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Geophysical siting of boreholes in crystalline basement areas of Africa

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Abstract - This paper assesses the effectiveness of surface geophysical methods namely electrical resistivity, electromagnetic, seismic refraction, magnetic, gravity and induced polarization for groundwater exploration in crystalline basement complex areas. Most of these geophysical techniques can provide quantitative information on the characteristics of the weathered zone which relate to the occurrence of an economic aquifer. The critical factors in the choice of a particular method include the local geological setting, the initial and maintenance costs of the equipment, the speed of surveying, the manpower required as field crew, the degree of sophistication entailed in data processing to enable a geologically meaningful interpretation, and anomaly resolution. The particular advantages and limitations of each technique are highlighted.

Several case histories from Nigeria and the rest of Africa indicate that electrical resistivity (both vertical sounding and horizontal profiling) is the most widely used, followed by electromagnetic traversing. These are often employed in combination to improve upon the percentage of successful boreholes. Due to the high cost of equipment, large scale of the field operations and difficulties in data interpretation, seismic refraction is not widely adopted in commercial-type surveys. Similarly, magnetic, gravity and induced polarization are used only sparingly.

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INTRODUCTION

The availability of a groundwater resource in areas underlain by largely impermeable crystalline igneous and metamorphic rocks is commonly due to the development of secondary porosity and permeability resulting from weathering and fracturing. The economic aquifers can be identified from aerial photographs. However, the use of remote sensing technique is generally restricted to the regional study level (Jones, 1987). It is not always easy to locate the features such as faults thus identified accurately in the field due to position-fixing errors. The importance of this limitation can be appreciated when it is realised that a location error of less than 5m can make all the difference between a productive borehole and a dry hole. The reason for this is the great variability and the unpredictability of the nature of basement aquifers (Palacky *et al.*, 1981; Carruthers, 1985).

To enable a more precise siting of boreholes, and thus optimizing the utility of the groundwater exploration tools, a ground geophysical survey is often carried out. In the present work, an evaluation has been made of the effectiveness of the various geophysical methods. Important conclusions are drawn from experience from different parts of Nigeria and comparing these with case histories from similar geological settings as reported in the literature. Fig. 1 shows the distribution of crystalline rocks in Africa, while Fig. 2 presents a typical weathered profile and the variation in hydraulic properties.

BOREHOLE SITING PHILOSOPHY

To ensure maximum and perennial yields, a borehole should be sited where it can penetrate the maximum possible thickness of the regolith. In this way, adequate storativity and transmissivity can be guaranteed, the greater drawdown thus made available increasing the well yield. It has been reported, for example, that in basement areas of Zimbabwe between 20 and 25 m of overburden is the minimum required before siting a borehole (Wright, 1990). Alternatively, the presence of joints and fractures within the bedrock may lead to the development of a high permeability which can support a productive well; the cone of depression being able to spread widely and draw on sufficient storativity from even a relatively thin regolith.

Geophysical surveys can provide information on the depth to bedrock, changes in subsurface layering and lithology, the extent of saturation and porosity of the regolith, and the location of steeply dipping structures such as faults and dykes. To save time and reduce costs, it is essential to restrict the use of geophysics to the most promising areas. Therefore, goephysical surveying should normally be preceded by an examination of all available topographic maps, geological maps and aerial photographs. Lineations interpreted from landsat images, aeromagnetic and airborne electromagnetic data can be chosen as prospective target for a more detailed ground geophysical investigation. The physical properties of the geological section

