DELINEATION OF BURIED STREAM CHANNELS USING GEOPHYSICAL TECHNIQUES

by

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SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN GEOHYDROLOGY, IN THE DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY, GRAHAMSTOWN.

ACKNOWLEDGEMENTS

This project was part of a larger and ongoing research project funded by the Water Research Commission. I am grateful for the Commission's support and their interest. Special thanks are due to Professor Willem Botha, Department of Geology, University of Pretoria for the use of geophysical equipment as well as welcome advice and criticism on geophysical theory. My supervisors, initially Dr. J. Herald of Rhodes University, and subsequently Professor C.A. Lewis, gave me invaluable advice, as did Professor D. Hughes. I thank them. I thank O.P. LeRoux for the use of his farm labour on the project and especially for rescuing me from his irrigated field on numerous occasions.

ABSTRACT

This study sets out to evaluate the use of geophysical methods for delineating buried stream channels, which can act as zones of preferential flow within a less hydraulically conductive aquifer. This information is important for gaining an understanding of flow dynamics of alluvial systems. The most reliable method of delineating the dimensions of aquifers is by drilling, which is an expensive proposition and is best preceded by a preliminary geophysical study to help define target zones for a drilling program.

The study area is located adjacent to the Coerney River in the Sundays River Valley. Geologically it consists of approximately 5 metres of alluvial fines, covering 3 metres of coarse cobbles and boulders, all underlain by alternating siltstone and sandstone beds of indeterminate thickness. Throughout the area the water is very shallow at approximately 2 metres depth and the groundwater tends to be very saline. An air photo study revealed an old oxbow channel that had been covered over by subsequent agricultural land use.

The geophysical methods available for the study were portable seismic refraction, electrical resistivity and electromagnetics. Preliminary field tests clearly showed that seismics did not produce valid results. The methods of electrical resistivity and electromagnetics produced good data and were subjected to further assessment. A grid was surveyed over the study area and both geophysical methods were applied at regularly spaced stations.

Soil samples were taken over the same survey grid and analyzed for electrical conductivity in a soils laboratory. The results were compared to the geophysical data in an attempt to quantify the relationship between geophysical response and soil salinity. The data from the electromagnetic survey showed areas of low electrical conductivity, which was a possible indication of zones of preferential groundwater flow. A transect of boreholes was drilled over selected electrical conductivity lows and successfully intersected the buried stream channel. A comparison of the borehole logs with the layered earth models from the Vertical Electrical Soundings indicated that the electrical resistivity method was not responding to the features of the buried stream channel and the cobblestone layer. This proved the electromagnetic method to be more valuable for this particular study.

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CHAPTER 1. INTRODUCTION

This study sets out to evaluate geophysical techniques that can be used to map buried stream channels. In particular this study is an attempt to delineate buried stream channels that may act as zones of preferential flow within a less hydraulically conductive aquifer.

An understanding of the groundwater flow dynamics of alluvial systems can be gained from information on the structure of the alluvial body. This information is usually gained from existing wells, boreholes, or from drilling programmes initiated specifically for this purpose. However this information is not always of sufficient detail required to produce an adequate assessment of the subsurface geological environment. Geophysical techniques, the primary functions of which are to assess subsurface geological and hydrological conditions, are becoming more useful in augmenting existing geological information. Geological assessment methods such as drilling or mapping can be very expensive. Geophysical techniques are useful in helping to target and minimize drilling programmes and also in extending the knowledge of subsurface geology, especially in areas of minimal outcrop or deep and continuous overburden (Driscoll, 1986; Mandell and Shiftan, 1981).

1.1. RESEARCH PROCEDURE

The main objective of the study is to assess geophysical techniques that can be used to delineate buried stream channels and to consequently gain a better understanding of subsurface hydrological characteristics of alluvial aquifers. A study site was selected in the lower Coerney River area of the Sundays River Valley, near Port Elizabeth in South Africa. An air photo study indicated the presence of a buried stream channel.

A field survey grid was established over the study area and the following geophysical techniques were applied: portable seismic refraction, electrical resistivity and electromagnetics. The techniques were selected on the basis of their portability, availability and their potential ability to acquire data within the environment of the chosen study area.

The geophysical survey was followed with a soil survey to a depth of 3 metres using the same grid. Soil samples were collected and analyzed for electrical conductivity (EC), which is a function of salinity. At the same points on the grid, where possible, the depth of the water table was measured.

A number of assessments were applied to the geophysical, soil EC, and water table data collected. Contouring of the data allowed for a comparison of the results between these parameters, enabling initial assumptions to be made from the geophysical techniques about the study area.

A multiple regression analysis was performed on the data obtained from the geophysical surveys, the soil salinity survey, and the depth to water table survey. The purpose was to assess the relationship between these variables and to predict (where possible) the characteristics of the subsurface geohydrology from the data collected. On the basis of the collected information, boreholes were drilled to verify the interpretation of the geophysical data by intersecting the buried stream channel.

1.2. STUDY AREA

The study area is in the lower Coerney River, which is a tributary of the Sundays River. The study area is approximately 0.5 square kilometres in area and is located about 5km north of the confluence of the Sundays and Coerney Rivers, which flows into Algoa Bay approximately 20 kilometres north of Port Elizabeth (Figure 1.1).

Geologically the area consists of alluvial deposits which include river terraces as well as buried channels in the Sundays River area. The alluvial material overlies Cretaceous bedrock, which consists of interbedded sandstones and mudstones, with a coarse conglomerate layer deposited on the bedrock surface (Engelbrecht et al, 1962).

Rainfall in the study area tends to be cyclonic and evenly distributed, with slightly higher precipitation in the spring and autumn (300 to 400 mm per year) . Although berg winds result in extreme temperatures, the average maximum daily temperature is

26°C in January and 19°C in July, and the average minimum daily temperature is 15°C in January and 7°C in July. The natural vegetation of this area is classified as Valley Bushveld, a subclassification of Coastal Thicket (Acocks, 1988). Very little of the original field cover is in evidence due to much of the ground being converted from its natural state into land-use for agricultural purposes. The Coerney River area is subject to widespread agricultural practice, with the main products being citrus and lucerne. The area is under intense irrigation with the water being supplied via canal from the Orange River system.

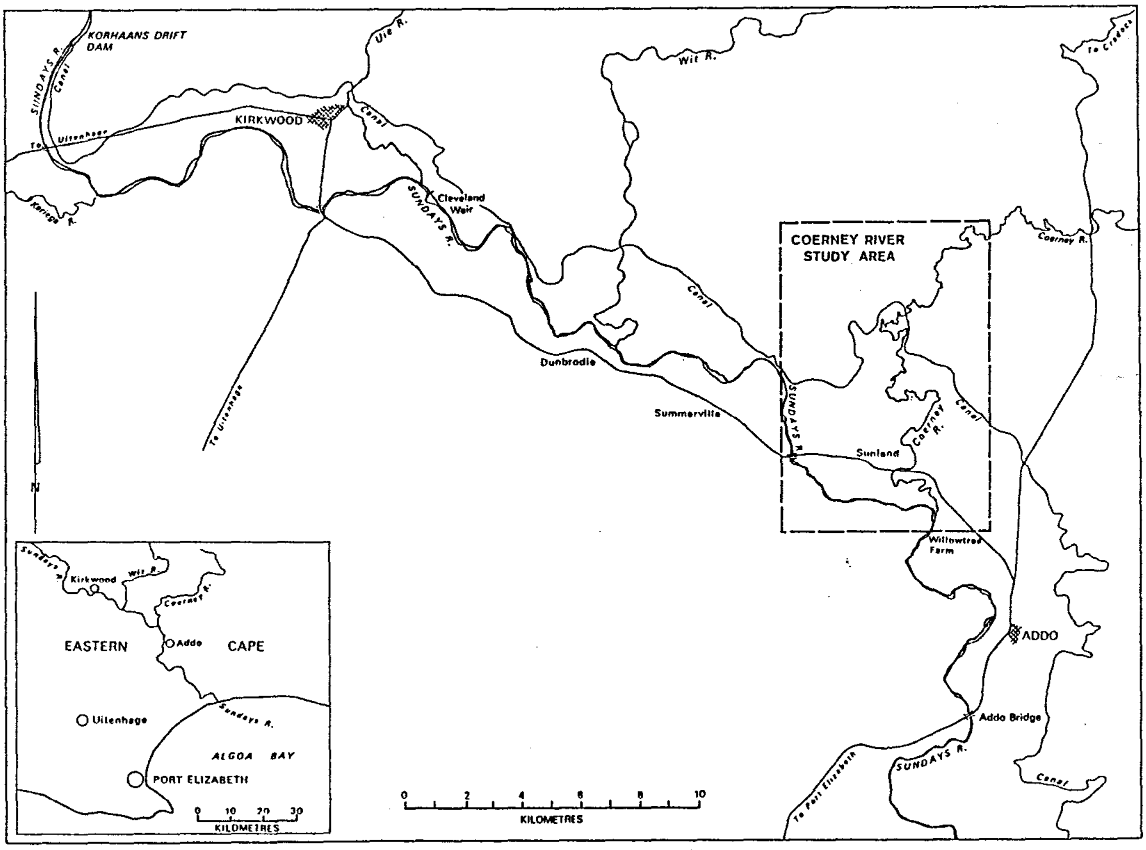


Figure 1.1. Location map of study area.

1.3. RESEARCH SIGNIFICANCE

Within South Africa there are major socio-economic sectors demanding their share of the nation's water resources. They include the increasing population, the industrial sector, and the agricultural sector which relies heavily on irrigation. Irrigation schemes on the banks of major rivers in southern Africa contribute to the general decline in water quality by saline irrigation return flow into the rivers. South Africa's growing population and developing economy, as well as necessitating a more intense utilization of its land and water resources, also contribute to the decline in surface and subsurface water quality by the introduction of domestic and industrial wastes into the river systems (Department of Water Affairs, 1986).

Better water management within an area is augmented by the knowledge of the dimensions of an aquifer and its hydrological characteristics . Aquifer characteristics can either enhance or deteriorate ground water quality, as they perform either a storage function or a conduit function (Johnson Division, 1982). Restricted ground water flow and/or a shallow water table can cause a near-surface buildup of materials such as salts to produce saline soils (Domenico and Schwartz, 1990) or it could also restrict the spread of polluted substances, as in the use of injection wells for sewage disposal (Rail, 1989). Fractured aquifers and alluvial deposits such as buried stream channels can act as drainage zones or zones of preferential flow within a groundwater system. Knowledge of such features can help in the overall assessment of drainage characteristics of an area. This is important in controlling or monitoring the saline irrigation return flow in agricultural areas (Department of Water Affairs, 1986). In terms of industrial application, the location of settling ponds in relation to zones of preferential subsurface flow can mean the difference between controlled leaching of industrial waste or widespread pollution (Rail, 1989).

The role of geophysics in this situation can be one of assessment of changes in the hydrogeological environment. This can include the assessment of subsurface geology as well as the monitoring of water quality. With information from a small number of control boreholes, geophysics can be used to map relative changes in groundwater and soil salinity over large areas. The movement of subsurface industrial or municipal waste pollution plumes is also monitored in the same fashion (Knuth, Jackson, and Whittemore, 1990; Mazac, Landa, and Kelly, 1989).

Knowledge of subsurface aquifer materials is essential to the management of changing ground water quality situations if the goal is to keep water and soil qualities within prescribed acceptable levels. This information can be provided by a well planned geophysics programme. It is important to assess the groundwater characteristics and flow dynamics within an area before commencing land use practices that could consequentially alter water and soil quality irreversibly (Biswas, 1986).

The significance of the present study is twofold: 1) it provides information about subsurface alluvial formations that affect the ground water flow dynamics of an area; 2) it evaluates geophysical techniques used to obtain this information. Not all geophysical techniques are productive for a given investigation.

CHAPTER 2. THEORETICAL BACKGROUND

INTRODUCTION

The central aim of this research is to assess a number of geophysical techniques for delineating buried stream channels within alluvial aquifers. Before undertaking this assessment, it is important to gain an understanding of the morphology of alluvial deposits and of the geophysical techniques to be assessed. The review that follows focuses on the development and morphology of alluvial aquifers and their hydraulic properties. General geophysical theory is introduced, followed by the seismic and electrical properties of earth materials, especially alluvial deposits. These properties are discussed in greater detail in chapter 3.

2.1.1. FORMATION OF ALLUVIAL SYSTEMS

Alluvial aquifers are water bearing formations constructed by rivers and streams as they deposit sands and gravels along their course. These formations are usually long and narrow due to their depositional source and are often located below the earth's surface. On surface they are seen as channels resulting from stream action or as alluvial terraces deposited when the stream was at a higher elevation than at present (Johnson Division, 1982).

Stream flow is almost exclusively turbulent due to the roughness of the channel banks, river bed variations resulting in irregular cross-sections, stream energy loss in river bends and the effects of bedload transport (Mangelsdorf *et al*, 1989). Distorted velocities, sinuous thalwegs, and asymmetrical shoals occur in straight channel patterns as a result of local flow disturbances between the straight banks. The outer bank of the curved section of the channel is subject to greater stream flow velocities and greater erosive energy than the inner bank (Morisawa,1985).

Meanders exhibit two types of movement. One type is a *meander sweep* which is a progressive downstream migration of the meander pattern. The second type is known as a *meander swing*, in which the channel moves laterally back and forth across its environment (Schumm *et al*, 1987). Meanders are a result of rivers attempting to reach dynamic equilibrium between their hydrologic regime (discharge, load, and meander length and sinuosity) and the local geomorphological environment. As the stream meanders it is constantly subjected to a new depositional environment, resulting in more channel pattern adjustments in an attempt to reach equilibrium. A stable meander pattern implies a steady state or a balance between the hydrologic regime and the geomorphological environment (Ferguson, 1977).

Streams are sensitive to alterations of their environment and can be affected by variations in precipitation or changes in land use (Dollar, 1992). Aspects of channel morphology that can be affected are channel width, depth of water, channel sinuosity, and sediment load (Gregory, 1983; Schumm *et al*, 1987).

In the early stages of channel development the stream has proportionally greater energy due to a steeper gradient, often resulting in rapid down cutting and the formation of river valleys. Over time, the stream moderates the relief of its environment and decreases its gradient by erosion and deposition. Eventually a flood plain develops and the stream increases its sinuosity, meandering over the expanse of the flood plain. The result includes the formation of abandoned stream channels such as cutoff and abandoned meanders, known as oxbows (Driscoll, 1986).

2.1.2. MORPHOLOGY OF ALLUVIAL AQUIFERS

Alluvial aquifers are alluvial deposits that contain water. These deposits result from fluvial sedimentation, which may be caused by a decrease in the transport velocity of a stream (the velocity required to carry load of a given calibre). Decreases in velocity are caused by a widening of the channel, a decreased gradient, or a decreased stream discharge (Morisawa, 1985).

Alluvial deposits in river valleys take various forms. Sands and gravels make up the bed load of a stream. They are usually deposited within the channel and provide the best aquifers. Thicknesses of deposits will vary due to the type of material carried by the stream and the stream's palaeohistory (Davis and DeWiest, 1966).

Long term geological and climatic controls affect the depositional environment of streams and rivers. Periods of glaciation and the resulting rise and fall of sea level dictate the transitions of stream behaviour from lateral erosion and meandering to vertical erosion or downcutting. Tectonic factors such as a rising or falling crust also alter the position of the river with respect to sea level, resulting in the same response in erosion behaviour. The degree to which a river has been subjected to these fluctuations is a deciding factor in the thickness of the alluvial deposit (Mangelsdorf *et al*, 1989).

Point bars, a form of alluvial deposit, develop in meandering channels. The thalweg, or the line of deepest water in the stream, tends to swing outwards on a stream bend, causing shear stress and erosion on the outer bank. The eroded material is removed and deposited on the inside of the next bend of the meander, where the water is shallower and the stream energy decreases. This deposition is termed a point bar (Figure 2.1). As erosion and subsequent deposition continues, the deposition of the point bars migrates downstream, leaving arc-like deposits with intervening depressions. These depressions are eventually infilled with fine material deposited from floods or high water (Selby, 1985). Similar to point bars are alternating bars which form in straight channel reaches, but on the inside of the stream thalweg which oscillates from bank to bank.

Two major forms of alluvial deposits produced are lateral and vertical deposits. Lateral deposits develop from the formation and migration of point bar deposits. Vertical deposits result from flood originated overbank deposits that subsequently infill the point bar arcs. When assessing an alluvial plain for types of alluvial deposits, the environment of deposition must be considered. Rivers with virtually non-migrating channels usually produce vertically layered sediments of overbank deposits and infilled basins. Rivers with rapidly shifting channels tend to produce laterally deposited sediments, with only isolated areas of vertical fill in pockets created by stream cutoffs such as oxbows or other sedimentary occlusions (Gregory, 1983; Morisawa, 1985).

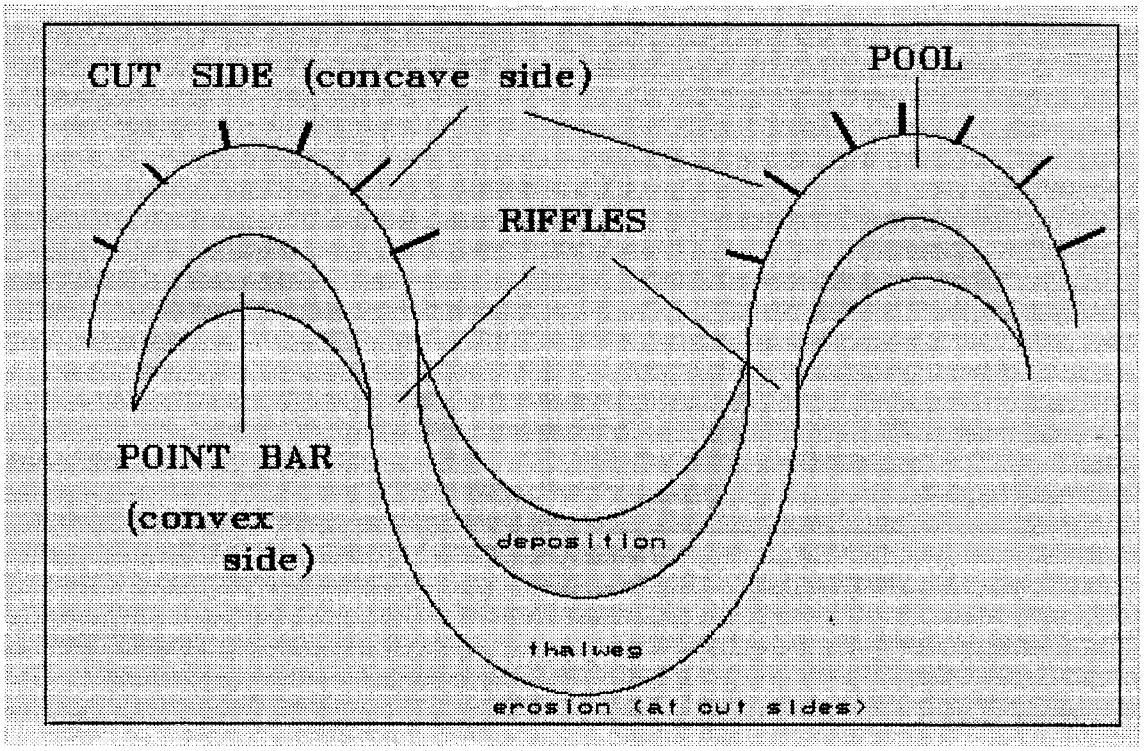


Figure 2.1. Meandering stream and location of point bar deposit (Reineck and Singh, 1980).

2.1.3. HYDRAULIC PROPERTIES OF ALLUVIAL AQUIFERS

The hydraulic properties of alluvial deposits are those that affect the ability of an aquifer to transmit water through its pore spaces. The main parameters governing hydraulic properties are permeability and specific yield. Permeability refers to the ability of water to flow through pore spaces and specific yield is the quantity of water that a unit volume of an unconfined aquifer gives up to gravity. These factors are dependent on shape, packing, size distribution and degree of cementation of particles (Driscoll, 1986). Angular particles compact poorly, producing comparatively high values of porosity, permeability and specific yield. Well rounded particles also compact poorly yielding similar high values. Slightly rounded particles compact very well and result in low values of porosity, permeability and specific yield. Plate-like particles can allow high porosities but when compressed yield almost no porosity. Sorting or particle size distribution affects hydraulic characteristics of an aquifer, with poorly sorted sediments having lower porosity, permeability and specific yield. The effect of depth on aquifer pore reduction is greater on clays and shales than it is on sands and gravels, with greater compression on clays and shales resulting from depth of overburden (Davis and DeWiest, 1966).

The movement of groundwater is governed by certain physical parameters that can be illustrated mathematically. This can be written as a formula known as Darcy's Law, named after Henri Darcy who quantified this relationship. It can be expressed as follows:

$$Q = KA \frac{(H_1 - H_2)}{L}$$

where Q = discharge (m^3/sec)

K = coefficient of hydraulic conductivity (metres/sec)

A = cross-sectional area of flow ($metres^2$)

$H_1 - H_2$ = change in water-level elevation

L = distance over which $H_1 - H_2$ occurs

(Domenico and Schwartz, 1990))

The equation shows that the discharge, Q, is proportional to the permeability or hydraulic conductivity of the medium, the change in hydraulic head, and the cross-sectional area; and inversely proportional to the length or distance of the flow travelled. For illustration of Darcy's Law, consider groundwater moving from points of high potential energy to points of low potential energy, taking the path of least resistance. This potential energy is a result of the elevation and pressure of the water body within the aquifer. As groundwater flows, it loses this energy due to the relative drop in elevation. This energy loss per unit of length of distance travelled is known as the hydraulic gradient (Driscoll, 1986).

The hydraulic gradient is dynamic and can increase, decrease or change direction. Where an aquifer is adjacent to a surface body of water, be it a river or lake, the aquifer either contributes water to the surface body of water or acquires water from this body. This movement of ground water depends on the direction of the hydraulic gradient that has been set up by the difference in potential energy between the surface water and the ground water. For example, dry climatic periods can result in the aquifer supplying water to the surface water body, while periods of high precipitation can result in the surface water body supplying the aquifer (Bear, 1979; Kovacs *et al*, 1981).

2.2. GEOPHYSICS AND EARTH MATERIALS

2.2.1. GENERAL GEOPHYSICAL THEORY

Geophysical techniques examine variations in the physical structure and composition of the earth's crust. This information may also be gained through expensive drilling programmes or by geological mapping. Geophysical information can be acquired by studying inherent or ambient fields within the earth, such as gravity and magnetics in the earth's crust, or by studying the effects of fields applied to the earth such as electrical fields or shock waves (Whitten and Brooks, 1987). Geophysics is less expensive and the equipment is more portable than for drilling. Geophysics does not require surface exposure of outcrop to produce geological information.

Geohydrological investigations often employ surface geophysical techniques during the preliminary stages of a field study. Geophysical methods can provide specific information on the stratigraphy of the local geological environment as well as its aquifer properties. Such stratigraphic information includes the type and extent of surficial material as well as the depth to, and nature of, underlying bedrock. Aquifer properties that can be initially assessed by surface geophysics include the extent of unconsolidated materials and depth to bedrock, the presence and extent of fracturing of bedrock, the presence of water, and the depth to water table (Driscoll, 1986).

2.2.2. SEISMIC PROPERTIES OF EARTH MATERIALS

Exploration seismology originally developed from earthquake seismology, wherein the seismic energy waves generated from an earthquake were recorded on seismographs at different locations. From this information deductions were made about the earth material between the epicentre (origin of the seismic shock) and the seismograph. This led to the development of modern seismology where a controlled artificial shock wave is applied to the earth's crust and the resulting energy wave or signal is measured by detectors or geophones. Translation of this signal produces a detailed picture of subsurface geology. Seismic methods are widely used for mapping deep layered sediments in oil and gas exploration, location of shallow sedimentary layers and water tables in hydrological investigations and structural site investigations for engineering purposes (Kearey and Brooks, 1991; Telford *et al*, 1982).

The speed that a seismic wave travels is influenced by the material through which it passes. Generally, the more dense the material, the faster and more easily the energy will be transmitted. Seismics are often used to map bedrock topography and identify features that affect the geohydrological environment. These features include bedrock channels, buried valleys, and structural faults (Erdelyi and Galfi, 1988). The degree of water saturation of the aquifer can also affect wave transmission by increasing the density of the earth media and the speed of the wave. In unconsolidated material, the water table registers as a separate layer in the seismic response (Erdelyi and Galfi, 1988; Davis and DeWiest, 1966; Todd, 1980).

2.2.3. ELECTRICAL PROPERTIES OF EARTH MATERIALS

Most soil and rock minerals are electrical insulators and are electrically resistive. However, if conductive earth materials such as metals occur in large enough quantities they can increase the conductivity of the subsurface material. However the main form of electrical conductivity of the subsurface is electrolytic and takes place through moisture-filled pores and passages that are contained within the insulating matrix. Overall, electrical conductivity is determined by porosity and permeability of the soil and rock material, moisture content, the concentration of dissolved electrolytes in the moisture, the temperature and phase state of the water, and the amount and composition of colloids or clay content of the soils (McNeill, 1980).

2.2.4. ELECTRICAL PROPERTIES OF ROCKS

Rock material itself rarely acts as a conductor unless it falls in the category of native metals such as copper, gold, or carbon (graphite). Native metals are effective conductors compared to other rock materials because their crystal structure has a more orderly arrangement of metal ions, surrounded by a cloud of valence electrons. This cloud is highly mobile, and the energy required to induce electrical conductivity (movement of electrons) in a metal is relatively small compared to other rock materials (Keller and Frischknecht, 1970).

For most rocks near the earth's surface, the conduction of electricity will be electrolytic conduction through the groundwater contained in the pores of the rocks. The conductive medium will usually be an aqueous solution of common salts contained in the pore structure of the rock or subsurface material (Keller and Frischknecht, 1970; McNeill, 1980; Telford *et al*, 1982). When an electrolyte goes into solution in water the compounds disassociate and move freely about as positive and negative ions until they are impelled by an electrical field (Masterton, *et al*, 1981).

Depending on rock type and structure, the porosity and the resistivity of different rock types vary. Types of porosity such as intergranular, jointing or fracture induced and vugular (large pores) are a function of the type of material (e.g. sedimentary or volcanic) as well as the structure of the material. The fracture porosity usually results in the highest rock electrical conductivity because of its simple shape (Keller,1989).

The quality of the water in the material changes with time, altering the water's electrical characteristics. This occurs because groundwater is subject to diagenetic changes during its passage through an aquifer (Galloway, 1984). These changes include such processes as dissolution, hydrolysis, precipitation, adsorption, ion exchange, oxidation and reduction. Once removed from the aquifer, the groundwater is no longer subject to these effects (Domenico and Schwartz, 1990; Matthess and Harvey, 1982).

The pore spaces of rock materials are not necessarily saturated with electrolytes. Above the water table, near-surface rock materials are only partially saturated in a zone of aeration. Moisture moves downward through this zone by infiltration, upward as capillary rise, and laterally as groundwater flow (Domenico and Schwartz, 1990). The circulation of moisture in the aerated zone is one important factor in determining near-surface resistivities. Another factor, due to the nature of capillary forces, is that finer grained materials hold more water than coarser grained materials, therefore having a lower electrical resistivity (McNeill, 1980).

There are numerous factors that need to be considered both separately and collectively when attempting to assess a rock aquifer situation. Changes in structure, porosity, or water quality within a region can yield the same electrical characteristics, leading to an incorrect geo-electrical assessment. Rock materials can also affect electrical properties of alluvial deposits by altering the chemical quality of pore water in the alluvial aquifer (e.g. coal or limestone). They can also affect overall porosity and permeability due to a large or a small fraction content, and also effect the electrical response with the presence of highly conductive materials such as relocated metals in the alluvium.

2.2.5. ELECTRICAL CONDUCTIVITY OF SOILS

As with rock materials, the conductivity of soils is primarily electrolytic. Soils are composed of mineral and organic matter as well as water and gas components (Foth, 1978). The distribution of these components affects the distribution of the electrical conductivity of the soil vertically and horizontally.

The clay content in soils has a strong effect on soil electrical conductivity. Sand and silt fractions of the soil are electrically neutral and good insulators, as is completely dry clay. However, the electrical conductivity properties of the clay content changes noticeably when moisture is introduced into the soil (McNeill,1980). This occurs because the laminar structured and fine texture of clay has a proportionately large surface area. Clay, more easily than sand and silt, retains a film of water and increases its electrical conductivity. As clay becomes increasingly hydrated, the water film surrounding each particle thickens. The retention of water and subsequent swelling of a confined clay body can produce pressures as high as several bars (Hillel, 1980).

Dissolved materials in the soil, often in the form of salts, greatly enhance the electrical conductivity of a soil. Soluble salts in soils consist largely of sodium, calcium, magnesium, chloride and sulphate. The original source for these salt constituents is the primary minerals in the soil. It is not always the situation that sufficient salts can accumulate in situ to form a saline soil. Saline soils also occur in areas receiving salts from other locations, with water being the main carrier. Irrigation water often brings with it salts, as does a shallow water table rising and falling near the surface. If there is insufficient precipitation, as in semi-arid regions, or if the soil moisture has a relatively high residence time, as in the case of clayey soils, an accumulation of salts occurs with the resulting change in the electrical conductivity of the soils (Richards, 1969).

CHAPTER 3. GEOPHYSICAL THEORY

INTRODUCTION

The general theory of the geophysical techniques used in the study is covered in this chapter. Specifically, the techniques include electrical resistivity, electromagnetics, and seismics. The two field techniques of electrical resistivity to be discussed include Vertical Electrical Sounding (VES) and Horizontal Profiling. For electromagnetics, the techniques of Frequency and Time Domain are covered. Theory of the two main methods of seismics are discussed in the final section: seismic reflection and seismic refraction.

3.1. ELECTRICAL RESISTIVITY

The electrical resistivity method is used for studying horizontal and vertical discontinuities in the electrical properties of the subsurface materials. This technique employs an artificially-generated electrical current which is introduced into the ground by two point electrodes at the surface. The resulting voltage (potential difference) that occurs between two additional measuring electrodes at the surface is then recorded (Kearey and Brooks,1991; Telford *et al*, 1982). It is not possible to measure ground resistivity by simply passing an electrical current through two grounded (connected to the earth by low resistance conductors) electrodes and then measuring the resulting voltage at these electrodes. This is a result of contact resistances with the earth being very high. This problem is overcome by measuring the resulting voltage across an additional pair of electrodes through which virtually no electrical current is passing (Milsom, 1989). Earth materials offer resistance to the passage of electrical current from one electrode to another, depending on the nature of subsurface materials (section 2.2.3)(figure 3.1). The positioning of the electrodes affects the measurement of the electrical field, with increased spacing between current electrodes resulting in a greater depth of current penetration and greater volumes of earth being measured both vertically and laterally (Kearey and Brooks, 1992; Van Zijl, 1977). Resistance is a function of the geometrical configuration of the electrodes and the electrical properties of the ground. Calculations from the measured values of the current output, the resulting voltage or potential difference, and the electrode spacing will give the value of the resistivity, which is measured in ohm-metres (section 3.1.1)(Griffiths and King, 1981; Van Zijl, 1985; Patra, 1968;).

A discussion is now necessary on the concept of apparent resistivity, written as $\rho\alpha$ where ρ is resistivity and α refers to its apparent character. For a given arrangement of electrodes, the electrical field that would be expected in an isotropic or homogenous medium is first determined. This measure is compared to the actual or field measured potential value. One takes the ratio of the measured potential to the theoretical potential as a basic parameter in deriving a mathematical expression for apparent resistivity. One can then solve the equation for resistivity in terms of measured electrical potential, the applied current, and the inter-electrode spacings. These quantities are the index of apparent resistivity, which is a function of the geo-electrical cross-section and the electrode configurations (Telford *et al*, 1982, Van Nostrand and Cook, 1966, and Van Zijl, 1985).

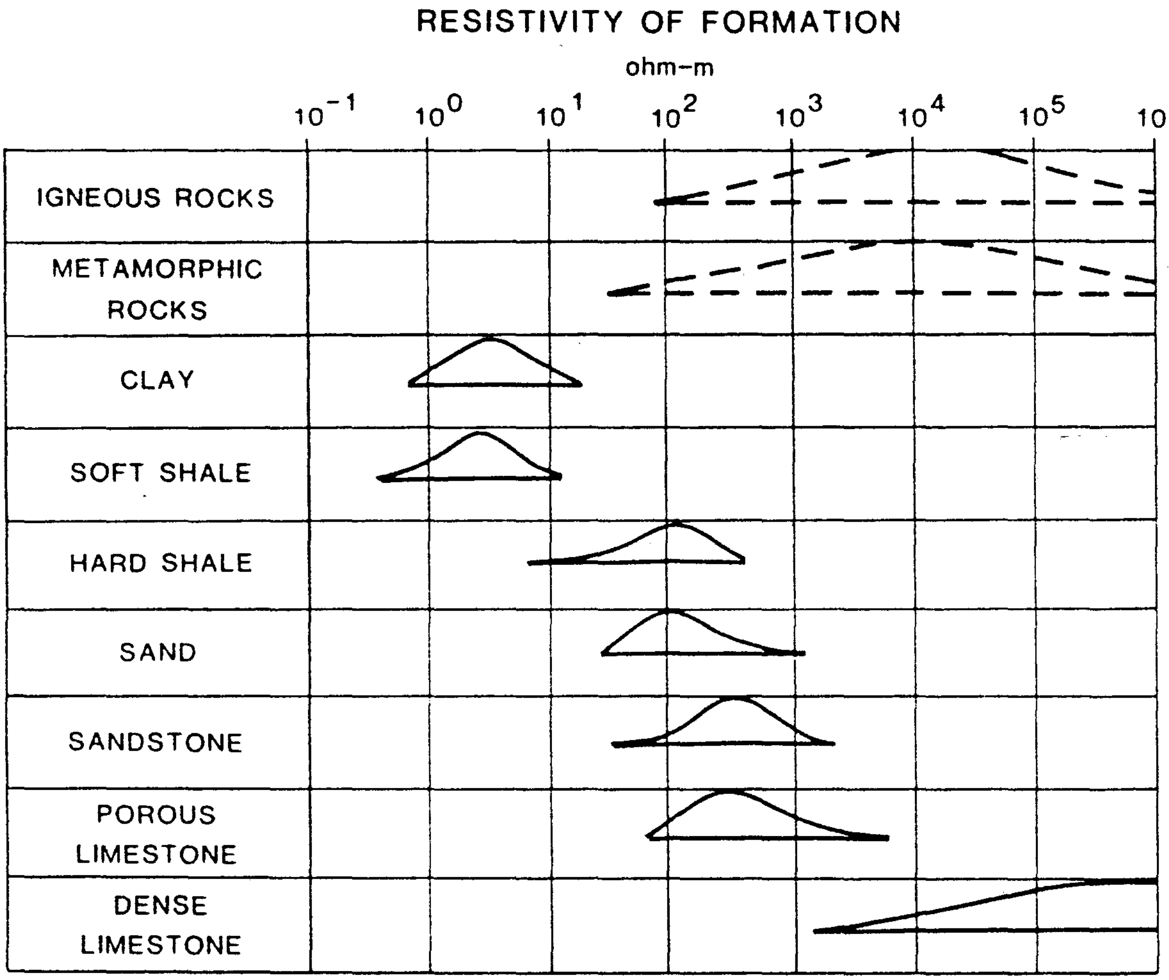


Figure 3.1. List of resistivity values in ohm-m for various earth materials (Mandel and Shiftan, 1981).

The apparent resistivity will usually fall within the range of the true resistivities of the earth materials being measured in an isotropic medium. However due to the anisotropy of earth materials (they are rarely isotropic or homogenous) the apparent resistivity often rises or falls above or below the true resistivities (Van Nostrand and Cook, 1966). Normally, in a homogenous earth medium, the current lines from an electrode will disperse radially, but as they cross boundaries into layers of different resistivities, the lines of current can be seen to diverge. This divergence is often greater if the current lines are passing into a layer of higher resistivity (Griffiths and King,1981). The thickness of the subsurface layers and the depth of the survey also affects the apparent resistivity response. Horizontal layers or beds near the surface can be surveyed quite accurately if they are relatively thick. With an increase in the depth of the bed and a decrease in the ratio of the thickness of the bed to the depth, it becomes more difficult to isolate the resistivity response of a particular bed unless its resistivity differs noticeably. As a result, apparent resistivity values obtained give more realistic values in shallow surveys which are not affected by layering or depth, and in homogenous earth situations where the effects of anisotropy can be minimized.

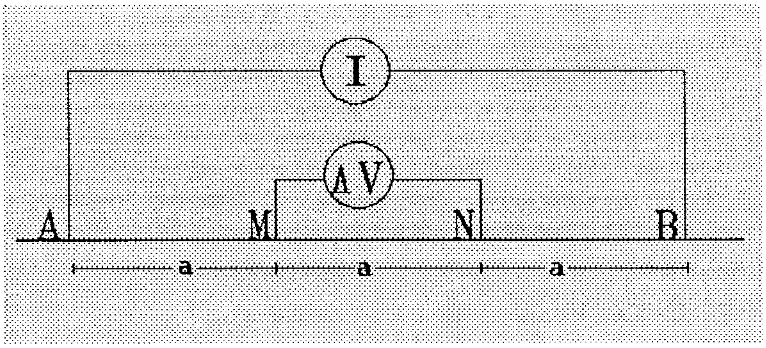
Resistivity has been used successfully for groundwater studies and exploration for potential aquifers and groundwater itself (Lennox and Carlson, 1967, Kovacs *et al*, 1981, Yazicigil and Sendlein, 1982, Van Zijl, 1985). As a preface to drilling, prospecting and exploration with electrical resistivity involves two approaches. One approach is horizontal profiling in which both the current and voltage electrodes are shifted without changing the configuration or distances between the electrodes. Usually a grid or a transect line is established over an area of interest and readings are taken at fixed points. The lateral distribution of the electrical resistivity is then studied at a depth of exploration that remains relatively constant (Van Zijl, 1985). Recorded resistivity values (in ohm-m) can be plotted to give an image of subsurface variations at the electrical depth of exploration across a horizontal plane, or as a cross-section. Profiling can detect lateral changes in resistivity and is most often used in searching for ore bodies, faults and fault zones, for evaluating sand and gravel deposits, delineating geological boundaries and for finding dipping contacts of different earth materials (Kearey and Brooks, 1992; Erdelyi and Galfi, 1988; Driscoll, 1986).

The second method of resistivity prospecting is called Vertical Electrical Sounding (VES) in which the vertical distribution of resistivity with depth is measured. This is done by expanding the current electrode spacing outwards from a point where the voltage electrodes remain at a fixed spacing, resulting in a greater theoretical depth of investigation. Initially the voltage electrode spacing remains unchanged but as the exercise proceeds it may be necessary to increase electrode spacing to obtain a measurable voltage (Kearey and Brooks, 1992; Erdelyi and Galfi, 1988). As the electrical current penetrates deeper it penetrates vertical layers of varying resistivities and with each layer the overall measured response is altered. The measured resistivities are average values for large volumes of earth, with this average taken over increasingly larger volumes of earth as depth of investigation increases. These measurements are plotted graphically (usually on a bilogarithmic scale) with resistivity a function of current electrode spacing, to form a sounding curve. These curves can be matched with theoretical or master curves to obtain layer thicknesses and resistivities (Kearey and Brooks, 1992; Van Zijl, 1977).

