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# PHY 461 GEOPHYSICS III

# ELECTRICAL AND ELECTROMAGNETIC METHODS

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## UNIT 1: ELECTRICAL PROPERTIES ASSOCIATED WITH ROCKS.

### 1.0 Introduction

In this unit, you will be introduced to the basic concept of Electric Current Methods. Basic Electrical Properties Associated with Rocks is the first topic or Concept you are required to study in this course. There are reasons among others why electrical current method should be first topic to study in this course

Several electrical properties of rocks and minerals are significant in electrical prospecting. They are natural electrical potentials, electrical conductivity, or the inverse electrical resistivity, and the dielectric constant. Of these, electrical conductivity is the most important, while others are of minor importance. Certain natural or spontaneous potential occurring in the subsurface are caused by electrochemical or chemical activity. The controlling factor is underground water.

Most rock-forming minerals are insulators, and electrical current is carried through a rock mainly by the passage of ions in pore waters. Thus most rocks conduct electricity by electrolytic rather than electronic processes.

### 2.0 Objectives

At the end of this unit, readers should be able to:

(i) Understand the basic concept of electric current methods
(ii) Identifying and understanding that Electrical prospecting uses three phenomena and properties associated with Rocks

(iii) Understand that Resistivity, or the reciprocal of conductivity, governs the amount of current that passes through the rock when a specified potential difference is applied.

(iv) show the behaviours of rocks and minerals when passing through electric current.

(v) Other objectives include how contrasts in electrical property of rock and mineral could be used to identify and name subsurface geology.

## 3.0 Main content

### *3.1 Electric Current Methods*

Many geophysical surveys rely on measurements of the voltages or magnetic fields associated with electric currents flowing in the ground. Some of these currents exist independently, being sustained by natural oxidation–reduction reactions or variations in ionospheric or atmospheric magnetic fields, but most are generated artificially. Current can be made to flow by direct injection, by capacitative coupling or by electromagnetic induction (Figure 1.1).

Surveys involving direct injection via electrodes at the ground surface are generally referred to as direct current or *DC* surveys, even though in practice the direction of current is reversed at regular intervals to cancel some forms of natural background noise. Currents that are driven by electric fields acting either through electrodes or capacitatively (rather than inductively, by varying magnetic fields) are sometimes termed *galvanic*. Surveys in which currents are made to flow inductively are referred to as electromagnetic or *EM* surveys.

Relevant general concepts are introduced in this note. Direct current methods are also considered which also describes the relatively little-used capacitative-coupled methods. Natural potential (*self potential* or *SP*) and *induced polarization* (*IP*) methods are covered. Also discussed are EM surveys using local sources and with VLF and CSAMT surveys, which use plane waves generated by distant transmitters.

### *3.2 Resistivity and Conductivity*

Metals and most metallic sulphides conduct electricity efficiently by flow of electrons, and electrical methods are therefore important in environmental investigations, where metallic objects are often the targets, and in the search for sulphide ores. Graphite is also a good 'electronic' conductor and, since it is not itself a useful mineral, is a source of noise in mineral exploration. Most rock-forming minerals are very poor conductors, and ground currents are therefore carried mainly by ions in the pore waters. Pure water is ionized to only a very small extent and the electrical conductivity of pore waters depends on the presence of dissolved salts, mainly sodium chloride (Figure 1.2). Clay minerals are ionically active and clays conduct well if even slightly moist.

This is *Ohm's law*. The constant of proportionality, *R*, is known as the resistance and is measured in ohms when current (*I*) is in amps and voltage (*V*) is in volts. The reciprocal, conductance, is measured in siemens, also known as mhos. The resistance of a unit cube to current flowing between opposite faces is known as its resistivity ($\rho$) and is measured in ohm-metres (Ωm). The reciprocal, conductivity, is expressed in siemens per metre (Sm−1) or mhos per metre. The resistance of a rectangular block measured between opposite faces is proportional to its resistivity and to the distance *x* between the faces, and inversely proportional to their cross-sectional area, *A*, i.e.

$R = \rho(x/A)$

*Isotropic* materials have the same resistivity in all directions. Most rocks are reasonably isotropic but strongly laminated slates and shales are more resistive across the laminations than parallel to them.

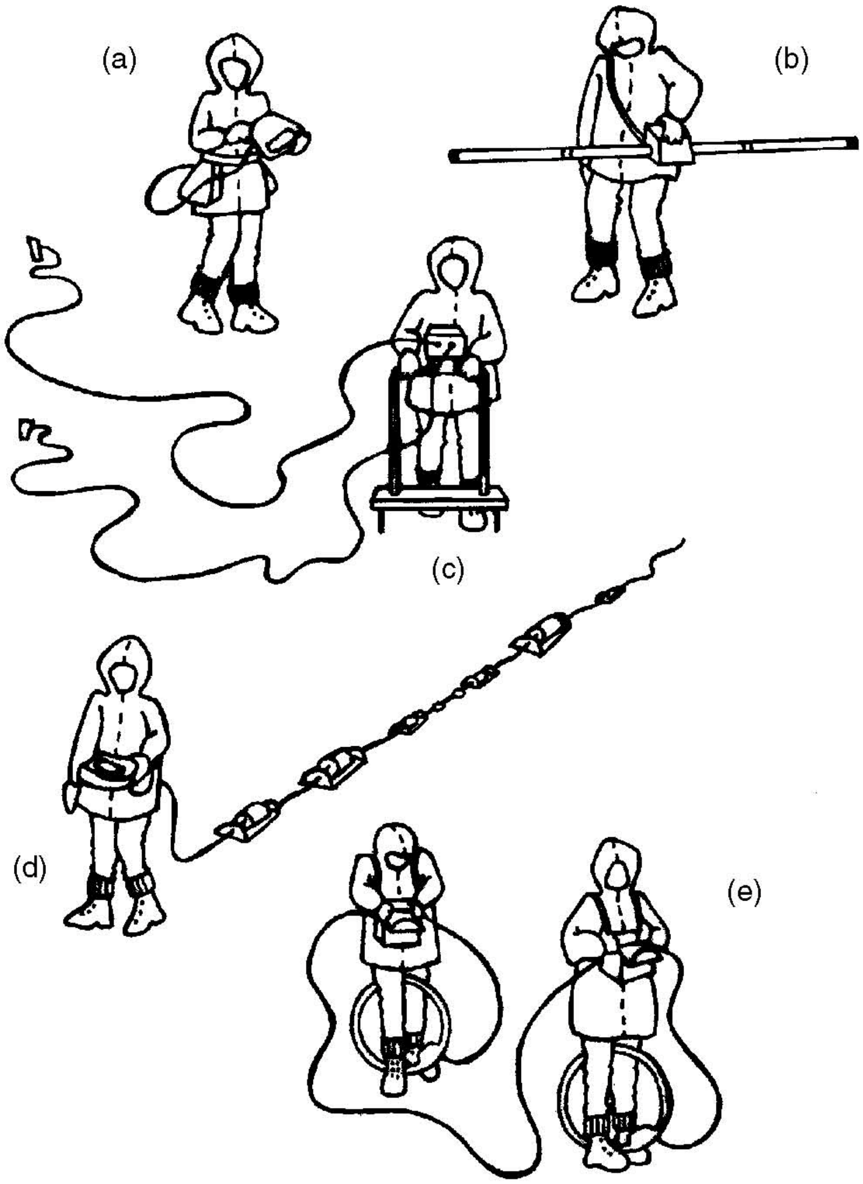


***Figure 1.1*** *Electrical survey methods for archaeology and site investigation. In (a) the operator is using an ABEM Wadi, recording waves from a remote VLF transmitter (). Local source electromagnetic surveys may use two-coil systems such as the Geonics EM31 (b) or EM37 (e) DC resistivity surveys (c) often use the two-electrode array (Section 1.2), with a data logger mounted on a frame built around the portable electrodes. Capacitative- coupling systems (d) do not require direct contact with the ground but give results equivalent to those obtained in DC surveys. There would be serious interference problems if all these systems were used simultaneously in close proximity, as in this illustration.*

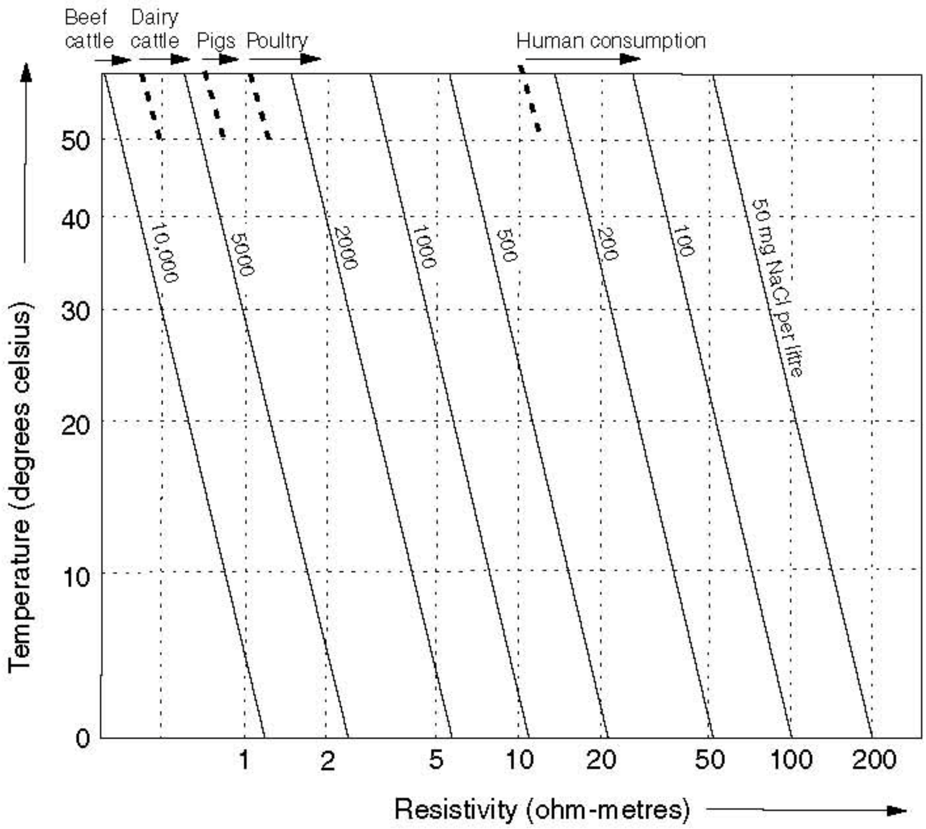


***Figure 1.2*** *Variation of water resistivity with concentration of dissolved NaCl. The uses that can be made of waters of various salinities are also indicated.*
*V = IR*

*3.3 Electrical resistivities of rocks and minerals*

The resistivity of many rocks is roughly equal to the resistivity of the pore fluids divided by the fractional porosity. *Archie's law*, which states that resistivity is inversely proportional to the fractional porosity raised to a power which varies between about 1.2 and 1.8 according to the shape of the matrix grains, provides a closer approximation in most cases. The departures from linearity are not large for common values of porosity (Figure 1.3). Resistivities of common rocks and minerals are listed in Table 1.1 Rocks and minerals are considered to be good, intermediate and poor conductors based on their resistivity contrast. Bulk resistivities of more than 10 000Ωm or less than 1Ωm are rarely encountered in field surveys.

*3.4 Apparent resistivity*

A single electrical measurement tells us very little. The most that can be extracted from it is the resistivity value of a completely homogeneous ground (a homogeneous *half-space*) that would produce the same result when investigated in exactly the same way. This quantity is known as the *apparent resistivity*. Variations in apparent resistivity or its reciprocal, *apparent conductivity*, provide the raw material for interpretation in most electrical surveys. Where electromagnetic methods are being used to detect very good conductors such as sulphide ores or steel drums, target location is more important than determination of precise electrical parameters. Since it is difficult to separate the effects of target size from target conductivity for small targets, results are sometimes presented in terms of the *conductivity –thickness product*.

*3.5 Overburden effects*

Build-ups of salts in the soil produce high conductivity in near-surface layers in many arid tropical areas. These effectively short-circuit current generated at the surface, allowing very little to penetrate to deeper levels. Conductive overburden thus presents problems for all electrical methods, with continuous wave electromagnetic surveys being the most severely affected. Highly resistive surface layers are obstacles only in DC surveys. They may actually be advantageous when EM methods are being used, because attenuation is reduced and depth of investigation is increased.

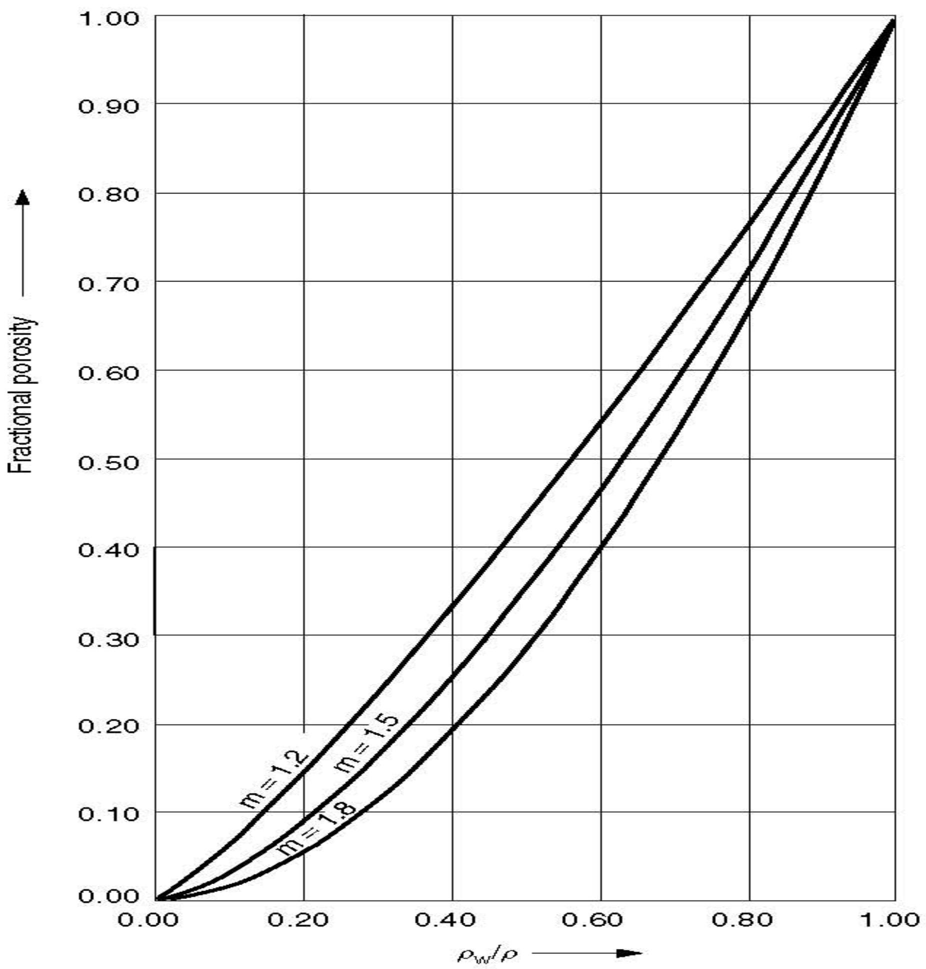

***Figure 1.3*** *Archie's law variation of bulk resistivity, ρ, for rocks with insulating matrix and pore-water resistivity* $\rho_w$. *The index, m, is about 1.2 for spherical grains and about 1.8 for platey or tabular materials*.

***Table 1.1*** *Resistivities of common rocks and ore (Ωm)*

| | |
|---|---|
| *Common rocks* | |
| Topsoil | 50–100 |
| Loose sand | 500–5000 |
| Gravel | 100–600 |
| Clay | 1–100 |
| Weathered bedrock | 100–1000 |
| Sandstone | 200–8000 |
| Limestone | 500–10 000 |
| Greenstone | 500–200 000 |
| Gabbro | 100–500 000 |
| Granite | 200–100 000 |
| Basalt | 200–100 000 |
| Graphitic schist | 10–500 |
| Slates | 500–500 000 |
| Quartzite | 500–800 000 |
| *Ore minerals* | |
| Pyrite (ores) | 0.01–100 |
| Pyrrhotite | 0.001–0.01 |
| Chalcopyrite | 0.005–0.1 |
| Galena | 0.001–100 |
| Sphalerite | 1000–1 000 000 |
| Magnetite | 0.01–1000 |
| Cassiterite | 0.001–10 000 |
| Hematite | 0.01–1 000 000 |

**4.0 Conclusion**

Of all the physical properties of rocks and minerals, electrical resistivity shows the greatest variation. Whereas, range in density, elastic wave velocity, and radioactive content is quite small. However, the resistivity of metallic minerals, may be as small as 0.00005Ohm-m, that of dry, close-grained rocks like gabbro may be as large as 10000000Ohm-m.

## 5.0 Summary

In a looser classification, rocks and minerals are considered to be good, intermediate and poor conductors within the following ranges:

(a) Mineral of resistivity $10^{-8}$ to about 1Ωm

(b) Minerals and rocks of resistivites 1Ωm to 100000000Ωm

(c) Minerals and rocks of resistivities of above 10000000Ωm.

## 6.0 Tutor Marked Assignments

(a) Differentiate between Ohm’s Law and Archie’s Law.
(b) Discuss the basic principles of electrical resistivity and induced polarization methods. Define conductivity and Resistivity.
(c) Name and classify rocks and minerals based on their resistivity contrasts.

## 7.0 References/Further readings

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp.
Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.
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# UNIT 2: DIRECT CURRENT RESISTIVITY METHODS (DC)

## 1.0 Introduction

The concepts of Resistivity and its corresponding definition as well as its properties are very crucial to the study of geophysical survey. Simple observation of any physical phenomena has made it imperative to be interested in how geophysical survey relies on measurements of the voltages or magnetic fields associated with electric currents flowing in the ground.

Electrical methods utilize direct currents or low frequency alternating currents to investigate the electrical properties of subsurface, in contrast to the electromagnetic methods that use alternating electromagnetic fields of higher frequency.

## 2.0 Objectives

At the end of this unit, readers should be able to:

(i) Understand clearly the Direct- Current Resistivity Methods especially its definition and application
(ii) Understand the usefulness of metal electrodes, Non polarising electrodes in application of DC Resistivity methods.
(iii) Know that DC surveys require current generators, voltmeters and electrical contact with the ground.
(iv) show how artificially generated currents are introduced into the ground and the resulting potential differences are measured at the surface.

## 3.0 Main Contents

### *3.1 Direct Current Resistivity Methods*

The currents used in surveys described as ‘direct currents’ or *DC* are seldom actually unidirectional. Reversing the direction of flow allows the effects of unidirectional natural currents to be eliminated by simply summing and averaging the results obtained in the two directions.  DC surveys require current generators, voltmeters and electrical contact with the ground. Cables and electrodes are cheap but vital parts of all systems, and it is with these that much of the noise is associated.

### *3.2 Metal electrodes*

The electrodes used to inject current into the ground are nearly always metal stakes, which in dry ground may have to be hammered into depths of more than 50 cm and be watered to improve contact. Where contact is very poor, salt water and multiple stakes

may be used. In extreme cases, holes may have to be blasted through highly resistive caliche or laterite surface layers. Metal stake electrodes come in many forms. Lengths of drill steel are excellent if the ground is stony and heavy hammering necessary. Pointed lengths of angle-iron are only slightly less robust and have larger contact areas. If the ground is soft and the main consideration is speed, large numbers of metal tent pegs can be pushed in along a traverse line by an advance party.
Problems can arise at voltage electrodes, because *polarization* voltages are generated wherever metals are in contact with the groundwater. However, the reversal of current flow that is routine in conventional DC surveys generally achieves acceptable levels of cancellation of these effects. Voltage magnitudes depend on the metals concerned. They are, for instance, small when electrodes are made of stainless steel.

*3.3 Non-polarizing electrodes*

Polarization voltages are potentially serious sources of noise in SP surveys, which involve the measurement of natural potentials and in induced polarization (IP) surveys. In these cases, non-polarizing electrodes must be used. Their design relies on the fact that the one exception to the rule that a metallic conductor in contact with an electrolyte generates a contact potential occurs when the metal is in contact with a saturated solution of one of its own salts. Most non-polarizing electrodes consist of copper rods in contact with saturated solutions of copper sulphate. The rod is attached to the lid of a container or *pot* with a porous base of wood, or, more commonly, unglazed earthenware (Figure 1.4). Contact with the ground is made via the solution that leaks through the base. Some solid copper sulphate should be kept in the pot to ensure saturation and the temptation to 'top up' with fresh water must be resisted, as voltages will be generated if any part of the solution is less than saturated. The high resistance of these electrodes is not generally important because currents should not flow in voltage-measuring circuits.

In induced polarization surveys it may very occasionally be desirable to use non-polarizing *current* electrodes but not only does resistance then become a problem but also the electrodes deteriorate rapidly due to electrolytic dissolution and deposition of copper. Copper sulphate solution gets everywhere and rots everything and, despite some theoretical advantages, non-polarizing electrodes are seldom used in routine DC surveys.

*3.4 Cables*

The cables used in DC and IP surveys are traditionally single core, multi-strand copper wires insulated by plastic or rubber coatings. Thickness is usually dictated by the need for mechanical strength rather than low resistance, since contact resistances are nearly always very much higher than cable resistance. Steel reinforcement may be needed for long cables.


***Figure 1.4*** *Porous-pot non-polarizing electrodes designed to be pushed into a shallow scraping made by a boot heel. Other types can be pushed into a hole made by a crowbar or geological pick.*

In virtually all surveys, at least two of the four cables will be long, and the good practice in cable handling described in Section 3.3 is essential if delays are to be avoided. Multicore cables that can be linked to multiple electrodes are becoming increasingly popular, since, once the cable has been laid out and connected up, a series of readings with different combinations of current and voltage electrodes can be made using a selector switch.  Power lines can be sources of noise, and it may be necessary to keep the survey cables well away from their obvious or suspected locations. The 50 or 60 Hz power frequencies are very different from the 2 to 0.5 Hz frequencies at which current is reversed in most DC and IP surveys but can affect the very sensitive modern instruments, particularly in time-domain IP work. Happily, the results produced are usually either absurd or non-existent, rather than misleading.

Cables are usually connected to electrodes by crocodile clips, since screw connections can be difficult to use and are easily damaged by careless hammer blows. Clips are, however, easily lost and every member of a field crew should carry at least one spare, a screwdriver and a small pair of pliers.

*3.5 Generators and transmitters*

The instruments that control and measure current in DC and IP surveys are known as *transmitters*. Most deliver square wave currents, reversing the direction of flow with cycle times of between 0.5 and 2 seconds. The lower limit is set by the need to minimize inductive (electromagnetic) and capacitative effects, the upper by the need to achieve an acceptable rate of coverage. Power sources for the transmitters may be dry or rechargeable batteries or motor generators. Hand-cranked generators (*Meggers*) have been used for DC surveys but are now very rare. Outputs of several kVA may be needed if current electrodes are more than one or two hundred metres apart, and the generators then used are not only not very portable but supply power at levels that can be lethal. Stringent precautions must then be observed, not only in handling the electrodes but also in ensuring the safety of passers-by and livestock along the whole lengths of the current cables. In at least one (Australian) survey, a serious grass fire was caused by a poorly insulated time-domain IP transmitter cable.

### *3.6 Receivers*

The instruments that measure voltage in DC and IP surveys are known as *receivers*. The primary requirement is that negligible current be drawn from the ground. High-sensitivity moving-coil instruments and potentiometric (voltage balancing) circuits were once used but have been almost entirely replaced by units based on field-effect transistors (FETs).

In most of the low-power DC instruments now on the market, the transmitters and receivers are combined in single units on which readings are displayed directly in ohms. To allow noise levels to be assessed and SP surveys to be carried out, voltages can be measured even when no current is being supplied. In all other cases, current levels must be either predetermined or monitored, since low currents may affect the validity of the results. In modern instruments the desired current settings, cycle periods, numbers of cycles, read-out formats and, in some cases, voltage ranges are entered via front-panel key-pads or switches. The number of cycles used represents a compromise between speed of coverage and good signal-to-noise ratio. The reading is usually updated as each cycle is completed, and the number of cycles selected should be sufficient to allow this reading to stabilize.

Some indication will usually be given on the display of error conditions such as low current, low voltage and incorrect or missing connections. These warnings may be expressed by numerical codes that are meaningless without the handbook. If all else fails, read it.

## 4.0 Conclusion

In this section, it has been shown that DC surveys require current generators, voltmeters and electrical contact with the ground. Cables and electrodes are vital parts of all systems, and it is with these that much of the noise is associated. In most of the low-power DC instruments now on the market, the transmitters and receivers are combined in single units on which readings are displayed directly in ohms. To allow noise levels to be assessed and SP surveys to be carried out, voltages can be measured even when no current is being supplied. In all other cases, current levels must be either predetermined or monitored, since low currents may affect the validity of the results.

In modern instruments the desired current settings, cycle periods, numbers of cycles, read-out formats and, in some cases, voltage ranges are entered via front-panel key-pads or switches. The number of cycles used represents a compromise between speed of coverage and good signal-to-noise ratio. The reading is usually updated as each cycle is completed, and the number of cycles selected should be sufficient to allow this reading to stabilize.

## 5.0 Summary

To conduct surveys with DC techniques, artificially – generated electric currents are used. Metal electrodes, non-polarizing electrodes, cables, generators and transmitters/receivers are required.

## 6.0 Tutor Marked Assignments

(a) Why was the currents used in DC surveys are termed ‘direct currents’?
(b) Name the essential accessories in DC survey instrument.
(c) What is the significant of noise in DC data?

## 7.0 References/Further readings

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.
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# UNIT 3: VARYING CURRENT METHODS

## 1.0 Introduction

In this unit, Varying Current Methods are discussed. Alternatively electrical currents circulating in wires and loops can cause currents to flow in the ground without actual physical contact using either inductive or capacitative coupling. Non- contacting methods are obviously essential in airborne work but can also be very useful on the ground, since making direct electrical contact is a tedious business and may not even be possible where the surface is concrete, asphalt, ice or permafrost.

Electromagnetic (EM) surveying methods make use of the response of the ground to the propagation of electromagnetic fields, which are composed of an alternating electric intensity and magnetizing force. The details of this technique are explained in module 4.

## 2.0 Objectives

At the end of this unit, readers should be able to:

(i) Know that current are caused to flow in the ground by alternating electrical or magnetic fields obtain their energy from the fields and so reduce their penetration

(ii) Understand that varying magnetic field associated with an electromagnetic wave will induce a voltage (emf) at right-angles to the direction of variation

(iii) Know that most continuous wave system, the energizing current has the form of a sine wave, but may not, as a true sine wave should, be zero at zero time (sinusoidal)

(iv) Show how alternating electric currents are used in the characterization of subsurface geology via transmitter and receiver system.

## 3.0 Main Contents

### *3.1 Varying Current Methods*

Alternating electrical currents circulating in wires and loops can cause currents to flow in the ground without actual physical contact, using either inductive or capacitative coupling. Non-contacting methods are obviously essential in airborne work but can also be very useful on the ground, since making direct electrical contact is a tedious business and may not even be possible where the surface is concrete, asphalt, ice or permafrost.

*3.2 Depth penetration*

Currents that are caused to flow in the ground by alternating electrical or magnetic fields obtain their energy from the fields and so reduce their penetration. Attenuation follows an exponential law governed by an attenuation constant ($\alpha$) given by:

$$\alpha = \omega[\mu_a \varepsilon_a\{(\sqrt{(1 + \sigma^2/\omega^2\varepsilon_a^2)} - 1\}/2]^{1/2}$$

$\mu_a$ and $\varepsilon_a$ are the absolute values of, respectively, magnetic permeability and electrical permittivity and $\omega$ (=$2\pi f$ ) is the *angular frequency*. The reciprocal of the attenuation constant is known as the *skin depth* and is equal to the distance over which the signal falls to $1/e$ of its original value. Since $e$, the base of natural logarithms, is approximately equal to 2.718, signal strength decreases by almost two-thirds over a single skin depth.

