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.

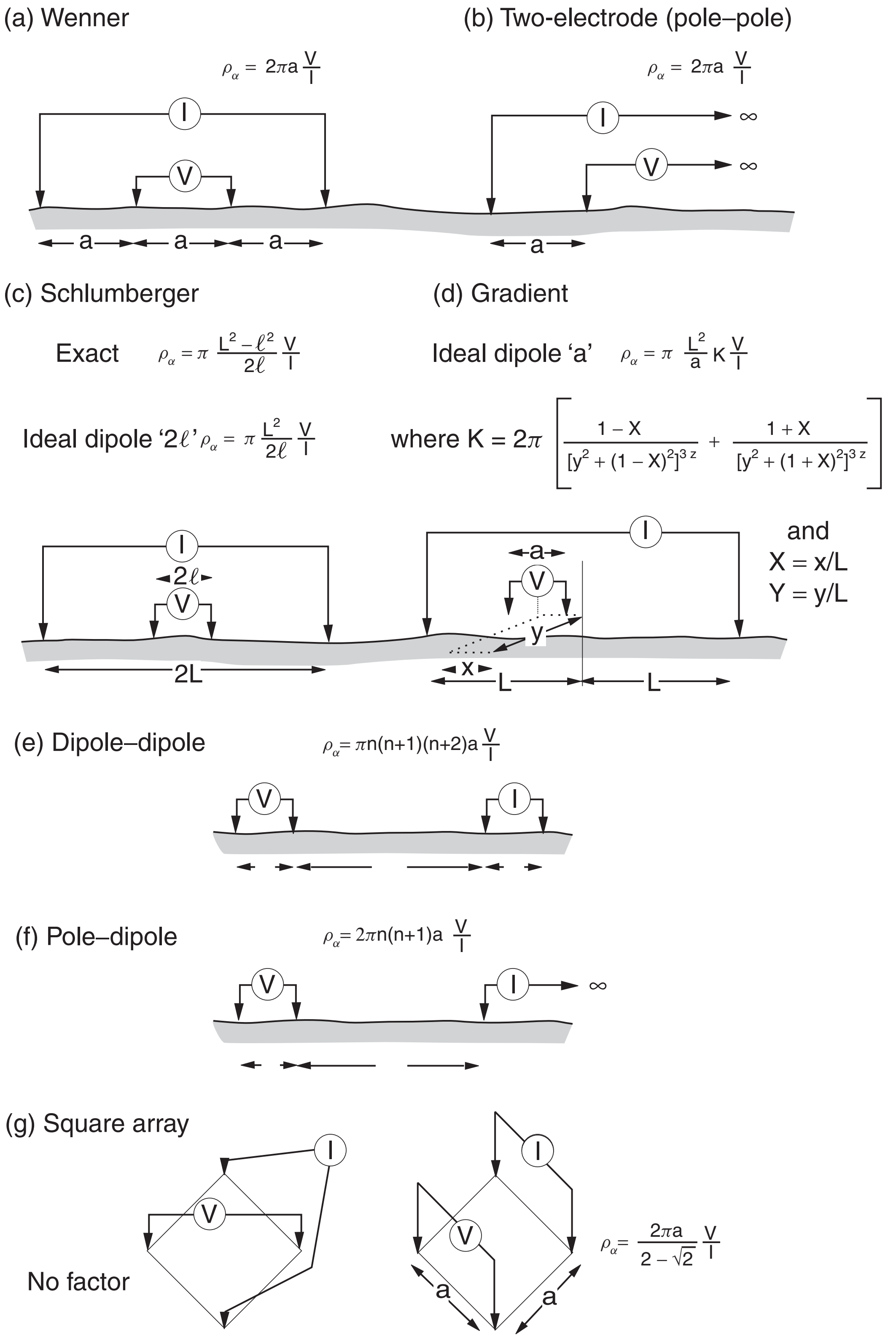

Figure 6.1 *Some common electrode arrays and their geometric factors. (a) Wenner; (b) Two-electrode; (c) Schlumberger; (d) Gradient; (e) Dipole–dipole; (f) Pole–dipole; (g) Square array; (left) Diagonal; (right) Broadside. There is no geometrical factor for the diagonal square array, as no voltage difference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

