5

ELECTRIC CURRENT METHODS – GENERAL CONSIDERATIONS

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 5.1). 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 chapter. Direct current methods are considered in more detail in Chapter 6, which also describes the relatively little-used capacitative-coupled methods. Natural potential (*self-potential* or *SP*) and *induced polarization* (*IP*) methods are covered in Chapter 7. Chapter 8 deals with EM surveys using local sources and Chapter 9 with VLF and CSAMT surveys, which use plane waves generated by distant transmitters.

5.1 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 5.2). Clay minerals are ionically active and clays conduct well if even slightly moist.

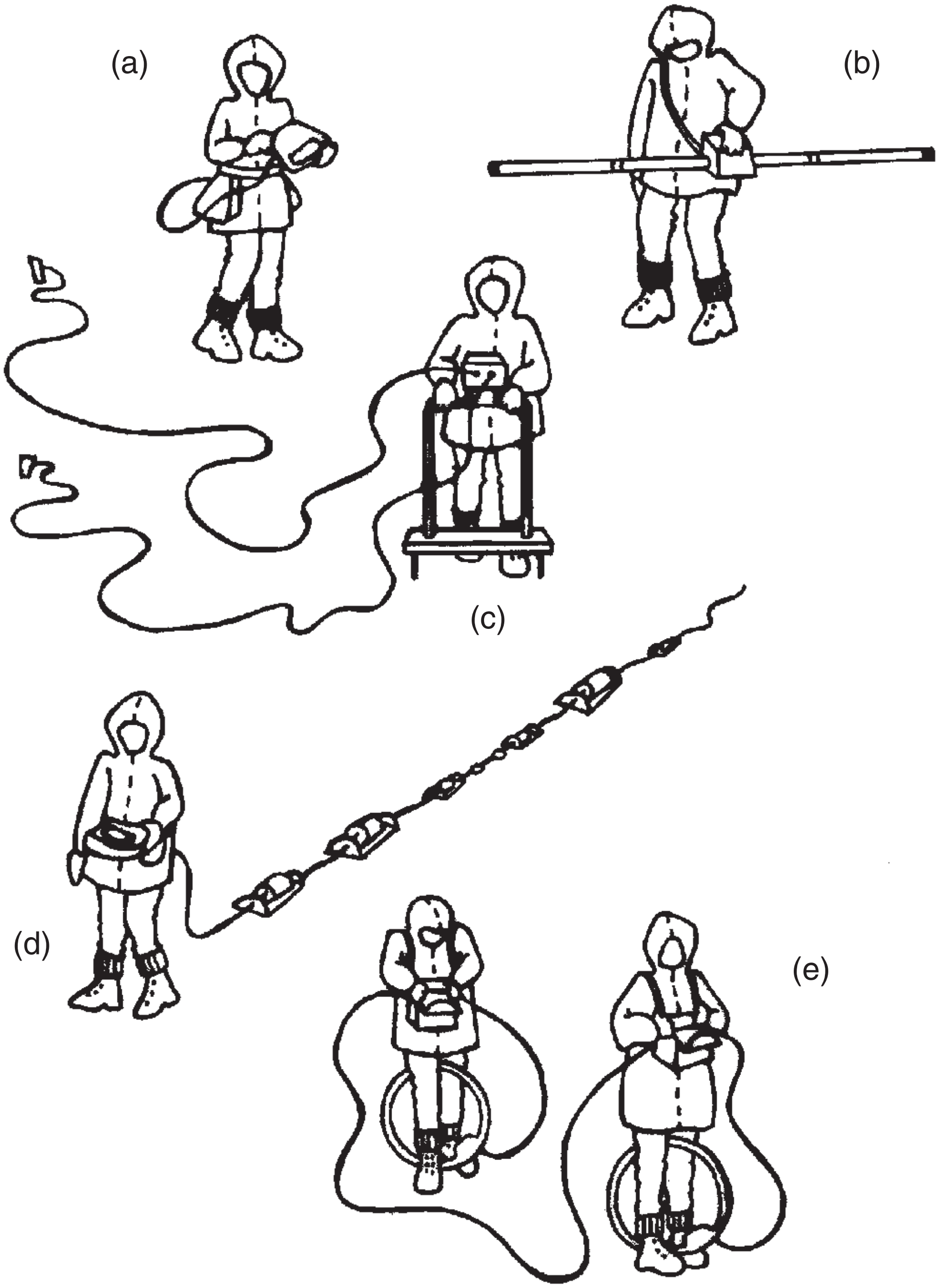