The rather daunting attenuation equation simplifies considerably under certain limiting conditions. Under most survey conditions, the ground conductivity, $\sigma$ , is much greater than $\omega\varepsilon_a$ and $\alpha$ is then approximately equal to $\sqrt{(\mu_a\sigma\omega)}$ . If, as is usually the case, the variations in magnetic permeability are small, the skin depth *(*=$1/\alpha$*)*, in metres, is approximately equal to 500 divided by the square roots of the frequency and the conductivity (Figure 1.5).

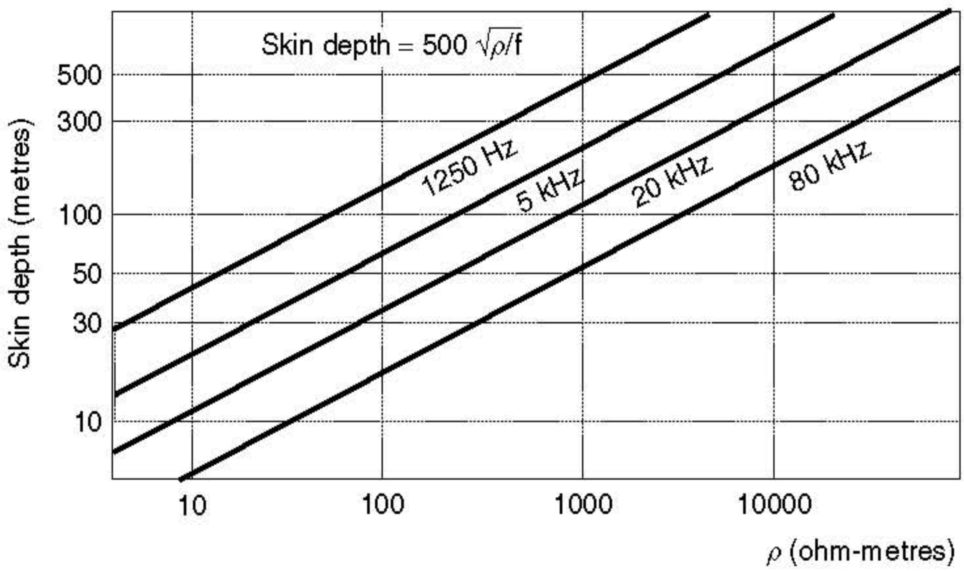


***Figure `1.5** Variation in skin depth,* d*, with frequency and resistivity.*

The depth of investigation in situations where skin depth is the limiting factor is commonly quoted as equal to the skin depth divided by √2, i.e. to about 350√ *(ρ/f )*. However, the separation between the source and the receiver also affects penetration and is the dominant factor if smaller than the skin depth.

*3.3 Induction*

The varying magnetic field associated with an electromagnetic wave will induce a voltage (electromotive force or *emf* ) at right-angles to the direction of variation, and currents will flow in any nearby conductors that form parts of closed circuits. The equations governing this phenomenon are relatively simple but geological conductors are very complex and for theoretical analyses the induced currents, known as *eddy currents*, are approximated by greatly simplified models.

The magnitudes of induced currents are determined by the rates of change of currents in the inducing circuits and by a geometrical parameter known as the *mutual inductance*. Mutual inductances are large, and conductors are said to be *well coupled* if there are long adjacent conduction paths, if the magnetic field changes are at right-angles to directions of easy current flow and if magnetic materials are present to enhance field strengths. When current changes in a circuit, an opposing emf is induced in that circuit. As a result, a tightly wound coil strongly resists current changes and is said to have a high *impedance* and a large *self-inductance*.

*3.4 Phase*

In most continuous wave systems, the energizing current has the form of a sine wave, but may not, as a true sine wave should, be zero at zero time. Such waves are termed *sinusoidal*. The difference between time zero and the zero point on the wave is usually measured as an angle related to the 360◦ or $2\pi$ radians of a complete cycle, and is known as the *phase angle* (Figure 1.6). Induced currents and their associated secondary magnetic fields differ in phase from the primary field and can, in accordance with a fundamental property of sinusoidal waves, be resolved into components that are in-phase and 90◦ out of phase with the primary (Figure 1.6). These components are sometimes known as *real* and *imaginary* respectively, the terms deriving originally from the mathematics of complex numbers. The *out-of-phase* component is also (more accurately and less confusingly) described as being in *phase quadrature* with the primary signal.

Since electromagnetic waves travel at the speed of light and not instantaneously, their phase changes with distance from the transmitter. The small distances between transmitters and receivers in most geophysical surveys ensure that these shifts are negligible and can be ignored.

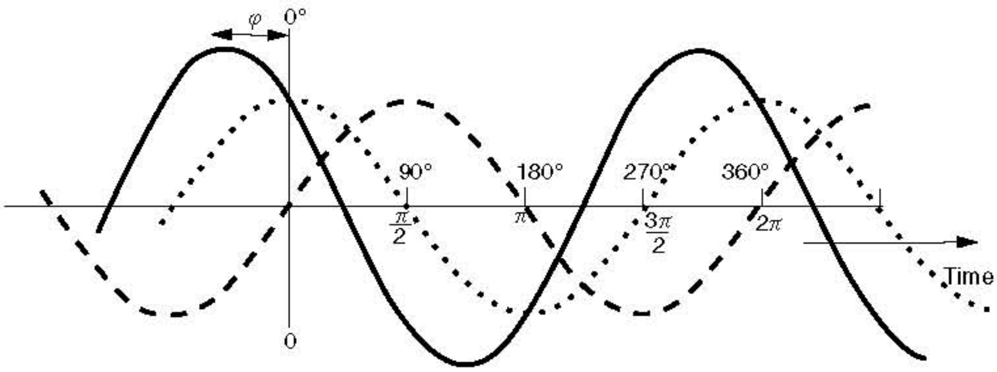


*__Figure 1.6__ Phase in sinusoidal waves. The wave drawn with a solid line is sinusoidal, with a phase angle φ, as compared to the 'zero phase' reference (cosine) sinusoid (dotted curve). The phase difference between the dashed (sine) and dotted waves is 90◦ or π/2 radians and the two are therefore in phase quadrature. The amplitudes are such that subtracting the sine wave from the cosine wave would reconstitute the solid-line wave.*

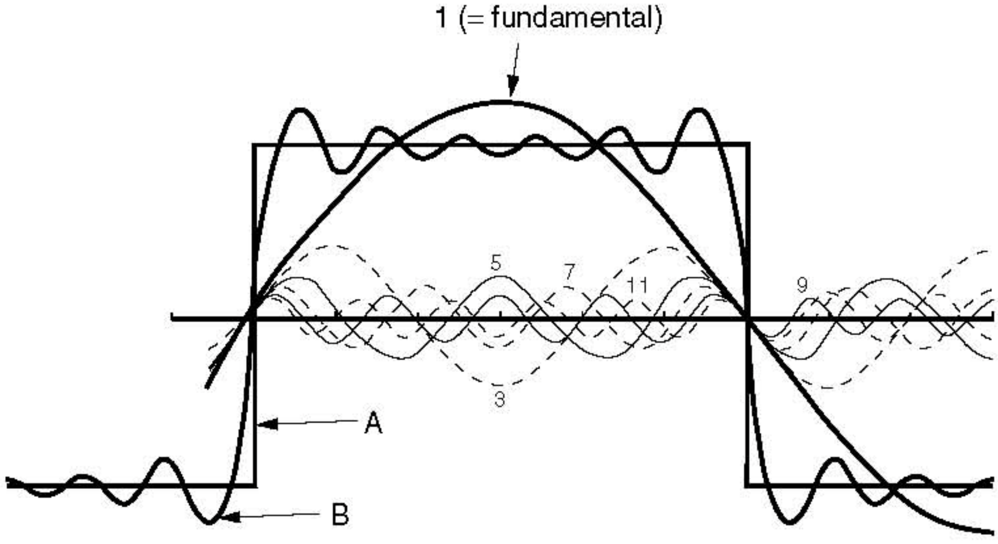


*__Figure 1.7__ The square wave as a multi-frequency sinusoid. A reasonable approximation to the square wave, A, can be obtained by adding the first five odd harmonics (integer multiples 3, 5, 7, 9 and 11) of the fundamental frequency to the fundamental. Using the amplitudes for each of these component waves determined using the techniques of Fourier analysis, this gives the summed wave B. The addition of higher odd harmonics with appropriate amplitudes would further improve the approximation.*

*3.5 Transients*

Conventional or *continuous wave* (*CW*) electromagnetic methods rely on signals generated by sinusoidal currents circulating in coils or grounded wires. Additional information can be obtained by carrying out surveys at two or more different frequencies. The skin-depth relationships (Figure 1.5) indicate that penetration will increase if frequencies are reduced. However, resolution of small targets will decrease. As an alternative to sinusoidal signals, currents circulating in a transmitter coil or wire can be terminated abruptly. These *transient electromagnetic* (*TEM*) methods are effectively multi-frequency, because a square wave contains elements of all the odd harmonics of the fundamental up to theoretically infinite frequency (Figure 1.7). They have many advantages over CW methods, most of which derive from the fact that the measurements are of the effects of currents produced by, and circulating after, the termination of the primary current. There is thus no possibility of part of the primary field 'leaking' into secondary field measurements, either electronically or because of errors in coil positioning.

Nomenclature is a problem in electrical work. Even in the so-called *direct current* (DC) surveys, current flow is usually reversed at intervals of one or two seconds. Moreover, surveys in which high frequency alternating current is made to flow in the ground by capacitative coupling (c-c) have more in common with DC than with electromagnetic methods, and are also discussed in this section.

**4.0 Conclusion**

Alternating electrical currents circulating in wires and loops can cause currents to flow in the ground without actual physical contact, using either inductive or capacitative coupling. Non-contacting methods are obviously essential in airborne work but can also be very useful on the ground, since making direct electrical contact is a tedious business and may not even be possible where the surface is concrete, asphalt, ice or permafrost. All anomalous bodies with high electrical conductivity produce strong secondary electromagnetic fields.

**5.0 Summary**

Electromagnetic (EM) surveying methods make use of the response of the ground to the propagation of electromagnetic fields, which are composed of an alternating electric intensity and magnetizing force. Primary electromagnetic fields may be generated by passing alternating current through a small coil made up of many turns of wire or through a large loop of wire. In the presence of a conducting body the magnetic component of the electromagnetic field penetrating the ground induces alternating currents, or eddy current, to flow in the conductor.

**6.0 Tutor Marked Assignments**

(a) When would you describe conductors as being well coupled?
(b) How can Nomenclature be a problem in electrical work?

## 7.0 References/Further readings

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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# MODULE 2

**Unit 1 Resistivity Method**

**Unit 2 Resistivity Profiling**

**Unit 3 Resistivity Depth Sounding**

## UNIT 1: RESISTIVITY METHOD

### 1.0 Introduction

In this method, like other DC techniques, artificially generated electric currents are introduced into the ground and the resulting potential differences are measured at the surface. Deviations from the pattern of potential differences expected from homogeneous ground provide information on the form and electrical properties of subsurface inhomogeneities.

### 2.0 Objectives

At the end of this unit, readers should be able to:

(i) Understand the concept of DC survey fundamentals which includes Apparent resistivity, electrode arrays and Wenner array.
(ii) Understand commons electrodes array such as wenner array, two electrode, Schlumberger and gradient methods of arrangement. etc.
(iii) Familiar with the common electrode arrays descriptions.
(iv) explain how resistivity contrasts could be used to unravel the subsurface geo-materials.
(v) Other objectives include explanation on how resistivity method could be used in hydrogeology, mineral and engineering studies.

### 3.0 Main Contents

*3.1 Survey Fundamentals*

The 'obvious' method of measuring ground resistivity by simultaneously passing current and measuring voltage between a single pair of grounded electrodes does not work, because of contact resistances that depend on such things as ground moisture and contact area and which may amount to thousands of ohms. The problem can be avoided if voltage measurements are made between a second pair of electrodes using a high-impedance voltmeter. Such a voltmeter draws virtually no current, and the voltage drop through the electrodes is therefore negligible. The resistances at the current electrodes limit current flow but do not affect resistivity calculations. A geometric factor is needed to convert the readings obtained with these four-electrode *arrays* to resistivity.

The result of any single measurement with any array could be interpreted as due to homogeneous ground with a constant resistivity. The geometric factors used to calculate this *apparent resistivity*, $\rho\alpha$, can be derived from the formula:

$$V = \rho I/2\pi a$$

for the electric potential $V$ at a distance $a$ from a point electrode at the surface of a *uniform half-space* (homogeneous ground) of resistivity $\rho$ (referenced to a zero potential at infinity). The current $I$ may be positive (if into the ground) or negative. For arrays, the potential at any voltage electrode is equal to the sum of the contributions from the individual current electrodes. In a four-electrode survey over homogeneous ground:

$$V = I\rho(1/[\mathrm{Pp}] - 1/[\mathrm{Np}] - 1/[\mathrm{Pn}] + 1/[\mathrm{Nn}])/2\pi$$

where $V$ is the voltage difference between electrodes P and N due to a current $I$ flowing between electrodes p and n, and the quantities in square brackets represent inter-electrode distances. Geometric factors are not affected by interchanging current and voltage electrodes but voltage electrode spacings are normally kept small to minimize the effects of natural potentials.

### *3.2 Electrode arrays*

Figure 2.1 shows some common electrode arrays and their geometric factors. The names are those in general use and may upset pedants. A dipole, for example, *should* consist of two electrodes separated by a distance that is negligible compared to the distance to any other electrode. Application of the term to the dipole–dipole and pole–dipole arrays, where the distance to the next electrode is usually from 1 to 6 times the ‘dipole’ spacing, is thus formally incorrect. Not many people worry about this.

The distance to a fixed electrode ‘at infinity’ should be at least 10, and ideally 30, times the distance between any two mobile electrodes. The long cables required can impede field work and may also act as aerials, picking up stray electromagnetic signals (inductive noise) that can affect the readings.

**Example 2.1**

Geometrical factor for the Wenner array (Figure 1.1a).

Pp = $a$  Pn = $2a$  Np = $2a$  Nn = $a$

$$V = I\rho\left(1 - \frac{1}{2} - \frac{1}{2} + 1\right)\Big/ 2\pi a = I\rho/2\pi a$$

i.e. $\rho = 2\pi a \cdot V/I$

*3.3 Array descriptions*

*Wenner array:* very widely used, and supported by a vast amount of interpretational literature and computer packages. The 'standard' array against which others are often assessed. *Two-electrode (pole–pole) array:* Theoretically interesting since it is possible to calculate from readings taken along a traverse the results that would be obtained from any other type of array, providing coverage is adequate. However, the noise that accumulates when large numbers of results obtained with closely spaced electrodes are added prevents any practical use being made of this fact. The array is very popular in archaeological work because it lends itself to rapid one-person operation. As the *normal* array, it is one of the standards in electrical well logging.

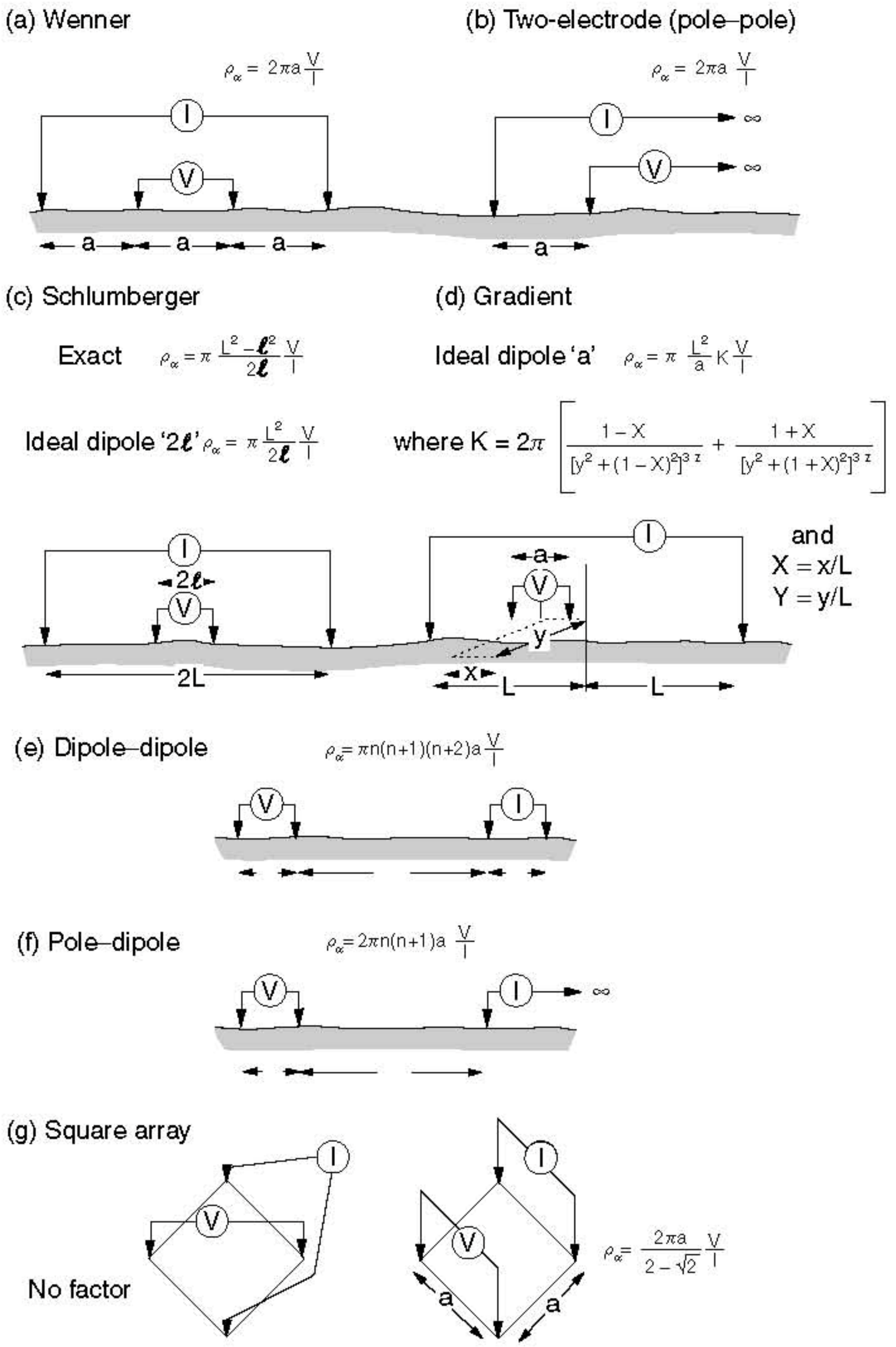


***Figure 2.1*** *Some common electrode arrays and their geometric factors. (a) Wenner; (b) Two-electrode; (c) Schlumberger; (d) Gradient; (e) Dipole–dipole; (f) Pole–dipole; (g) Square array; (left) Diagonal; (right) Broadside. There is no geometrical factor for the diagonal square array, as no voltage difference is observed over homogeneous ground.*

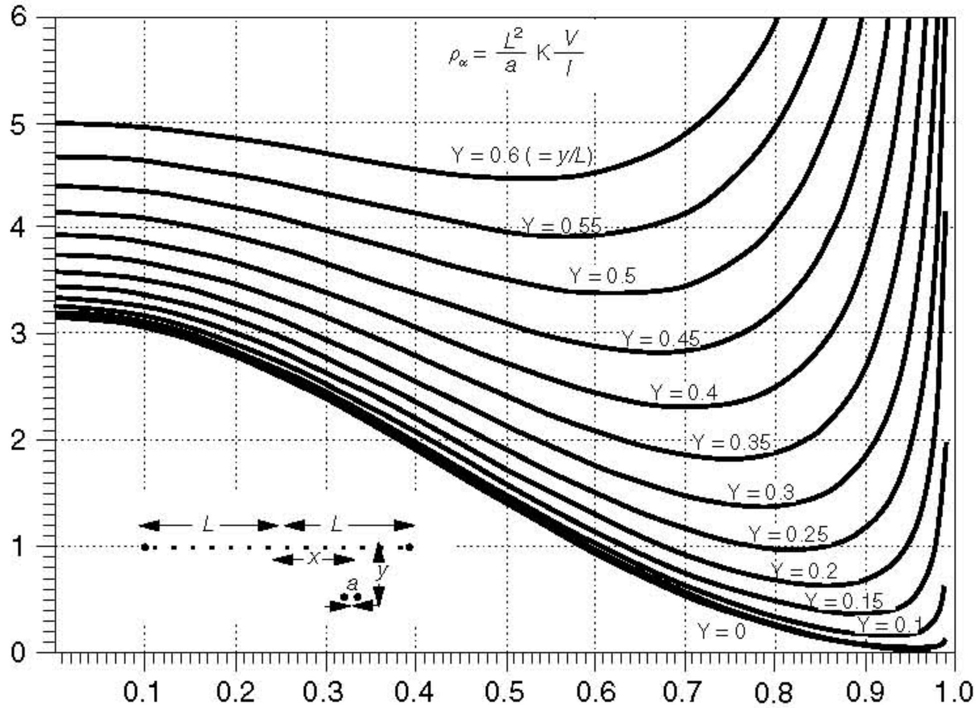


***Figure 2.2****Variation in gradient array geometric factor with distance along and across line. Array total length* 2*L, voltage dipole length a*.

*Schlumberger array:* The only array to rival the Wenner in availability of interpretational material, all of which relates to the 'ideal' array with negligible distance between the inner electrodes. Favoured, along with the Wenner, for electrical depth-sounding work.

*Gradient array:* Widely used for reconnaissance. Large numbers of readings can be taken on parallel traverses without moving the current electrodes if powerful generators are available. Figure 2.2 shows how the geometrical factor given in Figure 2.1d varies with the position of the voltage dipole.

*Dipole–dipole (Eltran) array:* Popular in induced polarization (IP) work because the complete separation of current and voltage circuits reduces the vulnerability to inductive noise. A considerable body of interpretational material is available. Information from different depths is obtained by changing *n*. In principle, the larger the value of *n*, the deeper the penetration of the current path sampled. Results are usually plotted as pseudo-sections .

*Pole–dipole array:* Produces asymmetric anomalies that are consequently more difficult to interpret than those produced by symmetric arrays. Peaks are displaced from the centres of conductive or chargeable bodies and electrode positions have to be recorded with especial care. Values are usually plotted at the point mid-way between the moving voltage electrodes but this is not a universally agreed standard. Results can be displayed as pseudo-sections, with depth penetration varied by varying $n$.

*Square array:* Four electrodes positioned at the corners of a square are variously combined into voltage and current pairs. Depth soundings are made by expanding the square. In traversing, the entire array is moved laterally. Inconvenient, but can provide an experienced interpreter with vital information about ground anisotropy and in-homogeneity. Few published case histories or type curves.

*Lee array:* Resembles the Wenner array but has an additional central electrode. The voltage differences from the centre to the two 'normal' voltage electrodes give a measure of ground in-homogeneity. The two values can be summed for application of the Wenner formula.

*Offset Wenner:* Similar to the Lee array but with all five electrodes the same distance apart. Measurements made using the four right-hand and the four left-hand electrodes separately as standard Wenner arrays are averaged to give apparent resistivity and differenced to provide a measure of ground variability.

*Focused arrays:* Multi-electrode arrays have been designed which supposedly focus current into the ground and give deep penetration without large expansion. Arguably, this is an attempt to do the impossible, and the arrays should be used only under the guidance of an experienced interpreter.

### *3.4 Signal-contribution sections*

Current-flow patterns for one and two layered earths are shown in Figure 2.3.
Near-surface in-homogeneities strongly influence the choice of array. Their effects are graphically illustrated by contours of the *signal contributions* that are made by each unit volume of ground to the measured voltage, and hence to the apparent resistivity (Figure 2.3). For linear arrays the contours have the same appearance in any plane, whether vertical, horizontal or dipping, through the line of electrodes (i.e. they are semicircles when the array is viewed end on).

A reasonable first reaction to Figure 2.3 is that useful resistivity surveys are impossible, as the contributions from regions close to the electrodes are very large. Some disillusioned clients would endorse this view. However, the variations in sign imply that a conductive near-surface layer will in some places increase and in other places decrease the apparent resistivity.

In homogeneous ground these effects can cancel quite precisely. When a Wenner or dipole–dipole array is expanded, all the electrodes are moved and the contributions from near-surface bodies vary from reading to reading. With a Schlumberger array, near-surface effects vary much less, provided that only the outer electrodes are moved, and for this reason the array is often preferred for depth sounding. However, offset techniques allow excellent results to be obtained with the Wenner.

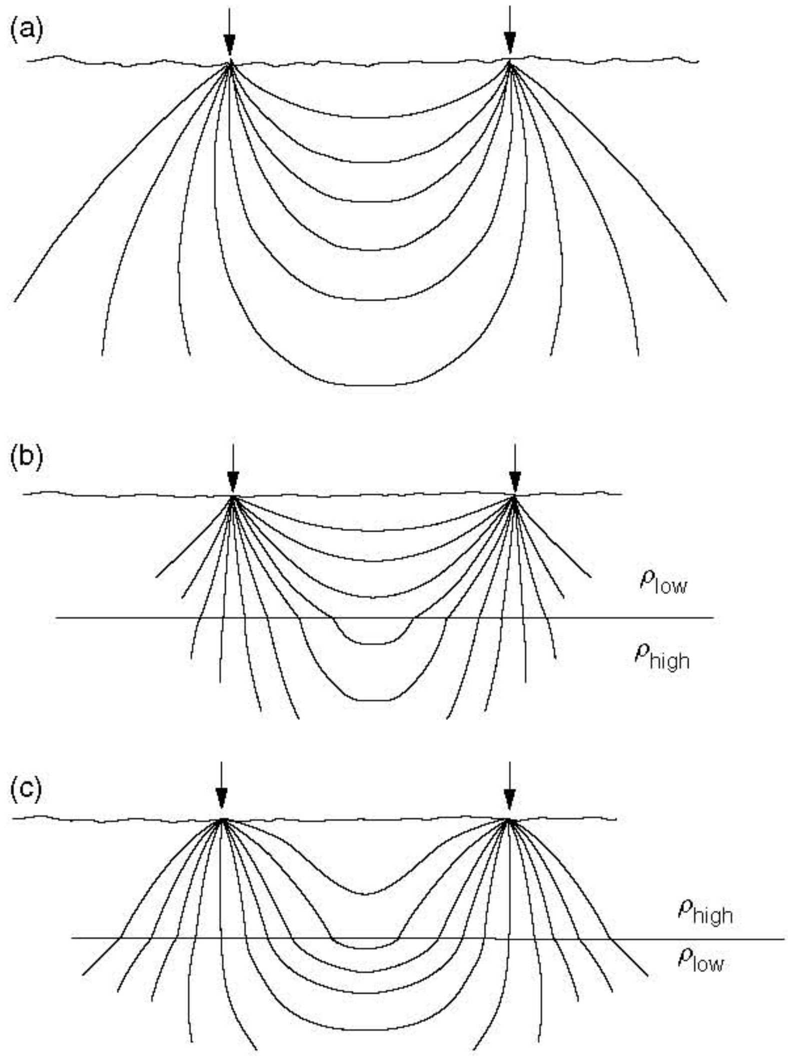


***Figure 2.3*** *Current flow patterns for (a) uniform half-space; (b) two-layer ground with lower resistivity in upper layer; (c) two-layer ground with higher resistivity in upper layer*.

