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Characterization of Aquifers in Crystalline and Crystallophyll Basement Zones Using the Electrical Resistivity Method (Trails and Electrical Soundings) in the Gagnoa Region, (Central-Western Côte d'Ivoire)

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Abstract

Introduction: Located in the central-western part of Côte d'Ivoire, the subsoil of the Gagnoa region is made up of sedimentary volcano formations and granitoids with developed fracturing. This complex Precambrian basement contains most of the region's water resources. This is at the origin of the high failure rate during the various hydrogeological prospecting campaigns. **Methodology**: The database consists of resistivities from 42 holes and 51 trails drilled as part of the implementation of high-throughput drilling in the study area. The objective of this study is to deepen the knowledge of the fissured basement by interpreting profile curves and electrical soundings. It will be a question of classifying the different types of anomalies obtained on the profiles and their shapes. The orientation of the lineaments observed on the profiles was determined. **Results**: The interpretation of the geophysical data revealed various anomalies, the main ones being of the CC (Conductor Compartment) and CEDP (Contact between two bearings) types. These types of anomalies are mainly expressed in various forms: the "V", "W" and "U" shapes. From these anomalies and the appearance of the electrical profiles, lineaments and their orientations were identified with N90-100, N130-140, N170-180 as major orientations. **Conclusion**: These results could contribute to a better understanding of the fractured environment of the Gagnoa region.

Keywords

Basement, Electrical Profiles, Sounding Curves, Resistivities

1. Introduction

The crystalline and metamorphic basement is full of immense groundwater reserves located across isolated aquifers of hard-to-manage fissured basement [1] [2] [3]. This is due to the structure of these aquifers being quite complex.

This is reflected in a high failure rate for projects carried out in the basement domain, which can reach peaks of 50% (IDB-2 project, 2008-2010) [4]. This high failure rate is due, in addition to the lack of knowledge of fractured environments, to a lack of in-depth studies during prospecting.

Many methods of hydrogeological investigation (geomorphology, remote sensing, geophysics, GIS) were adopted for a better understanding of the fractured environment. The use of geophysical methods for the installation of water boreholes has yielded satisfactory results, with an estimated failure rate of 12% (WAEMU 2010 project in the N'Zi region) [5]. Geophysics is therefore a very valuable tool for conducting a hydrogeological research programm, whether to identify new resources or to improve knowledge of an aquifer reservoir [6]. It is in this perspective that this work is inscribed, which aims to deepen the geological knowledge of the basement of the study area.

The most widely used geophysical method is the electrical resistivity method (trailed and electrical sounding), its interpretation and implementation easy and above all for the high reliability of the results. This study will make it possible to identify anomalies and fractures in the study area and to highlight the different geological layers.

2. Study Framework and Geological Contex

Located in the central-western part of Côte d'Ivoire, the Gagnoa region belongs to the Proterozoic domain. From a petrographic point of view, crystalline rocks and Crystallophyllians consisting mainly of granitoids and volcano-sedimentary formations. The volcano-sedimentary formations are represented by fine-grained amphibolites with a distinctly schist structure, chloritic schists, sericitous schists and tuffs of grey-green colour with generally very fine grains (**Figure 1**).

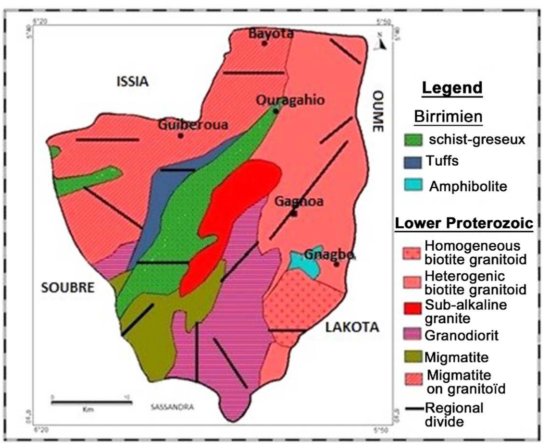


Figure 1. Modified geological map of the Gagnoa region [7].