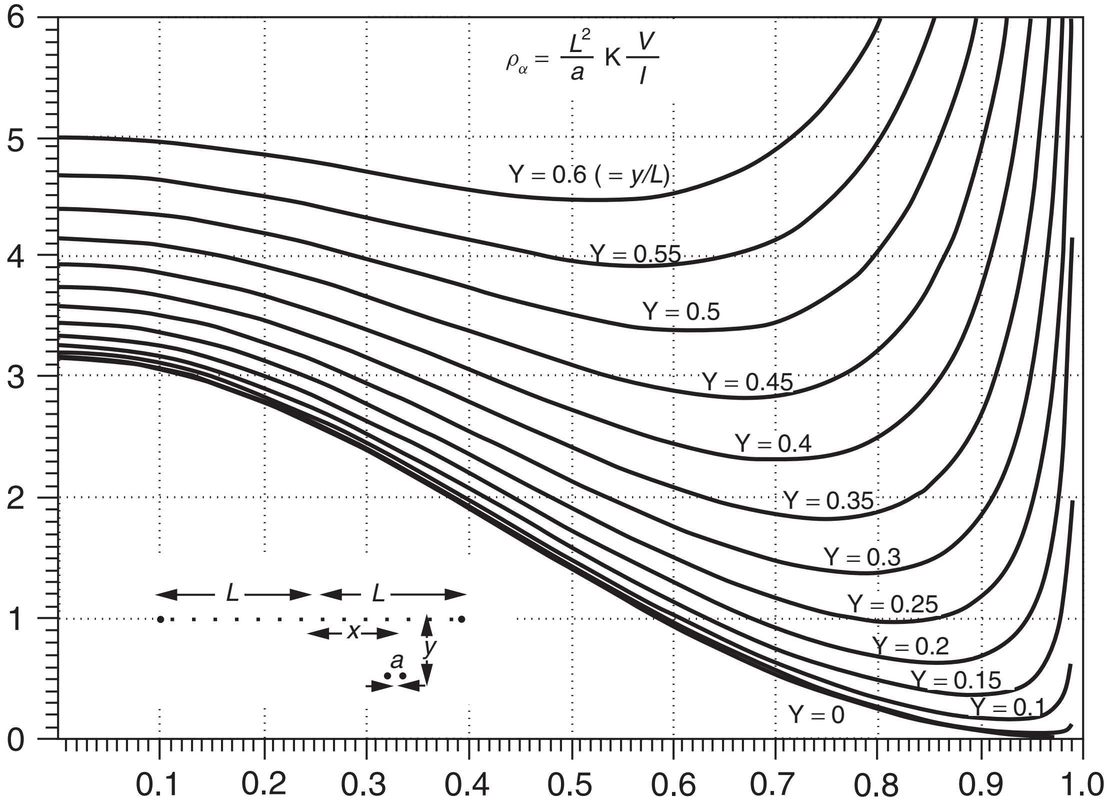

Figure 6.2 *Variation in gradient array geometric factor with distance along and across line. Array total length* $2L$*, voltage dipole length* a*.*

