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.

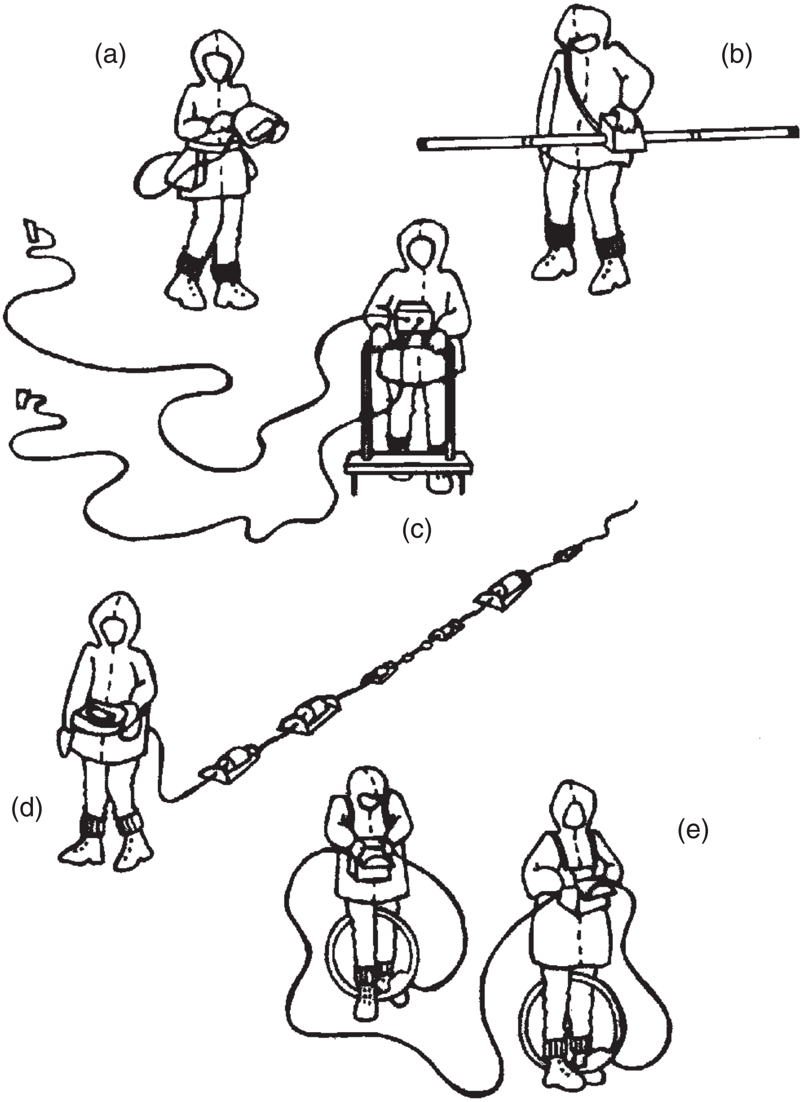

Figure 5.1 *Electrical survey methods for archaeology and site investigation. In (a) the operator is using an ABEM Wadi, recording waves from a remote VLF transmitter (Chapter 9). Local source electromagnetic surveys (Chapter 8) may use two-coil systems such as the Geonics EM31 (b) or EM37 (e). DC resistivity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

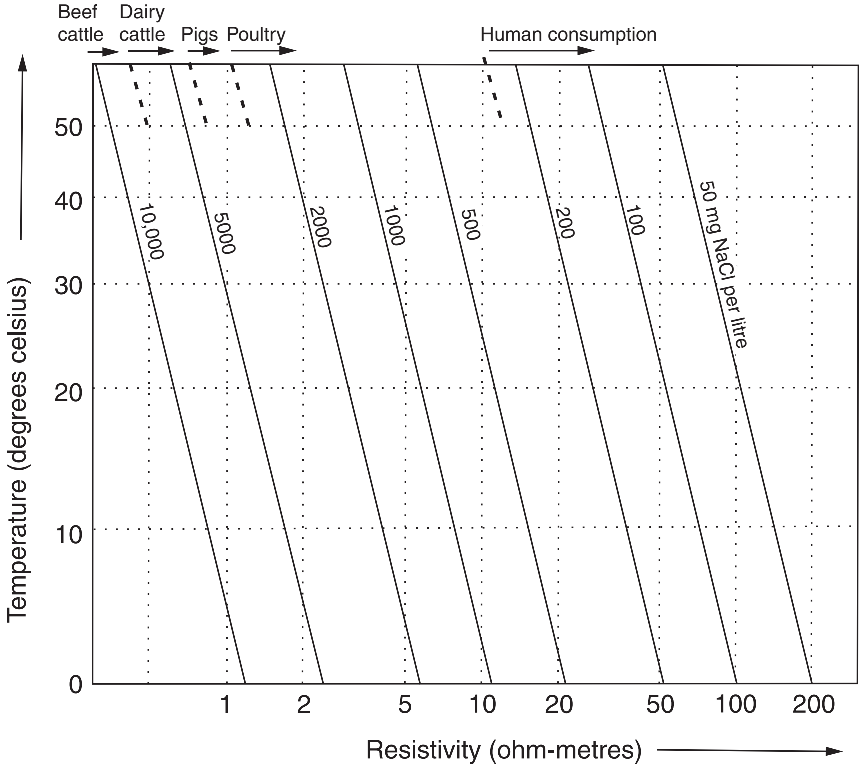

Figure 5.2 *Variation of water resistivity with concentration of dissolved NaCl. The uses that can be made of waters of various salinities are also indicated.*

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.

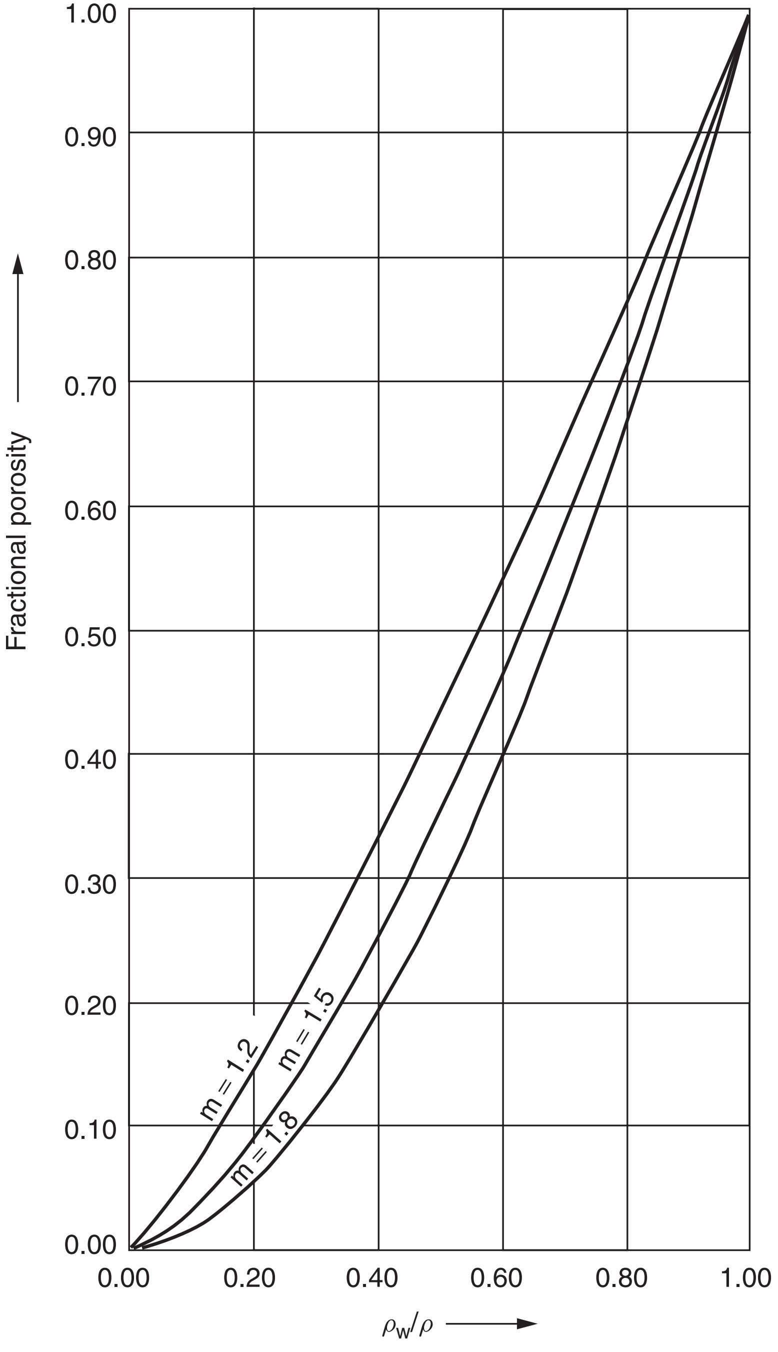

Figure 5.3 *Archie's law variation of bulk resistivity, ρ, for rocks with insulating matrix and pore-water resistivity ρ_w. The index, m, is about 1.2 for spherical grains and about 1.8 for platey or tabular materials.*

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, 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 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).

