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Electromagnetic Profiling for Groundwater in Precambrian Basement Complex Areas of Nigeria

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Ground electromagnetic profiling, using a Geonics EM34-3 instrument, has been employed to identify areas of high conductivity in a Precambrian basement complex terrain of Nigeria.

Field examples, conducted as part of a rural water supply programme, are presented. They indicate that the apparent conductivities are generally lower than about 60 mmho m^{-1}. Subsequent borehole drilling suggests a good correlation between high EM34 anomalies, deep weathering and high well yield (> 1 l s^{-1}). On the other hand, boreholes sited on conductivity lows penetrated a thinner regolith with relatively lower yields.

Introduction

On account of good horizontal resolution of anomalies and cost effectiveness, electromagnetic (EM) profiling is now widely used in the selection of borehole sites in areas underlain by crystalline igneous and metamorphic rocks (Palacky *et al.* 1981, Carruthers 1985, Smith 1990, de Rooy 1986, White 1987). The aim of EM surveys is the identification of areas of high conductivity normally thought to be due to deep weathering. Sharp high conductivity anomalies can also be related to the occurrence of narrow conductive bodies such as faults, joints and dyke contact zone, all of which might be water-bearing.

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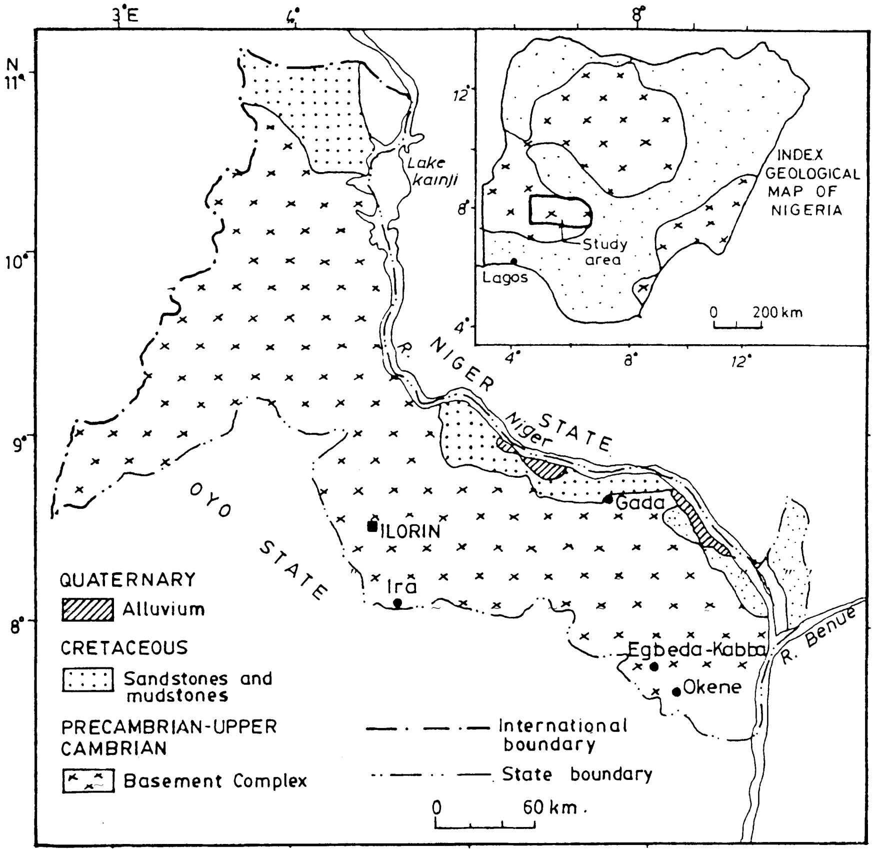

Fig. 1. Generalised geological map of Kwara State, Nigeria, showing survey locations. (inset: map of Nigeria).

During 1985, several line-kilometres of EM traverses were conducted in basement areas of central Nigeria (inset to Fig. 1), as part of integrated geophysical and hydrogeological investigations. The object of the surveys was the selection of sites suitable for the drilling of abstraction wells. This paper presents typical field examples from the Nigerian surveys.