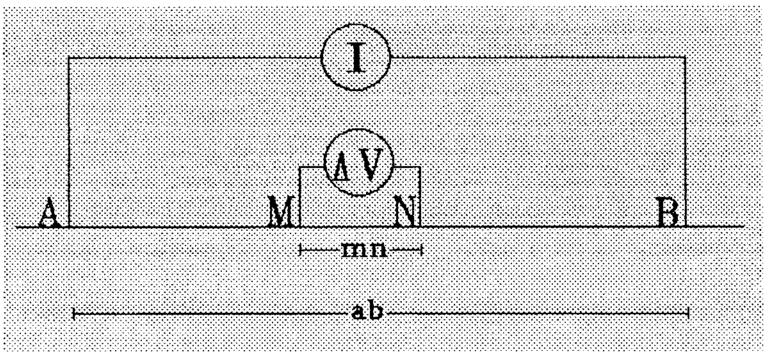
As with horizontal profiling, a series of survey points are established over an area in the form of a grid or a transect with soundings taken at each point. The resistivity layers interpreted from individual sounding curves can be plotted as a resistivity cross-section chart. The common resistivity values can then be joined together to illustrate subsurface resistivity layering. Resistivity values from a survey grid can also be plotted against given electrode spacings and then contoured to form isoresistivity curves. This illustrates resistivity highs and lows at selected geo-electrical depths (Erdelyi and Galfi, 1988). The effectiveness of Vertical Electrical Soundings is best in simple geologic settings where the geology can be modelled as horizontal layers parallel to the ground surface. As these parameters change, the data acquired becomes more qualitative (Driscoll, 1986).

There are many electrode arrays that can be used, but two of the most common are the Wenner and the Schlumberger configurations (Figure 3.2). For both of these arrays the current electrodes are on the outside of the configuration and the potential electrodes are on the inside. The outer current electrodes are schematically termed AB and the inner potential electrodes are termed MN. For the Wenner array the four electrodes are placed in a line at equal distances apart with the inner two electrodes used as the potential electrodes. Instead of equal spacings, the Schlumberger array uses a ratio of current electrode to potential electrode separation that is less than or equal to 1/5 (Van Zijl, 1985; Griffiths and King, 1981).

a) THE WENNER RESISTIVITY ARRAY



b) THE SCHLUMBERGER RESISTIVITY ARRAY



A & B = current electrodes

M & N = voltage or potential electrodes

I = ammeter

ΔV = voltmeter

a = equal spacing between electrodes for Wenner array

ab = spacing between outer AB electrodes

mn = spacing between inner MN electrodes

Figure 3.2 a) Wenner and b) Schlumberger resistivity arrays (adapted from Van Zijl, 1985; Griffiths and King, 1981).

The Wenner array, when used for Vertical Electrical Soundings, expands with equal separation of all electrodes, requiring all electrodes to be moved during a survey. Initially the Schlumberger array only requires the movement of the outer AB electrodes. The potential or MN electrodes remain stationary until it becomes necessary to increase the spread between the inner MN electrodes to maintain a measurable electrical potential. This makes the Schlumberger array logistically easier to work with for Vertical Electrical Soundings (Milsom, 1989;Erdelyi and Galfi, 1988; Van Zijl, 1977). Another reason the Schlumberger array is favoured over Wenner for soundings has to do with near surface electrode effects. When current or potential electrodes are moved over a resistivity anomaly, the voltage between the potential (MN) electrodes is affected. When the outer current electrodes pass over the anomaly, the result is termed an AB effect and when the inner potential electrodes move over the anomaly the result is termed the MN effect. The MN effect is much larger than the AB effect for both conductive and resistive anomalies. Considering that the purpose of VES is to produce a smooth sounding curve, the array that delivers the least electrode effects is the most favourable (Milsom,1989; Van Zijl, 1977).

3.1.1. CALCULATION OF RESISTIVITY

The calculation of resistivity is initially derived from Ohm's Law which deals with the theory of current flow through a homogenous medium. In mathematical form, Ohm's Law states that:

$$R = V/I$$

where I = current in a conducting body

V = potential difference between two surfaces of constant potential (equipotential)

R = constant called the resistance between the above mentioned equal potential surfaces (Griffiths and King, 1981)

If one considers a conductor carrying current lines of flow over a cross-sectional area A, the resistivity (not resistance) is defined as:

$$\rho = RA/L$$

where ρ is the resistivity, R is the resistance measured between two equipotential surfaces separated by distance L. This equation illustrates that resistivity has the dimensions of length multiplied by a resistance (Griffiths and King, 1981; Van Zijl,1985).

Regarding the Wenner and Schlumberger arrays, apparent resistivity is calculated using the following formulae. For the Wenner array:

$$\rho\alpha = \frac{2\pi a V}{I}$$

where

$\rho\alpha$ = apparent resistivity

a = distance between adjacent electrodes

V = potential difference measured between MN electrodes

I = current applied to outer AB electrodes

(Van Nostrand and Cook, 1966)

For the Schlumberger array:

$$\rho\alpha = \frac{K\Delta V}{I}$$

where $$K = \frac{2\pi}{(1/AM - 1/AN) - (1/BM - 1/BN)}$$

$\rho\alpha$ = apparent resistivity

V = potential difference measured between inner MN electrodes

I = current applied through AB electrodes

K = a constant referring to a geometric factor with dimensions in metres (Van Nostrand and Cook, 1966)

For a homogenous, isotropic halfspace, the formulae will give a value close to the true subsurface resistivity.

3.1.2. DEPTH OF PENETRATION

The effective depth of penetration of the current is important in designing the survey, for it is necessary that the spread of electrodes allows for sufficient penetration of current to the depth of the phenomena to be studied. In the past it was assumed that with the Wenner array there was a close correlation between current electrode spacing and depth penetration. This has proved inaccurate as highly resistive layers can reduce the depth of investigation (Barker, 1989, and Mandel and Shiftan, 1981). For the Wenner array it was suggested that the depth of investigation corresponded to $L/3 \equiv a$, L being the distance between the outer AB electrodes and a referring to inter-electrode spacing. For the Schlumberger array, depth of investigation was empirically judged to be AB/4 (Roy and Apparao, 1971; Barker, 1989; Milsom, 1989). Later studies have shown that there is a relationship between electrode spacing of current and potential electrodes, but that it may be less than the earlier empirical formulae suggested.

Table 3.1 illustrates a comparison of depth of investigation values from two recent studies, one performed by Roy and Apparao (1971) (values in parentheses) and a more recent study by Barker (1989) (Table 3.1).

Type of Array	Depth of Investigation
Wenner array	0.17L (0.11L)
Schlumberger array	0.19L (0.125L)

Table 3.1. Depths of investigation for Wenner and Schlumberger arrays.

where L is the distance between the outer (AB) current electrodes (Barker, 1989, and Roy and Apparao, 1971).

3.2. ELECTROMAGNETIC METHOD

One of the problems associated with the direct-current resistivity sounding method is its inability to penetrate through a zone of high resistivity. This problem encouraged the development of the magnetotelluric and telluric methods, which measure electrical and magnetic fields associated with induced currents in the earth's subsurface. Magnetotelluric fields are large scale, low frequency natural magnetic fields that exist within and around the earth. Telluric currents are natural alternating electrical fields that are induced into the earth by the magnetotelluric fields. These natural source methods respond to zones of high electrical conductivity as opposed to zones of resistivity or low electrical conductivity (Dobecki and Romig, 1985; Slaine and Greenhouse, 1982; Van Zijl and Kosten, 1985). This aspect of current behaviour allowed for penetration through a very resistive zone where it is difficult to get penetration using galvanic or direct current techniques (Kaufman and Keller, 1983; Sherrif, 1974). The origin of the induction field is an electro-magnetic field, associated with natural phenomena such as thunder storms and solar activity, that are propagated over long distances between the earth's surface and the ionosphere (Kearey and Brooks,1992; Kaufman and Keller,1983; Telford *et al*,1982). These currents can be measured by setting up two stations and measuring the field signals between them. If the ground is homogenous there is little alteration of the signal. If the geological structure is non-homogenous at either station the current flow will be distorted, registering an anomaly within the electromagnetic field (Telford *et al*,1982). Transmitters are not required for natural source methods, and the low frequencies of natural sources allow for depths of penetration of the electromagnetic field up to several kilometres (Vozoff, 1989).

Natural source methods have some limitations. Electromagnetic noise such as that generated by power lines or by fluctuations in the ionospheric currents in which the required signal strength is not always available can make extraction of useful data difficult (Swift Jr., 1989; Vozoff, 1989). To overcome these difficulties an electromagnetic induction method was developed utilizing a signal frequency and a source geometry that could be controlled by the geophysicist. However there are compromises with a controlled source that include the financial and logistical problems of a transmitter and the expense and difficulty of generating a low frequency signal from a controlled source. The difficulty in generating a low frequency signal means that controlled source electromagnetic (EM) methods are limited in their depths of penetration (Swift Jr., 1989).

An alternating magnetic field is used as a source and can be generated by passing AC current through a loop or a cable grounded at both ends. The magnetic field corresponds to that of a magnetic dipole perpendicular to the area or plane of the loop (if the loop is horizontal, a vertical magnetic dipole is formed and vice versa) (Figure 3.3).

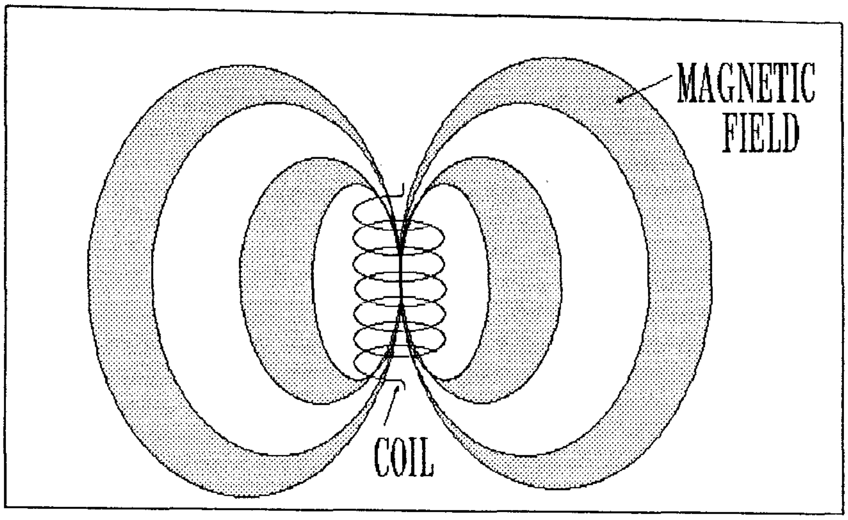


Figure 3.3. Magnetic field of a coil represented as a magnetic dipole perpendicular to the plane of the coil.

If there is any conductive material within this magnetic field, induction or eddy currents will dissipate into this conductive zone. These eddy currents set up their own secondary magnetic fields which will have the same frequency but not necessarily the same phase as the primary or inducing field. A receiver coil or loop is used to measure the response. The total resultant field measured consists of a primary field due to the source current and a secondary field due to the eddy currents formed around the conductor (Parasnis, 1972).

In more detail, the resultant electromagnetic field contains two oscillatory fields of the same frequency (ie. the frequency of the primary alternating source) but out of step or out of phase with each other. Spatially, the electromagnetic field is characterized by amplitude and phase components. The amplitude is the maximum value that the field strength can attain as it oscillates at a given frequency. Phase refers to the position of the maxima and minima of the signal wave in relation to time, or more specifically, how far into the period of oscillation the signal wave has advanced (Sherrif, 1974; Parasnis, 1966). When a conductor is subjected to an alternating magnetic field, a voltage of the same frequency as the inducing field is set up in the conductor. This voltage lags behind in signal phase from the inducing or primary field (ie. it reaches its maxima and minima a portion of period behind the inducing field). Due to the conductor's properties of resistance and inductance (the capability of a conductor to produce voltage), the current in the conductor lags behind the induced voltage and consequently behind the primary field. The secondary electromagnetic field that is produced from the induced current lags also behind the primary electromagnetic field. The combination of the primary and secondary fields yields a resultant electromagnetic field. This field is what the detecting coil picks up and it differs in amplitude and phase from the primary field. This phase lag is basically a time delay that is equal to lag multiplied by period (Parasnis, 1966) (see Figure 3.4)

The phase difference between the primary and secondary fields can be expressed as follows:

$$\theta p - \theta s = \pi/2 + \theta$$

where:

$\pi/2$ = 90° phase lag behind the primary signal resulting from inductive coupling between transmitter/receiver coils.

θ = additional lag depending on the properties of the subsurface body as an electrical conductor.

θp = primary field.

θs = secondary field.

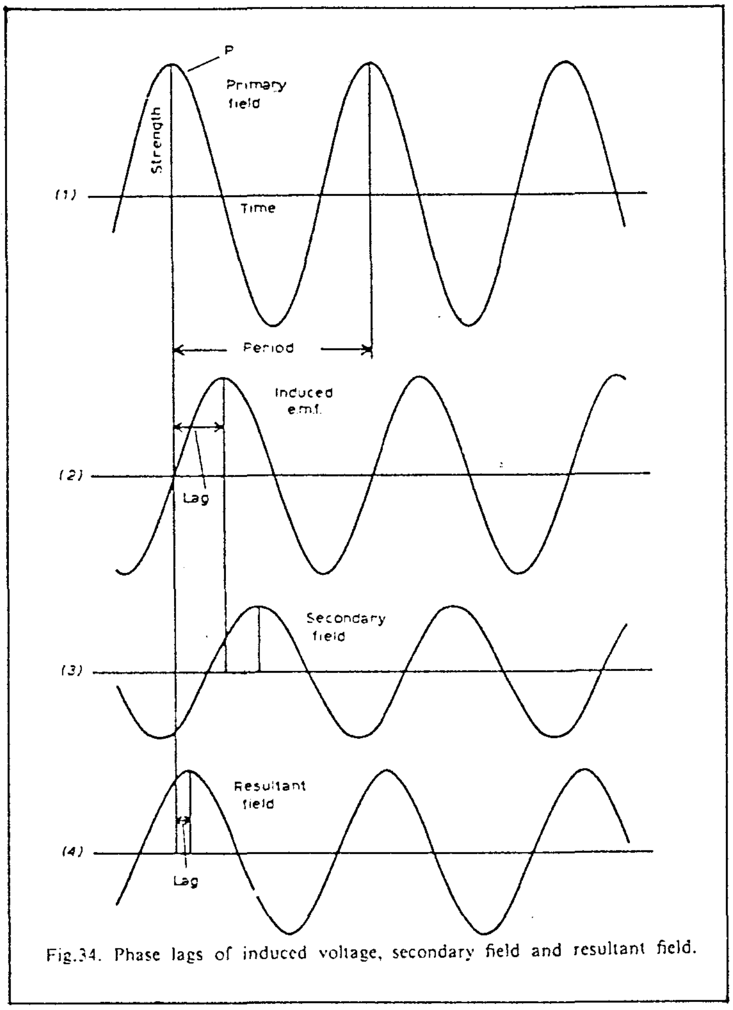


Figure 3.4. Phase lags of induced e.m.f (voltage), secondary field and resultant field. (Parasnis, 1966)

Problems can be encountered with EM systems that use maximum signal coupling between transmitter and receiver. The receiver tends to measure the primary wave as well as the secondary wave induced by the conductor. The primary wave can tend to swamp the secondary signal, so it must be reduced or neutralized. One way this can be done is to introduce into the receiver an artificial signal with the use of a compensating network. The network produces a signal that is the same frequency and amplitude of the primary signal but opposite in phase. This serves to cancel the main primary field and other unwanted signals (Telford et al, 1982).

3.2.1. FREQUENCY DOMAIN AND TIME DOMAIN

There are two main methods used in controlled source electromagnetics: frequency domain and time domain. Frequency domain involves the use and measurement of fixed frequency sine waves. The transmitter coil produces a signal source or input that can be equated to a sine wave of a given frequency and amplitude. The receiver loop receives an output signal regarded as a sine wave of the same frequency but with a phase that differs from the input. This phase difference between the input signal and the output is affected by the electrical properties of subsurface materials (section 3.2).

Time domain methods use a square wave for the input, and the output of induced voltage is measured over various times when the transmitter switches off between pulses. The square wave has a slow build-up and a rapid switch off. The eddy currents do not cease flowing instantly when the transmitted current is switched off, but decay gradually. Their presence is indicated by these decaying or transient voltages induced in the receiver loop. These transients are a means of measuring the conductors below surface. The better the conductor, the longer the transients persist. Time domain EM is also known as transient EM (Van Zijl and Kősten, 1985).

3.2.2. SKIN EFFECT

When the frequency of an AC current is increased in a wire conductor, the current begins to concentrate closer to the wire's surface. This phenomenon is described as the skin effect. This skin effect also occurs in conductors within the earth and determines the effective investigation depth attained with the EM method. The effect depends on the frequency of the current, the conductivity of the subsurface, and the distance between source and receiver. If the conductivity or the frequency is high, the penetration of electromagnetic waves is strongly attenuated (Telford *et al*, 1982; Weigmans, 1990). A deeper penetration is acquired by increasing the source/receiver separation or decreasing the frequency (Van Zijl and Kósten, 1985).

3.2.3. EM SYSTEMS

There are two main types of land-based EM systems; fixed source-moving receiver systems and moving source-moving receiver systems. The fixed source system consists of a stationary controlled source with a receiving coil or set of coils that is moved over a prearranged grid or set of lines relative to the source. This system works in both the frequency and the time domains. An example of a fixed source frequency domain method is the Turam method that utilizes a large rectangular loop as a source and two receivers recording at stations on lines running perpendicular to the source loop (Van Zijl and Kösten, 1985).

The moving source-moving receiver method is characterized by a mobile source as well as a mobile receiver arrangement. The source usually consists of a light-weight portable coil similar to the receiver coil. The transmitter and the receiver are held at a fixed distance apart and are moved simultaneously over the survey area. Due to the mobility of the system, field work is relatively simple and flexible. The survey need not be bound to stake or grid lines and once anomalies or conductors have been located it is easy to detail the investigation. These characteristics have made the moving source-moving receiver EM systems very popular but there are some constraints. For practical reasons the coil separation cannot be too great (25-100 metres) with the result that, within the frequency domain approach, the depth of penetration is limited and stray anomalies from near-surface can interfere with deeper source anomalies. Usually the source and receiver are not connected to each other rigidly but are attached by a fixed length of flexible cable, the mid-point of which is regularly used as the observation point (Parasnis, 1972).

An example of a moving source-moving receiver system is the Geonics series of EM systems manufactured in Canada. The Geonics-made EM-34 is a two-man portable unit in which the transmitter and receiver coils are connected with a reference cable of fixed lengths ranging from 10, 20, and 40 metres. These fixed lengths serve to vary the effective depths of penetration of the primary signal as they are also linked to fixed frequencies (Table 3.2). The transmitter and receiver units carried by the operators are powered by disposable D-cell and C-cell batteries respectively (Van Zijl and Kosten, 1985). It should be noted here that the instrument response of the EM is integrated over the depth of investigation, and small or localized variations in conductivity can become lost in the overall EM response (Stewart, 1982).

INTERCOIL SPACING (M)	OPERATING FREQUENCIES (KHZ)	COIL PENETRATION DEPTHS in METRES	
		HORIZONTAL	VERTICAL
10	6.4	15	7.5
20	1.6	30	15.0
40	0.4	60	30.0

Table 3.2 Exploration depths of various intercoil spacings and fixed operating frequencies (Wiegmans, 1990).

The Geonics EM-34 instrument is designed to read apparent electrical conductivity in milli-mhos per metre. The orientation of the transmitter coil and the receiver coil affects their sensitivity to subsurface conductors. As previously discussed, the source loop is equivalent to a magnetic dipole at *right angles* to the plane of the loop. This becomes important when one considers the geometry and the orientation of the conductor below surface. As a result of the different orientations of the magnetic fields, the horizontal coil (vertical dipole) will have a greater penetration than the vertical coil of its primary magnetic field and a more sensitive response to apparent conductivity with depth. The vertical coil (horizontal dipole) will be more sensitive to shallower lateral variations in apparent conductivity, producing a different response (McNeill, 1980, Stewart, 1982; Van Zijl and Kösten, 1985; Wiegmans, 1990).

An example of both vertical and horizontal coil orientations passing over a thin vertical conductor is illustrated below. Figure 3.5 shows the subsurface conductor generating a secondary magnetic field with the same upward orientation as the primary field from the horizontal-loop transmitter at point R_1. At point R_2 the secondary field from the conductor is opposite in direction to the primary field, which will result in a damping effect.

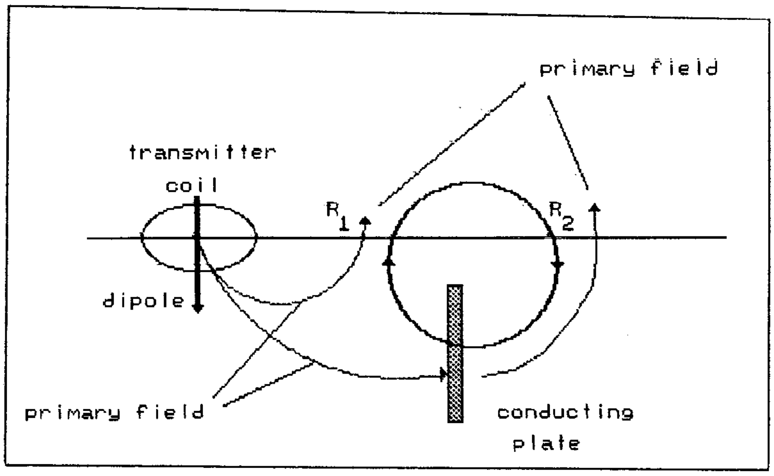


Figure 3.5 Comparison of a primary field from a horizontal-loop transmitter to a secondary field generated by a conductor (adapted from Parasnis, 1986).

Figure 3.6 a) illustrates the field picked up by the receiver as the horizontal system is moved over the conductor. The maximum damping (negative anomaly) occurs when the mid-point of the transmitter-receiver system is over the conductor. When either the transmitter or the receiver is over the conductor the field response is positive, and equal to the primary field.

Figure 3.6 b) illustrates the field response from the vertical-loop configuration EM as the system is passed over the same conductor. In this situation the field response shows an augmentation to the primary field (positive anomaly) when the mid-point of the vertical-loop system is over the conductor (Parasnis,1986).

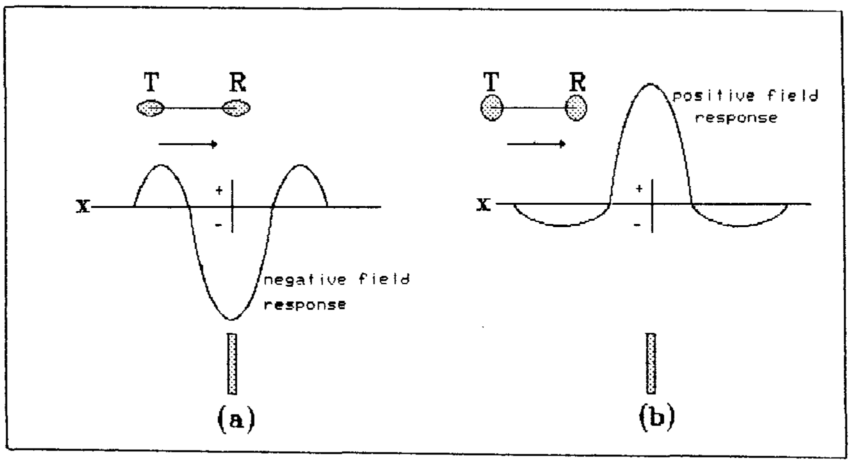


Figure 3.6. Response to conductor with vertical and horizontal loop orientation (Parasnis, 1986).

3.3. SEISMIC METHODS

Seismic methods are based on the observation of the speed of propagation of elastic waves within rock or other subsurface materials that make up the earth's crust. An artificial shock is created by either detonation of a charge or the use of vibrating and impacting techniques. Detectors, or geophones, are placed at various distances and directions from the source. These are connected to a recording instrument that records the travel time of the waves which are reflected or refracted to the surface (Mandel and Shiftan, 1981). Three types of waves are produced; two body waves and one surface wave. The surface wave is confined to the region close to the surface. Its amplitude falls off rapidly within a distance from the surface of the same order of magnitude as the wavelength of the disturbance. The body waves travel through the body of the medium and are known as P (compressional and/or primary) waves and S (shear and/or secondary) waves. P waves are faster and result from direct compression, while the slower S waves (also known as shear waves or transverse waves) have a particle motion of energy that is perpendicular to the direction of propagation. The velocities of these two wave types are related to the elastic constants and the density of the medium through the following equations.

$$Vp = \sqrt{\frac{k + 4/3\ n}{\rho}}$$

$$Vs = \sqrt{\frac{n}{\rho}}$$

where Vp = velocity of the P wave

Vs = velocity of the S wave

k = the bulk modulus (incompressibility)

n = the shear modulus (rigidity)

ρ = the density

(Griffiths and King, 1981)

The S wave travels at just over half the velocity of the P wave in most rock materials. It does not propagate in fluids, where n = 0 (Griffiths and King, 1981).

Different earth materials have different densities and elastic moduli, which is the ratio of the stress applied to the strain produced on a body. Rocks and rock materials of a relatively high porosity will be poor transmitters of seismic energy and will yield low velocities. The velocity depends on the degree of compaction and cementation, rather than the composition of the sediments. The elastic moduli of these materials increase with compaction, and the ratios of k/ρ and n/ρ (which determine seismic velocities) also increase with depth, providing that the material remains homogenous. The type of cementation, degree of saturation, and the pressure of fluids affects the porosity and therefore the elastic moduli of the earth materials. Saturated earth materials of medium to high porosity will yield high velocities and shorter wave travel-times compared to unsaturated earth materials (Kearey and Brooks, 1992; Griffiths and King, 1981).

The main objective of seismic surveys remains the identification of different wave-velocity layers, determination of their depth and thickness, and the identification of known or assumed stratigraphic units and structural features. Compressional wave velocities (Vp) are used to convert seismic wave travel times into depths and they also give an indication of the lithology of the rock or the nature of pore fluids within the rock (Kearey and Brooks, 1992; Griffiths and King, 1981; Mandel and Shiftan, 1981) (Table 3.3). Generally, compressional wave velocities increase with confining pressure. For example sandstone and shale produce a velocity increase with depth of burial and with age due to the effects of progressive compaction and cementation. For many of the sedimentary rocks compressional wave velocity is related to density, and characteristic velocities have been established (Kearey and Brooks, 1992)

ROCK TYPE	COMPRESSIONAL VELOCITY (km/s)
Unconsolidated Materials	
sand (dry)	0.2-1.0
sand (water saturated)	1.5-2.0
clay	1.0-2.5
glacial till (saturated)	1.5-2.5
permafrost	3.5-4.0
Sedimentary Rocks	
Tertiary sandstone	2.0-2.5
Carboniferous sandstone	4.0-4.5
Cambrian quartzite	5.5-6.0
Cretaceous chalk	2.0-2.5
Jurassic oolites & bioclastic limestones	3.0-4.0
Carboniferous limestones	5.0-5.5
dolomites	2.5-6.5
salt	4.5-5.0
anhydrite	4.5-6.5
gypsum	2.0-3.5

Table 3.3. Characteristic compressional wave velocities of rock types (adapted from Kearey and Brooks, 1992).

3.3.1. SEISMIC REFLECTION AND REFRACTION

The two major seismic methods are reflection and refraction. The refraction method utilizes the principle portion of the wave path as it moves along the interface between two rock layers. The wave path that enters the second layer and moves parallel to the boundary must do so within a critical angle (αc). Seismic waves meeting the boundary with a greater than critical angle of incidence are totally reflected and no energy is refracted into the higher velocity layer. The critically refracted waves moving along the interface within the lower layer create stresses that produce waves that are refracted back up to the upper layer. These waves are known as head waves and they depart the boundary at the critical angle of incidence (Kearey and Brooks, 1992;Redpath, 1973). Thicknesses of the upper two to three velocity layers can only be determined with refraction where the density of successive layers and the velocity of the shock wave increases with depth (Driscoll, 1986, Mandel and Shiftan, 1981, and Telford *et al*, 1982).

Travel-time equations form the bases of seismic reflection and refraction methods for determining depth to an interface. The refraction method relies largely on measuring the travel time of the first arrivals of seismic waves at the geophones. Reflected waves occur later and continuously, being more complex to record as they are of smaller amplitude.

For seismic refraction, the thickness of the upper layer can be calculated using the following equation.

$$D = R/2 \sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

where D = depth in metres

V_1 = velocity of shock wave in upper layer in km/s

V_2 = velocity of shock wave in second layer in km/s

R = distance, in metres, to velocity change as indicated by the graph

(Johnson Division, 1982)

Travel-time graphs are used to determine the velocity of the refracted waves in one or more layers. Travel-time is plotted on the y-axis and source-geophone distance (x) is plotted on the x-axis (Figure 3.7).

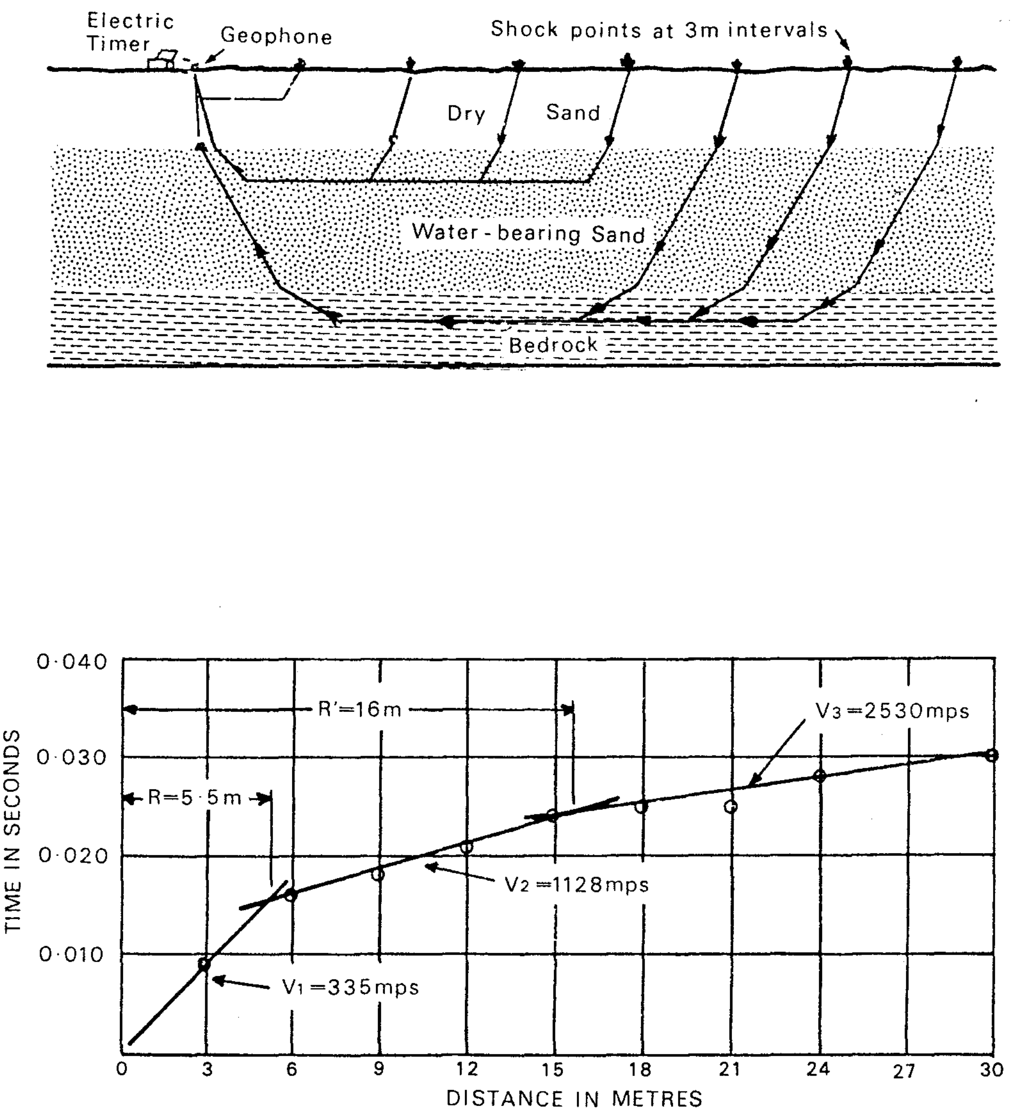


Figure 3.7. Refracted ray paths and travel-time graph for two horizontal interfaces. Shock waves travel faster by refracted paths than by more direct paths through the overlying strata (Johnson Division, 1982, and Mandel and Shiftan,1981).

The reflection method detects seismic waves that are reflected from a subsurface interface where there is change of density and wave velocity (acoustic impedance) of earth materials. There is a relatively large amplitude of reflection signals in comparison to refraction generated from the same horizon, meaning that a smaller signal source is required to generate reflections. The greater amplitude of reflection signals also serves to generate greater detail of overburden structure and bedrock topography (Hunter *et al*, 1987).

The time-distance relationship for the reflected pulse can be illustrated as follows:

$$tr = \frac{2\sqrt{h^2 + x^2}}{v}$$

where h = layer thickness in metres

x = source-to-geophone distance in metres

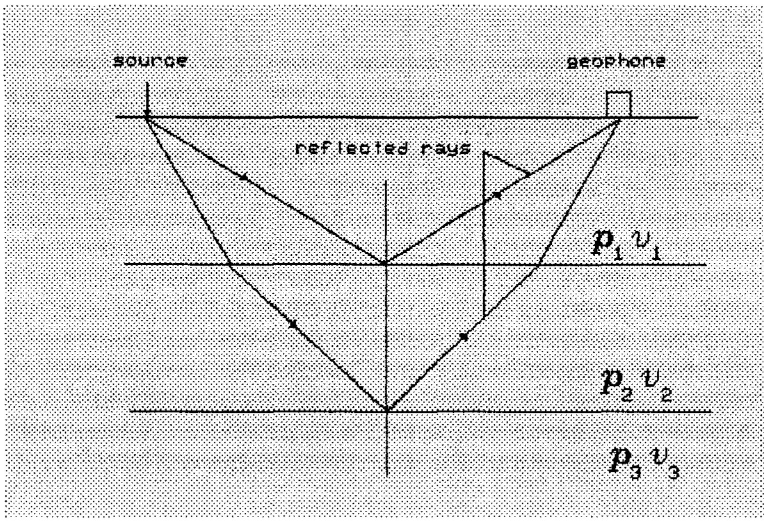
tr = travel-time in seconds

v = velocity in m/sec

(Griffiths and King, 1981)

This formula refers to a single layer single interface, but can be expanded to include two or more horizontal interfaces. As with seismic refraction, reflection travel-time graphs are drawn to portray velocity behaviour through the various layers (figures 3.8 a and b).

(a)



b)

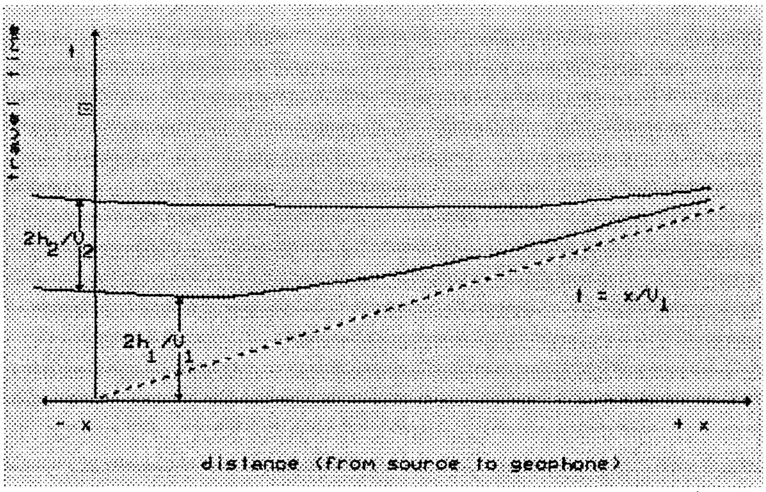


Figure 3.8. Reflected rays between two horizontal interfaces and their travel-times plotted against distance measured along the surface (Griffiths and King, 1981)

The seismic reflection method was developed in the oil and gas industry, which was able to invest in and develop field procedures, digital recording, and computer processing of the data. These methods, however, are still very expensive for engineering, groundwater, and geotechnical applications. As a result, refraction methods have been used almost exclusively in fields where shallow subsurface structural information was required. Refraction methods measure only the time of the first arrival of seismic energy rather than a whole seismic wave train. Seismic refraction surveys can be carried out with relatively simple and inexpensive equipment and are more amenable to shallower surveys, where most engineering, geotechnical, and geohydrological interests occur. Seismic reflection for shallower depth surveys have only just begun to be used as it is only recently that low cost seismic equipment has allowed for the routine application of reflection techniques for engineering and groundwater problems. One major benefit of reflection over refraction is that one is not restricted to working on the assumption that velocity increases with depth (Haeni, 1988; Hunter *et al*, 1987).

CHAPTER 4. RESEARCH DESIGN AND METHODOLOGY

4.1. RESEARCH DESIGN FOR GEOPHYSICAL SURVEYS

The main purpose of geophysical surveys is to locate subsurface structures and if possible to measure the dimensions and physical properties of these structures. Structural and stratigraphic information is sought after in oil prospecting and groundwater surveys, physical properties of subsurface structures is of value for mining exploration, and engineers require information on all of these properties for site investigations (Erdelyi and Galfi, 1988; Griffiths and King, 1981).

It is important to select the appropriate geophysical techniques for a particular study. Usually a primary geophysical technique is selected and then augmented with additional geophysical methods. For a survey of a groundwater situation, the selection of two or more geophysical methods that measure different parameters is recommended (Mazac *et al*, 1989).

The type of information required must also be taken into consideration. If the quality of the groundwater is the focus of the study then seismics, which delivers information only on an aquifer's structural characteristics, would be bypassed in favour of geo-electrical methods (Kearey and Brooks, 1992; Driscoll, 1989). With geo-electrics a preliminary knowledge of the electrical properties of earth materials and groundwater is necessary (Mazac *et al*, 1987).

The second important step in geophysical surveys is site selection. This should be the result of a preliminary assessment of information about the study area. This includes data from maps, air photos, geological reports, borehole logs, as well as data from local administrative sources such as Water Boards or other relevant planning and management authorities.

Geophysical surveys can be influenced by physical factors. For example, uneven or hilly terrain can interfere with EM data collection where the necessary coplanar transmitter and receiver coil orientations can easily be misaligned (McNeill, 1980; Van Zijl & Kösten, 1985). With seismics, situations arise where hydrological boundaries such as the interface between unconsolidated material and underlying weathered bedrock may not be measurable (Haeni, 1988).

An initial desktop assessment of the physical factors of the study area is necessary and includes a study of maps, air photos and geological as well as other available data. The desktop study is followed up by a field evaluation of the data and conditions on the ground as well as an equipment check for performance and viability (Driscoll, 1989; Milsom, 1989; Hazell, Cratchley and Preston, 1988; Erdelyi and Galfi, 1988).

Once the techniques have been chosen and the site established, the design of the field study can be considered. This includes factors such as the physical orientation of the field study and the density of the measuring network. Orientation of the field study refers to the line of direction between the transmitters and receivers of energy for the various geophysical techniques, and should be carefully considered when planning the survey. For example, horizontal profiling with electrical resistivity should be carried out perpendicular to the strike of anomalies or formations being studied in order to obtain the best field distortion (Van Zijl, 1985).

