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Electrical Resistivity Contrasts and High Flow Rates Discontinuous Aquifers Identification in a Sheared Crystallophyllian Basement Zone at Boniérédougou (North-Central Côte d'Ivoire)

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Abstract

This study proposes an alternative approach to the investigation of high flow hydrogeological fractures within the basement in the Dabakala region of north-central Côte d'Ivoire. The used approach consists of exploring the subsurface by measuring electrical resistivity contrasts along the main shear direction within crystallophyllian rocks. Electrical resistivity profiling and vertical electrical sounding techniques, coupled with boreholes monitoring, have identified fractured aquifers whose best flow rates are around 96 and 116 m^3/h. These aquifers mostly hosted in granodiorite have an average strength of 10 meters and are located at depth of around 100 meters. They are associated with open fractures created by tangential shear stresses that have affected the Dabakala volcano-sedimentary trench formations. The search for fractured aquifers along the main shear direction offers great perspective for obtaining high flow rates.

Keywords

Shear, Fractured Aquifer, High Flow Rate, Côte d'Ivoire

1. Introduction

Access to safe drinking water is the main issue for governments and is one of the main UN Millennium Development Goals (MDG). Indeed, in sub-Saharan Africa, surface water is the main source of consumption. However, it causes many waterborne diseases, because it is exposed to pesticides and agro-pastoral wastes (Gascuel et al., 1998; Laurent, 2012) and to toxic products from mining activities (Laperrière et al., 2009; Goix, 2012). It is also subject to seasonal fluctuations due to the effects of climate change (Goula et al., 2006; Ouhamdouch et al., 2018). And, the northern and central regions of Côte d'Ivoire are not spared from this. Faced to this situation, the exploitation of groundwater opens the way to sustainably mitigate these problems. Thus, authors such as Kouakou (2012), Loukou (2017), Kouakou et al. (2015) have been able to identify fracture aquifers, with relatively medium flows, within the crystallophyllian basement from the electrical resistivities studies in the Bondoukou and Dabakala regions. The present study proposes, on the other hand, a contribution to the identification of large flow hydrogeological fractures within shear-affected volcano-sedimentary folds. It presents an approach based on electrical resistivity contrasts measurement in the direction of the main shear in order to identify high flow fracture aquifers and to estimate their depths and average powers for the implantation of groundwater catchment structures for consumption.

2. Geographical and Geological Context

The work was carried out on three sites in Boniérédougou, an area located southwest of Dabakala in north-central Côte d'Ivoire (**Figure 1**). It is covered by a wooded savannah dominated by few hills.

The geology of these localities is made up of a crystallophyllian basement where intrusives (Granite and Granodiorite, Tonalite and Diorite) and volcano-sediments composed of basalts and tuffs, and filling sediments (Tagini, 1971; Allou, 2014) rarely outcrop. These formations are oriented NNE-SSW and N-S and are affected by a low to medium degree of metamorphism that characterises

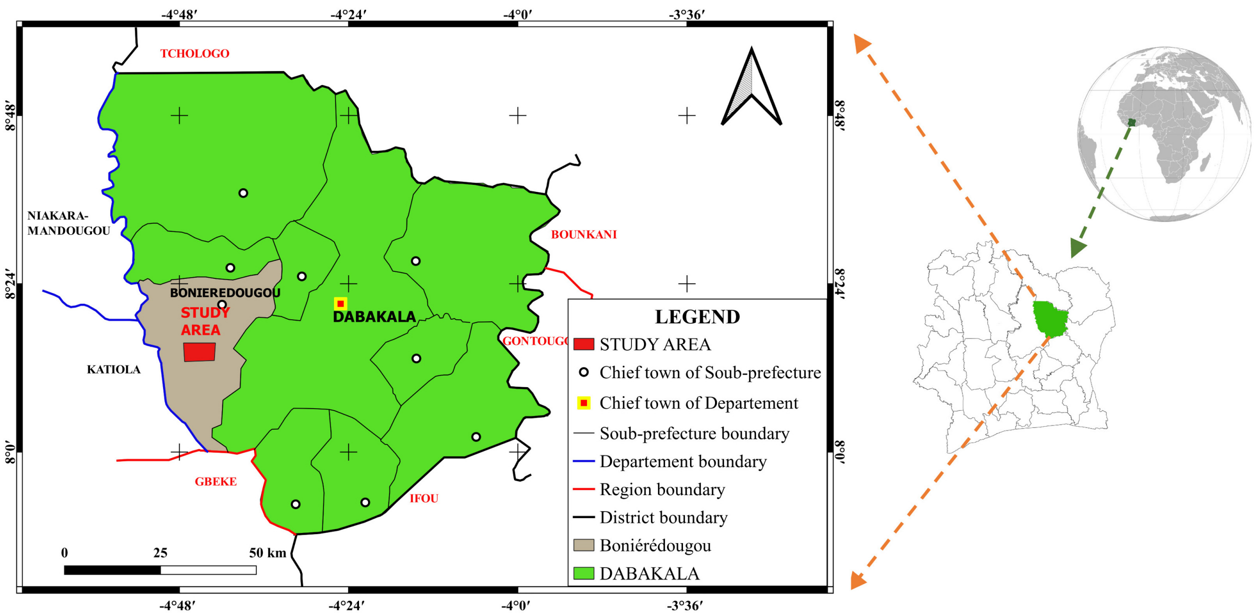


Figure 1. Geological location.

the Birimian (Bessoles, 1977; Lemoine, 1988). The tectonics is marked by a NE-SW oriented shear corridor within the volcano-sedimentary series in the well-known Fetekro birimian synform (Yacé, 1976; Lemoine, 1985) (**Figure 2**).

3. Methods

This study is based on the measurement of electrical resistivity contrasts with a Syscal Pro in two modes: electrical resistivity profiling and vertical electrical sounding.

