

Groundwater Exploration using 1D and 2D Electrical Resistivity Methods

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Abstract
Integrated geophysical techniques involving 2D electrical resistivity imaging (ERI) and vertical electrical sounding (VES) were used to delineate groundwater potential zones for borehole siting in the Pru District of the Brong Ahafo Region of Ghana. The ABEM Terrameter LS was employed in the survey. A total of fifteen (15) 400 m - ERT profiles and thirty-one (31) VES points were investigated using the Schlumberger protocol. The Res1DINV and Res2DINV inversion software were used for data analysis. The 2D ERI images showed a lot of fractures within the subsurface of the study area. The results of the VES generally revealed either three or four subsurface geological layers at the selected points. The second and third layers were found to possess relatively low-to-moderate resistivity values indicative of potential aquifer zones. The resistivity of the fourth layer indicated the presence of slightly-fractured to fresh bedrock. The borehole logs depict four sequences: brownish or lateritic sandy clay overlying highly weathered sandstone which is underlain by moderately weathered sandstone and highly fractured sandstone basement.
Keywords: Electrical resistivity tomography, vertical electrical sounding, groundwater, aquifer, geological layer and hydrogeology.

1. Introduction

According to the United Nations, about 1.1 billion people around the world do not have access to potable water. In sub-Saharan Africa, however, about 60 percent of the population (300 million people) do not have access to potable water (WHO/UNICEF, 2003). The vulnerable group of individuals, who are mostly affected are usually poor and live in rural communities. In Ghana about 80 percent of diseases which affect people are attributed to unsafe drinking water and poor sanitation sources. In the report of Water-Aid Ghana, it has been revealed that more than 3,000 children die yearly under the age of five (5) due to poor water and sanitation conditions in Ghana. The Water and Sanitation Sector Monitoring Platform (WSMP) of Ghana 2009, indicated that 3.5 million Ghanaians do not have access to potable water (WSMP-Ghana, 2010). According to a British Geological Survey's technical report, groundwater has proven to be the most reliable natural resource for resolving rural water supply problem in sub-Saharan Africa (MacDonald et al, 2008). Groundwater, therefore, is the realistic solution to this challenge in most parts around the globe. Stakeholders of water related issues are admonished to take critical steps to solve the problem by providing water supply system to the local communities. A major challenge confronting the communities in the Pru District is lack of safe drinking water as the existing surface water sources (streams, rivers) are polluted by means of chemicals, which are infiltrated from fertilizer application during agricultural activities at the river banks. Cattle also use the river and streams as their main source of water supply. Natives in the Pru District, who are users of the contaminated river and stream sources are usually attacked by guinea worm, bilharzia, river blindness and other water related diseases. Individuals especially women and children have to walk long distances in search for potable water. This daily practice of "survival of the fitters" takes precedence over all other concerns, which leads to poor standards in education for children.

The government and non-governmental organizations (NGOs) over the years have initiated several interventions with the provision of boreholes to curtail the situation. However, the drilling program usually ended up unsuccessfully with either dry or marginal boreholes (yield < 13.5 l pm) as no scientific based techniques were used in such a difficult terrain such as the study area. As the communities are underlain by difficult geological conditions, groundwater occurrences are expected to be barely difficult (MacDonald and Davies, 2000). Large amount of financial resources were involved in the unsuccessful event of drilling dry boreholes in such a terrain.

Foster and Chilton (2003) observed that groundwater is the world's most extracted resource which forms the pillar of the Asian green revolution and constitutes about 70 percent of the European Union pipe water supply system. This proves beyond prejudice the essential role that groundwater can play in community development. Whereas rivers and streams sources are highly susceptible to contamination, seasonal variations and have to be channelled to the point of demand, rainwater harvesting is costly and requires good rainfall all year round. Groundwater resources on the other hand, can withstand drought and can be discovered nearer to the users, has excellent natural quality, which requires little or no treatment before use.

Generally, groundwater development is cheap on long-term basis, has low level contamination and is easily manageable by the local community. Gyau-Boakye and Dapaah-Siakwan (2004) indicated that groundwater is economical and dependable by rural communities. This project seeks to support the achievement of the Millennium Development Goal 7 for Ghana in terms of provision of water supply and sanitation. To minimize the drilling of the dry and/or marginal borehole outcome in the study area, this project employed ultra-modern integrated resistivity techniques to delineate aquifer zones to guide the borehole drilling program (Keary and Brooks, 1992; Telford et al, 1990).

2. Geology and hydrogeology of the study Area

The Pru District is situated between latitudes 7^0 50' N and 8^0 22' N and longitudes 0^0 30' W and 1^0 26' W with a size of 2,195 km^2 and it is located in the Brong Ahafo Region of Ghana. The district capital is Yeji. The study area (Figure 1) is underlain by the rocks of the Voltaian Supergroup geological formation (Middle and Lower Voltaian). The Kamampa, Bassa Chief, Gbarenkwanta and Zabrama-West Communities are underlain mainly by sandstones of the Lower Voltaian Formation (Afaton, 2008; Carney et al., 2008; Griffis et al., 2002). The remaining twelve (12) communities are underlain by shale, mudstone and siltstone of the Obosom group of the Middle Voltaian Formation (Ó Dochartaigh et al., 2011a). The Voltaian formation is intrinsically not permeable but it acquires its permeability through secondary porosity such as fracturing and weathering.

