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Hydrogeophysical Characterization of a Fractured Aquifer by Using Cumulative Resistivity Method: Case Study of Obuasi Aquifer (Ghana)

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Abstract: Knowledge of the structure and geometry of aquifers is an important prerequisite when one wishes to sit a borehole. Such knowledge is currently obtained by VES (Vertical Electrical Soundings) whose interpretation is not always unequivocal in the sense that several resistivity models derived from VES can explain the same data set. The present study conducted in Obuasi region in Ghana aims at demonstrating the robustness of "cumulative resistivity" method in the characterization of the geometry of aquifers. The methodology developed consisted firstly in carrying out VES. These measurements were then interpreted using "cumulative resistivity method". Secondly, drillings are conducted at the VES sites and lithologs established from cuttings were compared to the results from VES interpretation. The study reveals that the investigated aquifer consists of a resistant layer consisting of phyllite over 30-40 m topped by a conductive layer of reddish clay 20-30 m thick. These two layers rest on a lower electrical conductivity formation downward. This description can be considered as a typical alteration profile in a volcano sedimentary context. The results also show that the method is quite precise in half of the cases studied but sometimes it is impossible to get rid of the phenomenon of suppression since several layers are merged into a single layer.

Key words: Aquifer, cumulative resistivity, drilling, alteration.

1. Introduction

When the hydrogeologist wants to mobilize groundwater from a hardrock aquifer, he has to think about several concerns. These include: What is the thickness of permeable zones? What is the quality of the reservoir (clayey)? Is there a clayey cover? [1]. These questions relating to the structure and geometry of reservoirs are commonly solved through the use of hydrogeophysical tools. Non-invasive, these methods provide an alternative or complement to direct observations [2]. Among these methods, one can notice the electrical methods which are based on the variation of a physical quantity: electrical resistivity. Electrical methods include electrical profiling, VES (Vertical Electrical Sounding) and electrical resistivity tomography. Since 1990, electrical resistivity tomography has been widely used because it makes it possible to obtain, two-dimensional subsurface imaging, and to obtain an optimized resolution of the lateral variations of resistivities that better account for the discontinuous geometries of hard rock aquifers [3]. Nevertheless, along with electrical profiles, VESs remain the most widespread electrical methods [4]. Indeed, these methods which make it possible to assess in one-dimension vertical variations of the electrical properties of the subsoil present a certain ease of implementation compared to the case of

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electric resistivity tomography. With regard to the interpretation of electrical soundings, a data inversion procedure allows proposing a geoelectrical model of the underlying terrain. The inherent problems of inversion procedure are principles of equivalence and suppression which can lead to different models for the same data set [5, 6]. In a paper relative to "an introduction to electrical resistivity in geophysics", Herman [7] described a so-called "cumulative resistivity" method which permits to identify unequivocally subsurface layers boundaries and to propose a stratified model of the investigated terrain. To our knowledge, very few studies have compared the results of this method with the results from drilling logs in the field of hydrogeology. However, application of this method may allow for distinguishing even very thin layers if there is significant contrast of physical properties at their boundary [8]. The work therefore aims mainly at testing "cumulative resistivity" method through a hydrogeophysical study conducted in Obuasi region in Ghana. Moreover, the study area located in a geological context of volcano-sedimentary rocks may prove difficult for drilling. The study also aims at having a better knowledge of weathering profile of the aquifers which conditions the productivity of the boreholes.

2. Study Site

2.1 Geographical and Climatic Context

The study site is Obuasi located in the South-Western part of the Ashanti Region 64 km from Kumasi (Fig. 1), the regional capital. Obuasi is located by its geographical coordinates which are 6.21° latitude and -1.66° longitude and by its elevation of 233 m above sea level with a rather undulated topography.