Regarding sample size and density, as Mazac *et al* (1989) have shown, there is an optimum number of data points per area, above which the need for more data diminishes, and below which the integrity of the statistical tests or the data portrayal can be compromised. A minimum density of measurements can be determined from initial trial measurements and also from the geophysical and hydrological parameters being measured. Deep Vertical Electrical Sounding surveys, for instance, have a diminishing ability to pick up changes in the resistivity response with increasing depth of investigation (section 3.1.1). The result is that an increase in the number of soundings will not necessarily enhance the value of data beyond a certain point.

4.2. CONCEPTUAL FRAMEWORK OF THE STUDY

To understand the groundwater flow dynamics of alluvial systems, knowledge of the structure of alluvial bodies is important (Hazell, Cratchley, and Preston, 1988). Techniques such as geophysics are used to facilitate the routine but more expensive methods of obtaining this information (Chapter 1). It is important that as much information as possible is acquired on the study area before geophysical techniques are applied. Existing boreholes, surface exposures in the form of road and river bank cuts, and rock outcrop are the main source of geological information. Other aspects of information on the study area important to the geophysical response are the depth to water table and soil or overburden qualities such as salinity. The water table can affect the response of both seismics and geo-electrics, while salinities can affect the geo-electrical properties of earth materials (sections 2.2.2 and 2.2.5).

The term 'soil' is used to identify surface and subsurface materials of a variety of properties covering the earth. *Pedalogically,* soils are studied in terms of their physical structure as they occur in nature. Soils are also analyzed *edaphalogically,* or from the standpoint of plants and plant production (Brady, 1974). For the purposes of this geophysical survey the total of unconsolidated surface materials within the study area will be referred to as overburden, although the immediate 2.0 to 3.0 metres will also be discussed and assessed from a 'soils' viewpoint .

Once information on the study area is acquired, the geophysical techniques to be assessed can be selected. The selection is done on the basis of the type of information required and the ability of the selected geophysical technique to function within the study area (section 4.1).

The final stage of the study is the assessment of the selected geophysical techniques and/or the data acquired within the study area. The first step is to qualitatively assess the data by comparing the geophysical data to the existing information on the study area. This helps to interpret the data in relation to the geology and hydrogeology of the study area. Qualitative assessment includes 1) the contouring of geophysical data and 2) the cross-sectional portrayal of the data in data line profiles (Erdelyi and Galfi, 1988; Slaine and Greenhouse, 1982). By studying the data for trends and anomalies it can be seen how closely results accord with information previously collected on the study area. At this point comparisons of the validity of individual geophysical techniques can begin.

Vertical Electrical Soundings can be assessed quantitatively by matching the sounding curves of data to a library of theoretical curves or by using computer programs to produce a multi-layered model (Kearey and Brooks, 1992; Van Zijl, 1977). Quantitative assessments can also be done between geophysical data and other collected data such as the depth to water table or " soil" salinities of the study area. The comparison of geophysical data to borehole data and information is the best method of assessment of geophysical techniques (Kearey and Brooks, 1992; Mazac, Kelly, and Landa, 1987)

4.3. RESEARCH DESIGN OF THE STUDY

4.3.1. SITE SELECTION

An air photo study was conducted for the purpose of selecting a potential site in the Coerney River valley, which is tributary to the Sundays River in the Eastern Cape (Figure 5.1). Air photos were examined for features that indicated the presence of abandoned surface channels and/or buried stream channels. These features included terrace boundaries, changes in soil colour, vegetation patterns, and surface depressions. The area of study is subject to intensive agriculture which has resulted in many of these landscape features being obscured. Air photos that predated major land development were obtained which aided greatly in site selection. The photos coverage included an area which showed an oxbow channel that had been covered by subsequent land use (Plates 4.1 and 4.2). Ground reconnaissance involved gaining geological information from road and stream cuts, and combining it with local borehole information to form an overall picture of the study site.

Plate 4.1. Aerial view of the oxbow channel before cultivation.

Plate 4.2. View of the same area under cultivation.

4.3.2. GEOPHYSICAL SURVEYS

The geophysical methods available for assessment were portable seismics, electrical resistivity, and electromagnetics. Of these techniques, electrical resistivity and electromagnetics were chosen to establish whether electrical conductivity would locate the buried stream channel by its effects on electrical conductivity. The seismic method was chosen to pick up any changes in earth material density between the buried stream channel and the surrounding host material. The machines used were the Chemtron Electrical Resistivity Meter model C-41, a CSIR designed (SYSDEV) electrical resistivity meter, and the Geonics EM-34 Terrain Conductivity Meter. A trial survey was carried out using a Bison 24-channel seismic refraction unit, which proved unable to generate any data below a very shallow theoretical depth. The equipment for each method is portable enough for small crews of two to four men to operate and all methods are well suited for shallow investigations of less than 50 metres.

4.3.3. SEISMIC REFRACTION

The initial study area covered approximately 0.60 square kilometres of a relatively level field. During an initial seismic refraction survey problems were encountered in obtaining data consistent with existing geological information on the study area. As a result, the seismic survey was discontinued. One source of the data collection problem was the heavy vehicular traffic in the area. Agricultural activity with heavy machinery was ongoing throughout much of the geophysical survey period with the study area being subject to ploughing, planting, cropping, and mechanized irrigation activities (section 5.1). Also, heavy excavation and earth-moving activity was occurring within 800 metres of the study area with the construction of a large diameter water pipeline for Port Elizabeth. Such ambient noise has shown in other cases to affect the quality of the seismic refraction data produced (Haeni, 1988). The same effects occurred in the present study which, together with the problems noted below, necessitated discontinuation of the seismic refraction survey.

Other problems may have arisen as a result of the geohydrological environment. The buried stream channel feature being investigated is not large in area or of a layered nature. The stream channel consists of a coarser material than the finer hosting alluvial material of the study area, and is also located below a shallow water table. Clay lenses are also found in the surrounding alluvial material (section 5.3). These factors all contribute to the poor seismic refraction response for the following reasons.

Firstly, the water table is located above the alluvial/bedrock interface and it will be perceived as a separate layer by seismic refraction (Driscoll, 1986). Secondly, the seismic signal, upon entering the saturated and therefore denser alluvial layer, will move faster and more efficiently than in the unsaturated surface layer. The buried stream channel, being at almost the same level as the existing Coerney River channel, is located below the shallow water table and in the saturated finer material of the host medium (section 5.3). The coarser material of the channel would act as a slower and less efficient conductor of seismic energy, tending to refract energy downwards and through to a layer of greater seismic conductivity rather than upwards (section 3.3.1). This would result in an erroneous reading that would prevent detection of the buried stream channel (Haeni, 1988; 1986). Third, the dense clay lenses within the overburden (section 5.3) would produce an irregular refractor surface that would produce inaccurate delay-times. With depths of investigation shallower than 15 to 21 metres, the limits of seismic refraction are approached and problems inherent with the method increase (Redpath,1973).

4.3.4. ELECTRICAL RESISTIVITY VERTICAL ELECTRICAL SOUNDINGS

The first stage of the geophysical survey was a Vertical Electrical Sounding (VES) survey using electrical resistivity in the Schlumberger configuration. For logistical and performance reasons already discussed in section 3.1, the Schlumberger array was chosen over other resistivity arrays. The Vertical Electrical Soundings were performed using a CSIR designed Electrical Resistivity meter (Plate 4.3). The equipment consists of a current meter and a volt meter. Readings from both meters are used to calculate resistivity in ohm-metres (ohm-m) of which the data can be portrayed to show a vertical distribution of resistivity values in a geological-electrical section. This allows for preliminary judgements of the subsurface geohydrology to be made. The Vertical Electrical Soundings were carried out over the study area with an east/west orientation, parallel to each other and with a maximum AB spread (Figure 3.2b) of 140 metres.

Plate 4.3. CSIR designed (SYSDEV) electrical resistivity metre.

4.3.5. ELECTRICAL RESISTIVITY HORIZONTAL PROFILING SURVEY

The horizontal profiling survey (Appendix 1) was carried out on one half of the initial field area,using a Chemtron Electrical Resistivity Meter model C-41 (Plate 4.4). The Chemtron meter calculates apparent resistivity automatically and is faster and more portable than the CSIR designed equipment used for the Vertical Electrical Sounding survey. The preliminary air photo reconnaissance showed that the feature to be surveyed did not extend throughout the whole study area (section 4.3.1). A dense survey grid was established over the portion of the study area in which the air photo study showed the feature was located. The grid points were established at 50 metre intervals with each point representing the centre point of subsequent survey sites (Figure 4.1).

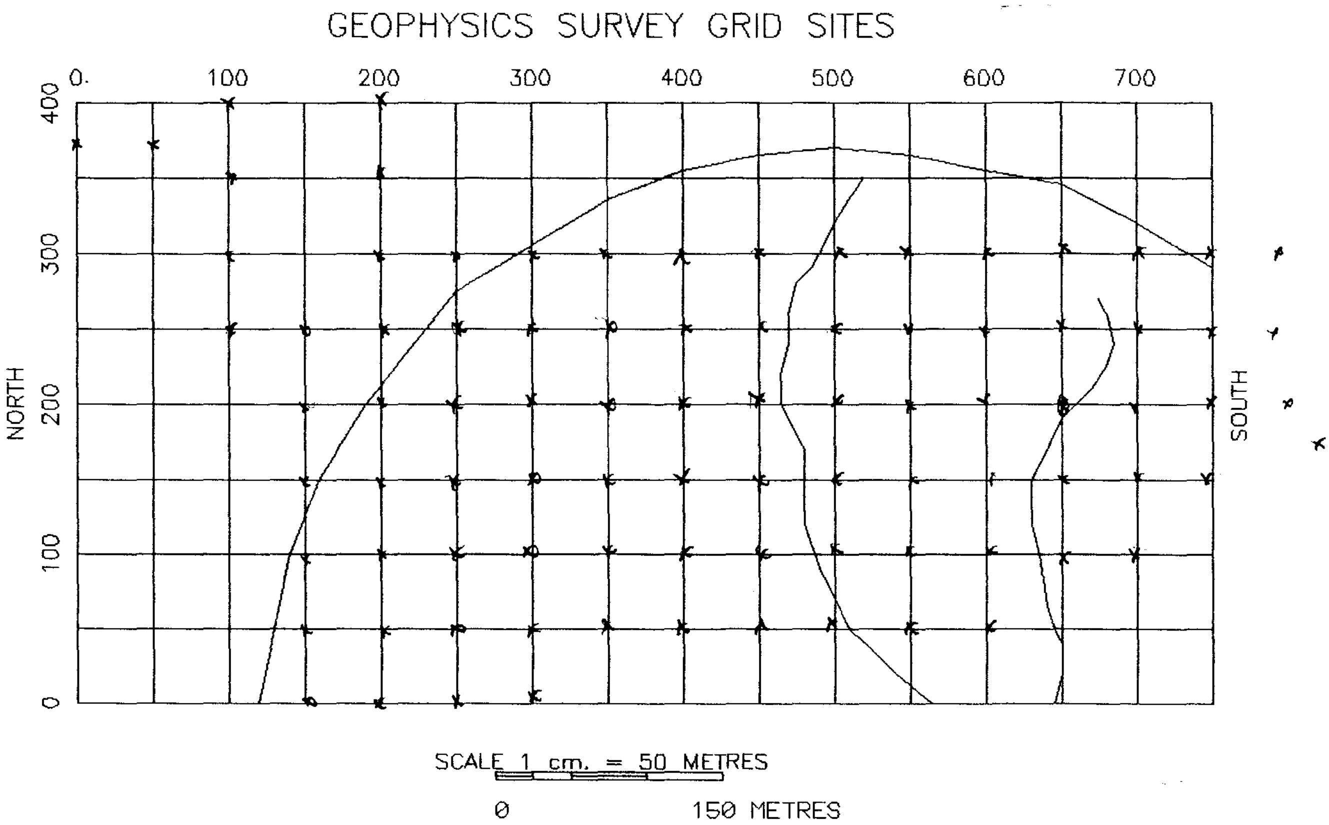


Figure 4.1. Geophysical survey grid sites as per co-ordinates in Appendices 1 and 2.

On the basis of multi-layered models produced from the VES curves (section 4.3.8) the parameters for the electrical resistivity horizontal profile survey (specifically the AB spreads to be used) were decided upon. Also used was information from logs of boreholes drilled in 1987 (section 5.3), riverbank cut stratigraphy, and air photo information covering the old channel site. The Wenner configuration (Figure 3.2a) was used with 3 AB spreads of 25, 50 and 70 metres. The 70 metre AB spread was judged wide enough to reach to the presumed bedrock depth of 8 to 10 metres and the remaining AB spreads to have adequate depths of penetration for the existing region between bedrock and the surface (section 3.1.2)(Table 3.1).

Plate 4.4. Chemtron electrical resistivity meter.

4.3.6. ELECTROMAGNETIC HORIZONTAL PROFILING SURVEY

The electrical resistivity profiling survey was followed by an electromagnetic horizontal profiling survey (Appendix 2) with the Geonics EM-34 Terrain Conductivity Meter (Plate 4.5) and utilizing the established survey grid (Figure 4.1). Electrical conductivity is measured in milli-mhos per metre (mmhos/metre), which is the opposite of electrical resistivity. The EM transmitter and receiver loops are used in both the horizontal and vertical plane, and the physical orientation of the EM survey is the same as that for the electrical resistivity survey.

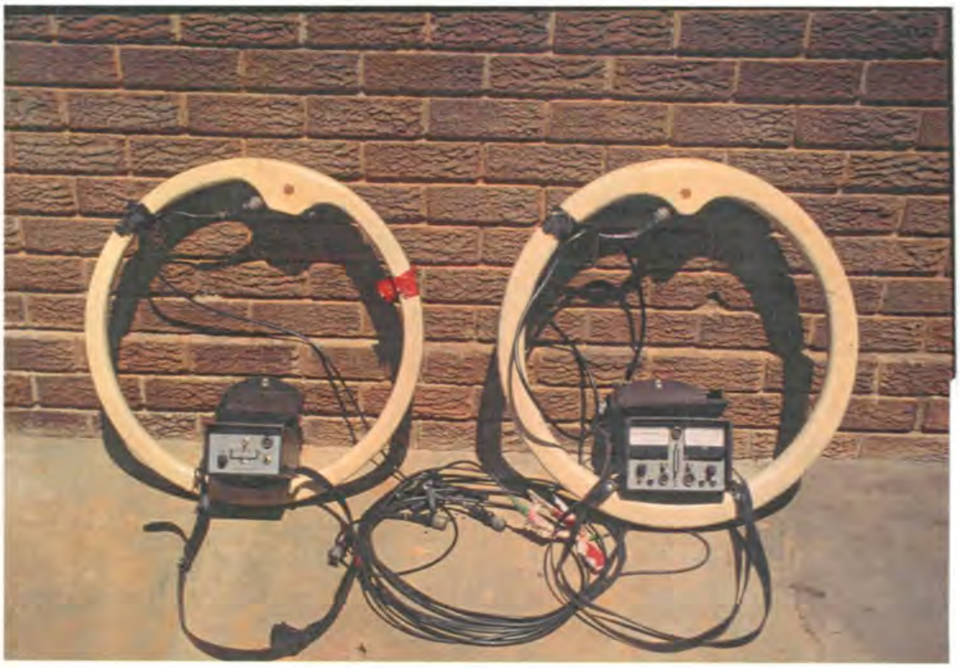


Plate 4.5. Geonics EM-34 terrain conductivity metre.

4.3.7. 'SOIL' SALINITY SURVEY

The remaining field work involved hand-augering holes to a depth of 3 metres, again using the same study grid reference points. 'Soil' samples from the holes were taken at the surface and then every 25 centimetres to a maximum of 3 metres. For the 'soil' survey, only every second station in the 50-metre grid was sampled.

In preparation for laboratory analysis, the 'soil' samples were crushed and sieved to a 1 mm fraction, and then baked in a soils oven to remove all traces of moisture. The samples were then mixed with distilled water to form a soil paste of a required consistency (Soil Science Society of South Africa, 1990; Rhoades, 1982) and measured for electrical conductivity (EC) in milli-Siemens per metre (mSm/m). The equipment consisted of soil cup sensors attached to a Zeiss CON 602 electrical conductivity meter.

Additional data on the study site was obtained from the Department of Agriculture, who were involved in a groundwater study in the area. Information obtained included a survey of the land surface and depth-to-water table measurements.

4.4. METHODS OF ASSESSMENT OF GEOPHYSICAL DATA

Vertical Electrical Sounding data can be assessed quantitatively because it measures depth and thickness of the subsurface layers. This is done by curve matching field data curves with theoretical curves or using computer programs for modelling multi-layered situations (Erdelyi and Galfi, 1988; Van Zijl, 1985).

The interpretation of horizontal profiling data is largely qualitative. Data is presented in the form of contoured maps, data profile lines, or geo-electric sections (Cameron *et al*, 1980; Corner and Antoine, 1989; Greenhouse and Harris, 1982; Mazac, Kelly, and Landa, 1987; Van Zijl, 1985). Profiled data can be better interpreted if it is supported by a vertical electrical sounding survey, thus allowing for a comparison of vertical layers of data with the lateral variations (Greenhouse and Harris, 1982, Mazac, Kelly, and Landa, 1987; Van Zijl, 1985).

The results of the VES survey were modelled on a RESIX resistivity modelling package. The data from the horizontal profiling surveys of both geophysical techniques were plotted on a grid and contoured on the SURFER data contouring package using the inverse squared distance technique . Both the land and water table surfaces were also contoured. The contouring methods available with the computer package on the data points include inverse squared distance, minimum curvature and kriging (Surfer, 1990).

Both minimum curvature and kriging are used to establish trends in the data, but can produce unpredictable results in areas of sparse data. The inverse squared distance method of contouring data is the simplest and the fastest technique. The data points are weighted such that the influence of one point on another declines with distance from the point being estimated. The greater the weighting power, the faster the decline in influence and the less effect points further out will have on interpolation. This reduces the tendency towards unpredictable results that are more noticeable when using kriging and minimum curvature contouring techniques (Surfer, 1990; Patrick, 1989).

Statistical analysis of the horizontal profiling data from the EM and the electrical resistivity techniques was the final step in data analysis, with the tests on the data performed using the STATGRAPHICS statistical graphics package (Statgraphics, 1989). Data from the EC tests on the 'soils' was compared to the resistivity and EM techniques statistically using a multiple regression to quantify possible relationships between the geophysical responses and the soil EC results. Soil EC values affect the electrical properties of the 'soil' and can contribute strongly to the geophysical response to the subsurface (section 2.2.5).

CHAPTER 5. STUDY AREA

5.1. GEOGRAPHICAL DESCRIPTION

The study area is located on the lower Coerney River, approximately 5 kilometres upstream of its confluence with the Sundays River (Figure 5.1). The study area covers approximately .60 square kilometres, and is located on Trenly Farm. The study area is under agricultural development, with citrus and lucerne being the main products. On the Trenly Farm study site, citrus trees have been planted in the centre pivot irrigation area adjacent to the Coerney River. As well as citrus trees, market cash crops such as potatoes, melons, pumpkins, and maize have been planted and will be crop rotated until the citrus orchard reaches maturity.

The farming region in the lower Sundays River Valley is under intense agriculture and irrigation, with the irrigation techniques varying from higher technology microjet drip and sprinkler systems to the simpler flooding methods (Pearce, 1987). The irrigation system on the Trenly Farm study site in 1991 consisted of a centre pivot system fed by a dam adjacent to the field. The dam storage was supplied by the Sundays River Irrigation Board canal system, which itself obtained water from the Orange River system.

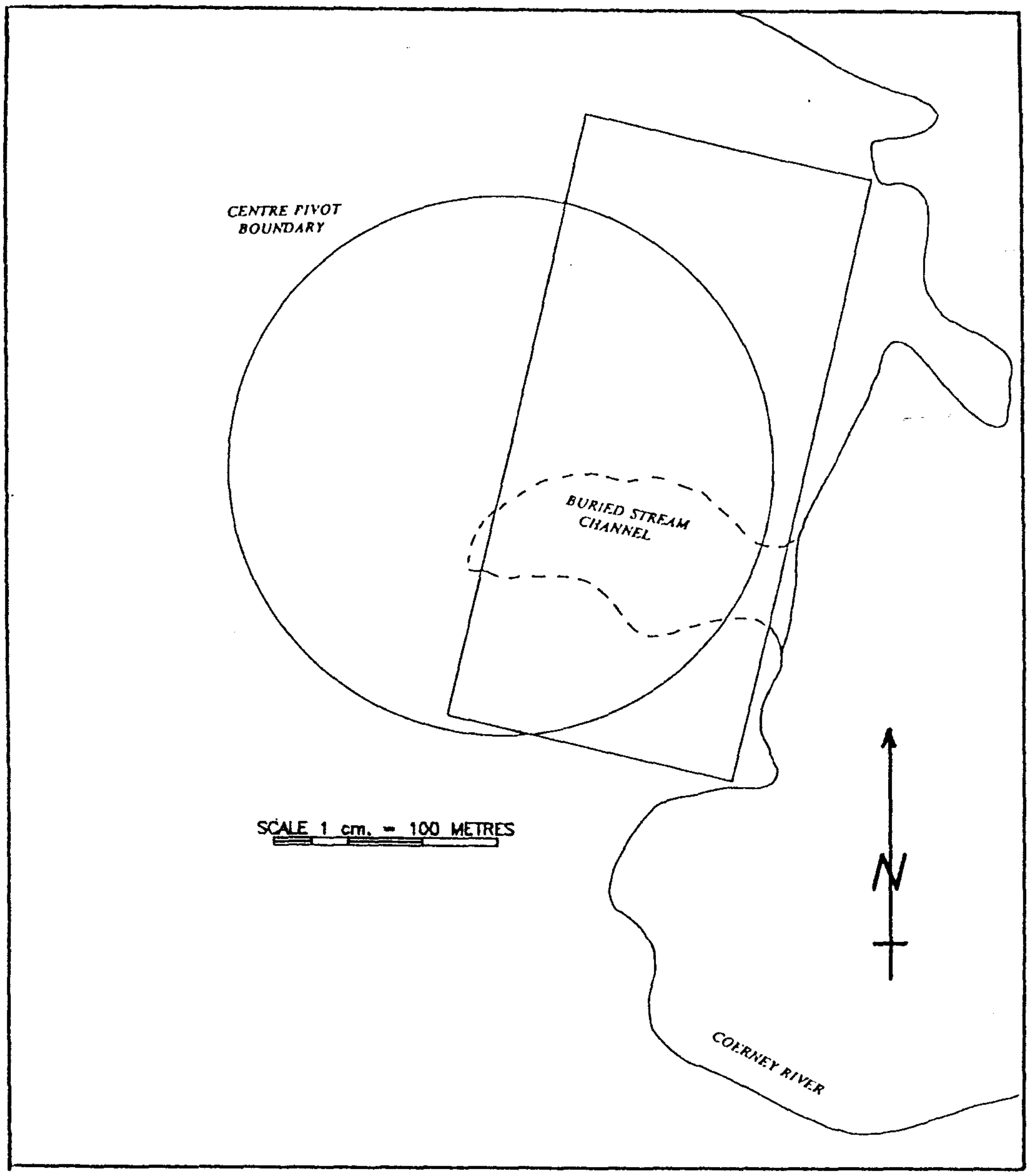


Figure 5.1. Location map of the geophysics survey area. The circle denotes the centre-pivot irrigation boundary.

5.2. REGIONAL GEOLOGY

The Coerney River flows into the Sundays River Valley which is part of the Algoa Sedimentary Basin, a larger regional structural feature. The Algoa Sedimentary Basin is almost 4000 square kilometres and is the largest occurrence of Cretaceous-Jurassic sediments (around 135 Ma) along the southern coast of Africa (Winter, 1973). Regional stress patterns caused by early

Cretaceous shearing on the southern continental margin caused tensional displacements on the Cape Fold Belt, resulting in a number of fault controlled basins. Structurally, the basins are characterized by a series of half-graben structures, synsedimentary faulting, and contemporaneous volcanism (Tankard *et al.*, 1982).

The Sundays River Trough, in which the Coerney River lies, is a half-graben structure. It is bounded on the north by the Zuurberg Fault, which marks the beginning of the Zuurberg Mountains, which are east-west trending fold ridges that are part of the Cape Fold Belt. The southern boundary of the Sundays River Trough consists of the upper edge of another fault block in the succession. The Sundays River Trough is asymmetrical and dips gently towards the south (Winter, 1973; Lock *et al.*, 1975; Dingle, Siesser, & Newton, 1983) (Figure 5.2).

In the lower Cretaceous, continued subsidence allowed marine encroachment. The Cretaceous clastic succession therefore begins with continental sediments (i.e. land-derived) and ends with marine sediments. The Group encompassing this sequence is referred to as the Uitenhage Group and consists of the Enon Conglomerate Formation, the Kirkwood Formation, and the Sundays River Formation. The three formations laterally and vertically inter-finger with each other and represent a sedimentary succession of continentally derived (Enon conglomerate) through fluviatile/estuarine (Kirkwood Formation) to shallow marine sediments (Sundays River formation) (Tankard *et al*, 1982; Dingle, Siesser & Newton, 1983; Shone, 1978).

AGE			GROUP	FORMATION	DERIVATION ENVIRONMENT	LITHOLOGY
QUATERNARY	HOLOCENE PLEISTOCENE		ALGOA	SCHELMHOEK NAHOON	AEOLIAN	VARIED
TERTIARY (0-65Ma)	PLIOCENE (2-7Ma)	UPPER		NANAGA	AEOLIAN	RED-YELLOW SANDS/CALC NODULES
	MIOCENE (7-26Ma)			ALEXANDRIA	MARINE	SAND/SHELL LIMESTONES & QUARTZITE PEBBLES
	OLIGOCENE (26-38Ma)					
	EOCENE (38-54Ma)	LOWER		BATHURST		
	PALEOCENE (54-65Ma)				MARINE	GRITTY LIMESTONES
CRETACEOUS (65-135Ma)		UPPER	UITENHAGE	SUNDAYS RIVER	SHALLOW MARINE AND ESTUARINE FROM MARINE INCURSIONS	GREY SHALES & SANDSTONES
		LOWER		KIRKWOOD	FLUVIATILE	RED-BROWN SILTY MUDSTONE, GREY-BLUE SHALES & SANDSTONES
				ENON	CONTINENTALLY DERIVED	COARSE CONGLOMERATE & INTERBEDDED SANDSTONES & CLAYS
JURASSIC (135-195Ma)				?		

Table 5.1. Stratigraphic table of the Uitenhage and Algoa Groups (after McMillan, 1990; LeRoux, 1990).

The Enon Conglomerate, at the base of the Uitenhage Group, consists of a coarse conglomerate interbedded with sandstones and mudstones. The Kirkwood Formation, the result of a fluviatile environment, consists mainly of clastic sediments of the valley-floor environment that lies conformably on the Enon Formation and interfingers with it. The Kirkwood consists of reddish-brown silty mudstones, grey shale beds, and sandstones closely associated with blue-grey shale beds. The sandstones contain pebble washes, clay pellets, and pieces of fossilized wood (Winter, 1973). The Sundays River Formation, derived from a shallow marine and estuarine environment from various marine incursions, consists of grey shales and sandstones with invertebrate fossils (McLachlan and McMillan, 1976).

The Sundays River Formation is overlain in the Sundays River region by the Alexandria Formation which is believed to be of Miocene to Pliocene age (Le Roux, 1990). The lower edge of this deposition is composed of sandy and shelly limestones and conglomerates dominated by well-rounded quartzite pebbles. The marine transgression during this time of deposition led to a smoothing out of the Sundays River Formation. Eventually the sea regressed, leaving cross-bedded pale to reddish-yellow aeolian sands and calcareous nodules of coastal dune character, designated the Nanaga Formation, on top of the Alexandria Formation. The Nanaga Formation is of Pliocene to Pleistocene age (McMillan, 1990; SACS, 1980).

The Tertiary/Quaternary deposits consist of calcified sands and fluvial gravels. The gravels form terraces along the ridges. The most recent sediments are alluvial and estuarine sediments associated with river flood plains, and marine terraces found near the sea (McMillan, 1990; LeRoux, 1990; Winter, 1973; Dingle, Siesser, & Newton, 1983).

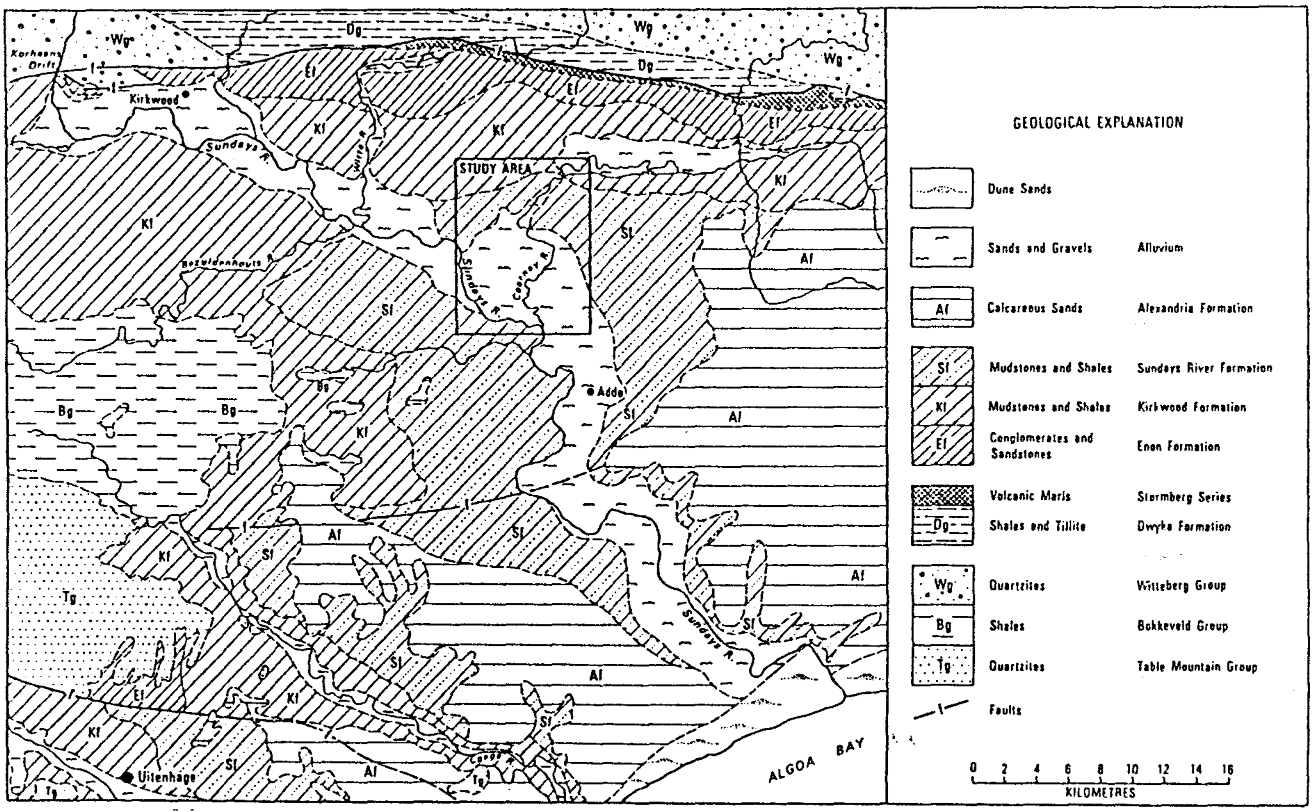


Figure 5.2 Geological map of study area (based on McLachlan and McMillan, 1976; Winter, 1973).

5.3. HYDROGEOLOGY OF THE STUDY AREA

Borehole logs were obtained from a drilling programme undertaken by the Hydrological Research Unit of Rhodes University in 1987. The logs (Figure 5.3) show that the study area comprises of approximately 10 metres of sandy clay deposits overlying 3 to 4 metres of Enon conglomerate, underlain by mudstones and sandstones of the Sundays River and Kirkwood Formations respectively. This information is confirmed from a bank cut on the Coerney River located approximately 0.5 kilometres downstream from the study site (Plate 5.1). The drilling samples were analyzed for their stratigraphic makeup (Figure 5.3). Sand and silt appear to be the major soil components with clay lenses present near the surface.

Dispersed throughout the area are isolated deposits of clast supported quartzite cobblestones derived from Enon Conglomerate. The lack of horizontality in the unconsolidated deposits, which form an alluvial aquifer, can be attributed to their being deposited in association with lateral migration of the Coerney River accompanied by intermittent flooding (section 2.1.2). The heterogeneity of the alluvial aquifer affects the hydraulic properties of that aquifer, resulting in varying hydraulic conductivities within the study area. Borehole studies indicate variations in the hydro-salinity and electrical conductivity of the groundwater with depth. A Department of Agriculture Technical Services field survey performed over the study area in January shallow in places, rising to as little as 2.0 metres below the surface (section 5.4).

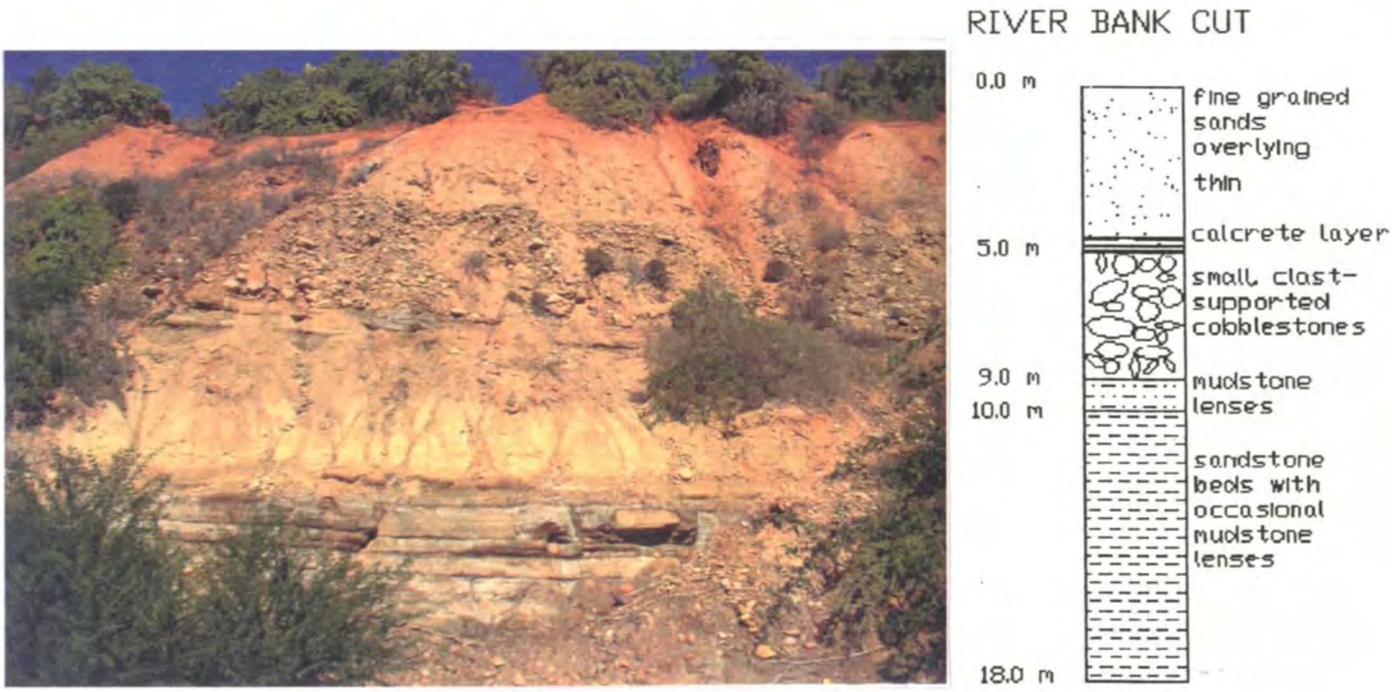


Plate 5.1. Bank cut showing fine grained sediments overlying clast-supported cobbles on top of sandstone beds.

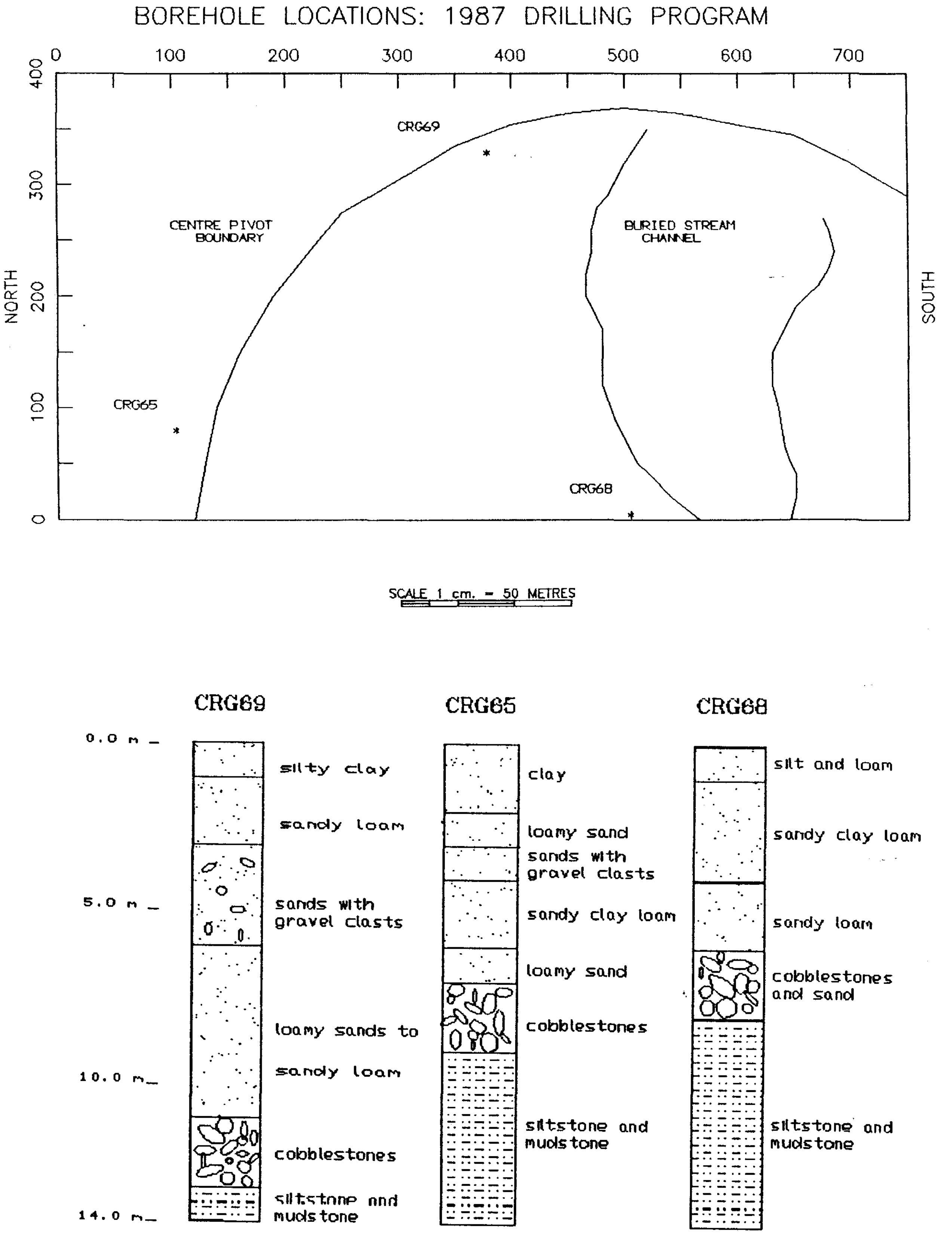


Figure 5.3. Selected borehole logs from the 1987 Sundays River drilling program.