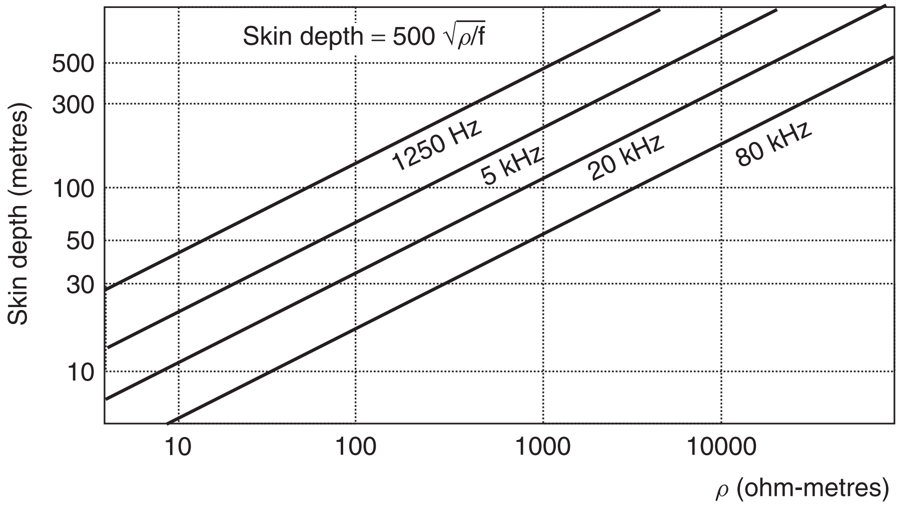

Figure 5.5 *Variation in skin depth,* d, *with frequency and resistivity.*

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.

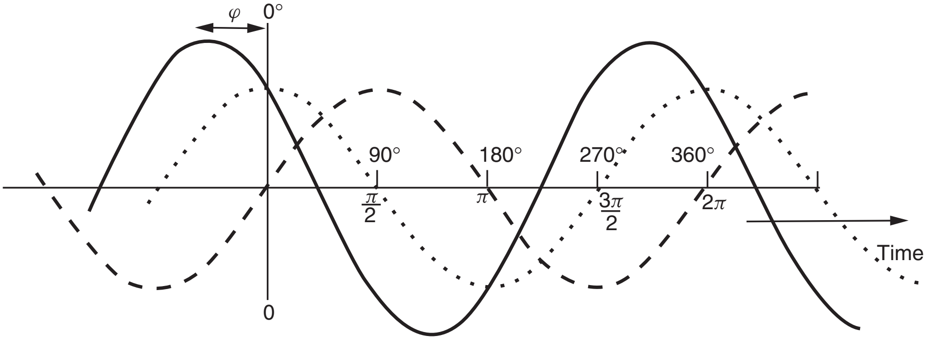

Figure 5.6 *Phase in sinusoidal waves. The wave drawn with a solid line is sinusoidal, with a phase angle ϕ, as compared to the 'zero phase' reference (cosine) sinusoid (dotted curve). The phase difference between the dashed (sine) and dotted waves is 90° or π/2 radians and the two are therefore in phase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

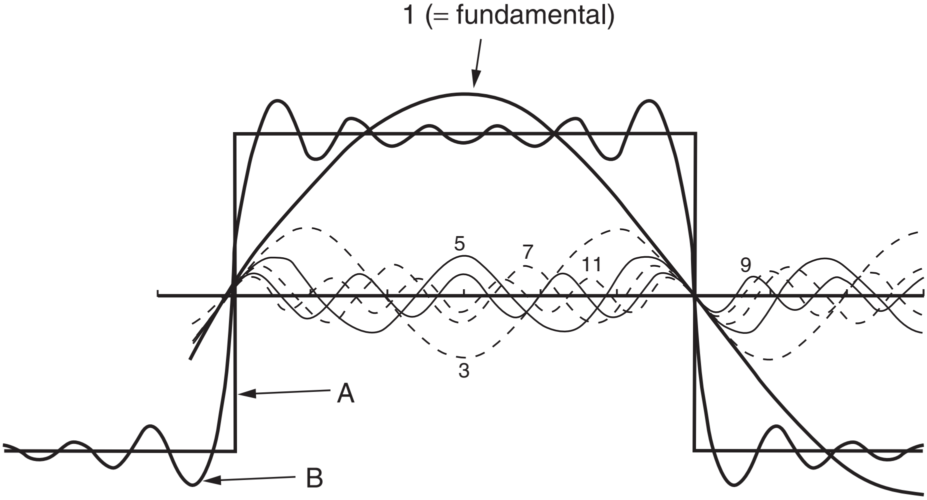

Figure 5.7 *The square wave as a multi-frequency sinusoid. A reasonable approximation to the square wave, A, can be obtained by adding the first five odd harmonics (integer multiples 3, 5, 7, 9 and 11) of the fundamental frequency to the fundamental. Using the amplitudes for each of these component waves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

6

RESISTIVITY METHODS

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 chapter.

6.1 DC Survey Fundamentals

6.1.1 Apparent resistivity

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 calcuations. 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*, ρ_α, 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 ρ (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.

6.1.2 Electrode arrays

Figure 6.1 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 6.1

Geometrical factor for the Wenner array (Figure 6.1a).

$\mathrm{Pp} = a \quad \mathrm{Pn} = 2a \qquad \mathrm{Np} = 2a \qquad \mathrm{Nn} = a$

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

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

6.1.3 Array descriptions (Figure 6.1)

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 (Section 6.2.2). As the *normal* array, it is one of the standards in electrical well logging.

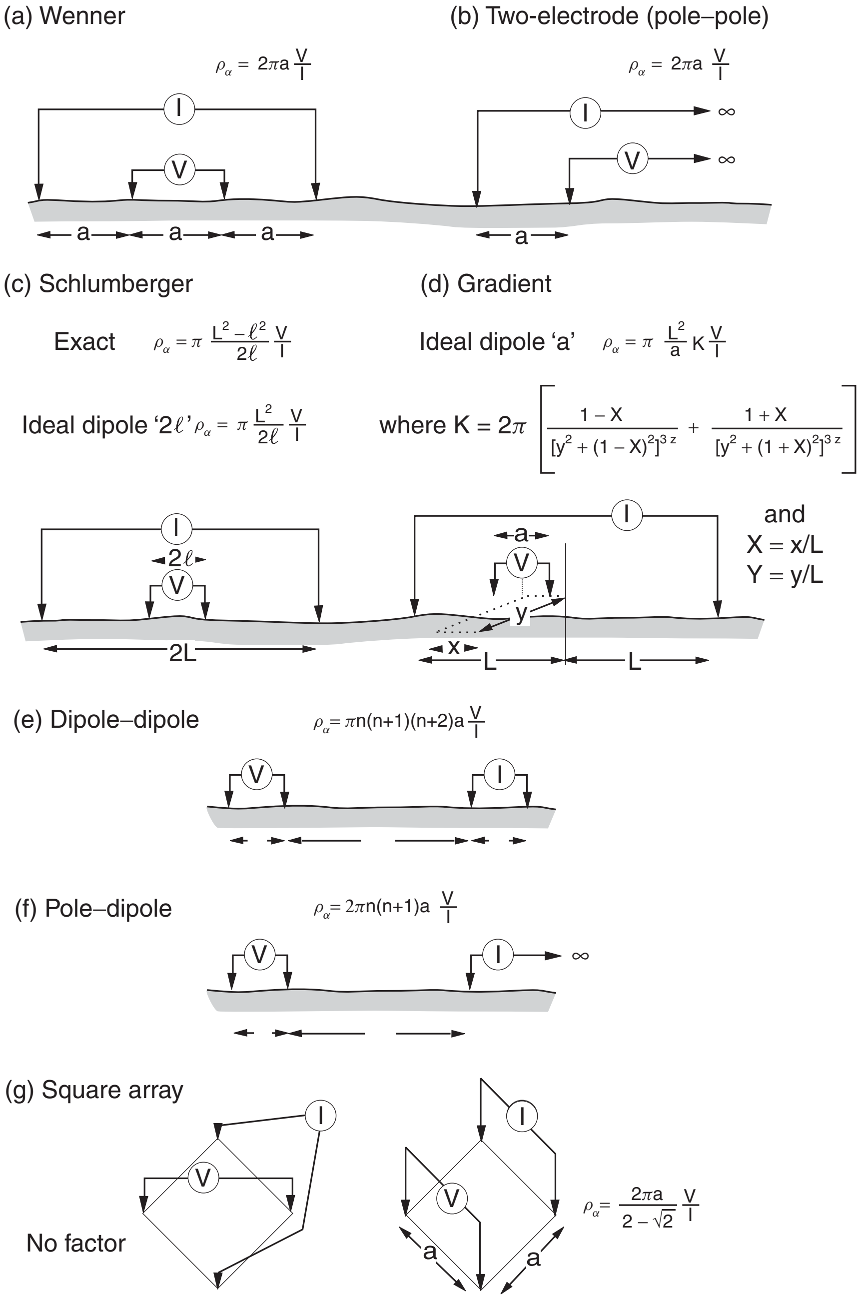

Figure 6.1 *Some common electrode arrays and their geometric factors. (a) Wenner; (b) Two-electrode; (c) Schlumberger; (d) Gradient; (e) Dipole–dipole; (f) Pole–dipole; (g) Square array; (left) Diagonal; (right) Broadside. There is no geometrical factor for the diagonal square array, as no voltage difference is observed over homogeneous ground.*