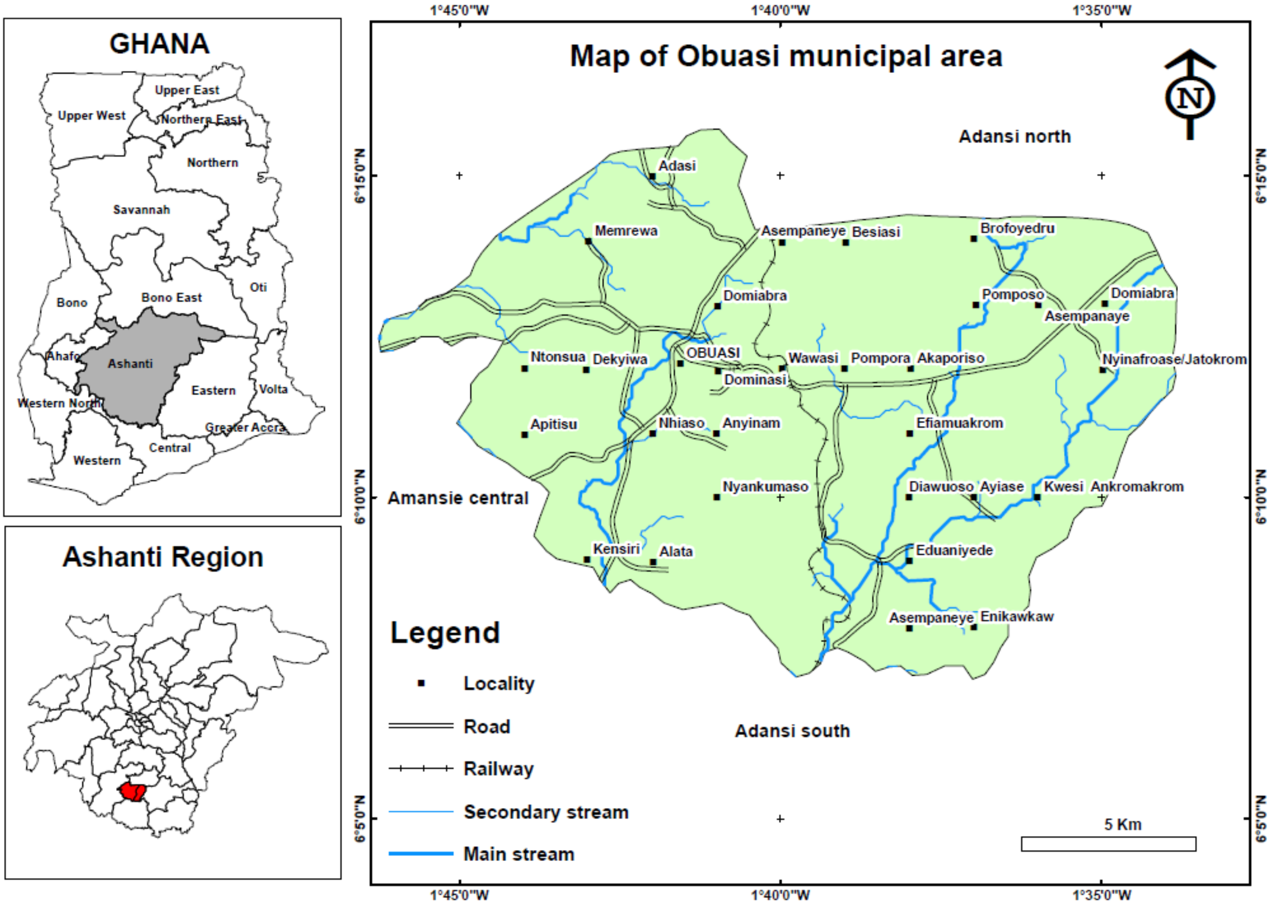

Fig. 1 Localization of the study area.

The climate is of Obuasi is of semi equatorial type with a double rainfall regime. Mean annual rainfall ranges from 1,250 mm and 1,750 mm. Mean average annual temperature is 25.5 °C and relative humidity is around 75% to 80% in the wet season. Summers in Obuasi are wet, while the winters months tend to be dry. Obuasi's yearly precipitation averages 1,450 mm. The wettest month (with the highest rainfall) is June (229 mm) and driest months (with the lowest rainfall) are January, February and August (25 mm).

2.2 Geological Context

Rocks in Obuasi are mostly of Tarkwain (Pre-cambrian) and Upper Birimian rocks which are noted for their rich mineral bearing potentials. Areas around Birimian and Tarkwain zones known as reefs are noted for gold deposits [9]. The general geology of the study area is generally made up of the Birimian supergroup with phyllite (argilitic, peletic sediment) as its dominant rock type. The main factors controlling the occurrence of groundwater in the area are the presence of secondary geological structures. The rocks are highly weathered to a depth of about 40 m. Generally, groundwater potential in this rocks type is fair and could further be enhanced when the rocks are intruded by quartz-veins. In the Precambrian rock terrain, such as occurring in the Obuasi area, groundwater is usually transmitted within joints and fractures that occur in the decomposed rock and stored in the saturated weathered zone. Fig. 2 shows the geological map of Obuasi. It shows that the area is composed by 60% of phyllite, schist, tuff and greywacke; 20% of quartzite, phyllite, grit, conglomerate, schist including basic intrusive; 15% of metamorphosed lava, pyroclastic rock, hypabyssal basic intrusive, phyllite and greywacke and 5% of granitoid undifferentiated.

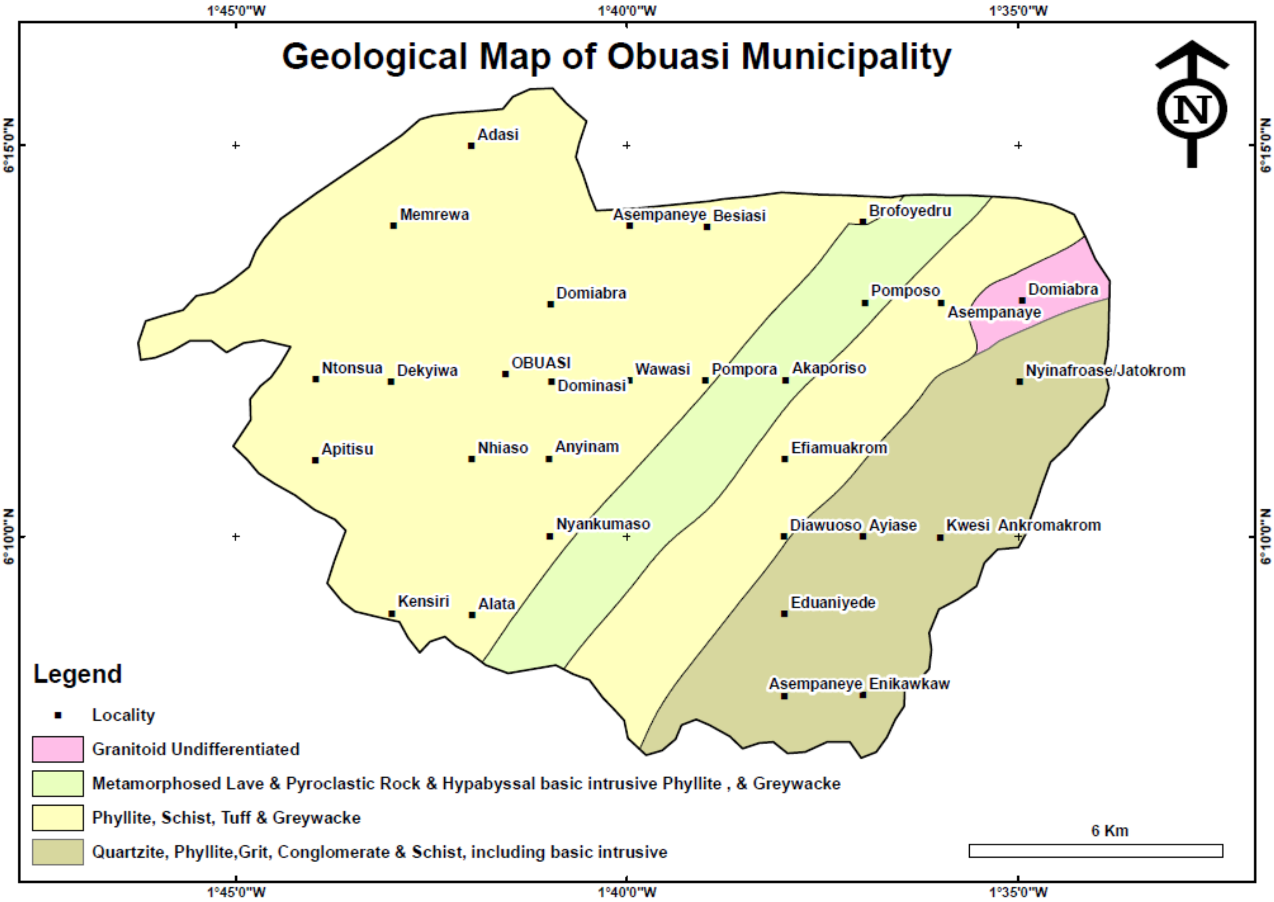

Fig. 2 Geological map of Obuasi.