5.4. GROUND SURFACE AND WATER TABLE

The field site is flat to gently undulating. The Department of Agriculture survey of 1991 provided information on the ground surface contours and the depths to water table from the surface. A three-dimensional representation of the data shows a land surface height of 21.5 metres above sea level at the north end of the study area, and a low of approximately 19.0 metres at the south end of the site. At the southern end, the surface begins to rise again (Figure 5.4).

The water table, also surveyed and subsequently contoured, appears to follow closely the contours of the land surface. The depth to water table is greater at the northern end of the study area where it is almost 3.0 metres below surface. At the southern end of the study site, where the ground surface is lowest, the water table is closest to the surface with only 2.0 metres depth (Figure 5.4)(Department of Agricultural Technical Services, 1991).

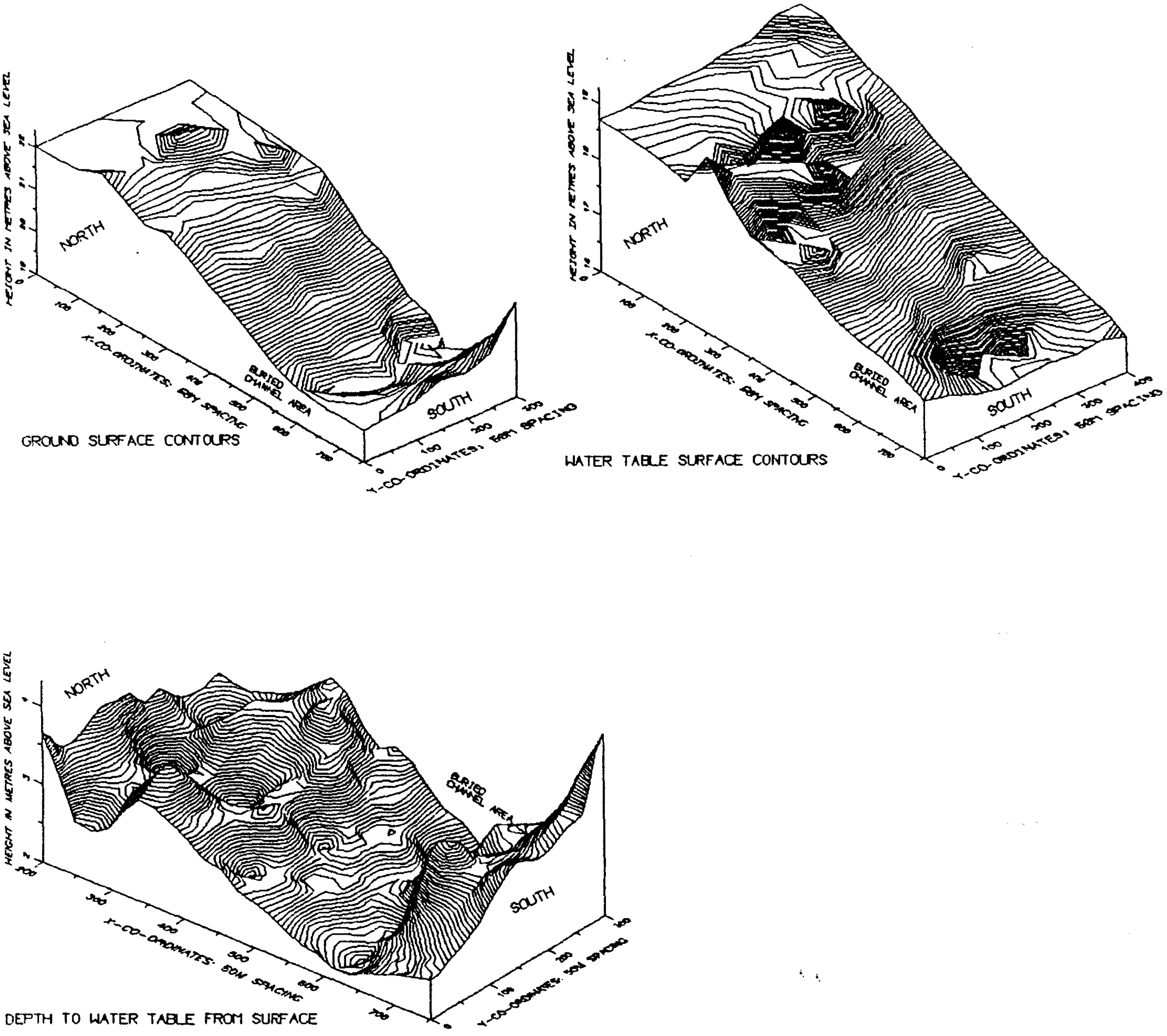


Figure 5.4. Surface contours of the ground surface, the water table, and the depth to water table. All units are in metres above sea level.

The contoured surface of the water table indicates the direction of groundwater flow. Groundwater moves towards the southern end of the study area and towards the Coerney River (Figure 5.5). This may indicate a topographical low, but could also signal an area of better groundwater drainage from the study region resulting in a slight drop in the water table in that particular area. Such a zone could be the water table responding to the coarser material of the alluvial channel which would allow for easier flow of groundwater compared to that in the surrounding overburden (section 2.2.3).

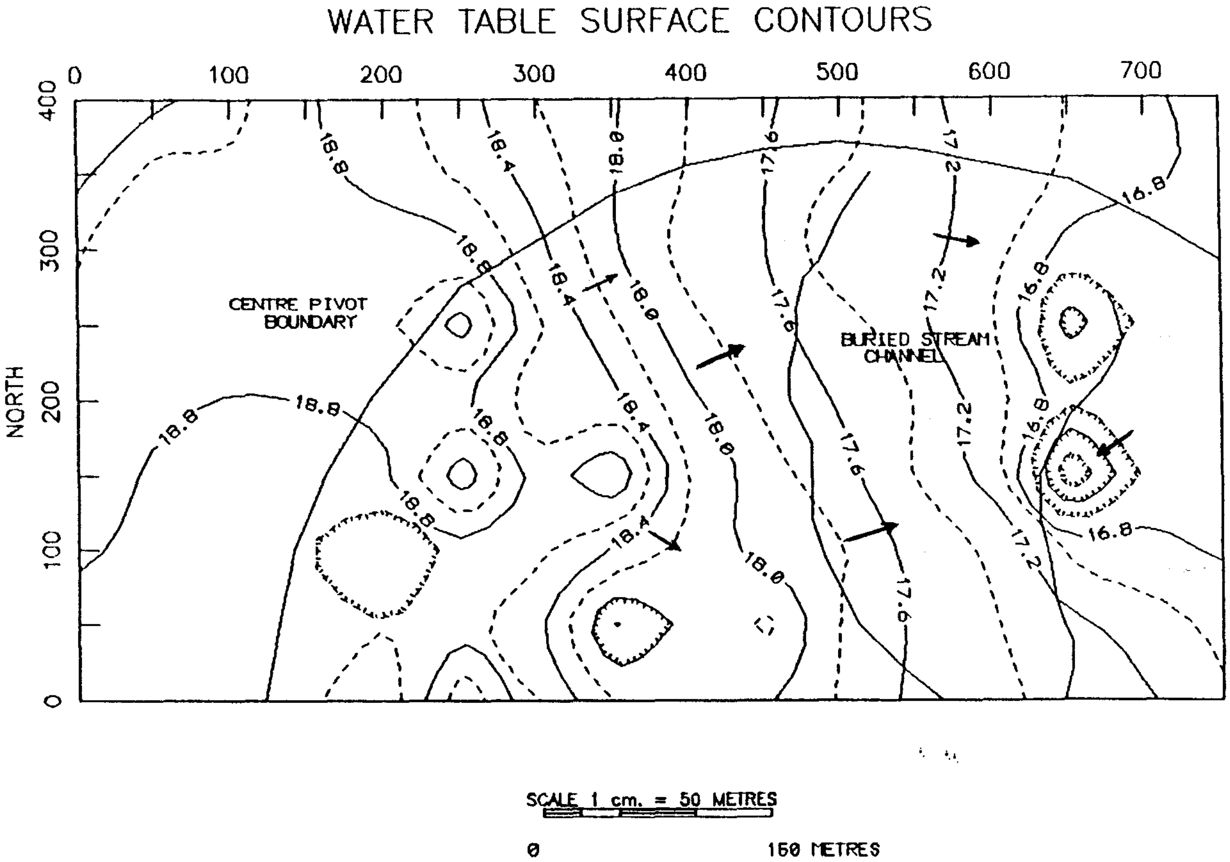


Figure 5.5. Contour map of the water table; arrows indicating direction of flow. The centre pivot boundary and buried stream channel are presented as per Figure 5.3.

5.5. 'SOIL' SALINITY

'Soil' EC profiles for each augur sample hole were drawn up from the data collected (Appendix 8) from the 'soil' survey (section 4.3.7). 'Soil' EC values from each sample site were plotted against depth to form a curve, and the curves characteristics were examined. The range of values for the 'soil' EC profiles formed four identifiable classes and four corresponding EC profile Area Type curves (Figure 5.6) represent these classes.

Area Type curve 1 shows consistently low 'soil' EC values of less than 200 mSm/m throughout the 'soil' horizon. For Area Type curve 2 the EC values rise to 300 mSm/m at a depth of 2 to 3 metres. 'Soil' EC values rise very sharply to 800 mSm/m after 2 metres depth for Area Type 3 curve. Area Type curve 4 shows high EC values throughout the majority of the 'soil' horizon sampled. The sites from which the 'soil' samples and data for each class were obtained were outlined on the study area grid (Figure 5.7) and assessed on spatial distribution over the study area. By laying out the classes on the grid, spatial trends for each of the 'soil' EC classes could be qualitatively assessed. These trends were subsequently compared with the contoured electrical resistivity and EM data(Appendices 4 and 6), the contoured ground surface and water table, and the irrigation boundary to see if a spatial relationship could account for 'soil' EC variations. The average 'soil' EC values to 3 metres depth increase as one proceeds downward from the soil surface. The range between maximum and minimum EC values also increase with depth, almost doubling at the bottom of the soil EC profile and showing a greater variation of 'soil' EC's with depth (Table 5.2).

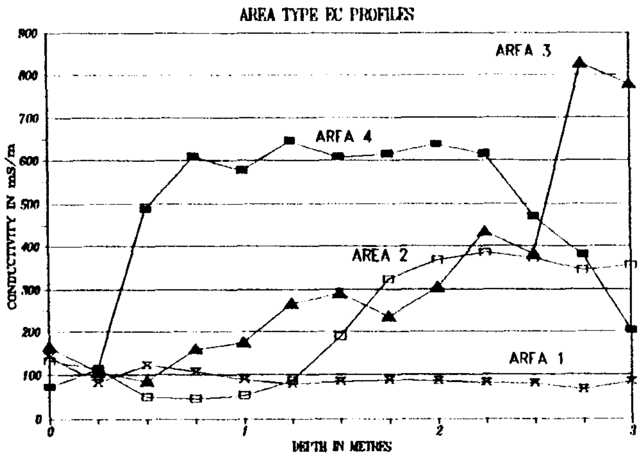


Figure 5.6. Soil EC profile Type curves representing EC types.

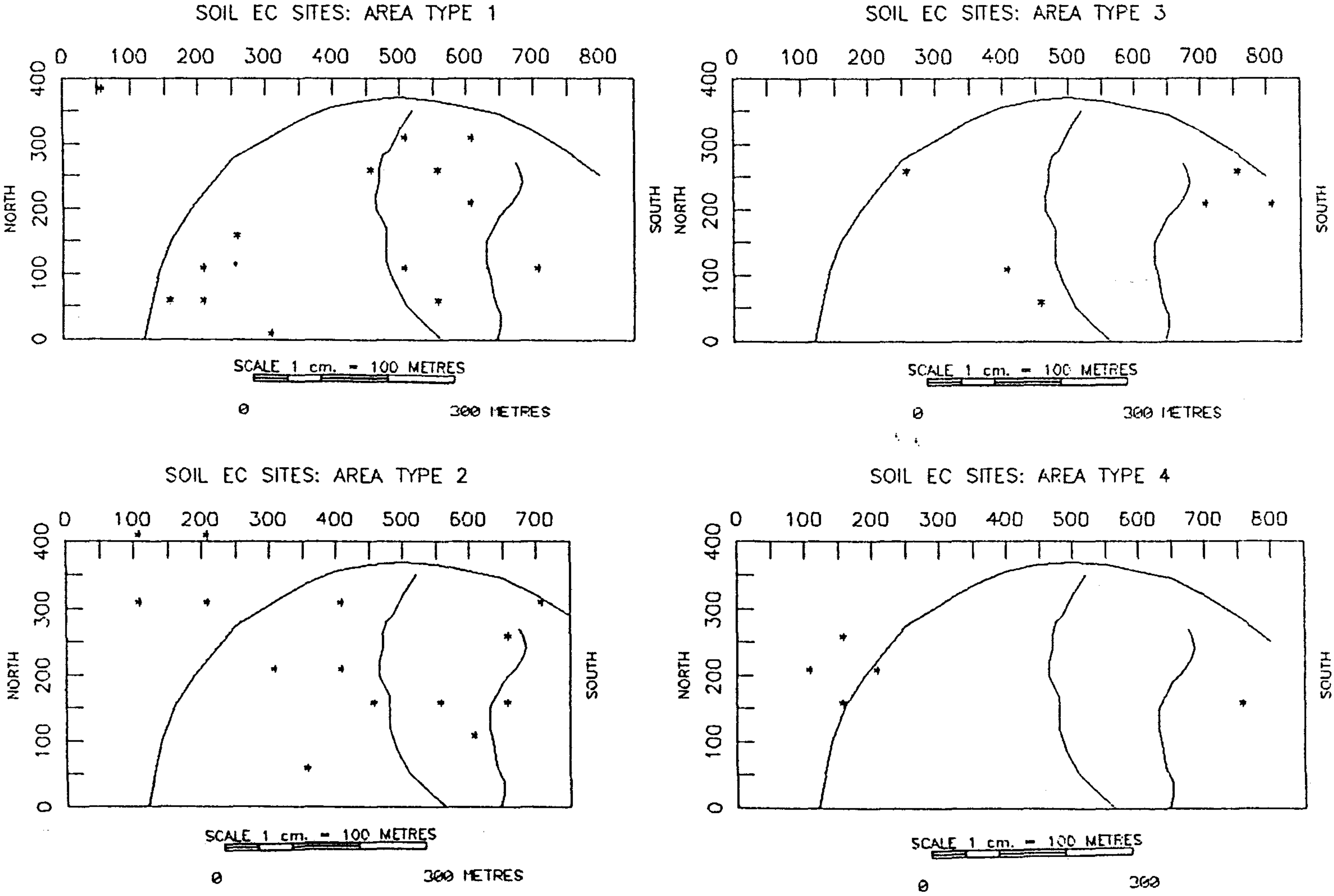


Figure 5.7. Soil EC profile Type classes and soil EC sites.

SOIL DEPTHS	AVERAGE EC	MINIMUM EC	MAXIMUM EC	MEDIAN	VARIANCE
0.00 m	122.84	33.00	387.00	109.00	4478.50
0.25 m	109.67	35.00	451.00	92.00	6187.27
0.50 m	135.87	39.00	552.00	97.00	14221.30
0.75 m	152.73	34.00	610.00	111.00	18872.20
1.00 m	159.22	33.00	578.00	122.00	17435.50
1.25 m	176.56	30.00	646.00	133.00	19910.60
1.50 m	199.87	36.00	608.00	151.50	18755.30
1.75 m	233.98	36.00	615.00	206.00	20456.70
2.00 m	258.40	38.00	639.00	230.00	24915.50
2.25 m	285.86	38.00	651.00	267.50	28055.70
2.50 m	292.22	48.00	668.00	270.00	21391.60
2.75 m	302.46	67.00	828.00	273.00	24213.60
3.00 m	324.49	85.00	778.00	300.00	21031.30

Table 5.2. Descriptive statistics of soil EC values.

5.5.1. SOIL EC PROFILE TYPES

EC profile type 1 consists of 14 sample sites whose soil EC values are as low as 38 mSm/m but do not exceed 300 mSm/m. Their distribution forms two distinct groupings; one in the northern half and one in the southern half of the study area (Figure 5.7). The group in the southern area comprises 8 sites and corresponds to the region of the lowest topography where the water table is closest to the surface (Figure 5.4). The grouping of 5 sites in the north is also in an area where there is a slight depression of the topography and where the water table is closer to the surface. The remaining 1 site with soil EC values below 300 mSm/m is located outside of the centre-pivot irrigation boundary.

Soil EC profile type 2 consists of 14 sample sites whose soil EC profiles have values less than or equal to 400 mSm/m. Four of these sites are located outside the irrigation boundary. The remainder are distributed in the central and southern portion of the study site.

Soil EC profile type 3 consists of 6 sites whose soil EC values exceed 500 mSm/m. Four of the sites are located at the edge of the irrigation boundary, 3 of which are at the southern edge of the field where the ground surface begins to rise and the water table falls away.

Soil EC profile type 4 consists of five sample sites whose soil EC profiles start with low EC values, rise sharply, and then drop sharply at 2.5 metres depth. Four of the sample sites are adjacent to each other and straddle the irrigation boundary in the northern half of the study area. The remaining site is near the irrigation boundary in the southern portion of the study area.

5.5.2. GENERAL COMMENTS ON SOIL SALINITY

The largest number of low EC values occurs where the depth to water table becomes very shallow, the ground surface is lowest and where the water table surface is lowest (Figure 5.4). Figure 5.5 indicates this as an area where the groundwater moves towards the southern limb of the buried stream channel. The presence of low soil EC's here can be an indication of a zone of a higher groundwater flow rate (section 2.2.5). Except for area 4, the majority of sites located outside of the irrigation boundary have low EC values, suggesting that irrigation or perhaps the agricultural land use is affecting the soil EC's in this area.

CHAPTER 6. ELECTRICAL RESISTIVITY ASSESSMENT

INTRODUCTION

The resistivity techniques of Vertical Electrical Sounding and Horizontal Profiling are assessed in this chapter. The modelled Vertical Electrical Sounding data and accompanying results are compared to geological information gathered from the stratigraphic exposure on the banks of the Coerney River and from borehole logs in the area. The Vertical Electrical Sounding models are used to establish what theoretical depth a particular AB electrode spacing is penetrating. The Horizontal Profiling survey and the information obtained is assessed on the basis of comparison with the soil EC data collected.

6.1. METHODS OF INTERPRETATION

Specific resistivity is not directly related to only geology, and as a result it is not possible to identify a particular rock or formation of material solely by a resistivity value (section 3.1). Geological sections differ from geo-electrical sections. The boundaries of their layers do not always coincide (section 3.2), therefore a study of the correlation between geological and geo-electrical parameters is necessary (Erdelyi and Galfi, 1988; Van Zijl, 1985).

Vertical Electrical Soundings (VES) can be assessed quantitatively by curve matching with theoretical curves (Orellana and Mooney, 1966) or with computer modelling programs (RESIX, 1993) that plot theoretical curves to match the data input, producing a layered earth model (section 4.2). The assessment of Horizontal Profiling is largely qualitative due to the way apparent resistivity changes from one geo-electrical layer to another. Compared to VES, mathematical analysis has been less well developed for Horizontal Profiling over two-dimensional structures and least well for three-dimensional bodies (Kearey and Brooks, 1992; Dobecki and Romig, 1985). However the initial shallow depth of investigation of the profiling survey can allow for a regression analysis between apparent resistivity and soil EC values. This is due to a greater possibility of geo-electrical homogeneity at shallower depths (section 3.1).

6.2. VERTICAL ELECTRICAL SOUNDINGS

Vertical Electrical Sounding curves (Appendix 7) were computer modelled using the RESIX resistivity modelling package. RESIX, developed by Interpex Ltd. (Golden, Colarado), uses mathematical modelling techniques to produce layered earth models. A knowledge of the local geology is important to effectively assess this technique and to develop layered models approximating the true geological situation.

6.2.1. LOCAL GEOLOGY

The stratigraphy of the local geology is used to establish a framework for the interpretation of the Vertical Electrical Soundings. Assuming that the geology of the area is continuous, it can be expected that three geo-electric layers should become apparent in the VES curves. These layers are the expected geo-electric response to a layer of fine grained alluvium (mostly composed of sands, clays and loams), followed by a layer of clast cemented conglomerate material of cobblestone size and underlain by bedrock composed of sandstone and siltstone/mudstone (section 5.3). Information obtained from the Department of Agricultural Technical Services (section 5.4) suggests the possibility of a fourth geo-electric layer occurring in the form of a shallow groundwater table within the upper layer of fine grained deposits. These stratigraphic layers were confirmed by a diamond drilling programme in 1991 undertaken as part of this research program, which were used to follow up the geophysics survey figure 6.1).

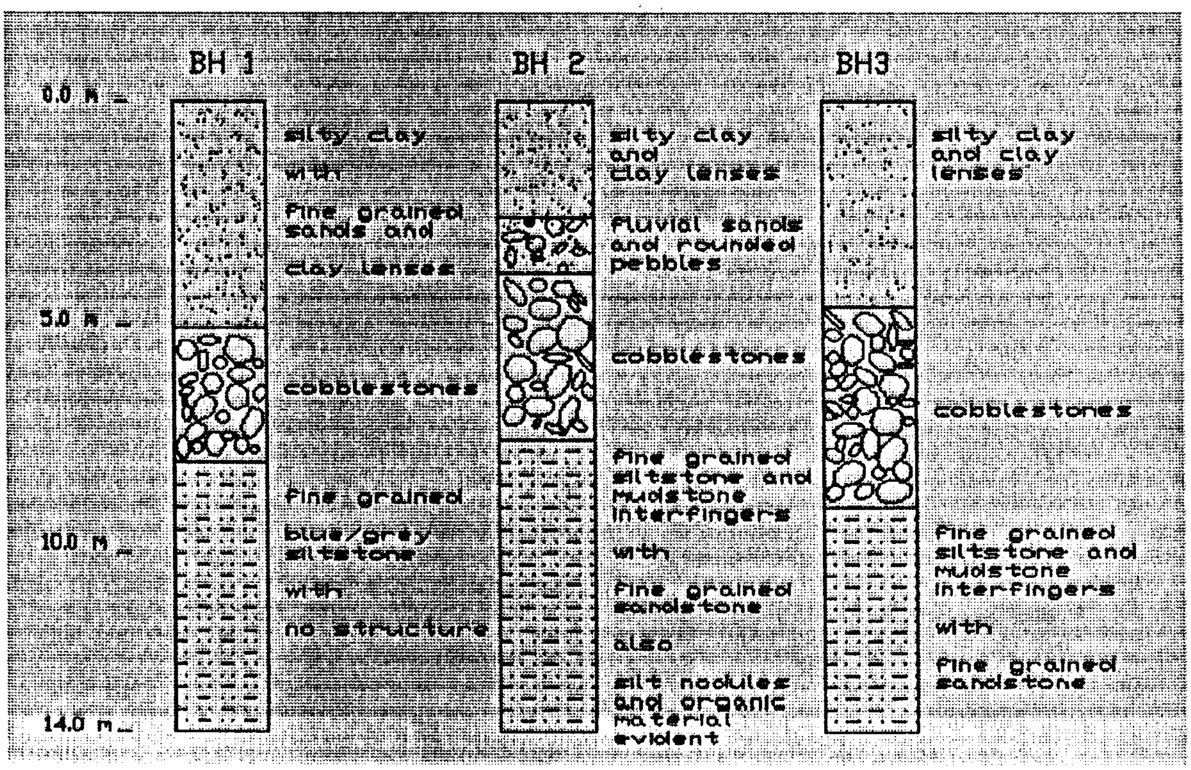


Figure 6.1. Borehole logs from 1991 drill program.

6.2.2. COMPARISON OF VES RESULTS TO LOCAL GEOLOGY

A number of Vertical Electrical Soundings were performed within and adjacent to the study area with a CSIR designed Electrical Resistivity meter (SYSDEV). Five VES curves were chosen that occurred within or closely adjacent to the horizontal profiling survey area (figure 6.2). The remaining VES curves not chosen delivered faulty data due to equipment related difficulties.

The VES curves which are shown in Appendix 7 are presented with a layered earth apparent resistivity model derived from the RESIX resistivity modelling package. The curves represent the plotted VES field data and the model represents, geo-electrically, the layered earth model which is derived from the field data and also best approximates the local geological information. The X-axis of the model represents the apparent resistivity of the geo-electrical layer, and the Y-axis represents the theoretical depth in metres of each layer (Figure 6.3).

All of the layered earth models produced from sounding curves indicate the presence of 4 layers (Appendix 7). Each shows a highly resistive geo-electric layer on the surface less than 2 metres thick. This is followed by a less resistive geo-electric layer of varying thicknesses for each of the models. Four of the geo-electrical models (Appendix 7: LR1, LR5, LR31 and LR6) produce a similar layered earth model. The third geo-electric layer is more resistive than the second, but less so than the surface layer. The fourth layer in these 3 layered earth models is less resistive than the third and of varying theoretical thickness. For the model for LR6 the third and the fourth layers have very similar formation resistivities. The layered earth model for LR3 is slightly different, with the second and third earth model layers having similar formation resistivities and the fourth layer being more resistive than the second and third layers (Appendix 7).

The VES layered earth models extend to an infinite depth with the fifth layer (Figure 6.2, y-axis). The relevant information for this study is considered to be within the four layers produced by the model and less than a model depth of 20 metres. In view of the probable depth of investigation for a 70 metre AB spread (section 3.1.2) anything greater than 20 metres is likely to be a modelling extrapolation.

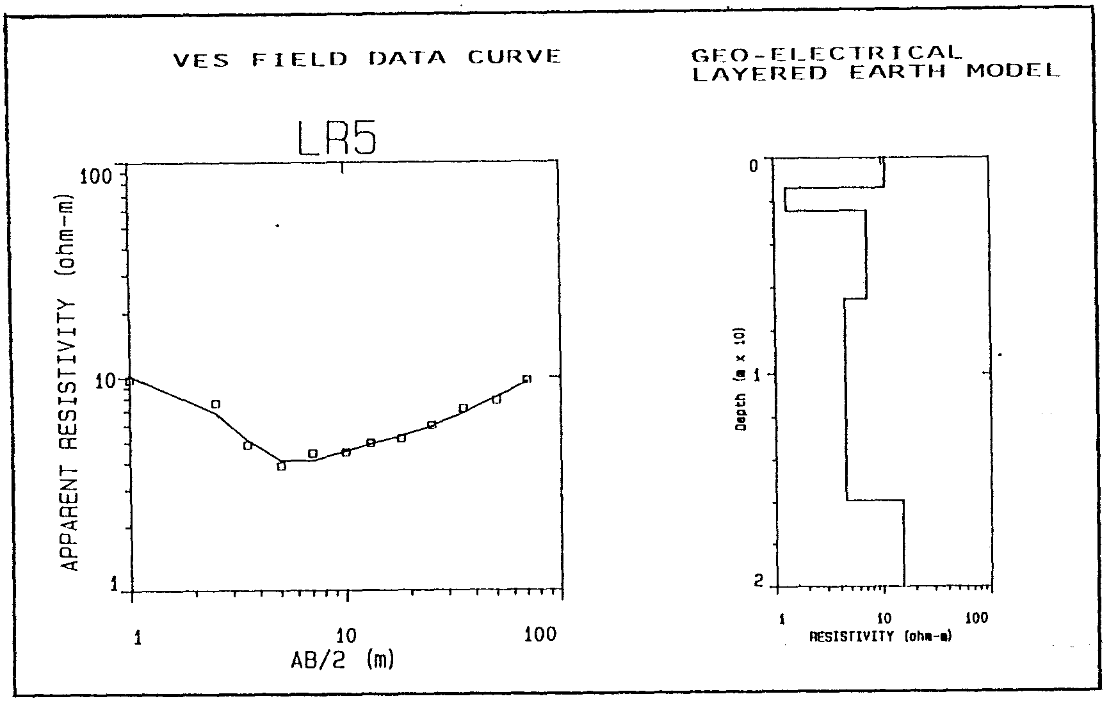


Figure 6.2. VES field data curve and theoretical model of the geo-electric layers of apparent resistivity.

6.2.3. DISCUSSION OF RESULTS

All modelled VES curves produced the expected 4 layered geo-electrical situation suggested by the geology (section 5.2) and the water table. All curves showed an initial shallow layer of 1 to 2 metres of relatively high resistivity (10 to 27 ohm-m), followed by a narrow layer of less resistive material (1.3 to 4.5 ohm-m). Layered earth models for VES curves LR1, LR5 and LR6 show a third layer (6.6 to 8 ohm-m) underlain by a fourth, less resistive layer (4.5 to 6.5 ohm-m) of varying thickness (Figure 6.2). The layered earth model produced from VES curve LR3 is similar to the models already discussed except that its third layer is less resistive than the fourth. Maximum depth of penetration with the spread of AB = 70 metres is theoretically estimated to be between 8.75 metres and 13.3 metres (section 3.1.2).

On the basis of depth and characteristic resistivities of formation, all the layered earth models correspond with the surface layer of dry fine sediments that has a high apparent resistivity down to the water table. The apparent resistivity drops significantly in the saturated fine deposits in the shallow water table. The shallow water table coupled with irrigation in the semi-arid environment is expected to produce saline conditions (section 2.2.5). Three layered earth models most closely approximate the geological information of the area (LR1, LR5 and LR6). The layer of quartzite cobblestones (coarse conglomerate) has a lesser % of fine sands and clays in its makeup than do the layers of fine saturated sediments above and the mudstone and soft sandstone layers below. This layer would be expected to have a higher formation resistivity than the confining upper and lower layers (section 3.1 and Figure 3.1) as indicated in layered earth models LR1, LR5 and LR6.

6.3. HORIZONTAL PROFILING: QUANTITATIVE ASSESSMENT

A step-wise regression was performed between the data from the three AB spreads of electrical resistivity as dependent variables, and the soil EC values taken at regular depths plus the depth to water table as independent variables. A standard linear regression is often plotted as a line on a scatter diagram which best fits the empirical relation between a dependent variable and an independent variable. Stepwise regression evaluates the relative importance of a set of independent variables for predicting the value of a dependent variable or for explaining the relationship of these variables in a model (Berkmen and Ryall, 1982; Krumbein and Graybill, 1965). A stepwise regression was done to assess the degree of relationship between the electrical resistivity response and the electrical conductivity of the soil represented by the soil EC values (Appendix 8) (section 2.2.5; section 4.2). The resistivity technique measures apparent resistivity, responding to the electrical conductivity of the soil which is enhanced by dissolved materials such as salts (section 2.2.5). For each of the three resistivity AB spreads (the distance between the outer AB electrodes) an R^2 value was obtained, and a regression equation developed between the dependent variable, resistivity data, and the independent variables of soil EC's and the depth to water table (Table 6.1).

The depth to water table was included in a separate regression analysis to note its effect on the R^2 value (Table 6.2). Considering that each AB electrode spread senses at different theoretical depths of investigation, it was possible to make inferences on the effects of soil EC values from different depths and of the water table on the geophysical response from electrical resistivity.

RESISTIVITY AB SPREAD	REGRESSION EQUATION WITH COEFFICIENTS AND SOIL EC VALUES FROM VARYING DEPTHS AS INDEPENDENT VARIABLES
25 METRES	Y = 23.5527 - 0.064359EC0 - 0.12586EC075 + 0.12702EC100 + 0.12935EC150 - 0.084911EC175 - 0.06507EC200 + 0.027606EC200
50 METRES	Y = 22.470609 - 0.04466EC0 - 0.24432EC050 + 0.092712EC150 - 0.065519EC175 - 0.0568EC200 + 0.05965EC225 - 0.029144EC275
70 METRES	Y = 22.623901 - 0.044344EC0 + 0.02021EC100 + 0.07701EC150 - 0.06416EC175 - 0.03856EC200 - 0.02497EC275

Table 6.1. Regression equations for the three resistivity horizontal profiling surveys. The independent variables in the models represent soil EC values, with EC0 the soil EC value at surface, EC025 the soil EC value at 0.25 metres depth, and so on to a depth of 3 metres.

RESISTIVITY AB SPREAD	R^2 REGRESSION COEFFICIENT	R^2 PLUS DEPTH TO WATER TABLE	CONFIDENCE LEVEL
25 METRES	0.71718	0.71718	99 %
50 METRES	0.70104	0.70284	99 %
70 METRES	0.46612	0.48352	99 %

Table 6.2. The R^2 values (multiple correlation squared) of the step-wise multiple regression for the 3 resistivity horizontal profiling surveys and soil EC values plus depth to water table.

The label WTAB represents the independent variable of the depth to water table (Table 6.4 and 6.5). A significance level of 0.01 was used for the regression. With both variables consisting of 46 degrees of freedom (n - 1), the resulting limiting F-value for the regression is 2.11 (Freund, 1984). The F-ratio, or variance ratio, is a statistic whose distribution measures the significance of the difference between two sample variances (Freund, 1984; Berkman and Ryall, 1982). Independent variables whose F-ratio fall below the limiting F-value established for the regression model (in this case 2.11) will not be entered into the regression model.

6.3.1. REGRESSION AT 25 METRE AB SPREAD

Resistivity data (HP 25 in Appendix 1) obtained with the 25 metre AB electrode separation yielded an R^2 value of 0.71718 (Table 6.3) after regression analysis. The variables in the model with the strongest relationship between resistivity and independent variables are soil EC values down to 2.25 metres below surface (represented by EC225, Table 6.3). The independent variable EC0 yields the best fit with an F-ratio of 27.3223 (Table 6.3). The regression model favours the variables corresponding with EC values from 0.75 to 2.25 metres depth. The independent variable of the depth to water table (WTAB) has no effect on the R^2 or the regression model.

VARIABLES IN MODEL	REGRESSION COEFFICIENTS	F-VALUES	VARIABLES NOT IN MODEL	F-VALUES
ECO	- 0.06436	27.3223	EC025	.1172
EC075	- 0.12586	12.1751	EC050	.0004
EC100	0.12702	9.7046	EC125	1.7237
EC150	0.12935	16.8525	EC250	.5184
EC175	- 0.08491	9.7644	EC275	1.1358
EC200	- 0.06507	8.2419	EC300	.5998
EC225	0.07261	12.1050	WTAB	.0129

Table 6.3. Model coefficients and the F-ratios of independent variables accepted and rejected from the model based on HP 25 data (Appendix 1).

6.3.2. REGRESSION AT 50 METRE AB SPREAD

Comparison of resistivity data from the 50 metre AB spread (HP 50, Appendix 1) to soil EC values yielded an R^2 value of 0.70104, only slightly less than that from the regression analysis for the 25 metre AB spread (Table 6.2). The independent variables with the strongest relationship between apparent resistivity and the EC variables range from EC150 to EC225. The apparent resistivity data from 50 metre AB survey should be a result of a greater depth of investigation in the soil profile than for the data from 25 metre AB survey (section 3.1.2). The regression analysis indicates that there is still a significant relationship between apparent resistivity and EC0 (Table 6.4), although less so than the relationship indicated in the regression analysis for 25 metre AB survey (Table 6.3).

The addition of the water table as an independent variable to the regression analysis increases the R^2 for the model slightly to 0.70284 (Table 6.2), but again this variable is not included in the final model as its F-ratio value of 1.6689 falls below the F-limit of 2.11 (section 6.3). The best fit for independent variables commences at EC150, but extends deeper in the soil profile to EC275.

VARIABLES IN MODEL	REGRESSION COEFFICIENT	F-VALUE	VARIABLES NOT IN MODEL	F-VALUES
EC0	- 0.04466	9.4885	EC025	.2517
EC050	- 0.02443	4.9044	EC075	.0229
EC150	- 0.09271	23.3934	EC100	.1216
EC175	- 0.06552	11.3417	EC125	.0151
EC200	- 0.05680	10.5334	EC250	.6590
EC225	0.05965	10.3796	EC300	.0067
EC275	- 0.02914	20.5972	WTAB	1.6689

Table 6.4. Model coefficients and F-values for independent variables accepted or rejected from the model based on Res 50 data.

6.3.3. REGRESSION AT 70 METRE AB SPACING

Comparison of resistivity data from the 70 metre AB spread (HP 70, Appendix 1) to soil EC data variables (Appendix 8) yielded an R^2 value of 0.46612, significantly lower than the previous regression models (Table 6.5). Again, relative to the F-values from other EC variables, EC0 still produces a strong relationship to resistivity in the regression model. The remaining independent EC variables included in the regression model are in a block, starting at EC150 and ending at EC275.

VARIABLES IN MODEL	CORRELATION COEFFICIENT	F-VALUES	VARIABLES NOT IN MODEL	F-VALUES
EC0	- 0.04434	10.1852	EC025	.0232
EC150	0.07701	8.8750	EC050	.1920
EC175	- 0.06416	6.6272	EC075	1.2312
EC200	- 0.03856	3.0685	EC100	.5102
EC250	0.02691	2.6204	EC125	.0096
EC275	- 0.02497	9.7432	EC225	2.0055
			EC300	.1689
			WTAB	1.5743

Table 6.5. Model coefficients and F-values for independent variables accepted or rejected from the model based on RES 70 data.

6.3.4. DISCUSSION OF RESULTS

Results indicate that the shallowest penetrating resistivity survey of 25 metre AB spacing, yields the best R^2 response to the soil EC variables (Table 6.1). With expanding AB arrays, and greater depth of investigation, the relationship between electrical resistivity and soil EC's begins to diminish. This suggests that the wider expanding electrode arrays are penetrating deeper into the surveyed soil profile and possibly including geo-electrical responses from outside of the soil EC investigation. This is illustrated by the fact that with each increasing AB electrode spread, the majority EC variables contributing to the model represent data obtained from greater depth (greater than EC150), as do the R^2 values. This is most noticeable with the 70 metre AB survey, which has one less independent variable in its regression model (Table 6.1).

The independent variable of the depth to the water table does not have an effect on the R^2 value of the regression for HP 25 data, but does have an effect on the regression coefficients for HP 50 and HP 70 data. In both of the latter cases with the addition of the water table variable, the R^2 value increases minimally. The water table variable was not included in any of the regression models and, as discussed by Krumbein and Graybill, this may possibly be attributed to the stepwise regression exercise itself. With stepwise regression, the strongest independent variable is initially obtained and then "held constant" statistically to identify the second strongest variable. A number of stepwise regression programs have built-in procedures to "fix" the **relative** importance of an independent variable for all subsequent stages of analysis (step by step addition of variables). This can lead to spurious results in that an independent variable that is weak in combinations of two or three variables may increase in relative importance as more variables are added to the model and vice versa (Krumbein and Graybill, 1965). This is the case with the STATGRAPHICS modelling package used, in which independent variables are checked at each stage regarding their significance to the regression model and either retained or rejected as the modelling process progresses (STATGRAPHICS, 1987).

It is also possible that the water table, due to its depth (1.8 to 3.5 metres) may only be contributing minimally the response measured by the 25 metre AB electrode spacing. The possible theoretical depths of investigation for the 25, 50, and 70 metre surveys in a homogenous situation are respectively: 2.75 to 4.25 metres, 5.5 to 8.5 metres, and 7.7 to 11.9 metres (Table 3.1). These depths are affected by subsurface layering and geo-electrical parameters. Factors such as a high electrically conductive layer near the surface will reduce the depth of investigation by effectively short circuiting current flow and limiting current penetration to deeper layers (Milsom, 1989). In the study area, the surface layer of the "soil" is unsaturated and heavily cultivated, producing a highly resistive surface layer. At a fluctuating level between approximately 2.25 to 3.75 metres below surface, within the theoretical depth of penetration of 25 metre AB survey, the water table creates a highly electrically conductive interface. A saturated "soil" zone will be even shallower than the upper water table limit of 2.25 metres. If one regards this conductive layer as an attenuating factor on depth of investigation, the 25 metre AB survey may gathering its response from the saturated "soil" and dry surface material interface. This interface will fluctuate with changing depths to water table.

