APPLICATION OF ELECTROMAGNETIC AND DIRECT-CURRENT RESISTIVITY METHODS TO GROUNDWATER EXPLORATION IN SELECTED VILLAGES IN NINGI L.G.A. BAUCHI STATE.

BY

AHMED DANLADI SHEHU

A THESIS SUBMITTED TO THE POST GRADUATE SCHOOL, AHMADU **BELLO** UNIVERSITY, ZARIA IN PARTIAL FULFILLMENT FOR THE AWARD OF MASTERS DEGREE IN APPLIED GEOPHYSICS.

DEPARTMENT OF PHYSICS

FACULTY OF SCIENCE

AHMADU BELLO UNIVERSITY, ZARIA.

NOVEMBER 1998

DEDICATION

This work is dedicated to my father, Mother and my Daughter Aisha.

DECLARATION

I hereby declare that:

The work presented in this report is the result of the actual research carried out by me and supervised by Dr. M.N.Umego and Prof. C.O.Ajayi.

This report has not been submitted to any other institution other than Ahmadu Bello University for the award of any degree.

Where other peoples work has been quoted, it is duly acknowledged and referenced.



Ahmed Danladi SHEHU.

CERTIFICATION

This thesis titled "Application of Electromagnetic and Direct-current Resistivity Methods to Groundwater Exploration in Selected Villages in Ningi L.G.A., Bauchi State." by Ahmed Danladi Shehu meets the regulations governing the award of degree of Master of Science (M.Sc.) of Ahmadu Bello University and is approved for its contribution to knowledge and literary presentation.

Dr. M.N.UMEGO Date: 16/7/99

Chairman, Supervisory Committee

PROF. C.O.AJAYI Date: 16/7/99

Member, Supervisory Committee

PROF. I.B.OSAZUWA Date: 16-7-99

Head of Department

Prof. J.Y. OLAYEMI Date: 22/12/04

Dean, Postgraduate School.

ACKNOWLEDGEMENT

I am grateful to my major supervisor, Dr. M. N. Umego, for his understanding and support in the course of writing this thesis. I am also grateful to Prof. C.O. Ajayi my second supervisor, for his strong criticisms and for being able to go through this work despite his tight schedule.

Many people deserve to be mentioned for one support or the other. Those in the water business are: Alh. Alhassan Jumba, Hamza K. Akuyam, Umar B. Ahmed , Sufi and Rotimi 'Kilos Ibinola. Also my class mates at Zaria, Messr Aminu Ahmed Lawal and Goodman B. Ishaya deserve to be mentioned for their support and encouragement. The same applies to my hosts in Kaduna Messrs Azaad, Mobe and the late Zakariya'u Muazu (May God have mercy on him).

I am also greatly indebted to my friends and colleagues, Mal. Sani Ali and all the staff of the Physics Programme, ATBU Bauchi especially Abbati and Nasiru.

I am grateful to the Physics Department, Ahmadu Bello University Zaria for giving me the academic capability to do this job. I thank the staff and students of the department for the help, guidance and assistance without which this job will never reach this stage.

Finally I want to thank my wife for her understanding.

Alhamdu Lillah.

ABSTRACT

The search for groundwater in an area covered by the basement complex and falls within the semi arid parts of Northern Nigeria requires good application of geophysics and the understanding of the geology of the area. This underlines the need for a better approach to groundwater studies under these geological conditions.

Two geophysical techniques, the EM and the electrical resistivity methods have been employed in his work to explore for groundwater in fifteen villages with acute water problem in Ningi L.G.A of Bauchi State.

Conductivity(EM) readings were recorded along short traverses of variable lengths in each village. The EM method employs two modes of recording conductivity values, the horizontal dipole mode and the vertical dipole mode. VES data were collected at sites where the conductivity value in the vertical dipole mode is greater than the horizontal dipole mode.

A total of 37 VES stations were established and drilling sites were recommended based on the geoelectric sections obtained from the interpreted VES data.

The work showed that the two geophysical techniques can be complimentarily applied to groundwater exploration in the basement complex. The EM method was used as a recoinassance tool, to determine areas with increasing conductivity with depth. The electrical resistivity method was then used to determine the depth to various conducting zones.

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LIST OF ABBREVIATIONS

G.S.N	= Geological Survey of Nigeria
BSADP	= Bauchi State Agricultural Development Project
N-S	= North - South
L.G.A	= Local Government Area
Fig.	= Figure
EM	= Electromagnetic
EMF	= Electromotive Force
EMT	= Electromagnetic Traverse
A.C.	= Alternating Current
D.C.	= Direct Current
VES	= Vertical Electrical Sounding
SWL	= Static Water Level
HDW	= Hand Dug Well
VS	= Versus

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION

Despite its importance and usefulness, potable drinking water is among the basic needs that are not adequately supplied in most developing countries like Nigeria. The situation of the rural dweller is more pathetic. In rural areas, the main sources of water are: rainfall, streams and wells. Rain falls for less than six months in the year in most parts of Northern Nigeria (Offodile, 1992). The streams dry up during the dry season and are subject to contamination by external factors. Hence, the most reliable source of water for them is groundwater either in form of hand-dug wells (HDW) or mechanized boreholes. Groundwater has some advantages over surface water in that it is not exposed to contaminants dumped in the latter; it is naturally filtered and the temperature and chemistry are subject to less changes. Given the advantages of groundwater over surface water, efforts should be geared towards exploration and proper exploitation of groundwater resources for human and industrial uses.

1.2 NEED FOR GROUNDWATER DEVELOPMENT

The drought, which occurred in the early nineteen seventies, swept through much of the Sahel region of

Africa, including Nigeria. Under the prevailing conditions, during those difficult days, surface water was in most areas completely dried up and groundwater provided the only reliable and alternative source of water supply. With this development in mind, it is clear that relying too much on surface water resources, in the face of the prevailing adverse and unpredictable climatic conditions is very risky. The circumstances of these days emphasize the need for a thorough study of groundwater resources in the developing nations.

In many developing countries, particularly Asian countries, development of groundwater resources is among the lines of development (United Nations, 1986). In Nigeria, Hanidu (1990) pointed out that quantification of groundwater resources is among the basic strategies for improving water supply levels. Unfortunately, the panic measures associated with the drought earlier mentioned set off a rather haphazard and indiscriminate exploitation of groundwater almost at the risk of destroying some of the country's most important groundwater sources (Offodile, 1992).

This work attempts to examine the issue of groundwater development from the angle of the exploration and quantification of groundwater resources. Quantification of groundwater resources can be done

through the identification of various aquifers (underground layers bearing water), their geometry, water availability and other aquifer characteristics. When groundwater is quantified, then its judicious use can be planned to meet multiple purposes.

1.3 APPLICATION OF GEOPHYSICAL TECHNIQUES IN GROUNDWATER EXPLORATION

The search for groundwater all over the world dates back far into history. Various methods have been used with varying degrees of success. The application of geophysical techniques to groundwater exploration have been going on for some 50 years (Hazel et al.,1988). The objective of any geophysical technique is to detect and locate subsurface geological structures of interest and, possibly, estimate their dimensions using measurement of some physical properties on the surface. The success of a geophysical technique in detecting a geological structure depends fundamentally on the existence of a contrast in physical properties (or physico-chemical properties) between the geological structure of interest and the environment in which it exists. In groundwater exploration, it is the resistivity contrast that is often exploited to locate areas that are prone to containing water in exploitable quantity, the EM method has been used as a recoinassance to locate the VES points. Geophysical techniques have been used for this purpose with varying

degrees of success (Hazel et al, 1988). Geophysical techniques might be an additional cost to the overall cost of water supply but, the cost is justified because of their success and also, with the increase in cost of drilling, careful siting of boreholes is necessary. In Kenya's Nyanza Province, geophysical techniques have proved very successful and have proved their cost effectiveness. About 80% of boreholes are now successful, producing 140% more water from half the depth of unsurveyed boreholes previously drilled (Odera, 1987). In Kwara State, Nigeria, out of the 218 boreholes drilled by Biwater, 78% have produced more than 5 litres per second, and an average yield in the basement boreholes has been 2.8 litres per second (Beale, 1987). Much of the success is attributed to the application of geophysical techniques in borehole siting.

1.4 GEOPHYSICAL METHOD USED

Groundwater mainly occurs in layers of the earth below the surface but could also be found, particularly in rocky areas, in cracks, fissures or fracture zones which are prevalent in the survey area. In theory, many factors are considered in selecting the best method to be used in groundwater exploration. Some of the factors considered are: the effectiveness of the method in determining the target structure, reliability of the result, ease with which the fieldwork is performed and the cost of

performing the fieldwork.

The resistivity or conductivity of rocks, is most affected by the water content (Telford et al, 1976). Hence, the resistivity method is chosen for this work not only for its effectiveness in determining depth to the basement, but on other factors such as cost and ease of performing the fieldwork. The resistivity method is complemented by the electromagnetic method in this work because the latter also gives a measure of terrain conductivity which is the inverse of resistivity. Other reasons for the choice of the complementary method are: relative ease with which the fieldwork is performed and also the experience of some people who worked with similar problems and under similar conditions. For example, Arandjelovic (1966) used the resistivity method in locating groundwater in Karst terrains with good success. Van Dam and Meulenkamp (1967) showed the success of application of resistivity method to groundwater exploration. Agwunobi and Onuoha (1988) used the combination of electrical resistivity and magnetic methods to site a borehole at Fobur in Plateau State. Shemang (1990) suggested that resistivity method be complemented with another geophysical method for subsurface investigations because a single method hardly gives all the required parameters. Daniyan (1978), though worked in a sedimentary area, suggested the use of complementary method of electrical resistivity and electromagnetic

methods. Dan-Hassan (1991) is of the opinion that faults and fractures should be explored in rocky areas for the purpose of groundwater supply and that these geological structures are best detected and located by electromagnetic method with resistivity backup where necessary. The complementary methods are used for this work mainly because, the two methods used give information about the two main features required for siting boreholes i.e. resistivity method gives the depth to the basement, while the EM gives the position of fractures and also determine areas that should be avoided.

Using the electrical resistivity and electromagnetic methods helps to eliminate some of the defects of either of the methods. With the electromagnetic method no electrical contact is required between instruments and the ground making it applicable even in areas with exposed rock surface. Above all combining the two methods gives two sets of data, which enhances the quality of the interpretation.

1.5 EXTENT OF THE PROJECT AREA

The area under study is within the Ningi Local Government Area of Bauchi State as shown in Figure 1.1. The whole of Ningi LGA is bounded by latitudes 10°45'N and 11°20'N and longitudes 8°45'E and 9°45'E. The survey is limited to some selected villages of the Ningi Local Government Area. The survey area occupies the NE part of

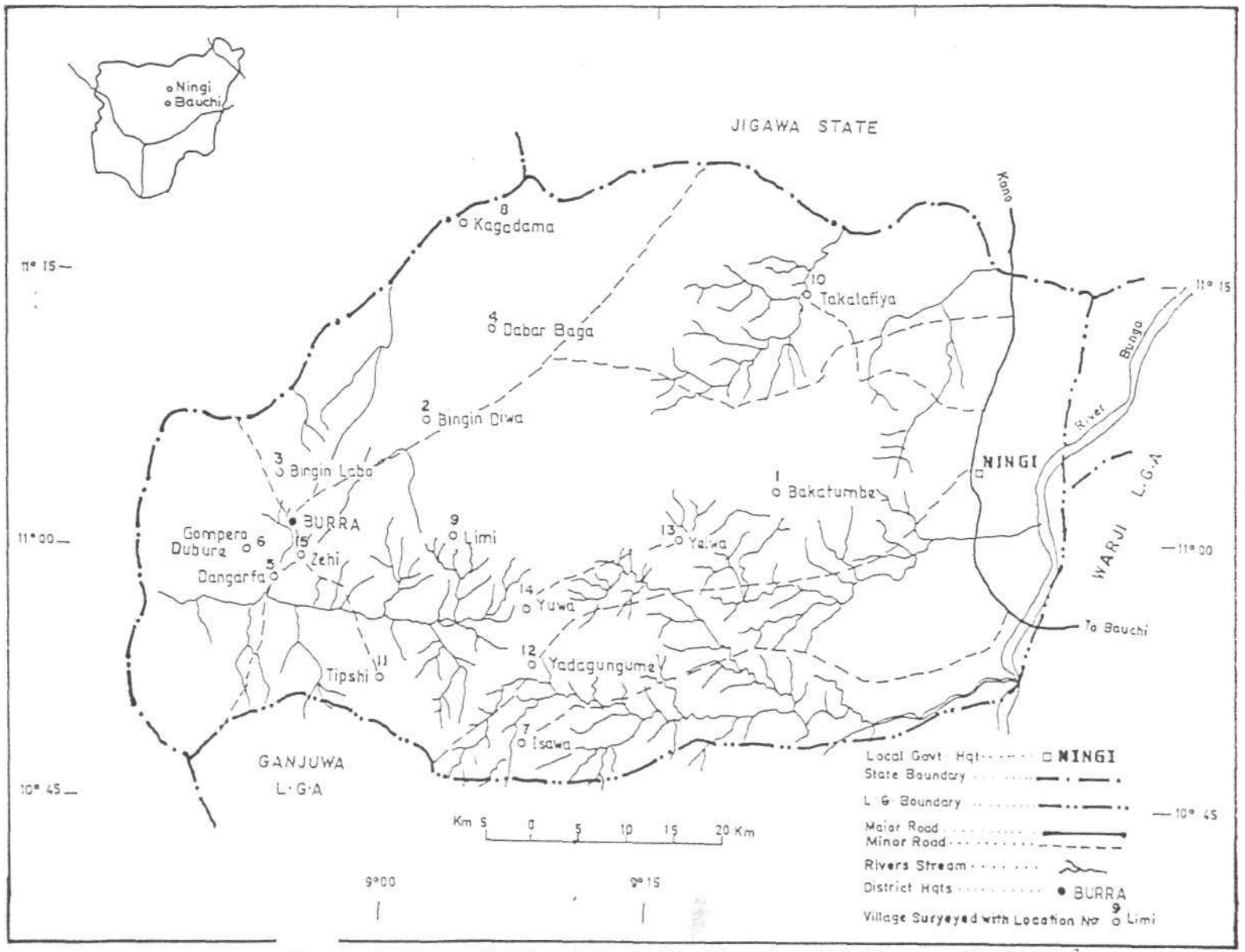


Fig 1.1 Map of Ningi L.G.A. Showing Villages Surveyed

sheet 126, the north-western part of sheet 127, the south-eastern part of sheet 105 and the south-western part of sheet 106 of the Nigerian Ordinance survey map. The Ningi Local Government Area borders Jigawa State in the northern and eastern parts and Plateau State in the western part. To the south, the Local Government shares the same boundary with the Ganjuwa Local Government Area of Bauchi State.

Ningi, the Headquarters of the Local Government, is accessible by road either from Kano or from Bauchi. Ningi is about 102 km north-west of Bauchi. The road network in the survey area is poor due to its hilly nature. Some parts of the study area are inaccessible during the rainy season because of streams and mud ponds.

The survey carried out in this work was not intended to give the general subsurface geology of the whole Local Government but to give localised subsurface information around specific villages and settlements with acute water supply problem, in respect of the best places to site boreholes in such villages/settlements.

1.6 CLIMATE AND ECONOMIC ACTIVITY

Ningi L.G.A falls within the 'tropical continental north' climatic region of Nigeria, where two seasons per year can be clearly distinguished; namely, a long dry

season from October to April and a rainy season from May to September. The area experiences no rainfall and, sometimes chilly atmosphere during the log dry season. Dust clouds are common during this season. The rainy season is accompanied by frequent storms in the area. The heavy rains cause considerable erosion to soil and laterite roads, making some areas inaccessible by road, particularly to the western part of the area.

Ningi experiences a mean annual rainfall of 780 mm, 96% of this falls between May and September. There is an almost abrupt change from rainy to dry season, with little or no rain falling in November to March. There is a wide variation in monthly temperature. During the months of December and January, temperatures are as low as 20^0 C and 23^0 C. However, in the months of April and May, just before the rains, temperatures rises as high as 30^0 C and 33^0 C (Mass Design and Associates, 1981).

The predominant economic activity in the area is farming of cash crops like beans and groundnut. This is complimented by little commerce during the dry season. The people of the area also engage in rearing of livestock.

1.7 PREVIOUS WORK DONE

Generally, water exploration work in Nigeria dates back to around 1917 when the Geological Survey of Nigeria

(GSN) was established, with among other objectives, to search for groundwater in the semi-arid areas of the former Northern Nigeria. Since then most of the published work of the GSN have been more geological than geophysical. Infact, almost all the work then centered on studying the hydrogeological conditions of Northern Nigeria on a regional scale (Raeburn and Jones, 1934; Thompson, 1956 and Barber, 1955; du Preeze and Barber, 1965).

The Bauchi State Agricultural Development Programme, in conjunction with the Water Surveys (Nigeria) Ltd., published a map (Bauchi State: Hydrogeology) indicating different geological units. The map gives the depths of boreholes in the area as ranging from 20-50 m and that the water level is generally within 25 m below the ground surface (BSADP, 1988a). The bedrock in the survey area is highly fractured as given by aerial photographs interpreted by M/s Mass Design and Associates (1981).

1.8 AIMS AND SCOPE OF THE PRESENT WORK

The area of Nigeria covered by the Basement Complex is considerable and mostly fall within the semi-arid parts of the country where surface water is non existent and groundwater would then be the only source of water. The search for groundwater in these regions requires good application of geophysics and the understanding of the

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geology of the area. This underlines the need for a better approach to groundwater studies under these geological conditions.

The aim of any groundwater exploration is to locate sites that will be suitable for drilling boreholes or wells. Therefore the primary aim of this work is to provide information on the suitable sites that can be drilled to provide water for the villages surveyed. Through the interpretation of resistivity and electromagnetic data, geoelectric sections will be drawn from which geologic sections will be inferred. The information so obtained will be used to give an estimate of the depth to the water table and to the basement rock over the area surveyed in each village. The nature and thickness of the pre-basement layer will also be determined within the area studied, so as to decide on the site to be recommended for drilling within the survey area. Finally, inferences will be drawn from the interpreted results of the sounding data, and, where necessary any local anomaly observed will be discussed.

CHAPTER TWO

GEOLOGY

2.1 INTRODUCTION

The Nigerian geological setting broadly comprises of sedimentary formations and the crystalline rocks of the Basement Complex type. The two rock types occur more or less in equal proportions all over the country. The sediments are mainly Upper Cretaceous to Recent in age, while the Basement Complex rocks are thought to be Precambrian (Rahaman, 1989).

The whole of the survey area is underlain by the rocks of the Basement Complex. There are outcrops of this rock type littering the area; about 80% of the villages surveyed have outcrops nearby. There are two ring complexes of the Younger Granite series in the area viz: the Tibchi and the Ningi-Burra Ring Complexes.

2.2 THE BASEMENT COMPLEX

The Nigerian Basement Complex covers about 50% of the land surface of Nigeria (Shemang, 1990; Offodile, 1992) as shown in Figure 2.1. According to Rahaman (1989), the Nigerian Basement Complex consists of five major groups of rocks, viz:

1. Migmatite gneiss complex, which comprises of biotite and biotite hornblende gneisses, quartzites and quartz schist and small lenses of calc-silicate rocks.

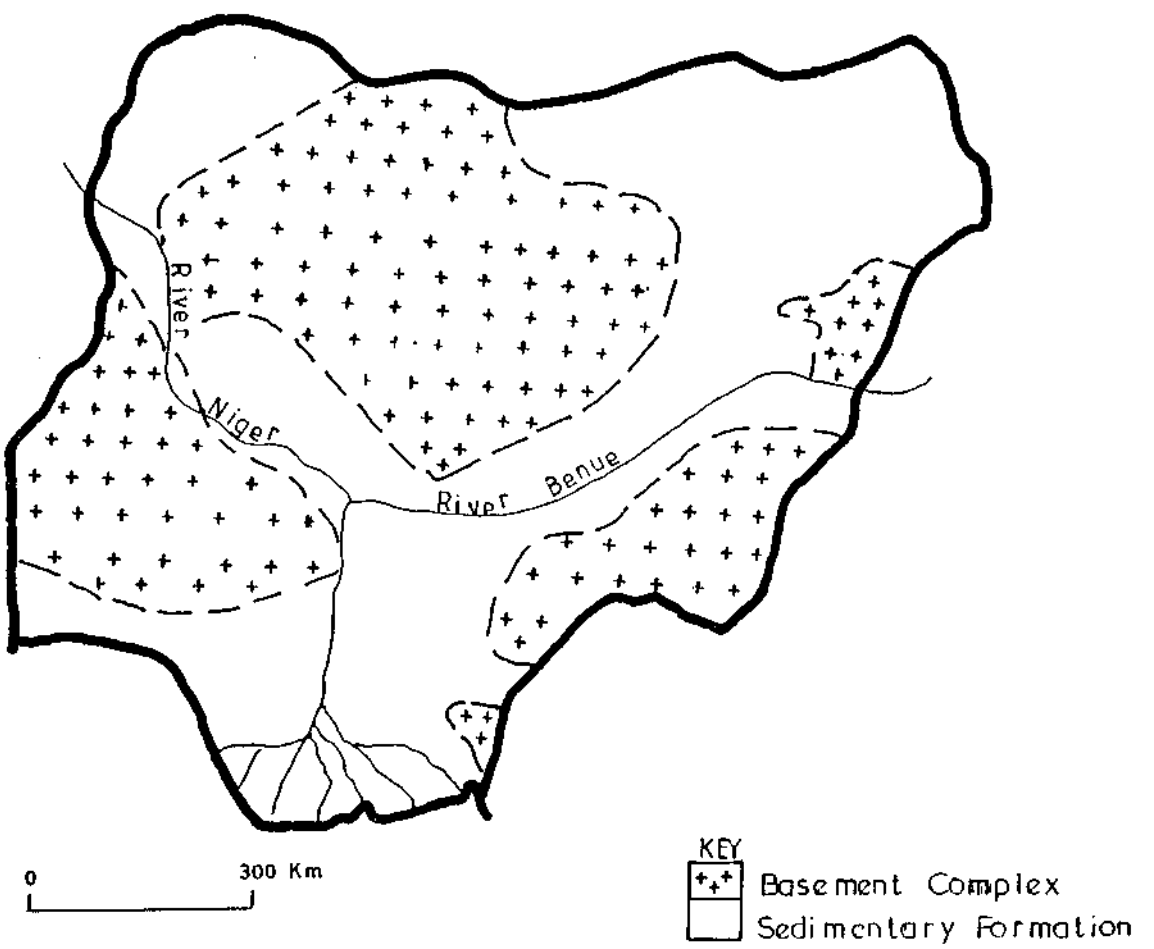


Fig 2.1 SIMPLIFIED GEOLOGICAL MAP OF NIGERIA

(Adapted and modified from Shemang 1990)

2. Slightly migmatised to unmigmatised paraschists and meta igneous rocks which consist of pelitic schists, quartzites, amphibolites telcose rocks metaconglomerates, marbles and calc-silicate rocks.
3. Charnokitic rocks.
4. Older granites which comprise of rocks varying in composition from granodiorite to true granites and potassium syenite.
5. Unmetamorphosed dolerite dykes, basic dykes and syenite dykes.

Wright (1989) gave an additional group as metamorphosed calc-alkaline volcanics and hypa-basal rocks.

The whole Basement Complex has been through at least two tectonic-metamorphic cycles and consequent metamorphism. Migmatisation and granitisation have extremely modified the original rocks so that they generally occur as relict rafts and xenoliths in migmatites and granites (McCurry, 1989).

The area under study is underlain by the Basement Complex with outcrops surrounding the area. The study area also contains two Ring Complexes of the Younger Granite namely: Ningi-Burra and Tibchi Ring Complexes. These geological structures have been studied extensively by Turner (1989) on a regional scale. The only geophysical survey of note in the survey area is that carried out by

Ajakaiye (1989) in respect of density sampling. The study showed that rock samples collected from the area have higher densities about 2720 Kg/m^3 than those from other areas of the Younger Granite series that range between 2610-2630 Kg/m^3.

Crystalline rocks weather more easily and deeply under humid conditions. More water is available for storage under favourable rainy conditions. Hence, in the Northern and semi-arid climatic conditions of the country, almost wholly underlain by basement rocks, groundwater is scarce and problematic.

2.3 YOUNGER GRANITE RING COMPLEXES

In Nigeria, there are about 50 Younger Granite massifs of varying sizes, many of the larger ones being made up of two or more overlapping ring complexes (Turner, 1989). They occur in a broad N-S zone centered on the Jos Plateau, where the greatest concentration of the ring complexes is found (Turner, 1989). The distribution of the ring complexes is as shown in Figure 2.2.

The Younger Granites of the Jos Plateau and surrounding areas are a petrologically distinctive group of alkali feldspar granites, associated with rhyolites and minor gabbros and syenites. They occur in subvolcanic

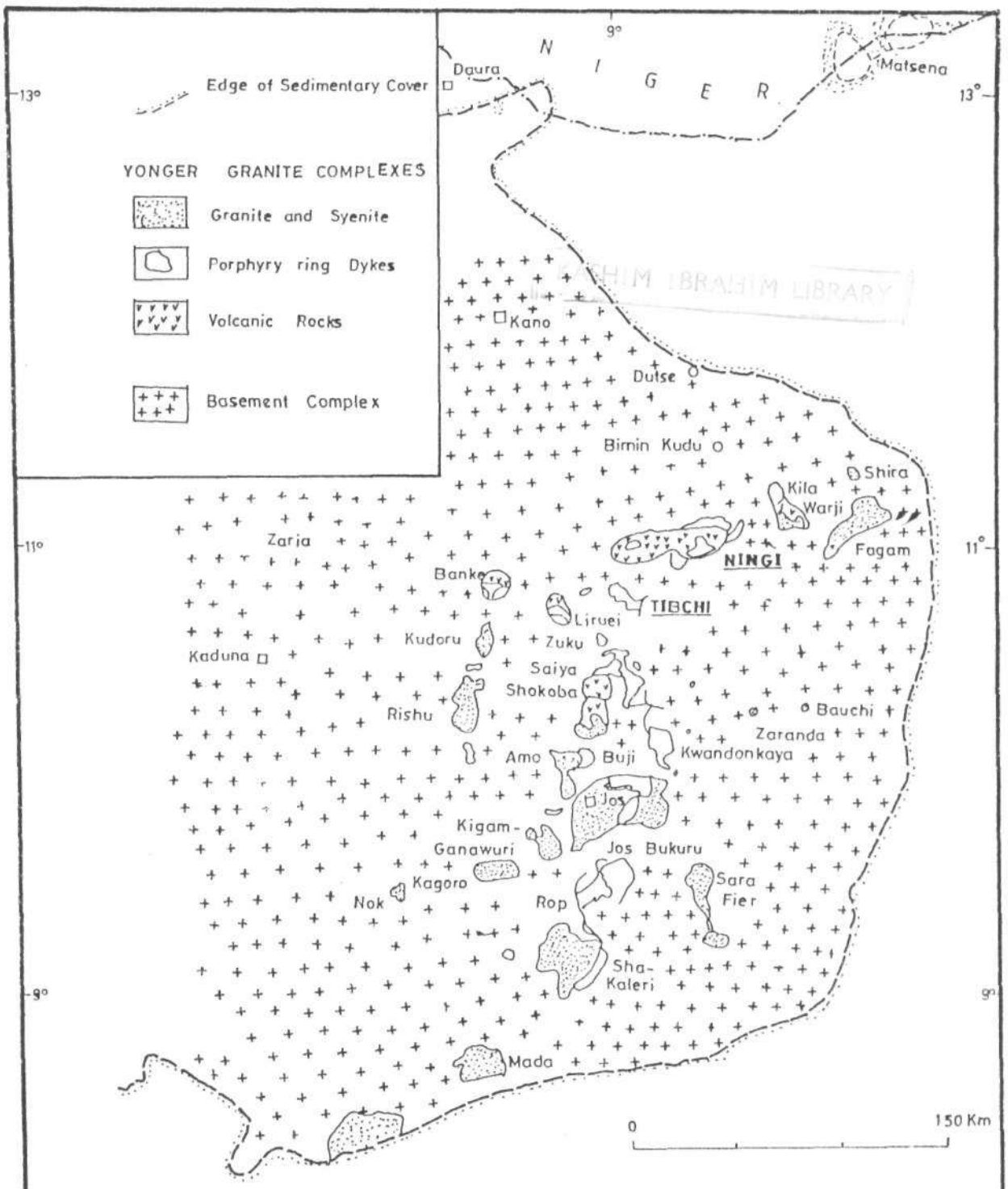


Fig 2 2 THE DISTRIBUTION OF YONGER GRANITE RING COMPLEX OF NIGERIA (Adopted from Turner, 1989)

intrusive complexes as ring dykes and related annular and cylindrical intrusions. They have undeformed post-tectonic character, in contrast to the foliated calc-alkaline Older Granites of the Basement Complex. The Younger Granites are a source of the tin mineralisation of the Jos Plateau area (Turner, 1989).

