Empirical analysis of electromagnetic profiles for groundwater prospecting in rural areas of Ibadan, southwestern Nigeria

O. A. Ehinola · A. O. Opoola · H. A. Adesokan

Abstract The Slingram electromagnetic (EM) survey using a coil separation of 60 and 100 m was carried out in ten villages in the Akinyele area of Ibadan, southwestern Nigeria to aid in the development of groundwater. Five main rock types including an undifferentiated gneiss complex (Su), biotite-garnet schist/gneiss (Bs), quartzite and quartz schist (Q), migmatized undifferentiated biotite/hornblende gneiss (M) and pegmatite/quartz vein (P) underlie the study area. A total of 31 EM profiles was made to accurately locate prospective borehole sites in the field.

Four main groups with different behavioural patterns were categorized from the EM profiles. Group 1 is characterized by a high density of positive (HDP) or a high density of negative (HDN) real and imaginary curves, Group 2 by parallel real and imaginary curves intersecting with negligible amplitude (PNA), Group 3 by frequent intersection of a high density of negative minima (FHN) real and imaginary curves, and Group 4 by separate and approximately parallel (SAP) real and imaginary curves. Qualitative pictures of the overburden thickness and the extent of fracturing have been proposed from these behavioural patterns.

A comparison of the borehole yield with the overburden thickness and the level of fracturing shows that the borehole yield depends more on the fracture density than on the overburden thickness. The asymmetry of the anomaly was also found to be useful in the determination of the inclination of the conductor/fracture.

Résumé Une prospection électromagnétique Silgram (EM) utilisant une séparation de 60 et 100 m, a été réalisée sur 10 sites villageois dans la zone d'Akinyele, Ibadan, au Sud-Ouest du Nigeria, pour le développement de l'exploitation des eaux souterraines. De cette manière il a été possible de définir cinq principaux types de roches comprenant un complexe gneissique indifférencié (Su), un schiste gneissique à biotite et garnet (Bs), une quartzite et un schiste quartzitique (Q), un gneiss migmatisé à hornblende et biotite indifférenciées (M) et une veine de pegmatite et quartz recouvrant la zone d'étude. Un total de 31 profils EM a été réalisé de manière à améliorer sérieusement la localisation des forages de reconnaissance.

Quatre groupes principaux ont été définis sur base de leur comportement dans les profils EM. Le Groupe 1 est caractérisé par une forte densité de courbes réelles et imaginaires, positives ou négatives (HDP ou HDN). Le Groupe 2 est caractérisé par des courbes parallèles, réelles et imaginaires, superposées à une amplitude négligeable (PNA). Le Groupe 3 rassemble les densités importantes de courbes réelles et imaginaires, d'amplitude négative minimum, fréquemment intersectées. Le Groupe 4 rassemble les courbes réelles et imaginaires, distinctes et sensiblement parallèles (SAP). Les images qualitatives de l'épaisseur de la couverture et la largeur des fractures ont pu être déterminées sur base du comportement des éléments précédemment cités.

La comparaison des débits de forage, de l'épaisseur de la couche supérieure, et du degré de fracturation, montre que le débit du forage dépend plus de la densité de forage que de l'épaisseur de la couverture. L'asymétrie des anomalies a par ailleurs été très utile pour déterminer l'inclinaison des fractures conductrices.

Resumen Se llevó a cabo un levantamiento electromagnético (EM) Slingram utilizando una separación de bobinas de 60 y 100 metros en 10 comunidades en el área Akinyele de Ibadan, suroeste de Nigeria para ayudar en el desarrollo de agua subterránea. Cinco tipos de rocas principales incluyendo un complejo de gneiss no diferenciado (Su), gneiss/esquisto de granate-biotita (Bs), cuarzita y esquisto de cuarzo (Q), gneiss de hornblenda/biotita migmatizado no diferenciado (M) y vetas de cuarzo/pegmatita (P) se encuentran en el área de estudio. Se levantaron un total de 31 perfiles EM para localizar con precisión sitios prospectivos para pozos en el campo. Se distinguieron cuatro grupos principales con diferente patrón de comportamiento a partir de los perfiles EM. El Grupo 1 se caracteriza por una alta densidad de curvas reales e imaginarias positivas (HDP) o negativas (HDN); el Grupo 2 por curvas paralelas reales e imaginarias que se

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O. A. Ehinola (✉) · A. O. Opoola · H. A. Adesokan
Department of Geology, University of Ibadan,
Ibadan, Nigeria
e-mail: oa.ehinola@mail.ui.edu.ng
Tel.: 234-8033819066
Fax: 234-02-8103043

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interceptan con amplitud despreciable (PNA); el Grupo 3 por intersección frecuente de curvas reales e imaginarias con mínimos negativos de alta densidad (FHN); y el Grupo 4 por curvas imaginarias y reales separadas y aproximadamente paralelas (SAP). A partir de estos patrones de comportamiento se han propuesto cuadros cualitativos del espesor del material superficial y la extensión de fracturamiento. Una comparación de la productividad del pozo en relación al espesor del material superficial y el nivel de fracturamiento muestra que la productividad del pozo depende más de la densidad de fracturamiento que del espesor del material superficial. También se encontró que la asimetría de la anomalía era útil en la determinación de la inclinación de la fractura/conductor.

Keywords Slingram electromagnetic · Anomaly · Overburden · Fracture · Empirical analysis

Introduction

An adequate supply of drinkable water is one of the prerequisites for every type of development programme. For this reason, the efforts connected with the location, development and conservation of aquifers are of fundamental economic importance for any country. The crystalline basement rocks in Nigeria occupy more than 50% of the total land area where 40% of the rural population resides. Apart from a shortage of electricity, good roads, and other modern amenities, water is generally very scarce. The people have to travel several kilometers in search of ponds and streams whose supplies are hardly potable. This has resulted in the construction of shallow hand-dug wells, which usually dry up in the dry season. The development of bored wells to tap the aquifers has become the only alternative where feasible. Crystalline basement rocks, which have a relatively low permeability and a low storage capacity, pose some water supply problems. The last decade has witnessed a tremendous increase in the application of geophysical techniques to locate groundwater supplies particularly in crystalline rock terrain where scrupulous geological and geophysical investigations are needed to accurately site productive wells. Potentially suitable hydrogeologic properties of hard rock aquifers are generally related to the presence of fissures and fractures as well as a permeable weathered overburden (Greenbaum 1985; Beeson and Jones 1988).