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

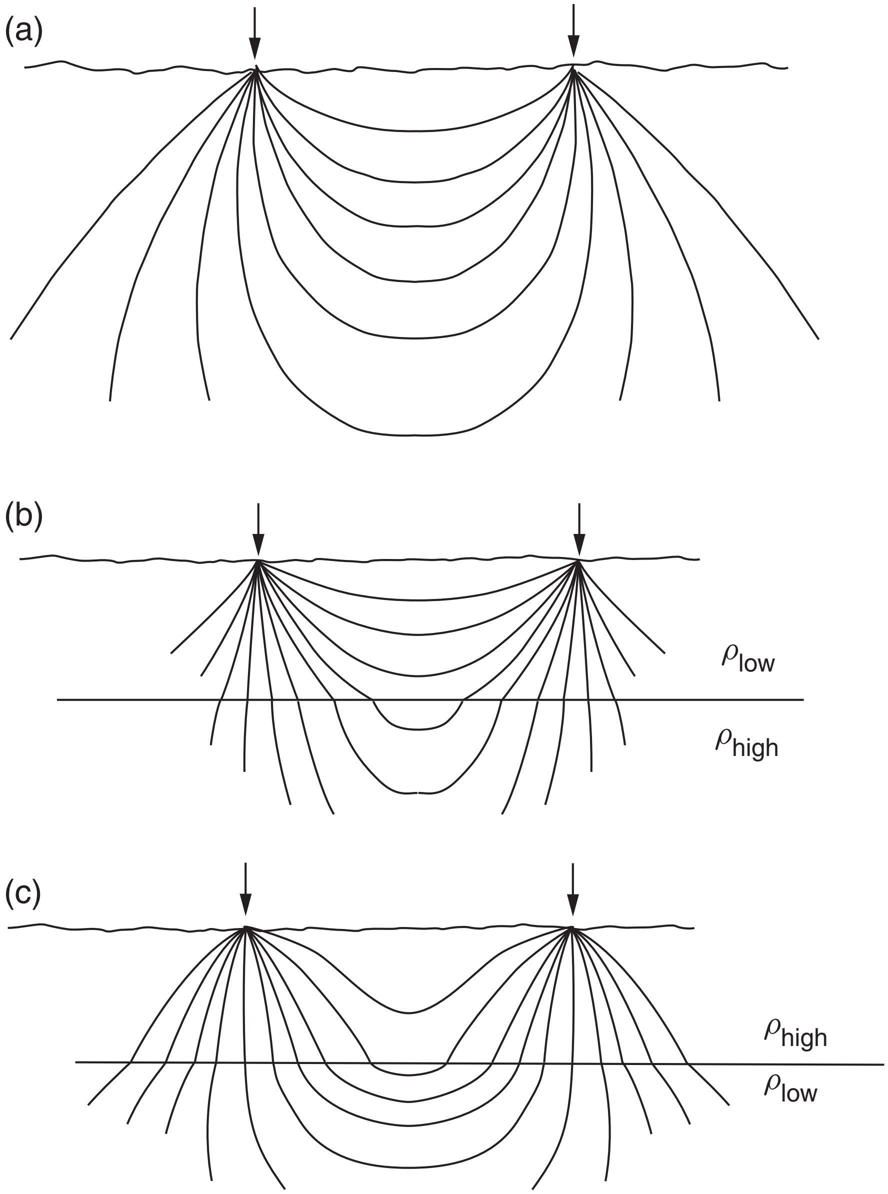

Figure 6.3 *Current flow patterns for (a) uniform half-space; (b) two-layer ground with lower resistivity in upper layer; (c) two-layer ground with higher resistivity in upper layer.*