3. Material and Methods

3.1 Geophysical Investigations

Six VESs were carried out at Mensahkrom, Adaasi, Abamu, Zongo, Abompekrom, Bogobiri using dipole-dipole array. All the sites investigated are located in a geological context made of phyllite subtratum (Fig. 3).

Dipole-dipole configuration is still widely used in resistivity surveys because of the low electromagnetic coupling between the current and potential circuits and because of its ability to probe deeper [10]. In the dipole-dipole array, the distance between the current electrodes and the distance between the potential electrodes (a) are smaller than the center (na) of the two dipoles (Fig. 4).

During the survey, the spacing "a" is kept constant from the initial while the spacing "na" is changed along the line. The spacing "n" is increased from three, four, five up to six in order to maximize the depth of investigation [11]. The depth of investigation is half of the distance between the dipoles. Table 1 presents the sequence of measurements used in this study.

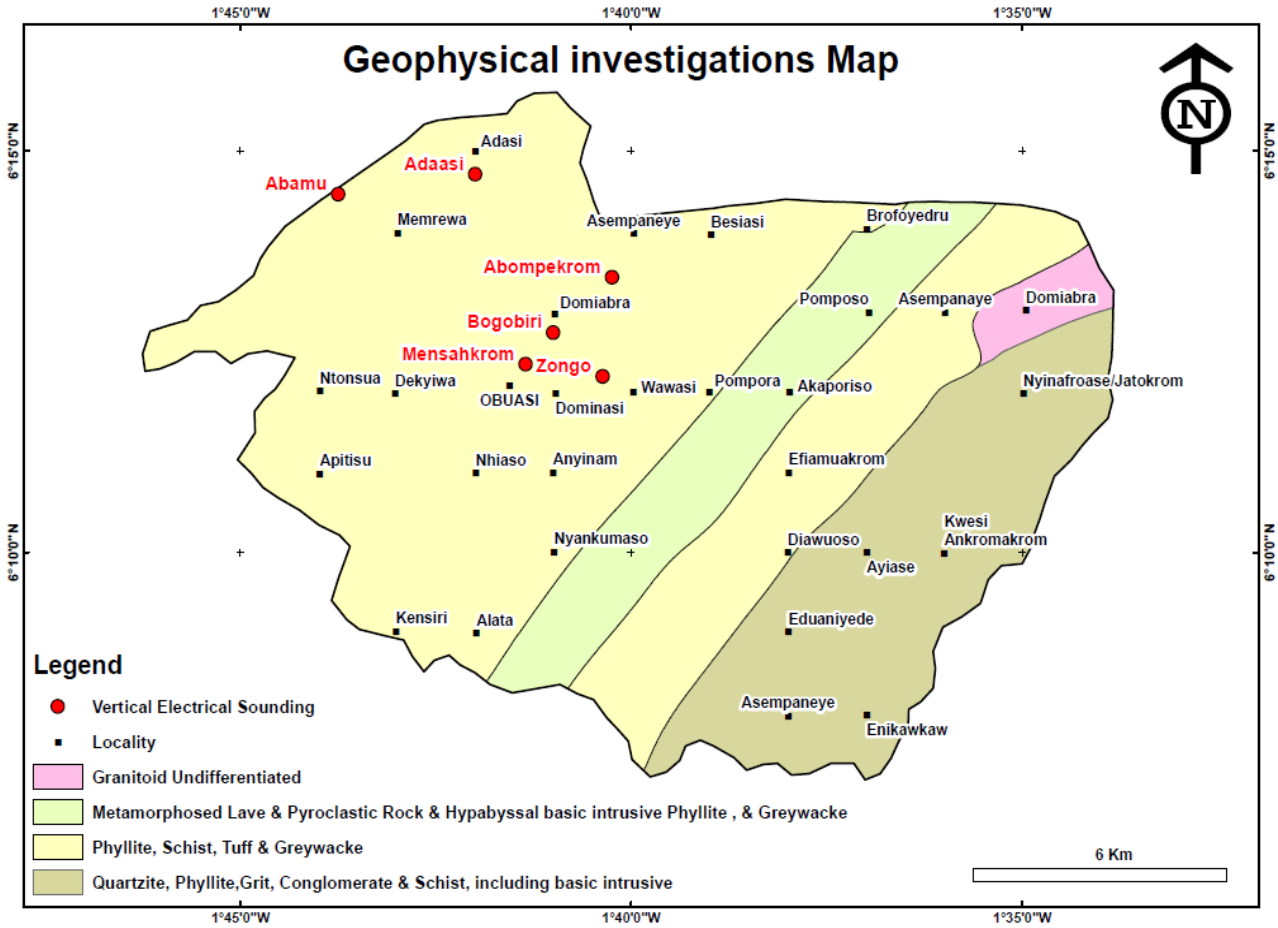

Fig. 3 Localization of VESs.

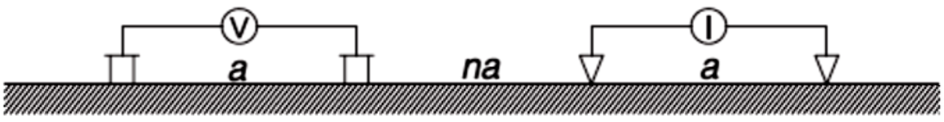

Fig. 4 Electrodes array in dipole-dipole configuration.

Table 1 The measurement sequences.

"a" separation	4	4	4	10	10	10	10	10	10	20	20
"n" separation	3	5	7	3	4	5	6	7	8	4	5
Depth z (m)	8	12	16	20	25	30	35	40	45	50	60

The measurements were conducted with a ABEM Terrameter LS geophysical instrument which provides apparent resistivities of the subsurface layers.

Apparent resistivity ρ is calculated by applying the following formula (Eqs. (1) and (2)).

$$\rho = K\frac{\Delta V}{I} \tag{1}$$

With K the geometric factor which for dipole-dipole array is obtained as follow:

$$K = \pi \cdot a \cdot n \cdot (n+1) \cdot (n+2) \tag{2}$$

ΔV is the potential difference measured between potential electrodes;

I is the current intensity between current electrodes.

3.2 Application of the "Cumulative Resistivity Method" to Determine Boundaries between Layers

Electrical resistivity measurements were used for determination of the depth of the boundaries between layers characterized by different physical properties. To do so the "cumulative resistivity method" described by Herman [7] was chosen. In this method, the sum of apparent resistivities $\Sigma\rho_{\text{app}}$ (referred as cumulative resistivity), versus the effective depth z is plotted. The set of points plotted is determined by Eq. (3):

$$\{(z, \Sigma\rho app)\} = \{(z_1, \rho_1), (z_2, \rho_1 + \rho_2), (z_3, \rho_1 + \rho_2 + \rho_3), \ldots, (z_n, \rho_1 + \cdots + \rho_n)\} \tag{3}$$

with couples of measured apparent resistivities and depths.