Figure 5.1 *Electrical survey methods for archaeology and site investigation. In (a) the operator is using an ABEM Wadi, recording waves from a remote VLF transmitter (Chapter 9). Local source electromagnetic surveys (Chapter 8) may use two-coil systems such as the Geonics EM31 (b) or EM37 (e). DC resistivity surveys (c) often use the two-electrode array (Section 5.2), 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.*

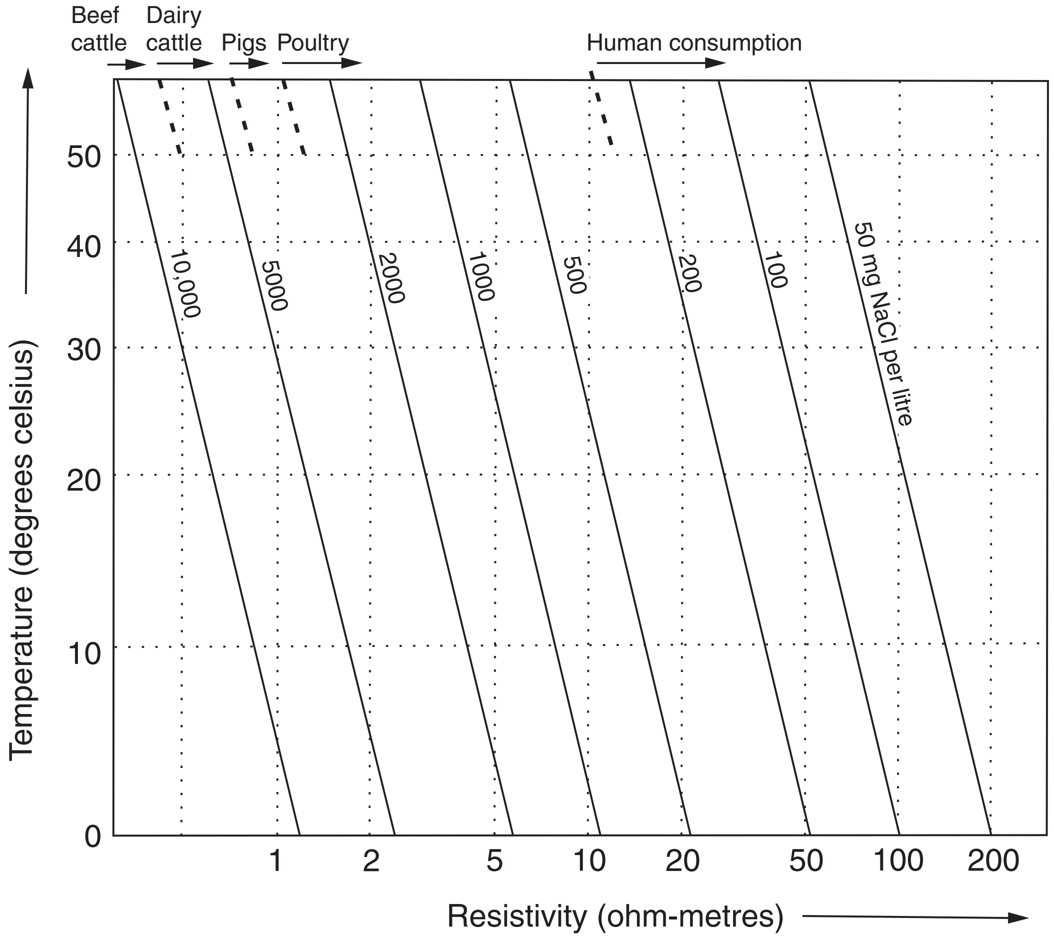

Figure 5.2 *Variation of water resistivity with concentration of dissolved NaCl. The uses that can be made of waters of various salinities are also indicated.*

5.1.1 Ohm's law and resistivity

The current that flows in a conductor is in most cases proportional to the voltage across it, i.e.

$$V = IR$$

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 (ρ) and is measured in ohm-metres (Ωm). The reciprocal, conductivity, is expressed in siemens per metre ($\mathrm{S\,m^{-1}}$) 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.