The fracturing of the Gagnoa region is heterogeneous. Statistical analysis of these networks indicates that they have reached an advanced stage of development, like the Precambrian basement fracture networks of Côte d'Ivoire [3] [4] [5] [6]. The more detailed analysis of the fractures revealed two families of fractures preponderant in direction: N0-10 and N90-100.

From a hydrogeological point of view, there are two types of aquifers: alterite aquifers and fissure aquifers. These two types of aquifers are generally superimposed, but it can happen that one is missing or is laterally and partially saturated or not, drained or draining [8].

3. Material and Methods

3.1. Study Material

3.1.1. Tools

The tools used come from Schlumberger's quadrupole device, which consists of:

- The Syscal Pro resistivity meter, consisting of a central unit combining the functions of current injection I and measurement of the potential difference generated;
- The 02 current emission electrodes I at points A and B to inject the current into the subsurface and the 02 M and N potential reception electrodes to measure the potential difference generated from the current injection;
- Coils (electrical cables) to connect resistivities to electrodes;
- Four electrodes, two of which are used for the injection of current I, the other two used for the measurement of the potential difference.
- A tape measure used to measure the distances between the electrodes;
- Hammers for fixing the electrodes to the ground;
- A compass used to measure the direction of the lanes and the orientation of geological structures.

3.1.2. Data

The data used in this study are exclusively electrical resistivity data acquired using electrical trailing and sounding techniques. These data were obtained from 51 drag tracks and 42 sampling points executed in the study area (**Table 1**).

Table 1. Different electrical trails and soundings carried out in the study area.

S/préfectures	Villages	Nombre de trainés	Nombre de Sondages
BAYOTA	Abodjekro	3	2
	Adjamé	3	2
	Bathelemykro	2	2
GAGNOA	Ahizabré	4	1
	Kakrédou	3	1
	Bénoitkro	3	2
	Behibokro	3	3

Continued

GNAGBODOUGNOA	Bamo 1	2	3
	Daliguépalegnoa	2	3
	Kragbalilié	3	2
GUIBEROUA	Allakonankro	2	3
	Alloukouassikro	4	2
	Briehoa	3	2
	Kouadiokro	3	3
OURAGAHIO	Cocotier 1	2	2
	Cocotier 2	3	2
	Drayo	1	2
	Dodougnoa	3	2
	Konankankro	5	2
	Manguehigouepa	3	1
TOTAL		57	42

3.2. Methodology

The methodology based on Schlumberger's quadrupole and aligned device will consist of injecting direct current I by means of two injection electrodes A and B and measuring the potential difference (ΔV) using two potential electrodes M and N (**Figure 2**).

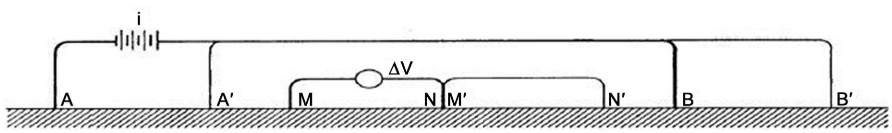


Figure 2. Illustrative diagram of horizontal prospecting (single trail).

The Sylcal Pro communicates the value of the electrical resistivity ρ of the geological formation.

The electrical survey methodology takes place in two (02) different phases: the acquisition of the electrical trail data (lateral or horizontal surveying), the acquisition of the electrical survey data (vertical surveying).

3.2.1. Acquisition of Lateral Prospecting Data (Electric Trail)

For the acquisition of the electric trail data, steps and procedures have been carried out:

- the determination of the preferred direction of the geological structures in the study area;
- the basic layon route parallel to this geological direction;
- the layout of the transverse tracks perpendicular to the geological direction with measuring steps of 10 m;