Such a plot has often different linear parts; changes of slopes of theses linear parts correspond to a boundary between two layers. Taking for example Fig. 4 from Hermann [7], there are two distinct linear sections to the curve. The first section represents the summation of the constant values of the resistivity of the upper layer. This yields a line of constant upward slope. The curve then deviates from this initial linear climb as the current encounters proportionally more of the lower layer. Eventually, the resistivity of the lower layer dominates and there is a new, smaller slope for the linear increase in the sum of the resistivities. In order to determine the depth of the boundary, straight lines are drawn along the two linear sections of the curve as shown in Fig. 5. A third straight line is drawn straight down from the intersection of the first two lines.

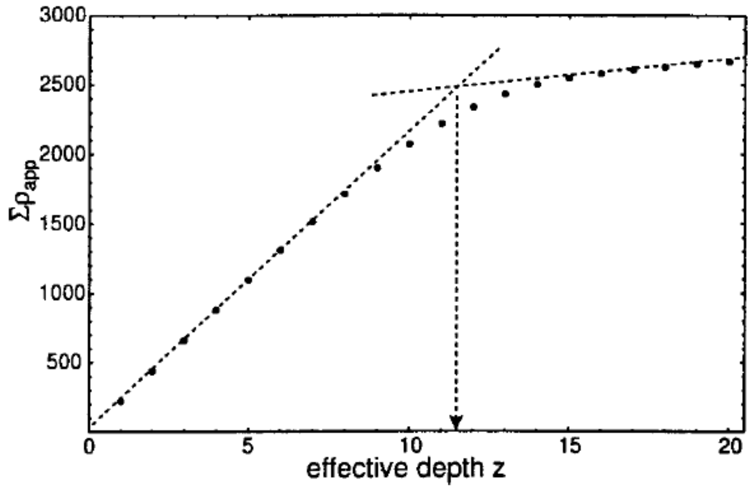

Fig. 5 Finding the depth to the boundary between the layers in a simple two-layer system using the method of cumulative resistivities [7].

3.3 Comparison with Borehole Logs

By applying cumulative resistivity method, the number of subsurface layers and their thicknesses were determined and compared to boreholes lithologs. Boreholes logs come from a drilling campaign carried out after the geophysical investigations. They present the nature of geological layers collected during drilling as well as their thicknesses. An example of borehole log is presented in Fig. 6.

The summary of the boreholes logs is presented in Table 2.

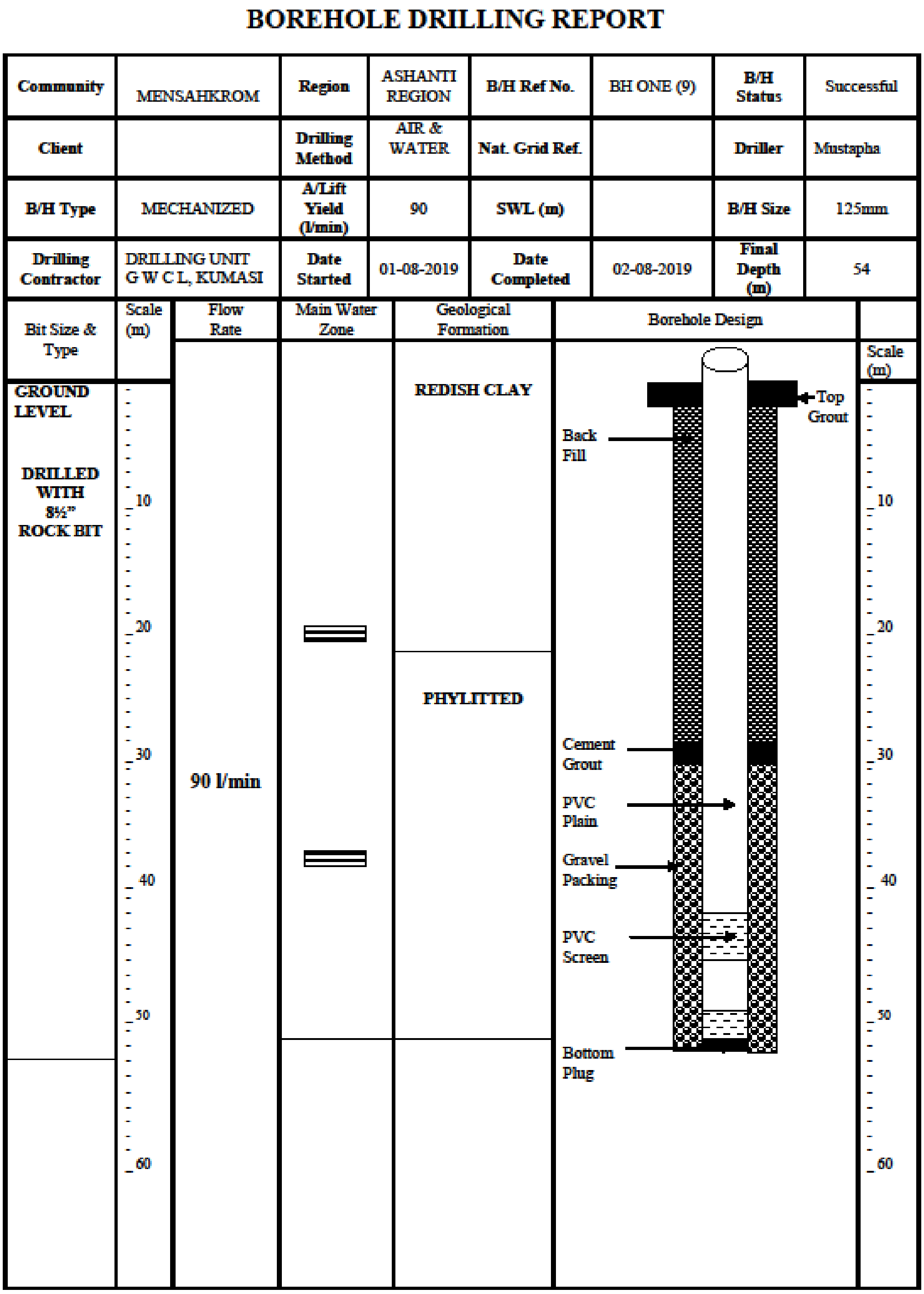

Fig. 6 **Borehole log of Mensahkrom.**

Table 2 Borehole logs information.