Near-surface effects may be large when a gradient or two-electrode array is used for profiling but are also very local. A smoothing filter can be applied.

*3.5 Depth penetration*

Arrays are usually chosen at least partly for their depth penetration, which is almost impossible to define because the depth to which a given fraction of current penetrates depends on the layering as well as on the separation between the current electrodes. Voltage electrode positions determine which

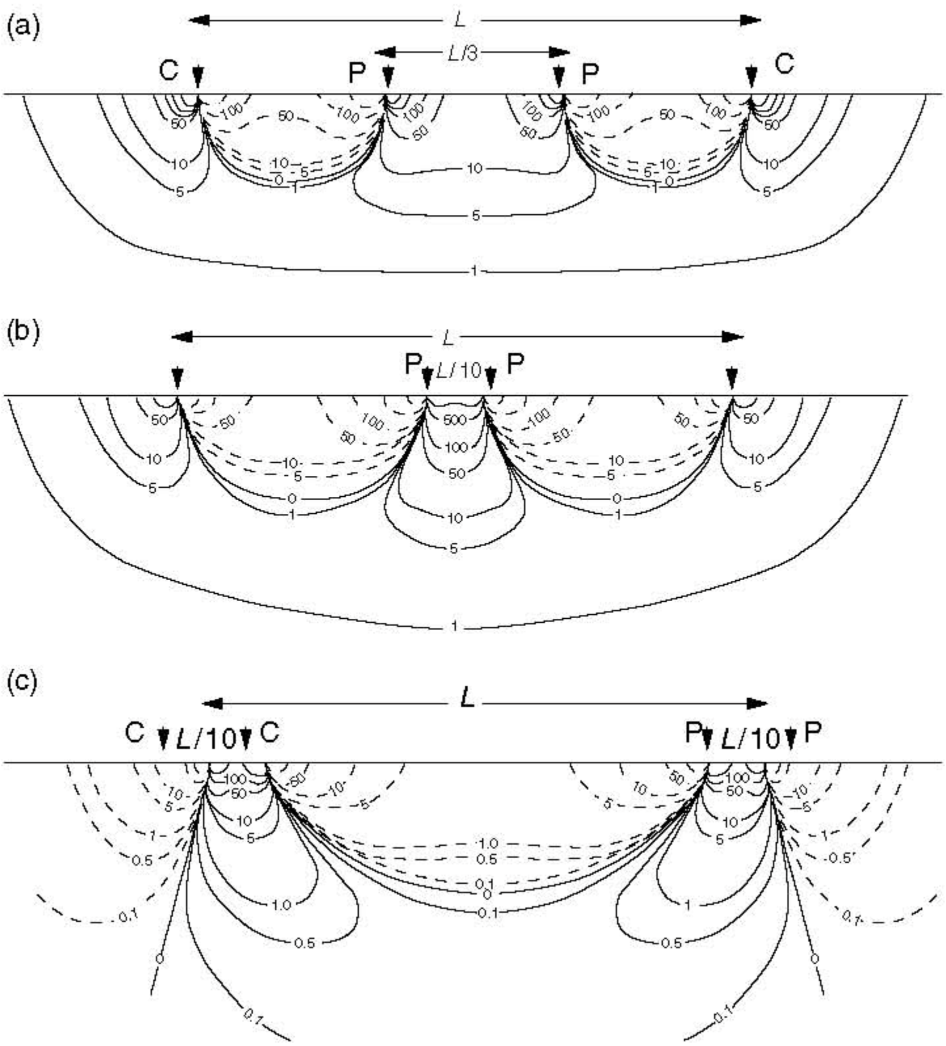


***Figure 2.4*** *Signal contribution sections for (a) Wenner; (b) Schlumberger and (c) dipole–dipole arrays. Contours show relative contributions to the signal from unit volumes of homogeneous ground. Dashed lines indicate negative values.*

part of the current field is sampled, and the penetrations of the Wenner and Schlumberger arrays are thus likely to be very similar for similar total array lengths. For either array, the expansion at which the existence of a deep interface first becomes evident depends on the resistivity contrast (and the levels of background noise) but is of the order of half the spacing between the outer electrodes (Figure 2.4). Quantitative determination of the resistivity change would, of course, require much greater expansion. For any array, there is also an expansion at which the effect of a thin horizontal layer of different resistivity in otherwise homogeneous ground is

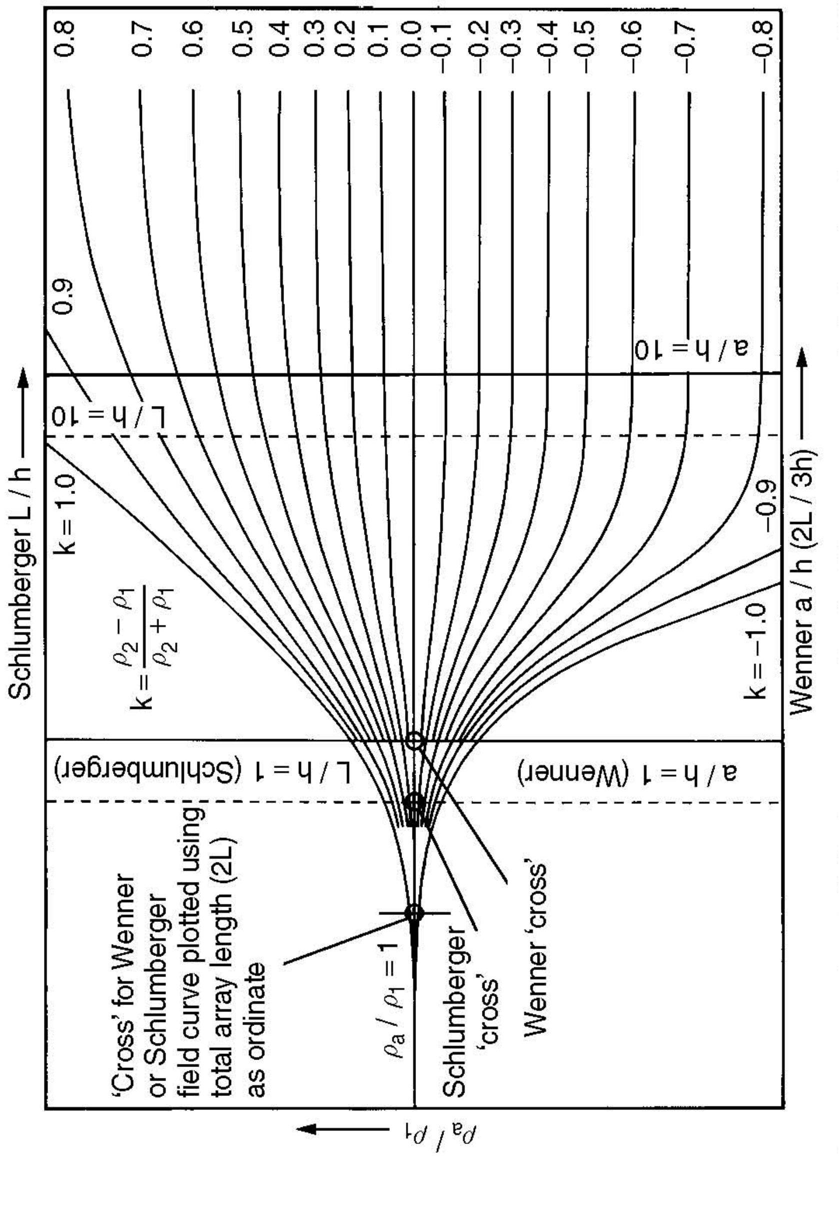


***Figure 2.5*** *Two-layer apparent resistivity type curves for the Wenner array, plotted on log-log paper. When matched to a field curve obtained over a two-layer earth, the line* $a/h = 1$ *points to the depth of the interface and the line* $\rho a/\rho 1 = 1$ *points to the resistivity of the upper layer. The value of k giving the best fit to the field curve allows the value* $\rho 2$ *of the lower layer resistivity to be calculated. The same curves can be used, to a good approximation, for Schlumberger depth sounding with the depth to the interface given by the line* $L/h = 1$.

a maximum. It is, perhaps, to be expected that much greater expansion is needed in this case than is needed simply to detect an interface, and the plots in Figure 2.6, for the Wenner, Schlumberger and dipole–dipole arrays, confirm this. By this criterion, the dipole–dipole is the most and the Wenner is the least penetrative array. The Wenner peak occurs when the array is 10 times as broad as the conductor is deep, and the Sclumberger is only a little better. Figure 2.5 suggests that at these expansions a two-layer earth would be interpretable for most values of resistivity contrast.

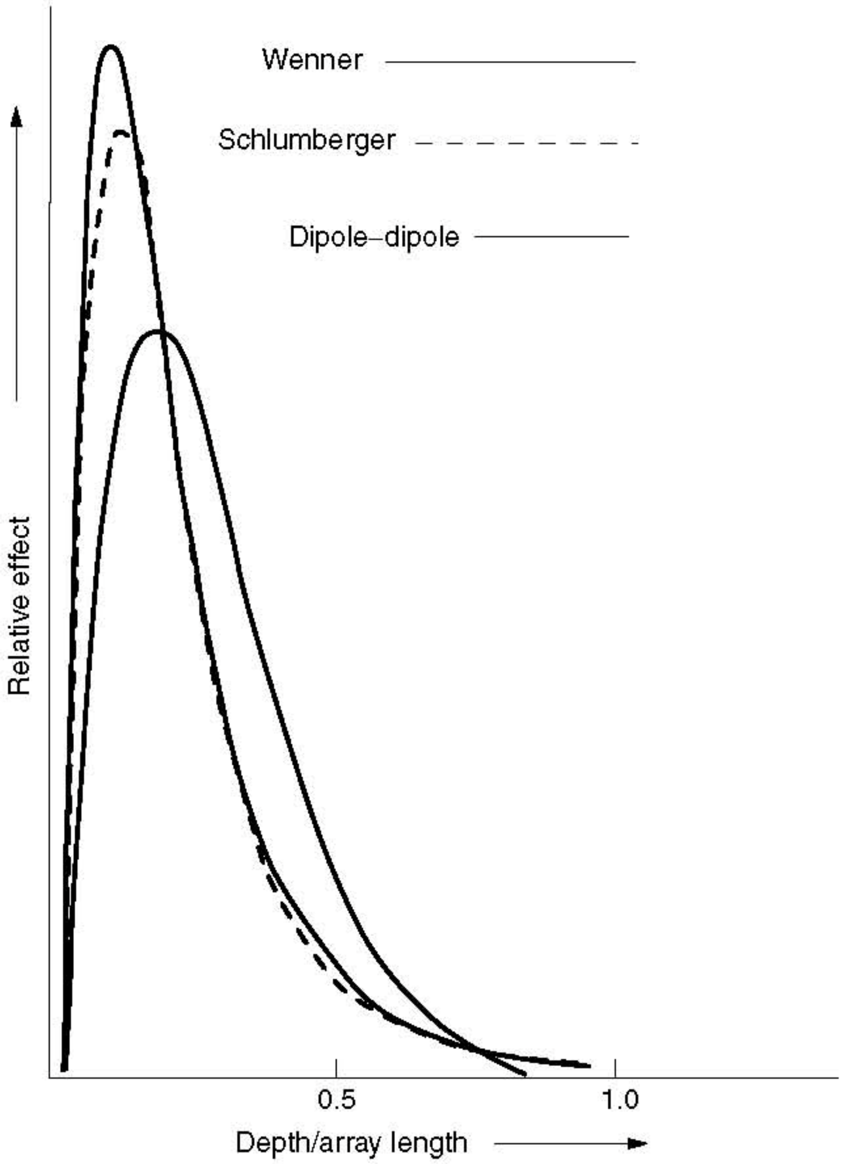


***Figure 2.6*** *Relative effect of a thin, horizontal high-resistance bed in otherwise homogeneous ground. The areas under the curves have been made equal, concealing the fact that the voltage observed using the Schlumberger array will be somewhat less, and with the dipole–dipole array very much less, than with the Wenner array.*

Figure 2.6 also shows the Wenner curve to be the most sharply peaked, indicating superior vertical resolving power. This is confirmed by the signal contribution contours (Figure 2.4), which are slightly flatter at depth for the Wenner than for the Schlumberger, indicating that the Wenner locates flatlying interfaces more accurately. The signal-contribution contours for the dipole–dipole array are near vertical in some places at considerable depths, indicating poor vertical resolution and suggesting that the array is best suited to mapping lateral changes.

*3.6 Noise in electrical surveys*

Electrodes may in principle be positioned on the ground surface to any desired degree of accuracy (although errors are always possible and become more likely as separations increase). Most modern instruments provide current at one of a number of preset levels and fluctuations in supply are generally small and unimportant. Noise therefore enters the apparent resistivity values almost entirely via the voltage measurements, the ultimate limit being determined by voltmeter sensitivity. There may also be noise due to induction in the cables and also to natural voltages, which may vary with time and so be incompletely cancelled by reversing the current flow and averaging. Large separations and long cables should be avoided if possible, but the most effective method of improving signal/noise ratio is to increase the signal strength. Modern instruments often provide observers with direct readings of *V/I*, measured in ohms, and so tend to conceal voltage magnitudes. Small ohm values indicate small voltages but current levels also have to be taken into account. There are physical limits to the amount of current any given instrument can supply to the ground and it may be necessary to choose arrays that give large voltages for a given current flow, as determined by the geometric factor. The Wenner and two-electrode arrays score more highly in this respect than most other arrays.

For a given input current, the voltages measured using a Schlumberger array are always less than those for a Wenner array of the same overall length, because the separation between the voltage electrodes is always smaller. For the dipole–dipole array, the comparison depends upon the $n$ parameter but even for $n = 1$ (i.e. for an array very similar to the Wenner in appearance), the signal strength is smaller than for the Wenner by a factor of three. The differences between the gradient and two-electrode reconnaissance arrays are even more striking. If the distances to the fixed electrodes are 30 times the dipole separation, the two-electrode voltage signal is more than150 times the gradient array signal for the same current. However, the gradient array voltage cable is shorter and easier to handle, and less vulnerable to inductive noise. Much larger currents can safely be used because the current electrodes are not moved.

**4.0 Conclusion**

Where the ground is uniform, the resistivity measured from the subsurface should be constant and independent of both electrode spacing and surface location. When subsurface in-homogeneities exist, however, the resistivity will vary with the relative positions of the electrodes. Any computed value is then known as apparent resistivity and will be a function of the form of the in-homogeneity.

**5.0 Summary**

Resistivity is one of the most variable of physical properties. Certain minerals such as native metals and graphite conduct electricity via the passage of electrons. Most rock forming minerals are, however, insulators, and electrical current is carried through a rock mainly by the passage of ions in pore water. It is apparent that there is considerable overlap between different rock types and, consequently, identification of a rock type is not possible solely on the basis of resistivity data alone.

**6.0 Tutor Marked Assignments**

(a) Name and describe the various array systems
(b) Discuss the depth of penetration of resistivity survey equipment.
(c) How would you enhance the signal to noise ration in resistivity survey?
(d) What criteria would you use in the choice of array method?

**7.0 References/Further reading**

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp.
Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.
Kearey, P., Brooks, M. and Hill, I. (2002) *An Introduction to Geophysical Exploration* (Third Edition), Blackwell Science, Oxford, 262 pp.
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## Unit 2: RESISTIVITY PROFILING

### 1.0 Introduction

In this unit, the concept Resistivity traversing is well appreciated and discussed for readers understanding. This is also called constant separation traversing (CST) or electrical profiling. The current and potential electrodes are maintained at a fixed separation and progressively moved along a profile. The method is useful in mineral prospecting to locate faults or shear zones and to detect localized bodies of anomalous conductivity. Resistivity traversing is also used to detect lateral changes.

As the array parameters are kept constant, the depth of penetration therefore varies only with changes in subsurface layering. Depth information can be obtained from a profile if only two layers, of known and constant resistivity, are involved since each value of apparent resistivity can then be converted into a depth using a two layer type-curve (Figure 2.6). Such estimates should, however, be checked at regular intervals against the results from expanding-array soundings of the type.

### 2.0 Objectives

At the end of the unit, the reader should be able to:

- (i) Know and understand the concept of Resistivity Profiling
- (ii) Know that resistivity traversing is used to detect lateral changes in subsurface..
- (iii) Know that depth information can only be obtained from a profile
- (iv) Understand the ideal traverse target is a steeply dipping contact between two rock types of very different resistivity
- (v) Know that the preferred arrays for resistivity traversing are those that can be most easily moved
- (vi) Know that the array parameters remain the same along the transverse, and array type, spacing and orientation.
- (vii) Show lateral variation of resistivity with depth.

## 3.0 Main Contents

### *3.1 Targets*

The ideal traverse target is a steeply dipping contact between two rock types of very different resistivity, concealed under thin and relatively uniform overburden. Such targets do exist, especially in man-modified environments, but the changes in apparent resistivity due to geological changes of interest are often small and must be distinguished from a background due to other geological sources. Gravel lenses in clays, ice lenses in Arctic tundra and caves in limestone are all much more resistive than their surroundings but tend to be small and rather difficult to detect. Small bodies that are very good conductors, such as (at rather different scales) oil drums and sulphide ore bodies, are usually more easily detected using electromagnetic methods.

### *3.2 Choice of array*

The preferred arrays for resistivity traversing are those that can be most easily moved. The gradient array, which has only two mobile electrodes separated by a small distance and linked by the only moving cable, has much to recommend it. However, the area that can be covered with this array is small unless current is supplied by heavy motor generators. The two-electrode array has therefore now become the array of choice in archaeological work, where target depths are generally small. Care must be taking in handling the long cables to the electrodes 'at infinity', but large numbers of readings can be made very rapidly using a rigid frame on which the two electrodes, and often also the instrument and a data logger, are mounted (Figure 1.1). Many of these frames now incorporate multiple electrodes and provide results for a number of different electrode combinations. With the Wenner array, all four electrodes are moved but since all inter electrode distances are the same, mistakes are unlikely. Entire traverses of cheap metal electrodes can be laid out in advance. Provided that DC or very low frequency AC is used, so that induction is not a problem, the work can be speeded up by cutting the cables to the desired lengths and binding them together, or by using purpose-designed multicore cables.

The dipole–dipole array is mainly used in IP work where induction effects must be avoided at all costs. Four electrodes have to be moved and the observed voltages are usually very small.

### *3.3 Traverse field-notes*

Array parameters remain the same along a traverse, and array type, spacing and orientation, and very often current settings and voltage ranges can be noted on page headers. In principle, only station numbers, remarks and *V/I* readings need be recorded at individual stations, but any changes in current and voltage settings should also be noted since they affect reading reliability. Comments should be made on changes in soil type, vegetation or topography and on cultivated or populated areas where non-geological effects may be encountered. These notes will usually be the responsibility of the instrument operator who will generally be in a position to personally inspect every electrode location in the course of the traverse. Since any note about an individual field point will tend to describe it in relation to the general environment, a general description and sketch map should be included. When using frame-mounted electrodes to obtain rapid, closely spaced readings, the results are usually recorded directly in a data logger and the description and sketch become all-important.

*3.4 Displaying traverse data*

The results of resistivity traversing are most effectively displayed as profiles, which preserve all the features of the original data. Profiles of resistivity and topography can be presented together, along with abbreviated versions of the field notes. Data collected on a number of traverses can be shown by plotting *stacked* profiles on a base map, but there will usually not then be much room for annotation.

Strike directions of resistive or conductive features are more clearly shown by contours than by stacked profiles. Traverse lines and data-point locations should always be shown on contour maps. Maps of the same area produced using arrays aligned in different directions can be very different.

## 4.0 Conclusion

Resistivity profiling is mostly conducted in hydro-geological and engineering investigations. The preferred arrays for resistivity traversing are those that can be most easily moved, such as, Gradient, and Wenner arrays.

The dipole–dipole array is mainly used in IP work where induction effects must be avoided at all costs. Four electrodes have to be moved and the observed voltages are usually very small.

## 5.0 Summary

The resistivity profiling is also known as electrical profiling or constant separation traversing. The method is suitable in hydrogeology to define horizontal zones of porous strata. Resistivity traversing is also used to detect lateral changes. The method is also useful in mineral prospecting to locate faults or shear zones and to detect localized bodies of anomalous conductivity. It is also used in geotechnical engineering to determine variations in bedrock depth and the presence of steep discontinuities. The preferred arrays for resistivity traversing are those that can be most easily moved.

## 6.0 Tutor Marked Assignments

(a) With annotated diagram, explain the working principle of CST method
(b) State the various areas of application of this method
(c) State the criteria to be considered on the choice of array for this method

## 7.0 References/Further readings

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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## Unit 3: RESISTIVITY DEPTH-SOUNDING

### 1.0 Introduction

This method is also called vertical electrical sounding or expanding probe. Here the current and potential electrodes are maintained at the same relative spacing and the whole spread is progressively expanded about a fixed central point. Resistivity depth-soundings investigate layering, using arrays in which the distances between some or all of the electrodes are increased systematically. Apparent resistivities are plotted against expansion on log-log paper and matched against type curves (Figure 2.3). Although the introduction of multicore cables and switch selection has encouraged the use of simple doubling, expansion is still generally in steps that are approximately or accurately logarithmic. The half-spacing sequence 1, 1.5, 2, 3, 5, 7, 10, 15 . . . is convenient, but some interpretation programs require exact logarithmic spacing. The sequences for five and six readings to the decade are 1.58. 2.51, 3.98, 6.31, 10.0, 15.8 . . . and 1.47, 2.15, 3.16, 4.64, 6.81, 10.0, 14.7 . . . respectively. Curves drawn through readings at other spacings can be resampled but there are obvious advantages in being able to use the field results directly. Although techniques have been developed for interpreting dipping layers, conventional depth-sounding works well only where the interfaces are roughly horizontal. The method is extensively used in geotechnical surveys to determine overburden thickness and also in hydrogeology to define horizontal zones of porous strata.

### 2.0 Objectives

At the end of the unit, readers will be able to:

(i) Investigate layering using arrays in which the distances between some or all of the electrodes are increased systematically.
(ii) Understand that the Wenner array is very popular but for speed and convenience, the Schlumberger array, in which only two electrodes are moved, is often preferred.
(iii) Know that site selection is extremely important in all sounding work, is particularly critical with the Schlumberger array, which is very sensitive.
(iv) Use resistivity depth sounding to investigate the vertical variation of resistivity with depth.

### 3.0 Main Contents

*3.1 Choice of array*

Since depth-sounding involves expansion about a centre point, the instrument generally stays in one place. Instrument portability is therefore less important than in profiling. The Wenner array is very popular but for speed and convenience the Schlumberger array, in which only two electrodes are moved, is often preferred. Interpretational literature, computer programs and type curves are widely available for both arrays. Local near-surface variations in resistivity nearly always introduce noise with amplitudes greater than the differences between the Wenner and Schlumberger curves.

Array orientation is often constrained by local conditions, i.e. there may be only one direction in which electrodes can be taken a sufficient distance in a straight line. If there is a choice, an array should be expanded parallel to the probable strike direction, to minimize the effect of non-horizontal bedding. It is generally desirable to carry out a second, orthogonal expansion to check for directional effects, even if only a very limited line length can be obtained. The dipole–dipole and two-electrode arrays are not used for ordinary DC sounding work. Dipole–dipole *depth pseudo-sections* are much used in IP surveys.

*3.2 Using the Schlumberger array*

Site selection, extremely important in all sounding work, is particularly critical with the Schlumberger array, which is very sensitive to conditions around the closely spaced inner electrodes. A location where the upper layer is very inhomogeneous is unsuitable for an array centre and the offset Wenner array may therefore be preferred for land-fill sites. Apparent resistivities for the Schlumberger array are usually calculated from the approximate equation of Figure 2.1c, which strictly applies only if the inner electrodes form an ideal dipole of negligible length. Although more accurate apparent resistivities can be obtained using the precise equation, the interpretation is not necessarily more reliable since all the type curves are based on the ideal dipole.

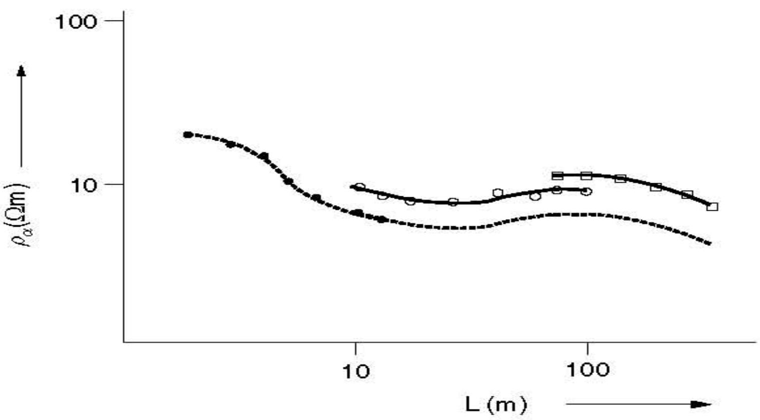


***Figure 2.7*** *Construction of a complete Schlumberger depth-sounding curve (dashed line) from overlapping segments obtained using different innerelectrode separations.*

In principle a Schlumberger array is expanded by moving the outer electrodes only, but the voltage will eventually become too small to be accurately measured unless the inner electrodes are also moved farther apart. The sounding curve will thus consist of a number of separate segments (Figure 2.7). Even if the ground actually is divided into layers that are perfectly internally homogeneous, the segments will not join smoothly because the approximations made in using the dipole equation are different for different *l/L* ratios. This effect is generally less important than the effect of ground in-homogeneities around the potential electrodes, and the segments may be linked for interpretation by moving them in their entirety parallel to the resistivity axis to form a continuous curve. To do this, overlap readings must be made. Ideally there should be at least three of these at each change, but two are more usual (Figure 2.7) and one is unfortunately the norm.

*3.3 Offset Wenner depth sounding*

Schlumberger interpretation is complicated by the segmentation of the sounding curve and by the use of an array that only approximates the conditions assumed in interpretation. With the Wenner array, on the other hand, near surface conditions differ at all four electrodes for each reading, risking a high noise level. A much smoother sounding curve can be produced with an *offset* array of five equi-spaced electrodes, only four of which are used for any one reading (Figure 2.8a). Two readings are taken at each expansion and are average to produce a curve in which local effects are

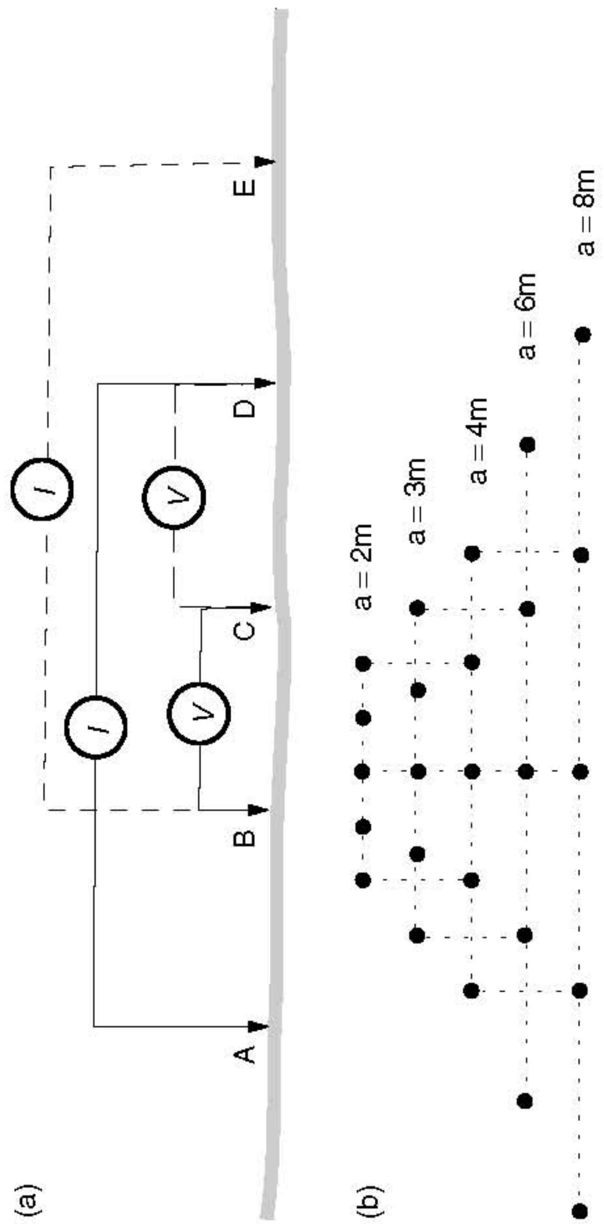


***Figure 2.8*** *Offset Wenner sounding. (a) Voltage readings are obtained between B and C when current is passed between A and D, and between C and D when current is passed between B and E. (b) An expansion system allowing reuse of electrode positions and efficient operation with multicore cables.*

suppressed.The differences between the two readings provide a measure of the significance of these effects. The use of five electrodes complicates field work, but if expansion is based on doubling the previous spacing (Figure 2.8b), very quick and efficient operation is possible using multicore cables designed for this purpose.