Data Acquisition and Analysis

The Geonics EM34-3 portable instrument (McNeill 1980) was used in measuring the EM response. The theory of the operation of this Slingram method has been given by McNeill (1982); only a very brief account relevant to the present discussion is mentioned here.

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The EM34-3 equipment is operated by two workers, one carrying the transmitter coil and the other carrying the receiver. The out-of-phase signal component is calibrated to read apparent conductivity (in mmho m^{-1}) directly. Such EM systems have an advantage in tropical areas since, unlike conventional resistivity surveying techniques, they do not require ground contact for their operation; poor contact, due largely to the presence of highly indurated surficial materials, limits current flow and increases noise levels (Wait 1982).

Coil configuration was common in the horizontal dipole mode, since in this configuration the measurement is relatively insensitive to coil misalignment which can otherwise introduce errors into the readings (Keller and Frischknecht 1966). A 20 m coil spacing was normally used, with an expected maximum depth of investigation of about 15 m. However, along some of the traverses where greater depths were considered necessary the vertical dipole mode was also used, giving a maximum depth of investigation of about 30 m with a 20 m coil spacing.

Quantification of EM profile data in terms of a depth versus conductivity section for different coil spacings and different coil configurations is very difficult due to the sensitivity of EM systems to near surface conductivity variations, especially where highly conductive regoliths are present, and because the horizontal and the vertical coil systems respond differently to near-surface variations in conductivity. For these reasons, only a qualitative interpretation of the EM data has been carried out in the examples presented in this work.

To estimate the depth to bedrock, which information is not directly provided by the EM34 measurements, vertical electrical soundings were often made at conductivity anomalies. The offset Wenner array (Barker 1981) was employed, this being an extremely fast method. An ABEM SAS 300 Terrameter was used for resistance measurements. A computer-assisted quantitative interpretation of the sounding data was carried out, along the lines proposed by Koefoed (1979).

Field Examples

Field results to demonstrate the usefulness of EM34 profiling, are discussed in this section. The measurements were made in a basement area of central Nigeria (Fig. 1) in order to locate sites suitable for the drilling of abstraction wells. A typical weathering profile developed over crystalline basement complex rocks and the variation in the hydraulic properties are shown in Fig. 2. The main aquifer zone, comprised largely of zone *c*, is found at the base of the profile where mineral decomposition has produced a gravel-like material. A borehole in this terrain is often continued, as an open hole, into the solid rock. Here, the optimal feasibility for groundwater exploitation consists of maximum permeability of the rock resulting from maximum fracturing combined with maximum storage due to a maximum thickness of weathering. Even in cases without any significant transition zone and