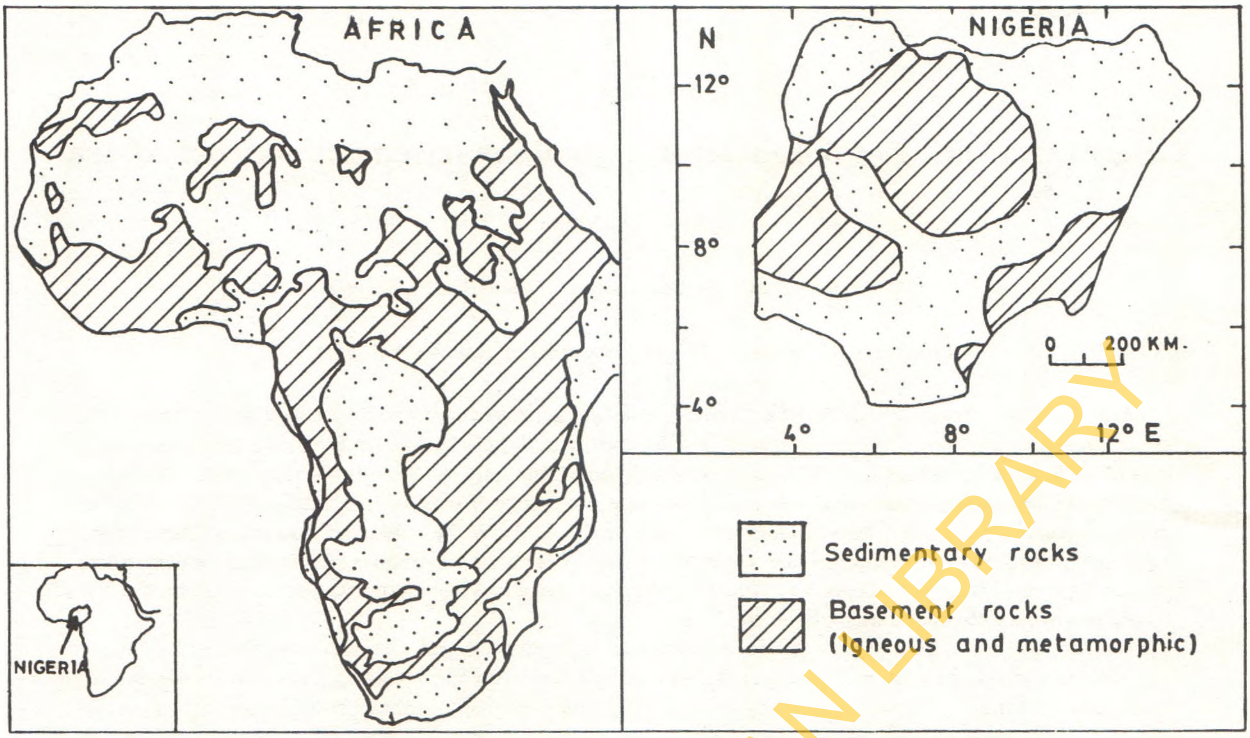
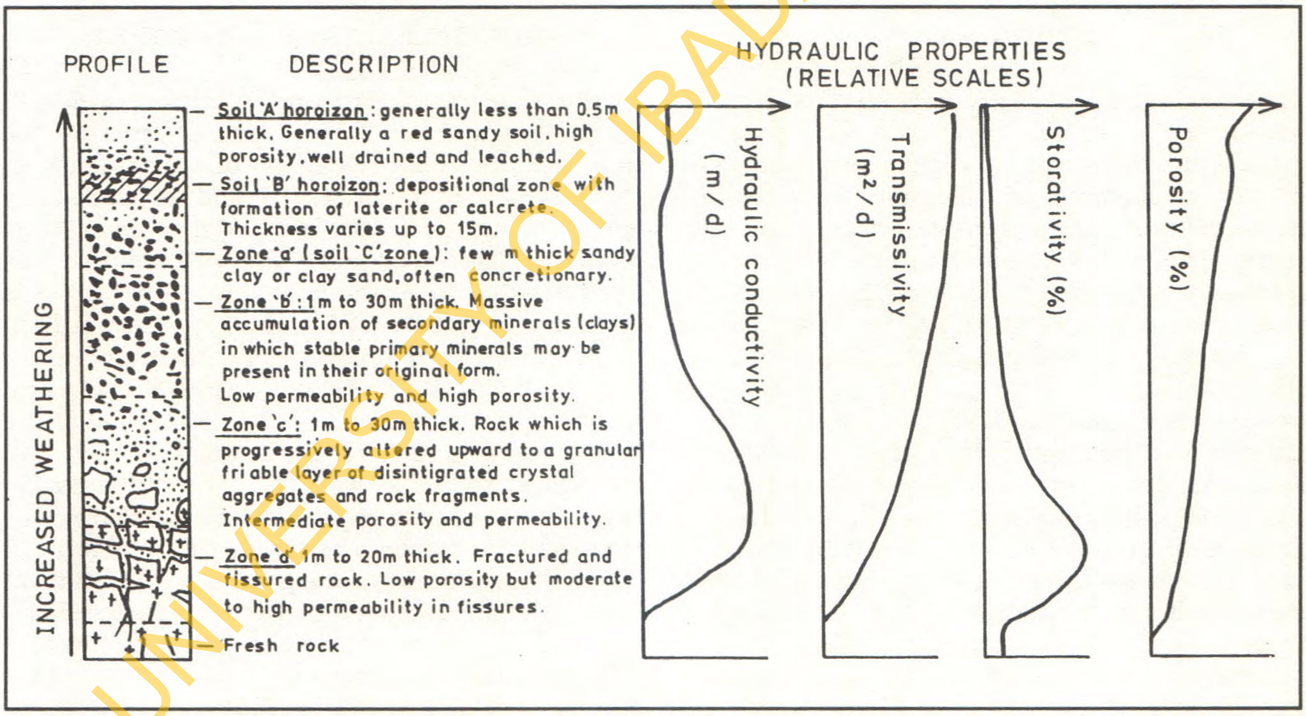


Fig. 1. Distribution of crystalline basement complex rocks in Africa (inset: generalised geological map of Nigeria).



