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ELECTROMAGNETIC GEOPHYSICAL SURVEY FOR GROUNDWATER EXPLORATION IN THE VOLTAIAN OF NORTHERN GHANA

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The electromagnetic (EM) geophysical method has been used widely in many areas for groundwater prospecting but interpretation of data for accurate location of water bearing features is still a problem. A simple method of data interpretation has been developed and applied in the sedimentary formation of the Voltaian basin of Ghana for groundwater exploration. The interpretation scheme is based on identifying EM highs along parallel traverses of EM profiling data that are presented on one-dimensional (1-D) plots. The results show terrain conductivity distribution in the range of 10-70mS/m for the vertical dipole (VD) mode of the device and 22-79 mS/m for the horizontal dipole (HD) mode pertaining to the general conductivity distribution of the area, using a 20m inter coil separation cable. The conductivities for the HD mode were generally higher than those for the VD mode. The plots show various patterns of EM signature as indications of possible water bearing features. On the basis of defined criteria, the best ranking drill targets were selected for boreholes. The interpretation of EM results helps to delineate water bearing features for a high success drilling rate. The signatures can easily be visualized from the plots facilitating data interpretation. Higher conductivity values for the HD modes suggest the existence of a subsurface clay layer.

INTRODUCTION

The northern parts of Ghana, comprising Northern, Upper West and Upper East Regions, record the highest incidence of poverty in the country (Rural Poverty Portal, 2007). The Northern Region of Ghana, which is the focus of this study, is home to some 1.8 million people, and ranked 5th out of the ten regions of Ghana in terms of population and housing census figures (Wikipedia, 2008). Most of the communities in the region may be considered as rural, according to the classification scheme of Ghana Statistical Service (2000) where rural communities in Ghana are defined as those with population of fewer than 5000 inhabitants. Many of the inhabitants do not have access to potable water and mostly drink from sources that are often polluted and unreliable, resulting in the prevalence of water born diseases. The need for alternative water supply systems puts groundwater as the most viable source of potable water supply to these scattered and remote communities. It is therefore not surprising that vigorous campaigns were launched in the region by the Government and some Non-Governmental Organizations (NOs) such as World Vision Ghana Rural water Project (GRWP), Northern Region Rural Integrated Project (NORRIP) and Canadian International Development Agency (CIDA) to develop the region's groundwater resources. Though many works were conducted in the area to drill boreholes, either lined or unlined as described in Akudago et al. (2007), the water supply needs of the people could not be met. Borehole drilling success rates have not been very encouraging and may be attributed to a non-holistic approach to finding water, where many private drilling companies are only interested in striking successful wells and mostly relegating detailed hydrogeological studies to the background. In the cases where contractors have attempted selecting sites for drilling, they mostly rely on cheap and nontechnical means of prospecting. An example of such methods is "water witching or divining" which has no scientific basis and is not reliable, as successful drilling results are very rare.

Detailed hydrogeological study is very important and is considered a priority in many groundwater exploration programs. Many geophysical methods have been used for groundwater prospecting. However, the most widely used method is the traditional electrical resistivity (ER) method. This well known geophysical method has been used in groundwater exploration and contaminant delineation in many countries with varying degrees of success as discussed in the literature (Hazell et al., 1988; Porsani et al., 2004). The ER method has also been widely used at different areas in Ghana for groundwater exploration (Cobbing and Davies, 2004; Banoneng and Armah, 2001; Boadu et al., 2005). In some cases, the ER method has produced good borehole drilling results, especially in granitic environments and in areas that have very good groundwater potential. Other geophysical methods that have gained favor in the groundwater sector, though not widely used in Ghana, are the electromagnetic (EM) methods. These methods have either been used exclusively or in combination with ER method (Omosuyi et al., 2007; Buselli and Kanglin, 2001; Danielsen et al., 2007; Olorunfemi et al., 1996). Though varying degrees of success have been achieved with the EM method, interpretation of data is still a problem. Detailed interpretation of geophysical data is useful for effective delineation of groundwater-bearing zones or features. Meulenbeld and Hattingh (1999) and Aked (1995), among other researchers, laid emphasis on careful interpretation of geophysical data as a useful tool to delineating water bearing features.

Personal communication with some groundwater consultants (K. Osman of Watersites Ltd. and A. Emmanuel of Water Vision Technology, Tamale, Ghana) indicated that many geophysical investigations have been conducted in the Voltaian of northern Ghana relying mostly on the ER method. Except in a few isolated areas where good results were obtained, the general investigation results for the entire area have not been good, leading to low drilling success rates. In areas where groundwater occurrences are structurally controlled, it is suitable to use a method that is sensitive to fractures. Among widely used geophysical methods, EM methods have been identified as good for detecting and delineating fracture zones. The EM systems as stated in McNeill et al. (1986) were originally developed for mineral exploration and later discovered to be very capable of detecting and measuring the small conductivity changes caused by the presence and quality of groundwater. They have also been used to detect geological structures favorable for groundwater such as faults and fracture zones.

One comparison between ER and EM methods as described in Hazell et al. (1988) is that the vertical ER sounding is effective in deeper weathered zones where a good contrast between the weathered zone and the fresh crystalline rock can be observed. It is, however, less effective in locating narrow steeply dipping fractures with deeper weathering. This notwithstanding, the EM method can reveal steeply dipping conducting bodies in the EM profile. The ER method has an advantage of being used for over 100m deep aquifer investigations. The EM method is limited to a maximum exploration depth of 60m. In areas where hardpan or rocks are superficially situated or outcropping, EM can be used since the current flow into the ground is by magnetic induction, contrary to ER in which pegging of electrodes on the hard rock will be difficult. In areas where there are iron and barbed wire fences or in the vicinity of power lines and underground pipe systems, the reading of EM data will be unreliable. EM measurements may not be affected by power lines or fences provided there is no problem with access for the survey. Since the study area is basically rural with aquifers generally less than 60m deep, these factors do not adversely affect the use of EM for groundwater exploration. Besides, groundwater potentials in the study area are structurally controlled and mostly tapped from fractured aquifers which can easily be detected by EM. The EM survey is therefore a better option for groundwater exploration in the area than the ER method.

With the exception of the GRWP that is known to use and be proficient in the EM method for groundwater survey in the area, there has not been any known information about the use of this method for groundwater prospecting in the area by others. Though varying degrees of success have been achieved by the GRWP with the use of EM, improvement is needed in the area of interpretation of the data. This paper focuses on detailed interpretation of EM data from various patterns of EM signature. The interpretation technique takes advantage of the sensitivity of EM equipment to detect fractures for the delineation of geological features or water bearing zones. It also considers the geology of the area and other hydrogeological factors. Many times, significant geologic features may be overlooked entirely due to an inability to recognize simple data patterns. Recognizing and carefully interpreting fractures or fracture systems in geophysical data can have a significant positive impact on borehole drilling results.