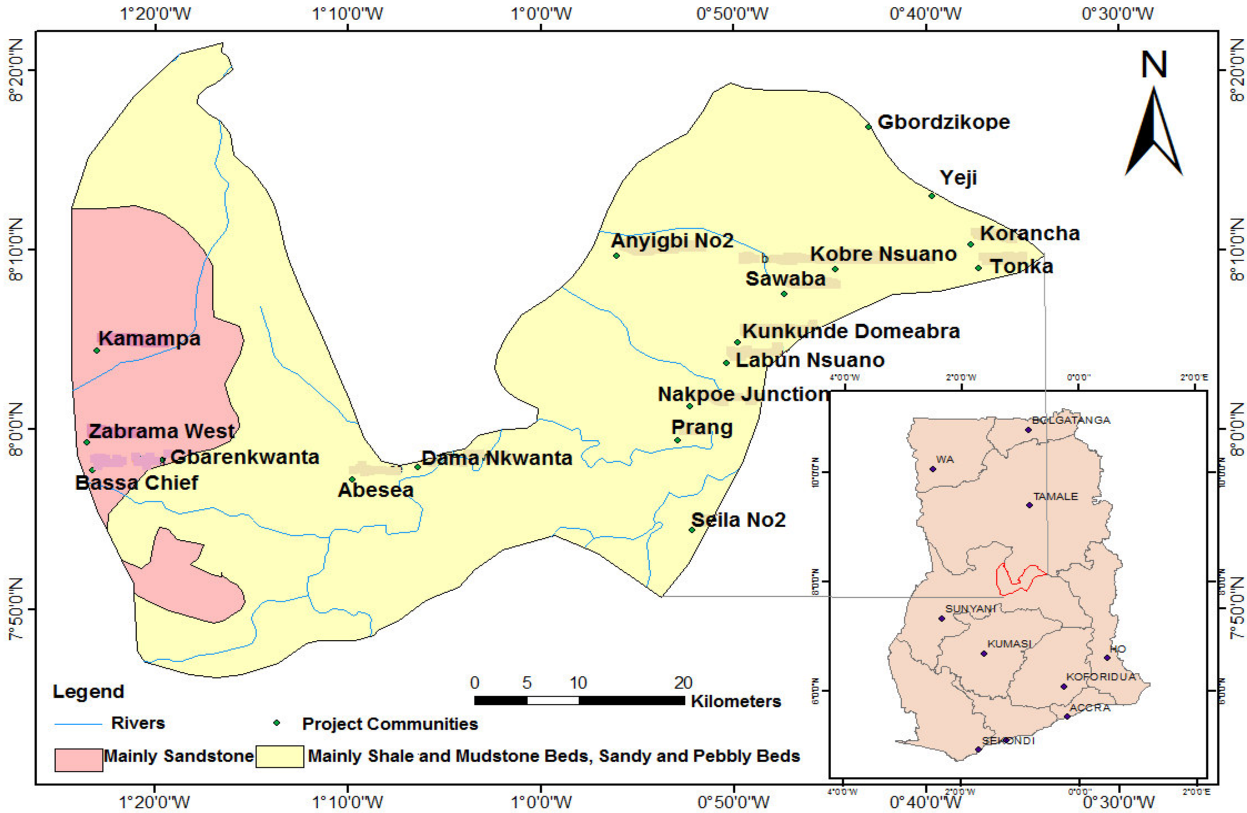

Figure 1 – Hydrogeological map of the Pru District showing rock formation and the project site

Information on existing boreholes in and around the vicinity indicates that the success rate of drilling a wet well is about 56% with yields ranging from 0.41- 9.0 m^3/h with an average yield of 6.2 m^3/h (Dapaah-Siakwan and Gyau-Boakye, 2000). The two (2) major rivers which drain the study area are the Volta and the Pru rivers. The wet semi-equatorial and tropical continental climatic condition prevails in the district. The average humidity is about 75% at a mean annual temperature of 27^0C and the annual rainfall ranges between 100-115 cm (Benneh and Dickson, 2001).

3. Geophysical Survey

Integrated geophysical techniques involving 2-dimensional electrical resistivity imaging (ERI) and electrical resistivity sounding (VES) were used to obtain the pseudo-section of the subsurface from which deductions of fracture zones and their thicknesses were made (Loke, 2001a).

Vertical electrical sounding which is also called electrical drilling, was carried out at selected moderate resistivity anomalous zones along the 2D-profile. Apart from the selected points along the 2D-profile, other points with favourable features such as ant-hills, big trees, lineaments (e.g.: river channel) were also considered for sounding. The ABEM Terrameter LS was set-up in the Schlumberger configuration with manual electrode expansion mode to probe up to 100 m below ground level. The ABEM Terrameter LS allows one to view the plotted in-situ curve on the field as sounding is in progress, such that values that appear unreasonable could be rejected and sounding repeated at the same spot as deemed necessary to achieve conformity in order to ensure data quality control. The field data was analysed using RES1DINV software to produce the VES curves and also to obtain the number of sub-surface geological layers and their corresponding thicknesses and apparent resistivity values.