There has been increased research on the evaluation, exploration and exploitation of groundwater in the crystalline basement complex of Nigeria (Amadi and Teme 1989; Olayinka 1990, 1992; Edet 1990; Nurudeen and Amadi 1990; Olayinka and Weller 1997). Application of the Slingram EM survey, the electromagnetic traversing method (EMT) using Geonics EM 34-3 and vertical electrical sounding (VES) using the ABEM SAS 300 Terameter has been extensively used for groundwater exploration. Boreholes or wells often fail to intersect suitable permeable rock, which provides the incentive for methods, which are simple to operate, cost effective, and able to locate a high yield aquifer. This study is a detailed account of the investigation to locate groundwater supplies in the rural areas of Ibadan, employing the empirical analysis of electromagnetic profiles (Slingram electromagnetic techniques).

Geological and hydrogeological setting

The study area lies between latitudes 7°27′ and 7°41′ N and longitudes 3°45′ and 4°00′ E, and is accessible by road linking Ibadan to Moniya, Oyo, Iseyin and Ayepola towns (Fig. 1). The drainage pattern in the area is dendritic (Fig. 1), and most of the rivers originate from the highland and flow south and southeast. The river channels are commonly deeply incised revealing the fresh underlying basement rocks.

The crystalline basement rocks in Nigeria have been subdivided into at least four major groups (Jones and Hockey 1964; Oyawoye 1970; Grant 1971; Elueze 1980; Rahaman and Malomo 1983). These include: the gneiss-migmatite complex of the Liberian (2,800±200 ma), the older granite of the Eburnean (1,900±250 ma), the metasediments of the Kibarian (800–1,000 ma) and the younger granite of the Pan African (550±50 ma) orogenies. However, two of these groups (gneiss-migmatite complex and the metasediments) underlie most of Ibadan and the neighbouring towns. The main rock types present in the study area include: undifferentiated gneiss complex (Su), biotite-garnet schist/gneiss (Bs), quartzite and quartz schist (Q), migmatized undifferentiated biotite/hornblende gneiss (M), and pegmatite/quartz vein (P) (Fig. 2).

The gneisses are leucocratic, and medium to coarse grained, migmatitic and often banded in foliation (Ehinola 2002). They occur as migmatized undifferentiated biotite/hornblende gneiss (M), an undifferentiated gneiss complex (Su) and biotite garnet schist/gneiss (Bs). The migmatized undifferentiated biotite/hornblende gneiss (M) covers about 57% of the study area (Fig. 2), showing alternation of mafic and felsic minerals. Samples are commonly fine to medium grained, with biotite, hornblende, feldspar and quartz as the dominant minerals. The undifferentiated gneiss complex (Su) and biotite-garnet schist/gneiss (Bs) are composed principally of feldspar and quartz with variable proportions of hornblende and biotite occurring as dark streaks and bands. Samples are commonly fine to medium grained. The gneisses with a high content of mafic minerals may weather to clayey soils and a regolith cover while the coarse grained, more granitic components may account for soils with more varying textures and less clay. Some of the gneisses may also contain in excess of 70% quartz, with muscovite and minor occurrences of calcite, magnetite and zircon (Oyawoye 1970).

The metasediments occur as quartzite and quartz schist (Q). The schists usually occupy the low-lying areas while the quartzites form the ridges. Samples are medium to coarse grained, jointed and fractured and contain minerals like quartz, feldspar and mica. Quartzites usually develop an integrated network of fractures, joints and planes of schistocity that aid the weathering processes. Calcsilicates are also known to occur within the schist belt and are