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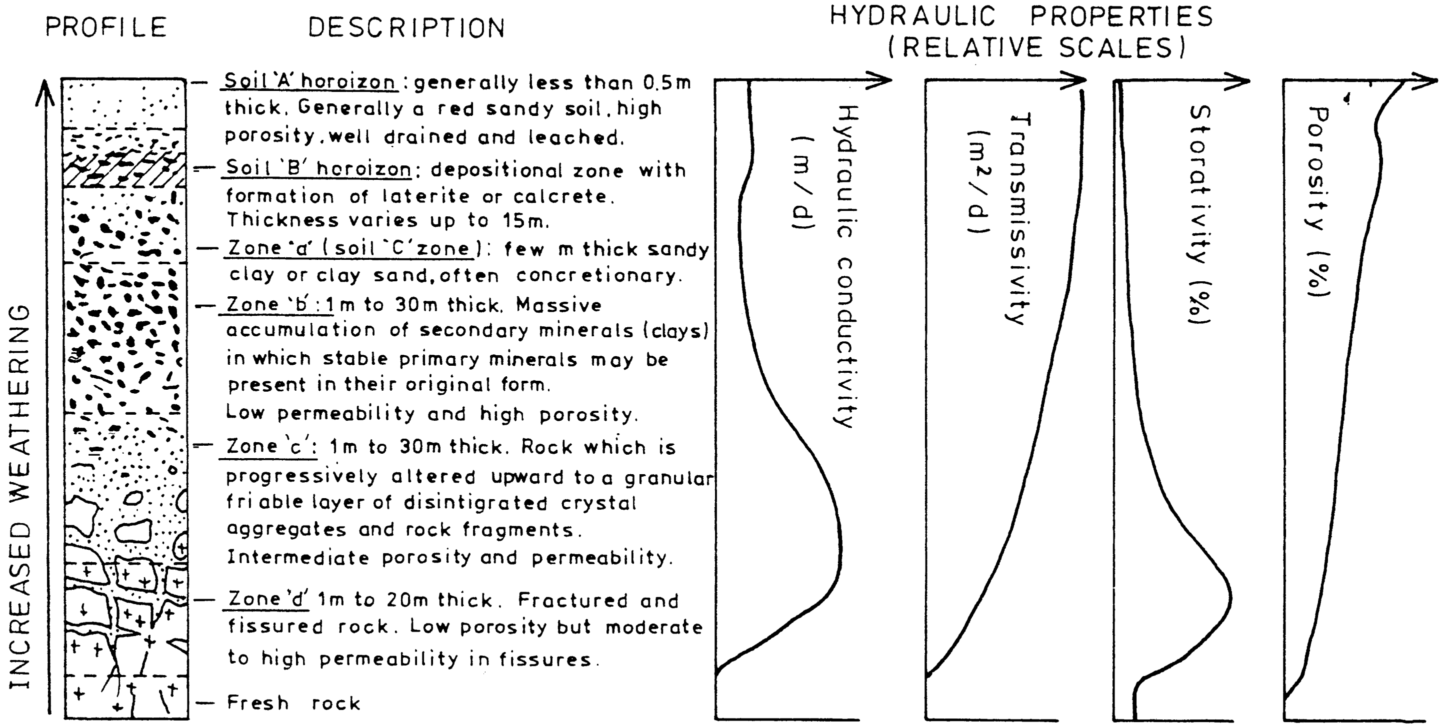

Fig. 2. Typical weathering profile developed upon crystalline basement rocks and variations in the hydraulic properties (adapted from Acworth 1987, Chilton and Smith-Carington, 1984, Buckley and Zeil 1984).

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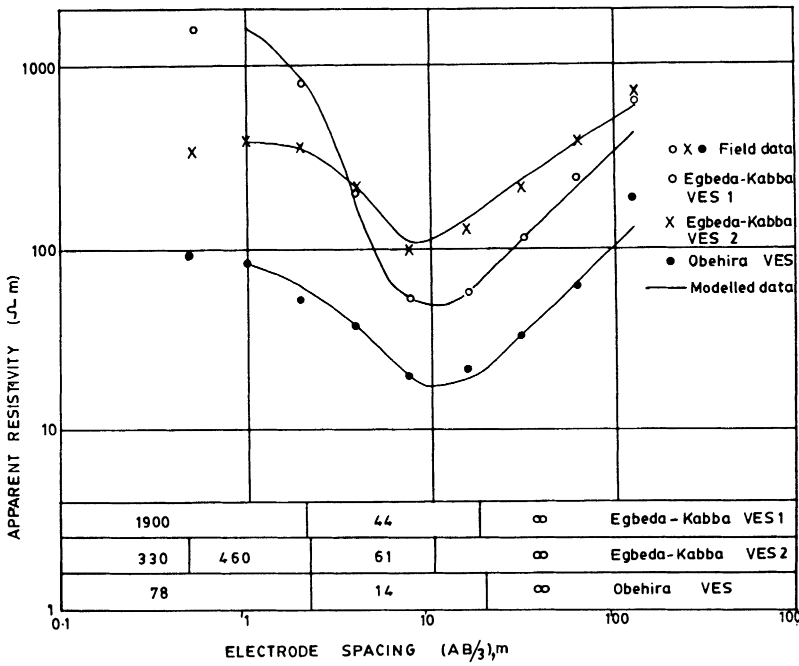

Fig. 3. Quantitative interpretation of offset Wenner soundings counducted along EM34 traverses.

with very clayey regolith, the storage of the latter can sustain a high-yielding borehole on a long term basis if the fracture system in the hard rock is widespread and well developed, and if the saturated thickness of the clayey overburden is at least 15 m (Acworth 1987, Rushton 1986, Clark 1985, Beeson and Jones 1988).