- the installation of equidistant wooden stakes marking the measurement points;
- the coordinates (in UTM) are taken by the GPS for each measurement point;
- the measurement of electrodes A - B (200 m) and electrodes M - N (20 m);
- The apparent resistivity is measured using the "Syscal Pro" resistivity meter. Before the measurements are taken, the electrodes A and B and those of M and N are fixed to the ground with a hammer. These electrodes are connected to each other by the electrical cables (coil) for the sending of current into the electrodes from the resistivity meter;
- after the device has been placed at each measuring point, the current I is injected into the electrodes from the SYSCAL PRO and the apparent resistivity is measured on the device;
- the same procedure is repeated by moving the entire measuring device along the different tracks in order to cover the prospecting grid on the road;
- the transfer to a semi-logarithmic scale having the distance AB on the x-axis and the different values of apparent resistivities obtained at each measurement step for each layon on the x-axis;
- the identification of conductive anomalies according to the classification [6] on the profile obtained from the data report;
- the determination of the orientation of the lineaments identified from the anomaly points.

A straight line connecting these two anomalies. This line is likely to represent a lineament. The process of drawing lineaments is shown in **Figure 3**.

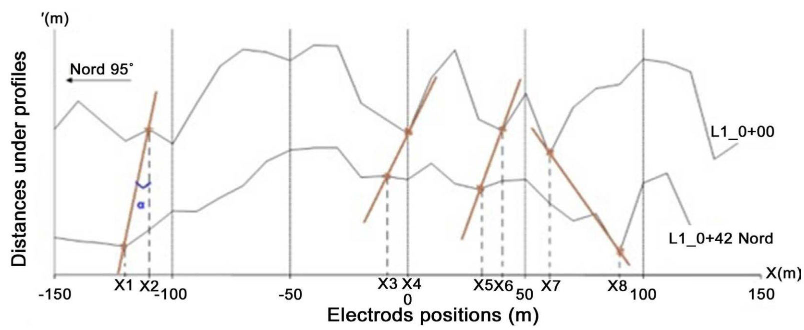


Figure 3. Identification of lineaments on electrical profiles [9].

The determination of the orientation of the orientation of these identified lineaments is done considering the orientation of the profile. Thus, in **Figure 3**, considering that the orientation of the first lineament is Ω we will have: $\Omega = 95^\circ + 90^\circ + a$ or $95^\circ - 90^\circ + a$ [9].

3.2.2. Acquisition of Data from Vertical Prospecting (Electrical Survey)

For the acquisition of electrical survey data, steps and procedures were carried out:

- carrying out borehole measurements on the various anomaly points identified.

- true resistivity measurements made by gradually moving the M N potential electrodes (0.8 m; 2 m and 10 m) away from the A B injection electrode (2 to 100 m).

This method makes it possible to study the vertical variation of resistivity as a function of depth in order to highlight the layers of terrain encountered. The depth of investigation is not only related to the length AB but also to the configuration of the subsoil (structures and resistivity contrasts between the different units). For each value of AB/2, the device gives a value of the apparent resistivity of the terrain through which the current flows. The resistivity values determined during the geophysical surveys are plotted on a bilogarithmic diagram with the corresponding apparent resistivity on the abscissa AB/2 and on the y-axis. This sounding curve can take a variety of forms.

By referring to the conceptual model composed of three types of terrain (alterites, fissured horizon and healthy basement) (**Figure 4**).