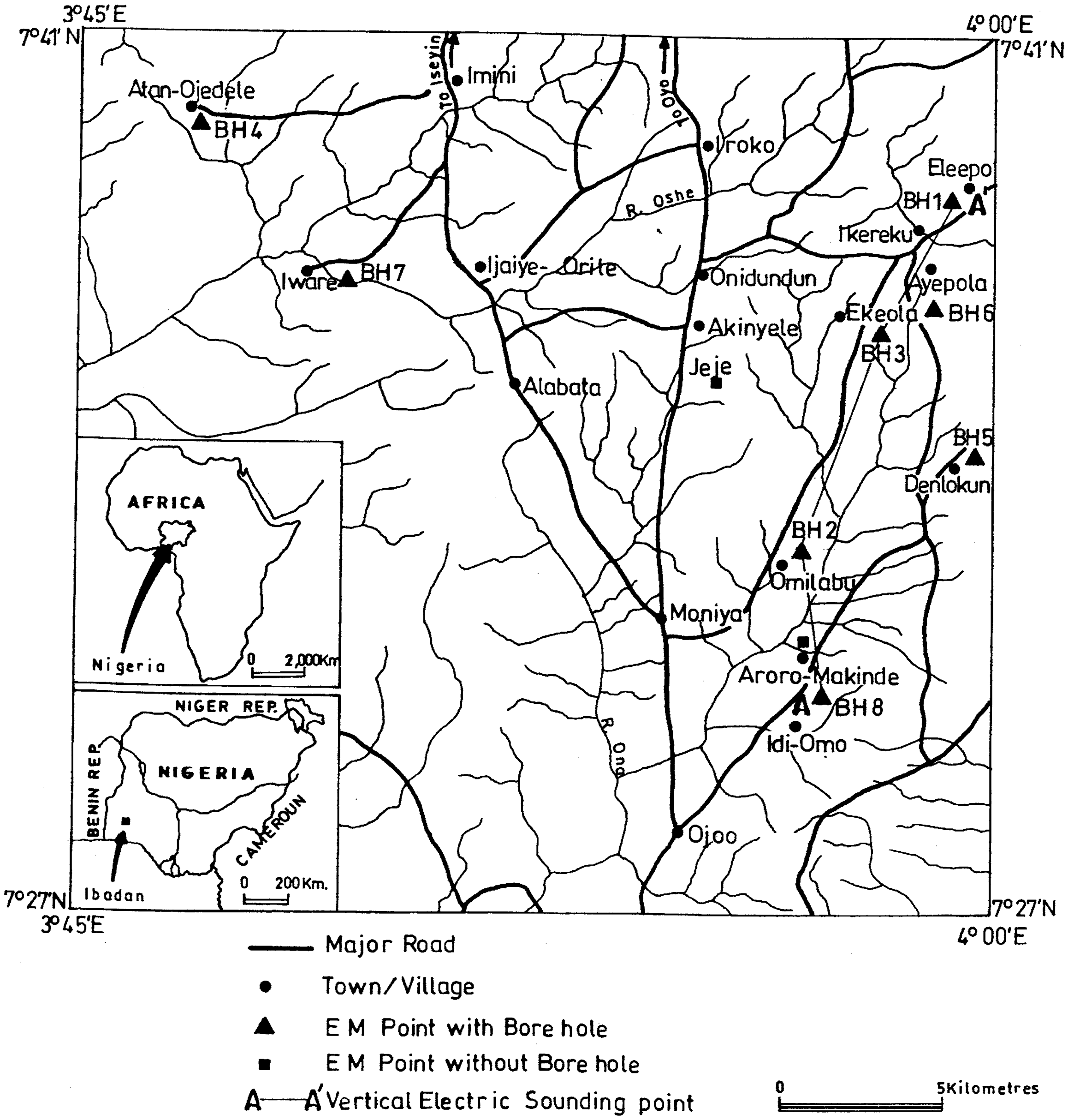

Fig. 1 Map of the study area showing access route, drainage and borehole locations

perhaps responsible for the occurrence of calcium feldspars (Elueze 1980).

In general, the various rock types of the basement complex weather to a regolith rich in sand and clay. The clay content varies in relation to the ferromagnesian and feldspar content of the parent material. The weathering of pegmatite and quartzites, for instance, introduces rock fragments and gravels. Pegmatites also contain feldspar, which readily weathers into kaolinite or illite depending on the hydrous nature of the environment and the pH of the soil (Amadi and Teme 1989). Schists tend to weather into a clay-rich regolith with a sand fraction high in quartz.

Within the crystalline basement rock region, two types of aquifer systems occur, which include: the fractured basement rocks and the weathered basement rocks (Greenbaum 1985; Beeson and Jones 1988). These two types usually occur together in the same profile, although they cannot be said to be mutually exclusive because at some places only one form occurs. The fracturing of the crystalline basement rocks is caused mainly by earth movement (tectonism). The capacity of the crystalline basement rocks to store water, allow its movement, and yield water chiefly depends on the extent, size, aperture and continuity of the fractures and on the degree to which the fractures are hydraulically connected. Aquifers formed by the weathering of the basement rocks are mainly in-situ decomposed rocks and water usually occur in the granular pores of the overburden material. In order to form a productive aquifer, the weathered profile must attain a minimal areal extent and thickness and have sufficient hydraulic conductivity and storage to yield groundwater to wells and boreholes that tap its fractures and/or fissures (Acworth 1987). Recharge is dependent on

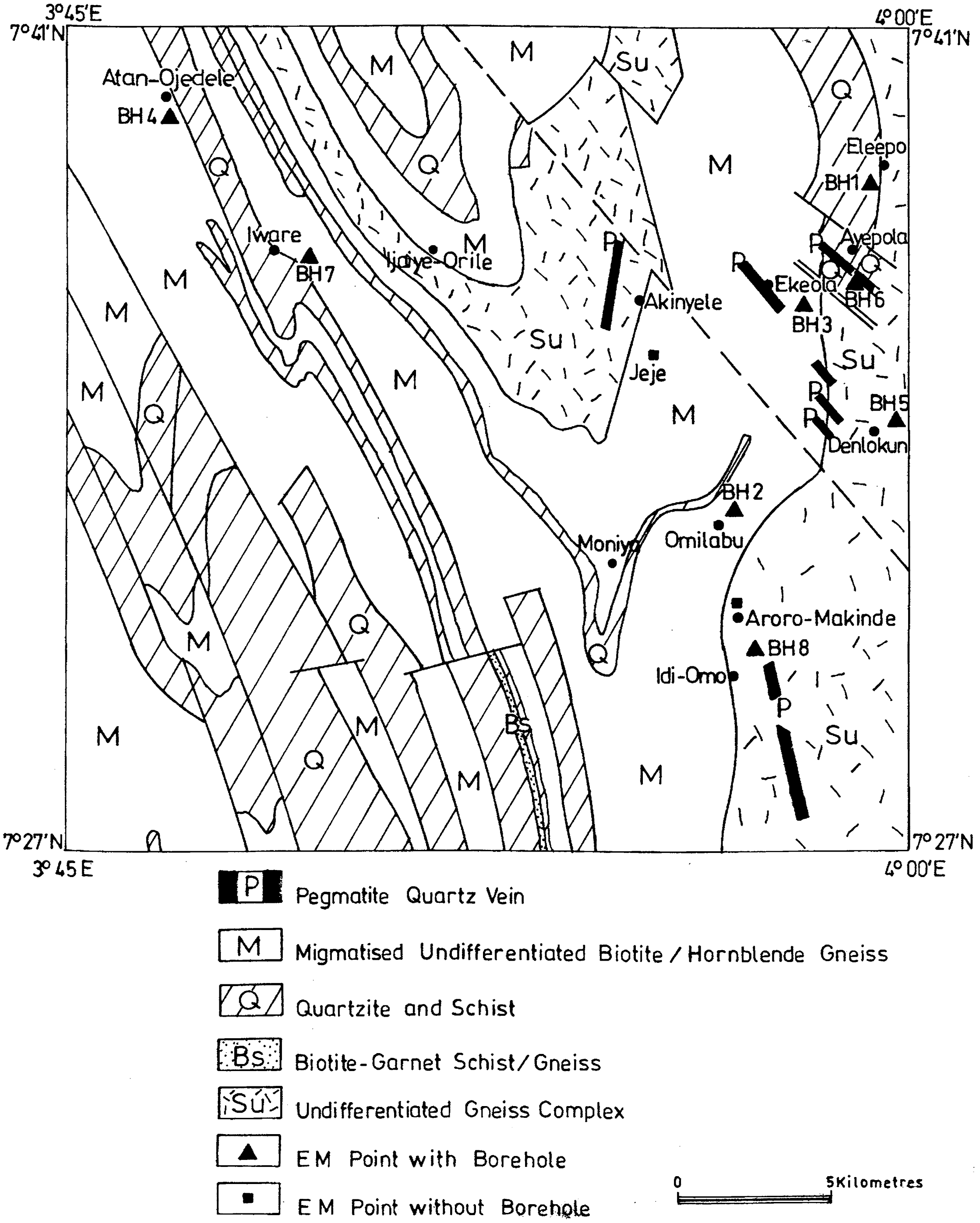

Fig. 2 Geological map of the study area (modified from Jones and Hockey 1964)

the variation in rainfall between the rainy and dry seasons, being dominant in the rainy season. The depth of weathering, saturated thickness and dimensions of the aquifers in the overburden determine the volume of water that can be held in storage.