Some of the offset Wenner soundings made in the study area, and their quantitative layered earth interpretations are shown in Fig. 3.

Ira Field Example

The dominant Precambrian basement complex rock type at Ira comprises gneissic metasediments which have been weathered to form a clayey and lateritic regolith. Four boreholes, namely BH1-BH4, had been drilled in a valley south of the village (Fig. 4) before the present survey. The lithologs show that the weathered zone is generally thin and predominantly clay. Of these boreholes only BH1 was consideres productive with a yield of 1.9 l s^{-1}. An EM34 profile was made to establish any relationship between the conductivity values and the borehole yield. There are no outcrops nearby, making it difficult to ascertain the geological strike. For this reason, the survey was conducted in a grid from, both parallel and perpendicular to the stream. The horizontal diple was employed with an intercoil separation of 20 m. The entire coverage was about 4 line kilometres.

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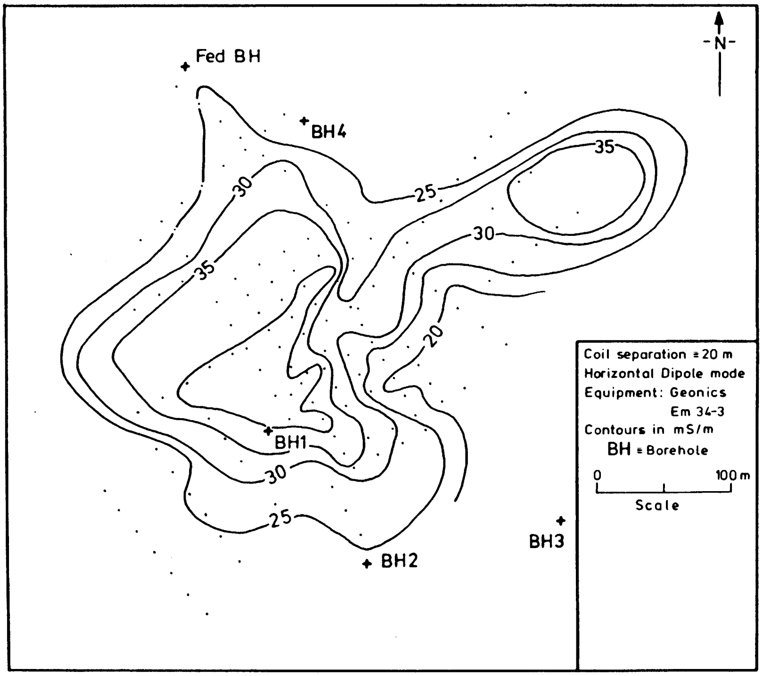

Fig. 4. Isoconductivity map, Ira survey area.

The isoconductivity map indicates a linear structure which is probably a fracture zone. There is a high conductivity anormaly (> 40 mmho m^{-1}) near the productive borehole, BH1. Conversely, the apparent conductivities are less than 25 mmho m^{-1} near the »dry« boreholes BH2 and BH4.

Egbeda-Kabba Field Example

The geological survey map of Lokoja (Sheet 62) suggests that the basement complex at Egbeda-Kabba comprises migmatised biotite gneisses intruded by granite and granodiorites. An EM34 profile was made along a N-S line near the village as part of a detailed follow-up geophysical survey to identify sites suitable for the drilling of a borehole. A coil separation of 20 m was employed, and readings were taken for both the horizontal and the vertical dipoles.