The electrical resistivity profiling was carried out with the rectangular gradient configuration. This setup is characterised by current injection with a large dipole (AB) which results in a better signal-to-noise ratio at a relatively constant depth of investigation; and measurement of the potential difference (pd) with several receiving dipoles (MN) (**Figure 3**). The measured apparent resistivity (ρ_a) incorporates the geometric parameters related to the separations between the active and passive electrodes and is determined by the following equation:

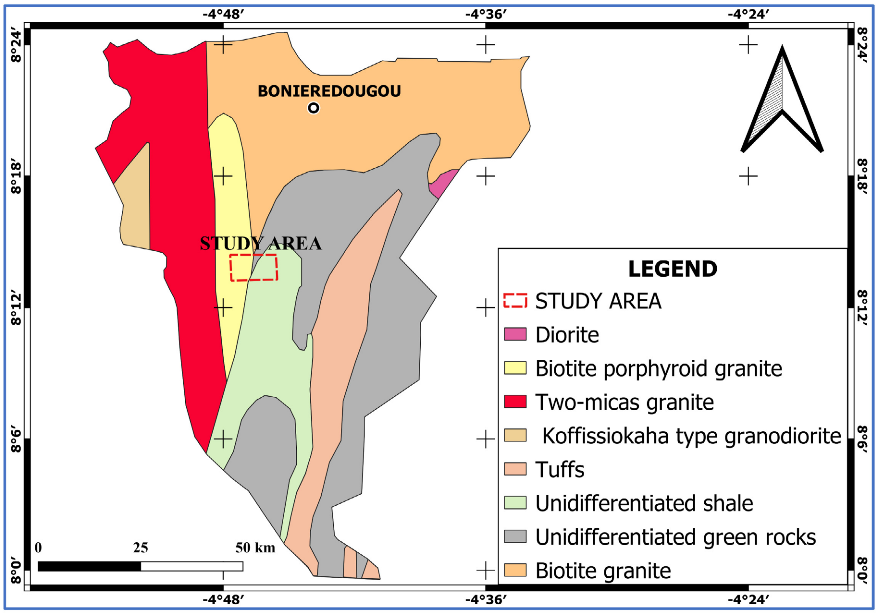


Figure 2. Geology map of the study area, Tagini (1971).

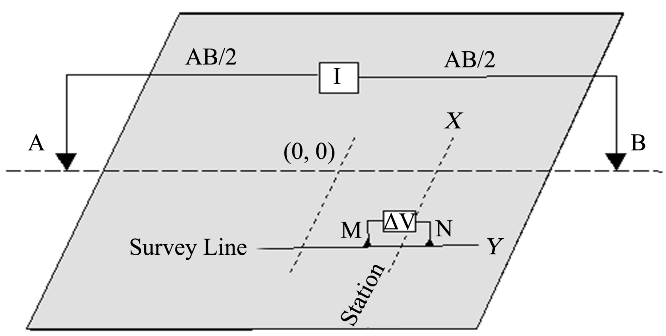


Figure 3. Rectangular gradient device, AB/2 = 800 m (Site 1 & 3) 400 (Grille 2) et MN = 10 m.

$$\rho_a = \frac{2 \cdot \pi \cdot V_p}{I \cdot \left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \right)} \quad (1)$$

where V_p: primary voltage (mV); I: injected current (mA).

Electrodes A and B are fixed electrodes, used for the transmission of electrical current. The MN receiving electrodes are moved at each measuring station. The surveys were carried out in the central third of the injection dipole AB over a width equivalent to half of AB. This technique gives excellent resolution on the lateral distribution of electrical resistivity contrasts which reflect lithological variations in the subsurface and thus allow the identification of fractures within the crystallophyllian basement (Boudoukha, 2008; CIEH, 2001; Kouakou, 2012; Kouakou et al., 2015; Sombo, 2012).

Electrical sounding offers a better resolution on the vertical distribution of resistivity at depth. This technique allows us to appreciate the evolution of resistivity contrasts that are associated with transverse variations in lithology. The depth and strength of the aquifers were determined from the geoelectric sections obtained after interpretation of the electrical drilling curves. A total of six electrical soundings (ES) were carried out with the Schlumberger device on the three prospects. This device is a symmetrical quadripole AMNB, with an active dipole (AB) and a passive dipole (MN) for the measurement of the residual potential which is used in the calculation of the resistivities according to Equation (1).

Six hydraulic boreholes were drilled at the electrical test points. They enabled geological sections to be established which, by correlation with the geo-electric logs, will contribute to a better characterisation of the identified fractured aquifers.