The Younger Granites are easily identified by their topographic distinctiveness as they occur as rocky hill massifs sharply contrasting with the smoother topography of the surrounding basement rocks. The main rock types are granites variously containing biotite, riebeckite or hornblende porphyries, rhyolites and minor syenites and gabbros. Many of the complexes consist of a series of distinct intrusion, often with a concentric arrangement with each intrusion having a characteristic petrographic feature.

The structural and petrographic evolution of the Nigerian ring complexes can be summarised as a sequence of three main stages as given by Turner(1989):

1. The building up of a large rhyolite volcano.
2. The early volcanic stage probably ended with the rapid eruption of ash flow tufts, partly emptying the magma reservoir leading to collapse of the centre of volcanic structure within a ring fault (ring dyke stage).
3. The final stage considered as a waning phase of igneous

activity in which successively smaller granite intrusions were emplaced at increasingly deeper levels (intrusive stage).

2.4 GEOLOGY OF NINGI AREA.

Ningi town and its nearby villages are set on a granite type rock in foothills of a hilly county, with an average elevation of 350 m above sea level (Mass Design and Associates, 1989). Most of the Ningi area is formed of igneous rocks of the Younger granite series. Particular rock types prevalent in the area include, porphyritic granites, granites intersected by aplites, syenites and gabbros occurring to the North-East of Ningi. There is an outcrop of rhyolitic lavas to the west of the town as shown on figure. 2.3.

Basement Complex outcrops which are present in the form of Older granites, surround the Younger Granites. The older rocks belong to undifferentiated Basement Complex; the remains of old sedimentary series transformed into analectic migmatites and granites. Metasediments in the area include quartz, feldspar rocks, biotite and horneblende gneisses, marble and calc-silicate rocks (Turner, 1989).

At the Ningi Ring Complex, the bedding and the flow banding have a fairly constant dip and it seems likely

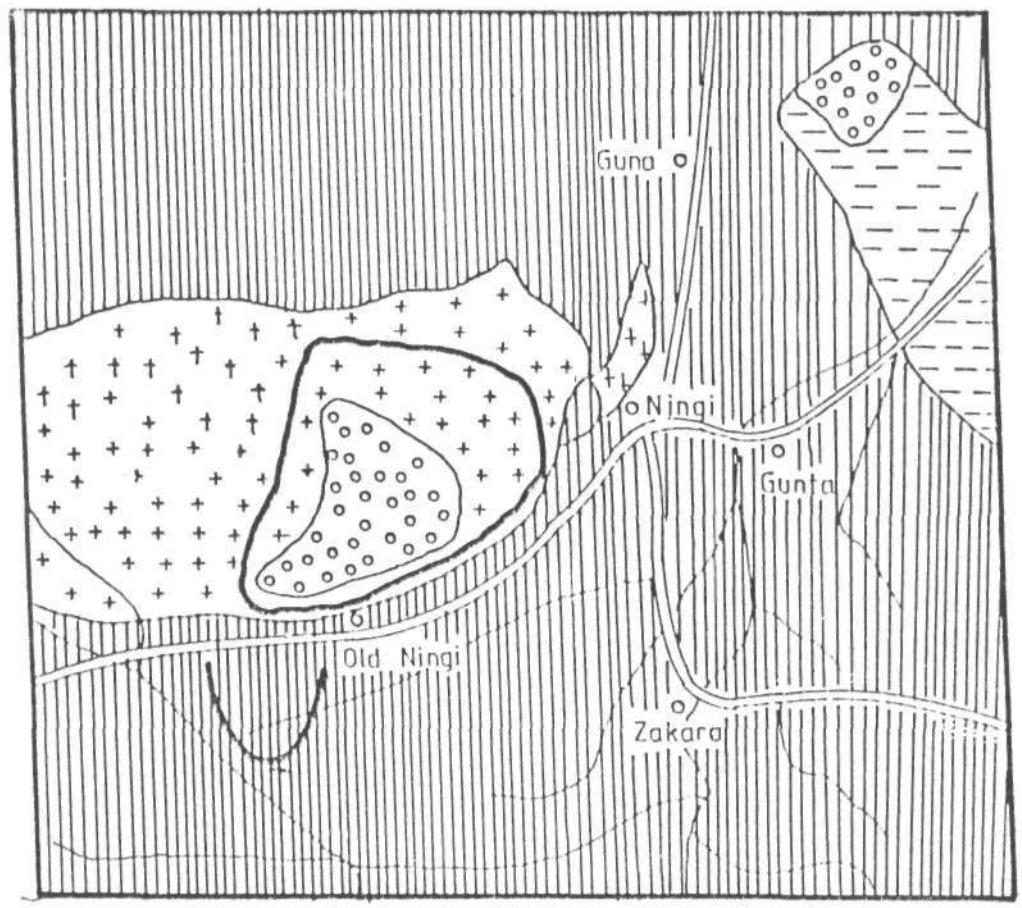


Fig2.3 Geological Map of Ningi Area

that the original volcanic landforms were broadshield volcanoes or plateaux. There are finely bedded tufts which must have been horizontal or gently dipping when they were deposited but now have a vertical attitude. The effects are due to faulting and tilting (Turner, 1989).

2.5 HYDROGEOLOGY

There is a thick cover of weathered materials washed down from the hilly county in the Ningi area. The weathering process has affected the feldspar in the igneous rocks which decompose under the action of carbon dioxide charged rainwater and high temperatures. This results in production of a gel-like mixture of silica and alumina and the formation of coarse sands and clay found in the low-lying areas. The low-lying areas form part of a dendritic drainage network which conveys run-off water from the mountains towards river Bunga to the east of the survey area (see fig.1.1). This network is responsible for widespread erosion in the area.

Groundwater constitutes the only possible source of water in most of the survey area occupied by granite outcrops. The presence of groundwater in the area is conditioned by both the thickness and presence of altered and fractured sections of the Basement Complex. The water bearing zones in the area are (Turner, 1989):

1. Fractured migmatites in poorly decomposed rocks.
2. Intergranular permeability in moderately decomposed

coarse grained igneous and metamorphic rocks.

3. Fractured pegmatite, aplite and quartz veins within highly and moderately decomposed gneiss and migmitites.

The porosity of rocks determines its hydrogeological properties and this depends on texture and mineralogy of the rocks. In fresh non-fractured crystalline rock, the porosity is often less than 3% (Todd, 1980). However, this could be considerably increased by fracturing.

The water bearing capabilities of metamorphic and plutonic rocks reduces with increasing depth of burial. This decrease, according to Davies and De Wiest(1970), is due to combined effect of the weight of overlying rocks and the tendency of surface disturbances to penetrate only short distance in to the bedrock. The increase in the weight of the overlying rocks tends to close joints, fractures and faults at depth. The distances between fractures increases with depth. Hence, as depth increases, the frequency of intercepting fractures decreases; which supports the fact that the best borehole is not necessarily the deepest.

CHAPTER THREE

THEORY AND DATA COLLECTION

3.1 INTRODUCTION

This work involves the application of two geophysical methods to the exploration of groundwater. These are the electromagnetic method and the direct-current resistivity method. To appreciate better the applicability of these methods, it is important to briefly discuss how the methods work and to discuss briefly the theory and background of the methods. Detailed treatment of the theory can be obtained from Wait,(1971); Keller and Frischknecht,(1966) and Grant and West,(1965).

3.2 THE ELECTROMAGNETIC METHOD

The electromagnetic method (EM) is most widely used in mineral exploration (Dobrin, 1976, Telford et al., 1976). Basically the EM method of exploration involves the propagation of time varying low-frequency EM fields in and over the earth (Telford et al., 1976, Griffiths and Kings, 1976) and the induction of these fields in buried conductors such as ore bodies (Dobrin, 1976) and highly conducting groundwater (Beck, 1981).

Generally, the EM arrangement involves the transmitter which transmits the EM wave at low-frequencies. The wave is passed to the ground through

loops of wire (the transmitter coil) and, in some cases, by direct contact (Telford et al., 1976). These waves passing through the conductor give rise to secondary EM fields which distort the primary field at the surface. The resultant field picked up by the receiver through the receiver coil will differ from the primary field in intensity, phase and direction, thus revealing the presence or absence of conductors a simplified representation is shown on figure 3.1.

3.2.1 Theory

The electromagnetic theory is very well developed in literature (Wait,1971; Grant and West,1965). As such, the relevant equations will just be quoted to illustrate the relevant application. The conclusions of the Maxwell equations for a wave travelling in a homogeneous isotropic medium are given as:

$$\mathbf{B} = \mu\mathbf{H}$$
$$\mathbf{D} = \varepsilon\mathbf{E} \qquad (3.01)$$
$$\mathbf{J} = \sigma\mathbf{E}$$

where σ = the permeability of the medium, ε = the permittivity of the medium, σ = the conductivity of the medium, **B** is the magnetic induction, **E** is the electric field, **H** is the magnetic field intensity, **D** is the electric displacement and **J** is the current density. Grant and West (1965) showed that for the medium considered above,

$$\nabla^2\mathbf{E} = \iota\omega\mu\sigma\mathbf{E} - \varepsilon\mu\omega^2\mathbf{E} \qquad (3.02)$$

and

$$\nabla^2\mathbf{H} = \iota\omega\mu\sigma\mathbf{H} - \varepsilon\mu\omega^2\mathbf{H} \qquad (3.03)$$

These indicate that E and H must propagate as a dissipative wave motion. In most electromagnetic methods, it is the magnetic component of the EM wave that is measured.

3.2.2 Mutual Inductance

Mutual Inductance is the term used to describe the electromagnetic interaction at a distance between electrical circuits due to electrical induction. This is the basis of the EM method because we are concerned with the interaction between two coils (the transmitter coil and the receiver coil). Consider the transmitter and the receiver to be simple loops of small winding cross-section held in fixed position and orientation with respect to one another. The electromotive force (emf) induced in the receiver coil is proportional to the rate of change of current in the transmitter. If the current in the receiver is I, then

$$(\text{emf})\ E_2 = -\iota\omega M_{12} I_1 \qquad (3.04)$$

where M_{12} is the co-efficient of mutual inductance and is also the constant of proportionality.

Any variation in electrical conductivity of the medium between the transmitter (T_x) and the receiver (R_x)

will affect the co-efficient of mutual inductance. A system of transmitter (T_x) and Receiver (R_x) is schematically shown on Figure 3-1.

When the transmitter is switched on, it induces voltages and, therefore, current in the receiver and in the subsurface conductor C. The subsurface conductor then acts as a secondary transmitter which in turn induces further currents in the receiver.

The total induced voltage E in the receiver is the vector sum of that due to the primary field (E_p), which is a function of the mutual inductance of the transmitter and the receiver M_{TR}, and that due to the secondary field (E_s) of the conductor, which is a function of the mutual inductance of the conductor to the receiver M_{CR}.

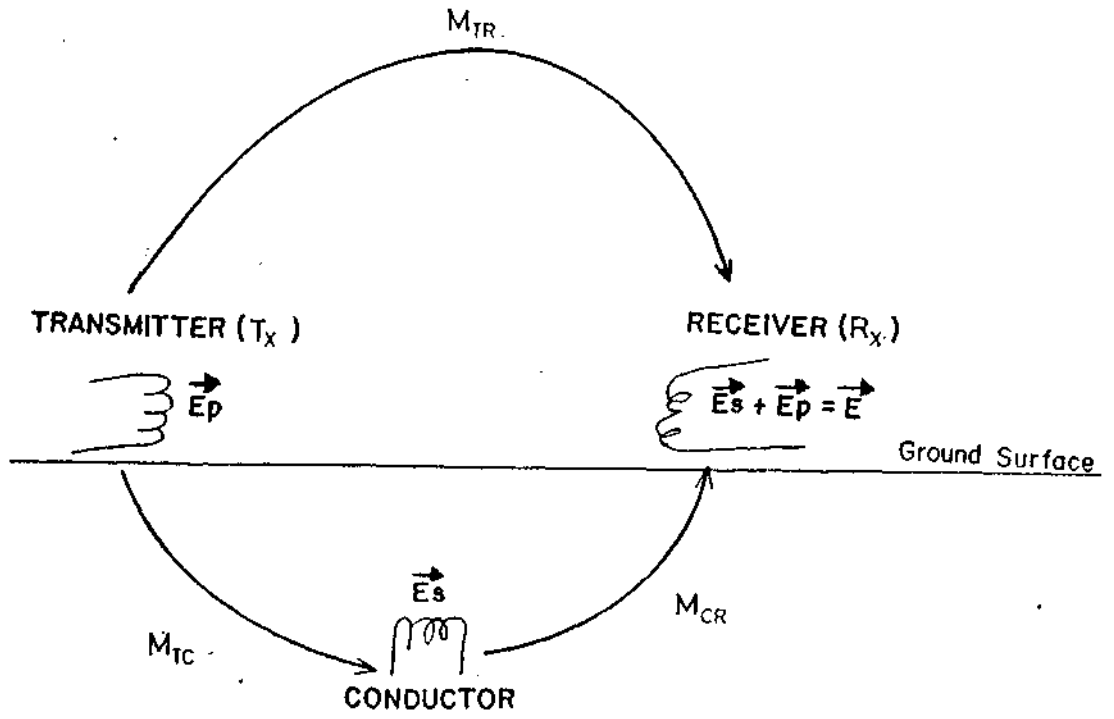


Fig 3.1 Schematic representation of induction (after Beck, 1981)

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In areas where there are no subsurface conductors it can be assumed that M_{TC} and M_{CR} are zero and there is no secondary component i.e. $E_s = 0$. If the arrangement is moved into a zone of subsurface conductors, then there will be change in the total field due to changes in M_{TC} and M_{CR}. In the real sense then, electromagnetic anomalies are simply those changes in the co-efficient of mutual inductance between a pair of coils brought about by their proximity to a conducting zone. This, Grant and West (1965) showed as

$$\Delta E_2/E_2 = \Delta M_{12}/M_{12} \qquad (3.05)$$

3.2.3 Coil Configuration

There are many coil configurations being used for electromagnetic survey depending on the aim of the survey. During this work, two coil configurations were employed. They were;

i) The Horizontal dipole mode in which the loops are co-axial as shown in figure 3.2(a).

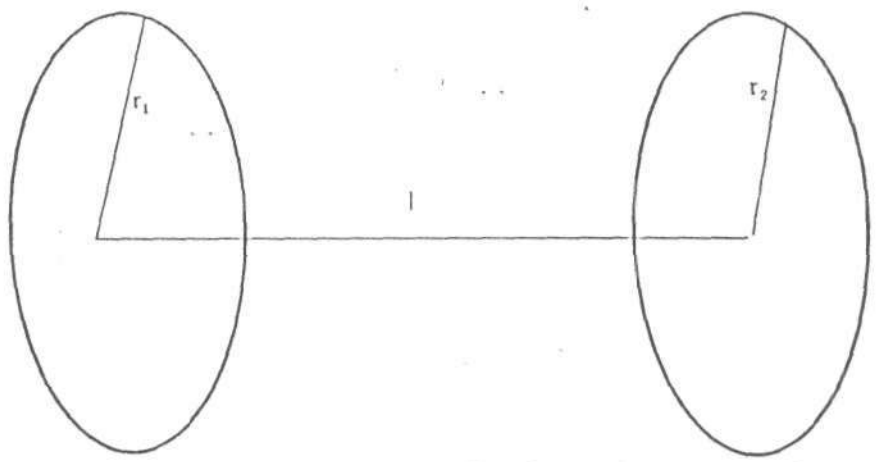
If the coils have radii r_1 and r_2, and their separation is l, such that $l >> r_1, r_2$ then, according to McNeill (1980b)

$$M_{12} = \mu_0 \pi r_1^2 r_2^2 I_1 / 2l^3 \qquad (3.06)$$

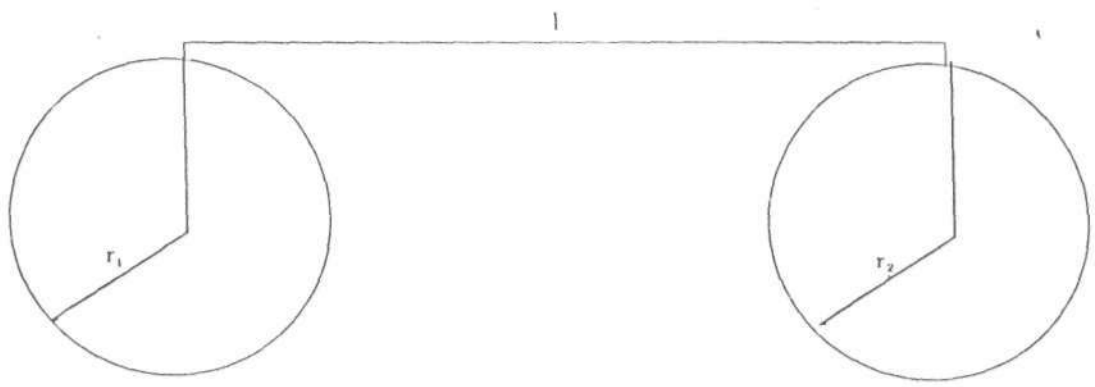
ii) The vertical dipole mode. In this case, the coils are coplanar as shown in Figure 3.2(b)

In this case the mutual inductance is given by McNeill (1980b) as

$$M_{12} = \mu_0 \pi r_1^2 r_2^2 I_1 / 4l^3 \qquad (3.07)$$



(a) Horizontal dipole mode



(b) Vertical dipole mode

Fig. 3.2 Coil Configurations of EM 34-3 used for Data Collection in this work.

These two arrangements are used because they have maximum coupling.

3.2.4 Theory of Operation

McNeil (1980b) shows that the ratio of the secondary to the primary field, when the coils are on the surface of a homogeneous half-space of conductivity s and the coil separation l, is given by

$$(H_s/H_p)_H = 2\{1-(3/(\gamma l)5)+[3+3\gamma l+(\gamma l)5]e^{\gamma l}/(\gamma l)5\} \qquad (3.08)$$

for horizontal dipole and,

$$(H_s/H_p)_v = [2/(\gamma l)5]\{9-[9 + 9\gamma l + 4(\gamma l)^2 + (\gamma l)^3]e^{-\gamma l}\} \qquad (3.09)$$

for vertical dipole

where $\gamma l = (\imath\omega\mu_o\sigma)^{1/2}$

$\omega = 2\pi f$,

f = the frequency of the transmitter.

A well known characteristic of homogeneous half-space is the electrical skin depth which is defined as the distance, in the half-space, which a propagating plane wave has travelled when its amplitude has been attenuated to 1/2.72 of the amplitude at the surface (Keller and Frischknetch, 1966).

The skin depth δ is given by

$$\delta = (2/\omega\mu_o S)^{1/2} = [(2\imath)^{1/2}/\gamma l] \qquad (3.10)$$

therefore,

$$\gamma l = (2\imath)^{1/2} * 1/\delta \qquad (3.11)$$

The ratio l/d is defined as the induction number B

$$\gamma l = (2\iota)^{1/2} * B \qquad (3.12)$$

Now B is much less than unity (i.e. $\gamma l << 1$). Hence equations 3.08 and 3.09 reduce to

$$(H_s/H_p)_V \sim (H_s/H_p)_H \cdot iB^2/2 = \iota\omega\mu_0\sigma l^2/4 \qquad (3.13)$$

To make B much less than unity, l must be very much less than d.

Thus,

$$\omega << 2/\mu_o\sigma l^2 \qquad (3.14)$$

The apparent conductivity σ_a is given from equation 3.13 as

$$\sigma_a = (4/\omega\mu_o l)\,(H_s/H_p)_{\text{Quadrature component}} \qquad (3.15)$$

The instrument measures the ratio of secondary to the primary field, the coefficient $4/\omega\mu_o l^2$ is a constant for a particular location. Hence, the apparent conductivity depends on this ratio.

3.2.5 Instrumentation

The instrument used for this work is the Geonics EM34-3. This instrument consists of a transmitter and a receiver each connected to its coil by a short cable. The transmitter (T_x) and the receiver (R_x) are connected together by a long cable that can give T_x - R_x separation of up to 40 m. The distance between the two is measured electronically. The coils have diameter of approximately 63 cm.

The transmitter is powered by 8 disposable "D" cells and the receiver with 8 disposable "C" cells. The source of the primary field is a self contained dipole transmitter. The instrument operates at 3 different frequencies depending on the intercoil spacing. At 10 m coil separation the frequency is 0.4 KHz while at 20 m separation it is 1.6 KHz and at 40 m separation it is 0.4 KHz. The relationship between coil separation and depth of exploration is given in Table 3.1.

The transmitter console weighs about 3.0 kg and the coil weighs about 8.8 kg. The receiver console weighs about 3.1 kg and its coil weighs about 5.6 kg. The connection diagram for the instruments is as shown in figure 3.3.

The receiver has a meter that gives the value of apparent conductivity value of the particular station.

3.2.6 Field Procedure

The EM34-3 electromagnetic set is a two-man portable instrument and connected by flexible coils. The intercoil spacing is measured electronically to agree to the value chosen by the transmitter operator. The receiver was carried ahead of the transmitter. The coil spacing was set to either 10, 20 or 40 m (so as to directly vary the effective depth of exploration as shown in Table 3.1). The receiver operator can check for the correctness of the spacing by reading the coil spacing

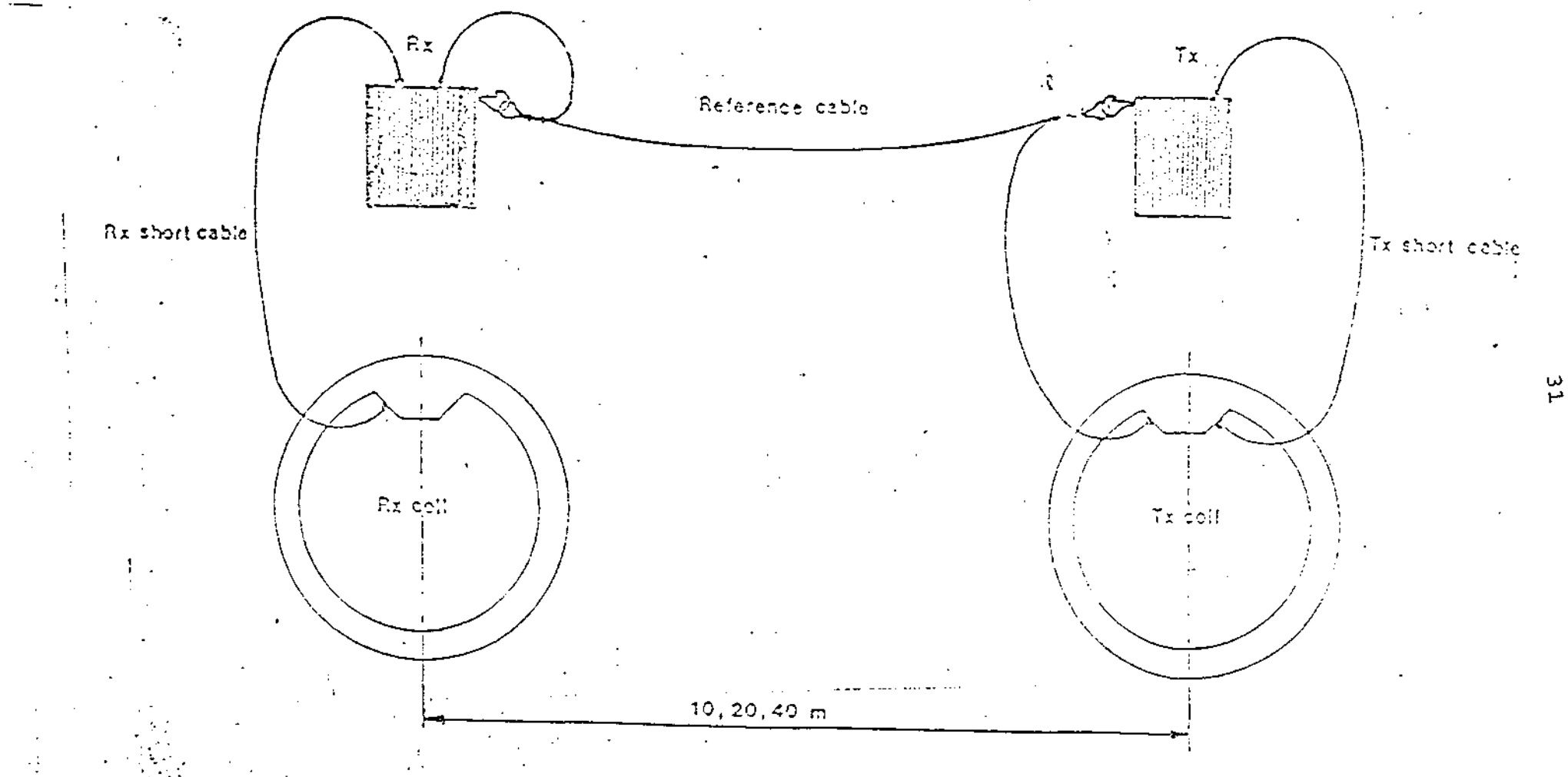


Fig. 3.3 EM-34-3 Cable connection diagram

meter. If it is in the correct region, the value of the apparent conductivity was read from the receiver, if the needle in the coil separation metre is in the wrong region, the coils were moved up or down or even tilted until the meter showed the correct response.

Wrong coil orientation can give wrong indication of coil separation so the coils have to be carried with their planes vertical (Horizontal dipole) or with their plane horizontal (vertical dipole). The horizontal dipole mode is less sensitive to coil misalignment than the vertical dipole (McNeill, 1980b).

Table 3.1 Exploration depths for Geonics EM34-3 at various inter-coil spacings. (McNeill, 1980b)

Coil Spacing (m)	Exploration Depth (m)	
	Vertical Dipole	Horizontal Dipole
10	7.5	15
20	15	30
40	30	60

3.3 THE DIRECT-CURRENT RESISTIVITY METHOD

The most commonly used methods of measuring earth resistivity are those in which current is driven into the ground using galvanic contacts. Generally, four-terminal

electrode arrays are used, since the effect of material near the current contacts can be minimized (Keller and Frischknecht, 1966).

The direct current resistivity method involves introducing direct-current (low frequency a.c could be used) into the ground by means of two electrodes. The resulting potential distribution on the ground is mapped by means of two probes as shown in figure 3.4b. The potential so measured gives information about the variation of resistivity of the subsurface.

3.3.1 Theory

The resistivity method is embodied in the Ohm's law which states that if a voltage V is applied across the ends of a body of constant cross-section, the current I is proportional to the voltage applied i.e.

$$V \alpha I \text{ or } V = IR \qquad (3.16a)$$

where R the constant of proportionality is called the resistance of the body. For a given material, the resistance is directly proportional to the length and inversely proportional to the cross-sectional area. That is,

$$R = \rho l/A \qquad (3.16b)$$

where ρ is called the resistivity of the material.

From equations (13.16a and 13.16b), we have

$$I = VA/\rho l \qquad (3.17)$$

Now consider a point source of current in a plane which is bound between a perfect insulator and a semi-infinite isotropic homogeneous conductor of resistivity ρ (This is the nearest approximation of the earth subsurface) as shown in fig 3.4a.

The potential at a point P is given by Beck (1981) as

$$V = \rho I/2\pi r \qquad (3.18)$$

This is the potential at a point P due to the current source S. If there are two current sources instead of one, the potential at any point close to them will be affected as shown on Fig 3.4b.