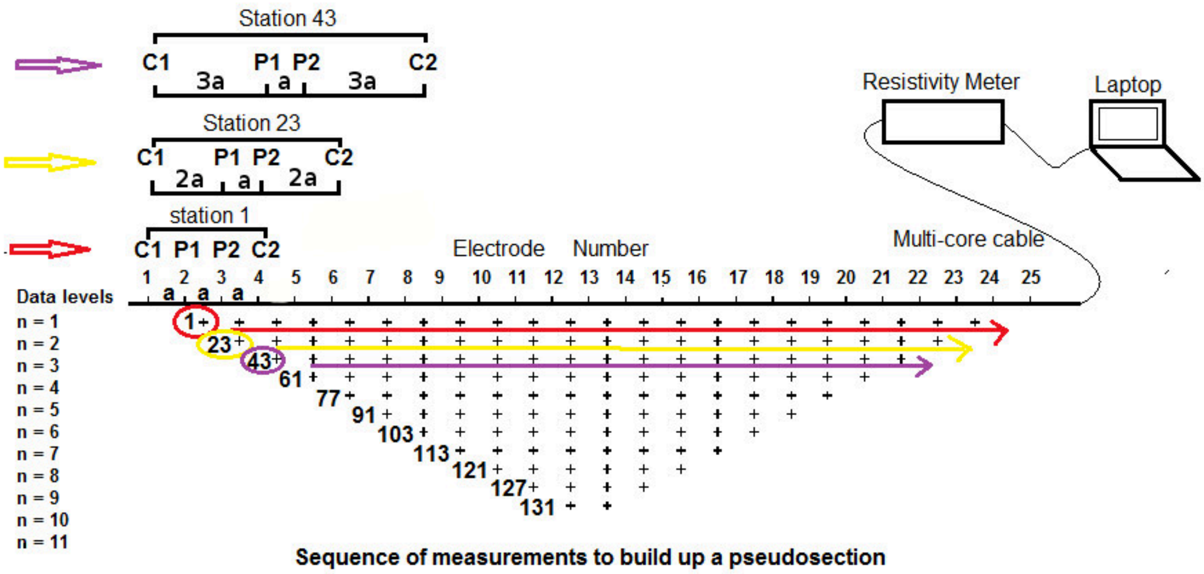

Figure 2 – Typical 2D-resistivity data measurement sequence in the Schlumberger array

This technique was employed for profiling to delineate the contrast between rock masses of slightly different resistivity values in the terrain (Colella et al., 2004; Giocoli et al., 2007). The ABEM Terrameter LS was connected in 400 m spread cable layout with 21 electrodes at 20 m take outs. The Schlumberger protocol was used throughout the imaging system at all the sites. This protocol was used due to its fair sensitivity to both vertical and lateral geological structures and its good horizontal and vertical resolutions. Electrode test was then carried out to check for each electrode performance and to ensure that each had good ground contact. The electrodes with poor contact were aided with salt solution to enhance their performance. The measurement sequence was carried out within 10 minutes period to probe as deep as 75 m below ground level with a 400 m spread. During the data acquisition, each of the four (4) basic electrodes can either be active or passive (Figure 2) since they are selected concurrently at a time. In the Schlumberger array protocol, the C1, P1, P2 and C2 have *a* as electrode spacing for each measurement sequence at the same level *n=1*. In order to probe deeper, the electrode spacing is then increased to *2a* among C1-P1 and P2-C2 while P1-P2 remains *a* at the new level *n=2*. This was used to take all the measurements sequentially and stepwisely at the same level. Furthermore, at a deeper level *n=3*, C1-P1 and P2-C2 would have electrode spacing to be increased to *3a* with P1-P2 still remaining *a*. These processes are automatically chosen and executed from inbuilt program within the ABEM Terrameter LS during the data acquisition. As the data was being collected, one can view a model pseudo section of the data on the screen of the ABEM Terrameter LS.

The resistivity values were calculated from the field data and modelled against electrode position using RES1DInv software to obtain a plot of apparent resistivity variation with depth at a potential borehole drilling point. The output model gives a signature curve with specific number of beds of different degrees of weathering as well as their resistivity and thickness (Loke et al, 2010). Usually, a fracture is associated with decreasing apparent resistivity with expanding current electrode separation. This phenomenon has been used to determine the presence of fractures in the study area (Nostrand and Cook, 1966).

4. Data Processing

Data from the geo-electrical survey were processed using mainly RES1DINV and RES2DINV to represent the data in the form that can be easily analysed and interpreted (Yaoguo and Oldenburg, 1994: Loke, 2001b).