*3.4 Depth-sounding notebooks*

In field notebooks, each sounding should be identified by location, orientation and array type. The general environment should be clearly described and any peculiarities, e.g. the reasons for the choice of a particular orientation, should be given. Generally, and particularly if a Schlumberger array is used, operators are able to see all the inner electrode locations. For information on the outer electrode positions at large expansions, they must either rely on second-hand reports or personally inspect the whole length of the line. Considerable variations in current strengths and voltage levels are likely, and range-switch settings should be recorded for each reading.

*3.5 Presentation of sounding data*

There is usually time while distant electrodes are being moved to calculate and plot apparent resistivities. Minor delays are in any case better than returning with un-interpretable results, and field plotting should be routine. All that is needed is a pocket calculator and a supply of log-log paper. A laptop in the field is often more trouble than it is worth, since all are expensive, most are fragile and few are waterproof.

Simple interpretation can be carried out using two-layer type curves (Figure 2.5) on transparent material. Usually an exact two-layer fit will not be found and a rough interpretation based on segment-by-segment matching will be the best that can be done in the field. Ideally, this process is controlled using auxiliary curves to define the allowable positions of the origin of the two-layer curve being fitted to the later segments of the field curve (Figure 2.6). Books of three-layer curves are available, but a full set of four layer curves would fill a library.

Step-by-step matching was the main interpretation method until about 1980. Computer-based interactive modelling is now possible, even in field camps, and gives more reliable results, but the step-by-step approach is still often used to define initial computer models.

*3.6 Pseudo-sections and depth sections*

The increasing power of small computers now allows the effects of lateral changes in resistivity to be separated from changes with depth. For this to be done, data must be collected along the whole length of a traverse at a number of different spacings that are multiples of a fundamental spacing. The results can be displayed as contoured *pseudo-sections* that give rough visual impressions of the way in which resistivity varies with depth (Figure 2.10a, b).

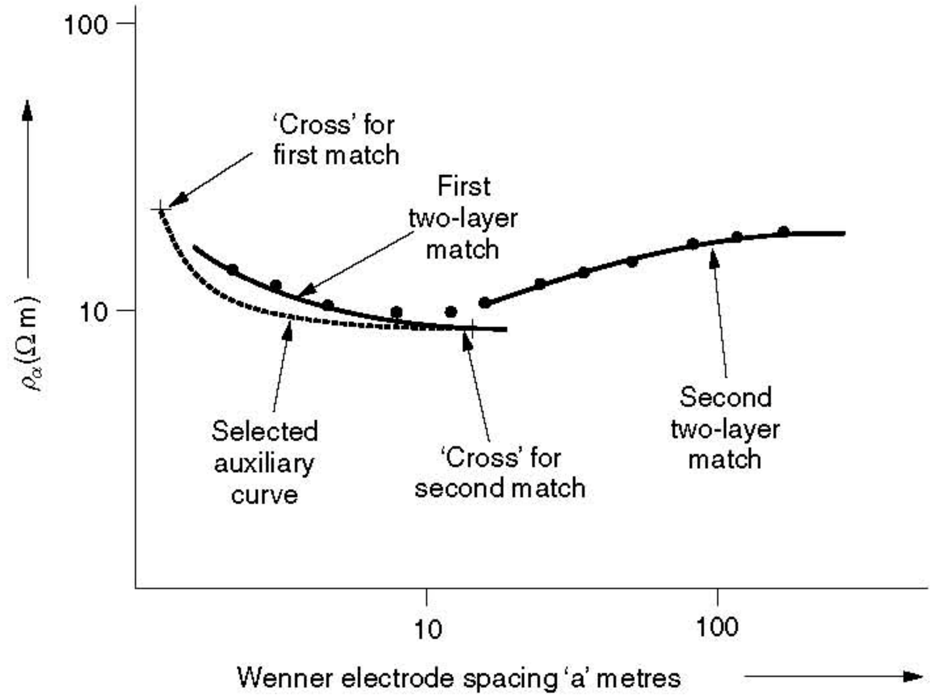


***Figure 2.9*** *Sequential curve matching. The curve produced by a low-resistivity layer between two layers of higher resistivity is interpreted by two applications of the two-layer curves. In matching the deeper part of the curve, the intersection of the* a/h = 1 *and* ra/r1 = 1 *lines (the 'cross') must lie on the line defined by the auxiliary curve.*

The data can also be *inverted* to produce revised sections with vertical scales in depth rather than electrode separation, which give greatly improved pictures of actual resistivity variations (Figure 2.10c). As a result of the wide use of these techniques in recent times, the inadequacies of simple depth sounding have become much more widely recognized. The extra time and effort involved in obtaining the more complete data are almost always justified by results.

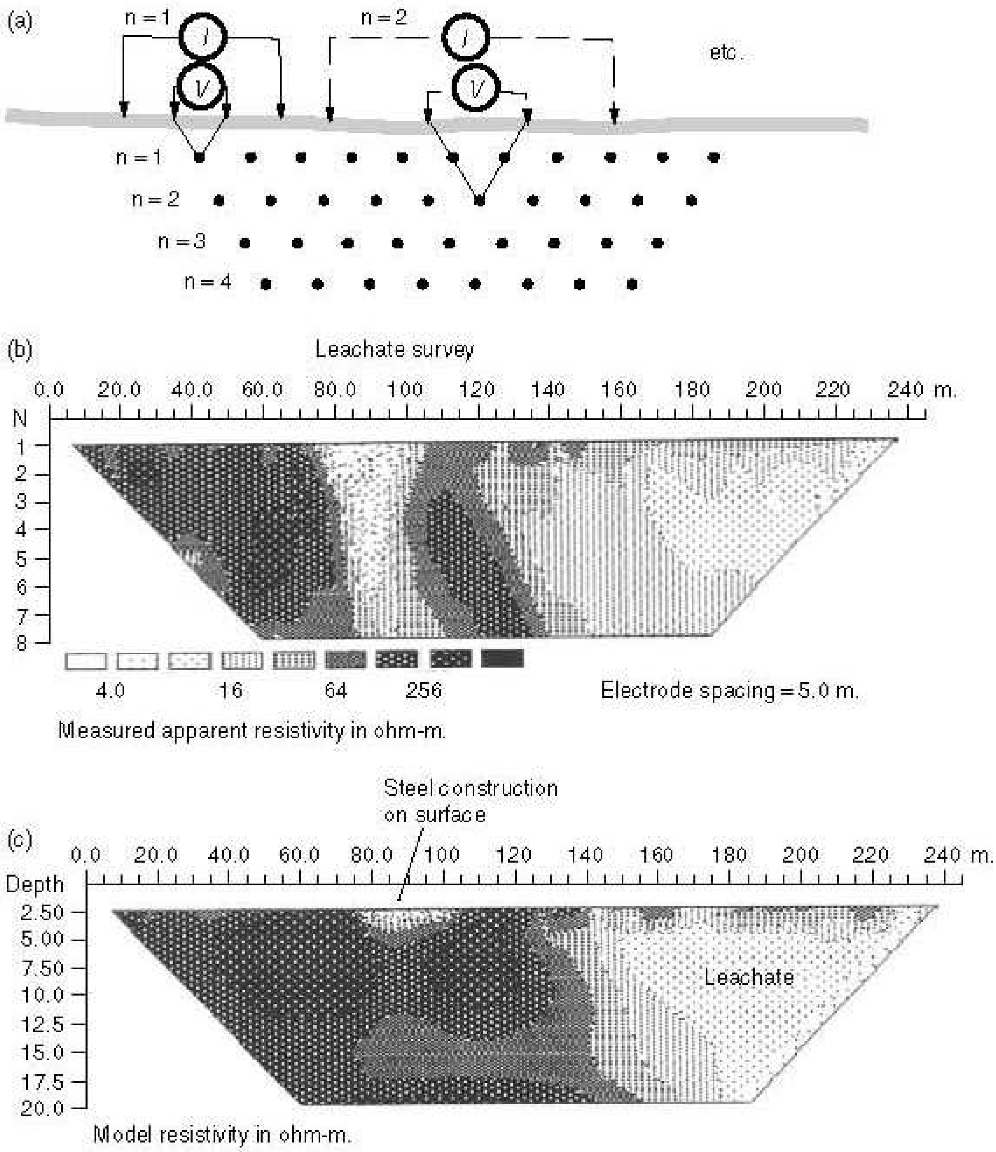


***Figure 2.10*** *Wenner array pseudo-sections. (a) Plotting system; (b) 'raw' pseudo-section; (c) pseudo-section after inversion. The low-resistivity (white) area at about 90 m was produced by a metal loading bay and railway line, i.e. by a source virtually at the ground surface.*

## 4.0 Conclusion

Resistivity depth sounding is mainly used in the horizontal or nearly horizontal interfaces. Consequently, readings are taken as the current reaches progressively greater depths. The common electrode arrays used are the Schlumberger and Wenner arrays. The method utilizes about two to three labour, unlike the profiling survey that employs more labours, because it involves the movement of both the current and potential electrodes.

## 5.0 Summary

In this method, the current and potential electrodes are maintained at the same relative spacing and the whole spread is progressively expanded about a fixed central point. Resistivity depth-soundings investigate layering, using arrays in which the distances between some or all of the electrodes are increased systematically. The Wenner array is very popular but for speed and convenience the Schlumberger array, in which only two electrodes are moved, is often preferred. Interpretational literature, computer programs and type curves are widely available for both arrays. Local near-surface variations in resistivity nearly always introduce noise with amplitudes greater than the differences between the Wenner and Schlumberger curves.

Step-by-step curve matching technique was the main interpretation method until about 1980. Computer-based interactive modelling is now possible, even in field camps, and gives more reliable results, but the step-by-step approach is still often used to define initial computer models.

## 6.0 Tutor Marked Assignments

(a) Discuss the concept of electrical depth sounding survey
(b) State the advantages of VES method over CST method
(c) Describe the interpretation mechanism of resistivity depth sounding method.

## 7.0 References/Further reading

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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# MODULE 3

**Unit 1 Electro-Magnetic Methods**

**Unit 2 Other CWEM (Continuous Waves Electromagnetic) Techniques**

**Unit 3 Transient Electromagnetic**

## UNIT 1: ELCTROMAGNETIC METHODS

### 1.0 Introduction

Electromagnetic (EM) induction, which is a source of noise in resistivity and IP surveys is the basis of a number of geophysical methods. These were originally mainly used in the search for conductive sulphide mineralization but are now being increasingly used for area mapping and depth sounding. Because a small conductive mass within a poorly conductive environment has a greater effect on induction than on 'DC' resistivity, discussions of EM methods tend to focus on conductivity ($\sigma$), the reciprocal of resistivity, rather than on resistivity itself. Conductivity is measured in mhos per metre or, more correctly, in siemens per metre (Sm−1).

There are two limiting situations. In the one, eddy currents are induced in a small conductor embedded in an insulator, producing a discrete anomaly that can be used to obtain information on conductor location and conductivity. In the other, horizontal currents are induced in a horizontally layered medium and their effects at the surface can be interpreted in terms of apparent conductivity. Most real situations involve combinations of layered and discrete conductors, making greater demands on interpreters, and sometimes on field personnel. Wave effects are important only at frequencies above about 10 kHz, and the methods can otherwise be most easily understood in terms of varying current flow in conductors and varying magnetic fields in space. Where the change in the inducing primary magnetic field is produced by the flow of sinusoidal alternating current in a wire or coil, the method is described as continuous wave (CWEM). Alternatively, transient electromagnetic (TEM) methods may be used, in which the changes are produced by abrupt termination of current flow.

### 2.0 Objectives

At the end of the unit, readers should be able to;

(i) Understand the concept of conductivity (r), the reciprocal of resistivity
(ii) Know that EM methods tend to focus on conductivity rather than resistivity itself.
(iii) Understand the system descriptions of continuous wave EM
(iv) Know that there is an alternative method called Transient EM to CWEM.
(v) Know that EM methods use higher frequency alternating electromagnetic fields through vertical and coplanar coils to study the real and imaginary components of the electrical properties of the subsurface geo- earth materials.
(vi) Also, EM method allows the measurement of the true conductivity of the subsurface geology.

## 3.0 Main Contents

*3.1 Two-coil CW Systems*

A current-carrying wire is surrounded by circular, concentric lines of magnetic field. Bent into a small loop, the wire produces a magnetic dipole field (Figure 1.4) that can be varied by alternating the current. This varying magnetic field causes currents to flow in nearby conductors.

*3.2 System descriptions*

In CW (and TEM) surveys, sources are (usually) and receivers are (virtually always) wire loops or coils. Small coil sources produce dipole magnetic fields that vary in strength and direction. Anomaly amplitudes depend on the coil magnetic moments, which are proportional to the number of turns in the coil, the coil areas and the current circulating. Anomaly shapes depend on system geometry as well as on the nature of the conductor.

Coils are described as horizontal or vertical according to the plane in which the windings lie. 'Horizontal' coils have vertical axes and are alternatively described as *vertical dipoles*. Systems are also characterized by whether the receiver and transmitter coils are *co-planar*, *co-axial* or *orthogonal* (i.e. at right angles to each other), and by whether the coupling between them is a maximum, a minimum or variable (Figure 3.1). Co-planar and co-axial coils are maximum-coupled since the primary flux from the transmitter acts along the axis of the receiver coil. Maximum coupled systems are only slightly affected by small relative misalignments
but, because a strong in-phase field is detected even in the absence of a conductor, are very sensitive to changes in coil separation. Orthogonal coils are minimum-coupled. The primary field is not detected and small changes in separation have little effect. However, large errors are produced by slight misalignments. In the field it is easier to

maintain a required coil separation than a relative orientation, and this is one reason for favouring maximum coupling.

*Dip-angle* systems, in which the receiver coil is rotated to determine the dip of the resultant field, were once very popular but are now generally limited to the *shoot-back* instruments used in rugged terrain. Shoot-back receiver and transmitter coils are identical and are linked to electronic units that can both transmit and receive. Topographic effects are cancelled by measuring and averaging the receiver coil dip angles with first one and then the other coil held horizontal and used as transmitter.

### *3.3 Slingram*

Most ground EM systems use horizontal co-planar coils (‘horizontal loops’), usually with a shielded cable carrying a phase-reference signal from transmitter to receiver. The sight of two operators, loaded with bulky apparatus and linked by an umbilical cord, struggling across rough ground and through thick scrub, has provided light entertainment on many surveys. Very sensibly, some instruments allow the reference cable to be also used for voice communication.

Fortunately, memory units have not (yet) been added to record the conversations. The Swedish term *Slingram* is often applied to horizontal-loop systems but without any general agreement as to whether it is the fact that there are two mobile coils, or that they are horizontal and co-planar, or that they are linked by a reference cable,that makes the term applicable.

### *3.4 Response functions*

In a Slingram survey, the electromagnetic *response* of a body is proportional to its mutual inductances with the transmitter and receiver coils and inversely proportional to its self-inductance, *L*, which limits eddy current flow. Anomalies are generally expressed as percentages of theoretical primary field and are therefore also inversely proportional to the mutual inductance between transmitter and receiver, which determines the strength of the primary field. The four parameters can be combined in a single *coupling factor,* $M_{ts} M_{sr}/M_{tr}L$.

Anomalies also depend on a *response parameter* which involves frequency, self-inductance (always closely related to the linear dimensions of the body) and resistance. Response curves (Figure 3.2) illustrate simultaneously how responses vary over targets of different resistivity using fixed-frequency systems and over a single target as frequency is varied. Note that the quadrature field is very small at high frequencies, where the distinction between good and merely moderate conductors tends to disappear. Most single-frequency systems operate below 1000 Hz, and even the multi-frequency systems that are now the norm generally work entirely below 5000 Hz.

Narrow poor-quality conductors may produce measurable anomalies only at the highest frequency or not at all (see Figure 3.10).

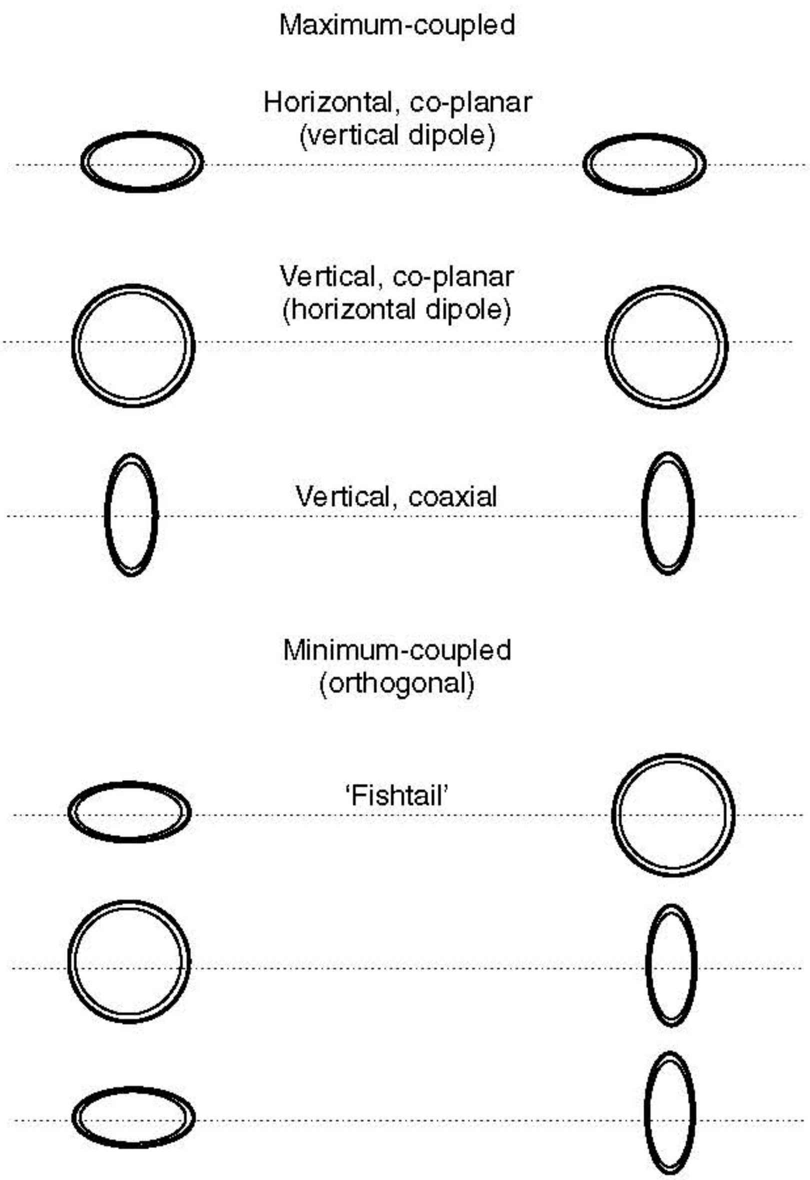


***Figure 3.1*** *Coil systems for electromagnetic surveys. The Geonics standard descriptions, in terms of magnetic dipole direction rather than loop orientation, are given in brackets. Relative orientation is variable in dip-angle systems, although usually the transmitter coil is held horizontal and the receiver coil is rotated to locate the direction for minimum signal.*

*3.5 Slingram practicalities*

The coil separation in a Slingram survey should be adjusted to the desired depth of penetration. The greater the separation, the greater the effective penetration because

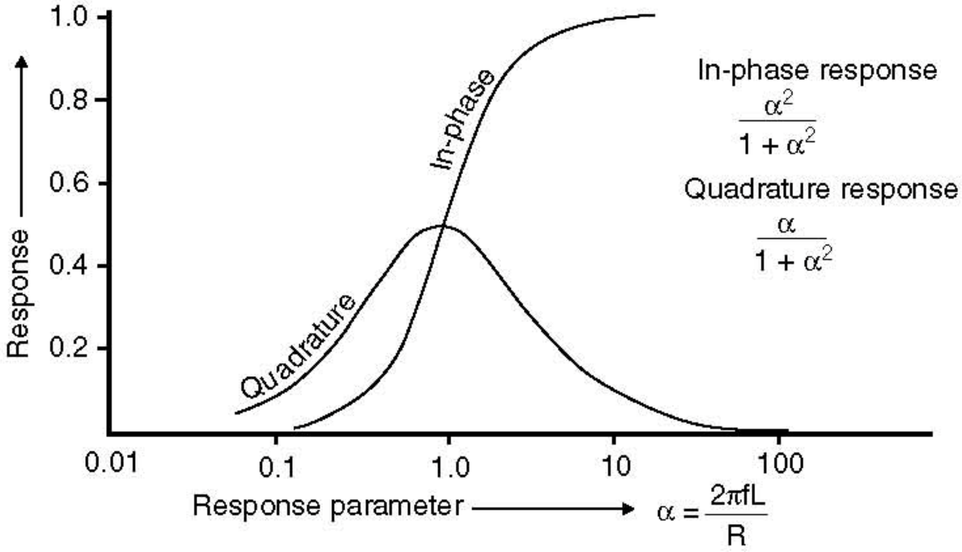


***Figure 3.2*** *Response of a horizontal-loop EM system to a vertical loop target, as a function of the response parameter (α). Note that the Response Parameter scale is logarithmic.* L *is the loop self-inductance,* R *its resistance and* f *is the frequency. The curves for more complex targets would have the same general form.*

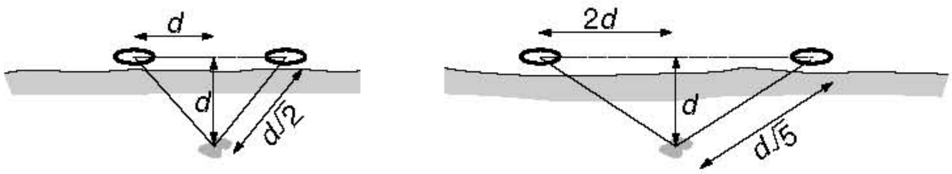


***Figure 3.3*** *Spacing and penetration. When the two coils are moved apart, the fractional change in distance between them is greater than between either and the conductor at depth. The increased separation thus increases the anomalous field as a percentage of the primary. In the example, doubling the separation increases the coil to target distances by about 60%.*

the primary field coupling factor *M*tr is more severely affected by the increase than are either *M*ts or*M*sr (Figure 3.3). The maximum depth of investigation of a Slingram system is often quoted as being roughly equal to twice the coil separation, provided that this is less than the skin depth (Figure 1.5) but this ignores the effects of target size and conductivity and may be unduly optimistic.

Because signals in Slingram surveys are referenced to primary field strengths, the *100% level* should be verified at the start of each day by reading at the standard survey spacing on ground which is level and believed to be non-anomalous. This check has to be carried out even with instruments that have fixed settings for allowable separations, because drift is a continual problem.

A check must also be made for any leakage of the primary signal into the quadrature channel (*phase mixing*). Instrument manuals describe how to test for this condition and how to make any necessary adjustments. Receivers and transmitters must, of course, be tuned to the same frequency for sensible readings to be obtained, but care is needed. A receiver can be seriously damaged if a transmitter tuned to its frequency is operated close by.

Figure 3.4 shows the horizontal-loop system anomaly over a thin, steeply dipping conductor. No anomaly is detected by a horizontal receiving coil immediately above the body because the secondary field there is horizontal. Similarly, there will be no anomaly when the transmitter coil is vertically above the body because no significant eddy currents will be induced. The greatest (negative) secondary field values will be observed when the conductor lies mid-way between the two coils. Coupling depends on target orientation and lines should be laid out across the expected strike. Oblique intersections produce poorly defined anomalies that may be difficult to interpret.

Readings obtained with mobile transmitter and receiver coils are plotted at the mid-points. This is reasonable because in most cases where relative coil orientations are fixed, the anomaly profiles over symmetrical bodies are also symmetrical and are not affected by interchanging receiver and transmitter. Even where this is not completely true, recording mid-points is less likely to lead to confusion than recording either transmitter or receiver coil positions. In all EM work, care must be taken to record any environmental variations that might affect the results. These include obvious actual conductors and also features such as roads, alongside which artificial conductors are often buried. Power and telephone lines cause special problems since they broadcast noise which, although different in frequency, is often strong enough to pass through the rejection (*notch*) filters. It is important to check that these filters are appropriate to the area of use (60 Hz in most of the Americas and 50 Hz nearly everywhere else). Ground conditions should also be noted, since variations in overburden conductivity can drastically affect anomaly shapes as well as signal penetration. In hot, dry countries, salts in the overburden can produce surface conductivities so high that CW methods are ineffective and have been superseded by TEM.