The electrically conductive layer will also attenuate the depths of investigation for the 50 and 70 metre AB surveys. The 50 metre AB survey appears to penetrate to the bottom of the "soil profile" (represented by EC variables in the regression model) and into the water table. The fact that the R^2 value for HP 50 data is only slightly less than that for HP 25 data suggests that the majority of the EC variables in both regression models contribute to the geo-electrical response for both resistivity spreads. The 70 metre AB survey, having a greater depth of investigation, may be more affected by the EC variables representing the lower half of the "soil profile". A better regression analysis on resistivity data from the 70 metre spacing would require soil EC information from a greater depth than is presently available. The fact that all resistivity spreads are effected by the EC0 variable could be a reflection of the high electrical resistivity of the surface layer.

6.4. HORIZONTAL PROFILING: QUALITATIVE ASSESSMENT

The qualitative assessment of the resistivity data utilized the methods of contouring the data, as well as profiling the data by plotting the data on a graph with distance on the horizontal axis.

6.4.1. CONTOURED RESISTIVITY DATA

The data from the horizontal profiling survey was contoured (Surfer, 1990) with the aim of highlighting general trends and anomalies in the electrical resistivity data. The most noticeable trend in values for the 25, 50,(Appendix 1) and 70 metre AB spreads (Figure 6.3) is the strong resistivity high in the northeast corner of the study area. It is located largely outside the irrigation boundary, and yields the highest response from the 25 metre AB spread. The lower resistivity values occur in the southern half of the study area, which is largely under the influence of the irrigation system.

Individual anomalies of high resistivity occur also in the southern portion of the study area, and are more prevalent for the 25 and 70 metre AB spreads. The 50 metre AB spread does not yield as many anomalies, showing a more moderated contoured surface. The 70 metre AB spread yields an east-west lineation of high apparent resistivity values at a point where the land surface and water table reach topographic lows in relation to the rest of the study area (section 5.4).

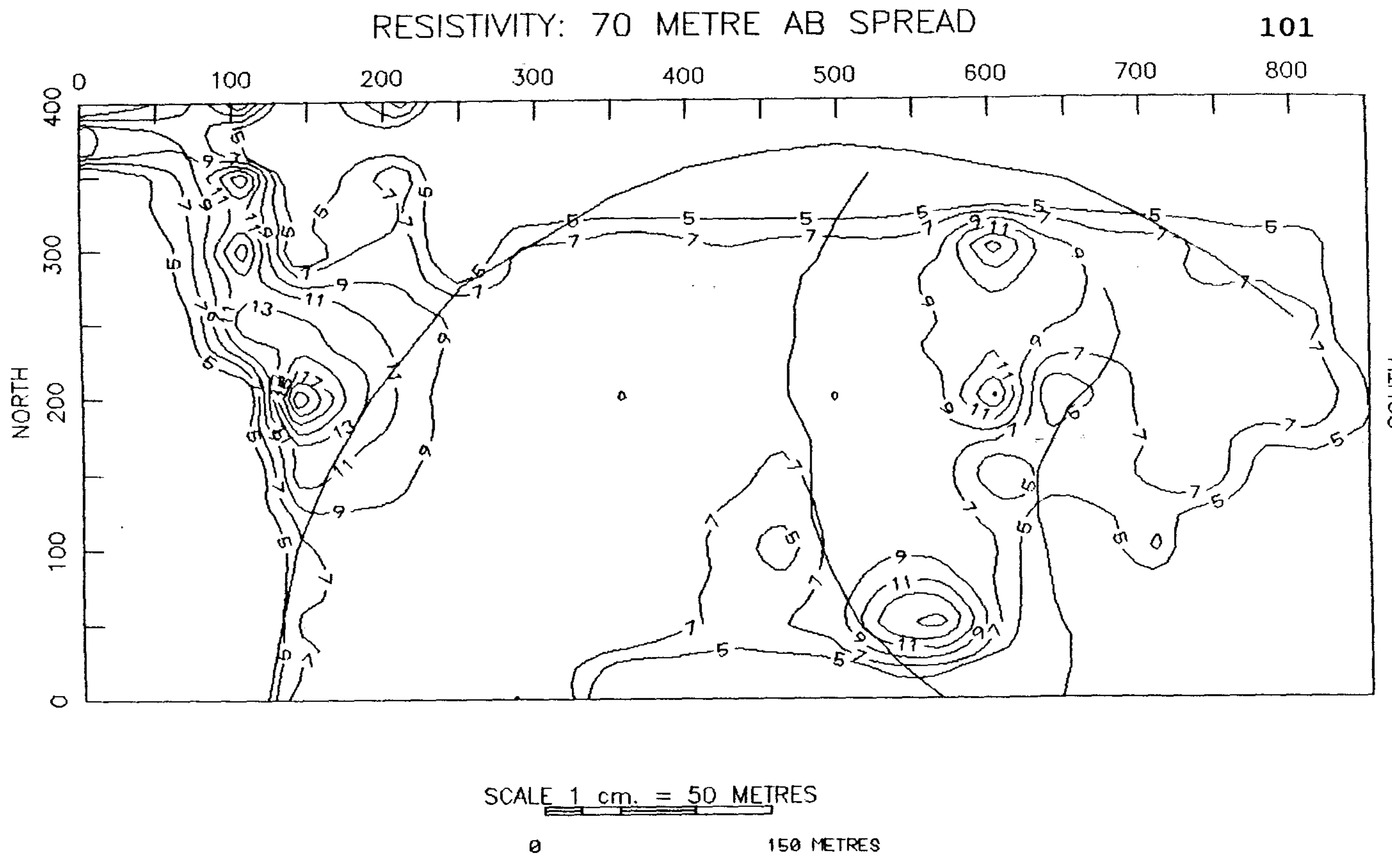


Figure 6.3. Contoured apparent resistivity data for the 70 metre AB spread with contoured values in ohm-m.

6.4.2. LINE PROFILES OF RESISTIVITY DATA

Resistivity data profile lines were plotted on a graph, using data listed in Appendix 1 from field lines commencing at and parallel to the study grid baseline, and traversing the study area from north to south (Figure 6.4). Lateral variations in resistivity become apparent, as they do on the contoured resistivity maps. These variations are depicted as a cross-section of the study area at a certain geo-electric depth and thickness. Compared to contouring of the data, line profiling yields more site specific information from which individual anomalies can be isolated. Contoured data always involves a degree of interpretation between data points (section 4.4), whereas data line profiles reflect only the actual data collected in the field. A study of the line profiles for the 70 metre AB survey illustrates the high resistivity trend that closely matches the topographical low of the ground surface and water table (section 5.4)(Figure 6.5). The 50 metre AB spread data shows fewer anomalous readings than the 25 and the 70 metre AB spreads, as is shown by a comparison of line profiles from the same area (Figure 6.6). The line for the 50 metre AB shows less fluctuation in apparent resistivity values than the 25 and 70 metre AB data line profiles.

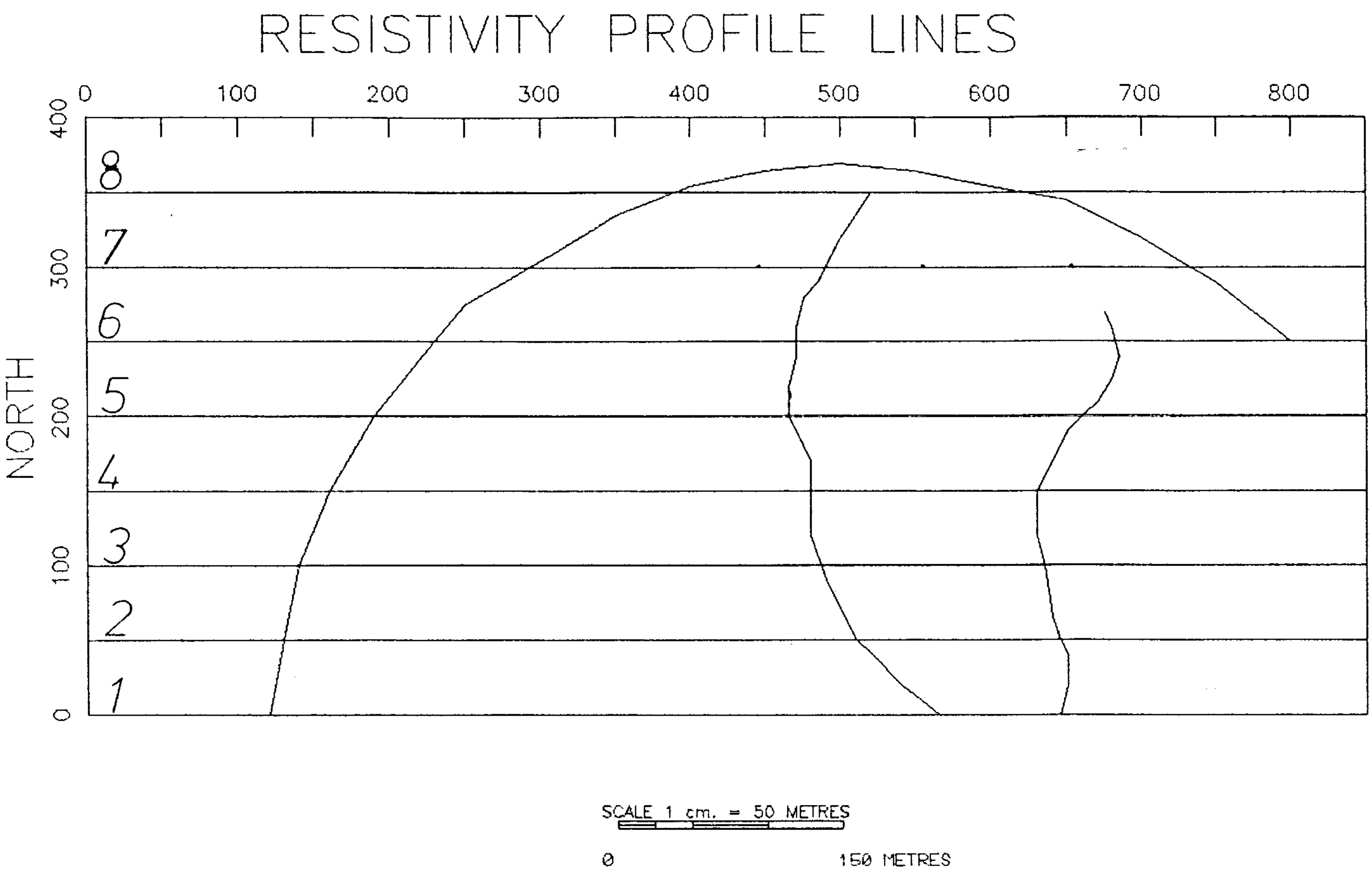
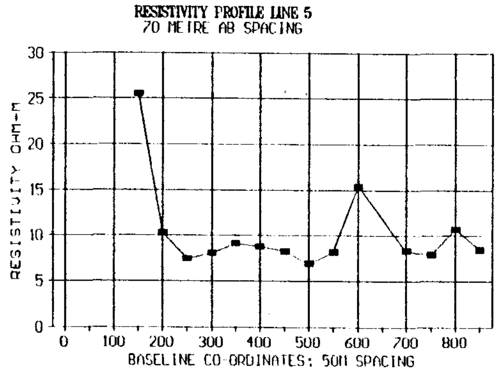
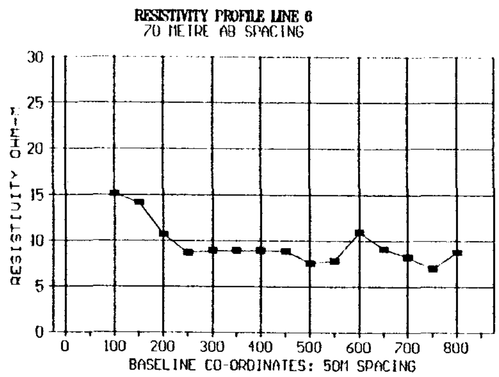


Figure 6.4. Layout of the apparent resistivity data line profiles.





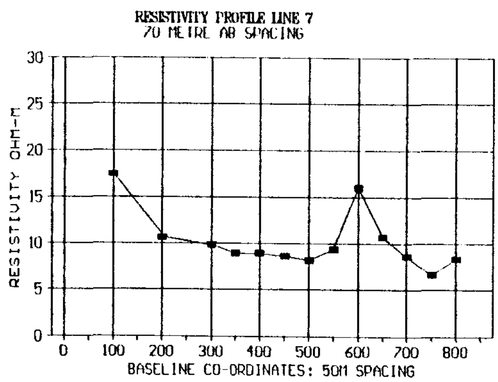


Figure 6.5. Apparent resistivity trends within data profile lines of the 70 metre AB survey. The peak at baseline co-ordinate 600 matches the topographical low.

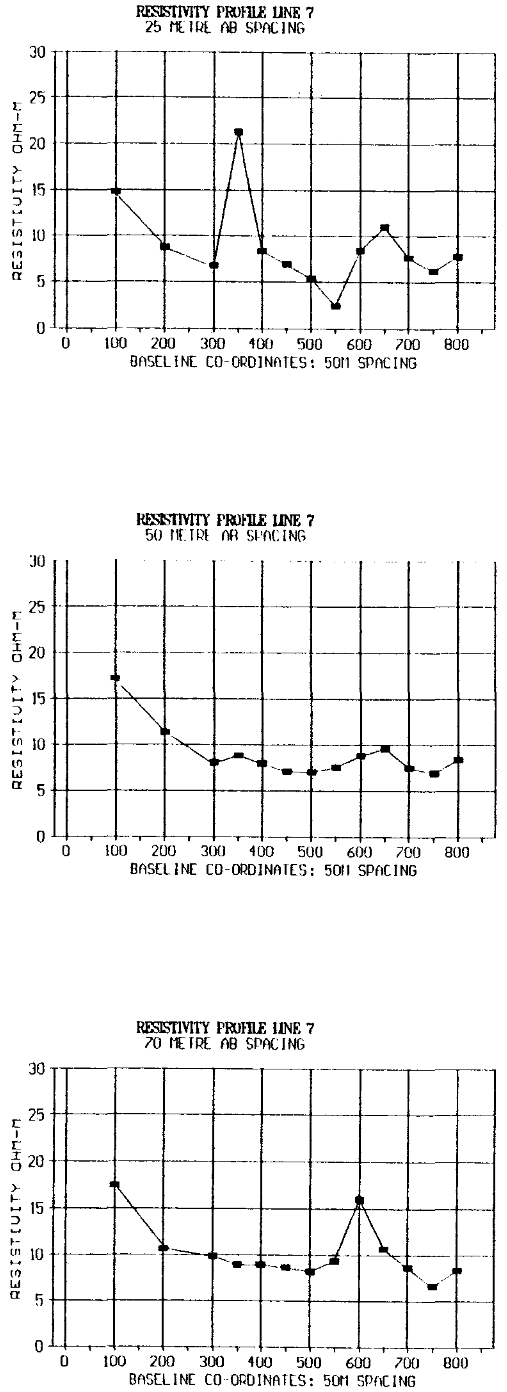


Figure 6.6. Comparison of data line profiles of a 25, 50, and 70 metre AB survey over the same area.

6.4.3. DISCUSSION OF RESULTS

The contoured resistivity data shows a high apparent resistivity trend in the region outside the irrigation boundary. This trend is strongest for the 25 metre AB survey, which measures closest to the surface. The highest anomalous values result from both the 25 and the 70 metre AB surveys. The high apparent resistivity anomalies for the 25 metre AB survey show little pattern. The 25 metre AB survey shows high apparent resistivity values within the irrigation boundary. This may be due to the heavy cultivation practice within the irrigation boundary and regular shifting of the top 1.5 metres of earth between crops (the farmer utilizes a specially designed vibrating ripper with a deeper than normal equipment capacity). A proper judgement on these anomalies would require a simultaneous soil analysis and geo-electrical survey during a period when the soil was not being disturbed by regular cultivation, as is the case outside the irrigation boundary.

The 50 metre AB survey shows a smoother response of resistivity values (compared to the 25 metre and 70 metre AB surveys) in the contoured and the profiled data (Figures 6.3 and 6.6). This suggests the bulk of the response is derived from a comparatively homogenous geo-electrical layer.

Trends of high apparent resistivity values can be seen for the 70 metre AB surveys, occurring within the low surface topographical region (Figure 5.4). VES curve layered earth models indicate a high apparent resistivity at a minimum depth of approximately 12 metres below surface, which local geology

(Figure 6.1) indicates is the cobblestone and bedrock interface. It is possible that the topographical low in the ground surface has brought the 70 metre AB depth of investigation close enough to the more resistive bedrock to produce the trend of higher apparent resistivity values in that region.

6.5. CONCLUSIONS

Modelled vertical electrical soundings produced a layered approximation to the geology. This was confirmed by the 1991 borehole logs (Figure 6.1). According to the regression model, the soil EC survey can be a useful technique for assessing geophysical data at shallow depths. For the study area, electrical resistivity at the 25 and 50 metre spreads appear to respond to shallow subsurface soil EC conditions, which in this case were measured to a depth of 3 metres. The regression analyses suggest that the 70 metre AB survey may be sensing below the 3 metre soil survey profile. It should be noted that the resistivity being measured is the apparent resistivity, and for each new geo-electrical layer penetrated (in this case the water table and a bedrock layer) the difference between apparent resistivity and true resistivity (as well as soil EC values) becomes increasingly greater (section 3.3.1).

The contoured data indicates that irrigation is a factor in the electrical resistivity response with the highest apparent resistivity values occurring outside the irrigation boundary. The area outside the irrigation boundary may be less electrically conductive due to less water in the surface sediments. Also, the non-irrigated area is not subject to a semi-arid irrigation environment that can produce saline conditions (section 2.2.5).

The 70 metre AB survey is the only survey that indicates a subsurface lineation of lower apparent resistivity values. These lineations of lower values are in the region where the air photo indicates the presence of a buried stream channel (section 4.3.1 and Figure 6.3). VES models and borehole information suggest that the 70 metre AB survey may be responding to the buried stream channel. The shallower sensing 50 metre AB electrode spread did not produce an anomalous response in the area of the buried alluvial channel. This suggests that the bulk of the response for the 50 metre AB survey originates from earth materials above the buried stream channel.

CHAPTER 7. ELECTROMAGNETICS ASSESSMENT

INTRODUCTION

The Electromagnetic Horizontal Profiling technique is assessed and methods of Electromagnetic (EM) data interpretation are discussed in this chapter. The Vertical Loop orientation EM data is given preference over the Horizontal Loop orientation data, as the depth of investigation of the Vertical Loop is shallower and closer to the depth of the physical features being studied.

7.1. METHODS OF INTERPRETATION

Telford *et al* (1982) state that the method of data interpretation more commonly used for EM is a comparison of EM field data with a measured response of the EM technique to models simulating geological formations such as dykes or other linear features, dipping beds and ore bodies (Telford *et al*, 1982). Computer models are also available for multi-layered earth interpretations, but due to the complicated nature of EM fields, they are limited to simple geometric shapes and layered earth situations (Corner and Antoine, 1989; Weigmans, 1990).

Cameron *et al* (1980) used regression analyses to compare soil EC profiles of 0.36 metres depth to apparent electrical conductivity from shallow EM surveys. The EM equipment used in that particular survey consisted of the EM-38 and EM-31 terrain conductivity meters (Geonics Ltd.). These are similar in design to the EM-34 terrain conductivity meter and sense to a maximum of 1.2 and 6 metres depth respectively (Cameron *et al*, 1980). The EM-34, however is not designed to pick up vertical variations of conductivity at depth, but provides information that enhances other vertical assessment techniques (such as DC resistivity) with its sensitivity to lateral variations (McNeil, 1980)(section 3.2.3).

7.2. QUANTITATIVE ASSESSMENT OF EM HORIZONTAL PROFILING DATA

The EM data (Appendix 2) shows that the apparent electrical conductivity values decrease with a greater depth of investigation, with the Horizontal Loop values being less than Vertical Loop values (section 3.2.3). The range of conductivity values for each coil separation (anisotropy causes lateral variations in electrical conductivity) also decreases with depth. This indicates that the electrical conductivity of the earth materials becomes more homogenous with depth.

The statistical range of apparent conductivities between the EM 20 metre Horizontal Loop coil separation (EM20H) and the EM 40 metre Vertical Loop coil separation (EM40V) are similar (Table 7.1). Values of electrical conductivity for EM20H are slightly lower. This suggests that both surveys may be responding to a similar geo-electrical situation and may be measuring to similar depths (approximately 30 metres)(Table 3.2). This is in keeping with theory and design specifications of the EM-34 (Weigmans, 1990)(section 3.2.3).

SAMPLE STATISTIC	EM10V	EM20V	EM40V	EM10H	EM20H	EM40H
MINIMUM	31	42	35	33	16	8
MAXIMUM	137	125	100	135	82	60
RANGE	106	83	65	102	66	52

Table 7.1. Statistical summary of apparent conductivity values for each EM-34 coil separation (eg. 10V = 10 metre coil separation/vertical loop, 40H = 40 metre coil separation horizontal loop).

A stepwise multiple regression was performed between the EM apparent conductivity values and the soil EC values plus the depth to water table. This was done to assess the degree of relationship between the EM-34 response and "soil" salinity (Table 7.2)(section 4.2). It is also a potential assessment of the validity of the regression technique for this analysis of EM data, bearing in mind that greater depths of investigation are occurring for the EM survey (sections 3.1.2. and 3.2.3.)
As dissolved salts are an important factor in determining electrical conductivity of the soil (section 2.2.5), the regression is an attempt to quantify the EM-34 response to soil EC values acquired from the "soil" survey. A significance level of 0.01 was used for the regression. With both variables consisting of 46 degrees of freedom (n-1), the resulting limiting F-value for the regression is 2.11.

EM COIL SPEPARATION AND ORIENTATION	R^2	CONFIDENCE LEVEL
EM10V	0.64830	99%
EM20V	0.6685	99%
EM40V	0.71205	99%
EM10H	0.49903	99%
EM20H	0.41551	99%
EM40H	0.23032	99%

Table 7.2. The R^2 values (multiple correlation squared) of the step-wise multiple regression between the 6 EM (electromagnetic) horizontal profiling surveys and the soil EC values plus depth to water table.

The EM-34 instrument used in this survey measures to greater depths of investigation than the Electrical Resistivity survey, ranging from 7.5 to 60 metres below surface (section 3.2.3). The EM-34 instrument response is integrated over the total depth of the survey and small variations at the surface can become lost in the overall response from the subsurface (Stewart, 1982). One must be careful in drawing conclusions from most of the regression results with the possible exception of the EM 10 Vertical Loop data (Table 7.2) which is theoretically the shallowest penetrating EM Loop orientation. The "soil" EC data (Appendix 8) is taken from a profile that is 3 metres deep and is less than half of the shallowest depth of investigation for the EM-34 of 7.5 metres (Table 3.2). This same "soils" data in regression analysis with data from 40 metre vertical loop EM survey (EM40V)(Appendix 2) indicates a strong relationship with an EM survey penetrating to a depth of 30 metres (Table 3.2). If on considers the skin effect of an electrically conductive layer near surface (section 3.2.2) as discussed in section 6.3.4, the possibility of the depth of investigation of the EM survey being attenuated does arise. However it is unlikely that this attenuation is enough to allow for a strong relationship between the EM20V or EM40V variables and "soil" EC values. This leaves the validity of the multiple regression analysis for the EM survey in question.

A possible explanation for the high regression coefficient values between the deeper sensing EM values and shallow "soil" EC variables (Table 7.2) is that the earth materials below the "soil" EC profile are geo-electrically homogenous. This situation would limit any fluctuations in apparent electrical conductivity to near-surface layers that correspond to the "soil" EC profile. Information on subsurface homogeneity is only available from the sedimentary analyses of the three 1987 borehole logs (Figure 5.3). The borehole logs depict definite sedimentary horizons and variations in clay content between the regions of the boreholes. Vertical as well as lateral geological variations occur. Whether a geo-electrical homogeneity exists or not below the soil EC profile can not be verified by existing borehole information, the soil EC data collected, or without more detailed geophysical studies such as borehole geophysics.

EM VARIABLE	REGRESSION EQUATION WITH COEFFICIENTS, SOIL EC VALUES FROM VARYING DEPTHS AND DEPTH TO WATER TABLE AS INDEPENDENT VARIABLES
EM10V	Y = 145.651363 - 29.0653**WTAB** -0.27266**EC100** + 0.31236**EC125** - 0.26166**EC150** + 0.12664**EC225** + 0.23070**EC300**

Table 7.3. The regression equation for the EM10V horizontal profiling survey.The independent variables in the model represent soil EC values, with EC100 being the soil EC value at a depth of 1 metre and so on to a depth of 3 metres. The label WTAB represents the independent variable of the depth to water table.

7.3. QUALITATIVE ASSESSMENT OF EM DATA

There are two main methods used for presenting EM apparent conductivity data. These are the contouring of the EM data and data line profiling, which involves plotting the data on a graph with distance on the horizontal axis (Figure 7.1).

7.3.1. CONTOURED EM DATA

Using terrain mapping computer software (Surfer, 1990), the EM apparent conductivity data was contoured to highlight general trends and specific anomalies in the data that might require closer investigation.

A common trend for all EM coil separations can be seen in the southern portion of the study area where the highest apparent conductivities were measured. The north eastern corner, which occurs outside the irrigation boundary, shows a definite drop in apparent conductivity. With the increase in depth of investigation, the decrease in conductivity becomes attenuated, suggesting a greater lateral homogeneity with increasing depth (Figure 7.1). In the southern half of the study area there are anomalous conductivity lows in the region where the buried stream channel appears on the air photo (section 4.3.1).

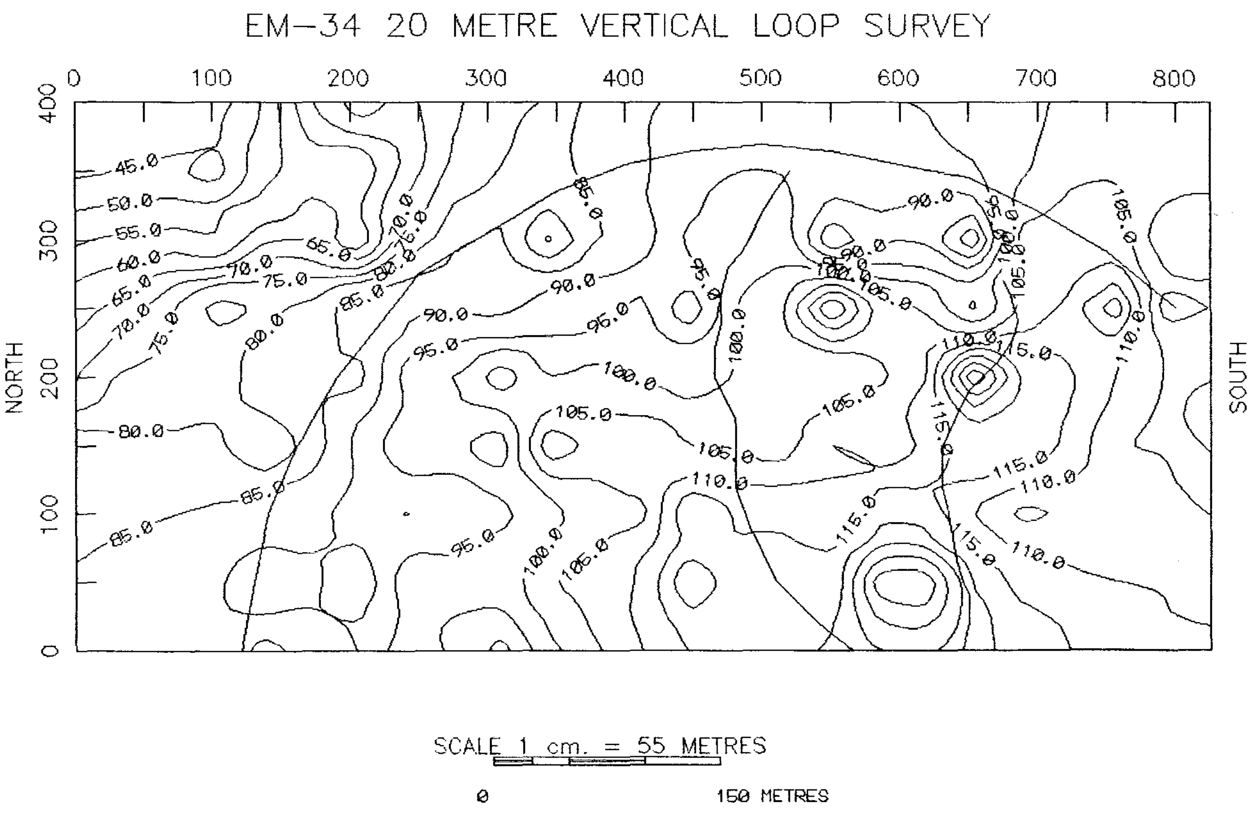
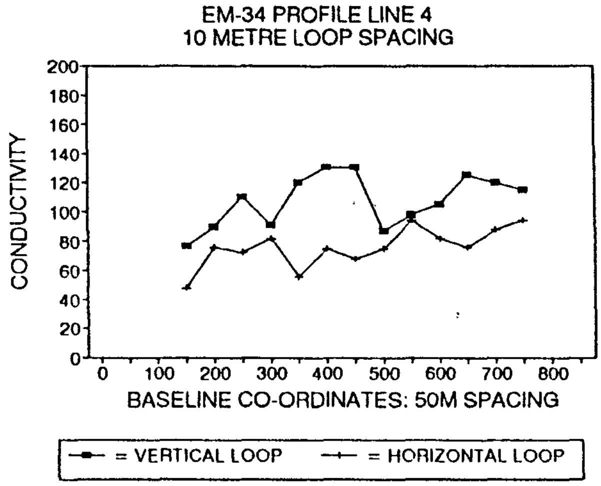
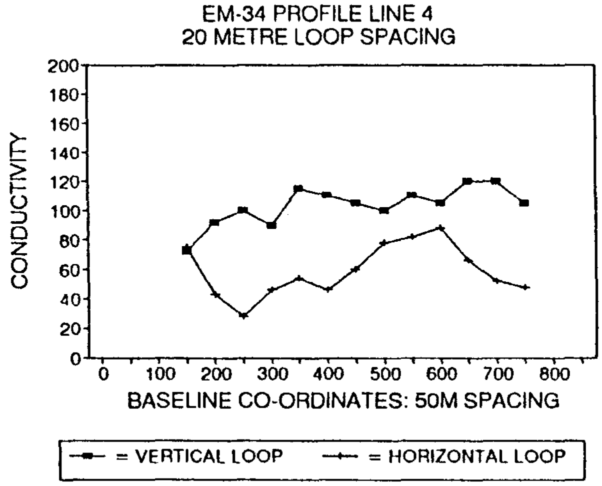


Figure 7.1. Contoured EM data (20 metre vertical loop) illustrating apparent conductivity trends with contoured values in mmhos/metre.

7.3.2. EM DATA LINE PROFILES

As with the electrical resistivity, data line profiles were drawn of the EM-34 data (Appendix 5) as shown in Figure 7.2. Profile lines were plotted parallel to the survey grid baseline, with the same layout used for resistivity data line profiles (section 6.4.2). The profile lines isolate the data points, showing site specific changes and the change in response for the increased coil separations. Apparent conductivity values for the Horizontal Loop configuration tend to be lower than for the Vertical Loop configuration. Also, EM values at the 40 metre coil separation (deepest EM penetration) are lower than those for the shallower EM profiles. This indicates decreasing conductivity with increasing depth of investigation with the EM-34. The data line profiles from the deeper sensing EM techniques also show that with increasing depth there is less variation (a greater homogeneity) in apparent conductivity values (Figure 7.2).





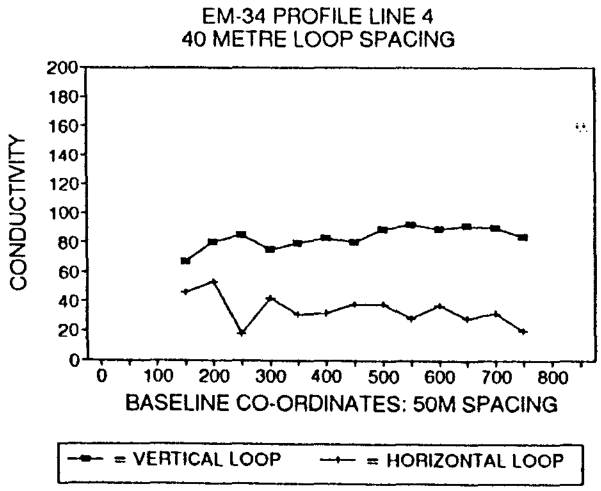


Figure 7.2. Data line profiles of EM apparent conductivity illustrating the different responses between vertical and horizontal coil orientation, and different coil separations.

7.4. BOREHOLE CONFIRMATION OF EM DATA INTERPRETATION

Soil EC's were only collected to a depth of 3 metres (due to equipment limitations), whereas the shallowest theoretical depth of investigation for the EM-34 is 7.5 metres. A deeper soil profile, or shallower sensing EM equipment would provide a more comprehensive EM technique assessment in this study area. Adequate soil auguring equipment for a deeper soil profile was not available although the Department of Water Affairs drilled holes in the study area. The resulting borehole logs (Figure 6.1) were used to confirm the interpretation of the EM-34 electrical conductivity data.

EM line profiles were studied for their response in the region of the study area where the buried stream channel was expected to be intersected, specifically along data line profiles 6 and 7 (section 6.4.2). Both profile lines showed apparent conductivity lows in the region of the baseline co-ordinates 600 and 650 (Figures 7.3 and 7.4). Three sites were selected and drilled along profile line 7, two at points of low apparent conductivity and one at a point of high apparent conductivity in the vicinity of the buried stream channel (Figure 7.5).

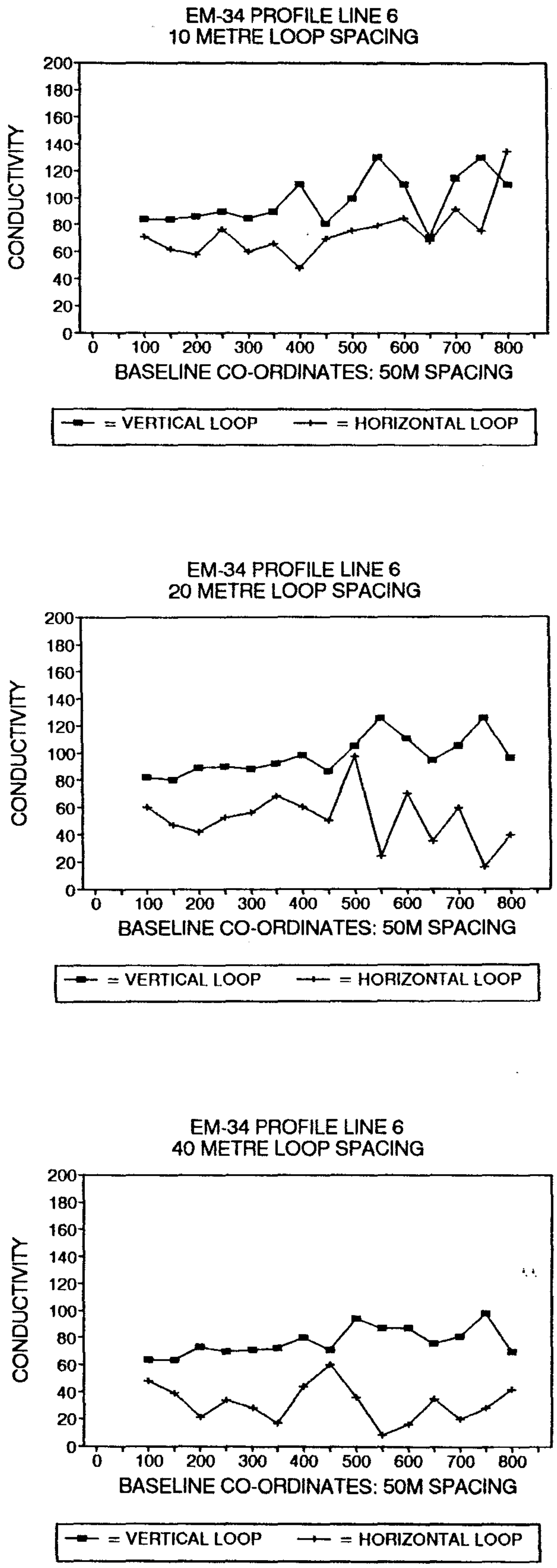


Figure 7.3. Data line profiles for line 6 showing apparent conductivity lows at baseline co-ordinate 650.

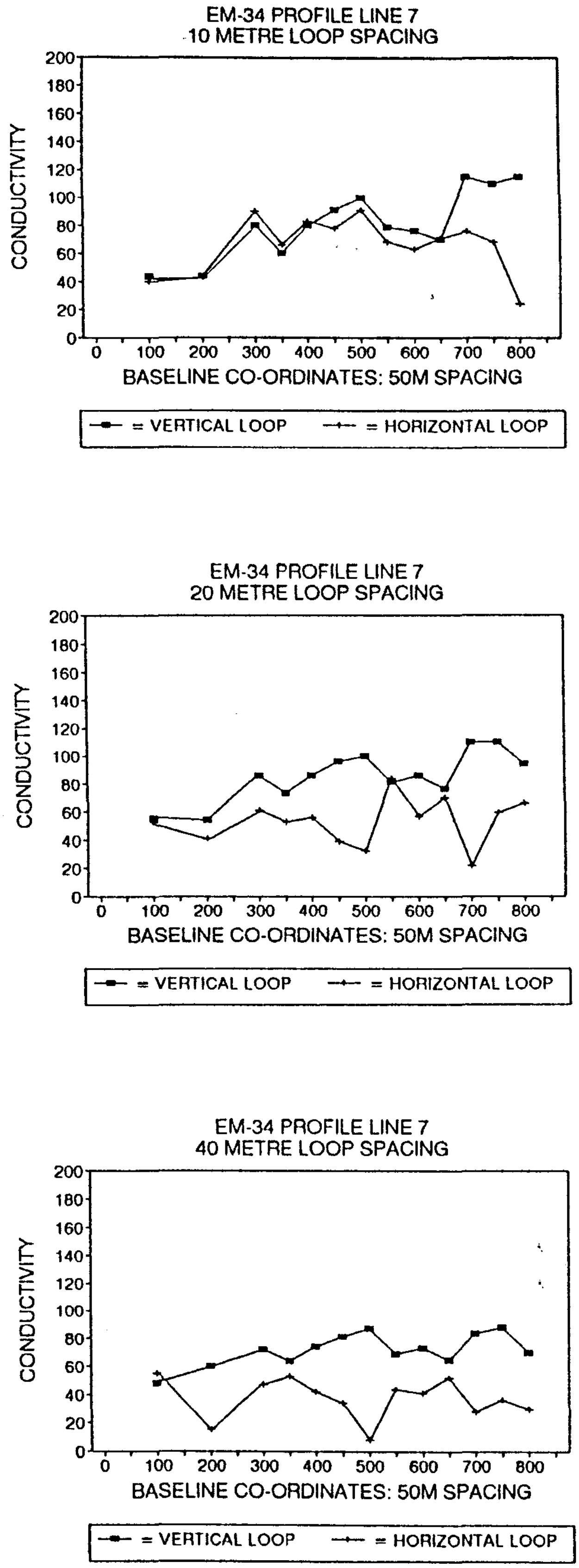


Figure 7.4. Data line profiles for line 7 showing apparent conductivity lows for baseline co-ordinates 600 and 650.