— Soil 'A' horoizon: generally less than 0.5m thick. Generally a red sandy soil, high porosity, well drained and leached.

— Soil 'B' horoizon: depositional zone with formation of laterite or calcrete. Thickness varies up to 15m.

— Zone 'a' (soil 'C' zone): few m thick sandy clay or clay sand, often concretionary.

— Zone 'b': 1m to 30m thick. Massive accumulation of secondary minerals (clays) in which stable primary minerals may be present in their original form. Low permeability and high porosity.

— Zone 'c': 1m to 30m thick. Rock which is progressively altered upward to a granular friable layer of disintigrated crystal aggregates and rock fragments. Intermediate porosity and permeability.

— Zone 'd' 1m to 20m thick. Fractured and fissured rock. Low porosity but moderate to high permeability in fissures.

— Fresh rock

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).

that can be determined from geophysical surveys include the electrical resistivity, seismic velocity, induced polarization, magnetic susceptibility, and density. The various surveying techniques based on these properties are outlined in the following sections.

RESISTIVITY SURVEYING

The factors which control the electrical resistivity of rocks include the amount and salinity of the water present, the amount and arrangement of the pore spaces, the matrix conductivity and the resistivity of the rock grains. All other things being

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equal, the resistivity of a water-bearing formation decreases as the amount of water present increases. The development of secondary porosity by jointing and fracturing results in a further reduction of the resistivity.

The tropical regolith, derived from the *in situ* chemical weathering of the parent rocks, is often very rich in clay. Commonly, the overburden resistivity is determined by the clay content. In the presence of even a small quantity of water, clay minerals have a high cation exchange capacity (Keller and Frischknecht, 1966). As a result, the conductivity of the pore fluid can be significantly increased. Moreover, clays can retain water by capillary action due to their fine-grained texture and this also results in a lowering of the resistivity. In this manner, the resistivity of a clay-rich regolith is normally much lower than that of more easily drained sandier materials. The highly resistive bedrock provides a good geophysical contrast, with the reflection coefficient at the base of the regolith often approaching 1.0 (Verma *et al.*, 1980). The near-surface topsoil (loose, dry, sandy/lateritic) is generally highly resistive, comprising principally undersaturated materials above the water table. Since the conductive weathered zone, which often constitutes an aquiferous unit, is bounded by highly resistive materials, resistivity measurements over tropical regoliths can generally be expected to be characterised by a low resistivity anomaly over the middle zone.

From the foregoing, the resistivity method is applicable for groundwater exploration in basement areas. Numerous case histories in the literature attest to this (e.g., Ako *et al.*, 1986; Agwunobi and Onuoha, 1988; McDowell, 1979; Martinelli, 1978; Olorunfemi and Olorunniwo, 1985). Both the soundings and profiling techniques are employed. Sounding curves in this geological setting show a basic 3-layer geoelectrical succession (Palacky *et al.*, 1981; McDowell, 1979) with the first and third layers having relatively high resistivities, characteristic of the topsoil and bedrock, respectively. The intermediate layer of low resistivity represents the decomposed crystalline rocks with a relatively high moisture content.

Based on experience from various parts of West Africa, Engalenc (1978) assigned resistivities to the various weathering units derived from different parent rock types (Table 1). While schists will commonly shear along the numerous partings to produce abundance of small fissures, the more massive granites are resistant to chemical weathering unless when subjected to considerable stress since they react to pressures by the formation of a few major fissures or joints (White and Chappel, 1977). A less intense degree of weathering, with a corresponding lower preponderance of clay materials is to be expected in granite areas. On the other hand, amphibolite being a high temperature rock is relatively unstable under surficial conditions for which reason it is highly susceptible to chemical weathering. For identical reasons, Houston and Lewis (1988) reported mean depth to granite and gneiss bedrocks of 18 and 29 m, respectively, in parts of Zimbabwe.

There have been attempts to correlate resistivities with the well yield. McDowell (1979) reported that in basement areas of Botswana the low yield boreholes are characterised by a generally higher resistivity level for the intermediate layer (i. e., weathered basement/saprolite). A similar conclusion has also been reached from a part of southwestern Nigeria (Fig. 3).