The field data was downloaded from the ABEM Terrameter LS equipment in **.dat* and **.txt* format. The raw data in the **.dat* format was read into RES2DINV software and modelled with series of about eight (8) iterations to obtain well refined and colourful model-section of the sub-surface. The elevation along the traverse was introduced into the analysis to obtain the topography of the terrain. The output model-section indicates a plot of apparent resistivity variation with depth along each 400 m profile as well as elevation of landscape with position along the traverse.

5. Results and Discussion

The ERT modelled-sections illustrate varying resistivity values ranging between 24 - 2053 Ωm within undulating terrain with elevation between 80 - 280 m at sites, which are underlain by the sandstone rocks (Figure 3). Within the shale and mudstone environment, however, the ERT modelled-sections indicate resistivity values between 2 - 1032 Ωm at elevations between 20 - 176 m as shown in Figure 4. Potential points were selected for VES to obtain the number of layers, layer resistivity, thickness of each layer and the signature curve at any particular point.

5.1. Communities underlain by sandstone of the Voltaian Formation

Four (4) beneficiary communities are located in the Lower Voltaian Formation of the Kwahu Morago group with mainly basal sandstone, which is characterized with deep-seated aquifers (CSIR, 2009; Ó Dochartaigh et al., 2011b). These aquifers serve as the targets for the geophysical survey.

The heterogeneity of the output modelled-section of Kamampa Community (Figure 3) that runs in the East-West direction indicates an anomaly that is probably a fracture. These zones were mapped for VES and the results show four (4) layers of rock masses (Figure 5A). The overburden is less than 10 m thick and the aquifer zone is expected to be in the third layer of highly weathered rock with resistivity of 200 Ωm and 11 m thick. The fresh bedrock has an apparent resistivity of 88,855 Ωm of extended thickness.

The output modelled-section of Gbarenkwanta Community (Figure 3) aligned in the SE-NW direction indicated a potential anomaly zone along the profile. The 160 m and 200 m points on the profile were selected for VES. Three other potential points located away from the profile were also investigated. The results show three (3) main beds in the form of $\rho_1 < \rho_2 > \rho_3$; where ρ_1, ρ_2, ρ_3 = resistivity of beds as shown in Figure 5C. The overburden was about 6 m thick and the bedrock is fractured to support groundwater development. The aquifer zone is expected to be located in the third bed beyond 45 m depth.

The ERI profile for Bassa Chief Community was run in the NW-SE direction and the modelled-section indicates continuous lateral and vertical inhomogeneous beds as shown in Figure 3. Suitable points such as the 160 m point along the traverse were selected for VES. The apparent resistivity of the basement rock was generally low and it ranged from 15 up to slightly above 56 Ωm. The overburden thickness is expected to be less than 2 m and the apparent resistivity depicts the order of $\rho_1 < \rho_2 > \rho_3 > \rho_4 < \rho_1$ (Figure 5D). This shows that the aquifer zone is expected to be located in the bedrock of apparent resistivity, $\rho_4 > 56$ Ωm. The low resistivity of the bedrock is characterized by well-defined fractures in the bedrock which could support groundwater storage beyond 25 m depth.

The Zabrama West Community ERI profile (Figure 3) was run at the outskirts of the community in the N-S direction. The output pseudo-section indicates a conductive anomalous zone below a buried rock mass, which stretches over 300 m along the profile and 50 m depth below ground level. Generally, the ERT gives resistivity values, which alternate between varying degrees of weathered sandstone beds in the range of 64 to over 2053 Ω m. The 160 m mark on the profile line was selected as the primary drilling point. The aquifer zone is expected to be intercepted about 70 m depth and its resistivity values range from 64 to 400 Ωm. However, the VES (Figure 5B) was carried out at a vantage point in the community revealed relatively high resistivity values and it was not marked for drilling.