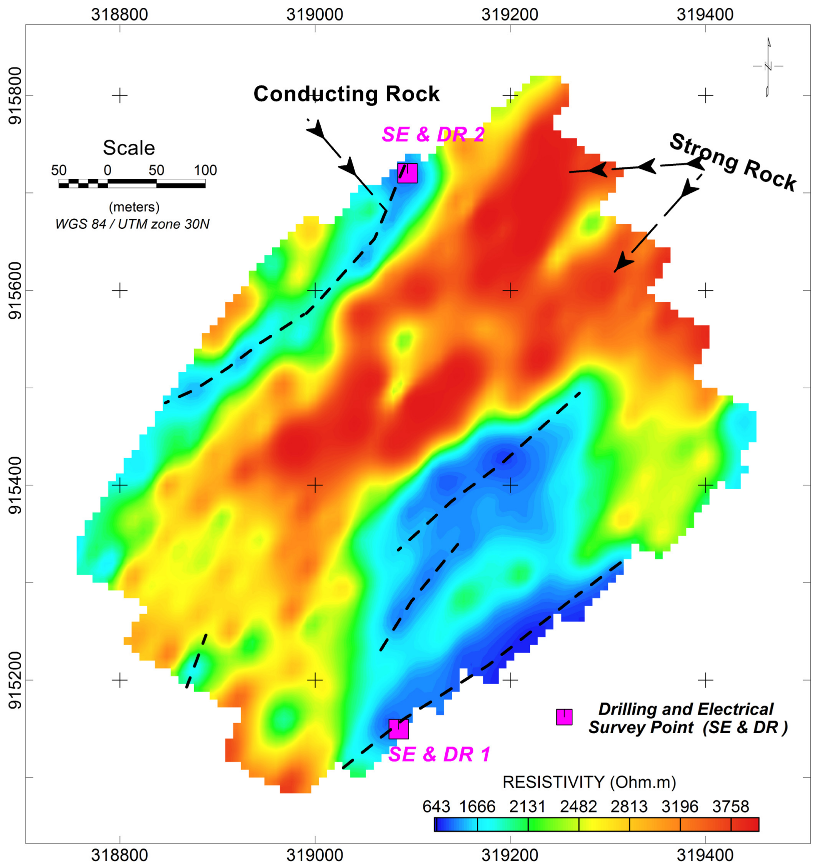
The electrical resistivity and hydraulic drilling data were processed with Geosoft, Winsev and Strater software respectively. Filters and topographic corrections were applied to the electrical resistivity data with Geosoft software (*Version 7.01*). The inversion of the electrical sounding curves was possible with the Winsev software (*Version 2.1*) and the geo-electrical logs and geological sections were established with the Strater software (*Version 3.0*).

4. Results and Discussion

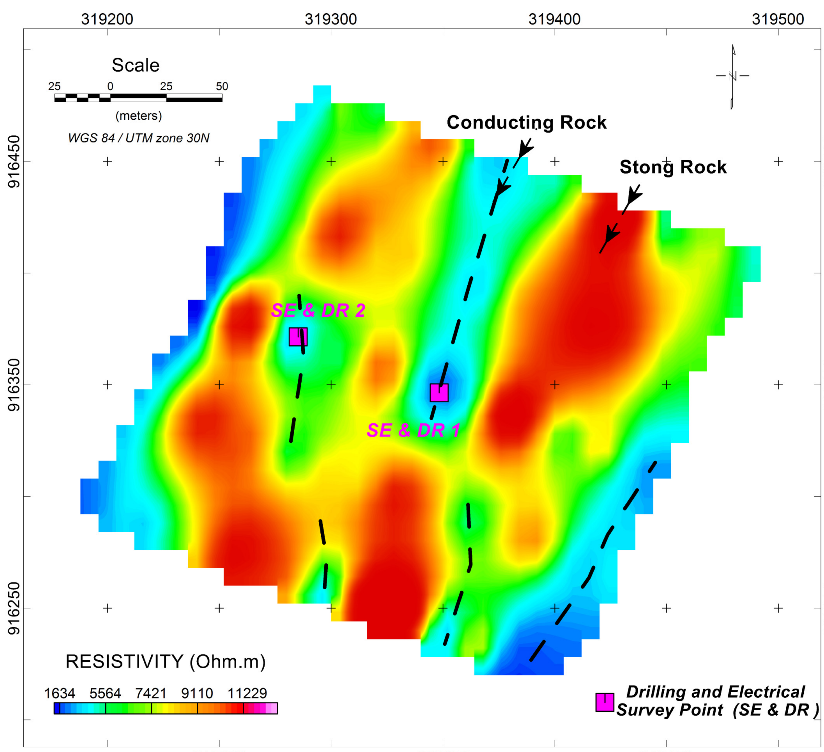
4.1. Electrical Resistivity Profiling

The electrical resistivity profiling results are presented in the form of an interpreted apparent resistivity map for the three prospects. These maps highlight resistive and conductive structures that are predominantly oriented NE-SW (**Figure 4**).

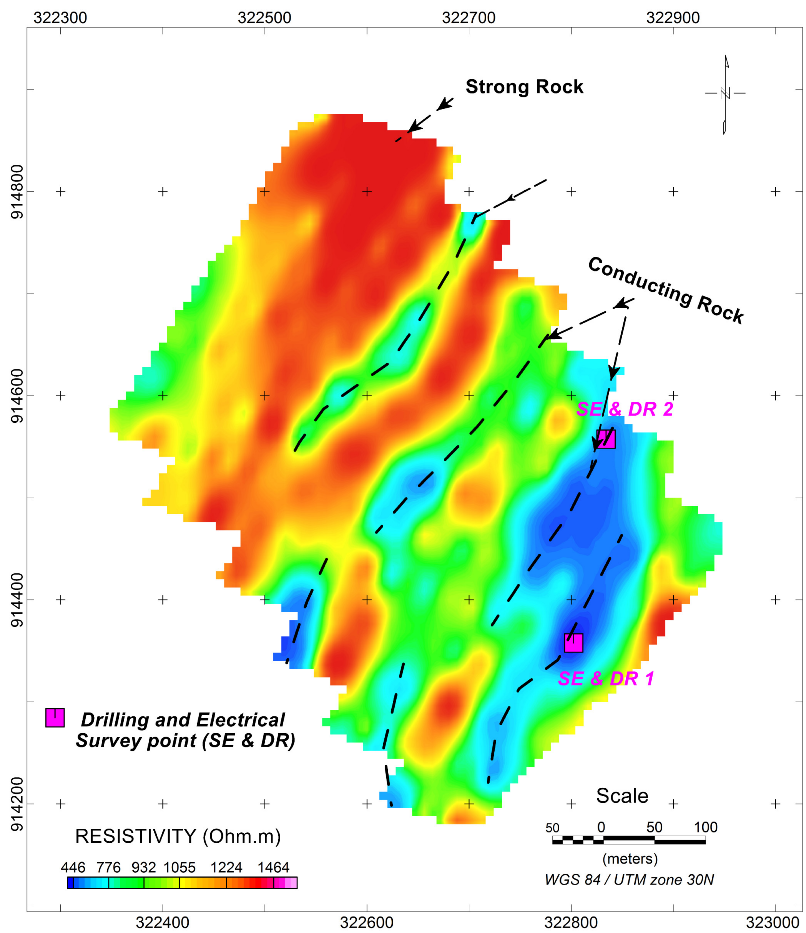
Analysis of these maps reveals two domains of resistivity. Firstly, a domain of high resistivity which occupies the middle part of prospects 1 and 2 and the western part of prospect 3. It is more developed northward than southward and is associated with the signature of quartzo-feldspathic rocks. The southern part