STUDY AREA

The study area is located at the northeastern corner of the Northern Region within Latitudes 8.5^o N and 10.5^o N and Longitudes 0.7^o E and 1^o W. It is bordered in the north by the West and East Mamprusi and Bunkpurugu-Yunyoo Districts, in the southwest by the Yendi, Nanumba north and south Districts and in the west by the Savelugu Nanton District. It also shares an international boundary with the Republic of Togo to the east (Figure 1). The areas investigated include the Gushiegu/Karaga, Saboba/Chereponi and Zabzugu/Tatale areas, which form a northwestern–southeastern trending stretch of land. The total land area is 11,516 km^2, and it represents 16% of the land area of the Northern Region (70,870 km^2) and 4.8% of the entire land area of Ghana (239,800 km^2).

The natural vegetation of the study area is that of a Savanna grassland with clusters of shrubs, short trees and drought-resistant trees such as the baobabs and ebony. Many of the trees are destroyed by man's activities such as bush burning, construction and farming. The inhabitants are mostly subsistence and peasant farmers, who commonly grow crops such as maize, yam, peanuts and millet. The area is characterized by distinct climatic conditions made up of one rainy season between May and October with an average annual rainfall of 750 to 1050 mm, followed by a prolonged dry season between November and April. Temperature levels vary between 14 °C at night and 40 °C during the day (Wikipedia, 2008).

GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

Over 80% of the study area is underlain by the sedimentary formation of the Voltaian basin (Figure 2). The Voltaian is thought to be about 3000 - 4000m thick and covers most of the Northern Region. The major lithologic units include the Lower Voltaian basaltic sandstone, Middle Voltaian shale and mudstone, Middle Voltaian siltstones and the Upper Voltaian sandstones. At the extreme southeastern end of the study area is the Buem Formation with the following lithologic units: phyllites, quartzite, shale and sandstones. This study is limited to the Voltaian Group and the study area is not underlain by the Lower Voltaian. The rocks in the Voltaian have almost completely lost their primary porosity through low-grade metamorphism. They are generally well consolidated and are not inherently permeable (Kesse, 1985). The presence of secondary porosity in the rocks such as fractures, joints and fissures, as a result of some amount of tectonic activities, contributes to groundwater storage.

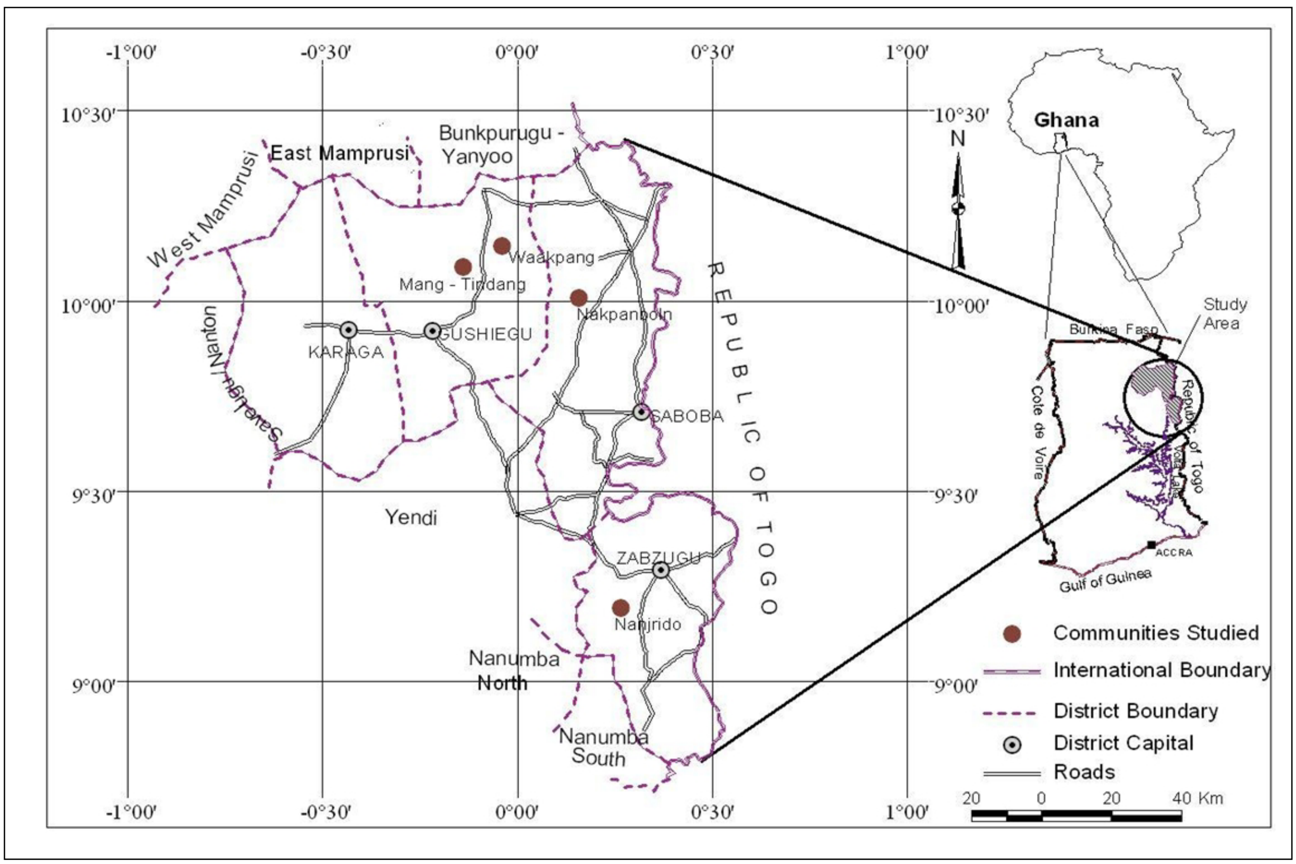

Figure 1. Location map of the study area.

Groundwater potential in the Voltaian has been observed to be in the order of Lower Voltaian (V1) > Middle Voltaian (V2) > Upper Voltaian (V3), where groundwater is tapped mainly from fractured aquifers. Regional hydrogeological studies have shown that fractures or joints in the area are erratic and even absent in some places. In isolated cases, the fractures are non productive. The area also exhibits three classes of hydrogeological units, related to the regional geological settings: (i) Very high groundwater potential areas - the eastern and southeastern parts of the study area, in the Zabzugu/Tatale areas showing very good prospects for boreholes; (ii) Medium groundwater potential areas - the central and north eastern parts of the area showing moderate prospects for groundwater potential; and (iii) Very low groundwater potential areas - the extreme western and southwestern parts of the area, showing very low prospects for groundwater potential. This suggests that groundwater potential in the area is diverse and requires thorough investigation techniques for high success. Borehole yields range from 5 to 1200 l/min, static water levels (SWL) from 1 to 20 m and water table fluctuation averages about 4m (Acheampong and Hess, 2000; Darko, 2002; Buckley, 1986). The estimated transmissivities range from 0.3 to 270 m^2/day (Darko, 2002). Most of the aquifers located in the formation are semi-confined to confined.