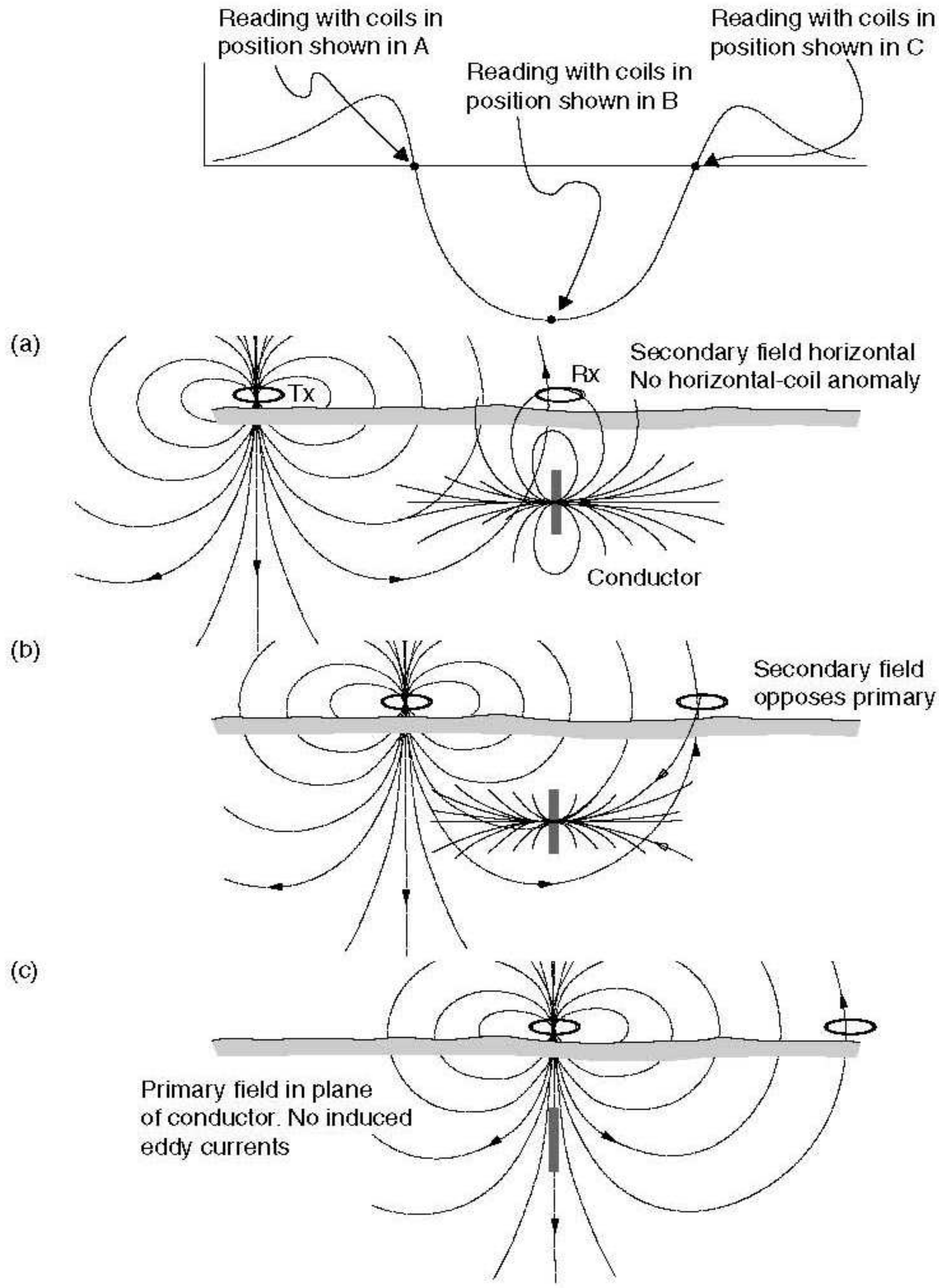


***Figure 3.4*** *Horizontal loop anomaly across a steeply dipping conductive sheet. Over a dipping sheet, the area between the side lobe and the distance axis would be greater on the down-dip side. Anomaly width is largely determined by coil separation, not by target width.*

*3.6 Effects of coil separation*

Changes in coupling between transmitter and receiver can produce spurious in-phase anomalies. The field at a distance *r* from a coil can be described in terms of radial and tangential components *F(r)* and *F(t)* (Figure 3.5). The amplitude factor *A* depends on coil dimensions and current strength. For co-planar coils, *F(r)* is zero because $\varphi$ is zero and the measured field, *F*, is equal to *F(t)*. The inverse cube law for dipole sources then implies that, for a fractional change *x*:

$$F = F_{\rm o}/(1 + x)^3$$

Where, *F*o is the field strength at the intended spacing. If *x* is small, this can be written as:

$$F = F_{\rm o}(1 - 3x)$$

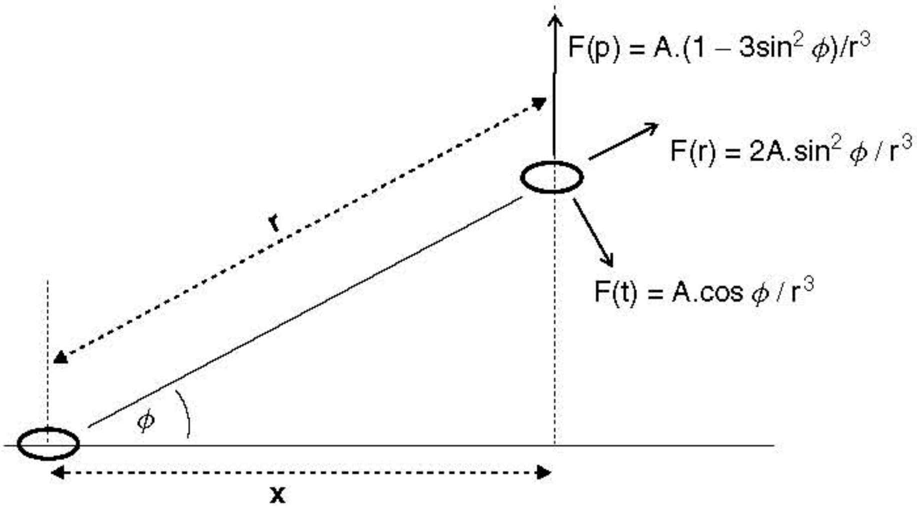


***Figure 3.5*** *Field components due to a current-carrying loop acting as a magnetic dipole source.* F(r) *and* F(t) *are radial and tangential components, respectively.* F(p), *obtained by adding the vertical components of both, is the primary field measured by a horizontal receiver coil.*

Thus, for small errors, the percentage error in the in-phase component is three times the percentage error in distance. Since real anomalies of only a few percent can be important, separations must be kept very constant.

*3.7 Surveys on slopes*

On sloping ground, the distances between survey pegs may be measured either horizontally (*secant chaining)* or along slope (Figure 3.6). If along slope distances are used in reasonably gentle terrain, coil separations should be constant but it is difficult to keep coils co-planar without a clear line of sight and simpler to hold them horizontal. The field *F(p)* along the receiver axis is then equal to the co-planar field multiplied by $(1 - 3\sin^2\theta)$, where $\theta$ is the slope angle (Figure 3.7). The correction factor $1/(1 - 3\sin^2\theta)$ is always greater than 1 (coils really are maximum-coupled when co-planar) and becomes infinite when the slope is 35° and the primary field is horizontal (Figure 3.7).

If secant-chaining is used, the distances along slope between coils are proportional to the secant (=1/cosine) of the slope angle. For co-planar (tilted) coils the ratio of the 'normal' to the 'slope' field is therefore $\cos^3\theta$ and the correction factor is $\sec^3\theta$. If the coils were to be held horizontal, the combined correction factor would be $\sec^3\theta/(1 - 3\sin^2\theta)$ (Figure 3.7).

Separations in rugged terrain can differ from their nominal values if the coil separation is greater than the distances over which slopes have been measured (Figure 3.6). Accurate surveying is essential in such areas and field crews may need to carry lists of the coil tilts required at each station. Instruments which incorporate tilt meters and communication circuits are virtually essential and even so errors are depressingly common and noise levels tend to be high.

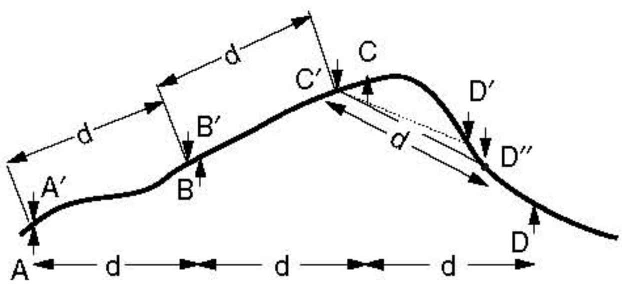


***Figure 3.6*** *Secant chaining and slope chaining. Down arrows show locations of stations separated by intervals of d metres measured along slope. Up arrows show locations of secant-chained stations, separated by d metres horizontally. Between C and D, where topographic 'wavelength' is less than the station spacing, the straight line distance from C_ to D_ (for which separation was measured as the sum of short along-slope segments), is less than d. The 'correct' slope position is at D*

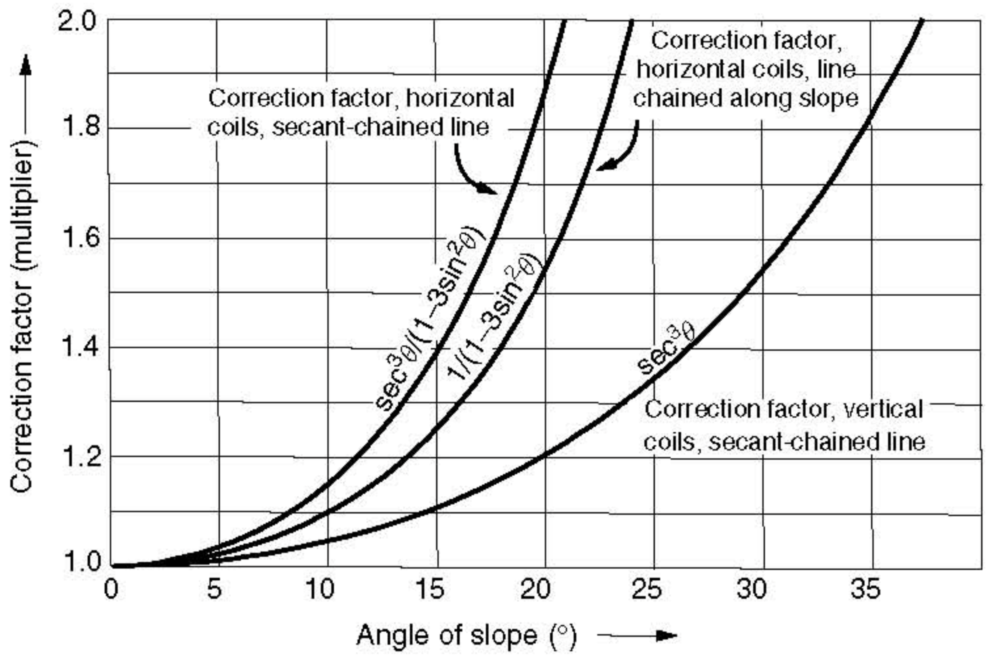


***Figure 3.7*** *Slope corrections for a two-coil system calibrated for use in horizontal, co-planar mode. Readings should be multiplied by the appropriate factors.*

*3.8 Applying the corrections*

For any coupling error, whether caused by distance or tilt, the in-phase field that would be observed with no conductors present can be expressed as a percentage of the maximum-coupled field *F*o. A field calculated to be 92% of *F*o because of non-maximum coupling can be converted to 100% *either* by adding 8% *or* by multiplying the actual reading by 100/92. If the reading obtained actually were 92%, these two operations would produce identical results of 100%. If, however, there were a superimposed secondary field (e.g. if the actual reading were 80%), adding 8% would correct only the primary field (converting 80% to 88% and indicating the presence of a 12% anomaly). Multiplication would apply a correction to the secondary field also and would indicate a 13% anomaly. Neither procedure is actually 'right', but the principles illustrated in Figure 3.3 apply, i.e. the deeper the conductor, the less the effect of a distance error on the secondary field. Since any conductor that can be detected is likely to be quite near the surface, correction by multiplication is generally more satisfactory, but in most circumstances the differences will be trivial.

Coupling errors cause fewer problems if only quadrature fields are observed, since these are anomalous by definition (although, as Figure 3.2 shows, they may be small for very good as well as poor conductors). Rough corrections can be made using the in-phase multipliers but there is little point doing this in the field. The detailed problems caused by changes in coupling between a transmitter, a receiver and a third conductor can, thankfully, be left to the interpreter, provided the field notes describe the system configurations and topography precisely.

*3.9 Ground conductivity measurement*

Slingram-style systems are now being used for rapid conductivity mapping. At low frequencies and low conductivities, eddy currents are small, phase shifts are close to 90 ◦ and the bulk apparent resistivity of the ground is roughly proportional to the ratio between the primary (in-phase) and secondary (quadrature phase) magnetic fields. Relatively high frequencies are used to ensure a measurable signal in most ground conditions. If the *induction number*, equal to the transmitter–receiver spacing divided by the skin depth, is significantly less than unity, the depth of investigation is determined mainly by coil spacing.

Induced current flow in a homogeneous earth is entirely horizontal at low induction numbers, regardless of coil orientation, and in a horizontally layered earth the currents in one layer hardly affect those in any other. Figure 3.8 shows how current flow varies with depth for horizontal and vertical inducing coils in these circumstances. One reason for preferring horizontal coils (i.e. vertical dipoles) is obvious. The response for vertical co-planar coils, and hence the apparent conductivity estimate, is dominated by the surface layer. The independence of current flows at different levels implies that the curves of Figure 3.8, which strictly speaking are for a homogeneous medium,
can be used to calculate the theoretical apparent resistivity of a layered medium (Figure 4.9). Using this principle, layering can to some extent be investigated by raising or lowering the coils within the zero-conductivity air ‘layer’. In principle it could also be investigated by using a range of frequencies, but the range would have to be very wide and inherently *broadband* methods such as TEM or CSAMT/MT are preferable.

The Geonics EM-31 (Figure 3.10) is an example of a co-planar coil instrument
that can be used, obtain rapid estimates of apparent resistivity (manmade conductors such as buried at some risk to life and limb on difficult sites, by one operator to drums and cables may also be detected). Normally the coils are held horizontal giving, at low induction numbers, a penetration of about 6 m and a radius of investigation of about 3 m with the fixed 3.7 m coil spacing. This compares very favourably with the 20–30 m total length of a Wenner array with similar penetration. Figure 2.4 shows the results of a very detailed EM-31 survey for sinkholes in chalk, carried out on top of a plastic membrane forming the lining of a small reservoir.

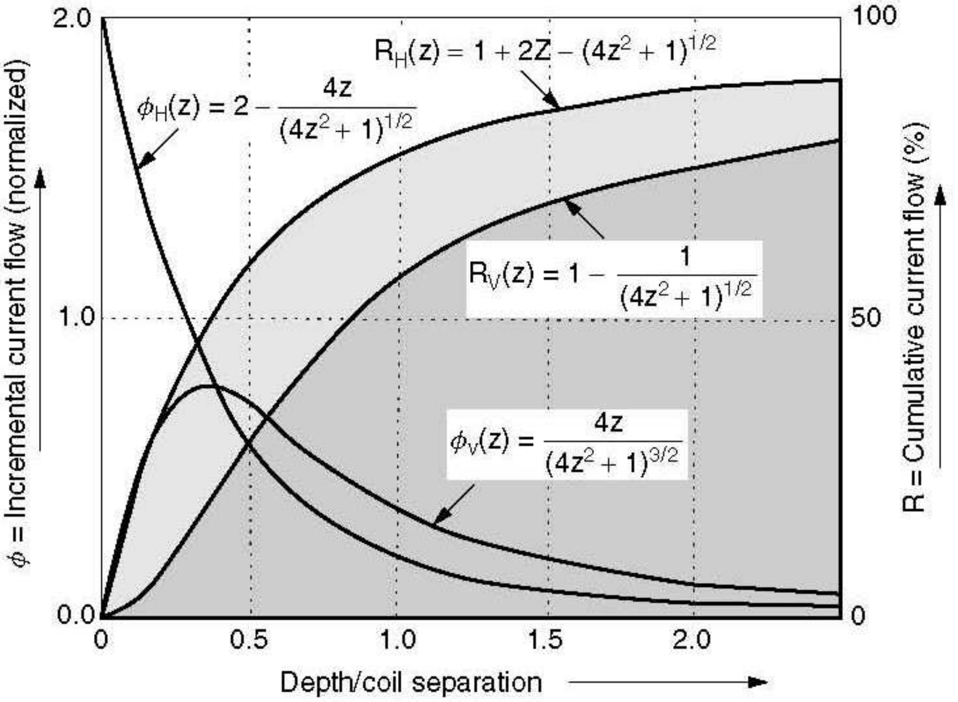


***Figure 3.8*** *Variation of induced current with depth in homogeneous ground, for co-planar coil systems operating at low induction numbers. 'Filled' curves show total current flowing in the region between the surface and the plane at depth, as a fraction of total current flow. Incremental curves are normalized. Subscripts 'h' and 'v' refer to horizontal and vertical dipoles, following the Geonics terminology used with the EM-31 and EM-34.*

Measurements can also be made (although not easily), with the coils vertical, halving the penetration. A shorter, and therefore more manoeuvrable version, the EM-31SH, is only 2 m long and therefore provides better resolution but only about 4 m of penetration. Both versions of the EM-31 operate at 9.8 kHz. The more powerful, two-person, Geonics EM-34-3 (Figure 1.1e) uses frequencies of 0.4, 1.6 and6.4 kHz with spacings of 40, 20 and 10 m respectively. The frequency is quadrupled each time the coil separation is halved, so the induction number remains constant. Coil separation is monitored using the in-phase signal. Penetrations are 15, 30 and 60 m for horizontal coils and 7.5, 15 and 30 m for vertical coils. As with the EM-31, the EM-34-3 is calibrated to read apparent conductivity directly in $mSm^{-1}$.

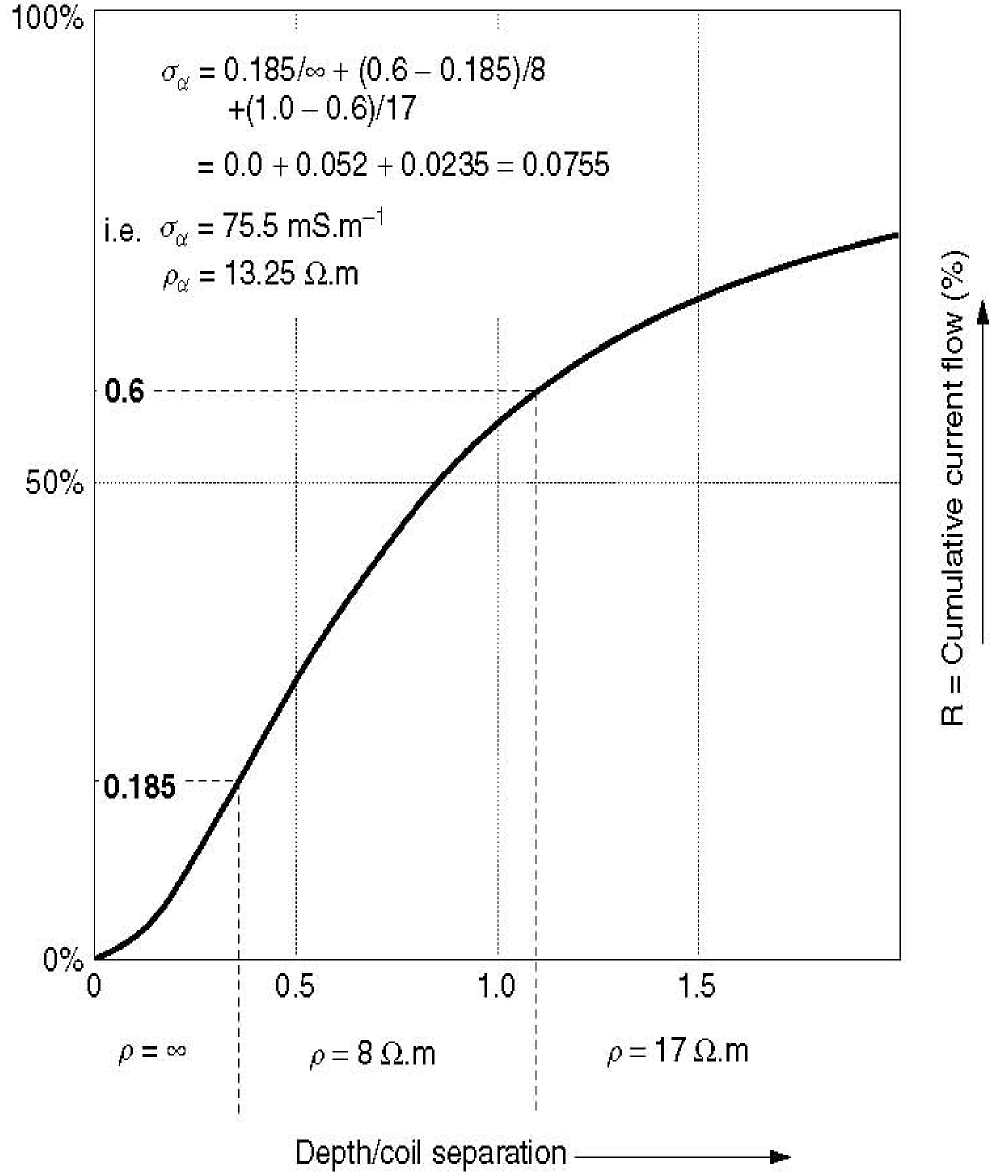


***Figure 3.9*** *Calculation of 'low induction number' apparent resistivity for a layered earth. The thickness of the first layer is determined by the height of the coils above the ground. This introduces an air layer with infinite resistivity and (in this example) a thickness of 1 m.*

## 4.0 Conclusion

Electromagnetic (EM) surveying methods make use of the response of the ground to the propagation of electromagnetic fields, which are composed of an alternating electric intensity and magnetizing force. Primary electromagnetic fields may be generated by passing alternating current through a small coil made up of many turns of wire or through a large loop of wire.

The primary electromagnetic field travels from the transmitter coil to the receiver coil via paths both above and below the surface. Where the subsurface is homogeneous there is no difference between the fields propagated above the surface and through the ground other than a slight reduction in amplitude of the latter with respect to the former. In the presence of a conducting body, the magnetic component of the electromagnetic field penetrating the ground induces alternating currents, or eddy currents, to flow in the conductor.

## 5.0 Summary

The differences between the transmitted and received electromagnetic fields reveal the presence of the conductor and provide information on its geometry and electrical properties. All anomalous bodies with high electrical conductivity produce strong secondary electromagnetic fields. For example, electromagnetic anomalies observed over certain sulphide ores are due to the presence of the conducting mineral pyrrhotite distributed throughout the ore body.

## 6.0 Tutor Marked Assignments

(a) With clear annotated diagram, discuss the general principle of EM surveying.
(b) What factors control the depth of penetration of EM fields?
(c) Discuss the operational mechanism of the Slingram method

## 7.0 References/Further readings

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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## Unit 2 OTHER CONTINOUS WAVES ELECTROMAGNETIC (CWEM)

### 1.0 Introduction

CWEM surveys can be carried out using long-wire sources instead of coils and many different system geometries. These can only be considered very briefly.

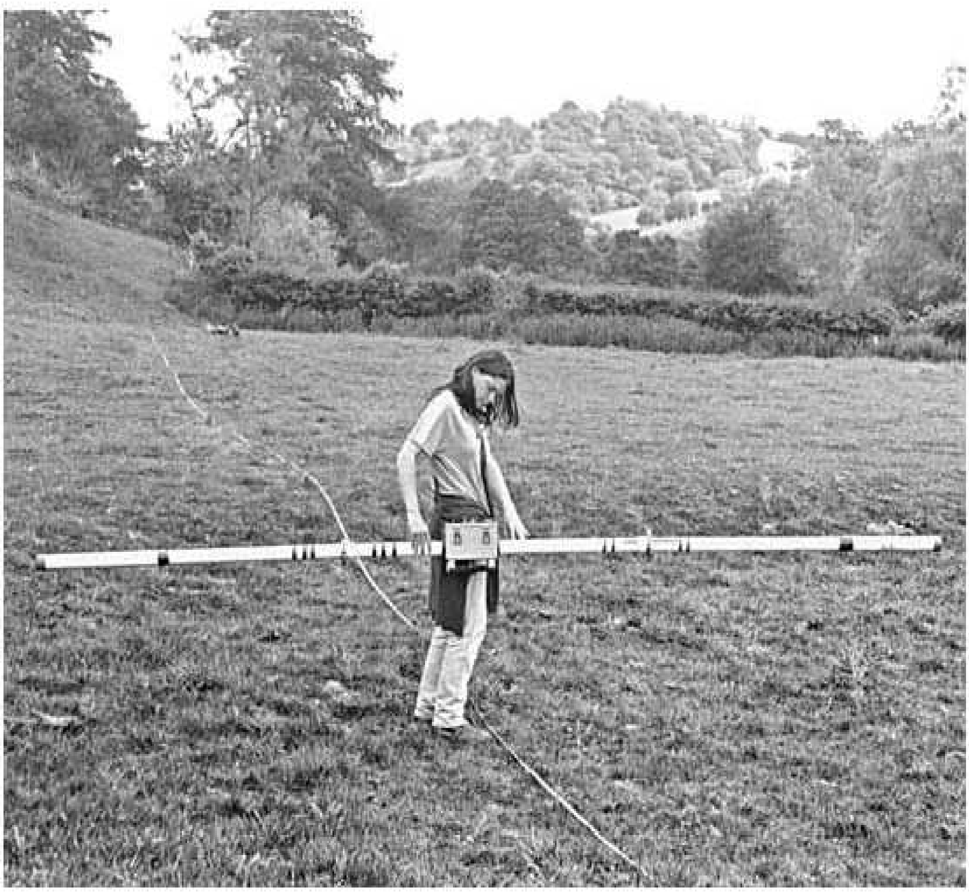

***Figure 3.10*** *EM-31 in use in open country.*

### 2.0 Objectives:

At the end of the unit, readers should be able to;

(i) Understand the concept of continuous wave electromagnetic Techniques.

(ii) Practicalise and demonstrate fixed source method and be able to apply it to measure dip angles or ratios of vertical to horizontal fields.

(iii) Use higher frequency alternating electromagnetic fields through long wire sources instead of vertical and coplanar coils to study the real and imaginary components of the electrical properties of the subsurface geo-earth materials.

(iv) Also, know that EM method allows the measurement of the true conductivity of the subsurface geology.

## 3.0 Main Contents

*3.1 Fixed-source methods*

The fields produced by straight, current-carrying wires can be calculated by repeated applications of the *Biot–Savart law* (Figure 3.12). The relationship for four wires forming a rectangular loop is illustrated in Figure 3.13. If the measurement point is outside the loop, vectors that do not cut any side of the loop have negative signs.

The Slingram anomaly of Figure 3.4 was symmetrical because the receiver and transmitter coil were moved over the body in turn. If the source, whether a coil or a straight wire, were to be fixed, there would be a zero when a horizontal receiver coil was immediately above a steeply dipping body and the anomaly would be anti-symmetric (Figure 3.14). Fixed-source systems often measure dip angles or (which is effectively the same thing) ratios of vertical to horizontal fields. *Turam* (Swedish: 'two coil') methods use fixed extended sources and two receiving coils separated by a distance of the order of 10 m. Anomalies are assessed by calculating *reduced ratios* equal to the actual ratios of the signal amplitudes through the two coils divided by the *normal* ratios that would have been observed over non-conductive terrain. Phase differences are measured between the currents in the two receiver coils and any non-zero value is anomalous.

There is no reference cable between receivers and transmitter, but absolute phases and ratios relative to a single base can be calculated provided that each successive reading is taken with the trailing coil placed in the position just vacated by the leading coil. CWEM Turam is now little used, but large fixed sources are common in TEM work.