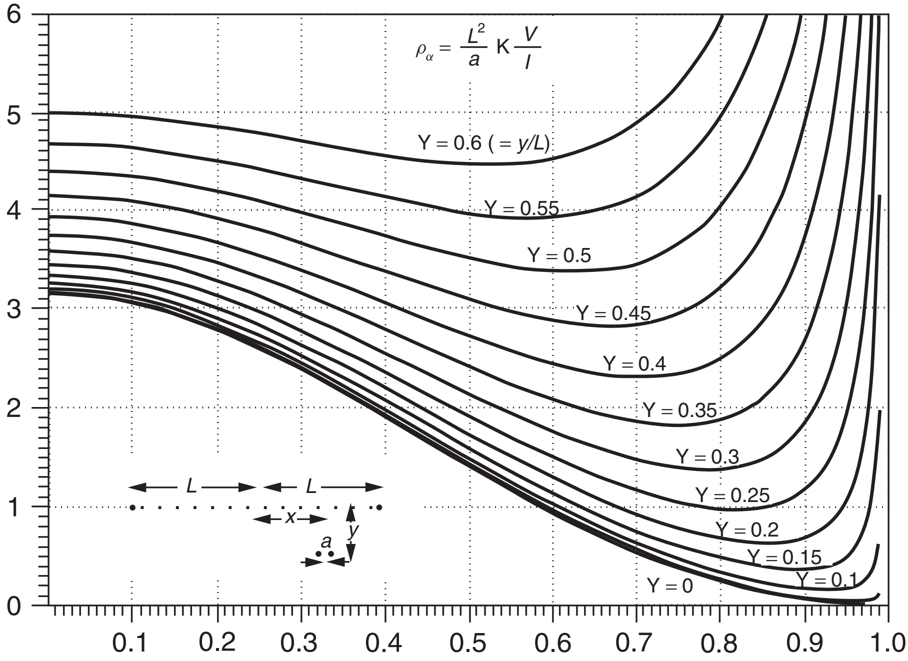

Figure 6.2 *Variation in gradient array geometric factor with distance along and across line. Array total length 2L, voltage dipole length a.*

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 6.2 shows how the geometrical factor given in Figure 6.1d 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 (Section 7.5.2).

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 inhomogeneity. Few published case histories or type curves.

Multi-electrode arrays (not shown).

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 inhomogeneity. 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.

6.1.4 Signal-contribution sections

Current-flow patterns for one and two layered earths are shown in Figure 6.3. Near-surface inhomogeneities 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 6.4). 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 6.4 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

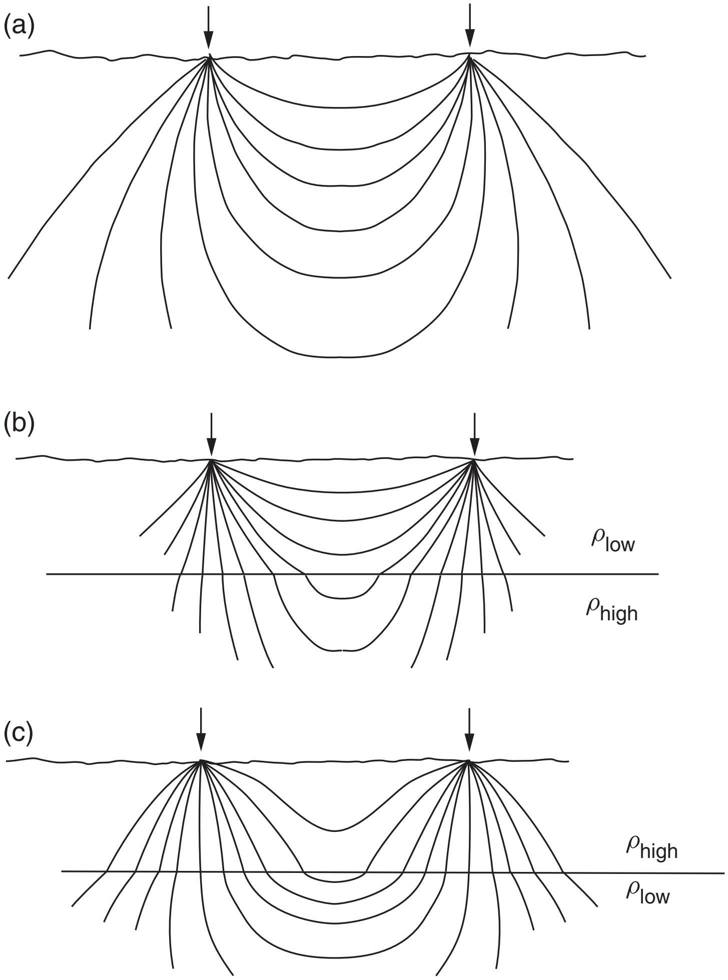

Figure 6.3 *Current flow patterns for (a) uniform half-space; (b) two-layer ground with lower resistivity in upper layer; (c) two-layer ground with higher resistivity in upper layer.*

the array is often preferred for depth sounding. However, offset techniques (Section 6.3.3) allow excellent results to be obtained with the Wenner.

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.

6.1.5 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

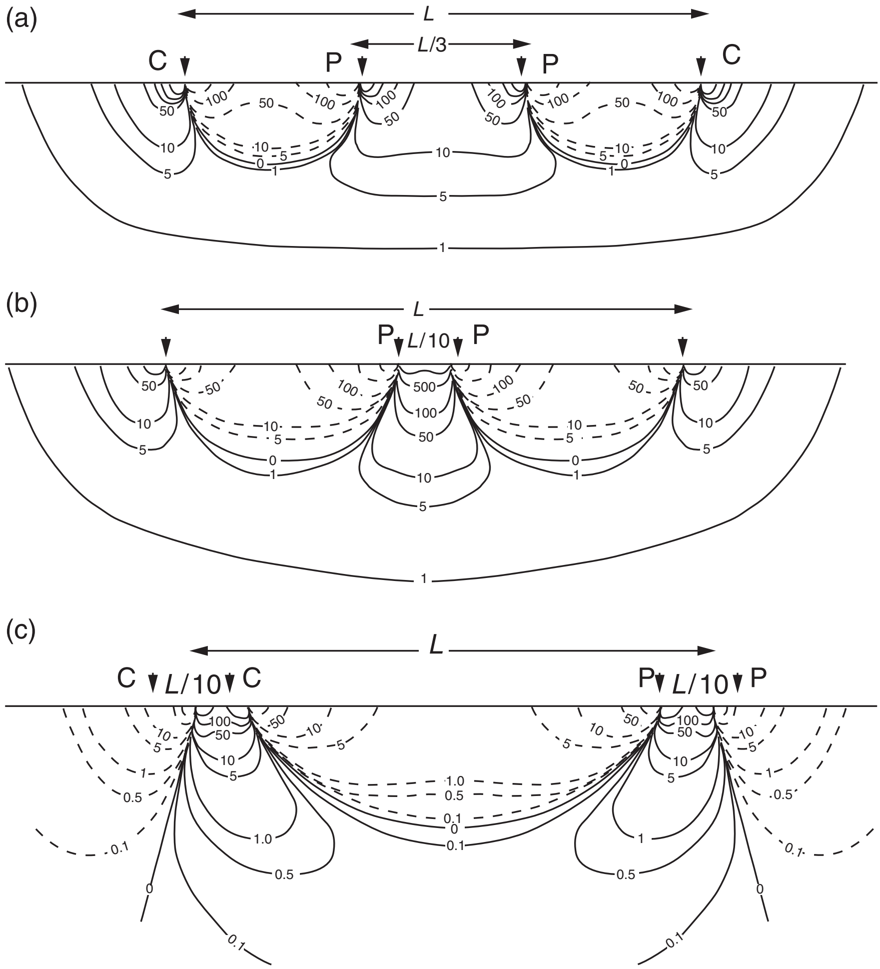

Figure 6.4 Signal contribution sections for (a) Wenner; (b) Schlumberger and (c) dipole–dipole arrays. Contours show relative contributions to the signal from unit volumes of homogeneous ground. Dashed lines indicate negative values. (Reproduced by permission of Dr R. Barker.)