318800
319000
319200
319400
915800
915600
915400
915200
Conducting Rock
SE & DR 2
Strong Rock
Scale
50 0 50 100
(meters)
WGS 84 / UTM zone 30N
SE & DR 1
Drilling and Electrical Survey Point (SE & DR)
RESISTIVITY (Ohm.m)
643 1666 2131 2482 2813 3196 3758

(a)


319200
319300
319400
319500
319250
319350
319450
916450
916350
916250
Scale
25 0 25 50
(meters)
WGS 84 / UTM zone 30N
Conducting Rock
Stong Rock
SE & DR 2
SE & DR 1
RESISTIVITY (Ohm.m)
1634 5564 7421 9110 11229
Drilling and Electrical Survey Point (SE & DR)

(b)



(c)

Figure 4. Interpreted apparent resistivity map of the explored prospects. (a) Prospect 1; (b) Prospect 2; and (c) Prospect 3.

of this domain also shows two structures with relatively low (**Figure 4(a)**) to medium (**Figure 4(c)**) resistivity. On prospect 2, it is characterised by a relatively low resistivity structure in the northwest (**Figure 4(b)**). The second domain is characterised by conductive corridors that occupy the western, eastern and central edges of prospects 1 and 2. On prospect 3, three conductive corridors stand out. Two axes occupy the central part while the other is located in the eastern part (**Figure 4(c)**). The latter is more spread out and develops from north to south. These conductive zones correspond to the signatures of fractures with significant hydrogeological potential and/or to rocks relatively rich in ferromagnesian elements (basic rocks). They mainly follow a NW-SE direction.

Distortions are observed on the axes of the resistant and conductive structures (**Figure 4**). They reflect the effect of secondary fractures which are oriented NW-SE and also affect the crystalline basement. Other fractures are superimposed on the geological contacts (Conductor-Resistant) and would probably be less potential. Some authors such as Engalenc et al. (1979) and Savane (1997) have shown in their previous works that fractures parallel to the direction of compressive stresses are open, while those orthogonal to it are closed. They argue that the tectonic phenomena of the region would have a major impact on the productivity of the structures. For example, NE-SW oriented fractures corresponding to the sinister shear zones (Kouassi et al., 2014) are considered to be deep slots and seem to be promising for groundwater extraction. This argument is reinforced by Kouakou (2012) when he states that the Eburnean trending fractures (N 40˚) are the most productive in the Bandama catchment area which encompasses the study area. The above arguments argue that the NW-SE oriented fractures are perpendicular to the NE-SW oriented stress and would therefore be closed and unpromising.

However, according to Loukou (2017), even if the existence of a conductive anomaly seems to be a relevant argument to evoke the presence of water, it is far from being the ultimate proof. Another criterion is then essential, namely the vertical electrical sounding curve. Thus, six (6) electrical boreholes (SE) were installed in line with these fractures in order to discriminate between the fracture aquifers (presence of water) and the lithological contacts.

4.2. Vertical Electrical Sounding

The results of the vertical electrical soundings are presented in the form of an inverted resistivity curve and log (**Figures 5-7**). They show the cross-sectional evolution of the different lithologies associated with the variations of resistivity and thus allow an estimate of the number of geoelectric layers, their thickness and the strength of the potential aquifers located within the crystallophyllian rocks.

Two electrical soundings were executed on prospect 1 (**Figure 5**). Their curves are dominated by a rising and irregular branch which indicates the presence of structures with variable resistivity. The analysis of these logs allowed the identification of two geoelectric layers. The first layer is superficial, conductive and approximately 18 meters thick. The second layer has high resistivity and is located under layer 1 (**Figure 5**). Conductive complexes are interspersed within these layers, of which four (04) are identified at sounding SE 1 (**Figure 5(a)**-SE 1) and two (02) at SE 2 (**Figure 5(b)**-SE 2). Among these, only the conductors located around 160 m depth are more developed and promising (**Figure 5**).

At prospect 2, the curves show an upward and highly variable trend, which reflects a deformed crystalline basement. Two geoelectric layers are also highlighted (**Figure 6**). Layer 1 is superficial, not very conductive and has a thickness of about 10 m. The second layer has a fairly high resistivity and underlies layer 1 (**Figure 6**). It is very heterogeneous, as shown by the intercalation of conductive complexes. At sounding SE 1, three (03) conductive complexes are intercepted at 45, 65 and 110 m depth (**Figure 6(a)**-SE 1). For SE 2, a conductive materiel located at around 100 m is highlighted (**Figure 6(b)**-SE 2).

