KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,

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FACULTY OF PHYSICAL SCIENCES

DEPARTMENT OF PHYSICS

INTEGRATED GEOPHYSICAL EXPLORATION FOR GROUNDWATER IN THE BAWKU WEST DISTRICT OF THE UPPER EAST REGION OF GHANA USING ELECTROMAGNETIC AND ELECTRICAL RESISTIVITY SOUNDING METHODS

BY

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Integrated Geophysical Exploration for Groundwater in the Bawku West District of the Upper East Region of Ghana Using Electromagnetic and Electrical Resistivity Sounding Methods.

A Thesis Submitted to the School of Graduate Studies, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, in partial fulfillment of the degree of M.Sc. (Geophysics).

By

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July, 2012

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DECLARATION

I hereby declare that this work is the result of my own investigation towards the award of M.Sc (Geophysics) degree and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of a University, except where due acknowledgment has been made in the text.

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DEDICATION

This thesis work is dedicated to my dear mother, Madam Mary Danquah, my father Mr. Adu-Manu Peter and all my siblings who have supported and encouraged me throughout my education.

ACKNOWLEDGEMENT

To the Almighty God is my greatest gratitude for granting me wisdom, protection and guidance throughout this Master of Science thesis work. I am also much grateful to my supervisors Prof. Aboagye Menyeh and Mr. Reginald Noye for their tireless suggestions, encouragement, contributions and corrections they made to see this work as a successful one. I again wish to express my heartfelt gratitude and appreciation to all the geophysics lecturers and the entire staff of the Physics Department especially Mr. D.D. Wemegah for their assistance, motivation and encouragement to make my dream come through. I am also grateful to the management and staff of World Vision International – Ghana Rural Water Project (WVI – GRWP) especially the head of operations Mr. Sampson Tettey, the senior hydrogeologist Mr. Samuel Edusei, Mr. Victor Boadi, Mr. Felix Kweku Otoo and Mr. Emmanuel Amoako for the opportunity given me to use their resistivity and electromagnetic (EM) equipment in collection of the data for this study. Also, to geologist Mr. Francis Boah who was a member of the siting team of the WVI – GRWP at the time of this project is my gratitude for his guidance and encouragement. Finally, I extend my profound gratitude to Mr. George Owusu of Centre for Remote Sensing and Geographic Information System (CERSGIS) – Ghana and to all my colleagues' Postgraduate students of Physics Department, Kumasi for their assistance in various ways. To them all I say may God richly bless in abundance.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The world`s human population growth and the effects of global warming have resulted in unprecedented demands for freshwater supplies for domestic and industrial uses. Globally, groundwater supply provides only about 20% of the water we use, but this number has increased as surface-water resources decrease (Marshak, 2005). We can easily see Earth`s surface water in lakes, rivers, streams, marshes, oceans and atmospheric water in clouds and rain. However, groundwater lies hidden beneath the surface in pores and cracks found within sediment or rock. It is therefore, necessary to get an overview of the subsurface geology conditions in early stages of planning and design of groundwater exploration projects. An alternative method of investigating subsurface geology is by drilling boreholes, but these are expensive and provide information only at discrete locations. Geophysical surveying, although sometimes prone to major ambiguities or uncertainties of interpretation, provides a relatively rapid and cost-effective means of deriving a really distributed information on subsurface geology (Kearey *et al.*, 2002).According to Northwest Geophysical Associates(NGA) (2011), geophysical methods can be very effective in the search for groundwater resources and that when combined with borehole data and other available geologic information, geophysical data can refine the conceptual model of the subsurface geology and provide additional information to the geologic interpretation. It must be emphasized that geophysical surveys, when used, usually form part of an integrated approach to exploration and should never be used in isolation (Daly, 1987).Integrated geophysics programme is the use of two or more geophysical techniques in the same area. The fact that this type of operation is common place shows that the exploration geophysicist, by suitable selection, say, four methods, may obtain much more than four times the information he would get from any one of them (Telford *et al.,* 1990).

Geophysical exploration methods, especially electromagnetic (EM) and resistivity methods have proved very popular with groundwater prospecting, since related parameters such as the conductance and resistivity of rocks and soils are highly dependent on moisture content. There are other geophysical techniques which can be used for groundwater exploration and these include gravity, self potential (sp), magnetic, controlled source audio magneto – telluric (CSAMT), and Very Low Frequency (VLF) techniques (NGA, 2011). Seismic reflection and refraction geophysical techniques are also very effective in groundwater prospecting. It is difficult to distinguish a useful fresh groundwater resource from an increase in clay content by the use of resistivity or EM techniques alone; and that is why geological triangulation is so important-the geophysical data must be interpreted in the light of some geological knowledge of the area (MacDonald *et al*., 2005). Most of the people in Bawku-West District live in dispersed rural areas where finding groundwater resources is difficult and therefore special scientific techniques such as geophysical methods are required to help locate potential groundwater zones close to or in a community. According to Daly (1987), the decision to include a geophysical survey in a groundwater exploration programme largely depends on economic factors, and that time and money can often be saved by eliminating 'barren' ground with a well designed geophysical survey which is included in the early stages of an exploration programme. Therefore, in this groundwater exploration project, electromagnetic and resistivity geophysical exploration methods were used since they have proven to be useful tools for groundwater exploration.

1.2 Statement of the Problem

Access to safe drinking water is a basic human right and necessary for good health and well-being. However, as a result of population growth, most of the Ghana`s populace in the rural areas in general and specifically in Bawku West District of the Upper East Region do not have access to safe drinking water. Even though the Bawku West District has supply of safe water sources such as boreholes, hand dug wells fitted with pumps and pipes they are not enough to meet the recent increased demand for water by the dispersed communities in the district. According to Ministry of Local Government, Rural Development and Environment (MLGRDE) in 2008, there was low quantity of water used daily per capita in this district, i.e. about 15 l/day/capita, which was by far below the World Health Organisation (WHO) standards of 35 litres/d/capita. This condition perhaps still exists since, for example in Gumbo community in the Bawku West District with about 95 households obtain their potable water source from only one borehole which is located at a distance of about 2km from the community. Therefore this exploratory study tends to focus on integrating electromagnetic (EM) and resistivity (VES) geophysical methods to help increase ~~access~~ to potable water in the Bawku West District as part of the ongoing phase V Ghana Rural Water Project (GRWP) of the World Vision International (WVI), which started in 2008.

1.3Research Purpose and Objectives

The major aim of the study is to provide potable drinking water to beneficiary communities in the Bawku West District in the Upper East region of Ghana. The specific objectives are to:

1. Delineate ground water bearing zones in the district.
2. Identify possible drilling sites in the beneficiary communities using vertical electrical sounding (VES) technique.
3. Evaluate the groundwater potential of the district on the basis of the drilling results.

1.4 Research Hypothesis

Following the objectives outlined above, the following hypotheses were developed to guide the study:

- Groundwater is found in the weathered zone or the fractured basement rock in the study area.
- Groundwater from the Bawku West District has suitable quality for domestic and industrial uses in the area.
- Groundwater that is tapped from highly-fractured basement rock in the Bawku West area can yield high volume of water for domestic and industrial needs.

1.5 Significance of the Study

The groundwater resources in the Bawku-West District have fairly good quality. Therefore, this study will be helpful in locating potential drilling sites in the study area thereby, assisting the people throughout the District to get enough access to potable water that will be close to the people. This will go a long way to improve upon the health and livelihood of the vulnerable rural poor people in the District. In fact, this study will help reduce the time spent by school children to walk long distances in search of water for their families before going to school. In addition, this study may increase food production in the district and will finally ease the burden on women in fetching water for their families from far distances. Hence the overall significance of the study is to enhance the socio-economic life and activities of the people in order to reduce poverty.

1.6 Scope of the Study

As part of the World Vision International (WVI) – Ghana Rural Water Project (GRWP) of the Upper East Region, this study integrated electromagnetic survey and electrical resistivity sounding methods to locate potential groundwater zones in the Bawku West District. Works associated with the exploration procedures will include the following:

- Geophysical field survey work in the beneficiary communities in the study area.
- Analysis and interpretation of the geophysical data to identify potential groundwater water sites/zones.
- Drilling of the selected sites in the communities in the study area.
- Comparison of geophysical results with drill results.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Prospecting for water requires a basic knowledge of the various kinds of groundwater – bearing formations that can be found in the Earth`s crust (Tsikudo, 2009). Groundwater usually accumulates in pores, voids, faults or fissures of subsurface geological formations. For rural water supply only groundwater at depths of less than 50 m, perhaps sometimes 100 m, can be practically and economically exploited (MacDonald *et al.*, 2005). According to Appiah (2002), many geophysical methods (gravity, seismic, electromagnetic, electrical, etc.) are employed in groundwater exploration. The most commonly used method for groundwater exploration are however, electromagnetic and resistivity methods.

2.2 The Underground Water

Groundwater is the water stored within pore spaces and fractures in rocks. According to MacDonald *et al*., (2005), the deeper the rocks are, the more compressed they become, and pores and fractures close up and that it is difficult to estimate the depth at which usable groundwater can be found. Subsurface water up to the depth of about 10 km forms the zone of groundwater which is contained in pores of sand and sandstones and fractures and crevices in hard rocks, such as limestone and granite that supplies wells and springs (Mathur, 2010).

2.3 The Sources of Groundwater

The primitive Earth got its water from volcanic emanations and then gave it to the atmosphere. According to Mathur (2010), there is a regular sequence of movement of moisture starting from its source in the oceans, through various paths on the land and back to the oceans, called the hydrological cycle. The hydrologic cycle is as shown in Fig. 2.1.Water is constantly recycled through the hydrologic cycle, also known as the water cycle (Kratzer, 2006). Groundwater is part of the hydrologic cycle (Harter, 2003b). Precipitation, Percolation/Surface Runoff, Evaporation/Transpiration, and Condensation are the four basic processes of a hydrological cycle. According to Mathur (2010) it starts from evaporation of water taking place from the oceans, lakes, rivers, etc. and which condenses in the atmosphere as clouds, which in turn precipitates as rain or snow; this water eventually returns to the oceans, then another cycle starts. When rain starts falling, it is first of all intercepted by buildings and other objects. When the rainfall rate exceeds the interception rate, water starts reaching the ground and infiltration starts. This is the source of groundwater storage (Harter, 2003).

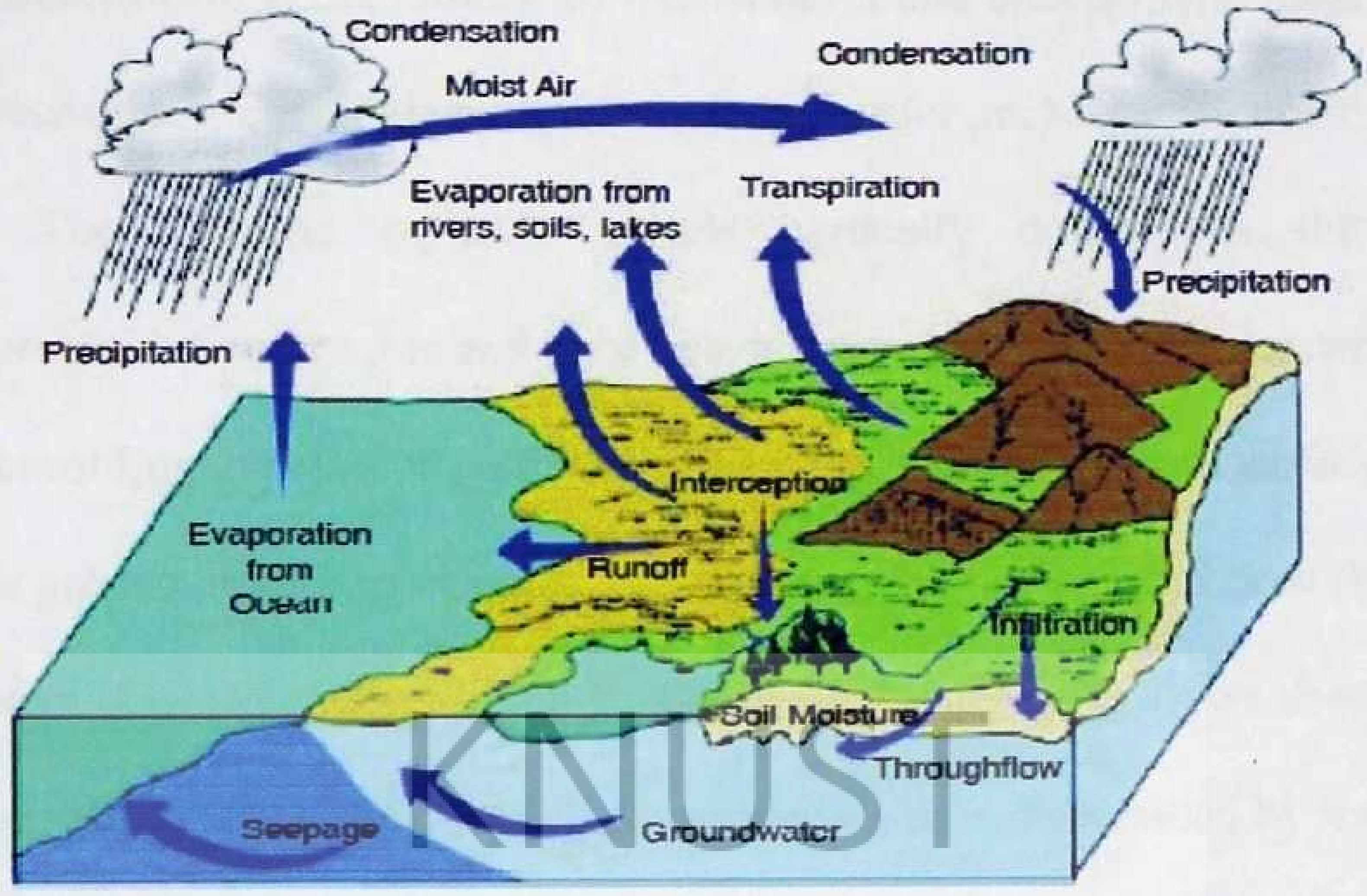

Figure 2.1 Hydrologic cycle (Source: Kirit, 2007).

2.4 Groundwater Occurrence and Movement

According to Alaska Department of Environmental Conservation (ADEC) (2009), groundwater occurs in two zones: an upper unsaturated zone where most of the pore spaces are filled with air, and a deeper saturated zone in which all the pore spaces are filled with water. In Fig. 2.2is a schematic diagram showing groundwater in the saturated zone. The upper surface of the zone of water that has percolated from the ground surface and got saturated into pores, cracks and fissures forms the water table (Mathur, 2010). Between the water table and the land surface is the unsaturated zone or vadose zone (Harter, 2003a). The vadose zone forms the undersaturated layer of underground water in the Earth`s crust above the permanent groundwater level of the water table. Groundwater may be still or moving, and have a pressure flow corresponding to hydrostatic conditions, pressure flow (as in artesian aquifer), or below atmospheric pressure, due to the effects of surface tension (Matzner, 2001).

According to MacDonald *et al*., (2005), all freshwater found underground must have had a source of recharge. The source of underground water recharge is mostly through precipitation. The recharge typically travels vertically downwards through the unsaturated zone to the water table and once below the water table groundwater can flow horizontally, according to pressure gradients, until water reaches the land surface where it flows from the ground as springs or seepages, providing the dry-weather flow (base flow) of lowland rivers (MacDonald *et al*., 2005). Groundwater generally flows downhill, just as surface water does. However, downhill for groundwater is determined by the slope of the barrier below it, not the ground above it. The slope of the underground barrier often is in the same direction as the ground above it, but that is not always the case (ADEC, 2009).

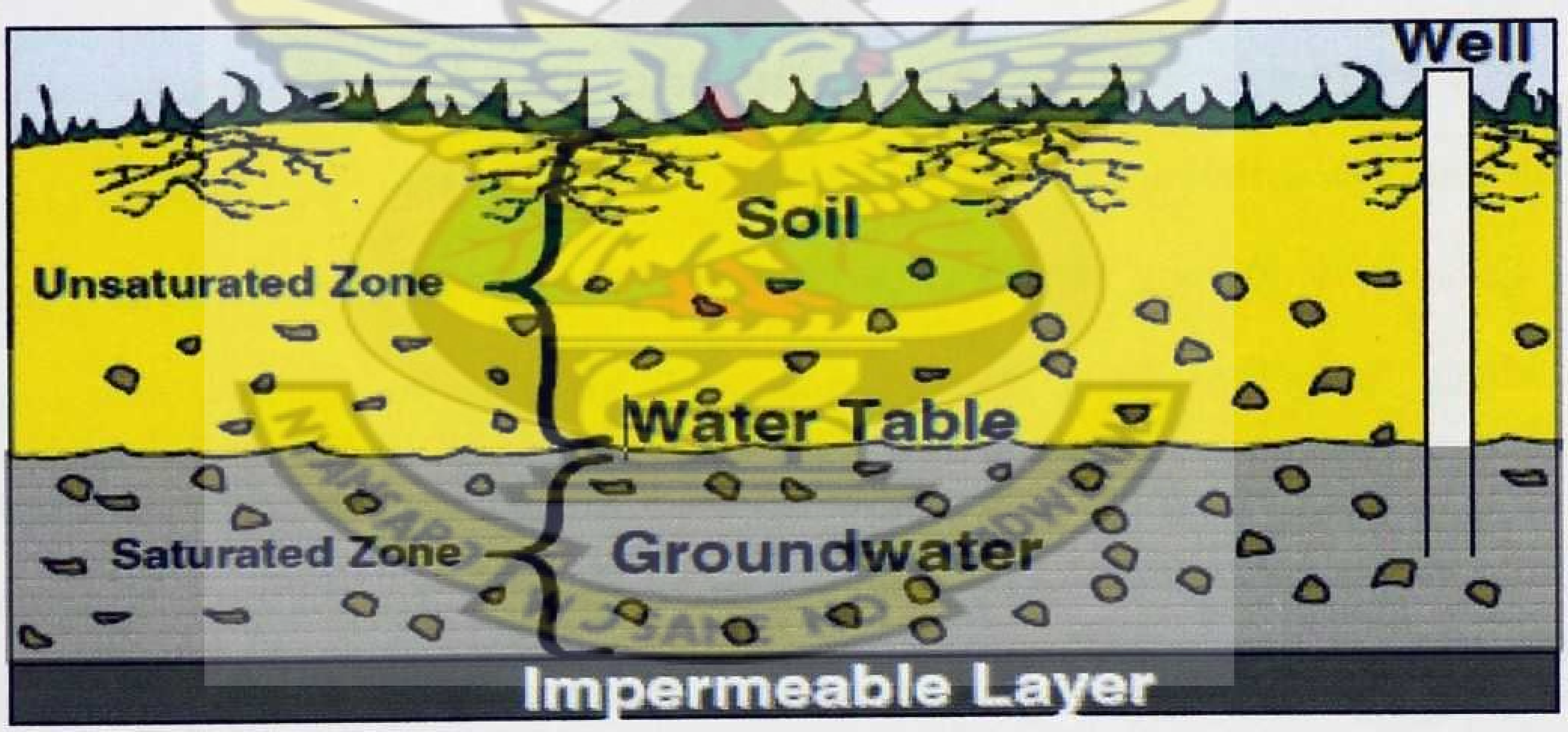

Figure 2.2 Schematic Diagram of Groundwater
(Source: ADEC, 2009).

2.5 Rock Properties Affecting Groundwater

The amount of water in a geological material depends on the porosity, which may be divided into two: primary porosity and secondary porosity (ABEM Instrument AB, 2005). According to Mathur (2010), the ratio of the fraction of voids or pores that occur between grains, expressed as the percentage of the volume of the rock, is called porosity and that the pores may be filled with a fluid or air. Matzner (2001), also defines porosity (Ø) mathematically as: $\emptyset = (V_a + V_w)/V_s$, where V_a is the volume of air in the sample, V_w is the volume of water in the sample and V_s is the total volume of soil or rock in the sample. Primary porosity consists of pore spaces between the mineral particles and occurs in soils and sedimentary rocks, whereas secondary porosity consists of fractures and weathered zones and this is the most important porosity in crystalline rock such as granite and gneiss (ABEM Instrument AB, 2005). Fig. 2.3shows various types of pore space in sediments and rocks. Unconsolidated granular sediments such as sands or gravels have very high porosity since they contain large amounts of pore space between their grains. However, according to MacDonald *et al.*, (2005), the porosity progressively reduces both with the proportion of finer materials such as silt or clay. In highly consolidated sedimentary rocks, the porosity may reduce to less than 10 per cent (MacDonald *et al.*, 2005). Consolidation is as a result of the cementation of the grains of sediments. In highly consolidated rocks such limestone groundwater is accumulated only in fractures. However, the total storage is relatively small compared with unconsolidated aquifers (MacDonald *et al.*, 2005). According to MacDonald *et al.*, (2005), in crystalline rocks, such as igneous and metamorphic rocks, groundwater is found only in fractures and rarely exceeds 1 per cent of the volume of the rock mass.

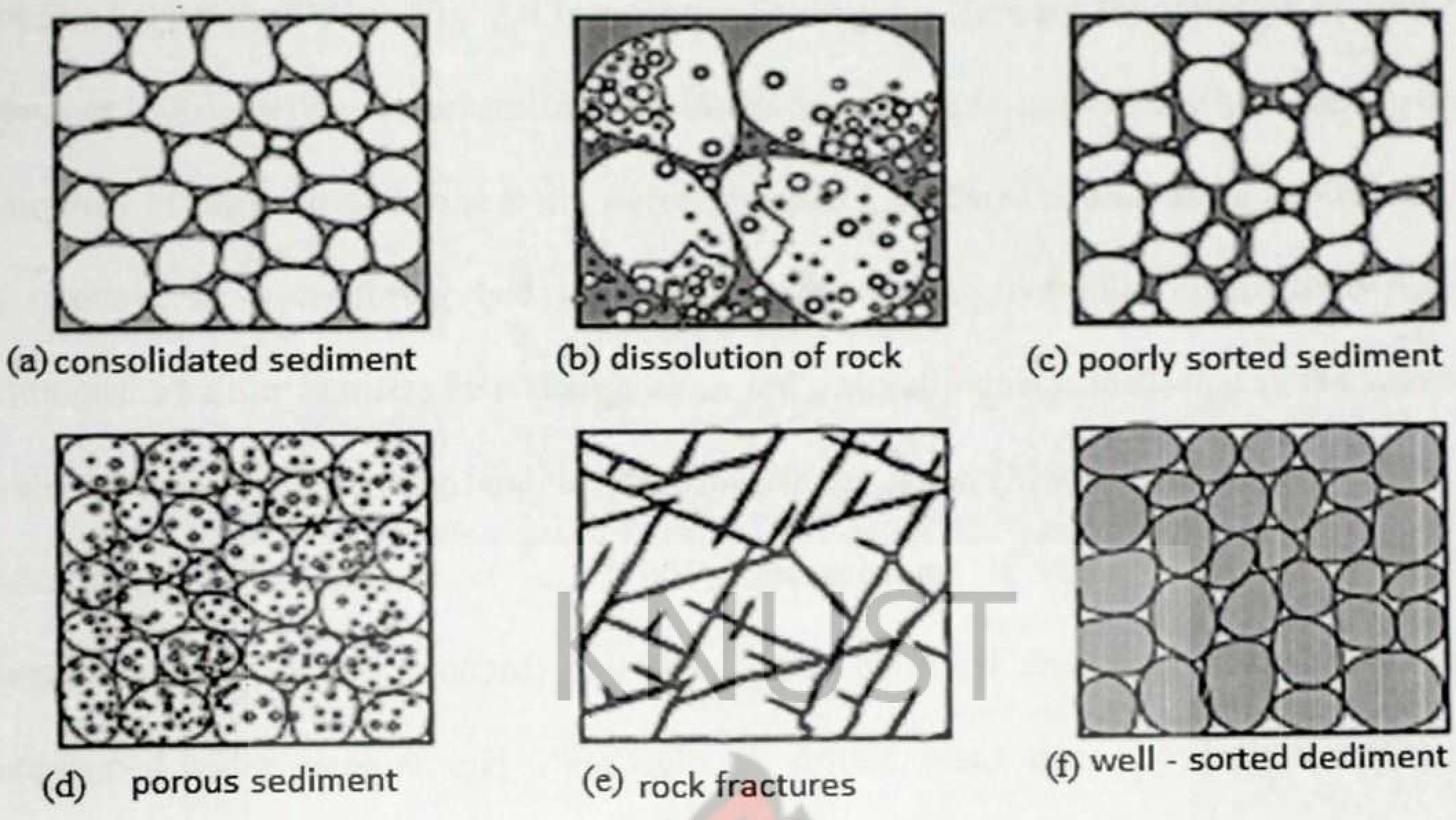

Figure 2.3 Types of pore space in sediments and rocks (source: Harter, 2003 (a)).

2.6 Types of Aquifers

An aquifer is a highly pervious geological formation, empirically defined as a geologic formation saturated with water and sufficiently permeable to transmit significant quantities of water under normal field conditions (Matzner, 2001). According to Mathur (2010) the ability of the rock to allow pore fluids to pass through it is permeability and it is governed by the extent to which pore spaces within the rock are connected. Aquifers typically consist of gravel, sand, sandstone, or fractured rocks such as limestones and that these materials are permeable because they have large connected spaces (pores) or fractures that permit water to flow through them (Plazinska, 2007). A material, such as dry clay, is said to be porous because it contains pores and allows water to be absorbed but it is said to be impermeable since it will not allow water to pass through it and therefore cannot be a good aquifer. Aquifers can be of two major types: unconfined or confined (Harter, 2003a). Fig. 2.4 is a schematic diagram showing the types of aquifers. Matzner (2001) defines an unconfined aquifer as a geologic formation in which the upper boundary of the saturated zone is the water table and a confined aquifer as an aquifer that is overlain by a confining bed with significantly lower hydraulic conductivity (an aquitard). Shallow aquifers in recharge areas are generally unconfined, that is the water table is within the aquifer and at atmospheric pressure (MacDonald *et al.*, 2005). According to MacDonald *et al.*, (2005), groundwater is often confined by low permeability rocks (an aquitard) and thus under confined conditions water may be intercepted under pressure, and when wells are drilled, water rises above the top of the aquifer, sometimes even above ground surface, to a level called the potentiometric surface.

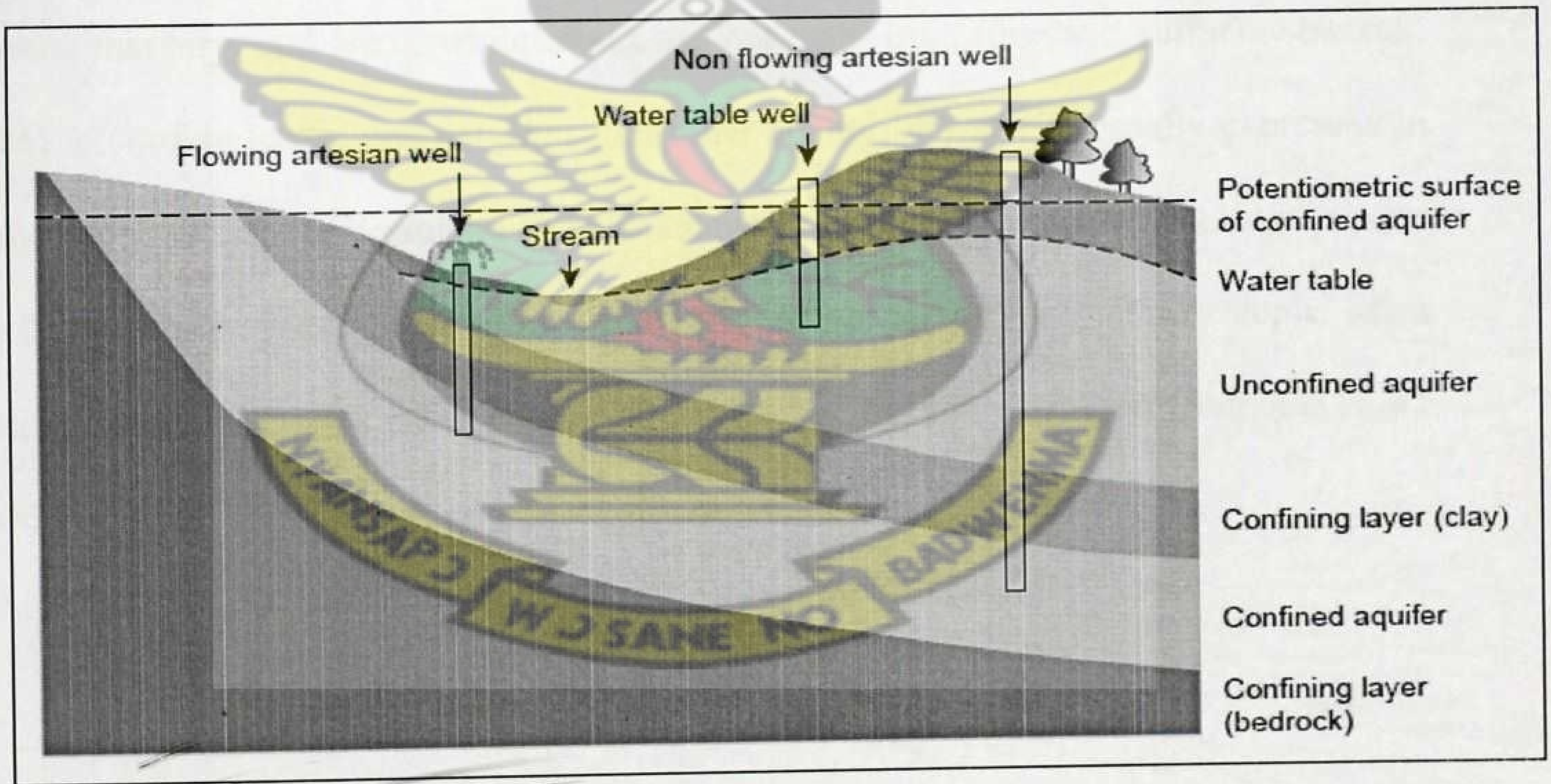

Figure 2.4 Types of aquifers (Source: Plazinska, 2007).

2.7 Groundwater Quality

Groundwater quality comprises the physical, chemical and biological qualities of groundwater (Harter, 2003b). The physical quality parameters include colour, taste, odour, turbidity, temperature. Rocks and sediment are natural filters capable of efficiently removing suspended solids (mud and solid waste) from groundwater, for these solids get trapped in the tiny pathways between pores (Marshak, 2005). According to Marshak (2005), clay flakes, because of their electrically charged surfaces, can remove certain ions from water. Thus, groundwater tends to be clear when it emerges from the ground in a spring or well. Table 2.1 indicates sources of groundwater occurrence in various rock formations. Nevertheless, dissolved, invisible organic and inorganic chemicals may be carried along with flowing groundwater; some dissolved chemicals are toxic (such as arsenic, mercury, and lead), while others are not (salt, iron, lime and sulfur) (Marshak, 2005).According to Shipman *et al.*, (2006), the quality of water is usually expressed in terms of the amount of dissolved chemical substances present as a concentration in parts per thousands (ppt), parts per million (ppm) or parts per billion (ppb). For example, when a sample contains 1 ppm salt, it contains 1 g of salt / 1 million g of water (Shipman *et al.*, 2006).

Table 2.1 Sources of groundwater occurrence

Rock Type	Areas of Groundwater Occurrence
Sand and Gravel	Pores
Sandstone	Pores and fissures
Limestone	Fissures often expanding into caves
Chalk	Pores and fissures
Clay	Very small pores
Massive	
Igneous	Fissures with pores in weathered zones
Lava	Fissures with pores in igneous zones
Metamorphic	Fissures with pores in weathered zones

(Modified after Tsikudo, 2009)

2.8 Groundwater Exploration

The siting for high potential aquifers, using geophysical methods, depends on clear understanding of the geology, hydrogeology, and the topography of the area and further about good interpretation of geophysical data (Appiah, 2002). Geological factors are chiefly concerned with geological structures which control possible groundwater sources in the survey area and physical property contrast such as resistivity, electrical conductivity or density associated with these geological structures, as well as the choice of suitable geophysical survey methods (Daly, 1987). In some areas, for example on major alluvial plains with abundant rainfall, groundwater may be widely available at relatively shallow depths. In these areas, little or no hydro - geological investigation is necessary as wells or boreholes may be successful wherever they are developed. Siting can therefore be determined by the local population alone. In environments which are more geologically heterogeneous, however, investigations ranging from simple field observation to more costly exploratory drilling and surveying may be necessary to ensure success (MacDonald *et al.*, 2005). According to MacDonald *et al.*, (2005), in certain areas, studying the geomorphology can be an excellent way of siting wells and boreholes. According to MacDonald *et al.*, (2005),

i) Valleys follow the lines of major faults, so the valleys may be a good place to site boreholes.

ii) Some basement areas where the topography is undulating, good boreholes sites have been found halfway down the slope towards the valley bottoms; the valley bottoms are too clayey, and the tops of the interfluves too unweathered, to support good boreholes.

iii) Inselbergs (also known as bornhardts, tors, Whale-backs or kopjes) in basement areas offer good borehole or well sites where gravels could found around the base of these large, rounded hills.

iv) Sedimentary areas, where sandstones and mudstones are interbedded, sandstone can often be identified by slight ridges or high ground.

2.9 The Electromagnetic (EM) Method

The Electromagnetic method can be classified into two main types. These are the Time Domain (TEM or TDEM) and Frequency Domain (FEM or FDEM) systems. FEM methods measure the bulk electrical conductivity of the ground, often referred to as ground conductivity (MacDonald *et al.*, 2005). TDEM achieves the same results by measuring the electrical response of the subsurface to a pulsed wave at several time intervals after transmission, longer time intervals measure greater depths (Hitzig *et al.*, 1997).Because a small conductive mass within a poorly conductive environment has a greater effect on induction than on 'direct current' resistivity, discussions of EM methods tend to focus on conductivity (σ), the reciprocal of resistivity, rather than on resistivity itself (Kearey *et al.*, 2002). The ground conductivity (also known as terrain conductivity) values are commonly measured in units of milliSiemens per metre (mS/m) or milli mhos/m (m mhos/m).

2.10 General Principle of the Electromagnetic (EM) Method

The electromagnetic (EM) survey method is concerned with the measurement of terrain conductivities by low frequency electromagnetic induction. The basic principle of operation of the electromagnetic method is illustrated in Fig.2.5.

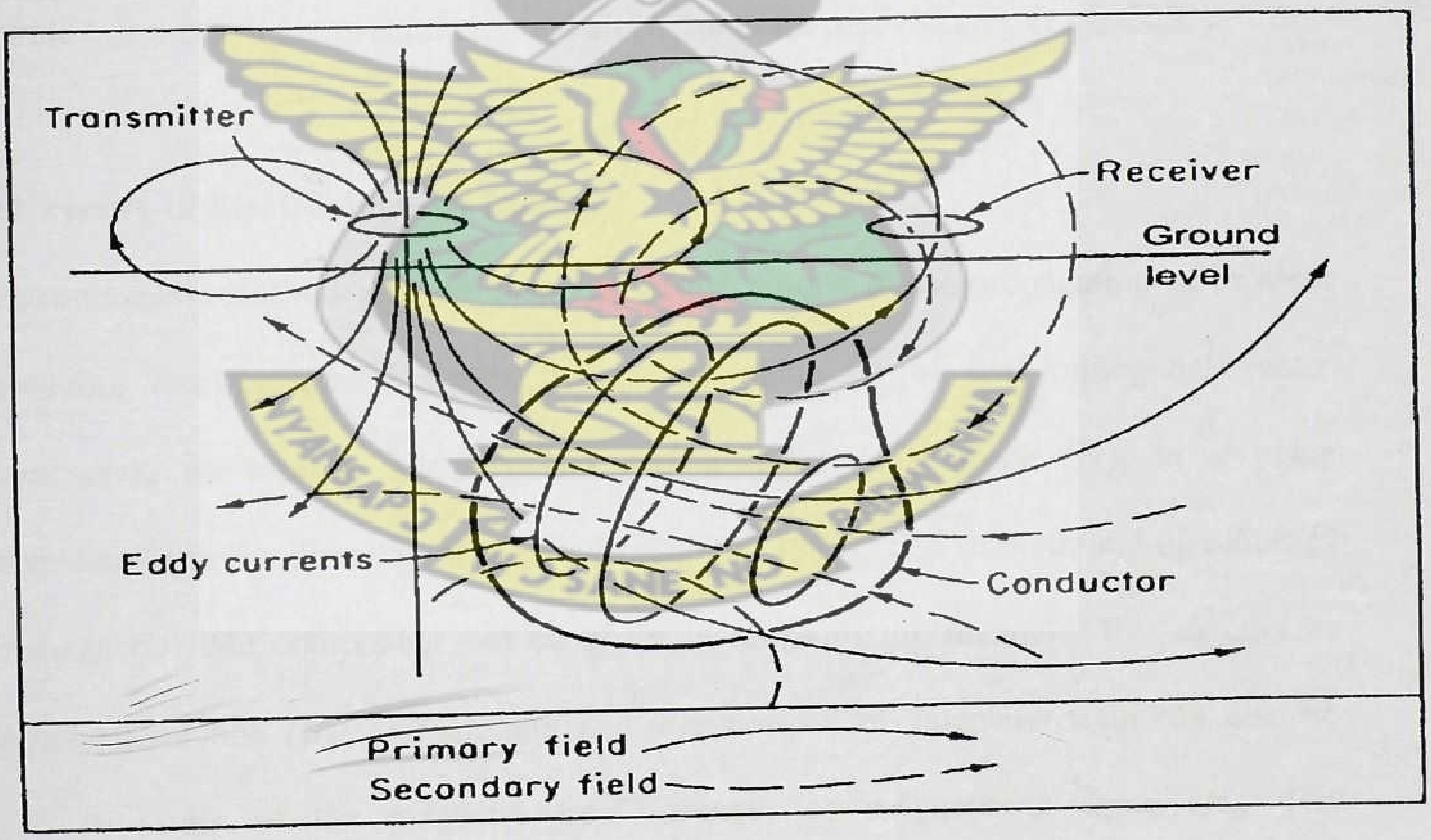

Figure 2.5 Generalized schematic operating principle of the EM survey method (Source: Reynolds, 1997).

A transmitter coil radiates a primary electromagnetic field which propagates above and below ground. Where the subsurface is homogeneous there is no difference between the fields propagated above the surface and through the ground other than a slight reduction in amplitude of the latter with respect to the former (Kearey *et al.*, 2002).If a conductive medium is present with the ground, the magnetic component of the incident EM wave induces eddy currents (alternating currents) within the conductor (Reynolds, 1997). Consequently, the eddy-currents produce secondary EM field which is detected (along with the primary field) by a receiver coil. The receiver then responds to the resultant of the arriving primary and secondary fields so that the response differs in both phase and amplitude from the response to the primary field alone. These differences between the transmitted and received electromagnetic fields reveal the presence of the conductor and provide information on its geometry and electrical properties (Kearey *et al.*, 2002).

2.11 Theory of Electromagnetic Method

Electromagnetic method uses the response of the ground to the propagation of incident alternating electromagnetic waves, which are made up of two orthogonal vector components, an electric intensity (***E***) and a magnetising force (***H***), in a plane perpendicular to the direction of travel (Reynolds, 1997). The strength and direction of the magnetic field component can be given in terms of the magnetic flux density or magnetic induction (***B***). The strength and direction of the magnetic field can also be given in terms of the magnetic field strength or magnetizing force (***H***). The electromagnetic wave with its varying electric field intensity (***E***) and magnetic field strength (***H***) components are as shown in Fig. 2.6.

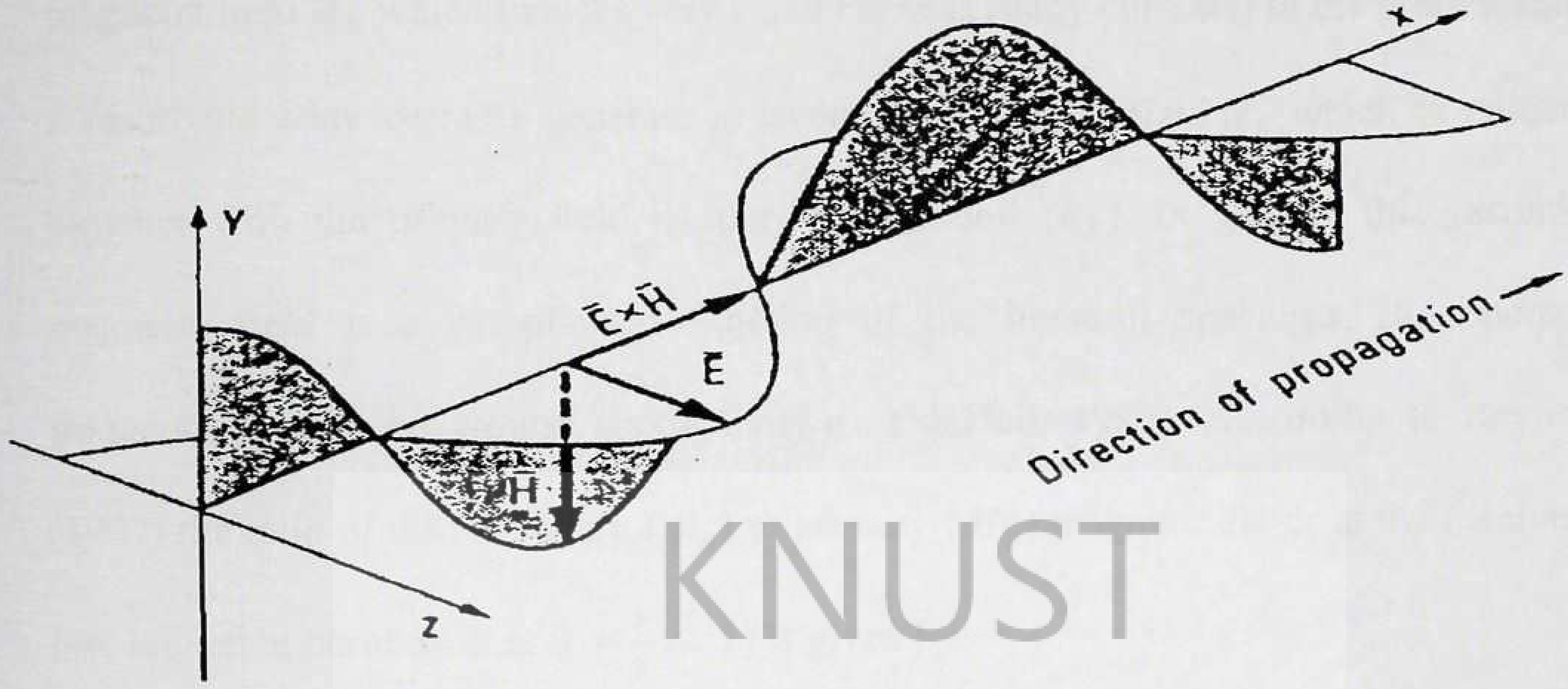

Figure 2.6 Basic elements of an electromagnetic wave, showing the two principal electric (***E***) and magnetic (***H***) components (Source: Reynolds, 1997)

The current flow at any point in a homogeneous half-spaced earth is as shown in a diagram in Fig. 2.7.

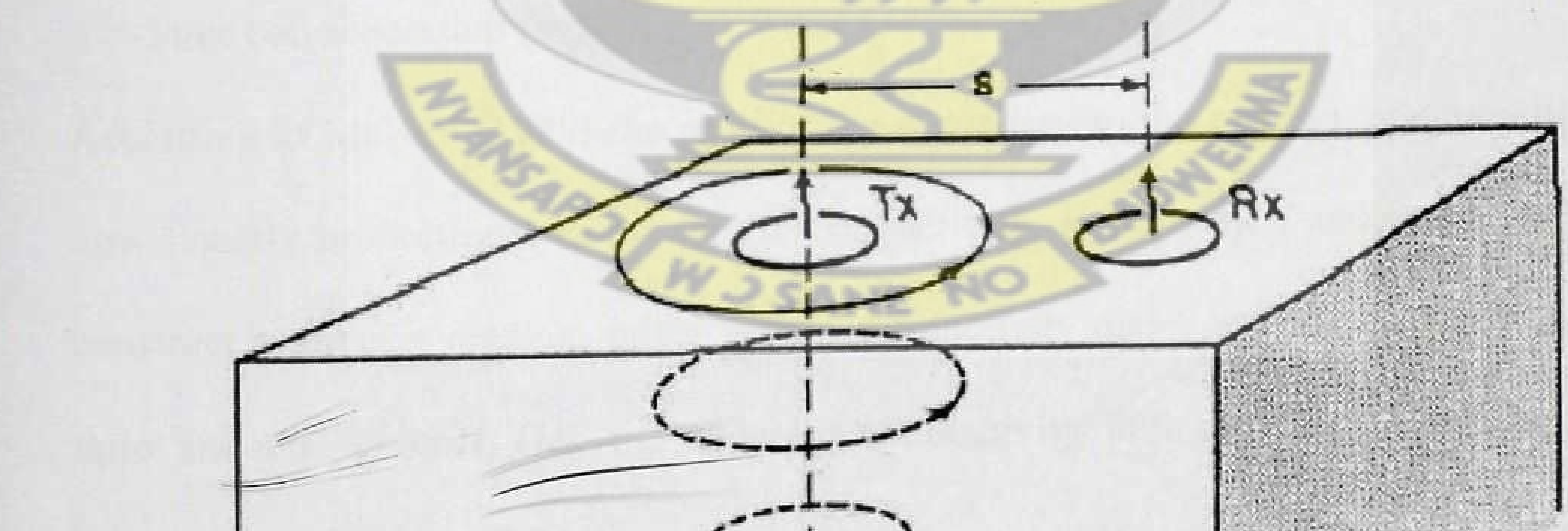

Figure 2.7 Induced current flow (homogeneous half space) (Source: McNeil, 1980).

In Fig. 2.7, transmitter coilT_X placed on the earth (assumed uniform) generates a primary magnetic field $\boldsymbol{H_p}$ which induces very small currents (eddy currents) in the ground and as a result the eddy currents generate a secondary magnetic field $\boldsymbol{H_s}$ which is detected, together with the primary field by the receiver coil (R_X). In general this secondary magnetic field is a complicated function of the intercoil spacing s, the operating frequency f, and the ground conductivity σ (McNeil, 1980). According to Reynolds (1997) the ratio of the secondary ($\boldsymbol{H_s}$) to primary ($\boldsymbol{H_p}$) magnetic fields at the receiver at low induction numbers (i.e. $B = \frac{s}{\sigma} \ll 1$) is given by:

$$H_s/H_p \approx iB^2/2 = i\omega\mu_o\sigma s^2/4 \quad \text{.............................. (2.11a)}$$

Where:

$\omega = 2\pi f$ and f is the frequency (Hz)

μ_o =Permeability of free space

$i = \sqrt{-1}$

σ =Conductivity

s = Inter-coil separation (m)

According to McNeil (1980) the ratio of the secondary to the primary magnetic field is now linearly proportional to the terrain conductivity, a fact which makes it possible to construct a direct – reading, linear terrain conductivity meter by simply measuring this ratio and that given $\boldsymbol{H_s/H_p}$ the apparent conductivity indicated by the instrument is defined from equation (2.11a) as

$$\sigma_a = \frac{4}{\omega\mu_o s^2}\left(\frac{H_s}{H_p}\right) \quad \text{.............................. (2.11b)}$$

2.12 Physical Quantities and Field Equations

To understand the propagation and attenuation of an electromagnetic field it is necessary to use a set of differential equations that describe space and time dependance of the electromagnetic field called the Maxwell`s equations. The Maxwell`s equations according to Bhattacharya, A. B and Bhattacharya, R (2008) are:

(i) $\nabla \cdot \mathbf{D} = \rho$

(ii) $\nabla \cdot \mathbf{B} = 0$

(iii) $\nabla \times E + \frac{\partial B}{\partial t} = 0$

(iv) $\nabla \times H = j + \frac{\partial D}{\partial t}$

Where $\boldsymbol{D}$is the electric displacement (Unit: C/m^2), ρ is the volume charge density (Unit: C/m^3), $\boldsymbol{j}$is the electric current density(Unit: A/m^2),$\boldsymbol{E}$is the electric field intensity (Unit: V/m), $\boldsymbol{B}$is the magnetic flux density [Unit: teslas (T)], $\boldsymbol{H}$is the magnetic field intensity(Unit: A/m). Below is Fig. 2.7 indicating the generation of the electric fieldand the magnetic fields according to the Maxwell`s equation (iii) and (iv).

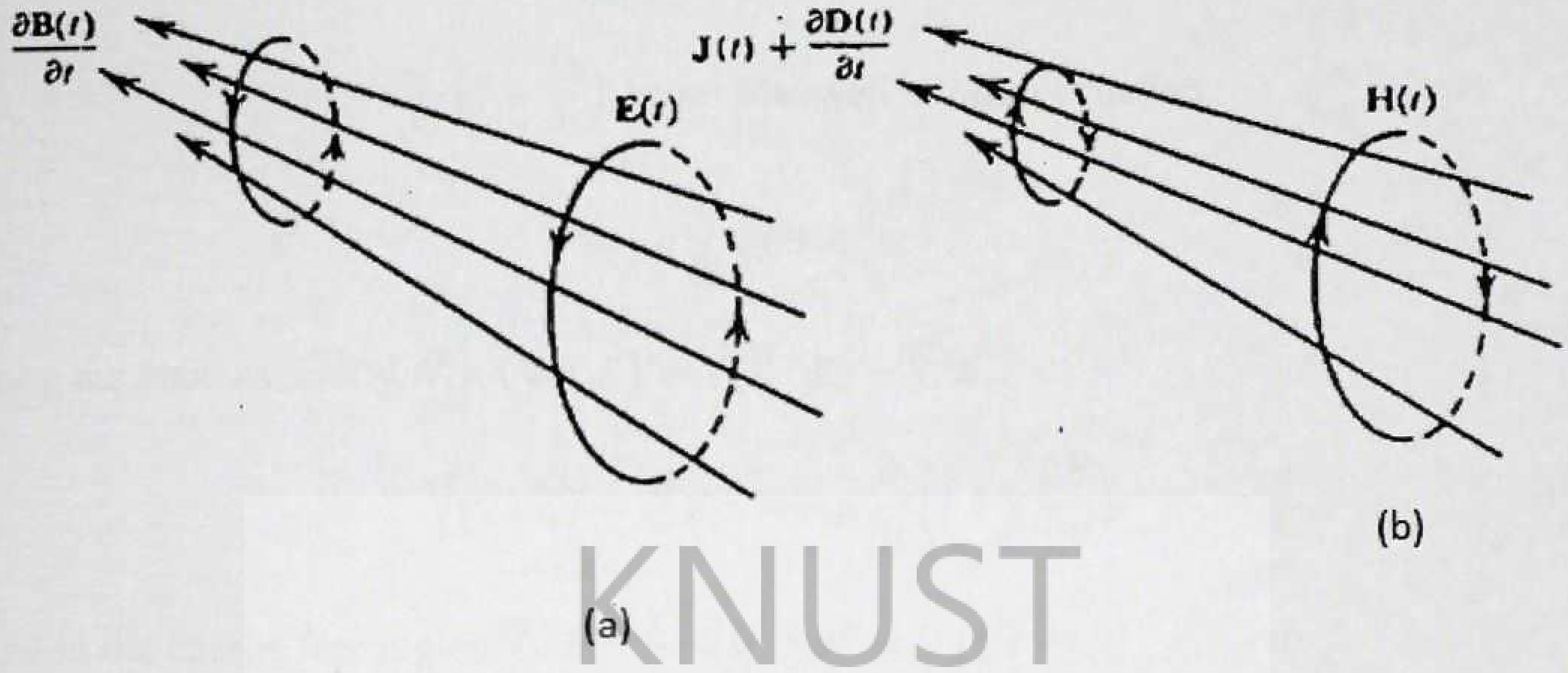

Figure 2.8 Electric and magnetic fields of equations (iii) and (iv).

(Source: Reynolds, 1997).

Fig. 2.8 (a) indicates that an electric field $\boldsymbol{E}$is generated by a changing magnetic field$\frac{\partial \boldsymbol{B}}{\partial t}$ and also, Fig. 2.8 (b) indicates that a magnetic field $\boldsymbol{B}$is produced by the current density $\boldsymbol{J}$and the changing displacement – current density$\frac{\partial D}{\partial t}$. In homogeneous or linear media it happens that$\boldsymbol{D} = \epsilon\, \boldsymbol{E}$, $\boldsymbol{B} = \mu\, \boldsymbol{H}$ where the quantitiesϵ, μ(usually ≈ 1 for non – magnetic soils or matter) are respectively called the dielectric constant and magnetic permeability of the medium. Furthermore, in equation (iv) an external current density is mentioned and that it is the source of the electromagnetic waves and therefore represents the antenna in the system (Ludwig *et al.*, 2011).The displacement current originates when charges are displaced but not separated from their atoms, causing an electric polarization; fluctuations in the polarization have the effect of an alternating displacement current. According to Bhattacharya, A. B and Bhattacharya, R (2008), it can be deduced from Maxwell`s third equation that:

$$\vec{\nabla}(\vec{\nabla} \times \boldsymbol{E}) = -\vec{\nabla} \times \frac{\partial \boldsymbol{B}}{\partial t} = -\frac{\partial}{\partial t}(\vec{\nabla} \times \boldsymbol{B}) = -\mu \frac{\partial}{\partial t}(\vec{\nabla} \times \boldsymbol{H})$$

$= -\mu \frac{\partial}{\partial t}\left(\vec{j} + \frac{\partial D}{\partial t}\right)$, From Maxwell's fourth equation

$$= -\mu \frac{\partial}{\partial t}\left(j + \epsilon \frac{\partial \boldsymbol{E}}{\partial t}\right)$$

Using the vector identity, $\vec{\nabla} \times (\vec{\nabla} \times \boldsymbol{E}) = \vec{\nabla}(\vec{\nabla} \cdot \boldsymbol{E}) - \vec{\nabla}^2 \boldsymbol{E}$.

$$\therefore \vec{\nabla}(\vec{\nabla} \cdot \boldsymbol{E}) - \vec{\nabla}^2 \boldsymbol{E} == -\mu \frac{\partial}{\partial t}\left(j + \epsilon \frac{\partial \boldsymbol{E}}{\partial t}\right).$$

Now in the charge free region, $\vec{\nabla} \cdot \boldsymbol{E} = \frac{1}{\epsilon} \cdot \vec{\nabla} \boldsymbol{D} = e^{\rho} = 0 \; [\because \rho = 0]$

$$\therefore \vec{\nabla}^2 \boldsymbol{E} = \mu \frac{\partial}{\partial t}\left(\sigma \boldsymbol{E} + \epsilon \frac{\partial \boldsymbol{E}}{\partial t}\right) = \mu\sigma \frac{\partial \boldsymbol{E}}{\partial t} + \mu\epsilon \frac{\partial \boldsymbol{E}}{\partial t}$$

Or,

$$\vec{\nabla}^2 \boldsymbol{E} - \mu\epsilon \frac{\partial E}{\partial t} - \mu\sigma \frac{\partial E}{\partial t} = 0 \quad \text{............ (2.12a)}$$

Equation (2.12a) is the general electromagnetic field equation that describes the propagation of the E field vector. In case of conducting medium, the third term of the equation is dominant hence the equation becomes

$$\vec{\nabla}^2 \boldsymbol{E} - \mu\sigma \frac{\partial E}{\partial t} = 0 \quad \text{............... (2.12b)}$$

For non – conducting medium;

$$\vec{\nabla}^2 \boldsymbol{E} - \mu\epsilon \frac{\partial E}{\partial t} = 0 \quad \text{................ (2.12c)}$$

From Maxwell`s fourth equation, exactly similar equations for $\boldsymbol{H}$can be obtained.

$$\vec{\nabla}^2 \boldsymbol{E} - \mu\varepsilon \frac{\partial H}{\partial t} - \mu\sigma \frac{\partial H}{\partial t} = 0 \quad \text{.................. (2.12d)}$$

And

$$\vec{\nabla}^2 \boldsymbol{E} - \mu\epsilon \frac{\partial D}{\partial t} = 0 \quad \text{....................... (2.12e)}$$

The solution of the differential equations (2.12c) and (2.12e) represent waves travelling with velocity

$$v = \sqrt{\frac{1}{\mu\varepsilon}}$$

From equations (2.12c) and (2.12e) it can be concluded that at any time, variations in electric or magnetic field are propagated with the same velocity:

$$v = \sqrt{\frac{1}{\mu\varepsilon}}$$

The type of wave which is obtained from the solution of equations (2.12c) and (2.12e) are plane waves. Thus, a plane wave is a wave in which the wave amplitude remains constant over all points of a plane perpendicular to the directions of propagation. If a plane wave is propagated in the plane of the x-axis, then the general wave equation takes the form

$$\frac{\partial^2\psi}{\partial x^2} - \frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2} = 0$$

The general solution of the above equation will be

$$\psi(x,t) = Ae^{i(kx-\omega t)} + Be^{-i(kx-\omega t)}$$

Where A and B are constants and $k = \frac{\omega}{v}$. Here we may assume that the plane wave field equations become:

$$\boldsymbol{E}(x,t) = \boldsymbol{E}_o e^{i(kx-\omega t)}$$

$$\boldsymbol{H}(x,t) = H_o e^{i(kx-\omega t)}$$

In the above equation we have assumed that $\boldsymbol{E}$and H are in phase (Bhattacharya A. B and Bhattacharya R, 2008).

2.13 Electromagnetic Field Attenuation

The wave is attenuated in travelling through some media but not in free space (Telford *et al.*, 1990). Tsikudo (2009) cited Sherrif (1991)that attenuation is the reduction in amplitude or energy caused by the physical characteristics of the transmitting media or system, including geometric effects such as the decrease in amplitude of a wave with increasing distance from the source.

2.14 Depth of Penetration of Electromagnetic Fields

A commonly used criterion for the penetration of electromagnetic waves is the skin depth (Telford *et al.*, 1990). According to Reynolds (1997), Sheriff (1991)defined skin depth as the depth at which the amplitude of a plane wave has decreased to $1/e$ or 37% of its initial amplitudeA_o . If $A_z$is the amplitude of EM radiation as a function of the depth of penetration z , then by definition:

$$A_z = A_o e^{-1} \quad \text{(2.14a)}$$

According to Matzner (2001) and Reynolds (1997), fluctuating external fields of angular frequency $\omega = (2\pi f)$ diffuse into a layer at the top of the mantle with a skin depthδ (in metres) given by

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} = \frac{503.8}{\sqrt{\sigma f}} \quad \text{(2.14b)}$$

Thus the depth of penetration increases as both the frequency f of the electromagnetic field and the conductivity σ of the ground decrease. The magnetic permeability of the medium μ is set to 1, since most materials related to groundwater exploration are not magnetizable. This is only violated, when soils with non-negligible iron content are studied (Ludwig *et al.*, 2011). The induced field is then essentially a reflection of this external field from the skin depth layer, and it has a phase relative to the external field that relates the conductivity structure of the layer to the frequency of the signal (essentially, long period signals penetrate deeper and therefore depend more on deeper conductivity than do short period signals) (Matzner, 2011).

Equation (2.3.6b) according to Kearey *et al.*, (2002) represents a theoretical relationship. Empirically, an estimate of the maximum depth to which a conductor would give rise to a detectable EM anomaly is $\approx \frac{\delta}{5}$(Kearey *et al.*, 2002 and Reynolds, 1997).

2.15 Electrical Conduction in Rocks

Technos (2004) cited McNeill (1980) that the electrical conductivity is a function of soil and rock type, porosity and permeability, as well as the composition of fluids that fill the pore spaces. Fig. 2.9 shows typical ranges of electric conductivities and resistivities of geological materials (soil and rock types). According to Technos (2004), the conductivity values may be related to groundwater properties such as specific conductance or total dissolved solids. According to Tsikudo (2009), basically the electrical conductivity (σ) of a substance is a measure of the ease or difficulty with which an electrical current can be made to flow through it.With the exception of metallic minerals, graphites and some clay-most soil materials are poor conductors and any significant current flow in these soils is mainly due to the included water and its ionic content (Tsikudo, 2009).For example clays and silts typically exhibit higher conductivity values because they contain a relatively large number of ions. Sands and gravels typically have fewer free ions in a saturated environment and, therefore, have lower conductivities (Hitzig *et al.*, 1997).All anomalous bodies that have high electrical conductivity values produce strong secondary electromagnetic fields (Kearey *et al*., 2002). The electrical conductivity is expressed as:

$\sigma = G\,L/A\ mhos/m$(Tsikudo cited McNeil and Snelgrove 1995)......... (2.15)

Where G = conductance = $I/V\ mhos$, A = area, V = voltage, and I = current.

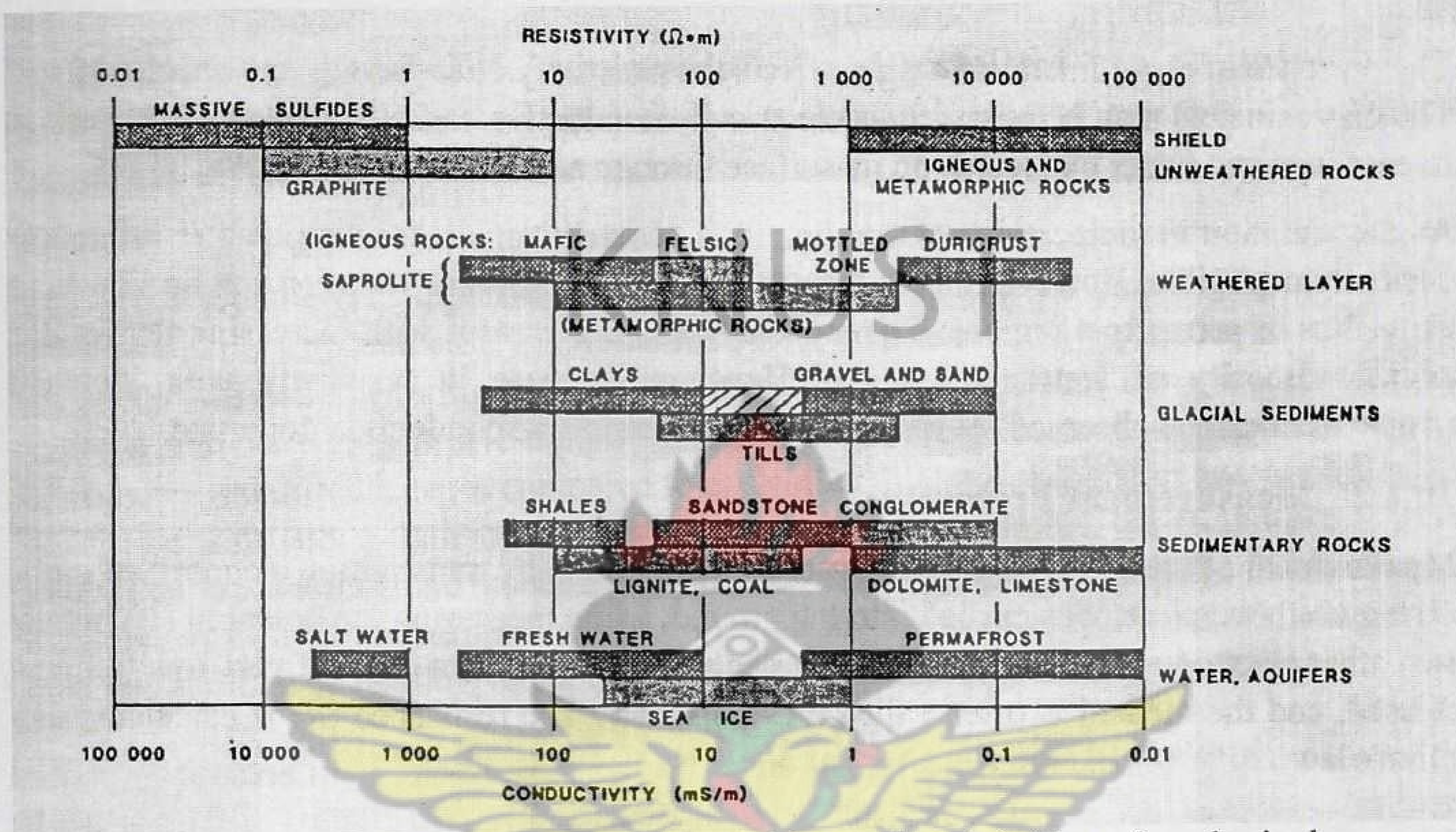

Figure 2.9 Typical ranges of electric conductivities and resistivities of geological materials

(Source: ABEM Instrument AB, 2005).

2.16 The Electromagnetic Method in Groundwater Prospecting

In surveying for groundwater, FEM has become popular due to the ease with which surveys can be carried out, and equipment, particularly Geonics EM34-3, is found in many parts of the world (MacDonald *et al*., 2005). With regards to the plane in which the transmitter (T_x) and receiver (R_x) coils of the electromagnetic equipment lie, the coils can be described as horizontal or vertical. In the field, the coils are typically carried with their planes horizontal or vertical as shown in Fig. 2.10, since in this arrangement the measurement is relatively insensitive to misalignment of the coils. According to MacDonald *et al.*, (2005), different orientation changes the direction of the inducing field:

- for vertical coils the inducing field is horizontal, so this orientation is sometimes called a horizontal dipole (HD) mode.
- for horizontal coils the inducing field is vertical, so this orientation is sometimes called a vertical dipole (VD) mode.