The potential at P_1 due to C_1 is

$$V_1 = \rho I/2\pi r_1 \qquad (3.19)$$

The potential at P_1 due to C_2 is

$$V_2 = -\rho I/2\pi r_2 \qquad (3.20)$$

The potential at P_1 due to C_1 and C_2 is

$$V_1 + V_2 = (I\rho/2\pi)(1/r_1 - 1/r_2) \qquad (3.21)$$

with the second electrode P_2 in place the potential difference

between P_1 and P_2 is given as

$$\Delta V = (I\rho/2\pi)\{(1/r_1 - 1/r_2) - (1/r_3 - 1/r_4)\} \qquad (3.22)$$

Rearranging we have

$$\rho = (\Delta V/I)\{2\pi/[(1/r_1 - 1/r_2) - (1/r_3 - 1/r_4)]\} \qquad (3.23)$$

The factor in curly brackets can be seen to depend only on

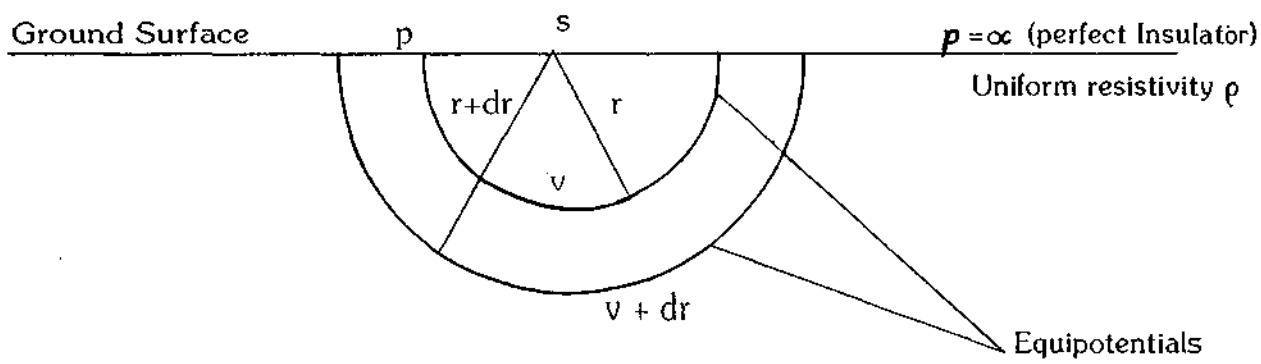


Fig. 3.4a Potential Distribution due to a point current source

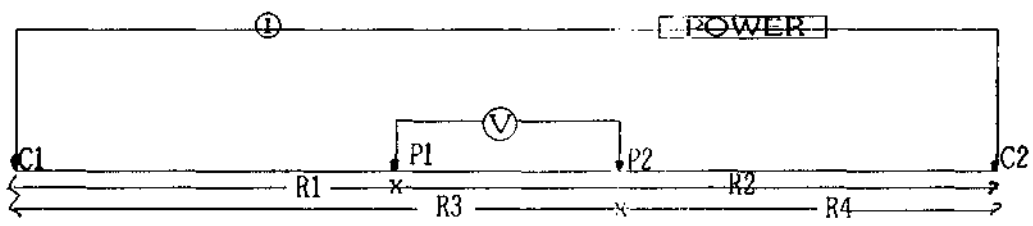


Fig. 3.4b Potential Distribution due to two current sources

the geometry of the electrode arrangement. It is called the geometric factor (K). The expression for ρ can be written as

$$\rho = K\Delta V/I \qquad (3.24)$$

where K = the "geometric factor".

The value of resistivity obtained from equation (3.24) above is for homogeneous and isotropic medium. If the medium is not homogeneous, as is practically the case with the earth's subsurface, the resistivity value as obtained from equation (3.24) is referred to as the "apparent resistivity", ρ_a. The apparent resistivity though diagnostic, to some extent, of the true resistivity of the layer of measurement, is not the actual resistivity (Telford et al, 1976). The apparent resistivity can only be the same as the true resistivity only when the ground is homogeneous and isotropic.

3.3.2. Instrumentation

The instrument used for this work is the ABEM SAS 500B terrameter. The terrameter output is a.c but at very low frequency. For normal use the standard factory programming is equivalent to d.c. surveying.

The terrameter has selectable currents of 0.2, 0.5, 1.0, 2.0, 5.0, 10.0 and 20 mA with maximum voltage output of 160 V. The instrument gives a direct measurement of the

resistance in ohms with a range of 0 - 1.9 Mohm. It has selectable number of cycles of measurements of 1, 4, 16 and 64. The terrameter is powered by a rechargeable 12 V Nickel - Cadnium battery. The terrameter weighs about 5.6 kg including the battery. The electrodes are of stainless steel.

3.3.3 Electrode Arrangement.

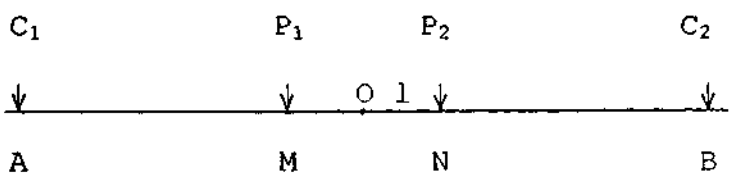
Various electrode arrangements have been used, at various times and at various places, for various reasons. But, essentially, they may be grouped into the following three classes as given by Keller and Frischknecht (1966).

1. Arrangement in which the potential difference between two widely spaced measuring electrodes is recorded.
2. Arrangement in which a potential gradient or electric field intensity is measured using a closely spaced pair of measuring electrodes.
3. Arrangement in which the curvature of the potential function is measured using a closely spaced current electrode pair as well as a closely spaced measuring electrode pair.

Any of the arrangements mentioned above can be used to study variations of resistivity with depth or lateral variations in resistivity. In studying the variations of resistivity with depth, sometimes called vertical electrical sounding (VES), the spacings between the

various electrodes are gradually increased. In studying lateral variations in resistivity, called horizontal profiling, a fixed separation is maintained between various electrodes and the array as a whole is moved along a traverse line.

For this work, the arrangement in which the potential gradient is measured, called the schlumberger arrangement, was chosen. The electrode positions for this configuration is as shown on Figure 3.5



C_1, C_2 =Current Electrodes P_1, P_2 =Potential Electrodes
O = Centre of the spread.
l = Half- potential electrodes separation
L = Half- current electrodes separation

Fig.3.5 Schematic diagram of the Schlumberger electrode arrangement.

The Schlumberger electrode arrangement measures the potential gradient. The expression for ρ_a simplifies to (Telford et al, 1976)

$$\rho_a = \pi L^2 \Delta V / 2lI \qquad (3.25)$$

L is the distance between current electrode and the centre of the spread, l is the distance between the potential

electrode and the centre of the spread.

For Vertical Electrical Sounding (VES), which was used during this fieldwork, the current electrodes were moved apart with the potential electrodes remaining fixed for a while. For large values of L, l may also be varied provided that the condition that L>5l is satisfied.

The Schlumberger arrangement was chosen from other electrode configurations for the following reasons:

1. The configuration gives greater probing depth.
2. It has ease of operation in that two electrodes are moved at a time unless occasionally when the potential electrode spacing is also increased.
3. The effects of near surface, lateral inhomogeneities are less apt to affect measurements.
4. More importantly the interpretation techniques are more fully developed and diversified (Zohdy et al,1990).

3.3.4. Field Procedure

The Electromagnetic Traverse (EMT) was taken first. The conductivity values are recorded and plotted against distance traversed. Two selection criteria are used to determine the VES points. These are:

1. When the conductivity value for the vertical dipole mode is greater than the conductivity for the horizontal dipole mode. This according to Beeson and Jones (1988) is indicative of a conductor at depth.

2. When the first condition cannot be obtained, the point with the highest conductivity value for the horizontal dipole mode is taken as the VES point.

Since the primary aim of any water supply programme is to provide water as close to the community as possible, sometimes, additional VES stations are established as close to the settlements as possible. Another consideration is to make two or three soundings parallel to each other to see if a certain pattern will emerge after interpretation.

When the VES point is selected, the current electrodes are expanded about the centre and readings taken until either the curve of apparent resistivity vs half current electrode spacing rises at 45^0 (Ede, 1991) or when the current electrode spacing reaches 300 m. This is so because the information given by BSADP (1988) is that the depth to the basement is less than 100 m. The distance between potential electrodes was increased when the distance between current electrodes became comparatively large (i.e. when L>>5l).

An ABEM SAS 300B resistivity equipment, which gives directly the value of the resistance of the sampled earth in ohms was used for the data collection in this work.

From equation 3.25, it can be seen that

$$\rho a = (\pi L^2/2l)R \qquad (3.26)$$

where $R = \Delta V/I$

multiplying the geometric factor K by R gives the apparent resistivity ρa for the particular electrode spacing as suggested by equation 3.26.

3.4 PROBLEMS ENCOUNTERED DURING THE FIELD WORK

As with any human effort, several problems were encountered during the field work. Specifically, the underlisted problems were encountered during the EM data collection stage:

1. Dragging large cable length greater than 40 m through shrubs was energy sapping, which was also frustrating whenever the cables got tangled or caught by shrubs.
2. The terrain in the survey area is rugged. Hence, it was very difficult to get the T_x and R_x coils to be co-planar or co-axial.

The specific problems encountered during the VES data collection stage were as follows:

1. Some of the villages investigated are inaccessible to vehicles. Hence, the equipment had to be hand-carried to and from such villages.
2. There was also the social problem whereby the local people assumed that the established VES points were the exact borehole locations. Hence, some ideal VES points could not be established due to pressure from the local community.

3. The problem of livestock crossing the survey area and dragging along the cables at different points and times of taking the VES readings.

4. Some VES points could also not be established due to insufficient space for expanding the array. The existence of physical obstacles such as rock outcrops, houses, etc. at or near such ideal VES points necessitated the shift in the VES points.

5. The problem of convincing the local people where the survey was carried out that the survey had no direct relationship with the promises for provision of boreholes from the Local Government.

CHAPTER FOUR

INTERPRETATION

4.1 INTRODUCTION

The basic aim of collecting any geophysical data is to interpret the data in terms of a geologically identifiable condition. This interpreted situation, usually called the model may, in some cases, differ, even if slightly from the actual geological situation. However it is the best that approximates the true geological situation. Thus, an interpretation is said to be satisfactory if the model approximates the actual geological situation very well.

There are mainly two forms of interpretation of geophysical data; qualitative and quantitative interpretations. Qualitative interpretation is usually a preliminary work that involves explanation of an anomaly based on the observations. On the other hand, quantitative interpretation is the main interpretation as it involves more than explanation, it gives complete description of whatever result is obtained. It is a more thorough and complete result of geophysical investigation.

4.2 Electromagnetic Data

The EM data obtained for the work under discussion is primarily meant to be interpreted qualitatively. The data

were collected in form of EM values along traverses of variable lengths. The aim of the data collection was to determine either lateral inhomogeneities or areas with increasing conductivity with depth.

Two methods for the quantitative interpretation of the EM data in terms of two-layered earth model were proposed by McNeill(1980b). The first method is similar to the partial curve matching formerly used for the interpretation of resistivity data. The second method is analytical. Ratios of the apparent conductivity values are calculated for the three coil spacings in both the horizontal and the vertical dipole modes. The ratios are then plotted on a set of master curves that directly gives the depth of the first layer.

These methods give model in terms of only two layers; where the earth consists of more than two layers; this calculation will often lead to an equivalent two layered model, which may prove useful.

The criterion used in this work for selecting a sounding point from the EM data was adopted from the method of Beeson and Jones (1988). The criterion involved measuring the static water level (SWL) in each village from the well(s). For SWL less than 15 m, 20 m coil spacing was used for the traverse. A point was accepted as

sounding data involves the following steps:

1. Studying the nature of the curve and determining the type of curve (ie whether H or A or K or Q or HA, etc), from which approximate layer properties can be determined.

2. Studying the types of sounding curves obtained and the nature of the areal distribution of these curves on a map of the survey area.

3. Preparation of apparent resistivity sections and geological sections.

These sections and profiles constitute the basis of qualitative interpretation which always precede quantitative interpretation of VES data.

4.3.2 Quantitative Interpretation.

Several methods are used for the quantitative interpretation of VES data. These methods are classified generally as being analytical, semi-empirical and empirical methods. The analytical methods are based on the calculation of theoretical sounding curves that match the observed curves. While the empirical and semi-empirical methods use some of the information obtained from the sounding data to determine some properties of the earth like the transverse resistance, longitudinal conductance or resistivity-thickness values (Zohdy et al, 1990). These methods are inexact, non-popular and tedious. The analytical methods are more developed for computers which make the calculations of the curves easier

and more exact, and above all, they use all the information given by the VES data (Zohdy et al,1990).

The method used for interpreting the VES data collected in this work is the analytical method. The interpretation was carried out using a computer-based resistivity interpretation programme, called "OFFIX". The programme is a forward and inverse modelling programme for the interpretation of resistivity sounding data written by Interpex Ltd. The steps for the interpretation are as follows:

1. The user reads the field data into the computer using a special edit menu.
2. The computer then plots the ρ_a versus half the current electrodes spacing on a logarithmic scale, and the plot is then displayed on the screen.
3. The user then suggests a model, i.e. the number of layers, the resistivities and the thicknesses of the model layers. The maximum number of layers the computer programme accepts is ten. Using the forward modelling mode, the computer calculates a synthetic resistivity sounding curve for the model and then compares the original curve with the synthetic curve and displays the two and the percentage mismatch.
4. The user can enter the average modelling mode, which allows him to obtain a model which best fits the data in a least square sense. This is done using ridge regression

(Inman, 1975) to adjust the parameters of a starting model supplied by the user in an iterative manner.

5. This procedure is repeated until the percentage mismatch is reduced to a low value, say 5%.

6. Finally, the reduced model and original curve are displayed together with the layer parameters of the reduced model with the percentage error between the model and the original data.

4.4 Deriving Geologic Sections.

A geolectric section is the result obtained after the interpretation of the sounding curves and each layer in a geoelectric section is defined by two fundamental properties. Its resistivity ρ_i and its thickness h_i where i indicates the position of the layer in the section (i = 1 for the uppermost layer). There are other geoelectric parameters that can be derived from the resistivity and thickness of a layer in a geoelectric section.

These are;

1. Longitudinal unit conductance, $S_i = h_i/\rho_i$

2. Transverse unit resistance, $T_i = h_i\rho_i$

3. Longitudinal resistivity, $\rho_L = h_i/S_i$

4. Transverse resistivity, $\rho_t = T_i/h_i$

5. Anisotropy, $= (\rho_t/\rho_L)^{1/2}$

These secondary geoelectric parameters are particularly important when they are used to describe a geoelectric section consisting of several layers.

A geologic section is an arrangement of layers in order of occurrence that are fundamentally different in lithology. A geologic section differs from a geoelectric section because the boundaries between geologic layers do not usually coincide with the boundaries between geoelectric layers. Thus, the electrical boundaries separating layers of different resistivities may or may not coincide with boundaries separating layers of different geologic age or lithological compositions. In this work, the geoelectric sections obtained from the interpreted sounding data were converted to a geologic section using the resistivity values in Table 4.1 and figures 4.1b to 4.15b.

It should be noted that table 4.1 serves as a guide to the physical interpretation. The distinction between the layers are not as sharp as the table indicates because, there are many overlaps. The resistivity value of a layer is not necessarily sufficient property to adequately describe the type of the layer but serves as a guide; other controls are geology and the hydrogeology of the area.

Table 4.1 Resistivity values for various rock types (After Shemang et al,(1992) and McNeill(1980a))

Rock type	Resistivity range (ohm-m)
Fadama loam	30 - 70
Silt and Sand	71 - 200
Sand and Gravel	100 - 180
Weathered Laterite	181 - 500
Fresh Laterite	501 - 1000
Weathered Basement/Clay	20 - 150
Fractured Basement	250 - 1000
Fresh Basement	> 1000

4.5 PRESENTATION OF RESULTS

The result of the Electromagnetic Traverse (EMT) is presented in form of profiles of conductivity vs distance traversed. The VES data and model curves are plotted on a logarithmic scale with the model plotted on the same graph. A brief description of the village by village situation is given below:

4.5.1 BAKATUMBE

Six EMTs were run and three VES sites where located based on the EMT data. Extra traverses were taken because of the appearance of a negative giong anomalies on the first three traverses taken. The negative anomalies were interpreted by partial curve matching (McNeill, 1983). The interpretation gives the width of the dyke to be about 5m.

VES 01 was sounded on traverse 01, VES 02 on traverse 02 and VES 03 on traverse 03 as indicated on figure 4.1a. The apparent resistivity curves and models for VES 01-03 are shown in figure 4.1b. All the apparent resistivity curves are H-type curves. VES 03 was chosen as the site for the borehole. The aquifer to be drilled in the village, in this case, is the weathered basement with an apparent resistivity value of 66.62 ohm-m and a thickness of 13.71 m compared with a thickness of 5.69m at VES 02 and 8.26 m at VES 01. The depth to the basement at VES 03 was found to be 14.16 m compared with 6.94 m at VES 02 and 11.29 m at VES 01. Drilling should be extended to 15 m.

4.5.2 BINGIN DIWA

Three EM traverses each of length 300 m were established in different directions at 20 m coil spacing.A VES station was also established on each of the profiles where the conductivity value in the vertical dipole mode is greater than the conductivity value in the horizontal dipole mode,as indicated on the conductivity-distance plots in fig. 4.2a. VES 04 was established on traverse 01 and VES 05 on traverse 02 while VES 06 was established on traverse 03. The apparent resistvity curves for VES 04 and VES 05 are the KH type while VES 06 is the HA type. VES 06 was found to be the preferred location for siting a borehole in the village because the weathered section is thicker there. That is, it has a thickness 25.28 m there

BAKATUMBE

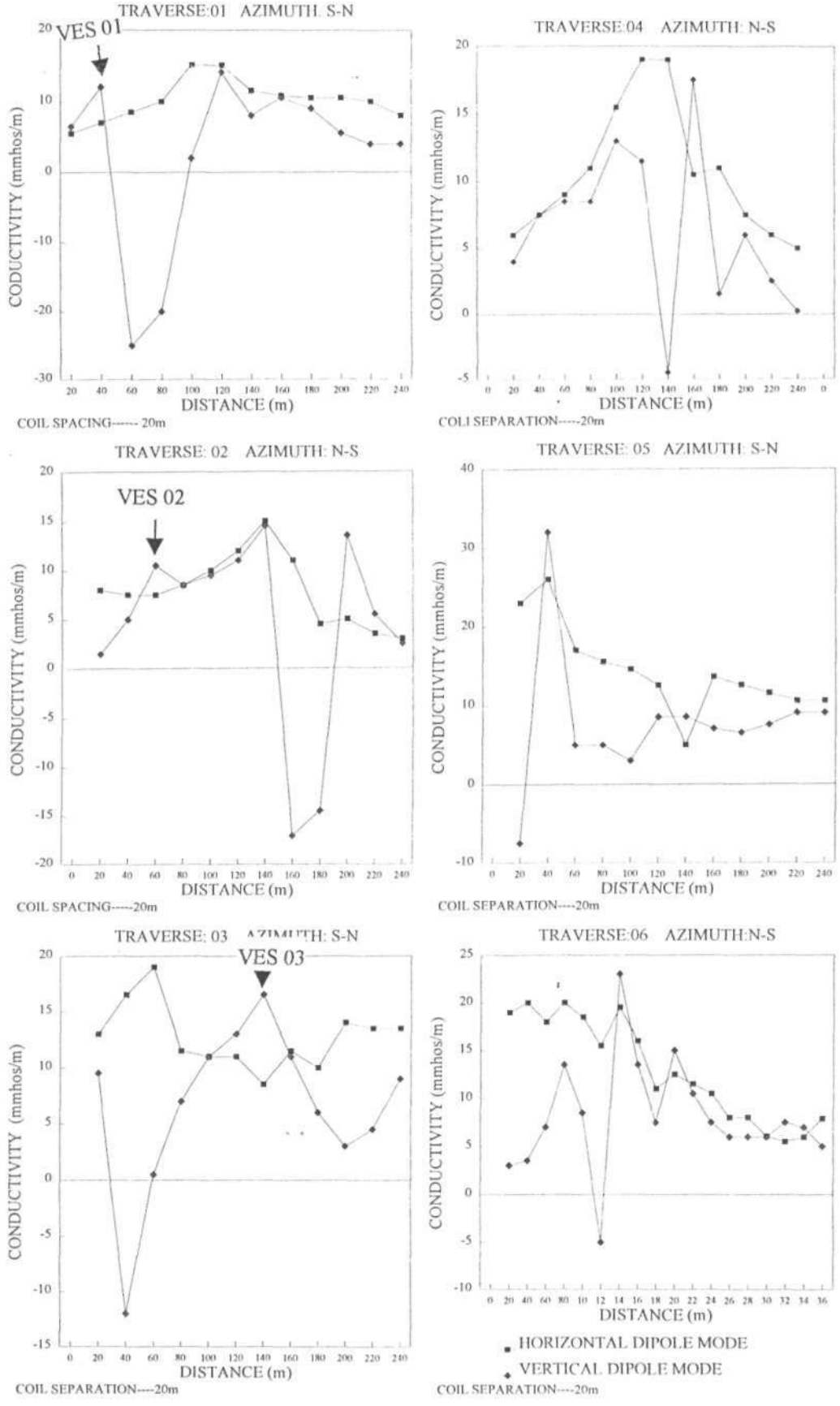
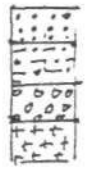
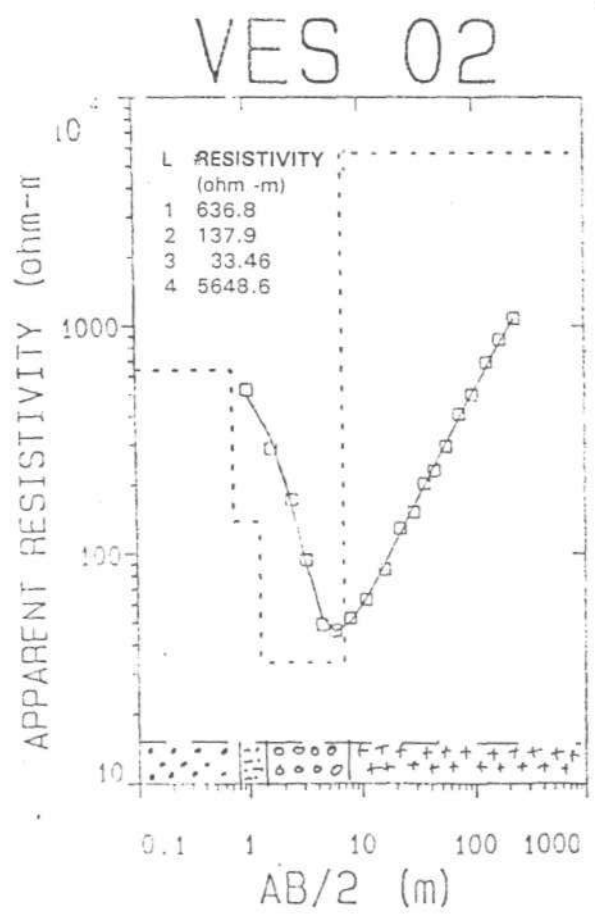


Fig. 4.1a Conductivity plots for Bakatumbe



Sand
Clayey Sand
Weathered Basement
Fresh Basement

Field data point
Model plot
Model curve



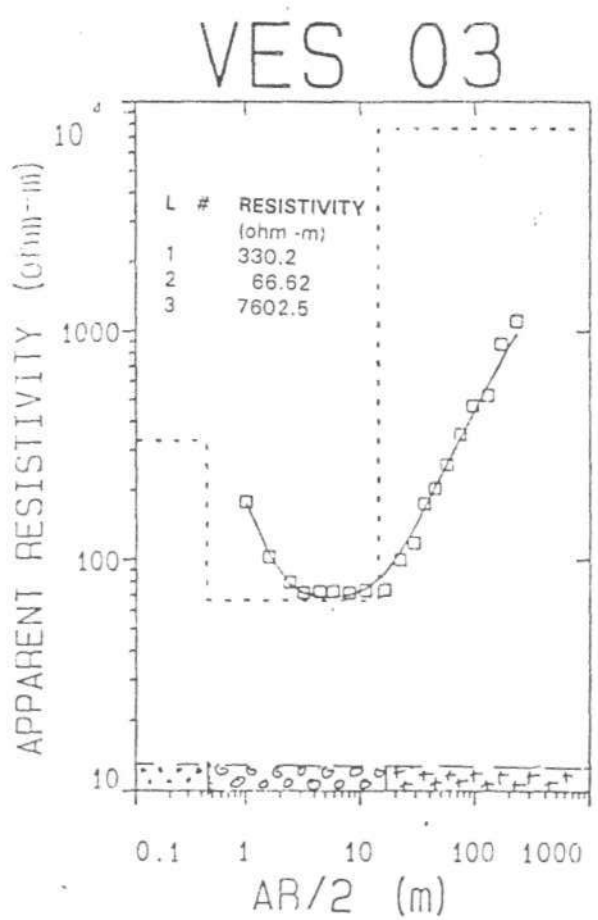


Fig 4.1b Apparent Resistivity Curves and Models for Bakatumbe

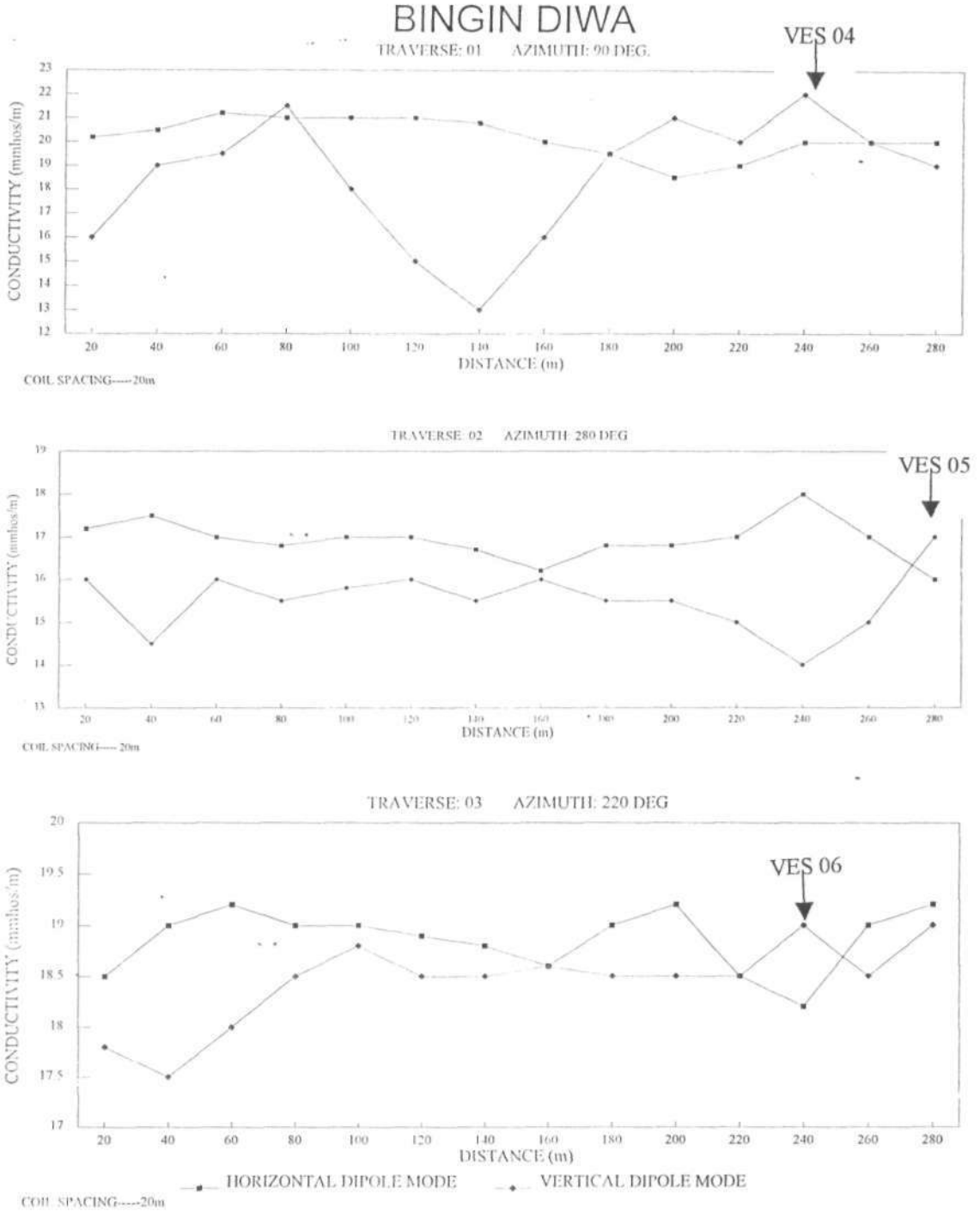


Fig 4.2a Conductivity plots for Bingin diwa

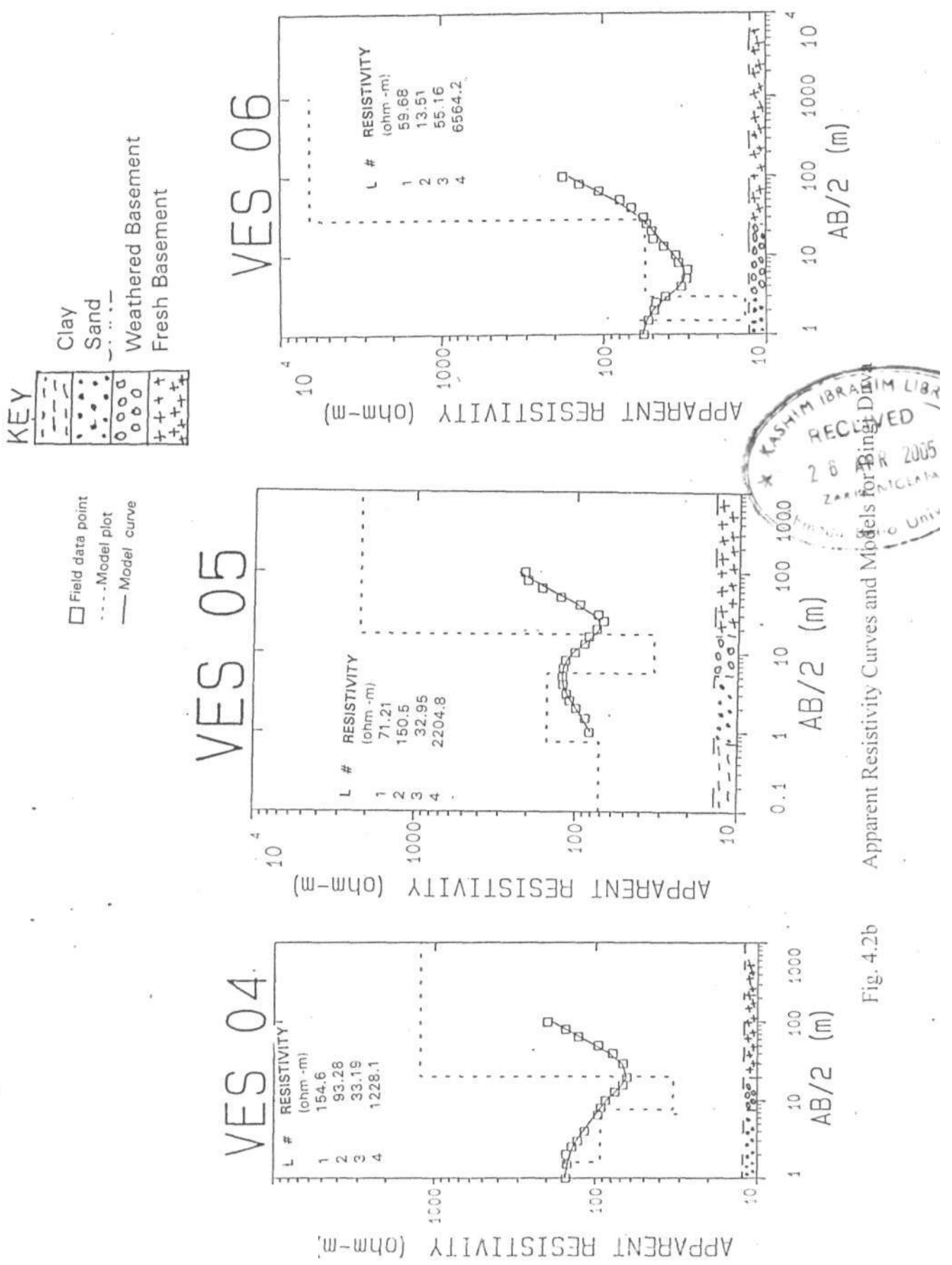


Fig. 4.2b Apparent Resistivity Curves and Models for Bingi, Dam

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when compared to a thickness of 11.58 m at VES 05 and 12.86 m at VES 04. The depth to the basement was found to be 28.26 m at VES 06; 17.11 m at VES 05 and 20.59 m at VES 04. The apparent resistivity curves and the models are shown in figure 4.2b.