Site	Mensahkrom	Abompekrom	Zongo	Bogobiri	Adaasi	Abaamu
Depth (m)	54	30	51	60	42	45
Yield (L/min)	90	198	18	90	135	135
Geological formation	Phyllite	Phyllite	Phyllite	Phyllite	Phyllite	Phyllite

3.4 Data Inversion to Obtain a 1D Resistivity Model

Zond-IP software was used to generate the subsurface 1D resistivity model from field apparent resistivities. The process permits to obtain true resistivities of each homogenous layer of the subsurface.

Data inversion was constrained with layers thicknesses obtained from the "cumulative resistivity method".

4. Results and Discussion

This section presents, for each VES, the interpretation with the cumulative resistivity method, the comparison with the boreholelogs and the 1D resistivity model obtained by data inversion.

4.1 VES 1: Mensahkrom Site

The cumulative curve of VES 1 (Mensahkrom site) consists of three layers with a top layer going up to 20 m, the second layer extends from 20 to 50 m and the third layer from 50 m downward (Fig. 7A). The borehole log which goes from ground surface to 54 m shows one layer made by reddish clay and a second layer made by phyllite.

A comparison between the cumulative curve and the borehole log (Fig. 7B) shows that the boundary between the reddish clay and phyllite is quite well estimated. Indeed, while the cumulative resistivity method indicates 20 m, the borehole logs indicate 21 m.

However, the change of structure noticed from 50 m by the cumulative resistivity method does not appear on the borehole log. This means that the nature of the formation is not the only parameter which influences the cumulative resistivity curve.

VES 1 can be represented by a three-layer resistivity model as shown in Fig. 7C. The resistivity model indicates that the reddish clay layer has a true resistivity of 99.53 Ω·m while the phyllite layer has a resistivity of 234.19 Ω·m. The third layer which is not represented on the borehole log has a resistivity of 2.09 Ω·m meaning that there might be a porous layer downward.

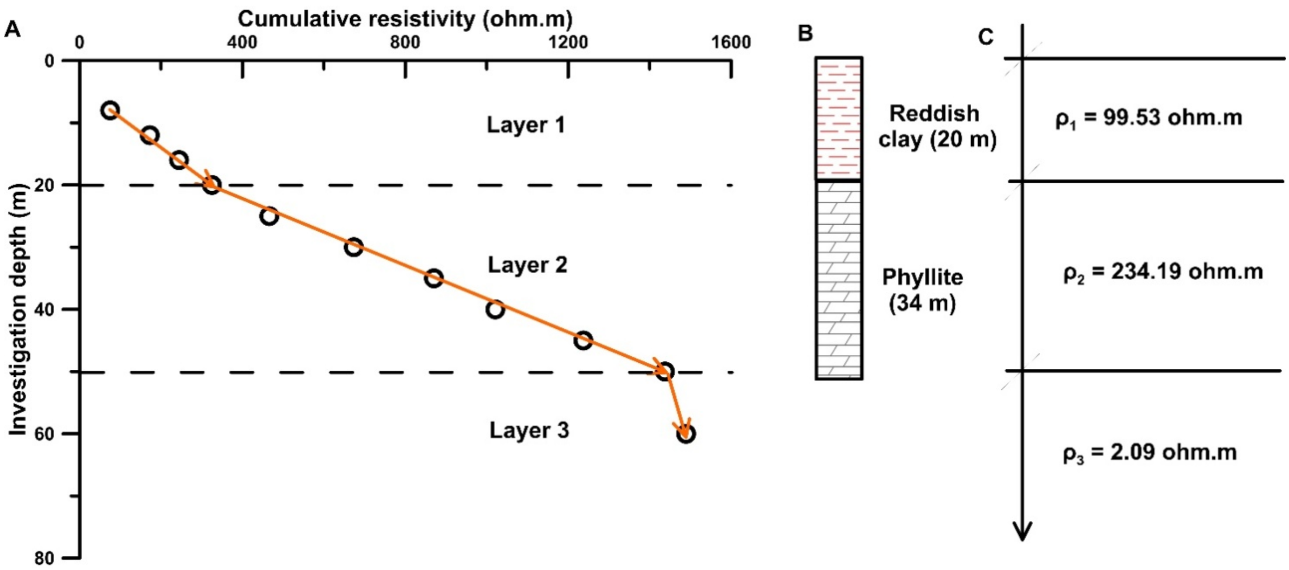

Fig. 7 Interpretation of VES 1. (A) Cumulative resistivity layer; (B) Borehole log; (C) 1D Resistivity model.

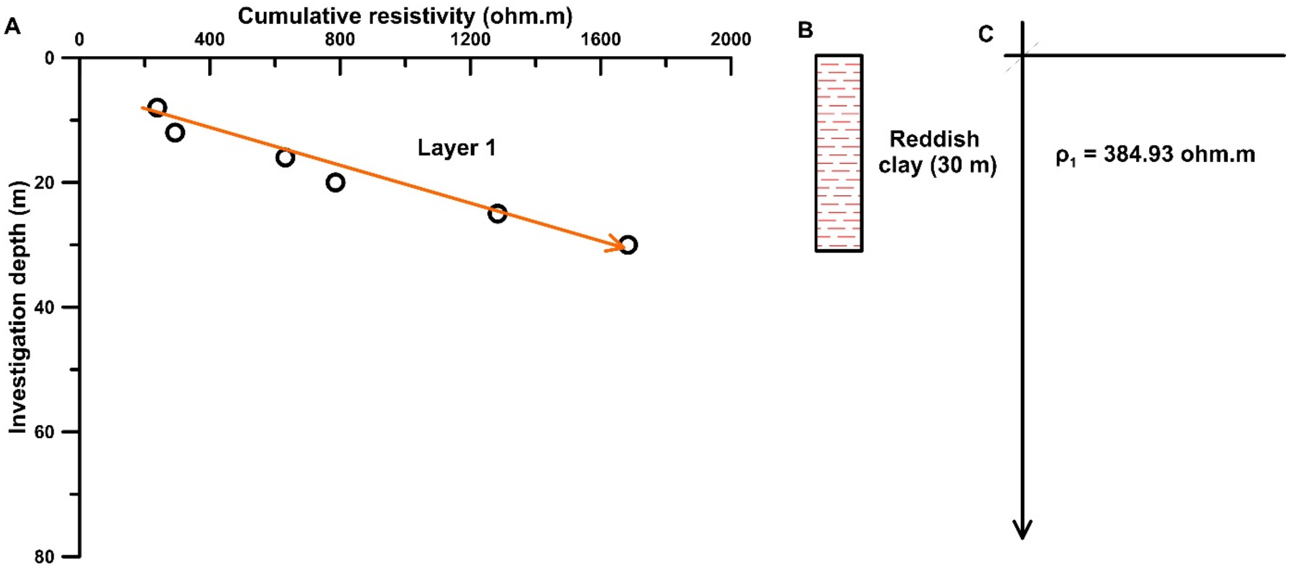

Fig. 8 Interpretation of VES 2. (A) Cumulative resistivity layer; (B) Borehole log; (C) 1D Resistivity model.