One of the main advantages of the EM methods in groundwater exploration is that the process of induction does not require direct contact with the ground, as in the case of electrical methods where electrodes have to be planted into the ground surface. Consequently, the speed with which surface EM surveys can be made is much greater than an equivalent survey using contacting electrical resistivity. Furthermore, the induction process also allows the method to be used from aircraft and ships, as well as down boreholes (Reynolds, 1997). The limitations of EM methods are primarily a result of the interferences, typically caused when this method is applied within 20 m of power lines buried metal objects (including rebar), radio transmitters, fences, vehicles, or buildings (Hitzig *et al.*, 1997). In addition, penetration is not very great, being limited by the frequency range that can be generated and detected and unless natural fields are used, maximum penetration in ground surveys is limited to about 500m, and is only about 50m in airborne work (Kearey ~~*et al.*, 2002~~). Furthermore, according to Hitzig *et al.*, (1997), its success depends upon subsurface conductivity contrasts. For example, the difference in conductivity between an Underground Storage Tank (UST) and surrounding natural or fill material is typically adequate for detection. However, mapping more subtle targets, such as fine versus coarse material or contamination, is less predictable (Hitzig *et al.*, 1997). As well as being caused by economic sources with a high conductivity such as ore bodies, electromagnetic anomalies can also result from non-economic sources such as graphite, water-filled shear zones, bodies of water and man-made features (Kearey *et al.*, 2002). According to Kearey *et al.*, (2002), superficial layers with a high conductivity such as wet clays and graphite-bearing rocks may screen the effects of deeper conductors. Also, horizontal currents are induced in a horizontally layered medium and their effects at the surface can be interpreted in terms of apparent conductivity. Most real situations involve combinations of layered and discrete conductors, making greater demands on interpreters, and sometimes on field personnel (Milsom, 2003). Finally, the quantitative interpretation of electromagnetic anomalies is complex (Kearey *et al.*, 2002).

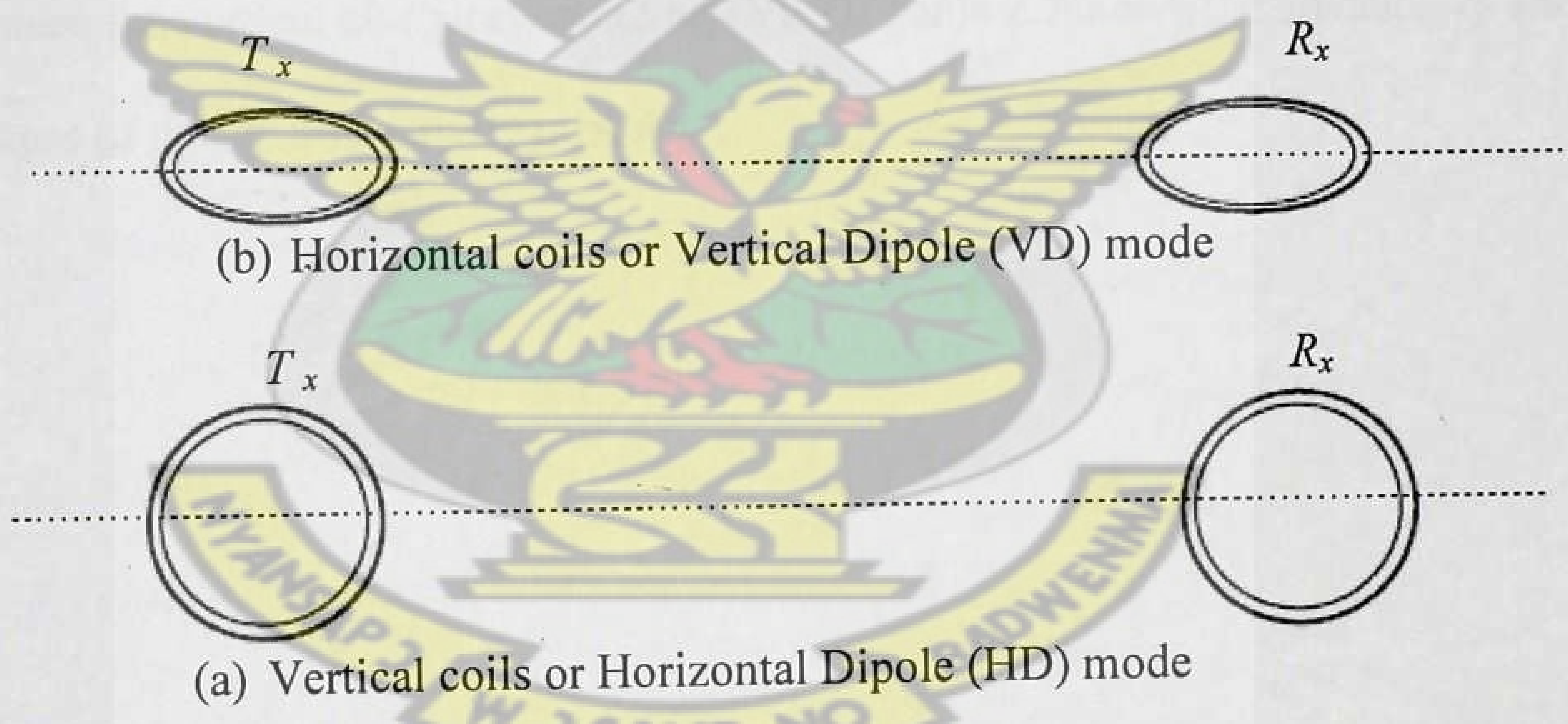

Figure 2.10Typical coil orientations for electromagnetic surveys.

2.17 The Electrical Resistivity Method

Electrical resistivity methods were developed in the early 1900s but have become very much more widely used since the 1970s, due primarily to the availability of computers to process and analyse the data (Reynolds, 1997). According to ABEM Instrument AB

(2005), direct current (DC) or an alternating current (AC) of very low frequency is used, and the method is often called DC - resistivity. The use of electrical resistivity measurements has been a favourite tool of geophysics for over 200 years because of the wide range of resistivity values found in nature (Anthony, 2006). Resistivity is also called specific resistance, which is the inverse of conductivity or specific conductance (ABEM Instrument AB, 2005).There are two main survey techniques: profiling (measuring changes of resistivity along traverse) and depth sounding (measuring changes of resistivity with depth at a certain point) (MacDonald *et al.*, 2005).In a general principle sounding measurements are carried out after profiling (Anthony, 2006). According to MacDonald *et al.*, (2005), profiling has largely been superseded by EM or VLF surveys. However, where more detail is required, 2D electrical resistivity imaging is now generally used for vertical electrical sounding (VES). Table 2.2shows the advantages and disadvantages of the VES resistivity method.

Table 2.2 The Advantages and Disadvantages of the Resistivity VES Method.

Advantages	Disadvantages
1. Can identify layers of different resistivity (in other words changes with depth) 2. Can penetrate deep into the ground 3. Not easily affected by metal objects at the surface 4. Robust, easily available equipment	1. Highly susceptible to bad electrode connections 2. Difficult to interpret 3. Laborious and slow 4. Can`t locate vertical fracture zones 5. Only takes a reading at one point 6. Requires the ground to be homogeneous

(Source: Mac Donald *et al.*, 2005).

2.18 Principle of the Resistivity Method

Surface electrical resistivity surveying is based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivities and distribution of the surrounding soils and rocks (Griffin, 1995).The electrical resistivity varies between different geological materials, dependent mainly on variations in water contents and dissolved ions in the water and resistivity investigations can thus be used to identify zones with different electrical properties, which can then be referred to different geological strata (ABEM Instrument AB, 2005). According to Bernard (2006), the resistivities of rocks generally depend on the water content (porosity), the resistivity of the water, the clay content and the content of metallic minerals. The presence of clay minerals strongly affects the resistivity of sediments and weathered rock and that the clay minerals may be regarded as electrically conductive particles, which can absorb and release ions and water molecules on its surface through ion exchange process (ABEM Instrument AB, 2005).The usual practice in the field is to apply direct current (DC) between two electrodes implanted in the ground and to measure the difference of potential between two additional electrodes that do not carry current (Griffin, 1995).Fig. 2.11 is a diagram showing the current and equipotential lines produced by a current source and a sink. Ohm`s law can then be used to calculate the resistance, and the resistance is then multiplied by a geometric factor (normally called a K factor) to calculate the resistivity (MacDonald *et al.*, 2005). When the current electrode spacing is increased, there are many more paths for the current to pass and the volume of ground sampled increased and hence, at large electrode spacings more information is given about the deeper layers (MacDonald *et al.*, 2005). The geometric factor (K; units m) is a term that describes the geometry of the electrode configuration being used (Reynolds, 1997). The apparent resistivity is defined as the resistivity of an electrically homogeneous and isotropic half – space that would yield the measured relationship between the applied current and the potential difference (Griffin, 1995). Variations in apparent resistivity or its reciprocal, apparent conductivity provide the raw material for interpretation in most electrical surveys (Milsom, 2003).

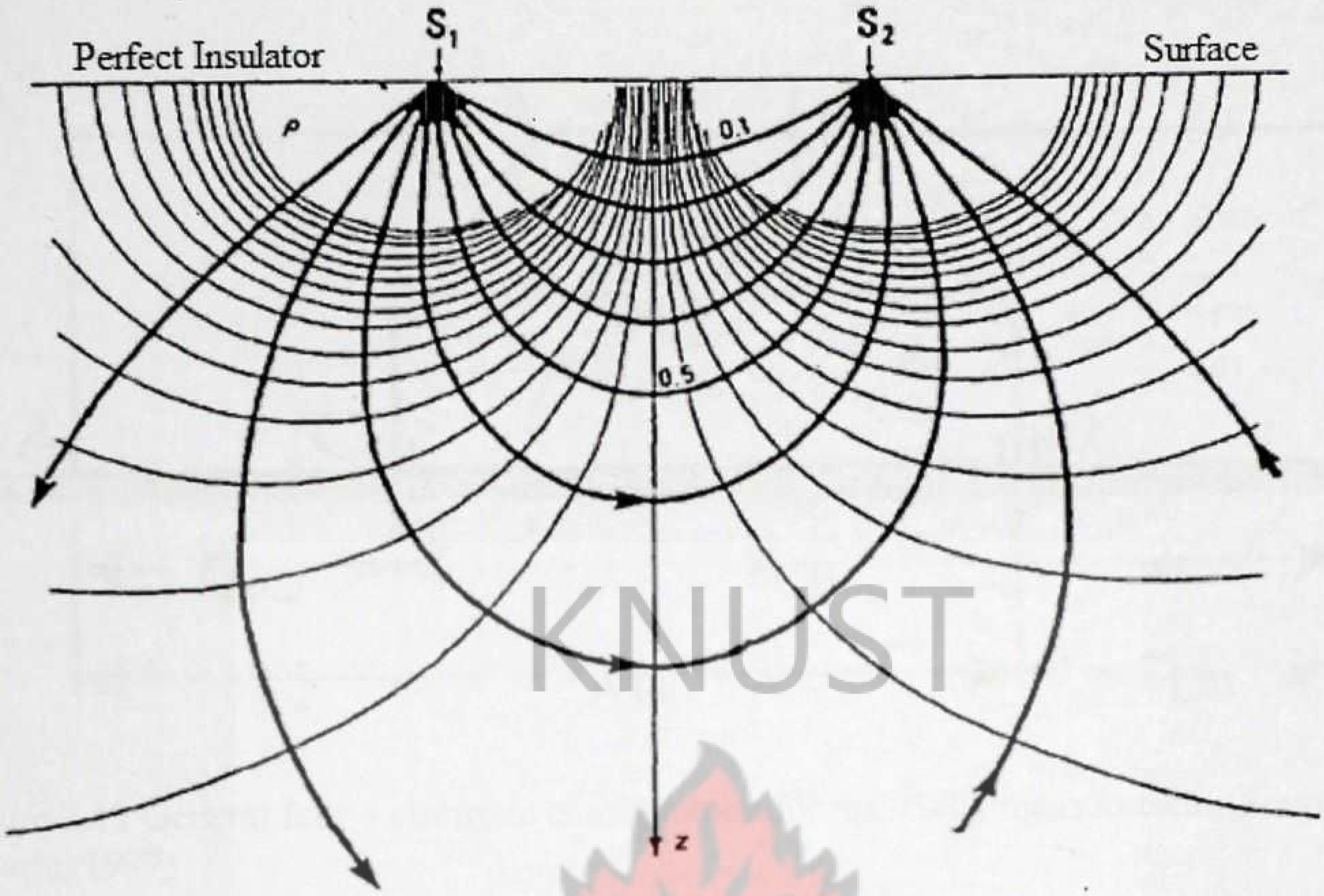

Figure 2.11 Current and equipotential lines produced by a current source and a sink (Source: Reynolds, 1997)

2.19 Theory of the Resistivity Method

In general, the resistivity methods commonly use four – electrode configuration as shown in Fig. 2.12. The configuration consists of a pair of current electrodes (e.g. A,B) and a pair of potential electrodes (e.g. C,D).The current electrodes A and B respectively act as source and sink.

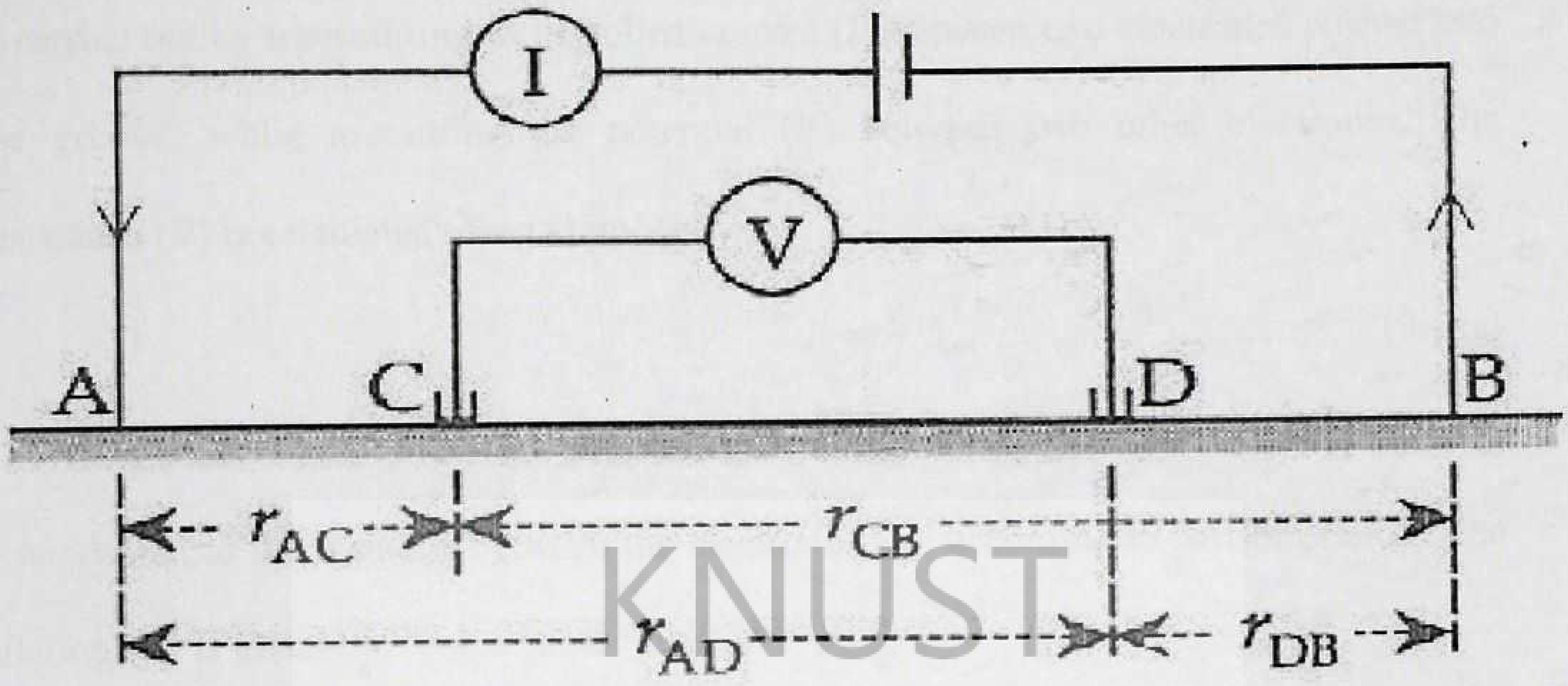

Figure 2.12 General four – electrode configuration for resistivity measurement (Source: Lowrie, 1997)

According to Lowrie (1997), at the detection electrode C the potential due to the source A is $+\rho I/(2\pi r_{AC})$, while the potential due to the sink B is $-\rho I/(2\pi r_{CB})$. The combined potential at C is

$$U_C = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) \quad \text{.............................. (2.18a)}$$

Similarly, the resultant potential at D is

$$U_D = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right) \quad \text{.............................. (2.18b)}$$

The potential difference measured by a voltmeter connected between C and D is

$$V = \frac{\rho I}{2\pi}\left[\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) - \left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right)\right] \quad \text{......................... (2.18c)}$$

All quantities in this equation can be measured at the ground surface except the resistivity, which is given by

$$\rho = 2\pi \frac{V}{I}\left[\frac{1}{\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) - \left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right)}\right] \quad \text{........................... (2.18d)}$$

According to ABEM Instrument AB (2005), measurement of the resistivity of the ground is carried out by transmitting a controlled current (I) between two electrodes pushed into the ground, while measuring the potential (V) between two other electrodes. The resistance (R) is calculated using Ohm`s law:

$$R = \frac{V}{I} \quad \text{......(2.18e)}$$

The resistance is also inversely proportional to the cross sectional area and directly proportional to the distance between the electrodes and according to Milsom (2003), the relationship is given by

$$R = \rho \frac{L}{A} \quad \text{......(2.18f)}$$

Where ρ is the true resistivity.The resistivity of the ground or apparent resistivity is related to the resistance via a geometrical factor as:

$$\rho_a = K \frac{V}{I} \quad \text{......(2.18g)}$$

Where the geometrical factor according to equation $(2.4.3d)$is given by:

$$K = 2\pi \left[\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}} \right) - \left(\frac{1}{r_{AD}} + \frac{1}{r_{DB}} \right) \right]^{-1} \quad \text{......(2.18h)}$$

In a homogeneous ground the apparent resistivity will equal the true resistivity, but will normally be a combination of all contributing strata. Thus, the geometrically corrected quantity is called apparent resistivity (ρ_a) (ABEM Instrument AB, 2005).

2.20 The Resistivity Method in Groundwater Prospecting

According to MacDonald *et al*., (2005), the resistivity technique is the longest – established geophysical method used to site wells and boreholes throughout the world. Highly resistive surface layers are obstacles only in DC surveys but they may actually be advantageous when EM methods are being used, because attenuation is reduced and depth of investigation is increased (Milsom, 2003).According to Kearey *et al*., (1997), the effective resistivity of a rock; that is, the resistivity of the rock and its pore water can also be expressed in terms of the resistivity and volume of the pore water present according to an empirical formula given by Archie (1942):

$$\rho = a\phi^{-b} f^{-c} \rho_w \qquad \text{.............................. (2.20a)}$$

Where ϕ is the porosity, f the fraction of pores containing water of resistivity ρ_w and a, b and c are empirical constants. ρ_w can vary considerably according to the quantities and conductivities of dissolved materials. Where $0.5 \leq a \leq 2.5$, $1.3 \leq b \leq 2.5$, and $c \approx 2$.Table 2.3 shows the electrical resistivity range for some typical natural waters. To carry out a depth sounding (VES), electrodes are expanded about a single point (MacDonald *et al*., 2005). There are various electrode configurations available for carrying out VES. Fig. 2.13 shows examples of different collinear electrode configuration in use: Wenner ($\propto, \beta, and\ \gamma$), Schlumberger, Dipole – dipole, and Pole –pole. The dipole – dipole array is one member of a family of arrays using dipoles (closely spaced electrode pairs) to measure the curvature of the potential field (Griffin, 1995).According to Griffin (1995), if the separation between both pairs of electrodes is the same a and the separation between the centres of the dipoles is restricted to $a\ (n+1)$, the apparent resistivity is given by

$$\rho_a = \pi\, a\, n(n+1)(n+2)\frac{V}{I} \qquad \text{........................... (2.20b)}$$

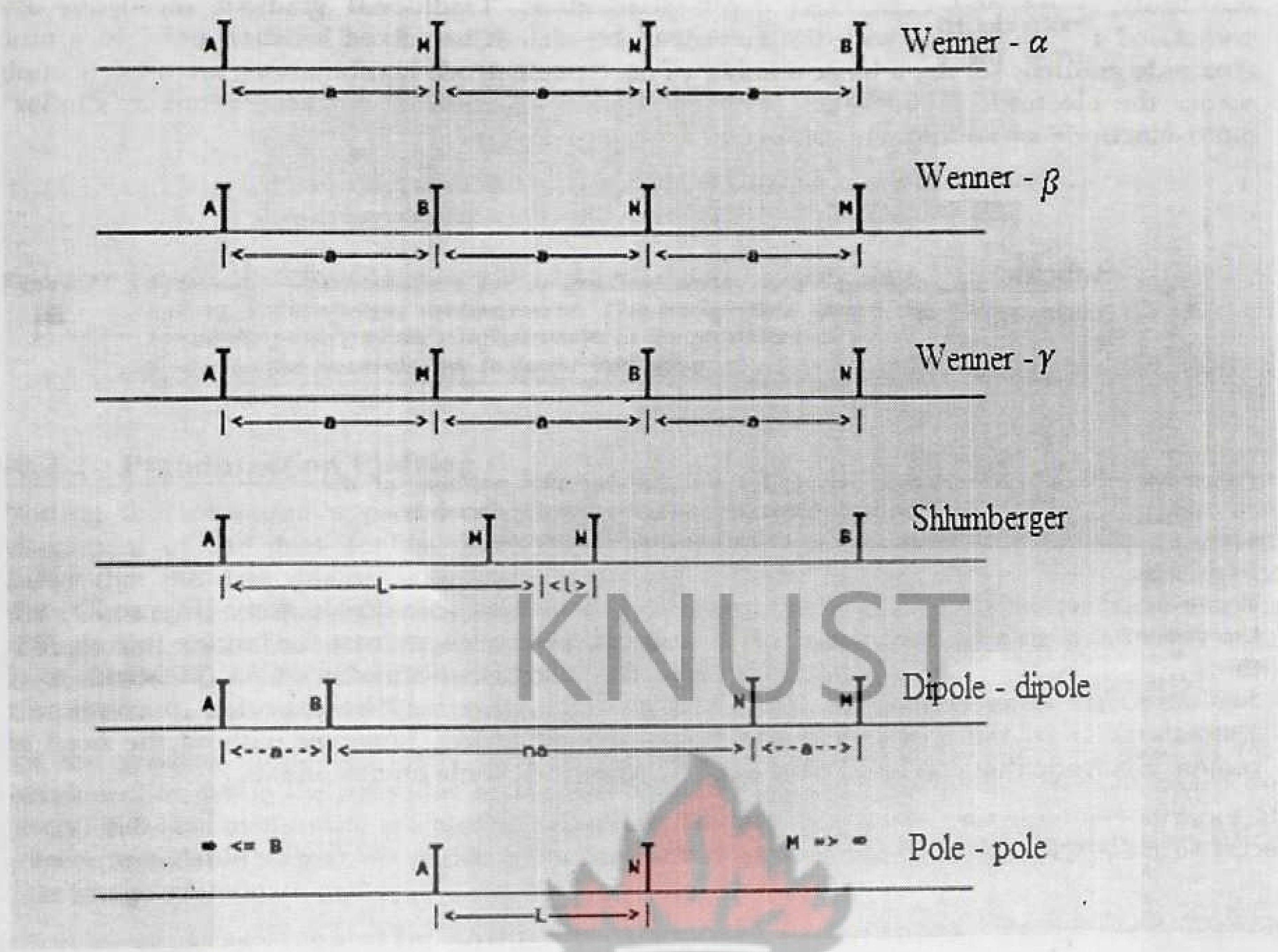

Figure 2.13 Examples of different electrode arrays (A and B represent current electrodes, M and N potential electrodes

(Source: ABEM Instrument AB, 2005).

Table: 2.3 Electrical resistivity of different types of natural waters

Type of water	Resistivity [Ωm]
Precipitation	30 - 1000
Surface water, in areas of igneous rock	30 - 500
Surface water, in areas of sedimentary rock	10 - 100
Groundwater, in areas of igneous rock	30 - 150
Groundwater, in areas of sedimentary rock	> 1
Sea water	≈ 0.2
Drinking water (max. salt content 0,25%)	> 1.8
Water for irrigation and stock watering (max. salt content 0,25%)	> 0.65

(Source: ABEM Instrument AB, 2005)

2.21 The Project Area

The study area – Bawku West District – is one of the 9 municipalities/districts in the Upper East Region (UER) of Ghana with Zebilla as the district capital. According to the Bawku West District Assembly (BWDA) in 2005, it is the fifth biggest district of the Upper East Region in terms of land area. According to Anayah and Kaluarachchi (2009), the Ghana Statistical Service (2000) reported that the UER has the largest proportion of poverty across the country and the mean annual household income is U.S $1,000, which is the second lowest, and Bawku West District is of no exception.

The Bawku-West District is a sparsely populated rural district with underdeveloped infrastructure and services. The Ministry of Local Government, Rural Development and Environment (MLGRDE) in 2008 stated that apart from Zebilla, with a population of 10, 000 inhabitants, all the other areas have less than 10,000 people. Indeed, this situation is partly due to lack of basic social facilities that prevent people from settling in these areas. The district has an estimated population of about 87,978 and an annual growth rate of 1.1% with 114 communities. The district has a surface area of about 1,070 sq km, i.e. 12% of the total land area of the region (MLGRDE, 2008). The predominant ethnic groups are Busangas, Frafras, Kusasis, Mamprusi, Kusaal and Moshies. However, other settlers such as Fulani and transferred government employees from all the regions of the country live in the District (Abotzabire, 2008). From the ethnic perspective, 61.6% are Kusasis and form the main ethnic group of the area (MLGRDE, 2008).Potable water supply in the district is a great challenge as the population lives with highly variable rainfall pattern and experiences drought during the long harmattan season. However, with support from Non – Governmental Organizations (NGO`s) such as World Vision International (WVI), Adventist Development Relief Agency (ADRA) and others, there has been tremendous improvement in groundwater development in the district to access to potable water through the provision of boreholes; but much still needs to be done to meet the recent demands of the inhabitants.

2.22 Location and Accessibility

The Bawku West District (BWDA) lies in the northeast of Upper East Region, Ghana and lies roughly between latitudes 10^0 30' N and 11^0 10' N, and longitudes 0^0 20' E and 0^0 35' E. The district shares common boundaries with the Republic of Burkina Faso in the North, East Mamprusi District in the South, Bawku Municipality and Garu Tempane District in the East and Talensi – Nabdam District in the West. In Fig. 2.14 is the location map of the Bawku West District.

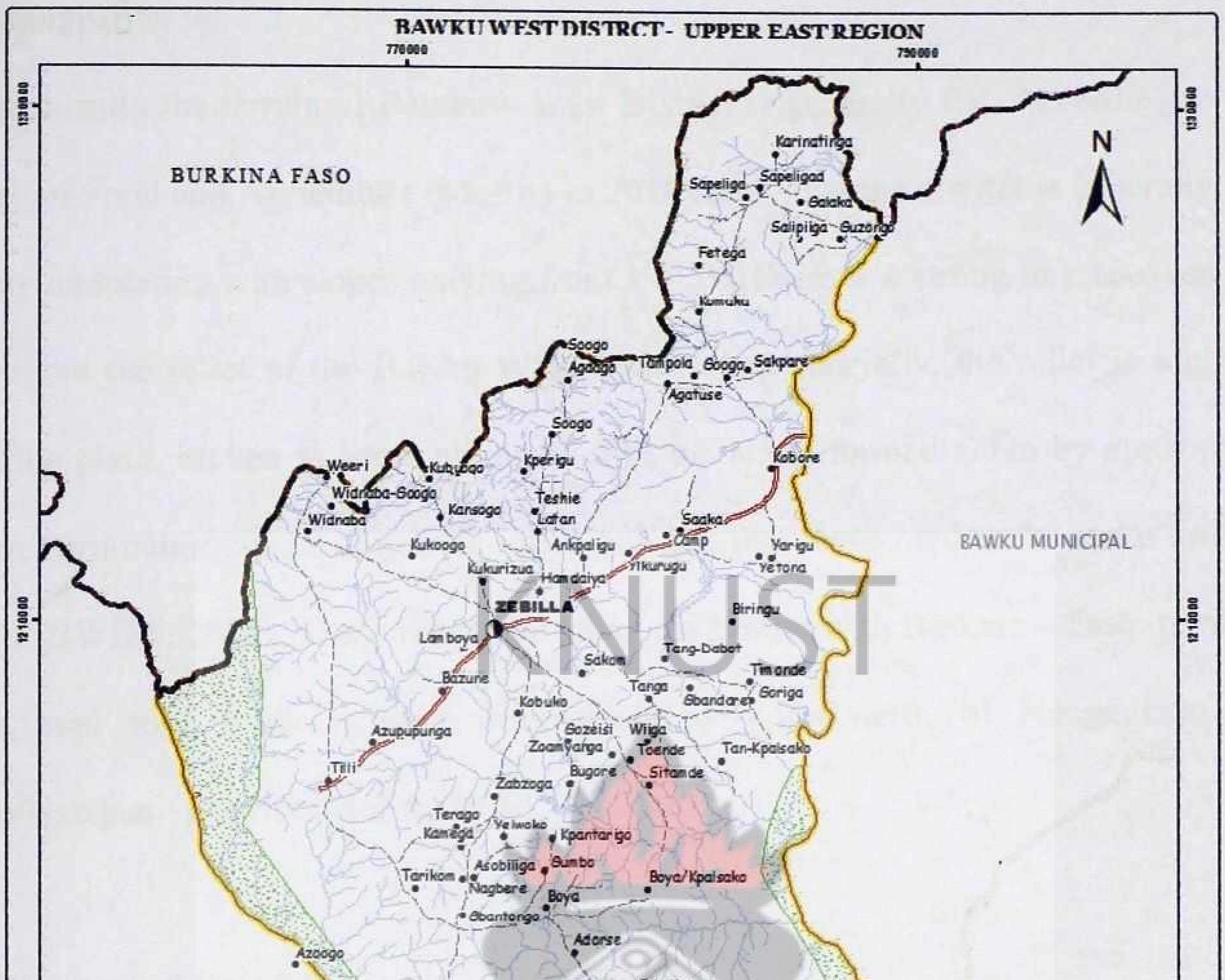

Figure 2.14 Location map of the Bawku West District

(Source: Centre for Remote Sensing and Geographic Information System – Ghana).

2.23 Topography

Topographically the terrain of Bawku – West District is generally flat. According to the Ministry of Food and Agriculture (MoFA) in 2010 stated that the district is generally flat to gently undulating with slopes ranging from 1 – 5%.There is a strong link between the geology and the relief of the Bawku West District and generally, the relief is a gentle undulating plain, broken in some places by hills or ranges formed either by outcrops of resistant Birimian rocks or of granite intrusions and that these hard rocks make drilling difficult (BWDA, 2005). These ranges lie along the border with Burkina – Faso, north of Zebilla, and turn south – west from the Red Volta north of Nangodi in the Talensi/Nabdam District (MoFA, 2010).

2.24 Climate and Rainfall

The climate of the Bawku West District is characterised by prolonged dry season between the months of November and April; and a single rainy season between the months of May and October annually. The dry season is accompanied by dry and dusty harmattan air mass and severe water shortages. Most rivers and springs dry up toward the end of the dry season making water a scarce commodity (MoFA, 2010). During such periods the people in the district depend on groundwater obtained from hand dug wells and boreholes. The rainy season is accompanied by warm, humid and wet monsoon air mass. The harmattan air-mass, which blows from the northeasterly direction across this area has been noted to originate from the Sahara, reaching its maximum southward extent in January; and that the Monsoon air mass, which blows from South to North passes over the area, reaching its maximum northward extent in August and September each year.

The mean annual rainfall varies from 900 mm to 1,150 mm and the annual potential evapotranspiration amounts to 2882 mm (BWDA, 2005 and MoFA, 2010). The temperatures in the district, during the dry season are usually very high. Available records indicate that mean monthly temperatures vary from 26 degrees Celsius in August to 32 degree Celsius in March (BWDA, 2005).

2.25 Vegetation and Soils

The Bawku West District is located in the Sudan and Guinea Savanna vegetative zones of Ghana and it is characterised by drought and fire resistant deciduous trees including Baobab, Sheanut and Ebony which are interspersed with open savanna grass land. Common grasses include '*Andropogan gayanus*' (Northern Gamber Grass) in the less eroded areas and *Hyparhenia spp*, *Aristida spp*, and *Heteropogan spp* (Spear glass) in the severely eroded areas (MoFA, 2010). It is noticed that parts of the natural tree vegetation is disappearing due mainly to human activities in the form of cultivation, construction, grazing, bush fires and charcoal burning (BWDA, 2005). The area`s main vegetation consists of the protected forest reserves along the White and Red Volta Rivers where onchocercias is precludes human settlement, but recent efforts at tree planting are yielding positive results as some degraded areas are being recovered, especially in the Googo community (MLGRDE, 2008).

The major soils mapped in the district belong to Luvisols, Lixisols, Leptosols, Gleysols and Fluvisols and other less extensive soils include Plinthosols, Regosols, Vertisols and Cambisols (MoFA, 2010). The soils here have been generally developed over the granitic rocks and over basic rocks mostly of the Birimian, Tanchera series, Kolingu series and the Mogo constitution (BWDA, 2005). Since these parent materials are coarse-textured, many of the soils have predominantly light textured surface horizons (sandy) with heavier textured soils (clayey) confined to valley bottoms; and there are also extensive areas of shallow concretionary and rocky soils, which have low water holding capacities and limited suitability for agriculture (MoFA, 2010).

2.26 Drainage Pattern

The Bawku-West District is drained mainly by the White and Red Volta and their tributaries, as far as drainage is concerned. The two major rivers (White Volta and the Red Volta) influence the drainage system, and run contiguous to the district`s eastern and western boundaries respectively to form tributaries of the main Volta River. The rivers over-flow their banks during the rainy season from July to October. During the dry season, the sand bars make it possible for people to cross the White Volta on foot or by motor cycles as observed at the Ghana – Burkina – Faso border at Sapelliga (MoFA, 2010).

2.27 Geology and Hydrogeology

The Bawku West District is underlain mainly by Birimian and Granitic geological formations belonging to the basement complex (comprising of Precambrian crystalline igneous and metamorphic rocks), which is one of the two main hydro - geological formations in Ghana. A map showing the geological setting of Ghana is presented in Fig 2.15.In Fig. 2.16 is a map showing the geological setting of the Bawku West District. The Basement Complex is subdivided into Birimian, granite, Dahomeyan, Togo and

Tarkwaian rock consisting mainly of gneiss, phyllites, schists, migmatites, granite – gneiss and quartzites (Kesse, 1985). The rocks of the basement complex have little or no primary porosity and therefore, groundwater occurrence in it is associated with the development of secondary porosity as a result of jointing, shearing, fracturing and weathering (Kortatsi, 1994). The Birimian rocks, often associated with granites, consist of steeply-dipping metamorphosed sediments and volcanic intrusions. The argillaceous rocks of the Birimian formation consist, among others, of phyllites, biotite, schists and quartzites, some of which are found north of Zebilla, South of Sapelliga and around Zongoyiri area and the volcanic group consists of greenstones, hornblende schists and phyllites (MoFA, 2010). According to Kesse (1985), the granitic rocks consist mainly of biotite and hornblende complex with potassium and sodium feldspars dominant in the biotite granite and biotite respectively, and that these granites are coloured pink, coarse grained and potassium rich. According to Kortatsi (1994), this has given rise to two main types of aquifers; the weathered zone aquifer and the fractured zone aquifers. Both types of aquifer are normally discontinuous and limited in extent. Due to the sandy-clay nature of the weathered overburden, the groundwater occurs mostly under semi-confined or leaky conditions (Kortatsi, 1994).A map showing the Geohydrological provinces of Ghana is presented in Fig.2.17.

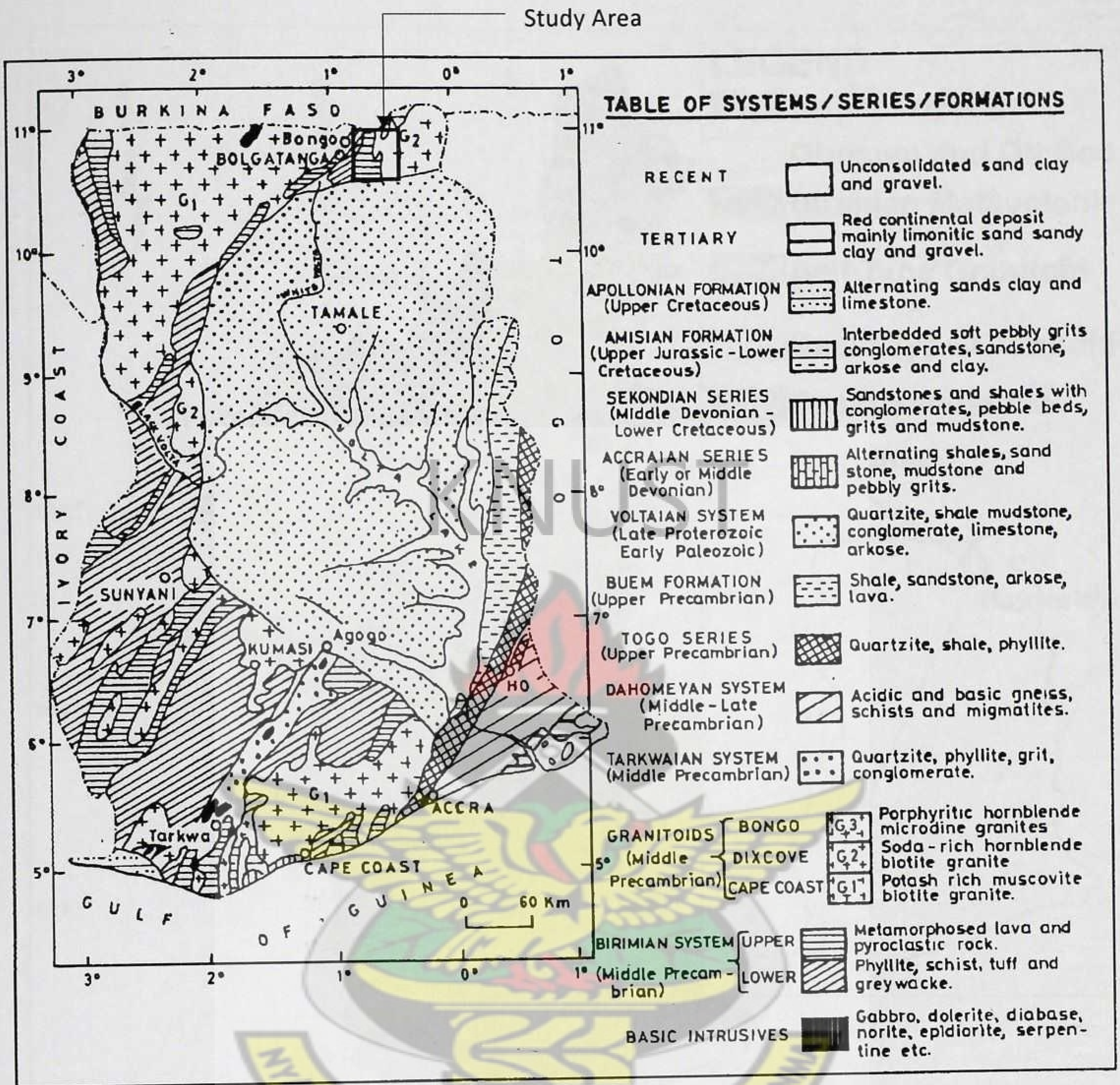

Figure 2.15 General Geological map of Ghana showing the study area (arrowed)

(Source: Kesse, 1985).

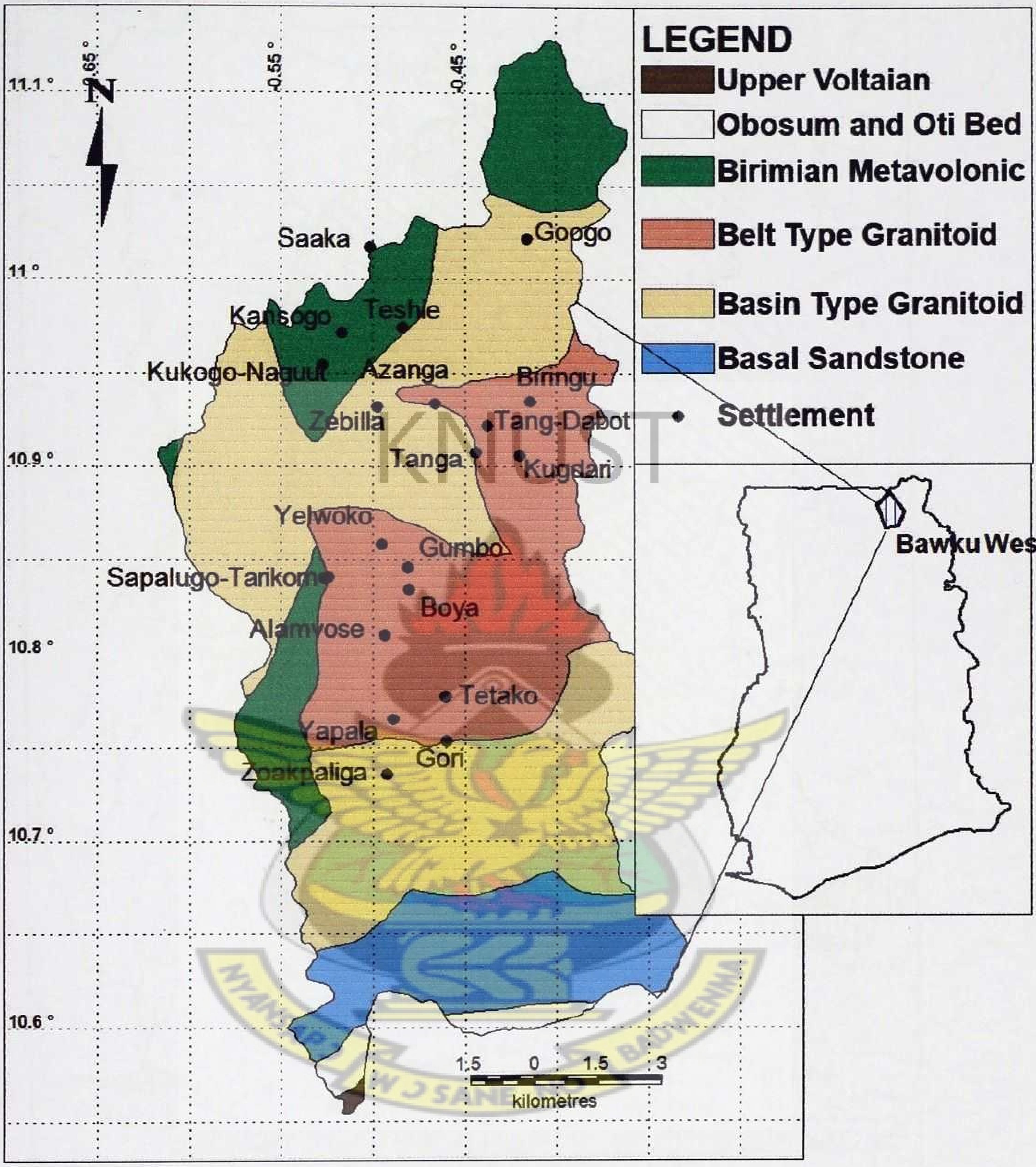

Figure 2.16 Geology of the Bawku West District of the Upper East Region of Ghana.

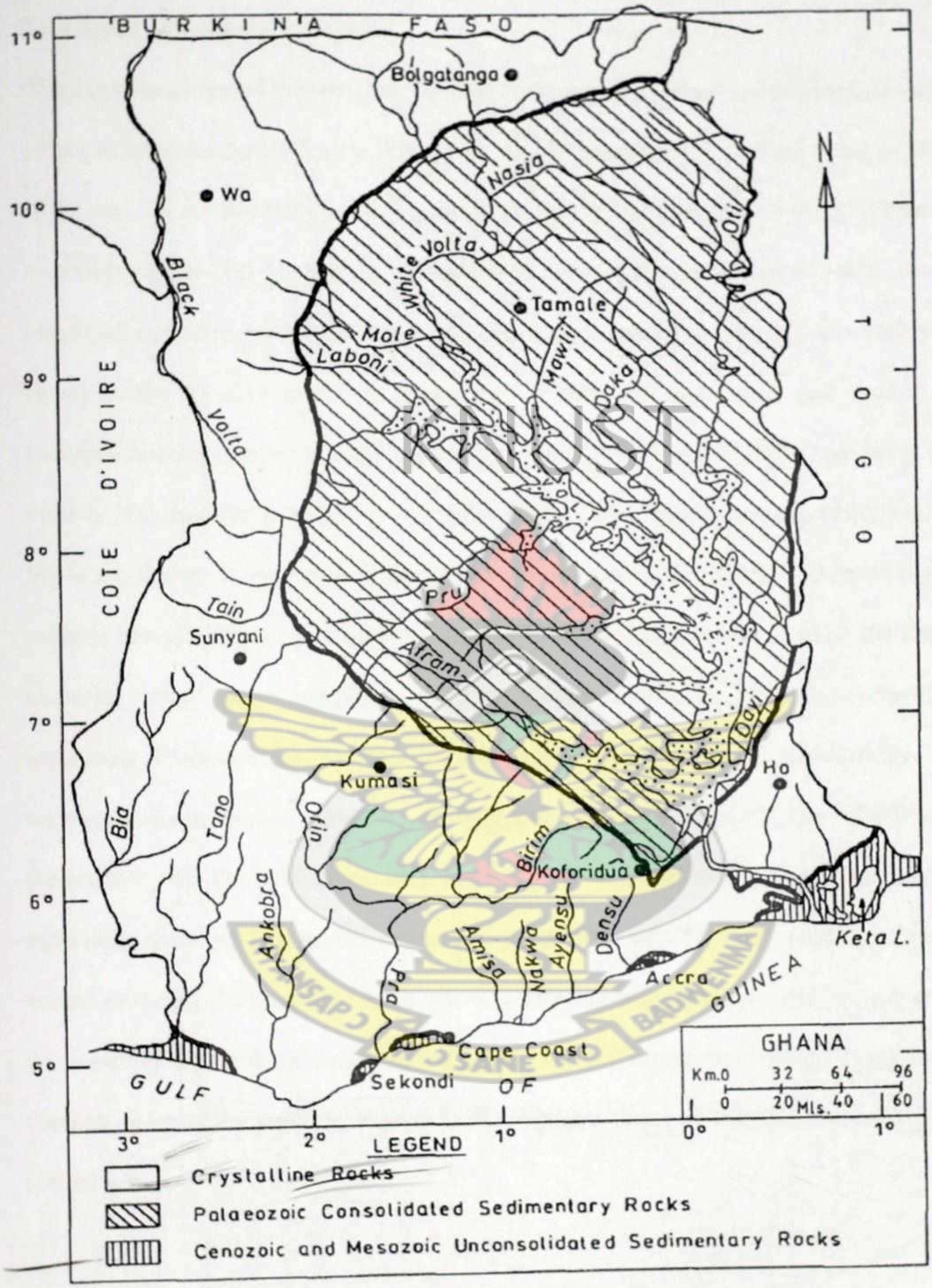

Figure 2.17 Geohydrological provinces of Ghana (Source: Kortatsi, 1994).

2.28 Socio – Economic Activities

The economic base of Bawku-West District hinges on Agriculture with about 80 percent of the inhabitants depending on it for their income generation. The food crops produced in the area are mainly millet, maize, rice, groundnut, soya beans and sorghum. The major vegetables grown by the farmers in the district include pepper, tomatoes, okro, carrots, watermelon, onions and garden eggs. Dawadawa and Sheanut are the only two cash crops found in the district. Moreover, agriculture is generally associated with fishing and livestock farming; however, these activities are conducted in a traditional manner and are more or less dependent on the rainfall (MLGRDE, 2008). Sheep, goats, cattle and guinea fowls are the main livestock raised by the inhabitants in the district. There is lack of modern manufacturing industries in Bawku-West District, but as in most developing countries, small scale industrial activities mainly sheabutter extraction, dawadawa processing, blacksmithing, motorcycles and vehicles repairs, pottery, rice husking, pito brewing, weaving and dressmaking, milling and groundnut oil production dominate in the economy of the district. Indeed there is high level of unemployment in the District, especially amongst the youth. According to BWDA (2005), the situation is further worsened during the long dry season when no farming activity takes place, except in few communities where there are small-scale dams for dry season gardening. This situation compels most of the youth to migrate to the southern sector of the country to search for menial jobs.

2.29 Previous Groundwater Exploration Projects in the District

According to 2008 household surveys report cited by MLGRDE (2008), there were 123 boreholes that existed in the Bawku West District as at 2008. Drilling of boreholes in the district began far back in the 1960s by the Community Water Project (COWAP) with the main aim of providing potable water supply to the various communities in the district. However, the few holes which were drilled did not show good results, resulting in the reduction of groundwater prospecting in the area, often based on the lack of experience, expertise and improper groundwater exploratory techniques. The drilling of boreholes in the area was later taken over by the Community Water and Sanitation Agency (CWSA) which is in charge of the water/sanitation sector in rural and urban areas. Since its inception in 1998 the CWSA has taken charge of water management and assisting the District Assembly to establish the District Water and Sanitation Teams (DWST). In addition to this role, the District Assembly selects the final users, identifies the locations for the water points and approves water price as they contribute up to 5% of the cost of the facilities (MLGRDE, 2008).As a result of the experiences gained from previous drillings, an increase trend of groundwater prospecting began within the last two decades when several NGOs, such as World Vision International, Water Aid, Church of Christ, European Union (EU) and United Nations Children's Fund (UNICEF) shifted their attention to providing potable water to the poor and most vulnerable communities in Ghana in general and in the Northern Ghana in general (Dochartaigh *et al*., 2011). These NGOs have been successfully siting boreholes by using techniques ranging from the traditional terrain evaluation method to geophysical survey methods in the complex crystalline formation in the Upper East Region. However, due to the complex nature of the geology, the drilling success rates are still low with some of the already existing boreholes drying up. Previous groundwater development in the Bawku-West District indicated that the yield of bore holes in areas within the White Volta Basin underlain by Birimian geological formations ranges from 0.0069 to 0.184 m^3/h with a mean of 0.014 m^3/h and the mean depth to aquifer is 15.3 m, with values ranging from 0.003 to 29.26 m (MoFA, 2010). According to MoFA (2010), in areas underlain by granites, the yield of boreholes range between 0.46 and 16.2 m^3/h with a mean of 2.26 m^3/h and the depth to aquifer ranges from 0 – 31.7 m with mean of 15.49 m.

CHAPTER 3

INSTRUMENTATION AND FIELD PROCEDURE

3.1 Instrumentation

The EM receiver and transmitter coils can be configured in many different ways, depending on the objectives of the survey (Hitzig *et al.*, 1997). The most common instruments for measurement of terrain conductivity are the Geonics EM31 and the EM34-3 (NGA, 2011a). Geonics EM34-3 will be discussed since it is the instrument used in this study. There are various resistivity meters used for VES investigation. However, the McOHM – EL resistivity meter will be discussed since it is the resistivity instrument used for the VES investigation in this exploration project.

3.2 Description of the Geonics EM 34-3 Equipment

The EM34-3, manufactured by Geonics, Ltd. is a frequency domain electromagnetic system and consists of a transmitting console, a receiving console, two coils, one transmitter coil and a receiver coil with three different inter-coil separation cables of 10 m, 20 m and 40 m lengths. The EM34-3 instrument used by WVI – GRWP is as shown in Fig.3.1. It has a transmitter coil with a diameter of about 98 cm and a receiver coil with a diameter of about 60 cm. The EM34-3 operates with three transmitter-receiver coil separations: 10, 20, or 40 meters (NGA, 2011a). The more powerful, two-person, Geonics EM-34-3 uses frequencies of 0.4, 1.6 and 6.4 kHz with intercoil spacings of 40, 20 and 10 m respectively (Milsom, 2003). EM34-3 is a two – man portable equipment with step wise selectable depths from 7.5 metres to a maximum of 60 metres (McNeil, 1998). Table 3.1 shows the depths of exploration using EM34-3 at various intercoil spacing. The two – man portable means that the instrument requires two operators.

This instrument does not require any ground contact or surface disturbance; therefore, they are rapid, relatively inexpensive, and can be run with little or no exposure to buried toxic materials (NGA, 2011b).

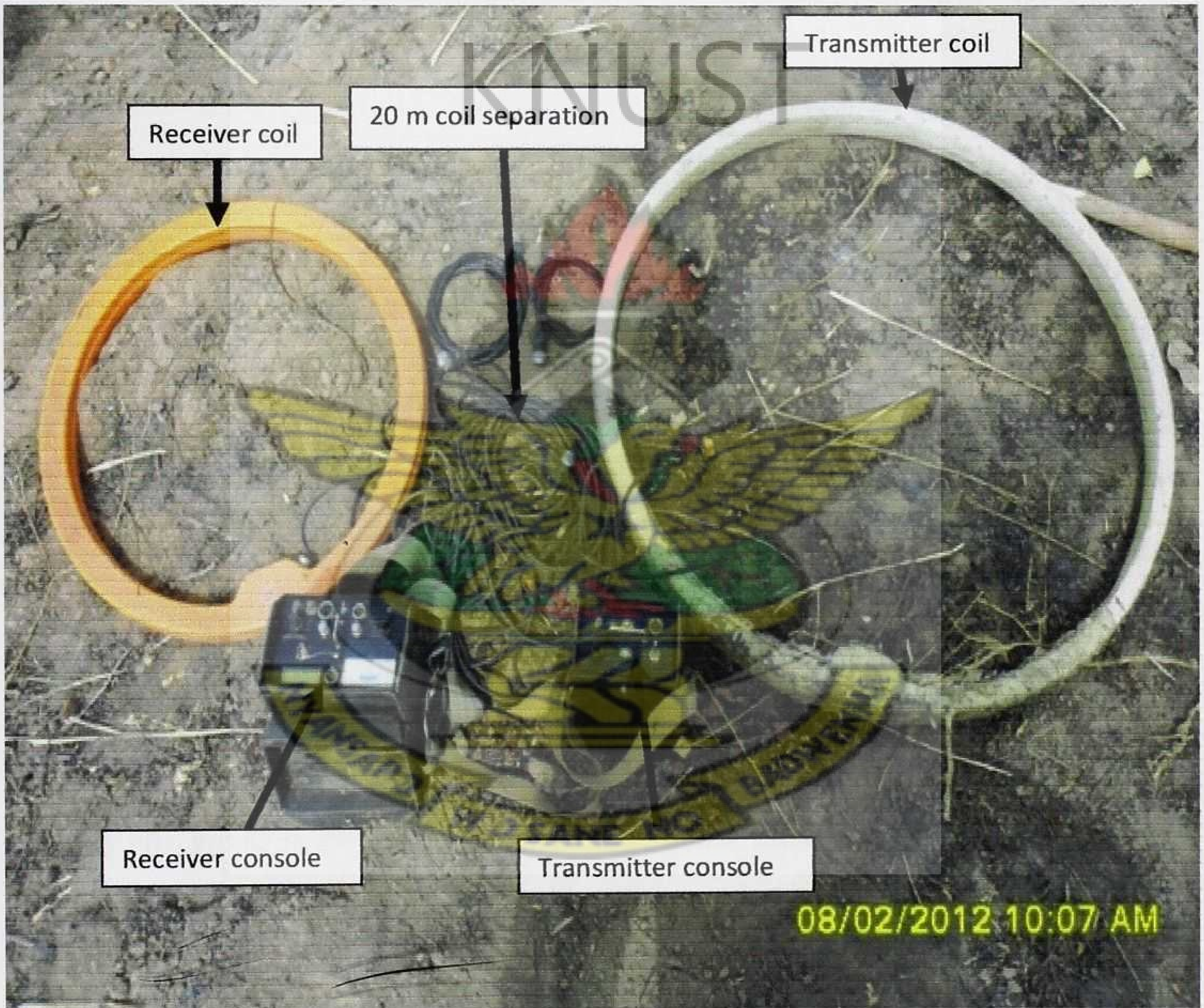

Figure 3.1Geonics EM 34-3 Equipment at WVI– GRWP.

Table 3.1 Exploration Depths for EM34-3 at Various Intercoil Spacings

Intercoil Spacing (metres)	Exploration Depth (metres)	
	Horizontal Dipoles (HD)	Vertical Dipoles (VD)
10	7.5	15
20	15	30
40	30	60

(Source: McNeil, 1980)

3.3 Principle of Operation of the EM 34-3 Equipment

Tsikudo (2009) cited Sharma (1997) that the operational range of the instrument is 1-1000 mS/m. For either the EM 31 or EM 34-3 it can be shown that in a homogeneous or horizontally – stratified earth the current flow is entirely horizontal. Furthermore, under the constraints by which the instruments are designed the current flow at any point in the ground is independent of the current flow at any other point since the magnetic coupling between all current loops is negligible. Finally, under these constraints the depth of penetration is limited only by the intercoil spacing. We say that the depth of penetration is ''source'' or ''geometry'' – limited rather than ''skin depth'' – limited since it is now controlled by the fall – off with distance of the dipolar transmitter field (McNeil, 1980).

3.4 Description of the McOHM - EL Resistivity Meter

The McOHM – EL (with Power Booster Controller attached) is the instrument accomplished upon incorporating the functions of the geophysical logging device into the electric prospecting device of digital stacking type, thus being suited for the wide applications. Thus the measurement function required for the electric prospecting from the ground surface and those required for the geophysical exploration to perform the geophysical logging by using the borehole are intensively embodied by a unit of this instrument (Oyo, 2001)

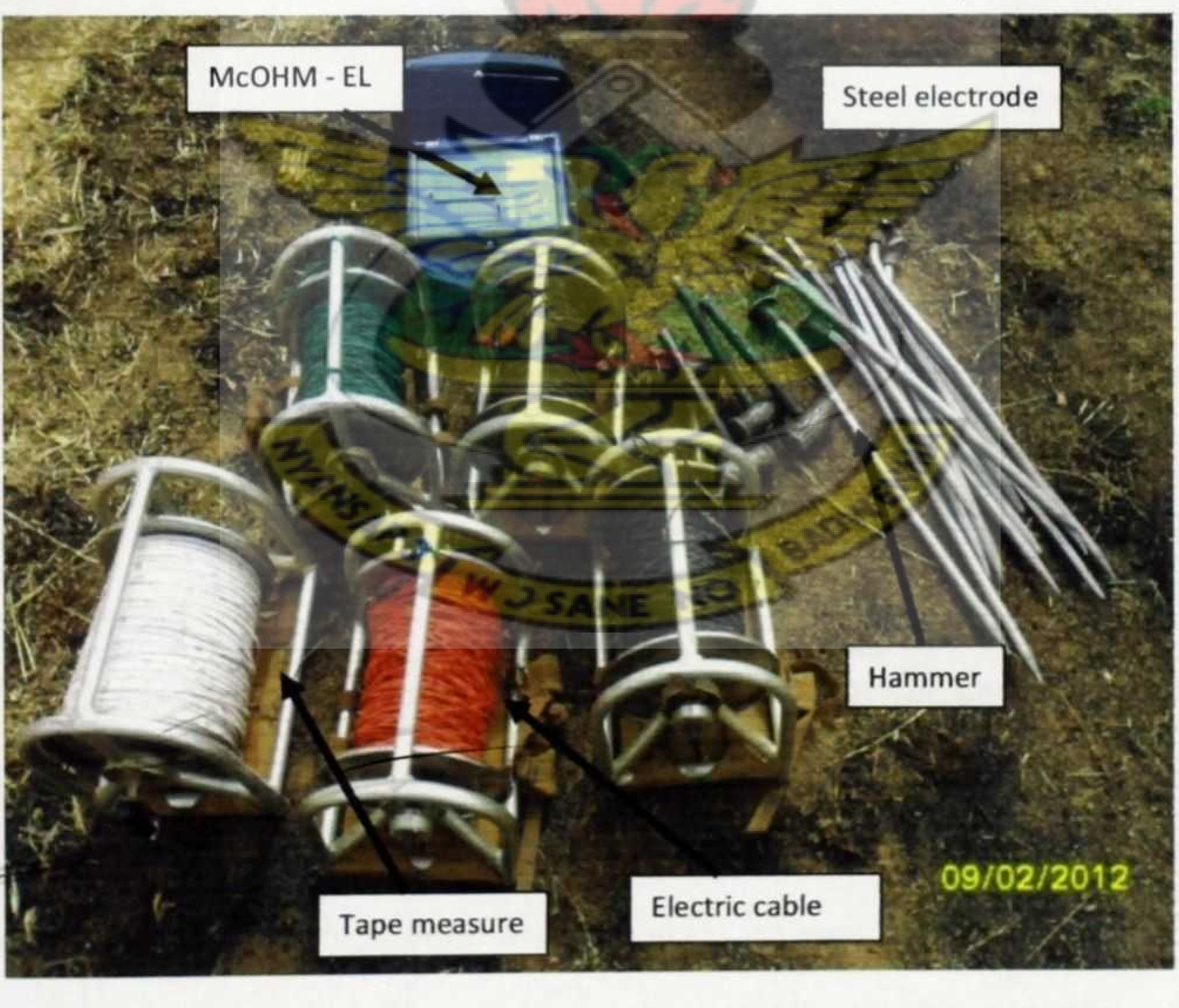

Figure 3.2 Resistivity equipment at WVI– GRWP.

3.5 Principle of Operation of the McOHM – EL Resistivity Meter (Oyo, 2001)

- Mere unit of this instrument is applicable for both electric prospecting and geophysical loggings (covering the normal electric logging, the temperature logging, and the caliper logging).
- With the electric conduction circuit of large capacity built in this instrument, the maximum electric conduction of 120 mA (400 V) is the level attainable by this instrument.
- Furthermore, using the Power Booster makes it feasible to conduct the current up to the maximum level of 800 mA (100 V).
- By adopting the 24 – bit Analog-to-digital (A/D) converter of sigma-delta ($\Delta\Sigma$) type, this instrument is feasible to detect the electric potential with the resolution of $1\,\mu V$.

3.6 Equipment Handling and Operation

To measure terrain conductivity the transmitter operator stops at the measurement station; the receiver operator moves the receiver coil backwards or forwards until his meter indicates correct intercoil spacing and he reads the terrain conductivity from a second meter (McNeil, 1980). According to McNeil (1980), the procedure takes 10 to 20 seconds. The EM-34-3 is calibrated to read apparent conductivity directly in mSm^{-1} (Milsom, 2003). Since, at some points in some communities, the electrodes were not able to be implanted in the ground as a result of exposed hard laterites rocks and the measurement needed to be stopped. Also, sometimes the meter registered current errors in some of the communities. This problem was overcome by checking connections of the electrodes. The EM survey profile lengths were also limited by structures such as electric cables, grave yards, buildings etc.

3.7 Field Procedure

The integrated geophysical exploration was conducted during the dry season period when the aquifers are not able to change significantly. The steps involved in this exploratory project were desk study, field reconnaissance survey, terrain evaluation and geophysical measurement.

3.8 Desk Study

During the desk study the existing hydrogeological and water resources information in and around the beneficiary communities were assessed. The main purpose of this was to establish the current knowledge about lineament patterns and fractures, the presence of suitable aquifers and their approximate thickness, groundwater quality, and water table depths and the expected lithological sequences in the area

3.9 Field Reconnaissance Survey

Fieldwork reconnaissance survey of the beneficiary communities was carried out by assessing topography, structural features, geological history as well as taking into consideration social, logistical and accessibility to locate target areas for geophysical surveys. Setting out traverse lines in the selected target areas was part the reconnaissance survey. Two surveys roughly at right angles extending outside the village often provide the best information and if reconnaissance has indicated a prevailing direction for fractures in the area, then the main survey lines should run perpendicular to this direction – this will maximize the chance of finding a fracture with the survey (MacDonald *et al*., 2005). According to MacDonald *et al*., (2005), generally a 20 m coil separation is most useful for reconnaissance.

3.10 Terrain Evaluation

Terrain evaluation precedes all geophysical surveys and involves the terrain surface assessment with the objective of identifying a noticeable feature such as mango trees, baobab trees, and fig trees which serve as subsurface water indicators. It also involves walking round the area where the survey is to be carried out and trying to locate good survey lines by bearing in mind where the community may want the borehole sited and where field geological information such as rock exposure, existing wells, stream patterns, slope of the terrain and exposed fractures are. The terrain evaluation also involves identifying an area free from significant influences such as power lines or metal roofs, cemeteries, rubbish dumps and toilets for the EM survey to be carried out.

3.11 Geophysical Measurement

The main field data acquisition, involving the electromagnetic (EM) terrain conductivity and vertical electrical sounding (VES) data acquisition were executed with Geonics EM 34-3 and McOHM - EL meter measurement respectively. The terrain conductivity data was carried out using the Geonics EM 34-3 operating at a low frequency of 1.6 Hz which corresponds to the 20 m coil separation. This low frequency signal helps to maintain a low induction number (McNeil, 1980).The McOHM – EL meter has resistivity measurement range between 0 and 10 kΩm.

3.12 Data Collection

To begin with the EM survey data collection, the Geonics EM34-3 was set up at each community and daily checks on the equipment, such as battery checks and nulling were carried out. Starting from noticeable features such as a large mango tree or baobab tree, the coils of the EM 34-3 instrument were set at 20 m spacing for all the profiles and held at the same position firstly in the vertical plane or horizontal dipole (HD) and secondly in a horizontal plane or vertical dipole (VD) with the receiver always trailing the transmitter. This helps to avoid confusion over distances. This allowed a maximum depth of 30 m deep to be explored. The readings were made every 10 m station interval with the transmitting coil start at zero mark for each traverse. Fig. 3.3 and 3.4 show an electromagnetic survey that was carried out at Sakpare – Googo community using the Geonics EM 34-3 arranged in the HD and VD modes. Potential groundwater sites were identified and further VES investigation done at those selected points. The VES data was acquired for 70 m depth of investigation at each EM selected point with direct current electrical resistivity equipment comprising McOHM – EL.