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 6.5). 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

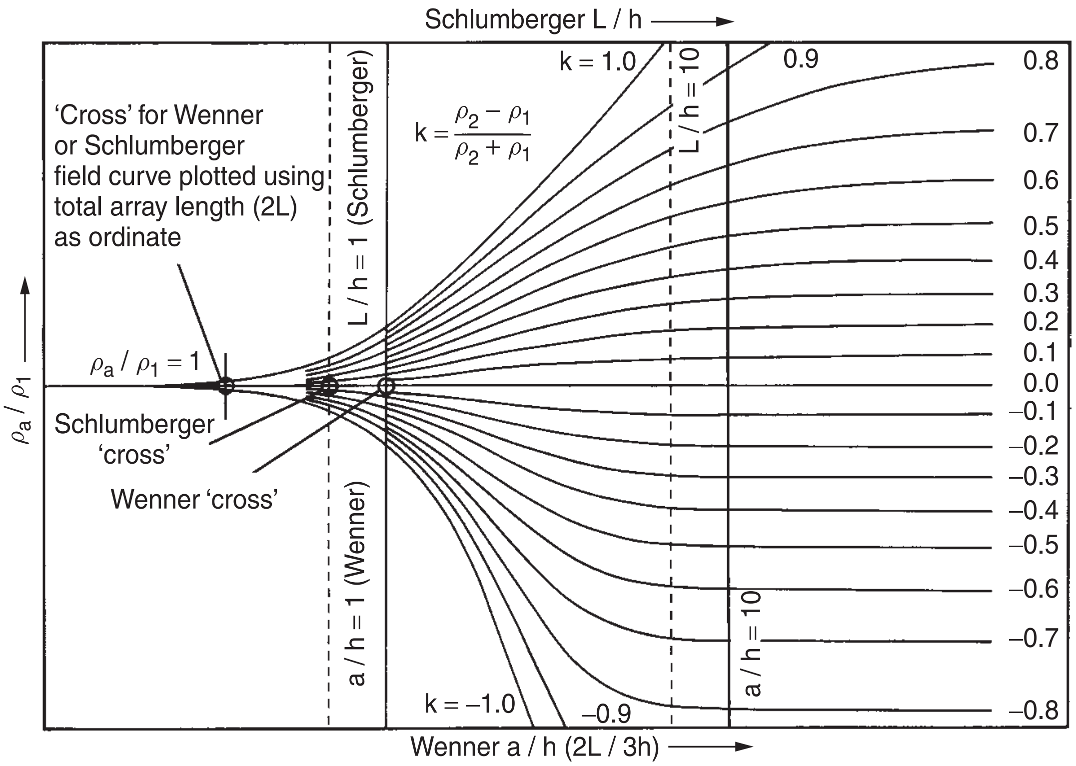

Figure 6.5 *Two-layer apparent resistivity type curves for the Wenner array, plotted on log-log paper. When matched to a field curve obtained over a two-layer earth, the line* $a/h = 1$ *points to the depth of the interface and the line* $\rho_a/\rho_1 = 1$ *points to the resistivity of the upper layer. The value of* k *giving the best fit to the field curve allows the value* ρ_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 6.6, 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

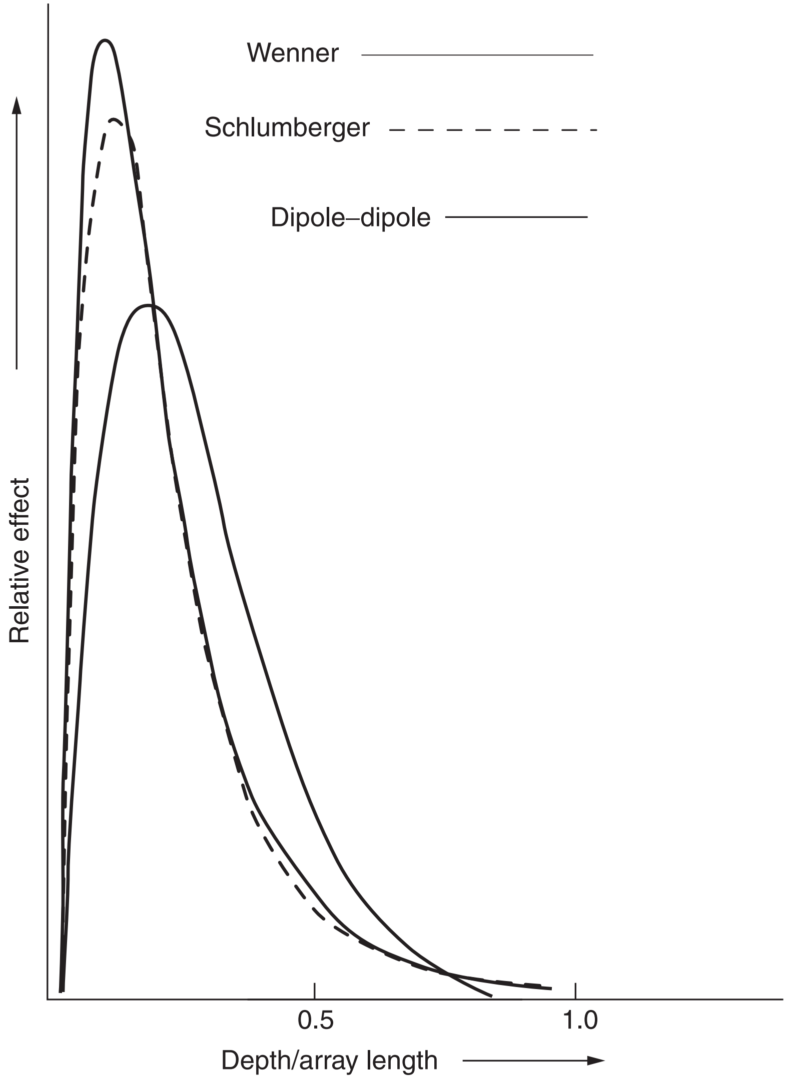

Figure 6.6 *Relative effect of a thin, horizontal high-resistance bed in otherwise homogeneous ground. The areas under the curves have been made equal, concealing the fact that the voltage observed using the Schlumberger array will be somewhat less, and with the dipole–dipole array very much less, than with the Wenner array.*

times as broad as the conductor is deep, and the Sclumberger is only a little better. Figure 6.5 suggests that at these expansions a two-layer earth would be interpretable for most values of resistivity contrast.

Figure 6.6 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 6.4), which are slightly flatter at depth for the Wenner than for the Schlumberger, indicating that the Wenner locates flat-lying 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.

6.1.6 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 than 150 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.

6.2 Resistivity Profiling

Resistivity traversing is used to detect lateral changes. Array parameters are kept constant and 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 6.6). Such estimates should, however, be checked at regular intervals against the results from expanding-array soundings of the type discussed in Section 6.3.

6.2.1 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 (Chapter 8).

6.2.2 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 5.1). 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 (Chapter 7), where induction effects must be avoided at all costs. Four electrodes have to be moved and the observed voltages are usually very small.

6.2.3 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.

6.2.4 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 (Section 1.3.10), 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.

6.3 Resistivity Depth-sounding

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 6.5). Although the introduction of multicore cables and switch selection has encouraged the use of simple doubling (Section 6.3.3), 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.

6.3.1 Choice of array

Since depth-sounding involves expansion about a centre point, the instruments generally stay 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*, much used in IP surveys, are discussed in Section 7.4.2.

6.3.2 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 (Section 6.3.3) may therefore be preferred for land-fill sites.

Apparent resistivities for the Schlumberger array are usually calculated from the approximate equation of Figure 6.1c, 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.

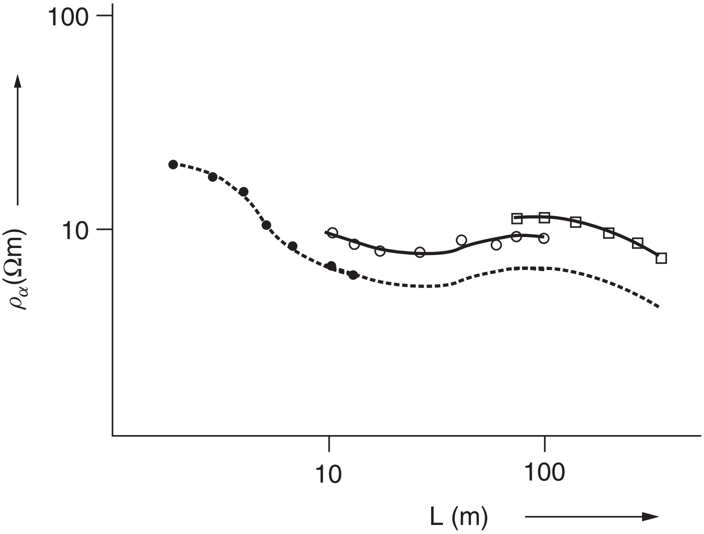

Figure 6.7 *Construction of a complete Schlumberger depth-sounding curve (dashed line) from overlapping segments obtained using different inner-electrode separations.*

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 6.7). 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 inhomogeneities 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 6.7) and one is unfortunately the norm.