Since the yield of boreholes also relates to bedrock fissuring, it is not unexpected that high yields could be recorded from areas of both shallow and deep weatherings. This probably partly explains the low correlation coefficient reportedly observed between the depth to bedrock and the well yield (Lewis, 1990; Olotu, 1990). In instances of productive wells sited where the basement is shallow, water is derived largely from fractures in an otherwise "fresh" rock. Here, the bedrock resistivity is commonly less than about 1000 ohm-m (Verma *et al.*, 1980; White *et al.*, 1988). For example, a borehole was drilled at the location of Kuroko VES 1 (Fig. 4) where the sounding interpre-

Table 1. Typical range of resistivities (in ohm-m) for weathering units developed upon different basement rocks in West Africa (after Engalenc, 1978).

	Granite	Schist	Amphibolite
Weathered layer	25-50	10-30	5-15
Transition zone	40-200	250-400	10-80
Fresh parent rock	1500	1000	500

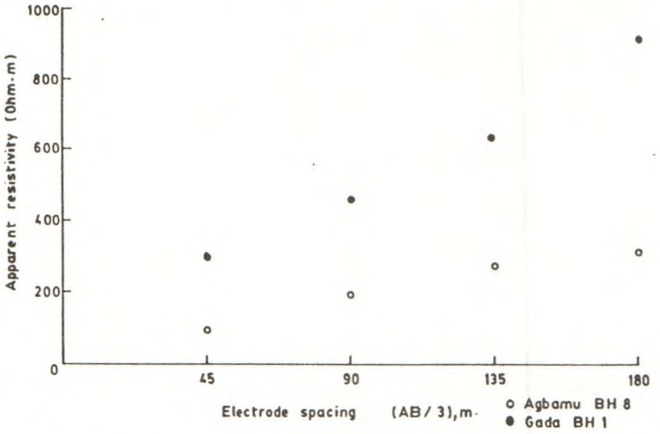

Fig. 3. Correlation of apparent resistivities (Wenner array) with well yields at two locations in Southwestern Nigeria. (Yield at Gada BH 1: 0.4 l/s; Agbamu BH 8: 4.0 l/s).

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tation indicated a depth to bedrock of 13.5m and a bedrock resistivity of 600 ohm-m. The borehole gave a very high initial airlift yield of 15 1/s, with the water being derived principally from the fractured gneissic bedrock.

The presence of a low resistivity layer sandwiched between much more resistive materials invariably causes electrical equivalence in interpretation. Theoretically at least, an infinite number of earth models in which the longitudinal unit conductance of the weathered layer is constant can fit the same set of field data. This necessarily leads to ambiguity in the interpreted layer thicknesses and resistivities. Two independent interpretations of a sounding are shown in Fig. 5 where a 52 % overestimation of the resistivity of the weathered layer in model 2 was accompanied by a 68 % overestimation in the depth of bedrock.

A relatively thin saprolite layer at the base of the weathering profile, which incidentally may be porous and permeable and thus constitute a target aquifer, may not be well resolved in the sounding interpretation. Such a layer is, in effect, suppressed. Moreover, lateral resistivity variations may make it difficult to carry out any geologically meaningful interpretation of the sounding data in terms of plane layering. Topfer (1976) discussed a field example from Zambia in which the sounding has been complicated by recumbent folding. In such instances, as well as where sub-vertical features exist, resistivity traversing is recommended (e.g., Bose and Ramakrishna, 1978).

To differentiate between near-surface geological structures and those that are more deep-seated, it is usual practice to employ more than one electrode spacing during profiling. The short spacing will be typical of the regolith while the larger spacings will be characteristic of the bedrock. The conventional approach to this involves repeated traversing of the array along a particular survey

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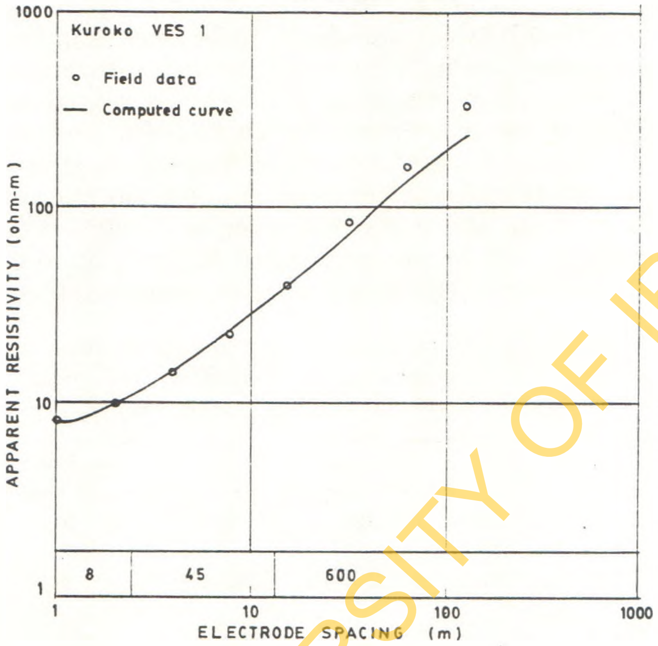
(a) Resistivity sounding interpretation