The VES method involved deploying a length of wire on the ground with twelve (12) steel electrodes in the dipole – dipole array configuration. Each electrode pair were positioned at the same time, 6 m and 10 m, 10 m and 14 m, 14 m and 18 m, 15 m and 25 m, 20 m and 30 m , 25 m and 35 m, 30 m and 40 m, 35 m and 45 m, 40 m and 50 m, 40 m and 60 m, 50 m and 70 m, 60 m and 80 m which corresponded to depths of 8 m, 12 m, 16 m, 20 m, 25 m, 30 m, 35 m, 40 m, 45 m, 50 m, 60 m and 70 m investigations respectively. At each electrode position, direct electric current output of magnitude 20 or 60 mA was injected into the ground through one pair of the steel electrode (current electrode) using a 12 V accumulator supply and the resistivity values of each VES site were read directly from the McOHM – EL meter after each four stack and then these values multiplied by the geometrical constant to obtain the apparent resistivity. The VES data for each community with the multiplication factors were presented as in appendix 2.Eleven (11) successful soundings were done on twenty (20)terrain conductivity anomalous points detected by the electromagnetic profiling method during the survey along the profile lines.

Figure 3.3 Using Geonics EM34-3 Equipment to measure ground conductivity in the horizontal dipole mode.

Figure 3.4 Using Geonics EM34-3 Electromagnetic Equipment to measure ground conductivity in the vertical dipole (VD) mode.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results obtained from the electromagnetic survey for 20 communities namely, Biringu Primary School, Sakpare – Tang Dabot, Tanga CHPS Centre, Gori – Kumzeogo, Tetako Primary School, Alamvose, Gumbo, Yelwoko – Azambare, Teshie Community – based Health Planning and Service (CHPS) Centre, Azanga Primary School, Tarikom – Kuug, Sapalugo, Kansogo – Aningbligu, Ananoore – Saaka, Kukogo – Naguut, Gumbare – Yapala, Zoakpaliga, Boya Primary School, Kugdari and Sakpare – Googo in the Bawku -West District of the Upper East Region are presented, analysed and discussed under this section. In Fig. is the map of Bawku-West District.

The electromagnetic survey helped in the identification of the expected weathered or the fractured zones of the project area which are the potential areas for groundwater accumulation. Eleven (11) VES were successfully conducted at the twenty (20) identified points obtained from the electromagnetic survey and the results presented in Fig.4.4a up to Fig.4.34c. The VES was helpful in the identification of zones of low resistivity with depth. The results of the lithological section of each drill sites are also presented in this section.

4.2 Bases for Interpretation

The terrain conductivity of the surveyed communities were read from the meter on the receiver console of the Geonics EM 34-3 instrument and presented in appendix 1. The results obtained during the electromagnetic survey were plotted against distance for interpretation. Anomalous points on the EM profiles were selected for further investigation using VES methodology. From the VES field data, the apparent resistivity was calculated by multiplying the resistance value read from the McOHM - EL resistivity meter and the geometrical (multiplication) factor and presented in appendix 2. The apparent resistivity values were then plotted against the depth/electrode spacing into curves on log – log graph for interpretation. These apparent resistivity curves were roughly of U – shaped. If the U – shape is broad, and the tail does not rise steeply, then it may indicate deeper weathering (or a more conductive weathered zone). If the tail rises very steeply (up to 45°) there is likely to be little or no weathering (MacDonald et al., 2005). According to Sabet (1975) among the advantages of the log – log plots are:

- It emphasizes near – surface resistivity variations and suppresses variations at greater depths. This is important because interpretation of the results depend largely on the small variations in resistivity occurring at shallow depths.
- If at two different sites the resistivities of the underlying layers (or their thicknesses) increase or diminish by the same constant multiple, the two resistivity curves would look alike, although they may be shifted horizontally or vertically relative to one another.
- The basement complex or the presence of a non-conducting basement is readily determined on the log ~~– log plot~~ by a 45° sloping straight line.

4.3 Interpretation of Data

Electromagnetic data can be analysed in a number of ways, according to the manner in which they have been acquired. The measured parameters may be plotted as profiles or gridded and contoured on which anomalous zones can be identified (Reynolds, 1997).These approaches tend to be qualitative and first – order interpretation. The quantitative interpretation of electromagnetic anomalies is complex (Kearey *et al*., 2002). Hence, the terrain conductivity curves for the HD and VD modes obtained from the graph of terrain conductivity against distance were interpreted qualitatively for each profile to identify the expected weathered or the fault zones of the study area for further VES investigation.

The vertical sounding field curves can be interpreted qualitatively using simple curve shapes, semi – quantitatively with graphical model curves, or quantitatively with computer modelling (Reynolds, 1997). Hence, the interpretation of the VES curve at each site identified from the electromagnetic survey was carried out qualitatively by identifying low resistivity anomaly zones with depth. For basement areas, the main target is the low resistivity weathered zone and High resistivity in the shallow soil layers (mainly due to lack of water in the soil), lower resistivity at moderate depths, corresponding to the weathered zone and higher resistivity at depth, where the basement is unweathered (MacDonald *et al*., 2005). Common resistivity curves and their interpretation in crystalline basement areas are presented in Fig. 4.1.According to Anthony (2006),in hard rock environment, which is considered very resistant to the flow of electric current, a low resistivity anomaly will be the target for groundwater and in a clayey or salty environment that is normally considered conductive, a comparatively high resistivity anomaly will most probably correspond to fresh water and thus will be the target in the case for groundwater exploration for domestic use.

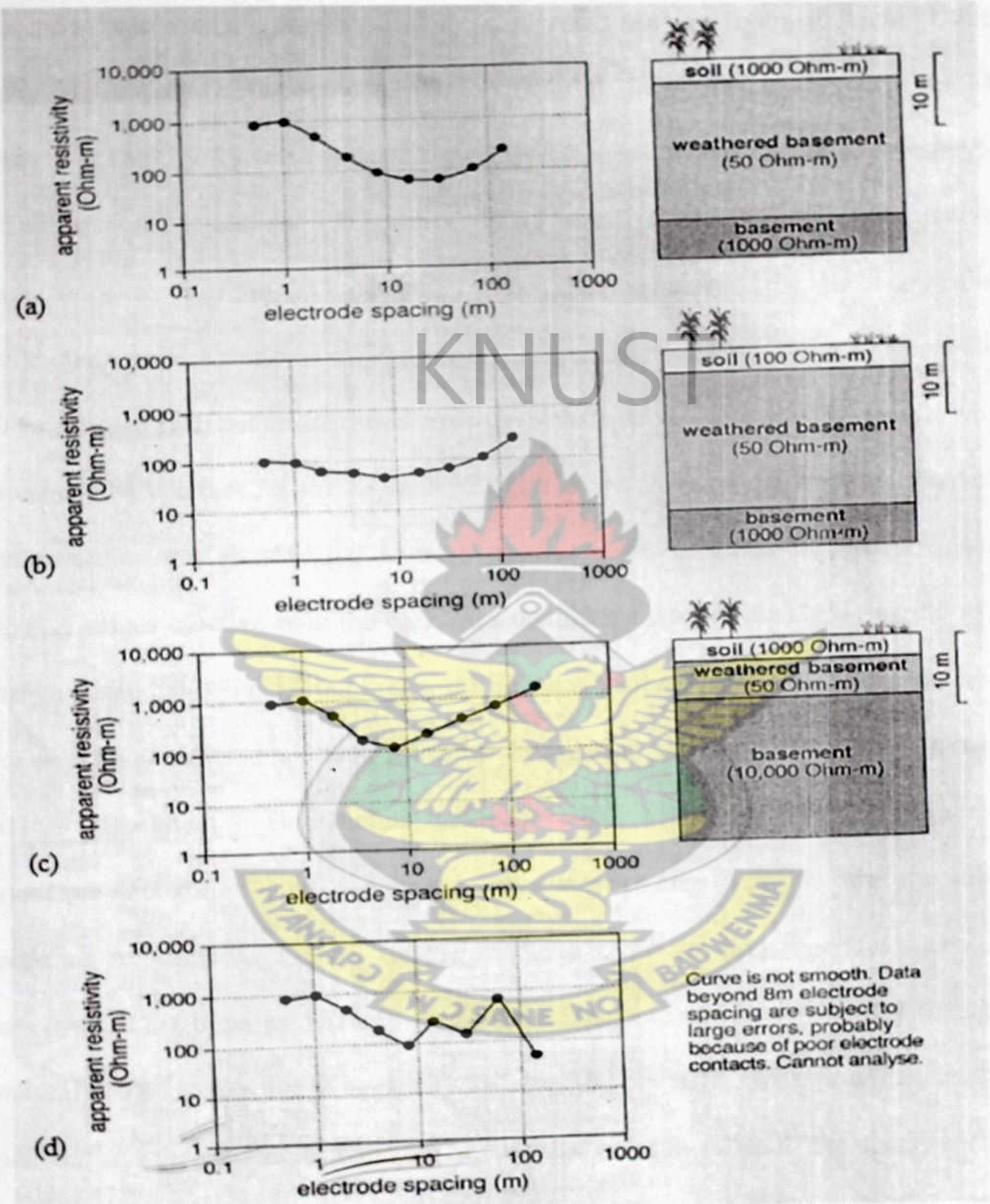

Figure 4.1 Common resistivity curves and their interpretation in crystalline basement areas. The first two curves are the most promising to drill

(Source: MacDonald *et al.*, 2005).

4.4 Bases for Selecting Drilling Sites

Crystalline basement rocks and volcanic rocks do not often conduct electricity because they have little primary porosity and in these rocks we are trying to identify thick weathering or deep fractured zones (MacDonald *et al.*, 2005). The objective of the EM survey is to identify fractured and deeply weathered zones, which have high potential for groundwater accumulation for further VES investigation. This is indicated by conductivity values of the VD mode being higher than the values of the HD or coinciding with the HD mode. Over a fault zone, the VD response values exceed the corresponding HD values, and such points are called cross-over-anomalous points. In other words, when the conductivity values for the HD and VD modes are plotted against station intervals, then according to Tsikudo (2009), sharp positive peaks of a deeper electromagnetic response values crossing over the peak of a shallower response dipole is referred to as cross-over anomaly. Fig. 4.2 (a,b) show the high conductivity anomalies of the VD mode over a deeply weathered and fault zones for 20 m, 30 m and 40 m coil separation using EM34-3 instrument. Unfractured basement rocks generally have low electrical conductivity (<1 mS/m) since they contain little water or clay (MacDonald *et al.*, 2005). According to MacDonald *et al.*, (2005), fractured zones are deep fractures (generally more than 20 m), often associated with faults and tectonic movement and that fractured zones tend to be conductive to electricity than the host crystalline rock since they contain water and also the increased circulation of water has helped to weather the nearby rock to produce some clay.

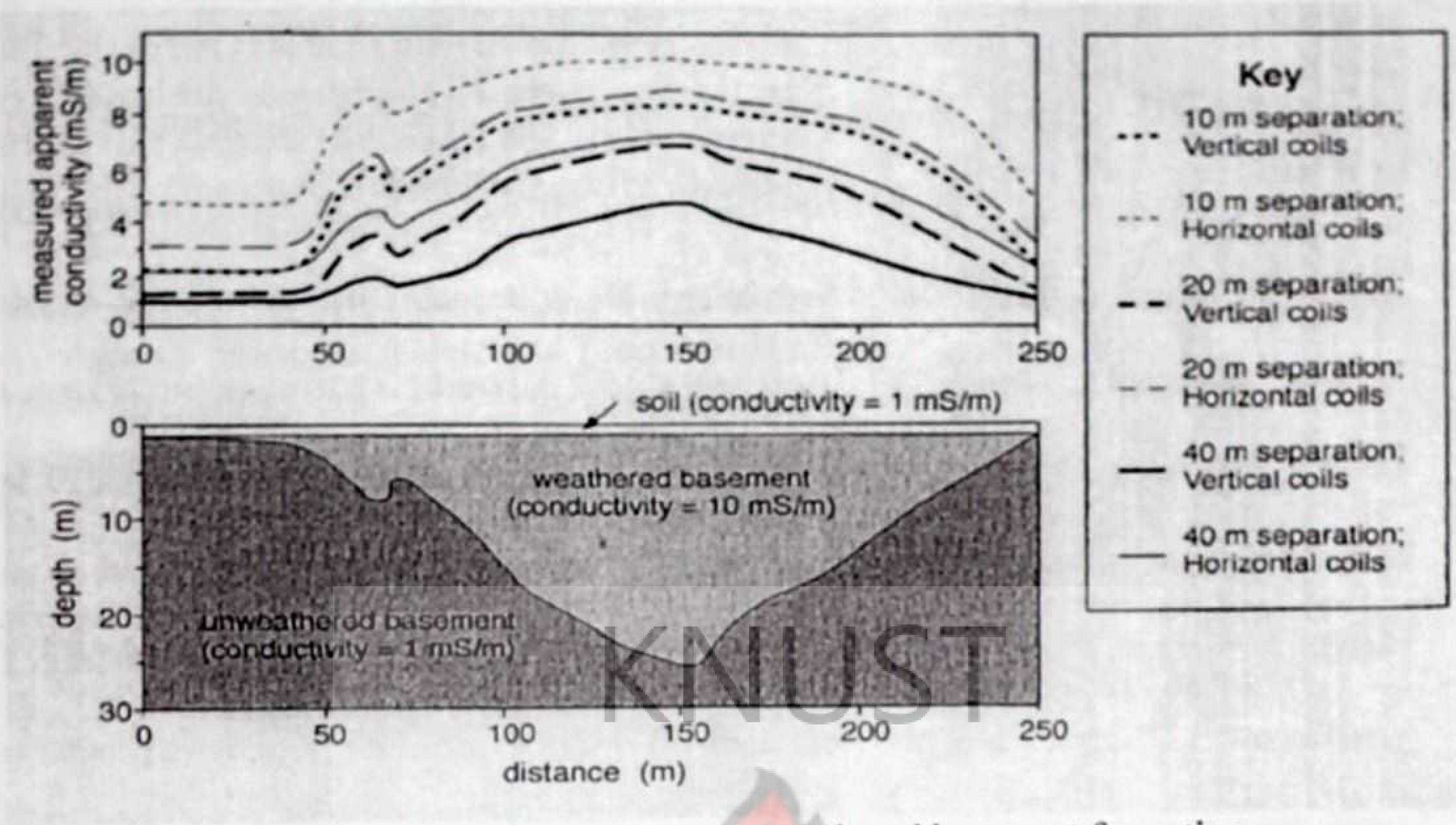

Figure 4.2a. Ground conductivity response over weathered basement formation

(Source: MacDonald *et al*., 2005).

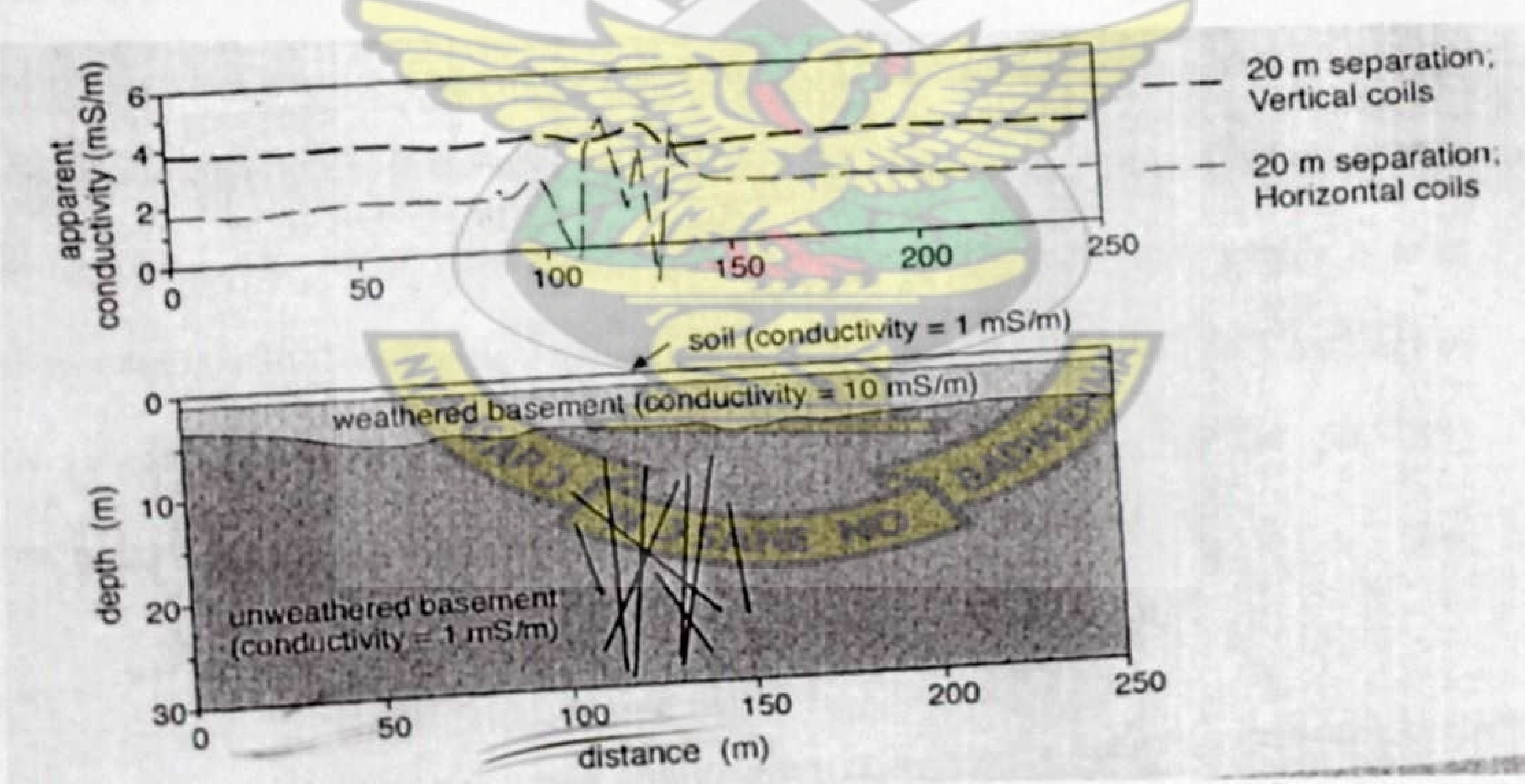

Figure 4.2b. Schematic diagram showing ground conductivity response over fracture zones in bedrocks

(Source: MacDonald *et al*., 2005).

4.5 Biringu Primary School Community

Two EM survey profiles were carried out in the community labelled A and B and the corresponding horizontal dipole (HD) and vertical dipole (VD) response curves are shown in Fig. 4.3 (a,b). Generally, the results showed a medium to high conductivity values in the range of 8 – 25 mS/m. Profile Aof length 100 m was conducted on a bearing of 010° and the results presented in Fig. 4.3a. Along profile A, the results for the HD mode indicate a gradual increase in terrain conductivity from 11 mS/m at point 10 m to 25 mS/m at point 100 m. For the VD mode, there is a sharp increase in terrain conductivity from 9 mS/m to 19 mS/m between the 10 m and 40 m . The conductivity then gradually decreased from 19 mS/m to a value of 18 mS/m at the 80 m point along the profile. From there, the terrain conductivity then increased again from 18 mS/m to 22 mS/m at the 100 m point. The anomalous area observed here was between 15 m and 48 m where thereis a crossover anomalypoint presumed to be fractured zone which may act as suitable aquifer, exists at the 40 m point.Hence its selection as a point for further VES investigation. The variation of terrain conductivity with distance along profile B is as shown in Fig.4.3b. This profile was conducted on a bearing of 320° with GPS readings of (N 10° 56' 3.194", E 0° 24' 49.801'') and (N 10° 56' 4.797", E 0° 24' 50.573'') respectively at the beginning and ending of the profile.

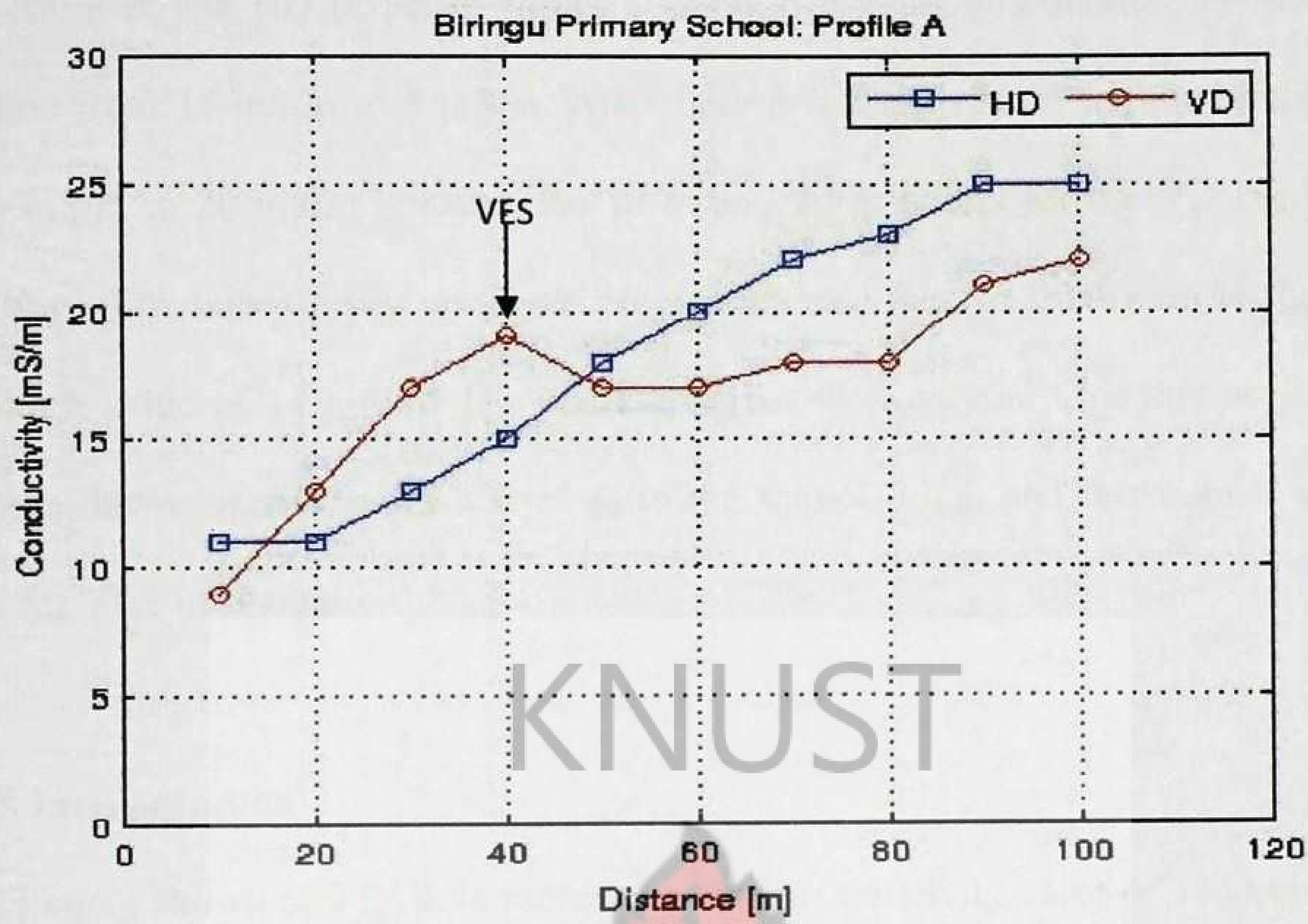

Figure 4.3a EM terrain conductivity profile for traverse A at Biringu Primary School.

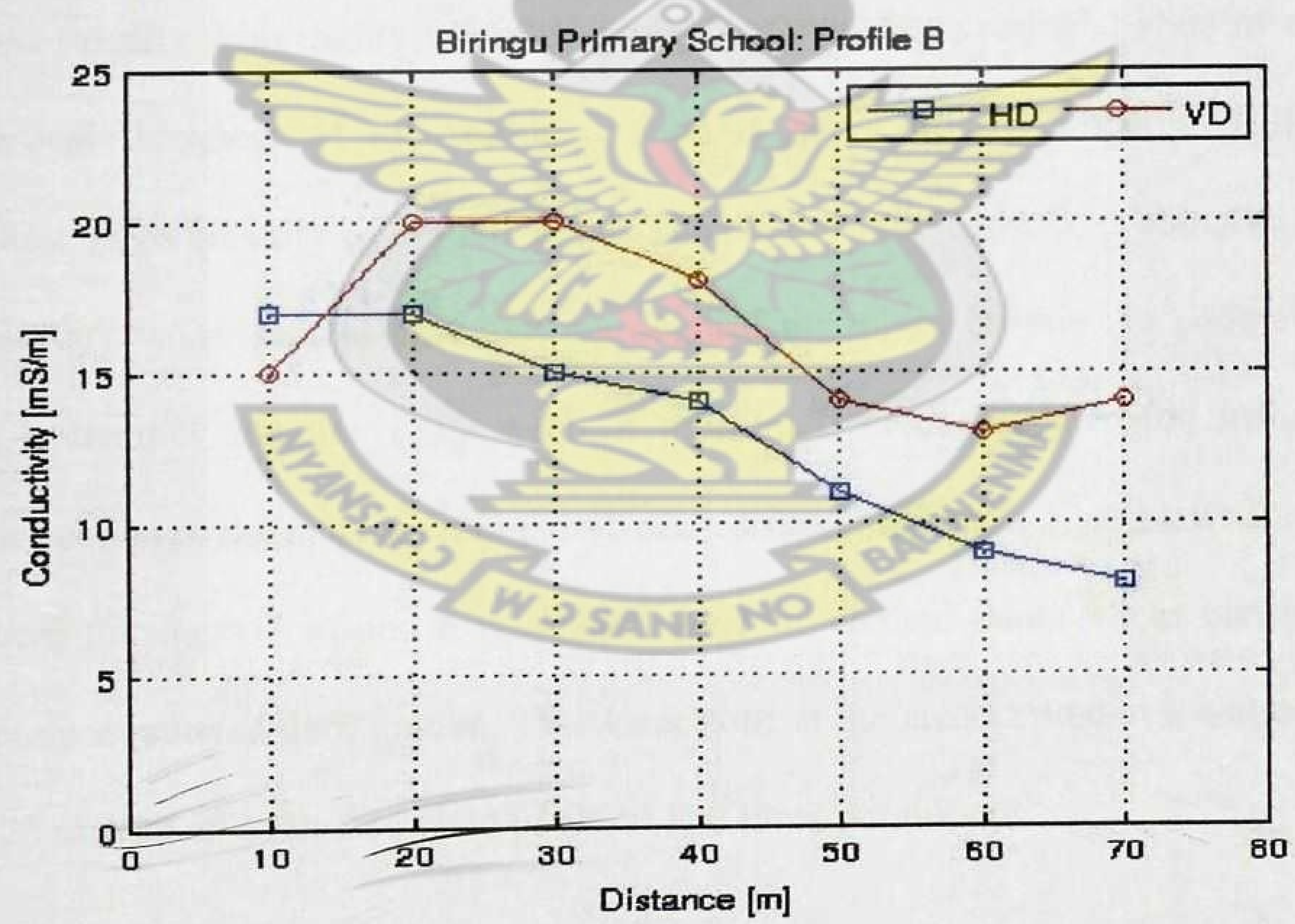

Figure 4.3b EM terrain conductivity profile for traverse B at Biringu Primary School.

Along profile B, the HD response shows a smooth decrease in conductivity along the profile line from 17 mS/m to 8 mS/m. Also there is a sharp rise in terrain conductivity from 15 mS/m to 20 mS/m between the 10 m and 20 m points for the VD mode. The conductivity then falls steeply up to the 50 m point and then gradually up to the 70 m point with a value of 14 mS/m. The observed cross over anomaly for this profile is at point 20 m, however, this point was close to the school urinal and therefore it was not selected for VES investigation.

4.6 VES Interpretation

The VES curve shown on Fig. 4.4a indicates a drop in resistivity value of 1343 ohm.m at the topsoildown to a minimum value of 66 ohm.m in the weathered zone, which correlates linearly with highly saturated groundwater in the weathered zone of the site. The vertical thickness of the wethered zone is about 40 m, which is suitable to accumulate large quantity of ground water. The depth to the bedrock is about 45 m with the resistivity value decreasing from this depth. This might be due to poor electrode contact or bedrock fracture. Point A 40 m was finally recommended for drilling. The geologic section of depth 43 m in Fig. 4.4b after drilling, indicates a hard lateritic top soil of vertical thickness 3 m and a weathered zone of vertical depth 43 m consisting of moderately weathered dark granite. The water zone at the area existed at a vertical depth below 25 m with an estimated yield of about 500 litres per minute.

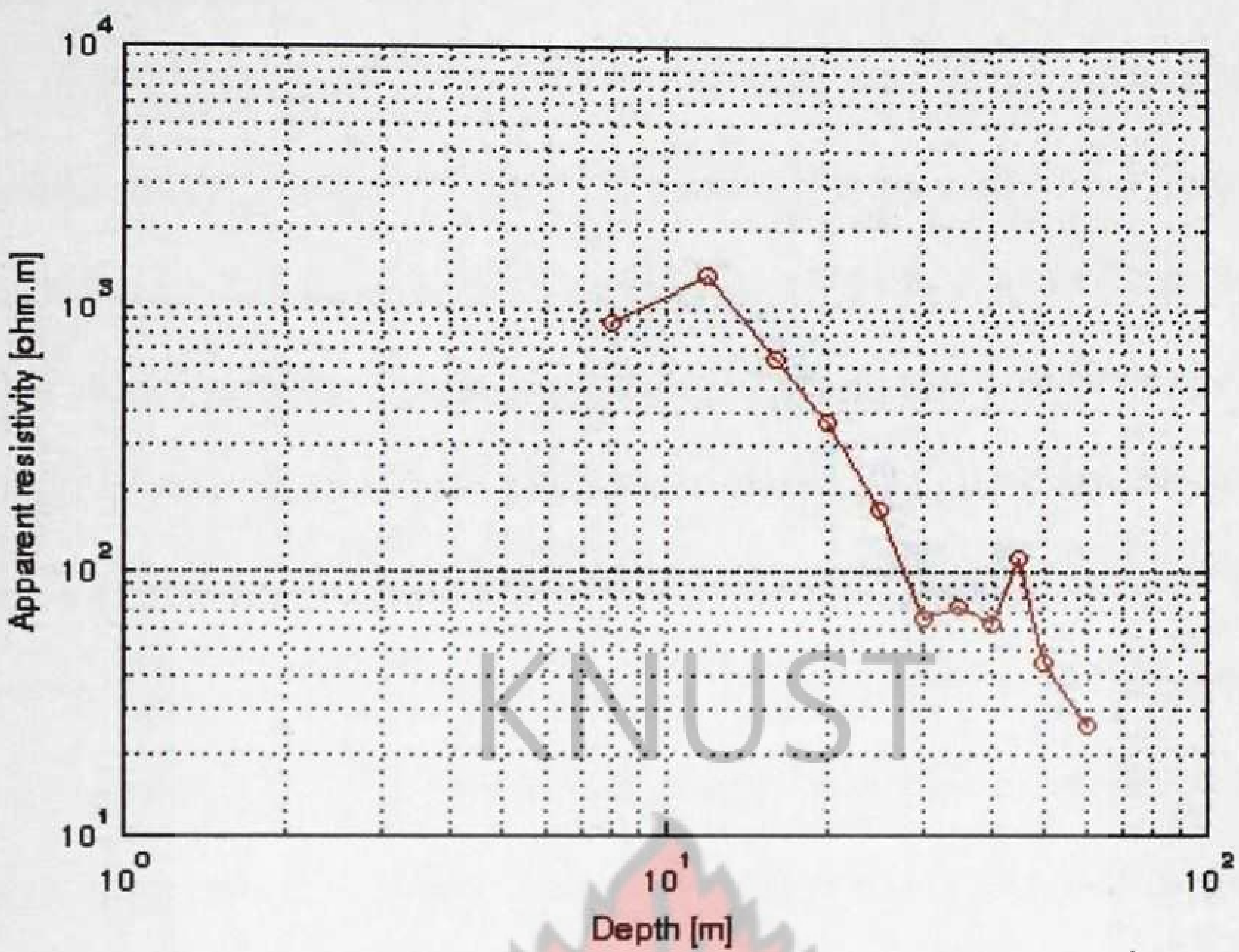

Figure 4.4a VES of Apparent resistivity against Depth at station A 40 m at Biringu Primary School.

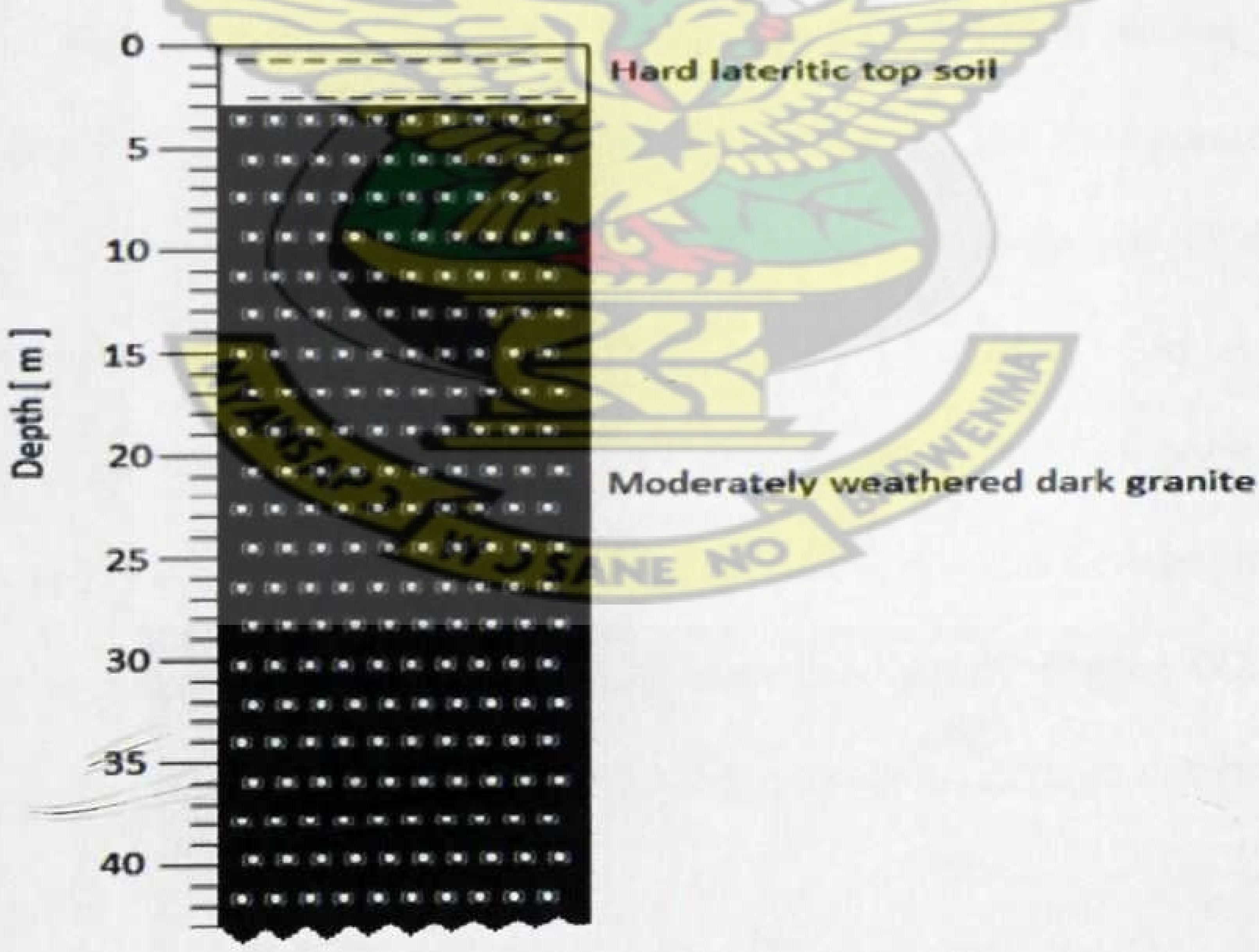

Figure 4.4b Lithologic Log of borehole drilled at the 40 m point of traverse A at the Biringu Primary School Community.

4.7 Sakpare – Tang Dabot Community

Fig. 4.5 (a - e) shows the results of the five profiles namely, A -E that were carried out in this community. Along profile A in Fig. 4.5a, profile length of 130 m and bearing 060°, the terrain conductivity of the HD mode decreases from 15 mS/m at the 10 m point down to 8 mS/m at the 50 m station. This conductivity value remains constant from the 50 m point up to the 70 m point and then followed by a sharp rise in the conductivity value up to 9 mS/m at the 80 m point. The terrain conductivity value decreases from the 9 mS/m at the 80 m point down to a value 6 mS/m at the 110 m, 120 m and the 130 m station points. However, the conductivity value for the VD mode falls and rise erratically between the terrain conductivity values 2 – 9 mS/m along the station points 10 – 120 m. Finally, the terrain conductivity value of 7 mS/m at the 120 m point remains the same up at the end of the profile at 130 m point. No station was selected along this profile for further VES investigation. Along profile B in Fig. 4.5b, profile length of 70 m and bearing 310 ° , the terrain conductivity for the HD mode decreases from 5 mS/m at the 10 m point down to 4 mS/m at the 20 m and 30 m stations. This is followed by sharp rise in the terrain conductivity from the 5 mS/m at the 30 m point to the value of 6 mS/m at the 50 m station. Finally, the conductivity value remains constant from the 50 m point up to the end of the profile at the 70 m point. The constant conductivity value between the 50 – 70 m points indicates a homogeneous formation between those points. For the VD mode, the terrain conductivity decreases from a value of 4 mS/m at the 10 m point down to 2 mS/m at the 20 m point.

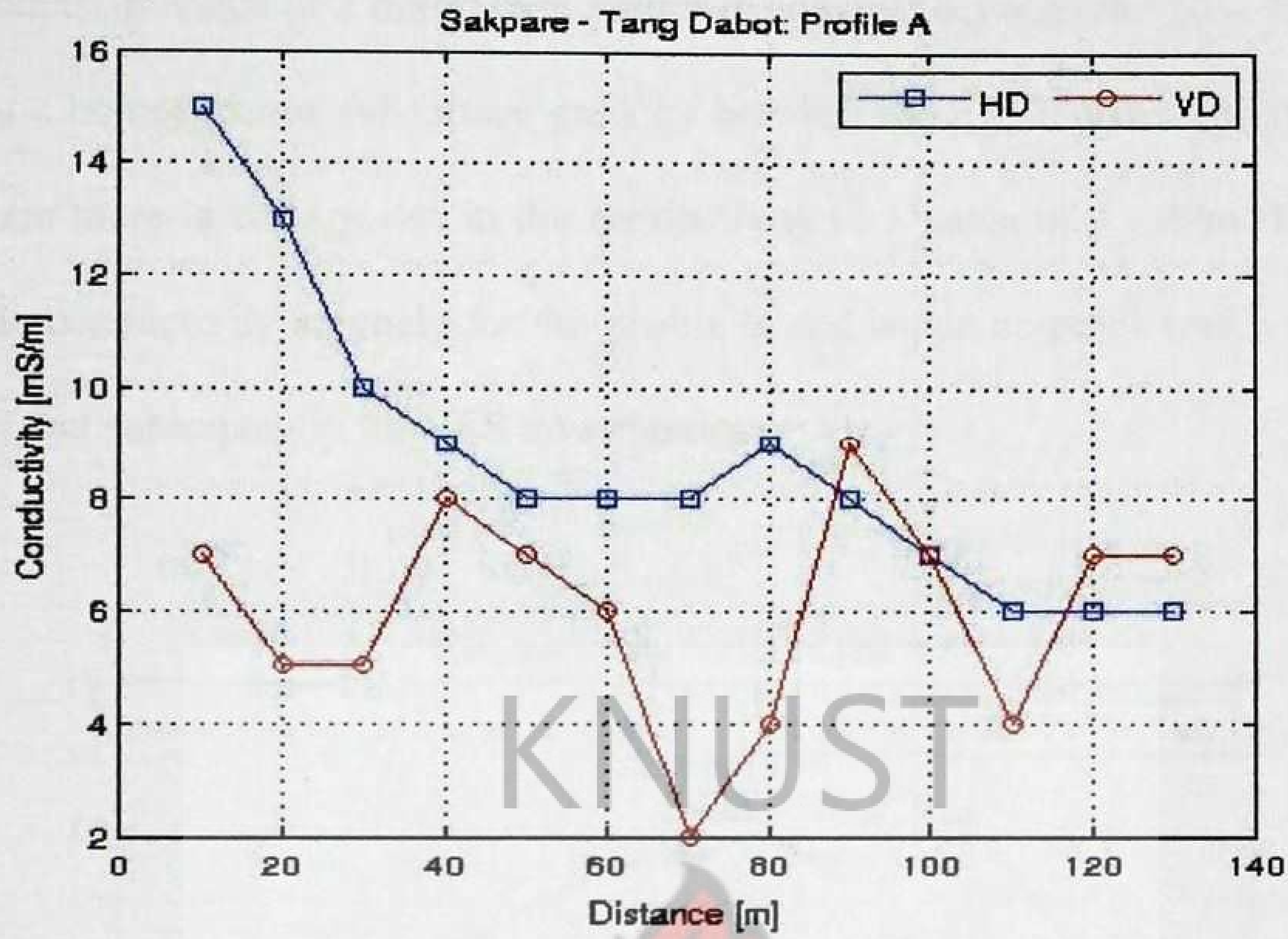

Figure 4.5a EM terrain conductivity profile for traverse A at Sakpare – Tang Dabot.

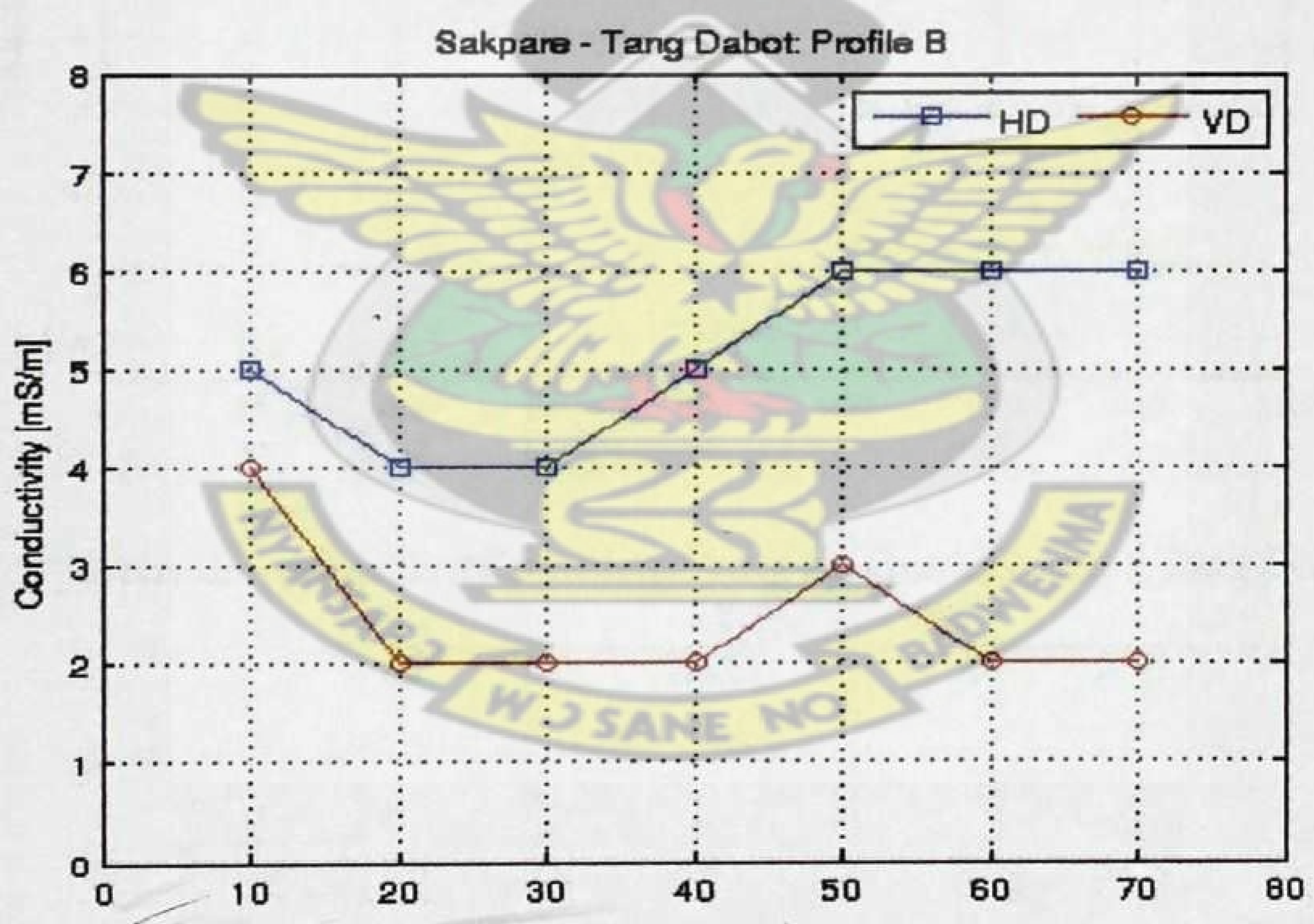

Figure 4.5b EM terrain conductivity profile for traverse B at Sakpare – Tang Dabot.

This conductivity value of 2 mS/m then remained constant between the 20 – 70 m points indicating a homogeneous subsurface geology between these points, except at the 50 m point where there is a sharp rise in the conductivity to a value of 3 mS/m. There is no observable conductivity anomaly for the profile B and hence no point was selected as a drill point and subsequently for VES investigation.

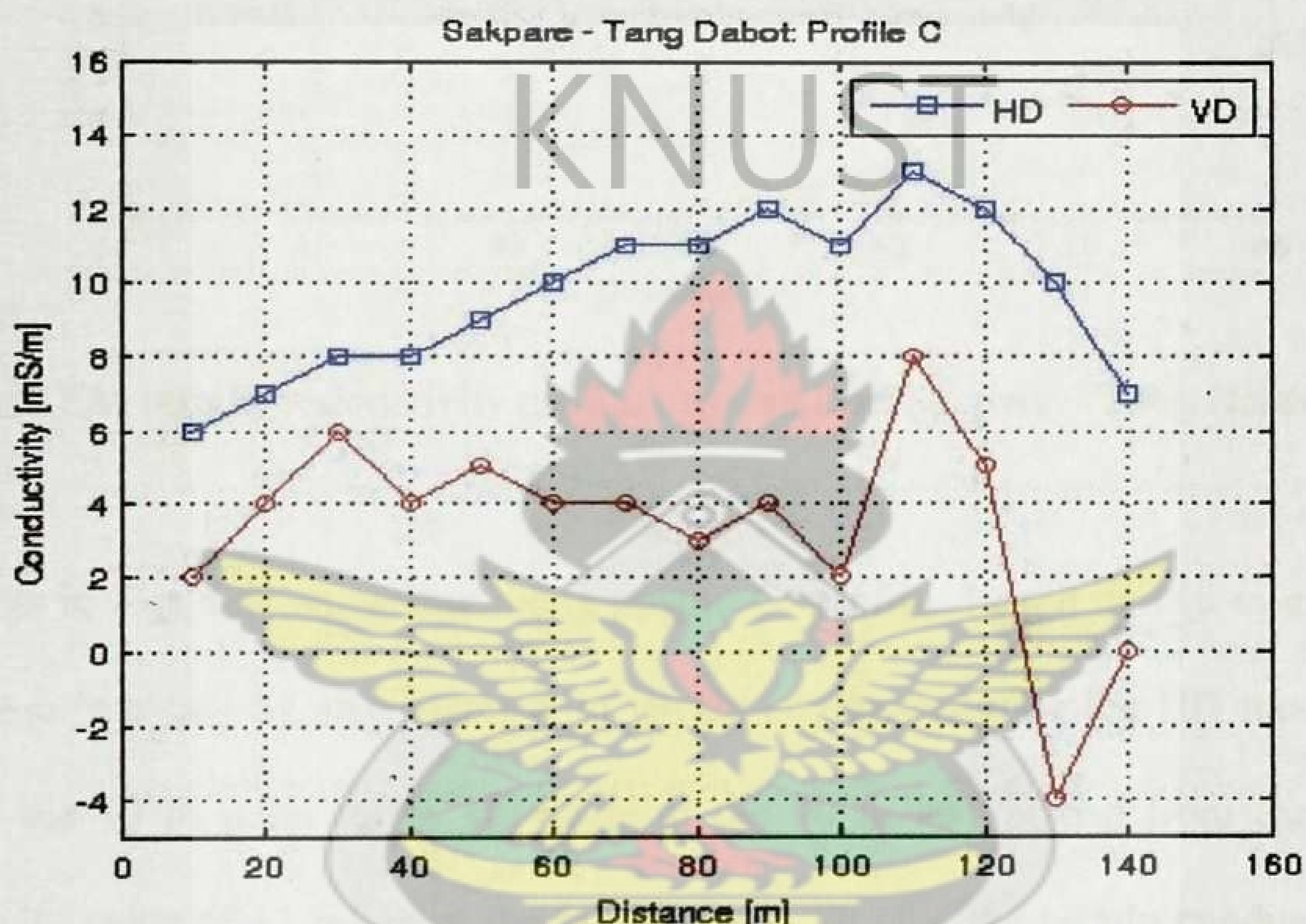

Figure 4.5c EM terrain conductivity profile of traverse C at Sakpare – Tang Dabot.

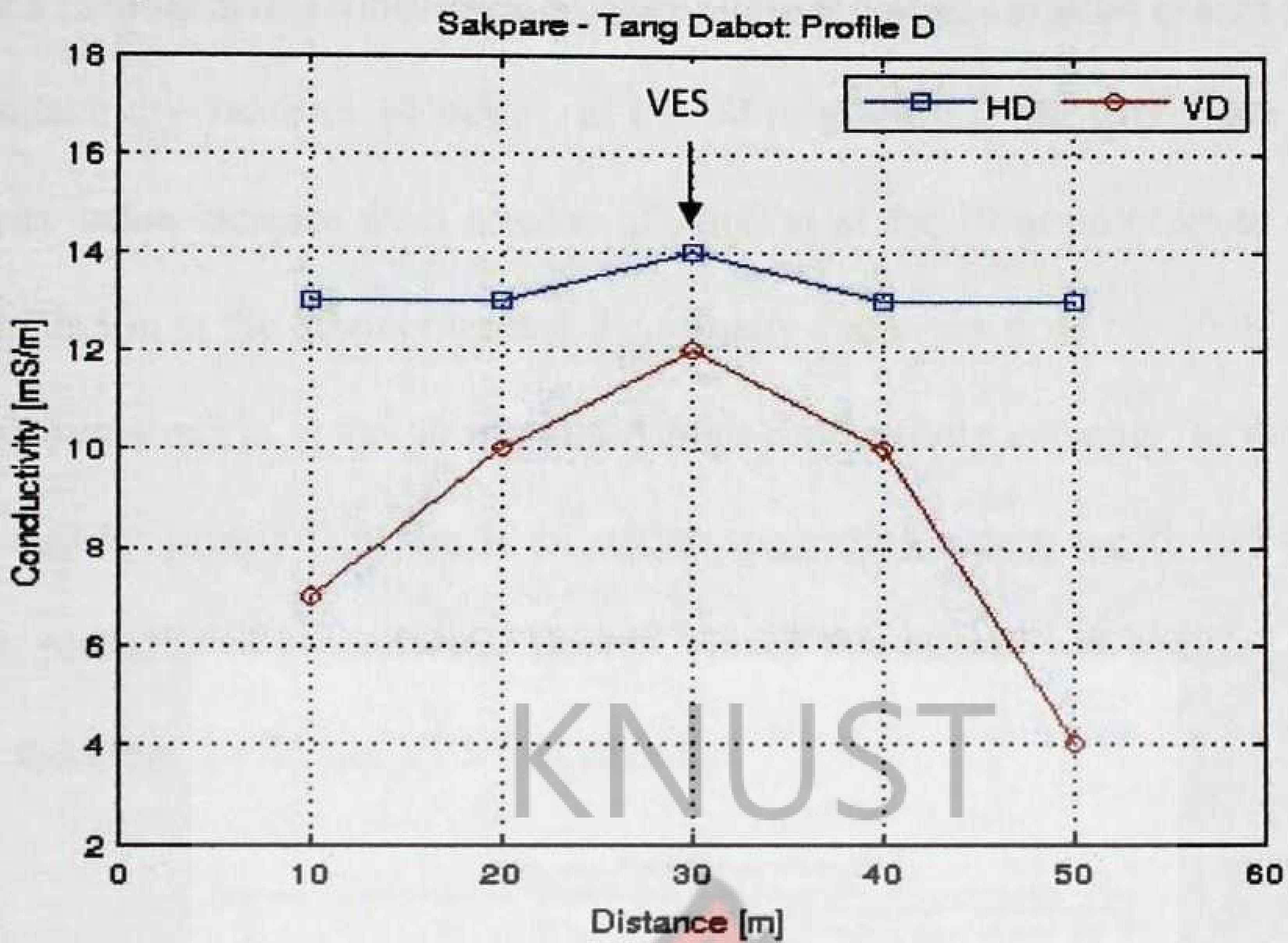

Figure 4.5d EM terrain conductivity profile traverse D at Sakpare – Tang Dabot.

The results in Fig. 4.5c show that along profile C, profile length of 140 m and bearing 315°, there is a step by step increase in terrain conductivity for the HD mode from 6 mS/m at the 10 m point up to 12 mS/m at the 90 m station and from there falls to conductivity value of 11 mS/m at the 100 m point. Finally, the terrain conductivity rises to 13 mS/m at the 110 m and falls gently to a value of 7 mS/m at the end of the profile at the 140 m station. For the VD mode the terrain conductivity rises and falls erratically between -4 and 140 mS/m between the station points 10 – 140 m. No conductivity anomaly was observed, hence, no station was selected as drill point and consequently for VES investigation.

The results along traverse D in Fig. 4.5d, profile length of 70 m and bearing 045°, indicate that the terrain conductivity value of 13 mS/m remains constant from the HD mode from the beginning of the profile at point 10 m to end of the profile at 50 m station indicating a homogeneous subsurface geology along the whole profile, except a sharp rise in the conductivity value to 14 mS/m at the 30 m point. For the VD mode the terrain conductivity value increase from a value of 7 mS/m at the 10 m point up to the highest value of 12 mS/m at the 30 m point and then finally decreases from the 30 m point to the lowest value of 4 mS/m at the 50 m point.A high conductivity anomaly of the VD mode was obseverd for profile D at the 30 m station suggesting a deep weathered zone which has a high probality of groundwater storage. Hence this station was selected as the drill point and therefore for further VES investigation.

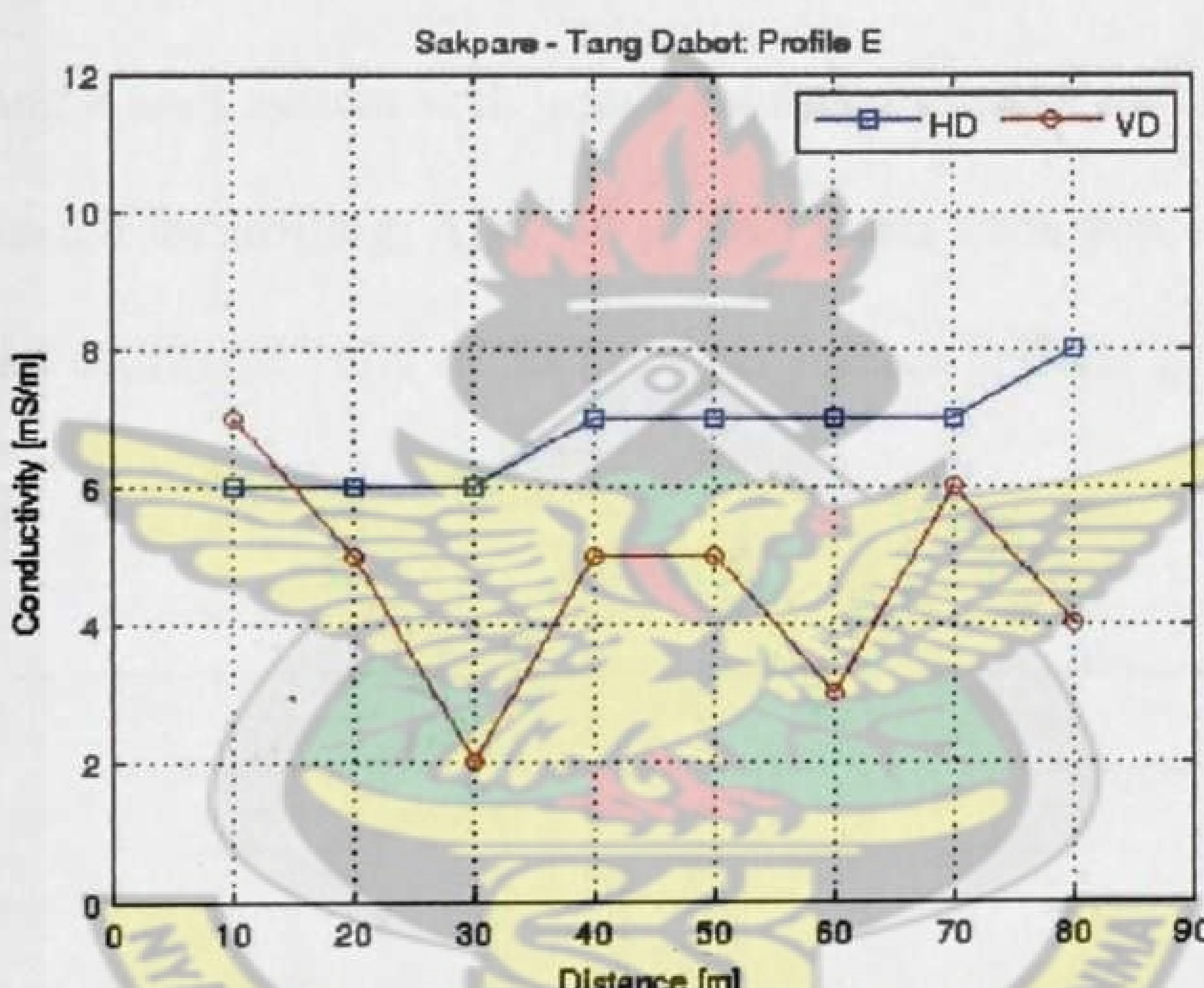

Figure 4.5e EM terrain conductivity profile traverse E at Sakpare – Tang Dabot.

Along profile E with results in Fig. 4.5e, profile length of 80 m and on bearing 320°, the 6 mS/m terrain conductivity value for the HD mode remains constant between the stations 10 – 30 m and from there rises sharply to a value of 7 mS/m at the 40 m point. The 7 mS/m value then remains constant between the stations 40 – 70 m. The terrain conductivity finally rises sharply to the value of 8 mS/m up to the 80 m point. The results of the VD mode indicate an erractic behaviour suggesting a complex geology with a fall and rise in terrain conductivity from the beginning of the profile at the 10 m point up to the end of the profile at the 80 m point between the values 7 – 2 mS/m. No station point was selected for further VES investigation along this traverse line.

4.8 VES Interpretation

In Fig. 4.6a, the VES curve rises in a resistivity value of 35 ohm.m to 51 ohm-m and then falls from the 51 ohm-m down to a minimum value of 26 ohm.m.This indicates a weathered zone from the beginning of the VES investigation down to a vertical depth of about 30 m.The depth to the bedrock is about 35 m with a high apparent resistivity value of 169 m suggesting a fault system with highly saturated ground water. Finally, this VES site was recommended for drilling. After 40 m drill water zone was intercepted at about 20 m depth with an estimated yeild of 50 litres per minute and the gelogic log as shown in Fig. 4.6b.

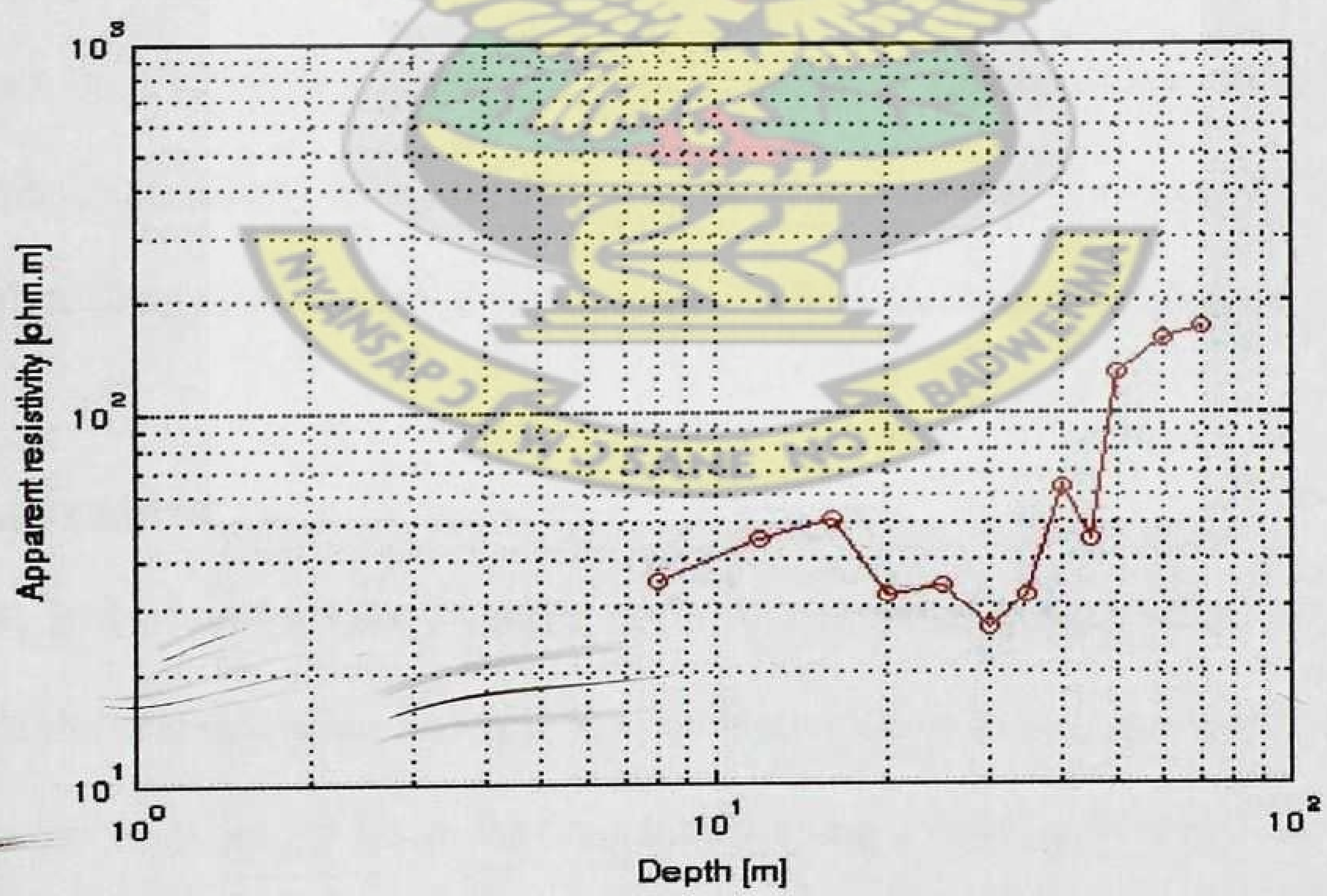

Figure 4.6a VES of Apparent resistivity against Depth at station D 30 m at Sakpare - Tang Dabot.

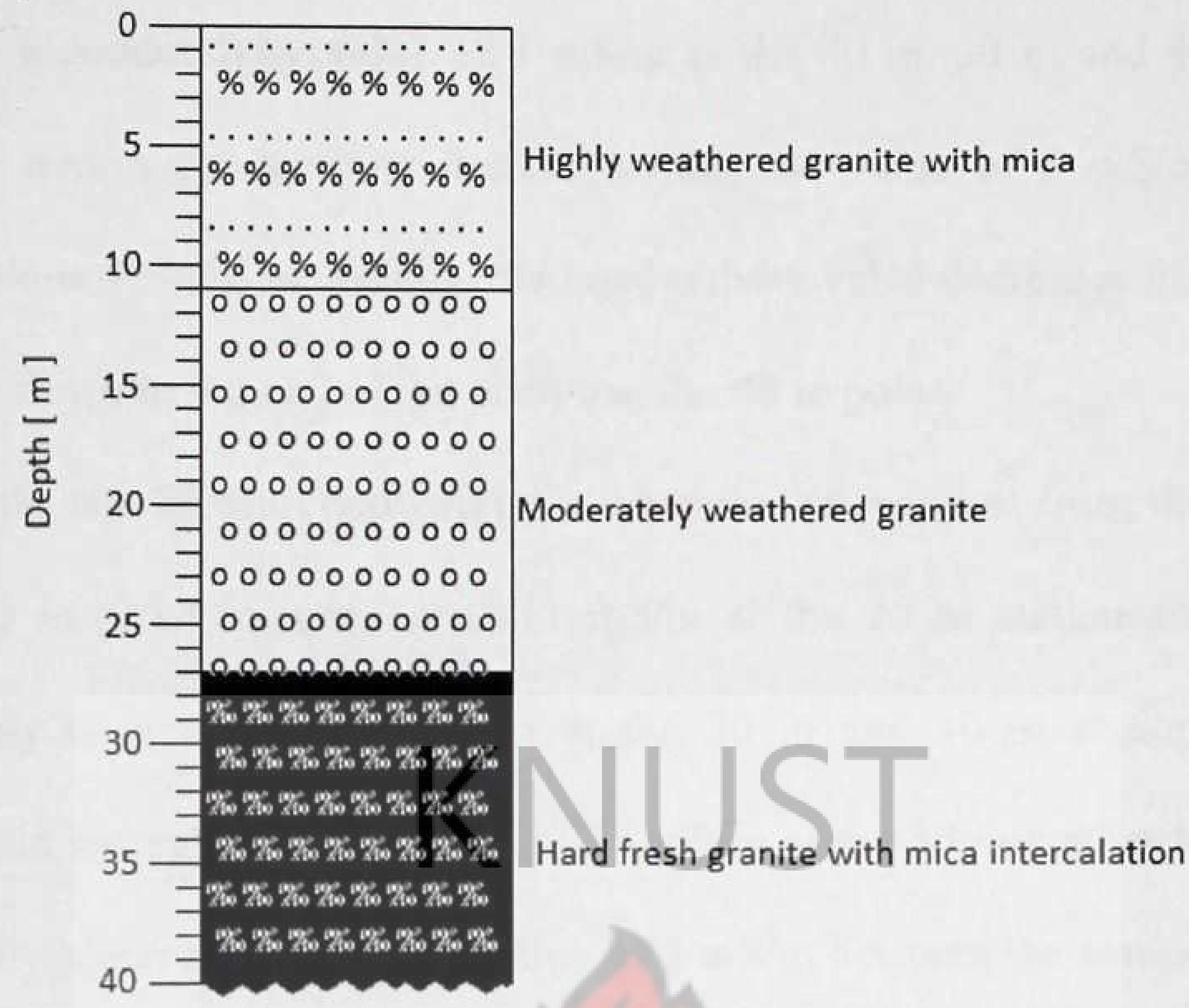

Figure 4.6b Lithologic Log of borehole drilled at the 30 m point of traverse D at Sakpare Tang Dabot.