Peak readings of about 17 mmho m^{-1} for both coil configurations were observed at a distance of about 220 m along the traverse (Fig. 5a). The relatively high reading on the vertical dipole profile, which has about twice the depth of investigation of the horizontal dipole for a given coil separation (McNeill 1982), may be indicative of adequate conductance at depth. An offset Wenner sounding (VES1) made at this location (Fig. 3) indicates that the depth to the geoelectrical basement is 19.4 m and the resistivity of the prebasement layer 44 ohm.m. By comparison,

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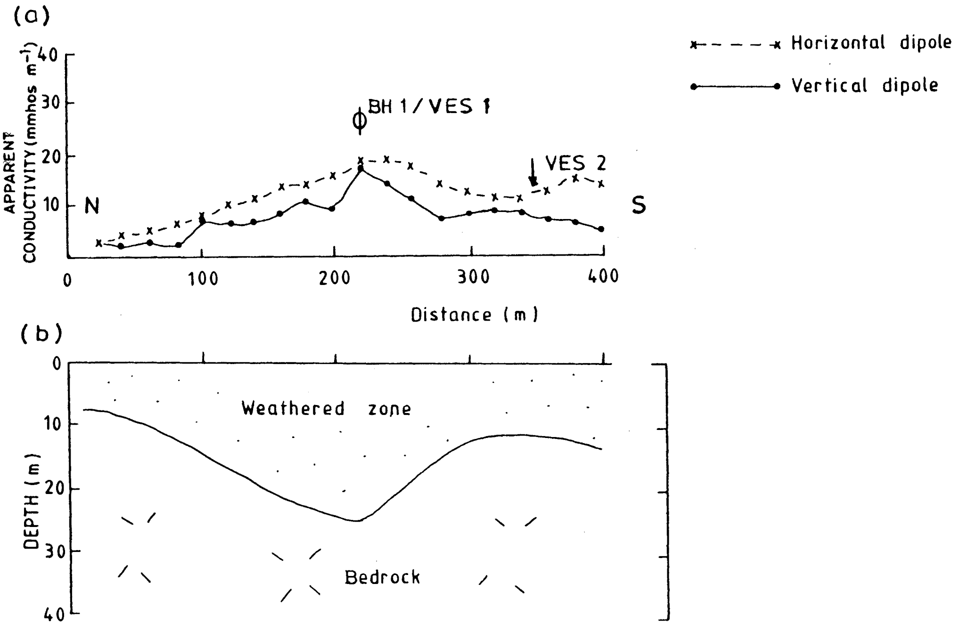

Fig. 5. (a) EM 34 traverse near Egbeda-Kabba. (b) Probable geological interpretation.

sounding VES2 conducted at another location along the traverse where the apparent conductivities on the EM34 profile are much lower gave less encouraging results with a shallower weathering of 11.4 m expected.

It was recommended that an exploratory borehole be drilled on the high conductivity anomaly where weathering and/or bedrock fracturing was considered probable. Subsequently, a borehole, Egbeda-Kabba BH1, was drilled at this location. It penetrated about 26 m of weathered gneiss. This is greater than what has been predicted from the sounding data by about 27 %. It is probable that a portion of the terminal branch on the sounding curve lies within the transitional zone between the weathered zone on top and the fresh bedrock below. The first water strike during drilling was at 7.4 m and the total depth of drilling 96 m. Pumping test was carried out for 1,300 minutes. The static water level is 2.0 m and the drawdown 33.0 m. The borehole gave a yield of 1 l s^{-1} and a transmissivity of 4.0 m^2 day^{-1} and was completed as a production well.

Obehira Field Example

The basement complex at Obehira, near Okene, consists of gneissic semi-pelites, glassy quartzite and interbedded biotite schists. An EM34 traverse near the village shows that the apparent conductivities are generally high, with peak values of about 60 mmho m^{-1} (Fig. 6a). The conductivity high at about a distance of 200 m along the traverse corresponds to a stream position.