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

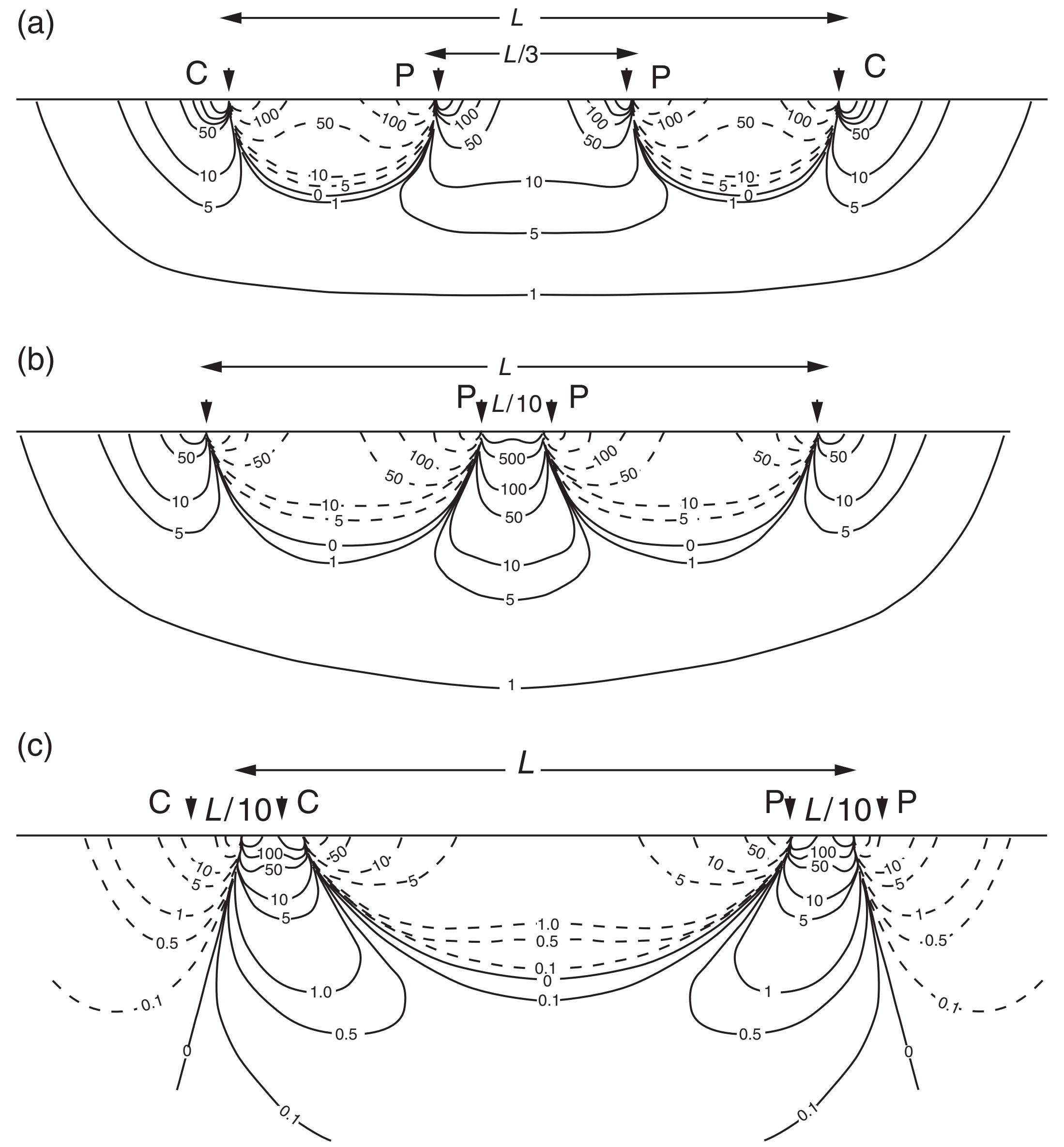

Figure 6.4 *Signal contribution sections for (a) Wenner; (b) Schlumberger and (c) dipole–dipole arrays. Contours show relative contributions to the signal from unit volumes of homogeneous ground. Dashed lines indicate negative values. (Reproduced by permission of Dr R. Barker.)*