PREVIOUS WORK

In general, development of groundwater resources of the Voltaian sediments dates back to the 1940s (Kwei, 1997). From 1963–65 the Geological Survey of Ghana and the Volta River Authority (VRA) drilled a number of boreholes to meet the water supply needs of the expanding population (Cobbing and Davies, 2004). Many Governmental, Non-Governmental Organizations (NGOs) and other consultancy firms such as Northern Region Rural Integrated Project (NORRIP), Canadian International Development Agency (CIDA), Water Vision Technology, Water Sites Limited and World Vision Ghana Rural Water Project (GRWP) have also worked in the Voltaian of Northern Ghana to develop the groundwater resources of the area.

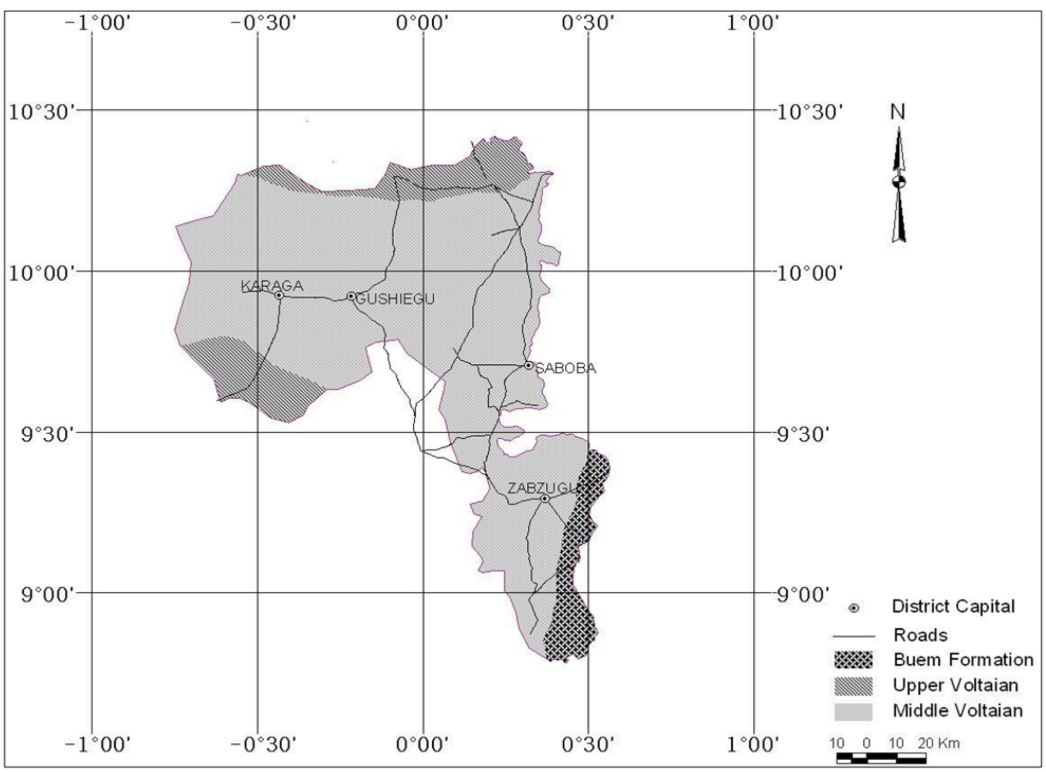

Figure 2. Geological map of the study area.

Geophysical investigations were carried out mostly using the ER method for the selection of sites for borehole drilling. Many of the boreholes drilled were unsuccessful except in isolated areas where the groundwater potentials were good and good drilling results were obtained. Generally, groundwater potentials in the study area are structurally controlled and are mostly tapped from fractured aquifers. The high unsuccessful drilling rate could be attributed to the inappropriate techniques employed for investigation in the area. The ER method is not very good at detecting steeply dipping fractures as compared to EM. The use of EM survey with detailed interpretation of data as discussed in this study can significantly improve on the drilling success rate.

METHODOLOGY

The sequence of prospecting consisted of desk study, which included study of topographical maps for the location of the localities and access routes, gathering of borehole drilling and hydrogeological investigation data about the area from existing literature; reconnaissance survey, which involved ground truthing to ascertain findings during the desk study as well as earmarking suitable areas for the preparation of traverses; and ground geophysical survey and drilling. The main method of geophysical survey was terrain EM conductivity profiling, conducted along parallel traverses using Geonics EM34 –3XL frequency domain ground conductivity meter.

The instrument provides a single apparent conductivity value, based on the presumption of a uniform earth, which is a function of the acquisition geometry. The instrument is composed of two coils (one is the active transmitter and the other, a passive receiver antenna) which are oriented parallel to one another, either flat on the ground (vertical dipole VD mode), or on edge (horizontal dipole HD mode), and at fixed offsets of 10, 20 and 40 m. Generally, the VD mode senses earth conductivity at depths deeper than those sensed by the HD mode, and the approximate depth of maximum sensitivity for a coil separation L is 0.75 x L for HD mode and 1.5 x L for VD mode. However, these are only crude estimates. For accurate measurement with the EM instrument, alignment of coils is very important during measurement of ground conductivity. From Geonics Technical Note TN – 6, the measurement is relatively insensitive to coil misalignment when in HD mode. During this mode the secondary magnetic field is perpendicular to the plane of the receiver coil and a small error in coil misalignment produces a (1 – cos è) error in the apparent conductivity. However, in the VD mode the secondary magnetic field is approximately 45° to the horizontal and points away from the transmitter. In this way, a small error è causes and error of the order of cos (è+ 45°), resulting in greater sensitivity to misalignment. So, as much as possible the two coils should be maintained as close to coplanar as possible at all times in either mode of operation for accurate measurement. It is therefore difficult to obtain accurate measurement in sloppy or rough terrains. The following terminologies were used during the survey: “crossover”, where the VD conductivity reading exceeded the HD reading and “neck”, when both readings were the same or almost the same. Details of the investigation are described in the subsection below.

Field Procedure

EM traversing or profiling was conducted along traverses that were prepared by considering the hydrogeological conditions of the area. Ten traverses at different locations in the area were considered for this study. Profiles were conducted along the traverses at station intervals of 10m. Two sets of measurements were taken at each observation station along the entire profile and the average value recorded. All measurements were taken with error correction of ±5%.

Prior to taking measurements, observations were made about the way certain indicators or features such as the ebony shrubs, mahogany, Daniela, fig and other water loving trees were aligned on the field. This might give clues to possible lineaments since there were no aerial photos to enable the study of lineament patterns of the area. Other features such as termites and ant hills that might give clues to the nature of weathering in the area were also considered. In areas where none of these indicators could be observed, the topography of the area was considered, where traverses were prepared along the flanks of slopes. Generally, traverses were run approximately perpendicular and to intersect suspected lineaments. Preparation of traverses was such that each traverse was made to begin at some distance away from the location of suspected lineaments so that any contrast from background could easily be observed. Generally, at least two traverses were conducted with reasonable spacing between traverses, not more than 80m as suggested in DRI (2003). This spacing allowed for adequate coverage of the areas of concern thus minimizing the potential for undetected anomalies. All traverses were kept as nearly parallel as possible so that any similarity of patterns observed in the EM data could give clues to the presence and continuity of fracture or geologic structure.