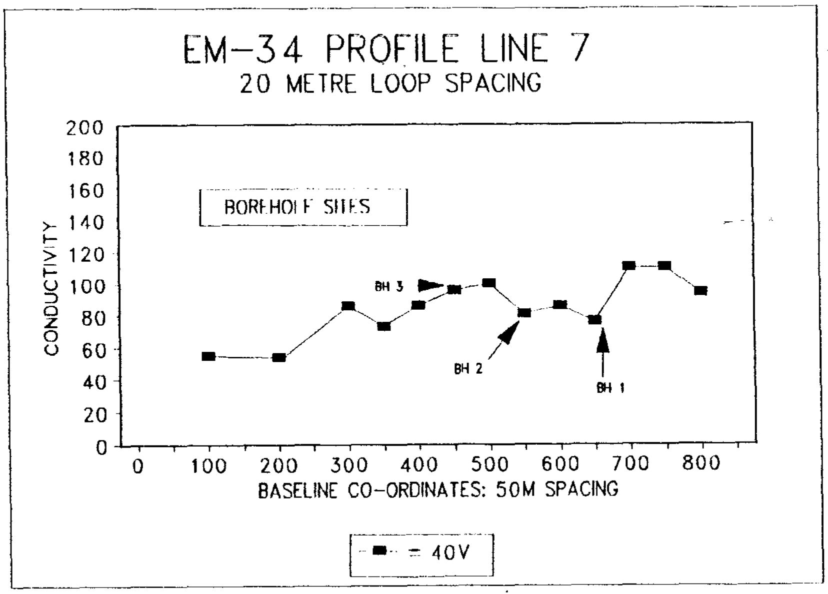


Figure 7.5. Borehole sites established on data profile line 7.

It was anticipated that the buried channel would be intersected at an electrical conductivity low. This is the expected electromagnetic response to the less saline water in an area of quicker groundwater flow within the coarser alluvial channel material (sections 1.3, 2.2.3, and 2.2.4). An intersection occurred with borehole number 2 (BH 2) on data line profile 7. The borehole log from BH 2 (Figure 6.1) shows a 1 metre thick deposit of fluvial sands and rounded pebbles located approximately 3 metres below surface, overlying a cobblestone layer. The remaining 2 borehole logs do not show an intersection of this deposit overlying a cobblestone layer.

7.5. DISCUSSION

As previously discussed, assessment of EM data is largely qualitative, in this case utilizing contoured data and data line profiles. It is difficult to explain the strong R^2values for the correlation between EM apparent conductivity values and soil electrical conductivity (EC) values. One possible exception is the EM 10 metre Vertical Loop response. This shallowest penetrating EM, according to the regression model, appears to respond strongly to the water table, which is from 2.5 to 3 metres below surface in the irrigated zone. Strong R^2 values for EM20V and EM40V may be a result of fluctuations in surface soil salinities or in variations in the depth to water table, but this was not confirmed. The 1991 drilling programme, which intersected the buried stream channel, confirmed the ability of the EM technique in revealing the buried channel (Figure 6.1).

7.6. CONCLUSIONS

Results from the Horizontal Profiling survey technique, identifying lateral variations in apparent conductivity, aided in siting a borehole intersection of the buried stream channel. One of the apparent conductivity low values from the data line profile chosen for a drill site (Figure 7.5, borehole 1) did not intersect channel. This may be a response of the EM-34 to lateral variations in electrical conductivity as the transmitter and receiver approach the target.

The depths of investigation for EM-34 theoretically preclude any strong relationship between the EM response and the soil EC data indicated by the R^2 values from the regression analyses. With the EM-34, the majority of the response is below the soil EC profile depth of 3 metres. Theoretically, only the EM10V response should be influenced to any large degree by the first 3 metres below the surface. A portion of the EM10V response is likely to have been generated by the presence of the water table, which changes the surface "soil" profile from a layer of low electrical conductivity to a layer of high electrical conductivity and creates a new geo-electrical layer. Considering the possibility of attenuation of depth of investigation (sections 3.2.2. and 7.2), there may be a direct relationship between the 10 metre vertical loop EM and the individual soil EC values.

CHAPTER 8. CONCLUSIONS

RESULTS

The purpose of the study was to evaluate geophysical techniques that can be used to delineate buried stream channels, and produced the following results:

1. The assessment of geophysical techniques was achieved with the intersection of the buried stream channel by the boreholes drilled in 1991 (Figure 6.1). The siting of the boreholes was based on information from the interpretation of electromagnetics data (Figure 7.5) in conjunction with electrical resistivity data (Figure 6.5)

2. Although the geophysical techniques of electrical resistivity and of electromagnetics respond to the electrical conductivity of earth materials, hydrogeological conditions can favour one technique over another.

3. Quantitative comparison between electrical resistivity and electromagnetics may be misleading because:

a) The techniques vary considerably in depth of investigation, with a theoretical maximum of 60 metres for the EM-34 compared to a theoretical maximum of 8 to 12 metres for the electrical resistivity survey.

b) The physical principles behind the techniques are different. Electrical resistivity measures a response to electrical current expanding radially below surface from point electrodes on surface. Apparent resistivity of the earth material is measured, and the depth of investigation cannot be assumed from electrode spacing alone. The EM technique generates an electromagnetic field that causes secondary electromagnetic fields to be generated by subsurface electrical conductors. The response generated by an electrical conductor is measured, and is not affected by any electrically resistive nature of earth materials. For the EM-34 terrain conductivity metre, the depth of investigation is closely predetermined by coil geometry and signal frequencies.

4. The Regression analysis of soil EC values and electrical resistivity indicates that

a) A strong relationship exists between the shallower 25 and 50 metre AB spread surveys and the soil EC's to a depth of 3 metres.

b) The 70 metre AB depth of investigation is sensing below the 3 metre soil EC profiles. Nevertheless, because the geo-electrical phenomenon being measured is apparent resistivity and not true resistivity, a direct relationship to soil EC values should not be made unless the subsurface is geo-electrically homogenous. When the addition of geo-electrical factors such as the water table, or changes in sedimentary texture and material are added to the geohydrological environment, the difference between apparent resistivity and true resistivity becomes greater, lessening the validity of any direct comparisons between apparent resistivity and actual soil EC values.

6. Quantitative comparison, such as regression analysis between apparent conductivity and soil EC values to a depth of 3 metres, cannot be validated with the data collected due to the depths of investigation of the EM-34. The shallowest sensing EM-34 survey is more likely to respond to the presence of the water table rather than to any individual soil EC values unless, as with electrical resistivity, homogeneity of the subsurface can be shown.

Qualitative portrayal of electrical resistivity data and the EM data in the form of data line profiles successfully indicated the location of the buried stream channel, as proved by a subsequent drilling program that located the channel at the position indicated by the data portrayal. The depth of intersection of the buried channel suggests that an attenuation to the depth of investigation of the geophysical survey is occurring.

LIMITATIONS OF THE STUDY

The main limiting factors in the study are the shallow depth of the soil survey and the limited number of boreholes available. Information acquired from deeper soil profiles would provide more data for a better quantitative comparison between soil EC values and geophysical response values. Deeper soil profiles would also give more insight on the degree of homogeneity of the subsurface. Additional boreholes could contribute similar information, as well as produce a more detailed delineation of the buried stream channel.

SUGGESTIONS FOR FUTURE RESEARCH

Possible future work could include a more extensive soil EC survey. The results of such a survey might better explain the relationship suggested by regression analyses between soil EC's and the geophysical responses. Similarly, shallower sensing electromagnetic techniques and a shallower electrical resistivity survey might also better define this apparent relationship. A followup borehole geophysics survey would also enhance understanding of the geo-electrical layered earth situation.

CONCLUSIONS

In conclusion, both the EM-34 and electrical resistivity proved to be valid techniques for the delineation of the buried stream channel in this particular geo-electrical environment. With regards to electrical resistivity, the vertical electrical soundings, in conjunction with geological information, were useful for gaining an understanding of the subsurface geo-electrical environment. The geological information acted as a control on the geophysical information, from which results could be modelled and judgements could be made on survey depths of investigation.

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APPENDICES

APPENDIX 1.

ELECTRICAL RESISTIVITY DATA FROM THE HORIZONTAL PROFILING SURVEY.

x-axis	y-axis	HP25		HP50		HP70
0.00	0.00	____	____	____	____	____
50.00	0.00	____	____	____	____	____
100.00	0.00	____	____	____	____	____
150.00	0.00	10.30	____	8.55	____	9.62
200.00	0.00	8.12	____	7.28	____	8.32
250.00	0.00	7.74	____	7.53	____	8.16
300.00	0.00	9.53	____	9.21	____	9.99
350.00	0.00	____	____	____	____	____
400.00	0.00	____	____	____	____	____
450.00	0.00	____	____	____	____	____
500.00	0.00	____	____	____	____	____
550.00	0.00	____	____	____	____	____
600.00	0.00	____	____	____	____	____
650.00	0.00	____	____	____	____	____
700.00	0.00	____	____	____	____	____
750.00	0.00	____	____	____	____	____
800.00	0.00	____	____	____	____	____
850.00	0.00	____	____	____	____	____
0.00	50.00	____	____	____	____	____
50.00	50.00	____	____	____	____	____
100.00	50.00	____	____	____	____	____
150.00	50.00	9.66	____	7.49	____	7.74
200.00	50.00	10.24	____	7.94	____	8.90
250.00	50.00	8.36	____	8.00	____	8.57
300.00	50.00	7.25	____	7.24	____	8.48
350.00	50.00	6.93	____	8.39	____	8.94
400.00	50.00	6.05	____	6.94	____	8.42
450.00	50.00	5.42	____	6.15	____	7.28
500.00	50.00	5.48	____	6.68	____	8.16
550.00	50.00	16.75	____	20.45	____	23.66
600.00	50.00	4.33	____	5.62	____	7.50
650.00	50.00	____	____	____	____	____
700.00	50.00	____	____	____	____	____
750.00	50.00	____	____	____	____	____
800.00	50.00	____	____	____	____	____
850.00	50.00	____	____	____	____	____
0.00	100.00	____	____	____	____	____
50.00	100.00	____	____	____	____	____
100.00	100.00	____	____	____	____	____
150.00	100.00	11.25	____	9.45	____	6.86
200.00	100.00	10.09	____	8.04	____	8.52
250.00	100.00	9.07	____	7.28	____	8.20
300.00	100.00	7.18	____	7.22	____	7.96

x-axis	y-axis	HP25		HP50		HP70
350.00	100.00	7.15		7.54		7.87
400.00	100.00	6.86		7.19		8.18
450.00	100.00	4.96		6.16		2.59
500.00	100.00	6.23		6.38		8.00
550.00	100.00	6.81		6.27		7.53
600.00	100.00	5.56		6.21		7.11
650.00	100.00	5.44		6.01		0.90
700.00	100.00	6.73		7.84		8.31
750.00	100.00					
800.00	100.00					
850.00	100.00					
0.00	150.00					
50.00	150.00					
100.00	150.00					
150.00	150.00	13.49		12.54		12.98
200.00	150.00	7.89		8.65		9.17
250.00	150.00	7.95		6.62		7.38
300.00	150.00	7.87		7.21		8.45
350.00	150.00	5.66		7.42		8.42
400.00	150.00	5.50		6.34		8.39
450.00	150.00	5.14		5.34		6.53
500.00	150.00	7.37		7.28		7.72
550.00	150.00	6.97		7.37		8.56
600.00	150.00	6.20		6.49		3.39
650.00	150.00	5.49		6.60		5.79
700.00	150.00	5.65		6.68		7.87
750.00	150.00	6.07		7.93		9.15
800.00	150.00					
850.00	150.00					
0.00	200.00					
50.00	200.00					
100.00	200.00					
150.00	200.00	10.48		11.43		25.50
200.00	200.00	8.91		9.31		10.20
250.00	200.00	6.88		7.65		7.40
300.00	200.00	6.07		7.10		8.03
350.00	200.00	5.25		7.52		9.05
400.00	200.00	7.46		8.06		8.74
450.00	200.00	6.52		7.06		8.21
500.00	200.00	6.03		6.25		6.89
550.00	200.00	6.42		7.29		8.18
600.00	200.00	6.59		7.09		15.38
650.00	200.00	6.29		7.80		0.24

x-axis	y-axis	HP25		HP50		HP70
150.00	350.00	—	—	—	—	—
200.00	350.00	15.52	—	13.32	—	12.88
250.00	350.00	—	—	—	—	—
300.00	350.00	—	—	—	—	—
350.00	350.00	—	—	—	—	—
400.00	350.00	—	—	—	—	—
450.00	350.00	—	—	—	—	—
500.00	350.00	—	—	—	—	—
550.00	350.00	—	—	—	—	—
600.00	350.00	—	—	—	—	—
650.00	350.00	—	—	—	—	—
700.00	350.00	—	—	—	—	—
750.00	350.00	—	—	—	—	—
800.00	350.00	—	—	—	—	—
850.00	350.00	—	—	—	—	—
0.00	375.00	24.14	—	20.12	—	15.95
50.00	375.00	27.10	—	17.03	—	17.86
100.00	375.00	—	—	—	—	—
150.00	375.00	—	—	—	—	—
200.00	375.00	—	—	—	—	—
250.00	375.00	—	—	—	—	—
300.00	375.00	—	—	—	—	—
350.00	375.00	—	—	—	—	—
400.00	375.00	—	—	—	—	—
450.00	375.00	—	—	—	—	—
500.00	375.00	—	—	—	—	—
550.00	375.00	—	—	—	—	—
600.00	375.00	—	—	—	—	—
650.00	375.00	—	—	—	—	—
700.00	375.00	—	—	—	—	—
750.00	375.00	—	—	—	—	—
800.00	375.00	—	—	—	—	—
850.00	375.00	—	—	—	—	—
0.00	400.00	—	—	—	—	—
50.00	400.00	—	—	—	—	—
100.00	400.00	29.33	—	20.51	—	14.17
150.00	400.00				—	—
200.00	400.00	24.15	—	15.95	—	15.15
250.00	400.00	—	—	—	—	—
300.00	400.00	—	—	—	—	—
350.00	400.00	—	—	—	—	—
400.00	400.00	—	—	—	—	—
450.00	400.00	—	—	—	—	—

APPENDIX 2.

ELECTROMAGNETIC DATA ACQUIRED FROM THE EM-34 HORIZONTAL PROFILING SURVEY.

x-axis	y-axis	10V	10H	20V	20H	40V	40H
0	0						
50	0						
100	0						
150	0	77	74	82	77	73	54
200	0	82	71	90	72	82	36
250	0	94	77	100	64	91	41
300	0	80	49	87	69	77	49
350	0						
400	0						
450	0						
500	0						
550	0						
600	0						
650	0						
700	0						
750	0						
800	0						
850	0						
0	50						
50	50						
100	50						
150	50	84	90	97	78	88	46
200	50	78	77	85	40	80	37
250	50	91	70	100	70	85	40
300	50	105	60	96	50	82	49
350	50	108	79	105	50	82	21
400	50	130	50	110	47	86	33
450	50	137	81	125	38	91	14
500	50	120	74	115	70	94	30
550	50	110	97	115	74	60	48
600	50	145	77	150	10	80	30
650	50						
700	50						
750	50						
800	50						
850	50						
0	100						
50	100						
100	100						
150	100	63	64	87	75	79	50
200	100	83	57	92	64	84	34
250	100	93	41	89	48	77	55
300	100	92	59	93	40	75	26

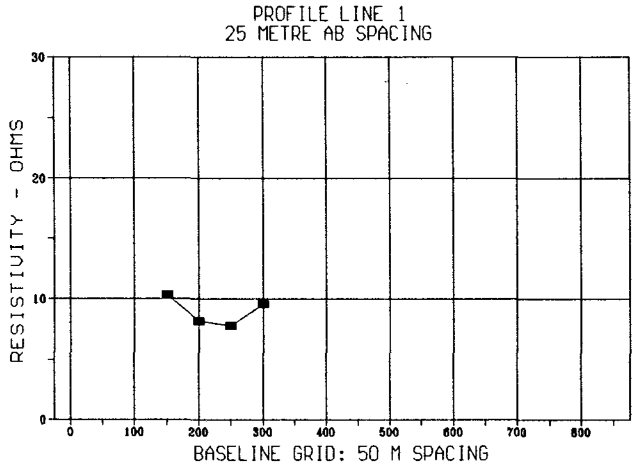
x-axis	y-axis	10V	10H	20V	20H	40V	40H
350	100	94	82	98	52	78	24
400	100	115	49	100	42	89	31
450	100	115	52	120	78	92	60
500	100	110	48	115	42	94	40
550	100	94	87	110	80	95	42
600	100	115	69	120	73	100	52
650	100	115	88	110	54	89	23
700	100	110	54	100	32	79	40
750	100						
800	100						
850	100						
0	150						
50	150						
100	150						
150	150	77	48	72	75	67	46
200	150	90	76	92	43	80	53
250	150	110	72	100	28	85	18
300	150	91	82	90	46	75	42
350	150	120	56	115	54	79	31
400	150	130	75	110	46	83	32
450	150	130	68	105	60	80	38
500	150	87	75	100	78	89	38
550	150	98	94	110	82	92	28
600	150	105	82	105	88	89	37
650	150	125	76	120	66	91	28
700	150	120	88	120	52	90	32
750	150	115	94	105	48	84	20
800	150						
850	150						
0	200						
50	200						
100	200	74	68	76	32	58	24
150	200	97	60	86	35	62	16
200	200	97	39	83	56	73	34
250	200	115	59	98	41	75	28
300	200	108	78	110	40	79	15
350	200	110	78	100	72	81	20
400	200	110	98	100	42	83	38
450	200	110	78	98	55	82	44
500	200	73	64	100	55	87	21
550	200	110	63	100	53	86	28
600	200	97	90	100	63	80	28
650	200	110	84	140	56	87	35

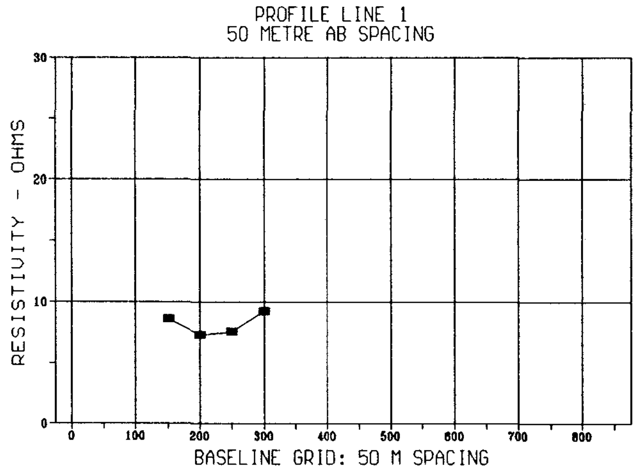
x-axis	y-axis	10V	10H	20V	20H	40V	40H
700	200	110	87	120	50	89	11
750	200	110	57	110	46	87	45
800	200	110	60	105	81	82	24
825	175	120	62	94	14	77	50
0	250						
50	250						
100	250	84	71	82	60	64	48
150	250	84	62	80	47	64	39
200	250	86	58	89	42	73	21
250	250	90	77	90	52	70	34
300	250	85	60	88	56	71	28
350	250	90	66	92	68	72	17
400	250	110	48	98	60	80	44
450	250	81	70	86	50	71	60
500	250	100	76	105	97	94	36
550	250	130	79	125	24	87	8
600	250	110	85	110	70	87	16
650	250	71	68	94	35	76	35
700	250	115	92	105	59	81	20
750	250	130	76	125	16	98	28
800	250	110	135	96	39	70	42
850	250						
0	300						
50	300						
100	300	44	40	55	53	48	55
150	300						
200	300	44	43	54	41	60	15
250	300						
300	300	80	90	86	61	72	47
350	300	60	66	73	53	64	53
400	300	80	83	86	56	74	42
450	300	91	78	96	39	81	34
500	300	100	91	100	32	87	8
550	300	79	68	81	84	69	44
600	300	76	63	86	57	73	41
650	300	70	71	76	70	65	52
700	300	115	76	110	22	84	28
750	300	110	68	110	59	88	36
800	300	115	24	94	66	70	30
850	300						
0	350						
50	350						
100	350	33	44	43	46	35	24

x-axis	y-axis	10V	10H	20V	20H	40V	40H
150	350						
200	350	41	43	55	57	54	52
250	350						
300	350						
350	350						
400	350						
450	350						
500	350						
550	350						
600	350						
650	350						
700	350						
750	350						
800	350						
850	350						
0	375	30	36	41	42	34	22
50	375	31	36	42	45	40	30
100	375						
150	375						
200	375						
250	375						
300	375						
350	375						
400	375						
450	375						
500	375						
550	375						
600	375						
650	375						
700	375						
750	375						
800	375						
850	375						
0	400						
50	400						
100	400	39	33	42	38	35	22
150	400						
200	400	71	67	73	48	47	48
250	400						
300	400						
350	400						
400	400						
450	400						

APPENDIX 3.

DATA LINE PROFILES OF THE ELECTRICAL RESISTIVITY DATA.


PROFILE LINE 1
25 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 1
50 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
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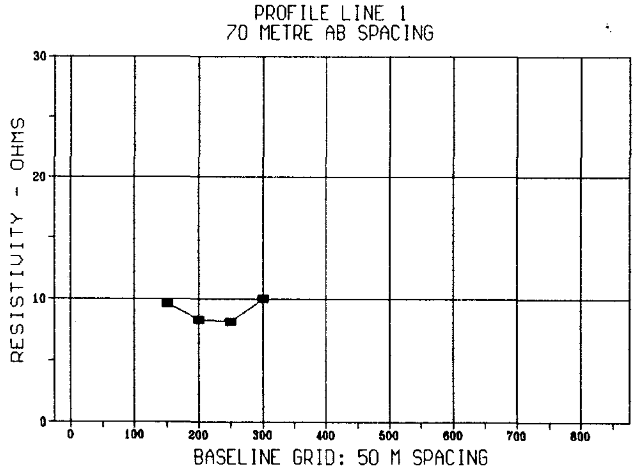
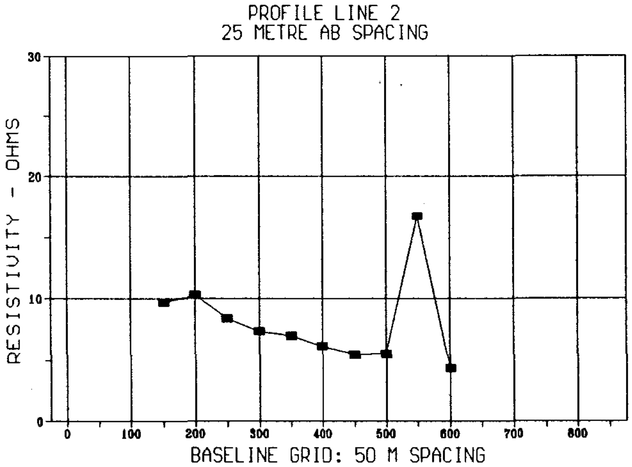
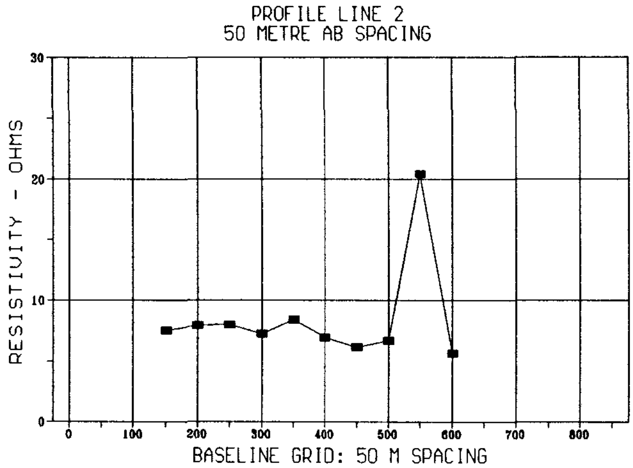
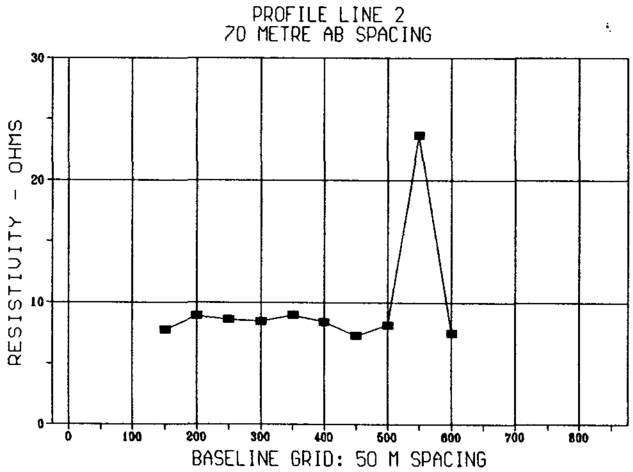
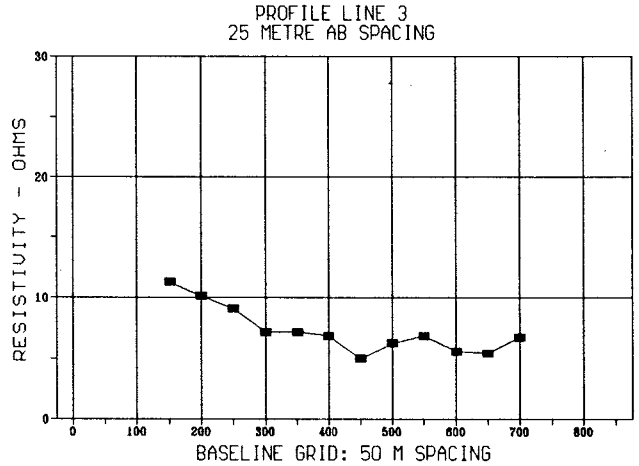
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 1
70 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 2
25 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 2
50 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 2
70 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 3
25 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
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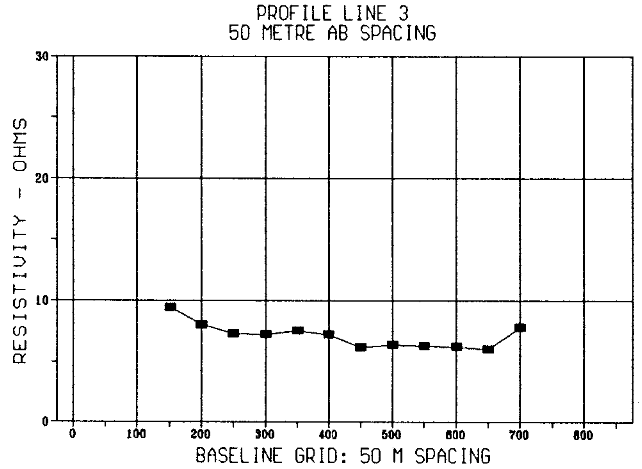
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 3
50 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
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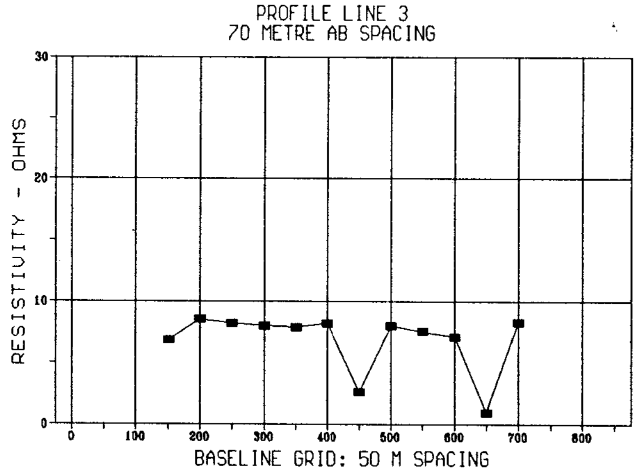
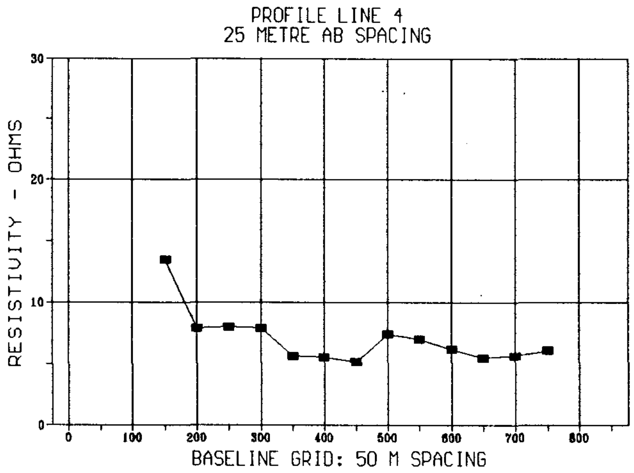
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 3
70 METRE AB SPACING
RESISTIVITY - OHMS
30
20
10
0
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 4
25 METRE AB SPACING
RESISTIVITY - OHMS
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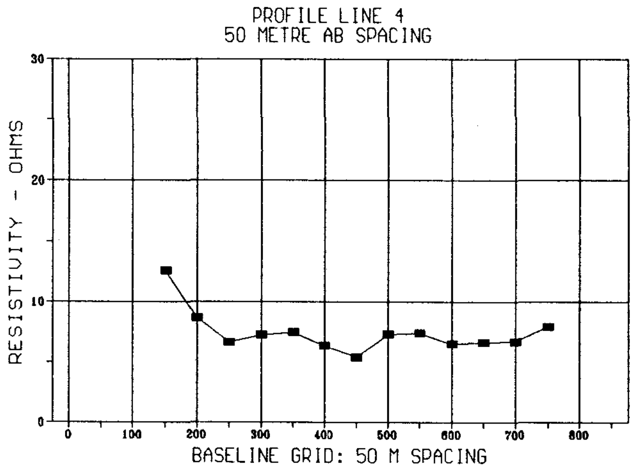
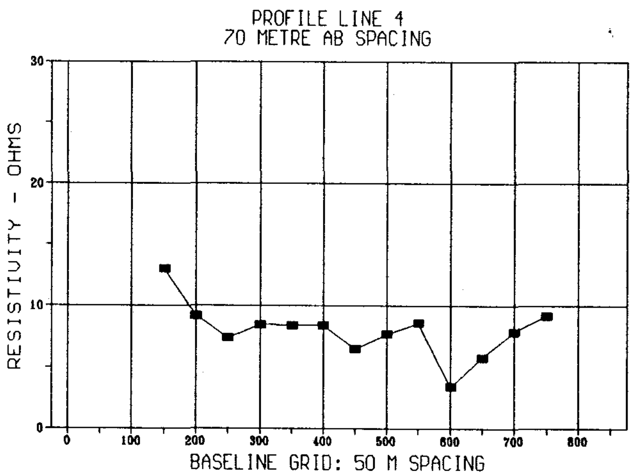
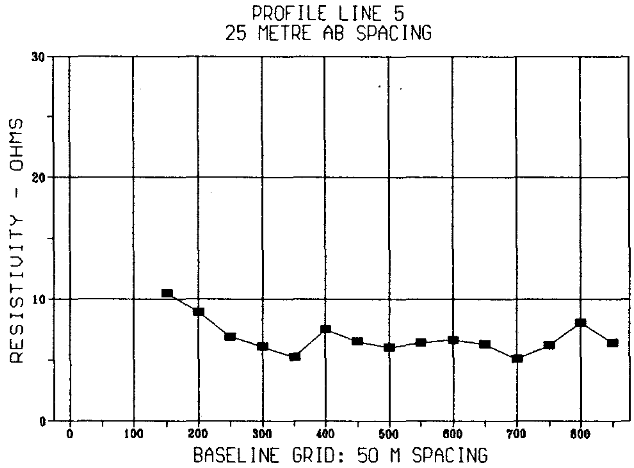
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 4
50 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 4
70 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 5
25 METRE AB SPACING
RESISTIVITY - OHMS
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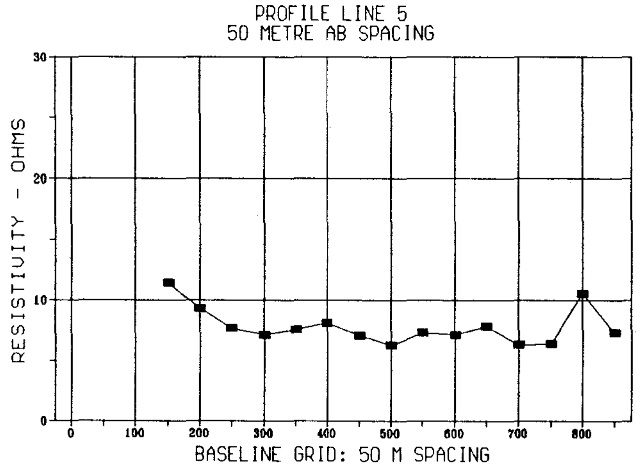
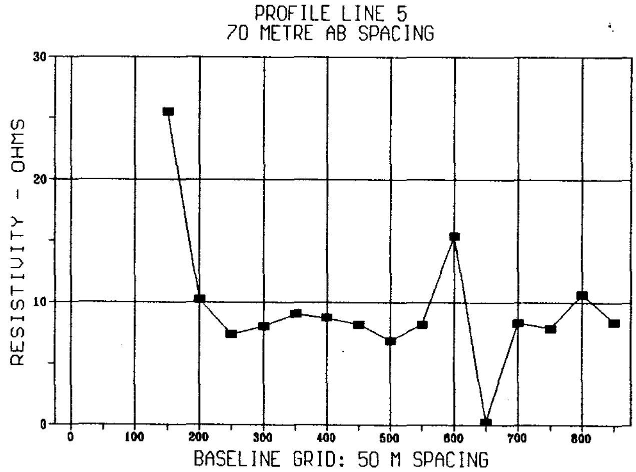
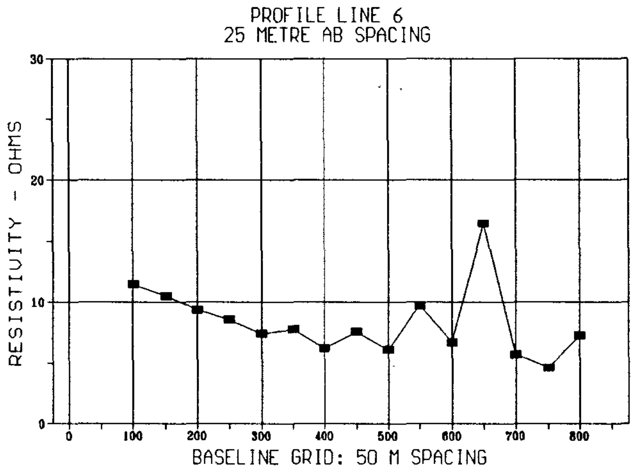
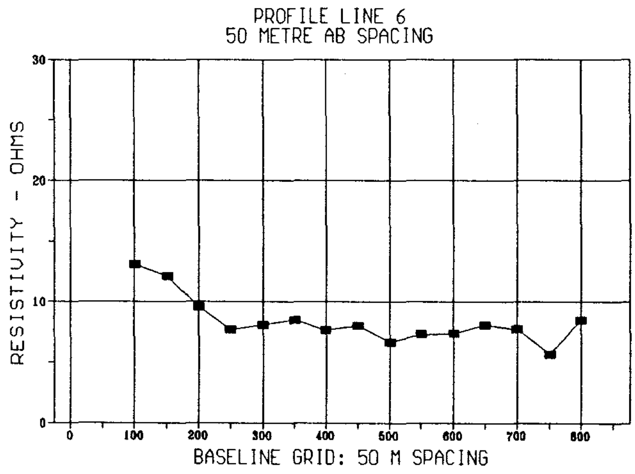
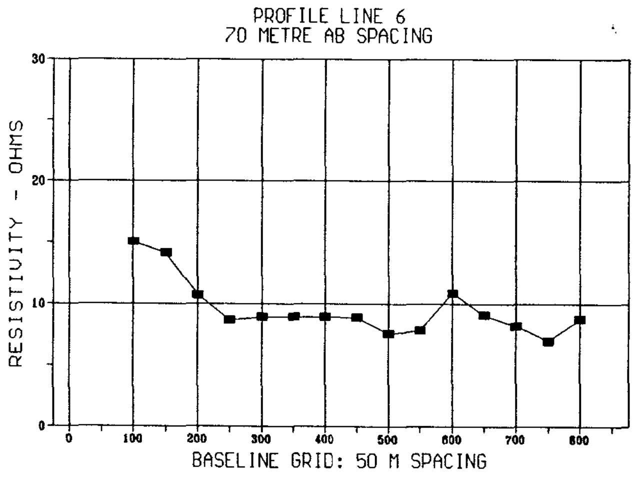
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 5
50 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING

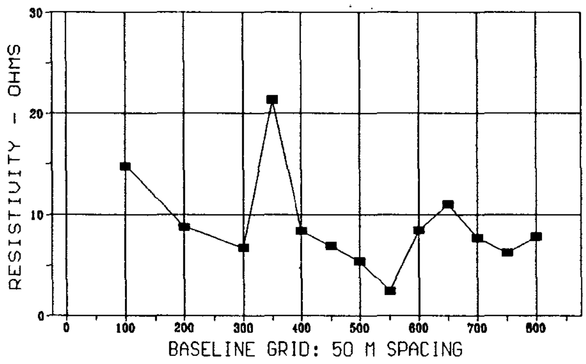

PROFILE LINE 5
70 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 6
25 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING

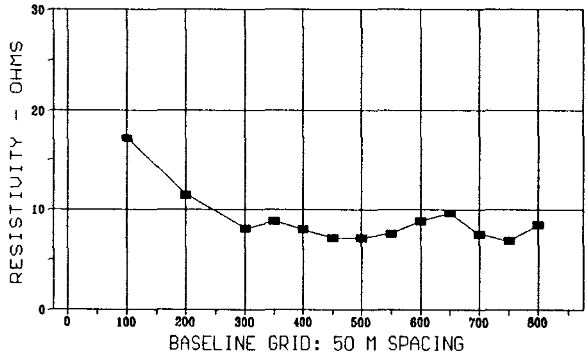

PROFILE LINE 6
50 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING


PROFILE LINE 6
70 METRE AB SPACING
RESISTIVITY - OHMS
0
10
20
30
0
100
200
300
400
500
600
700
800
BASELINE GRID: 50 M SPACING