6.3.3 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 6.8a). Two readings are taken at each expansion and

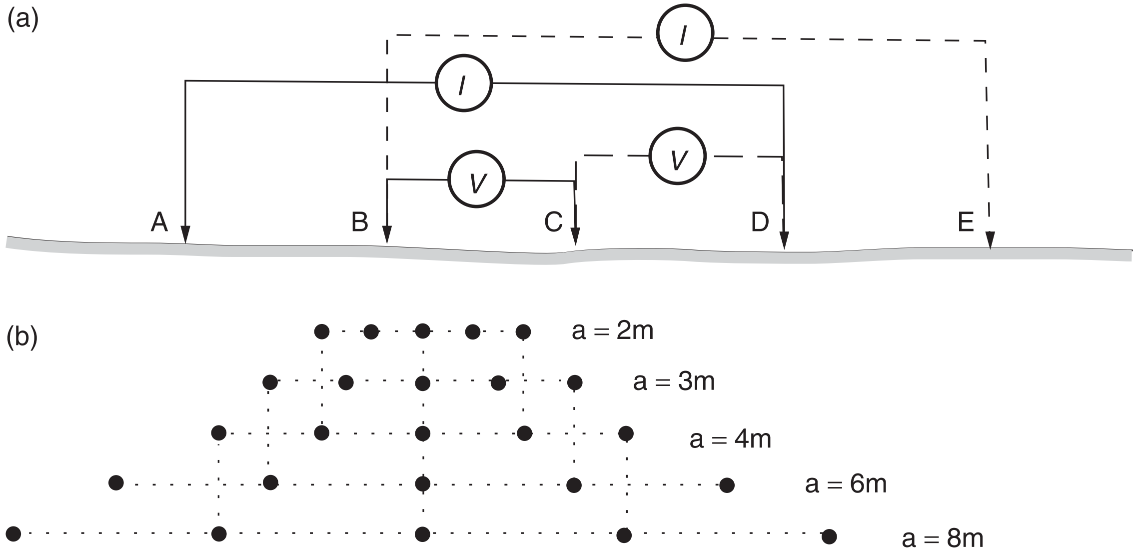

Figure 6.8 *Offset Wenner sounding. (a) Voltage readings are obtained between B and C when current is passed between A and D, and between C and D when current is passed between B and E. (b) An expansion system allowing reuse of electrode positions and efficient operation with multicore cables.*

are averaged to produce a curve in which local effects are 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 6.8b), very quick and efficient operation is possible using multicore cables designed for this purpose.

6.3.4 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.

6.3.5 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 uninterpretable 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 6.5) 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 6.9). 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.

6.3.6 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

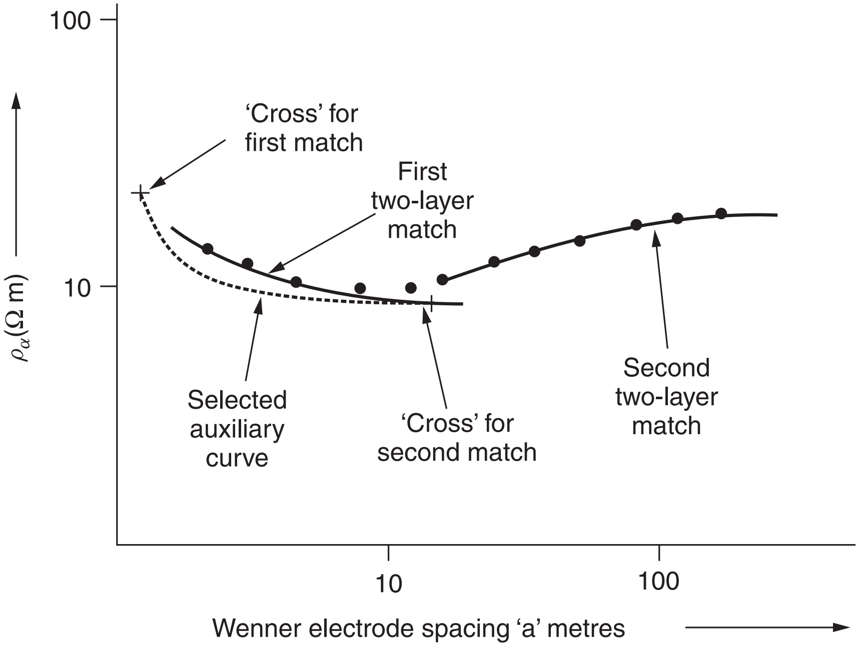

Figure 6.9 *Sequential curve matching. The curve produced by a low-resistivity layer between two layers of higher resistivity is interpreted by two applications of the two-layer curves. In matching the deeper part of the curve, the intersection of the* $\mathrm{a/h} = 1$ *and* $\mathrm{r}_a/\mathrm{r}_1 = 1$ *lines (the 'cross') must lie on the line defined by the auxiliary curve.*

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 6.10a, b). 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 6.10c). 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.

6.4 Capacitative Coupling

A number of instruments have been introduced, relatively recently, in which electrical fields due to currents in insulated conductors cause currents to flow in the ground without direct contact. Because the *aerials* can be dragged along the ground, either manually or mechanically, resistivity can be measured continuously.

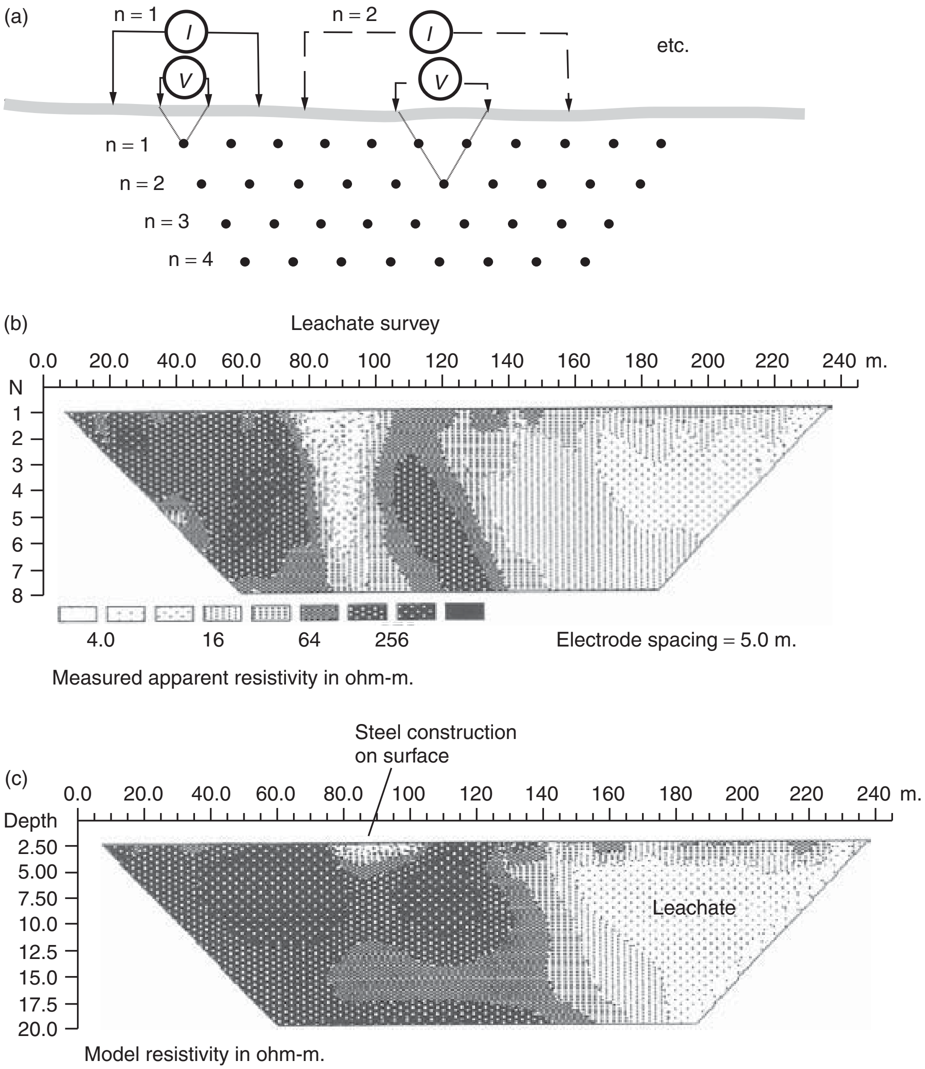

Figure 6.10 *Wenner array pseudo-sections. (a) Plotting system; (b) 'raw' pseudo-section; (c) pseudo-section after inversion. The low-resistivity (white) area at about 90 m was produced by a metal loading bay and railway line, i.e. by a source virtually at the ground surface. (Pseudo-sections reproduced by permission of Dr R. Barker.)*

6.4.1 Capacitative principles

If the current electrodes in a conventional electrical survey were to be removed from the ground and placed on insulating pads, and then connected to a power source, current would flow only until the electrical potential produced by the charges on the electrodes was equal and opposite to that produced by the current source. The ability of a system to store charge in this way is termed its electrical *capacity* and is measured in farads.

The fact that the electrodes would be charged, even when insulated from the ground, implies the existence of an electric field between them that can cause charged particles in the ground to move. Again, this current flow would be brief, persisting only until equal and opposite reverse potentials had been established. If, however, polarity is reversed, there will be further flow of charge until a new equilibrium is established. An alternating voltage of sufficiently high frequency will thus cause alternating current to flow in the ground, despite the presence of the insulators. This is capacitative coupling.

6.4.2 Instrumentation

The Geometrics ‘OhmMapper’ (Figure 5.1d) is typical of the instruments now exploiting the advantages of capacitative coupling. Alternating current is supplied at a frequency of 16.6 kHz to a dipole aerial that, in standard configurations, is made up of 2 m or 5 m lengths of cable. The signal is received at a second, similar aerial towed behind the first and separated from it by a non-conductive linkage, also usually several metres long. Transmitter and receiver electronics and power sources are enclosed in nacelles situated at the midpoints of their respective aerials. The entire system is designed to be dragged or towed along the ground. Results are recorded at fixed time intervals in a data logger that, when the system is being dragged, is strapped to the operator’s belt. The belt also takes the strain on the cable. The logger display can show the resistivity profile as it develops, and several parallel profiles simultaneously. The precautions discussed in Section 1.3.3 need to be observed to ensure data validity.