In most cases, the 20m separation cable was used. This gave an exploration depth of about 30m which in most cases proved to be sufficient for detecting water bearing features. Measurements were taken by first placing the coils vertically and coplanar on the ground. Measurement stations were taken midway between the inter coils spacing. The depth of exploration is mainly a function of the inter coil spacing and the orientation of the coils. When a location was found to indicate good or promising anomaly during measurement, it was cross checked by running a short perpendicular traverse or short parallel traverses to determine the width or the extent of the feature. The location was also checked by swapping the transmitter and the receiver to ascertain if the measured conductivity value at the observed location was due to the effect of the feature or just a mere instrument or human error. Preliminary site selections were conducted. This involved putting marks/labels on pegs to identify the potential drill targets and taking GPS locations of the points. Final site selection was ranked in order of priority based on defined criteria to ensure the selection of viable drill targets.

RESULTS

The EM data acquired from the field represent a general study for the area under investigation. Apparent ground conductivity values ranged from 10 to 76 mS/m for the VD mode and 22 to 79 mS/m for the HD mode. The survey results were correlated with the geological logs of the drilled boreholes and penetration rates. An increased penetration rate was an indication of a fracture zone being encountered. Table 1 shows apparent conductivity values along three, parallel, 200m traverses A, B and C, running SW - NE in a locality called Mang-Tindang. The local geology is siltstone. The EM signature for this data can clearly be seen and interpreted as in Figure 3 which shows the plots of apparent conductivity versus distance along the traverse. High conductivity values of 24, 24, 25, 28, 27, 23 and 29 mS/m were observed at stations 20, 40, 60, 80, 120, 150 and 190, respectively, along traverse A in the vertical dipole mode with a crossover at station 190. Along traverse B in the VD mode at stations 30, 50 and 160, high conductivity values of 21, 26 and 24 mS/m respectively can be observed. On traverse C, there is little variation in the VD conductivity data.

Table 1 also gives the EM data conducted in a second locality (Waakpang) with a local geology observed as siltstones. The data consist of three parallel traverses A, B and C on a bearing of 102°, spaced 40m apart, each of length 200m. The plots of apparent conductivity versus distance along the traverses show that there are moderate indications of fracturing in the VD mode of traverse A at stations 30, 60, 110 and 150 (Figure 4). Strong indications of fracturing are exhibited at stations 50, 100 and 150 on traverse B; and stations 30, 50, 140 and 170 on traverse C. A crossover can also be observed at station 170 on traverse C.

EM data of the third locality (Nakpanboln) are shown in Table 2, consisting of two traverses A and B running parallel to each other in a northeast to southwest direction, each of length 160m. The local geology is shale. The apparent conductivity plots show almost no peaking values on traverse A as indicated by little variation of conductivity values (Figure 5). However, a conductivity peak is seen at station 100 on traverse B for the VD mode.

Nanjrido is a community in the Zabzugu/Tatale areas. The geology is mainly shales. Two parallel traverses in the northeast direction were conducted. The length of each traverse was 150m (Table 2 and Figure 6). Peaks or conductivity highs occurred on traverse A at stations 50 and 110. The reading at station 50 shows a neck and the reading at station 110 shows a crossover. Traverse B also shows a similar pattern of fracturing at stations 40 and 90. Both readings at these locations show classic crossovers.

DISCUSSION

Interpretation of geophysical data such as EM data normally requires a good knowledge of the geology, hydrogeology and field experience in the area. Weathering products of the rocks in the area contain a lot of clays which normally contribute to the increase of subsurface electrical conductivity. The electrical conductivity of a soil or rock is a measure of the ability to conduct electric current though it. With the exception of metallic minerals and some clay, most soil

Table 1. Data of EM profile conducted at Mang-Tindang and Waakpang communities.

Community:	**Mang – Tindang**						**Waakpang**					
	Apparent Conductivity (mS/m)											
Station	Traverse A		Traverse B		Traverse C		Traverse A		Traverse B		Traverse C	
	VD	HD	VD	HD	VD	HD	VD	HD	VD	HD	VD	HD
10	16	28	17	26	13	22	55	72	61	76	52	70
20	24	29	19	27	16	25	55	73	59	76	52	68
30	20	32	21	30	17	26	59	72	62	74	57	67
40	24	35	19	34	15	30	56	74	62	71	52	66
50	15	39	26	36	13	32	59	73	67	71	59	68
60	25	36	24	39	13	35	64	72	65	70	58	69
70	21	37	14	38	12	34	59	70	56	69	51	69
80	28	40	22	38	13	34	61	69	57	73	56	69
90	21	41	22	39	15	35	61	68	51	74	57	69
100	19	42	20	40	16	39	62	68	65	71	59	69
110	15	41	20	39	16	41	64	67	64	70	58	70
120	27	41	18	37	15	40	63	69	61	71	58	70
130	22	37	18	36	15	39	61	70	59	71	60	71
140	18	35	19	36	15	39	58	72	57	69	64	71
150	23	31	22	36	16	39	61	71	64	70	50	71
160	21	30	24	34	13	35	58	72	61	70	61	70
170	14	29	13	33	10	33	60	71	53	70	70	67
180	25	29	14	32	10	31	61	72	55	68	58	69
190	29	26	18	32	10	31	60	72	56	68	63	69
200	21	24	21	30	13	32	60	71	58	67	60	68

Table 2. Data of EM profile conducted at Nakpanboln and Nandrijo communities.

Community:	Nakpanboln				Nanjrido			
Apparent Conductivity (mS/m)								
Station	Traverse A		Traverse B		Traverse A		Traverse B	
	VD	HD	VD	HD	VD	HD	VD	HD
10	45	69	43	65	45	69	56	65
20	43	65	39	68	43	65	48	57
30	46	63	41	68	46	63	50	55
40	44	64	41	72	44	64	58	52
50	46	66	45	71	58	58	51	63
60	47	63	50	71	53	63	43	62
70	50	67	47	69	50	67	39	62
80	48	66	47	67	48	66	53	58
90	48	71	56	68	48	70	64	60
100	48	72	58	67	48	65	58	67
110	51	71	56	63	66	60	54	72
120	52	71	47	67	62	71	54	70
130	51	72	47	66	51	72	59	74
140	49	72	50	67	49	72	61	76
150	50	69	55	77	50	75	60	79
160	44	66	53	77	-	-	-	-

materials are poor conductors. Any significant flow of current in these materials is mainly due to the included water and its ionic contents in the soil or fractures. A good contrast between the conductivity of fractured rocks and undisturbed hard rocks would be observed if fractures were filled with groundwater. Fractured rocks show higher conductivity than unfractured rocks.