4.5.3 BINGIN LABO

At this location, 3 EM traverses, each of length 300m were run at the coil spacing of 20m. The plots of conductivity vs distance gives 3 sounding points, where the vertical conductivity is greater than the horizontal conductivity as shown in fig. 4.3a. VES 07 was established on traverse 01, VES 08 on traverse 02 and VES 09 on traverse 03. An additional point can be seen on traverse 03, this point was not sounded because the limited lateral extent of the region. All the apparent resistivity curves are the KH type. The interpreted data suggest that VES 07 will be a better site for drilling a borehole. At VES 07, the weathered basement has a resistivity of 39.85 ohm-m and a thickness of 13.10 m. At VES 08 where the thickness of this layer is 8.0 m while it is 6.7 m at VES 09. The basement resistivity, as given by the VES 07 data (562.2 ohm-m), suggests that the basement is highly fractured. The apparent resistivity curves and models are shown in fig.4.3b.

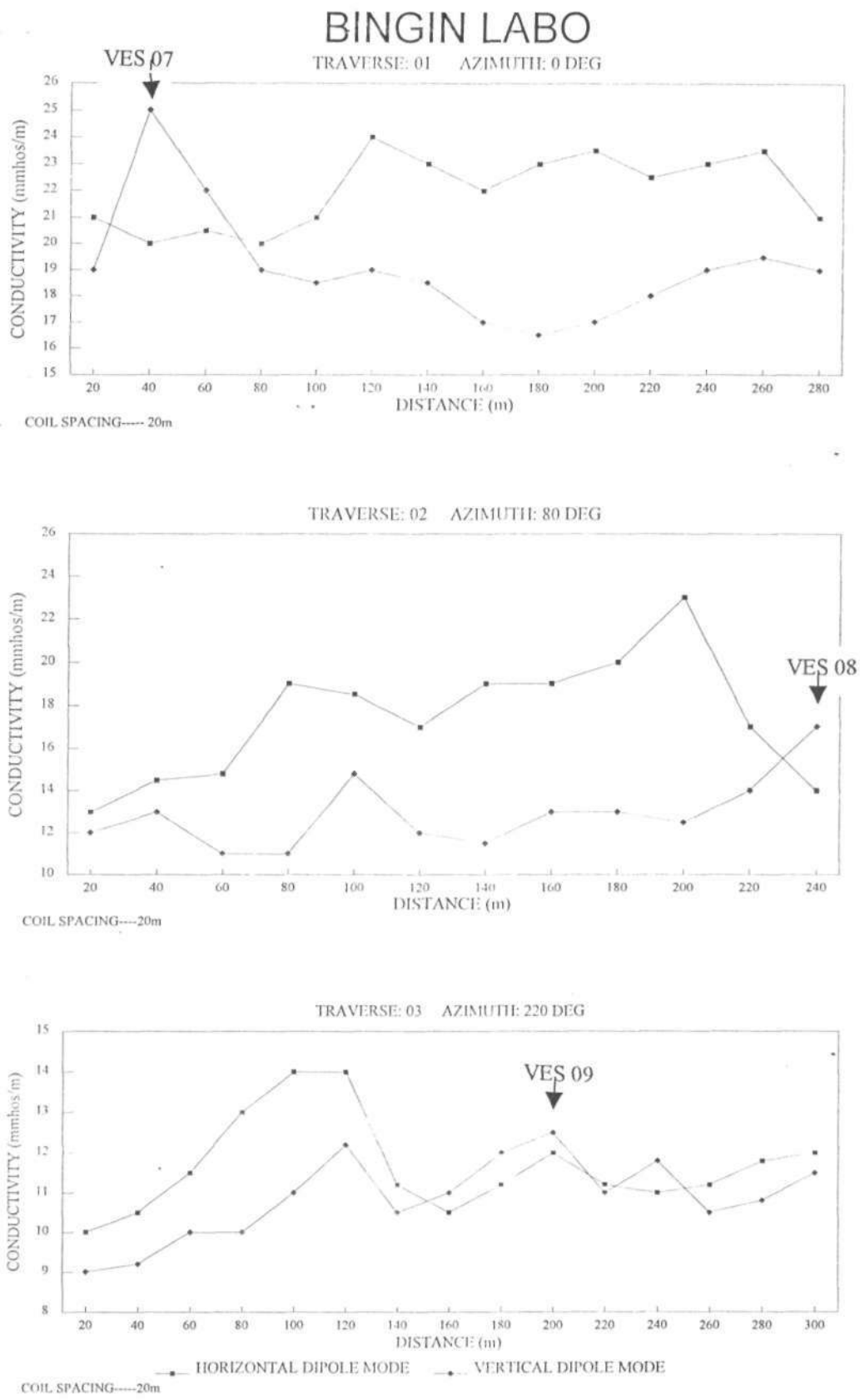
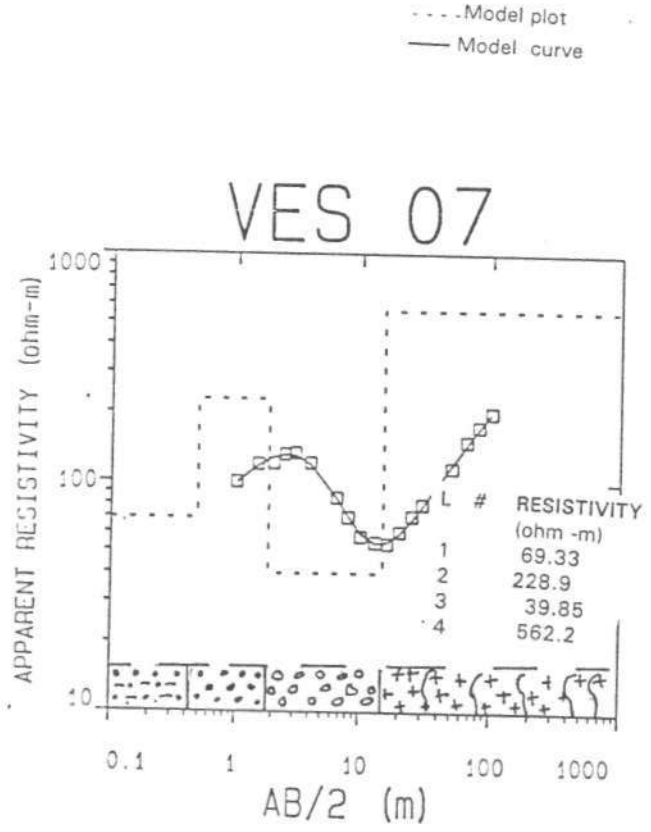
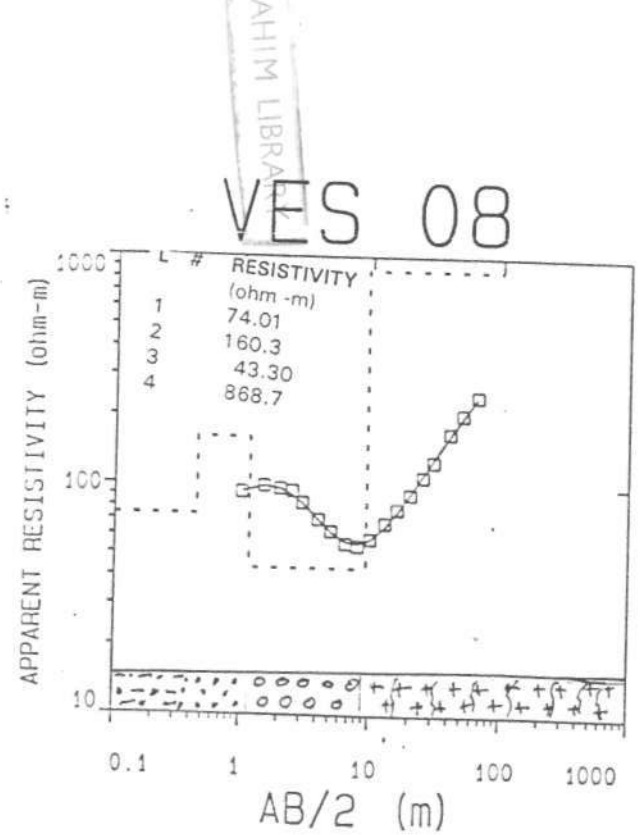


Fig. 4.3a Conductivity plots for Bingin labo



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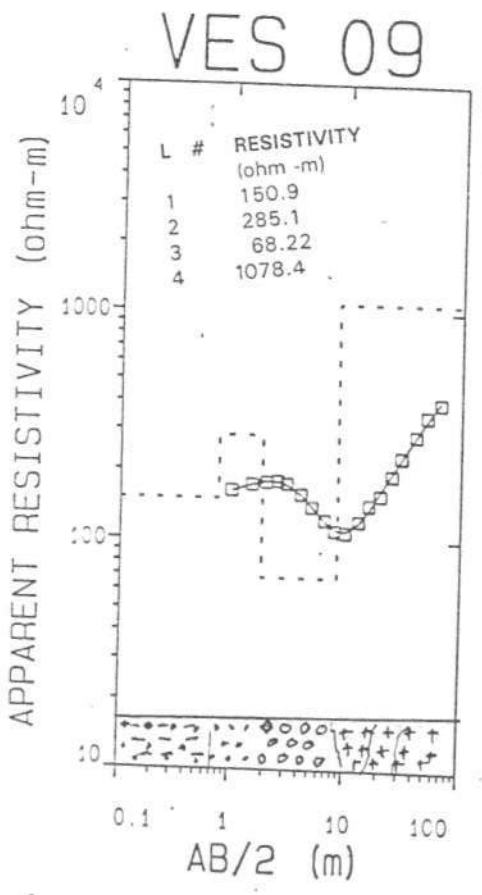


Fig. 4.3b Apparent Resistivity Curves and Models for Bingin Labo

4.5.4 DABAR BAGA

At Dabar Baga 3 EM traverses, each of length 560 m, totalling a distance of 1620 m where taken at 40 m coil spacing. The conductivity vs distance plots are shown in figure 4.4a. The plots indicate 3 regions where the conductivity value for the vertical mode is greater than that for the horizontal mode. VES 10 was sounded on traverse 01, VES 11 and VES 12 on traverse 02, because there is an additional region where the conductivity value at the 40 m vertical mode is greater than 25 mmhos/m and VES 13 on traverse 03. The apparent resistivity curves are shown in figure 4.4b. The apparent resistivity curves for VES 10, 11, and 12 are KH type and for VES 13 is HA type. The geoelectric sections in figure 4.4b indicate that VES 13 is the best site to locate a borehole because the weathered basement is thicker with thickness of 21 m, compared to a thickness of 15 m on VES 10, 8 m on VES 11 and 4.8 m on VES 12.

4.5.5 DANGARFA

Two Em traverses covering a distance of 460 m, were established at 20 m coil spacing. The conductivity-distance plots for these traverses are shown on figure 4.5a. VES data were obtained at the positions indicated on the plots. No sounding was done on traverse 02 position 160 m because the conductivity values are lower than those at the beginning of the traverse.

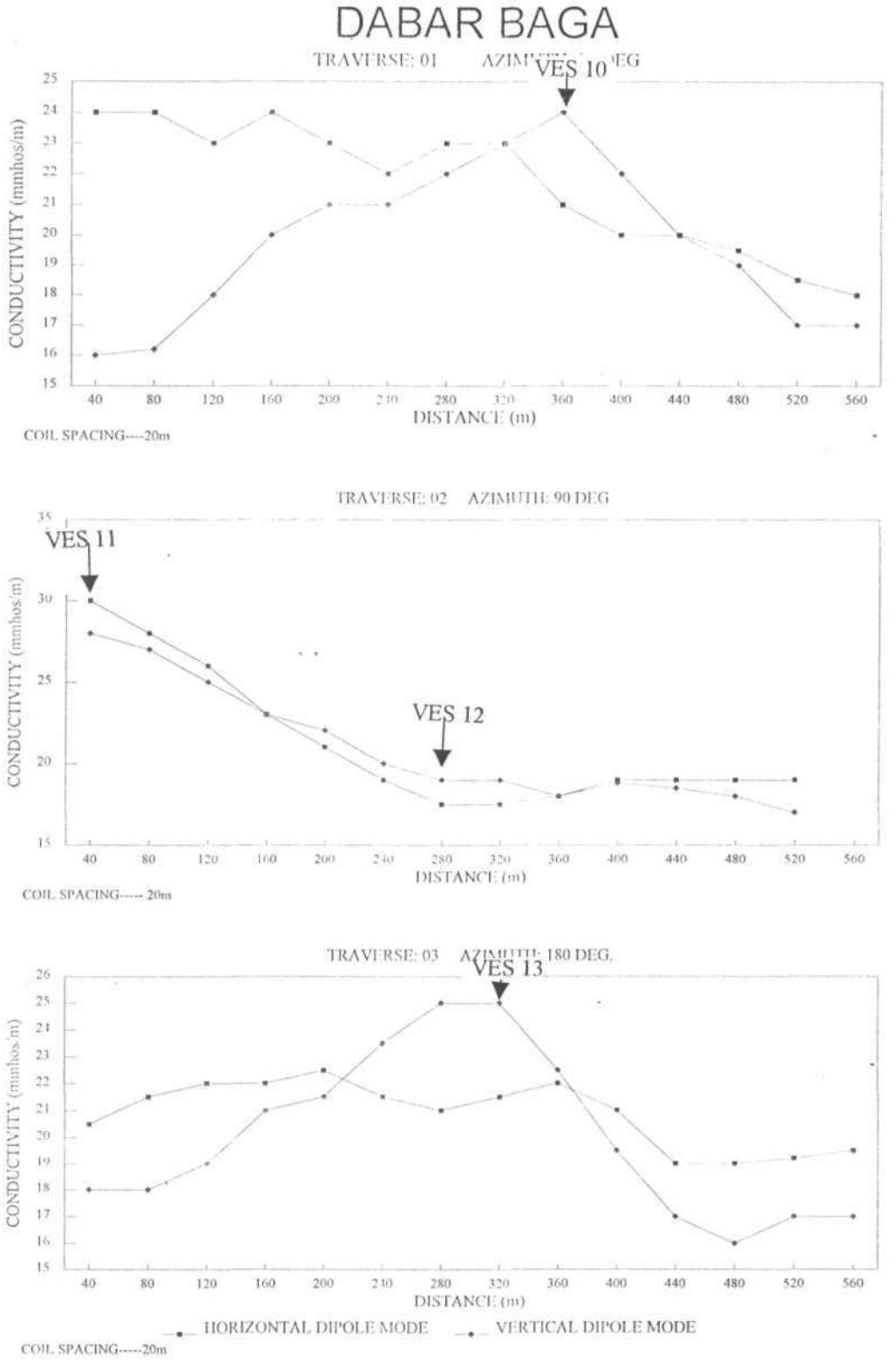


Fig. 4.4a Conductivity plots for Dabar baga

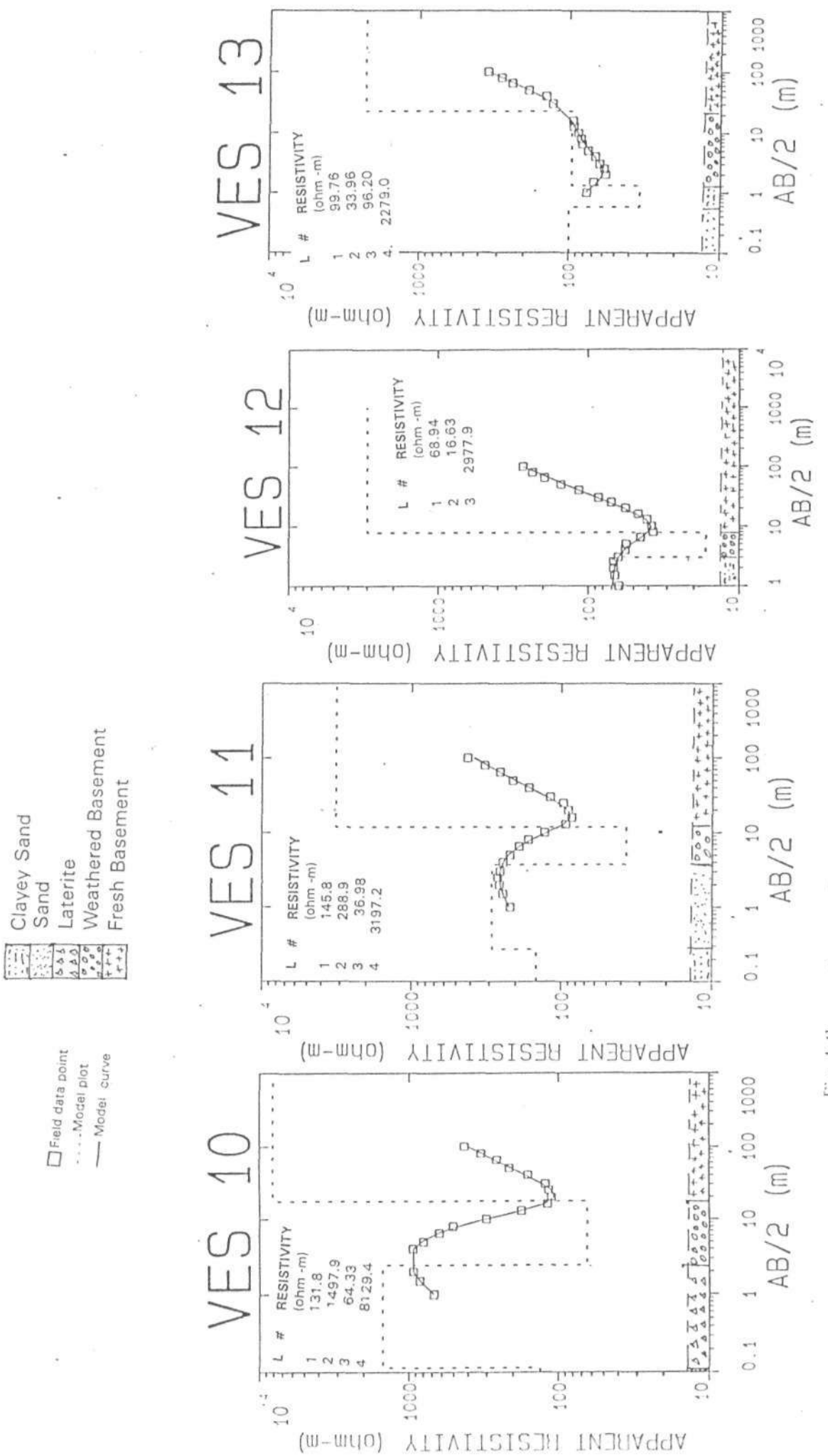


Fig. 4.4b Apparent Resistivity Curves and Models for Dabar baga

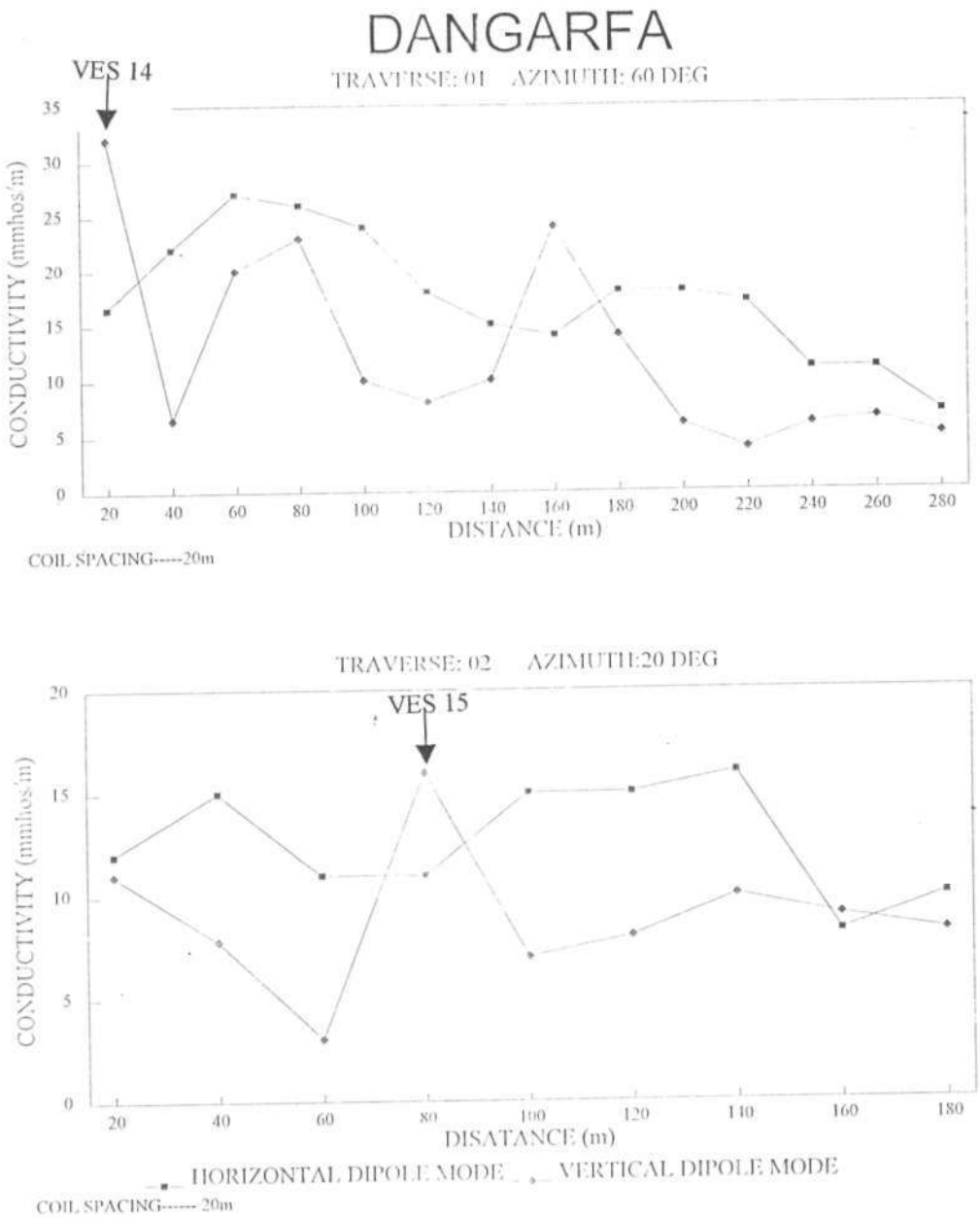


Fig. 4.5 Conductivity plots for Dangarfa

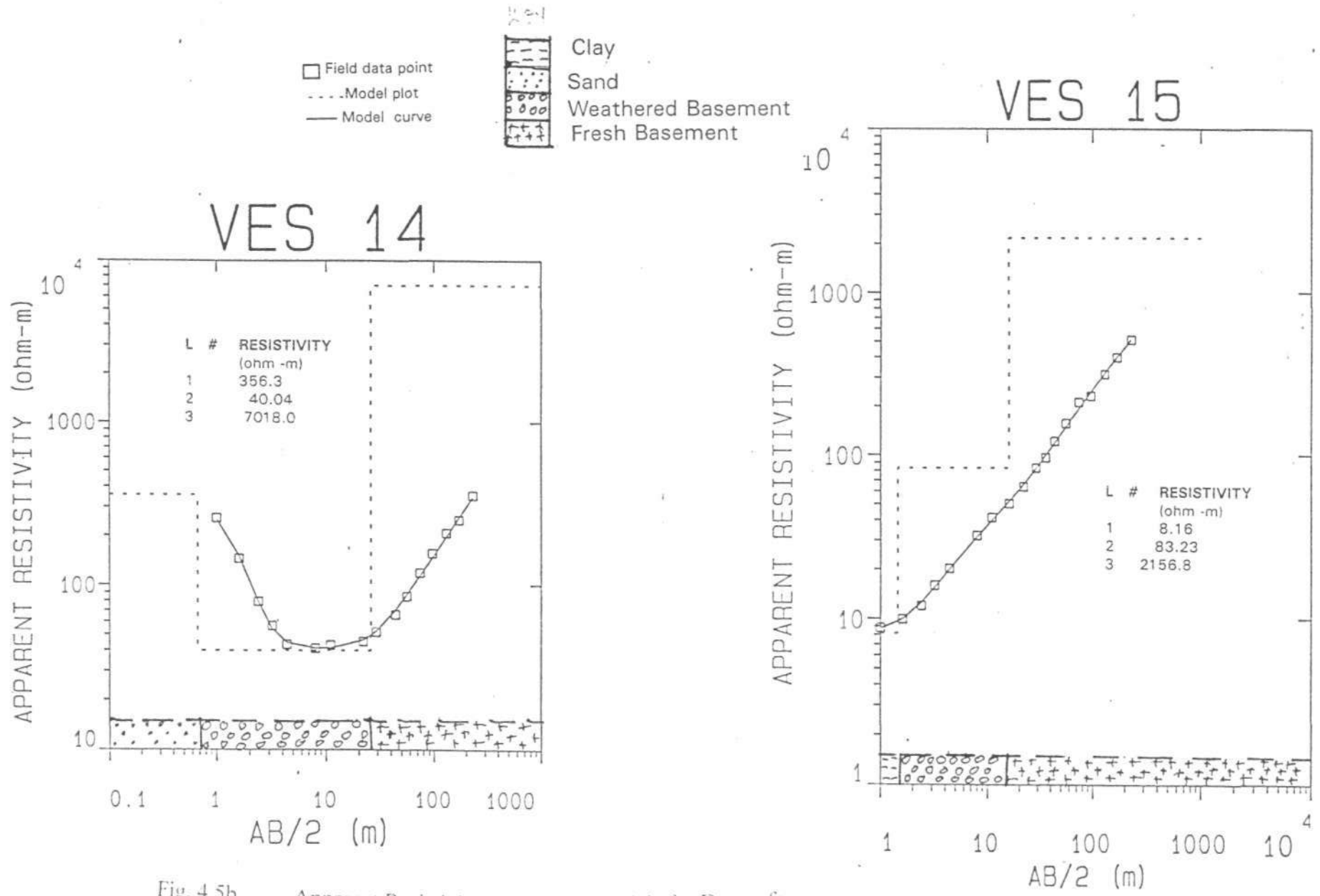


Fig. 4.5b Apparent Resistivity Curves and Models for Dangarfa

VES 14 was sounded on traverse 01 while VES 15 was sounded on traverse 02. VES 15 is the h type while VES 15 is the A type. VES 14 was recommended for drilling because the aquifer there is thickest. The thickness of the aquifer here is 28.5 m while it is only 14.4 m at VES 15. Also, the depth to the basement at this point is 30 m while it is only about 16 m at VES 15. Drilling should be extended to 29 m. The apparent resistivity curves and models derived from them are as shown in figure. 4.5b.