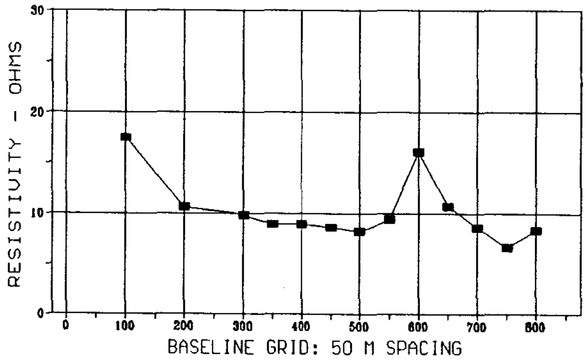
PROFILE LINE 7
25 METRE AB SPACING



PROFILE LINE 7
50 METRE AB SPACING

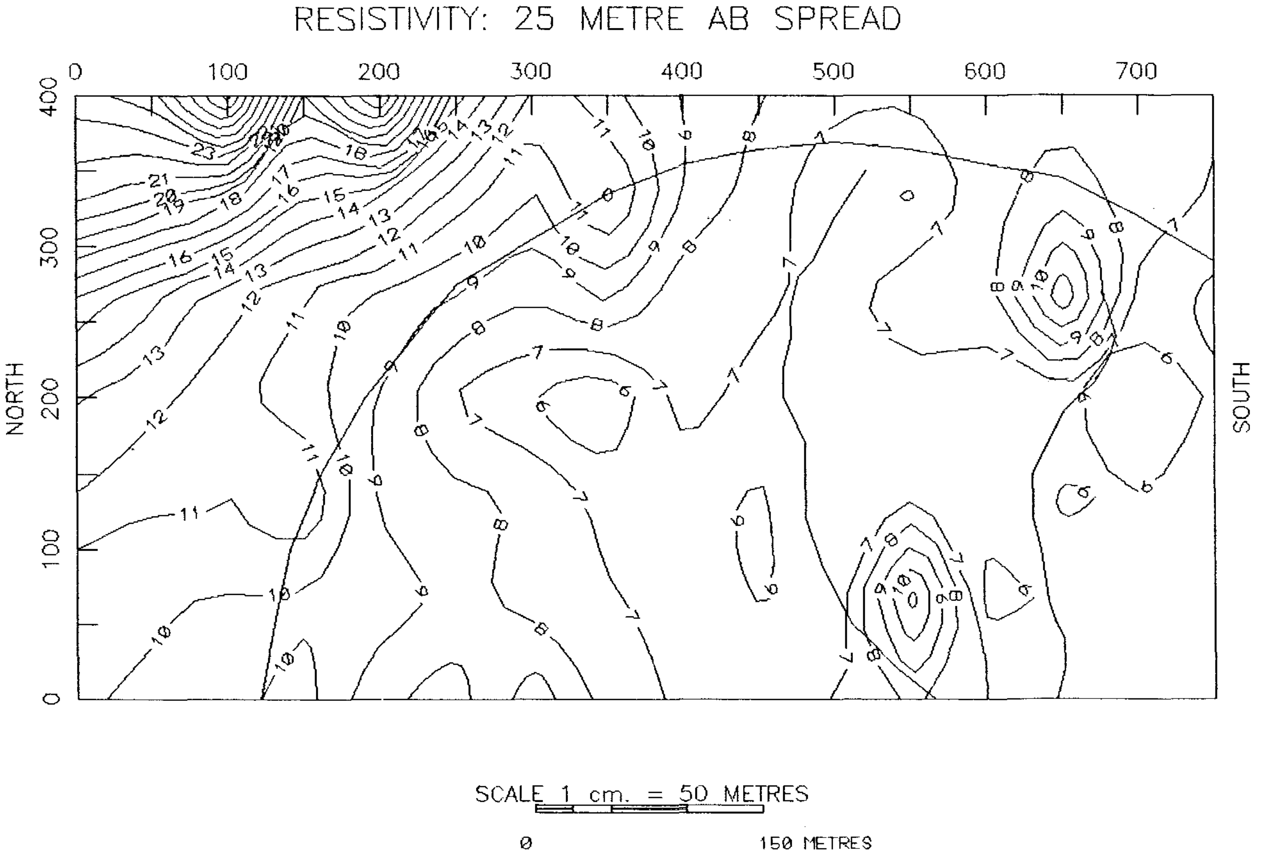


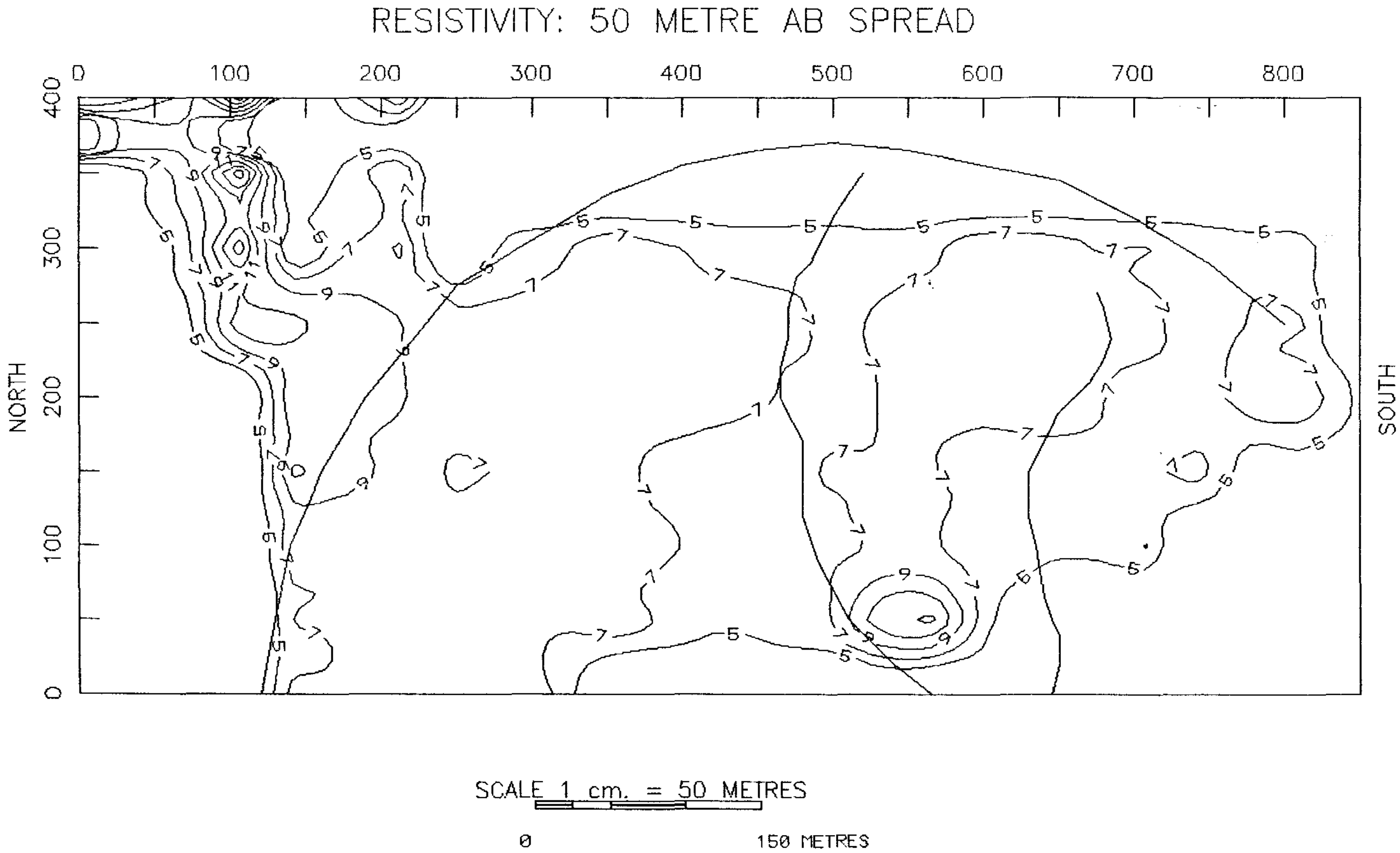
PROFILE LINE 7
70 METRE AB SPACING

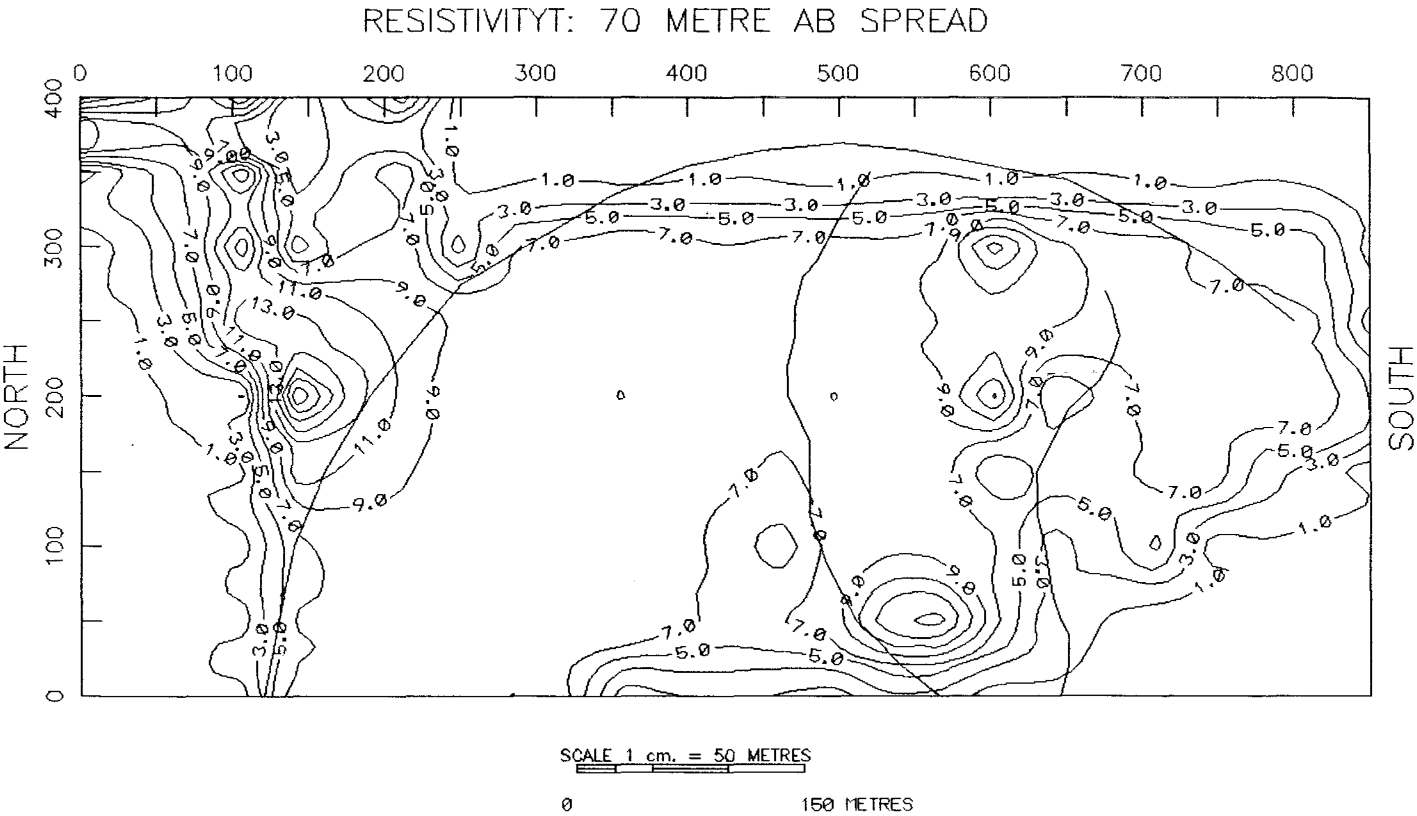


APPENDIX 4.

CONTOURED ELECTRICAL RESISTIVITY DATA FOR THE HORIZONTAL PROFILING SURVEY


RESISTIVITY: 25 METRE AB SPREAD
NORTH
SOUTH
SCALE 1 cm. = 50 METRES
0
150 METRES

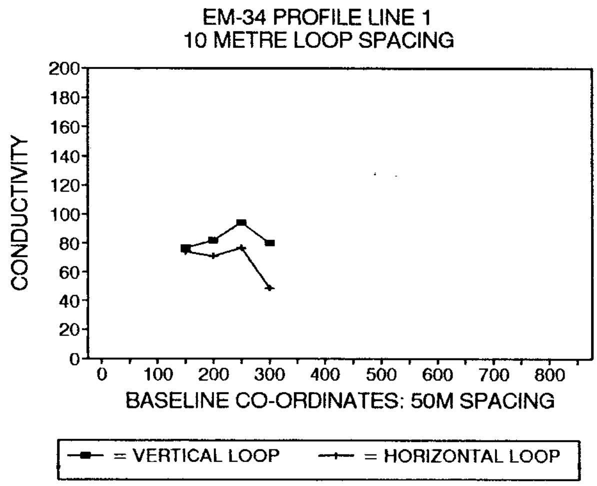

RESISTIVITY: 50 METRE AB SPREAD
NORTH
SOUTH
SCALE 1 cm. = 50 METRES
0
150 METRES

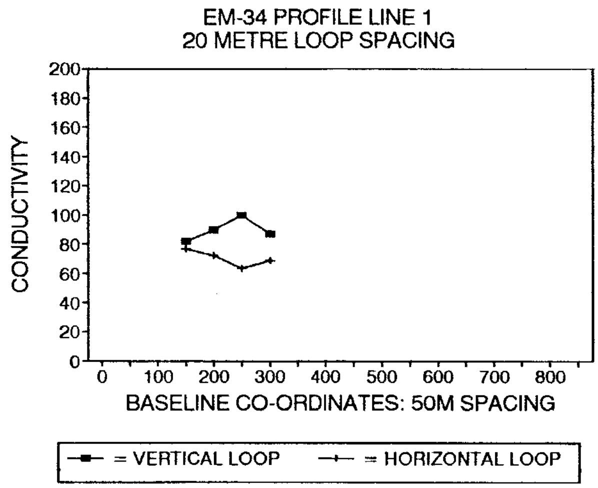


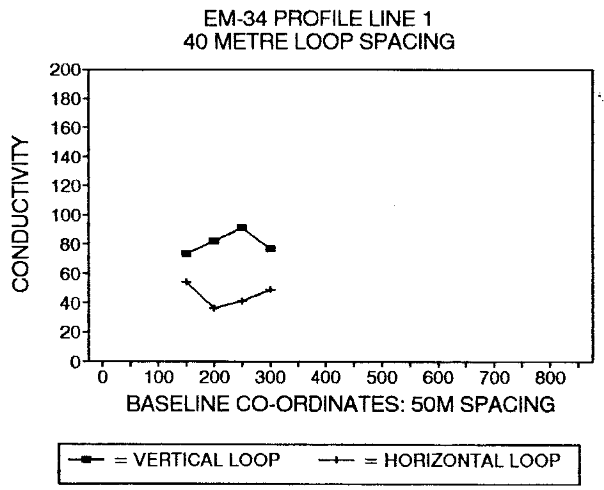
RESISTIVITYT: 70 METRE AB SPREAD
NORTH
SOUTH
0
100
200
300
400
500
600
700
800
SCALE 1 cm. = 50 METRES
0
150 METRES

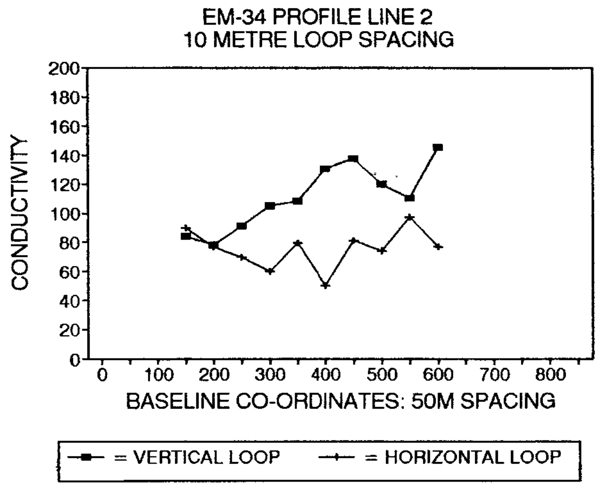
APPENDIX 5.

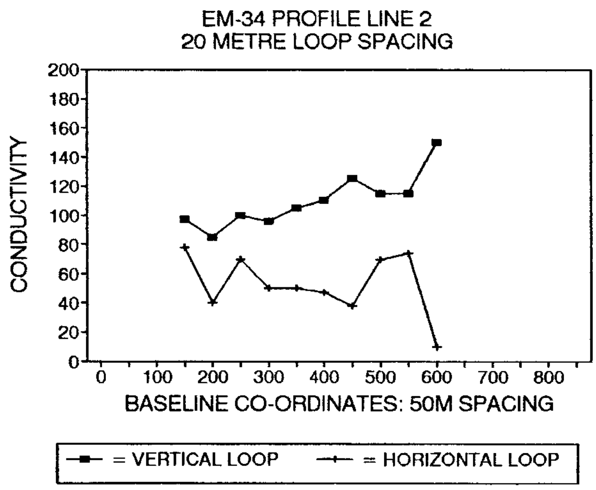
DATA LINE PROFILES OF THE ELECTROMAGNETIC DATA.

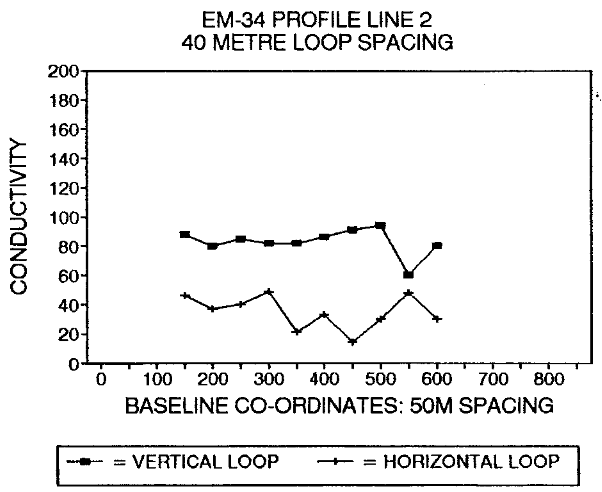

EM-34 PROFILE LINE 1
10 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

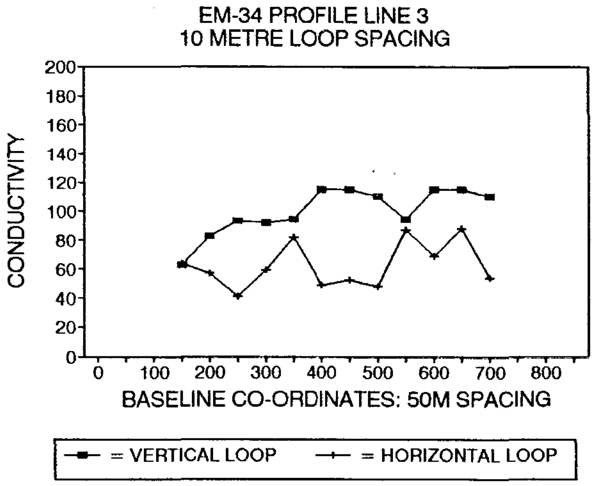

EM-34 PROFILE LINE 1
20 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

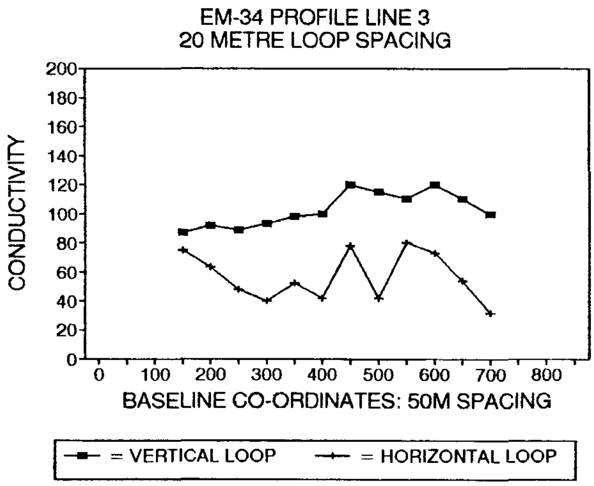

EM-34 PROFILE LINE 1
40 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

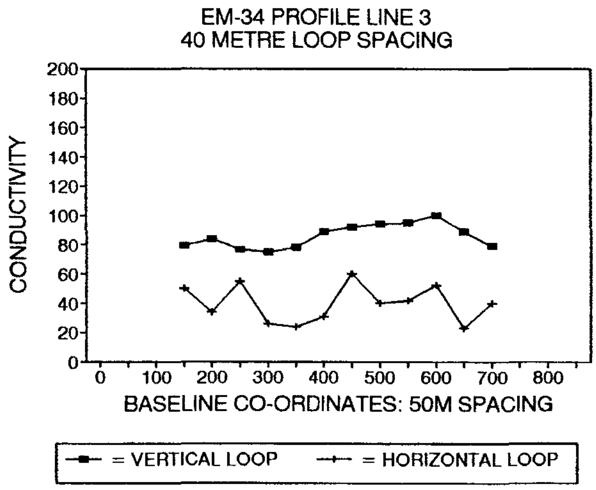

EM-34 PROFILE LINE 2
10 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 2
20 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

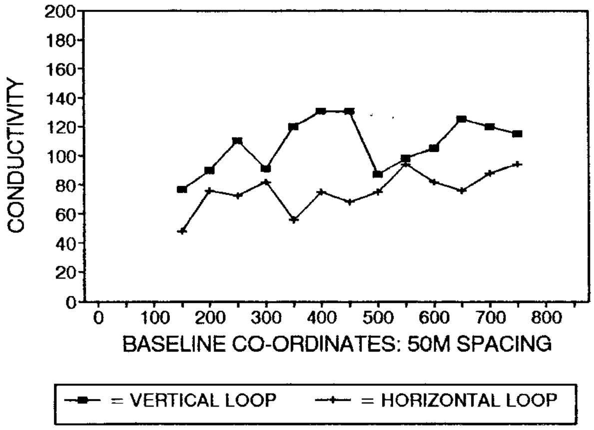

EM-34 PROFILE LINE 2
40 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 3
10 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

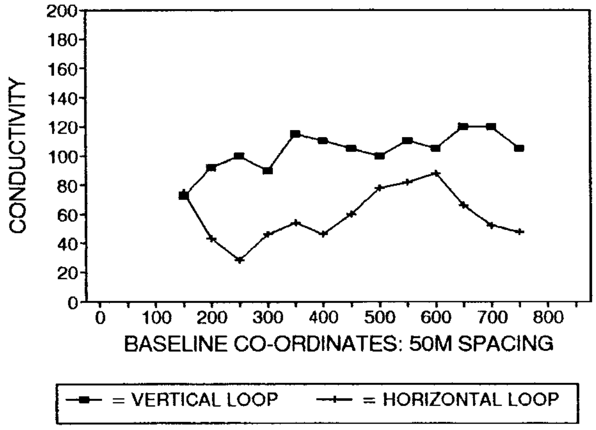

EM-34 PROFILE LINE 3
20 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 3
40 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

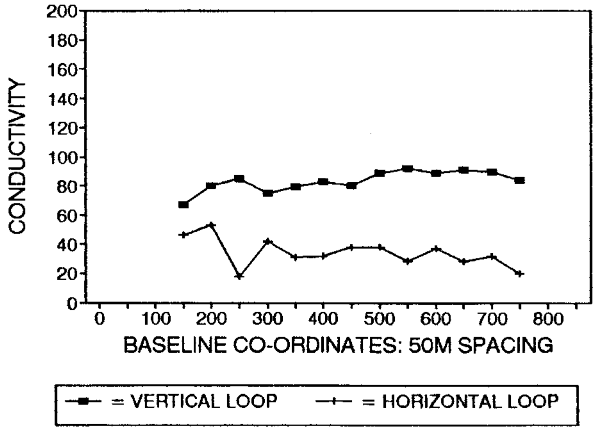
EM-34 PROFILE LINE 4
10 METRE LOOP SPACING

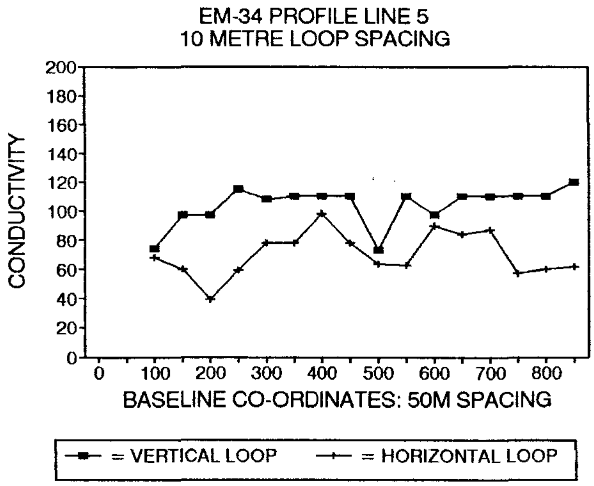


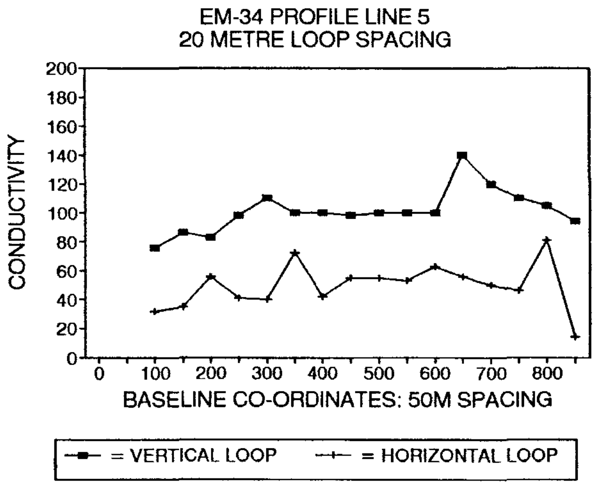
EM-34 PROFILE LINE 4
20 METRE LOOP SPACING

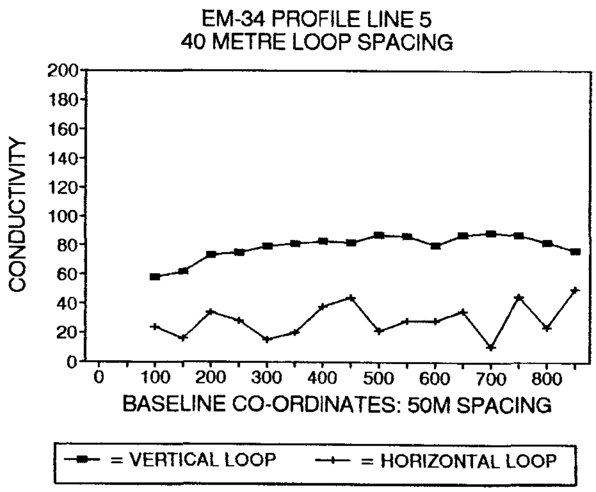


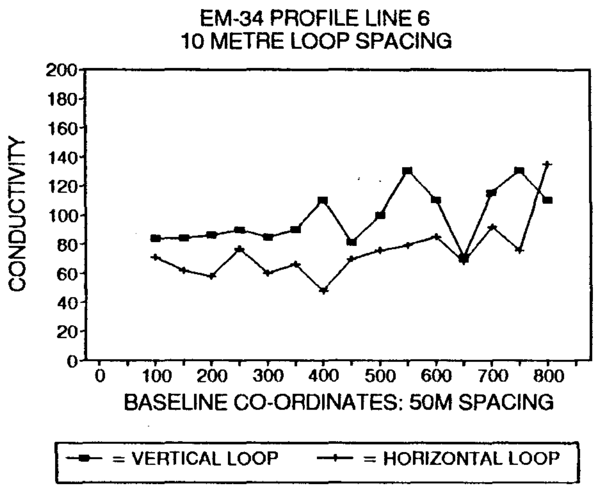
EM-34 PROFILE LINE 4
40 METRE LOOP SPACING

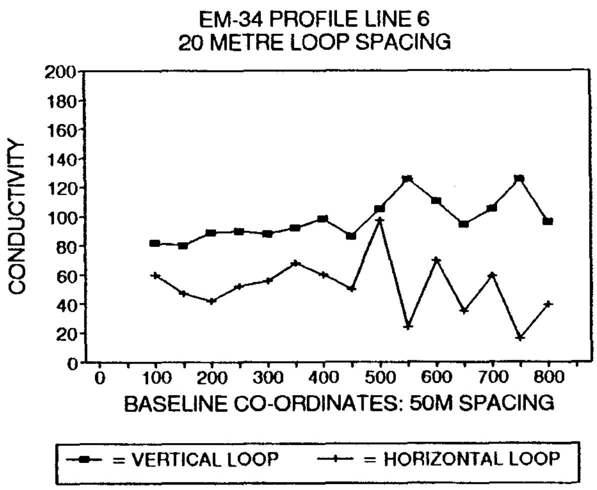


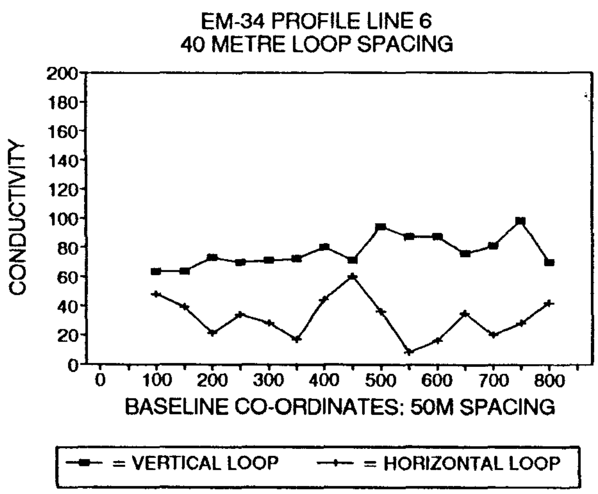

EM-34 PROFILE LINE 5
10 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0 100 200 300 400 500 600 700 800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

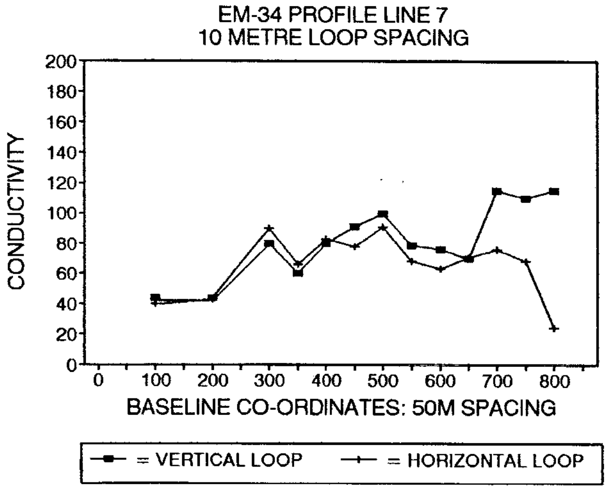

EM-34 PROFILE LINE 5
20 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0 100 200 300 400 500 600 700 800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

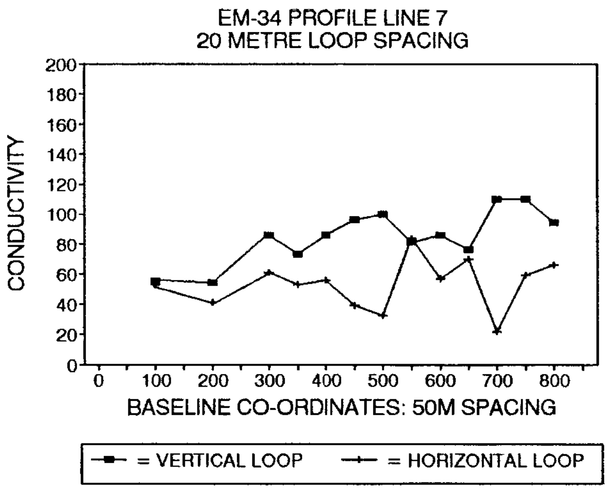

EM-34 PROFILE LINE 5
40 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0 100 200 300 400 500 600 700 800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

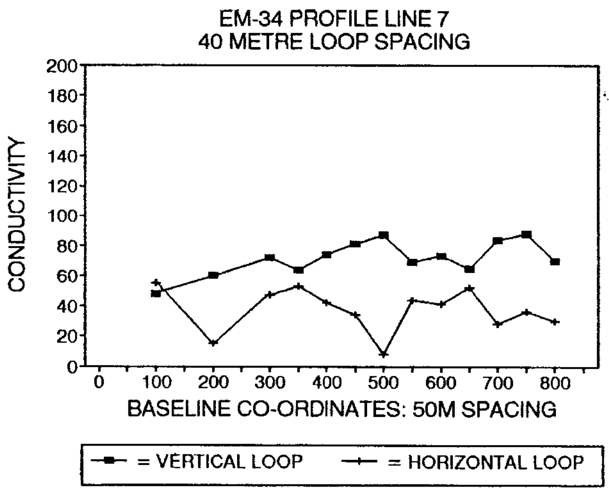

EM-34 PROFILE LINE 6
10 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

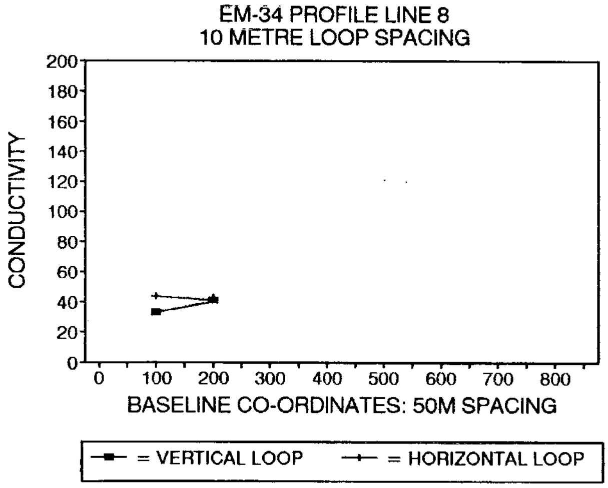

EM-34 PROFILE LINE 6
20 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

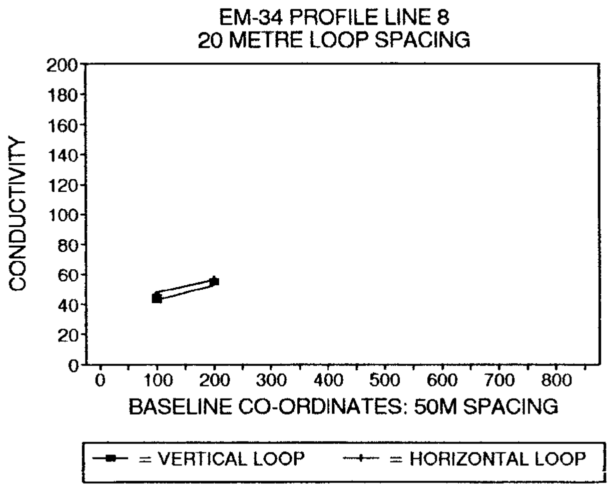

EM-34 PROFILE LINE 6
40 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

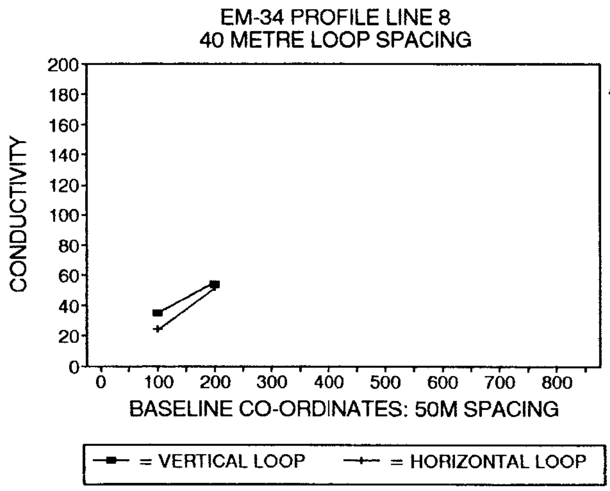

EM-34 PROFILE LINE 7
10 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

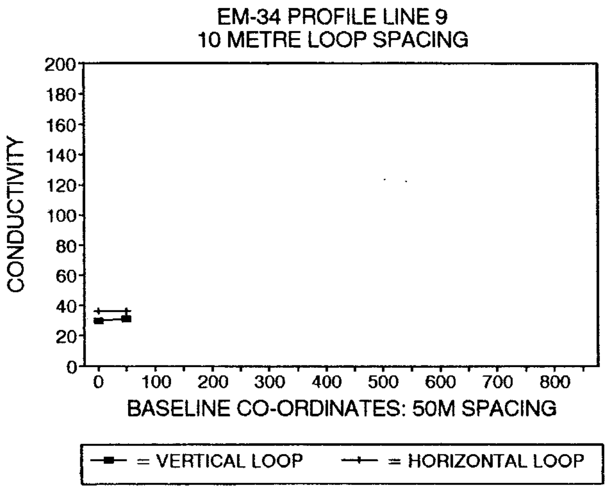

EM-34 PROFILE LINE 7
20 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

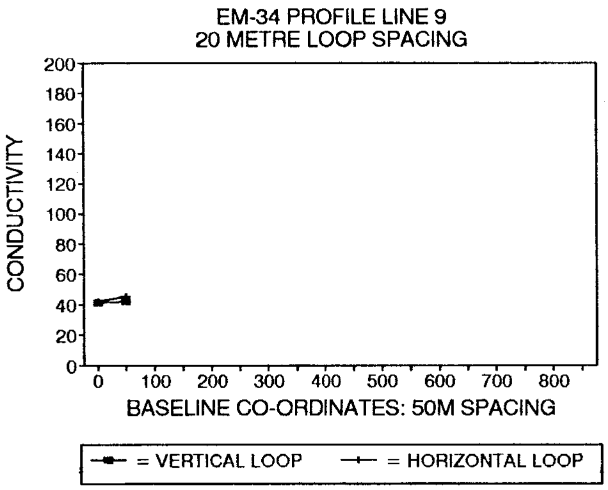

EM-34 PROFILE LINE 7
40 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

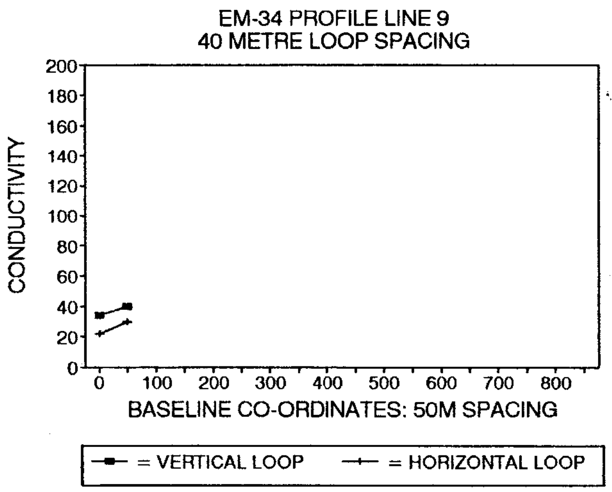

EM-34 PROFILE LINE 8
10 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 8
20 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 8
40 METRE LOOP SPACING
CONDUCTIVITY
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 9
10 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

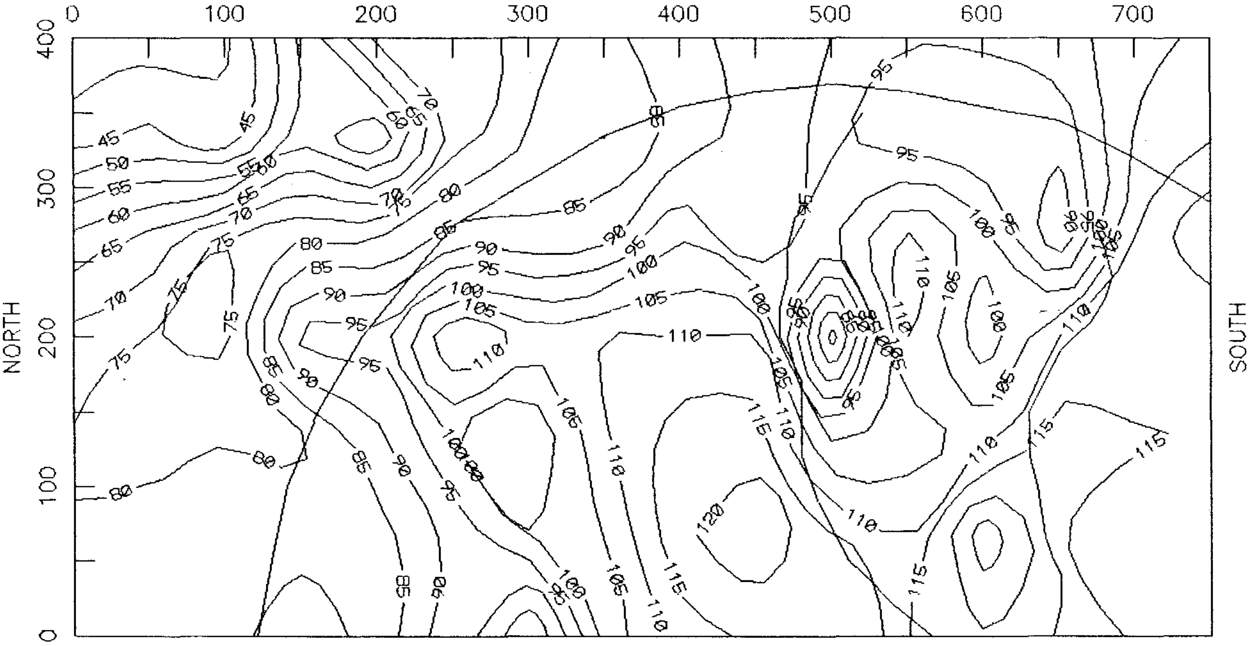

EM-34 PROFILE LINE 9
20 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP


EM-34 PROFILE LINE 9
40 METRE LOOP SPACING
CONDUCTIVITY
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
700
800
BASELINE CO-ORDINATES: 50M SPACING
= VERTICAL LOOP
= HORIZONTAL LOOP

APPENDIX 6.