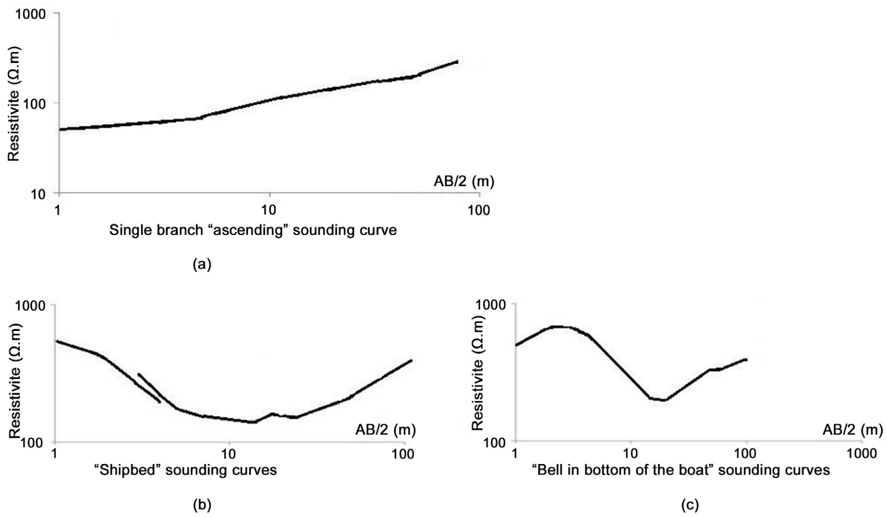


Figure 4. Some sounding curves [10].

4. Results

4.1. Characterization of Anomalies Based on Electrical Profiles

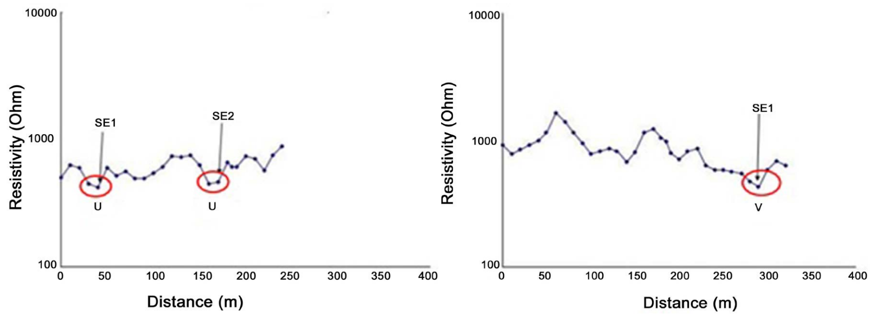
The electrical profiles used in this study are those from which the surveys were carried out. These different profiles display various anomaly configurations.

4.1.1. Form and Type of Anomaly

1) Driver compartment (CC) fault

Figure 5 shows an electrical profile oriented N143˚, made in the village of Adjamé with a "V" shaped anomaly configuration.

On this profile, we observe a non-significant variation in resistivity (700 - 1200 Ω·m). This monotonous pace was interrupted by an anomaly at the 290 m measuring point. At this point, there is a sudden drop in resistivity and then an increase.



(a) (b)

Figure 5. Narrow conductor compartment type ("V" shape) at Adjamé (a) and ("U" shape) at Kragbalilié (b).

Figure 5 shows an electrical profile oriented N90˚ with "U" shaped anomalies made in the village of Kragbalilie. The anomaly is remarkable on two measurement points, *i.e.* 40 - 50 m and 160 - 170 m. The degree of fracturing is therefore identical between these two points.

The forms of H anomalies are identified on the N155˚ oriented electrical profile executed in the village of Mangbehigouepa (**Figure 6**).

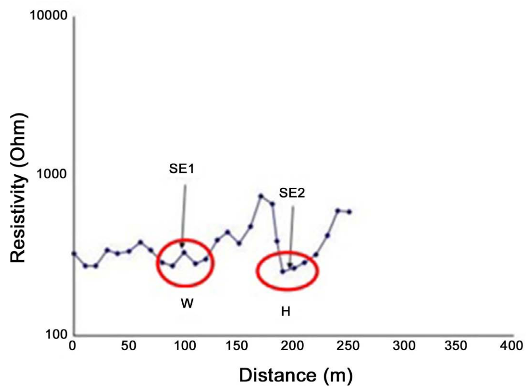


Figure 6. Conductive compartment type anomaly from (shape "W" and (shape "H") to Mangbehigouepa.

This anomaly observable at the 190 m measurement point is similar to a U-shaped anomaly with a slight curvature. On this same profile, a "W" shape anomaly was also detected. The "W" shape anomaly is identified by alternating levels of high apparent resistivity values (horst with sub-outcropping bedrock) and low apparent resistivity values within the main anomaly.

2) Contact anomaly between two bearings

Figure 7 shows a contact anomaly between two bearings.