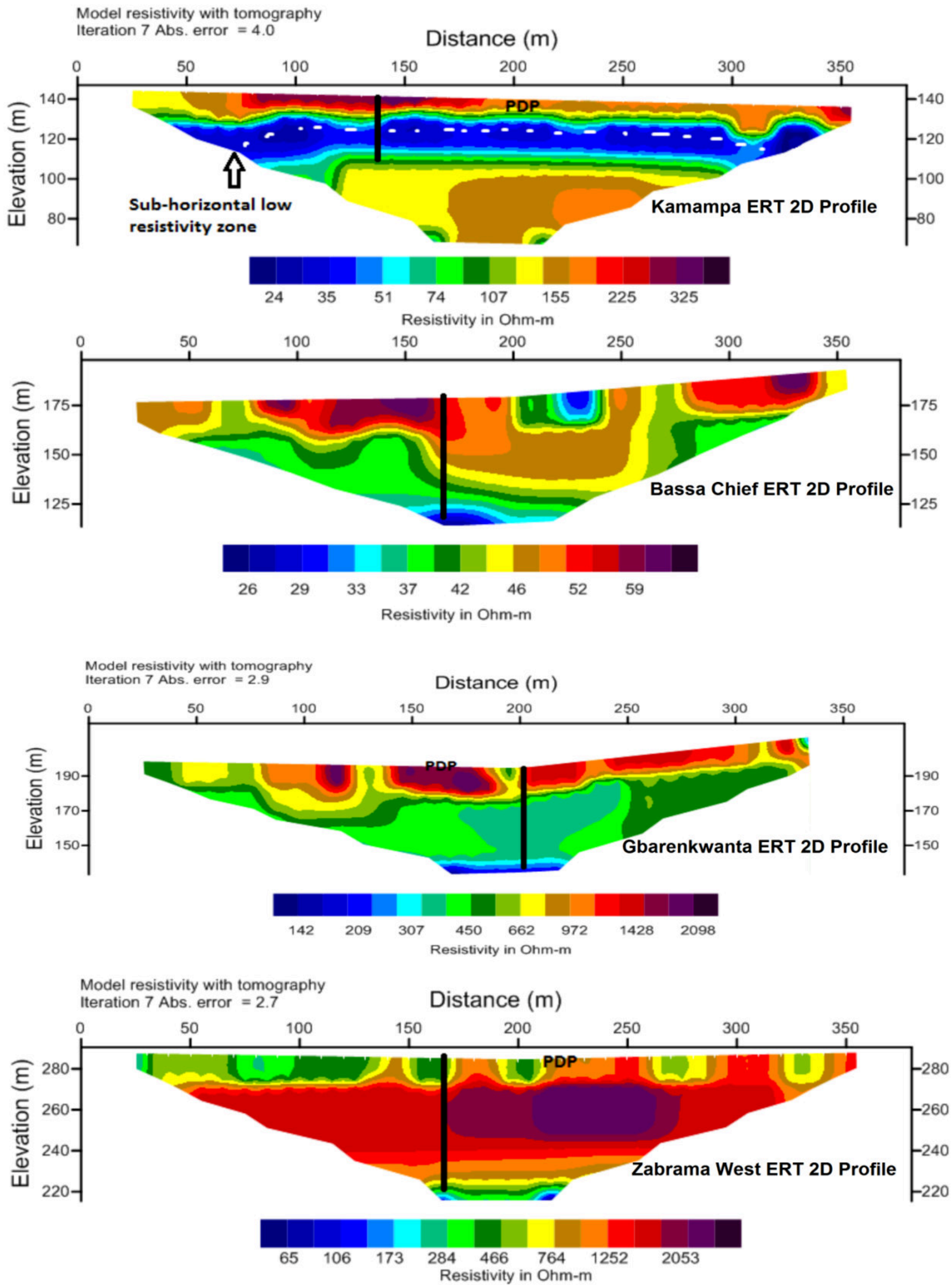

Figure 3 – Selected 2D resistivity modelled-section of the project sites underlain by sandstone basement rock formation showing potential borehole drilling points (thick black vertical line) and alternative drilling point (APD).

5.2. Communities underlain by shale and mudstone of the Middle Voltain Formation (Obosum group)

According to a technical report by CSIR (2009) on previous works done in similar geological setting, mudstone and siltstone rocks are usually highly conductive and boreholes in these areas are mostly low yielding or dry. Areas of medium-to-high apparent resistivity values above 50 Ωm of the subsurface rock are therefore preferable for drilling (Ó Dochartaigh et al., 2011b). Four (4) beneficiary communities were selected.