The most productive boreholes in the basement rock terrain are always those that penetrate the fractured and fissured rock (Beeson and Jones 1988). The fractures account for a high permeability while the weathered overburden provides a high storativity. In the case of a weathered basement rock aquifer either a hand-dug well or a borehole can be used to abstract the water. Some other processes have also been recently invoked which involves downscaling methodology combining GIS and multicriteria analysis to delineate field prospecting zones (Taylor and Howard 2000; Lachassagne et al. 2001).

In the study area, four vertical electrical soundings (VES) were made to identify the hydrological characteristics and thickness of subsurface layers (Ehinola et al. 2001). The results of the soundings show a system of three to four

Table 1 Summary of the VES interpretation

VES/villages	Layer	Resistivity (Ohm-m)	Thickness (m)	Lithology	Hydrogeological significance
1	1	137.2	0.92	Top soil	–
Idi-Omo	2	144.2	5.83	Clay	Aquitard
	3	57.7	3.38	Sandy Clay	Medium aquifer
	4	24.3	4.91	Weathered basement	Probable water saturated fissures present
2	1	428.4	2.46	Top soil	–
Omilabu	2	21.5	0.92	Clay	Aquitard
	3	405.6	–	Weathered basement	Probable water saturated fissures present
3	1	200.0	0.31	Top soil	–
Ekeola	2	17.1	0.61	Clay	Aquitard
	3	48.0	0.91	Sandy clay	Medium aquifer
	4	58	4.61	Weathered basement	Probable water saturated fissures present
4	1	174.6	1.5	Top soil	–
Eleepo	2	82.1	7.0	Clay	Aquitard
	3	19.5	0.6	Sandy clay	Medium aquifer
	4	25.1	11.3	Weathered basement	Probable water saturated fissures present

geoelectric layers (Table 1) with varying thickness of lateritic clay (0.5–2.1 m), clay (0.3–18.8 m), sandy clay (1.1–22.6 m) and weathered basement rocks (2.4–28.2 m).

Data collection and analysis

The Slingram electromagnetic unit (Maxmin 1–6 model) with an operating frequency of 3.6 kHz was used. Both the transmitter and the receiver were connected and oriented in a coplanar fashion with a separation distance of 60 and 100 m. Measurements were taken at 10 m intervals.

At each measuring station, the readings of the real (Inphase or I/P) and the imaginary (Out of Phase or O/P) components of the secondary field are recorded and confronted with the respective readings of the primary fields which are simultaneously transmitted to the subsurface through the cable connecting both the transmitter and the receiver. Two or more profiles at about 10–15 m apart are made at each location. The electromagnetic traverse (EMT) was carried out in different directions.

In similar electromagnetic surveys, a qualitative interpretation of dip, depth and ground conductivity quality is made (McNeill 1980). The technique involves a plot of the secondary to primary electromagnetic fields against the EM profile distance. The plot enables one to interpret a favourable fracture and weathered zone target. A minimum depth of 60 m can be penetrated using 40 m coil spacing and the coils in the vertical dipole mode (McNeill 1980; Olayinka 1992). The objective of a well siting traverse is to locate areas where the pattern of ground conductivity matches a hydrogeological and geophysical model for a high yield aquifer (Palacky et al. 1981). Where foliation is apparent in the rocks, traverses are conducted perpendicular to the strike of the foliation.

The geophysical model or target is based on experience in a particular region (Palacky et al. 1981). Three common models for high-yield aquifers in crystalline rock in order of relative importance are the deep weathering zone,

Fig. 3 Basic criteria for picking conductive zones. ‘A’ is a minimum inflection flanked by maxima, and ‘B’ is identical shapes of real and imaginary curves

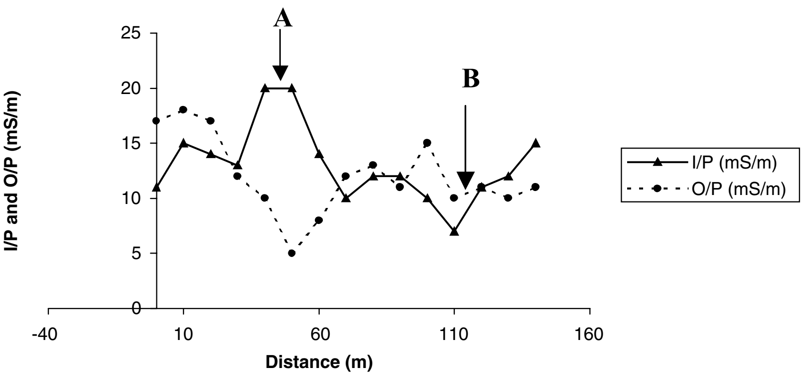

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Table 2 Slingram electromagnetic survey data for Groups 1, 2, 3 and 4