(b) Correlation of sounding result with borehole lithology

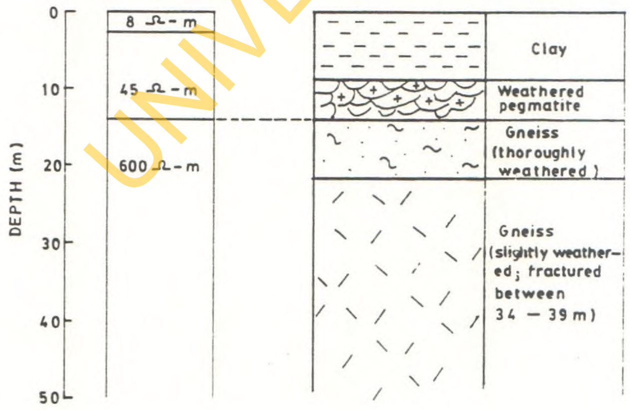


Fig. 4. Sounding interpretation at a site with a relatively shallow but fractured bedrock.

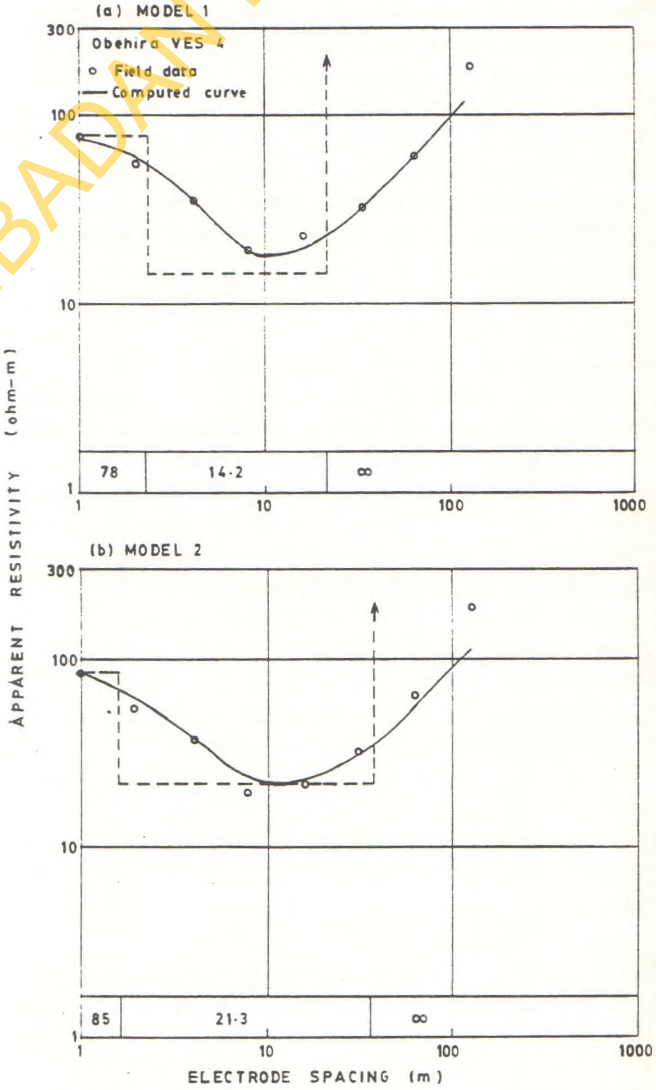


Fig. 5. Two alternative interpretations of a sounding curve (offset Wenner array).

line across the geological strike. The interelectrode separation is increased for successive traverses until sufficient data would have been acquired. Quite clearly, this procedure is slow and laborious, especially when large separations are involved. The field technique has now been automated with the development of the Microprocessor controlled Resistivity Traversing (MRT) system by Griffiths and Turnbull (1985). The MRT has been successfully employed as part of a borehole siting programme in a crystalline basement area around Ilorin and Kabba, Southwestern Nigeria (Olayinka and Barker, 1990).

A high density of water-filled fracture zones can often produce a measurable response as a low resistivity anomaly. McDowell (1979), Palacky *et al.* (1981) and Olorunfemi *et al.* (1986) have shown that over Precambrian crystalline areas of Botswana, Burkina Faso, and Southwestern Nigeria, respectively, these resistivity lows correspond to fractured bedrock. Moreover, such zones of weakness are more likely to be associated with the deeply-weathered basins than in the adjacent country rocks where weathering is much thinner.