4.2 VES 2: Abompekrom Site

The cumulative curve of VES 2 (Abompekrom site) shows a single layer going up 30 m depth (Fig. 8A). The cumulative method is thus in adequation with the borehole log which shows a single layer of reddish clay from the ground surface to 30 m (Fig. 8B).

A one-layer resistivity model has been considered. The resistivity of this reddish clay layer has been calculated as the average of apparent resistivities, which is 384.93 Ω·m (Fig. 8C).

4.3 VES 3: Zongo Site

VES 3 (Zongo site) can be represented as a three-layer model with the top layer going up to 20 m, followed by the second layer from 20 to 50 m. The third layer is from 50 m downward (Fig. 9A). The borehole log (Fig. 9B) confirms the cumulative resistivity result because it shows the presence of 2 layers (reddish clay from 0 to 20 m and phyllite from 20 to 51 m). No much detail can be given on the third layer because of the lack of information given by the borehole log.

The resistivity model indicates (Fig. 9C) that the reddish clay layer has a true resistivity of 103.93 Ω·m while the phyllite layer has a resistivity value of 236.49 Ω·m. The third layer which is not represented on the borehole log has a resistivity value of 1.85 Ω·m meaning that there might be a porous layer downward.

4.4 VES 4: Bogobiri Site

The cumulative curve of VES 4 (Bogobiri site) consists of three layers with a top layer going up to 25 m, followed by the second layer from 25 to 50 m and the third layer beyond 50 m (Fig. 10A). The first layer identified by the cumulative resistivity matches the reddish clay layer although it can be noticed that the limit of the reddish clay is not well identified. Indeed, on the borehole log (Fig. 10B), this limit is located at 18 m rather than 25 m.

The phyllite layer observed on the borehole log is represented by the cumulative resistivity method by the combination of two layers (one from 25 to 50 m and the other from 50 to 60 m). Such a situation can be explained by the fact that the phyllite has different structures, one of them being more altered.

The resistivity model (Fig. 10C) indicates that the top layer has a resistivity of 374.76 Ω·m from the top to 25 m, the second layer has a resistivity of 390.50 Ω·m from to 25 to 50 m and the last layer has resistivity of 295 Ω·m from 50 m downward.

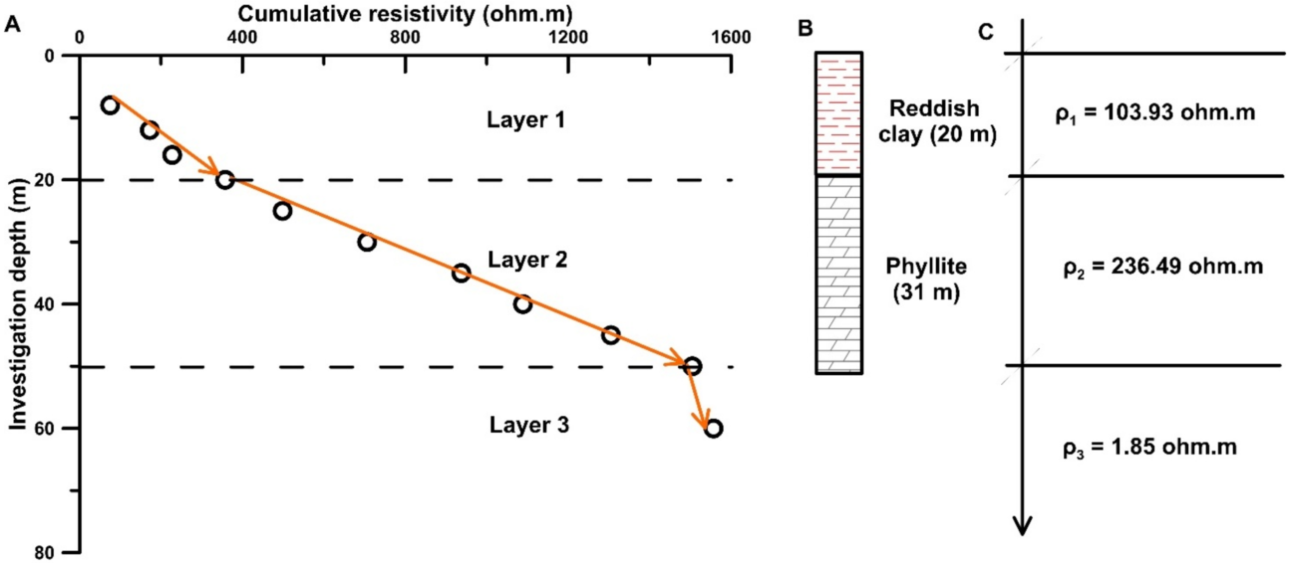

Fig. 9 Interpretation of VES 3. (A) Cumulative resistivity layer; (B) Borehole log; (C) 1D Resistivity model.