This profile carried out in the village of Behibrokro clearly shows the existence of two consecutive levels. The contact between these two bearings is located at the measurement point 120 m with a fallout of resistivity (689 Ω·m). The first bearing has an average resistivity of about 900 Ω·m. While the second has an average resistivity of 600 Ω·m. It is at this second level of about 170 m that the borehole was carried out.

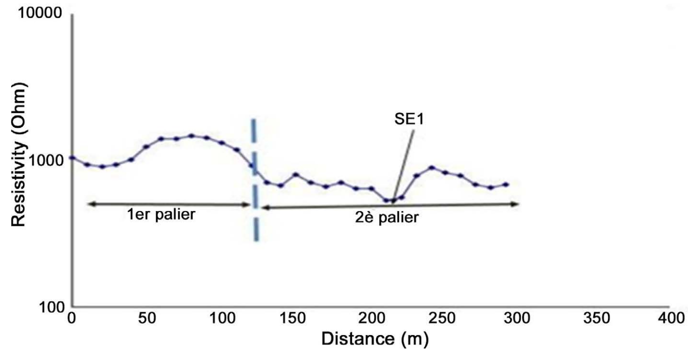


Figure 7. Anomaly type contact between two bearings at Behibrokro.

4.1.2. Identification of Lineaments

The lineaments were detected by parallel electrical trails (**Figure 8**).

These two trails are 15 m apart and oriented N 62˚. The two resulting profiles have the same appearance and a similar variation of electrical resistivities as a function of the distance AB/2 over their entire length. Similar conductive anomalies are identified on these profiles. The lineament is assimilated to the line joining these anomalies. Thus, we were able to materialize 52 lineaments on all the profiles. These lineaments have the preferred direction of the N90-100, N130-140, N170-180 directions (**Figure 9**).

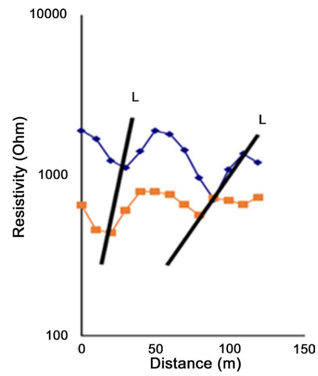


Figure 8. Drawing of lineaments on two parallel profiles in the village Dalililie.

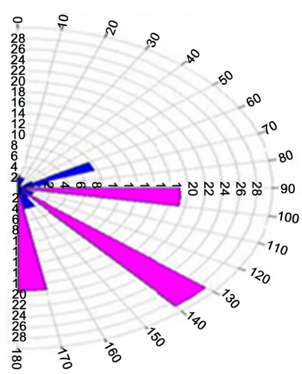


Figure 9. Directional rosette for lineaments from electrical profiles (N = 52).

4.2. Characterization of Sounding Curves

The electrical soundings carried out in the study area have made it possible to identify three types of sounding curve. The "A" type curve, called "uphill" single-branch sounding curves, is the most common with more than 80%, followed by the "KH" type curve which begins with a bell "and ends at the bottom of the boat" and the H-type curve, *i.e.* the "curve at the bottom of the boat".

4.2.1. Sounding Curves with a Single "Ascending" Branch

This type of curve is indicative of only two plots of land (**Figure 10**). The first layer is 25 m thick and has a resistivity varying from 100 to 168 Ω·m. The second layer represents the basement with increasing resistivities (≥200 Ω·m).