The fracture pattern in crystalline rocks can be deduced from radial soundings in which for a sounding location apparent resistivities are measured along different azimuths (Mallik *et al.*, 1983; Olorunfemi and Opadokun, 1987; Shemang *et al.*, 1990). For an isotropic and homogeneous medium the resistivity map is a circle and any deviation from this to give an elliptical map is attributed to anisotropy. In particular, the azimuth of the major axis of the ellipse corresponds to the principal direction of the predominant structural feature causing the inhomogeneity. A field example from Southwestern Nigeria is shown in Fig. 6. The NW-SE direction of the major axis was interpreted as the orientation of the fractures. A productive borehole, with an airlift yield of 1.0 1/s, was subsequently sited within this zone.

The array in electrical soundings should be expanded along strike in order for lateral resistivity variation not to be superposed on the sounding data as this would lead to erroneous interpretation of the layer resistivities and thicknesses. On the other hand, profiling should be along azimuths at right angles to strike, this permitting measurement of the maximum apparent resistivity contrast.

Depending on the minimum electrode spacing used, narrow fracture zones might be missed by resistivity profiling. For example, it has been reported that in parts of the basement complex of Northern Nigeria the width of productive fracture zones can be as narrow as 5 m (Beeson and Jones, 1988). In such instances, electromagnetic traversing may have distinct advantages.

ELECTROMAGNETIC PROFILING

Electromagnetic (EM) profiling enables the determination of a qualitative picture of the extent of weathering. The technique has been found to be fast and cheap. Moreover, once the induction of current flow results from the magnetic component of the electromagnetic field, it does not require ground contact for its operation and this can be an advantage over the conventional resistivity surveying where poor electrode-ground contact limits current flow and increases noise levels. The depth of investigation in EM systems is directly proportional to the coil spacing and inversely proportional to both the operating frequency and the subsurface conductivity. The EM-16 VLF equipment, the horizontal loop EM and the EM 34-3 are the most commonly used EM systems.

The VLF equipment consists of a receiver and thus requires only one operator. The primary EM field is generated by powerful transmitters which may be situated thousands of kilometres away. The frequency range is generally between 15 and 25 KHz. The technique has been employed by Palacky *et al.* (1981) and Smith (1990). Some of the problems these workers have identified are that the signal strength from the closest remote transmitters may be too weak and that the strike of the conductors, which may be random, may not be favourable with respect to the available transmitters.

Palacky *et al.* (1981) employed the horizontal loop EM system with frequencies of 222, 444, 888,

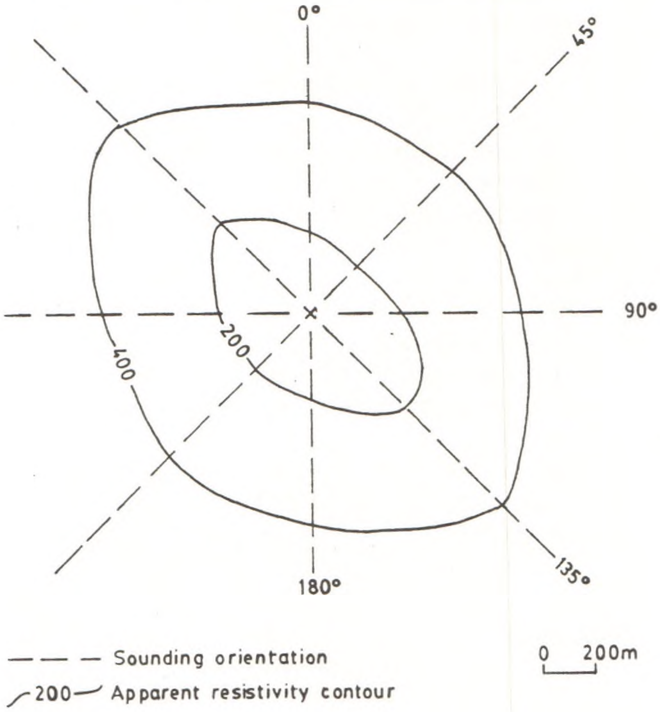


Fig. 6. Resistivity map constructed from radial soundings at Egbeda-Kabba, Southwestern Nigeria.

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1777, 3555 Hz and a coil spacing of 50 m. They established that the method is more sensitive to minute changes in resistivity than conventional resistivity profiling.

de Rooy *et al.* (1986) employed a Slingram EM unit for ground water exploration in basement areas of Kwara and Gongola States of Nigeria. The operating frequency was 3.6 KHz. The characteristic shape of the anomaly profile over conductive anomalies comprised two maxima and one minimum inflexion while the amplitude depends on the overburden thickness and the contrast in conductivity between the conductive fracture zone and the country rock. They also indicated that for the borehole to be productive, the curves of the real and imaginary components should have identical shapes.