5.1.2 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 5.3).

Resistivities of common rocks and minerals are listed in Table 5.1. Bulk resistivities of more than 10 000 Ωm or less than 1 Ωm are rarely encountered in field surveys.

5.1.3 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*.

5.1.4 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.

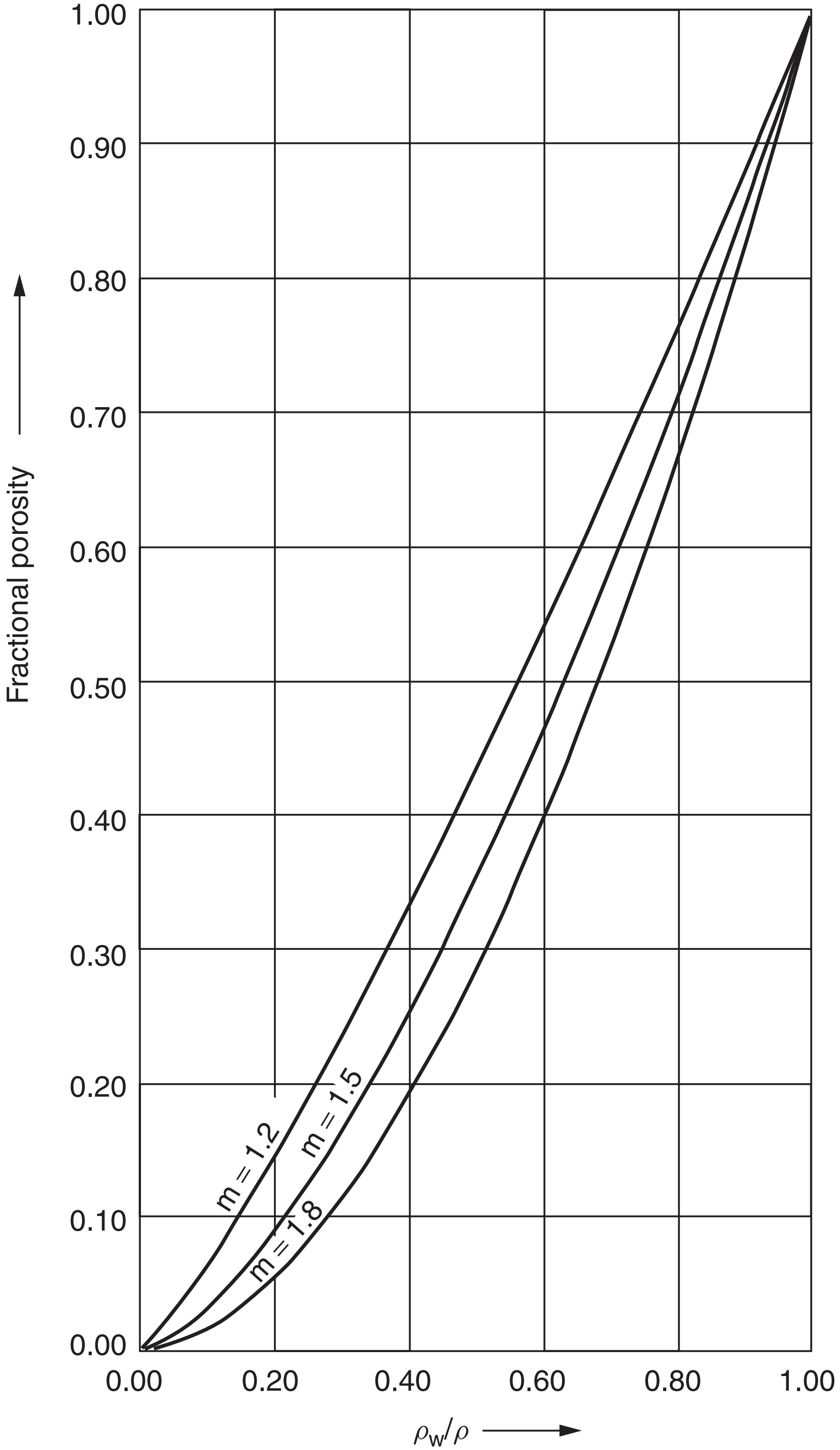

Figure 5.3 *Archie's law variation of bulk resistivity, ρ, for rocks with insulating matrix and pore-water resistivity ρ_W. The index, m, is about 1.2 for spherical grains and about 1.8 for platey or tabular materials.*

Table 5.1 *Resistivities of common rocks and ore minerals (ohm-metres)*

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

5.2 DC Methods

The currents used in surveys described as ‘direct current’ 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.