The geologic log in Fig. 4.7b is made up of two sections. The first section is the weathered zone of vertical depth of 27 m consisting of highly weathered granite mixed with white mica on top of moderately weathered granite and the second section is the basement rock consisting of hard fresh granite with black mica intercalation.

4.9 Tanga CHPS Centre Community

Two EM survey profiles were carried out in the community labelled A and B and the results of the corresponding HD and VD conductivity curves are shown in Fig.4.7 (a, b). The Profile A of length 90 m was conducted along a bearing of 110° and the results presented in Fig. 4.7a. Whilst, profile B of length 80 m was carried out along a bearing of 070° and the results presented in Fig. 4.7b. The results of profile A indicate for the HD mode, a gradual decrease in terrain conductivity from a value of 4 mS/m at the 10 m station down to a conductivity value of 3 mS/m at the 20 m, 30 m and 40 m stations. From there the terrain conductivity increases from the value of 3 mS/m to 7 mS/m between the stations 40 – 80 m. Finally, the conductivity value decreases from 7 mS/m at the 80 m station down to the end of the profile at the 90 m point.

For the VD mode, the terrain conductivity is observed to increase from the value of 10 mS/m at the 10 m point to a value of 11 mS/m at the 20 m station and from there decreases sharply to a value of 8 mS/m at the 30 m and 40 m station points. The conductivity again increases sharply back to 11 mS/m at the 50 m station from the 40 m station and finally, decreases down to a value of 5 mS/m between the stations 50 – 90 m. No point was selected for VES investigation even though high conductivity values of the VD mode were measured at 20 m and 30 m points, they were attributed to the influence of roofing sheets of a building close to the survey line.

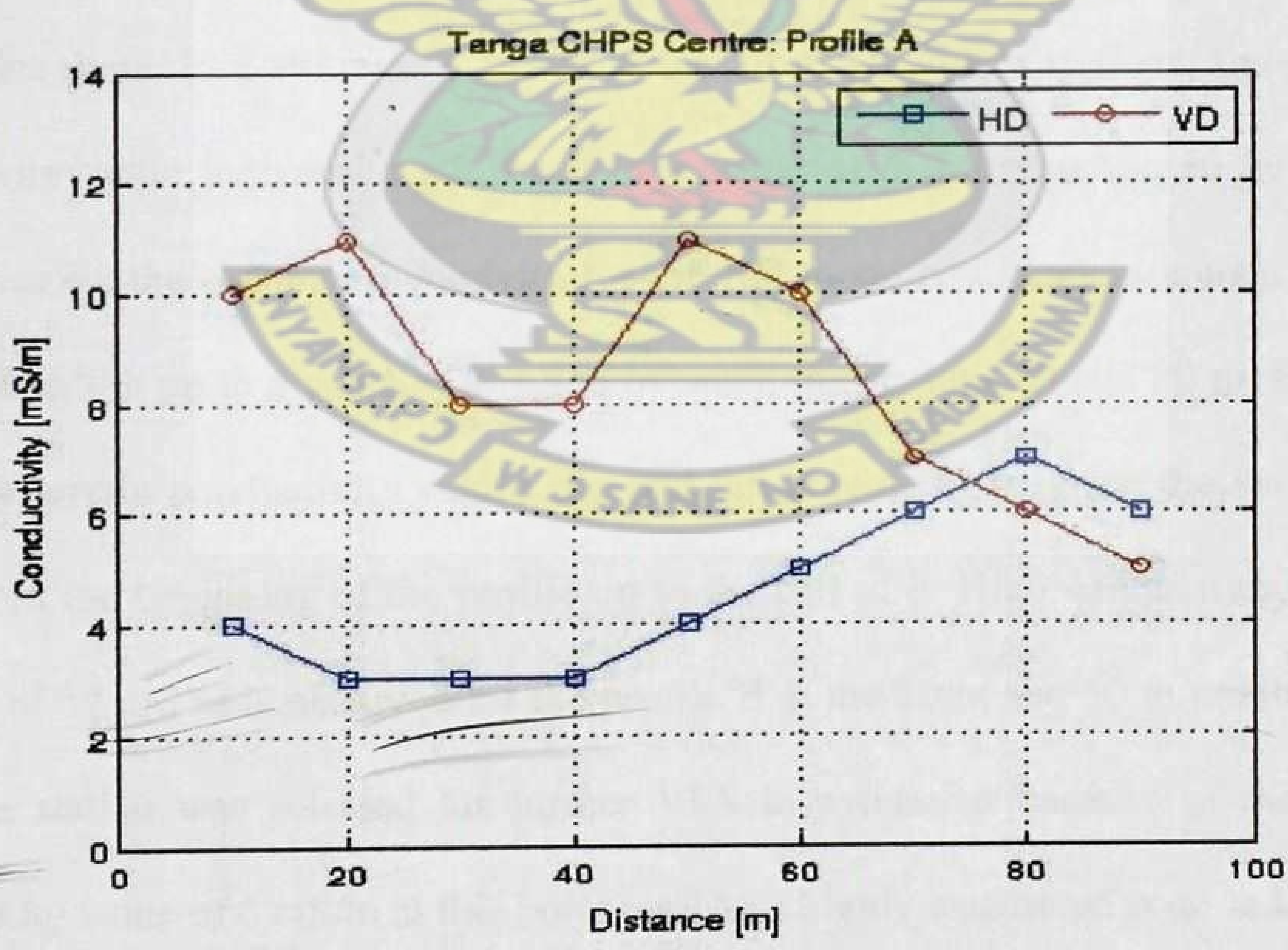

Figure 4.7a EM terrain conductivity profile for traverse A at Tanga CHPS Centre.

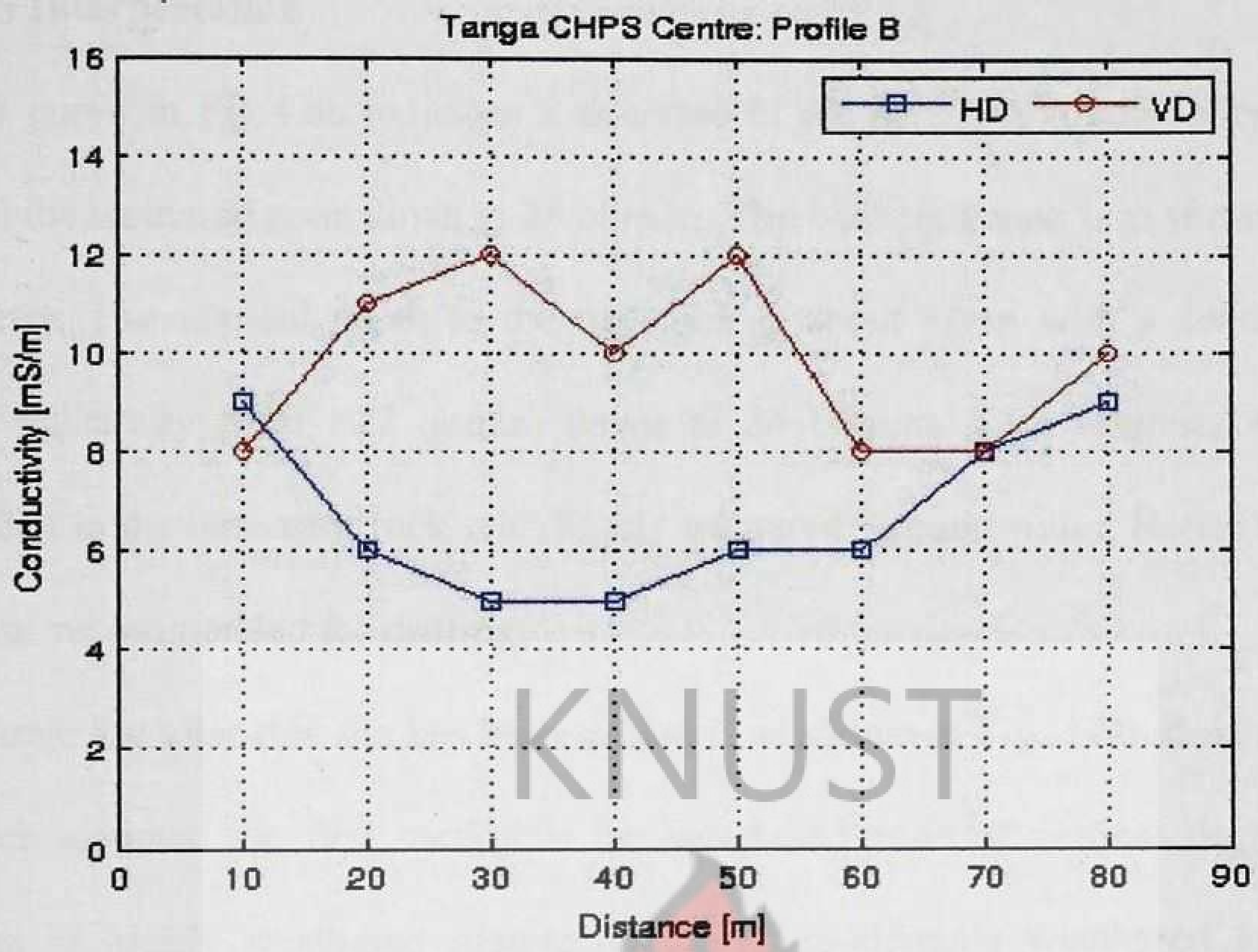

Figure 4.7b EM terrain conductivity profile for traverse B at Tanga CHPS Centre.

The results of profile B depicts a decrease in terrain conductivity value of 9 mS/m at the 10 m point down to a value of 5 mS/m at the 30 m and 40 m stations, from there the conductivity value increases again back to a value of 6 mS/m at the 50 m and 60 m points. Finally, the terrain conductivity for the HD mode continues to increase from the value of 6 mS/m up to a value of 9 mS/m between the stations 60 and 80 m. For the VD mode, the terrain conductivity values rise and fall repeatedly between the values 8 – 12 mS/m from the beginning of the profile up to the end of it. High conductivity crossover anomaly of 12 mS/m is observed for the profile B at the 30 m and 50 m points, however the 50 m station was selected for further VES investigation because of the high HD conductivity value of 6 mS/m at this point may be a highly weathered zone at 15 m depth.

4.10 VES Interpretation

The VES curve in Fig.4.8a indicates a decrease in the apparent conductivity from 108 ohm.m in the wethered zone down to 26 ohm.m. The wethered zone is at vertical depth of about 30 m. The vertical depth to the bed rock is about 40 m with a decrease in the apparent resistivity from 127 ohm.m down to 84 ohm.m. This suggests a structural deformation in the basement rock with highly saturated ground water. Hence the B 50 m station was recommended for drilling.

The geologic log after this site has been drilled is as shown in Fig. 4.8b. It is made up of two major sections, the first section is the weathered zone of vertical depth of 36 m consisting of highly weathered granite on top of moderately weathered granite with quartz and the second section is the basement rock consisting of hard fresh fractured granite.The aquifer zone was intercepted at a depth of about 21 m with an estimated yield of 152 litres per minute.

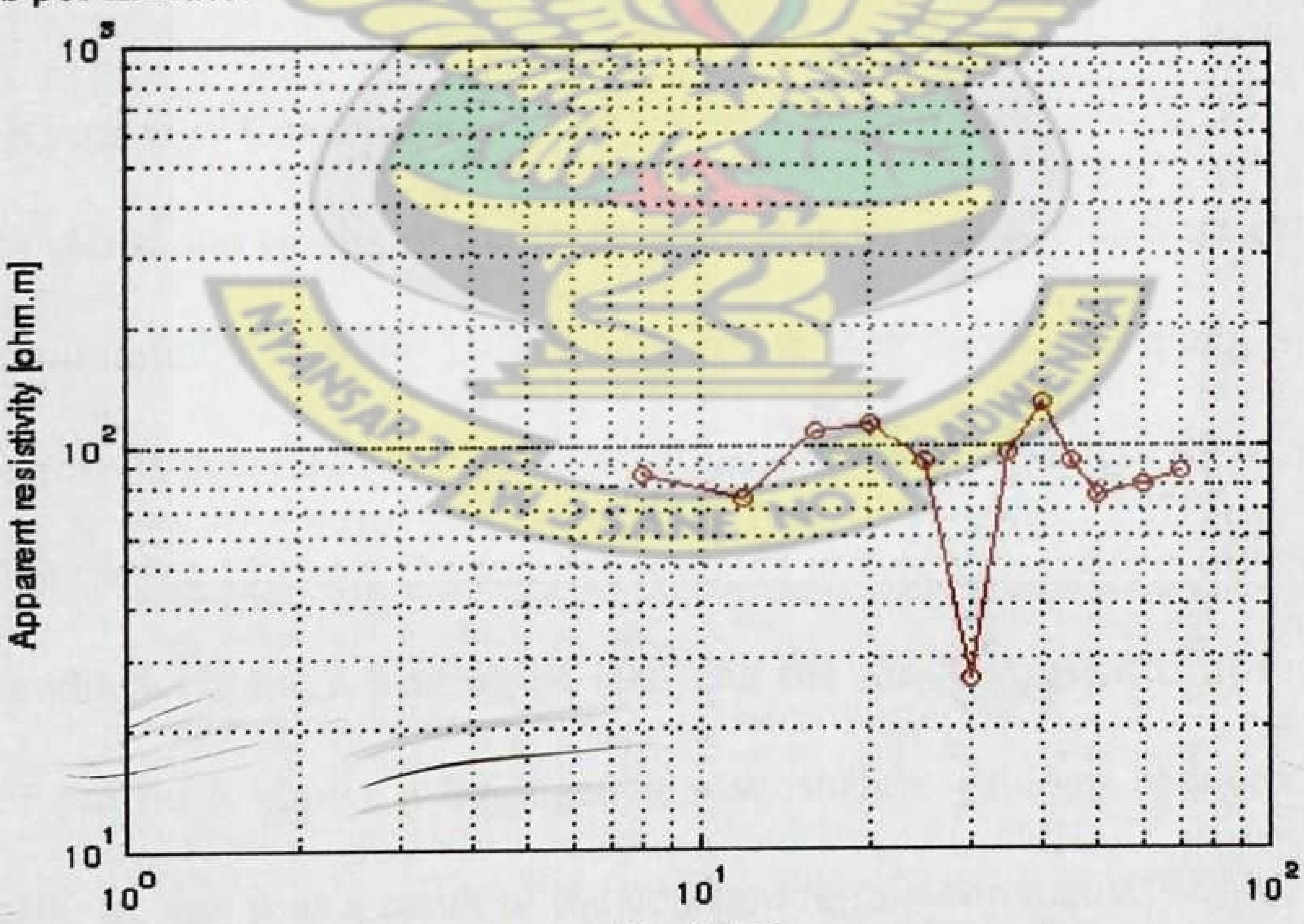

Figure 4.8a VES of Apparent resistivity against Depth at station B 50 m at Tanga CHPS Centre.

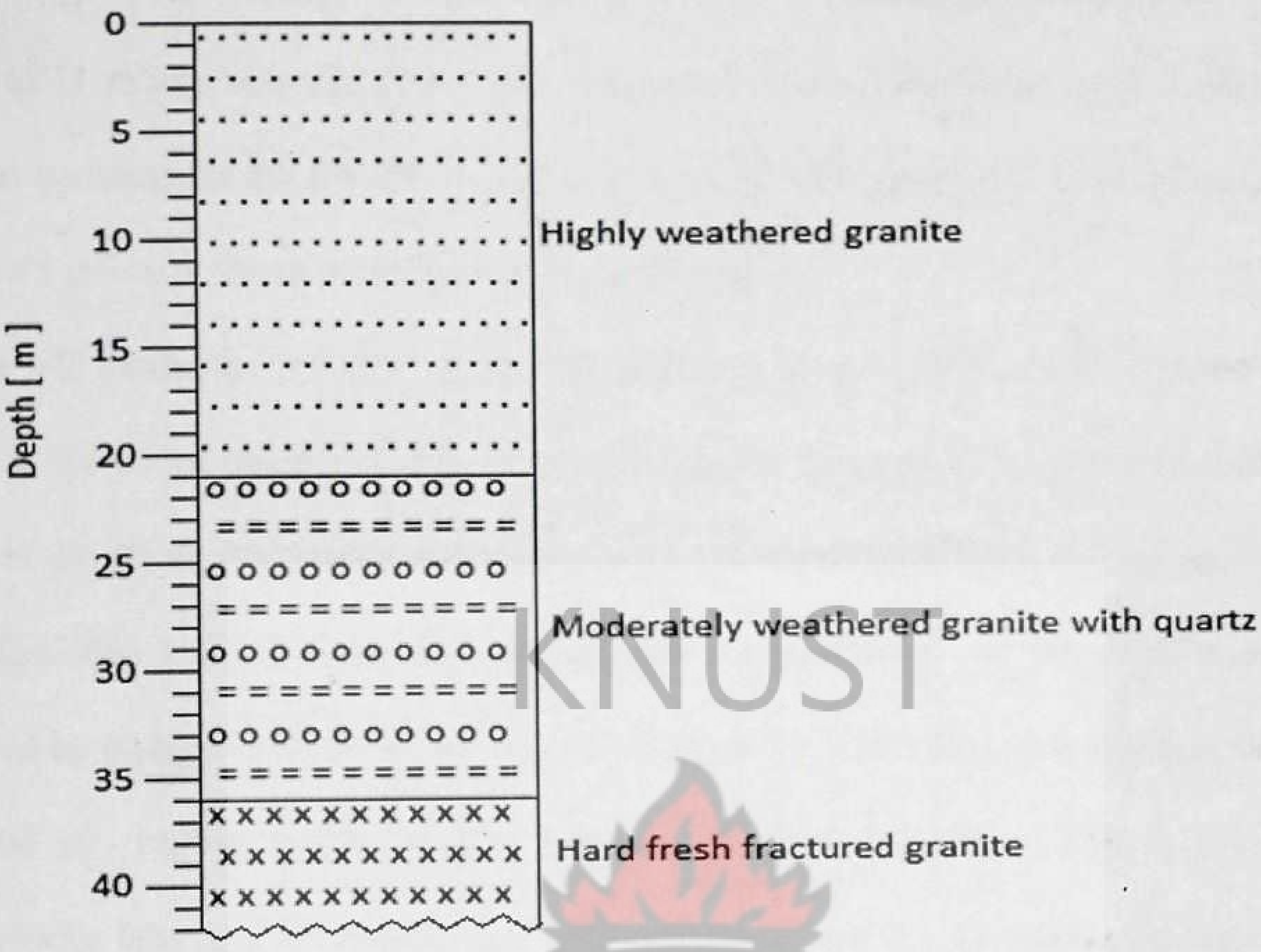

Figure 4.8b Lithologic Log of boreholes drilled at the 50 m point of profile B at Tanga CHPS Centre.

4.11 Gori - Kumzeogo Community

Fig. 4.9 (a-c) shows the results of the three profiles A, B and C that were carried out in the Kugdari community. Profile A of length 220 m was conducted along a bearing of 075° and the results presented in Fig. 4.9a. whilst, profile B of length 80 m was carried out along a bearing of 150° and the results presented in Fig.4.9b. Also, profile C of length 80 m was conducted along a bearing of 100° and the results presented in Fig. 4.9c.The HD mode of profile A shows a homogeneous subsurface geology between the station points 10 – 100 m. this is as a result of the constant terrain conductivity value of 3 mS/m observed between the 10 – 100 m points, except at the 40 m and 80 m points where there is a sharp rise and fall of the terrain conductivity to values 4 mS/m and 2 mS/m respectively. This is followed by a step by step rise in the terrain conductivity from 3 mS/m to 11 mS/m between 100 – 190 m stations. The conductivity value 3 mS/m then remains constant for the the 200 m and 210 m points and finally decreases sharply to the value of 9 mS/m at the end of the profile at 220 m point.

For the VD mode, the terrain conductivity increases from -1 mS/m at 10 m point up to 5 mS/m at the 30 m point and then decreases sharply down to a conductivity value of 1 mS/m at the 50 m, from there the conductivity increases again back to 3 mS/m at the 70 m station. The 3 mS/m value then remains the same between the 70 – 100 m stations, followed by a sharp decrease in the terrain conductivity to a value of 2 mS/m at the 90 m and 100 m station point. Finally, between the stations 100 – 220 m the terrain conductivity falls and rises repeatedly between the values 2 – 10 mS/m. No point along profile A was selected for further VES investigation.

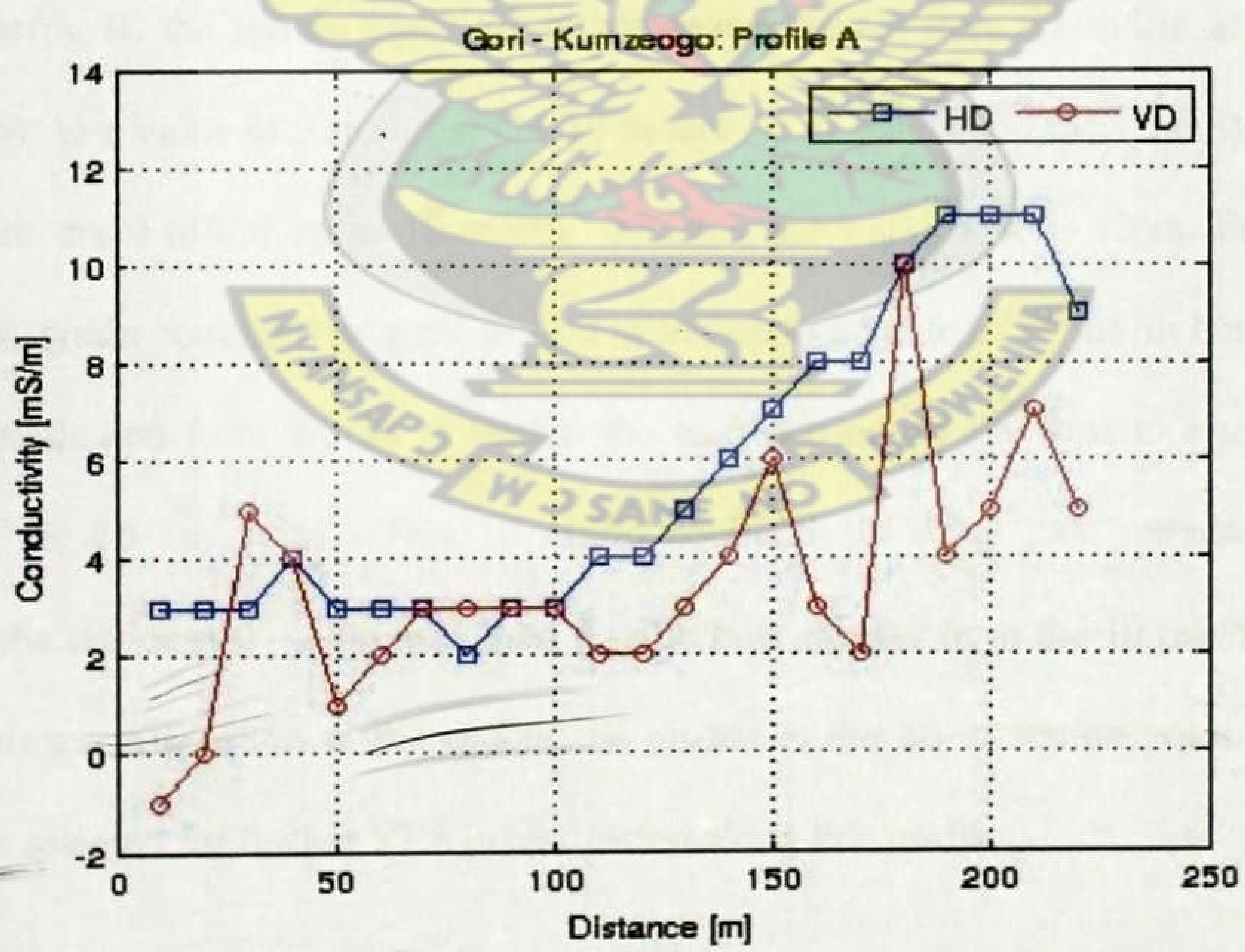

Figure 4.9a EM terrain conductivity profile for traverse A at Gori - Kumzeogo.

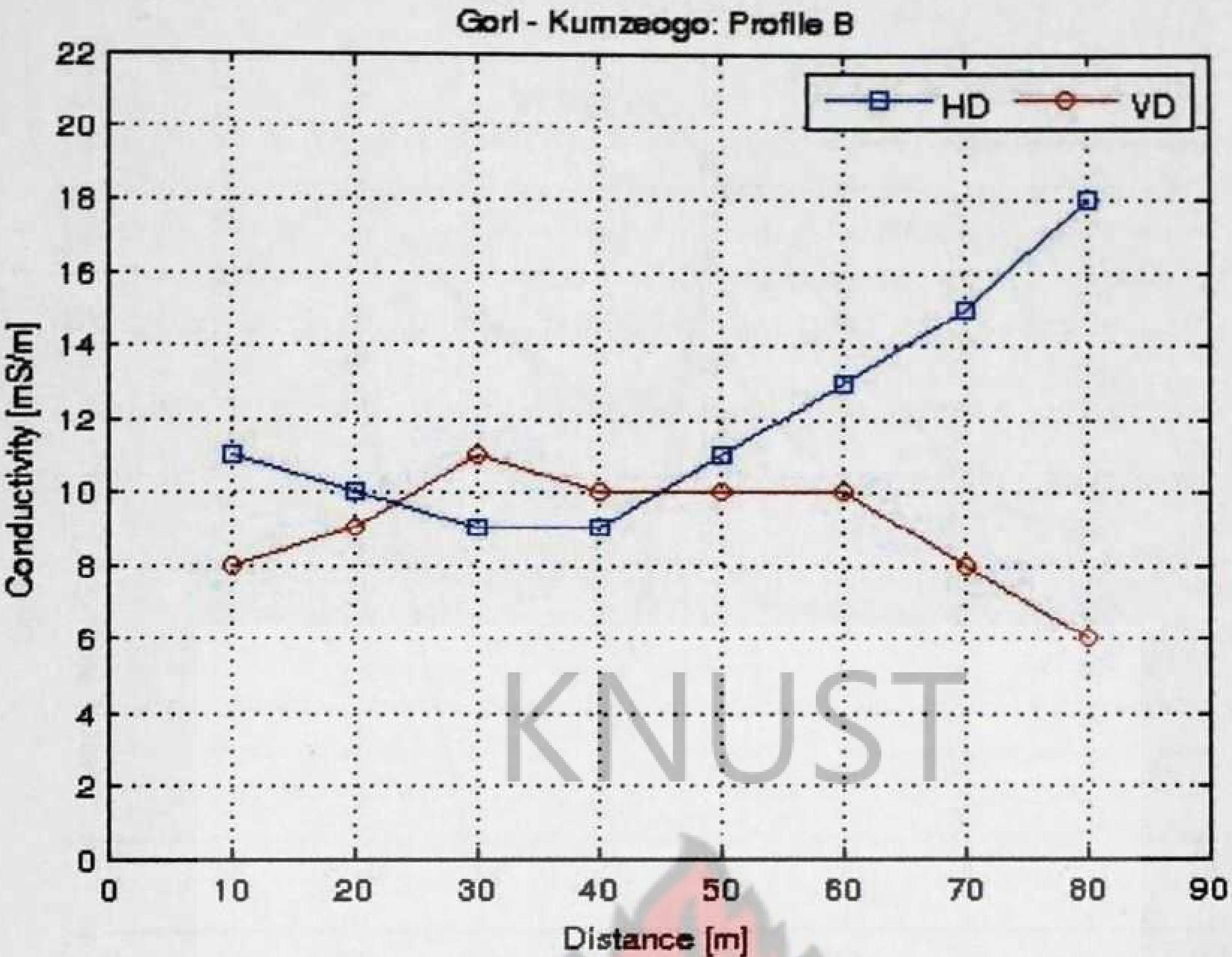

Figure 4.9b EM terrain conductivity profile for traverse B at Gori - Kumzeogo.

Along profile B, the terrain conductivity degreases gently from 11 mS/m at the 10 m point down to a value of 9 mS/m at the 30 m and 40 m points and then finally increases again from the 9 mS/m up to 18 mS/m between the stations 40 – 80 m. For the VD mode, the terrain conductivity rises from 8 mS/m up to a value of 11 mS/m between 10 – 30 m stations and from the 30 m station the terrain conductivity falls to a value of 10 mS/m at the 40 m point. This 10 mS/m conductivity value then remains constant between the stations 40 – 60 m and then finally, falls sharply from the 10 mS/m at the 60 m point down to 6 mS/m at the end of the profile at the 80 m station point. Again no point was selected for further VES investigation along this profile.

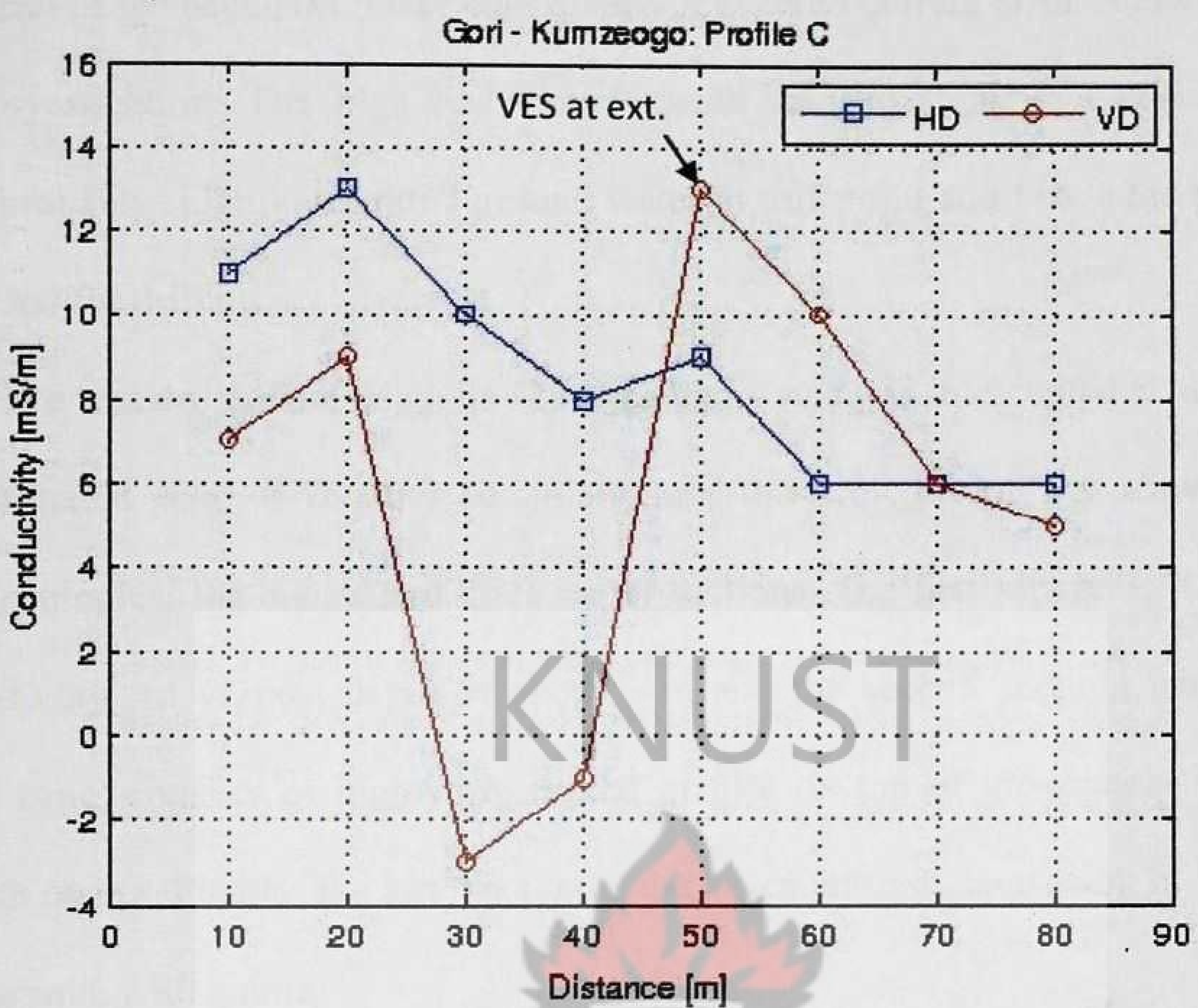

Figure 4.9c EM terrain conductivity profile for traverse Cat Gori - Kumzeogo.

Along profile C the terrain conductivity for the HD and VD modes show an erratic rise and fall in the terrain conductivity from the beginning of the profile at the 10 m point to the end of the profile at the 80 m between the values 6 – 13 mS/m for the HD mode and -3 – 13 mS/m for the VD mode. The only highest conductivity crossover anomaly for the VD mode was observed at the 50 m station along profile C. This may suggest a subsurface geology with faults or fractures which have high potential to accumulate groundwater and hence the 50 m point was selected for further VES investigation. However, a verification short EM profile perpendicular to profile C at the 50 m point indicated a high terrain conductivity of 15 mS/m for the VD mode and 8 mS/m for the HD mode at 10 m from profile C. This was called the C 50 m extension and was selected for the VES investigation instead of the station C 50 m. However, the VES was not successful as the McOHM meter consistently registered current error below the 20 m depth of investigation. The high EM survey result for the C 50 m extension point suggested probably highly saturated ground water at this point and hence the point was recommended for drilling.

When this site was drilled to a depth of 42 m, ground water was intercepted at about 27 m with an estimated yeild of 75 litres per minute and the geologic logis as shown in Fig. 4.9d. The geological log consists of three major sections. The first section is made up of laterite and clay of vertical depth of about 3 m and the second section, which is the weathered zone, consists of highly weathered granite on top of moderately weathered granite with quartz. Finally, the last section is the basement rock consisting of hard fresh fractured granite with quartz.

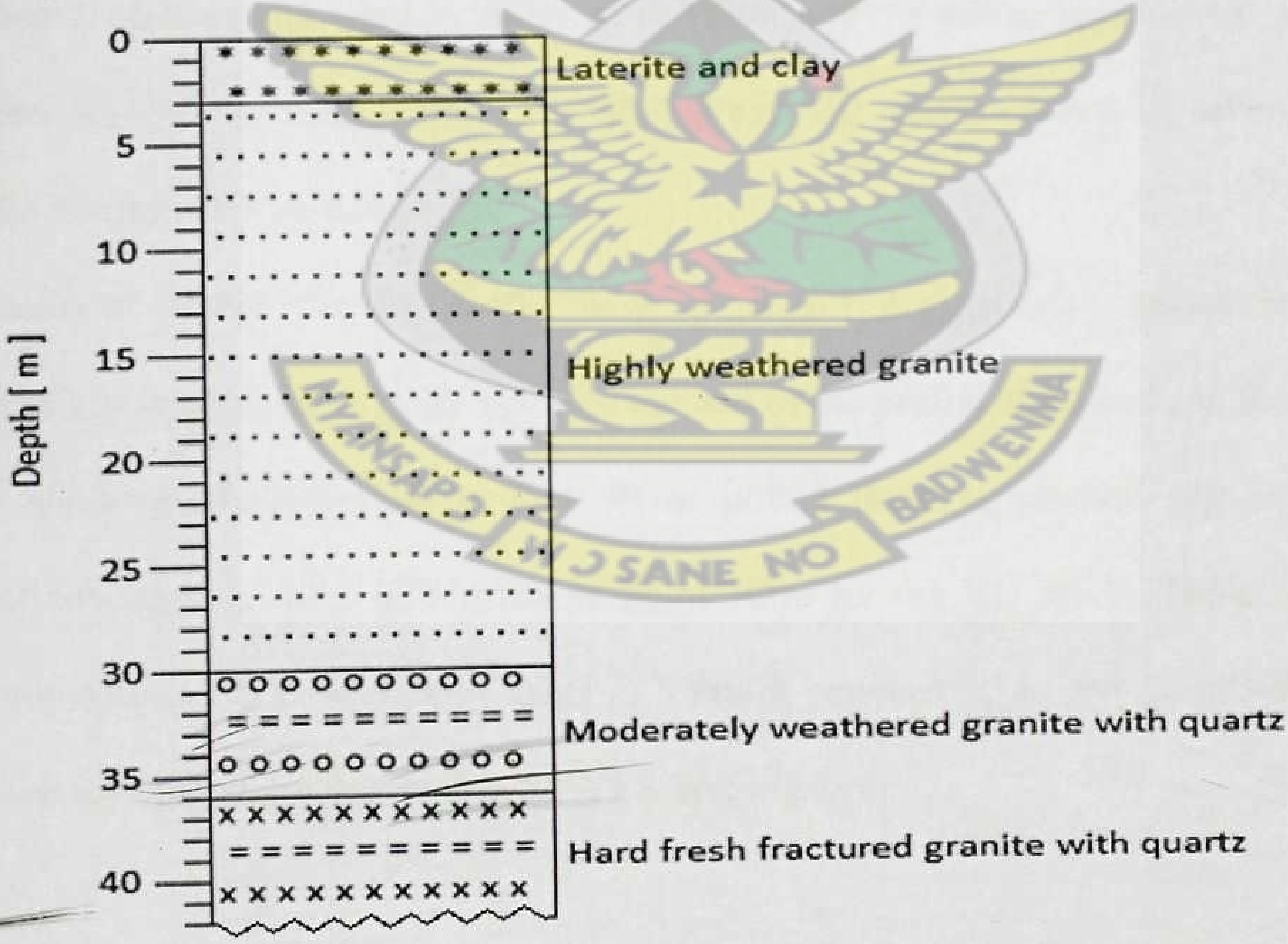

Figure 4.9d Lithologic Log of borehole drilled at the 50 m extension point of profile C at the Gori – Kumzeogo.

4.12 Tetako Primary School Community

Three EM survey profiles were carried out in the community labelled A – C. Fig. 4.10 (a-c) show the variation of terrain conductivity of the corresponding HD and VD modes. Profile A conducted along a bearing of 045° beginning at GPS coordinates of (N 10° 46' 41.652", E 0° 27' 43.728'') and ending at GPS coordinates (N 10°46' 38.807", E 0° 27' 45.890'') shows that the conductivity response of this area is on average low between the 10 m and 70 m points with values ranging from 9 mS/m – 4 mS/m for the HD mode. The conductivity values then rises sharply from 100 m point to 120 m point to a value of 6 mS/m.The VD mode shows that the conductivity at a depth of 30 mis contineusly varying along the profile line for this community. With crossover points at points 30 m, 60 m and 90 m of the same conductivity value 9 mS/m. However, verification across each point indicated a high terrain conductivities of 4 mS/m and 10 mS/m respectively at 10 m extension (ext.) from point A 90 m for the HD and VD modes. Hence its selection as a point for further VES investigation.

The results of profile B in Fig. 4.10b, shows a gentle rise in terrain conductivity values from 6 mS/m at point 10 m to 10 mS/m at the end of the profile at point 50 m for the HD mode. However, between 10 m and 30 m points there is gradual rise in terrain conductivity up to a value of 9 mS/m at point 30 m for the VD mode. There is then a sharp decrease in the conductivity value to 5 mS/m between 30 m and 50 m points. No point was selected along this profile for VES investigation.

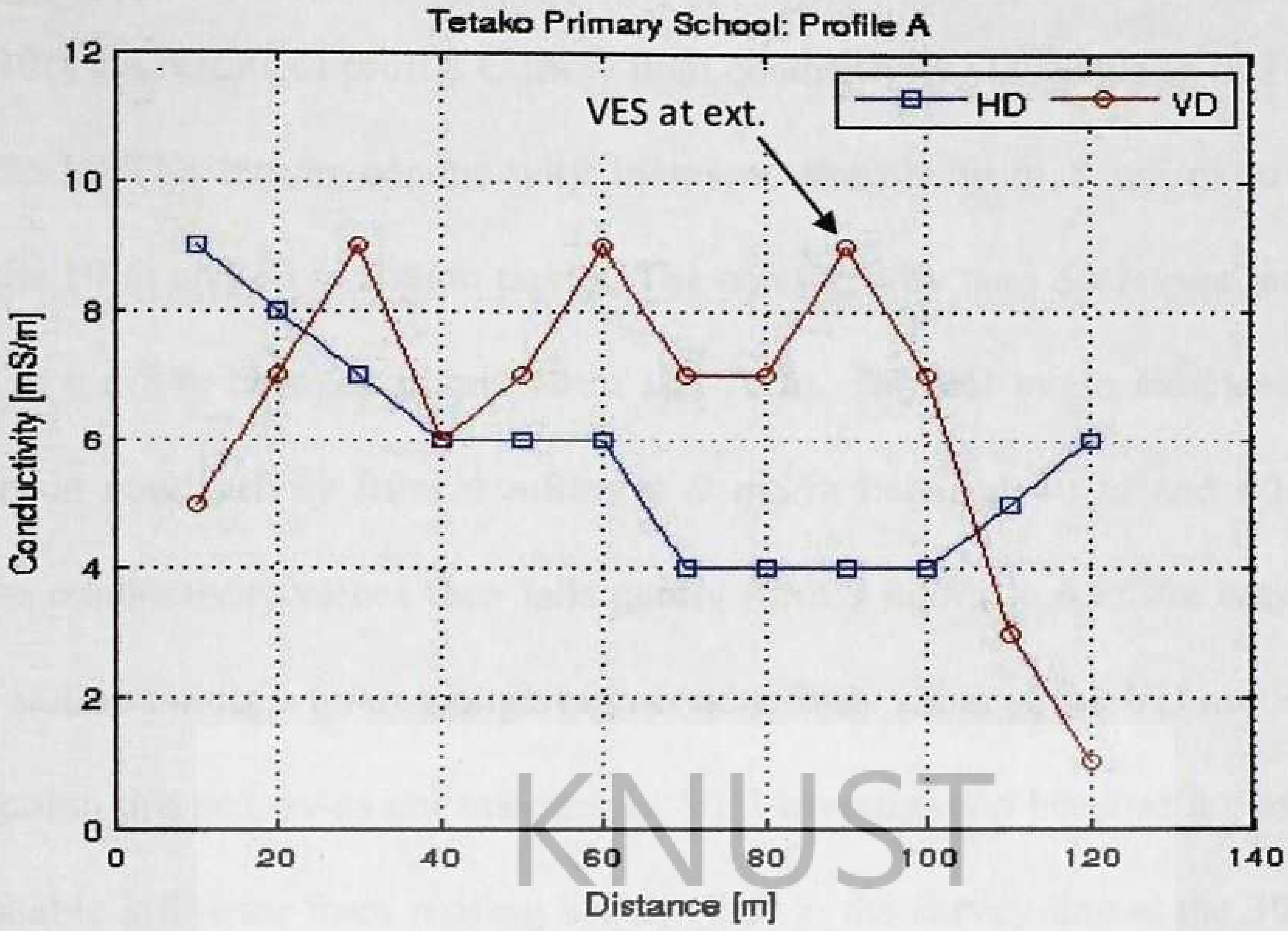

Figure 4.10a EM terrain conductivity profile for traverse A at Tetako primary school.

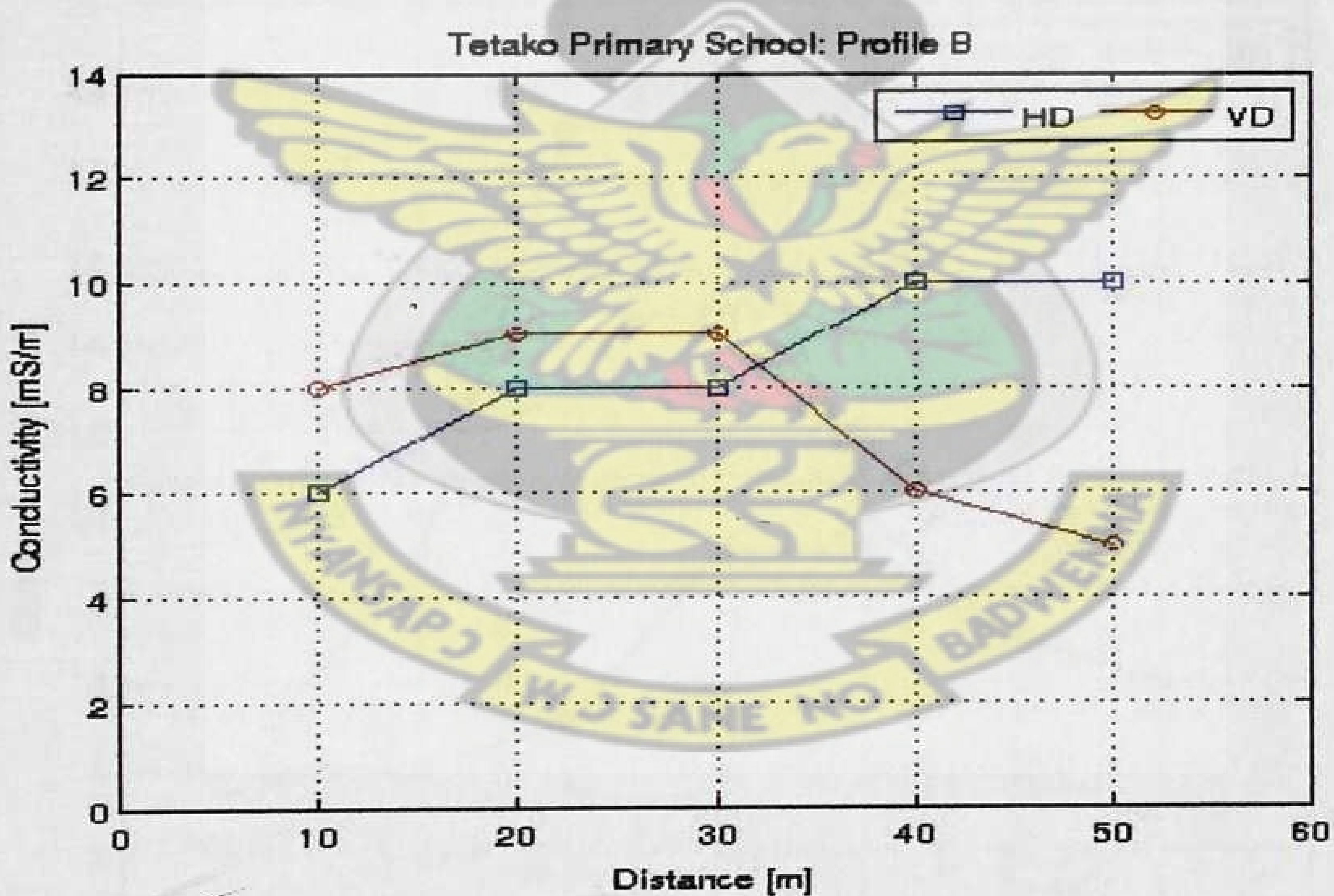

Figure4.10b EM terrain conductivity profile for traverse B at Tetako primary school.

In Fig. 4.10c, the results of profile C show high conductivity values along this profile for the VD mode. The terrain conductivity increases sharply from 5 mS/m to 19 mS/m between the 10 m and 30 m station points. The conductivity then decreases sharply from 19 mS/m to 6 mS/m between points 40 m and 70 m. The HD mode indicates a smooth rise in terrain conductivity from 4 mS/m to 9 mS/m between 10 m and 40 m station points. The conductivity values then falls gently from 9 mS/m to 6 mS/m between 50 m and 70 m station points. Even though high conductivity value of the VD mode occurs at the 30 m point, this point was not selected for VES investigation because it was attributed to the probable influence from roofing sheets close to the survey line at the 30 m and 40 m points.

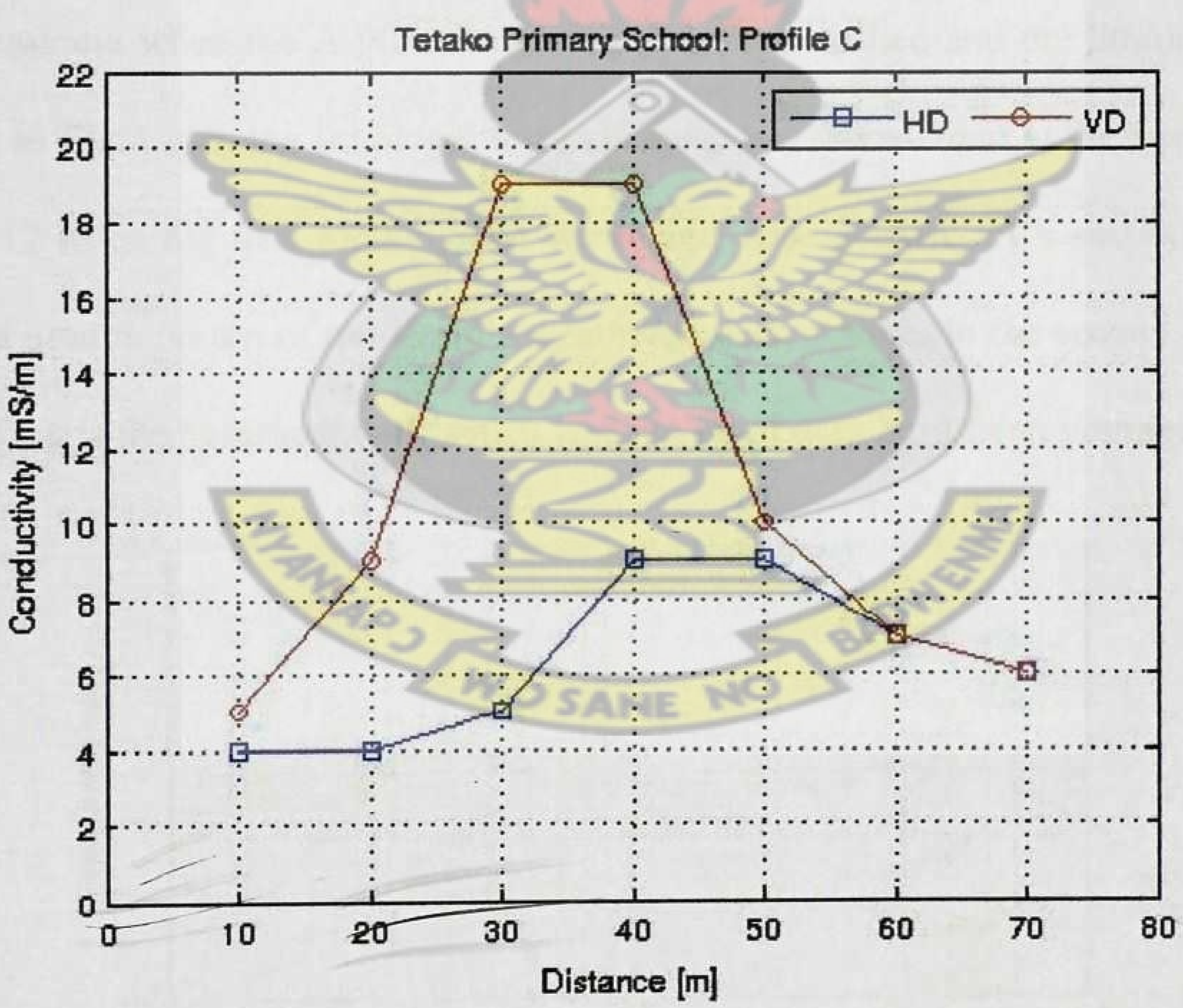

Figure4.10c EM terrain conductivity profile for traverse Cat Tetako primary school.

4.13 VES Interpretation

The resistivity curve obtained after the A 90 extension point at the Tetako primary school was drilled as shown in Fig.4.11a. The resisitivity curve indicates a decrease in the apparent resisitivity value from 110 ohm.m in the overburden down to 57 ohm.m in the weathered zone. This indicates that the weathered zone may be highly saturated with ground water and hence the site recommended for drilling. The vertical depth of the weathered zone is about 16 m which correlates linearly with large quantity of ground water storage at the site. The depth to the bedrock is approximately 20 m with a high apparent resisitivity value of 296 ohm.m.

Groundwater zone was intercepted at a depth of about 17 m with an estimated yield of 10 litres per minute when the A 90 m extension point was drilled and the lithologic log as presented in Fig.4.11b. the lithologic log indicatesa weathered zone at the vertical depth of about 12 m as the first section. The weathered zone consists of a section of highly weathered granite on top of moderately weathered dark granite. In the second section the lithologic log is the basement rock which is made up of dark hard fresh granite.

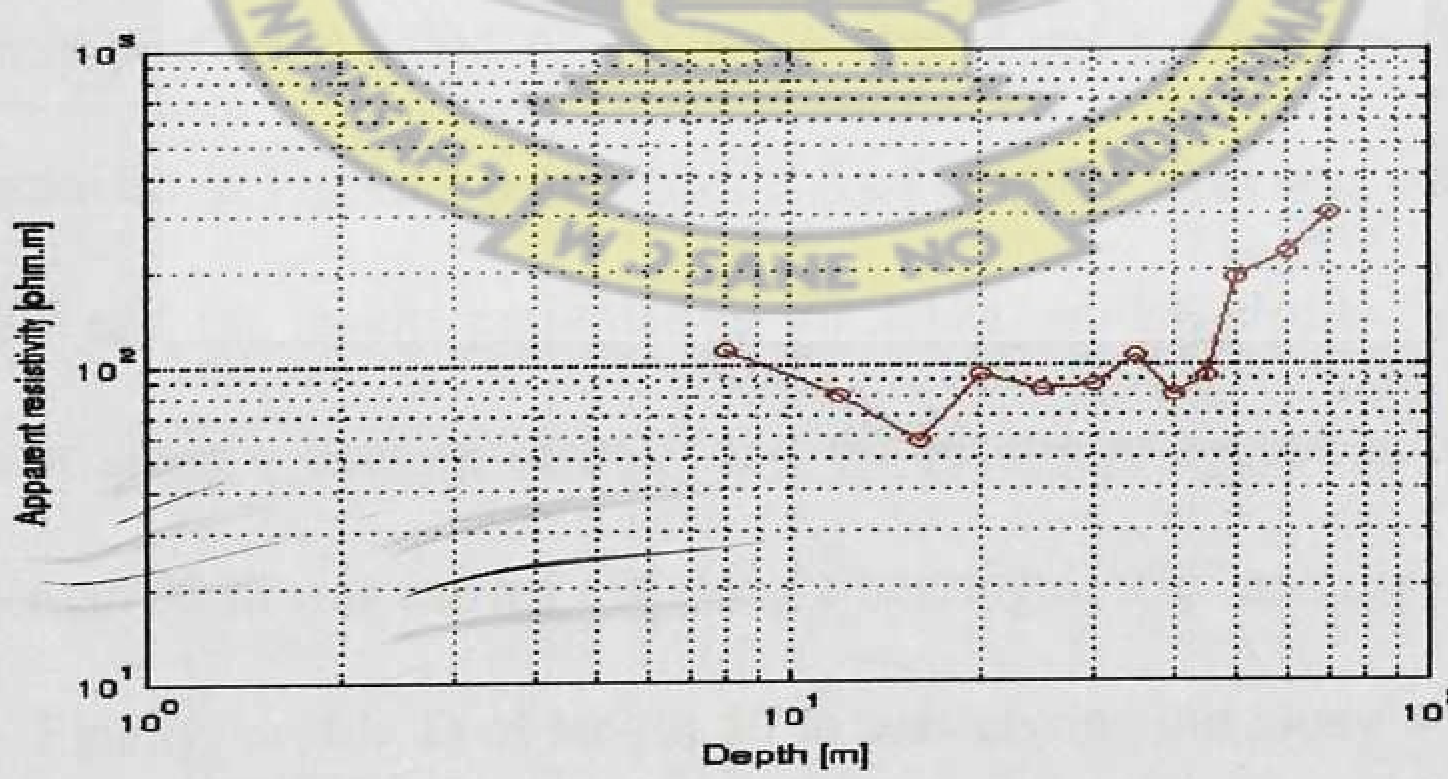

Figure 4.11a VES of Apparent resistivity against Depth at station A 90 extension at Tetako Primary School.

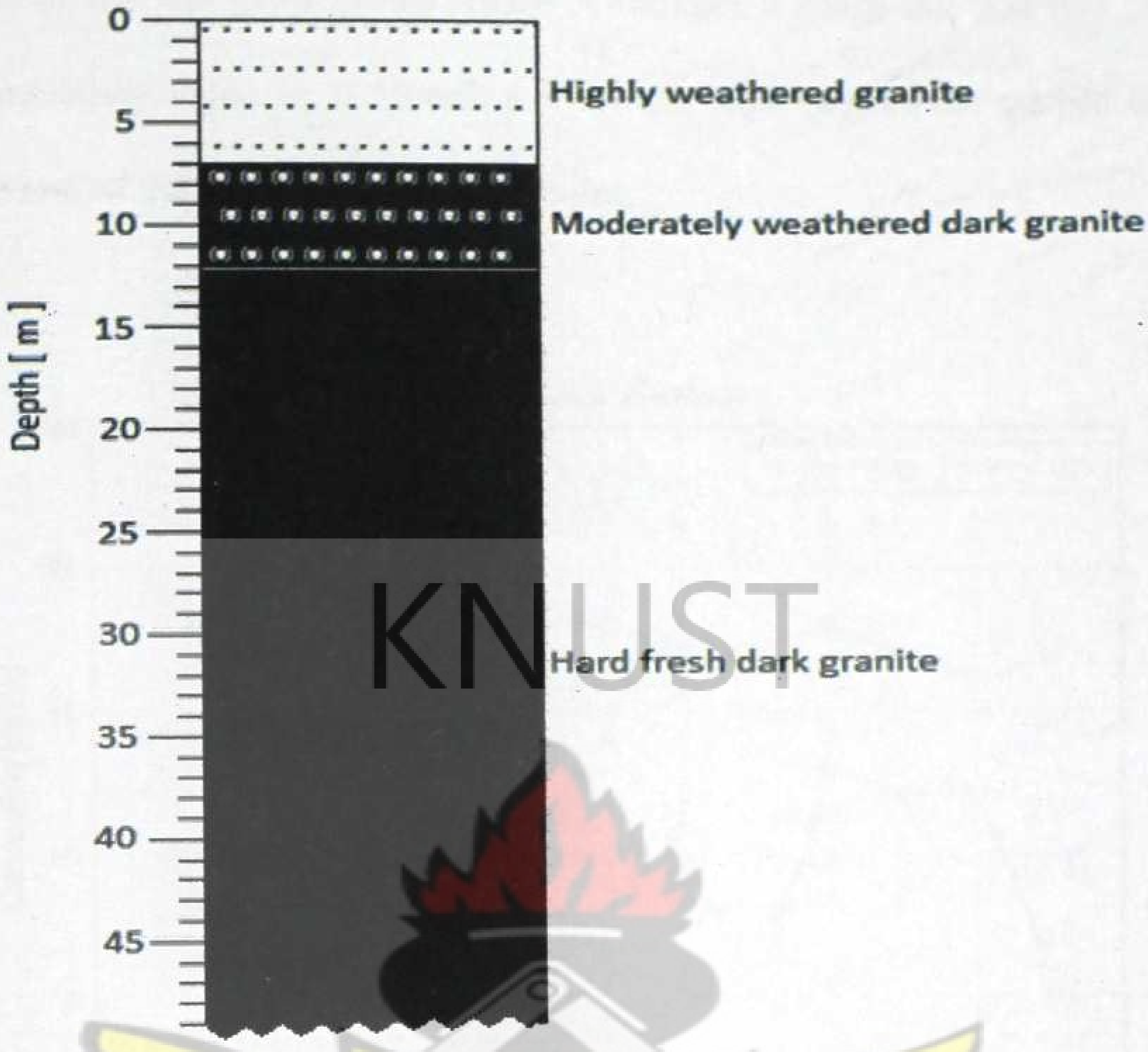

Figure 4.11b Lithologic Log of borehole drilled at the 90 m extension point of profile A at Tetako Primary School.

4.14 Alamvose Community

Four EM survey profiles labelled A – D, were carried out in Alamvose community and the results presented in Fig.4.12 (a-d). Profile A of length 130 m was conducted along a bearing of 080° and the results presented in Fig.4.12a. whilst, profile B of length 80 m was carried out along a bearing of 360° and the results presented in Fig. 4.12b. also, profile C of length 90 m was carried out along a bearing of 030° and the results presented in Fig. 4.12c. Finally, profile D of length 50 m was carried out along a bearing of 360° and the results presented in Fig. 4.12d.

The results of the HD mode along profile A indicate a sharp fall and rise between the terrain conductivty value 19 – 15 mS/m from the beginning of the profile at the 10 m point tothe end of the profile at the 130 m point.

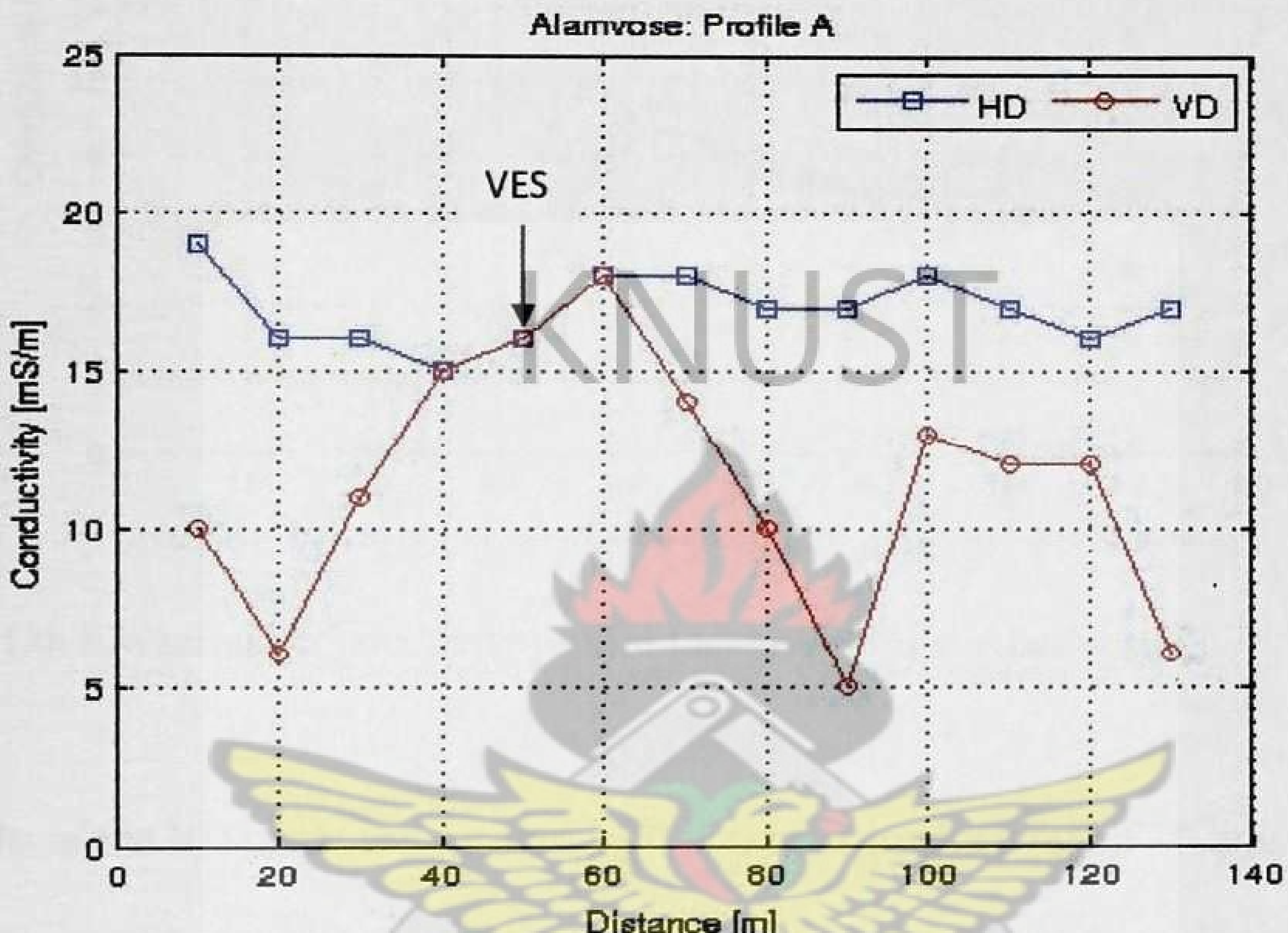

Figure 4.12a EM terrain conductivity profile for traverse A at Alamvose.