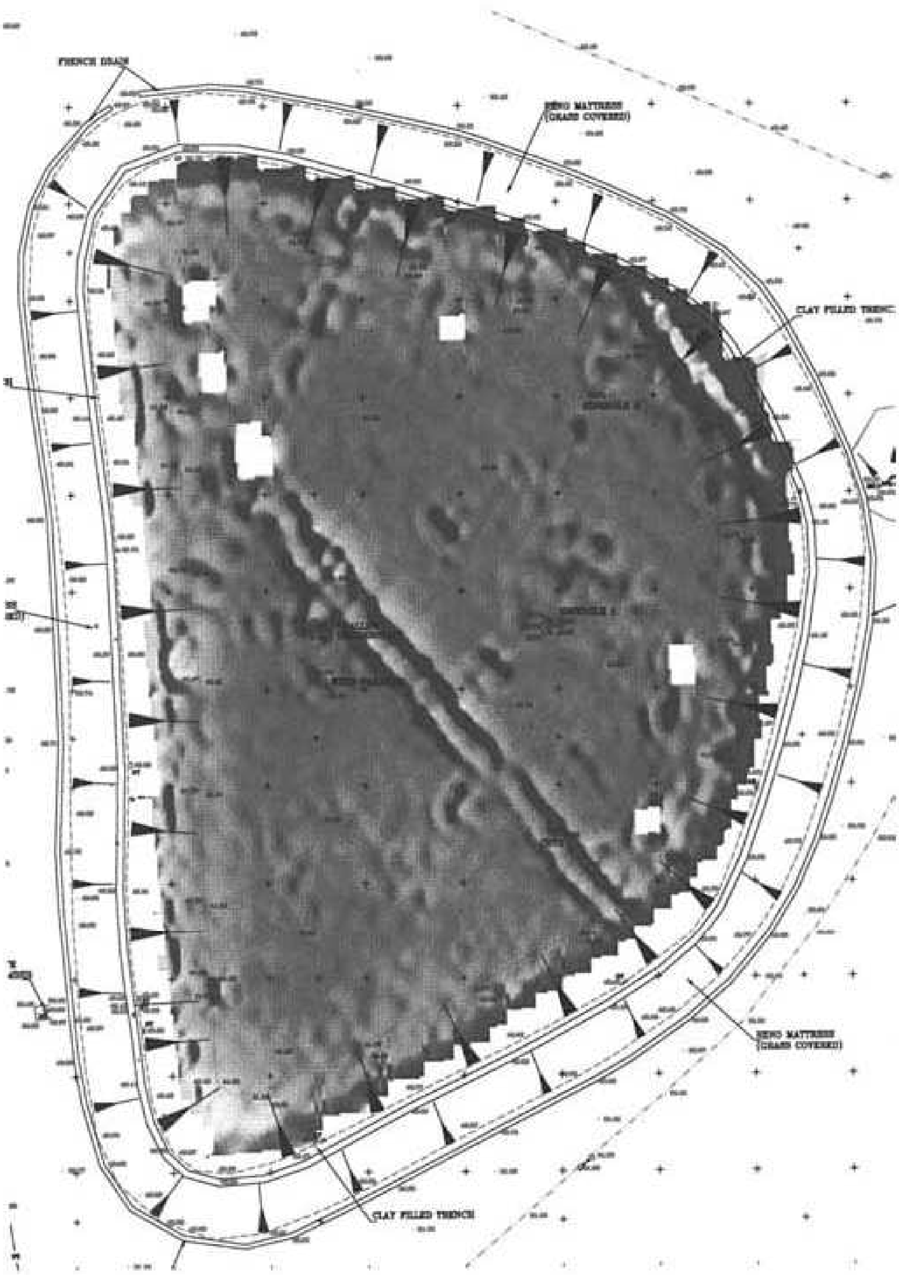


***Figure 3.11*** *Results of detailed EM-31 resistivity survey, plotted as an image. (Reproduced by permission of Geo-services International (UK) Ltd.)*

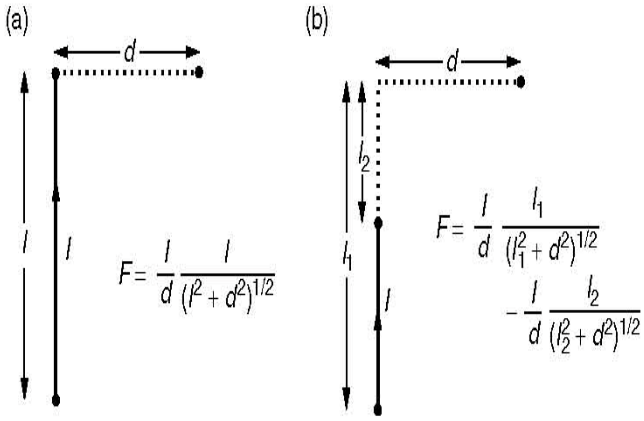


***Figure 3.12*** *The Biot–Savart law. Any long-wire transmitter can be regarded as made up of elements of the type shown in (a). Two such elements, with currents in opposite directions, can be used to calculate cases such as (b) where the observation point is beyond the end of the wire.*

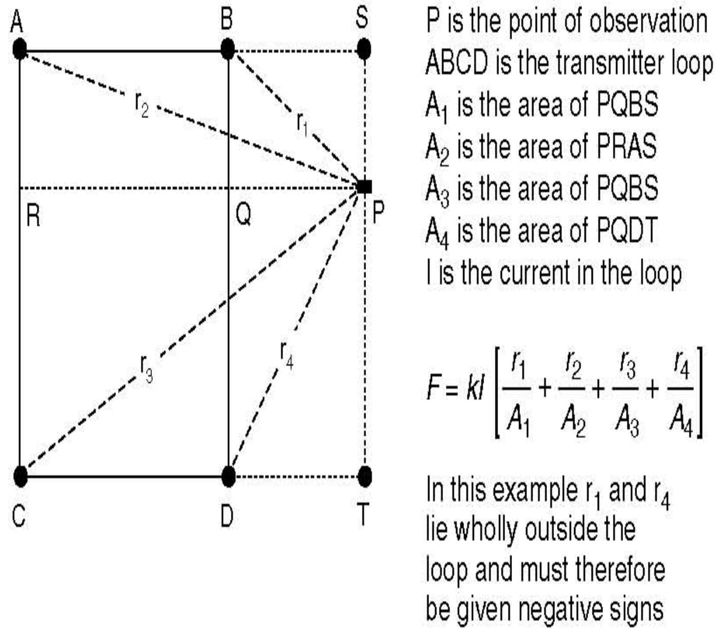


***Figure 3.13*** *Primary field due to a fixed, rectangular loop carrying a current* I. *If* I *is measured in amps and distances are in metres,* $k = 10^{-7}$ *for* F *in Weber* $\cdot$ $m^{-2}$.

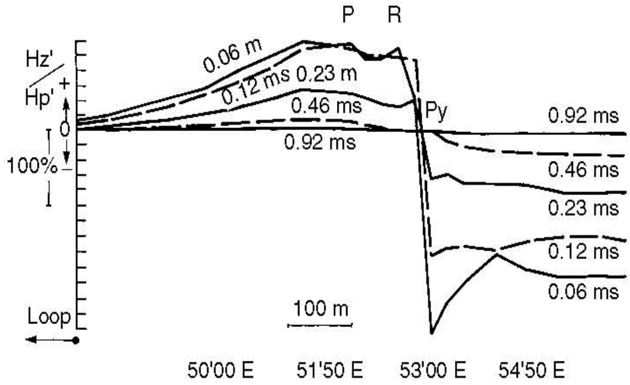


***Figure 3.14*** *Fixed-loop UTEM vertical component anomaly at Que River, Tasmania. Reading interval 25 m. The weak anomaly at P indicates economic mineralization, whereas the large anomaly at R is produced by barren pyrite. (Reproduced by permission of the Australian Society of Exploration Geophysicists.)*

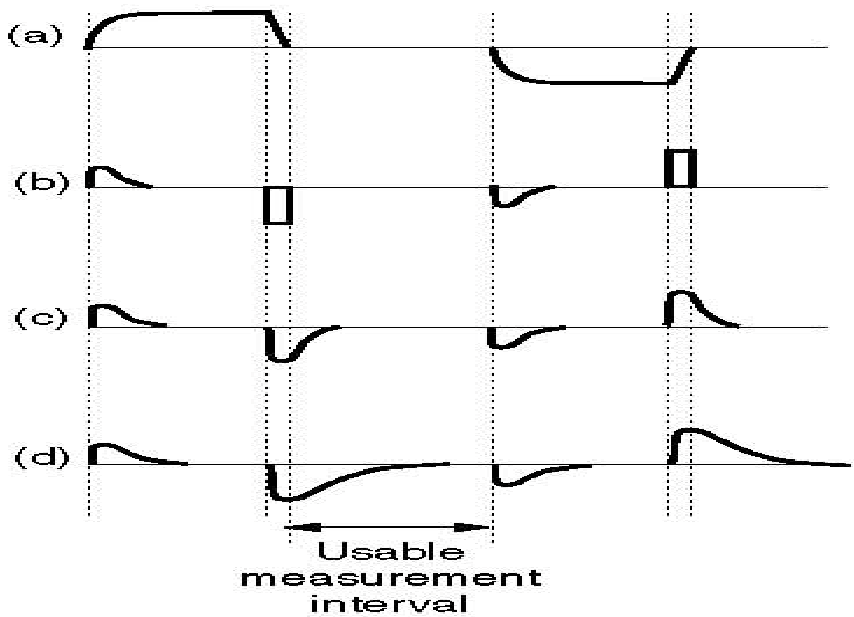


***Figure 3.15*** *TEM waveforms. (a) Transmitter waveform. Note the taper on the up ramp. The slope on the down ramp is drawn deliberately shallow, for clarity. (b) Signal induced in receiver due to primary field. (c) Signal induced in receiver due to currents circulating in a poor conductor. (d) Signal induced in receiver due to currents circulating in a good conductor. The beginning of the usable measurement interval is defined by the termination of the current induced by the primary, and the end by the beginning of the following up ramp.*

## 4.0 Conclusion

Anomalies are assessed by calculating *reduced ratios* equal to the actual ratios of the signal amplitudes through the two coils divided by the *normal* ratios that would have been observed over non-conductive terrain. Phase differences are measured between the currents in the two receiver coils and any non-zero value is anomalous.

## 5.0 Summary

If the source, whether a coil or a straight wire, were to be fixed, there would be a zero when a horizontal receiver coil was immediately above a steeply dipping body and the anomaly would be anti-symmetric (Figure 3.14). Fixed-source systems often measure dip angles or (which is effectively the same thing) ratios of vertical to horizontal fields. *Turam* (Swedish: 'two coil') methods use fixed extended sources and two receiving coils separated by a distance of the order of 10 m. There is no reference cable between receivers and transmitter, but absolute phases and ratios relative to a single base can be calculated provided that each successive reading is taken with the trailing coil placed in the position just vacated by the leading coil.

## 6.0 Tutor marked Assignments

(a) What are the advantages of straight wire sources EM over coils EM system.

## 7.0 References/Further readings


John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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## UNIT 3: TRANSIENT ELECTROMAGNETICS (TEM)

### 1.0 Introduction

TEM systems provide multi-frequency data by repeated sampling of the transient magnetic fields that persist after a transmitter current is terminated. A modified square wave of the type shown in Figure 3.15 flows in the transmitter circuits, and transients are induced in the ground both on the up-going and down-going *ramps*. Observations are made on currents induced during the down-going ramps only, since it is only these that can be measured in the absence of the primary field. It is therefore desirable that the up ramp transients should be small and decay quickly, and the up-ramp is often *tapered*, reducing induction. In contrast, the current flow is terminated as quickly as possible, in order to maximize induction in the ground. This means that transmitter's self-induction must be minimized, and single-turn loops are preferred to multi-turn coils.

### 2.0 Objectives

At the end of the unit, readers should be able to;

(i) Know Transient that Electromagnetic are used for depth sounding
(ii) Familiarise with both CWEM, TEM and time domain IP systems
(iii) Understand that transient electromagnetic was developed to overcome some of the disadvantages in CWEM.
(iv) Know that CWEM and TEM are theoretically equivalent, but have different advantages and disadvantages.
(v) Provide multi-frequency data by repeated sampling of the transient magnetic fields that persist after a transmitter current is terminated.

### 3.0 Main C ontents

*3.1 TEM survey parameters*

A system in which the primary field is not present when secondary fields are being measured can use very high powers, and TEM systems are popular in areas where overburden conductivities are high and penetration is skin-depth limited. Since measurements are made when no primary field is present, the transmitter loop, which may have sides of 100 m or more, can also be used to receive the secondary field. Alternatively, a smaller receiver coil can be positioned within the loop. This technique can be used in CWEM surveys only with very large transmitter loops because of the strong coupling to the primary field.

It is also possible to carry out TEM ‘Slingram’ surveys, and most commercial systems can employ several different loop configurations. They differ in portability and, in detail, in sampling programs. The SIROTEM may be taken as typical. It produces a square-wave current with equal on and off times in the range from 23 to 185 msec. The voltage in the receiver coil can be recorded at 32 different times during eddy-current decay, and signals can be averaged over as many as 4096 cycles.

An alternative approach is provided by the UTEM system, in which current with a precisely triangular waveform and a fundamental frequency of between 25 and 100 Hz is circulated in a large rectangular loop. In the absence of ground conductivity, the received signal, proportional to the time derivative of the magnetic field, is a square wave. Deviations from this in the vertical magnetic and horizontal electric fields are observed by sampling at eight time delays. In mineral exploration, TEM data are usually presented as profiles for individual delay times (Figure 3.14). The results at short delay times are dominated by eddy currents in large volume, relatively poor conductors. These attenuate quite rapidly, and the later parts of the decay curves are dominated by currents circulating in any very good conductors that may be present.

*3.2 TEM depth sounding*

TEM methods were originally developed to overcome some of the disadvantages of CWEM methods in mineral exploration but are now also being widely used for depth sounding. In homogeneous or horizontally layered ground, termination of current flow in the transmitter loop induces a similar current loop or ring in the adjacent ground. This current then decays, inducing a further current ring with a slightly greater radius at a slightly greater depth. The induced current thus progresses through the subsurface as an expanding ‘smoke ring’ (Figure 3.16), and the associated magnetic fields at progressively later times are determined by current flow (and hence by resistivity) at progressively greater depths. TEM surveys with 100 m transmitter loops have been used to obtain estimates of resistivity down to depths of several hundred metres, something requiring arrays several kilometres in length if conventional DC methods are used.

If localized good conductors, whether buried oil drums or sulphide ore bodies, are present, the effects of the eddy currents induced in them will dominate the late parts of decay curves and may prevent valid depth sounding data from being obtained. A relatively minor shift in position of the transmitter and receiver loops may be all that is needed to solve the problem.

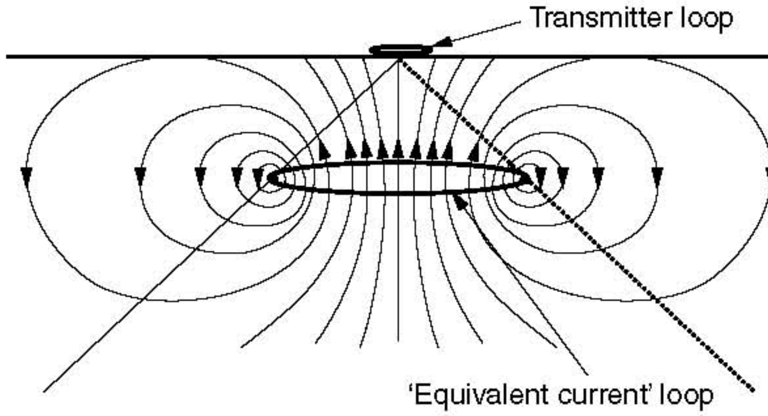


***Figure 3.16*** *The TEM 'expanding smoke ring' in a layered medium. The equivalent current loop' defines the location of maximum circulating current at some time after the termination of current flow in the transmitter loop. The slant lines define the cone within which the loop expands. Arrows are on lines of magnetic field.*

*3.3 TEM and CWEM*

CWEM and TEM methods are theoretically equivalent but have different advantages and disadvantages because the principal sources of noise are quite different. Because noise in CWEM surveys arises mainly from variations in the coupling between transmitter and receiver coils, the separations and the relative orientations of the coils must either be kept constant or, if this is not possible, must be very accurately measured. The receiver circuitry must also be very precisely stabilized, but even so it is difficult to ensure that the initial 100% (for the in-phase channel) and 0% (for the quadrature channel) levels do not drift significantly during the course of the day. Because all these possible sources of noise are associated with the primary field, their effects cannot be reduced merely by increasing transmitter power. On the other hand, in TEM surveys the secondary fields due to ground conductors are measured at times when no primary field exists, and coupling noise is therefore negligible. The very sharp termination of transmitter current provides a timing reference that is inherently easier to use than the rather poorly defined maxima or zero crossings of a sinusoidal wave, and the crystal-controlled timing circuits drift very little.

The most important sources of noise in TEM surveys are external natural and artificial field variations. The effect of these can be reduced by increasing the strength of the primary √ field and by *N*-fold repetition to achieve a *N* improvement in signal-to-noise ratio. There are, however, practical limits to these methods of noise reduction. Transmitter loop magnetic moments depend on current strengths and loop areas, neither of which can be increased indefinitely. Safety and generator power, in particular, set fairly tight limits on usable current magnitudes. The large loops that are necessary for deep penetration are inevitably difficult to use and can be moved only slowly. Multiple repetitions are not a problem in shallow work, where virtually all the useful information is contained in the first few milliseconds of the decay curve, but can be time consuming in deep work, where measurements have to be extended to time delays of as much as half a second.

Moreover, repetition rates must be adjusted so that power-line noise (which is systematic) is cancelled and not enhanced, and the number of repetitions must be adequate for this purpose. It may take more than 10 minutes to obtain satisfactory data at a single point when sounding to depths of more than 100 m (this does, of course, compare very favourably with the time needed to obtain soundings to similar depths with Wenner or Schlumberger arrays). In Slingram CWEM systems, resolution is determined by the spacing between the transmitter and receiver coils. Because the two coils can be superimposed in a TEM survey, the resolving power can be very high. TEM is thus much more suitable than CWEM for precise location of very small targets. Most modern metal detectors, including 'super metal detectors' such as the Geonics EM-63, which was designed specifically to detect unexploded ordnance (UXO) at depths of a few metres, use TEM principles.

*3.4 TEM and IP*

TEM superficially resembles the time-domain IP methods discussed earlier. The most obvious difference is that currents in most IP surveys are injected directly into the ground and not induced by magnetic fields. However, at least one IP method does use induction and a more fundamental difference lies in the time scales. Time-domain IP systems usually sample after delays of between 100 msec and 2 sec, and so avoid most EM effects. There is a small region of overlap, from about 100 to 200 msec, between the two systems and some frequency domain or phase IP units are designed to work over the whole range of frequencies from DC to tens of kHz to obtain conductivity spectra. However, it is usually possible in mineral exploration to regard the EM and IP phenomena as completely separate and to avoid working in regions, either of frequency or time delay, where both are significant.

## 4.0 Conclusion

TEM methods were originally developed to overcome some of the disadvantages of CWEM methods in mineral exploration but are now also being widely used for depth sounding. In homogeneous or horizontally layered ground, termination of current flow in the transmitter loop induces a similar current loop or ring in the adjacent ground. This current then decays, inducing a further current ring with a slightly greater radius at a slightly greater depth. TEM surveys with 100 m transmitter loops have been used to obtain estimates of resistivity down to depths of several hundred metres, something requiring arrays several kilometres in length if conventional DC methods are used.

## 5.0 Summary

TEM systems provide multi-frequency data by repeated sampling of the transient magnetic fields that persist after a transmitter current is terminated. A modified square wave flows in the transmitter circuits, and transients are induced in the ground both on the up-going and down-going *ramps*. Observations are made on currents induced during the down-going ramps only, since it is only these that can be measured in the absence of the primary field.TEM systems are popular in areas where overburden conductivities are high and penetration is skin-depth limited.

In TEM surveys the secondary fields due to ground conductors are measured at times when no primary field exists, and coupling noise is therefore negligible. The most important sources of noise in TEM surveys are external natural and artificial field variations. The effect of these can be reduced by increasing the strength of the primary √ field and by *N*-fold repetition to achieve a *N* improvement in signal-to-noise ratio. There are, however, practical limits to these methods of noise reduction.

## 6.0 Tutor Marked Assignments

(a) Compare and contrast TEM with CWEM
(b) Compare and contrast TEM with IP
(c) Describe the concept of TEM depth sounding

## 7.0 References/Further readings


John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

Kearey, P., Brooks, M. and Hill, I. (2002) *An Introduction to Geophysical Exploration* (Third Edition), Blackwell Science, Oxford, 262 pp.

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# MODULE 4

## Unit 1 Very low Frequency (VLF) Radiation

## Unit 2 VLF Instruments

## Unit 3 Presentation of VLF Results

## Unit 4 Natural and Controlled-Source Audio- magneto telluric

## UNIT 1 VERY LOW FREQUENCY (VLF) RADIATION

### 1.0 Introduction

Some geophysical instruments make use of high-power military communications transmissions in the 15–25 kHz band. Termed *very low frequency* (VLF) by radio engineers, these waves have frequencies higher than those used in conventional geophysical work, but allow electromagnetic surveys to be carried out without local transmitters.

Natural electromagnetic radiation covers a much broader range of frequencies. Longer wavelengths (lower frequencies) are generally due to ionospheric micro-pulsations, while much of the radiation in the audible range is generated by distant thunderstorm activity. These latter signals, known as *sferics*, form the basis of audio-magneto-telluric (AMT) methods in mineral exploration and resistivity depth sounding. Because sferic signal strengths vary considerably with time, methods have been developed of producing signals similar to the natural ones using controlled sources (CSAMT). Instruments such as the Geometrics Stratagem allow both natural and CSAMT signals to be used at the same time but over different frequency ranges.

### 2.0 Objectives

At the end of this unit, readers should be able to;

(i) Know that natural electromagnetic radiation covers a much broader range of frequencies.
(ii) Understand that electromagnetic wave consist of a coupled alternating electrical and magnetic field directly at right angles to each other
(iii) Familiarise with the VLF TRANSMISSIONS

(iv) Understand the difference between magnetic field and electric field.
(v) Know the origin of elliptical polarized waves.
(vi) Show how VLF method is used in measuring spatial variations in the tilt angle of the resultant field of a dipping bed.

## 3.0Main Contents

### *3.1 VLF Radiation*

An electromagnetic wave consists of coupled alternating electrical and magnetic fields, directed at right angles to each other and to the power vector defining the direction of propagation (Figure 4.1). Electric field vectors will always align themselves at right angles to perfectly conductive surfaces and a wave can therefore be *guided* by enclosing conductors. The extent to which this is possible is governed by the relationship between the wavelength of the radiation and the dimensions of the guide. Waves at VLF frequencies propagate very efficiently over long distances in the waveguide formed by the ground surface and the ionosphere.

### *3.2 VLF transmissions*

Neither the Earth nor the ionosphere is a perfect conductor, and some VLF energy penetrates the ground surface or is lost into space. Without this penetration, there would be neither military nor geophysical uses. As it is, the waves can be detected tens of metres below the sea surface and are ideal for communicating with submarines. Amplitudes decrease exponentially with depth and the secondary fields produced in subsurface conductors are similarly attenuated on their way to the surface, i.e. VLF surveys are *skin-depth limited* (Figure 1.5).

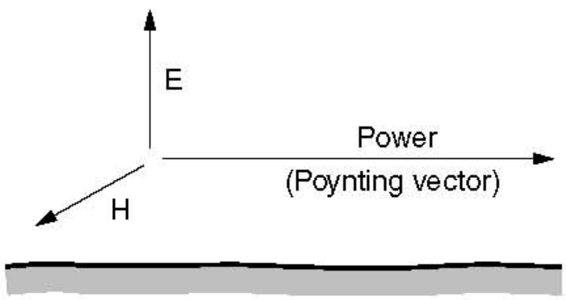


***Figure 4.1*** *Electromagnetic wave vectors close to a perfect conductor. The magnetic (H) and electric (E) fields are at right angles to each other and to the power or Poynting vector that defines the direction of propagation.*

There are more than a score of stations around the world transmitting VLF signals continuously for military purposes (Figure 4.2). The message content is generally superimposed by frequency modulation on a sinusoidal carrier wave, but occasionally the transmission is chopped into dots and dashes resembling Morse code. Making geophysical use of these *quenched-carrier* signals is extremely difficult. Transmission patterns and servicing schedules vary widely but the makers of VLF instruments are usually aware of the current situation and provide information on their websites.

### *3.3 Detecting VLF fields*

A geophysical user of a VLF signal has control over neither the amplitude nor the phase of the signal. Readings of a single field component at a single point are therefore meaningless; one component must be selected as a reference with which the strengths and phases of other components can be compared. The obvious choices are the horizontal magnetic and vertical electric fields, since these approximate most closely to the primary signals. VLF magnetic fields are detected by coils in which currents flow in proportion to the number of turns in the coil, the core permeability and the magnetic field component along the coil axis. No signal will be detected if the magnetic field is at right angles to this axis.

A VLF electric field will induce alternating current in an aerial consisting of a straight conducting rod or wire. The signal strength is roughly proportional to the amplitude of the electric-field component parallel to the aerial, and to the aerial length.

### *3.4 Magnetic field effects*

Eddy currents induced by a VLF magnetic field produce secondary magnetic fields with the same frequency as the primary but generally with different phase. Any vertical magnetic component is by definition anomalous, and most VLF instruments compare vertical with horizontal magnetic fields, either directly or by measuring tilt angles. The directions of the changes in the secondary magnetic fields are always in opposition to the changes in the primary field. Directly above a steeply dipping sheet-like conductor this secondary field may be strong but will be horizontal and will not be detected by most systems. On either side there will be detectable vertical fields, in opposite directions, defining an anti-symmetric anomaly (Figure 4.3). Steeply dipping contacts also produce VLF anomalies, which are positive or negative depending upon the sign convention (Figure 3.4). The classical anti-symmetric ‘thin conductor’ anomaly can be looked upon as being produced by two contacts very close together. Two steeply dipping conductors close to each other produce a resultant anomaly that is generally similar to the sum of the anomalies that would have been produced by each body singly. Where, however, one of the bodies is steeply dipping and the other flat lying, the results are more difficult to anticipate. Conductive overburden affects, and can actually reverse, the phase of the secondary field.

*3.5 Electric field effects*

Because the Earth is not a perfect conductor, VLF electric vectors near its surface are tilted, not vertical, having horizontal components. Above homogeneous ground the horizontal field would differ in phase from the primary (vertical) field by 45◦, would lie in the direction of propagation and would be proportional to the square root of the ground resistivity. Over a layered earth, the magnitude of the horizontal electric field (or tilt of the total field) records average (apparent) resistivity, strongly biased towards the resistivity of the ground within about half a skin depth of the surface. The phase angle will be greater than 45◦ if resistivity increases with depth in a layered earth and less than 45◦ if it decreases. Sharp lateral resistivity changes distort this simple picture and very good (usually artificial) conductors produce secondary fields that invalidate the assumptions upon which the resistivity calculations are based.

*3.6 Elliptical polarization*

If horizontal primary and secondary fields that differ in phase are combined, the resultant is also horizontal but differs from the two components in both magnitude and phase. A secondary field that is vertical and in phase with the primary produces a resultant which has the same phase but is tilted and stronger. A vertical secondary field in phase quadrature with the primary produces an elliptically polarized wave (Figure 4.5). These are special cases. In the general case of an inclined secondary field that is neither in phase nor in phase quadrature with the primary, a tilted, elliptically polarized wave is produced.