From the results of the study, the EM conductivity values for the horizontal dipole mode were generally higher than the values for vertical dipole mode because the HD mode is very sensitive to near surface materials and the response decreases with depth. Conductivity highs or peaks (peaking values) in the EM signature were good indications of fracture systems or geologic structures. Generally, the peaks were the most significant factors, among others considered when selecting drilling targets. Crossover patterns occurring in conductivity peaks were mostly selected as drill targets. Though they may yield wet boreholes, classic crossover patterns do not necessarily indicate water-bearing fractures. It is therefore very important to recognize and interpret fracturing systems carefully. The nature of a peak was observed to have a relation with a buried depth of a conductive body. A sharp rising peak was an indication of a superficial buried conducting body and a gentle rising peak indicated a deeply situated conductive body. A vertical fracture is suggested by a symmetrical signature of the EM data. More information about vertical fractures is captured elsewhere (McNeill, 1980).

Figure 3 shows significant variation of conductivity data in the VD mode along traverse A from stations 10 to 200. This suggests that the highest fracturing density occurs along traverse A, as more peaks are encountered within a distance of about 190m on traverse A. The VD data for traverse B suggests less fracturing than in A, as few peaks or conductivity highs could be observed. However, the relative locations of stations 190 and 160 on traverses A and B suggest that two fractures encountered in traverse A have also been encountered in traverse B (traceable fracture). Traverse C indicates no fracturing, as no peaking can be observed. However, its location with respect to traverses A and B suggests that the continuity of the feature encountered in A and B has not extended that far to be intersected by traverse C. Table 3 shows the ranking of drill targets in order of priority from which the point at station 190 on traverse A was selected for drilling. Generally, prioritization of drill targets was based on the following criteria (DRI, 2003): (i) indications of multiple fractures or a fracture zone, (ii) traceability of feature across multiple parallel traverses, (iii) indication of a vertical fracture (relatively high peak to trough amplitude) and (iv) occurrence of crossover or neck pattern.

Correlation of interpreted EM signature with drill logs (Figure 4) shows a subsurface clay layer indicated by the high conductivity values of the HD. The increase in penetration rate after 15m drill

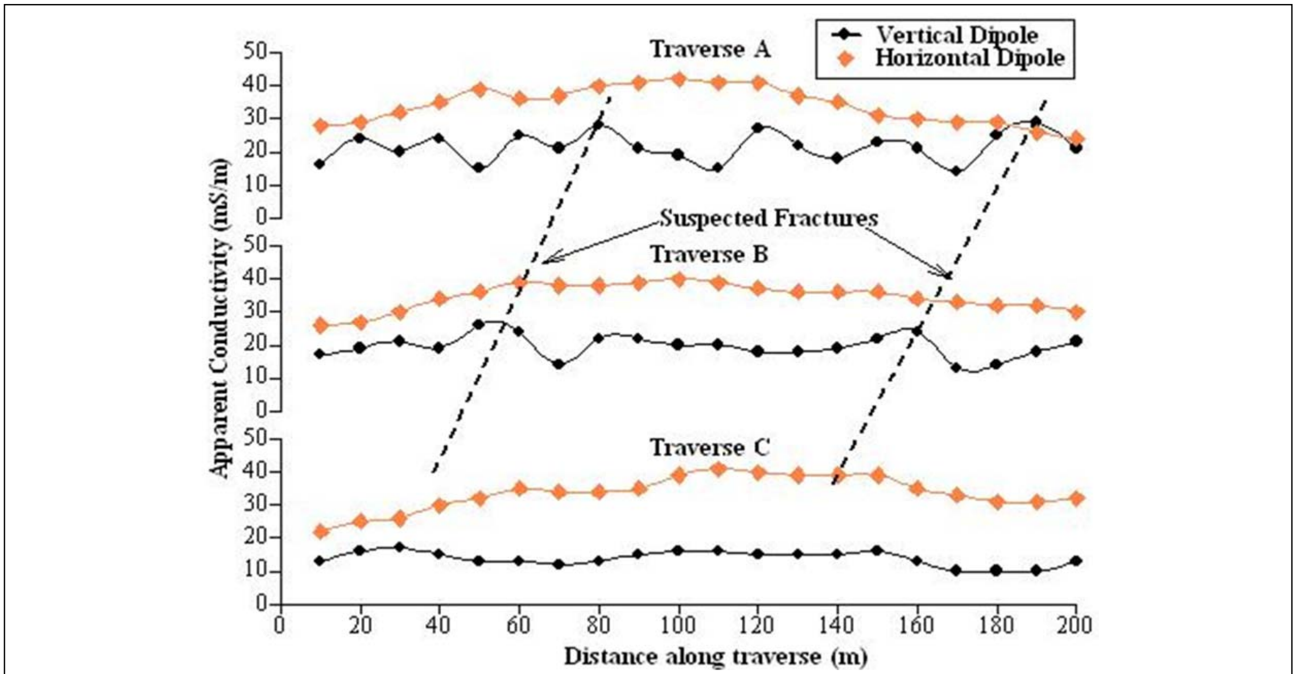

Figure 3. Conductivity versus distance along profile for community, Mang - Tindang.

Table 3. Ranking of potential drill targets in order of priority.

Community	Rank	Traverse	Station	Comments/Reasons
Mang-Tindang	1	A	190	High fracture density on A, Cross-over at 190 and Traceable feature from B
	2	A	80	High fracture density on A and traceable feature from B
	3	B	50	Same traceable feature to A
Waakpang	1	C	170	Cross-over on C at station 170 and traceable feature from A.
	2	B	50	Traceable feature from C which is also traced to A at station 60
	3	B	150	Traceable feature from C
Nakpanboln	1	B	100	Gentle rising peak. Also based on favorable hydrogeological indicators around.
Nanjrido	1	B	90	Cross-over at station 90, traceable feature to traverse A
	2	A	110	Cross-over and traceable feature
	3	B	40	Cross-over and trace able feature
	4	A	50	Neck and traceable fracture

depth is an indication of the drill bit hitting a fracture. The first water strike was encountered at 17m. The drilling yielded a successful well at a final depth of 31m with air lift discharge of 50 l/min. Borehole drill log with construction details is shown in Figure 4.

Conductivity highs at stations 50 and 170 on traverse C can be correlated to the indications at 50 and 150 respectively on traverse B. This suggests that traceable fractures have been intersected by the traverses A and B but these fractures seem to be terminating at traverse A as indicated by moderate fracturing on traverse A (Figure 5). Though drill targets could be obtained from any of Traverses B and C, the best ranking drill target was selected at station 170 on traverse C based on the criteria shown in Table 2. A successful well was drilled at this point yielding 65 l/min with first water strike at 15m. The well was drilled to final depth of 33.5m. Figure 6 shows the construction details of the well with the drill logs.

Figure 7 shows little variation of conductivity on traverse A. This is an indication of weak fracturing on traverse A. The high values of conductivity in the HD mode could be indications of a subsurface clay layer. The peak at station 100 on traverse B is not a crossover. However, the gentle rising peak suggests a possible shallow conductive feature or fracture. Drill target at station 100 was selected based on the peak value and on judgment due to experience of interpreters, drawing inferences from favorable hydrogeological indicators observed around the area. The target yielded a successful well of 85 l/min with first water strike at 14m, The well was completed to a final depth of 37.7m as shown from the drill log in Figure 8.