The curves of prospect 3 show a rising and irregular branch (**Figure 7**). In a similar way, two geoelectric layers are highlighted. The first is fairly conductive,

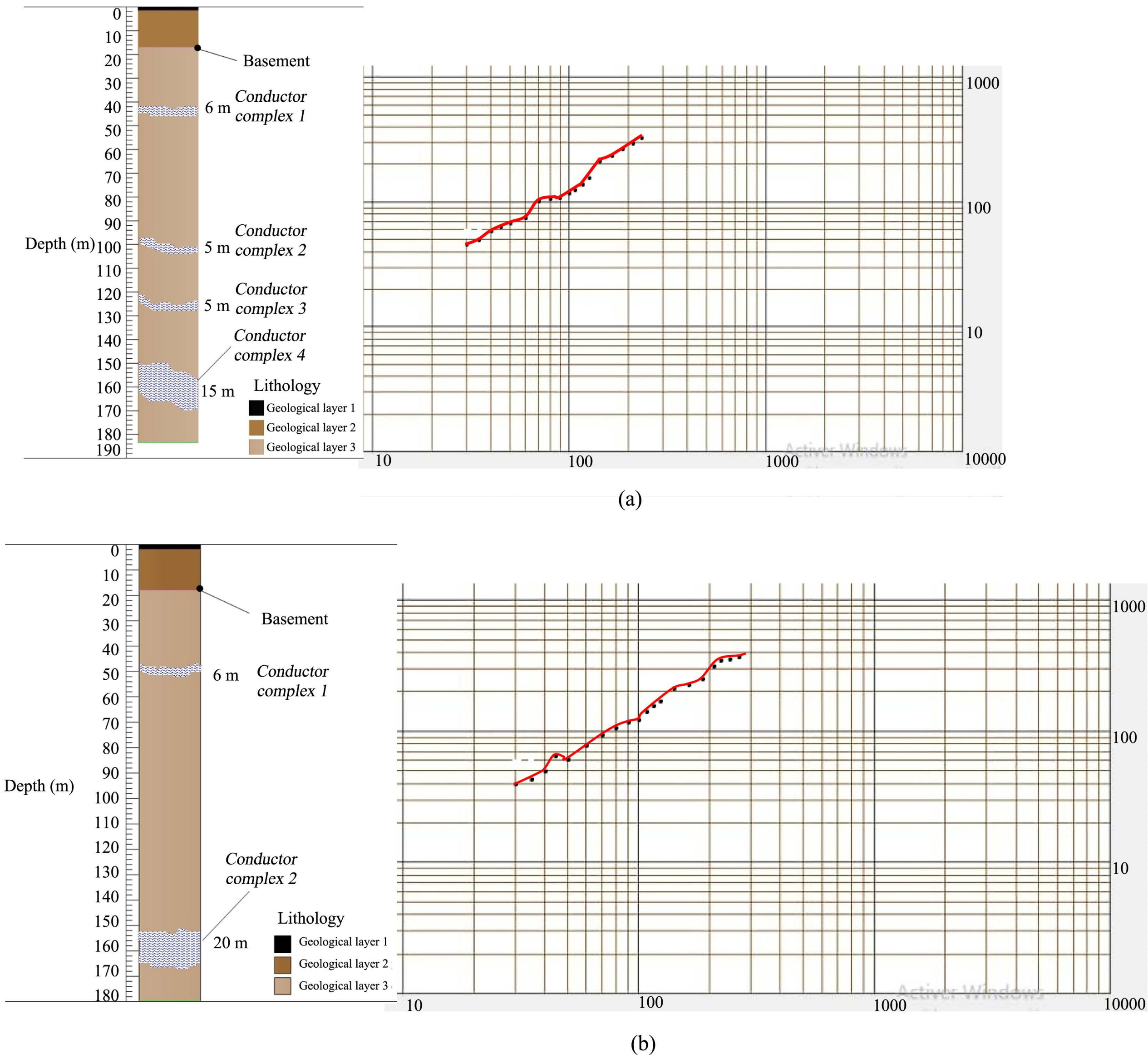
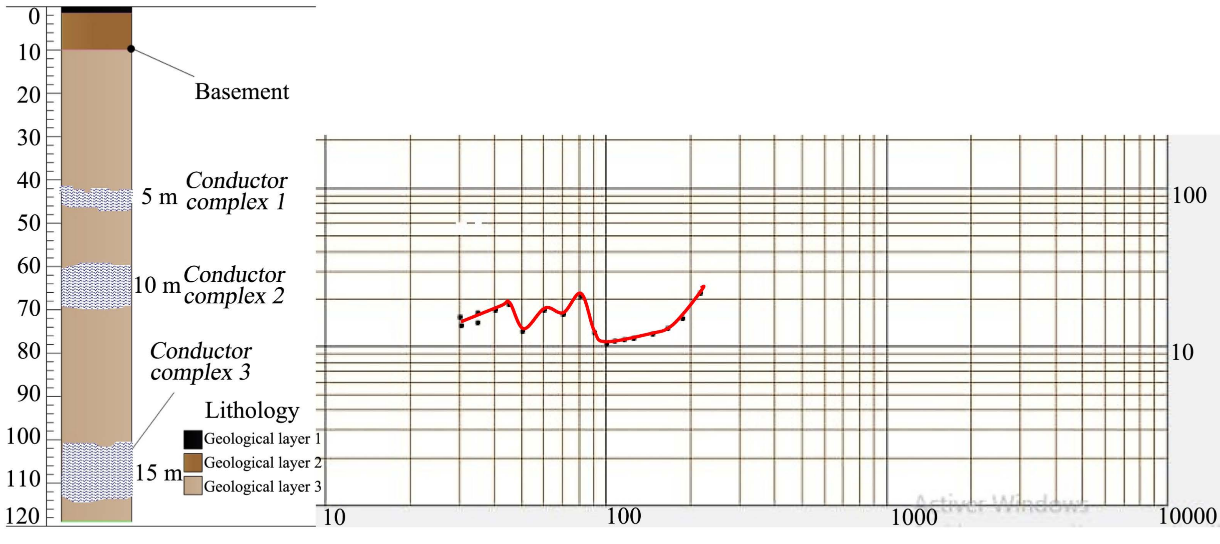