mS/m	Group 1								Group 2		Group 3		Group 4	
	Eleepo village profile 3 (BH-1)		Omilabu village profile 3 (BH-2)		Denlokun village profile 1 (BH-5)		Iware village profile 1 (BH-7)		Ayepola village profile 4 (BH-6)		Ekeola village profile 2 (BH-3)		Atan Ojedele village profile 3 (BH-4)	
Distance (m)	I/P	O/P	I/P	O/P	I/P	I/P	I/P	O/P	I/P	O/P	I/P	O/P	I/P	O/P
0	5.0	8.6	5.7	4.0	−1.0	−5.6	11.0	4.5	−3.0	−3.4	−2.4	−1.2	7.0	3.8
10	3.6	9.1	6.5	6.3	−2.6	−5.2	10.0	5.3	−3.3	−3.8	−3.0	−0.5	7.5	3.6
20	4.0	10.0	5.0	3.5	−1.5	−5.3	9.6	5.4	3.4	−3.4	−1.4	−0.3	8.4	4.5
30	3.7	12.5	3.4	1.5	−2.0	−4.9	9.2	7.6	3.4	3.2	−1.5	−1.2	6.4	4.4
40	4.0	12.0	4.5	2.2	−2.2	−4.6	9.2	7.9	3.4	3.6	−1.7	−2.5	6.0	1.0
50	2.5	11.0	3.4	0.3	−2.0	−4.6	11.0	8.0	3.7	3.7	−1.6	−1.6	6.3	1.6
60	6.0	13.0	4.1	1.6	−1.8	−4.0	9.2	5.6	3.6	3.6	−1.6	−0.2	7.5	2.9
70	2.6	10.0	5.2	2.1	−1.8	−2.0	8.5	4.6	4.5	4.6	−1.0	−0.5	5.5	−0.2
80	6.0	11.0	5.8	4.5	−2.6	−4.5	11.0	7.0	4.5	4.6	−0.5	−0.8	7.2	1.9
90	2.0	6.8	6.4	5.9	−3.5	−2.0	11.0	7.1	4.6	4.6	−0.6	−0.7	5.5	2.4
100	8.4	15.0	7.0	7.4	−4.0	−2.0	12.0	8.0	5.0	5.0	−1.3	−0.5	7.7	3.9
110	5.6	10.0	5.9	6.4	−3.6	−1.5	13.0	7.6	5.2	5.5	−2.2	−1.7	3.6	−0.3
120	4.5	8.3	8.0	8.5	−2.0	−1.5	12.5	9.0	5.0	5.4	−0.7	−2.6	5.5	0.0
130	5.3	7.7	7.0	7.2	−1.2	−2.0	11.0	8.4	4.8	5.1	−1.5	−4.1	5.2	−0.6
140	4.0	10.0	6.5	8.4	−1.8	−1.5	8.0	4.4	4.8	4.8	−2.2	−3.5	5.0	0.0
150	3.4	11.0	4.9	5.4	−6.0	−1.7	10.0	3.2	5.1	5.1	−0.8	−2.7	4.5	−0.5
160	3.9	12.0	4.5	3.2	−5.0	−1.5	10.0	8.4	5.3	5.4	−0.8	−2.4	5.7	2.4
170	2.7	14.0	2.5	−0.3	−5.0	−1.6	9.9	6.4			−0.8	−2.0	6.9	4.7
180	1.7	1.0	2.2	−0.6	−4.0	−1.7	9.6	4.5			−0.4	−1.5	5.6	2.9
190	2.2	9.0	3.9	−1.0	2.0	−2.0	11.0	4.5			−0.6	−1.2	7.0	3.5
200	3.5	13.0	2.6	−2.2	0.2	2.0	14.0	7.2			−1.2	−1.2	5.5	1.9
210	0.6	10.0	5.0	−0.6	−4.0	3.0	13.0	7.4			−1.6	−1.4	4.6	0.9
220	−1.0	9.5	5.5	1.4	−2.5	−4.5	12.5	8.0			−1.5	−1.3	4.0	0.5
230	0.2	11.0	5.0	2.4	−3.5	−3.0	12.0	6.3			−2.5	−3.2	5.0	0.8
240	2.5	10.0	17.5	5.0	−4.5	−4.0	16.0	11.0			−2.5	−2.0	3.9	−0.1
250	0.6	9.9			−5.5	−5.6	14.0	9.3			−2.0	−2.3	4.2	0.4
260	−0.5	9.3			−5.3	−5.3	16.0	8.4			−1.3	−1.6	4.5	0.0
270	−0.8	8.3			−4.0	−1.0	−1.0	−8.5			−1.5	−1.0	3.5	−0.6
280	1.6	5.5			−2.5	−0.6	14.0	4.0			−1.4	−1.0	4.0	0.0
290	−2.5	7.4			−3.5	0.6	11.0	3.2			−1.0	−0.8	4.0	0.5
300	−0.4	7.6			−2.5	2.0	11.0	2.0			−2.5	−1.2		
310	0.3	8.0			8.0	−2.0	9.6	1.5			−2.5	−1.6		
320	1.2	6.9			0.5	−4.5	15.0	5.5			−2.2	−1.9		
330	1.0	7.3			−0.2	−3.8	−10.0	−13.0						
340	1.5	7.6			−1.0	−4.0	11.0	2.6						
350					−1.5	−2.5	12.0	5.7						

Table 2 Continued.

mS/m	Group 1								Group 2		Group 3		Group 4	
	Eleepo village profile 3 (BH-1)		Omilabu village profile 3 (BH-2)		Denlokun village profile 1 (BH-5)		Iware village profile 1 (BH-7)		Ayepola village profile 4 (BH-6)		Ekeola village profile 2 (BH-3)		Atan Ojedele village profile 3 (BH-4)	
Distance (m)	I/P	O/P	I/P	O/P	I/P	I/P	I/P	O/P	I/P	O/P	I/P	O/P	I/P	O/P
360							14.0	5.9						
370							9.4	4.8						
380							11.0	10.0						
390							10.0	9.7						
400							6.9	5.4						
410							9.2	5.5						
420							8.0	4.8						
430							7.3	3.6						

the fracture zone and the vertical highly conductive dike. Often, local experience is used to define a target value for apparent conductivity, which may be a function of the measured groundwater and electrical conductivity, annual regional precipitation, or general rock type (Beeson and Jones 1988).

In this study, however, all available borehole information, especially with respect to the depth to basement rock and yield, was incorporated into the interpretation as a geological control. Two basic criteria were used to pick conductive zones in the basement rock terrain using EM (de Rooy 1986). These include: a minimum inflection flanked on either side by maxima, and for a productive borehole, the real (I/P) and imaginary (O/P) curves should have identical shapes (Fig. 3).

Results and interpretation

The In-Phase (I/P) and Out of Phase (O/P) data (Table 2) obtained from the EM profiles were used to categorize the observed behaviour pattern of the 31 EM curves which were made. An attempt was also made to relate these patterns to hydrogeologic and geologic conditions of the study area. The EM profiles selected for each group of behavioural patterns are shown in Figs. 4–7. Four main categories of curves were observed and interpreted from the 31 profiles.

Group 1: High density of positive (HDP) or high density of negative (HDN) real (I/P) and imaginary (O/P) data points

The predominance of HDP real and imaginary data points is an indication of minor fractures and relatively thick overburden (Fig. 4a). This is observed at profile 2 (BH-7) of Iware village with an overburden thickness of 26.7 m and a yield of 1.00 l/s (Table 3). Other profiles in this category include Eleepo [profiles 3 (location of BH-1) and 4], Iware (profiles 1, 3 and 4), Atan Ojedele (profiles 1 and 2), Omilabu [profiles 2 and 3 (location of BH-2)], Idi-Omo [profile 1 (location of BH-8)], and Jeje (profiles 1 and 2) villages. However, HDN real and imaginary data points indicate relatively shallow overburden but reveal major fractures (Fig. 4b). This is indicated on profile 1 (BH-5) of Denlokun village with an overburden thickness of 9 m and a yield of 1.25 l/s (Table 3). Other profiles under this group are: Ayepola (profiles 1, 2 and 3), Denlokun (profile 2), Ekeola (profiles 3 and 4), and Aroro Makinde (profiles 1 and 2) villages (Table 3).