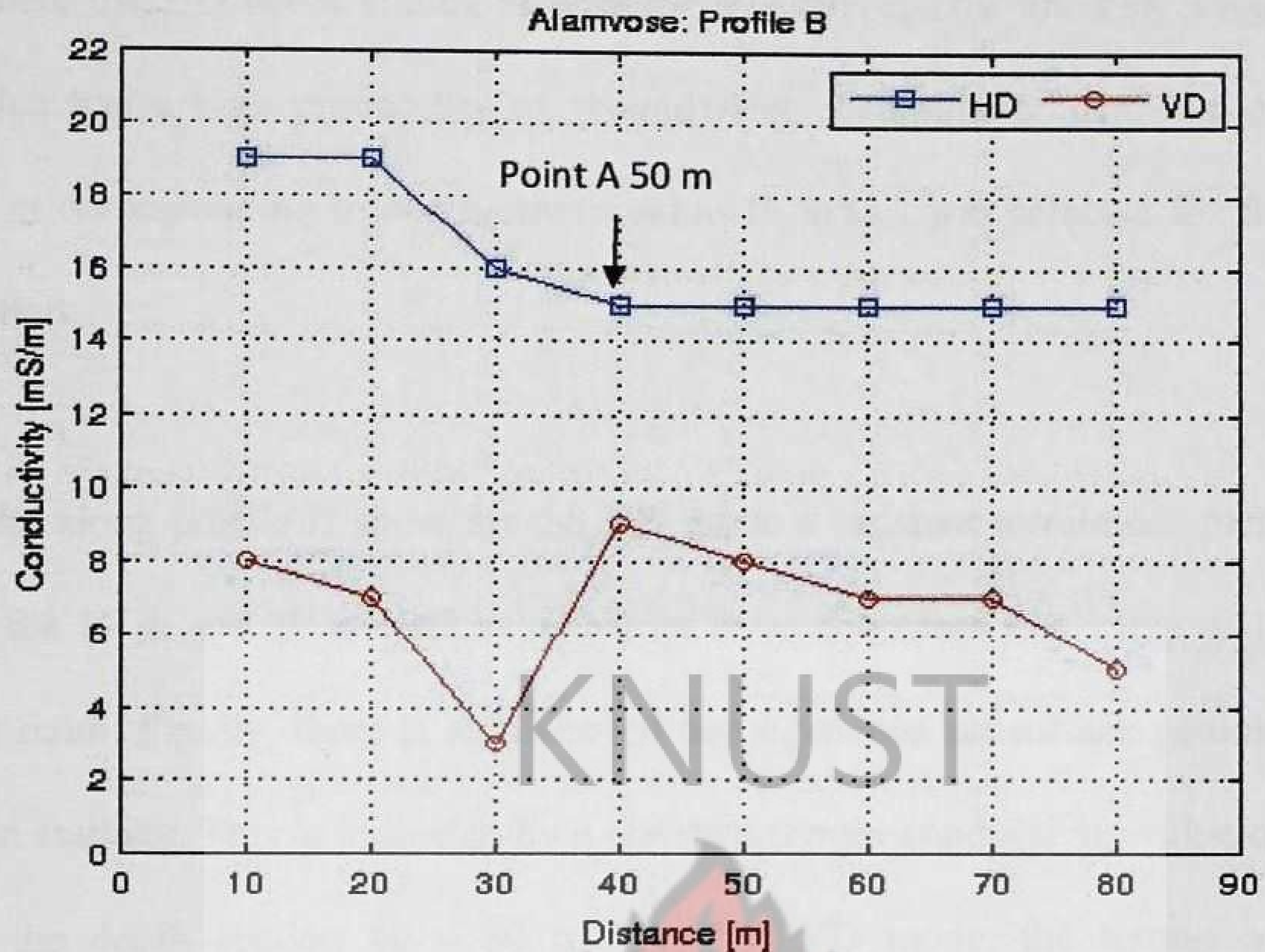

Figure 4.12b EM terrain conductivity profile for traverse B at Alamvose.

The results of the VD mode show a sharp fall in terrain conductivity of 10 mS/m at the 10 m point down to a value of 4 mS/m at the 20 m station and from there the conductivity value increases until it coincided with that of the HD mode at the 40 m station with corresponding terrain conductivity of 15 mS/m. This coincidence of the HD and VD conductivity values increases for both modes up to a value of 18 mS/m and 16 mS/m respectively at the 60 m station. The terrain conductivity for the VD mode then decreases sharply from 16 mS/m at the 60 m down to a value of 5 mS/m at 90 m, which is then followed by a sharp rise in the conductivity value up to a value of 13 mS/m at 100 m station. Again, the conductivity value for the VD mode decreases slowly from 13 mS/m at 100 m point down to 12 mS/m at 110 m and 120 m station points and then finally falls sharply from the value of 12 mS/m at the 120 m station down to a value of 6 mS/m at 130 m station. Theobserved high conductivity anomaly is observed between the 40 – 60 m points where the HD curve coincides with the VD curve. This anomaly suggest a fault zone which has a high probability of groundwater accumulation and hence the mean point 50 m corresponding to conductivity value 16 mS/m was selected for further VES investigation.

The results along profile B show for the HD mode a canstant terrain conductivity of 19 mS/m at the 10 m and 20 m stations and from there decreases to a value of 15 mS/m at the 40 m point. Finally, there is an observed homogeneous subsurface geology between 40 – 80 m stations. This is indicated by a constant terrain conductivity value of 15 mS/m between the depth section 40 – 80 m.. For the VD mode, the terrain conductivity decreases from 8 mS/m at the 10 m station to 3 mS/m at the 30 m station and from there a sharp rise in the terrain conductivity to a value of 9 mS/m is observed between 30 and 40 m points. This is followed by a gradual decrease in the conductivity from 9 mS/m at 40 m point down to 7 mS/m at the 60 m and 70 m points and then finally decreases again from 70 m point to a value of 5 mS/m at the end of the profile at the 80 m point. No conductivity anomaly was observed and subsequently no point was selected for VES investigation.

Along profile C, the terrain conductivity for the HD mode increases from 13 mS/m at the 10 m point to 15 mS/m at the 20 m and 30 m station points, from there the conductivity value decreases from 30 m down to a value of 14 mS/m at 40 m and 50 m points. This is followed by an increase in the terrain conductivity from the value of 14 mS/m up to 17 mS/m between the stations 50 – 70 m. Finally, the conductivity value of 17 mS/m remains the same for the 70 m and 90 m points, except a marginal decrease in value to 16 mS/m at the 80 m point. For the VD mode the terrain conductivity value of 8 mS/m remains the same for the 10 m and 20 m points and then decreases down to 7 mS/m at 30 m, from there a sharp rise in the conductivity value up to 11 mS/m is observed for the 40 m and 50 m points. This is followed by a continuous fall in the terrain conductivity from 11 mS/m at the 50 m point down to a value of 6 mS/m at the 60 m point and then increases from the 60 m up to the value of 9 mS/m at 70 m point. Finally, the terrain conduccity decreases from 9 mS/m down to the lowest value of 2 mS/m between the stations 70 – 90 m. No point was selected for VES investigation along this profile.

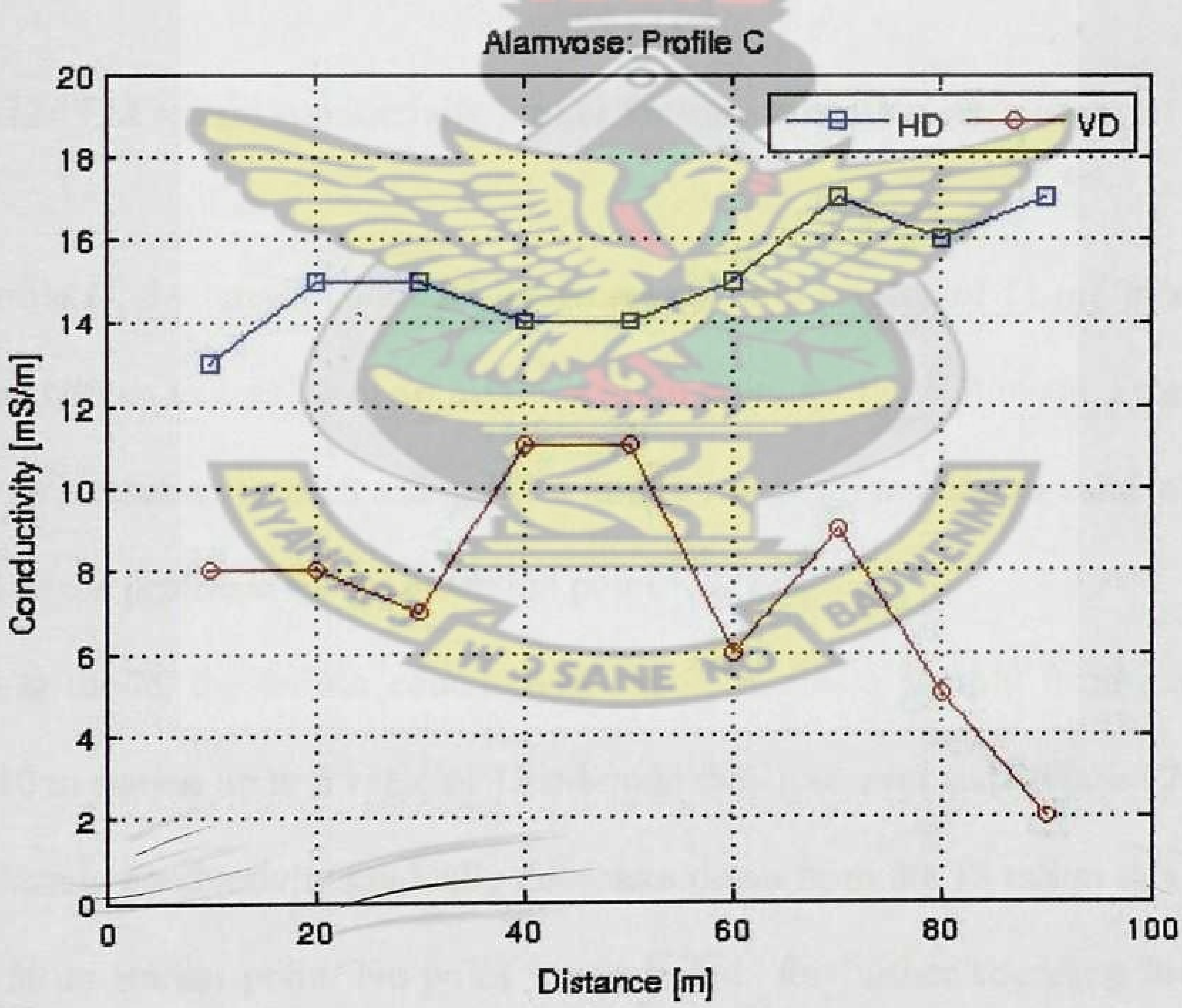

Figure 4.12cEM terrain conductivity profile for traverse C at Alamvose.

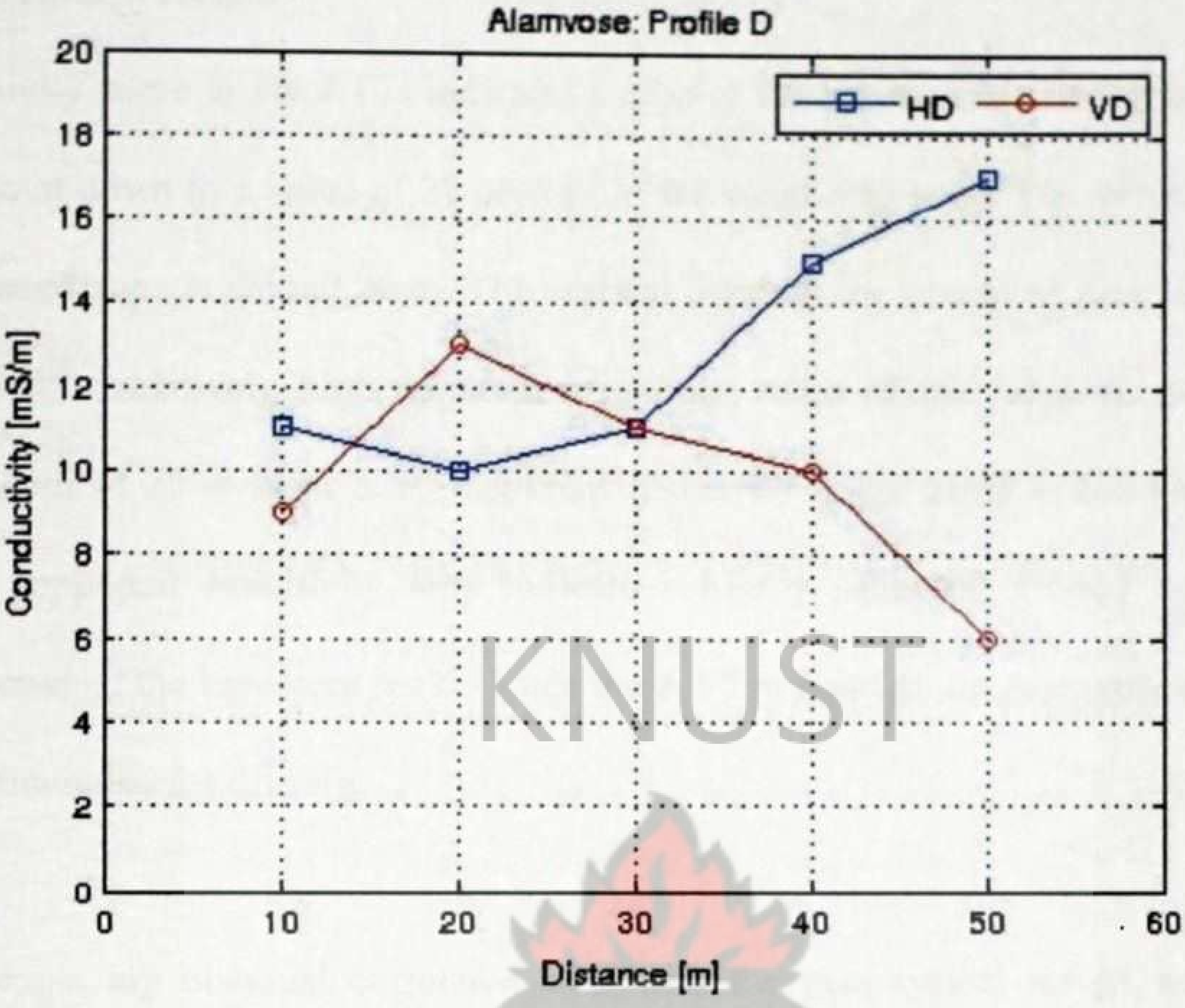

Figure 4.12d EM terrain conductivity profile for transverse D at Alamvose.

Along profile D, the terrain conductivity decreases from a value of 11 mS/m at the 10 m station point down to a value of 10 mS/m at 20 m point for the HD mode. From there the conductivity decrease from 10 mS/m till it finally reaches a maximum value of 17 mS/m at the end of the profile at the 50 m station point.

For the VD mode, the terrain conductivity value increases sharply from a value of 9 mS/m at 10 m station up to a value of 13 mS/m at the cross over station point 20 m. From there the terrain conductivity gradually decreases down from the 13 mS/m to a value of 6 mS/m at 50 m station point. No point was selected for further sounding investigation along traverse D.

4.15 VES Interpretation

The resistivity curve in Fig.4.13a indicates a drop in the apparent resisitvity from a value of 26 ohm-m down to a value of 21 ohm-m in the weathered zone. The vertical depth of the weathered zone is around 20 m. The vertical depth to the basement rock is around 21 ohm-m with a relatively high apparent resistivity value of 206 ohm-m. Between the vertical depth of 25 – 40 m is the apparent resistivity range of 68 – 106 ohm-m. This range of appparent resisitivity may indicate a highly saturated ground water in the fracture zones of the basement rock. Hence the A 50 m point at the Alamvose community was recommended for drilling.

The lithologic log obtained correlated well with the geophysical results as shown in Fig.4.13b. The lithologic log indicates three main sections, with the brown loose caly, lateritic top soil at a depth of about 3 m being the first section. The second section is the weathered zone, which consists of highly – weathered granite and clay on top of slightly weathered granite with quartz. The last section is the basement rock consisting of hard fresh fractured granite on top of hard fresh fractured greenish granite. Groundwater zone was intercepted at a depth of about 21 m with an estimated yield of 110 litres per minute.

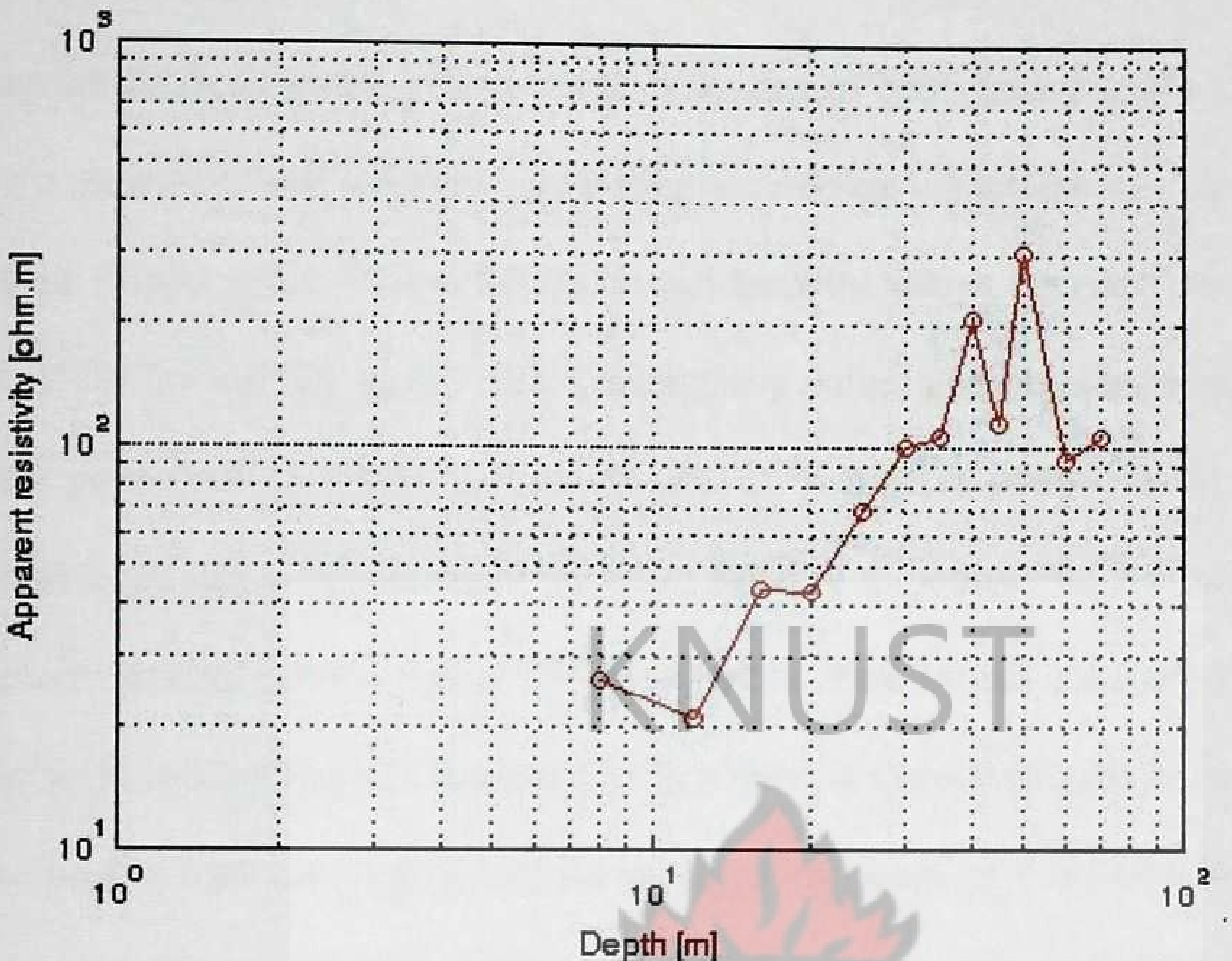

Figure 4.13a VES of Apparent resistivity against Depth at station A 50 m in Alamvosecommunity.

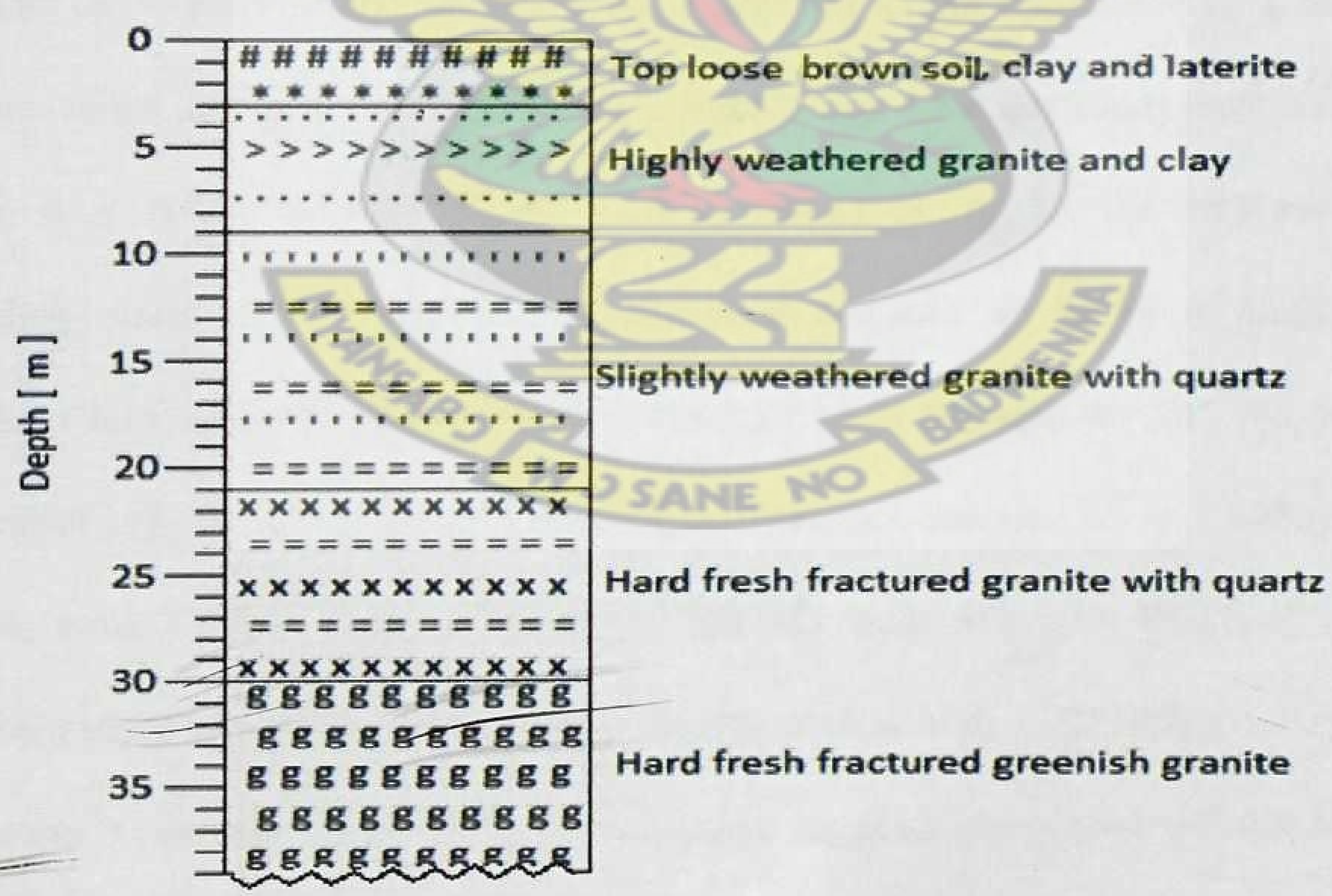

Figure 4.13b Lithologic Log of borehole drilled at the 50 m point of profile A at the Alamvose community.

4.16 Gumbo Community

Along profile A, of length 180 m and on a bearing of 130°, both the HD and VD curves show a general erratic behavior suggesting a complex subsurface geology (Fig. 4.14a). Between station points 10 m – 90 m, the conductivity values increases from a value of 0 to 8 mS/m for the HD mode. This conductivity value then remains constant up to the station point 110 m where it falls steeply to 6mS/m at point 120 m indicating a homogeneous subsurface between the 90 m and 110 m points. The HD mode curve then increases between station points 130 m – 180 m from terrain conductivity values of 7 mS/m to 13 mS/m. The VD mode shows that there is a low conductivity values along the entire profile with the highest terrrain conductivity value of 8 mS/m occuring between 130 m and 140 m points.No point was therefore selected for VES investiation along profile A.

The results of profile B in the Gumbo community with length 120 m and on a bearing of 040° is as shown in Fig. 4.14 b. The terrain conductivity value decreases marginally from 9 mS/m to 7 mS/m between 10 m - 20 m station points for the HD mode. The conductivity value of 7 mS/m is then remained constant up to 60 m station point indicating a homogeneous subsurface at a depth of 15 m between the 20 – 60 m points. The conductivity values for the HD mode then increases between 60 m – 120 m station points from the 7 mS/m value to 26 mS/m. The VD mode of profile B shows a general erratic behaviour along the entire profile length with a high conductivity value of 15 mS/m at the "crossover" point of 90 m. This point suggests a probable fault zone of high groundwater storage, hence selected for VES investigation. However, verification profile perpendicular to profile B across the point 90 m gave high terrain conductivities of 13 mS/m and 17 mS/m respectively for the HD and VD modes at 10 m extension (Ext.) from the 90 m point. As a result the VES investigation was made for this extension point rather than the 90 m station point.

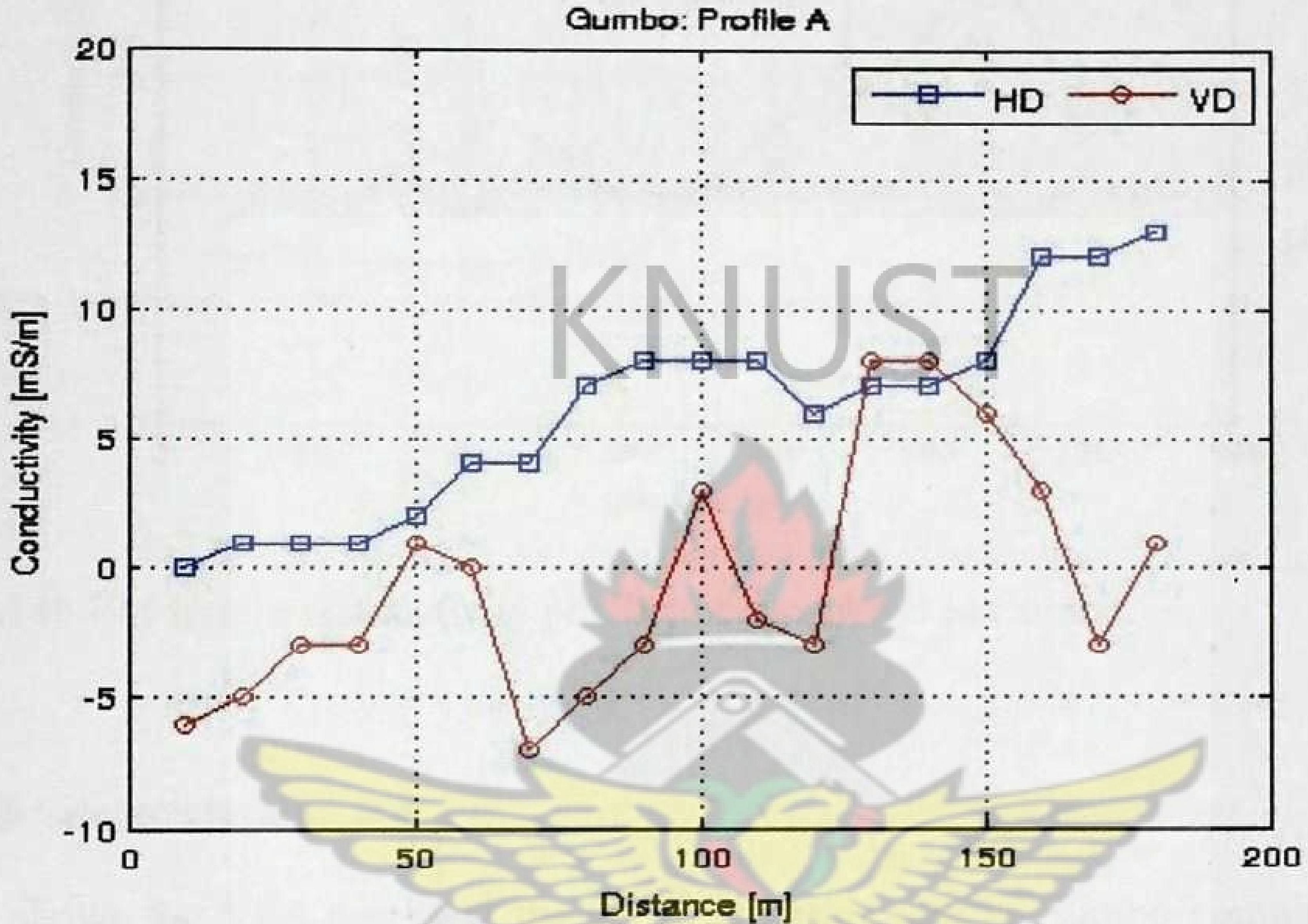

Figure 4.14a EM terrain conductivity profile for traverse A at Gumbo.

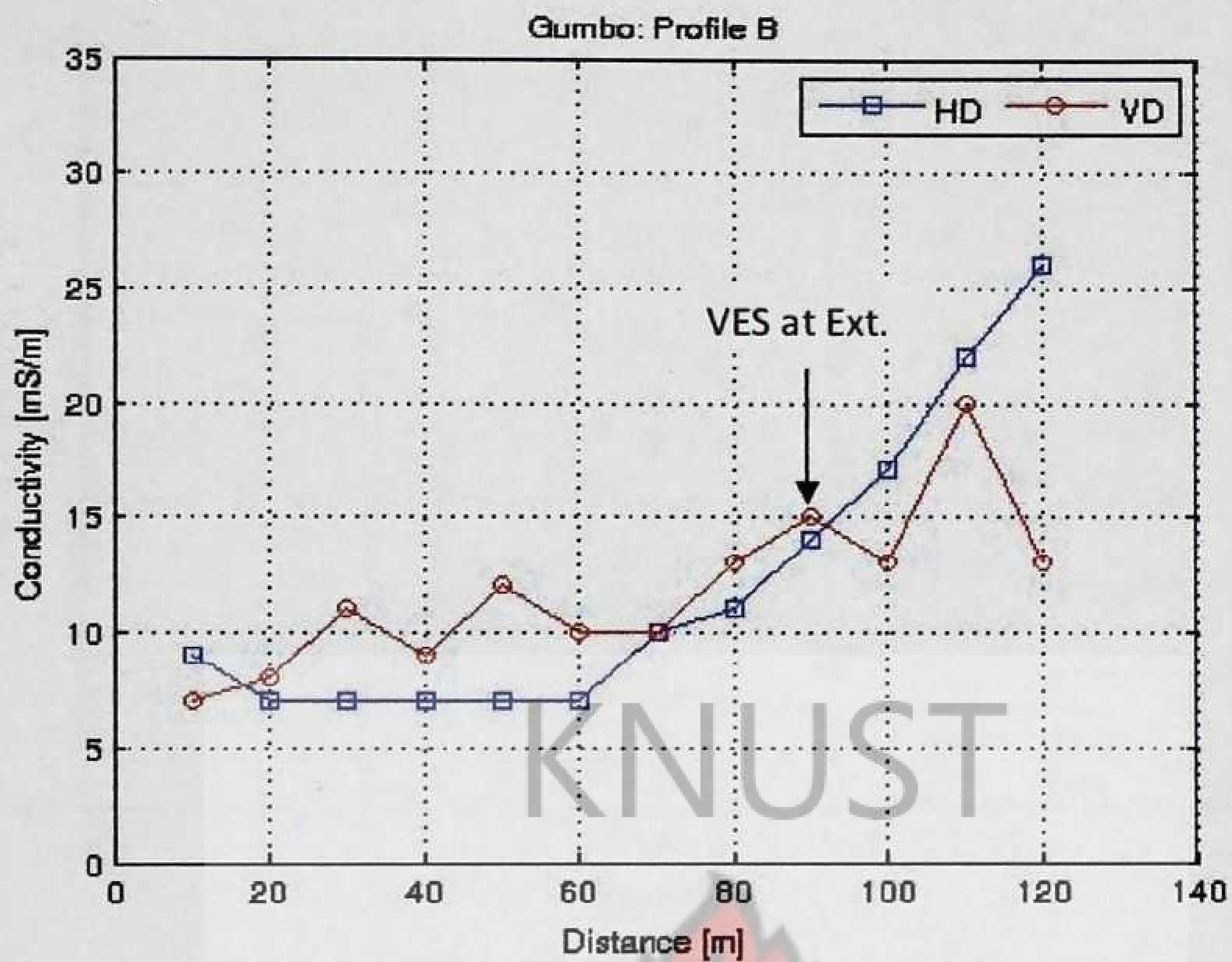

Figure 4.14b EM terrain conductivity profile for traverse B at Gumbo.

4.17 VES Interpretation

Fig.4.15 shows the VES results at the 90 m extension site in Gumbo community. The VES curve indicates a drop in apparent resistivity from 57 ohm-m at a depth of 16 m down to a value of 23 ohm-m. The depth to the basement rock is about 20 m. Between the vertical depth 45 – 70 m within the basement rock is the apparent resistivity value lying in the range of 53 – 75 ohm-m. This may indicate a highly saturated groundwater in the fractures of the basement rock and hence the site recommended for drilling. When the site was drilled on the first day, a good yield of 12 l/m was obtained. However, on the second day the measurement of the yield had reduce to 6 l/m. The borehole was therefore declared dry.

Figure 4.15 VES of Apparent resistivity against Depth at station B 90 m extension in Gumbocommunity.

4.18 Yelwoko – Azambare Community

Profiles A of length 120 m and bearing 110°and profile B of length 60 m and on bearing 110° are the profiles that were conducted in this community and the results are as shown in Fig. 4.16 (a,b). The results of the HD mode for profile A in Fig 4.16a, shows a constant terrain conductivity of value – 2 mS/m for the station points 10 m, 20 m and 30 m. The coductivity value then rises gently to a value of 12 mS/m at 100 m point and remains the same at 110 m station point. The conductivity value further increased from the 110 m point to the end of the profile at a value of 13 mS/m. For the VD mode, a sudden decline in conductivity value from -2 mS/m at 10 m point to -6 mS/m at point 20 m can be observed. From there the conductivity value then rises to a value of 0 mS/m at the 40 m point. The conductvity value again decline to a very low value of -16 mS/m at the 60 m point and further increases erratically to -15 mS/m at the 80 m survey point. This is followed by a smooth rise in the conductivity from -15 mS/m to 1 mS/m between 80 – 110 m points and then decline sharply to a value of -5 mS/m at the end of the profile. No station point was selected for further investigation using the VES method.

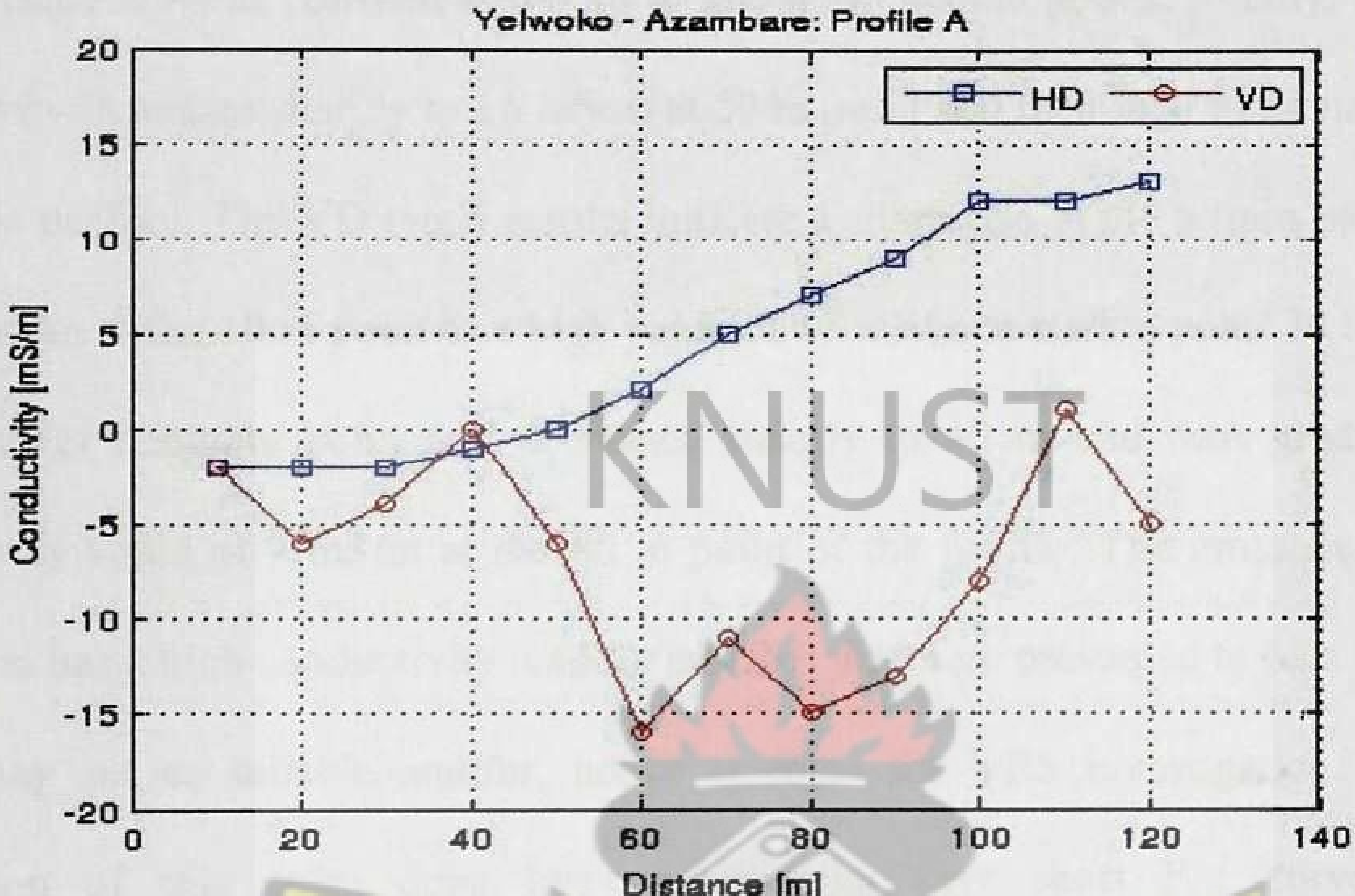

Figure 4.16a EM terrain conductivity profile for traverse A at Yelwoko - Azambare.

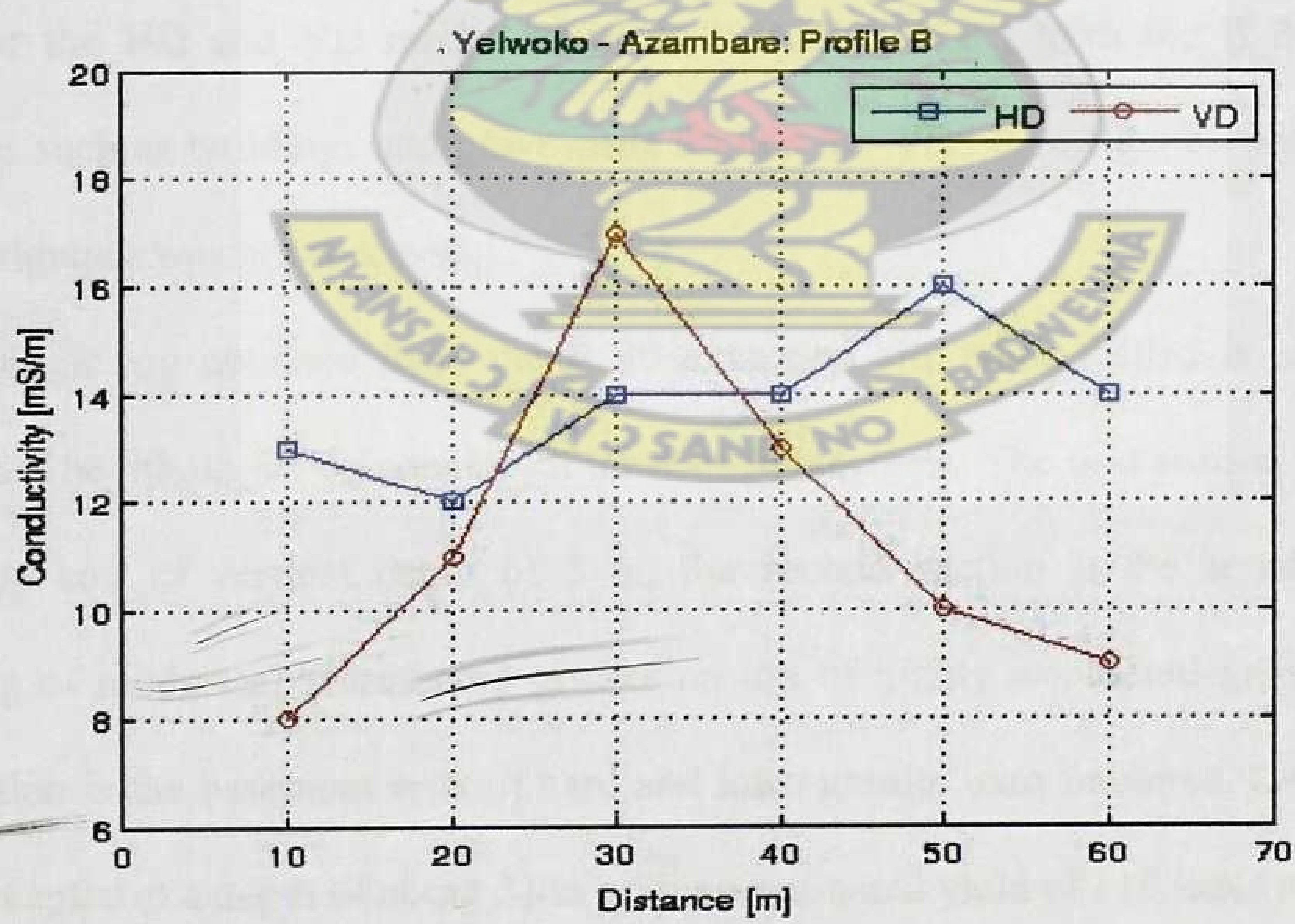

Figure 4.16bEM terrain conductivity profile for traverse Bat Yelwoko - Azambare.

Profile B shows an erratic behaviour for the HD mode with a sharp decline in conductivity value from 13 mS/m at the 10 m point, and 12 mS/m at the 20 m point. The conductivity value then increase slightly to a value of 14 mS/m at the 30 m profile point and this value remains constant at the 30 m and 40 m station points. Finally, the terrain conductivity increases sharply to 16 mS/m at 50 m point and then falls to 14 mS/m at the end of the profile. The VD mode results indicate a sharp rise in the terrain conductivity from 8 mS/m at the 10 m point to a high value of 17 mS/m at station point 30 m which is the crossover anomaly point and decreases sharply to 40 m and then gradually to a conductivity value of 9 mS/m at the 60 m point of the profile. The crossover anomaly point 30 m has a high conductivity reading and it is therefore presumed to be a fault zone, which may act as suitable aquifer, hence selected for VES investigation. However, verification of this point done by conducting a very short EM survey profile perpendicular to profile B and across point B 30 m indicated high terrain conductivity values for the HD and VD modes at 10 m extension (Ext.) from the B 30 m point. Structures such as buildings and graveyards limited the VES investigation and therefore, the investigation was not successful.

The lithologic log obtained from the B 30 extension site when drilled is as shown in Fig.4.16c. The lithologic log consists of three major sections. The first section is the loose brown top soil of vertical depth of 3 m, the second section is the weathered zone consisting of moderately weathered granite on top of highly weathered granite and the third section is the basement rock of hard and intro-granite with fractures. Ground water was intercepted at a depth of about 21 m with an estimated yield of 110 litres per minute.

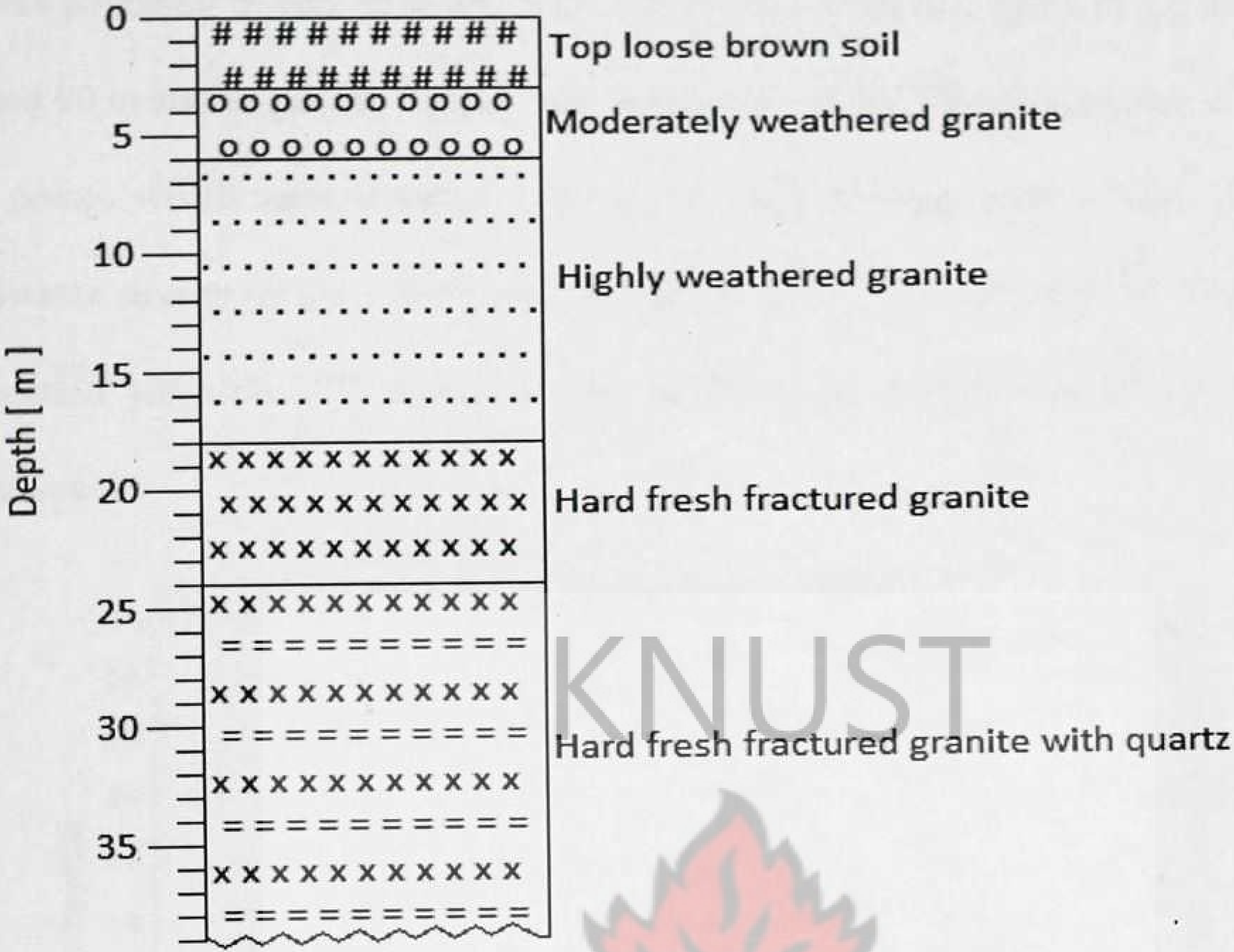

Figure 4.16c Lithologic Log of borehole drilled at the 30 m extension point of profile B at the Yelwoko – Azambare.

4.19 Teshie CHPS Centre Community

The results of profile A in Fig.4.17a, profile length 90 m and on a bearing 010°, show a gentle increase in terrain conductivity along the profile from the 10 m point at the value of 15 mS/m to a value of 18 mS/m at the 40 m and 50 m points point for the HD mode. The conductivity value then rises sharply to a high value of 21 mS/m at the 60 m point and then falls sharply back to 15 mS/m at the station point 70 m and 80 m. Finally, the value falls gently from 15 mS/m at the 80 m point to 14 mS/m at 90 m point. For the VD mode, the conductivity value of 13 mS/m is constant for the 10 m and 20 m points along the survey traverse and then suddenly decreases to a value of 8 mS/m at the 40 m point. From there, the conductivity value increases back to the highest value of 22 at the crossover points 60 m and 70 m and then falls sharply back to a value of 12 mS/m at the 80 m and 90 m station points. The crossover anomaly of the VD mode occurs at 60 m and 70 m points which may indicate faulting or fracture zone with a high probability groundwater accumulation. However, the 60 m point was selected for further VES investigation since the HD mode reading at the point is high which may suggest a fracture zone.

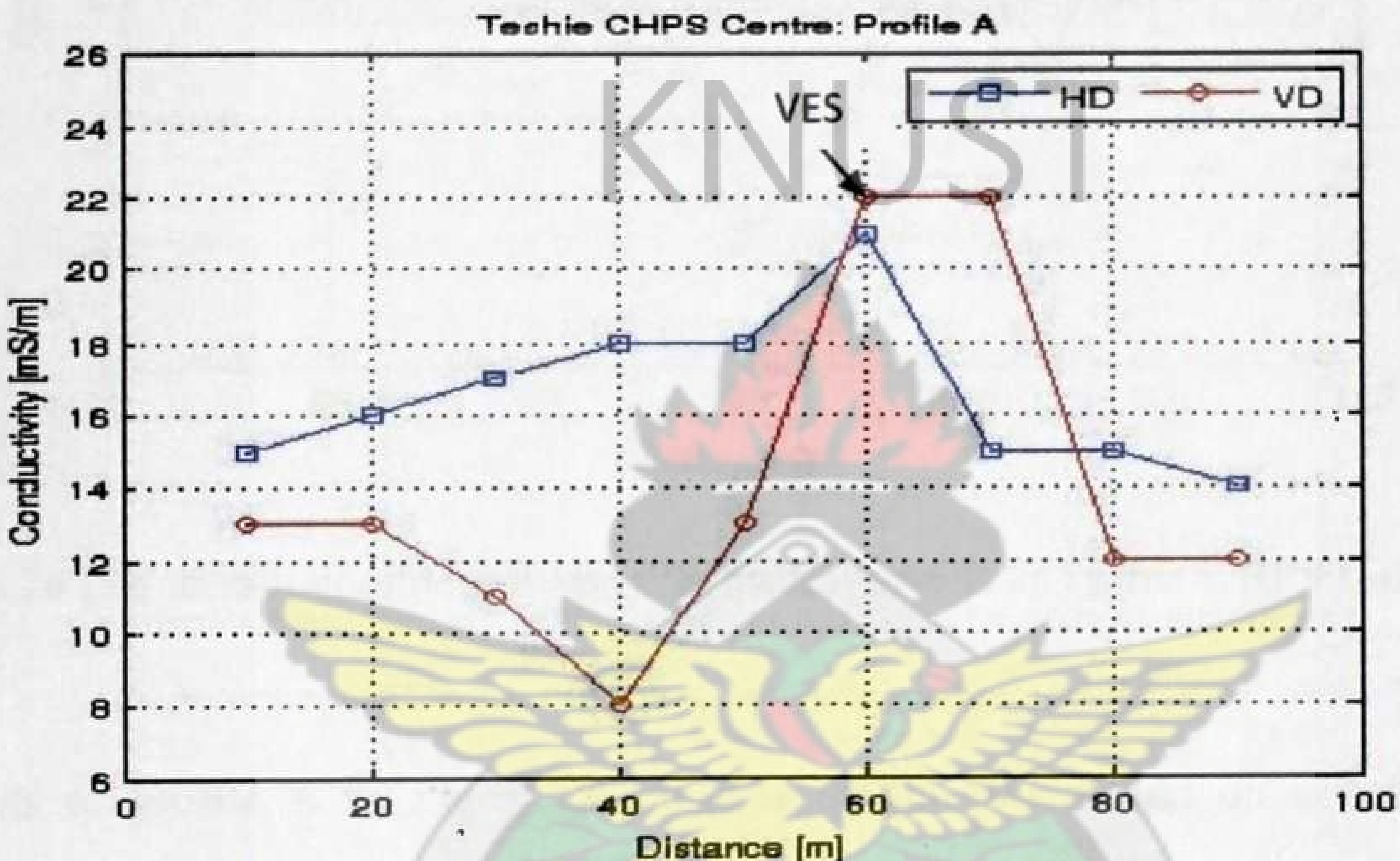

Figure 4.17a EM terrain conductivity profile for traverse A at Teshie CHPS Centre.

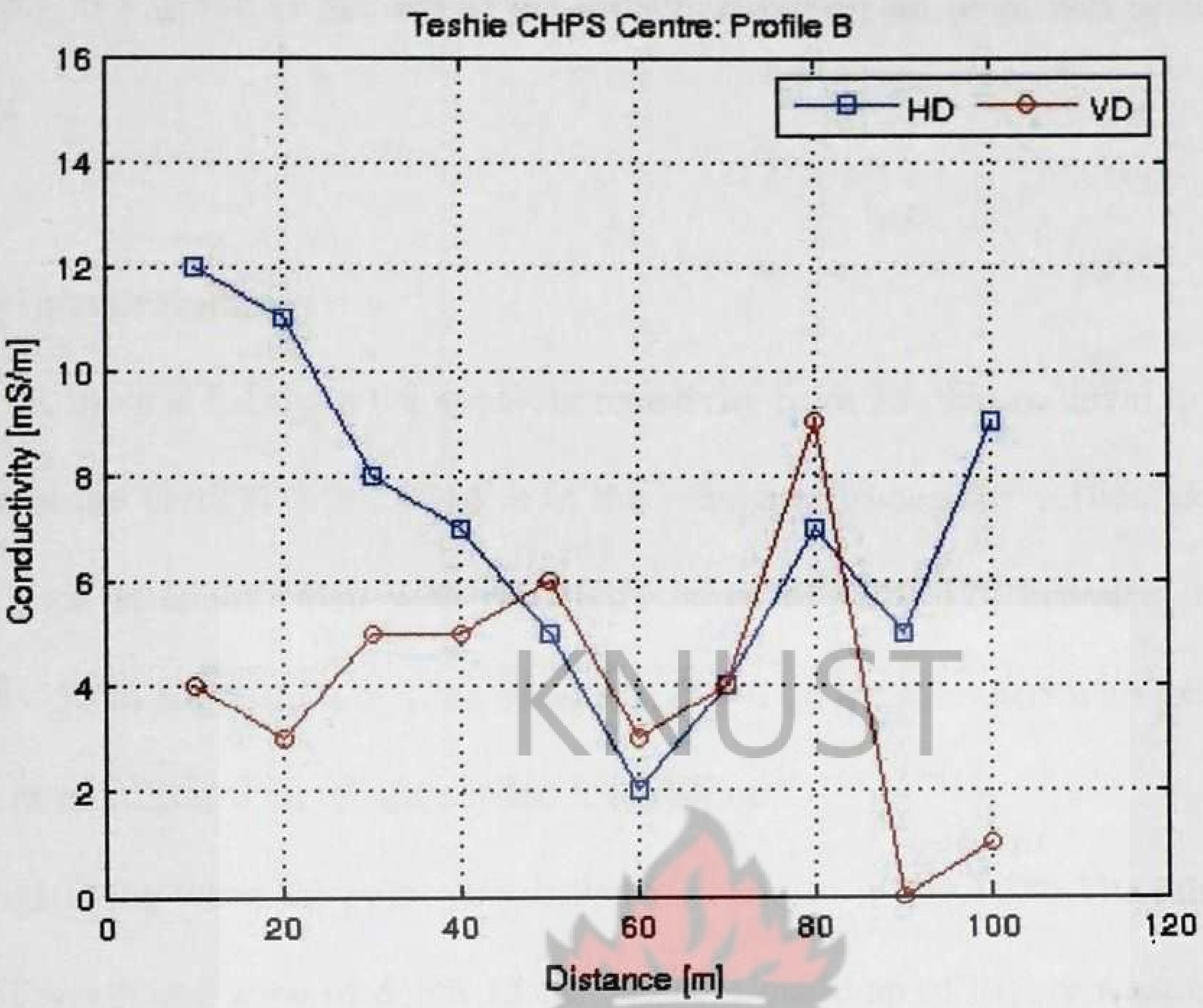

Figure 4.17b EM terrain conductivity profile for traverse B at Teshie CHPS Centre.

The results of profile B in Fig. 4.17b, profile length 100 m and on a bearing 010°, indicate a continuous decrease in terrain conductivity from 12 mS/m to 2 mS/m between 10 – 60 m station points and then increase shaply to a value of 7 mS/m at the 80 m point for the HD mode. Again, the conductivity value decreases sharply from 7 mS/m at point 80 m to 5 mS/m at point 90 m and then finally increases sharply to a value of 9 mS/m. The VD mode results along profile B also indicate a decrease in conductivity from a value of 4 mS/m at 10 m profile point to 3 mS/m at 20 m profile point. The conductivity response values increases sharply to 5 mS/m at points 30 m and 40 m and then increses gently to a value of 6 mS/m at 50 m station. From the 50 m point the terrain conductivity decrease sharply to a value of 3 mS/m at 60 m station point and then increases back to 9 mS/m at the 80 m point. From there the conductivity falls sharply to 0 mS/m and then rises sharply to 1 mS/m at the end of the profile. However no point was selected along this profile.

4.20 VES Interpretation

In Fig.4.18a, there is a drop in the apparent resistivity from 55 ohm-m down to a value of 25 ohm-m at the vertical depth of 16 m in the weathered zone. The vertical depth to the basement rock is about 16 m with resistivity range of 40 – 120 between the vertical depths 20 – 50 m suggesting that the basement fractures are saturated with groundwater. The A 60 m point was then recommended for drilling.

The geological log when the point was drilled is as shown in Fig.4.18b.The lithologic log consists of weathered zone of depth 12 m, which is made up of highly weathered basalt with mica on top of moderately weathered dark basalt as the first section. The second section is the basement rock which is made up of hard fresh dark fractured basalt. The ground water zone was intercepted at a depth of 14 m with an estimated yield of 80 litres per minute.

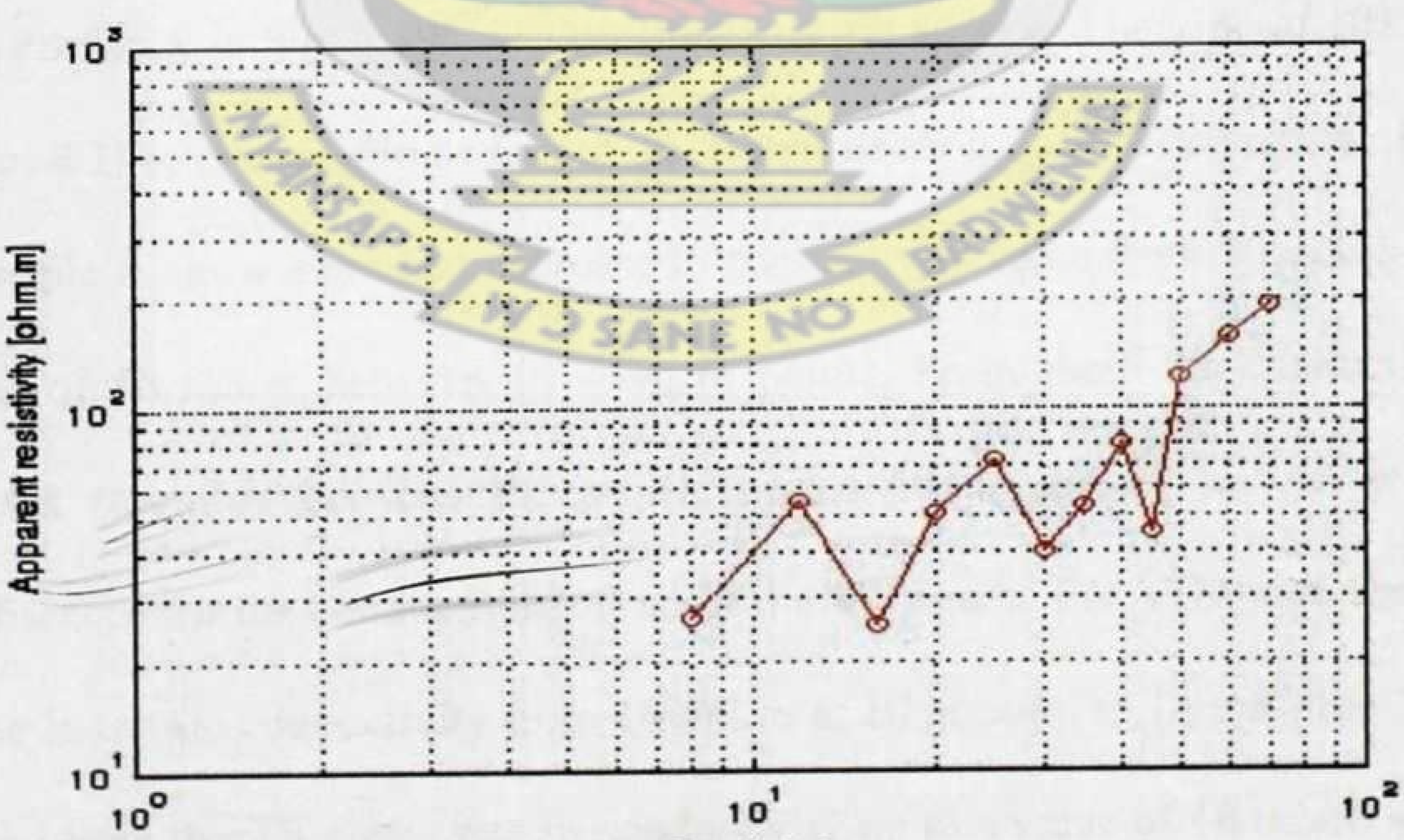

Figure 4.18a VES of Apparent resistivity against Depth at station A 60 m at Teshie CHPS Centre.

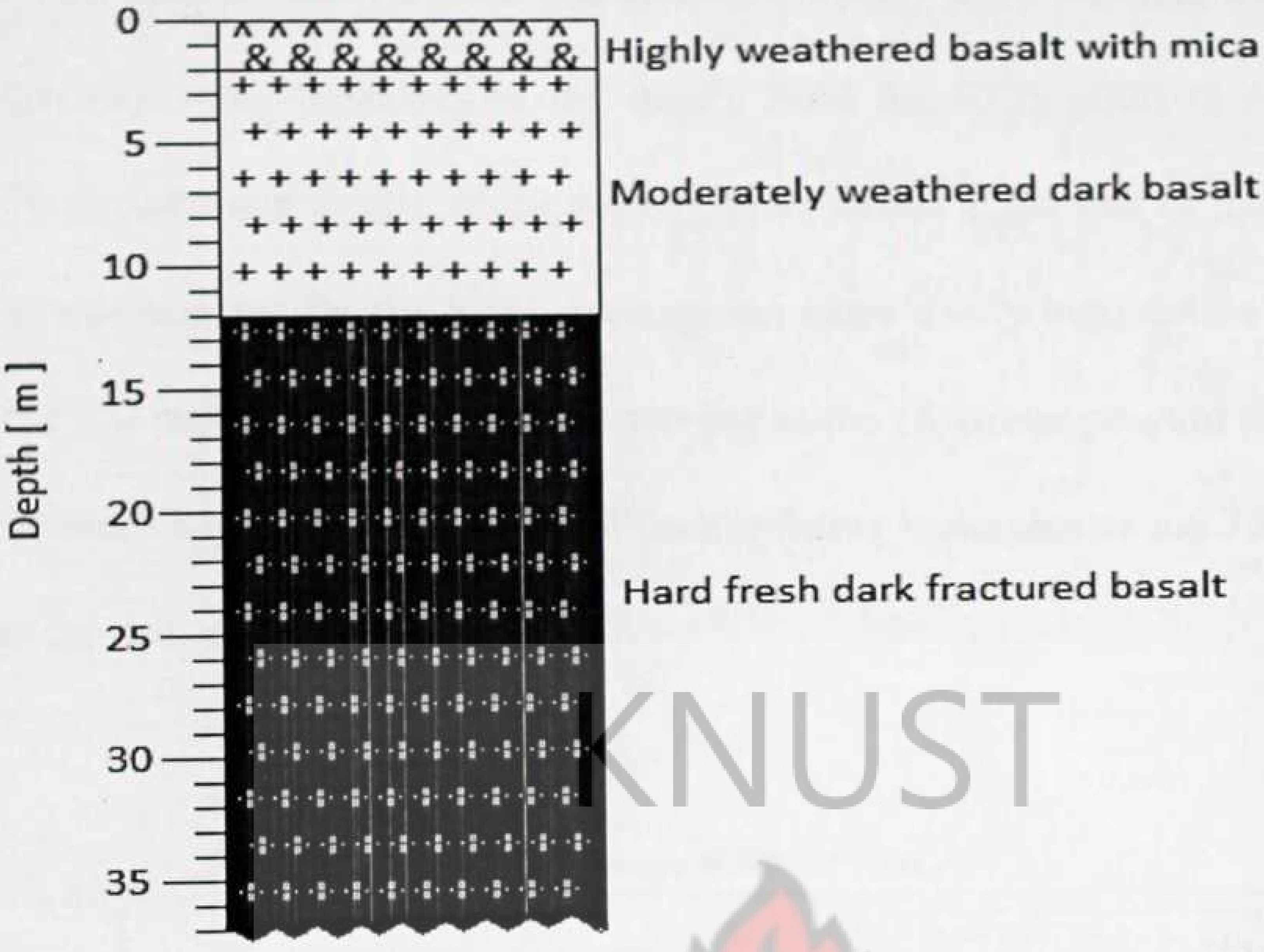

Figure 4.18b Lithologic Log of borehole drilled at the 60 m point of profile A at the Teshie CHPS Centre.