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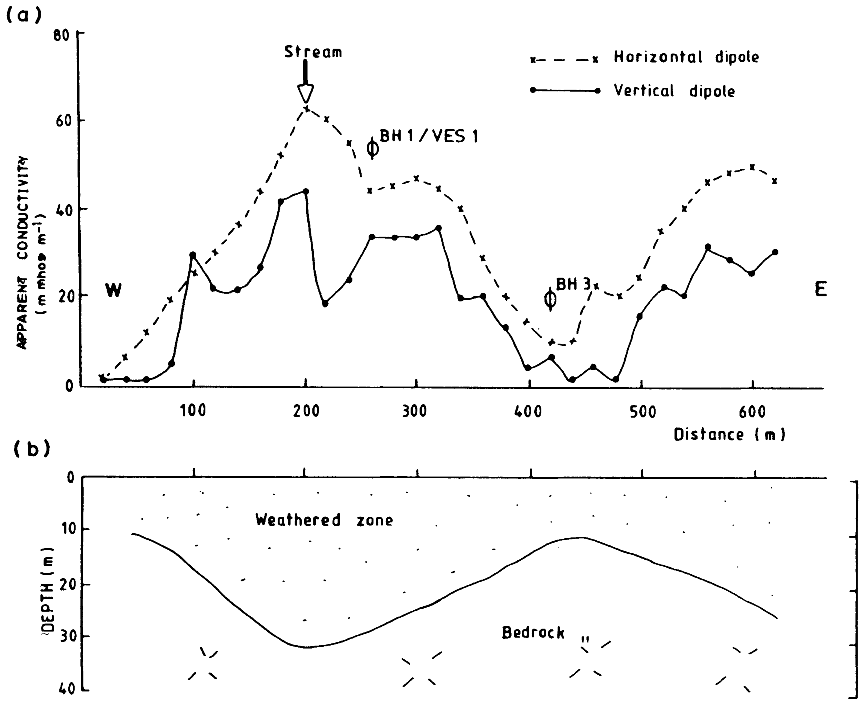

Fig. 6. (a) EM34 traverse near Obehira-Okene. (b) Probable geological interpretation.

A depth to bedrock of 21.3 m was interpreted from a sounding made within the high conductivity area (see Fig. 3). Based on the EM34 and sounding results, a borehole was drilled. The borehole, Obehira BH1, penetrated about 30 m of weathered and partially weathered/fractured materials.

Water was derived largely from fractures within the partially weathered gneiss, migmatite and schist. Water was first struck at a depth of 15.2 m and the total depth of drilling was 86 m. Pumping test was carried out for 2,600 minutes. The static water level is 1.2 m and the drawdown 25.8 m. The borehole gave a yield of 3 l s^{-1} and a transmissivity of 9.0 m^2 day^{-1}.

The sounding interpretation of a 14 ohm.m saturated weathered zone is in agreement with the high apparent conductivities in the EM34 survey. Moreover, the drilling investigations gave indications of a clayey regolith.

It is perhaps significant to mention that a borehole drilled on a conductivity low along this traverse (position marked BH3 in Fig. 6a) was much less successful with a yield of 0.5 1 s^{-1}. The weathered zone here is only about 10 m thick. The apparent conductivities measured about this location are less than 10 mmho m^{-1} as against 32 and 43 mmho m^{-1} at the location of the productive borehole BH1 at a horizontal distance of about 160 m away.