CONTOURED ELECTROMAGNETIC DATA FOR HORIZONTAL LOOP SURVEYS

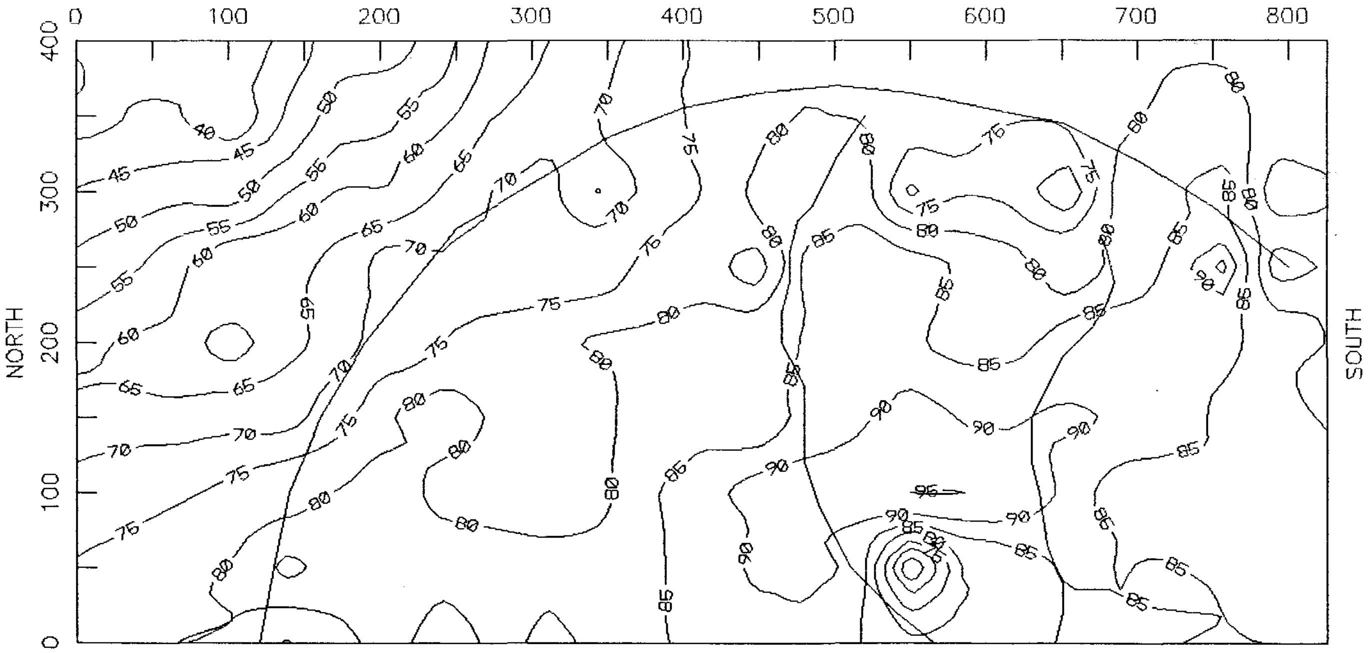
EM-34 10 METRE VERTICAL LOOP SURVEY



SCALE 1 cm. = 50 METRES

0 150 METRES

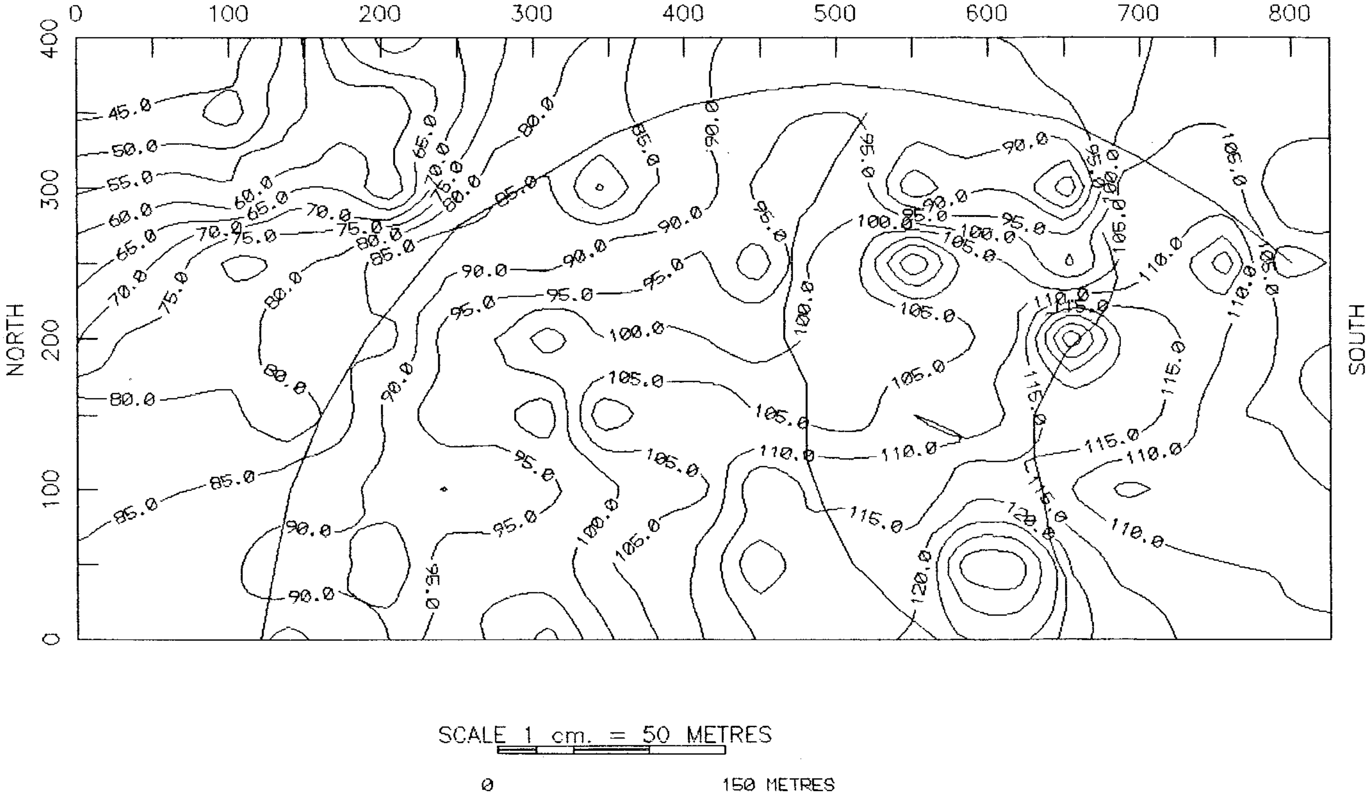
EM-34 40 METRE VERTICAL LOOP SURVEY



SCALE 1 cm. = 50 METRES

0 150 METRES

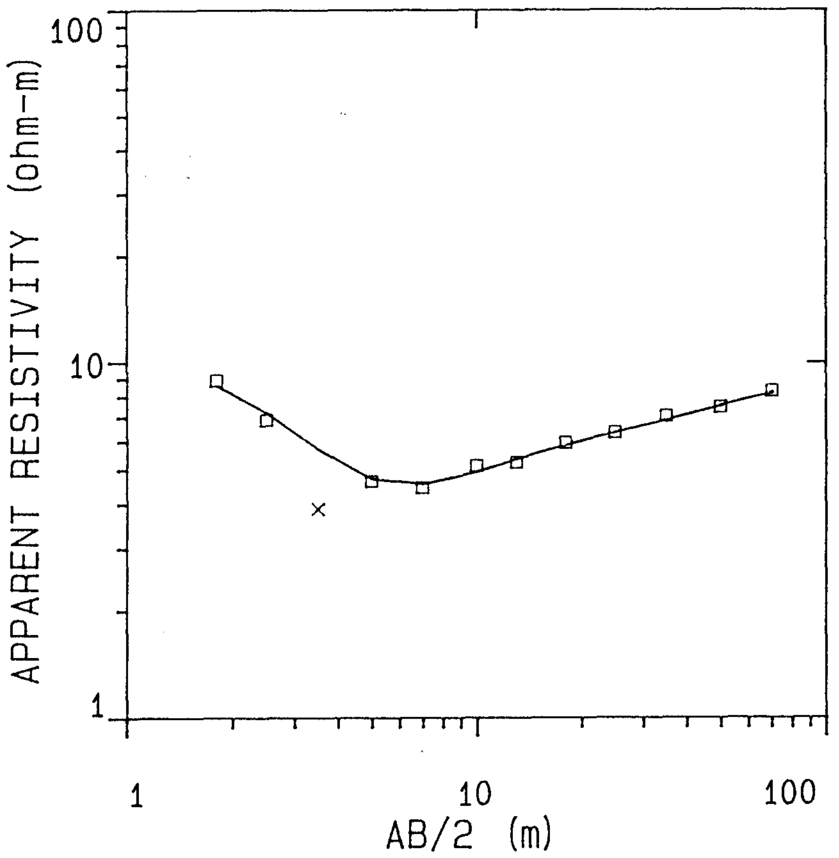
EM-34 20 METRE VERTICAL LOOP SURVEY

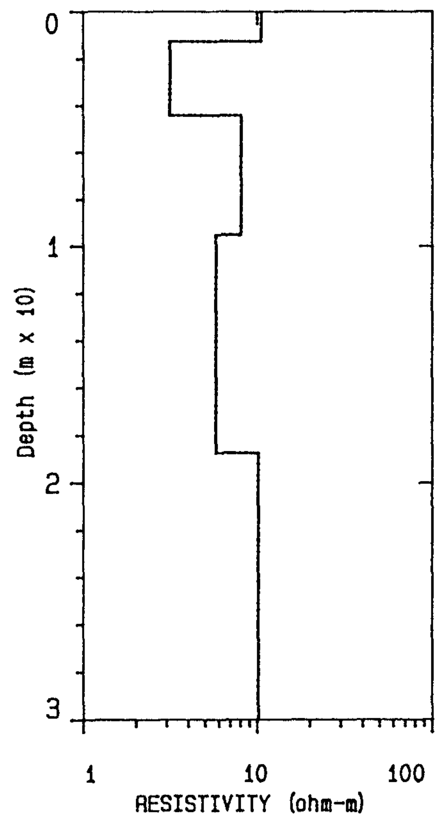


APPENDIX 7.

VES CURVES AND ACCOMPANYING GEO-ELECTRIC LAYERED EARTH MODELS

LR1


APPARENT RESISTIVITY (ohm-m)
100
10
1
1
10
100
AB/2 (m)


Depth (m x 10)
0
1
2
3
1
10
100
RESISTIVITY (ohm-m)

DATA SET: LR1

CLIENT: WATER RESEARCH COMMISSION
LOCATION: LEROUX FARM
COUNTY: SUNDAYS RIVER VALLEY
PROJECT: MSc THESIS GEOHYDROLOGY
ELEVATION: 3063.00
SOUNDING COORDINATES: X: 4944.0000 Y: 7152.0000

DATE: 1991
SOUNDING: LR1
AZIMUTH: 11.5 Deg N-NE
EQUIPMENT: CSIR SYSDEV

Schlumberger Configuration

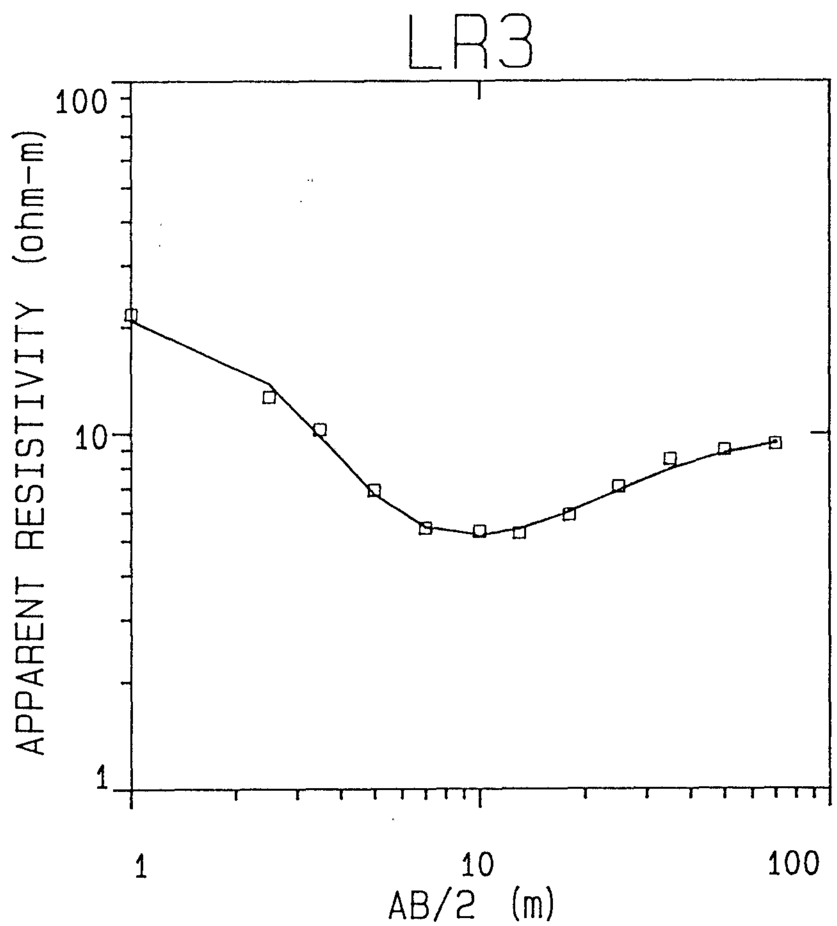
FITTING ERROR: 2.462 PERCENT

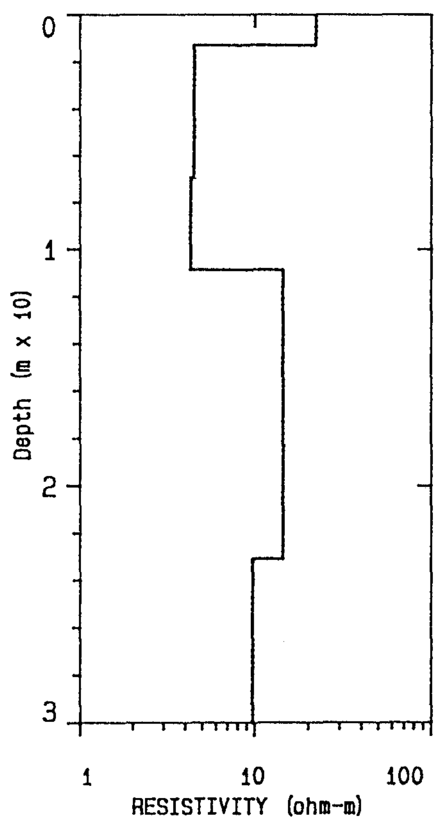
L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	LONG. COND. (Siemens)	TRANS. RES. (Ohm-m^2)
			3063.0		
1	10.55	1.27	3061.7	0.120	13.43
2	3.15	3.15	3058.5	0.999	9.92
3	8.04	5.10	3053.4	0.634	41.12
4	5.79	9.20	3044.2	1.58	53.39
5	10.08				

ALL PARAMETERS ARE FREE

No.	SPACING (m)	RHO-A (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)
1	1.80	8.88	8.61	3.06
2	2.50	6.86	7.20	-4.84
3	3.50	3.87	5.70	-47.36
4	5.00	4.64	4.70	-1.30
5	7.00	4.44	4.54	-2.09
6	10.00	5.12	4.93	3.70
7	13.00	5.24	5.36	-2.24
8	18.00	5.95	5.87	1.20
9	25.00	6.35	6.36	-0.243
10	35.00	7.05	6.90	2.00
11	50.00	7.48	7.57	-1.25
12	70.00	8.30	8.23	0.819

CURRENT RESOLUTION MATRIX NOT AVAILABLE


LR3
APPARENT RESISTIVITY (ohm-m)
100
10
1
1
10
100
AB/2 (m)


0
1
2
3
Depth (m x 10)
1
10
100
RESISTIVITY (ohm-m)

DATA SET: LR3

CLIENT: WATER RESEARCH COMMISSION
LOCATION: LEROUX FARM
COUNTY: SUNDAYS RIVER VALLEY
PROJECT: MSc THESIS GEOHYDROLOGY
ELEVATION: 3063.00
SOUNDING COORDINATES: X: 4944.0000 Y: 7152.0000

DATE: 1991
SOUNDING: LR2
AZIMUTH: 11.5 Deg N-NE
EQUIPMENT: CSIR SYSDEV

Schlumberger Configuration

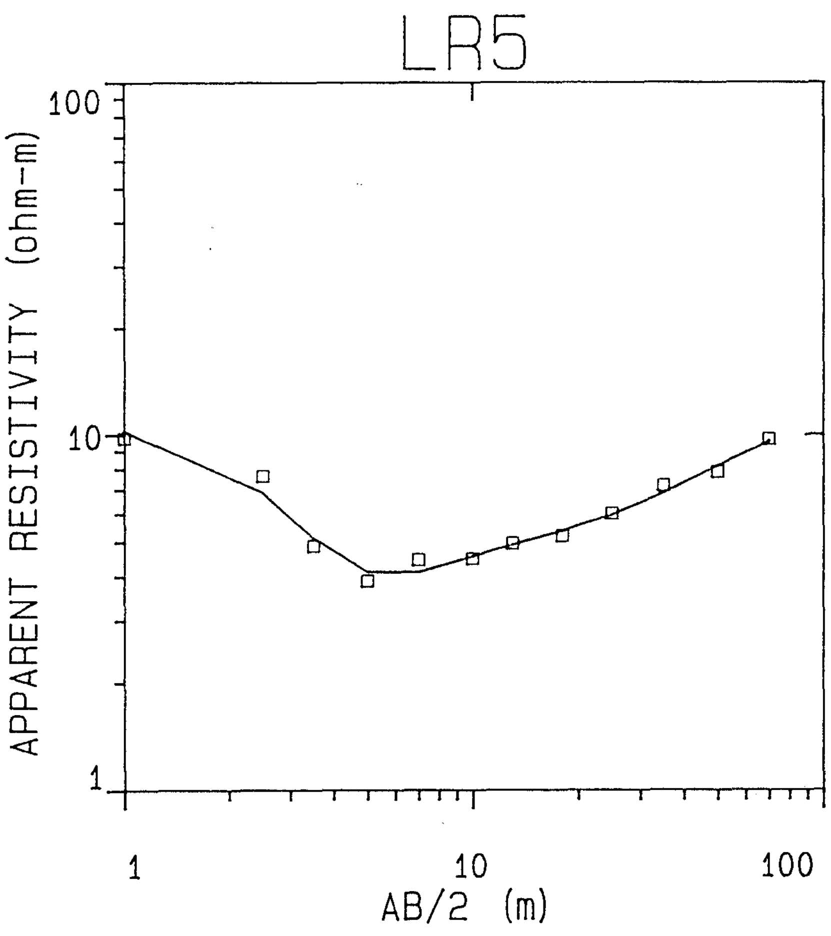
FITTING ERROR: 3.884 PERCENT

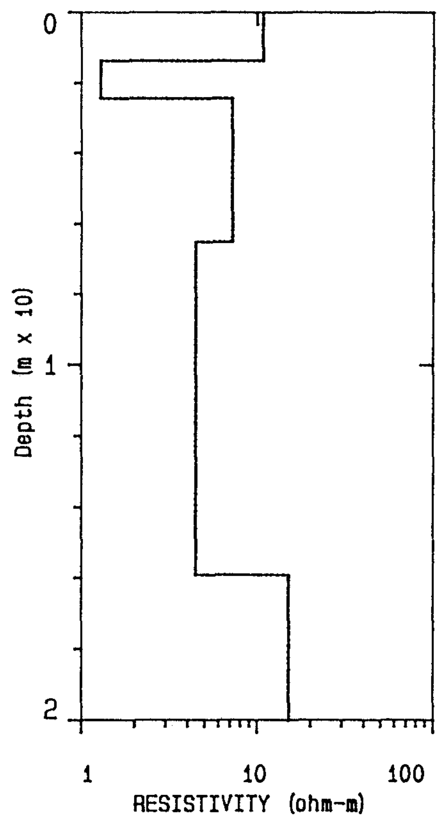
L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	LONG. COND. (Siemens)	TRANS. RES. (Ohm-m^2)
			3063.0		
1	22.08	1.30	3061.6	0.0589	28.74
2	4.49	5.66	3056.0	1.26	25.44
3	4.31	3.91	3052.1	0.909	16.89
4	14.41	12.20	3039.9	0.847	175.9
5	9.78				

ALL PARAMETERS ARE FREE

No.	SPACING (m)	RHO-A (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)
1	1.00	21.66	20.85	3.73
2	2.50	12.63	13.75	-8.87
3	3.50	10.22	9.79	4.22
4	5.00	6.89	6.74	2.16
5	7.00	5.40	5.44	-0.666
6	10.00	5.29	5.18	2.10
7	13.00	5.23	5.39	-3.04
8	18.00	5.89	6.01	-2.10
9	25.00	7.08	6.92	2.14
10	35.00	8.44	7.94	5.95
11	50.00	8.97	8.85	1.33
12	70.00	9.31	9.43	-1.25

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER
P 1 0.98
P 2 -0.01 0.94


LR5
APPARENT RESISTIVITY (ohm-m)
100
10
1
1
10
100
AB/2 (m)


Depth (m x 10)
0
1
2
1
10
100
RESISTIVITY (ohm-m)

DATA SET: LR5

CLIENT: WATER RESEARCH COMMISSION
LOCATION: LEROUX FARM
COUNTY: SUNDAYS RIVER VALLEY
PROJECT: MSc THESIS GEOHYDROLOGY
ELEVATION: 3063.00
SOUNDING COORDINATES: X: 4944.0000 Y: 7152.0000

DATE: 1991
SOUNDING: LR2
AZIMUTH: 11.5 Deg N-NE
EQUIPMENT: CSIR SYSDEV

Schlumberger Configuration

FITTING ERROR: 5.241 PERCENT

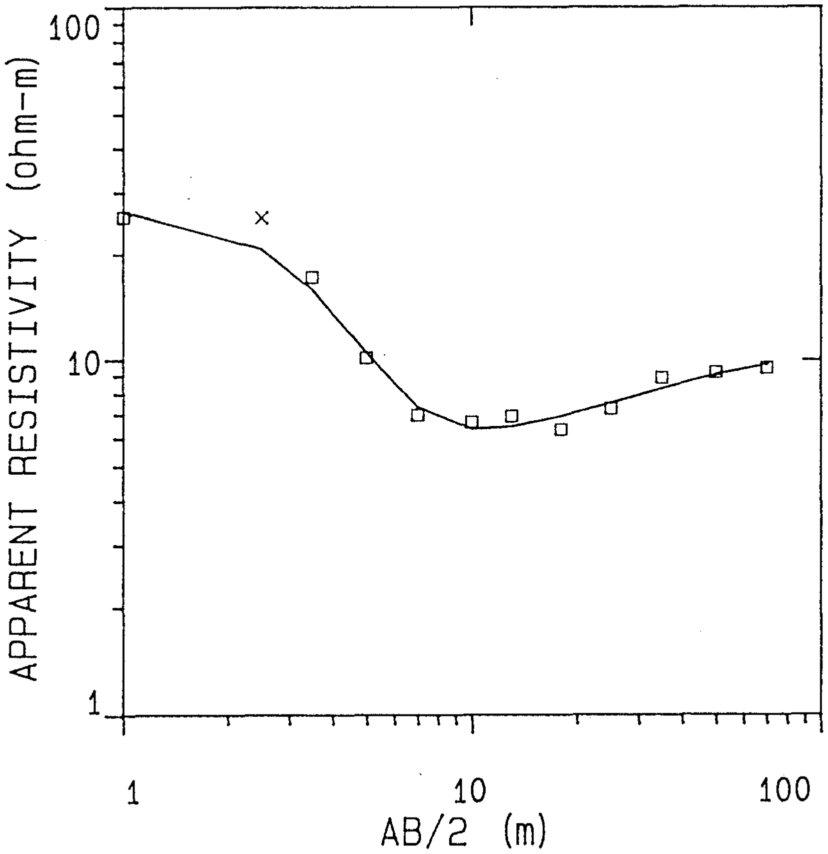
L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	LONG. COND. (Siemens)	TRANS. RES. (Ohm-m^2)
			3063.0		
1	10.78	1.37	3061.6	0.127	14.80
2	1.28	1.06	3060.5	0.825	1.36
3	7.20	4.09	3056.4	0.568	29.45
4	4.47	9.38	3047.0	2.10	41.96
5	15.12				

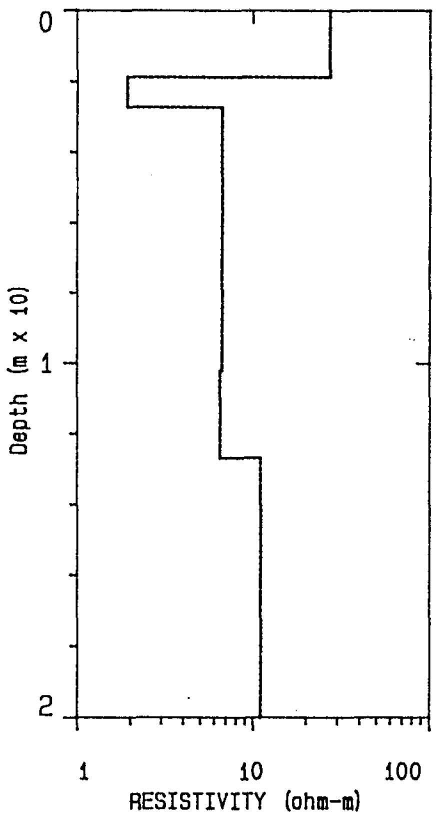
ALL PARAMETERS ARE FREE

No.	SPACING (m)	RHO-A (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)
1	1.00	9.76	10.21	-4.58
2	2.50	7.64	6.87	9.97
3	3.50	4.87	5.14	-5.49
4	5.00	3.88	4.12	-6.14
5	7.00	4.45	4.11	7.68
6	10.00	4.49	4.56	-1.63
7	13.00	4.96	4.93	0.517
8	18.00	5.20	5.39	-3.53
9	25.00	6.01	5.98	0.540
10	35.00	7.21	6.89	4.43
11	50.00	7.86	8.19	-4.20
12	70.00	9.70	9.58	1.28

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER
P 1 0.98
P 2 -0.01 0.45

LR6


APPARENT RESISTIVITY (ohm-m)
100
10
1
1
10
100
AB/2 (m)


Depth (m x 10)
0
1
2
1
10
100
RESISTIVITY (ohm-m)

DATA SET: LR6

CLIENT: WATER RESEARCH COMMISSION DATE: 1991
LOCATION: LEROUX FARM SOUNDING: LR6
COUNTY: SUNDAYS RIVER VALLEY AZIMUTH: 11.5 Deg N-NE
PROJECT: MSc THESIS GEOHYDROLOGY EQUIPMENT: CSIR SYSDEV
ELEVATION: 3063.00
SOUNDING COORDINATES: X: 4944.0000 Y: 7152.0000

Schlumberger Configuration

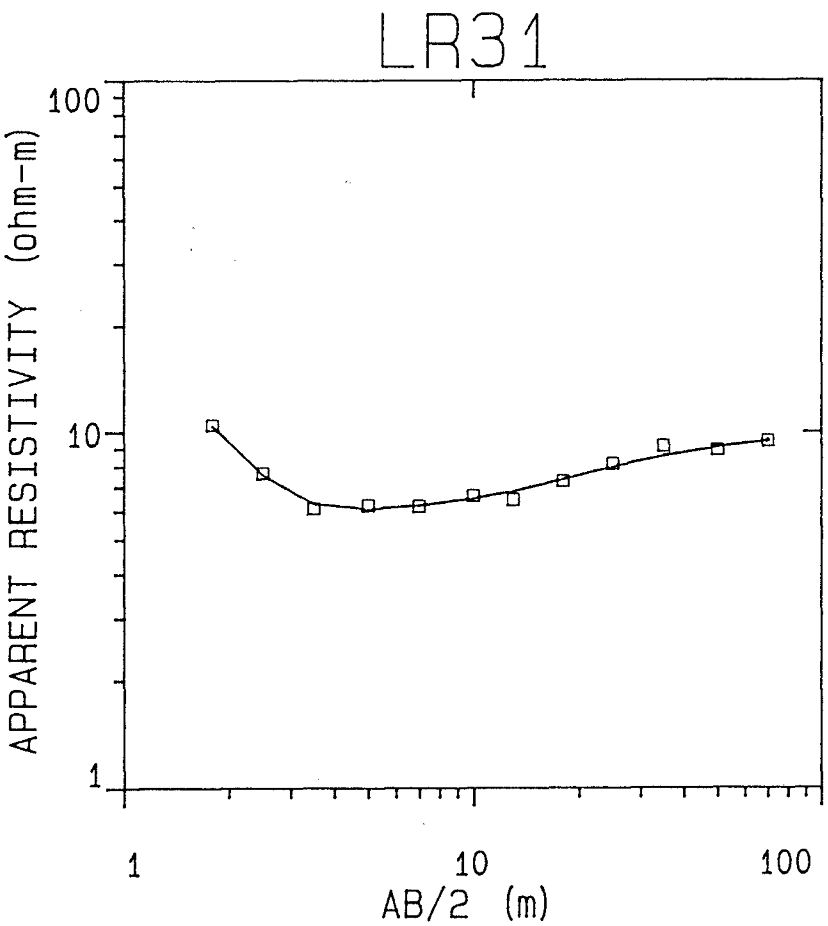
FITTING ERROR: 5.638 PERCENT

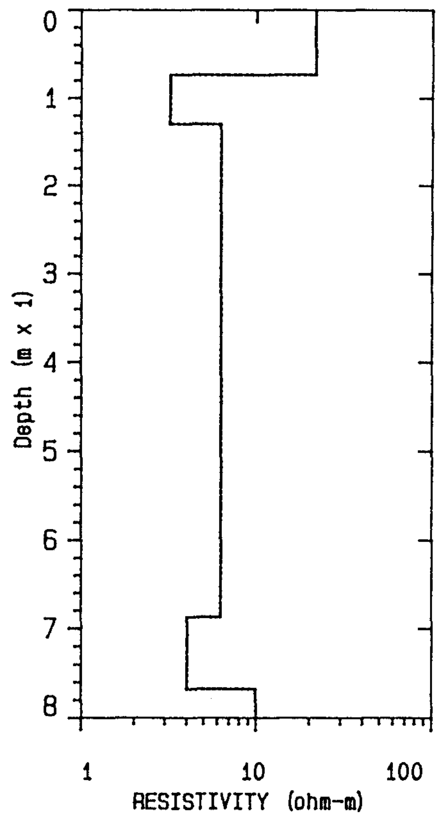
L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	LONG. COND. (Siemens)	TRANS. RES. (Ohm-m^2)
			3063.0		
1	27.10	1.88	3061.1	0.0695	51.04
2	1.91	0.841	3060.2	0.439	1.61
3	6.62	7.50	3052.7	1.13	49.75
4	6.48	2.45	3050.3	0.379	15.95
5	11.01				

ALL PARAMETERS ARE FREE

No.	SPACING (m)	RHO-A (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)
1	1.00	25.50	26.42	-3.61
2	2.50	25.42	20.73	18.43
3	3.50	17.19	15.84	7.84
4	5.00	10.14	10.50	-3.54
5	7.00	6.97	7.34	-5.42
6	10.00	6.65	6.37	4.28
7	13.00	6.92	6.48	6.46
8	18.00	6.34	6.93	-9.20
9	25.00	7.28	7.55	-3.75
10	35.00	8.90	8.31	6.71
11	50.00	9.21	9.10	1.24
12	70.00	9.48	9.73	-2.63

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER
P 1 0.97
P 2 -0.01 0.06


LR31
APPARENT RESISTIVITY (ohm-m)
100
10
1
1
10
100
AB/2 (m)


Depth (m x 1)
0
1
2
3
4
5
6
7
8
1
10
100
RESISTIVITY (ohm-m)

DATA SET: LR31

CLIENT: WATER RESEARCH COMMISSION
LOCATION: LEROUX FARM
COUNTY: SUNDAYS RIVER VALLEY
PROJECT: MSc THESIS GEOHYDROLOGY
ELEVATION: 3063.00
SOUNDING COORDINATES: X: 4944.0000 Y: 7152.0000

DATE: 1991
SOUNDING: LR31
AZIMUTH: 11.5 Deg N-NE
EQUIPMENT: CSIR SYSDEV

Schlumberger Configuration

FITTING ERROR: 2.952 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	LONG. COND. (Siemens)	TRANS. RES. (Ohm-m^2)
			3063.0		
1	21.67	0.738	3062.2	0.0340	16.00
2	3.24	0.559	3061.7	0.172	1.81
3	6.27	5.57	3056.1	0.887	34.99
4	4.06	0.805	3055.3	0.198	3.27
5	10.00				

ALL PARAMETERS ARE FREE

No.	SPACING (m)	RHO-A (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)
1	1.80	10.47	10.45	0.192
2	2.50	7.65	7.59	0.834
3	3.50	6.09	6.29	-3.17
4	5.00	6.22	6.08	2.28
5	7.00	6.19	6.23	-0.677
6	10.00	6.62	6.52	1.51
7	13.00	6.45	6.83	-5.97
8	18.00	7.28	7.37	-1.20
9	25.00	8.15	7.99	1.98
10	35.00	9.14	8.60	5.96
11	50.00	8.90	9.12	-2.47
12	70.00	9.44	9.47	-0.311

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER
P 1 0.66
P 2 -0.10 0.14

APPENDIX 8.

SOIL EC DATA COLLECTED FROM 0 TO 3.00 METRES DEPTH

x-axis	y-axis	0	0.25	0.5	0.75	1	1.25	1.5
200	0	312	194	170	144	151	165	197
250	0	61	44	39	34	33	30	36
300	0	136	111	103	98	71	59	78
150	0	169	63	47	44	49	38	51
200	50	143	81	123	107	89	79	84
350	50	168	190	180	143	141	141	144
450	50	65	70	136	206	227	332	391
550	50	89	74	63	53	46	68	135
200	100	165	56	53	40	48	48	68
300	100	170	102	153	189	218	241	304
400	100	116	78	80	105	127	127	187
500	100	81	68	74	58	44	62	99
600	100	82	61	39	36	60	82	133
700	100	81	76	78	81	84	82	83
150	150	73	112	488	610	578	646	608
250	150	92	115	94	0	96	94	103
350	150	112	132	133	128	136	150	157
450	150	135	123	124	104	102	93	87
550	150	132	114	50	45	53	86	189
650	150	131	146	104	97	111	121	124
750	150	88	92	166	190	211	359	360
100	200	107	60	283	476	469	498	483
200	200	387	451	493	544	578	575	528
300	200	131	82	75	78	95	107	120
400	200	107	110	184	228	238	250	362
500	200	94	65	55	53	94	112	184
600	200	95	70	50	50	67	57	85
700	200	121	102	88	117	88	108	140
150	250	78	280	552	534	460	463	444
250	250	123	106	88	111	139	172	298
350	250	210	346	370	301	267	294	371
450	250	210	111	131	119	123	112	100
550	250	99	0	58	66	86	143	188
650	250	162	111	114	79	166	168	146
750	250	109	136	119	117	122	153	194
800	250	165	106	84	160	174	266	290
100	300	41	45	75	135	85	197	225

x-axis	y-axis	0	0.25	0.5	0.75	1	1.25	1.5
200	300	0	45	58	103	0	148	202
300	300	94	135	160	192	190	165	93
400	300	56	53	0	152	177	112	97
500	300	194	132	134	146	146	119	100
600	300	151	89	97	64	66	54	62
700	300	66	54	97	140	173	213	222
50	375	43	62	80	67	69	78	97
100	400	51	35	41	67	99	139	190
200	400	33	47	131	262	319	316	355

x-axis	y-axis	1.75	2	2.25	2.5	2.75	3
200	0	236	392	475	413	218	226
250	0	36	38	0	0	0	0
300	0	65	83	66	140	0	0
150	0	52	70	291	162	127	0
200	50	88	86	82	80	67	85
350	50	152	168	194	208	293	319
450	50	500	485	436	464	458	493
550	50	145	146	165	226	228	261
200	100	76	99	70	129	140	152
300	100	354	373	420	0	0	0
400	100	264	308	381	370	410	521
500	100	206	201	203	237	242	289
600	100	178	252	312	371	0	0
700	100	142	174	175	244	239	273
150	150	615	639	616	470	380	203
250	150	0	91	84	102	131	165
350	150	176	0	0	0	0	0
450	150	95	83	114	179	254	306
550	150	324	368	385	373	346	356
650	150	139	142	164	208	273	333
750	150	472	485	443	372	183	215
100	200	497	497	496	404	302	269
200	200	505	501	489	409	233	225
300	200	143	153	146	164	206	310
400	200	359	396	313	270	276	295
500	200	326	380	375	0	0	0
600	200	204	230	244	306	285	306
700	200	225	502	597	582	570	510
150	250	420	443	459	467	421	346
250	250	370	370	414	469	598	620
350	250	362	396	473	453	388	299
450	250	99	113	103	120	135	160
550	250	191	197	197	238	238	0
650	250	197	316	318	300	289	300
750	250	350	431	651	668	633	608
800	250	236	305	434	382	828	778
100	300	206	161	200	343	311	310
200	300	248	288	161	0	255	356

x-axis	y-axis	1.75	2	2.25	2.5	2.75	3
300	300	58	39	38	48	155	143
400	300	101	113	161	392	316	379
500	300	110	124	141	250	255	254
600	300	58	55	53	49	0	0
700	300	257	232	197	209	321	419
50	375	121	134	137	176	136	226
100	400	245	169	291	171	211	250
200	400	326	400	414	363	445	445