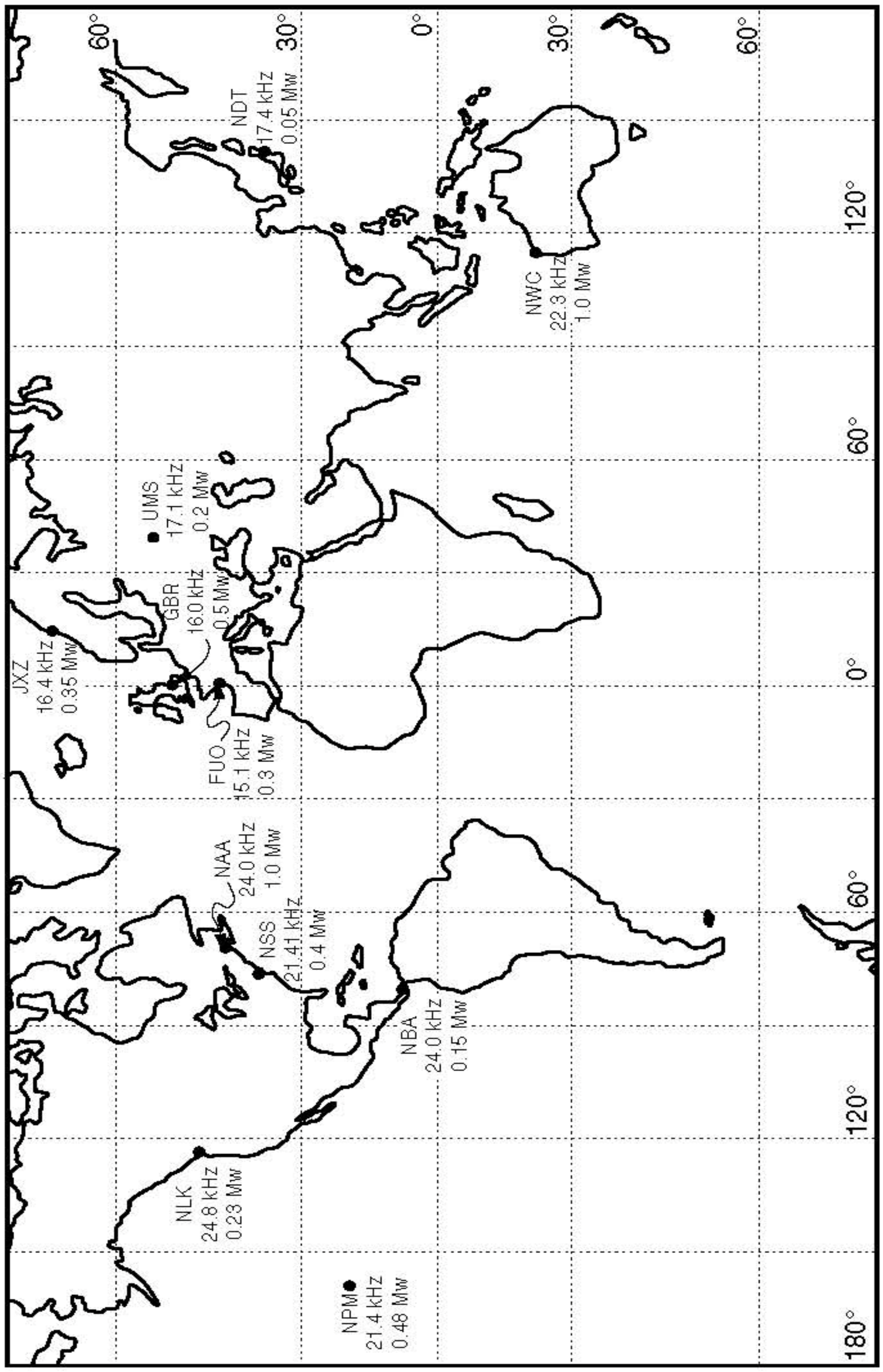


***Figure 4.2*** *Major VLF transmitters. Data blocks identify station codes (e.g. NAA), frequencies in kHz and power in Megawatts. Frequencies and powers are liable to change without much notification.*

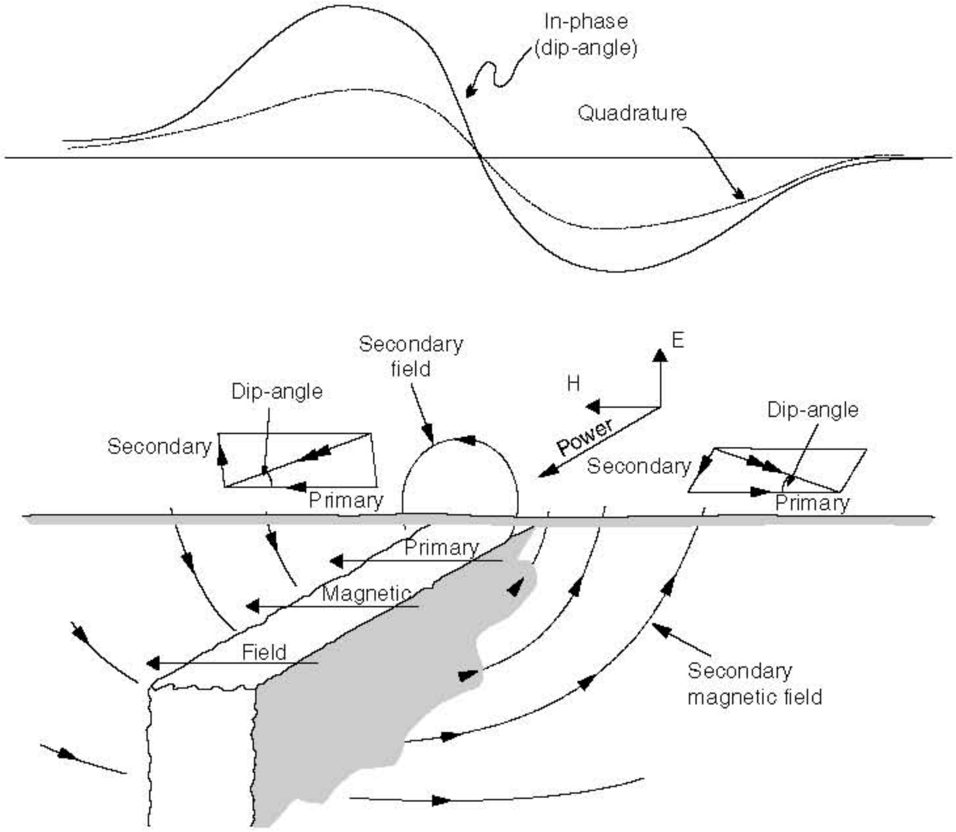


***Figure 4.3*** *VLF magnetic component anomaly over a vertical conducting sheet striking towards the transmitter. Note the need for a sign convention.*

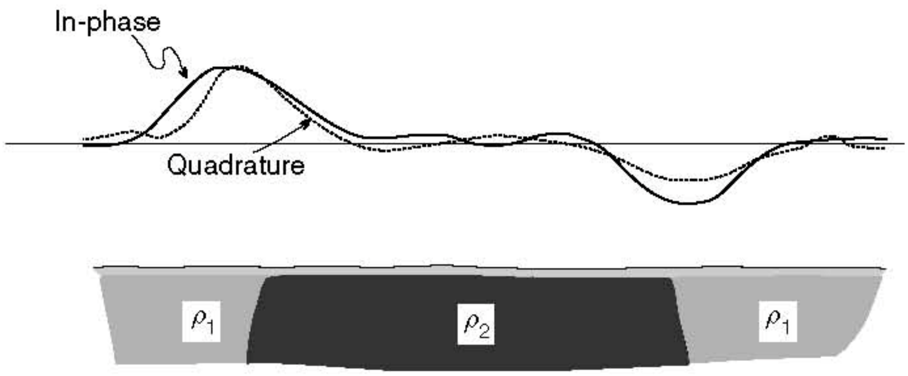


***Figure 4.4*** *VLF magnetic field anomalies at the margins of an extended conductor. Sign convention as for Figure 4.3.*

Because the secondary field has a horizontal component, the tangent of the tilt angle is not identical to the ratio of the vertical secondary field to the primary and, because of the tilt, the quadrature component of the vertical secondary field does not define the length of the minor axis of the ellipse. This seems complicated, but VLF dip-angle data are usually interpreted qualitatively and such factors, which are only significant for strong anomalies, are usually ignored. Quantitative interpretations are based on physical or computer model studies, the results of which can be expressed in terms of any quantities measured in the field.

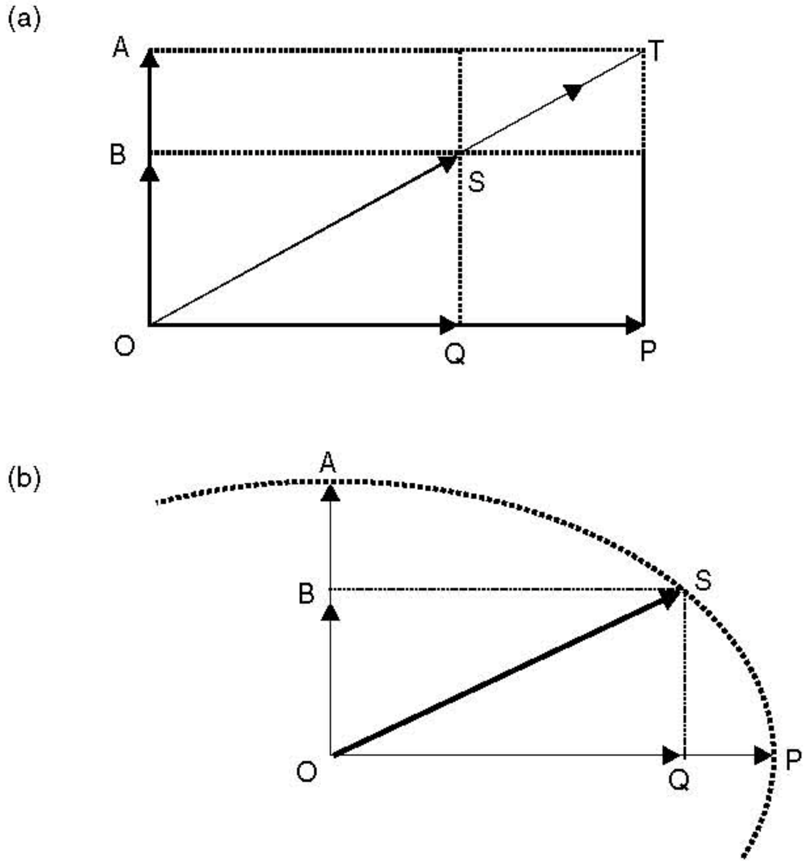


***Figure 4.5*** *Combination of alternating vertical and horizontal magnetic field vectors. (a) Horizontal and vertical fields in-phase: the vertical vector has its maximum value OA when the horizontal vector has its maximum value OP and the resultant has its maximum value OT. At any other time (as when the vertical field has value OB and the horizontal field has value OQ), the resultant (OS) is directed along OT but with lesser amplitude. All three are zero at the same time. (b) Phase-quadrature: the vertical vector is zero when the horizontal vector has its maximum value OP, and has its maximum value OA when the horizontal vector is zero. At other times, represented by OB, OQ and OS, the tip of the resultant lies on an ellipse.*

*3.7 Coupling*

The magnetic-component response of a good conductor depends critically on its orientation. This is also true in conventional EM surveys but EM traverses are usually laid out at right angles to the probable geological strike, automatically ensuring good coupling. In VLF work the traverse direction is almost irrelevant, the critical parameter being the relationship between the strike of the conductor and the bearing of the transmitting station. A body that strikes towards the transmitter is said to be *well coupled*, since it is at right angles to the magnetic vector and eddy currents can flow freely. Current flow will otherwise be restricted, reducing the strength of the secondary field. If the probable strike of the conductors in a given area is either variable or unknown, two transmitters, bearing roughly at right angles to each other, should be used to produce separate VLF maps. A Mercator projection map such as Figure 4.2 is of only limited use in determining the true bearings of VLF transmitters. The all-important *Great Circle* paths can be found using a computer program or a globe and a piece of string.

**4.0 Conclusion**

The VLF method has the advantages that the field equipment is small and light, being conveniently operated by one person, and that there is no need to install a transmitter. However, for a particular survey area, there may be no suitable transmitter providing a magnetic vector across the geologic strike. A further disadvantage is that the depth of penetration is somewhat less than that attainable by tilt-angle methods using a local transmitter. The VLF method can be used in airborne EM surveying.

**5.0 Summary**

The source utilized by the VLF method is electromagnetic radiation generated in the low frequency band of 15-25 kHz by the powerful radio transmitters used in long range communications and navigational systems. A geophysical user of a VLF signal has control over neither the amplitude nor the phase of the signal. Readings of a single field component at a single point are therefore meaningless; one component must be selected as a reference with which the strengths and phases of other components can be compared. Eddy currents induced by a VLF magnetic field produce secondary magnetic fields with the same frequency as the primary but generally with different phase.

Because the Earth is not a perfect conductor, VLF electric vectors near its surface are tilted, not vertical, having horizontal components. Above homogeneous ground the horizontal field would differ in phase from the primary (vertical) field by $45^{\circ}$, would lie in the direction of propagation and would be proportional to the square root of the ground resistivity. If horizontal primary and secondary fields that differ in phase are combined, the resultant is also horizontal but differs from the two components in both magnitude and phase. A secondary field that is vertical and in phase with the primary produces a resultant which has the same phase but is tilted and stronger.

## 6.0 Tutor Marked Assignments

(a) Discuss the advantages of VLF method over other EM methods

(b) A significant problem with many of the EM survey methods is that a small Secondary field must be measured in the presence of a much larger primary field. Discuss.

(c) How could this problem be overcomed?

## 7.0 References/Further readings

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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Sharma, P.V. (1997) *Environmental and Engineering Geophysics*, Cambridge University Press, Cambridge, 475 pp.

# UNIT 2 VERY LOW FREQUENCY INSTRUMENTS

## 1.0 Introduction

The first commercially available geophysical VLF instrument, the Ronka-Geonics EM-16, used only magnetic fields, although horizontal electric fields can now be measured with the EM-16R add-on module. The EM-16 is still widely used and serves to illustrate principles which, in some other instruments, are concealed by processing software.

## 2.0 Objectives

At the end of this unit, readers should be able to;

(i) To demonstrate EM-16 add-on module to measure horizontal electric field
(ii) Know that EM-16 is still widely used and serves to illustrate practical principle which are concealed by processing software in some instruments
(iii) Be familiar with other VLF instruments.
(iv) present the various VLF instruments available for the survey.
(v) Know the operational principle of each instrument and their advantages and disadvantages.

## 3.0 Main Contents

*3.1 The EM-16*

The EM-16 consists of a housing containing the electronics, to which is attached a conventional sighting clinometer, and a T-shaped handle containing two coils at right angles (Figure 4.6). Controls include a two-position stationselector switch, a calibrated quadrature control and a knob that amplifies an audio tone which, although often extremely irritating, can be almost inaudible in areas such as forests on windy days, where other noises compete. With the phase control at zero, the strength of the tone is determined by the setting of the volume control and by the component of the VLF magnetic field parallel to the axis of the main coil. Measurements are made by finding orientations of this coil that produce nulls (minima). This is easiest if the volume control is set so that at the 'null' the tone is only just audible. Before reading, the direction of the minimum horizontal component (the direction of the power vector) must be determined. Unless there is a significant secondary field, this also gives the bearing of the transmitter. The instrument is held with both coils horizontal, most conveniently with the short coil at right angles to the stomach (Figure 4.7). The

***Figure 4.6*** *EM-16 in normal reading position.*

***Figure 4.7*** *Searching for the station with the EM-16.*

observer turns until a null is found, at which stage the magnetic field is at right angles to the main coil and parallel to the short coil. It is occasionally necessary to adjust the quadrature control during this process; it should be reset to zero before attempting to observe the vertical field. There is no way of telling, and no importance in knowing, whether the transmitter is to the left or right of the observer.

Without changing position, the observer then rotates the instrument *about the short coil as axis* into the upright position and then tilts it in the plane of the clinometer (which should now be at eye level). The signal minimum occurs when the long coil is at right angles to the major axis of the polarization ellipse. The null will be poorly defined if the quadrature component (minor axis field) is large or if the plane of the polarization ellipse is not vertical. Definition can be improved by using the quadrature control to subtract a measured percentage of the phase-shifted major-axis field, detected by the short coil, from the quadrature field detected by the long coil. At the null, with the instrument held in the tilted position, the quadrature reading gives the ratio of the ellipse axes and the tangent of the tilt angle defines the in-phase anomaly.

### *3.2 EM-16 sign conventions*

At a null, the long handle of the EM-16 points towards the region of higher conductivity. An observer with the conductor to the front will have to lean backwards to obtain a null and will see a positive reading on the clinometer. Viewed from the opposite direction, the reading would be negative. To avoid confusion, all readings should be taken facing the same direction and this should be recorded in the field notes even if, as is recommended, a standard range of directions (e.g. N and E rather than S or W) is adopted on all surveys. Quadrature anomalies usually show the same polarity as in-phase anomalies but may be reversed by conductive overburden. Reversed in-phase anomalies can be caused by steeply dipping insulators enclosed in conductive country rock, which are rare, or by active sources such as live power lines.

### *3.3 The EM-16R*

With the additional circuitry contained in the EM-16R plug-in module and a 2 m length of shielded cable acting as an aerial, the EM-16 can be used to measure horizontal electric fields. The cable is stretched out towards the transmitter and the two ends are pegged down. The long coil must point towards the transmitter and, for convenience, the instrument is usually laid on the ground. The short coil then detects the maximum magnetic-field component. A null is obtained by rotating the 16R control, giving a reading directly in ohm-metres. Phase shifts are also monitored.

EM-16R resistivities, which use the horizontal magnetic field as a phase reference, assume a fixed ratio between the horizontal magnetic and vertical electric components. This is not the case if significant secondary magnetic fields are present, and use of the more stable vertical electric field as a reference is to be preferred in instruments that provide this option.

*3.4 Other VLF instruments*

Most of the alternatives to the EM-16 also record magnetic field variations but measure field components and their ratios rather than dip angles. Major advances include direct recording of data, often into a memory as well as to a front panel display, and elimination of the use of an audible tone. Some instruments can measure natural magnetic and two-transmitter VLF fields simultaneously, and some have been made self-orientating to increase speed of coverage. Amplitudes may also be measured but a base instrument is then needed to correct for amplitude variations caused by meteorological changes along the long transmission paths. Horizontal magnetic field directions are occasionally recorded but are generally less sensitive and less diagnostic than changes in tilt angle and require a directional reference. Many instruments rely, as does the EM-16, on crystal-controlled tuning to lock to the desired station but others use high-Q tuning circuits. The ABEM Wadi scans the entire VLF band and presents the user with a plot of signal strength against frequency, allowing an informed choice of station.

## 3.0 Conclusion

The maximum detection depth of any VLF equipment is about half the transmitter-receiver separation. Field work is simple and requires a crew of only two or three operators. The spacing and orientation of the coils is critical as a small percentage error in spacing can produce appreciable error in measurement. The coils must be kept accurately horizontal and coplanar as small relative tilts can produce substantial errors.

## 5.0 Summary

Several VLF instruments are available to carry out good quality investigations. But a significant problem with many of the EM survey methods is that a small secondary field must be measured in the presence of a much larger primary field. This problem may be overcome by using a primary field which is not continuous but consists of a series of pulses between which no primary is generated. The secondary field induced by the primary is then measured only when the primary is inactive. The better the conductivity of the body, the longer do eddy currents flow in it and the longer is the duration of the secondary field.

## 6.0 Tutor Marked Assignments

(a) Name the various types of VLF instruments

(b) Discuss the operational mechanism of any of the above named instruments.

## 7.0 References/Further readings

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.
Kearey, P., Brooks, M. and Hill, I. (2002) *An Introduction to Geophysical Exploration* (Third Edition), Blackwell Science, Oxford, 262 pp.
McCann, D.M., Fenning, P. and Cripps, J. (Eds) (1995) *Modern Geophysics in Engineering Geology*, Engineering Group of the Geological Society, London, 519 pp.
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Sharma, P.V. (1997) *Environmental and Engineering Geophysics*, Cambridge University Press, Cambridge, 475 pp.
Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A. (1990) *Applied Geophysics* (Second Edition), Cambridge University Press, Cambridge, 770 pp.
Bhattacharya, B.B. and Sen, M.K. (1981) Depth of investigation of collinear electrode arrays over an homogeneous anisotropic half-space in the direct current method. *Geophysics*, 46, 766–80.

## UNIT 3 PRESENTATION OF VERY LOW REQUENCYF RESULTS

### 1.0 Introduction

Dip-angle data can be awkward to contour and dip-angle maps, on which conductors are indicated by steep gradients, may be difficult to assess visually. Large artificial conductors produce classic anti-symmetric anomalies but geological conductors are often indicated merely by gradients (Figure 4.8). VLF results tend to be rather noisy, being distorted by minor anomalies due to small local (usually artificial) conductors and electrical interference.

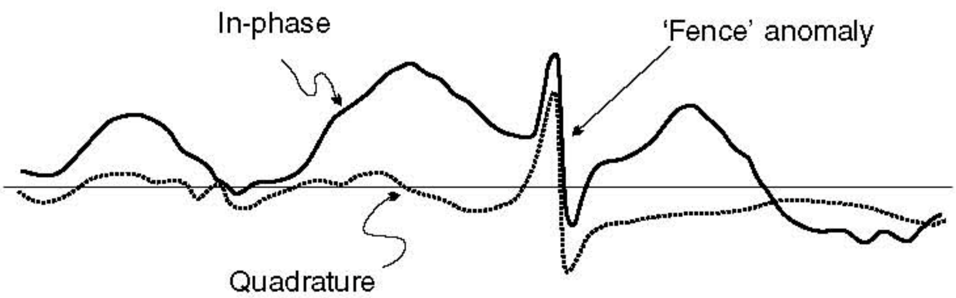


***Figure 4.8*** *Typical EM-16 profile in area of high geological noise, with superimposed anomaly due to rabbit-proof fence*.

### 2.0 Objectives

At the end of this unit, readers should be able to ;

- (i) Explain filtering and the purpose why noise has to be filtered
- (ii) Understand that VLF dip angle data are mostly effectively presented as stacked profiles
- (iii) Understand the VLF system operate at a relatively high frequencies at which most conductors appear good.
- (iv) Show how VLF results could be presented in a simplistic, qualitative and interpretative form.

## 3.0Main Contents

*3.1 Filtering*

Noise can be reduced by adding together results recorded at closely spaced stations and plotting the sum at the mid-point of the station group. This is the simplest form of low-pass filter. The asymmetry inherent in dip-angle data may be removed by differencing adjacent readings to obtain average horizontal gradients. Two filters designed to carry out both these operations are in common use (Figure 4.9). The *Fraser filter* uses four equi-spaced consecutive readings. The first two are added together and halved. The same is done with the second two and the second average is then subtracted from the first. The more complicated *Karous–Hjelt* filter utilizes six readings, three on either side of a central reading that is not itself used. The ABEM Wadi instrument (Figure 1.1a) automatically displays K–H filtered data unless ordered not to do so.

Filtered data are usually easy to contour, especially if, as is normal practice with the Fraser filter, negative values are discarded. Steeply dipping VLF dip-angle data (%) steeply conductors produce positive anomalies and are very obvious. However, it is a geophysical axiom that processing degrades data. Filters can destroy subtle but possible significant features and, more importantly, will distort anomalies due to sources other than simple, conductive sheets. For example, an isolated peak or trough due to a steeply dipping interface between materials of differing conductivity will be transformed by both the Fraser and K–H filters into an anti-symmetric anomaly (Figure 4.9). If negative values are then ignored, this feature will be interpreted as indicating a dipping conductor some distance from the region of actual conductivity change.

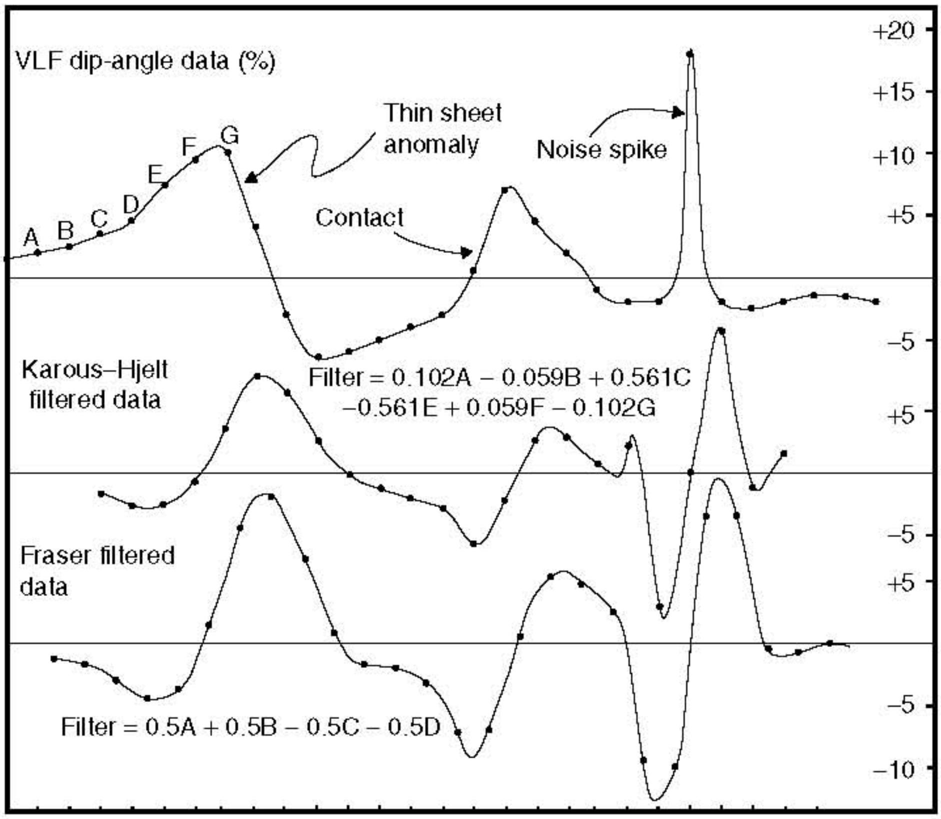


***Figure 4.9*** *EM-16 profile showing typical 'thin-sheet' and 'contact' anomalies and a noise spike, with Fraser and K–H filtered equivalents. The filters convert the thin-sheet anomaly to a peak but render the other anomalies almost unrecognizable.*

It is suggested in the Wadi manual that the K–H filter can be used to compute current-density pseudo-sections. However, VLF data cannot be used to determine patterns of simultaneous current flow at different depths. What can be provided are the magnitudes of the currents that would have to flow at single selected depths to produce a given anomaly. The results of calculations for a number of depths are then presented using a variable density display, and the depths of the sources can then be roughly estimated.

*3.2 Displaying VLF data*

Since raw dip-angle data are difficult to contour and there are valid objections to filtering, VLF dip-angle data are most effectively presented as stacked profiles. These display all the original data, correctly located on the map, and sections of profile on which there are gradients indicating a conductor can be emphasized by thickened lines. In order for a map to be interpreted, even qualitatively, the direction to the transmitter must be shown so that the degree of coupling can be assessed. Conductors striking at right angles to this direction will not be well coupled and may not be seen. The map must also show which of the two possible reading directions has been used, since it is otherwise not possible to distinguish 'normal' gradients in which values decrease in the facing direction from 'reversed' gradients which may be due to active sources such as power and telephone lines.

*3.3 VLF/EM comparisons*

VLF systems operate at relatively high frequencies at which most conductors appear good (Figure 3.2) and usually locate many more anomalies than do CWEM surveys over the same ground (Figure 4.10). The method is best suited to mapping near-vertical contacts and fractures. Conductive mineralization may be detected, but the magnitudes of anomalies associated with very good conductors may be no greater than those produced by un-mineralized but water-filled fractures, which are likely to occupy larger volumes. VLF measurements can be made quickly and conveniently by a single operator, and are therefore sometimes used to assess the electromagnetic

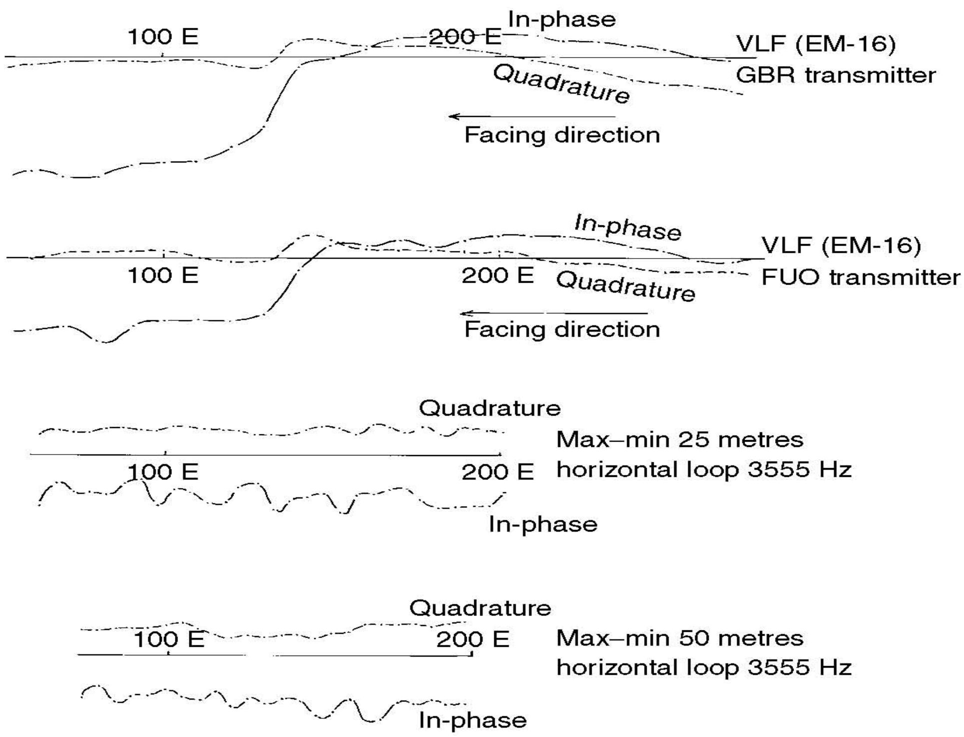


***Figure 4.10*** *Comparison of EM-16 and horizontal loop EM results across a shear zone in granite. The in-phase variations on the EM profiles are due to small errors in coil separation, which are more serious when actual separations are small. Note that the source of the strong VLF anomaly was detected by the EM system only in the quadrature channel and then only at the 50 m spacing and the highest frequency of which the instrument was capable.*

characteristics of an area before the expense of a conventional EM survey is incurred. This is especially useful in populated areas where noise from manmade electrical sources is to be expected. VLF surveys are becoming increasingly popular in hydrogeology. The targets (steeply dipping water bearing fractures in basement rocks) are important in parts of Africa where the military signals are weak or poorly coupled to the dominant conductors. Portable transmitters are now marketed that allow the method to be used in these areas.