5.2.1 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 in to 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.

5.2.2 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 (Chapter 7). 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 5.4). 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.

5.2.3 Cables

The cables used in DC and IP surveys are traditionally single core, multistrand 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 5.4 *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 1.2.2 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 (Section 7.3). 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.

5.2.4 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.

5.2.5 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.

5.3 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.

5.3.1 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 (Section 1.1.6) governed by an attenuation constant (α) given by:

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

μ_a and ε_a are the absolute values of, respectively, magnetic permeability and electrical permittivity and ω ($=2\pi f$) 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, σ, is much greater than $\omega\varepsilon_a$ and α 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 5.5).

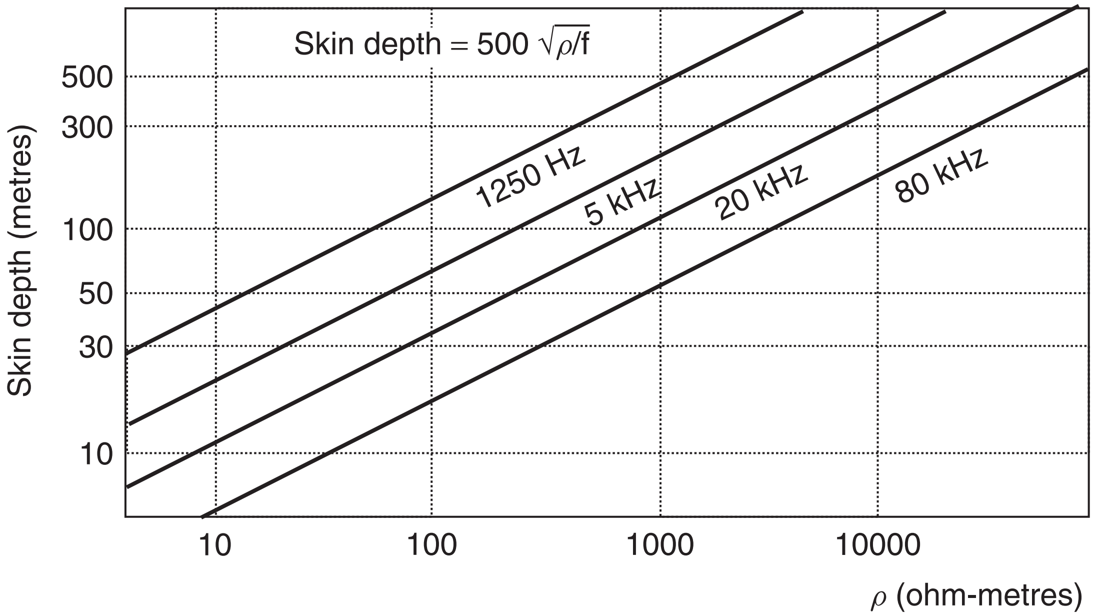

Figure 5.5 *Variation in skin depth,* d*, with frequency and resistivity.*

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

5.3.2 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*.

5.3.3 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 2π radians of a complete cycle, and is known as the *phase angle* (Figure 5.6).

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 5.6). 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.