Group 2: Parallel real (I/P) and imaginary (O/P) curves intersecting with negligible amplitude (PNA)

The appearance of approximately parallel curves with a more attenuated amplitude shows a terrain with shallow overburden. This is irrespective of the distribution of the I/P and O/P data points over the positive or negative regions

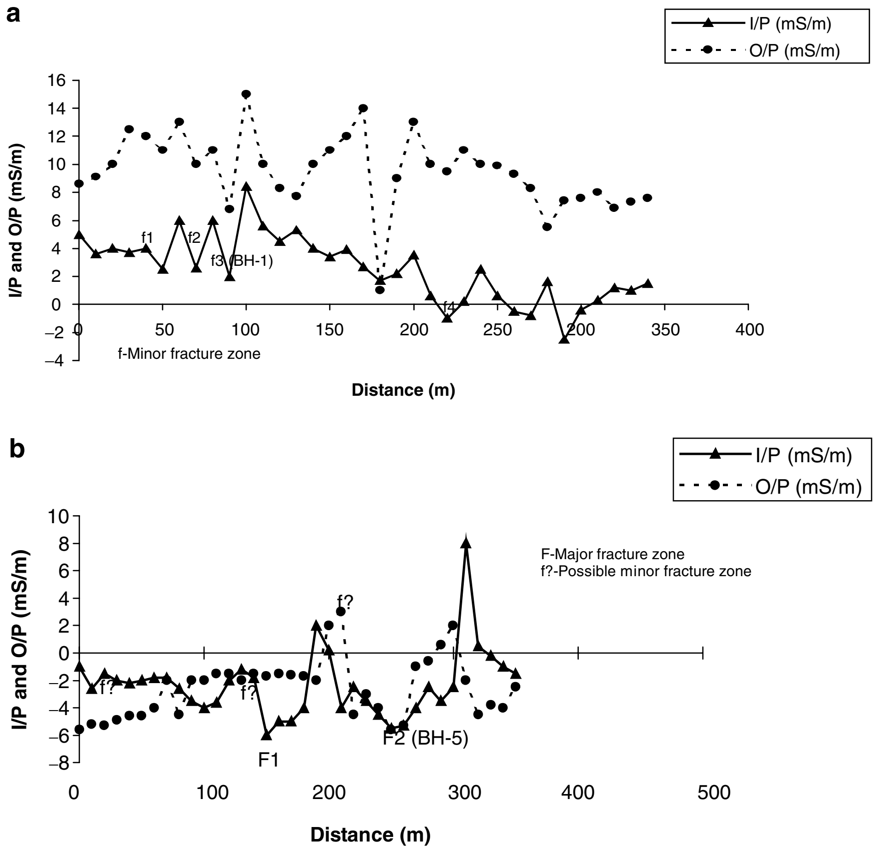

Fig. 4 a: High density of positive real and imaginary data points (HDP) at a profile in Eleepo village (Group 1) b: High density of negative real and imaginary data points (HDN) at a profile in Denlokun village (Group 1)

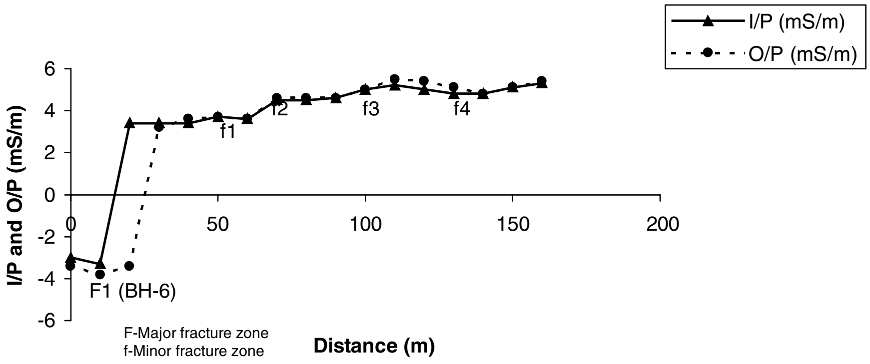

Fig. 5 Parallel real and imaginary curves intersecting with negligible amplitude (PNA) at a profile in Ayepola village (Group 2)

of the plotted EM graph (Fig. 5). This is indicated on profile 4 (BH-6) of Ayepola village with an overburden thickness of 10.2 m and a yield of 1.10 l/s (Table 3).

Group 3: Frequent intersection of a high density of negative minima (FHN)

The plotted profiles of this group indicate a multiple wave-like form with many negative anomalies of different magnitudes and frequent intersection of the I/P with the O/P curves (Fig. 6). This represents intensely fractured areas with interconnected fractures. Siting of boreholes in such areas will therefore be quite easy as there is no need to be very precise as to the exact drilling location such as on profiles 1 (of which BH-3 is located) and 2 of Ekeola village with an overburden thickness and yield of 9 m and 1.25 l/s, respectively. This group was also identified in the Gongola area of northeastern Nigeria by de Rooy (1986).

Group 4: Separate and approximately parallel (SAP) real and imaginary curves

The occurrence of separate and approximately parallel real (I/P) and imaginary (O/P) curves, which at no point intersect each other and characterizing a "Field EM profile" represent the overburden thickness in the subsurface. Whether the O/P curve is below or above the I/P curve, the basement substratum is far from the surface (thick overburden). This is indicated on profile 5 of Eleepo and on profile 3 (BH-4) of Atan Ojedele villages (Fig. 7) with an overburden