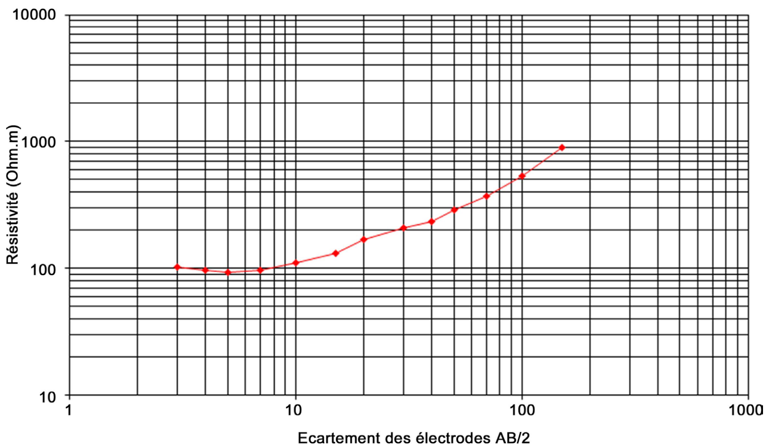


Figure 10. Single branch "ascending" sounding curve at Dalilié.

The sounding curve obtained in the village of Allakonankro shows a variant of the A-type curve and is referred to as the "stepped curve on the ascending branch" (**Figure 11**). This curve is composed of two asymmetrical parts separated by an intercalation. This intercalation is characterized by a brief drop and then an increase in resistivities. This zone represents a rupture zone comparable to a fracture. It can materialize a significant water inflow.

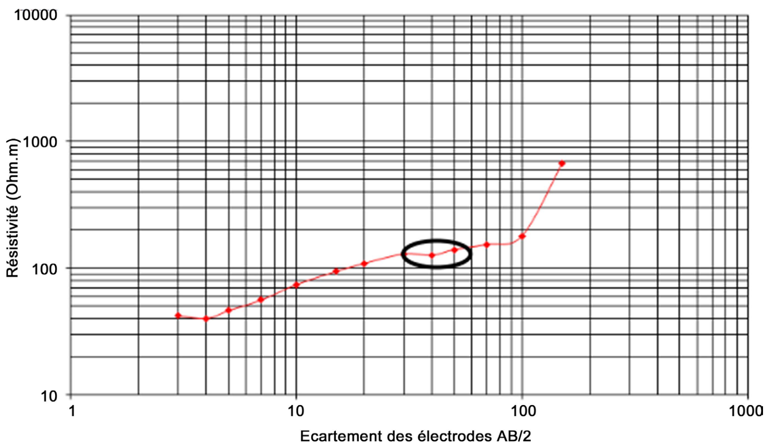


Figure 11. "Staired sounding curve on the rising branch" at Allakonankro.

4.2.2. "Bell in the Bottom of the Boat" Sounding Curves

The "shipbed" sounding curve is characteristic of highly armoured regions and highlights the superposition of three distinct resistivity layers:

- Superficial covering: this is the lateritic cover (cuirasses and lateritic clays) with high resistivity (200 to 250 Ω·m).
- The highly conductive intermediate layer corresponds to the part between the base of the laterites and the roof of the resistant basement. The thickness of this layer is a function of the degree of weathering in the area. It is characterized by a drop in resistivity and then a rise bringing out a rounded curve "at the bottom of the boat". On this curve, the lowest resistivity value recorded is 30 Ω·m with a thickness of 40 m.
- The resistant basement: this layer is characterized by a rise in the curve which indicates the presence of a resistant rock of a crystalline or crystallophyllian nature depending on the angle of the ascent (**Figure 12**).

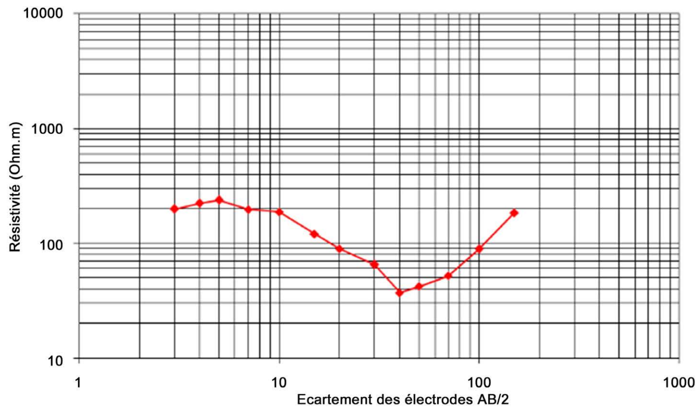


Figure 12. "Shipbed" sounding curves at Benoitkro.