The OhmMapper utilizes only signal amplitudes, but there will generally also be a difference in phase between the currents circulating in the receiving and transmitting aerials, and this can provide additional useful information. Instruments are under development, notably by the British Geological Survey, that make use of this fact.

6.4.3 Depth of investigation

The depth of investigation in a DC survey is determined mainly by the separation between the electrodes. Similarly, in c-c systems, it is determined by the separation between the aerials and by their lengths. A rough rule of thumb is that the investigation depth is equal to the distance between the centre points of the two aerials.

The use of high-frequency alternating fields introduces an additional factor. The currents in the ground obtain their energy from the varying field and so reduce its strength. Attenuation follows an exponential law (Section 1.1.6), governed by the attenuation constant (α) of Section 5.3.1. The depth of investigation will be determined, or at least influenced, by the skin depth unless this is significantly greater than the distance between receiver and transmitter. The graph in Figure 5.5 suggests that, at the frequencies and separations characteristic of the OhmMapper, there will usually be some element of skin-depth limitation.

6.4.4 Advantages and disadvantages of capacitative coupling

Capacitative coupling allows resistivity data to be obtained very rapidly even in areas where ground contact via electrodes would be difficult or impossible. Traverses can be repeated with different separations between the aerials, and commercially available inversion programs allow resistivity cross-sections to be constructed from multispaced data. However, as with all geophysical methods, there are problems, both practical and theoretical.

Capacitative results will be reliable only if the coupling between the ground and the aerials remains reasonably constant, and this limits the acceptable variations in the insulating gap between ground and aerial. Changes in coupling due to surface irregularities thus introduce a form of noise. Noise is minimized by weighting the aerials but this has obvious disadvantages in one-person operations. Considerable effort may be needed to pull the system over anything but the smoothest terrain, and especially uphill. Even more effort may be needed with later versions of the OhmMapper, which use two receiver aerials to obtain data at two different spacings.

Readings are obtained essentially continuously, and intervals at which they are recorded can be made very small. This does not, however, imply an ability to resolve very small targets, since resolution is determined by aerial length and separation.

7

SP AND IP

Natural, unidirectional currents flow in the ground and produce voltage (self-potential or SP) anomalies that can amount to several hundreds of millivolts between points on the ground surface. They have applications in exploration for massive sulphides, and in some other situations.

Artificial currents flowing in the ground can cause some parts of the rock mass to become electrically polarized. The process is analogous to charging a capacitor or a car battery, and both capacitative and electrochemical effects are involved. If the current suddenly ceases, the polarization cells discharge over periods of several seconds, producing currents, voltages and magnetic fields that can be detected at the surface. Disseminated sulphide minerals produce large polarization effects and *induced polarization* (*IP*) techniques are therefore widely used in exploring for base metals. Arrays are similar to those used in conventional resistivity work. The gradient and dipole–dipole arrays are especially popular (for reconnaissance and detailed work, respectively) because current and voltage cables can be widely separated to minimize electromagnetic induction.

7.1 SP Surveys

SP surveys were at one time popular in mineral exploration because of their low cost and simplicity. They are now little used because some near-surface ore bodies that are readily detected by other electrical methods produce no SP anomaly.

7.1.1 Origins of natural potentials

Natural potentials of as much as 1.8 V have been observed where alunite weathers to sulphuric acid, but the negative anomalies produced by sulphide ore bodies and graphite are generally less than 500 mV. The conductor should extend from the zone of oxidation near the surface to the reducing environment below the water table, thus providing a low-resistance path for oxidation–reduction currents (Figure 7.1).

Small potentials, seldom exceeding 100 mV and usually very much less, may accompany groundwater flow. Polarity depends on rock composition and on the mobilities and chemical properties of the ions in the pore waters but most commonly the region towards which groundwater is flowing becomes more electropositive than the source area. These *streaming potentials* are

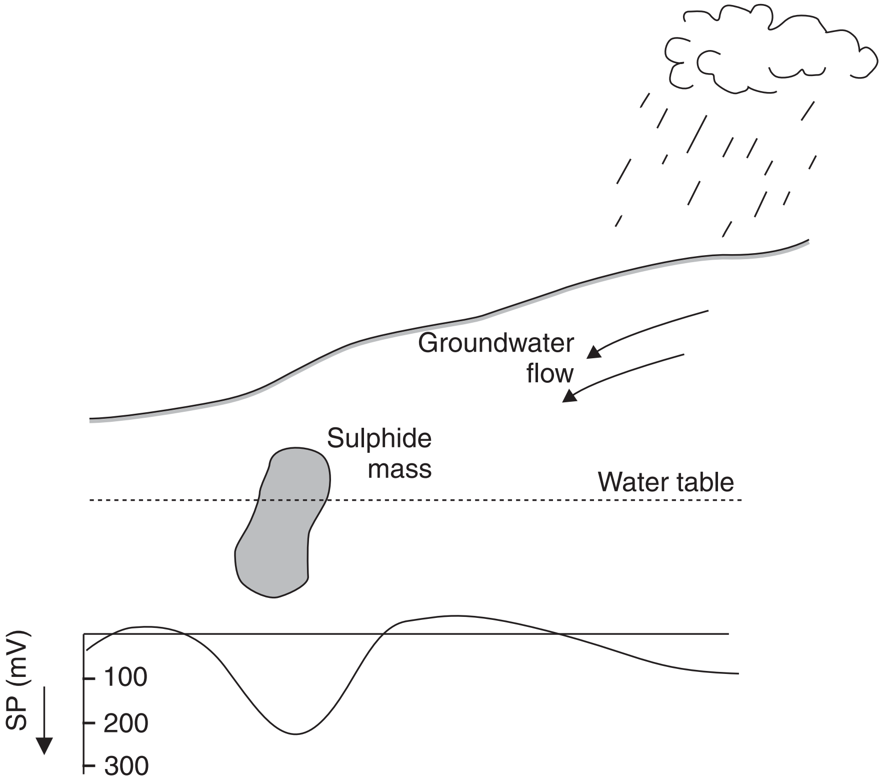

__Figure 7.1__ Sources of SP effects. The sulphide mass straddling the water table concentrates the flow of oxidation–reduction currents, producing a negative anomaly at the surface. The downslope flow of groundwater after rain produces a temporary SP, in this case inversely correlated with topography.

sometimes useful in hydrogeology but can make mineral exploration surveys inadvisable for up to a week after heavy rain.

Movements of steam or hot water can explain most of the SPs associated with geothermal systems, but small (<10 mV) voltages, which may be positive or negative, are produced directly by temperature differences. Geothermal SP anomalies tend to be broad (perhaps several kilometres across) and have amplitudes of less than 100 mV, so very high accuracies are needed.

Small alternating currents are induced in the Earth by variations in the ionospheric component of the magnetic field and by thunderstorms (Section 9.4). Only the long-period components of the associated voltages, seldom amounting to more than 5 mV, are detected by the DC voltmeters used in SP surveys. If, as is very occasionally the case, such voltages are significant, the survey should be repeated at different times of the day so that results can be averaged.

7.1.2 SP surveys

Voltmeters used for SP work must have millivolt sensitivity and very high impedance so that the currents drawn from the ground are negligible. Copper/copper-sulphate 'pot' electrodes (Section 5.2.2) are almost universal, linked to the meter by lengths of insulated copper wire.

An SP survey can be carried out by using two electrodes separated by a small constant distance, commonly 5 or 10 m, to measure average field gradients. The method is useful if cable is limited, but errors tend to accumulate and coverage is slow because the voltmeter and both electrodes must be moved for each reading. More commonly, voltages are measured in relation to a fixed base. One electrode and the meter remain at this point and only the second electrode is moved. Sub-bases must be established if the cable is about to run out or if distances become too great for easy communication. Voltages measured from a base and a sub-base can be related provided that the potential difference between the two bases is accurately known.

Figure 7.2 shows how a secondary base can be established. The end of the cable has almost been reached at field point B, but it is still possible to obtain a reading at the next point, C, using the original base at A. After differences have been measured between A and both B and C, the field electrode is left at C and the base electrode is moved to B. The potential difference between A and B is thus estimated both by direct measurement and by subtracting the B to C voltage from the directly measured A to C voltage. The average difference can be added to values obtained with the base at B to obtain values relative to A.

7.1.3 Errors and precautions

If two estimates of a base/sub-base difference disagree by more than one or two millivolts, work should be stopped until the reason has been determined. Usually it will be found that copper sulphate solution has either leaked away or become undersaturated. Electrodes should be checked every two to

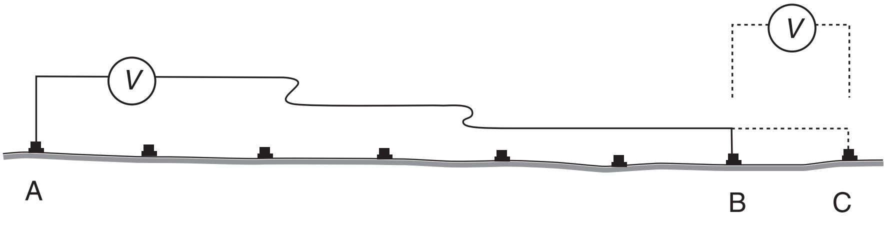

Figure 7.2 Moving base in an SP survey. The value at the new base (B) relative to A is measured directly and also indirectly by measurements of the voltage at the field point C relative to both bases. The two estimates of the voltage difference between A and B are then averaged.

three hours by placing them on the ground a few inches apart. The voltage difference should not exceed 1 or 2 mV.