4.5.6 GOMPERO/DUBURE

At Gompero/Dubure two EM traverses were run, each of length 600 m using the 20 m coil spacing. The conductivity- distance plots from the traverses are shown in figure 4.6a. Traverse 01 shows two positions where the vertical mode conductivity value is greater than the horizontal mode conductivity value. Position 540 m was preferred because of large conductivity values. VES 16 was established on traverse 01 and VES 17 on traverse 02. All the VES curves are H type. VES 16 was recommended for drilling because the inferred aquifer is 25.62 m thick there while it is only 4.47 m at VES 17. The aquifer resistivity value of 396.4 ohm-m at VES 19 is indicative of a fractured basement while the low resistivity (15.19 ohm-m) layer beneath VES 17 indicates that it might be clayey. The apparent resistivity curves and models are shown in figure 4.6b. The depth to the basement is 34 m at VES 16, while it is only about 5 m at VES 17.

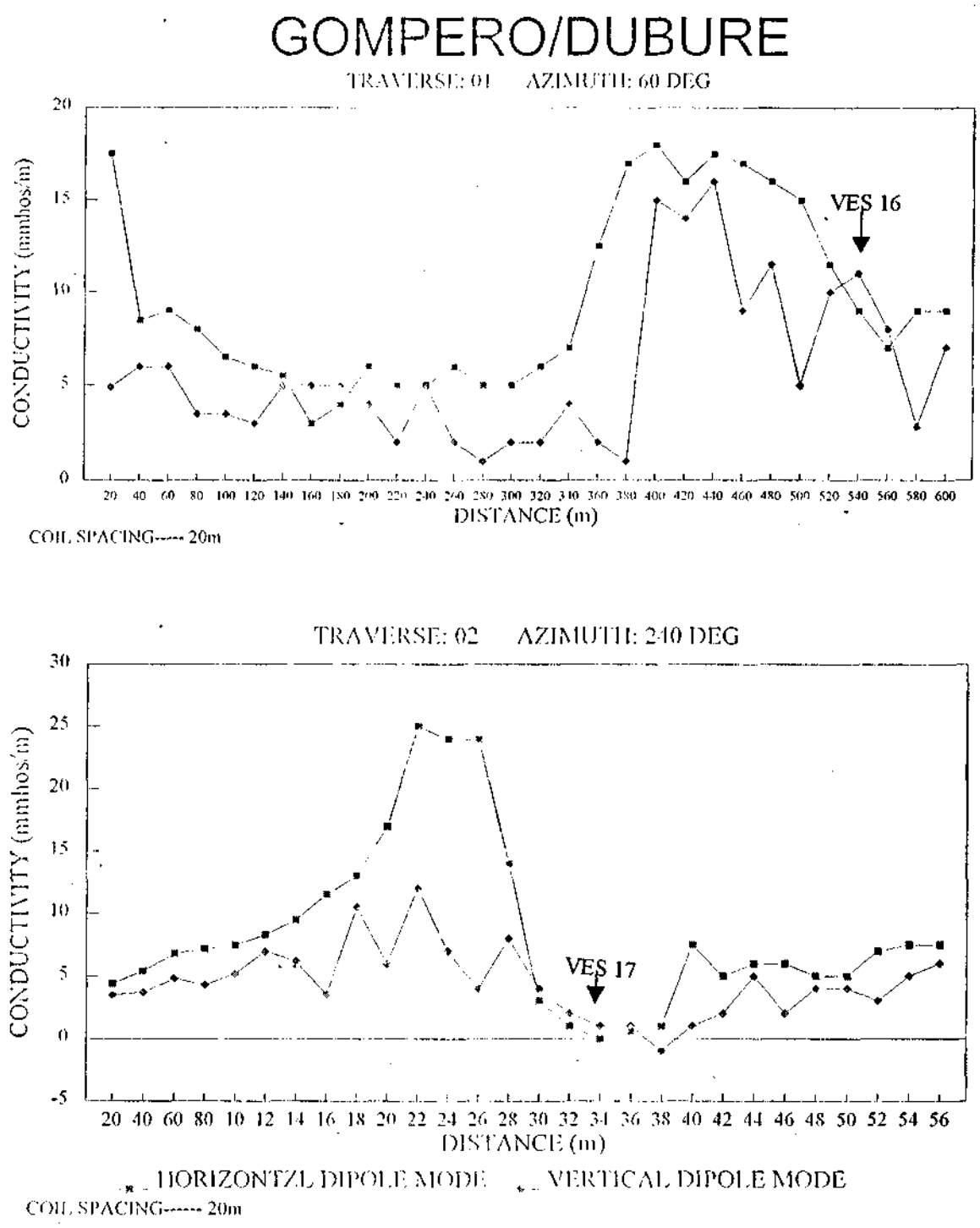
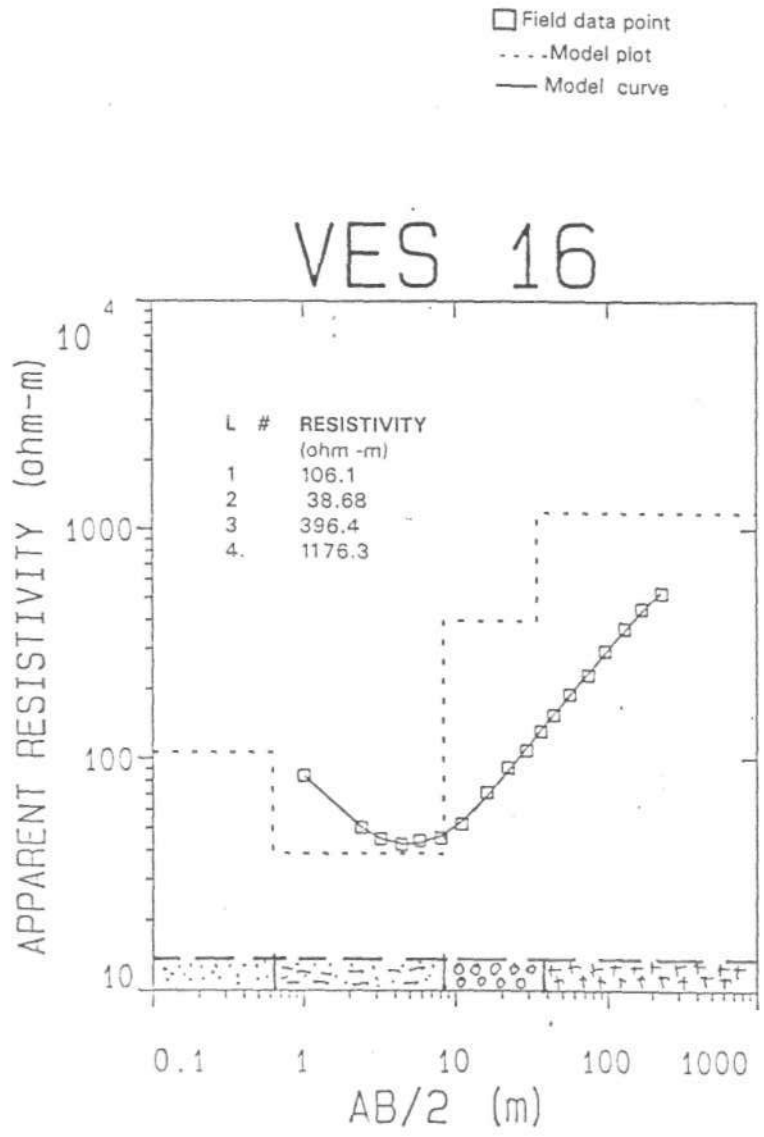
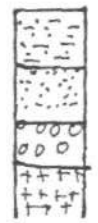


Fig. 4.6 Conductivity plots for Gompero/Dubure





Clayey Sand
Sand
Weathered Basement
Fresh Basement

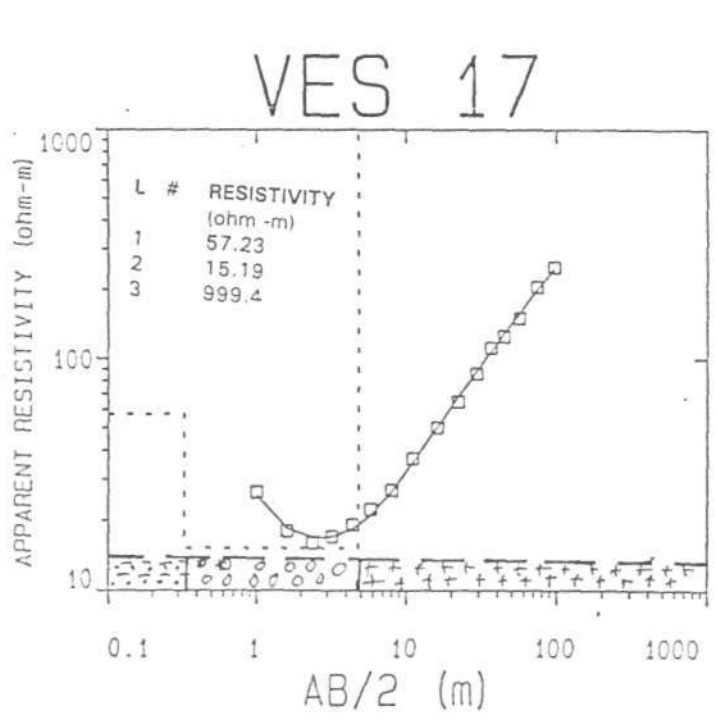


Fig. 4.6b Apparent Resistivity Curves and Models for Gompero/Dubure

4.5.7 ISAWA

The average water level, as measured from wells in the village was 5.6 m. Some of the wells in the village ended in the fresh basement. A borehole had been drilled in 1988 but the yield was so little for any pump installation. Two EMTs totalling a distance of 440 m were taken at a coil spacing of 20 m. The conductivity vs distance plots are as shown in figure 4.7a. VES 18 was established on traverse 01 while VES 19 was sounded on traverse 02. The apparent resistivity curve for VES 18 is KH type and that of VES 19 is the H type. VES 18 was recommended for drilling because the weathered basement is thicker, (18.76 m thick) at the point compared with a thickness of 10.69 m at VES 19. The apparent resistivity value of 19.91 ohm-m at VES 18 suggest that the aquifer is probably saturated with water otherwise it will be clay. Hence drilling should be carried out there and should be extended to 21 m. The apparent resistivity curves and models are shown in figure 4.7b.

4.5.8 KAGADAMA

At Kagadama three EM traverses, totalling a distance of 2280 m, were established at 40 m coil spacing. The conductivity vs distance plots are shown in figure 4.8a. The plots suggest three sites for carrying out d.c resistivity sounding.

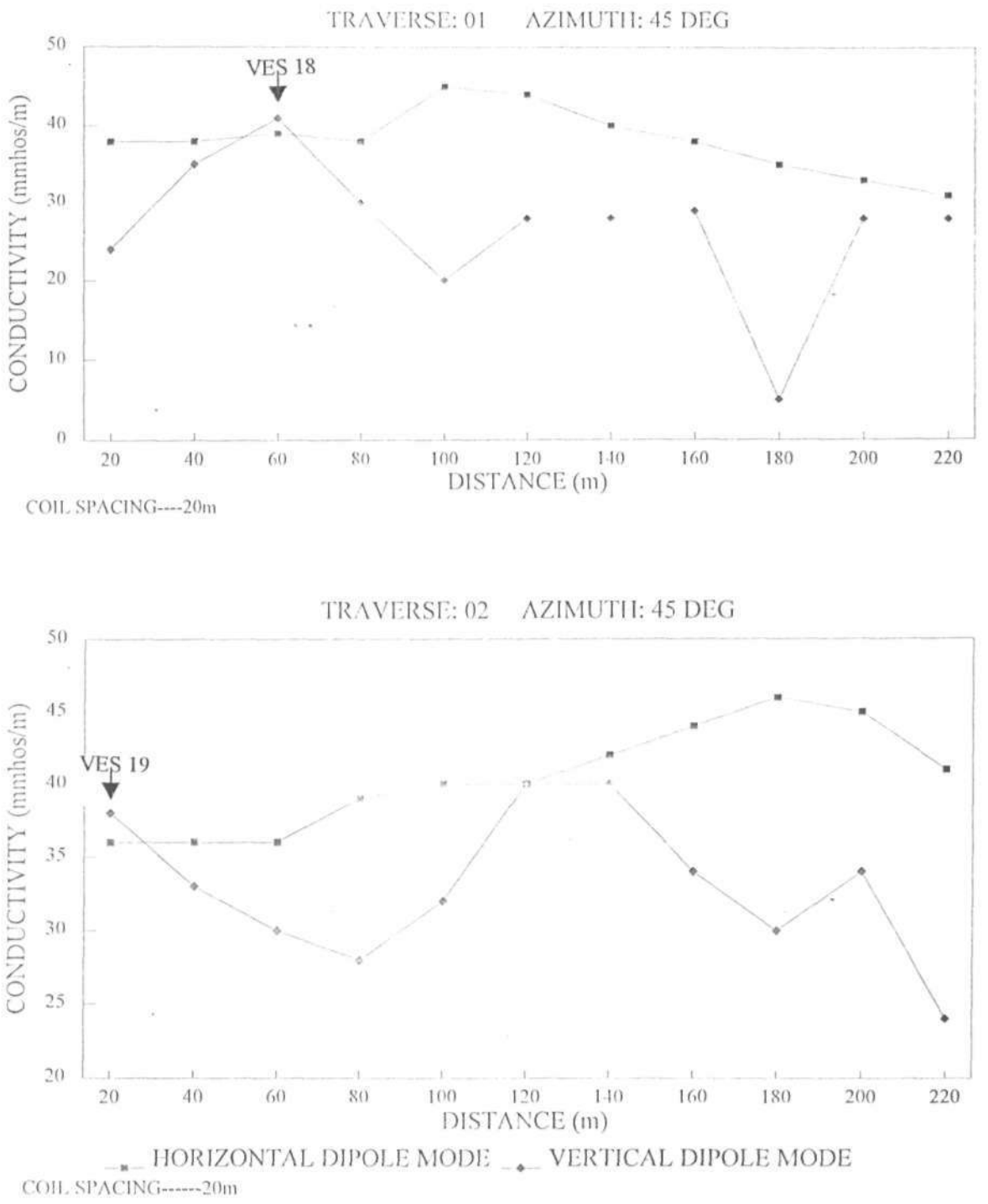


Fig. 4.7a Conductivity plots for Isawa

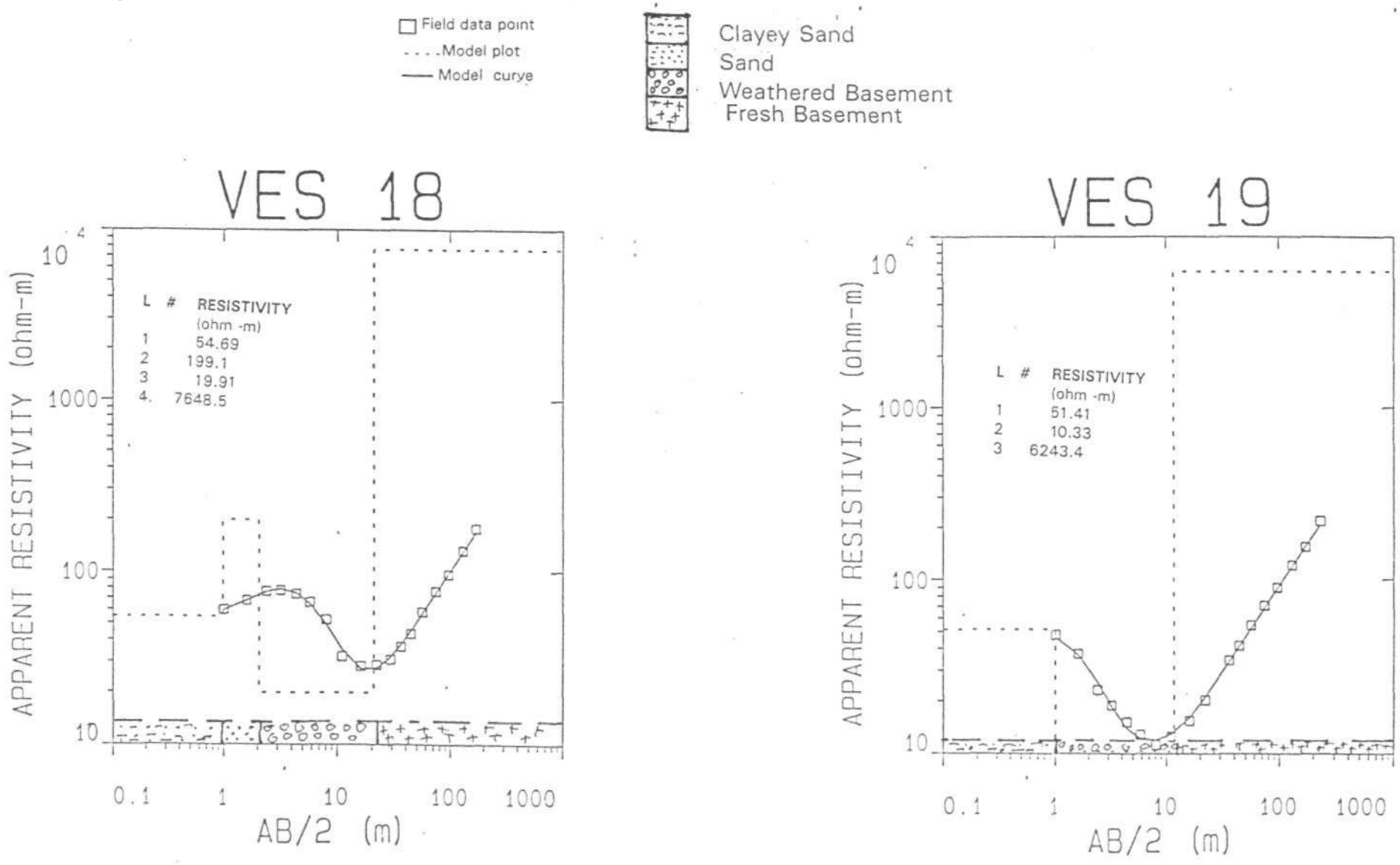


Fig. 4.7b Apparent Resistivity Curves and Models for Isawa

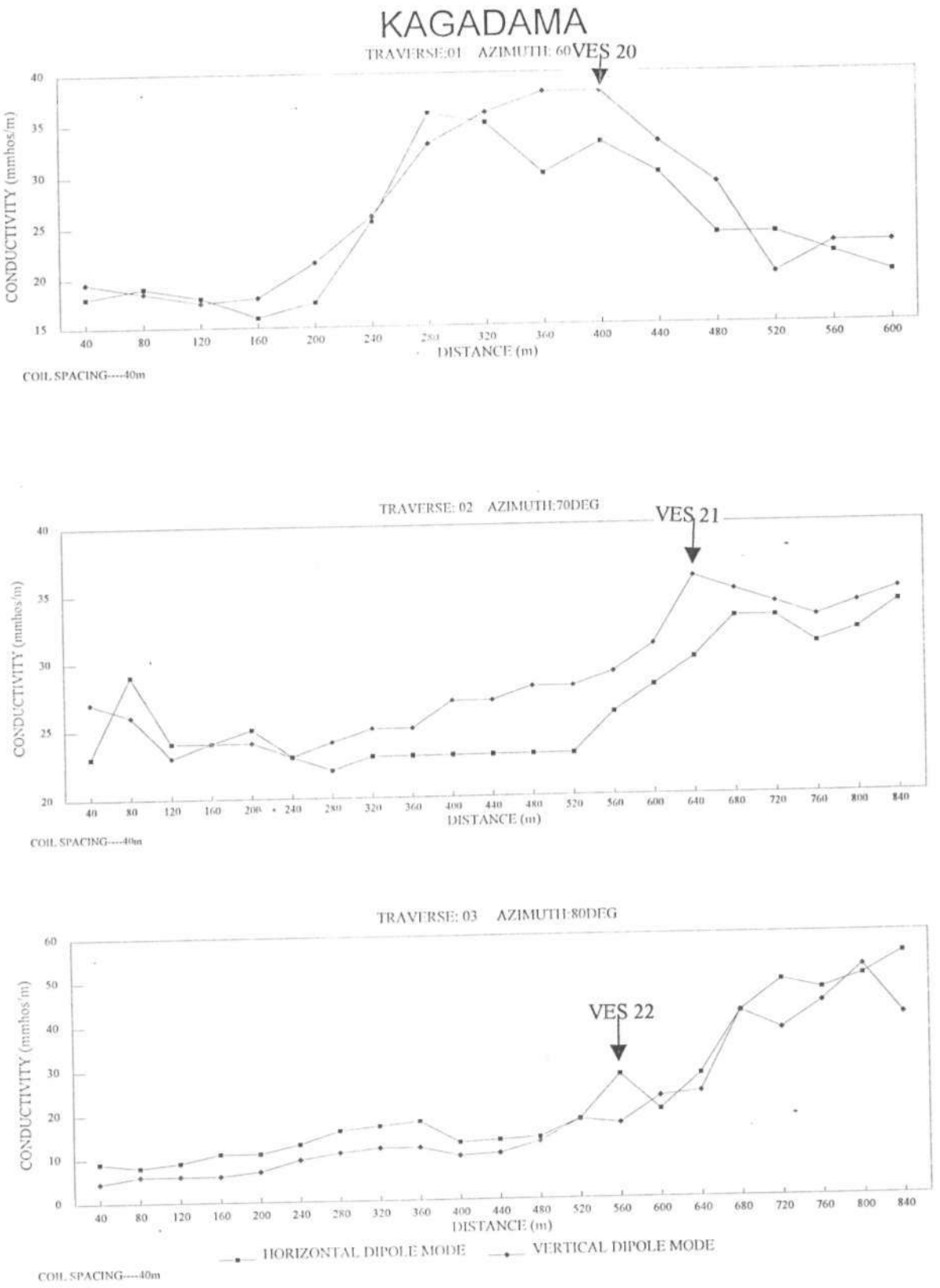


Fig. 4.8a Conductivity plots for Kagadama

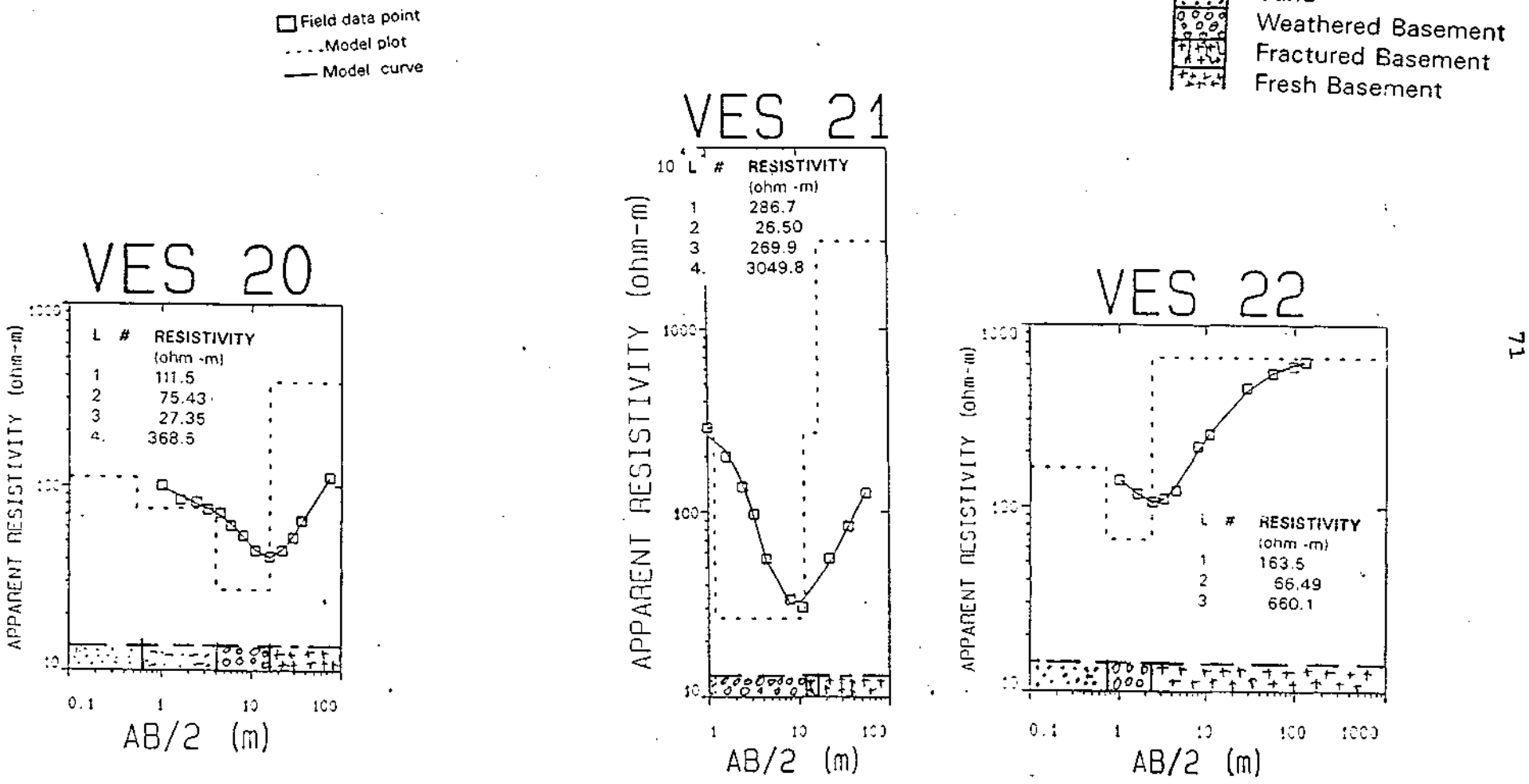


Fig. 4.8b **Apparent Resistivity** Curves and Models for Kagadama

There are two regions on traverse 01 where the vertical mode conductivity is greater than the horizontal mode conductivity value, the region with greater conductivity values was sounded. Hence, VES 20 was established on traverse 01, VES 21 on traverse 02 and VES 22 on traverse 03. The VES models and curves are shown in figure 4.8b. The apparent resistivity curves for VES 20 is the QH type, VES 21 is H type and VES 22 is A type. The interpreted resistivity data suggest that VES 21 will be a better site for siting a borehole. Though the low resistivity layer is thicker (11.98 m) at VES 20, compared with 10.36m at VES 21 and 1.64m at VES 22. On VES 21 another layer appears before the basement with apparent resistivity of 269.9 ohm-m. This geoelectric layer is thought to be a fractured basement and its thickness is appreciable (5.20m).