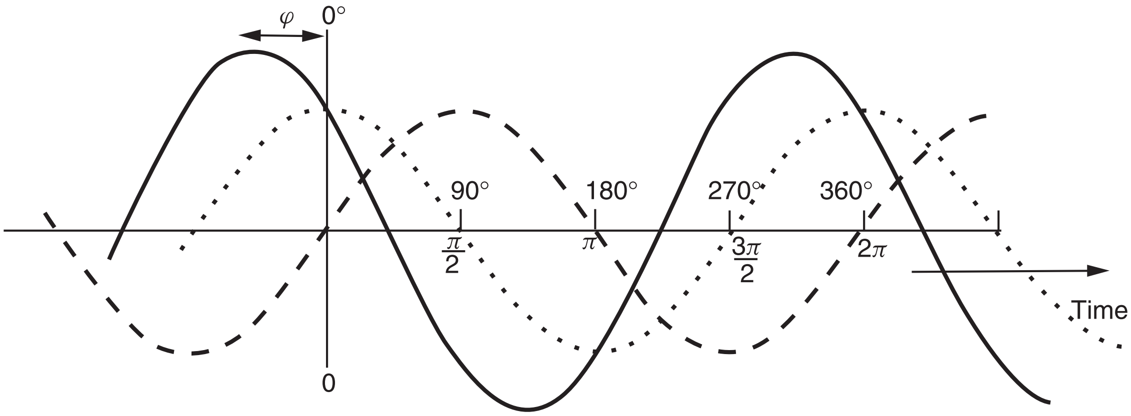

Figure 5.6 *Phase in sinusoidal waves. The wave drawn with a solid line is sinusoidal, with a phase angle* ϕ*, as compared to the 'zero phase' reference (cosine) sinusoid (dotted curve). The phase difference between the dashed (sine) and dotted waves is* 90° *or* $\pi/2$ *radians and the two are therefore in phase quadrature. The amplitudes are such that subtracting the sine wave from the cosine wave would reconstitute the solid-line wave.*

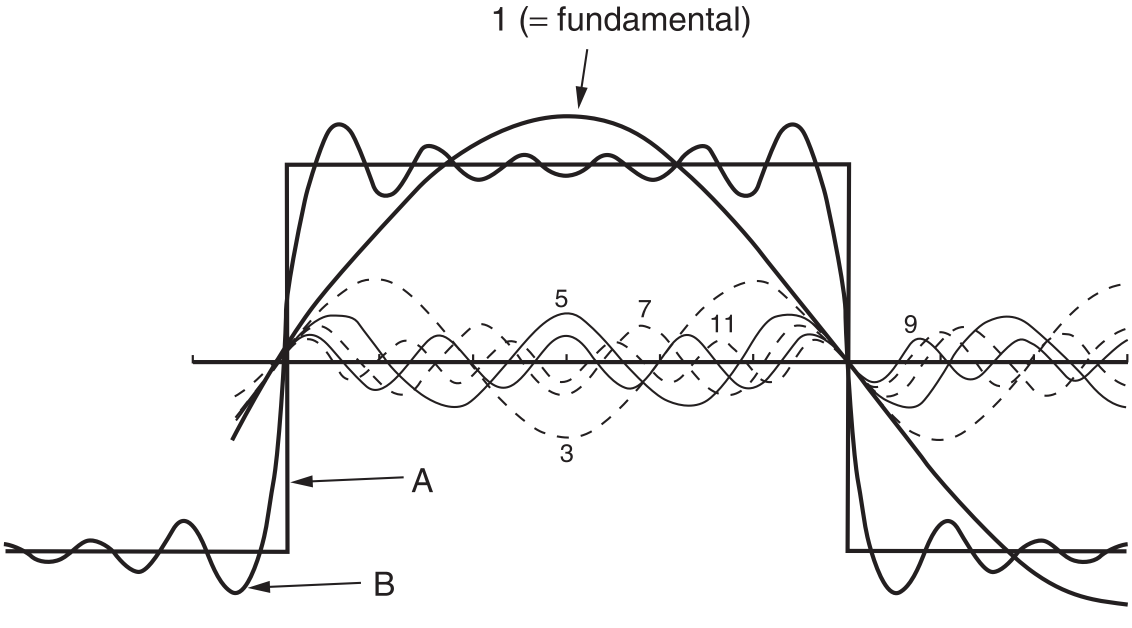

Figure 5.7 *The square wave as a multi-frequency sinusoid. A reasonable approximation to the square wave, A, can be obtained by adding the first five odd harmonics (integer multiples 3, 5, 7, 9 and 11) of the fundamental frequency to the fundamental. Using the amplitudes for each of these component waves 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.*

5.3.4 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 5.5) 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 5.7). 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.