A variant of the "bottom of the boat" sounding curve, the "bell curve at the bottom of the boat" differs from it by the presence of a conductive layer of topsoil. It is observed on the sounding curve carried out in the village of Alloukouassikro (**Figure 13**). This layer has a low resistivity of 92 to 95 Ω·m at Alloukouassikro and 107 to 137 Ω·m at Briehoa.

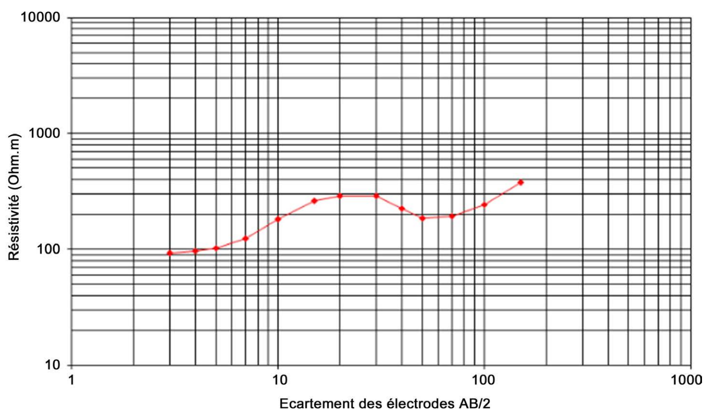


Figure 13. "Bell in the bottom of the boat" sounding curves at Alloukouassikro.

5. Discussions

The identification of the type of anomaly on the electrical profiles is linked to the measurement step used, and therefore to the depth of investigation during the survey. Indeed, a relatively large measurement step masks the real type of anomaly or has the disadvantage of confusing certain geological structures. Also, a fault can be assimilated to a geological contact.

To differentiate between them, the prospector will have to change the depth of investigation as soon as an anomaly is discovered. In addition, the sub-surface investigation method used is not suitable for the identification of these structures insofar as they are important at depth. Nevertheless, several geological structures (faults, geological contacts, shear zones, fractures, etc.) could be identified on these electrical profiles as is the case in the work of [9] [10] [11] in Bidi in Burkina Faso and in Tanda. The profiles carried out in the Gagnoa region have also made it possible to identify geological structures. In many tropical regions of West Africa, the interpretation of the sounding curves obtained has revealed a structure of three electrically distinct horizons [12] [13] [14] [15] [16]. The "upward" single branch sounding curve, the most common in the Gagnoa highlights two horizons. This is due to the predominance of erosion in the study area. There is therefore an outcrop of level II. This level characterises the sandy clay alterites, most often saturated with water, which are made up of clays and granular arenas. It corresponds to a set of geological formations whose common characteristic is to present low resistivities that are different from those of the upper lateritic and lower levels of the underlying basement [9]. Some sounding curves in the study area have a bell "like appearance and end at the bottom of a boat". This type of curve is frequently found in regions of dense forests where the vegetation cover and rainfall favour soil development [1]-[16]. Indeed, weathering plays a crucial role in the degradation of geological formations, favouring the formation of soil and lateritic armour. The use of models specific to homogeneous and semi-infinite layers, such as sedimentary media, for the interpretation of sounding curves would represent an extrapolation [9] in [17]. Also, the crushed area is difficult to spot on the sounding curves.

6. Conclusion

The interpretation of the different electrical profiles has made it possible to identify two types of profile "conductor compartment (CC) and contact between two bearings (CEDP)". Various forms of anomalies have been identified: the "V", "W" and "U" shapes. From these anomalies and the appearance of the electrical profiles, lineaments have been identified whose major orientations are N90-100, N130-140, N170-180. The appearance of the borehole curves (curve with a single "rising" branch and "bell in the bottom of the boat") highlights zones of significant alteration and low apparent resistivities, and the geological nature of the subsurface horizons. This qualitative interpretation represents an asset in hydrogeological prospecting and in the understanding of the functioning of fissured aquifers.

Conflicts of Interest

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

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