4.21 Azanga Primary School Community

Two profiles namely A and B were conducted in Azanga primary school community as in Fig. 4.19 (a,b). Profile A in Fig. 4.19a, is a profile of length 80 m and bearing of 105°and profile B in Fig. 4.19b, is a profile of length 50 m and bearing 350°. The results of the HD mode of profile A show a gradual decrease in conductivity value from 20 mS/m to a minimum value of 16 mS/m between 10 – 40 m points. From there the conductivity values then rises smoothly between the profile points 40 m and 80 m. An erratic behaviour is observed for the conductivity curve of the VD mode. For VD mode there is a sharp increase in terrain conductivity from 10 mS/m at 10 m point to 14 mS/m at 20 m station point and from there a gentle rise in conductivity up to a value of 16 mS/m at the 40 m point. From the 40 m point the conductivity the rises steeply to a highest value of

23 mS/m at the crossover point 50 m and then falls steeply to 15 mS/m at the 60 m point. The conductivity value continues to fall gently from the 60 m point to a value of 11 mS/m at 70 m point and finally rising slightly to 13 mS/m at the end of the profile. The point 50 m was selected for the VES investigation since a very high terrain conductivity value on the VD mode exists at this point serving as the crossover point to suggest a fault zone. Fault zones have high probability of accumulating water; hence the 70 m point was selected as the drill site in the community.

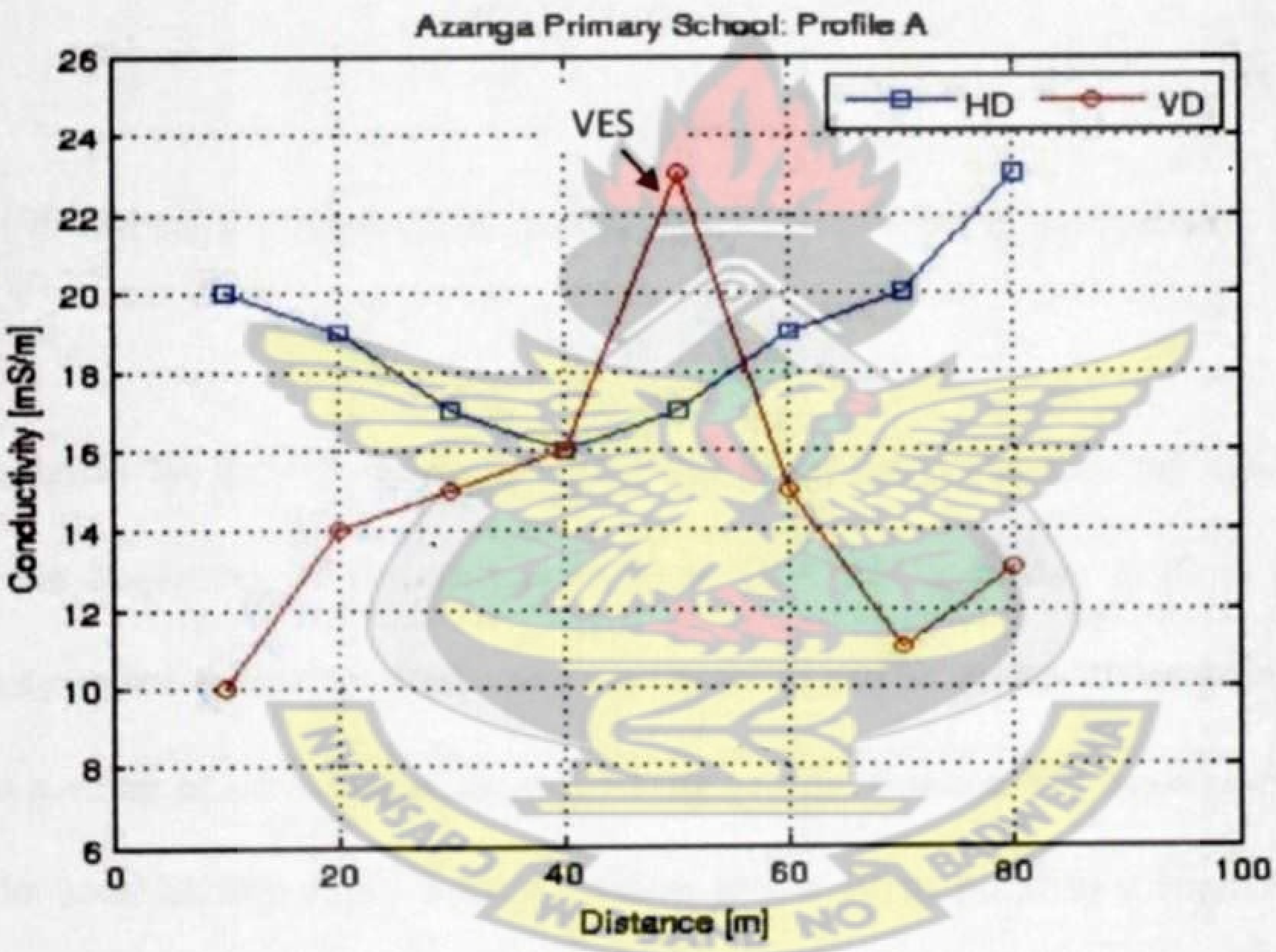

Figure 4.19a EM terrain conductivity profile for traverse A at Azanga primary school community.

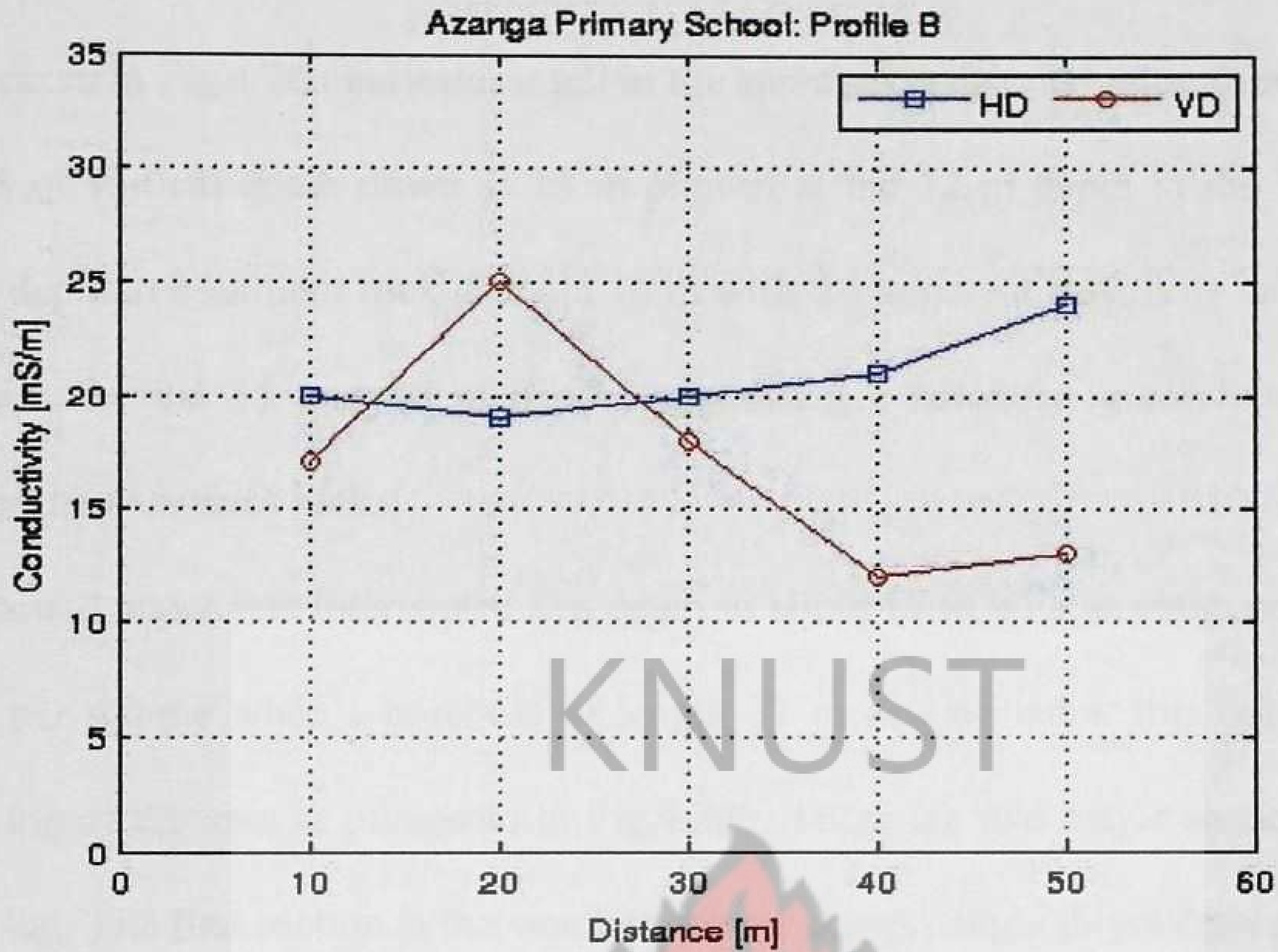

Figure 4.19b EM terrain conductivity profile for traverse B in Azanga primary school community.

Profile B shows for the HD mode, a very gentle decrease in conductivity value from 20 mS/m at the beginning of the profile at 10 m point to 19 mS/m at 20 m point. The conductivity value then rises first very gently to 21 mS/m at the 40 m point and then sharply to a value of 24 mS/m at the end of the profile. For the VD mode, there is sharp increase in conductivity value from 17 mS/m at the 10 m point to a highest value 25 mS/m at the crossover point 20 m and then a sharp decline in conductivity to a value of 12 mS/m at the 40 m point. This crossover point occurs exactly at the crossover point A 50 m of profile A in the community. Finally the conductivity values for the VD mode rises gradually from 12 mS/m at the 40 m point to 13 mS/m at the end of the profile at the 50 m point.

4.22 VES Interpretation

The VES curve in Fig.4.20a indicates a fall in the apparent resisitvity value from 35 ohm-m at the 8 m vertical depth down to 13 m ohm-m at the 12 m depth in the weathered zone. The depth to basement rock is about 16 m with the apparent resistivity values of 63 ohm-m each for the 35 and 40 m depths suggesting a saturated gruondwater in the fractures of the basement rocks.

Zone of ground water was intercepted at a depth of about 17 m with an estimated yield of 130 litres per minute when a borehole of length 37 m was drilled at this point and the lithologic log of the area as presented in Fig.4.20b. There are two major sections for the lithologic log. The first section is the weathered zone comprisinghighly weathered granite with clay on top of moderately weathered granite and the second section is the basement rock consisting of hard fresh fractured granite at the site.

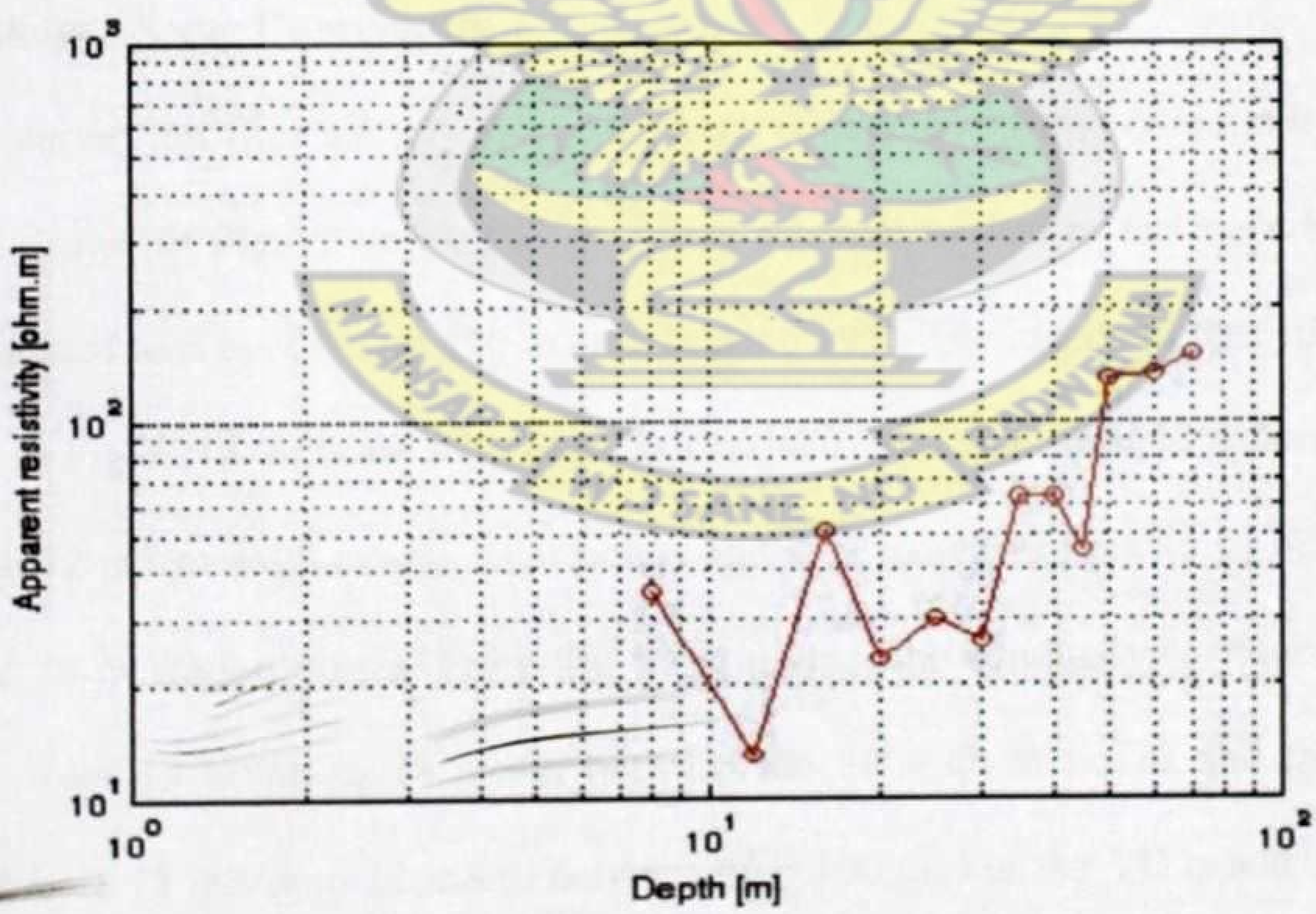

Figure 4.20a VES of Apparent resistivity against Depth at station A 50 m at Azanga Primary School.

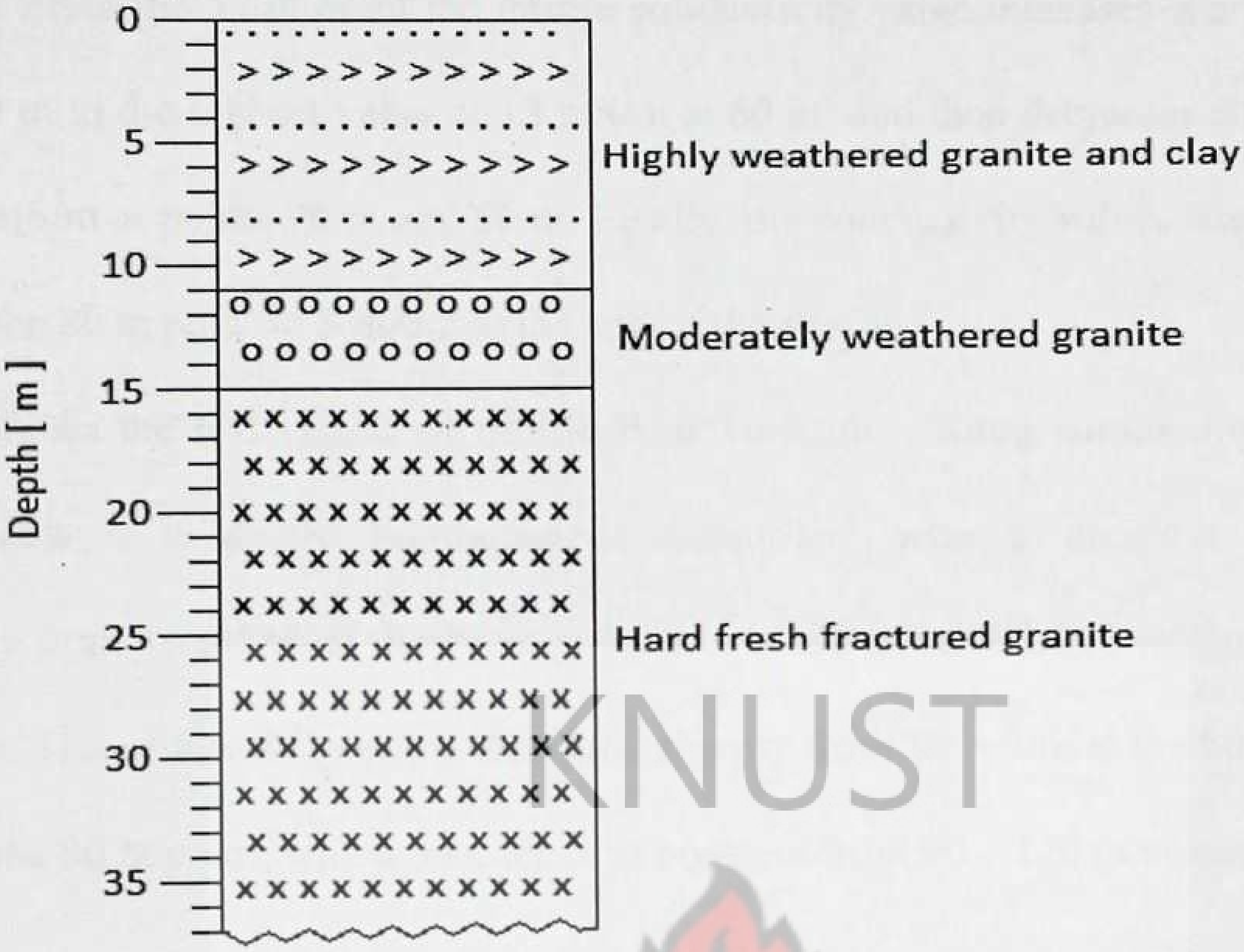

Figure 4.20b. Lithologic Log of borehole drilled at the 50 m point of profile A at Azanga Primary School.

4.23 Tarikom - Kuug Community

Two EM survey profiles namely A and B were conducted in this community and the results as shown in Fig.4.21(a,b). Profile A has a length of 100 m and on a bearing of 300° while profile B is of length 120 m and bearing 195°. The results of the HD mode on profile A in Fig.4.21a, indicate a decrease in conductivity value from 13 mS/m at the 10 m point to 12 mS/m at 20 m and 30 m points and then increases back to 13 mS/m at the 40 m and 50 m station points. From the 50 m point, the conductivity value increases gradually from 13 mS/m to 18 mS/m between the 50 – 80 m points and then finally decreases from 18 mS/m to 12 mS/m between 80 – 100 m. For the VD mode the ground conductivity rises sharply from 4 mS/m at the 10 m point to a value of 12 mS/m at 30 m point and then followed by a decrease in conductivity to 6 mS/m from the 12 m point to

50 m point. From the 50 m point the terrain conductivity value increases sharply from 6 mS/m at 50 m to the highest value of 13 mS/m at 60 m and then decreases slightly to a value of 8 mS/m at points 70 m and 80 m. Finally, the conductivity values decrease from 8 mS/m at the 80 m point to 3 mS/m at the end of the profile.

Fig.4.21b shows the EM results of profile B at Tarikom – Kuug community. The HD mode indicate a relatively homogeneous subsurface with a decrease in terrain conductivity from 16 mS/m at the 10 m point to a constant value of 10 mS/m from 50 – 80 m points. The conductivity value then falls sharply from 10 mS/m at the 80 m point to 8 mS/m at the 90 m point, which then remains constant from 90 – 120 m points.

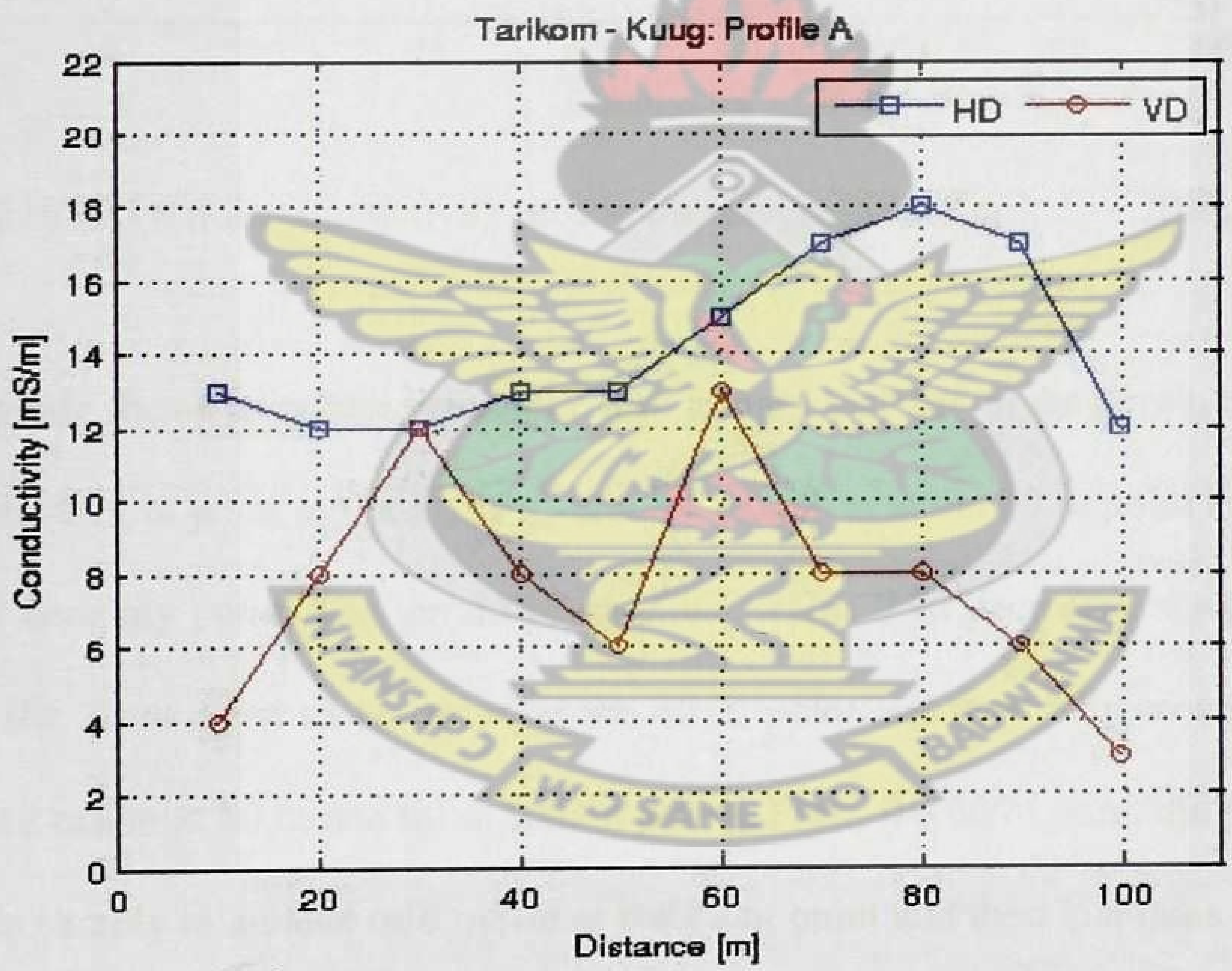

Figure 4.21a EM terrain conductivity profile for traverse A at Tarikom - Kuug.

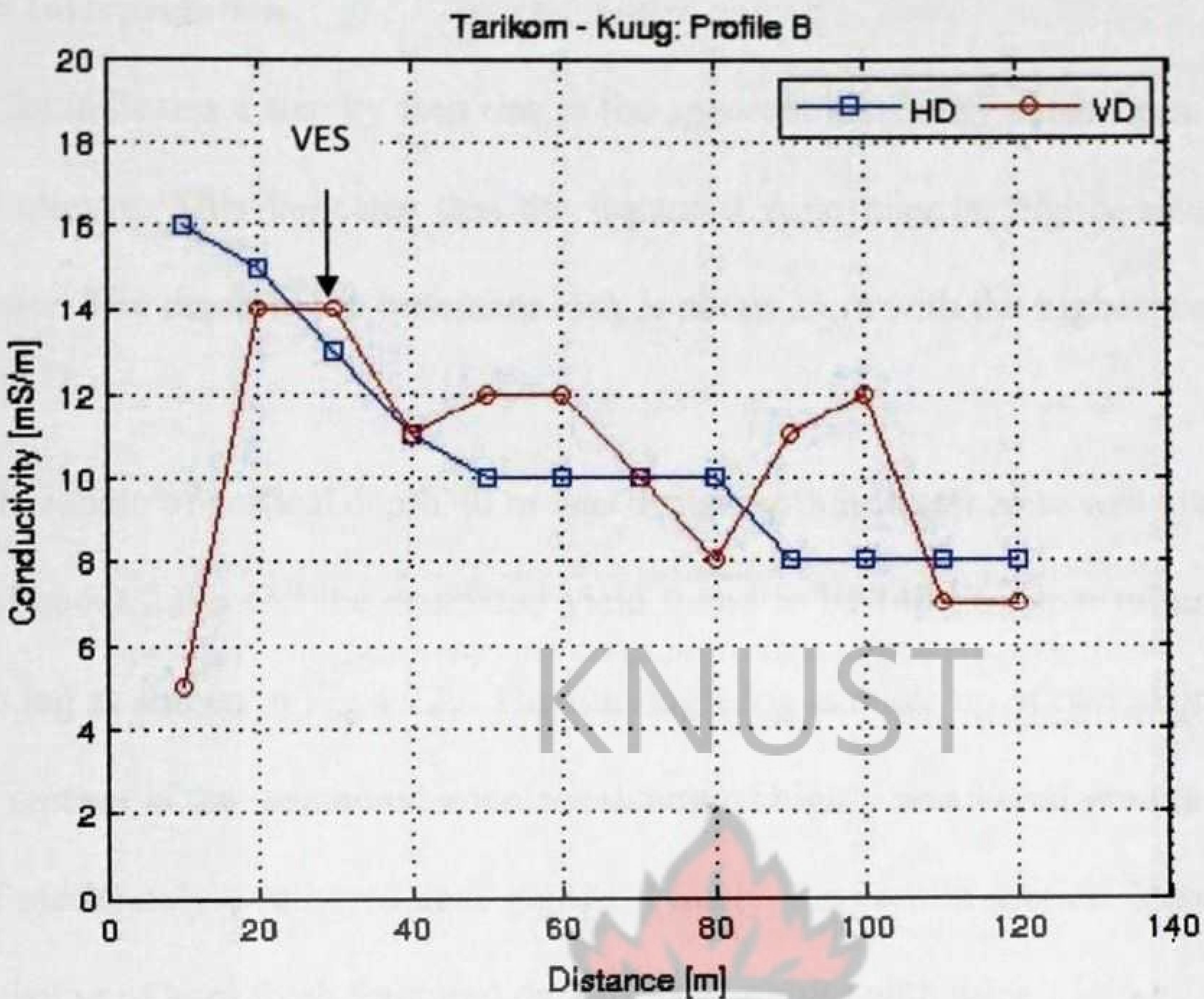

Figure 4.21b EM terrain conductivity profile for traverse B at Tarikom – Kuug.

The VD mode shows an erratic behaviour with a sharp increase in the terrain conductivity of 5 mS/m at 10 m point to the highest value of 14 mS/m at the 20 m point and the 30 m crossover anomaly point. The terrain conductivity value then decreases sharply from 14 mS/m at the 30 m point to 11 mS/m at the 40 m point and then increases sharply to a value of 12 mS/m at 50 m and 60 m station points. From the 60 m point the conductivity value falls sharply to a value of 8 mS/m at the 80 m point and then increases to 12 mS/m at the 100 m point. Finally, the terrain conductivity falls sharply from the 12 mS/m at 100 m point to 7 mS/m at 110 m and 120 m station. The crossover point 30 m was selected for further VES investigation because the VD mode shows a high conductivity value suggesting fractured zone which may have high potential of water storage.

4.24 VES Interpretation

In Fig.4.22a,indicates a step by step rise in the apparent resistivity value from 29 ohm-m up to 90 ohm-m. This indicates that the fractured zone may be highly saturated with groundwater. The depth to the basement rock is about 25 m with the highest resisitvity of 253 m.

When a borehole of vertical depth 40 m was drilled, groundwater zone was intercepted at a depth of about 22 m and the estimated yield found to be 140 litres per minute with the lithologic log as shown in Fig.4.22b. The lithologic log is made up of two major sections. The first section is the weathered zone consisting of highly weathered granite with mica on top of moderately weathered dark granite. Finally, the second section is the basement rock consisting of hard fresh fractured dark to light granite with mica.

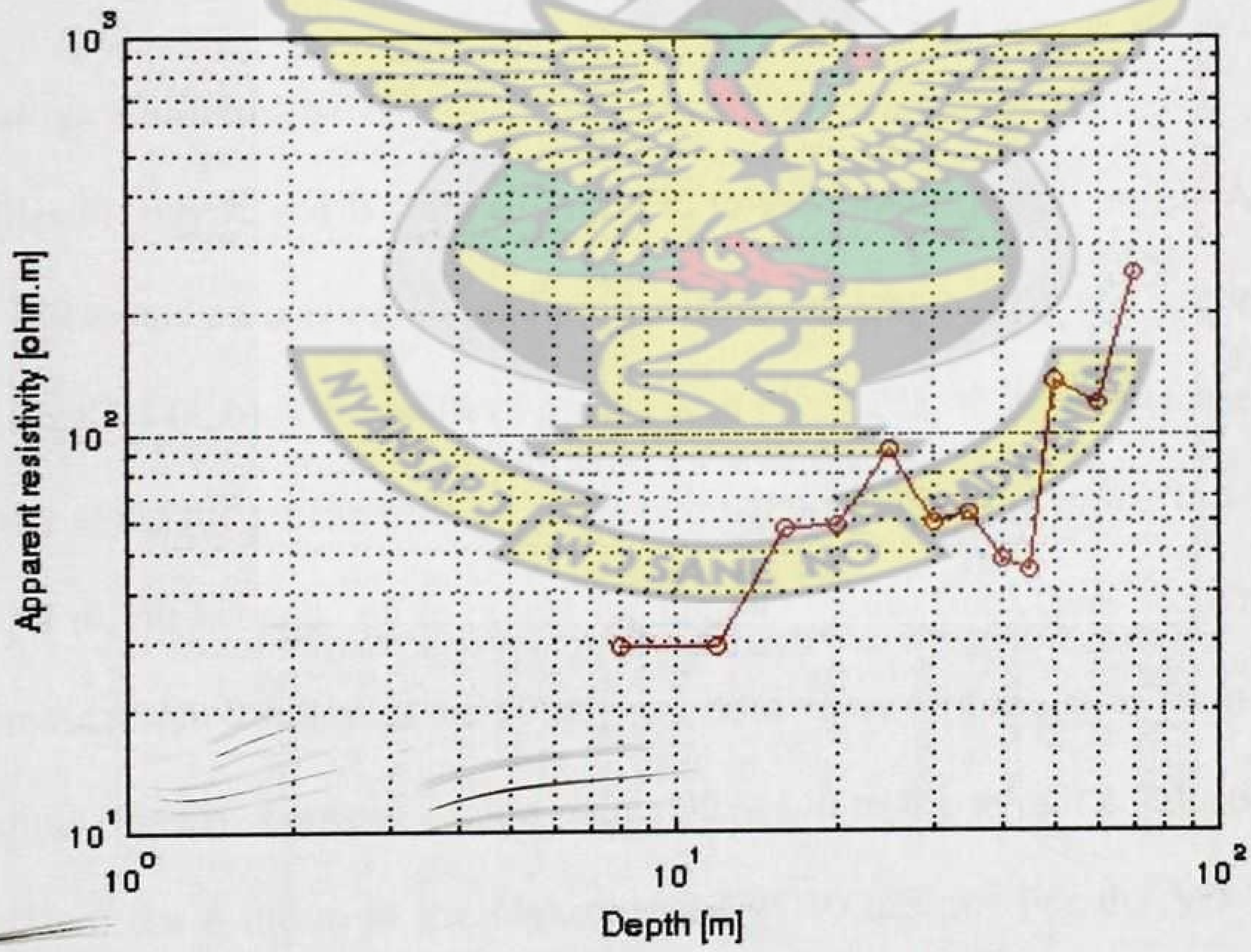

Figure 4.22a VES of Apparent resistivity against Depth at station B 30 m at Tarikom - Kuug.

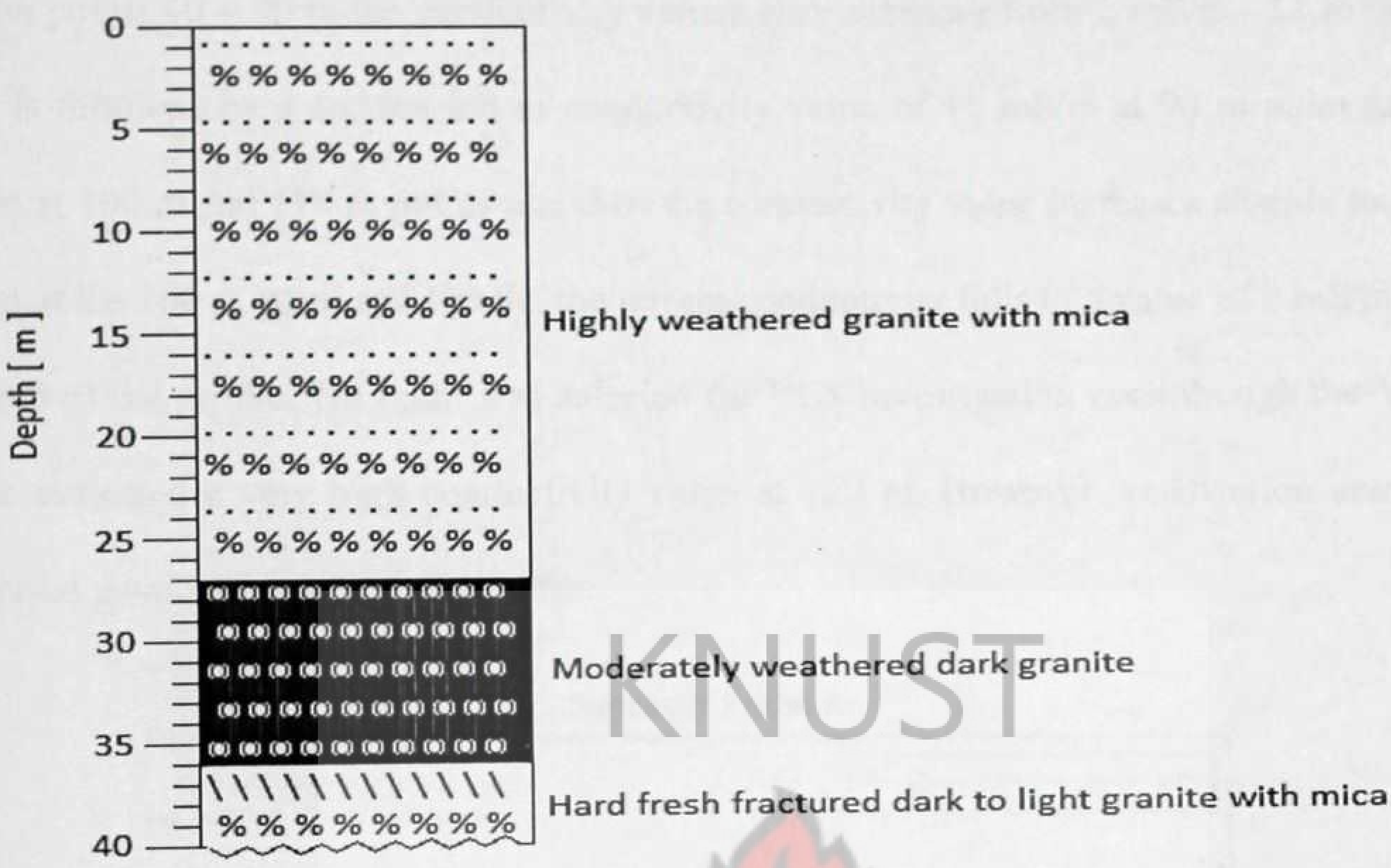

Figure 4.22b Lithologic Log of borehole drilled at the 30 m point of profile B at the Tarikom – Kuug.

4.25 Sapalugo Community

Two profiles namely A and B were surveyed in this community with profile A having a length of 140 m and on bearing 60° and profile B having length 60 m and bearing 150° as shown in Fig.4.23 (a, b). The results of profile A in Fig. 4.23a, show an increase in terrain conductivity along the profile from the 10 m point at the value of -1 mS/m to a value of 2 mS/m at 40 m, 50 m and 60 m points for the HD mode, from there the conductivity value increases from 2 mS/m at the 60 m point to a value of 4 mS/m at 80 m and 90 m station points. Finally, between station points 90 – 140 m the terrain conductivity value increases from the 4 mS/m to the highest value of 10 mS/m. For the VD mode, the terrain conductivity rises sharply from a value of 3 mS/m at the 10 m point to 4 mS/m at the 20 m point and falls sharply to a value of 2 mS/m at the 40 m point. Between the station points 40 – 90 m the conductivity values also increases from 2 mS/m - 11 mS/m. This is followed by a sudden fall in conductivity value of 11 mS/m at 90 m point to 7 mS/m at 100 m and 110 m points and then the conductivity value increases sharply to 14 mS/m at the 100 m point and finally, the terrain conductivity falls to a value of 2 mS/m at the end of the profile. No point was selected for VES investigation even though the VD mode indicated a very high conductivity value at 120 m. However, verification across this point gave low conductivity values.

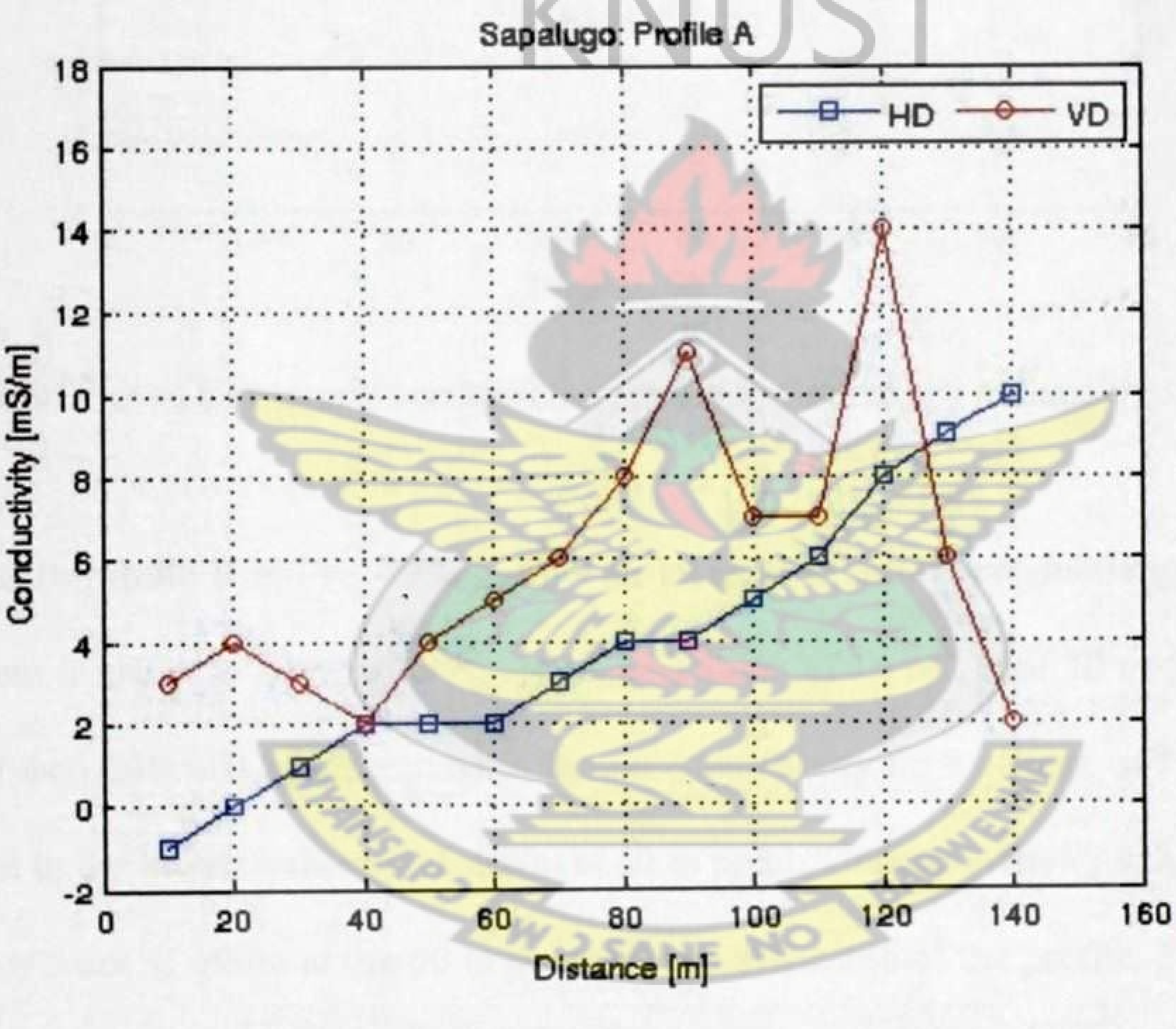

Figure 4.23a EM terrain conductivity profile for traverse A at Sapalugo.

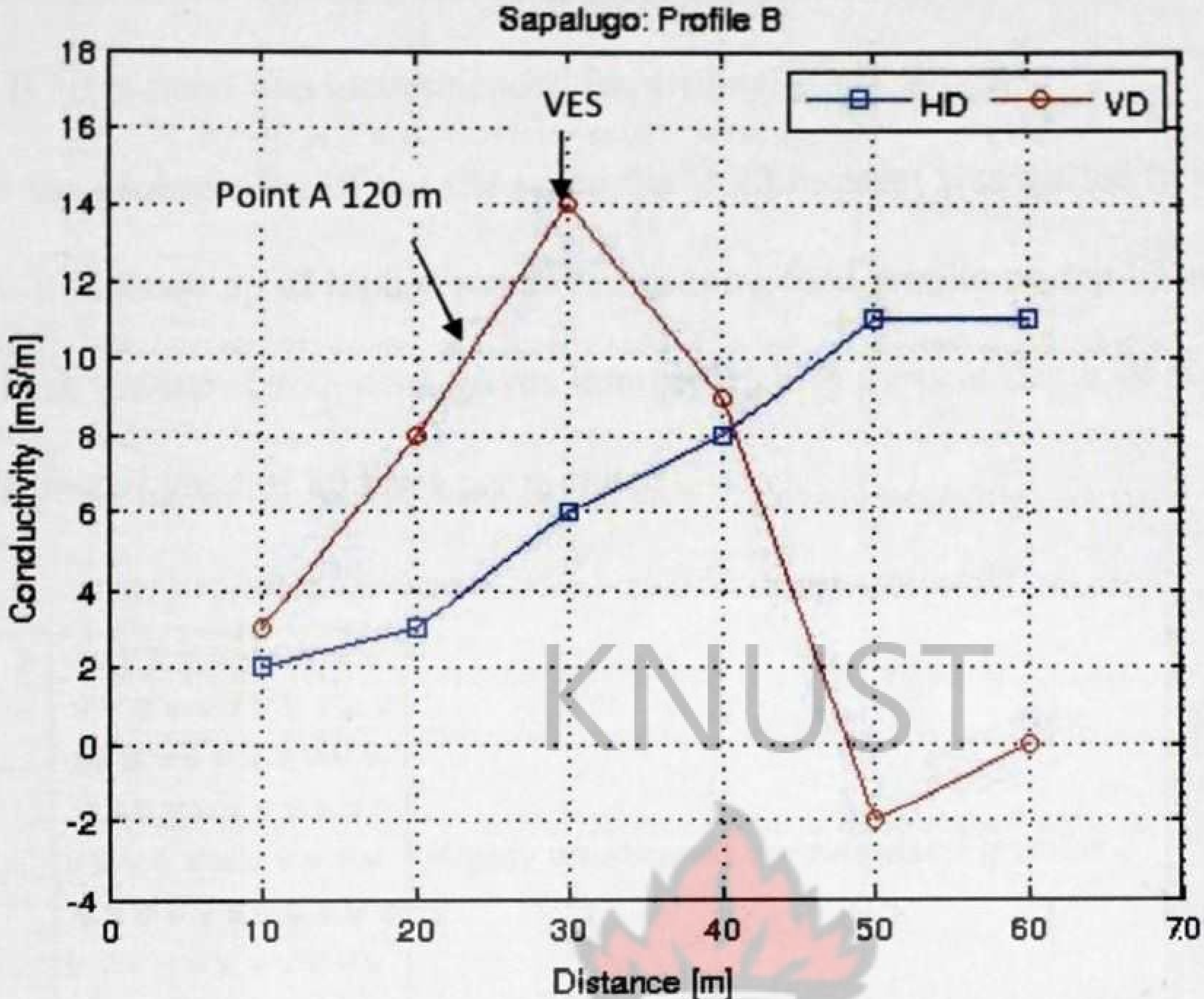

Figure 4.23b. Plot of EM terrain conductivity profile for traverse B at Sapalugo.

The results of profile B in Fig. 4.23b, show an increase in terrain conductivity along the profile from 3 mS/m at 10 m point to the highest value of 14 mS/m at 30 m for the VD mode and then followed by a decrease in terrain conductivity from a value of 14 mS/m at 30 m point to the lowest value of -2 mS/m at 50 m point. The conductivity values finally, rise sharply from -2 mS/m at the 50 m point to zero at the end of the profile. For the HD mode, there is a gradual increase in terrain conductivity from a value of 3 mS/m at the 10 m station point to the highest value of 11 mS/m at the 50 m and 60 m points. Since the highest conductivity value of the VD mode occurs at crossover anomaly point at 30 m and indicates a subsurface fracture zone, it was thus selected for further VES investigation. However, the VES was not successful as the McOhm meter consistently registered current error. On the basis of the results obtained from the electromagnetic survey, the B 30 m point was recommended for drilling.

Fig.4.23c is the geologic log of the site when the B 30 m point was drilled to a depth of about 27 m. It is made up of highly weathered decomposed granite on top of moderately weathered dark granite. Groundwater was intercepted at a vertical depth of about 16 m with a an estimated yield of 80 litres per minute.

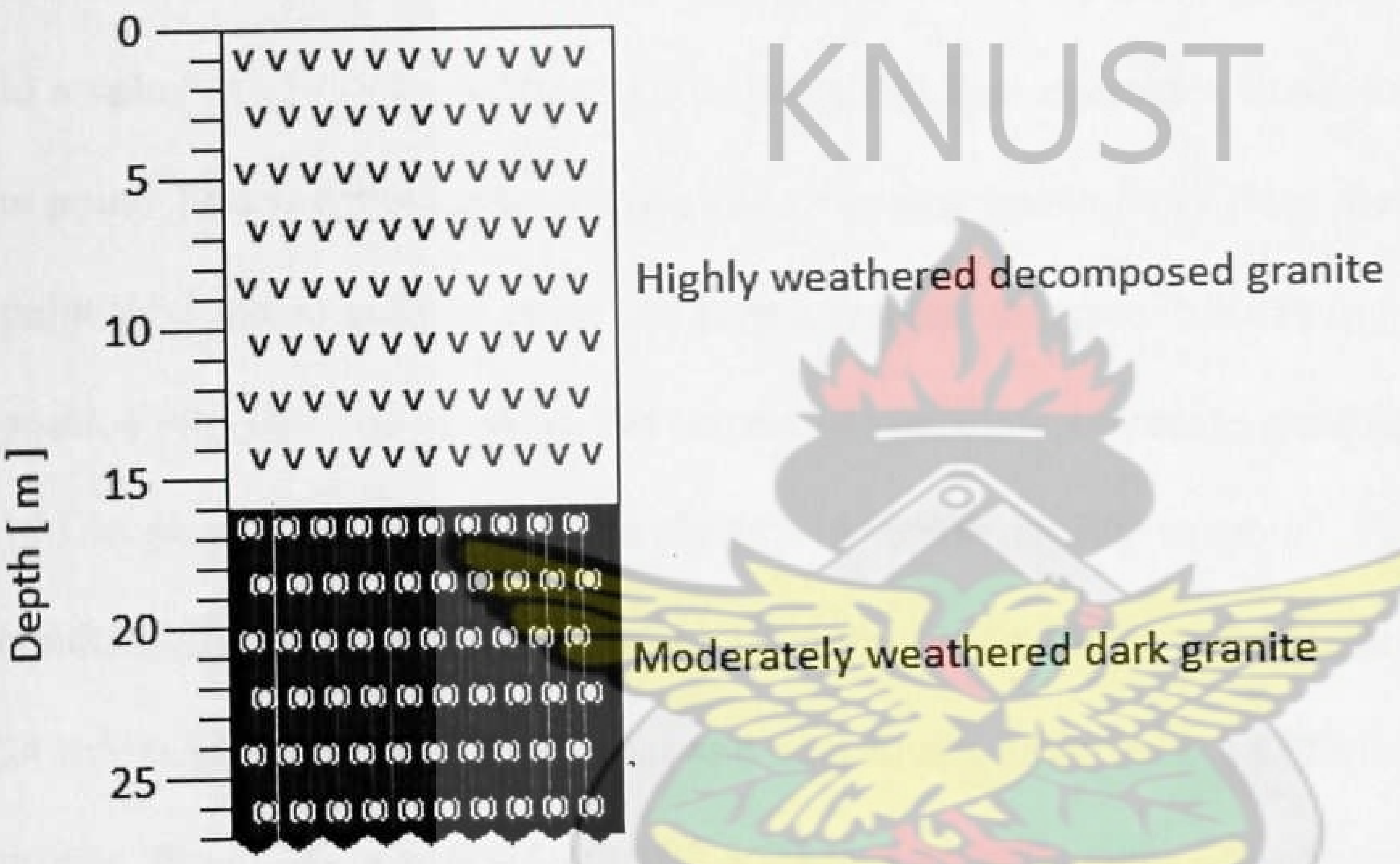

Figure 4.23c Lithologic Log of borehole drilled at the 30 m point of profile B at the Sapalugo.

4.26 Kansogo - Aningbligu Community

Only one profile (A) of length 230 m and bearing 050° was surveyed in this community and the results presented in Fig.4.24a. Since the whole area is covered by mountain ranges no other profiles were possible. In general, the results on both the HD and VD modes indicated an erratic behaviour in the conductivity curves suggesting a complex subsurface geology. The HD mode shows an increase in terrain conductivity from 7 mS/m at 10 m to 9 mS/m at 20 m point and from there an erratic decrease in conductivity value from 9 mS/m to -3 mS/m between 20 – 120 m station points. This is followed by a gradual increase in conductivity value from -3 mS/m at 120 m point to 7 mS/m at 180 m station point and rises sharply to a value of 21 mS/m at the 190 m point. Finally, there is a gradual decrease in terrain conductivity of 21 mS/m at 190 m point to 6 mS/m at the end of the profile. For the VD mode, the terrain conductivity decreases gradually from -1 mS/m at 10 m point to -5 mS/m at 50 m point, from there the conductivity value increases to a value of -3 mS/m at 70 m station point and then decreases sharply to -4 mS/m at 80 m point. This is followed by a sharp rise in terrain conductivity from the -4 mS/m at 80 m point to -3 mS/m at 90 m point and then a gradual decrease in value to -5 mS/m at 110 m point. From the 110 m point, the terrain conductivity increases gradually to 9 mS/m at 160 m point and then falls sharply to -19 mS/m at 180 m point. Finally, the terrain conductivity increases sharply from -19 mS/m at the 180 m point to the highest value of 24 mS/m at 200 m crossover point and then finally reduces to 13 mS/m at the end of the profile. Point 200 m was selected for VES investigation since the crossover anomaly with high VD mode value at this point indicating area of fault or fracture zones. However,the VESwas not successful because the whole area is almost covered by igneous rock outcropes.

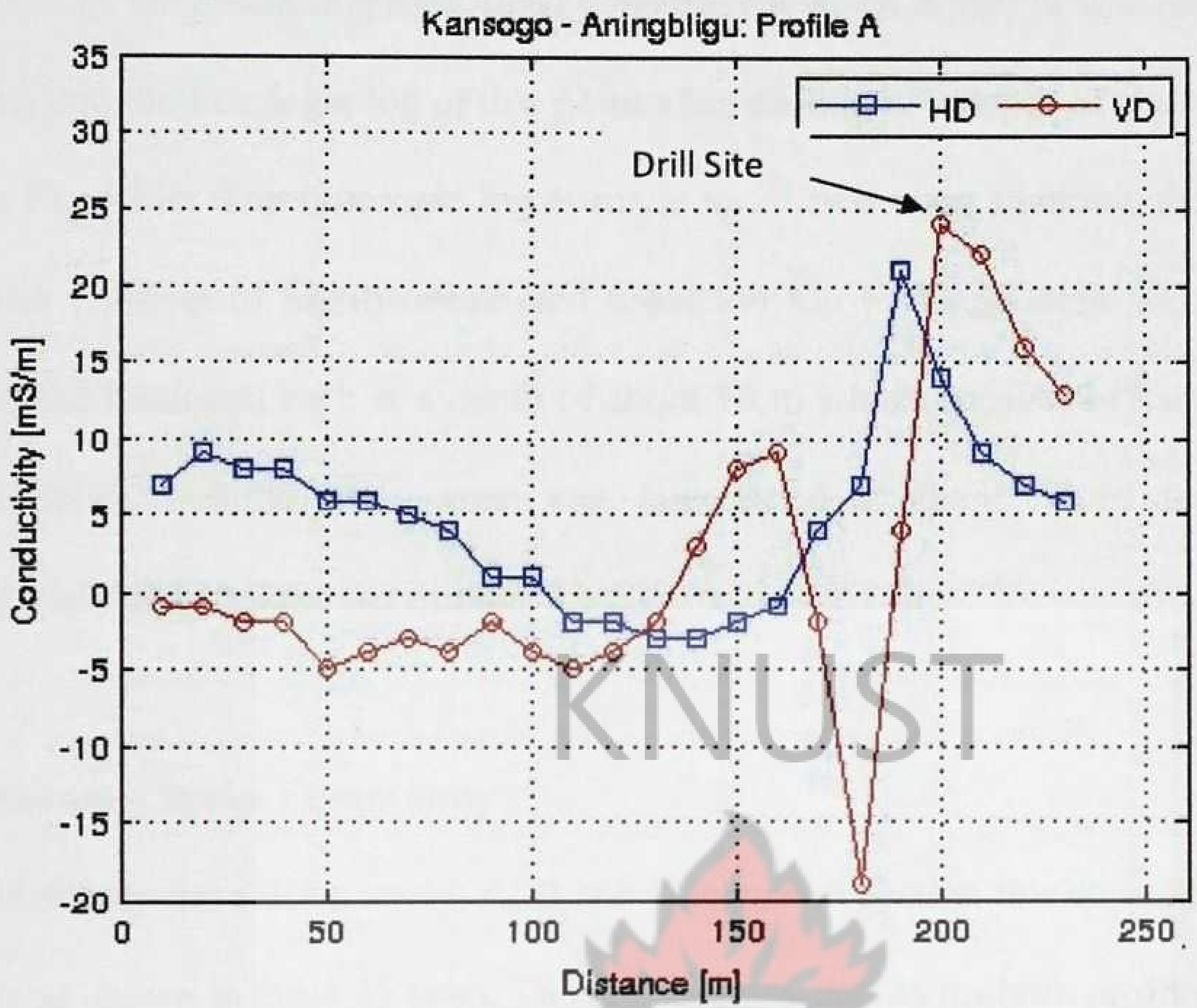

Figure 4.24aEM terrain conductivity profile for traverse A at Kansogo – Aningbligu.

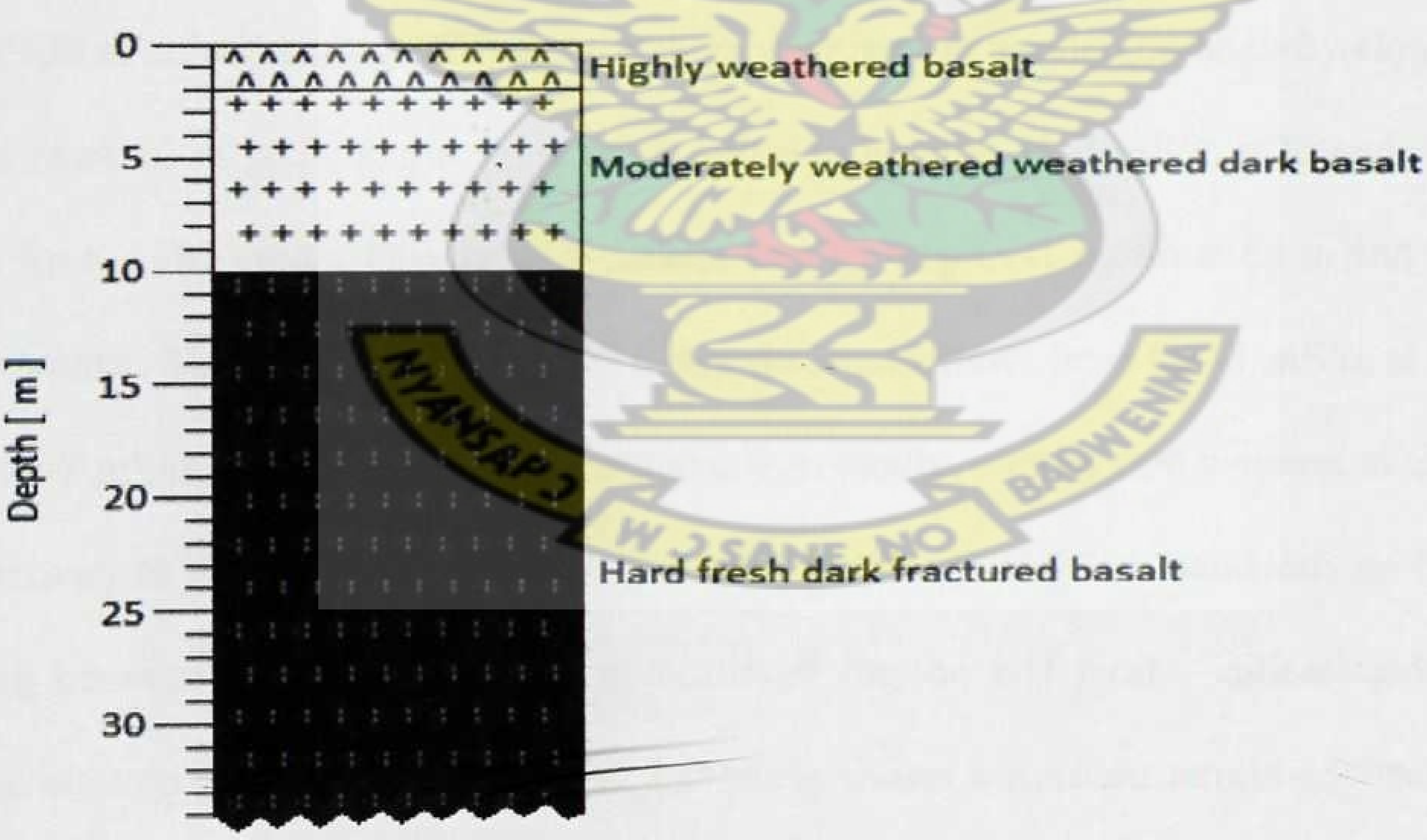

Figure 4.24b Lithologic Log of borehole drilled at the 200 m point of profile A at Kansogo - Aningbligu.

On the basis of the electromagnetic survey results, the point A 200 m was recommended for drilling and the lithologic log of this point after drilling to a depth of about 34 m is as shown in Fig.4.24b. The lithologic log is made up of two main sections, the weathered zone which consists of highly weathered basalt on top of moderately weathered dark basalt and the basement rock at a depth of about 10 m which consists of hard fresh dark fractured basalt. Ground water zone was intercepted at about 10 m deep with an estimated yield of 140 litres per minute.

4.27 Ananoore - Saaka Community

Three EM survey traverses namely, A, B and C were surveyed in this community and the results are as shown in Fig.4.25 (a-c). The conductivity curves for both profiles depicts an erratic behaviour suggesting a complex subsurface geology.The results of profile A, of length 130 m on thebearing 105°, show a sharp decrease in terrain conductivity along the profile from 10 m point at the value of -1 mS/m to a value of -3 mS/m at20 and 40 m points for the HD mode. This value increases step by step to -1 mS/m at 60 m and 70 m station points. This is followed by a fall in terrain conductivity from the -1 mS/m at 70 m point to -2 mS/m at 80 m and 90 m points and then finally, step by step increase in terrain conductivity to zero at 120 m and 130 m station points. A very low conductivity values ranging between 0 and -3 mS/m were observed for the HD mode, indicating low – weathering upper surface geology. The VD mode shows a constant terrain conductivity value of 2 mS/m from the beginning of the survey traverse to the end of it at the 120 and 130 m points, except a sharp fall to zero and 1 mS/m at the 30 m point and 70 – 80 m and

100 – 110 m stations respectively. No conductivity anomaly was observed and therefore no station point was selected for VES investigation.

The results of profile B in Fig.4.25b, profile length 120 m and on the bearing 135°show for the HD mode a decrease in conductivity value from 3 mS/m at the 10 m point to 1 mS/m at the 20 m and 30 m points. This is followed by a sharp rise in conductivity value to 2 mS/m at 40 m and 50 m points which then decreases step by step from the 50 m point to the lowest conductivity value of -3 mS/m at 100 m point. Finally, the ground conductivity value rises sharply from the station point 100 m to a value of -1 mS/m at the 110 m and then decreases sharply to -2 mS/m at 120 m point. For the VD mode, the terrain conductivity value of 4 mS/m remains the same for the 10 m and 20 m station points and from there it reduces to a value of 1 mS/m at the 40 m point. From the 40 m point, the conductivity then increases to a value of 3 mS/m at the 60 m and 70 m and then decreases to a value of 2 mS/m at the 80 m point. Finally, between the 80 and 120 m points the conductivity curve indicates a homogeneous subsurface geology as a result of the constant value of 2 mS/m between the points with the exception of the 100 m point where there is a sharp increase in terrain conductivity to 4 mS/m. No anomaly was observed and therefore no point was selected for further VES investigation.

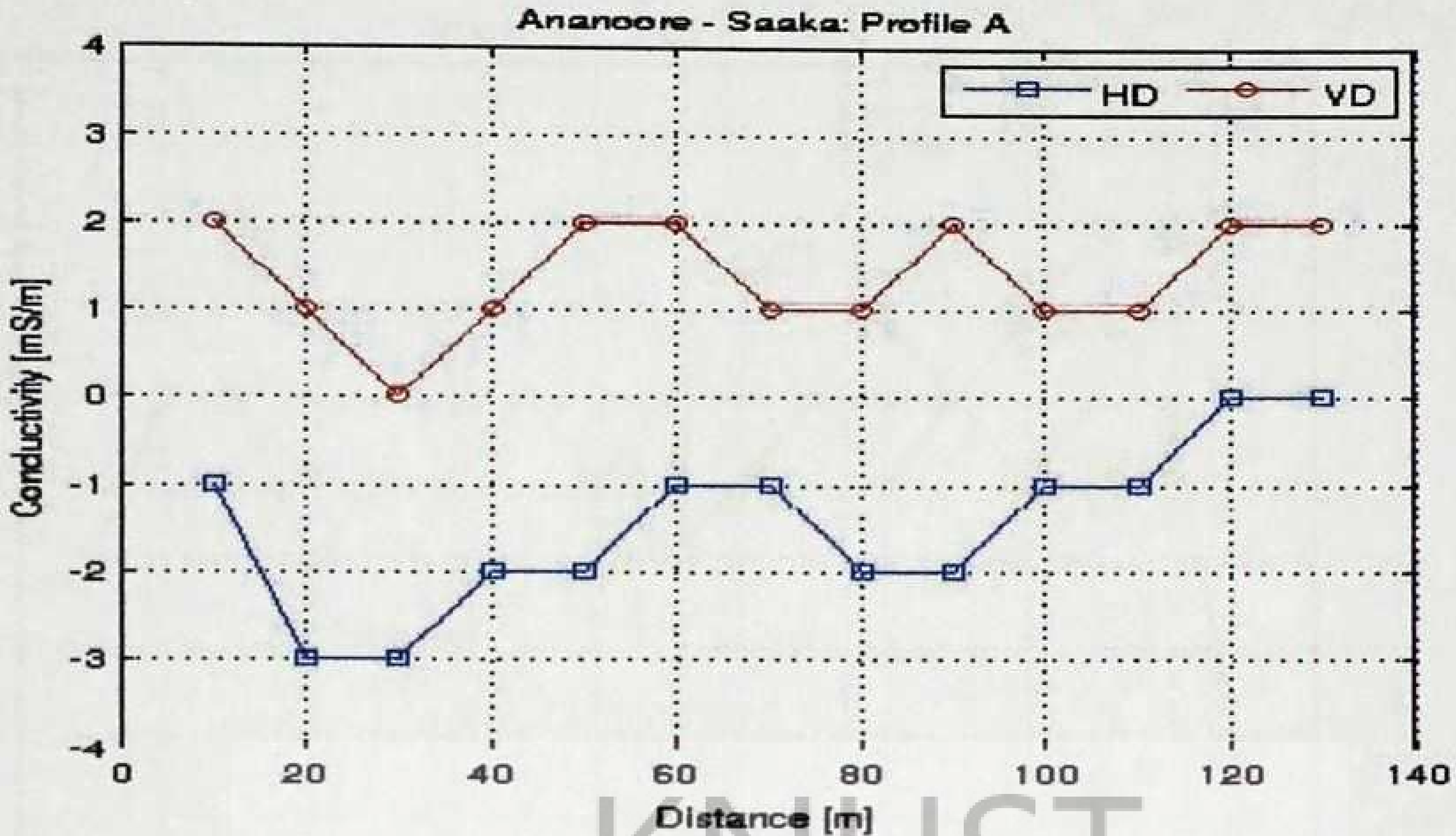

Figure 4.25aEM terrain conductivity profile for traverse A at Ananoore - Saaka.