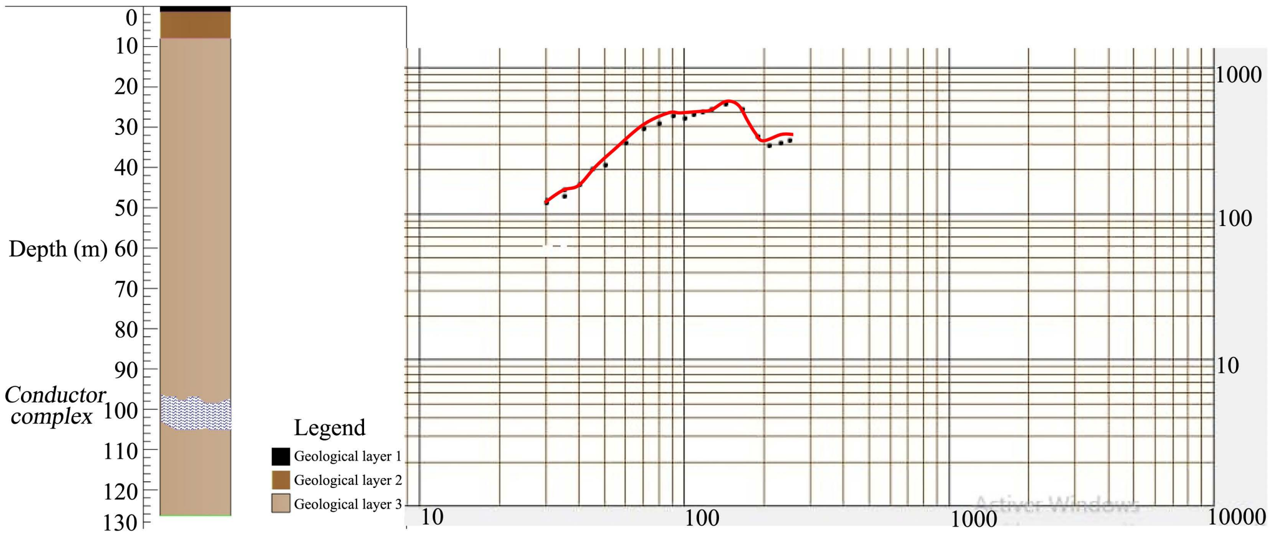
Figure 5. Electrical sounding curves and logs of Prospect 1. (a) SE 1; (b) SE 2.

superficial and has an average thickness of 18 m. The second layer has high resistivity and develops beyond layer 1 (**Figure 7**). Its structure is not very homogeneous and is characterised by the intercalation of conductive materials, among which two are identified at sounding SE 1, at 100 and 125 m (**Figure 7(a)**-SE 1). As for the sounding SE 2, layer 2 highlights three conductive elements which are located at 60, 100 and 175 m depth (**Figure 7(b)**-SE 2).

Overall, the vertical electrical soundings carried out in south of Bonieredougou show irregular rising "single branch" curves. They confirmed the conductive zones previously detected with the electrical profiling. Indeed, according to Kouakou et al. (2015), vertical electrical sounding can show evidence of fracturing which is reflected by a trailing rise or a change in inflection on the rising branch. However, the vertical electrical sounding curves obtained at the studied



(a)



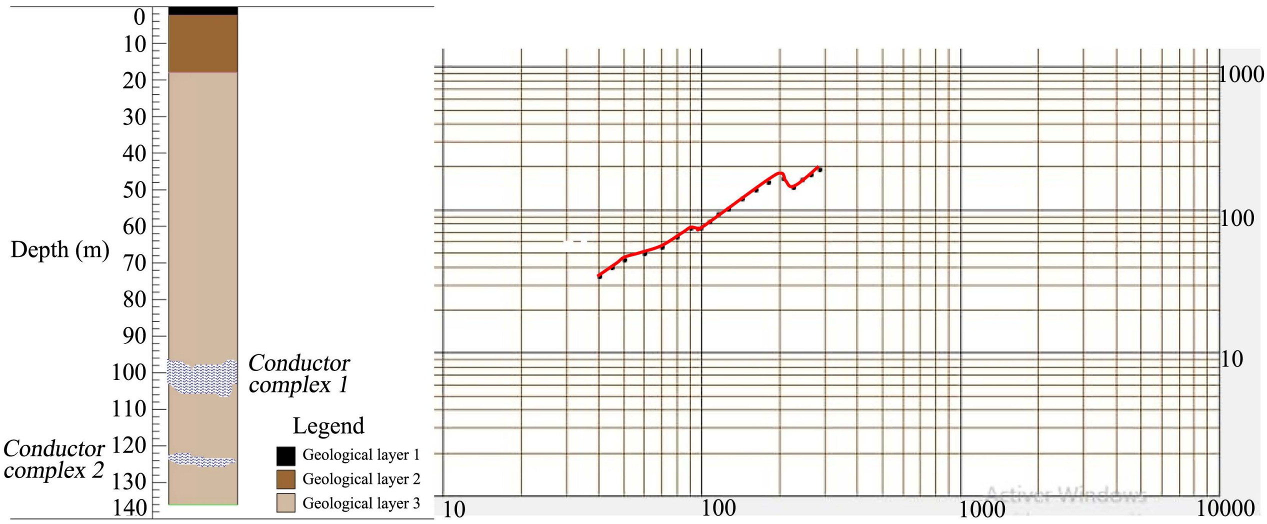
(b)

Figure 6. Electrical sounding curves and logs of Prospect 2. (a) SE 1; (b) SE 2.