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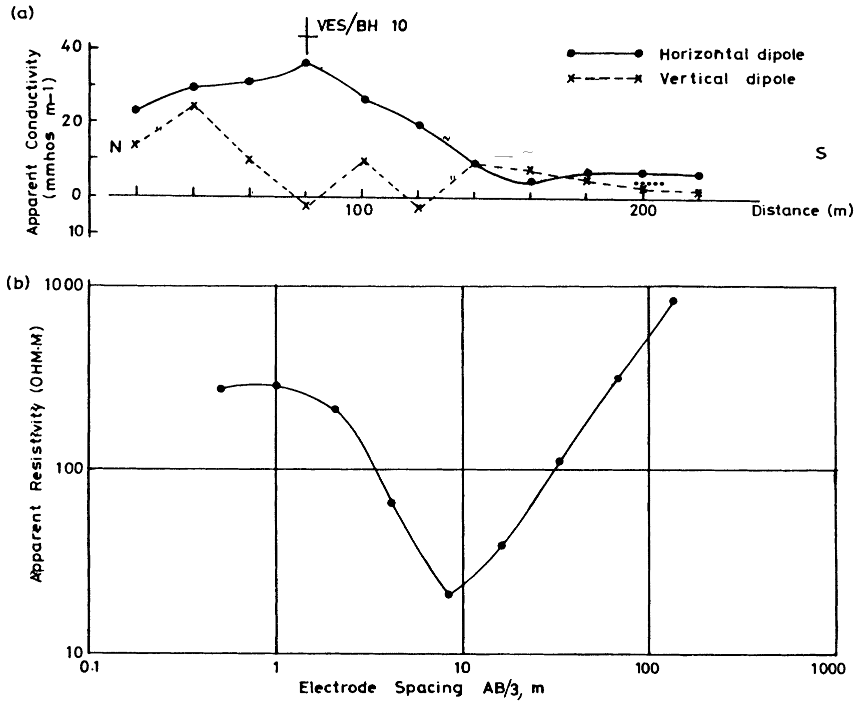

Fig. 7. (a) EM34 traverse near Gada. (b) Offset Wenner sounding curve at a conductivity anomaly, Gada survey area.

Gada Field Example

The dominant basement rock type at Gada is quartz-biotite gneiss. Most of the rock exposures are fractured and it was hoped that the fracturing would continue at depth. A 20 m coil separation was employed and measurements were taken for both the horizontal and the vertical dipole modes. A conductivity anomaly, with a high reading on the horizontal dipole and a negative reading on the vertical, was identified at a distance of 80 m along the line (Fig. 7a). Negative readings are typical of highly conductive material to which the Geonics EM34 equipment responds non-linearly (McNeill 1982).

A sounding conducted on the apparent conductivity anomaly is distorted with the terminal branch of the curve rising too steeply at an angle of about 55° with respect to the abscissa axis (Fig. 7b). It is probable that the distortion resulted from the influence of strong lateral resistivity effects on the sounding. For this reason, no quantitative interpretation has been carried out as such an exercise may not be geologically meaningful.

Based on the EM34 profiling results, it was recommended that an exploratory

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borehole be drilled on the conductivity anomaly. The borehole, Gada BH10, was subsequently drilled at this location to a total depth of 60 m. A lateritic top soil and sandy clay was penetrated to a depth of 4.5 m, with the sand content increasing with depth. The interface is at about 11 m. A highly fractured gneissic bedrock was intersected between 12-14 m. The response from this relatively shallow zone must have contributed significantly to the EM34 readings. Minor fracturing was also noted at 51 m. The first water strike was at 9.0 m while the static water level is 6.0 m. The well was pump tested for 6,000 minutes. The drawdown was 19.0 m with a discharge of 2.6 $l\ s^{-1}$. The well was completed as a production borehole.

Discussion and Conclusion

In this paper, results have been presented of the use of EM34 ground conductivity profiling in identifying deeply weathered sites and/or bedrock fracture zones in a part of the Nigerian crystalline basement complex. Borehole drilling has demonstrated that sites with high conductivity anomalies can be reasonably expected to be economic aquifers. A complex inter-relationship between apparent conductivity the clay content of the regolith (and consequently, the permeability of a weathered basement aquifer), and the probable well yield is indicated. While a very low apparent conductivity is most likely suggestive of low well yield on account of either a very shallow weathering or a large depth to the static water level, high conductivities do not necessarily imply a groundwater resource; apart from deep weathering, such conductivity highs could result from a predominantly clayey regolith.

The deductions made from this study are preliminary in nature, the inferred geological sections being influenced by electrical equivalence in the sounding interpretation for which reason they are necessarily non-unique. Further work in similar climatic and hydrogeological environments are needed before firmer predictions of the expected borehole yield could be made from a qualitative assessment of the EM conductivity values. Nonetheless, the surveys have shown that the EM surveying technique holds great promise as an exploratory tool for groundwater.

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