4.5.9 LIMI

At Limi two EMTs were run covering a distance of 840 m at a coil spacing of 20 m. The conductivity plots for these are as shown in figure 4.9a. VES 23 was established on traverse 01 and VES 24 on traverse 02. The VES plots and models are as shown in figure 4.9b. The apparent resistivity curve for VES 23 is H type and that of VEs 24 is the HA type. VES 24 was recommended as the site for drilling a borehole. The geoelectric section of VES 23 gives 3 layers with a depth to the basement of 4.05 m. On the other hand the geoelectric section of VES 24 gives four layers.

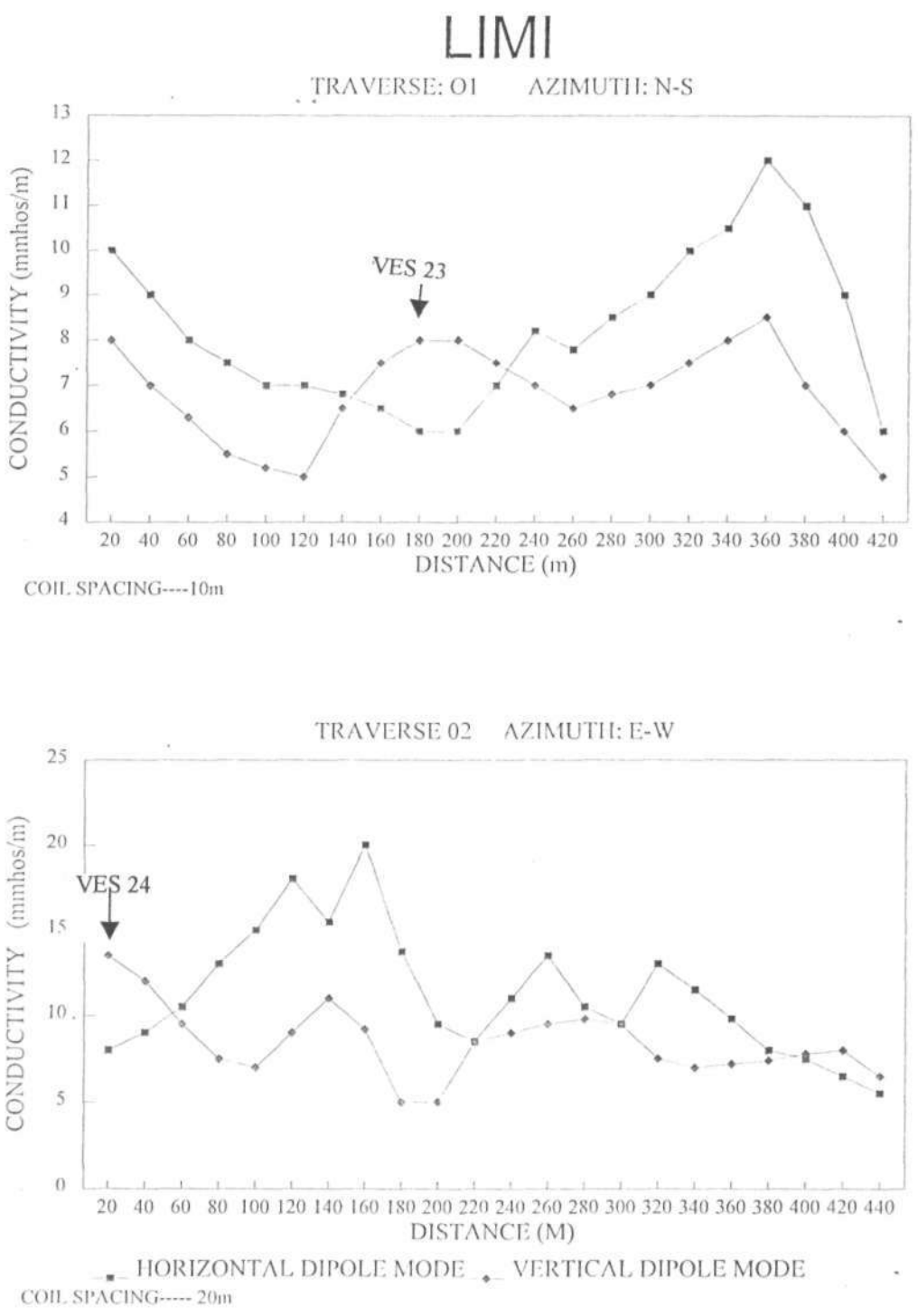


Fig. 4.9 Conductivity plots for Limi

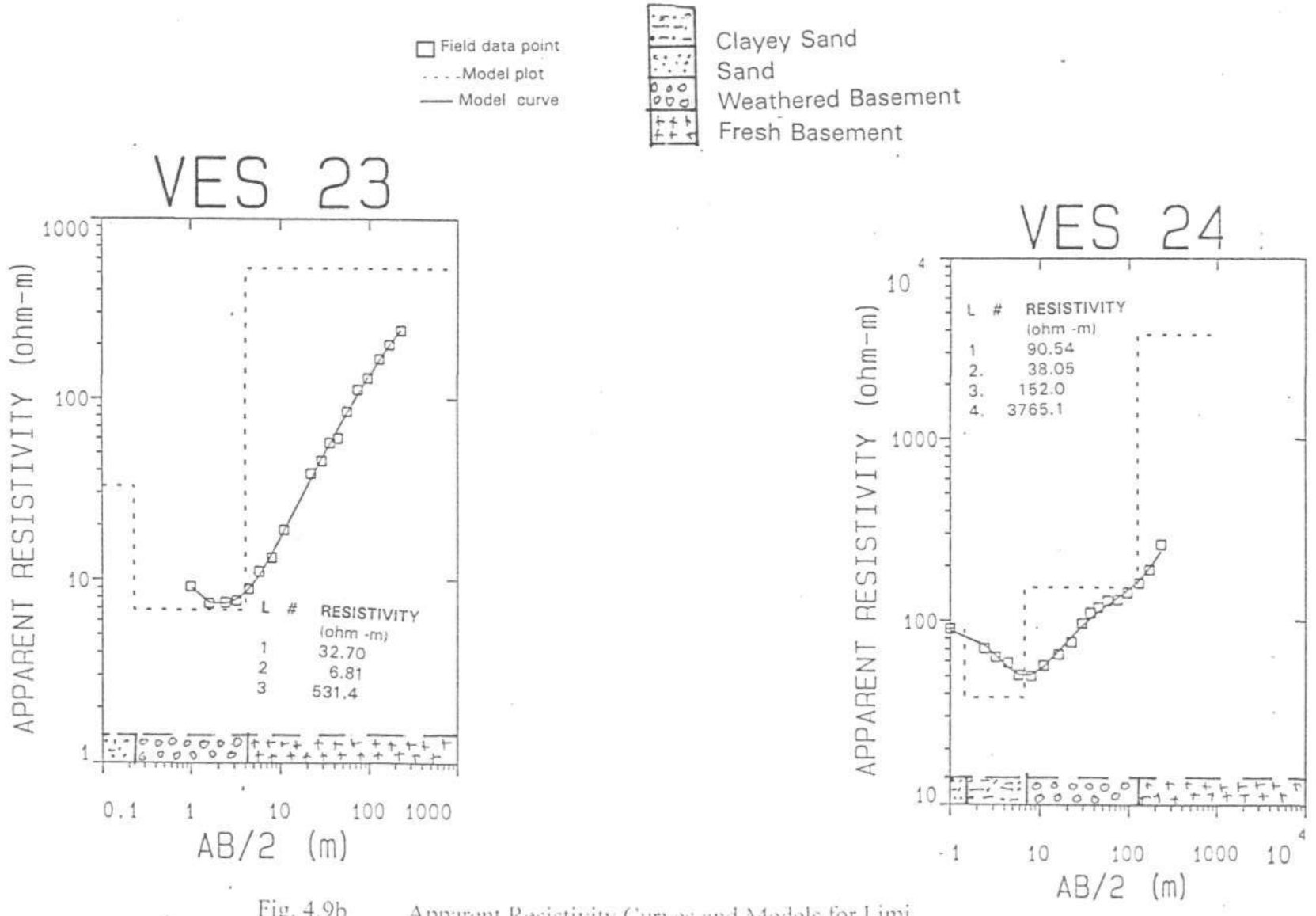


Fig. 4.9b Apparent Resistivity Curves and Models for Limi

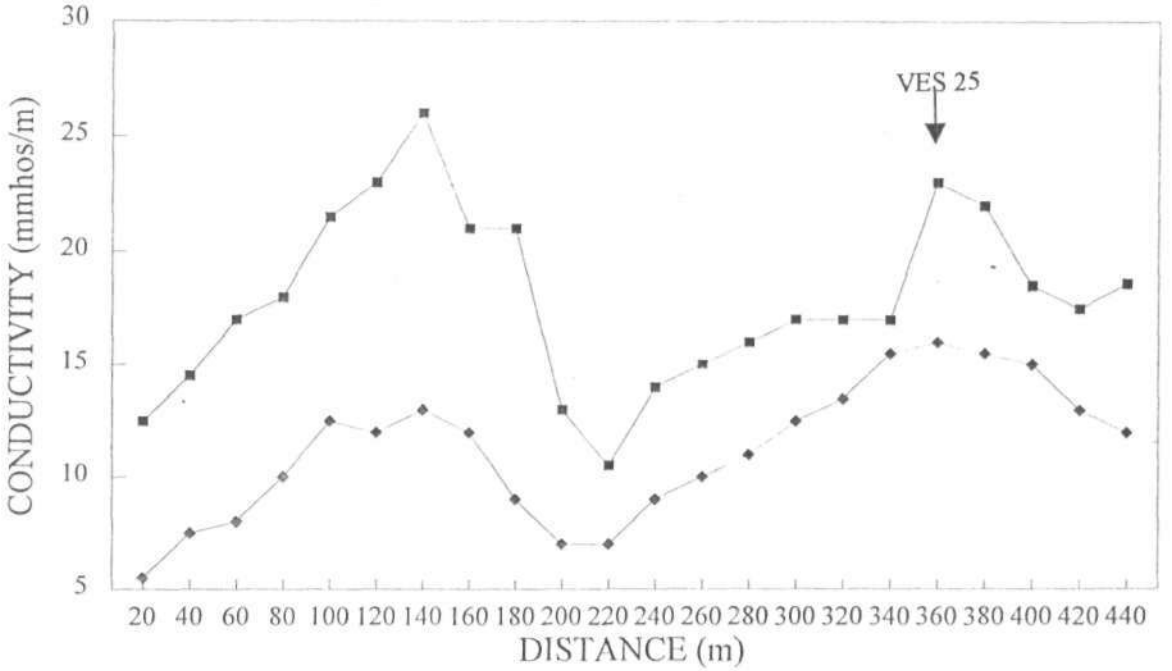
The additional layer is the weathered basement with resistivity of 152 ohm-m, this suggest that this layer is highly weathered. Drilling should be extended to 25 m. The depth to the basement is about 25 m at VES 24, because the inferred aquifer is thicker with thickness of 5.33 m compared to a thickness of 3.82 m at VES 23. It is also inferred that the layer beneath the aquifer is fractured zone judging from the resistivity value (152 ohm-m) which is less than that for fresh basement.

4.5.10 TAKALAFIYA

Two EMTs covering a distance of 740 m were run at a coil spacing of 20 m. The conductivity vs distance plots are shown on figure 4.10a. Traverse 01 does not show any region where the vertical dipole conductivity is greater than the horizontal dipole conductivity. At position 160-180 m on traverse 01 the conductivity values are all relatively large. Hence VES 25 was established on this position. VES 26 was established on traverse 02, although two regions are seen where the vertical dipole mode conductivity is greater than the horizontal dipole mode conductivity, the region choosen has the greater vertical dipole mode conductivity. The apparent resistivity curves and their interpreted models for these two VES data are shown in figure 4.10a. All the VES curves are KH type. The geoelectric sections of VES 25 and VES 26 indicate three layers for each VES station.

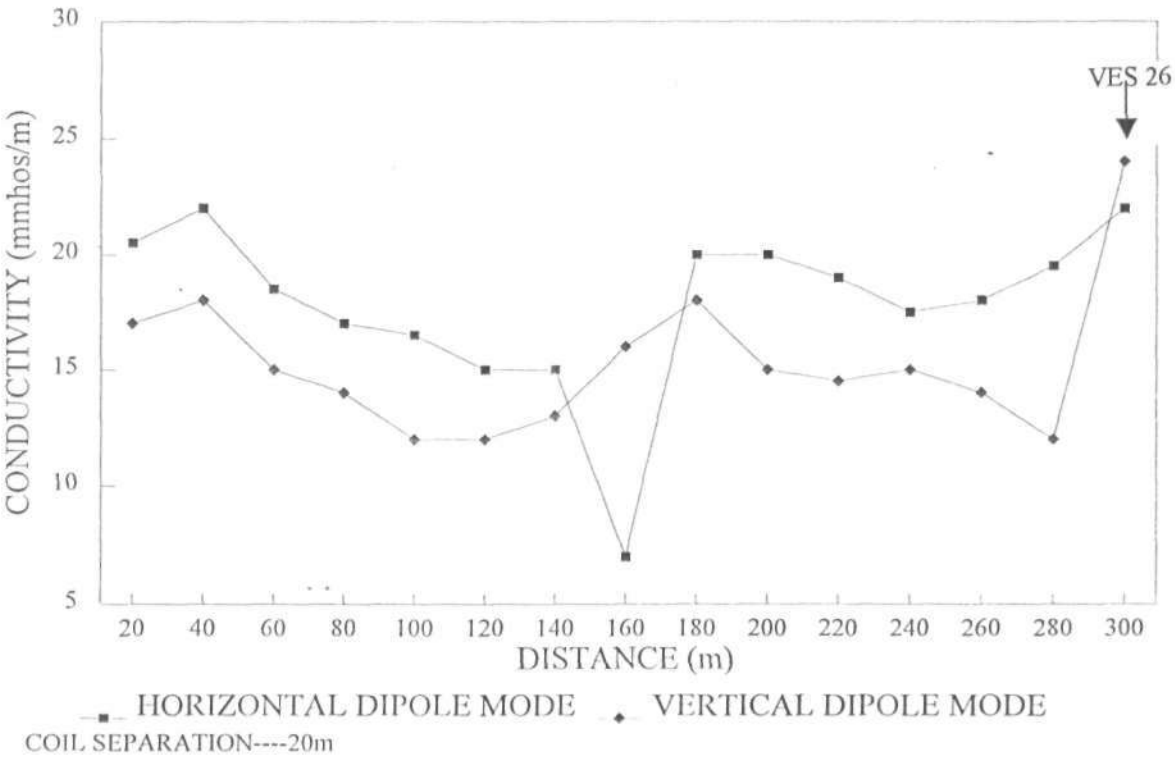
TAKALAFIYA

TRAVERSE: 01 AZIMUTHE: E-W



COIL SPACING----20m

TRAVERSE:02 AZIMUTH:W-E



COIL SEPARATION----20m

Fig. 4.10 Conductivity plots for Takalafiya

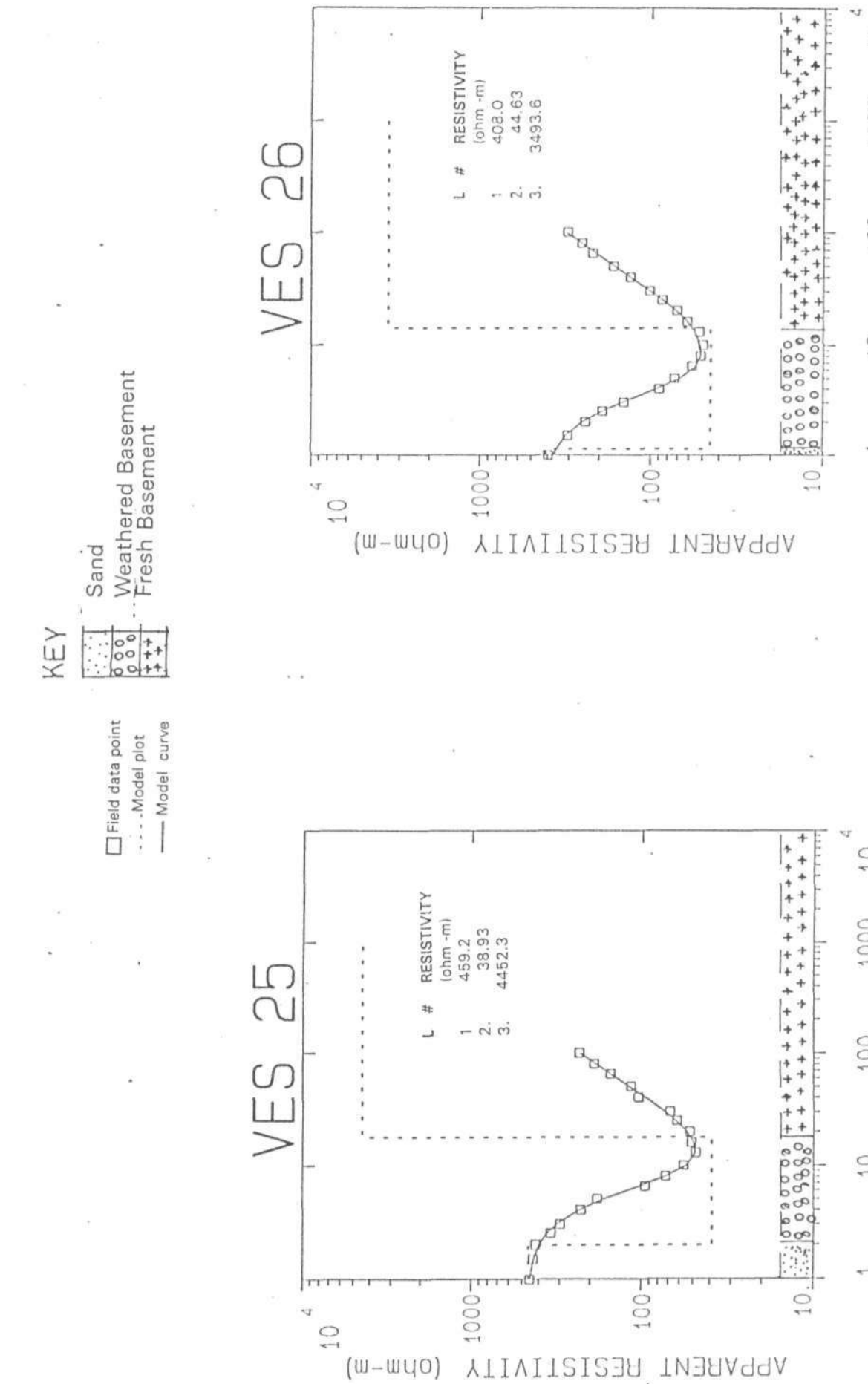


Fig. 4.10b Apparent Resistivity Curves and Models for Takalafiya

The first layer is the overburden with a resistivity value of 408.0 ohm-m on VES 25 and is 1.97 m thick, while the corresponding layer on VES 26 is 1.13 m thick. The second layer which is the inferred aquifer has a resistivity of 38.93 ohm-m on VES 25 and 44.63 ohm-m on VES 26. The thickness of this layer on VES 25 is 15.84 m and 12.85 m on VES 26. The interpreted data suggest that VES 25 will be a better site to drill a borehole than VES 26. The weathered basement thickness at VES 25 is 15.84 m compared with 12.65 m at VES 26 and depth to the basement is about 18 m at VES 25 as against 14 m on VES 26.

4.5.11 TIPSHI

At Tipshi, two EMTs covering a total distance of 640 m were run. The first traverse (traverse 01) was run at a coil spacing of 40 m. The other traverse was run at a coil spacing of 20 m. The coil spacing is different for the two traverses because the water level as measured in the wells near these traverses is different. The conductivity vs distance plots suggest the sounding of two VES locations as shown in figure 4.11a. The apparent resistivity curve for VES 27 is the A type and that of VES 28 is KH type. VES 27 was established on traverse 01 and VES 28 on traverse 02. The VES curves and interpreted models are as shown in figure 4.11b. VES 27 was recommended for drilling because VES 28 has a relatively shallow (9.02 m) depth to the basement.

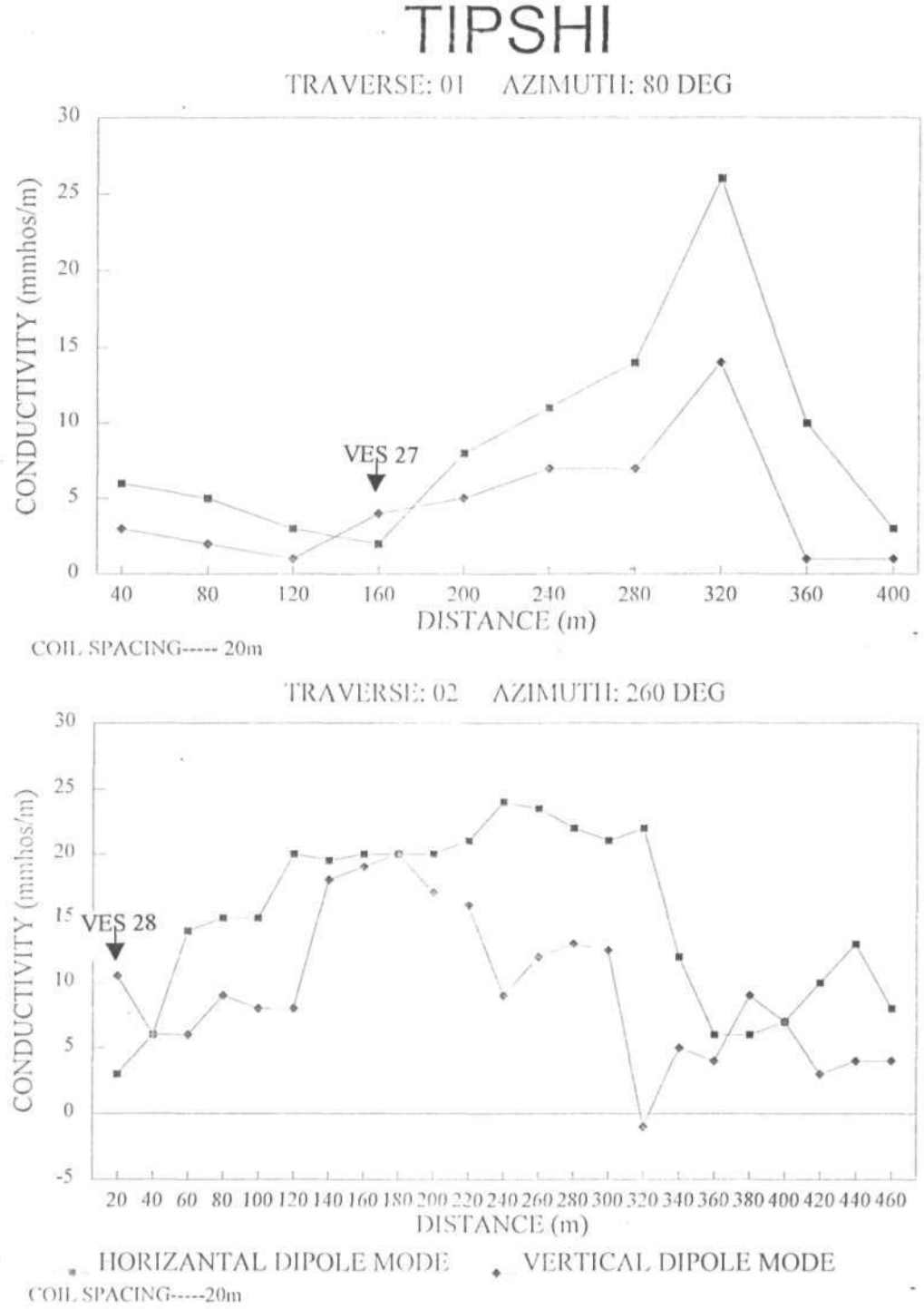


Fig. 4.11a Conductivity plots for Tipshi

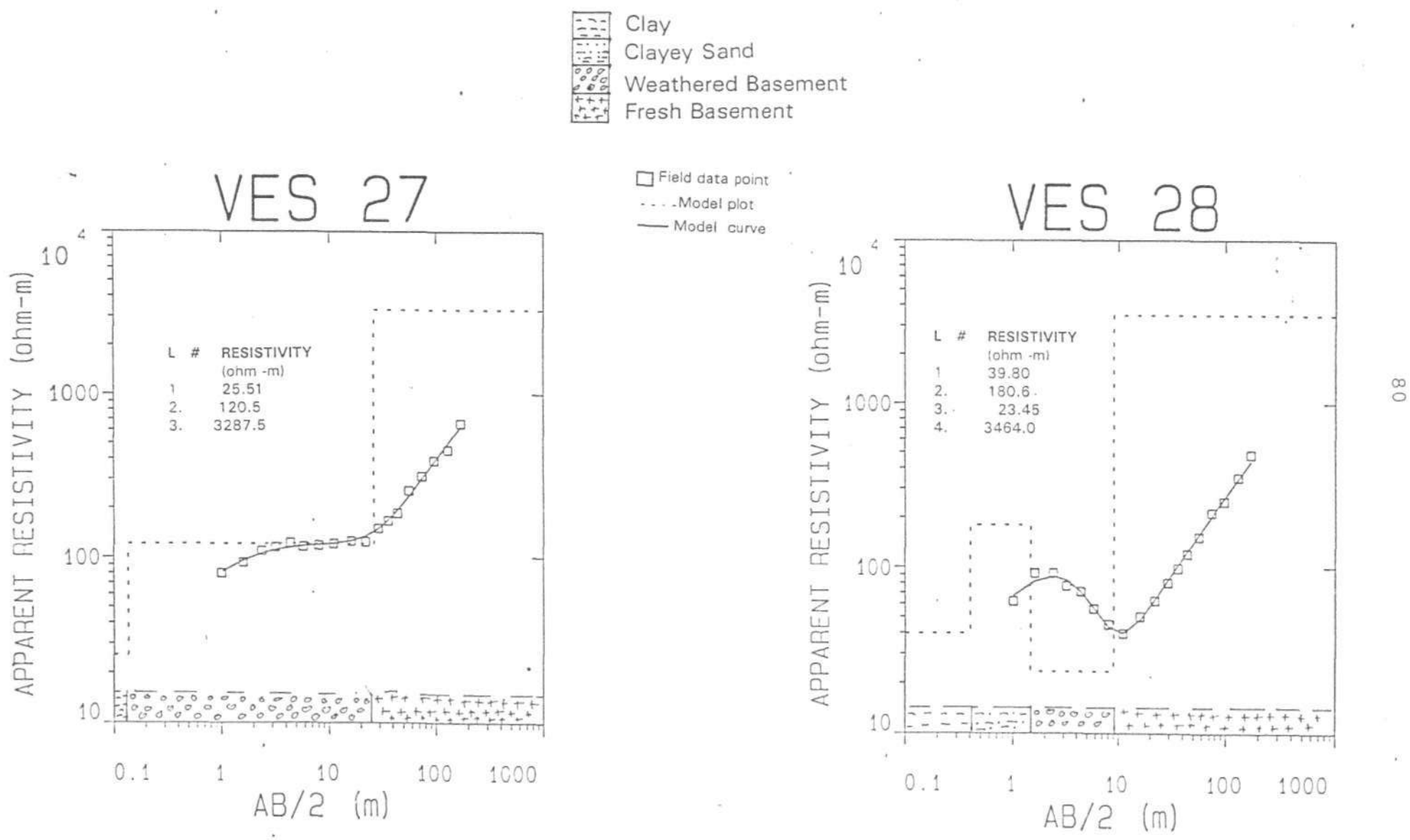


Fig. 4.11b Apparent Resistivity Curves and Models for Tipshi

On the other hand, the depth to the basement at VES 27 was 26.5 m, therefore VES 27 is selected as the site for drilling.

4.5.12 YADAGUNGUME

There are rock outcrops surrounding the village. This location has the largest population compared to the other villages surveyed. Attempt had earlier been made by the BSADP to drill a borehole in this village without success. In the present work, four EMTs totalling a distance of 1380 m were run at 20 m coil spacing to provide four sounding locations where the vertical dipole conductivity is greater than the horizontal dipole conductivity as shown on the conductivity plots in figure 4.12a. VES 29 was established on traverse 01, VES 30 on traverse 02, VES 31 on traverse 03 and VES 32 On traverse 04. The curves and interpreted models for these VES data are shown in figure 4.12b. The apparent resistivity curve for VES 29 is the A type, VES 30 and 31 are H type and VES 32 is KH type. The interpreted model shows that the weathered basement at VES 30 is thicker (21 m) than at VES 29 (9.58 m), at VES 31 (13.6 m) and at VES 32 (9.3 m). The depth to the basement is greater at VES 30 (25 m) compared to VES 29 (12.22 m), VES 31 (14.5 m) and VES 32 (10.72 m). All the VES sections, except VES 31, show four layers but the position of the layers varies. VES 30 is the most suitable site for drilling a borehole because of the thickness of the weathered layer.