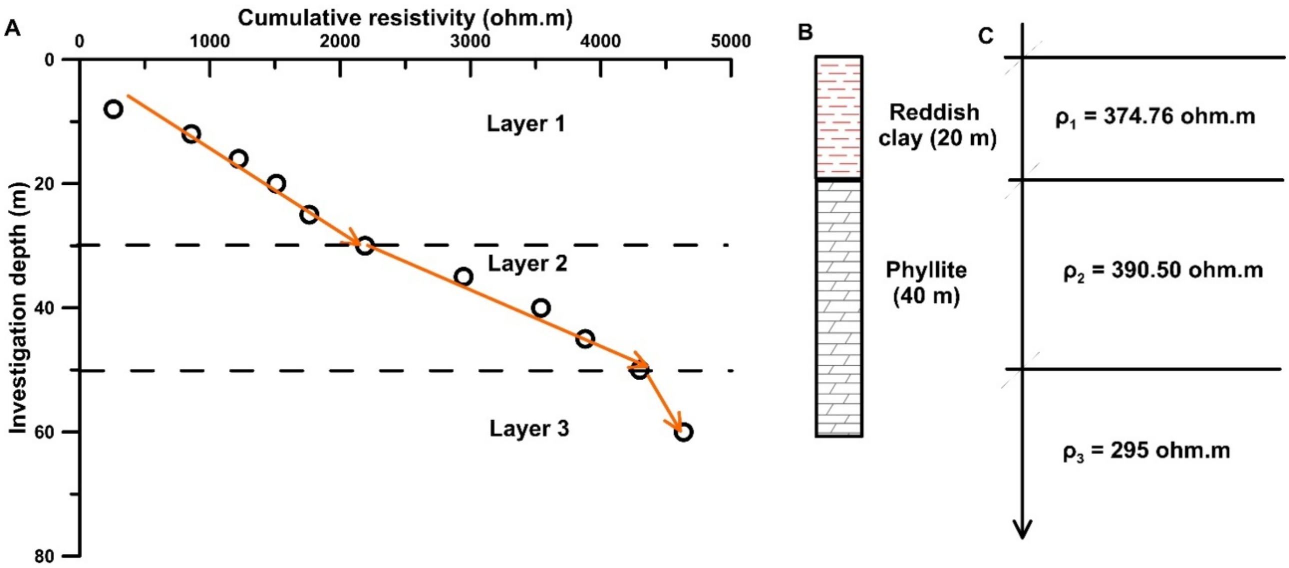

Fig. 10 Interpretation of VES 4. (A) Cumulative resistivity layer; (B) Borehole log; (C) 1D Resistivity model.

4.5 VES 5: Adaasi Site

The case of VES 5 (Adaasi site) shows the situation where the layers of reddish clay (from 0 to 20 m) and phyllite clay (20 to 42 m) (Fig. 11A) are identified by the cumulative resistivity method as a unique layer (Fig 11B). Such a situation corresponds to the phenomenon of suppression. In the present case, it has maybe occurred because the reddish layer and the phyllite layer have similar resistivities. The method therefore does not make it possible to get rid of suppression phenomenon.

The resistivity model (Fig. 11C) indicates that the top layer has a resistivity of 527.87 Ω·m from the top to 40 m, the second layer has a resistivity of 8.93 Ω·m from 25 to 50 m and the last layer has resistivity of 0.96 Ω·m from 50 m downward.

4.6 VES 6: Abaamu Site

The case of VES 6 (Abaamu site) is a confirmation of the precedent case above. The reddish clay layer (from 0 to 22 m) and the phyllite layer (from 22 to 45

m) are identified by the cumulative resistivity method as a unique layer from the ground surface to 60 m (Figs. 12A and 12B).

A one-layer resistivity model has been considered. The resistivity of this reddish clay layer has been calculated as the average of apparent resistivities which is 122.7 Ω·m (Fig. 12C).

4.7 Discussion on the Structure and Geometry of the Obuasi Aquifer

Two types of rocks have been identified through boreholes logs: reddish clay and phyllite. The layers thicknesses are not uniform throughout the study area. It varies from one location to the other. Otherwise, resistivity values of the different layers vary from one site to site. The phyllite layer has a resistivity value of 234.19-236.49 Ω·m with a thickness of 31-40 m. Reddish clay has a resistivity of 99.53-384.93 Ω·m with a thickness of 20-30 m.

In most of the cases, the resistivity models show a layer with low value of resistivity downward. More precisely, the VES curves obtained are "K" type (Fig. 13) that is to say that a layer of high resistivity is sandwiched by two layers of lower resistivities. This

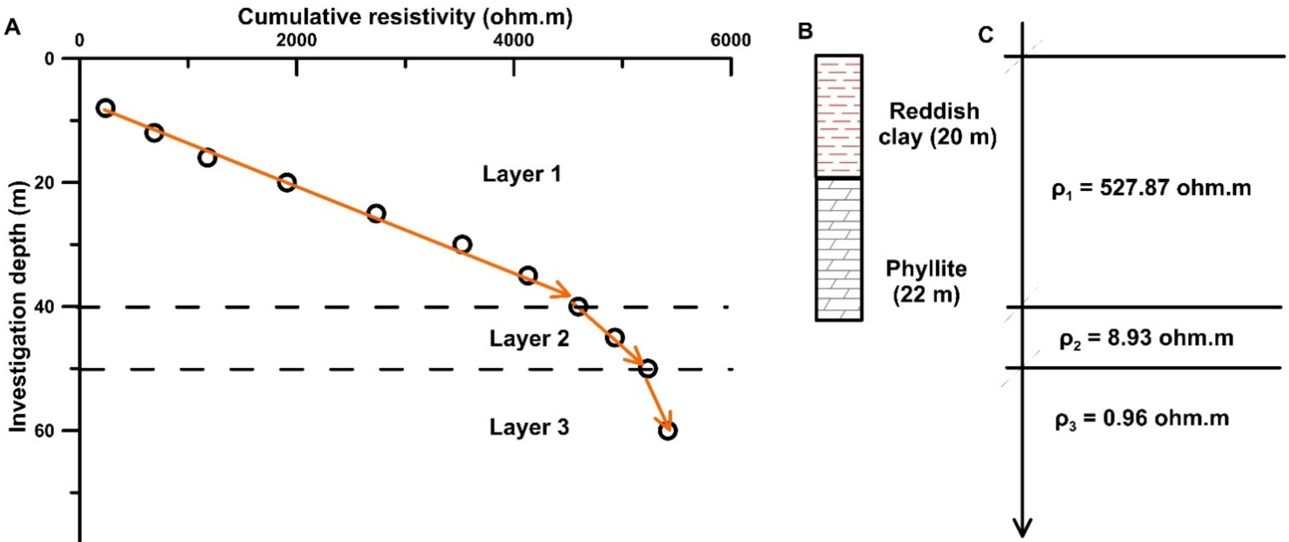

Fig. 11 Interpretation of VES 5. (A) Cumulative resistivity layer; (B) Borehole log; (C) 1D Resistivity model.