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

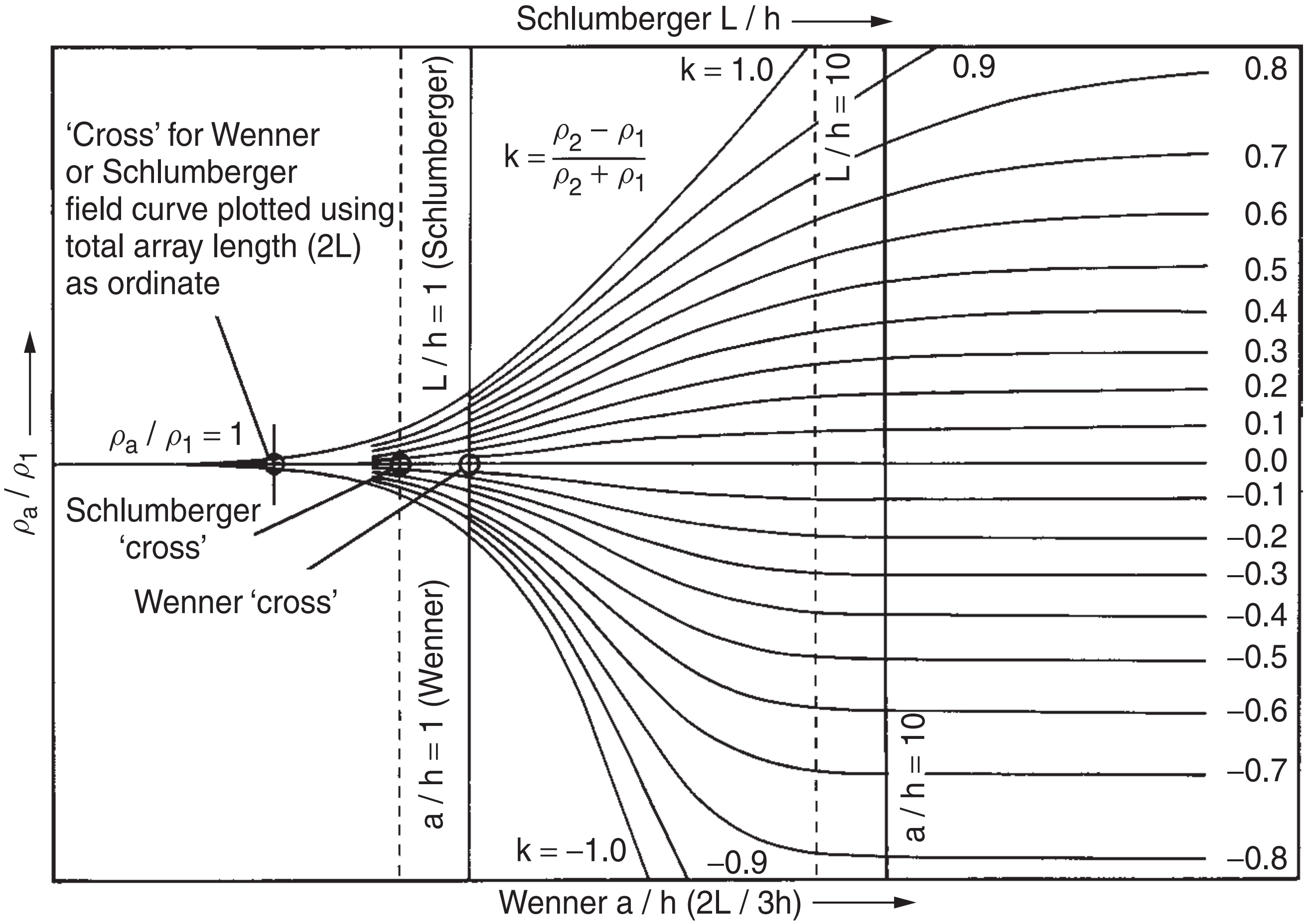

Figure 6.5 *Two-layer apparent resistivity type curves for the Wenner array, plotted on log-log paper. When matched to a field curve obtained over a two-layer earth, the line* $a/h = 1$ *points to the depth of the interface and the line* $\rho_a/\rho_1 = 1$ *points to the resistivity of the upper layer.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