In Figure 9, the relative locations of the anomalies detected by the EM 34-3XL are indications of two fractures or geological features being intersected by the traverses A and B. Four potential drill targets were selected. However, from the order of ranking (Table 3), the target on traverse B at station 90 was selected for drilling. The target on traverse B was successfully drilled to a final depth of 30.9m with air lift yield of 120 l/min and first water encounter at 20m. Well construction details and drill logs are shown in Figure 10.

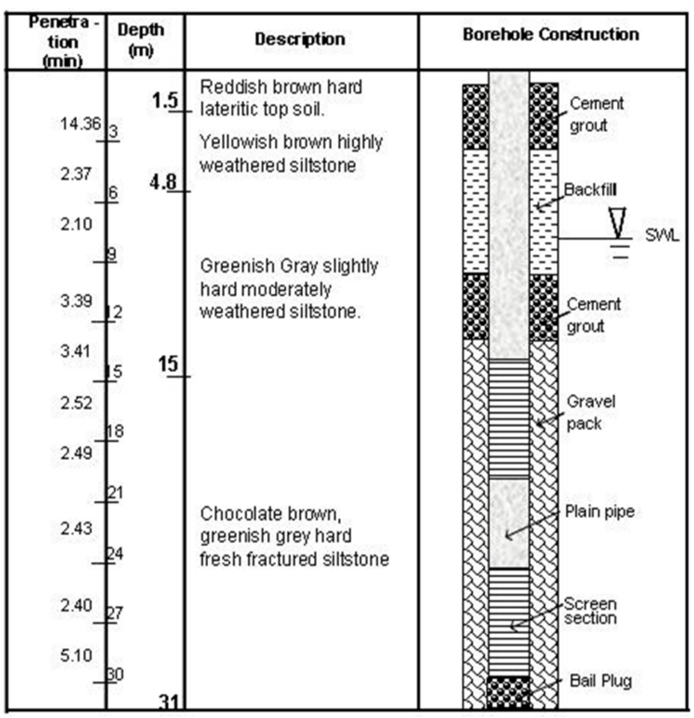

Figure 4. Drill logs and well construction details for community, Mang - Tindang.

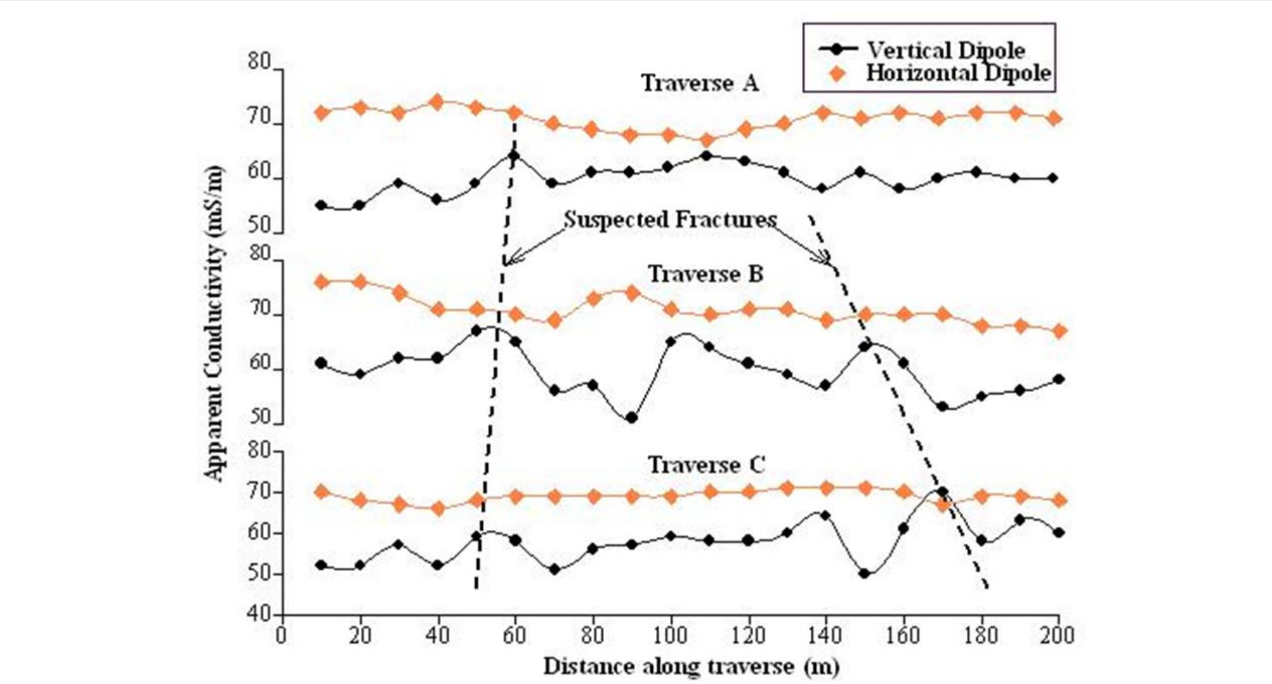

Figure 5. Conductivity versus distance along profile for Waakpang community.

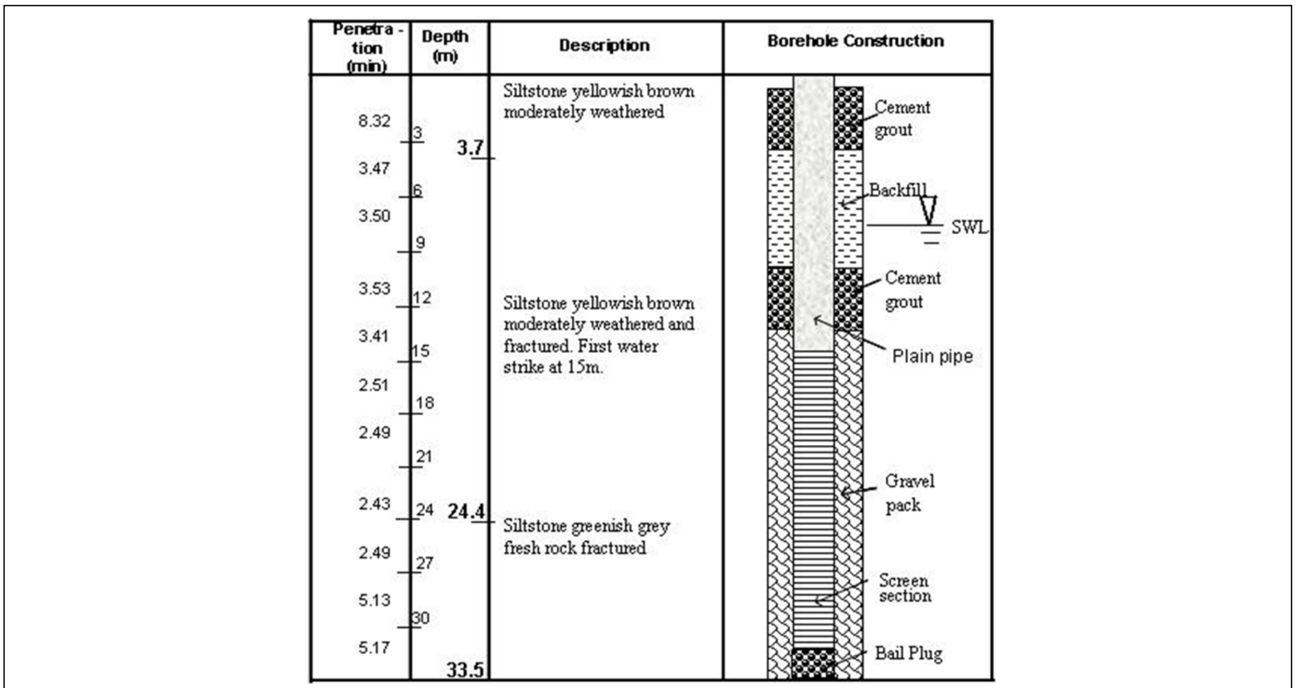

Figure 6. Drill logs and well construction details for Waakpang community.