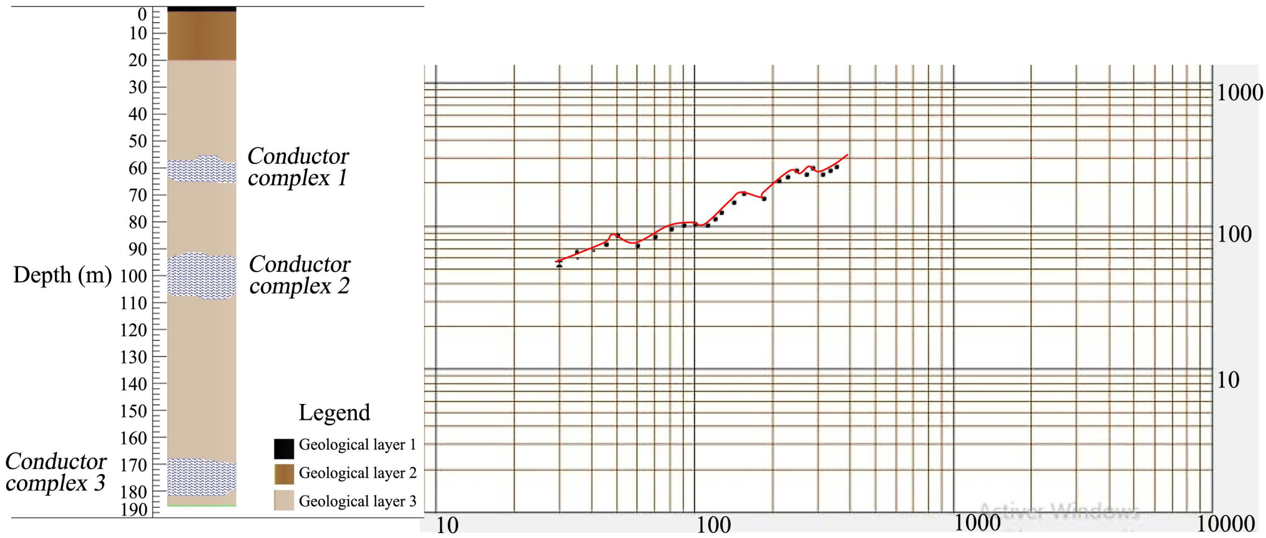
sites mostly exhibit these characteristics. The "single branch" curves showed a succession of two (2) geological layers composed of a superficial cover followed by an alteration horizon (sandy-clay layer) and finally an altered/fractured basement. These results corroborate those of Sombo (2012) who describes a succession of two layers with the curves with a "single branch" rising.

Based on the six (6) vertical electrical soundings, the average thickness of the alteration is around 10 m. In contrast, the work of Kouakou (2012) in the region set the average thickness of the alteration at 23 m.

From the above analyses and interpretations, it appears that the crystalline basement of the prospect contains numerous conductive structures whose lithological nature will be determined with the hydraulic drilling logs.



(a)



(b)

Figure 7. Electrical sounding curves and logs of Prospect 3. (a) SE 1; (b) SE 2.

4.3. Geo-Electrical and Drilling Logs Correlation

The analysis of the electrical diagrams and the hydraulic drilling logs makes it possible to establish correlations between the geo-electric layers and the associated lithologies (**Figure 8**).

At prospect 1, the drilling logs confirm the effective presence of three (03) lithological units composed mainly of alterite, gabbro and granodiorite (**Figure 8(a)** and **Figure 8(b)**). Within these formations, five (05) fractured aquifers were identified for SE 1 (**Figure 8(a)**) and three (03) for SE 2 (**Figure 8(b)**). The first aquifers are located in gabbro and are very close together; this is reflected on the drilling curves by a single conductive complex. The other conductive materials, which are mainly associated with granodiorite, were clearly highlighted by the