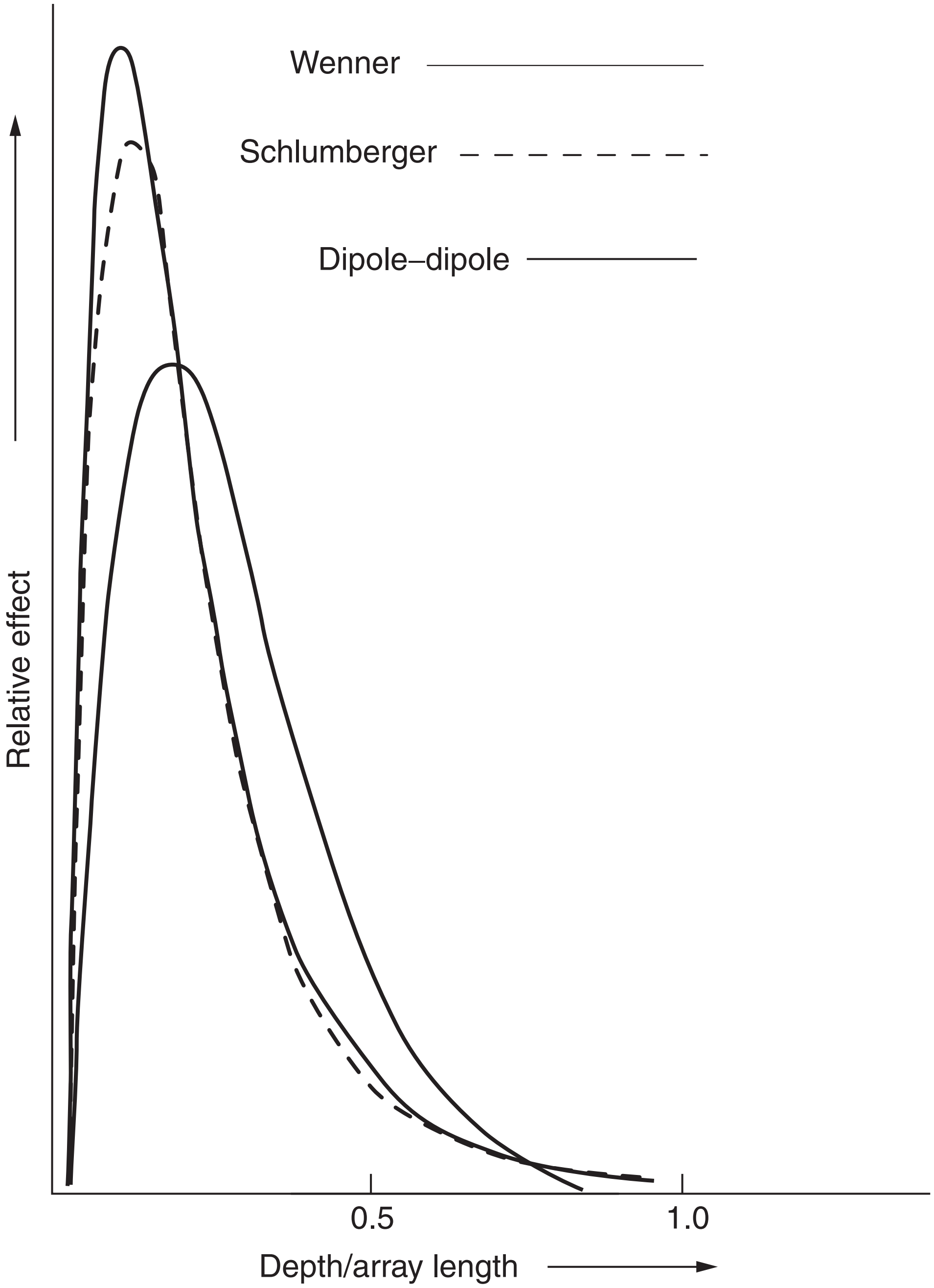

Figure 6.6 *Relative effect of a thin, horizontal high-resistance bed in otherwise homogeneous ground. The areas under the curves have been made equal, concealing the fact that the voltage observed using the Schlumberger array will be somewhat less, and with the dipole–dipole array very much less, than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

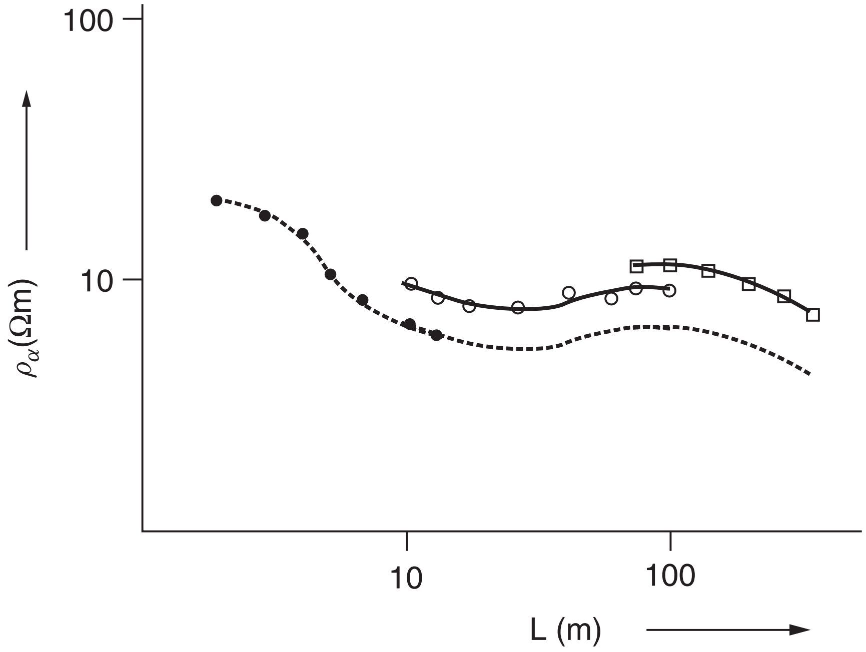

Figure 6.7 *Construction of a complete Schlumberger depth-sounding curve (dashed line) from overlapping segments obtained using different inner-electrode separations.*