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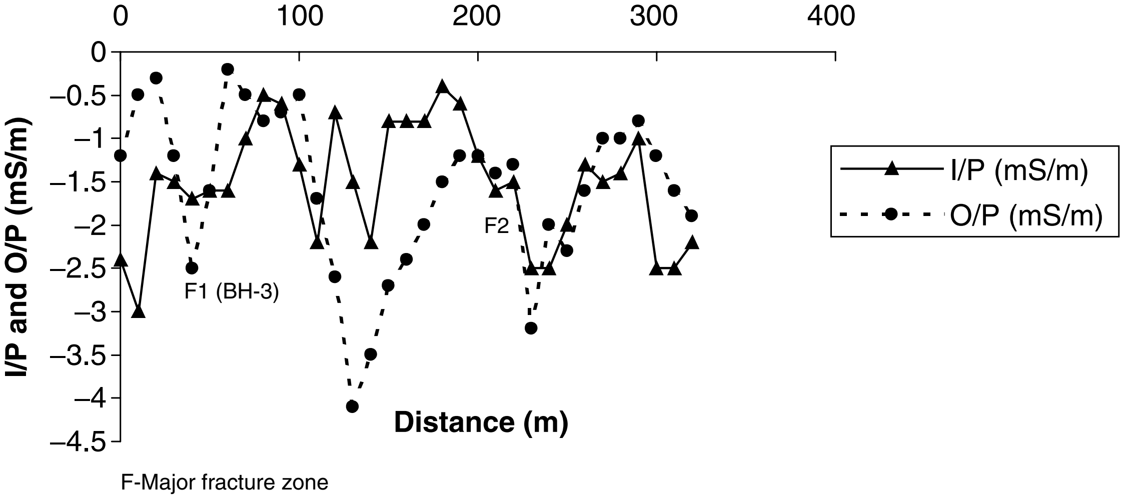
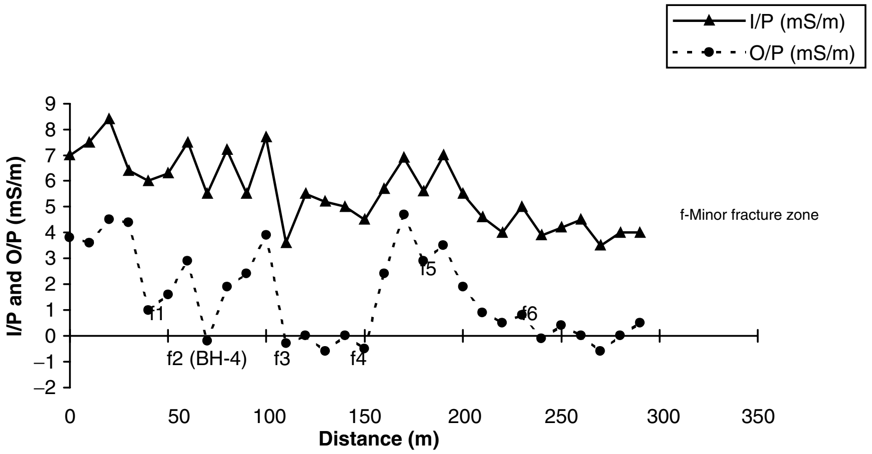


Fig. 6 Frequent intersection of high density of negative minima (FHN) at a profile in Ekeola village (Group 3)

Fig. 7 Separate and approximately parallel (SAP) real and imaginary data point at a profile in Atan Ojedele (Group 4)



thickness of 32.7 and 33 m and a yield of 1.21 and 0.90 l/s, respectively (Table 3).

Discussion

The yield of the boreholes depends not only on the overburden thickness but also on the extent of fracturing in the basement rock. The Slingram Electromagnetic (EM) data were employed to determine the overburden thickness and extent of fracturing in the study area based on their behavioural patterns. The result of the vertical electric sounding (VES) in the area indicates a system of three to four geoelectric layers with varying thickness (Table 1 and Fig. 8).

At Eleepo (BH-1), Omilabu (BH-2), Iware (BH-7) and Idi-Omo (BH-8) villages, the overburden thickness is relatively high (>20.4 m) but the wells have a relatively low yield compared to that at Denlokun (BH-5) with a shallow overburden (<10 m) and wells with a relatively high yield (Table 3). BH-1, BH-2, BH-7 and BH-8 are characterized by a high density of positive real (I/P) and imaginary (O/P) curves while BH-5 is characterized by a high density of negative I/P and O/P curves. Boreholes (BH) located in areas with the most negative anomalies produce correspondingly high yields (Nurudeen and Amadi 1990). These behavioural patterns have been classified under Group 1 with a high density of positive I/P and O/P curves representing a thick overburden and minor fractures while a high density of negative I/P and O/P curves indicate a shallow overburden and major fractures.

A Group 2 behavioural pattern is not very common in the study area, but it seems to be recognized in Ayepola village. The negative anomaly consists of major fractures and a shallow overburden while the positive anomalies have minor fractures and a relatively thick overburden (Fig. 5). The parallelism of I/P and O/P curves with negligible amplitude also make this group unique. If a borehole is sited on the negative anomaly, a shallow depth with major fractures would be encountered. However, if it were on the positive anomalies, a thick overburden with minor fractures would be encountered. BH-6 at Ayepola village has been located using this behavioural pattern in the study area, with a high density of negative real (I/P) and imaginary (O/P) data points suggesting a shallow overburden and major fractures.

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Table 3 The behavioural pattern of various profiles in the rural areas of Ibadan

Location/villages	Profiles	Behavioural pattern	Overburden thickness of the drilled borehole (m)	Bearing of profile	Estimated yield (l/s)
Denlokun	1*	HDN	9.0	50°	1.25
	2	HDN			
Atan Ojedele	1	HDP			
	2	HDP			
	3*	SAP	32.7	110°	1.21
	4	SAP			
Eleepo	1	SAP			
	2	SAP			
	3*	HDP	33.0	200°	0.90
	4	HDP			
	5	IBR			
Ekeola	1	FHN			
	2*	FHN	9.0	70°	1.25
	3	HDN			
		HDN			
Omilabu	1	SAP			
	2	HDP			
	3*	HDP	20.4	70°	1.31
Ayepola	1	HDN			
	2	HDN			
	3	HDN			
	4*	PNA	10.2	140°	1.10
Iware	1	HDP			
	2*	HDP	26.7	100°	1.00
	3	HDP			
	4	HDP			
Idi-Omo	1*	HDP	31.5	100°	1.25
	2	HDP			
Jeje	1	HDP	–	70°	–
	2**	HDP			
Aroro Makinde	1	HDN	–	90°	–
	2**	HDN			

KEY
HDN: High density of negative real and imaginary data points
HDP: High density of positive real and imaginary data points
PNA: Parallel real (I/P) and imaginary (O/P) curves intersecting with negligible amplitude
FHN: Frequent intersection of a high density of negative minima
SAP: Separate and approximately parallel real (I/P) and imaginary (O/P) curves
*Drilled profile
**Recommended profile

A Group 3 behavioural pattern is characterized by a multiple wave-like form with many negative anomalies which is an indication of major fractures. The frequent intersection of I/P and O/P curves is an indication of an intensely fractured area with possible extensive interconnections. BH-3 of Ekeola was located using this behavioural pattern, and it is important to note that the interconnectedness of the fractures would facilitate the abstraction of groundwater and there would be no need for a precise location of the drill site. Profiles 1 and 2 of Ekeola village clearly demonstrate this behavioural pattern and indicate the probability of locating a high yield aquifer in the area (Fig. 6).