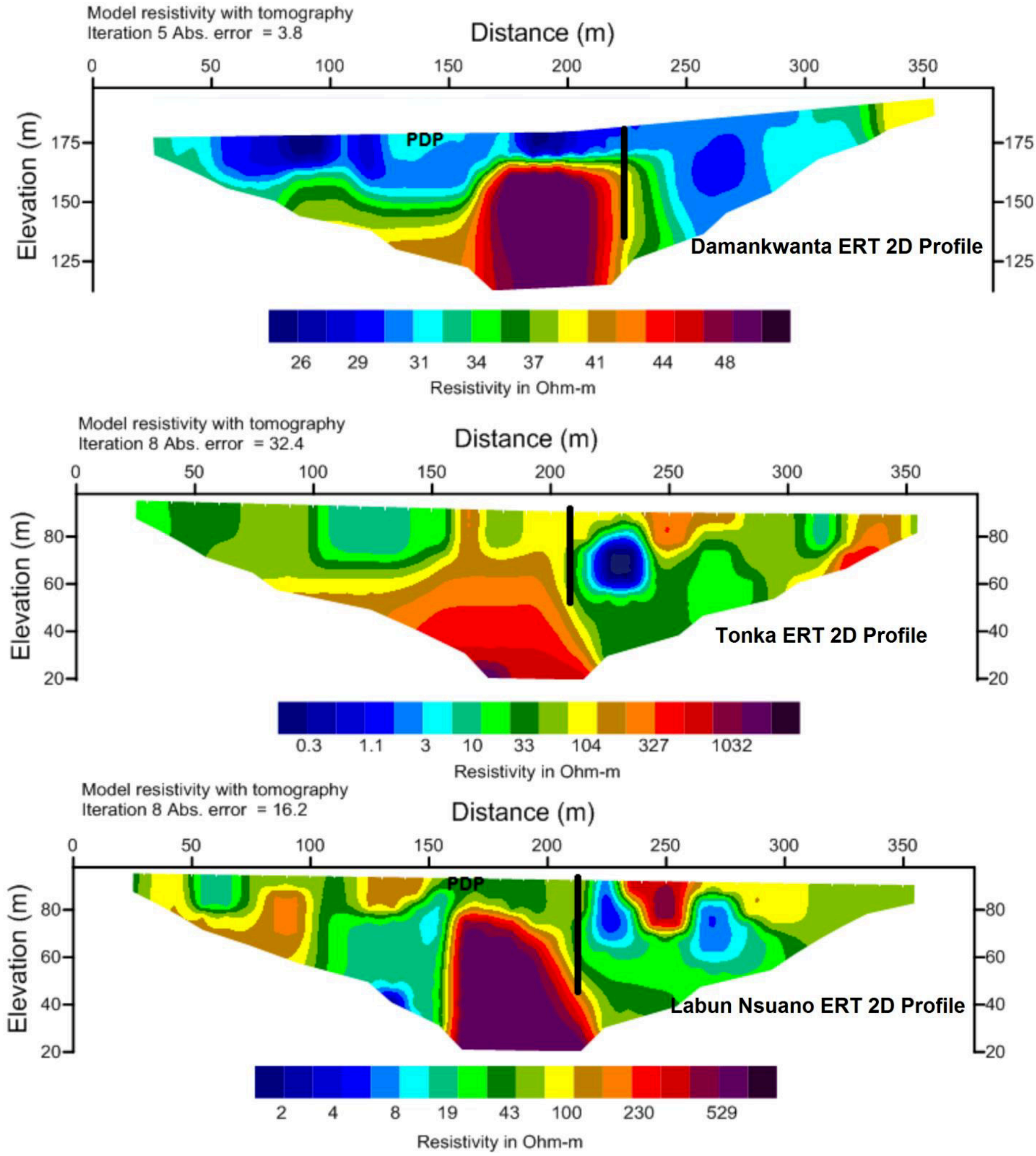

Figure 4 – Selected 2D resistivity pseudo-section of the project sites underlain by mudstone and shale rock formation showing potential borehole drilling points (thick black vertical line) and alternative drilling point (APD).

Two ERI profiles were selected in the SE-NW and SW-NE directions respectively at Damankwanta Community to map the lineaments. The profiles were oriented along external features such as ant-hills and trees in the area, which are some indicators of primary and secondary porosity alignments. The modelled-sections show massive block at about 30 m below the ground level, which covers at least 100 m spread across the centre of the profile (Figure 4). Potential drilling points were then selected for VES.

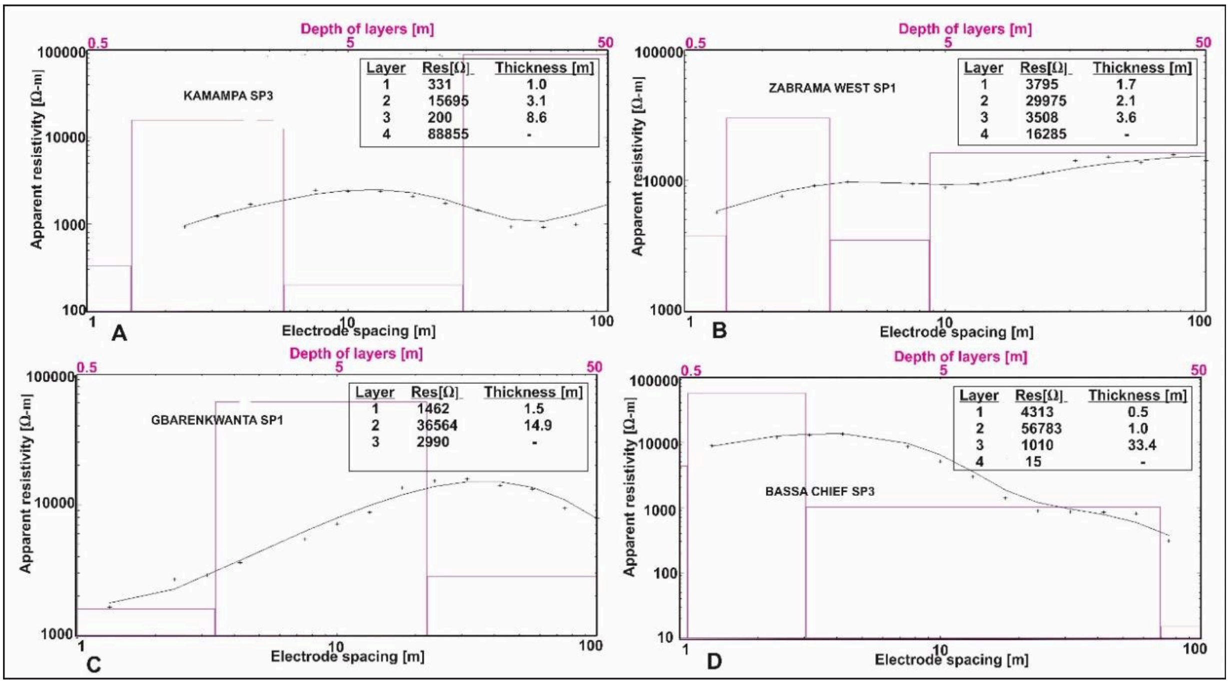

Figure 5 – Selected VES modelled curves of project sites underlain by basal sandstone rock formation.