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

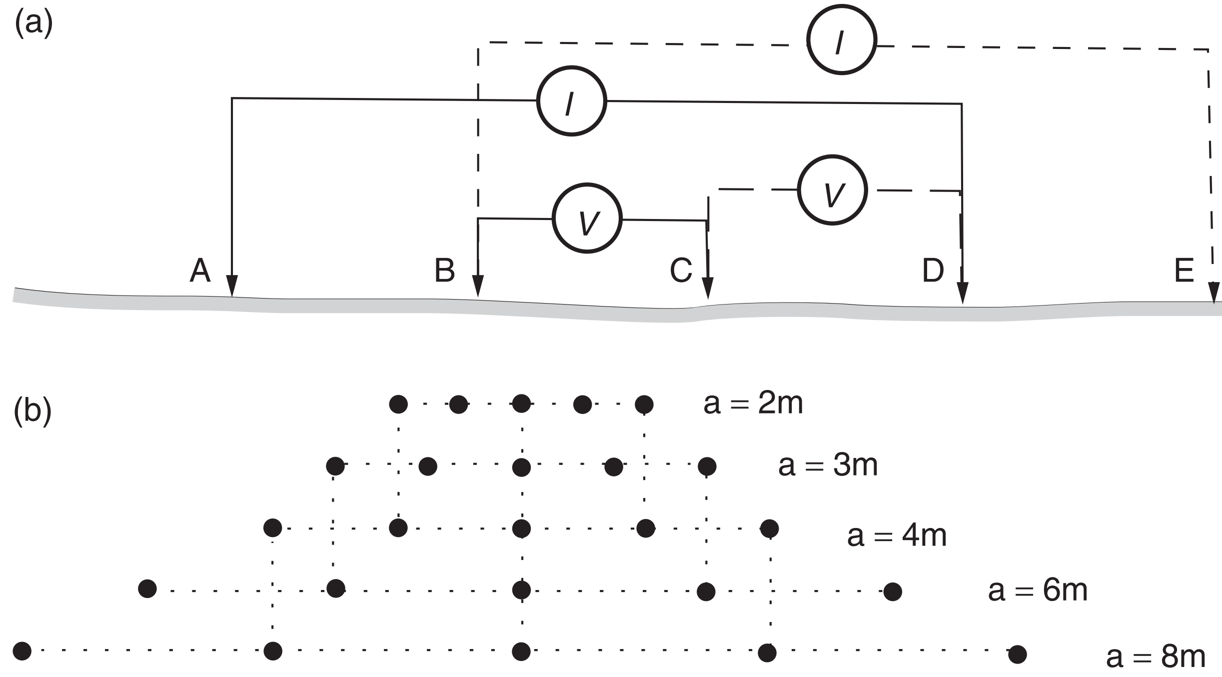

Figure 6.8 *Offset Wenner sounding. (a) Voltage readings are obtained between B and C when current is passed between A and D, and between C and D when current is passed between B and E. (b) An expansion system allowing reuse of electrode positions and efficient operation with multicore cables.*

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

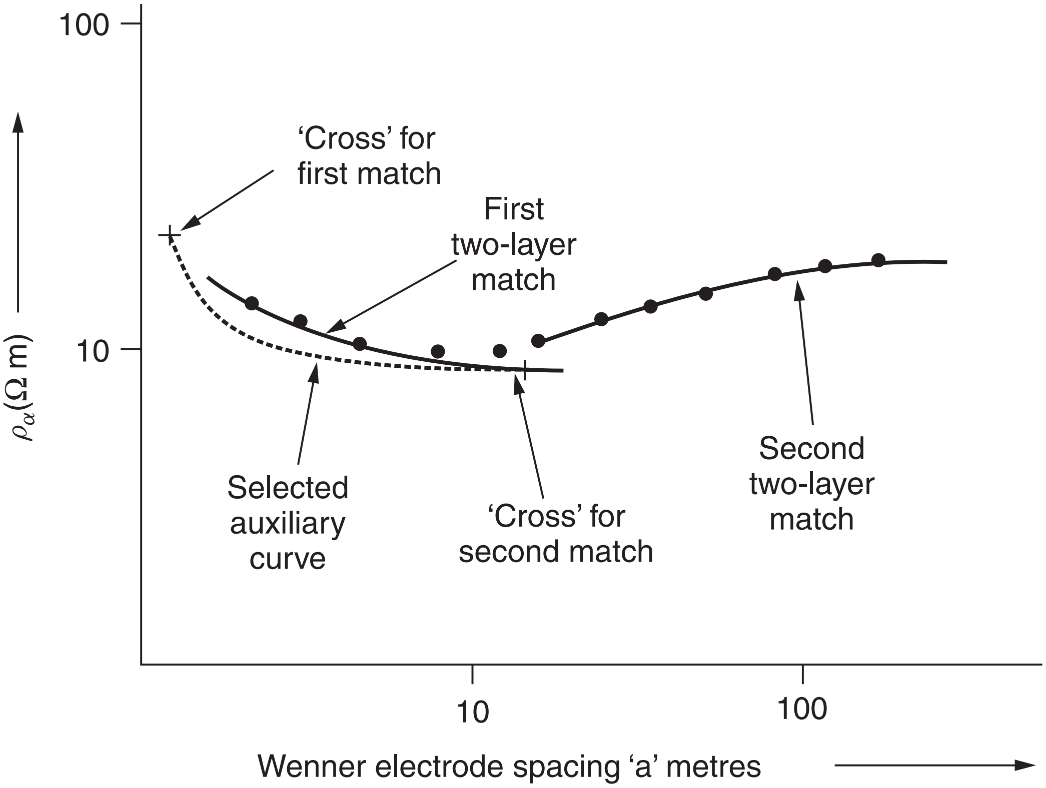

Figure 6.9 *Sequential curve matching. The curve produced by a low-resistivity layer between two layers of higher resistivity is interpreted by two applications of the two-layer curves. In matching the deeper part of the curve, the intersection of the* $a/h = 1$ *and* $r_a/r_1 = 1$ *lines (the 'cross') 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.