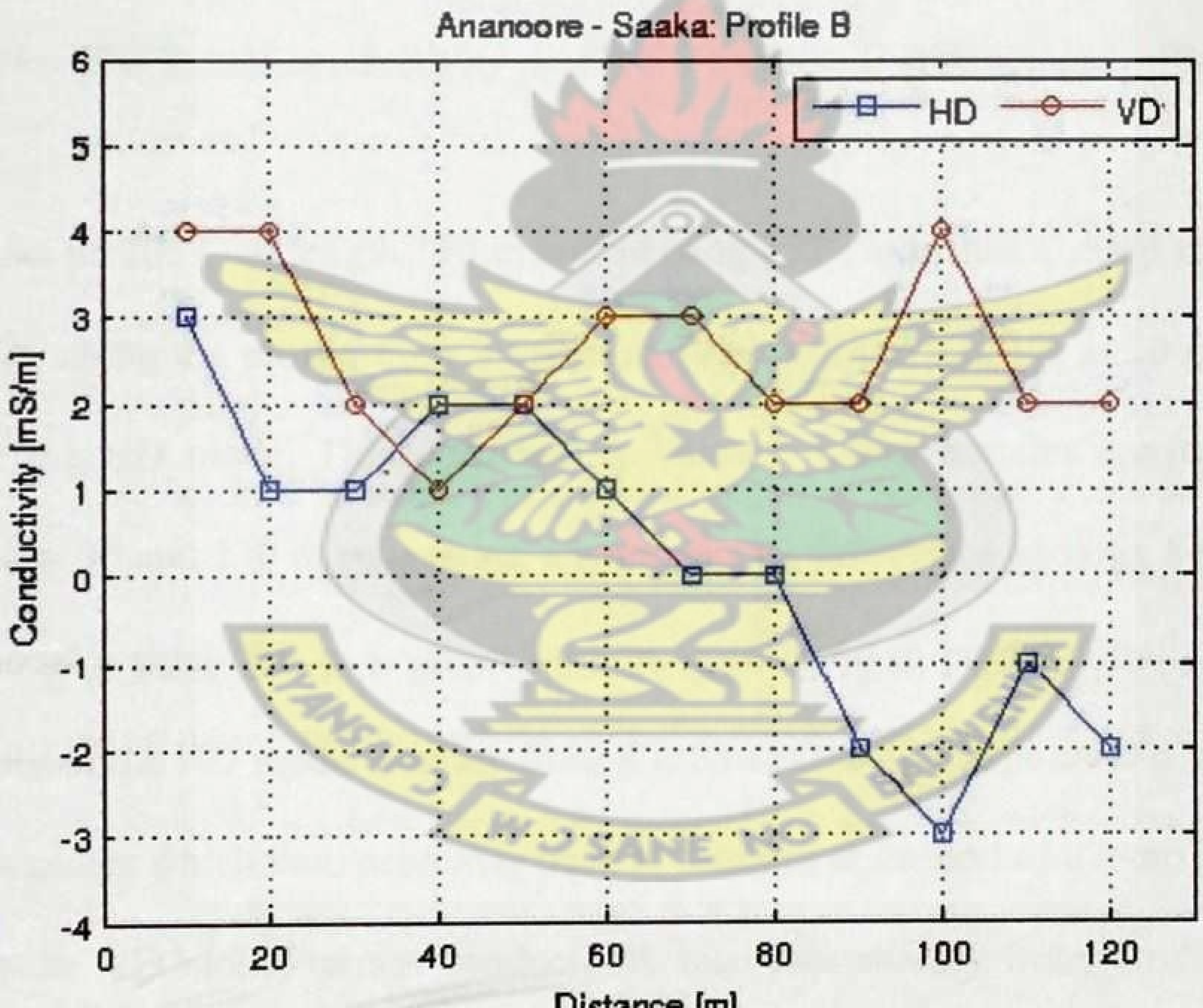

Figure 4.25b EM terrain conductivity profile for traverse B at Ananoore – Saaka.

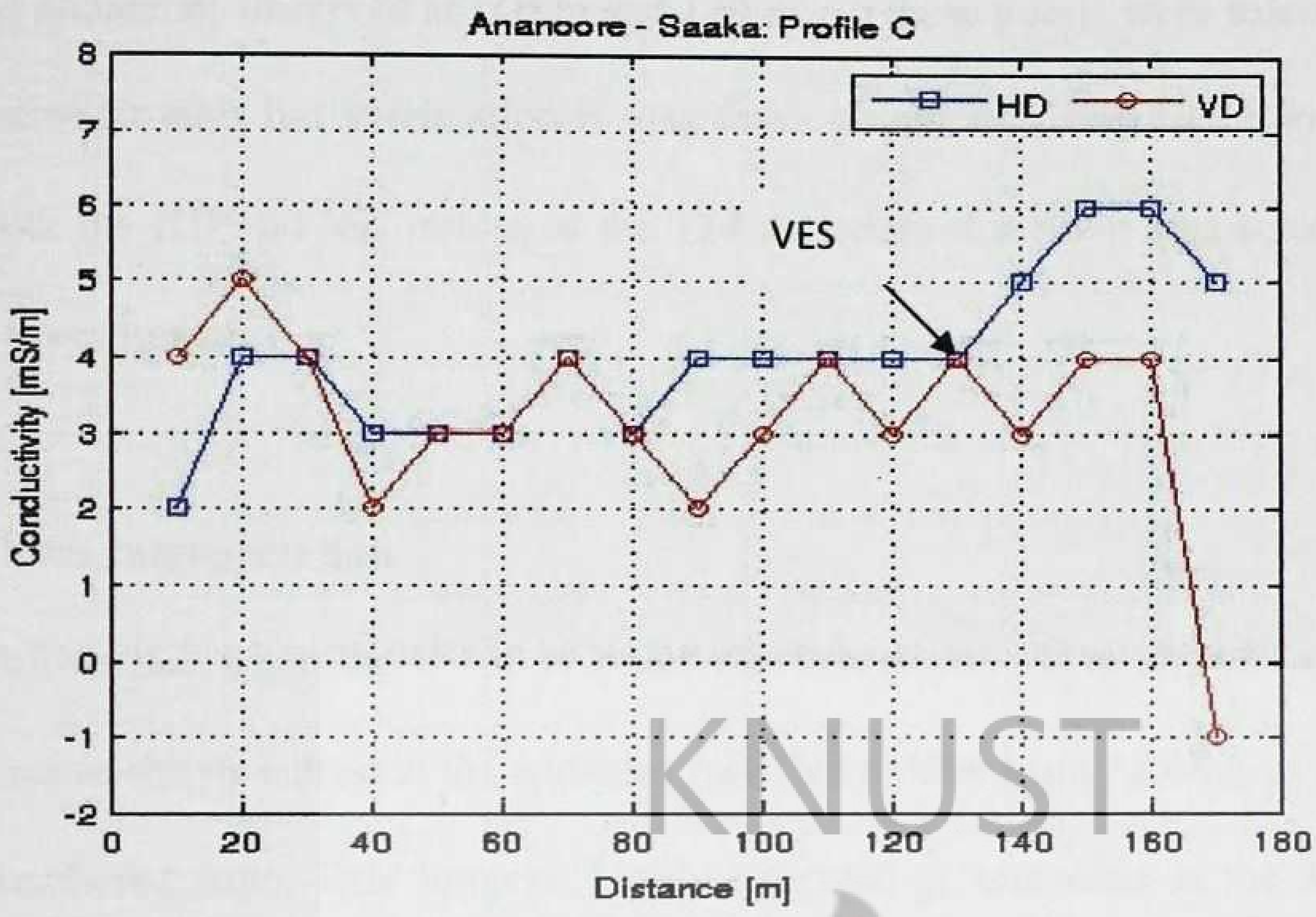

Figure 4.25 c EM terrain conductivity profile for traverse C at Ananoore – Saaka.

In Fig.4.25c, profile C of length 170 m and bearing 355°, indicates a sharp rise in terrain conductivity along the profile from 2 mS/m at 10 m point to 4 mS/m at 20 m and 30 m points for the HD mode. This condcutivity value 2 mS/m remains constant between station points 30 and 130 m suggesting a homogenous subsurface geology between these points, except a sharp fall to a value 3 mS/m at 40 to 60 m points. Finally, the terrain conductivity of the HD mode increase from 4 mS/m at the 130 m point to 6 mS/m at 150 and 160 m points which then decreases back to 5 mS/m at the end of the profile at 170 m point. For the VD mode, terrain conductivity increases sharply from 4 mS/m at 10 m point to 5 mS/m at 20 m and then decreases sharply to 2 mS/m at 40 m point, which is then followed by a sharp increase in the conductivity to 3 mS/m at 50 m and 60 m points. The conductivity value continues to rise and fall between values 2 and 4 mS/m occurring between station points 60 and 160 m and then finally falls sharply to a conductivity value of -1 mS/m at the end of the profile at 170 m. Crossover anomaly is observed at point 20 m and anomalies observed at 110 m and 130 m. So these points were selected as potential groundwater sites but verification across these points indicates high conductivity value for both the HD and VD modes at the 130 m, hence this point was selected for further VES investigation.

4.28 VES Interpretation

The VES result when the C 130 m point was investigated is as shown in Fig.4.26a. The VES curve shows a drop in the apparent resistivity value from 58 ohm-m to 48 ohm-m in the weathered zone. This suggests highly saturated groundwater in the weathered zone. The depth to the bed rock is about 16 m with the highest apparent resistivity value of 205 ohm-m. This point was finally recommended for drilling and the lithologic log after drilling is as shown in Fig.4.26b. The lithologic log is made up of three major sections. The top and the first sections consist of laterite and clay with the second section been weathered zone of highly weathered granite on top of moderately weathered granite. The last section is the basement rock consisting of hard fresh fractured granite on top of hard fresh fractured reddish granite.

Zone of groundwater was intercepted at a depth of about 24 m with an estimated yield of 411 litres per miunute.

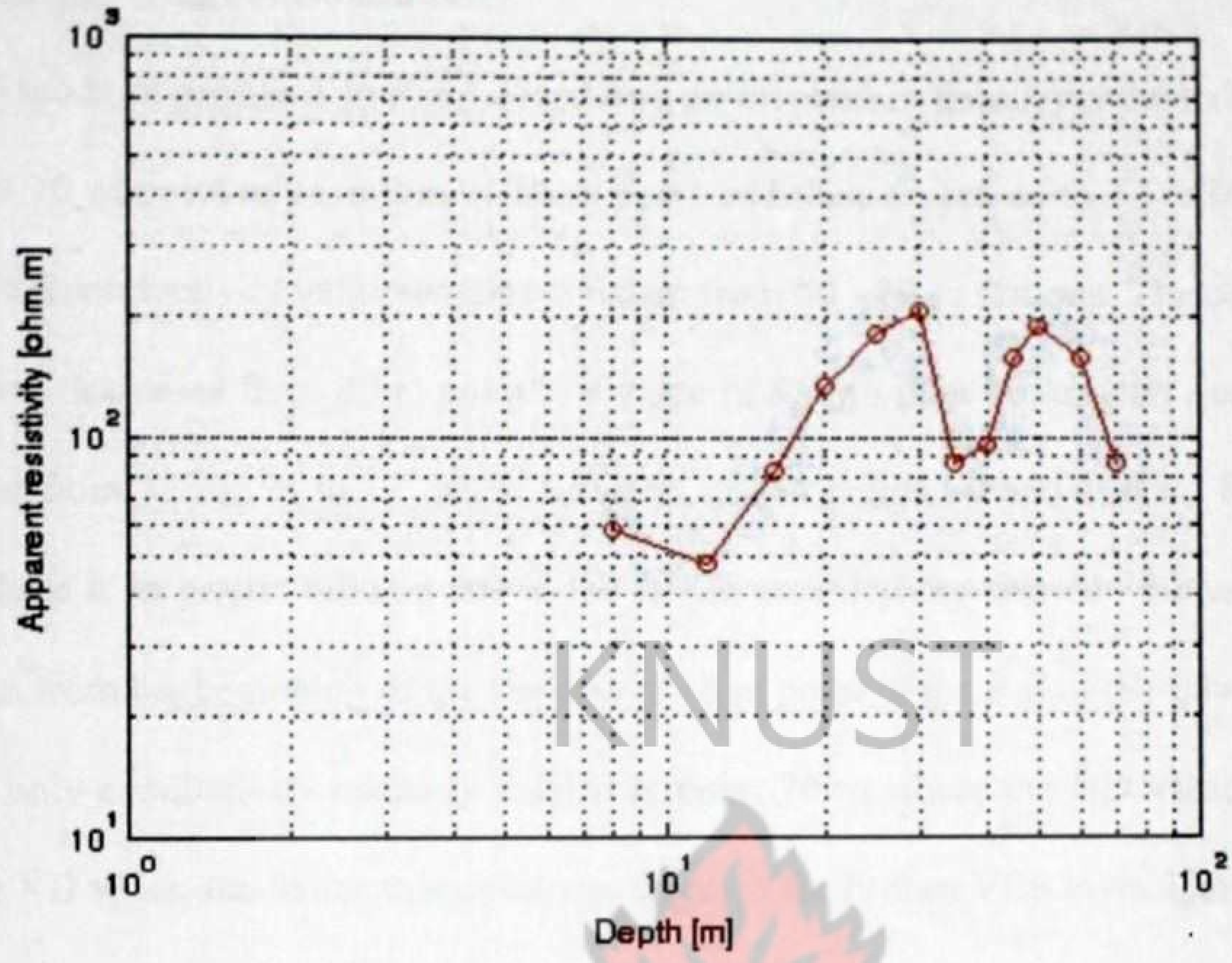

Figure 4.26a VES of Apparent resistivity against Depth at station C 130 m at Ananoore Saaka.

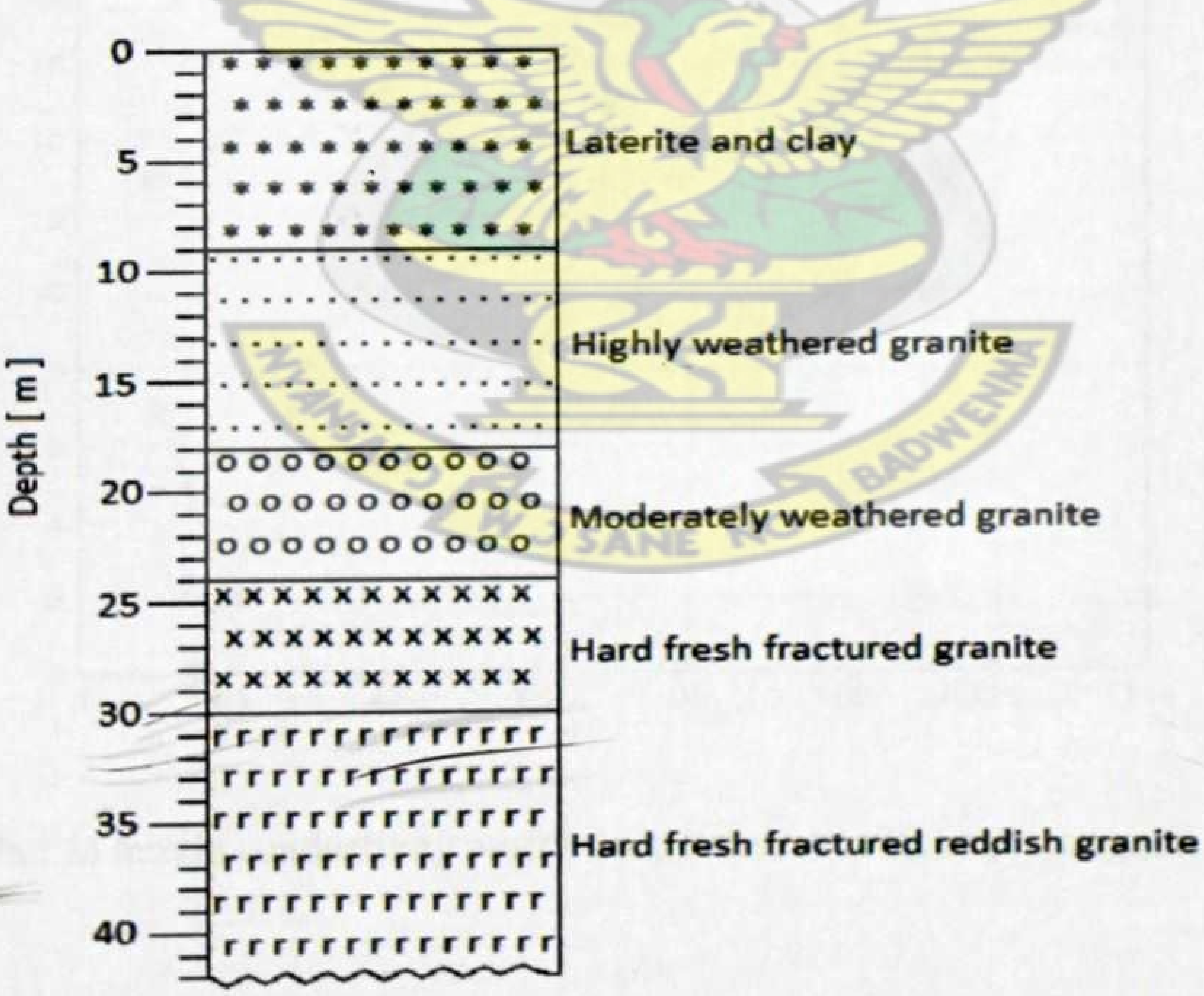

Figure 4.26b Lithologic Log of borehole drilled at the 130 m point of profile C in Ananoore – Saka community.

4.29 Kukogo – Naguut Community

The HD mode of profile A in Fig.4.27a shows an increase in terrain conductivity from 13 mS/m at 10 m point to 16 mS/m at 30 m point and then decreases to 14 mS/m at 50 m point. This conductivity value remains constant from 50 - 80 m stations. The conductivity value then decreases from 80 m point to a value of 13 mS/m at 90 m point and it finally, increases from 13 mS/m to 17 mS/m between station points 90 and 130 m. For the VD mode, there is an erratic fall and rise in the terrain conductivity between the values 2 and 14 mS/m from the beginning of the traverse at 10 m point to the end of the traverse at 130 m. The only conductivity anomaly existed at point 70 m where the HD value coincided with the VD value and hence this point was selected for further VES investigation.

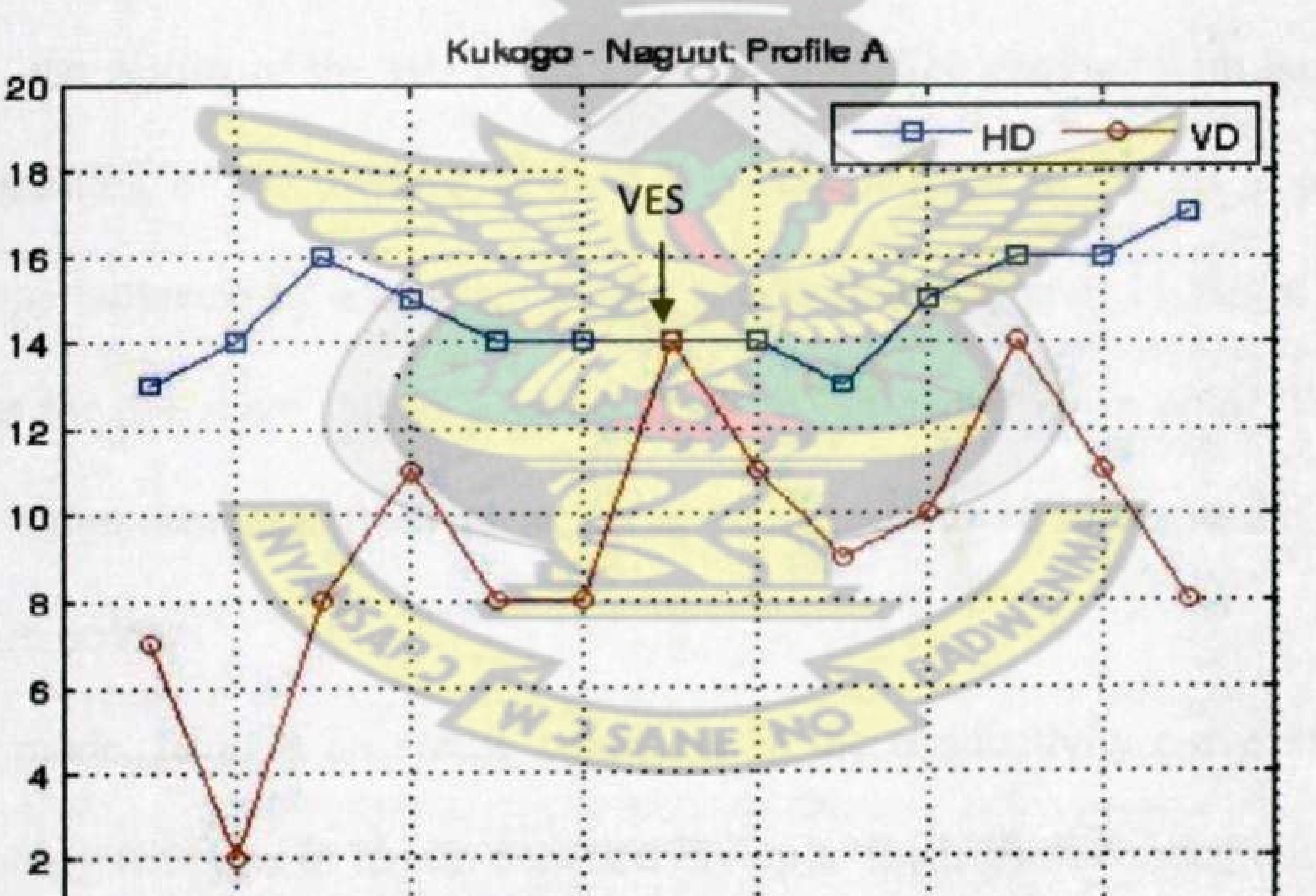

Figure 4.27a EM terrain conductivity profile for traverse A at Kukogo - Naguut.

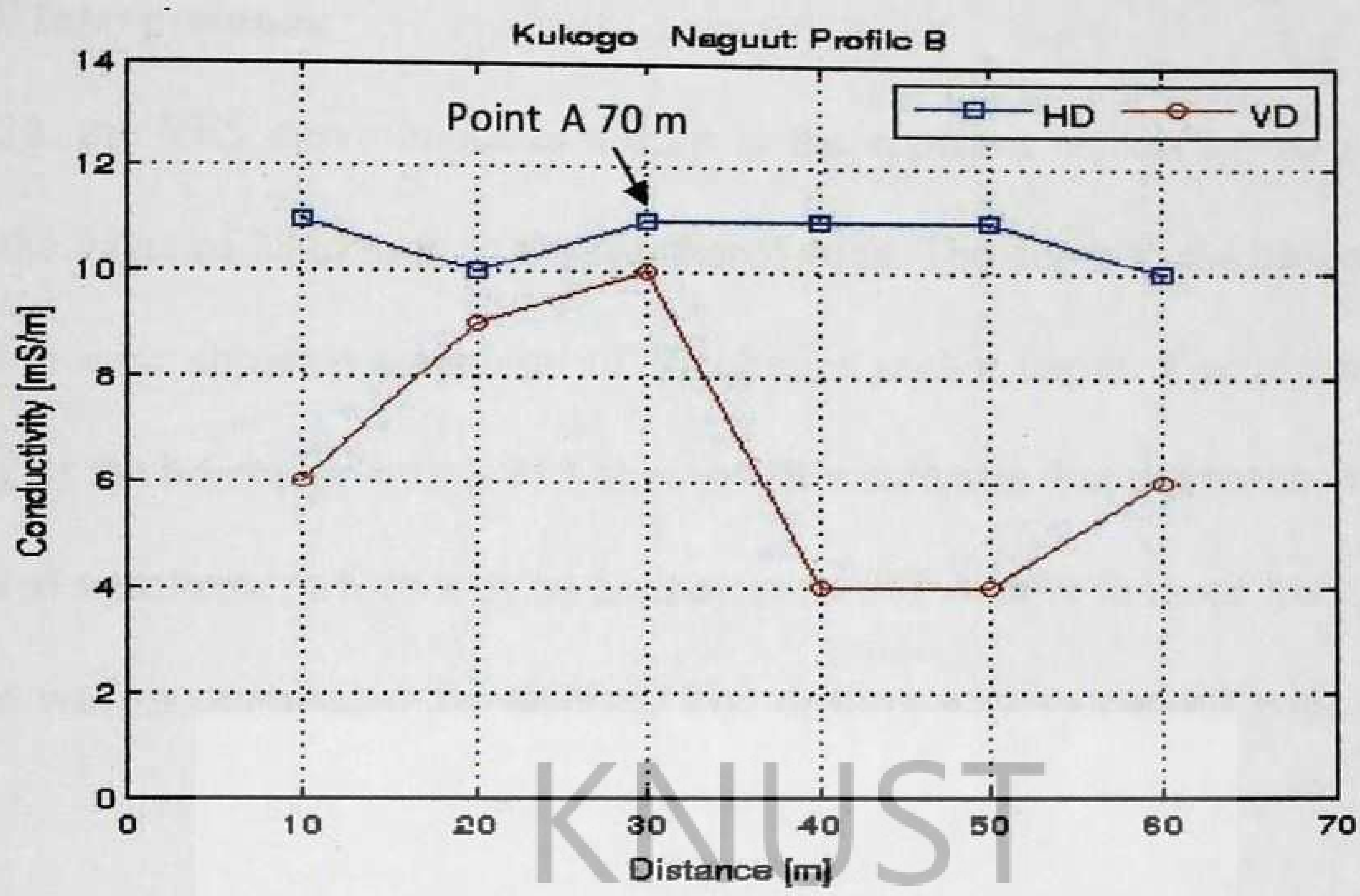

Figure 4.27b EM terrain conductivity profile for traverse B at Kukogo - Naguut.

In Fig.4.27b, the results of the HD mode show a subsurface geology with homogeneity from the beginning of the traverse at the 10 m station point to the 50 m point. This homogeneity is indicated by a constant terrain conductivity value of 11 mS/m from 10 – 50 m, except for the sharp fall to a value of 10 mS/m at the 20 m point. Finally, the conductivity value decreases from 11 mS/m at 50 m point to 10 mS/m at the end of the profile at 60 m point.

For the VD mode, there is an erratic behaviour in the conductivity curve indicating a complex geology with rise in terrain conductivity up to the highest conductivity anomaly of 10 mS/m at the 30 m point which is the point that corresponds to the point A 70 m on profile A. From the 30 m point the ground conductivity declines sharply to a value of 4 mS/m at 40 m and 50 m points and finally, the terrain conductivity increases slightly to a value of 6 mS/m at the end of the profile.

4.30 VES Interpretation

In Fig.4.28, the VES curve indicates a drop in the apparent resistivity from 48 ohm-m down to the value of 38 ohm-m in the weathered zone. The depth to the basement rock is about 20 m with apparent resistivity of 57 ohm-m at that depth. The highest apparent resistivity of the basement rock is 113 ohm-m. This indicates that the basement rock may be fractured weathered, which may be an indication of moisture in those fractures. Hence this point was recommended for drilling. The drilling was successful with appreciable yield.

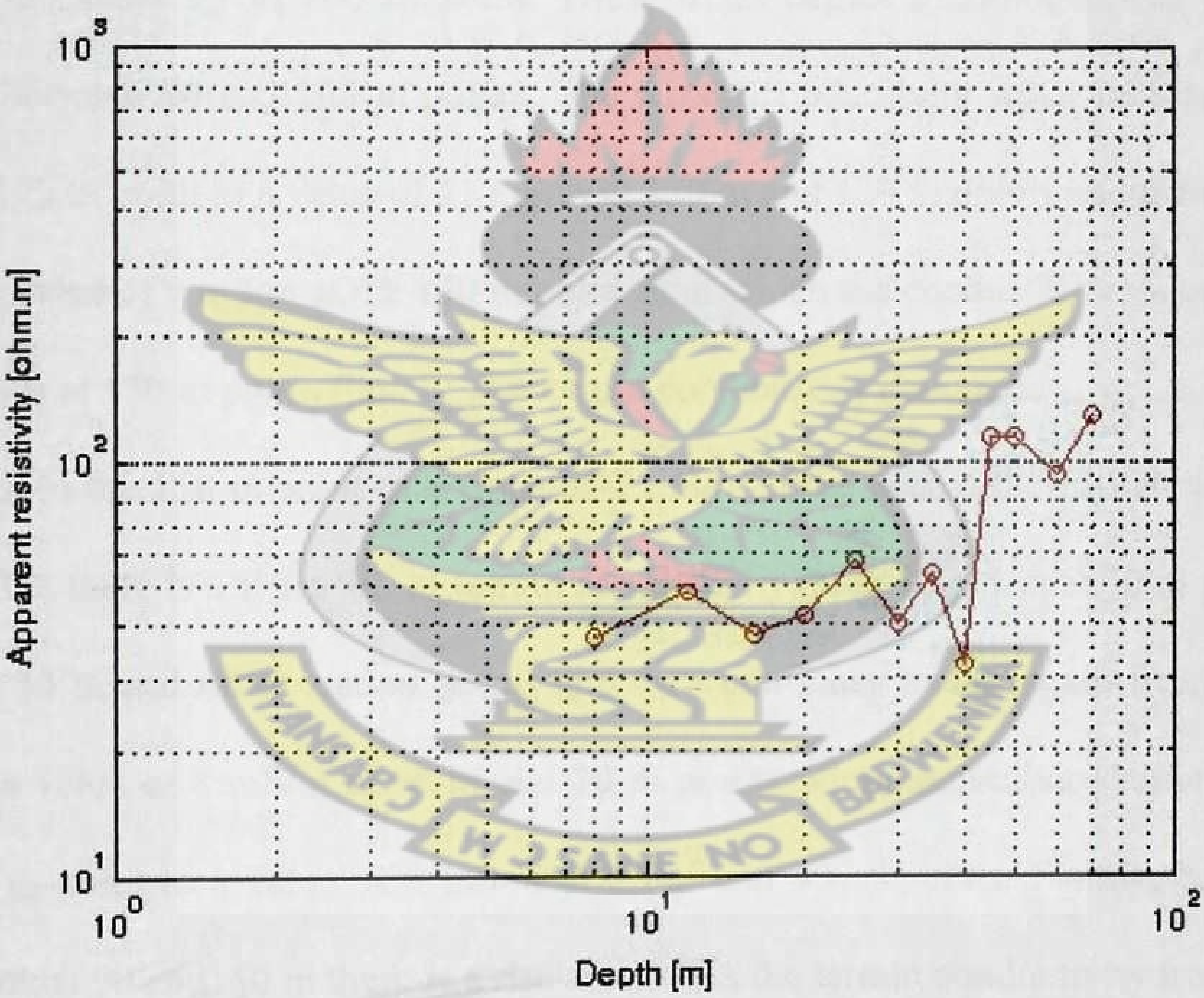

Figure 4.28 VES of Apparent resistivity against Depth at station A 70 m at Kukogo – Naguut.

4.31 Gumbare - Yapala Community

The results of two profiles namely, A and B along which the survey was conducted in this community are shown in Fig.4.29 (a,b). The results of profile A in Fig.4.29a, of length 160 m and on the bearing 070°, shows a sharp increase in terrain conductivity along the profile from the 10 m point at the value of 10 mS/m to a value of 12 mS/m at 20 and 30 m points for the VD mode. This is followed by sharp decrease in terrain conductivity to the value of 10 mS/m at 50 m and 60 m points and then decreases again from the 60 m point down to a conductivity value of 8 mS/m at 70 m point, which then remains the same up to 100 m point. These trend depict a homogeneous subsurface geology between 70 and 100 m points. The terrain conductivity again increases from 8 mS/mat 100 m point to a value of 11 mS/m at 120 m and 130 m points and then decreases back to a value of 9 mS/m at the 140 m point from which the conductivity value increases to 10 mS/m at 150 m point. Finally, the terrain conductivity decreases

sharply from the 150 m point to a value of 7 mS/m at the end of the EM survey profile. For the HD, there is a sharp fall in terrain conductivity from 12 mS/m at 10 m point to 10 mS/m at 30 m and 40 m station points and then continues to fall again from the 40 m point to a value of 8 mS/m at 60 m and 70 m points. The conductivity value then rises from 70 m point to a value of 9 mS/m at 80 m and 90 m points. Finally, between the station points 90 and140 m there is a rise and fall in the terrain conductivity from 9 mS/m to 10 mS/m, this 10 mS/m remains the same up to the end of the profile at 160 m. No point was selected for further VES investigation along this traverse.

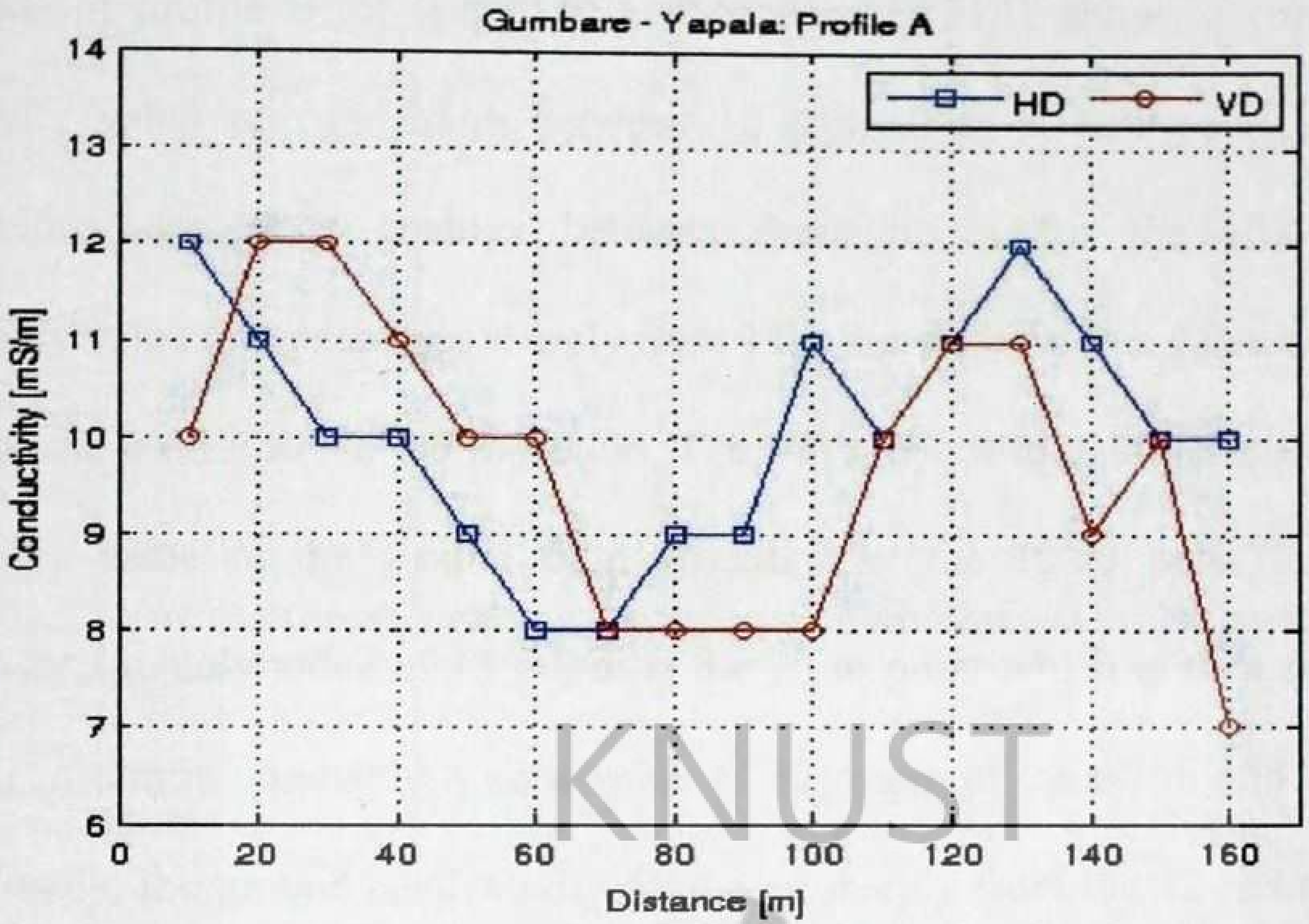

Figure 4.29aEM terrain conductivity profile for traverse A at Gumbare - Yapala.

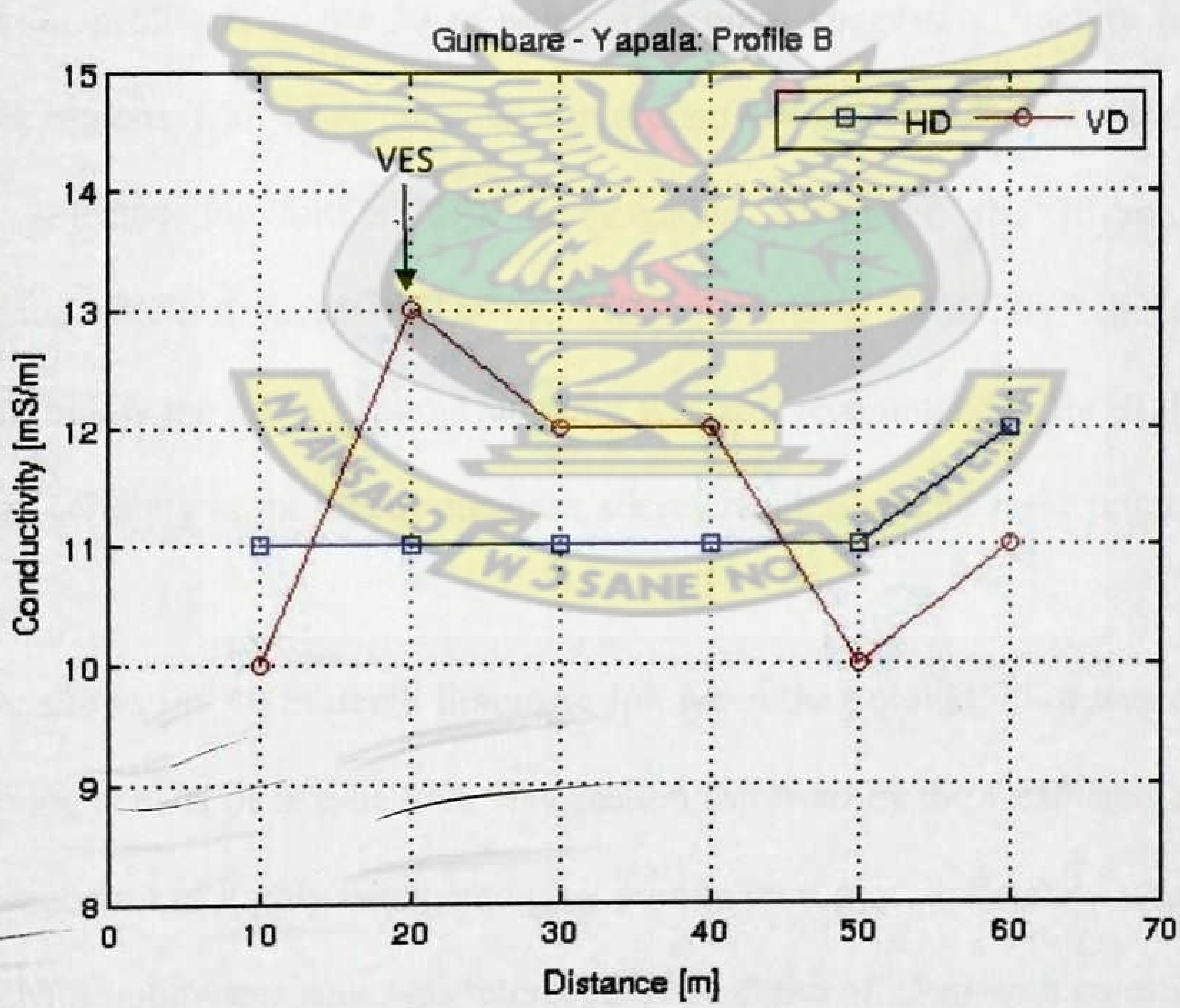

Figure 4.29bEM terrain conductivity profile for traverse B at Gumbare - Yapala.

The results of profile B, of length 60 and on bearing 310°, show a constant terrain conductivity value of 11 mS/m between 10 and 50 m station points indicating a homogeneous subsurface geology between these points for the HD mode. The conductivity value then increases sharply from 11 mS/m at 50 m to a value of 12 mS/m at the end of the profile at the 60 m station. The VD mode results indicate a sharp rise in conductivity value of the ground from 10 mS/m at the 10 m point to the highest conductivity anomaly value of 13 mS/m at the 20 m point which is then followed by a sharp fall in terrain conductivity to a value of 12 mS/m at the 30 m and 40 m station points. Finally, the ground conductivity decreases sharply from the 12 mS/m at 40 m to 10 mS/m at 50 m point and then followed by a sharp rise in conductivity to a value of 11 mS/m at 60 m point. The only very high terrain conductivity and crossover anomaly is observed for profile B at the 20 m point. This point suggests a fracture or fault zone which are regions with high potential for groundwater accumulation. This point was therefore selected for further VES investigation. However, the 70 m depth VES investigation was not successful as the McOhm meter consistently registered current error from below the 35 m depth. This point was still recommended for drilling because of the high certainty of the electromagnetic survey result obtained at the point.

Fig. 4.29c shows the 40 m depth lithologic log when the point B 20 m was drilled. The lithologic log consist of laterite ~~with clay~~ section followed by the weathered zone section which is made up of highly weathered pink granite on top of moderately weathered pink granite. The groundwater zone was intercepted at a depth of 25 m with an estimated yield of 180 litres per minute.

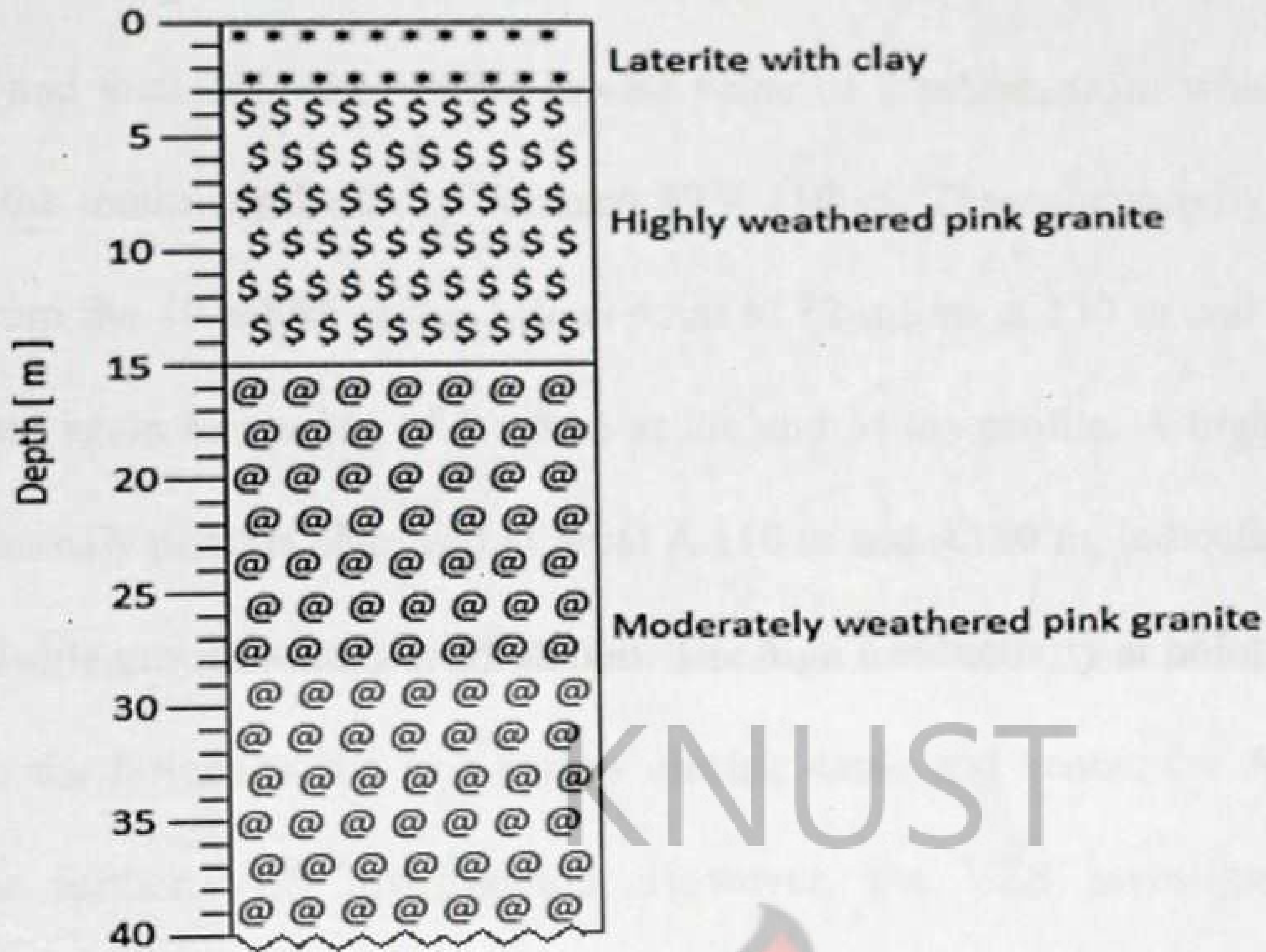

Figure 4.29c Lithologic Log of borehole drilled at the 20 m point of profile B at Gumbare - Yapala.

4.32 Zoakpaliga Community

Fig.4.30 (a,b) shows the results of the two profiles A and B that were carried out in the Kugdari community. Profile A has length of 150 m and a bearing of 265° whilst profile B has a length of 90 m and a bearing of 262°.In Fig.4.30a, the results of profile A, show for the HD mode, an increase in terrain conductivity along the profile from 10 m point at the value of 12 mS/m to a value of 15 mS/m at 30 m point and then falls sharply to a value of 14 mS/m at 40 m and 50 m station points. This is followed again by an increase in the terrain conductivity from 14 mS/m at 50 m point to 19 mS/m at 90 m and 100 m points. Finally, the terrain conductivity falls from 100 m point to a value of 16 mS/m and then rises back to a value of 18 mS/m at 140 m and 150 m points. Whilst, the results of the VD mode show a constant conductivity value of 6 mS/m for the 10 m and 20 m points and then increases sharply to 9 mS/m at 30 m and 40 m points from the 20 m point. This is followed by an increase in the terrain conductivity from the 40 m point up to 11 mS/m at 60 m point and then decreases to the lowest value of 2 mS/m, from which there is an increase in the terain conductivity between 80 – 110 m. The conductivity value finally decreases from the 19 mS/m at the 110 m point to 12 mS/m at 130 m and 140 m points and continues again to a value of 5 mS/m at the end of the profile. A high conductivity crossover anomaly point is observed at point A 110 m and A120 m, indicating a wethered zone of probable groundwater accumulation. The high conductivity at point A 110 m was attributed to the influence due to a nearby electric cable and hence, the A 120 m point selected for further VES investigation. However, the VES investigation was not successful since the McOhm meter consistently registered current error and all possible causes such as improper connections were checked but proved fruitless.

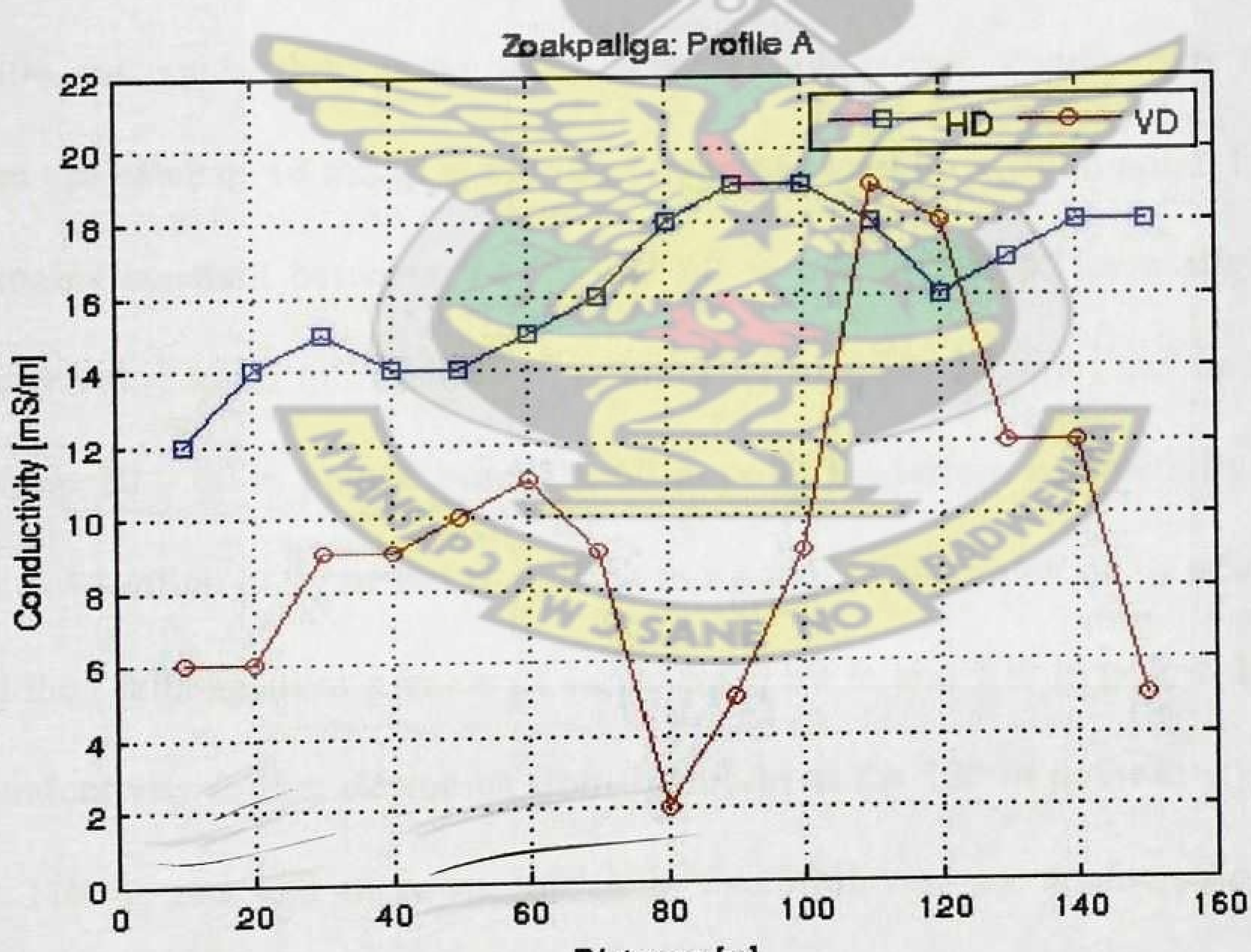

Figure 4.30aEM terrain conductivity profile for traverse A at Zoakpaliga.

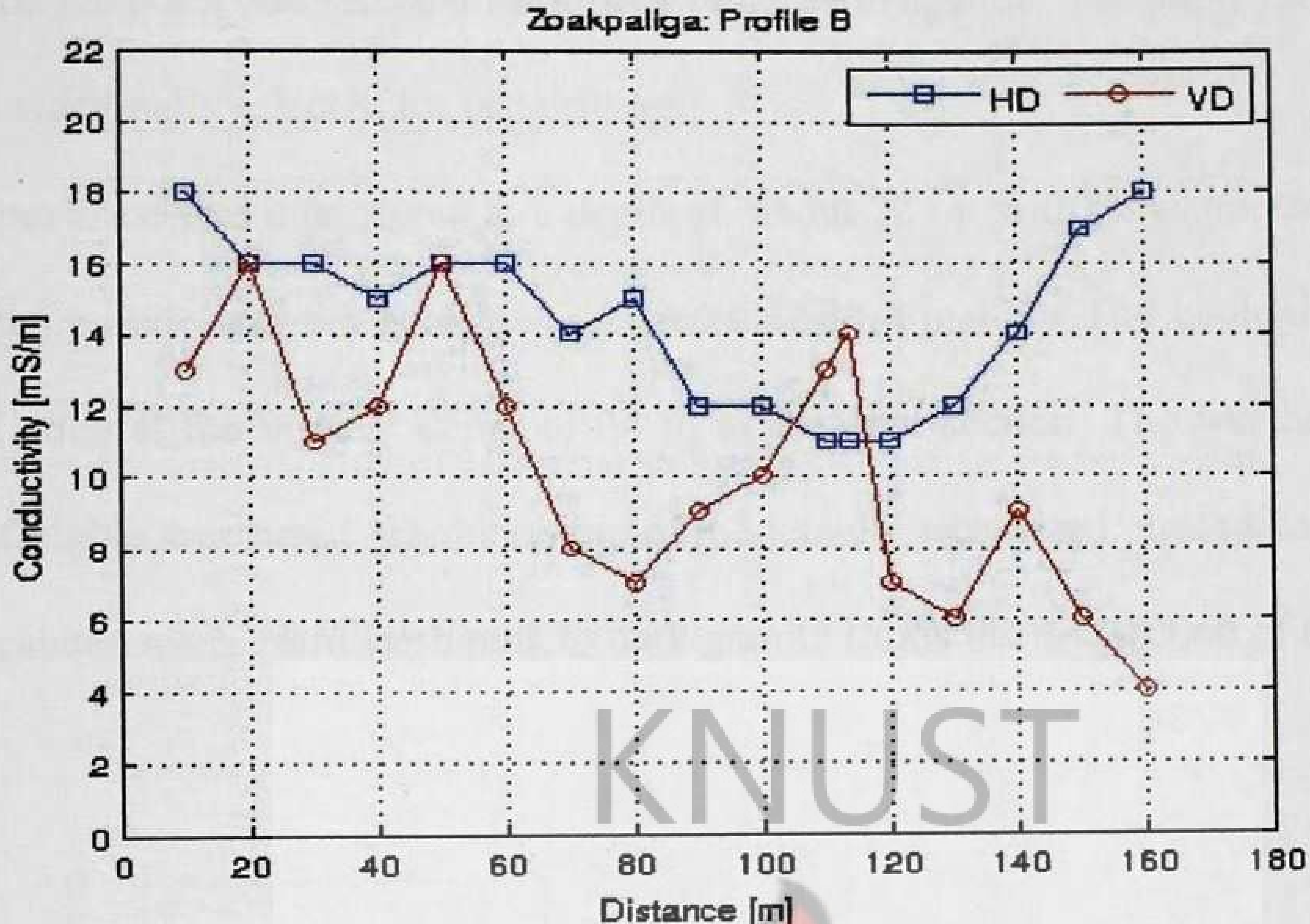

Figure 4.31b EM terrain conductivity profile for traverse B at Zoakpaliga.

In Fig.4.30b, the conductivity curve shows a decrease in terrain conductivity for the HD mode from the value of 18 mS/m at the 10 m point to 16 mS/m at 20 m point, from the 16 mS/m remains constant between the 20 and 60 m points, except for a slight drop in conductivity value to 15 mS/m at 40 m point. This suggests a homogeneous subsurface geology from 20 – 60 m points. From the 60 m point the terrain conductivity falls from 16 mS/m to 14 mS/m at 70 m and rises back to a conductivity value of 15 mS/m at 80 m point and then falls again to a value of 12 mS/m at 90 m and 100 m points. Finally, the terrain conductivity further decreases from 12 mS/m at the 100 m point to a value of 11 mS/m at 110 m and 120 m point, which is then followed by an increase in terrain conductivity from 11 mS/m at 120 m point to a value of 18 mS/m from 120 – 160 m. For the VD mode, the terrain conductivity erratically rise and fall from the begining of the profile at 10 m point up to the end of the profile at 160 m point between the values of 16 and 4 mS/m. No point was selected for further VES investigation. The point 120 m along traverse A was finally selected for test drilling.

Groundwater zone was intercepted at a depth of about 22 m with an estimated yield of 14 litres per minute and the geologic log presented is Fig.4.30c.The geologic log has weathered zone at the vertical depth of 24 m as the first section. The weathered zone consists of highly weathered granite on top of moderately weathered pink to dark granite with intercalated mica. Hard fresh pink to dark granite forms the last section of the log.

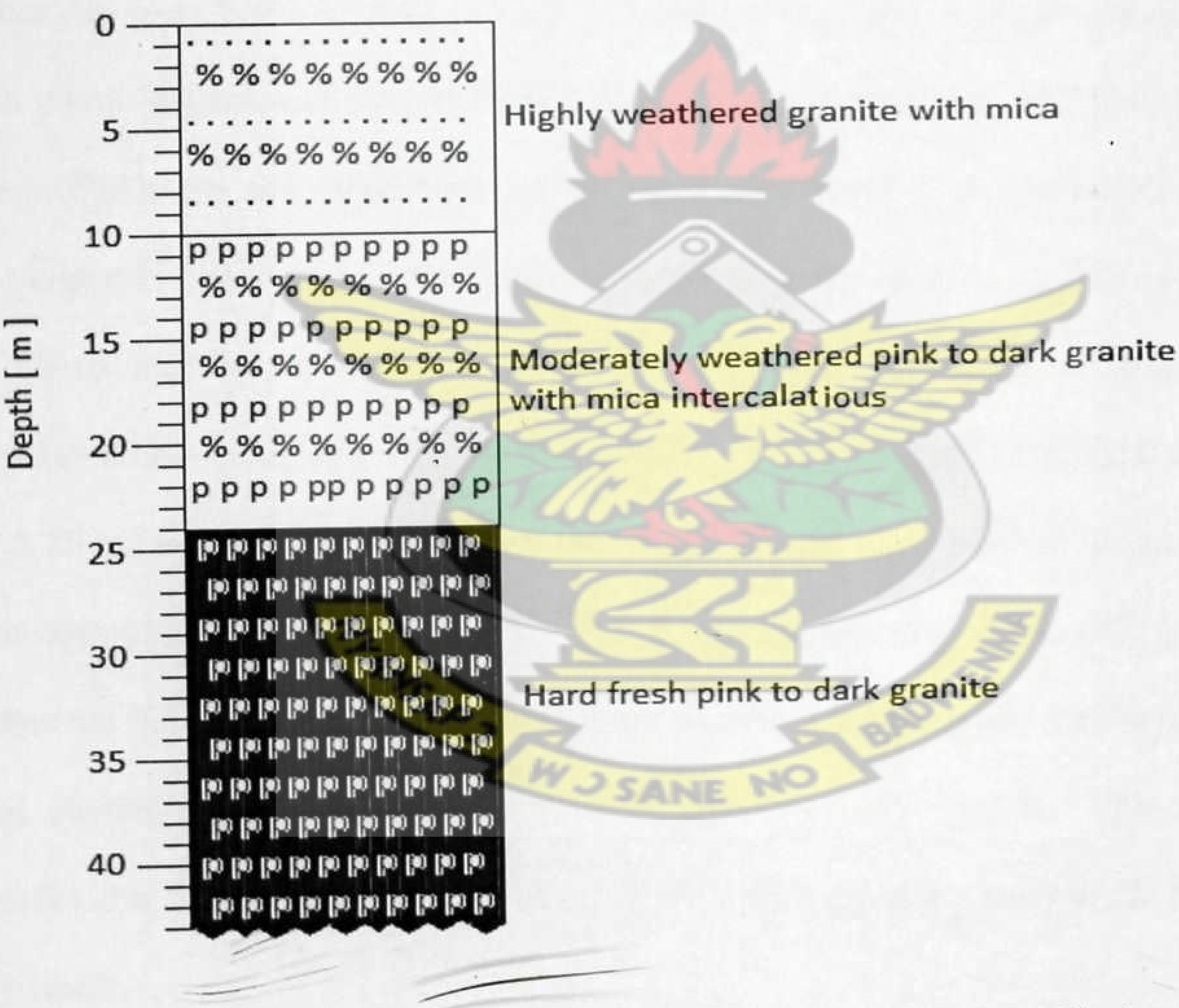

Figure 4.30c Lithologic Log of borehole drilled at the 120 m point of profile A at the Zoakpaliga.

4.33 Boya Primary School Community

Fig.4.31 (a,b) shows the results of two EM surveys along two profiles A and B in Boya Primary School Community. The results of the HD mode along profile A in Fig.4.31a, of length 120 m and on bearing 265°, indicate between 10 and 30 m a constant terrain conductivity value of 6 mS/m suggesting a homogenous subsurface geology between these points and then from there, the 30 m point the conductivity value increases to 8 mS/m at 50 m and 60 m points. Again there is a sharp fall in terrain conductivity to a value of 7 mS/m at 70 m and 80 m stations; and finally a fall and rise in terrain conductivity from 7 mS/m at 80 m point to 7 mS/m at the end of the profile at 120 m station point. The results of the VD mode show an erratic behaviour from the beginning of the profile to the end indicating a probably complex nature of the subsurface geology with a high conductivity crossover anomaly occurring at the 30 m point. The anomaly at the 30 m indicates a fault or fracture zone of high probabilty of groundwater accumulation. However, a verification profile of 1 m intervals along profile and about the point A 30 m indicated high conductivity readings of 6 mS/m and 9 mS/m for the HD and VD modes respectively. Hence the point A 29 m was selected as the drill point and therefore the VES investigation site. However subsurface laterites made it difficult for the current electrodes to be implanted into the ground and therefore the VES was not successful. But this point was still recommended for drilling on the basis of the high EM survey results.

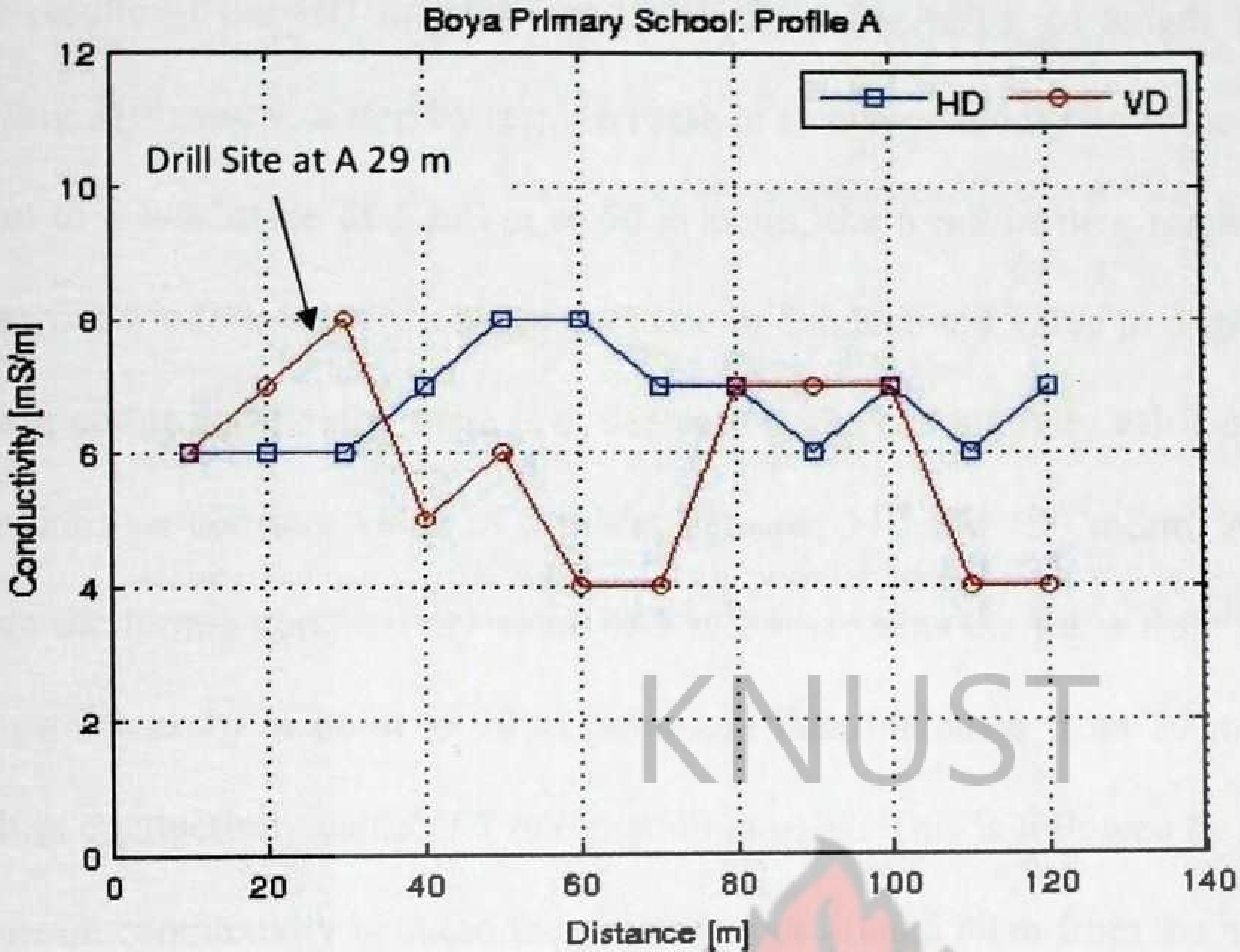

Figure 4.31a EM terrain conductivity profile for traverse A at Boya Primary School.

