gamma(h) = 4.68 + 28.8 \quad \text{for} \ h > 47 \text{ km} \quad (11)
\]
Figure 11: Distribution of fractures spacing of Soubré area in bi-logarithmic diagram.

E. Fracturing at Centre area: Oumé and Katiola

1) Fracturing of Oumé:

Fracturing map highlights 2,559 fractures with variable sizes oscillating between 0.9 and 47 km, with an average of 4.5 km. The lengths of fracture spread over 2 orders of magnitude. In majority, lengths of fracture (97%) are lower than 10 km. Fractures spacing oscillate between 0.13 and 4,853 m with an average of 802 m. Spacings spread over 4 orders of magnitude. More than 70% of spacings are lower than 1,000 m. The statistical analysis of length and fractures spacing indicates that these two parameters are distributed following power law whose exponent characteristic respectively equal to 2.75 and 2.57 (figures 12 and 13).

Figure 12: Distribution of fractures length of Oumé area in bi-logarithmic diagram.

These power laws respectively characterize the lengths of fractures from 1.64 to 9.25 km and spacings spread between 900 m to 2,000 m.

Vario gram of fracturing is characterized by three practical ranges ($a_1 = 31.16$ km, $a_2 = 60.72$ km and $a_3 = 78.52$ km) whose last one seems not finished (figure 14).

Figure 13: Distribution of fractures spacing of Oumé area in bi-logarithmic diagram.

Figure 14: Vario gram of fracturing density in Oumé area.

The maximum range is 78.52 km. The structural modeling equation of vario gram is known by the expression below (Eq. 12):

$$\gamma(h) = 9.24 + 28.98 \times \left[1 - \exp \left(-\frac{h}{31.16}\right)\right] + 24.37 \times \left[1 - \exp \left(-\frac{h}{60.72}\right)\right] + 16.88 \times \left[1 - \exp \left(-\frac{h}{78.52}\right)\right]$$

(12)

On this vario gram, nugget effect represents 35.37% of total dispersion.
2) Fracturing of Katiola:

The fracturing map of Katiola displays 2 621 fractures whose lengths vary between 0.43 and 32 km with an average of 7.27 km. These lengths spread over 2 orders of magnitude. The main part of fractures has a length between 5 m and 10 km. Fractures spacing oscillates between 9 m and 15.71 km with an average of 2 529 m. Values of spacing spread over 4 orders of magnitude. More than 52% of spacing’s values do not exceed 2 000 m. Length and spacing of fractures are distributed respectively according to power and lognormal laws. The α value is equal to 2.79 (figure 15).

\[
\gamma(h) = 250.22 \times \left[ \frac{3}{2} \times \frac{h}{82.81} - \frac{1}{2} \times \left( \frac{h}{82.81} \right)^{\alpha} \right] + 83.33 \quad \text{for } h \leq 82.81 \text{ km}
\]

\[
\gamma(h) = 250.22 + 83.33 \quad \text{for } h > 82.81 \text{ km}
\]

V. DISCUSSION

A. Statistical analysis

Precambrian basement of Côte d’Ivoire is abundantly fractured. It is attested by various studies ([14], [16], [24], [10] and [26]). These studies update previous fracturing maps by highlighting many fractures which were unknown before. Some of these accidents were badly known because they never indexed in previous works ([17]). Indeed, former studies about the fracturing of Côte d’Ivoire were fragmentary realized in small areas in one hand and focused on the determination of main direction of fracturing in the other hand ([1] and [3]).

This study confirmed some fractures identified by previous studies carried out by many authors ([27], [28], [29], [1], [30], [31] and [32]). Fracturing intensity is different from one area to another according to tectonic and geological contexts. According to petrographical view, archaean and paléoproterozoic are not similar fields. Various tectonic events occurred on each field led to create developed fracturing. The statistical analyses pointed up the dominance of small fractures.

These small fractures significantly control the connectivity of fracture networks and regional flows. Many high-density of fracturing are met in Man-Danané, Korhogo and Bondoukou areas. The fracturing on Precambrian basement of Côte d’Ivoire generally is slightly heterogeneous or homogeneous. The directions of fracturing usually met are N-S and E-W. The lengths of fractures spread at least over than 2 orders of magnitude which highlight heterogeneity of the studied areas. Lengths of fractures are distributed following power law in the two fields of Precambrian basement. This distribution is in accordance with previous works ([33], [34] and [35]).