CONCLUSIONS

In order to recognize and identify geologic or water bearing features from various patterns of the EM signature, profiling data were examined and analyzed with the aim of delineating water bearing features for the selection of targets for borehole drilling.

The following conclusions can be drawn from the study:

(i) The EM profiles proved to be very sensitive to fractured zones which could be traced by this method, especially when traverses are run parallel to each other for which traceable fractures could be observed.

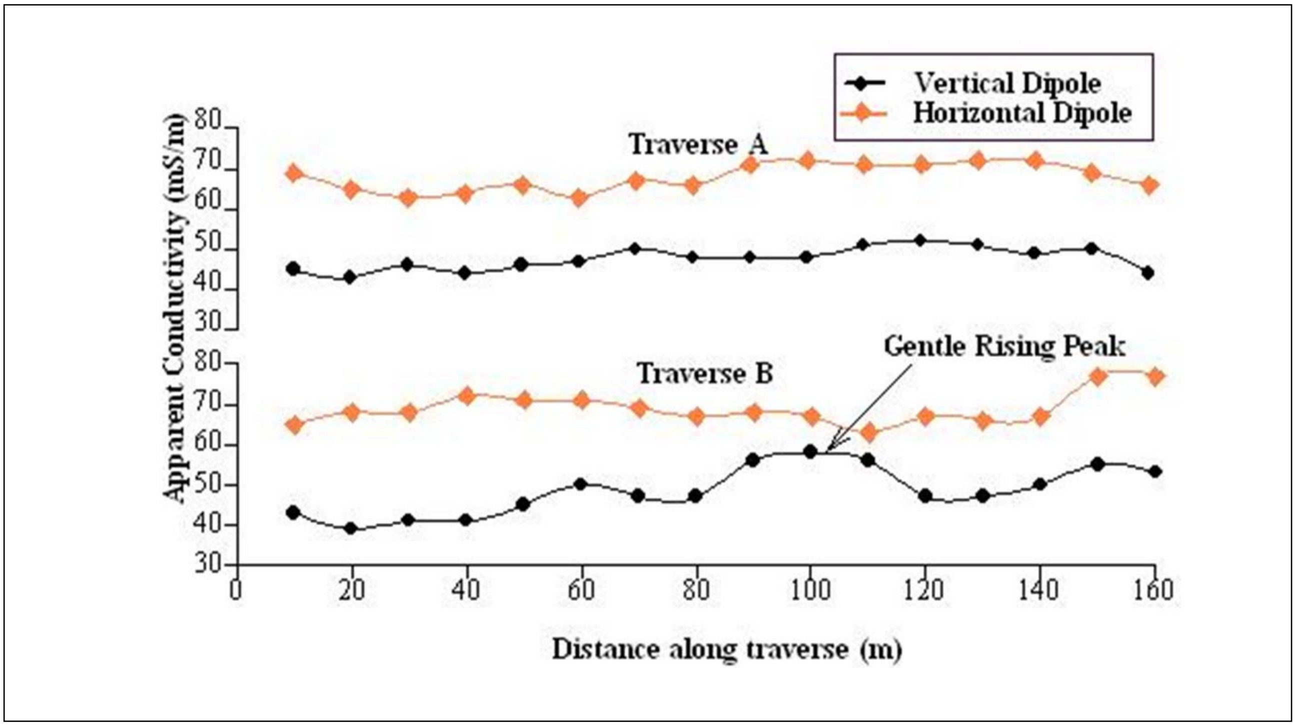

Figure 7. Conductivity versus distance along profile for Nakpanboln community.

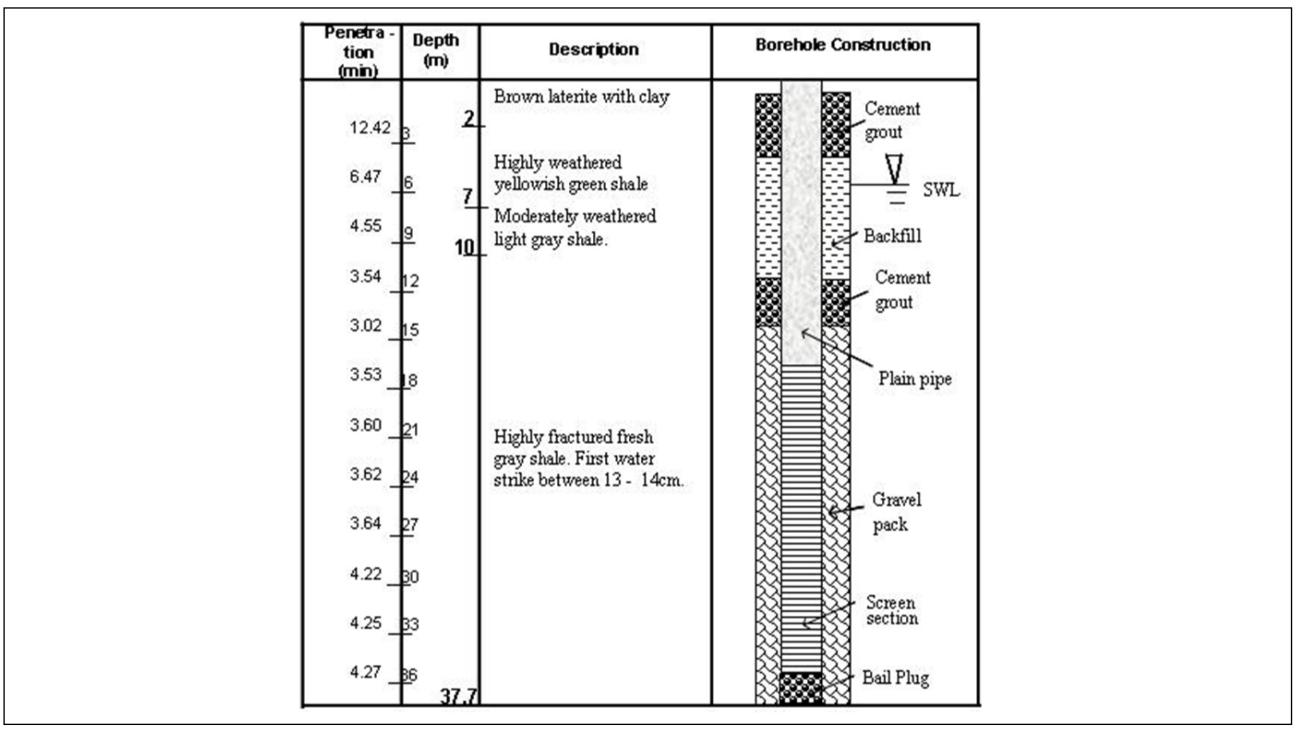

Figure 8. Drill logs and well construction details for Nakpanboln community.