The Geonics EM 34-3 is a portable instrument operated by two workers, one carrying the transmitter coil and the other carrying the receiver. The design of the equipment is such that the ratio of the secondary to the primary magnetic field is linearly proportional to the ground conductivity; as a result, apparent conductivity is read directly (McNeill, 1980). The coils can be carried with their planes either vertical (horizontal dipole mode) or horizontal (vertical dipole mode). Although the latter has about twice the depth of investigation of the former, it is more sensitive to coil misalignment which can introduce large errors into the readings (Keller and Frischknecht, 1966).

Smith (1990) reported the use of the Geonics EM34 in the identification of a dyke-like body in the Masvingo Province of Zimbabwe which was interpreted as a fracture system, the width of the conductive zone being given by the distance between the zero-crossing of the conductivity curve less the cable length. A borehole siting philosophy that has been widely adopted in many parts of Africa involves the use of the Geonics EM34 for rapid reconnaissance while the high conductivity anomalies thus identified are further investigated by soundings (Beeson and Jones, 1988; Hazell *et al.*, 1988; White *et al.*, 1988; Carruthers, 1990). The conductivity highs often correlate with the deeply weathered sites that are a target in hydrogeological investigations. An example from Nigeria is shown in Fig. 7.

It may be stressed that the combined use of EM34 and resistivity has often led to a significant improvement in the percentage of successful boreholes. For example, White (1986) reported a 82 % success rate with the EM method when employed alone in a groundwater supply project in Zimbabwe, while those with resistivity alone gave 85 %; on the other hand, a very high rate of 90 % was attained when the two methods were combined.

SEISMIC REFRACTION

There is often a very sharp difference in seismic velocity between the overburden and the bedrock and for this reason the seismic refraction method has a potential as an exploratory tool for groundwater in crystalline basement areas. The number of intersecting segments on the time-distance graph is equal to the number of subsurface layers. Quite commonly, the first refractor corresponds with the water table and the last correlates with the bedrock interface. The range of compressional wave velocities reported from different parts of Africa is summarised in Table 2.

In Uganda, Faillace (1973) employed seismic refraction to detect low velocity zones in metamorphic rocks which were interpreted as faults or smash zones. These were, therefore, expected to be water-bearing. The average yield of the boreholes sited on basis of the seismic data was 2.7 1/s and this was much higher than the average for the entire district. Similarly, Bro *et al.* (1981) used refraction for locating fractured basement aquifers in Mali.

Quite commonly, seismic refraction is used as a detailed surveying method to investigate anomalies suspected by another geophysical technique. For example, Topfer and Legg (1974) made refraction measurements across zones of low resistivity for the final siting of boreholes near Lusaka, Zambia.

One limitation of the method is that the equipment can be very costly and may require sophisticated servicing facilities to maintain them in good condition. There are also problems with the energy source. Explosives which are the best source, in ensuring strong signals, may not be readily available. Moreover they can be dangerous, so there are restrictions as to their handling, storage and transportation. The weight drop is an alternative but it requires considerable time and effort while a high level of noise is also generated. Irregular and discontinuous curves have been reported (Smith, 1990; Carruthers, 1990), therefore extra care is required in interpretation to avoid errors. If the thickness of a fractured bedrock is not appreciable and/or the velocity contrast between it and the overlying and underlying horizons is not substantial, the target layer may not be resolved on the time-distance graph, resulting in erroneous interpretation.

The refraction method is often not cost-effective due to the large scale of the field operation. To ensure that the cross over distance is well exceeded so that refracted arrivals may be detected as first arrivals, the minimum spread length is often several times greater than the anticipated depth to the refractor. However, it has been shown by Okwueze (1988) that this length decreases as the