The characterization by power law requires data spread at least over than two or three orders of magnitude ([35]). This condition is satisfied in the various fracture networks studied in Côte d’Ivoire. For [34] and [35], natural fractures networks should have their lengths distributed according to a power law at the end of their development. This power law indicates that various fractures networks reached advanced development level.
However, values of exponent characteristic of power-law show that fracturing development varies through areas. Indeed, the value of the exponent characteristic \( \alpha \) oscillates from 2.37 to 2.98. These values are compatible with data from the literature which generally vary between 1 and 3 ([33] and [17]). The exponent characteristic \( \alpha \) gives indications about the proportion of shorter and greater fractures ([34] and [35]).

Values of exponent characteristic \( \alpha \) define different steps of fractures networks development ([3], [34], [35] and [17]). The distribution of fractures lengths according power-law seems permanent in Precambrian rocks. It is remarkable and would be related to heterogeneity of the areas and development of fractures networks.

According to values of \( \alpha \), fracture networks of south-west (Soubré and San Pedro) are less developed. The fractures networks of Man-Danânë and Bondoukou reached the most advanced stage of development. That can be due to intensity of fracturing, i.e. the various tectonic events occurred on these areas. The networks of these two areas have similar \( \alpha \) coefficients \( \alpha = 2.91 \) and \( \alpha = 2.98 \) respectively for Man-Danânë and Bondoukou.

The spatial organization of these two fractures networks is similar ([17]). This result would implicate similar tectonic behaviors for these two areas.

[35] remarks that distribution of lengths can evolve through exponential, lognormal or power laws according to fracture networks development. This argument could explain the variability of distribution laws of fractures length met in the literature ([36], [33], [3] and [17]).

The fracture networks described by power law are characterized by self-similarity properties, which means that small and long fractures are a fractal character ([33], [3] and [17]). These studies show that areas of paleoproterozoic domain were not affected by the same types and intensities of tectonic events; it is the case of Korhogo, Bondoukou and Soubré.

The statistical distribution of fractures spacing is variable on the studied areas; gamma, exponential or power laws. The variability of spacing distribution agrees with data of literature. The great number of small spacing’s of fractures inform about the stage of fracturing of areas. These results could be explained by biases which affect measurements or window of sampling. [37] interpret this variability as a stage of development.

B. Geostatistical analysis

Fracturing in studied areas behave like a regionalized variable more or less structuring. Variograms present a nugget effect that testifies irregularity of the phenomenon studied ([3] and [38]). This nugget effect is interpreted like combined action of heterogeneities over smaller scale and uncertainties of measurements [3], [17], [38] and [39]).

Practical ranges oscillate between 44.25 and 90.8 km on variograms of fracturing and between 11.1 and 25.79 km on variograms of fracture families. The presence of several elementary variograms on the global variogram indicates the complexity of studied fractures networks from Precambrian basement of Côte d'Ivoire ([3] and [17]). It is the case of north, north-East and Centre regions of the country. The most significant practical ranges of variogram were obtained in these areas, and variogram structuring is also better.

The best structured variograms for fracture families is met at Man-Danânë area. Following spatial directions, the behavior of fracturing is not the same. This can be explained by the intensity and occurrences of tectonic events and orientation of main constraints ([3], [17], [38] and [40]).

Development of fracturing on Precambrian basement of Côte d'Ivoire is not made randomly but following a structured and organized way. Behavior of variograms of fractures family study sustain this assumption. Statistical and geostatistical studies showed that South-western is the least developed and organized area about fracturing of Precambrian basement of Côte d'Ivoire.

VI. Conclusion

The remote sensing led to get interesting documents for prospecting groundwater. The size of the fractures spreads over than 2 orders of magnitude that highlights heterogeneity of areas. The Precambrian basement of Côte d'Ivoire is abundantly fractured and the fracture networks are well organized. The statistical analysis indicates that these networks reached advanced development stage according to exponent characteristic \( \alpha \).

Fracture networks development on the basement is variable in the areas. The most developed and organized fracture networks are met at western and north-eastern areas. The south-western area seems to be the area that reached the weakest stage of development of their fracture networks.
The practical ranges of variograms oscillate between 44.25 and 90.8 km for the fracturing and between 11.1 and 25.79 km for the fracture families. The complexity of the areas was highlighted by multi-regionalization of the fracturing. Variograms present a nugget effect more or less developed according to areas.

The organization of fractures is not similar in the different areas. Fracturing of Precambrian basement is developed fracturing. Variograms present a nugget effect more or less developed according to areas. Fracturing of Precambrian basement is complex and characterized by several types of deformations.

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