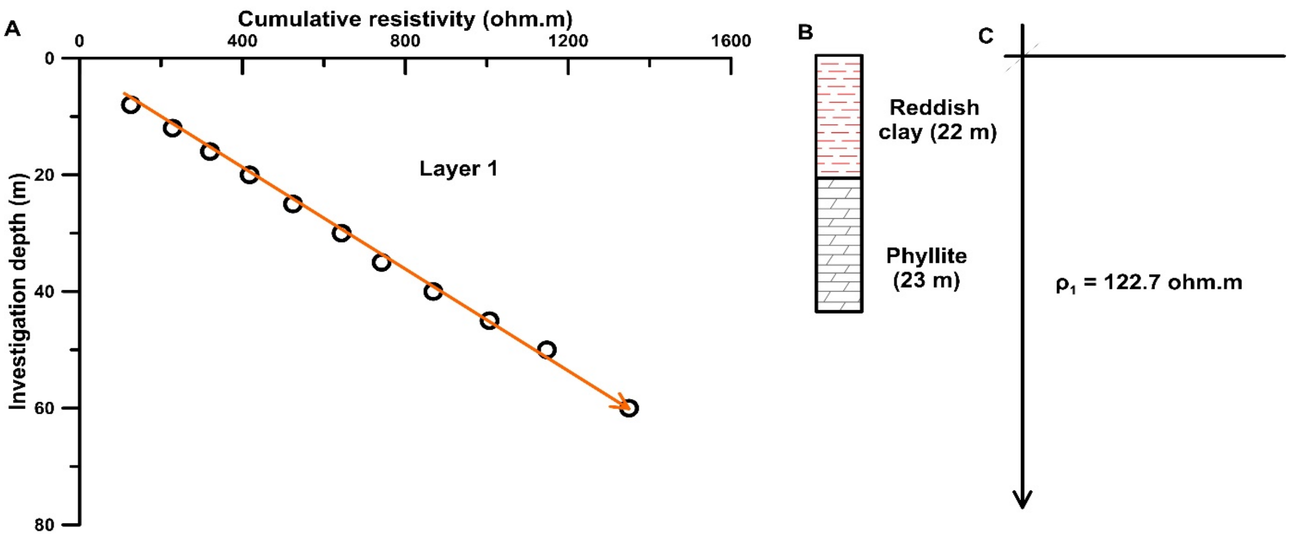

Fig. 12 Interpretation of VES 6. (A) Cumulative resistivity layer; (B) Borehole log; (C) 1D Resistivity model.

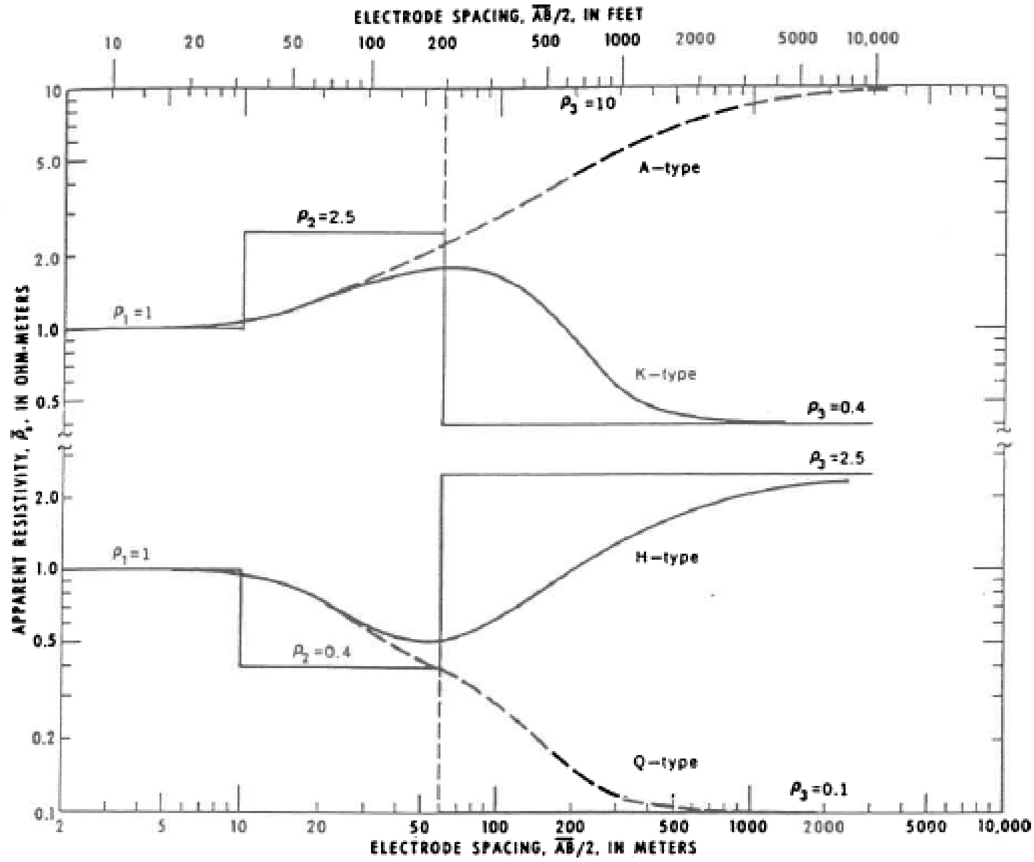

Fig. 13 Types of three-layer electrical curves [13].

situation contrasts with the three-layer models observed for hardrock aquifers. Indeed Koïta et al. [12] have established through a statistical study in this context that the most recurrent types of three-layer models in these media are of the H and KH type.

Low values observed downward on the study area means the presence of a very porous layer. This is due to the fact that phyllite is a volcano-sedimentary rock. This situation is contrary with the conceptual hydrogeological model of a classic basement rock aquifer proposed by Wyns et al. [14]. Indeed, in such a model, the bearing fractured zone located under alteration of 20-30 m has values of resistivities of the order of 228-871 Ω·m [15].

5. Conclusion

At the end of this geophysical characterization study of the Obuasi aquifer, which applied the cumulative resistivity method, the assessment of the adequacy between the results of this method and the reality provided by the borehole logs is mixed. In fact, among the VESs studied, the method made it possible to correctly identify the geometry of the layers for some of them (half of the cases studied). Indeed, for VES 1 and 3, the limit between the layer of reddish clay and phyllite is well identified; moreover, for VES 3, the method has lead to a single-layer model corresponding to the reddish clay layer. On the other hand, the application of the method for VES 5 and 6 has shown that the method does not make it possible to get rid of the phenomenon of suppression since the layers of reddish clay and phyllite are merged into a single layer.

In addition, the weathering profile of the Obuasi aquifer, located in a volcano-sedimentary zone, is typically composed of a resistant layer sandwiched between two conductive layers: this corresponds in geophysics to sounding curves of type "K". This type of profile contrasts with that of hardrock aquifers which leads to soundings of type “H” or “KH”.

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