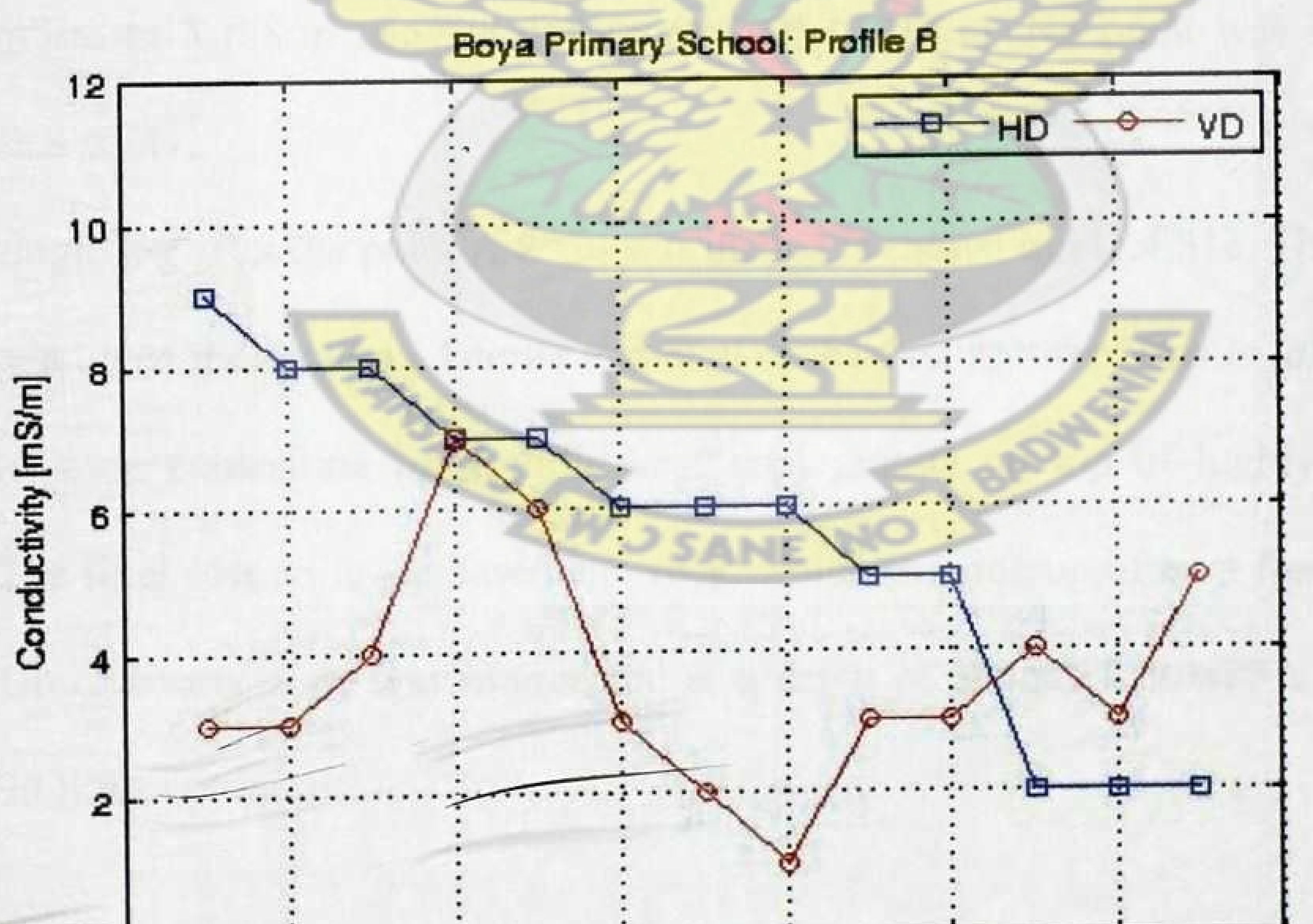

Figure 4.31b EM terrain conductivity profile for traverse B at Boya primary school.

The results of the HD mode along profile B in Fig.4.31b, of length 110 m and on a bearing 310°, show a step by step decrease in terrain conductivity value of 9 mS/m from 10 m to a low value of 6 mS/m at 60 m point, the 6 mS/m then remained up to 80 m point. This is followed by a sharp decrease in conductivity value to 5 mS/m at 90 m and 100 m points and finally, there is a decrease in the conductivity value of 5 mS/m at 100 m point to a constant value of 2 mS/m between 110 and 130 mS/m. Also, for the VD mode the terrain conductivity value of 3 mS/m remains the same from the beginning of the profile at 10 m point to 20 m point and then increases from 20 m point up to the highest conductivity value of 7 mS/m at 40 m point. This is followed by a continuous fall in terrain conductivity between the station points 40 and 80 m from the highest value of 7 mS/m to the lowest value of 1 mS/m and from there the terrain conductivity increases to 3 mS/m at 90 m and 100 m points. Finally, there is a rise and fall in terrain conductivity from 3 mS/m to 5 mS/m between the points 100 – 130 m. No point was selected for further VES study.

The lithologic log after the point A 29 m was drilled is shown in Fig.4.31c. The lithologic log is made up of the sections, laterite and clay as the first section. This is followed by a weathered zone consisiting of slightly weathered granite on top of highly weathered granite. The final section is the basement rock, which is made up of hard fresh fractured granite. Groundwater zone was intercepted at a depth of about 27 m with an estimated yield of 90 litres per minute.

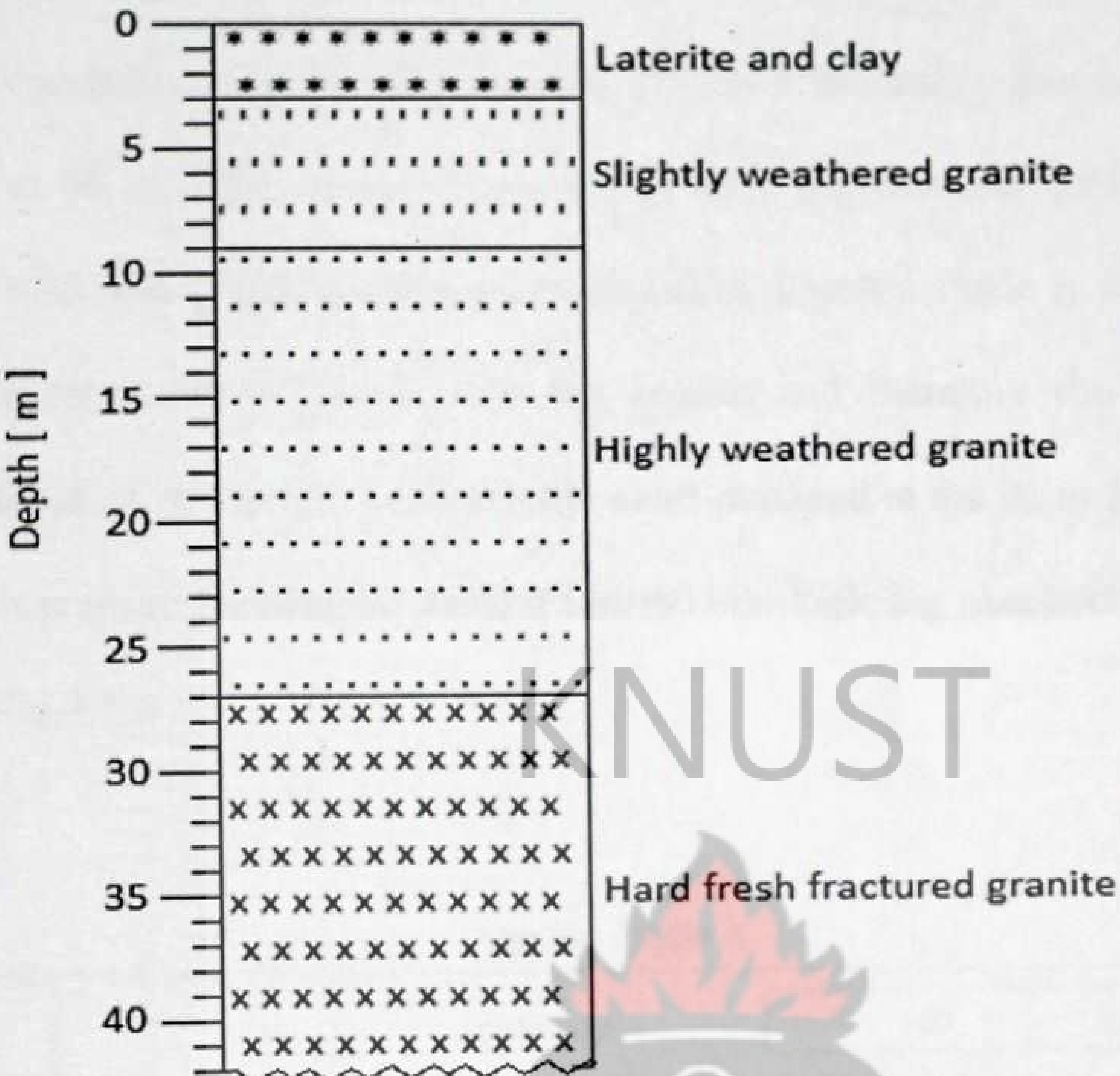

Figure 4.31c Lithologic Log of borehole drilled at the 29 m point of profile A at the Boya Primary School.

4.34 Kugdari Community

Fig. 4.32 (a,b) shows the EM results along two profiles A and B in the Kugdari community. Profile A has length of 150 m and on a bearing of 265° whilst profile B has length 90 m and on a bearing of 262°.In Fig.4.32a, the conductivity curve of the HD mode of profile A increases step by step from 11 mS/m to 17 mS/m between station points 10 to 60 m, decreasing to a value of 15 mS/m at 80 m point and then rises sharply to a value of 18 mS/m at 90 m point. Finally, from the 90 m point there is a sharp decrease in conductivity value to 14 mS/m at 110 m, followed by an increase in conductivity value to the end of the profile at a value of 21 mS/m at station 150 m.The results of the VD mode depicts a non – homogeneous subsurface because of the erratic nature of the conductivity curve, with the only crossover anomaly occurring with a value of 21 mS/m at 90 m. This crossover point may be a fracture zone and was therefore selected for VES investigation. However subsurface laterites made it difficult for the current electrodes to be implanted into the ground and therefore the VES was not successful. Based on the terrain conductivity result obtained at the 90 m point, this point on profile A was recommended for drilling and the lithologic log obtained after drilling is as shown in Fig.4.32c.

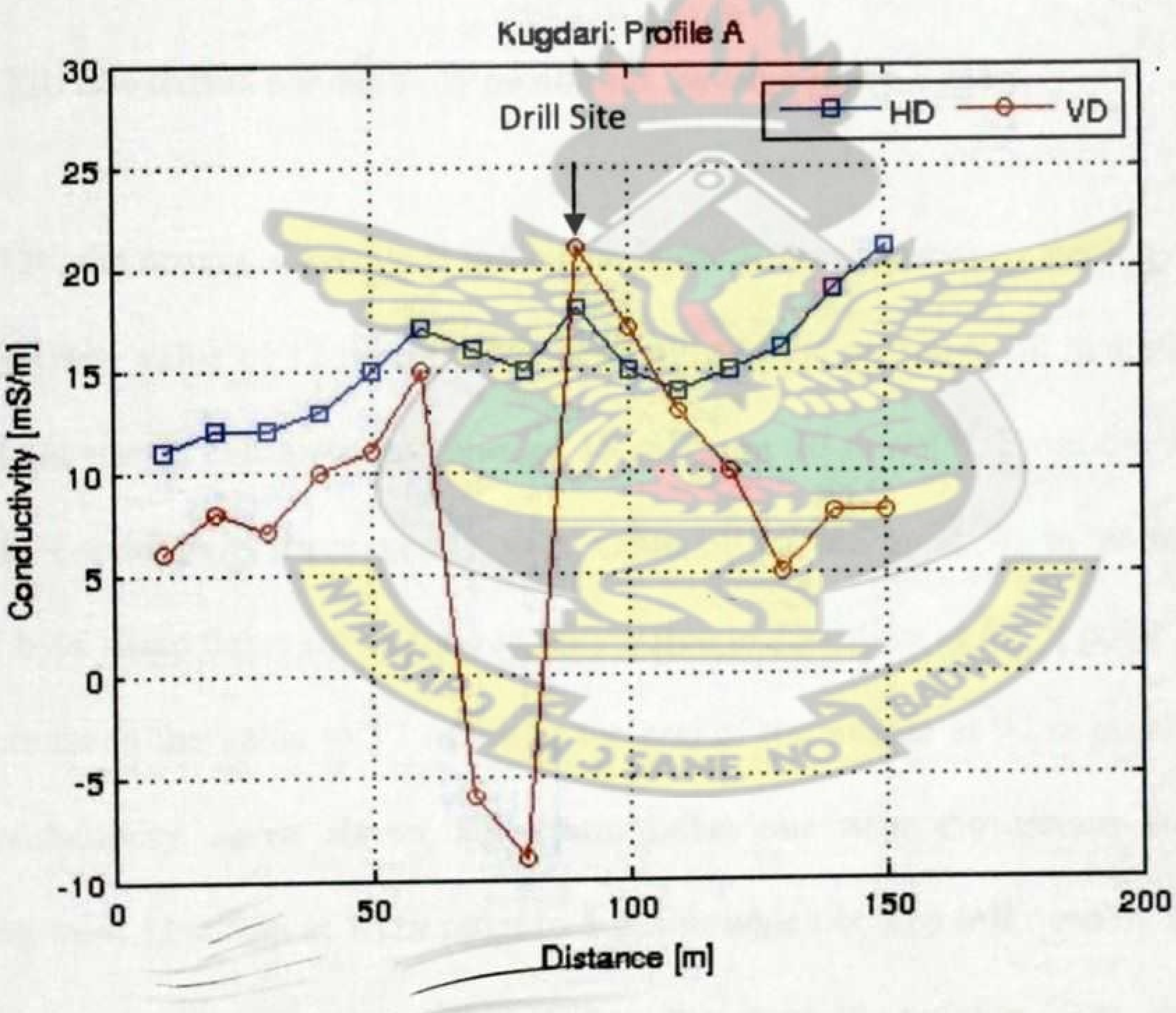

Figure 4.32a EM terrain conductivity profile for traverse A at Kugdari.

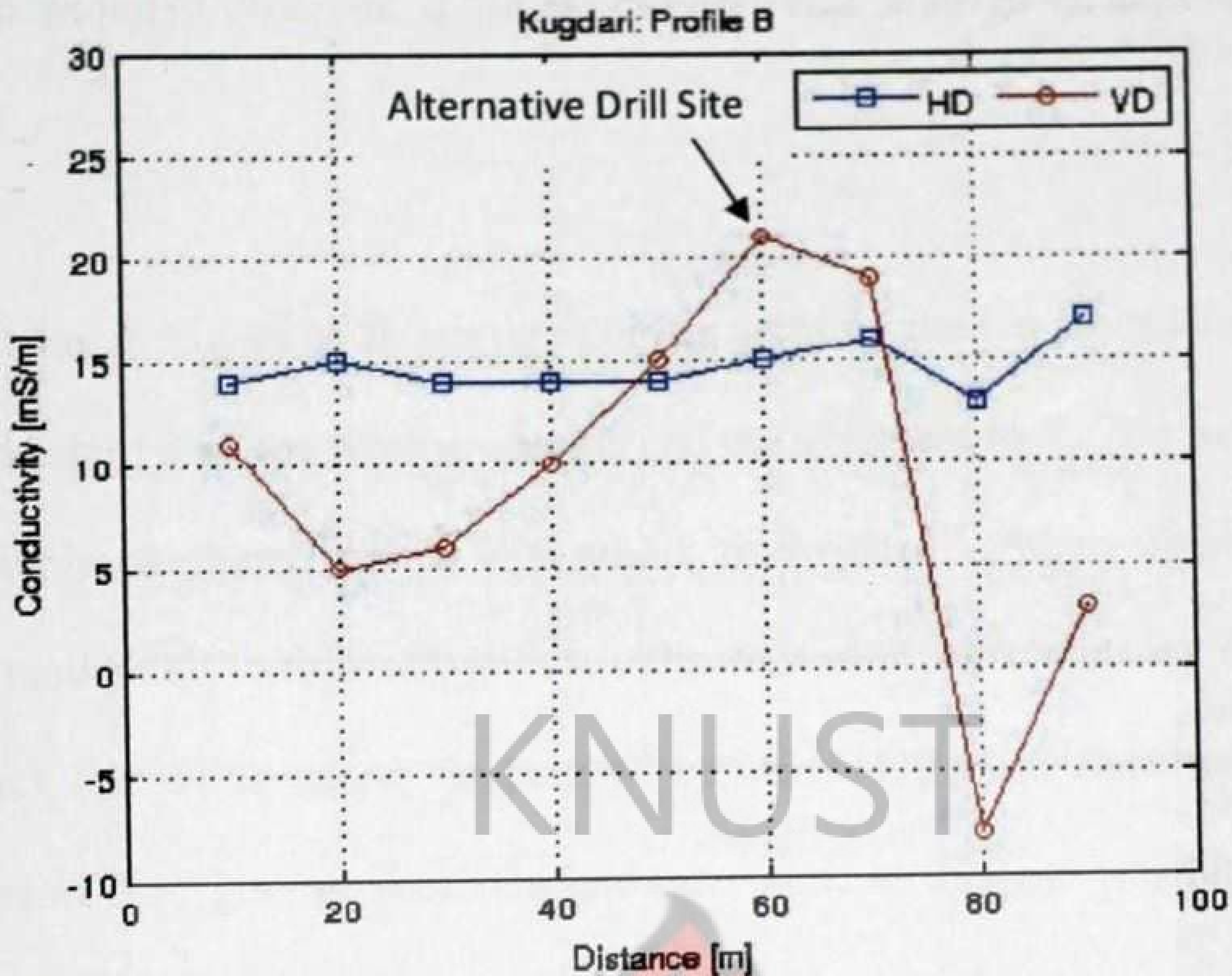

Figure 4.32b EM terrain conductivity profile for traverse B at Kugdari.

In Fig.4.32b, the results of profile B indicate a homogenous subsurface geology shown by the conductivity value of 12 mS/m at the beginning of the profile to 50 m station, except for the slight rise in conductivity value of 15 mS/m at 20 m point. From the 50 m point the terrain conductivity rises gently to a value of 16 mS/m at 70 m point which is followed by a sharp decrease in conductivity value to 13 mS/m at 80 m point and then a sharp increase in the value to 17 mS/m at the end of the profile at 90 m point. The VD mode conductivity curve shows an erratic behaviour with the terrain conductivity decreasing from 11 mS/m at 10 m point to 5 mS/m which is then followed by an increase in the value to the highest value of 21 mS/m at the crossover point at 60 m. From the 60 m point, the terrain conductivity gently falls to 19 mS/m at 70 m which then continues to fall but this time sharply to the lowest value of -8 mS/m at 80 m and finally, the conductivity value increases steeply to 3 mS/m at the end of the traverse at 90 m point.

The crossover anomaly observed at the 60 m point was selected as an alternative drill site.

The lithologic log in Fig.4.32c shows three major sections, the top loose laterite and clay at a vertical depth of 3 m, the weathered zone and the basement rock. The weathered zone consists of highly weathered granite with quartz sandwiched between slightly weathered granite and moderately weathered granite. The basement rock consists of hard fresh fractured black and white quartz sandwiched between hard fresh fractured quartzitic – granite and semi hard granitic rock. Groundwater zone at this site was intercepted at a depth of about 18 m with an estimated yield of 110 litres per minute.

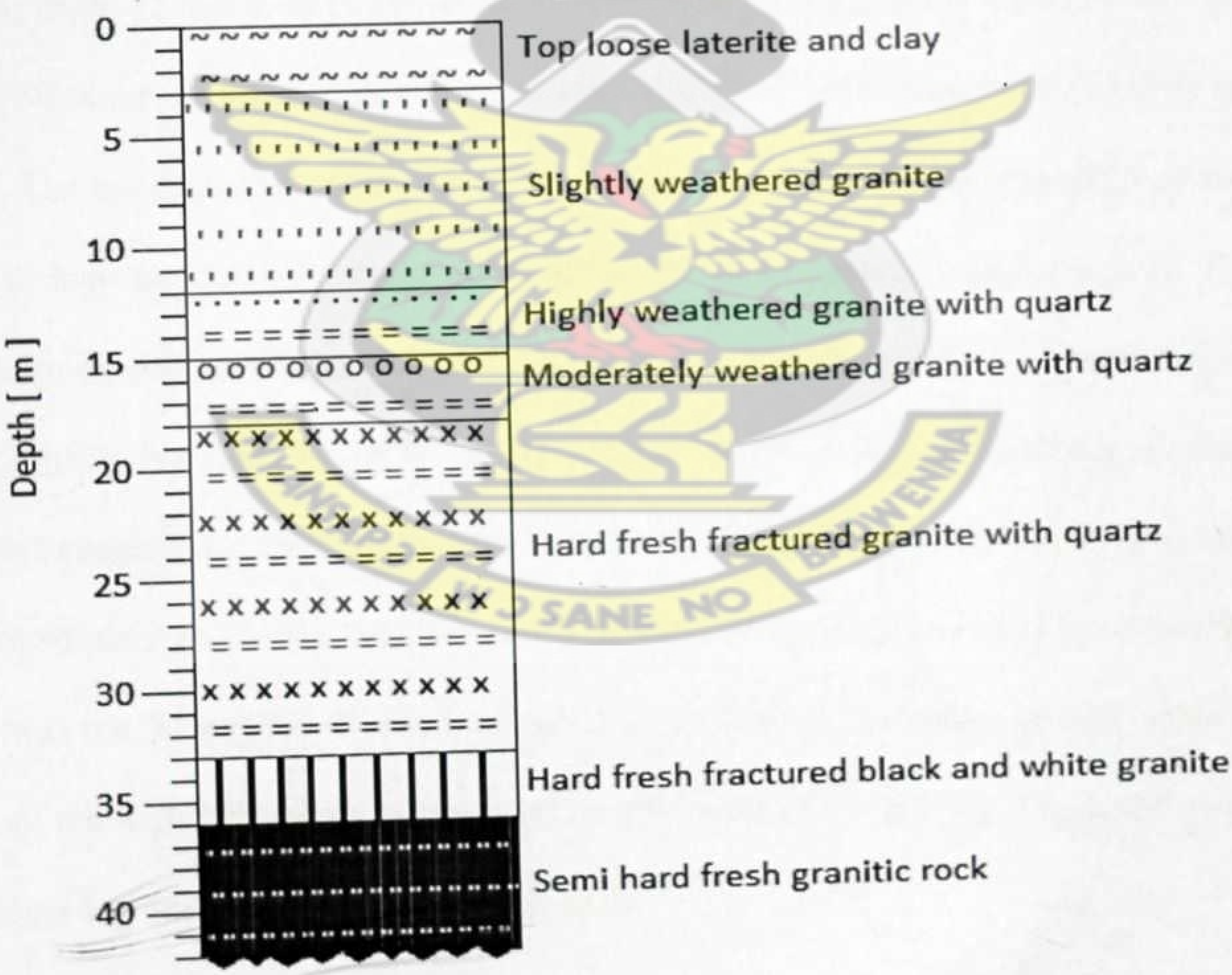

Figure 4.32c Lithologic Log of borehole drilled at the 90 m point of profile A at the Kugdari.

4.35 Sakpare Googo Community

The results of three EM survey profiles namely, A, B and C are shown in Fig.4.33 (a – c). The results indicate that the EM terrain conductivity vary between low and high values of 1 mS/m and 15 mS/m. The results along profile A of length 160 m and on the bearing of 110° shows an erratic behaviour for the curves of both the HD and VD modes with an increase in conductivity value from 10 mS/m to 15 mS/m between 10 and 40 m station points for the HD mode. The conductivity value then falls to 12 mS/m at 60 m point , it then risessuddenly to 14 mS/m at 70 m point and then reduces to a value of 8 mS/m at 90 m survey point. Finally, the conductivity value increases from 8 mS/m to 15 mS/m between the points 100 and 150 m. For the VD mode, the terrain conductivity decreases sharply from 11 mS/m at 10 m station to 2 mS/m at 20 m point and maintaining this value at the 30 m point. The conductivity response value then falls sharply to -1 mS/m at 40 m point. The conductivity value of -1 mS/m remained constant for 50 m point also and then rises to high conductivity value of 12 mS/m at the "crossover" anomaly point at 90 m. The terrain conductivity then declines to 4 mS/m, rises sharply to 7 mS/m and then falls back 2 mS/m from the survey points 90 – 150 m. The high VD conductivity reading at 90 m point suggested a fault or fractured zone, which may have potential for accumulation of groundwater and hence selected as a drill site and for VES investigation. However, the VES was not successful. Because of the high possibility of finding ground water on the basis of the high EM result, this site was recommended for drilling. Fig.4.33d shows the lithologic log at point A 90 m when drilled.

The results of profile B of length 110 m and on a bearing 290°, show an increase in terrain conductivity along the profile from 10 m point at a value of 10 mS/m to a value of 12 mS/m at 20 and 40 m points for the HD mode. It then decreases to 11 mS/m at the 40 and 50 m points and from there decreases to 10 mS/m at 60 m point. This is followed by a rise in terrain conductivity to 11 mS/m at 70 m and then falls again to 10 mS/m at 80 m, from there the 10 mS/m conductivity value remains constant from 80 – 110 m points. The results for the VD mode indicate an erratic behavior starting with an increase in terrain conductivity from the value of 1 mS/m at the 10 m point to 2 mS/m at the 20 m point and then increases again to a value of 6 mS/m at 30 m point. This is followed by a decrease in conductivity value to 3 mS/m at 40 m point and then rises back to a value of 7 mS/m from the 40 – 60 m points. Furthermore, the terrain conductivity decreases from 7 mS/m at 60 m point to 2 mS/m at 80 m point and from there increases to a value of 8 mS/m at the station point 100 m. Finally there is a sharp fall in conductivity value from the 8mS/m at 100 m point to 4 mS/m at the end of the profile. No conductivity crossover anomaly was observed on this profile.

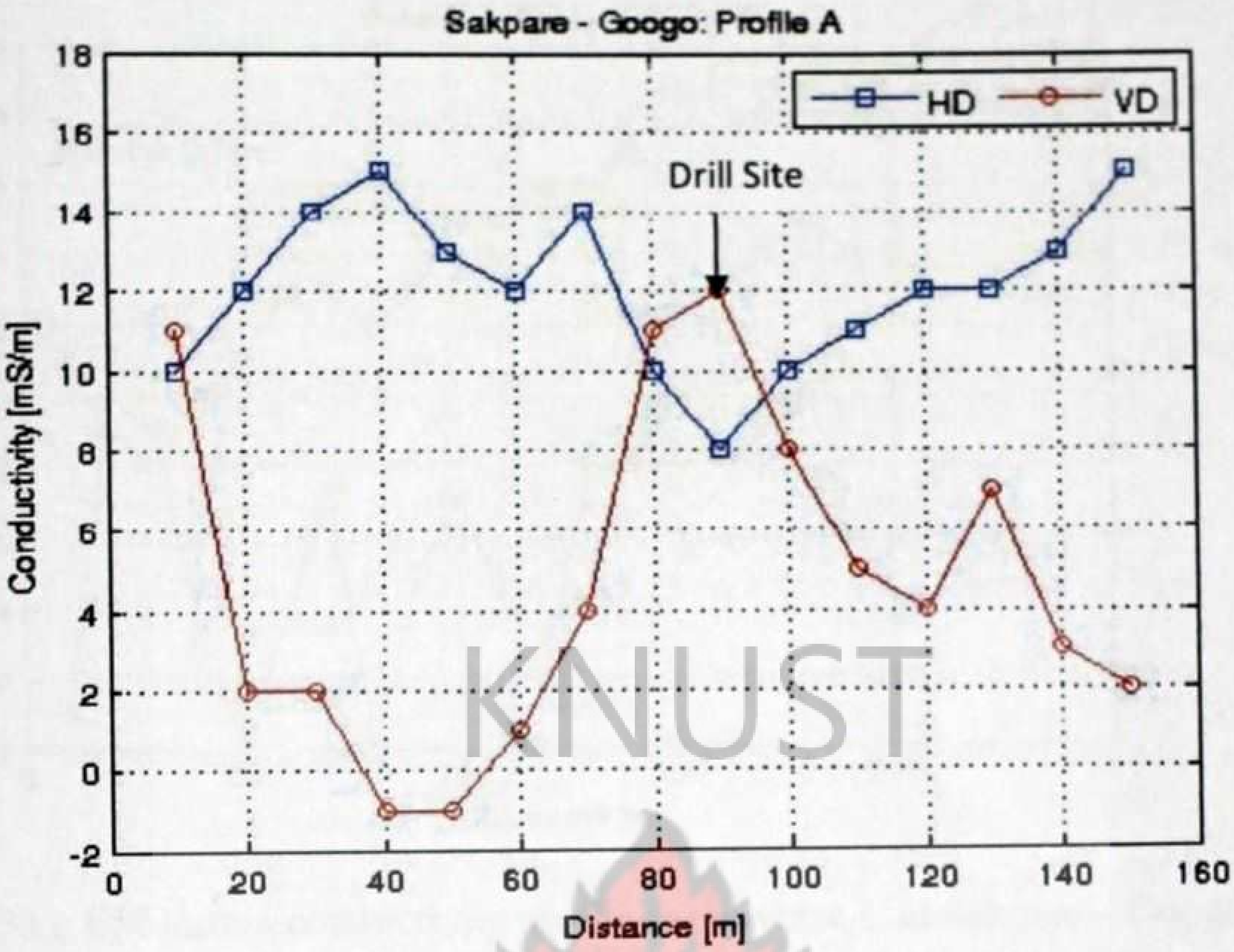

Figure 4.33aEM terrain conductivity profile for traverse A at Sakpare - Googo.

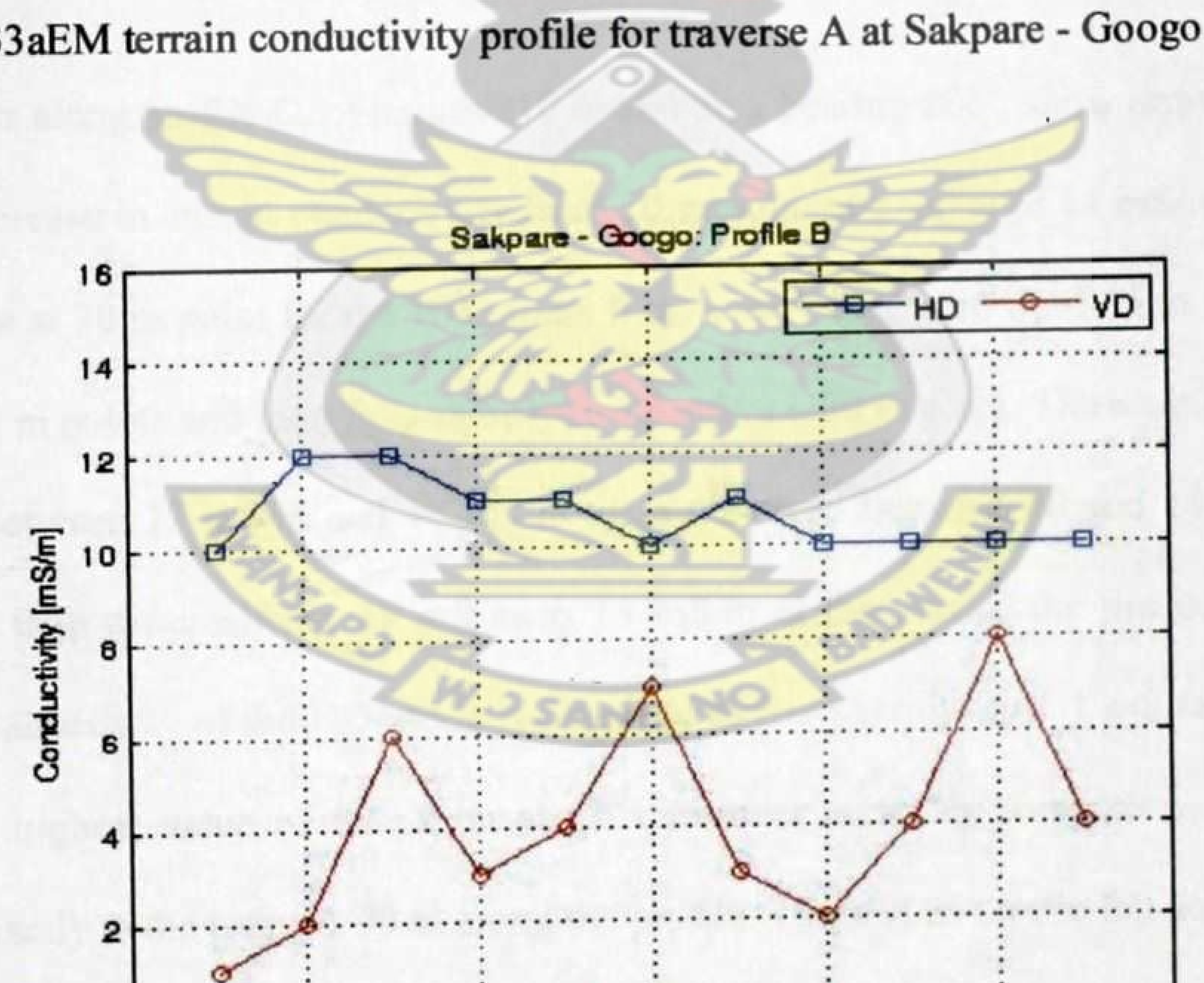

Figure 33b EM terrain conductivity profile for traverse B at Sakpare - Googo.

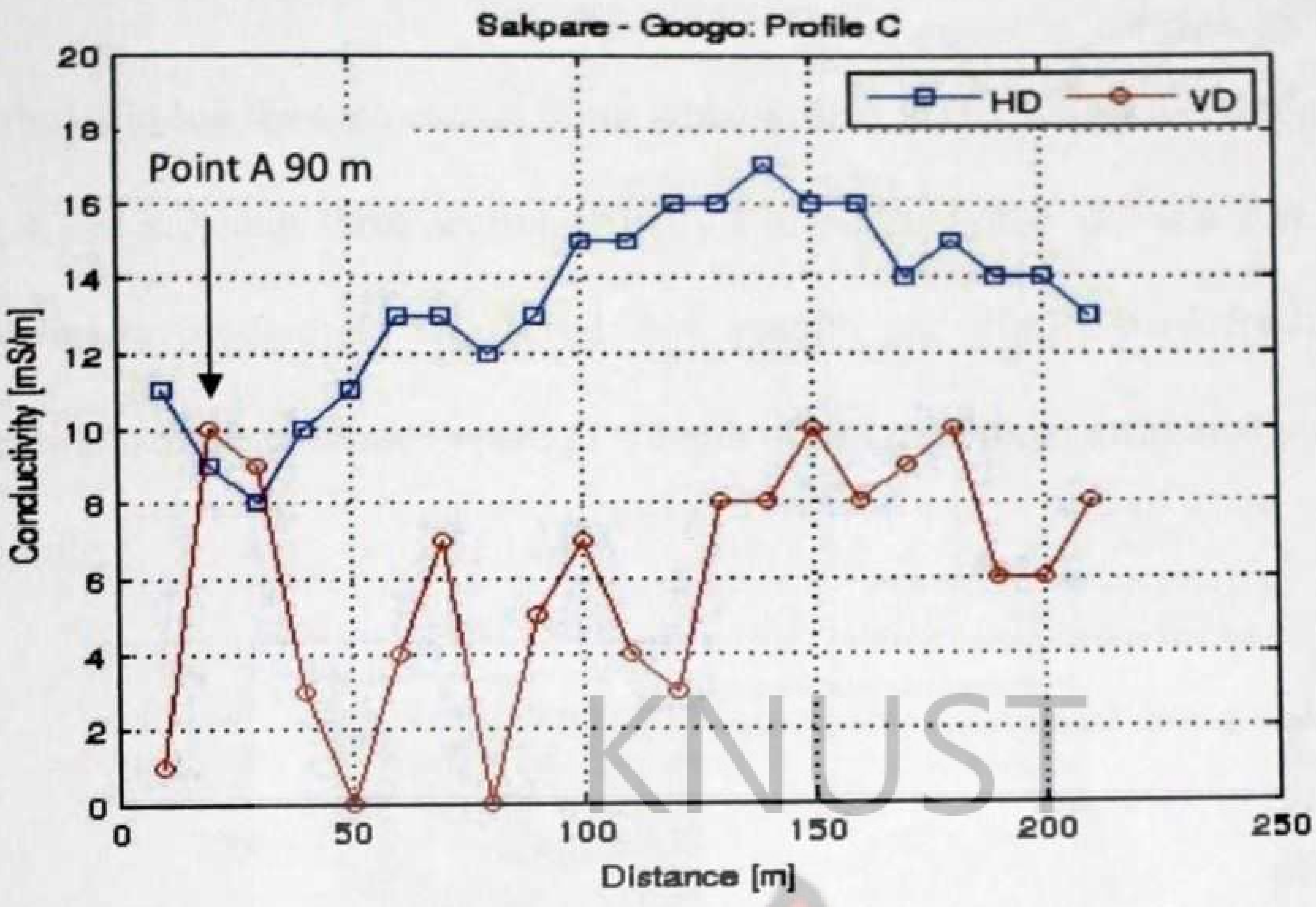

Figure 4.33 c EM terrain conductivity profile for traverse C at Sakpare – Googo.

The results along profile C, of length 210 m and on a bearing 200°, show erratic response with a decrease in terrain conductivity from 10 m point at a value of 11 mS/m to a value of 8 mS/m at 30 m point for the HD mode. It then increases from 8 mS/m to 13 mS/m at 60 and 70 m points and then falls sharply to 12 mS/m at80 m point. The erratic behaviour ranging between 12 mS/m and 17 mS/m were observed between 80 and 140 m station points. It then droppedfrom 17 mS/m to 13 mS/m at the end of the profile. Also, the terrain conductivity of the HD mode is observed to rise sharply from 1 mS/m at point 10 m to the highest value of 10 mS/m at the crossover anomlay point 20 m. This point occurs exactly at the point A 90 m along the profile. There is an erratic fall and rise in the conductivity value from 20 mS/m at 90 m point back to 20 mS/m at 180 m point. Finally, there is a sharp decrease in the conductivity value from 20 mS/m at 180 m to 6 mS/m at 190 m and 200 m points and then a sharp increase in conductivity value from the 6 mS/m at the 200 m point to 8 mS/m at the end of the profile.

The lithologic log for the point A 90 m when drilled in the Sakpare – Googo Community in Fig.4.33d indicates three sections, firstly a loose sandy top soil at a vertical depth of 2 m, secondary moderately weathered dark granite and thirdly hard fresh dark granite. Groundwater zone was intercepted at a depth of 40 m with an estimated yield of 80 litres per minute.

Figure 4.33d Lithologic Log of borehole drilled at the 90 m point of profile A at the Sakpare - Googo.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

With the help of the two geophysical techniques used in this study, EM and resistivity methods, it was possible to effectively and efficiently identify the occurrence of groundwater resources in selected communities in Bawku – West District of the Upper East Region of Ghana. The geophysical techniques identified groundwater zones by delineating areas of subsurface anomalously high apparent electrical conductivity and low apparent resistivity values. The EM method was found to be more useful in the study area than the resistivity method as a result of outcrops of laterites that made implantation of the resistivity electrodes very difficult in some of the communities and the consistency with which the McOHM – EL registered current errors in some of the communities. In all eleven (11) VES investigations were successfully conducted out of twenty (20) identified electromagnetically – anomalous points. However, all the 20 points were recommended for drilling. Only one of the points was unsuccessful after the points were drilled. The borehole success rate in this area was therefore found to be 95 %.The usefulness of the EM method in this exploration project was limited to areas free from electrical power lines, metallic structures, graveyards and wire fencing, whilst the resistivity method was limited to areas free from outcrops, buildings and graveyards.

First, local experience with the use of the EM and resistivity methods was considered the key component in the success of the study. This was achieved through initial EM survey testing at existing successful and unsuccessful exploratory wells or boreholes and the close interaction between hydrogoelogist and geophysicists at WVI – GRWP who were involved in the study. The geophysical data interpretations were confirmed by lithologic interpretation obtained from confirmatory drilling work. This indicated water – bearing zones at depths between 10 and 40 m in the study area with an estimated yield between 10 and 500 litres per minute. The average yield was estimated to be 136.8 litres per minute. Interpretations of the geophysical data correlated well with the lithologic interpretation to delineate the water potential zones in the study area, which were mainly deep weathered zones and fracture zones in the basement rock.

5.2 Recommendations

Based on the findings from the study, the problem with identifying aquifer zones in the study area or any other area of similar geological setting in future groundwater projects may be reduced by taking into consideration the following recommendations.

(1) The use of geophysical equipment which do not require ground contact such as the ground penetrating radar (GPR) will be very important in addition to the EM equipment. This effectively replaces the resistivity method which needs ground contact.

(2) If the need arises, the alternative points in the various communities should be drilled to provide large quantity of potable water for the communities.

(3) It is advisable to apply a quicker and cheaper EM method combined with resistivity prospecting.

(4) The geophysical data should always be correlated with the results from the drilling work in order to identify potential ground water zones.

(5) Geophysical methods such as EM which do not involve introducing current into the ground are highly recommended in areas that are overlain by Lateritic, since the application of electrical resistivity method becomes rather difficult in such areas.

(6) Point source contaminants (e.g. landfills and graveyards) should be at a minimum of 30 m away from targeting.

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APPENDICES

APPENDIX 1 A

COMMUNITY: BIRINGU PRIMARY SCHOOL PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	9	
20	11	13	
30	13	17	
40	15	19	VES
50	18	17	
60	20	17	
70	22	18	
80	23	18	
90	25	21	
100	25	22	

APPENDIX 1 A

COMMUNITY: BIRINGU PRIMARY SCHOOL PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	17	15	
20	17	20	
30	15	20	
40	14	18	VES
50	11	14	
60	9	13	
70	8	14	

APPENDIX 1 B

COMMUNITY: SAKPARE – TANG DABOT PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	15	7	
20	13	5	
30	10	5	
40	9	8	
50	8	7	
60	8	6	
70	8	2	
80	9	4	
90	8	9	
100	7	7	
110	6	4	
120	6	7	
130	6	7	

APPENDIX 1 B

COMMUNITY: SAKPARE – TANG DABOT PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	5	4	
20	4	2	
30	4	2	
40	5	2	
50	6	3	
60	6	2	
70	6	2	

APPENDIX 1 B

COMMUNITY: SAKPARE – TANG DABO **PROFILE: C**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	6	2	
20	7	4	
30	8	6	
40	8	4	
50	9	5	
60	10	4	
70	11	4	
80	11	3	
90	12	4	
100	11	2	
110	13	8	
120	12	5	
130	10	-4	
140	7	0	

APPENDIX 1 B

COMMUNITY: SAKPARE – TANG DABOT **PROFILE: D**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	13	7	
20	13	10	
30	14	12	VES
40	13	10	
50	13	4	

APPENDIX 1 B

COMMUNITY: SAKPARE – TANG DABOT **PROFILE: E**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	6	7	
20	6	5	
30	6	2	
40	7	5	
50	7	5	
60	7	3	
70	7	6	
80	8	4	

APPENDIX 1 C

COMMUNITY: TANGA CHPS CENTRE **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	4	10	
20	3	11	
30	3	8	
40	3	8	
50	4	11	
60	5	10	
70	6	7	
80	7	6	
90	6	5	

APPENDIX 1 C

COMMUNITY: TANGA CHPS CENTRE PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	9	8	
20	6	11	
30	5	12	
40	5	10	
50	6	12	VES
60	6	8	
70	8	8	
80	9	10	

APPENDIX 1 D

COMMUNITY: GORI – KUMZEOGO **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	3	-1	
20	3	0	
30	3	5	
40	4	4	
50	3	1	
60	3	2	
70	3	3	
80	2	3	
90	3	3	
100	3	3	
110	4	2	
120	4	2	
130	5	3	
140	6	4	
150	7	6	
160	8	3	
170	8	2	
180	10	10	
190	11	4	
200	11	5	
210	11	7	
220	9	5	

APPENDIX 1 D

COMMUNITY: GORI – KUMZEOGO **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	8	
20	10	9	
30	9	11	
40	9	10	
50	11	10	
60	13	10	
70	15	8	
80	18	6	

APPENDIX 1 D

COMMUNITY: GORI – KUMZEOGO **PROFILE: C**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	7	
20	13	9	
30	10	-3	
40	8	-1	
50	9	13	
60	6	10	
70	6	6	
80	6	5	

APPENDIX 1 D

COMMUNITY: GORI – KUMZEOGO PROFILE: D

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	6	5	
20	5	8	
30	4	10	C 50
40	4	10	DRILL SITE
50	4	10	

APPENDIX 1 E

COMMUNITY: TETAKO PRIMARY SCHOOL PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	9	5	
20	8	7	
30	7	9	
40	6	6	
50	6	7	
60	6	9	
70	4	7	
80	4	7	
90	4	9	VES at Ext.
100	4	7	
110	5	3	
120	6	1	

APPENDIX 1 E

COMMUNITY: TETAKO PRIMARY SCHOOL PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	6	8	
20	8	9	
30	8	9	
40	10	6	
50	10	5	

APPENDIX 1 E

COMMUNITY: TETAKO PRIMARY SCHOOL PROFILE: C

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	4	5	
20	4	9	
30	5	19	
40	9	19	
50	9	10	
60	7	7	
70	6	6	

APPENDIX 1 F

COMMUNITY: ALAMVOSE **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	19	10	
20	16	6	
30	16	11	
40	15	15	
50	16	16	VES
60	18	18	
70	18	14	
80	17	10	
90	17	5	
100	18	13	
110	17	12	
120	16	12	
130	17	6	

APPENDIX 1 F

COMMUNITY: ALAMVOSE PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	19	8	
20	19	7	
30	16	3	
40	15	9	
50	15	8	
60	15	7	
70	15	7	
80	15	5	

APPENDIX 1 F

COMMUNITY: ALAMVOSE PROFILE: C

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	13	8	
20	15	8	
30	15	7	
40	14	11	
50	14	11	
60	15	6	
70	17	9	
80	16	5	
90	17	2	

APPENDIX 1 F

COMMUNITY: ALAMVOSE PROFILE: D

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	9	
20	10	13	
30	11	11	
40	15	10	
50	17	6	

APPENDIX 1 G

COMMUNITY: KUMBO **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	0	-6	
20	1	-5	
30	1	-3	
40	1	-3	
50	2	1	
60	4	0	
70	4	-7	
80	7	-5	
90	8	-3	
100	8	3	
110	8	-2	
120	6	-3	
130	7	8	
140	7	8	
150	8	6	
160	12	3	
170	12	-3	
180	13	1	

APPENDIX 1 G

COMMUNITY: KUMBO PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	9	7	
20	7	8	
30	7	11	
40	7	9	
50	7	12	
60	7	10	
70	10	10	
80	11	13	
90	14	15	VES at Ext.
100	17	13	
110	22	20	
120	26	13	

APPENDIX 1 H

COMMUNITY: YELWOKO - AZAMBARE PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	-2	-2	
20	-2	-6	
30	-2	-4	
40	-1	0	
50	0	-6	
60	2	-16	
70	5	-11	
80	7	-15	
90	9	-13	
100	12	-8	
110	12	1	
120	13	-5	

APPENDIX 1 H

COMMUNITY: YELWOKO - AZAMBARE PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	13	8	
20	12	11	
30	14	17	Drill Site at Extension
40	14	13	
50	16	10	
60	14	9	

APPENDIX 1 I

COMMUNITY: TESHIE CHPS CENTRE **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	15	13	
20	16	13	
30	17	11	
40	18	8	
50	18	13	
60	21	22	VES
70	15	22	
80	15	12	
90	14	12	

APPENDIX 1 I

COMMUNITY: TESHIE CHPS CENTRE **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	12	4	
20	11	3	
30	8	5	
40	7	5	
50	5	6	
60	2	3	
70	4	4	
80	7	9	
90	5	0	
100	9	1	

APPENDIX 1 J

COMMUNITY: AZANGA PRIMARY SCHOOL PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	20	10	
20	19	14	
30	17	15	
40	16	16	
50	17	23	VES
60	19	15	
70	20	11	
80	23	13	

APPENDIX 1 J

COMMUNITY: AZANGA PRIMARY SCHOOL **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	20	17	
20	19	25	A 50
30	20	18	
40	21	12	
50	24	13	

APPENDIX 1 K

COMMUNITY: TARIKOM – KUUG **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	13	4	
20	12	8	
30	12	12	
40	13	8	
50	13	6	
60	15	13	
70	17	8	
80	18	8	
90	17	6	
100	12	3	

APPENDIX 1 K

COMMUNITY: TARIKOM – KUUG PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	16	5	
20	15	14	
30	13	14	VES
40	11	11	
50	10	12	
60	10	12	
70	10	10	
80	10	8	
90	8	11	
100	8	12	
110	8	7	
120	8	7	

APPENDIX 1 L

COMMUNITY: SAPALUGO PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	-1	3	
20	0	4	
30	1	3	
40	2	2	
50	2	4	
60	2	5	
70	3	6	
80	4	8	
90	4	11	
100	5	7	
110	6	7	
120	8	14	
130	9	6	
140	10	2	

APPENDIX 1 L

COMMUNITY: SAPALUGO PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	2	3	
20	3	8	
30	6	14	DRILL SITE
40	8	9	
50	11	-2	
60	11	0	

APPENDIX 1 M

COMMUNITY: KANSONGO - ANINGBLIGU **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	7	-1	
20	9	-1	
30	8	-2	
40	8	-2	
50	6	-5	
60	6	-4	
70	5	-3	
80	4	-4	
90	1	-2	
100	1	-4	
110	-2	-5	
120	-2	-4	
130	-3	-2	
140	-3	3	
150	-2	8	
160	-1	9	
170	4	-2	
180	7	-19	
190	21	4	
200	14	24	DRILL SITE
210	9	22	
220	7	16	
230	6	13	

APPENDIX 1 N

COMMUNITY: ANANOORE - SAAKA PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	-1	2	
20	-3	1	
30	-3	0	
40	-2	1	
50	-2	2	
60	-1	2	
70	-1	1	
80	-2	1	
90	-2	2	
100	-1	1	
110	-1	1	
120	0	2	
130	0	2	

APPENDIX 1 N

COMMUNITY: ANANOORE - SAAKA **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	3	4	
20	1	4	
30	1	2	
40	2	1	
50	2	2	
60	1	3	
70	0	3	
80	0	2	
90	-2	2	
100	-3	4	
110	-1	2	
120	-2	2	

APPENDIX 1 N

COMMUNITY: ANANOORE - SAAKA PROFILE: C

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	2	4	
20	4	5	
30	4	4	
40	3	2	
50	3	3	
60	3	3	
70	4	4	
80	3	3	
90	4	2	
100	4	3	
110	4	4	
120	4	3	
130	4	4	VES
140	5	3	
150	6	4	
160	6	4	
170	5	-1	

APPENDIX 1 O

COMMUNITY: KUKOGO - NAGUUT PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	13	7	
20	14	2	
30	16	8	
40	15	11	
50	14	8	
60	14	8	
70	14	14	
80	14	11	
90	13	9	
100	15	10	
110	16	14	
120	16	11	
130	17	8	

APPENDIX 1 O

COMMUNITY: KUKOGO - NAGUUT **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	6	
20	10	9	
30	11	10	VES
40	11	4	
50	11	4	
60	10	6	

APPENDIX 1 P

COMMUNITY: GUMBARE – YAPALA PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	12	10	
20	11	12	
30	10	12	
40	10	11	
50	9	10	
60	8	10	
70	8	8	
80	9	8	
90	9	8	
100	11	8	
110	10	10	
120	11	11	
130	12	11	
140	11	9	
150	10	10	
160	10	7	

APPENDIX 1 P

COMMUNITY: GUMBARE – YAPALA **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	10	
20	11	13	VES
30	11	12	
40	11	12	
50	11	10	
60	12	11	

APPENDIX 1 Q

COMMUNITY: ZOAKPALIGA **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	12	6	
20	14	6	
30	15	9	
40	14	9	
50	14	10	
60	15	11	
70	16	9	
80	18	2	
90	19	5	
100	19	9	
110	18	19	
120	16	18	
130	17	12	
140	18	12	
150	18	5	

APPENDIX 1 Q

COMMUNITY: ZOAKPALIGA PROFILE: B

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	18	13	
20	16	16	A 120
30	16	11	
40	15	12	
50	16	16	
60	16	12	
70	14	8	
80	15	7	
90	12	9	
100	12	10	
110	11	13	
114	11	13	DRILL SITE
120	11	7	
130	12	6	
140	14	9	
150	17	6	
160	18	4	

APPENDIX 1 R

COMMUNITY: BOYA PRIMARY SCHOOL PROFILE: A

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	6	6	
20	6	7	
30	6	8	DRILL SITE
40	7	5	
50	8	6	
60	8	4	
70	7	4	
80	7	7	
90	6	7	
100	7	7	
110	6	4	
120	7	4	

APPENDIX 1 R

COMMUNITY: BOYA PRIMARY SCHOOL **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	9	3	
20	8	3	
30	8	4	
40	7	7	
50	7	6	
60	6	3	
70	6	2	
80	6	1	
90	5	3	
100	5	3	
110	2	4	
120	2	3	
130	2	5	

APPENDIX 1 S

COMMUNITY: KUGDARI **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	6	
20	12	8	
30	12	7	
40	13	10	
50	15	11	
60	17	15	
70	16	-6	
80	15	-9	
90	18	21	DRILL SITE
100	15	17	
110	14	13	
120	15	10	
130	16	5	
140	19	8	
150	21	8	

APPENDIX 1 S

COMMUNITY: KUGDARI **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	14	11	
20	15	5	
30	14	6	
40	14	10	
50	14	15	
60	15	21	
70	16	19	
80	13	-8	
90	17	3	

APPENDIX 1 T

COMMUNITY: SAKPARE - GOOGO **PROFILE: A**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	10	11	
20	12	2	
30	14	2	
40	15	-1	
50	13	-1	
60	12	1	
70	14	4	
80	10	11	
90	8	12	DRILL SITE
100	10	8	
110	11	5	
120	12	4	
130	12	7	
140	13	3	
150	15	2	

APPENDIX 1 T

COMMUNITY: SAKPARE - GOOGO **PROFILE: B**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	10	1	
20	12	2	
30	12	6	
40	11	3	
50	11	4	
60	10	7	A90
70	11	3	
80	10	2	
90	10	4	
100	10	8	
110	10	4	

APPENDIX 1 T

COMMUNITY: SAKPARE - GOOGO **PROFILE: C**

Distance [m]	Terrain Conductivity [mS/m]		Remarks
	HD	VD	
10	11	1	
20	9	10	A 90
30	8	9	
40	10	3	
50	11	0	
60	13	4	
70	13	7	
80	12	0	
90	13	5	
100	15	7	
110	15	4	
120	16	3	
130	16	8	
140	17	8	
150	16	10	
160	16	8	
170	14	9	
180	15	10	
190	14	6	
200	14	6	
210	13	8	

APPENDIX 2 A

COMMUNITY: BIRINGU PRIMARY SCHOOL **VES STATION: A**

40 m

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	1.156	754.1	872	
4	5	10	14	12	0.509	2639.3	1343	
4	7	14	18	16	0.101	6334.3	640	
10	3	15	25	20	0.194	1885	366	
10	4	20	30	25	0.045	3770.4	170	
10	5	25	35	30	0.010	6598.2	66	
10	6	30	40	35	0.007	10557.1	74	
10	7	35	45	40	0.004	15835.7	63	
10	8	40	50	45	0.005	22622.4	113	
20	4	40	60	50	0.006	7540.8	45	
20	5	50	70	60	0.002	13196.4	26	

APPENDIX 2 B

COMMUNITY: SAKPARE – TANG DABOT **VES STATION: D 30 m**

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	0.047	754.1	35	
4	5	10	14	12	0.017	2639.3	45	
4	7	14	18	16	0.008	6334.3	51	
10	3	15	25	20	0.017	1885	32	
10	4	20	30	25	0.009	3770.4	34	
10	5	25	35	30	0.004	6598.2	26	
10	6	30	40	35	0.003	10557.1	32	
10	7	35	45	40	0.004	15835.7	63	
10	8	40	50	45	0.002	22622.4	45	
20	4	40	60	50	0.017	7540.8	128	
20	5	50	70	60	0.012	13196.4	158	
20	6	60	80	70	0.008	21114.2	169	

APPENDIX 2 C

COMMUNITY: TANGA CHPS CENTRE VES STATION: B 50 m

A	n	Electrode Position [m]		Depth	Resistance	Mult.	App. Resist.	Remarks
		Inner	Outer	[m]	[ohm]	Factor	[ohm.m]	
4	3	6	10	8	0.111	754.1	84	
4	5	10	14	12	0.028	2639.3	74	
4	7	14	18	16	0.017	6334.3	108	
10	3	15	25	20	0.060	1885	113	
10	4	20	30	25	0.024	3770.4	90	
10	5	25	35	30	0.004	6598.2	26	
10	6	30	40	35	0.009	10557.1	95	
10	7	35	45	40	0.008	15835.7	127	
10	8	40	50	45	0.004	22622.4	90	
20	4	40	60	50	0.010	7540.8	75	
20	5	50	70	60	0.006	13196.4	79	
20	6	60	80	70	0.004	21114.2	84	

APPENDIX 2 D

COMMUNITY: TETAKO PRIMARY SCHOOL VES STATION: A 90 m EXTENSION

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	0.146	754.1	110	
4	5	10	14	12	0.030	2639.3	79	
4	7	14	18	16	0.009	6334.3	57	
10	3	15	25	20	0.049	1885	92	
10	4	20	30	25	0.022	3770.4	83	
10	5	25	35	30	0.013	6598.2	86	
10	6	30	40	35	0.010	10557.1	106	
10	7	35	45	40	0.005	15835.7	79	
10	8	40	50	45	0.004	22622.4	90	
20	4	40	60	50	0.025	7540.8	189	
20	5	50	70	60	0.017	13196.4	224	
20	6	60	80	70	0.014	21114.2	296	

APPENDIX 2 E

COMMUNITY: ALAMVOSE **VES STATION: A**

50 m

A	n	Electrode Position [m]		Depth	Resistance	Mult.	App. Resist. [	Remarks
		Inner	Outer	[m]	[ohm]	Factor	ohm.m]	
4	3	6	10	8	0.035	754.1	26	
4	5	10	14	12	0.008	2639.3	21	
4	7	14	18	16	0.007	6334.3	44	
10	3	15	25	20	0.023	1885	43	
10	4	20	30	25	0.018	3770.4	68	
10	5	25	35	30	0.015	6598.2	99	
10	6	30	40	35	0.010	10557.1	106	
10	7	35	45	40	0.013	15835.7	206	
10	8	40	50	45	0.005	22622.4	113	
20	4	40	60	50	0.040	7540.8	302	
20	5	50	70	60	0.007	13196.4	92	
20	6	60	80	70	0.005	21114.2	106	

APPENDIX 2 F

COMMUNITY: GUMBO VES STATION: B

90 m EXTENSION

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	0.039	754.1	29	
4	5	10	14	12	0.019	2639.3	50	
4	7	14	18	16	0.009	6334.3	57	
10	3	15	25	20	0.012	1885	23	
10	4	20	30	25	0.009	3770.4	34	
10	5	25	35	30	0.005	6598.2	33	
10	6	30	40	35	0.003	10557.1	32	
10	7	35	45	40	0.004	15835.7	63	
10	8	40	50	45	0.004	22622.4	90	
20	4	40	60	50	0.010	7540.8	75	
20	5	50	70	60	0.004	13196.4	53	
20	6	60	80	70	0.007	21114.2	148	

APPENDIX 2 G

COMMUNITY: TESHIE CHPS CENTRE VES STATION:

A 60 m

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	0.035	754.1	26	
4	5	10	14	12	0.021	2639.3	55	
4	7	14	18	16	0.004	6334.3	25	
10	3	15	25	20	0.027	1885	51	
10	4	20	30	25	0.019	3770.4	72	
10	5	25	35	30	0.006	6598.2	40	
10	6	30	40	35	0.005	10557.1	53	
10	7	35	45	40	0.005	15835.7	79	
10	8	40	50	45	0.002	22622.4	45	
20	4	40	60	50	0.016	7540.8	121	
20	5	50	70	60	0.012	13196.4	158	
20	6	60	80	70	0.009	21114.2	190	

APPENDIX 2 H

COMMUNITY: AZANGA PRIMARY SCHOOL VES STATION:

A 50 m

A	n	Electrode Position [m]		Depth	Resistance	Mult.	App. Resist.	Remarks
		Inner	Outer	[m]	[ohm]	Factor	[ohm.m]	
4	3	6	10	8	0.047	754.1	35	
4	5	10	14	12	0.005	2639.3	13	
4	7	14	18	16	0.008	6334.3	51	
10	3	15	25	20	0.012	1885	23	
10	4	20	30	25	0.008	3770.4	30	
10	5	25	35	30	0.004	6598.2	26	
10	6	30	40	35	0.006	10557.1	63	
10	7	35	45	40	0.004	15835.7	63	
10	8	40	50	45	0.002	22622.4	45	
20	4	40	60	50	0.017	7540.8	128	
20	5	50	70	60	0.010	13196.4	132	
20	6	60	80	70	0.007	21114.2	148	

APPENDIX 2 I

COMMUNITY: TARIKOM - KUUG **VES STATION:**

B 30 m

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	0.038	754.1	29	
4	5	10	14	12	0.011	2639.3	29	
4	7	14	18	16	0.009	6334.3	57	
10	3	15	25	20	0.031	1885	58	
10	4	20	30	25	0.024	3770.4	90	
10	5	25	35	30	0.009	6598.2	59	
10	6	30	40	35	0.006	10557.1	63	
10	7	35	45	40	0.003	15835.7	48	
10	8	40	50	45	0.002	22622.4	45	
20	4	40	60	50	0.018	7540.8	136	
20	5	50	70	60	0.009	13196.4	119	
20	6	60	80	70	0.012	21114.2	253	

APPENDIX 2 J

COMMUNITY: ANANOORE - SAAKA **VES STATION: C 30 m**

A	n	Electrode Position [m]		Depth	Resistance	Mult.	App. Resist.	Remarks
		Inner	Outer	[m]	[ohm]	Factor	[ohm.m]	
4	3	6	10	8	0.077	754.1	58	
4	5	10	14	12	0.018	2639.3	48	
4	7	14	18	16	0.013	6334.3	82	
10	3	15	25	20	0.071	1885	134	
10	4	20	30	25	0.048	3770.4	181	
10	5	25	35	30	0.031	6598.2	205	
10	6	30	40	35	0.008	10557.1	84	
10	7	35	45	40	0.006	15835.7	95	
10	8	40	50	45	0.007	22622.4	158	
20	4	40	60	50	0.025	7540.8	189	
20	5	50	70	60	0.012	13196.4	158	
20	6	60	80	70	0.004	21114.2	84	

APPENDIX 2 K

COMMUNITY: KUKOGO - NAGUUT VES STATION: B 30 m

A	n	Electrode Position [m]		Depth [m]	Resistance [ohm]	Mult. Factor	App. Resist. [ohm.m]	Remarks
		Inner	Outer					
4	3	6	10	8	0.049	754.1	37	
4	5	10	14	12	0.018	2639.3	48	
4	7	14	18	16	0.006	6334.3	38	
10	3	15	25	20	0.022	1885	41	
10	4	20	30	25	0.015	3770.4	57	
10	5	25	35	30	0.006	6598.2	40	
10	6	30	40	35	0.005	10557.1	53	
10	7	35	45	40	0.002	15835.7	32	
10	8	40	50	45	0.005	22622.4	113	
20	4	40	60	50	0.015	7540.8	113	
20	5	50	70	60	0.007	13196.4	92	
20	6	60	80	70	0.006	21114.2	127	

APPENDIX 3

Summary of log results and success rate for the Bawku West District

Community	Boreholes Drilled	Borehole Depth [m]	Borehole Status	Aquifer Depth [m]	Basement Rock Depth [m]	Estimated Yield [litres/min]
Biringu Primary School	1	43	Successful	25		500
Sakpare – Tang Dabot	1	40	Successful	20	27	50
Tanga CHPS Centre	1	42	Successful	21	36	152
Gori – Kumzeogo	1	42	Successful	27	36	75
Tetako Primary School	1	49	Successful	17	12	10
Alamvose	1	39	Successful	21	21	110
Gumbo	1		**Not** Successful			
Yelwoko – Azambare	1	39	Successful	21	18	110
Teshie CHPS Centre	1	37	Successful	14	12	80
Azanga Primary Sch.	1	37	Successful	17	15	130
Tarikom – Kuug	1	40	Successful	22	36	140
Sapalugo	1	27	Successful	16		80
Kansogo – Aningbligu	1	34	Successful	10	10	140
Ananoore – Saaka	1	42	Successful	24	24	411
Kukogo – Naguut	1		Successful			
Gumbare – Yapala	1	40	Successful	25		180
Zoakpaliga	1	43	Successful	22	24	14
Boya Primary School	1	42	Successful	27	27	90
Kugdari	1	42	Successful	18	18	110
Sakpare – Googo	1	52	Successful	40	5	80
Total	**20**	**730**		**387**	**321**	**2462**
Average		**40.6**		**21.5**	**21.4**	**136.8**
Minimum		**27**		**10**	**5**	**10**
Maximum		**52**		**40**	**36**	**500**
Success Rate [%]			**95**			