(ii) Moderate to high distributions of conductivity data for the HD mode are possible indications of subsurface clay deposits.

(iii) The EM signature gives a good understanding of data pattern recognition and visualization thereby facilitating EM data interpretation.

(iv) Though drilling at crossover sites mostly produced water, crossover patterns in the EM signature do not necessarily indicate water-bearing features. It is therefore important to interpret

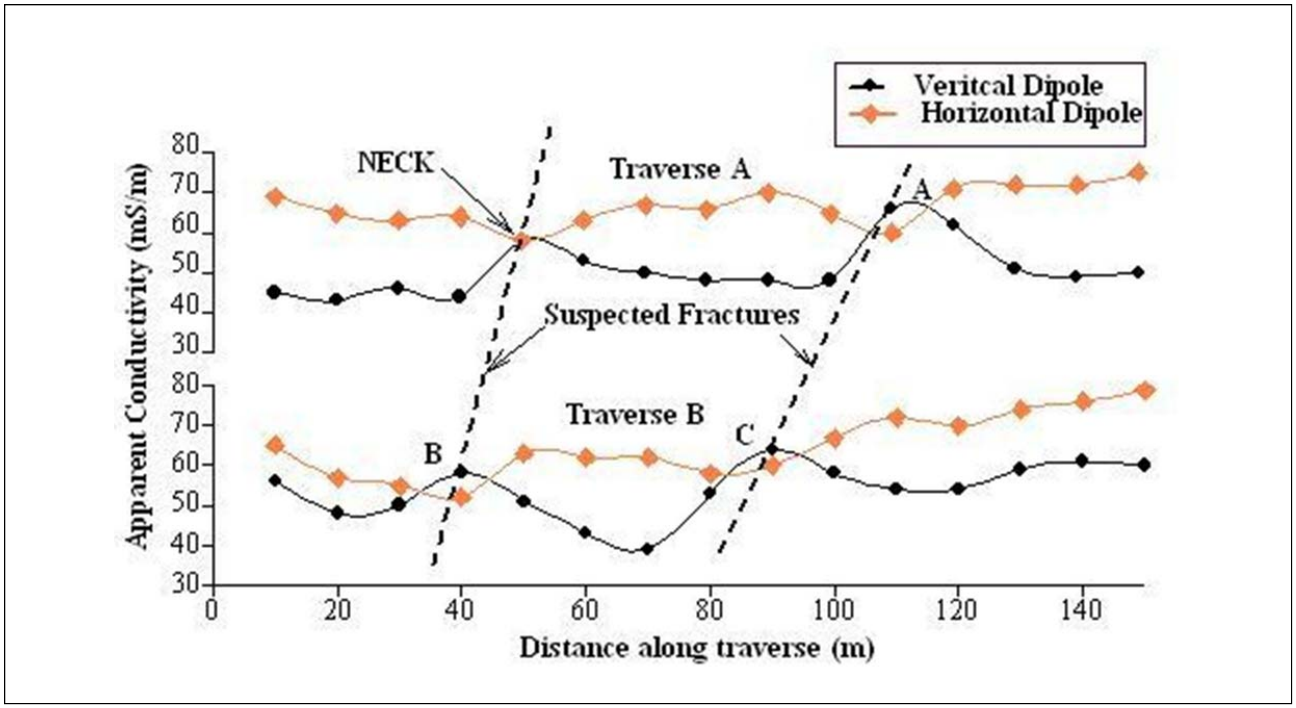

Figure 9. Conductivity versus distance along profile for Nanjrido community, showing crossover at A, B and C, and a neck on Traverse A.

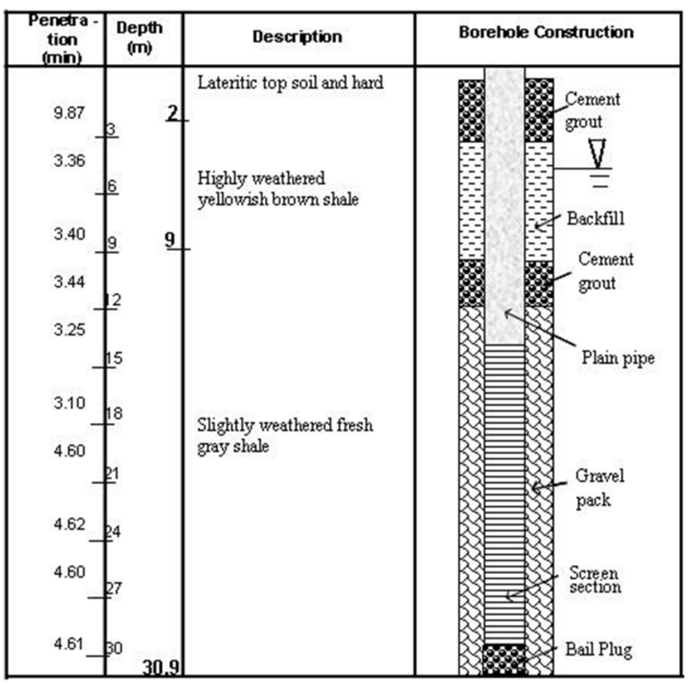

Figure 10. Drill logs and well construction details for Nanjrido community.

fracturing systems carefully, taking into account the geology of the area and other hydrogeological factors such as water loving trees and alignment of trees, etc.

(v) The EM technique described has been used successfully for the location and delineation of geologic feature or water bearing zones in the hard rocks of the Voltaian sedimentary basin of the study area.

(vi) The equipment is effective and very simple to use. It has the advantage of being employed

Table 3. Ranking of potential drill targets in order of priority.

Community	**Rank**	**Traverse**	**Station**	**Comments/Reasons**
Mang-Tindong	1	A	190	High fracture density on A, Neck at 190 and Traceable feature from B
	2	A	80	High fracture density on A and traceable feature from B
	3	B	50	Same traceable feature to A
Waakpang	1	C	170	Cross-over on C at station 170 and traceable feature from A.
	2	B	50	Traceable feature from C which is also traced to A at station 60
	3	B	150	Traceable feature from C
Nakpanboln	1	B	100	Gentle rising peak. Also based on favorable hydrogeological indicators around.
Nandrijo	1	B	90	Cross-over at station 90, traceable feature to traverse A
	2	A	110	Cross-over and traceable feature
	3	B	40	Cross-over and trace able feature
	4	A	50	Neck and traceable fracture

for geophysical investigations in areas outcropped by hard lateritic pan since no pegging of electrodes are required. It is however, limited in areas of cultural interference and maximum exploration depth of 60m.

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