The ERI profile at Tonka was oriented in the N-S direction and the modelled-section reveals a block rock at 40 m depth with extensive coverage (Figure 4). Potential points were noted for VES (Figure 6C) and the results indicate weathered sub-surface with moderately fractured bedrock with resistivity of 572 Ωm beyond 60 m depth.

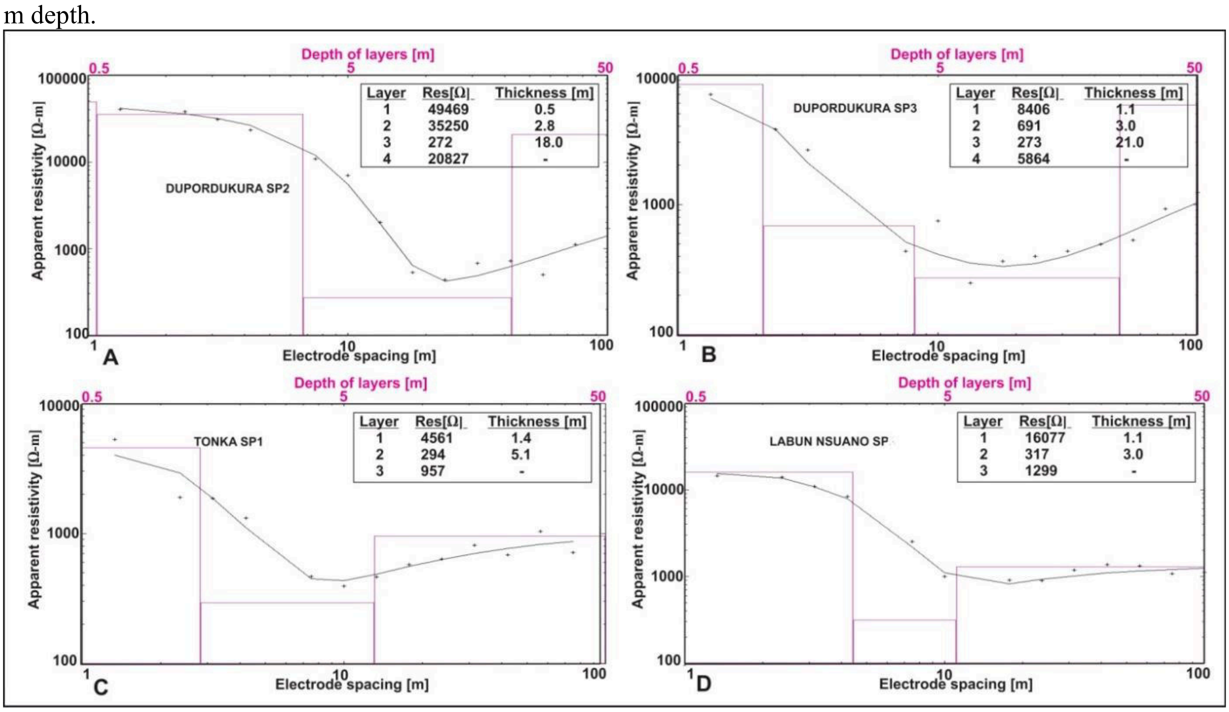

Figure 6 – Selected VES modelled curves of project sites underlain by shale and mudstone rock Formation.

The 400 m ERI profile at Labun Nsuano which is oriented in the W-E direction shows multiple modelled-sections of weathered rock and a clearly mapped massive block anomaly of about 40 m diameter apex at 65 m depth, which spreads out downward in conical form (Figure 4). The VES results at selected points indicate a definite hard-pan less than 2 m thick as topsoil (Figure 6D), moderately weathered overburden of about 20 m thick and highly weathered bedrock, which bears the aquifer horizon with apparent resistivity of less than 630 Ωm at 50 m depth. The borehole is expected to yield at least 26 *l/m* to meet the freshwater demand of about 37,080 *l/day* for the Labun Nsuano community.

The VES at Dupordorkura community (Figure 6A and 6B) was carried out at selected points and indicated an overburden of less than 25 m thick with a hard pan of 1.4 m topsoil. The existing rock is poorly weathered but the aquifer zone is expected to be located in the slightly fractured bedrock, which is expected to yield at least the required water demand to the Dupordorkura community.

6. Drilling Logs

During the drilling process, logging and sampling of the drilling cuttings were made at every one metre interval. This was to identify the precise fracture sections to allow placement of screens during construction. Measurements of the yields at the various aquifer sections were estimated and recorded as aquifer zones were intercepted. Figure 7 shows the drilling log for three test wells at Bassa Chief, Gbarenkwanta and Kamampa. The logs reveal four layers with the top layer being either lateritic or brownish sandy clay of thickness of about 3 m underlain by highly weathered sandstone of width 7 m which overlies moderately weathered sandstone. The fractured sandstone is principally present below 30 m. The aquifer was intercepted averagely at a depth of about 20 m.