Accumulation of errors in large surveys can be minimized by working in closed and interconnecting loops around each of which the voltages should sum to zero (Section 1.4.3).

7.2 Polarization Fundamentals

IP surveys are perhaps the most useful of all geophysical methods in mineral exploration, being the only ones responsive to low-grade disseminated mineralization. There are two main mechanisms of rock polarization and three main ways in which polarization effects can be measured. In theory the results obtained by the different techniques are equivalent but there are practical differences.

7.2.1 Membrane polarization

The surfaces of clays and some other platey or fibrous minerals are negatively charged and cause *membrane polarization* in rocks with small pore spaces. Positive ions in the formation waters in such rocks congregate near the pore walls, forming an *electrical double layer*. If an electric field is applied, the positive ion clouds are distorted and negative ions move into them and are trapped, producing concentration gradients that impede current flow. When the applied field is removed, a reverse current flows to restore the original equilibrium.

7.2.2 Electrode polarization

The static *contact potentials* between metallic conductors and electrolytes were discussed in Section 5.2.2. Additional *over-voltages* are produced whenever currents flow. This *electrode polarization* occurs not merely at artificial electrodes but wherever grains of electronically conducting minerals are in contact with the groundwater. The degree of polarization is determined by the surface area, rather than the volume, of the conductor present, and polarization methods are thus exceptionally well suited to exploration for disseminated *porphyry* ores. Strong anomalies are also usually produced by massive sulphide mineralization, because of surrounding disseminated haloes.

Although, for equivalent areas of active surface, electrode polarization is the stronger mechanism, clays are much more abundant than sulphides and most observed IP effects are due to membrane polarization.

7.2.3 The square wave in chargeable ground

When a steady current flowing in the ground is suddenly terminated, the voltage V_o between any two grounded electrodes drops abruptly to a small

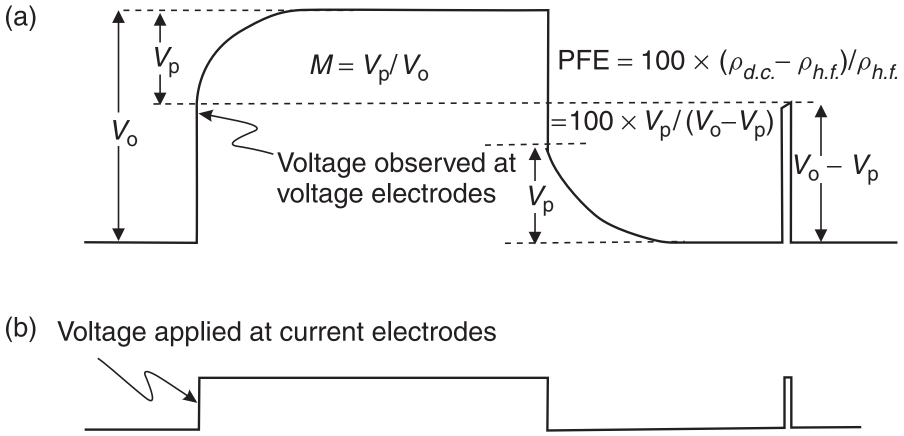

Figure 7.3 Ground response to a square-wave signal and to a spike impulse. The ratio of V_o to V_p is seldom more than a few percent. Input voltage waveform is for reference only. In practice its amplitude will be many times greater than the measured voltage, the exact values depending on the array being used.

polarization voltage V_p and then declines asymptotically to zero. Similarly, when current is applied to the ground, the measured voltage first rises rapidly and then approaches V_o asymptotically (Figure 7.3). Although in theory V_o is never reached, in practice the difference is not detectable after about a second.

Chargeability is formally defined as the polarization voltage developed across a unit cube energized by a unit current and is thus in some ways analogous to magnetic susceptibility. The *apparent chargeability* of an entire rock mass is defined, in terms of the square wave shown in Figure 7.3, as the ratio of V_p to V_o. This is a pure number but in order to avoid very small values it is generally multiplied by a thousand and quoted in millivolts per volt.

The ratio of V_p to V_o cannot be measured directly since electromagnetic transients are dominant in the first tenth of a second after the original current ceases to flow. The practical definition of time-domain chargeability, which is in terms of the decay voltage at some specified delay time, is only tenuously linked to the theoretical definition. Not only do different instruments use different delays, but also it was originally essential and is still quite common to measure an area under the decay curve using integrating circuitry, rather than an instantaneous voltage. The results then depend on the length of the integration period as well as on the delay and are quoted in milliseconds.

7.2.4 Frequency effects

Figure 7.3 also shows that if a current were to be terminated almost immediately after being introduced, a lower apparent resistivity, equal to $(V_o - V_p)/I$

multiplied by the array geometrical factor, would be calculated. The IP frequency effect is defined as the difference between the 'high frequency' and 'DC' resistivities, divided by the high-frequency value. This is multiplied by 100 to give an easily handled whole number, the *percent frequency effect* (PFE). The origin of the theoretical relationship between the PFE and the chargeability:

$$M = [PFE]/(100 + [PFE])$$

is illustrated in Figure 7.3.

Because of electromagnetic transients, the theoretical PFE cannot be measured and the practical value depends on the frequencies used. To cancel telluric and SP noise, 'DC' measurements are taken with current reversed at intervals of the order of a few seconds, while the 'high' frequencies are usually kept below 10 Hz to minimize electromagnetic induction.

7.2.5 Metal factors

A PFE can be divided by the DC resistivity to give a quantity which, multiplied by 1000, 2000 or 2000π, produces a number of convenient size known as the *metal factor*. Metal factors emphasize rock volumes that are both polarizable and conductive and which may therefore be assumed to have a significant sulphide (or graphite) content. Although this may be useful when searching for massive sulphides, low resistivity is irrelevant and can be actually misleading in exploration for disseminated deposits. As usual when factors that should be considered separately are combined, the result is confusion, not clarification.

7.2.6 Phase

The square-wave of Figure 7.3 can be resolved by Fourier analysis into sinusoidal components of different amplitudes and frequencies. The asymmetry of the voltage curve implies frequency-dependent phase shifts between the applied current and the measured voltage. In *spectral* IP surveys, these shifts are measured, in milliradians, over a range of frequencies.

7.3 Time-domain IP Surveys

Large primary voltages are needed to produce measurable IP effects. Current electrodes can be plain metal stakes but non-polarizing electrodes must be used to detect the few millivolts of transient signal.

7.3.1 Time-domain transmitters

A time-domain transmitter requires a power source, which may be a large motor generator or a rechargeable battery. Voltage levels are usually selectable within a range of from 100 to 500 V. Current levels, which may be controlled through a current limiter, must be recorded if apparent resistivities are to be calculated as well as IPs.

Current direction is alternated to minimize the effects of natural voltages, and cycle times can generally be varied from 2 to 16 seconds. One second each for energization and reading is not generally sufficient for reliable results, while cycles longer than 8 seconds unreasonably prolong the survey.

7.3.2 Time-domain receivers

A time-domain receiver measures primary voltage and one or more decay voltages or integrations. It may also be possible to record the SP, so that chargeability, resistivity and SP data can be gathered together.

Early *Newmont* receivers integrated from 0.45 to 1.1 secs after current termination. The SP was first balanced out manually and the primary voltage was then *normalized* by adjusting an amplifier control until a galvanometer needle swung between defined limits. This automatically ratioed V_p to V_o for the M values recorded by a second needle. Experienced operators acquired a ‘feel’ for the shape of the decay curve from the rates of needle movement and were often able to recognize electromagnetic transients where these persisted into the period used for voltage sampling.

With purely digital instruments, the diagnostic information provided by a moving needle is lost and enough cycles must be observed for statistical reduction of noise effects. Digital systems allow more parameters to be recorded and very short integration periods, equivalent to instantaneous readings. Natural SPs are now compensated (*backed-off* or *bucked-out*) automatically rather than manually. Memory circuits store data and minimize note taking.

The receiver must be tuned to the cycle period of the transmitter so that it can lock on to the transmissions without use of a reference cable (which could carry inductive noise). Cycle times of 4, 8 or 16 seconds are now generally favoured. Changing the cycle time can produce quite large differences in apparent chargeability, even for similar delay times, and chargeabilities recorded by different instruments are only vaguely related.

7.3.3 Decay-curve analysis

With readings taken at several different delay times, curve analysis can be attempted. A method suggested for use with Huntec receivers assumed that each decay curve was a combination of two exponential decays, corresponding to electrode and membrane polarizations, which could be isolated mathematically. This is far too drastic a simplification and the separation, using a limited number of readings, of two exponential functions that have been added together is in any case virtually impossible in the presence of even small amounts of noise. Nonetheless, research continues into the controls on decay-curve shapes, and chargeabilities should be recorded at as many decay times as are conveniently possible in areas of interesting anomaly. In non-anomalous areas a single value generally suffices.