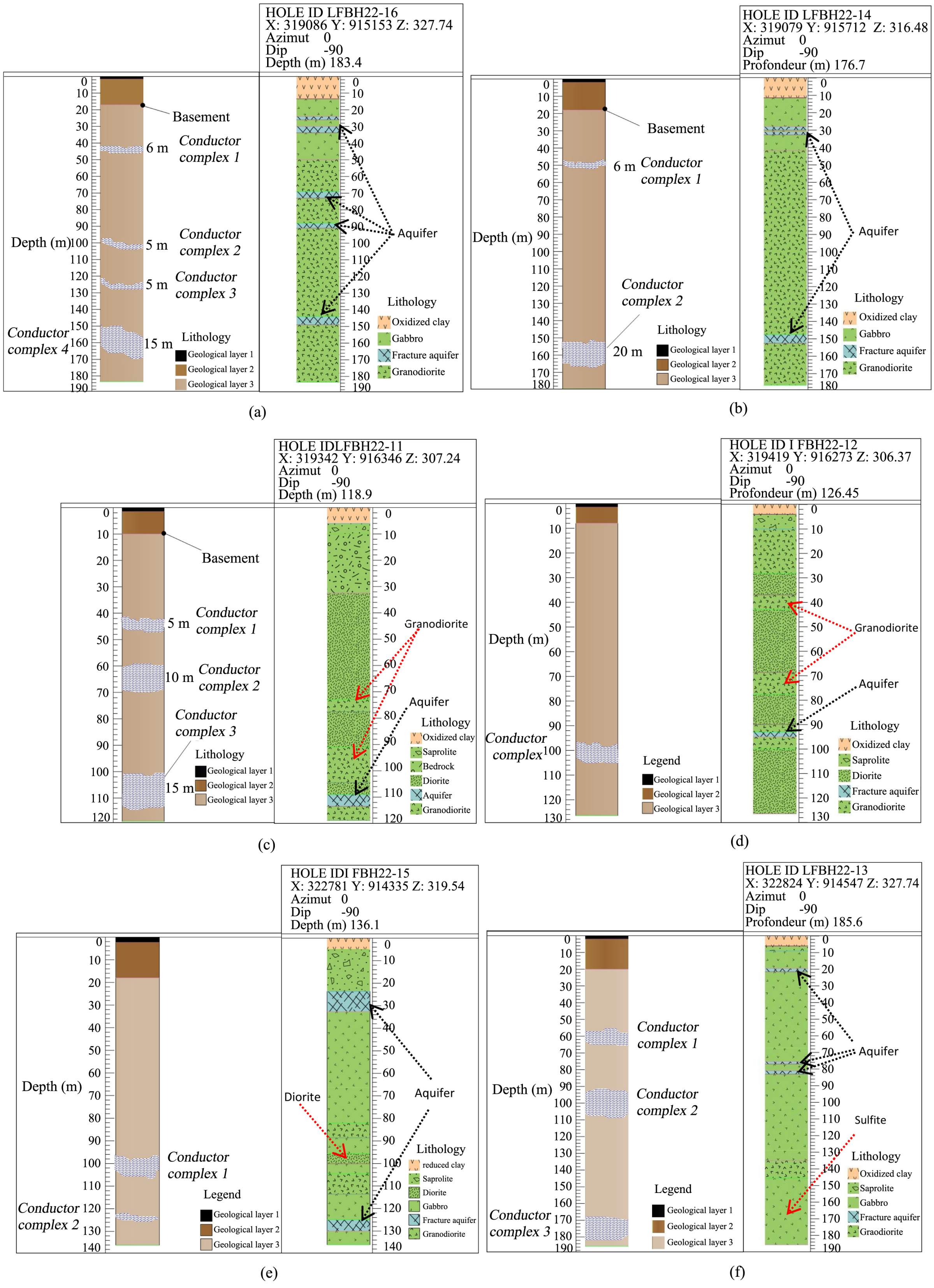


Figure 8. Correlation electrical sounding and hydraulic drilling logs. (a) Survey-Drilling 1; (b) Survey-Drilling 2; (c) Survey-Drilling 1; (d) Survey-Drilling 2; (e) Survey-Drilling 1; (f) Survey-Drilling 2.

sounding curves. The geological logs of the first site indicate that the best aquifers are located at a depth of 150 m. They also indicate that the basement is located at 13 m for SE 1 and 11 m for SE 2 whereas the sounding logs indicated 17 m for SE 1 and 18 m for SE 2 (**Figure 8(a)** and **Figure 8(b)**).

The geological sections of Site 2 show mainly four (04) lithologies composed of granodiorite and diorite overlaid by saprolite and sandy clay (**Figure 8(c)** and **Figure 8(d)**). In hydrogeological context, a single fractured aquifer has been identified in the granodiorite. It is associated with the conductive complex 3 detected on SE 1 at a depth of 100 to 115 m, and the single conductive element at sounding SE 2 which is located at 100 m (**Figure 8(c)** and **Figure 8(d)**). Also, the geological logs indicate that the crystalline basement is located at 7 m for SE 1 and 4 meters for SE 2 while the electrical borehole logs indicate approximately 10 m for SE 1 and 9 m depth for SE 2.

The third site logs indicate two conductive materials for SE 1 and three for SE 2. However, only the second conductive complex of each electrical sounding is associated with a fractured aquifer, the others correspond to the electrical signatures of diorite (Conductor 1 of SE 1) and sulphide gabbro respectively (Conductors 1 & 3 of SE 2). Thus, the two identified aquifers are carried by the gabbro and are located at 128 m for SE 1 and 76 m for SE 2 (**Figure 8(e)** and **Figure 8(f)**). The thickness of the alteration layer is 28 m for SE 1 and 8 m for SE 2, while the electrical soundings indicate 10 m for SE 1 and 9 m for SE 2.

Overall, the electrical sounding curves for prospect 2 show strong disturbance which is reflected in the high variation on the rising branches. The sounding curves of SE 1 (Site 1) and SE 2 (Site 3) are less irregular compared to those of Site 2. Also, the other curves (SE 2 Site 1 and SE 1 Site 3) are less disturbed than the others. Authors such as Weng et al. (2004), Dewandel et al. (2006) and Kouassi et al. (2014) have linked the intensity of basement fracturing with the disturbances observed on the rising trend of the electrical sounding. Thus, according to these authors, a deeply fractured crystalline basement could develop significant hydrogeological potential. Their results are corroborated by the pumping tests carried out during this study. Indeed, the boreholes at Site 2 yielded 96 m^3/h for SE 1 and 116 m^3/h for SE 2. At Site 1, boreholes at SE 1 and SE 2 gave 12 m^3/h and 4 m^3/h respectively. At site 3, the flow rates are 4 m^3/h for SE 1 and 12 m^3/h for SE 2. The large flow rates obtained at site 2 corroborate the presence of open fractures resulting from the effects of tangential stresses of the Fetekro-Dabakala shear mentioned by authors such as Yacé (1976), Lemoine (1985) and Savane (1997). Also, the depths of the different aquifers are generally less than 10 m except for SE 1 at sites 1 and 2.

It is therefore important to note that the large flows are not related to the geometric characteristics of the fractured aquifers but rather to the summation effect of the conjugated fractures.

Furthermore, the conductive complexes detected are well superimposed on the fractured aquifers or intercalated diorite lenses revealed by the drilling logs. However, some hydrogeological fractures have no obvious signal on the geo-electrical logs; this could be explained by the thinness of the opening of these fractures.

5. Conclusion

The electrical surveys conducted in the Bonieredougou area revealed conductive and high resistivity structures within the Paleoproterozoic basement. The examination of the contrasts allowed the identification of two types of conductive complex that follow the NE-SW direction. Hydraulic test drilling revealed that these conductive materials are associated with fractured aquifers and diorite lenses. These aquifers have operating flow rates of 116 m^3/h, 96 m^3/h and 12 m^3/h within the granodiorite and 4 m^3/h within the diorite. Overall, they have a strength of around 10 m and are located at around 100 m depth. They are thought to have arisen from open fractures created under the effect of the shear stresses that affected the formations of the Dabakala volcano-sedimentary trench. The search for fractured aquifers in the main shear direction offers great prospects for obtaining high flow rates. This approach, based on the study of resistivity contrasts within the shear-affected basement, could be exported to other African contexts to ensure the success of hydraulic projects.

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Conflicts of Interest

All authors have read and agreed to submit this work to a scientific publication journal. The authors declare no conflicts of interest.

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