A Group 4 behavioural pattern has been observed at Atan Ojedele (BH-4) and Eleepo villages, where the overburden is relatively thick (>32 m) and minor fractures predominate. This is an indication of high positive anomalies (high density of positive I/P and O/P curves). The difference between Group 1 and Group 4 is that there is a separate and approximately parallel I/P and O/P curve without any intersection (Fig. 7).

The thickness of the overburden of the various behavioural patterns shows significant variation, which is locally deeper than its mean thickness and could be related to tectonic fractures rather than the weathering of fractures

Table 4 Gradients at the drilled sites in the ten villages in the Akinyele Area of Ibadan (Ehinola et al. 2001)

Locations/villages	Drilled sites	Gradients at the drilled sites	Orientation of dip	Borehole depth (m)
Denlokun	P_1F_1 (BH 5)	0.09	Down	30.3
		0.07	Up	
Atan Ojedele	P_3f_2 (BH 4)	0.31	Down	51.5
		0.21	Up	
Eleepo	P_3f_3 (BH 1)	0.42	Up	54.5
		0.82	Down	
Ekeola	P_3f_3 (BH 3)	0.20	Up	45.4
		0.70	Down	
Omilabu	P_3F_1 (BH 2)	0.12	Up	20.1
		0.16	Down	
Ayepola	P_2F_1 (BH 6)	0.03	Down	34.8
		0.01	Up	
Iware	P_2F_1 (BH 7)	−1.35	Down	48.4
		−2.50	Up	
Idi-Omo	P_1f_3 (BH 8)	0.21	Up	45.4
		0.94	Down	
Jeje	P_2F_1 (−)	0.28	Up	–
		0.04	Down	
Aroro Makinde	P_2F_2 (−)	0.26	Down	–
		0.07	Up	

KEY
PF (f): Drilled points
BH: Borehole located

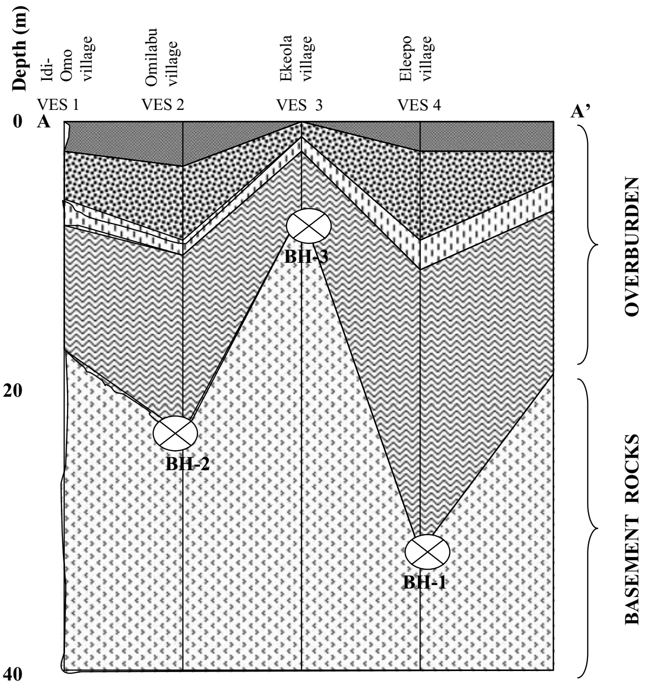

Fig. 8 Geoelectric model of the section A-A’ of Fig. 1 of the study area

in the study area. However, the thickness of the overburden aquifer (at lease when mostly saturated with water) might not influence the short-term yield of the well, but mainly the long-term yield (Taylor and Howard 2000; Lachassagne et al. 2001). The behavioural pattern of Groups 1, 2 and 4 will possibly result in short-term yields if the fractures are not interconnected while that in Group 3 will result in long-term yields as the major fractures are interconnected.

Another important factor to be considered in the siting of boreholes is the inclination of the conductor/fracture. Calculating the gradients on both sides of the conductor revealed the asymmetry of the anomalies and seems to be a diagnostic feature of the conductor, with the maximum gradient occurring on the down dip side of the conducting body (Table 4). This is consistent with the up dip side of the fracture coinciding with the smaller of the two maxima flanking the minimum inflection (de Rooy 1986) and is a very important feature when siting boreholes in the crystalline basement complex. Any shift of the borehole site towards the up dip side of the fracture, which coincides with the minimum gradient could either result in a dry or low-yield borehole. The situation is explained by the fact that groundwater usually flows down the dip of the fracture under unconfined conditions, thus the best yields are obtained, most of the time, by locating the borehole at the down dip side of the fracture.

Conclusions

Since the yields of the boreholes depend on the overburden thickness and also on the extent of fracturing in the basement rock, the empirical analysis of the EM survey in the rural areas of Ibadan has been assessed to provide hydrogeological information on the depth as well as the extent of fracturing. The empirical analysis of the EM survey revealed four groups of behavioural patterns, which has been designated as Group 1, 2, 3 and 4. Group 1 is characterized by a high density of positive (HDP) or a high density of negative (HDN) real (I/P) and imaginary (O/P) curves. If HDP predominates, a thick overburden with minor fractures is likely but, if HDN predominates, a shallow overburden with major fractures is suggested. Group 2 is characterized by the parallelism of I/P and O/P curves with a negligible amplitude (PNA) on the positive anomaly. Group 3 is characterized by the frequent intersection of a high density of negative (FHN) I/P and O/P curves indicating intensely fractured basement terrain. Group 4 is different from the other groups because there is a separate and approximately parallel I/P and O/P curve without any intersection on a positive anomaly, suggesting a thick overburden with minor fractures predominating. However, a lithological or composition change may lead to misinterpretation of the aquifer depth or thickness in the case of resistivity or EM techniques (Geonic). A combined use of empirical analysis with resistivity is useful when the need is for the rapid evaluation of the overburden thickness and level of fracturing. However, understanding the local geology as well as its relation to vertical electric soundings (VES) would definitely give a better result for borehole siting.

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