7.4 Frequency-domain Surveys

Quite small currents and voltages can be used for resistivity measurements, and frequency-domain transmitters can therefore be lighter and more portable than their time-domain equivalents. Especial care has to be taken in positioning cables to minimize electromagnetic coupling. Coupling is increased by increasing the spacing within or between dipoles, by increasing frequency and by conductive overburden. Unfortunately, field crews have very limited control over this final factor in many areas. They may also be forced to use large electrode separations if deep targets are being sought.

7.4.1 Frequency-domain transmitters

Square waves are commonly used for work in the frequency as well as in the time domain, and most modern IP transmitters can be used for both. Measuring resistivity at two frequencies in separate operations is time consuming and does not allow precise cancellation of random noise. Transmitters may therefore be designed to permit virtually simultaneous readings on complex waveforms made up of two frequencies. Simple square waves may be used if the receiver can analyse the voltage waveform to extract the high-frequency effects.

7.4.2 Frequency/phase receivers

Sophisticated receivers are needed to analyse waveforms and extract frequency effects from either single- or dual-frequency transmissions but this sophistication is normally not apparent to an operator recording PFEs from a front panel display.

To measure phase differences for multi-frequency (spectral) IP surveys, a common time reference for transmitter and receiver is essential. Because a reference cable could increase inductive coupling and might also be operationally inconvenient, crystal clocks are used. These can be synchronized at the start of a day’s work and should drift no more than a fraction of a millisecond in 24 hours.

7.4.3 Phase measurements

A typical spectral IP plot is shown in Figure 7.4. The frequency at which the maximum phase shift occurs is dependent on grain size, being higher for fine-grained conductors. The sharper the peak, the more uniform the grain size. Most attempts to distinguish between different types of IP source are now based on analysis of these spectral curves, since grain size may be correlated

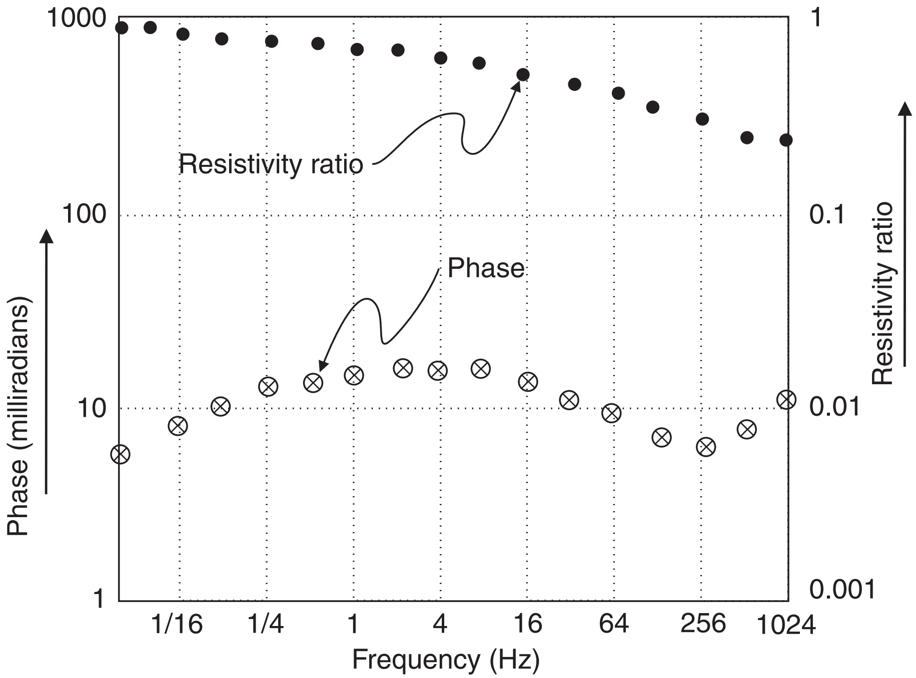

Figure 7.4 *Typical plot of IP phase and amplitude against frequency.*

with mineral type. However, exploration programs soon reach the point at which further theoretical analysis of IP curves is less effective than drilling a few holes.

The general pattern of increasing phase shift at high frequencies is caused by electromagnetic coupling. Simple *decoupling* calculations involve readings at three different frequencies and assume a quadratic relationship (i.e. $\varphi = A + Bf + Cf^2$) between phase-shift and frequency. The three readings allow this equation to be solved for A, the *zero-frequency* phase shift value. At most survey points only the value of A will be worth recording, but at points that are clearly anomalous an entire phase spectrum, using many more than the three basic frequencies, may be stored for further processing.

7.4.4 Comparison of time- and frequency-domain methods

The relationship between polarization and current is not precisely linear. This not only limits the extent to which time, frequency and phase measurements can be interrelated, but can also affect comparisons between different surveys of the same type. The effects generally do not exceed a few percent, but provide yet another reason for the very qualitative nature of most IP interpretation.

The relative merits of time- and frequency-domain IP have long been argued, especially by rival instrument manufacturers. Time-domain surveys are essentially multi-frequency and the shapes of decay curves provide information equivalent to that obtained by measurements at several different frequencies in frequency-domain or phase work. It is, moreover, generally conceded that PFEs and phase shifts are more vulnerable to electromagnetic interference than are time-domain chargeabilities, and that the additional readings needed if correction factors are to be calculated take additional time and demand more sophisticated instruments. However, frequency-domain surveys require smaller currents and voltages and may be preferred as safer and involving more portable instruments. The final choice between the two usually depends on personal preference and instrument availability.

7.5 IP Data

The methods used to display IP data vary with the array. Profiles or contour maps are used for gradient arrays, while dipole–dipole data are almost always presented as pseudo-sections. In surveys with either array, the spacing between the voltage electrodes should not be very much greater than the width of the smallest target that would be of interest.

7.5.1 Gradient array data

Current paths are roughly horizontal in the central areas investigated using gradient arrays, and chargeable bodies will be horizontally polarized. Profiles can be interpreted by methods analogous to those used for magnetic data, with approximate depths estimated using the techniques of Section 3.5.2.

7.5.2 Dipole–dipole data

Dipole–dipole traverses at a single n value can be used to construct profiles but multispaced results are almost always displayed as pseudo-sections (Figure 7.5). The relationships between the positions of highs on pseudo-sections and source body locations are even less simple with dipole–dipole than with Wenner arrays (Section 6.3.6). In particular, the very common *pant's leg* anomaly (Figure 7.5) is usually produced by a near-surface body with little extent in depth; every measurement made with either the current or the voltage dipole near the body will record high chargeability. Anomaly shapes are thus very dependent on electrode positions, and the directions of apparent dip are not necessarily the directions of dip of the chargeable bodies. Even qualitative interpretation requires considerable experience as well as familiarity with model studies.

Pseudo-sections are nearly always plotted in relation to horizontal baselines, even in rugged terrain. Referencing them to topographic profiles (using construction lines similar to those of Figure 7.5 but at 45° to the actual ground

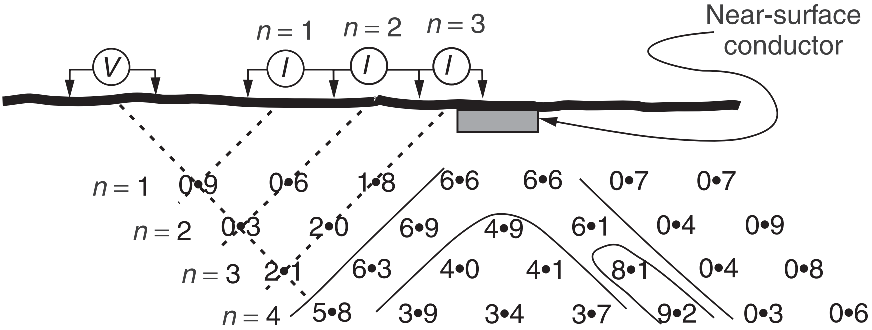

Figure 7.5 *Pseudo-section construction. The three different positions of the current dipole correspond to three different multiples of the basic spacing. Measured values (of IP or resistivity) are plotted at the intersections of lines sloping at 45° from the dipole centres. The plotting 'point' often doubles as a decimal point for IP values. The* pant's leg *anomaly shown is typical of those produced by small, shallow bodies.*

surface) has its dangers, since it might be taken as implying much closer correlation with true sub-surface distributions of resistivity and chargeability than actually exist. However, steep and varied slopes do influence dipole–dipole results and it is better that they be displayed than ignored.

7.5.3 Negative IPs and masking

Negative IP effects can be caused by power or telephone cables or, as shown, by signal contribution sections (Figure 6.4), or by lateral inhomogeneities. Layering can also produce negative values, and can conceal deeper sources, most readily if both the surface and target layers are more conductive than the rocks in between. In these latter circumstances, the penetration achieved may be very small and total array lengths may need to be 10 or more times the desired exploration depth.

Interactions between conduction and charge in the earth are very complex, and interpreters generally need more reliable resistivity data than is provided by the dipole–dipole array, which performs poorly in defining layering. A small number of Wenner or Schlumberger expansions, carried out specifically to map resistivity, may prove invaluable. Also, any changes in surface conditions that might correlate with changes in surface conductivity should be noted. The detectability of ore is likely to be quite different beneath bare rock ridges and under an intervening swamp.