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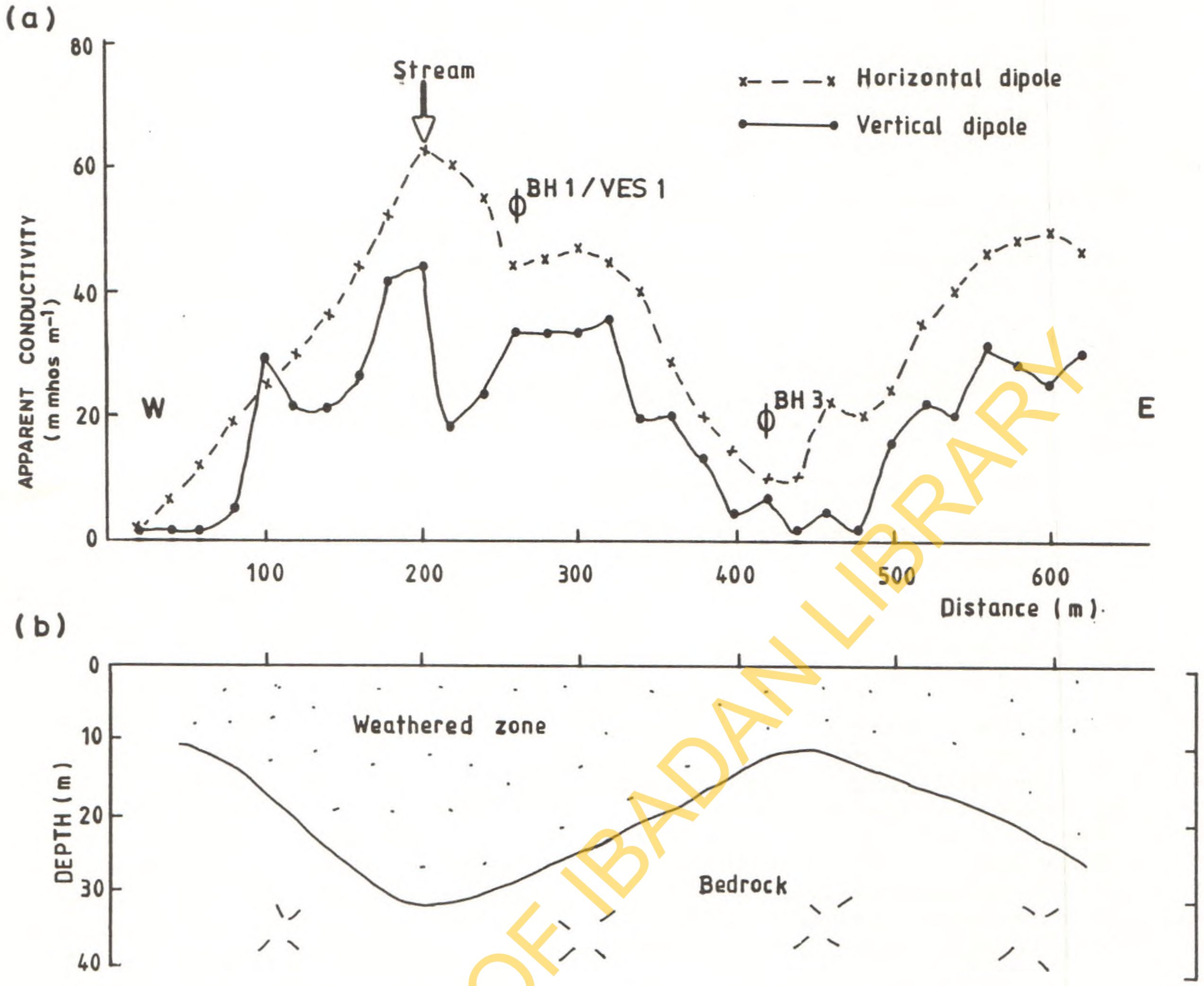

Fig. 7. (a): EM34 traverse near Obehira - Okene, Southwestern Nigeria. BH 1 gave a yield of 3 l/s while BH 3 gave only 0.5 l/s.
(b): Probable geological interpretation.

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velocity contrast increases in response to a decrease in the critical angle.

Smith (1990) presented a comparison of the cost effectiveness of seismic refraction and EM traversing from Zimbabwe. A weight drop was the seismic energy source with the arrivals detected and recorded on a 24-channel ABEM Terraloc digital system, while a Geonics EM34 was employed for the conductivity traversing. Along a 690 m long profile, the refraction survey required 6 man-days for field measurement and at least one day interpretation time in the office. By comparison, the EM field measurement took only 4 man-hours while the interpretation was made directly in the field.

For the reasons outlined above, and in spite of claims by Carruthers (1985); Clark (1985) and Van Overmeeren (1981) that seismic refraction is the most accurate geophysical method in determining the depth to hard rock, available evidences indicate that the technique is not as widely used as electrical resistivity or electromagnetics.

MAGNETIC SURVEYING

Rock formations, particularly the more basic types such as dolerite dykes, can have a high magnetic susceptibility which might thus aid in their identification. Suitable processing of the data can also be very useful in estimating the depth to the top of the causative feature (Birch, 1984; Olorunniwo and Olorunfemi, 1987). The contacts between different rock types can form zones along which decomposition starts more readily than in homogeneous formations. Differential rates of weathering can be expected to take place in the two contiguous formations because of their different mineralogical and chemical compositions.

A common approach in the geophysical siting of boreholes which utilises magnetometer surveying is to employ the magnetic method as a rapid

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