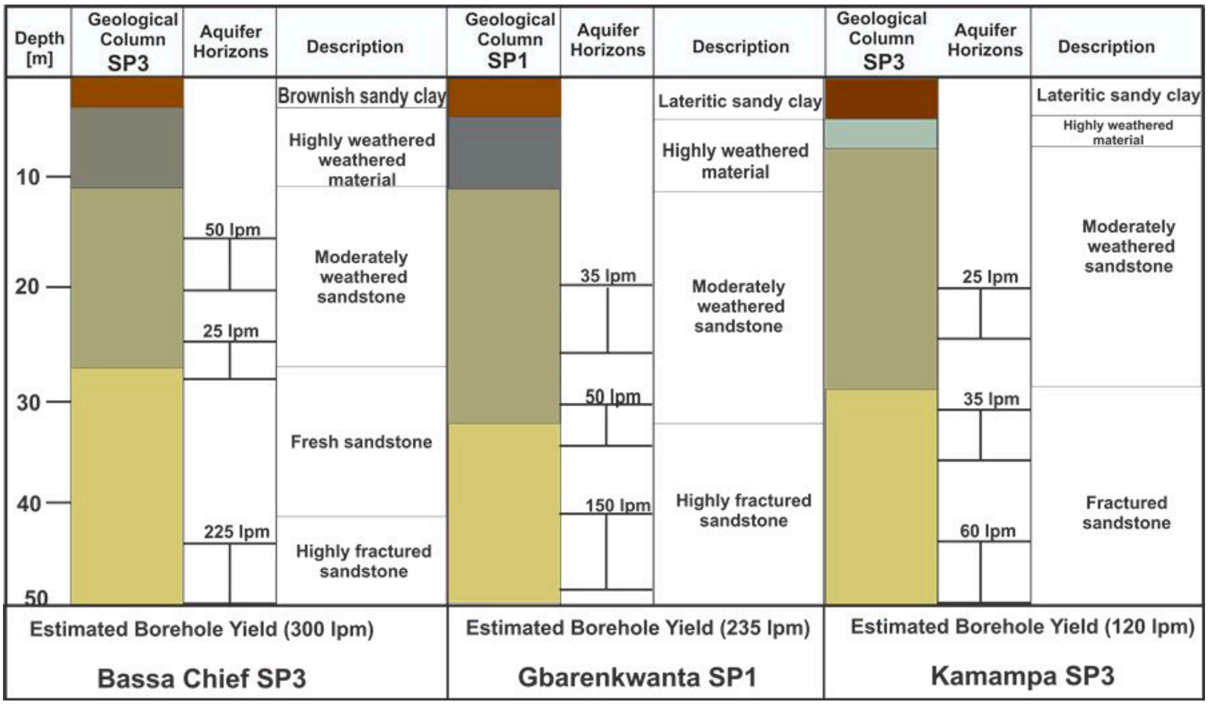

Figure 7 – Drilling log for three wells at Bassa Chief, Gbarenkwanta and Kamampa with estimated yield and depth.

7. Conclusion

The ERT profiling and VES results were used to delineate and characterize the anomalous zones such as weathered, fractured, contact zones, faults and dike-like structures. These geological features serve as targets and have groundwater storage potential for borehole drilling. The delineated aquifer zones were classified as having high (20 to 200 m), moderate (200 to 600 Ωm) and low (600 m and above) groundwater potential (GwP). In Kamampa and Anyigbi No-2, sub-horizontal resistivity zones were mapped which may be high groundwater potential zones. The delineation of dike-like structures in Labun Nsuano indicates that groundwater potential in those communities was expected to range from moderate-to-high. Tonka and Kobre Nsuano communities were found to have low-to-moderate groundwater potential. The VES points revealed three (3) subsurface geological layers in most cases and four (4) in few cases.

For the three layer model, the resistivity and thickness of the top soil (first layer) ranges from 1462 to 16,077 Ωm and 1 to 1.5 m respectively. The second layer (aquifer zone) has resistivity of 294 to 36,546 Ωm and the thickness from 3 to 15 m. Also, the third layer (bedrock) has resistivity from 957 to 2990 Ωm. In the four layer model, the top soil (first layer) has resistivity of 331 to 49,469 Ωm with thickness from 0.5 to 1.7 m. The second layer (aquifer zone) has resistivity from 691 to 56,783 Ωm and with thickness of 1 to 3.1 m respectively. The third layer (aquifer zone) has resistivity of 200 to 3508 Ωm and with thickness ranging from 3.6 to 33.4 m. The fourth layer (sub-rock and the bedrock) resistivity ranged between 15 to 88,855 Ωm which is expected to produce moderate-to-high groundwater potential. The subsurface up to a depth of about 50 m consists of sandstones which are either weathered or fractured.

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