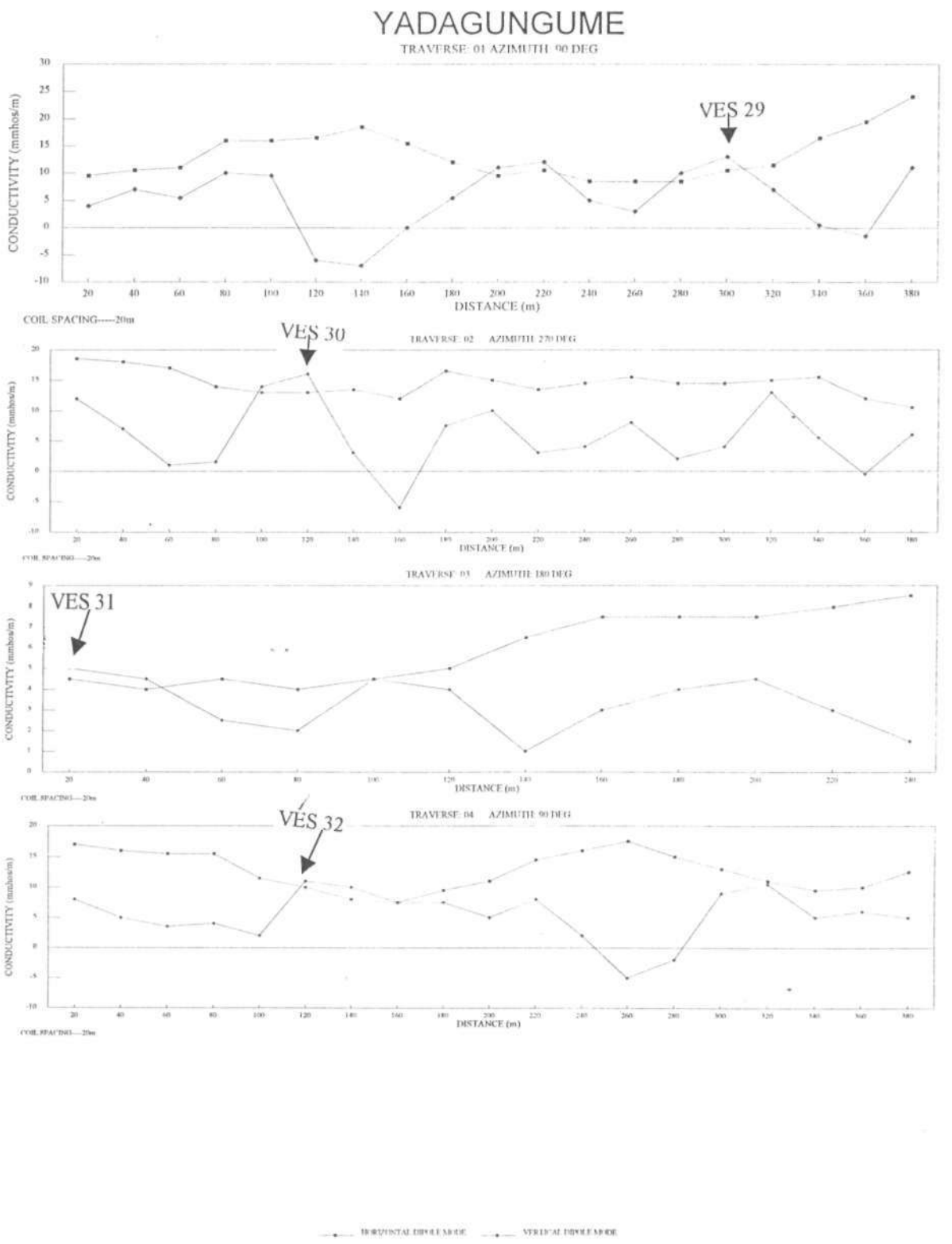


Fig. 4.12a Conductivity plots for Yadagungume

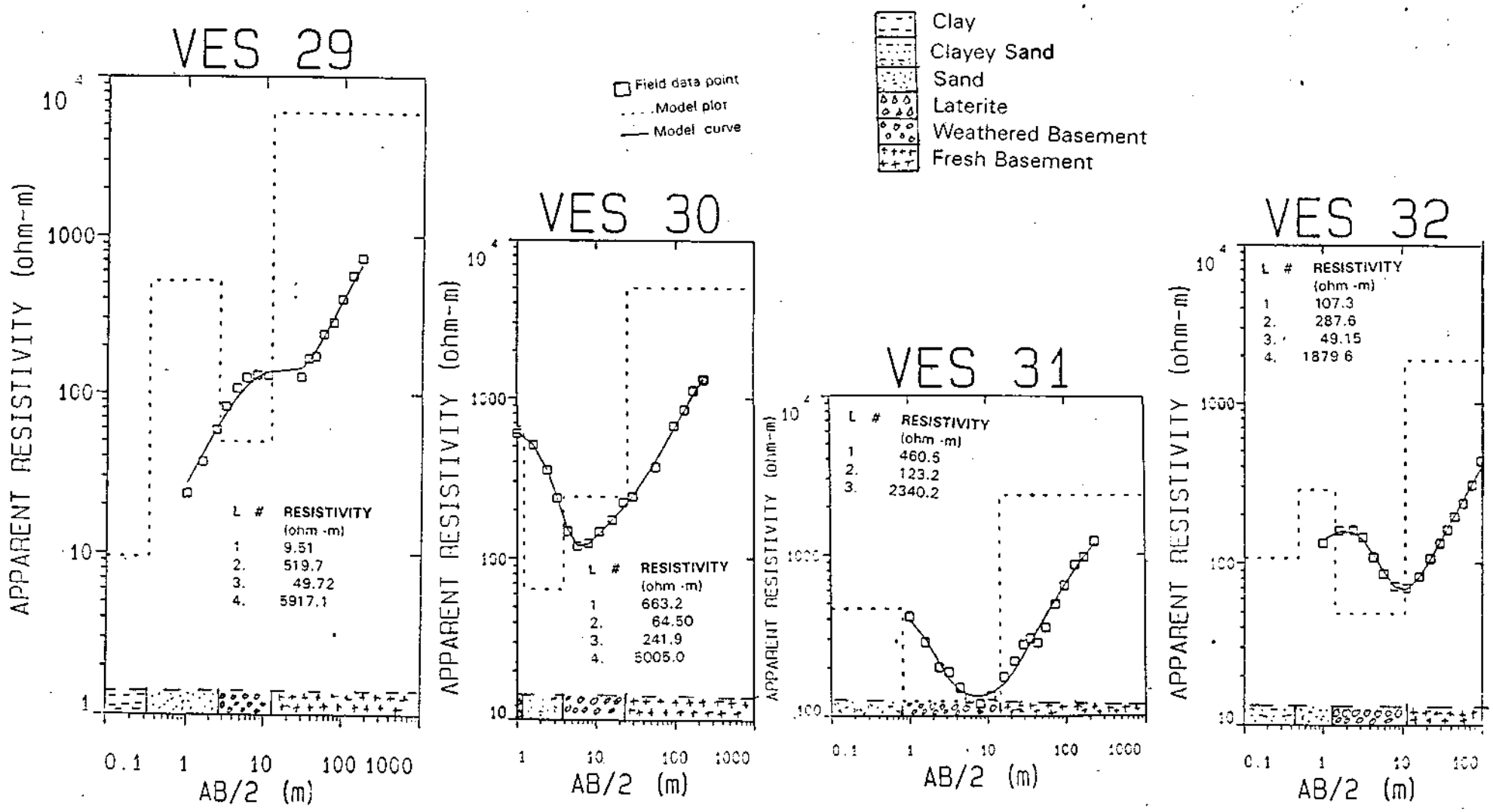


Fig. 4.12b Apparent Resistivity Curves and Models for Yadagungume

4.5.13 YELWA

The static water level as measured from wells in this community falls within 6.2 - 7.2 m. Two EMTs were run covering a total distance of 860 m at 20 m coil spacing. The conductivity plots suggest many locations for collecting VES data, particularly on traverse 01 as shown in figure 4.13a. VES 33 was established on traverse 01 on the position indicated because of the extent of the region of high vertical conductivity. VES 34 was established on traverse 02. The VES curves and models are as shown in figure 4.13b. The apparent resistivity curve of VES 33 is HA type and VES 34 is the H type.The interpreted sections suggest that VES 33 is better for siting a borehole than VES 34. The site is recommended because the aquifer is thicker (31.6 m) compared with 15.32 m at VES 34. VES 33 gives four geoelectric layers while VES 34 gives three. The additional layer on VES 33 is the second layer of resistivity 29.6 ohm-m and thickness of 2.55m.

4.5.14 YUWA

The water level in this village as determined from two wells is 6.9 and 9.4 m of the surface. One EMT profile with a total distance of 680 m, with a 40 m coil spacing was run in the village which suggested only one sounding location. Though, there are regions on the curve that have vertical dipole mode conductivity is greater than the horizontal dipole mode conductivity, the one with the

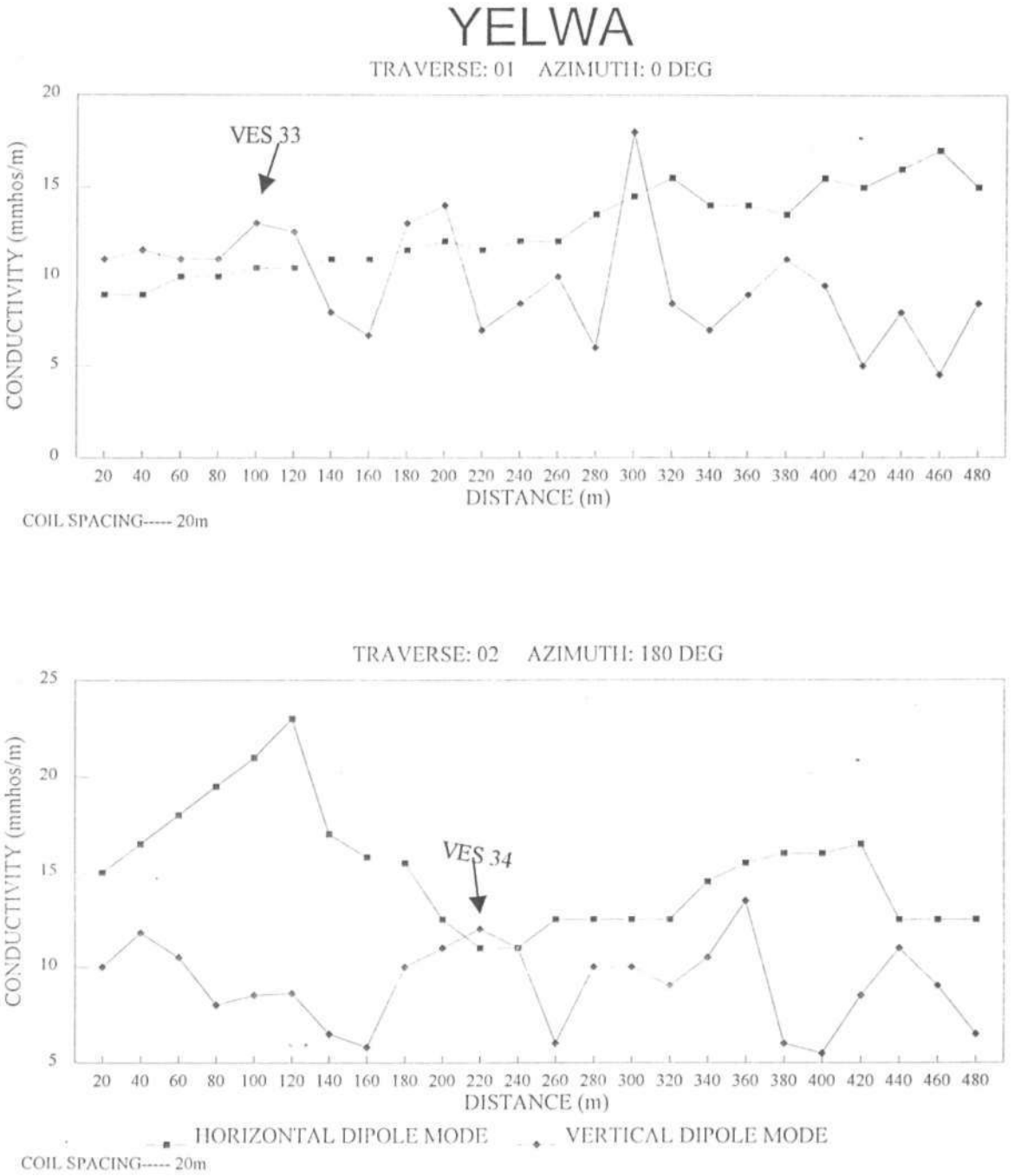


Fig. 4.13a Conductivity plots for Yelwa

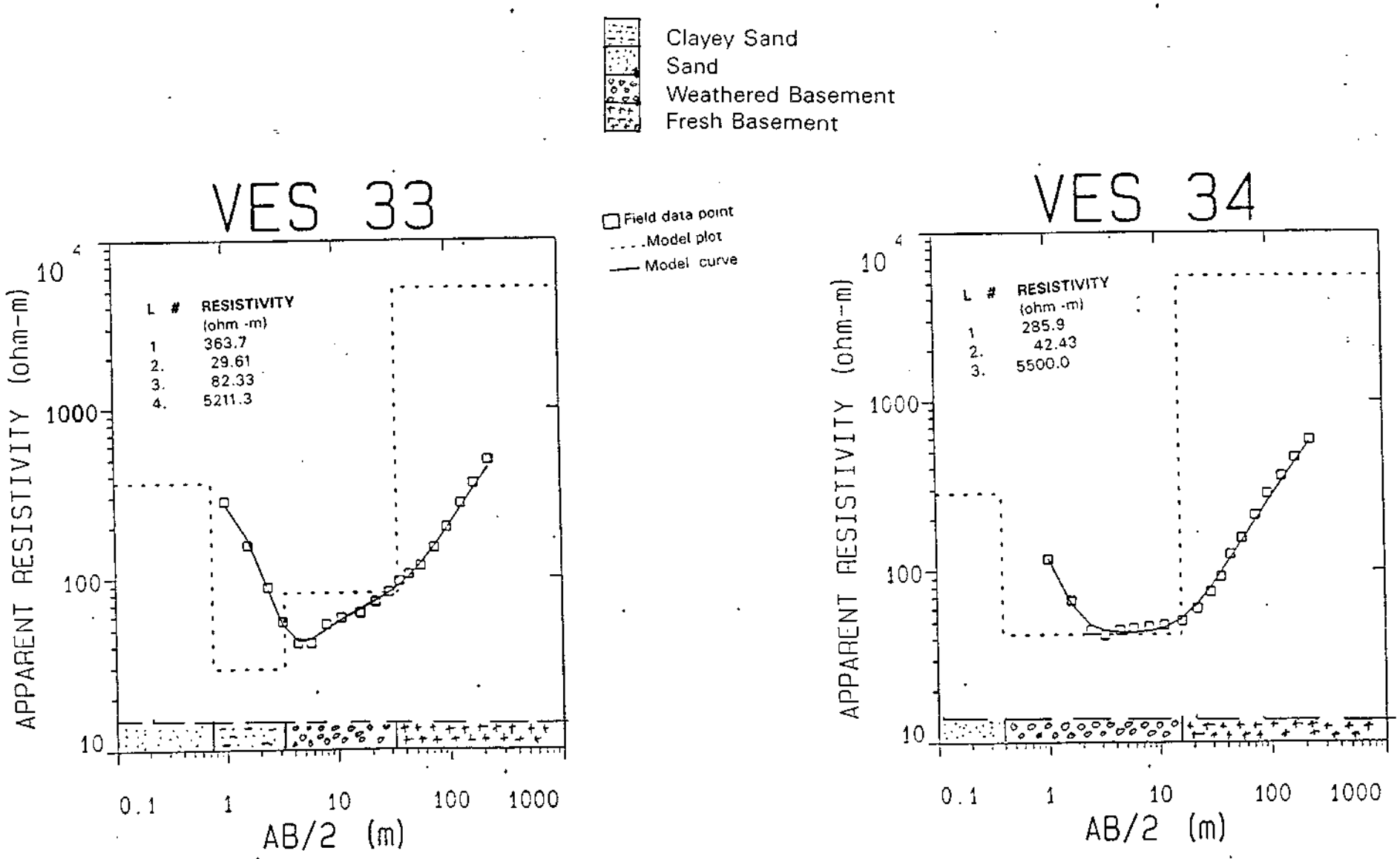


Fig. 4.13b Apparent Resistivity Curves and Models for Yelwa

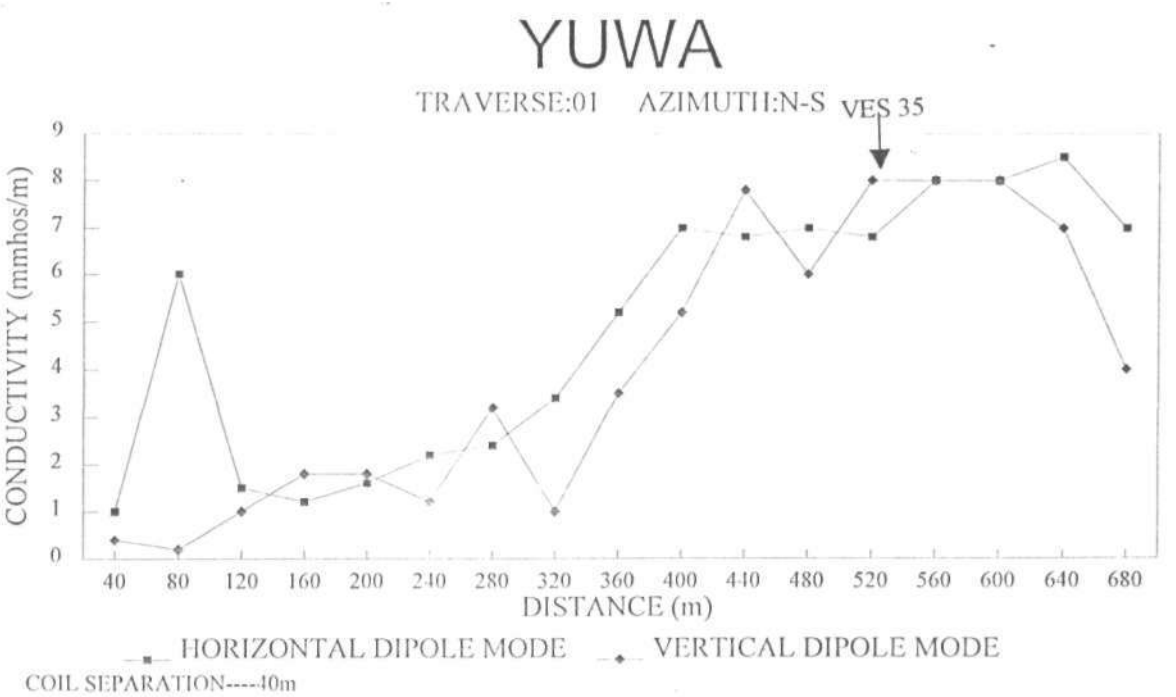


Fig 4.14a Conductivity vs Distance plot for Yawa

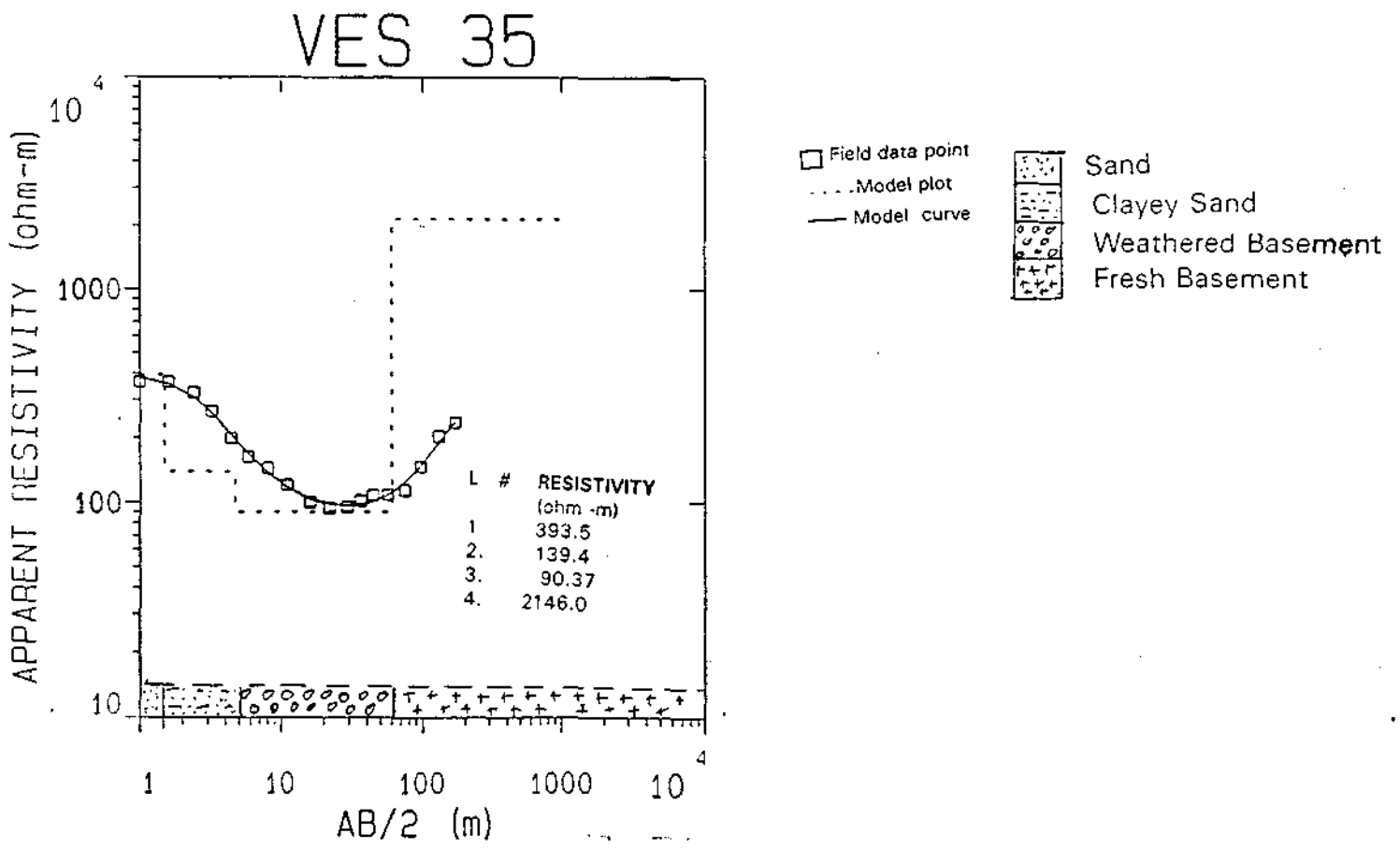
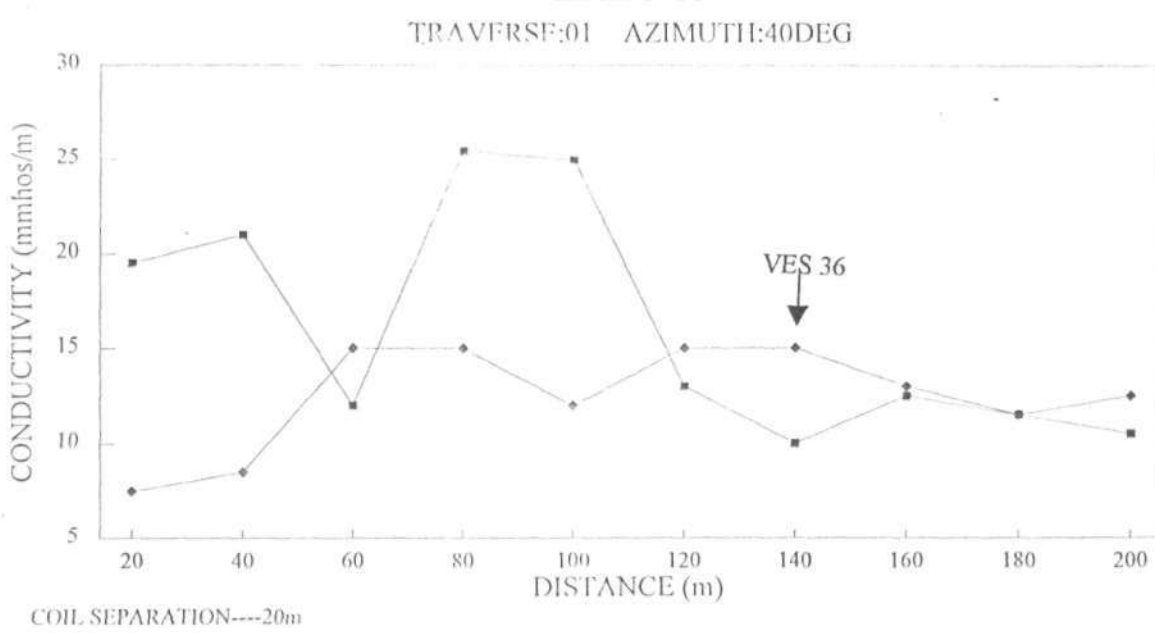


Fig. 4.14b Apparent Resistivity Curves and Models for Yuwa

greater extent was selected for sounding. The conductivity plot for this profile is as shown in figure 4.14a. The apparent resistivity curve is the KH type. The curve and the interpreted model of the VES data are shown in figure 4.14b. The interpreted data suggests that the weathered basement resistivity is about 80 ohm-m and the depth to the basement at the location sounded is about 60 m. Furthermore the interpreted section suggests the existence of four geoelectric layers in that location. The inferred aquifer is the third layer with a resistivity of 90.37 ohm-m and thickness of about 30 m. The depth to the basement is the greatest (59.77 m) throughout the survey area. Hence VES 35 is recommended for drilling.

4.5.15 ZEHI

In this location, some hills exist to the east of the village but there are no rock outcrops in the immediate vicinity of the village. Water level in the wells in the village was generally found to be within 8.0 - 10 m of the ground surface. Two EM profiles, covering a distance of 400 m were run at 20 m coil spacing. The conductivity plots for these traverses are shown in figure 4.15a. VES 36 was established on traverse 01 and VES 37 on traverse 02. The VES curves and models are as shown in figure 4.15b. The apparent resistivity curves for all the VES are the KH type. The interpreted VES curves suggest that VES 37 is a better site for siting a borehole than VES 36.