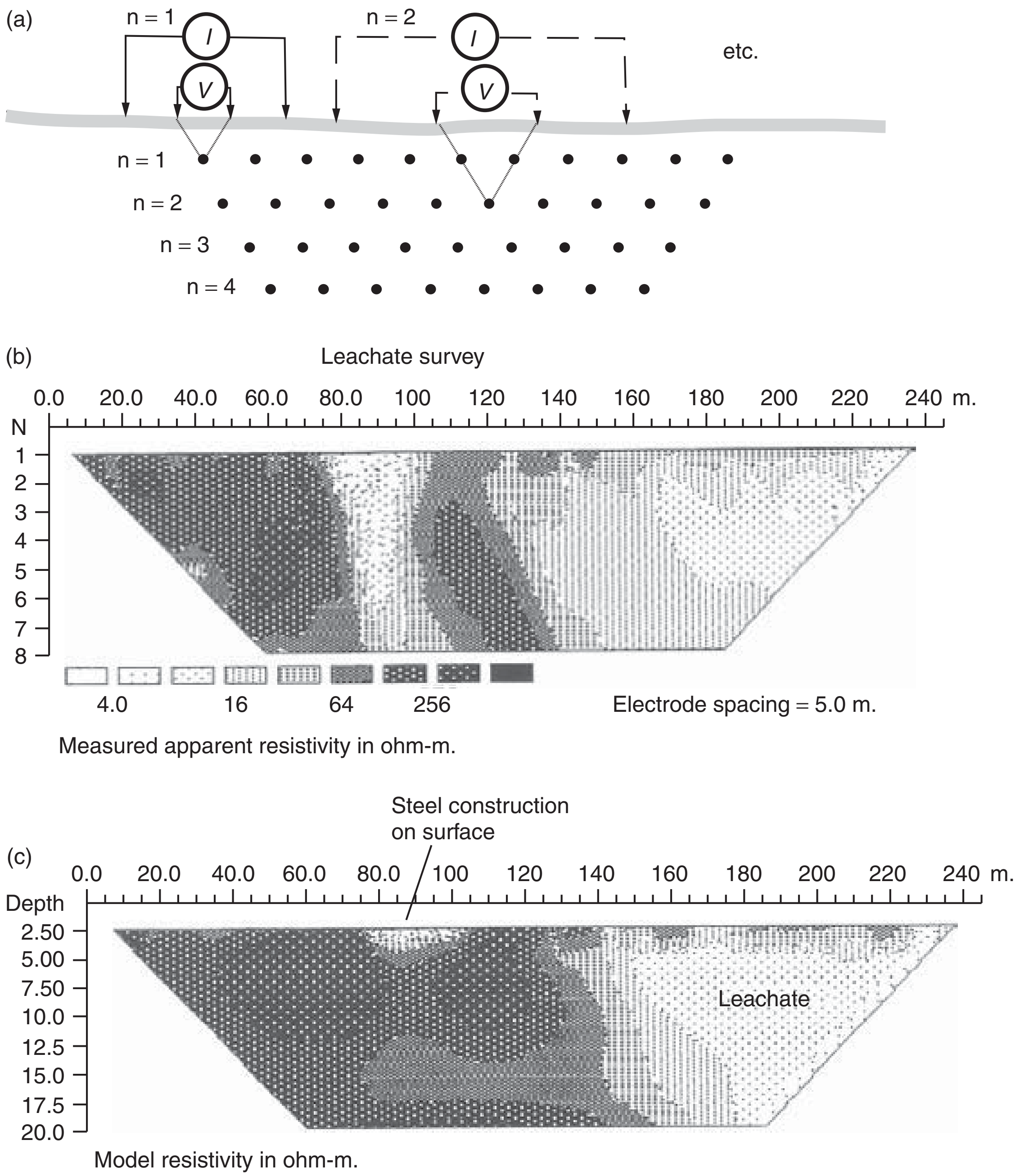

Figure 6.10 *Wenner array pseudo-sections. (a) Plotting system; (b) 'raw' pseudo-section; (c) pseudo-section after inversion. The low-resistivity (white) area at about 90 m was produced by a metal loading bay and railway line, i.e. by a source virtually at the ground surface. (Pseudo-sections reproduced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