## 4.0 Conclusion

VLF dip-angle data are most effectively presented as stacked profiles. These display all the original data, correctly located on the map, and sections of profile on which there are gradients indicating a conductor can be emphasized by thickened lines. In order for a map to be interpreted, even qualitatively, the direction to the transmitter must be shown so that the degree of coupling can be assessed. The map must also show which of the two possible reading directions has been used, since it is otherwise not possible to distinguish 'normal' gradients in which values decrease in the facing direction from 'reversed' gradients which may be due to active sources such as power and telephone lines.

## 4.0 Summary

VLF measurements can be made quickly and conveniently by a single operator, and are therefore sometimes used to assess the electromagnetic characteristics of an area before the expense of a conventional EM survey is incurred. This is especially useful in populated areas where noise from manmade electrical sources is to be expected.

To ensure good data quality, noise can be reduced by adding together results recorded at closely spaced stations and plotting the sum at the mid-point of the station group. This is the simplest form of low-pass filter. The asymmetry inherent in dip-angle data may be removed by differencing adjacent readings to obtain average horizontal gradients. The method has become increasingly popular in hydrogeology and environmental investigations.

## 6.0 Tutor Marked Assignments

(a) Discuss succinctly the importance of filtering in VLF data
(b) List the limitations of EM method.

## 7.0 Reference/Future readings

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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## Unit 4 NATURAL AND CONTROLLED-SOURCE AUDIO-magnetotellurics

### 1.0 Introduction

A broad band of naturally occurring electromagnetic radiation exists and can be used geophysically. These *magnetotelluric* fields are partly sourced by ionospheric currents and partly by thunderstorm activity (*sferics*). The most useful signals, in the frequency range from 1 Hz to about 20 kHz, are commonly referred to as *audio-magnetotelluric* (AMT). These propagate down into the Earth as roughly planar wavefronts oriented parallel to the Earth's surface.

### 2.0 Objectives

At the end of the unit, readers should be able to;

- (i) Explain the source of controlled sources, Auto- Magneto Telluric (CSAMT) and its principles
- (ii) Know the parameters mostly commonly measured in CSAMT
- (iii) Compare results of AMT and CSAMT sounding over a simple layer earth
- (iv) Demonstrate CSAMT practicalities.
- (v) Show how large scale, low frequency and natural magnetic fields within and around the earth were used in prospecting.

### 3.0 Main Contents

*3.1 CSAMT principles*

The source for a CSAMT survey is usually a long (2 km or more) grounded wire in which current is 'swept' through a range of frequencies that may extend from as low as 0.1 Hz to as high as 100 kHz. A variety of parameters can be measured, but the horizontal electrical field parallel to the source wire ($E$x) and the horizontal magnetic field at right angles to it ($H$y) are the most commonly used. Magnetic fields are measured using small vertical coils, electric fields using short grounded electrode pairs (dipoles) set out parallel to the transmitter. Provided that the transmitter wire is laid out parallel to the regional strike, the magnetic field usually varies comparatively slowly, and reconnaissance CSAMT surveys are often made using measurements at between five and 10 electric dipoles, short distances apart, for every magnetic measurement.

At the *far-field* distances of several kilometres at which AMT equations can be applied to CSAMT data, both magnetic and electric field strengths decrease as the inverse cube of distance from the transmitter. Signals are inevitably weak and, despite the inevitable loss of resolution, it may be impractical to use receiver dipoles less than 20 m in length. Even so, noise may exceed signal by a factor of 10 or more, and long recording times may have to be used during which large numbers of records are obtained to allow very high folds of stacking.

*3.2 CSAMT data*

The parameters most commonly measured in CSAMT surveys are the ratios of *E*x to *H*y and the phase differences (the *impedance phases*) between them. The amplitude ratio is used to calculate a quantity known as the *Cagniard resistivity*, which is given by $\rho a = (Ex/Hy)2/5f$ The Cagniard resistivity is often regarded as an estimate of average resistivity down to a depth equal to the skin depth divided by √2, i.e. to approximately 350 √ (*ρ*a/*f* ). The range of frequencies used in CSAMT surveys allows this average to be estimated at depths from a few metres to several kilometres.

Plots prepared in the field are usually of Cagniard resistivity and phase difference against frequency. At a single point the variation may be illustrated by a curve (Figure 4.11), but it is usual to plot pseudo-sections for CSAMT traverses (Figure 4.12).

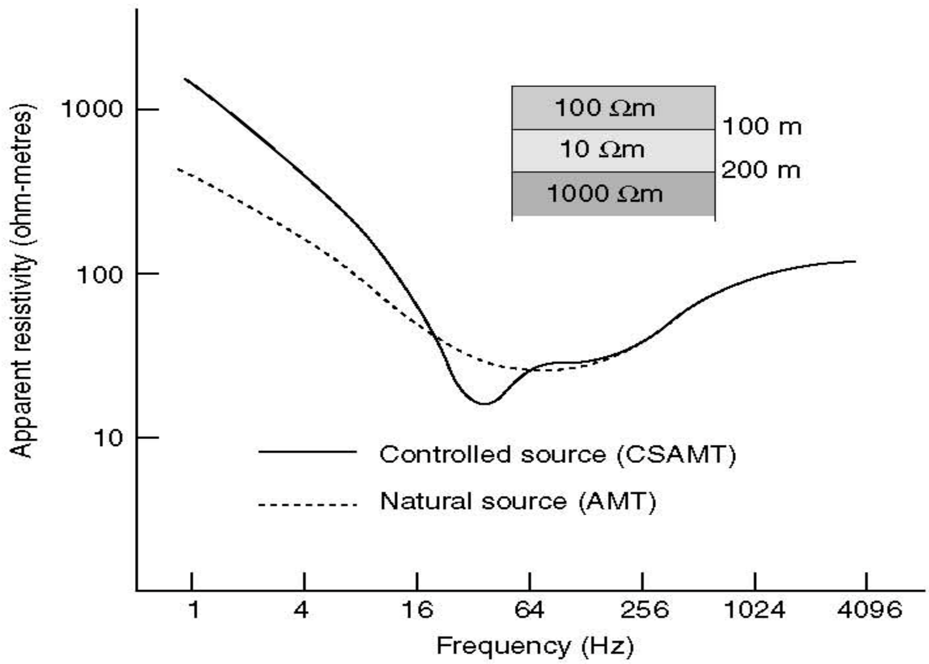


***Figure 4.11*** *Comparison of the results of AMT and CSAMT soundings over a simple layered earth (overburden, resistivity 100 _m, thickness 100 m, overlying low resistivity substrate, resistivity 10 _m, thickness 100 m, on bedrock of 1000 _m resistivity). The AMT signal provides a plane wavefront at all frequencies. The CSAMT wavefront, from a grounded wire 2 km long, 8 km from the measurement point, ceases to be effectively planar at a frequency of between 100 and 200 Hz (after van Blaricom, 1992).*

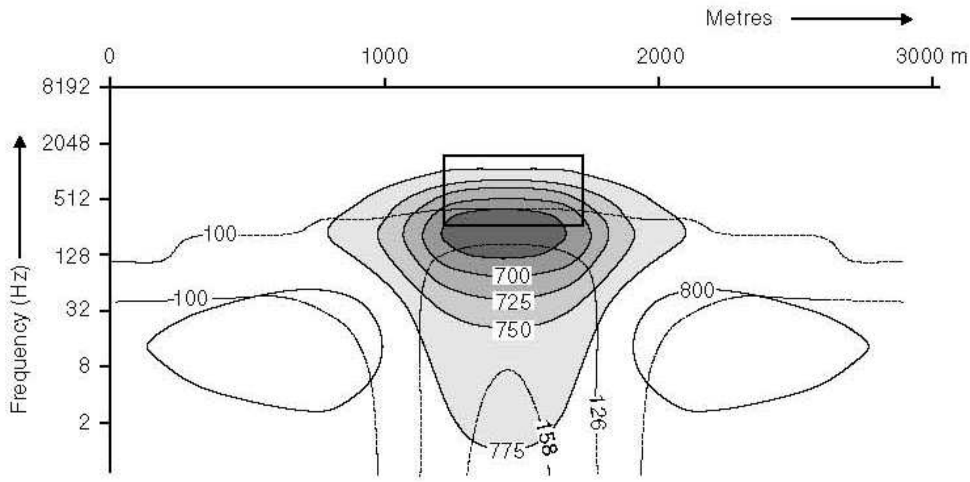


***Figure 4.12*** *AMT response of a resistive (5000 _m) prism buried in a 100 m medium. Solid contours and shading are* Ex/Hy *phase difference ('impedance phase') in milliradians (contour interval 25 milliradians). Dotted lines are apparent resistivity, in _m. The vertical scale is in frequency, not depth, and the prism (black solid outline) could be made to coincide with the phase anomaly peak by an arbitrary adjustment of scale. The phase anomaly indicates a body with limited extent in depth, something not apparent from the resistivity contours (after van Blaricom, 1992).*

Programs can be run on laptop PCs to carry out one-dimensional (horizontal layering) and two-dimensional inversions of Cagniard resistivities to actual resistivities. To estimate the resistivity at a given depth, the Cagniard resistivities must be obtained down to at least three times that depth. However, the fact that the depth of investigation is itself dependent on resistivity implies a degree of circularity in the calculations and the modelling process is inherently ambiguous.

Phase differences are used mainly for investigating small sources, rather than layering. It may, for example, be possible to see both the top and the base of a buried source using phase measurements, even though only the top is visible on the corresponding resistivity plots (Figure 4.12).

*3.3 CSAMT practicalities*

The use of controlled sources eliminates some of the problems associated with natural fields but introduces others. Very high currents are required if long-wire sources are to generate sufficiently strong signals at the kilometre distances required by the far-field approximation, and it is seldom easy to find sites where kilometres of wire carrying many amperes of current can be laid out on the ground safely (or even at all). Even where this can be done, topographic irregularities may create significant distortions in the signal. Closed loop sources can be considerably smaller but require currents even larger (by factors of as much as 10) than those needed for line sources.

The far field for CSAMT measurements is commonly considered to begin at a distance of three skin depths from a long-wire source, and is therefore frequency dependent. On a single sounding plot, the onset of intermediate field conditions can usually be recognized by an implausibly steep gradient in the sounding curve (Figure 5.11). A simple rule of thumb that can be used in planning surveys is that, to ensure far-field conditions, the distance from source to receiver should be at least six times the required depth of investigation. The layout may, however, have to be modified in the light of actual field conditions. In principle, quite different equations must be used in intermediate and near-field interpretation, but quality control in the field is usually carried out using only the far-field approximations.

## 4.0 Conclusion

The broad AMT frequency band allows conductivity variations to be investigated over a correspondingly wide range of depths, from a few metres to several kilometres. However, the signals, like so many other things that come for free, are not always reliable. Short- and long-term amplitude fluctuations cause many problems, and unacceptably long times may be needed to obtain satisfactory readings because of low signal strengths. In particular, signals tend to be very weak in the 1–5 kHz range that is crucial for exploration of the upper 100 m of the ground. It is therefore now common to generate similar signals from controlled sources (CSAMT), and to use these to either supplement or replace the natural signals.

## 5.0 Summary

The AMT method is applicable to oil exploration as it is capable of detecting salt domes and anticlinal structures, both of which constitute potential hydrocarbon traps. As such, the method has been used in Europe, North Africa and the USSR. The use of controlled sources eliminates some of the problems associated with natural fields but introduces others.

## 6.0 Tutor Marked Assignments

(a) Discuss the field procedure of AMT method.
(b) Enumerate the problems associated with AMT surveying method.

## 7.0 References/Further readings

John, M. (2003) Field Geophysics (Third Edition). John Wiley and Sons Ltd. England, 249pp

Hoover, D.B., Heran, W.D. and Hill, P.L. (Eds) (1992) *The Geophysical Expression of Selected Mineral Deposit Models*, United States Department of the Interior Geological Survey Open File Report 92-557, 128 pp.

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## MODULE 5

## FIELD WORK EXCERCISE

### Unit 1: Major Fields Application of Electrical and Electromagnetic Methods

### 1.0 Introduction

There are many methods of electrical surveying. Some make use of naturally occurring fields within the earth while others require the introduction of artificially – generated currents into the ground. The resistivity method is used in the study of horizontal and vertical discontinuities in the electrical properties of the ground, and also in the detection of three – dimensional bodies of anomalous electrical conductivity. It is routinely used in engineering and hydro-geological investigations to investigate the shallow subsurface geology. The induced polarization method makes use of the capacitative action of the subsurface to locate zones where conductive minerals are disseminated within their host rocks. The self potential method makes use of natural currents flowing in the ground that are generated by electrochemical processes to locate shallow bodies of anomalous conductivity.

### 2.0 Objectives

At the end of the unit, readers should be able to

(i) Know the major fields of application of electrical and electromagnetic methods.
(ii) Show precisely where electrical and electromagnetic methods are suitable in mineral and environmental studies.
(iii) Show how the various geophysical methods complement one another.
(iv) How geophysical data may be integrated with the known geology to solve a very wide variety of problems related to the subsurface.

### 3.0 Main Contents

3.1 Electrical and Electromagnetic Methods in Mineral Exploration

Geophysical methods are extensively used in the search for economically valuable mineral deposits. Many materials fall into this category, including the bulk minerals sand, gravel and limestone, but in this section consideration is restricted to selected ore deposits which are of major importance to the metalliferous mining industry, namely massive sulphides, disseminated sulphides and iron ores. These deposits differ significantly from their host rocks in their physical properties and consequently give rise to geophysical anomalies of various types.

The initial aim of a geophysical survey for ore deposits is to locate mineralized areas of potential- interest. For this purpose the airborne magnetic and electromagnetic techniques are eminently suitable since large areas can be surveyed rapidly at relatively low cost. Airborne measurements, however, especially electromagnetic, are limited in their depth of penetration and may not detect deeply buried ore bodies.

Once possible target areas are determined, further information on causative bodies within the anomalous zones is obtained by ground surveys which enable the prospector to determine whether the anomalous bodies are of economic importance. Ground verification surveys frequently involve the use of several different survey techniques. If ore bodies are present, the geophysical data will provide information on their depth, extent and attitude and consequently control the location of exploratory boreholes or trenches.

It is customary to refer to the “returns-ratio” for geophysical surveys, defined as the ratio of the estimated value of the ore to the cost of the geophysical work. That geophysical surveying is of major importance in mineral exploration is shown by the fact that for many ore deposits this ratio is several hundred to one.

Several examples of the use of electrical and electromagnetic methods in the location of ores deposits are discussed bellow. In the case studies described below, stress is also placed on the importance of integrating the results from several geophysical methods to derive the maximum information about the ore deposits concerned.

### *3.1.1 Massive sulphide ores*

Massive sulphide ore bodies are usually considered to be a single mass with a cross-sectional area of at least 100 $m^2$ comprising 50% or more of metallic sulphides. Such ore has a minimum density of 3800$kgm^{-3.}$ It may contain the magnetic minerals pyrrhotite and magnetite, and if these are present in reason able quantity the ore will produce large magnetic anomalies. The electrical conductivity of massive sulphides is normally very high, in the range $10^2$-$10^4$ $S.m^{-1}$. Consequently, the geophysical methods applicable to the search for such ores are those responding to very dense, highly magnetic and conductive materials.

Airborne prospecting techniques for massive sulphides usually exploit the property of high conductivity, and extensive use is made of electromagnetic methods. The survey aircraft usually also carries a magnetometer to provide additional information at little extra cost, as the coincidence of electromagnetic and magnetic anomalies is highly indicative of massive sulphides.

Subsequent ground surveys similarly employ electrical and electromagnetic methods. Self potential methods are cheap and effective if the correct subsurface conditions exist and the ore body lies at a depth of less than about 30 m. Standard moving source-receiver EM methods are extensively used, although in rugged or forested terrain the AFMAG method may be more cost-effective as no heavy equipment is required and there is no need to cut tracks for survey lines. If it is required to establish the relationship of the conducting body to its host rock, resistivity rather than EM methods are employed as they provide estimates of absolute conductivity rather than simply revealing bodies with a high relative conductivity.

Gravity surveying is essentially a secondary ground exploration tool because of the high cost of obtaining gravity coverage over large areas and ambiguities in interpretation. It does, however, provide accurate estimates of ore tonnage on the basis of the total mass anomaly once the location of the ore body has been established.

Although electrical and electromagnetic methods are the major exploration techniques, they suffer from the drawback that anomalies may result from non-economic sources such as graphite or water-filled shear zones. However, by use of a combination of electrical, magnetic and gravity methods it is possible to eliminate most non-economic sources.

An example of an integrated geophysical study of a massive sulphide ore body in Quebec, Canada has been described by White (1966). Ninety-five percent of the area prospected is covered by glacial deposits about 15 m thick. All exposures of bedrock are high-grade metamorphic rocks of Precambrian age, although younger volcanic rocks are known to occur in neighbouring areas. The airborne survey revealed an EM anomaly 1.2-1.6 km in length with a ratio of real to imaginary secondary field components exceeding unity, indicating the presence of a good conductor. The eastern part of the causative body was later found to consist of massive pyrrhotite in a host of andesite, rhyolite and silicified tuff, while the western part contained up to 20% sulphides but was mainly graphitic in nature.

The airborne survey was followed by a sequence of ground surveys. A series of EM traverses was made with a coplanar horizontal coil system operating at a frequency of 1600 Hz with a source-receiver separation of 61 m. The results enabled the subsurface conductor to be accurately located, and the asymmetry of the profiles allowed estimates to be made of the conductor dip.

Profiles of the vertical field magnetic anomalies were made along the same traverses. The strong correlation between electromagnetic and magnetic anomalies suggested that a high proportion of pyrrhotite was present, a conclusion in accord with the composition of other known ore bodies in the region. The- change in character of the anomalies between surveyed traverses indicated a change in nature of the conductor from sulphides to graphitic sediments as the conductor was at approximately the same depth beneath both profiles. The decrease in anomaly amplitude towards the east resulted from an increased overburden thickness, but indicated that pyrrhotite-bearing ore continued at least to traverse 12 E.

The geophysical data were subsequently employed to control the location of several boreholes which allowed the nature of the conductor to be determined in the most cost-effective manner.

### *3.1.2 Disseminated sulphide ores*

Disseminated sulphide deposits are defined as those bodies in which sulphides are scattered as specks and vein-lets throughout the host rock and constitute not more than 20% of the total volume. A disseminated ore body contains metallic sulphides usually of copper and/or molybdenum) at a mineable depth and must normally exceed $100^2$ in horizontal section to be profitable.

The density distribution in such bodies is complex since, although the metallic sulphides themselves are very dense, the density of the host can be highly variable. Consequently the gravity method is not applicable to the direct search for such ores. Similarly, their magnetic susceptibility is normally low so that magnetic surveying cannot be relied upon to provide a direct indication of a disseminated sulphide ore.

The electrical and eletromagnetic methods appear to be the most suitable surrey techniques. However, the conductivity of a disseminated sulphide ore body is highly variable because of the irregular dispersion of the sulphides throughout the host. Consequently, diagnostic resistivity and EM anomalies are unlikely to be encountered.

Since electrical conduction through the metallic sulphides is electronic, but electrolytic through the host, the conditions in disseminated sulphide ore bodies exist to produce strong induced polarization anomalies so the IP method is the most likely to detect such bodies. However, the physical properties of economically important sulphides such as chalcopyrite ores are not great different from zones of disseminated uneconomic minerals such as pyrite. Hence the economic importance of a deposit cannot be judged solely from its IP response and further geological and geochemical surveying need to be executed prior to any costly drilling programme.

## 3.2 Electrical and Electromagnetic Methods in Hydrogeology.

Many geophysical methods find application in- locating and defining subsurface water resources. They provide rapidly collected information on the geological structure and prevailing lithologies of a region without the large cost of extensive drilling programme. The geophysical survey results determine location of the minimum number of exploratory boreholes required for both essential aquifer tests and control of the geophysical interpretation.

The magnetic method is rarely used in this context, but may find occasional application in the location of faults and shear zones which could affect the pattern of ground water flow. The gravity method is widely used in regional reconaissance surveys to delineate the form and extent of porous sedimentary deposits such as buried valley-fills. The method has also been used to determine groundwater volumes from anomalous mass calculations. The technique, however, suffers from the weakness that small geological changes are difficult to detect so the method is of little use in the solution of detailed hydrogeological problems.

The most widely used geophysical methods in hydrogeology are the electrical techniques. Resistivity surveys are routinely employed in groundwater exploration to locate zones of relatively high conductivity corresponding to saturated strata at depths down to about 400 m. As well as providing structural and lithological information, resistivity surveys may also provide indications of groundwater quality. The method provides adequate depth penetration and quantitative results.

Most constituent minerals of sedimentary rocks are insulating and the passage of electricity thus takes place mainly by ionic conduction in the pore waters. The resistivity of the rock is thus controlled by the volume of water present and will decrease as the salinity of the water increases. Consequently, in an homogeneous aquifer, it is possible to distinguish fresh from saline groundwater and even to trace the subsurface flow of contaminated groundwater resulting from pollution if the polluted water has a distinctive resistivity.

The resistivity method has been used by Bugg & Lloyd (1976) for the quantitative delineation of fresh water lenses in the Cayman Islands of the northern Caribbean. In many small oceanic islands such lenses constitute the main source of potable water.

Because of their relatively low density, fresh water lenses rest on top of the saline water that penetrates the substrate of the islands from the sea. Since the densities $\rho_w$. and $\rho_s$ of fresh and salt water are known, under static conditions where there is an immiscible contact, the thickness $z_w$ of fresh water beneath mean sea-level can be predicted from the height $z_s$ of the fresh water table above this datum, according to the Ghyben-Herzberg relationship.

$$z_w = \frac{\rho w}{(\rho s - \rho w)} zs = kzs$$

where k is a constant. For $\rho s$ = 1026 kg m$^3$ and $\rho w$ = 1000 kg m-$^{3,}$ k = 38.

Fresh water lenses are subject to the dynamic effects of tides so that significant saline transition zones develop along their lower boundaries. Consequently, modified form of density relationship must be employed with the constant k in the Ghyben-Herzberg relationship decreased to about 25. Theoretically, the base of the freshwater lens could be determined by measurement of the height of the water table. Practically though, due to the tidal effects, this would require simultaneous measurement at a large number of boreholes. Thus, in the Cayman Islands study a different approach was adopted, employing geophysical methods.

Surface resistivity techniques thus provide a rapid and cheap method of mapping the base of fresh water lenses and substantially reduce the cost of drilling investigations.

Merkel (1972) has described the use of resistivity methods in the delineation of contaminated mine discharge in Pennsylvania. A large quantity of acid mine drainage originates from deep and shallow coal mining operations in this area. It renders the water unfit for recreational use and necessitates costly treatment before it can be used for industrial purposes. The sources of such contamination are usually difficult to identify since the acid water, after mixing with natural groundwater, can travel considerable distances before emergence and the location of many of the old workings is unknown. In the area studied bedrock consists of a sequence of shales, clays, sandstones and coal, the latter having been extensively mined.

Investigation of the local mine waters revealed a linear relationship between log resistivity and log ion concentration. The groundwater becomes more conductive as the level of contamination increased, fresh water having a resistivity of 60-200 ohm m and acid water 6-12 ohm m. The polluted groundwater normally flows either in the highly jointed coal seams or, if their basal clays are breached, in the underlying sandstones. The coal consequently has a high resistivity when above the water table, a moderate resistivity when associated with groundwater and a significantly lower resistivity if the groundwater is contaminated.

The resistivity technique is thus effective in locating polluted groundwater and tracing its source. The contaminating ions cannot be identified by such methods, but if the geology is sufficiently well known the degree of contamination can be determined. If, then, electrodes were sited in a borehole penetrating the water table, periodic measurement of the resistivity could be used to reveal the onset and extent of acid mine drainage and to monitor the degree of contamination by use of the type of relationship.

### 3.3 Electrical and Electromagnetic Methods in engineering geology.

Geophysical methods are frequently used in an initial site investigation to determine subsurface ground conditions prior to excavation and construction work.

The geophysical methods used to locate mineshafts fall into two main categories depending upon the properties of the shaft that they exploit. Micro-gravimetric and resistivity methods are used to detect the presence of the subsurface void of the shaft which constitutes both a mass deficiency and a highly resistive zone. Magnetic and electromagnetic methods detect metallic objects associated with either the capping, infilling or lining of the shaft. The latter two methods are usually preferred since they are more rapidly executed. A recent development in this field is the use of a ground based radar transmitter which provides, essentially, a shallow penetration continuous profile of the subsurface similar to a seismic section. The technique has proved highly successful on certain sites (Leggo 1982).

Barker & Worthington (1972) have used electric profiling techniques to produce an apparent resistivity contour map of an area of old mine workings in Warwickshire, England. A shaft was believed to be present at a depth of some 1.5m. Consequently the profiling was performed using a Wenner configuration with anelectrode spacing of 1.5m. The contour map shows a marked anomaly A above the local noise level with a form characteristic of a buried vertical cylindrical void. Subsequent excavations revealed a brick-lined shaft of 1.8m diameter, 0.15m below the surface.

## 4.0 Conclusion

The resistivity method is used in the study of horizontal and vertical discontinuities in the electrical properties of the ground, and also in the detection of three – dimensional bodies of anomalous electrical conductivity. It is routinely used in engineering and hydro-geological investigations to investigate the shallow subsurface geology. The induced polarization method makes use of the capacitative action of the subsurface to locate zones where conductive minerals are disseminated within their host rocks. The self potential method makes use of natural currents flowing in the ground that are generated by electrochemical processes to locate shallow bodies of anomalous conductivity.

## 5.0 Summary

A wide range of geophysical surveying methods exists, for each of which there is an operative physical property to which the method is sensitive. The type of physical property to which a method responds clearly determines its range of applications.

## 6.0 Tutor Marked Assignments

(a) Outline the operative physical properties and measured parameters of electrical and electromagnetic methods.
(b) List the various applicable areas of electrical and electromagnetic methods.

## 7.0References/Further readings

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