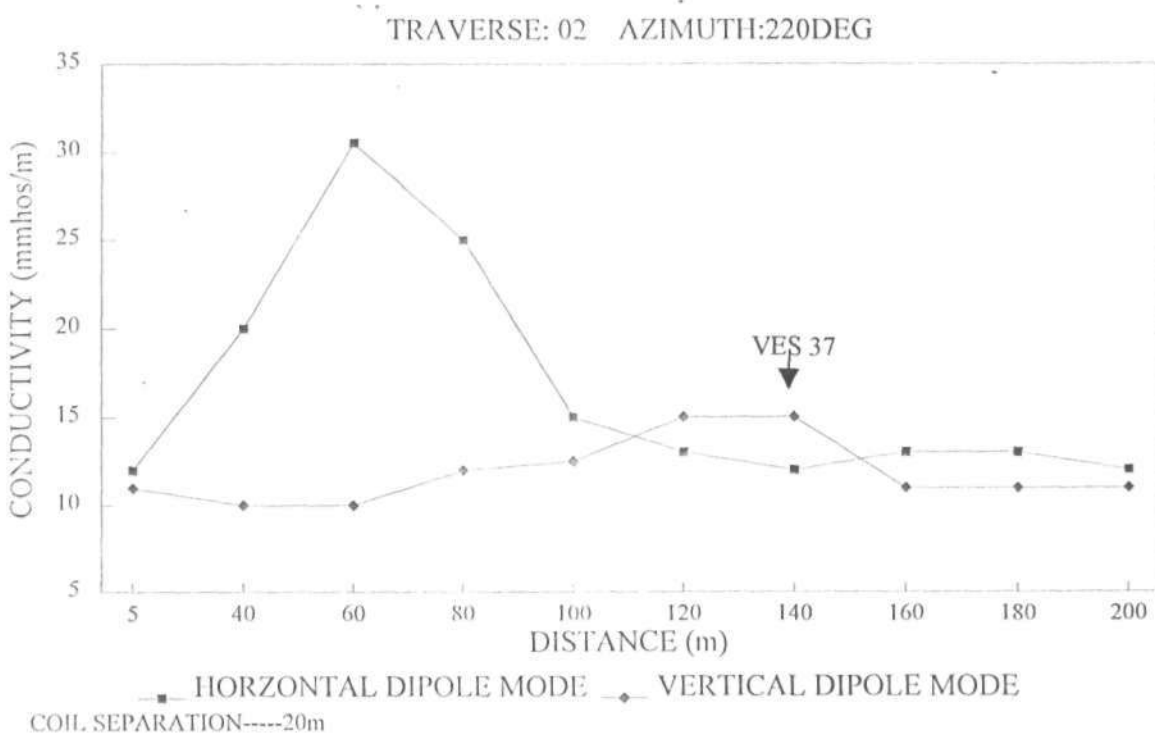


Fig. 4.15a Conductivity plots for Zehi

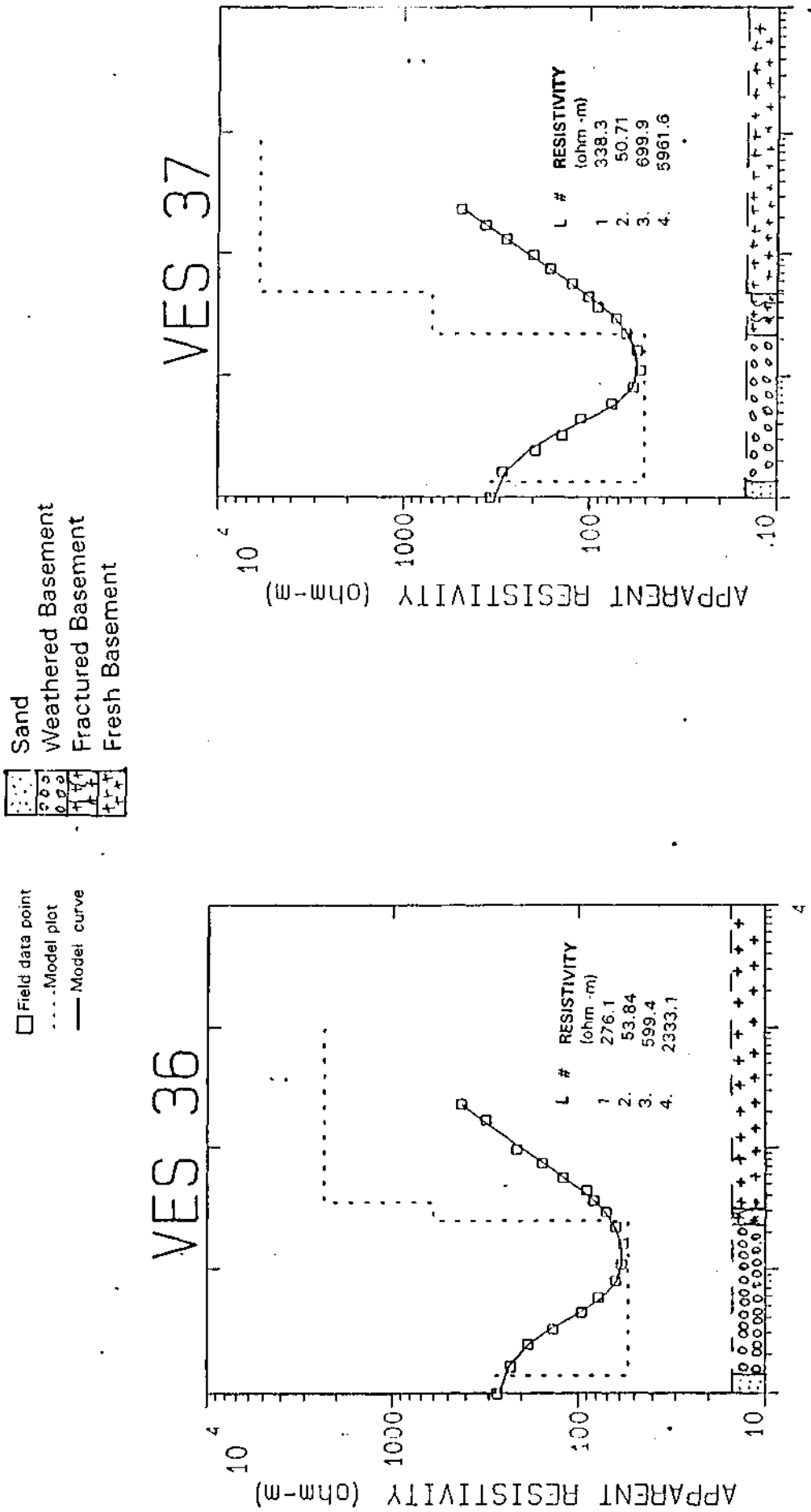


Fig. 4.15b Apparent Resistivity Curves and Models for Zehi

Although the weathered basement is thicker (23.3 m) at VES 36 than at VES 37 where its thickness is only 20.5 m. The third layer on the geoelectric sections with a resistivity of 599.4 ohm-m at VES 36 and a resistivity of 699.9 ohm-m at VES 37, is considered to be fractured basement. This layer is more extensive at VES 37 with a thickness of 26.02 m, than at VES 36 with a thickness of 10.26 m. The depth to the basement is also greater at VES 37 (47.81 m) than at VES 36 (34.94 m).

CHAPTER FIVE

DISCUSSIONS, SUMMARY, SUGGESTIONS AND CONCLUSIONS

5.1 DISCUSSION

Based on the interpreted geoelectric sections obtained in Chapter IV, an attempt is hereby made in this chapter to express these sections in terms of the general geology of the area and to, ultimately make some specific deductions and conclusions. The general observations are as discussed below.

When interpreting the resistivity data, sounding curves of various shapes were encountered. Some distortions of the sounding curves prevent perfect match between the calculated curve and the curve obtained from the field data. Some of these distortions, according to Zohdy *et al* (1990), are mainly caused by lateral inhomogeneities in the ground, errors due to measurement and equipment failure. Common distortions observed generally were:-

(i) Formation of cusps - This is usually as a result of lateral inhomogeneity or due to poorly insulated cables (Zohdy *et al*, 1990) and sometimes a sand lens (resistive lateral inhomogeneity) or a clay pocket (conductive lateral inhomogeneity). During the interpretation that part of the curve is usually smoothed or masked.

(ii) Sharp maximum - The maximum or peak value on a K-

type sounding curve should be gentle and broad. The formation of a sharp peak generally indicates that the middle resistive layer has a limited lateral extent.

(iii) Equivalence - It should be noted that the interpretation of a multilayer sounding curve is generally not unique (Zohdy et. el, 1990). This means that a given electrical sounding curve can correspond to variety of subsurface distribution of layer thicknesses and resistivities. Effort has been made to minimize this by taking into consideration the local geology and also the rock types and hydrogeology of the area during interpretation.

Generally almost all the curves are four layer curves. Normally, three layers are expected i.e. the top soil, the weathered basement and the fresh basement. The additional layer observed in this work is considered to be the fractured basement. It occurs between the weathered basement and the fresh basement. The resistivity value of this layer is usually lower than the fresh basement but higher than the weathered basement.

5.1.1 Top Soil thickness.

The top soil is thinnest at Tipshi with a thickness of 0.136 m and thickest at Yuwa with a thickness of 4.64 m (see Table 5.1). The locations that have top soil thickness less than 1 m are Tipshi, Dangarfa, Gompero/Dubure, Limi and Bakatumbe. These are areas that have rock outcrops in the vicinity of the locations. The

locations that have top soil thickness 1-2 m are: Yadagungume, Zehi, Bingin Labo, Dabar Baga and Takalafiya. While those with topsoil thickness greater than 2 m are; Isawa, Yuwa, Yelwa, Bingin Diwa and Kagadama.

5.1.2 Thickness of the Weathered Basement.

The aquifer within the survey area is thinnest at Limi, with a thickness of 4.6 m, and thickest at Yuwa, with thickness of 55.09 m (see Table 5.1). The locations that have aquifer thicknesses between 11-20 m are; Isawa, Bakatumbe, Bingin Labo, Kagadama and Takalafiya. Those locations with aquifer thicknesses in the range of 21-30 m are; Yadagungume, Tipshi, Dangarfa, Zehi, Bingin Diwa and Dabar Baga. Those with aquifer thickness greater than 30 m are; Gompero/Dubure, Yelwa and Yuwa.

5.1.3 Depth to the Basement.

The depth to the basement varies from 5.43 m at Limi to 59.22 m at Yuwa. The locations with depth to basement less than 20 m are; Bakatumbe, Limi, Bingin Labo, Kagadama and Takalafiya. Those locations with basement depths within 21-30 m from the ground surface are; Yadagungume, Isawa, Tipshi, Dangarfa, Bingin Diwa and Dabar Baga. A borehole drilled at Yadagungume gives the following formation log: (BSADP, 1988b)

0 - 17 m highly to moderately decomposed gneiss

17 - 40 m moderately decomposed gneiss.

Another borehole drilled at Tipshi gives the following fomation log: (BSADP, 1988b)

0 - 5 m brown clayey sand

5 - 7 m light brown medium grained sand

7 - 9 m pink to browm highly decomposed dry rock

9 - 17 m pink moderately weathered granite

17 - 21 m pink to grey moderately weathered granite

21 - 24 m dark to grey strong and fresh granite

24 - 30 m pink granite with some black dots.

The locations with basement depth greater than 30 m are; Zehi, Gompero/Dubure, Yuwa and Yelwa. The site indicated at Yuwa gives the following formation log: (BSADP, 1988b)

0 - 2 m laterite

2 - 3 m coarse quartz sand

3 - 24 m decomposed crystalline rock.

The depth to the Basement for the various locations are contoured as shown on figure 5.1. The contour map showed that the depth the basement is highest towards the western part of the survey area. There is a closure of 40 m around location 15. The depth decreases towards location 7 to the southern part of the survey area and location 2 to the northern part.

5.2 SUMMARY

The main aim of this work is to locate places where underground water can be obtained, to at least minimally satisfy the water demands of the people in the villages

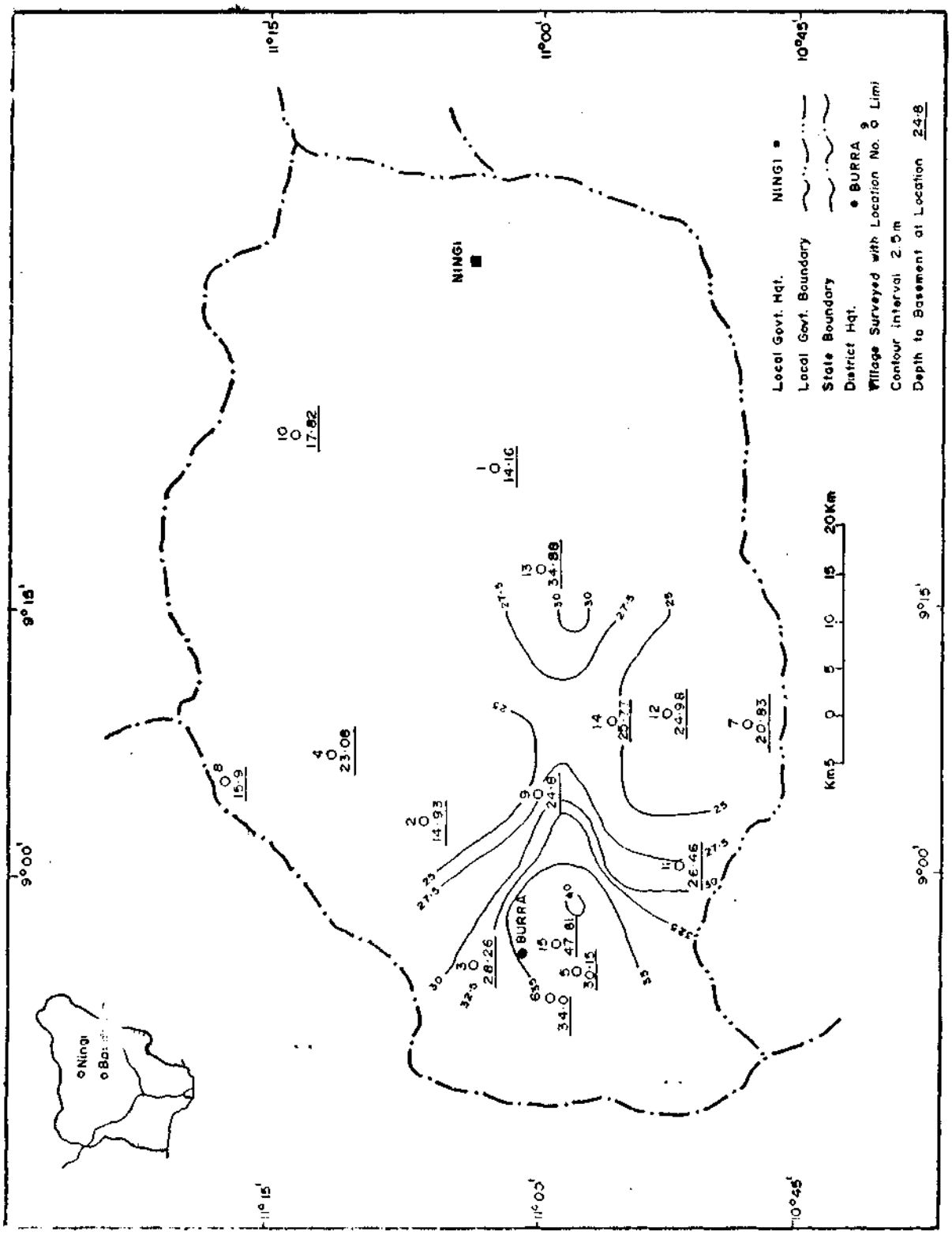


Fig 5.1 Depth to the Basement Contour map of the Survey area.

surveyed. The most promising areas where this can be achieved are those that have thicker weathered basement layer with low resistivity value, the reason being that, there is a thicker layer to tap water from and rate of recharge will be greater.

Infact a highly fractured basement or weathered basement layer is more preferable than a very low resistivity layer of the same thickness and depth of burial. This is so because, in most cases, the low-resistivity layer may be clayey. When boreholes are drilled at such sites, clay particles clog around the screen of the borehole thereby blocking water from entering the borehole.

A total EMT length of 16.42 km was traversed to yield 37 VES points. The interpretation of these 37 VES points gives 15 points which are considered suitable for drilling of boreholes. The apparent resistivity curves of 12 out of the 37 VES points are the H type, 16 are KH type, 4 are HA type, 4 are A type and 1 QH type. The total number of four layer types are 21 while the rest (16) are the three layer types. The predominance of the four layer types is indicative of the extent of fracturing in the area as discussed in section 5.1. A summary of the results is given in Table 5.1.

Table 5.1 Summary of VES result

Location No	VES No	Layer 1 Resistivity (ohm-m)	Thickness (m)	Layer 2 Resistivity (ohm-m)	Thickness (m)	Layer 3 Resistivity (ohm-m)	Thickness (m)	Layer 4 Resistivity (ohm-m)	Depth to Basement (m)
1	01	458.1	0.929	99.60	2.10	55.04	8.26	503	11.29
	02	636.8	0.741	137.9	0.508	33.46	5.69	5684.6	6.94
	03	330.2	0.443	66.62	13.71	7602.5			14.16 *
2	04	69.33	0.483	228.9	1.34	39.85	13.10	562.2	14.93 *
	05	80.23	0.5	180.5	0.50	48.8	8.2	882.1	9.2
	06	150.9	0.769	285.1	1.08	68.22	6.65	1078.4	8.5
3	07	154.6	1.59	93.28	6.13	33.19	12.86	1228.1	20.59
	08	71.21	0.749	150.5	4.77	32.95	11.58	2264.6	17.11
	09	59.68	1.49	13.51	1.47	57.16	25.28	6564.2	28.26 *
4	10	150	0.15	1500	2.1	53.2	18.81	8143	21.06
	11	145	0.272	288.9	3.45	36.98	8.11	3197.2	11.84
	12	68.94	2.99	16.63	4.80	2977.9			7.8
	13	99.76	0.577	33.96	0.738	96.2	21.76	2279.0	23.08 *
5	14	422	1.25	28.5	28.9	3520			30.15 *
	15	8.16	1.44	83.25	14.48	2156			15.92
6	16	106.1	0.622	38.68	7.75	396.4	25.62	1176.3	34.0 *
	17	57.23	0.329	15.9	4.47	999.4			4.8
7	18	54.69	0.981	119.1	1.08	19.91	18.76	7648.5	20.83 *
	19	51.41	0.996	10.33	10.69	6243.4			11.69
8	20	111.5	0.529	75.43	3.40	27.35	11.98	368.5	15.9 *
	21	286.7	1.18	26.5	10.36	269.9	5.20	3049.8	16.75
	22	163.5	0.707	66.49	1.64	660.1			2.35
9	23	32.7	0.229	6.81	3.82	531.4			4.04
	24	90.54	1.44	38.05	5.33	152.0	18.0	3765.1	24.8 *
10	25	459.2	1.97	38.75	15.84	4452.3			17.82 *
	26	408.0	1.13	44.63	12.84	3493.6			13.98
11	27	25.51	0.136	120.5	26.33	3287.5			26.46 *
	28	39.8	0.401	180.6	1.05	23.45	7.57	3464	9.02
12	29	9.51	0.329	519.7	2.30	49.72	9.58	5917	12.22
	30	663.2	1.21	64.5	2.67	241.9	21.09	5005	24.98 *
	31	460.5	0.811	123.2	13.64	2340.2			14.45
	32	107.3	0.493	287.6	0.919	49.15	9.30	1879.6	10.70
13	33	363.7	0.754	29.61	2.55	82.33	31.57	5211.3	34.88 *
	34	285.9	0.39	42.43	15.32	5500			15.71
14	35	393.5	1.49	139.4	3.18	90	55.09	2146	59.77 *
15	36	276.1	1.36	53.84	23.31	599.4	10.26	2333.1	34.93
	37	338.3	1.33	50.71	20.45	699.9	26.02	596.6	47.81 *

* Recommended Borehole Drilling Site

5.3 SUGGESTIONS FOR FUTURE WORK

Every geophysical method of exploration has its limitations and speciality. The information and results given here are not all comprehensive and improvements can still be made. It is, therefore, suggested that further work be done to obtain more detailed information in the whole of the area. Hence, it is suggested that a detailed resistivity survey should be carried out on pre-determined grid locations which are more closely spaced. The EM Survey should also be done on a detailed scale using all the three coil spacings. This will allow more exact quantitative analysis and will consequently delineate better areas of fractures/faults, as well as the position and geometry of the dykes.

Drilling should be carried out in some locations in the area and the boreholes logged to provide control information regarding the subsurface geology of the area.

5.4 CONCLUSIONS

The conclusions drawn from the interpretation of both the EM and VES data obtained in this work are as follows:-

1. The top soil within the area is generally thin. The thickness ranges from 0.136 m around Tipshi with a resistivity of 25.51 ohm-m to about 4.67 m around Yuwa with a resistivity of 393.5 ohm-m.

2. The aquifer thickness within the project area varies from a minimum of 4.6 m at Limi to about 55.09 m at Yuwa. Also the aquifer resistivity varies from a minimum of 22.5 ohm-m to a maximum of 90 ohm-m.

3. The depth to the basement also varies from a minimum of 5.43 m at Limi to a maximum of 59.77 m at Yuwa.

4. Sites for drilling of boreholes for the various communities have been selected and indicated.

5. An area that is likely to have occurrence of dykes have been mentioned (Bakatumbe).

6. The study also confirms that the aquifer resistivity towards the North of the area has almost a uniform resistvity value of about 45 ohm-m. Also, the aquifer thickness and depth to the basement are almost uniform with values of about 12 and 17 m respectively. These confirm the division of the area into two hydrogeological units, as earlier identified by BSADP (1988a); namely, the Basement foreland to the north and the crystalline basement to the south.

7. From the formation logs given in section 5.1.3 of this report, it is clear that geophysical methods of EM and resistivity can be used to give a good estimate of depths to various subsurface layers once there is a contrast in resistivity/conductivity. Hence the combined EM and resistivity methods can be applied to situations requiring depth estimates.

On the whole, it was found that the application of EM and D.C resistivity methods to groundwater exploration is advantageous in that non-productive areas are easily identified and avoided. The success of the methods in this work confirm that the methods may be useful in any water supply project involving well-site location within areas of crystalline basement as suggested by Beeson and Jones, (1988) and Hazel et al (1988).

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APPENDIX

FIELD DATA

HALF CURRENT ELECTRODES SEPARATION (AB)/2 (m)	APPARENT RESISTIVITY OHM-M								
	VES 01	VES 02	VES 03	VES 14	VES 15	VES 16	VES 17	VES 18	VES 19
1.0	410.0	522.0	178.0	256.2	8.78	54.15	26.5	59.9	47.7
1.6	301.0	288.0	103.0	144.8	9.94		18.0	67.7	37.2
2.4	218.0	172.0	80.0	79.49	12.0	50.06	16.0	76.8	23.1
3.2	154.0	94.0	72.0	56.47	15.91	44.86	17.0	77.2	18.8
4.4	110.4	49.0	73.0	43.54	20.19	42.32	19.0	74.7	15.1
5.8	86.3	46.0	73.0			43.96	22.3	66.3	12.8
8.0	79.2	52.0	72.0	41.18	32.04	45.16	26.9	52.4	11.2
11.0		63.0	74.0	43.03	41.29	51.98	36.87	32.2	12.5
16.0	82.2	84.85	74.18		50.26	71.16	50.2	28.3	15.4
22.0	112.8	128.5	100.3	45.37	63.81	91.23	64.8	28.8	20.2
29.0	142.7	151.7	118.9	51.86	83.13	108.6	86.1	30.9	
36.0	150.2	201.8	176.7		96.29	130.8	111.3	36.6	34.1
44.0	170.3	230.1	205.0	61.17	121.4	155.1	125.3	43.5	41.3
56.0	190.6	293.1	260.1	85.56	156.3	190.3	150.3	58.2	54.4
74.0	245.8	406.5	353.3	119.0	211.3	230.8	205.1	76.9	70.6
96.0	292.2	495.6	471.7	156.3	230.7	292.8	250.3	96.2	89.9
130.0	340.1	688.4	521.9	208.2	314.2	366.7		132.8	121.3
170.0		866.2	876.9	250.3	399.1	447.2		178.2	155.1
230.0		1047.2	1105.3	354.0	511.2	523.9			219.3

FIELD DATA CONT'D

HALF CURRENT ELECTRODE SPACING (AB)/2 (M)	APPARENT RESISTIVITY (OHM-M)											
	VES 04	VES 05	VES 06	VES 07	VES 08	VES 09	VES 10	VES 11	VES 12	VES 13	VES 25	VES 26
1.0	151.5	82.3	56.55	99.68	92.59	163.5	678.5	217.8	62.5	76.1	450.1	390.2
1.5	149.6	87.34	52.89	119.00	98.70	173.8	843.9	243.2	66.6	68.9	432.2	303.7
2.0	151.2	99.51	48.70	120.30	96.20	178.2	933.0	256.7	67.9	57.4	418.1	240.1
2.5	139.6	109.2	47.53	131.60	93.86	180.6		264.1	68.0	58.6	340.0	190.8
3.0	128.6	114.1	41.51	133.30	83.51	175.8		255.5	63.3	62.7	300.0	143.2
4.0	118.6	119.7	33.12	120.70	70.62	158.3	937.5	243.1	56.9	67.1	227.6	88.97
5.0		121.5	30.17		62.78	139.5	795.7	218.5	56.1	74.9	181.0	72.34
6.5	96.61	119.5	30.21	85.30	55.46	122.5	621.2	189.8	45.2	81.67	95.0	57.4
8.0	92.49	116.1	34.45	70.13	54.20	110.3	504.0	165.0	37.4	83.3	72.0	51.1
10.0	86.6	101.5	35.80	57.70	58.16	100.3	302.0	128.5	38.3	87.0	56.5	49.5
13.0	76.1	88.55	42.35	54.50	68.35	121.6	175.7	93.3	41.0	93.3	48.3	51.98
16.0	68.1	83.52	49.21	53.70	78.73	143.1	117.6	84.9	46.8	94.7	50.9	61.3
20.	64.21	74.64	50.04	60.50	91.30	157.6	110.8	90.0	56.7		52.3	70.1
25.0		67.80	54.12	71.00	108.80	192.5	115.4	97.2	70.5		62.0	85.5
30.0	67.8	73.32	56.40	79.90	126.90	231.6	121.7	118.4	85.5	129.2	68.0	101.2
40.0	78.63	95.36	66.90	93.68	168.80	287.7	158.8	163.8	115.4	142.2	104.0	131.7
50.0	96.79	125.5	78.48	115.1	204.00	350.5	211.8	209.2	151.7	185.7	115.1	165.5
65.0	128.2	163.6	106.1	150.3	245.30	400.7	256.7	254.1	194.5	238.8	152.2	219.3
80.0	154.1	201.0	140.7	174.2			328.6	322.3	234.5	281.2	189.6	253.8
100.0	198.8	209.3	177.8	200.8			423.5	420.2	272.2	345.5	232.3	305.1

FIELD DATA CONT'D

HALF CURRENT ELECTRODES SPACING (AB)/2 (m)	APPARENT RESISTIVITY (OHM-M)															
	VES 20	VES 21	VES 22	VES 23	VES 24	VES 27	VES 28	VES 29	VES 30	VES 31	VES 32	VES 33	VES 34	VES 35	VES 36	VES 37
1.0	100.7	288.0	140.0	9.15	90.2	80.0	62.0	23.5	599.0	411.7	133.5	284.0	117.0	365.0	270.6	337.7
1.6	83.9	200.3	118.2	7.41		93.0	92.0	37.1	508.7	284.7	160.2	156.0	67.0	364.0	227.8	289.2
2.4	81.9	136.8	106.0	7.5	70.3	109.0	92.0	58.9	354.2	199.8	161.2	89.0	45.0	324.0	184.8	193.5
3.2	74.8	97.2	111.2	7.7	63.1	115.0	77.0	82.5	236.3	186.6	145.7	56.0	42.0	266.0	135.2	139.1
4.4	71.5	55.9	123.1	8.9	58.7	121.8	71.0	107.4	147.8	149.6	109.8	42.0	45.0	199.0	95.4	111.0
5.8	60.9			11.1	50.2	116.0	56.0	125.6	119.0	127.2	86.8	42.0	46.0	163.0	77.9	75.7
8.0	53.8	33.5	214.5	13.23	49.8	118.0	45.0	130.8	124.2	119.1	72.5	54.0	47.0	144.0	62.8	57.8
11.0	44.5	30.4	250.8	18.8	56.9	121.0	39.76	130.0	146.3	133.8	70.8	59.0	48.2	120.2	58.5	53.2
16.0	41.3				65.2	125.2	50.23		173.3	174.2	82.9	63.0	51.0	100.5	57.2	55.48
22.0	44.5	56.0		38.4	76.2	134.2	62.79		223.1	218.3	107.8	73.0	60.7	94.3	62.4	63.3
29.0	52.4		450.3	45.3	96.6	150.2	80.58	127.6	242.8	276.6	134.3	81.0	75.2	95.3	70.8	71.6
36.0	64.5	83.80		56.9	110.4	167.3	98.37	166.3		301.0	163.2	96.0	92.0	101.5	82.5	90.2
44.0	111.6			60.31	117.9	186.1	120.4	172.8		282.7	196.7	105.0	124.0	107.7	89.7	101.4
56.0		126.5	542.9	85.0	128.6	254.8	153.0	238.7	371.2	351.6	238.3	118.0	155.0	108.6	119.4	123.4
71.0			593.0	112.6	130.3	311.8	214.2	283.7		493.1	310.2	151.0	211.0	113.5	155.1	162.5
96.0			628.0	130.5	142.5	387.5	251.1	400.5	673.9	643.2	436.7	199.0	283.0	146.3	212.0	200.3
130.0				167.2	160.3	450.3	351.0	563.2	850.2	862.7		275.0	358.0	202.8		278.7
170.0				200.7	189.8	655.2	483.6	725.9	1121.9	963.7		361.0	460.0	235.7	312.3	362.7
230.0				240.3	261.6				1317.1	1208.9		494.0	586.0		422.7	487.2