7.4 MODES OF DEPLOYMENT

There are two main modes of deployment of electrode arrays. One is for depth sounding (to determine the vertical variation of resistivity) – this is known as *vertical electrical sounding* (VES). The other is for horizontal traversing (horizontal variation of resistivity) and is called *constant separation traversing* (CST) (also called 'electrical resistivity traversing', ERT). In the case of multi-electrode arrays, two forms are available. Microprocessor-controlled resistivity traversing (MRT) is used particularly for hydrogeological investigations requiring significant depths of penetration. Sub-surface imaging (SSI) or two-dimensional electrical tomography is used for very high resolution in the near-surface in archaeological, engineering and environmental investigations.

7.4.1 Vertical electrical sounding (VES)

As the distance between the current electrodes is increased, so the depth to which the current penetrates is increased. In the case of the dipole–dipole array, increased depth penetration is obtained by increasing the inter-dipole separation, not by lengthening the current electrode dipole. The position of measurement is taken as the mid-point of the electrode array. For a depth sounding, measurements of the resistance ($\delta V/I$) are made at the shortest electrode separation and then at progressively larger spacings. At each electrode separation a value of apparent resistivity (ρ_a) is calculated using the measured resistance in conjugation with the appropriate geometric factor for the electrode configuration and separation being used (see Section 7.3). The values of apparent resistivity are plotted on a graph ('field curve') the x- and y-axes of which represent the logarithmic values of the current electrode half-separation ($AB/2$) and the apparent resistivity (ρ_a), respectively (Figure 7.16). The methods by which these field curves are interpreted are discussed in detail in Section 7.5.

In the normal Wenner array, all four electrodes have to be moved to new positions as the inter-electrode spacings are increased (Figure 7.17A). The offset Wenner system has been devised to work with special multicore cables (Barker 1981). Special connectors at logarithmically spaced intervals permit a Wenner VES to be completed by using a switching box which removes the necessity to change the electrode connections physically. Note that the offset Wenner array requires one extra electrode separation to cover the same amount of the sub-surface compared with the normal Wenner array. When space is a factor, this needs to be considered in the survey design stage.

In the case of the Schlumberger array (Figure 7.17C), the potential electrodes (P_1P_2) are placed at a fixed spacing (b) which is no more

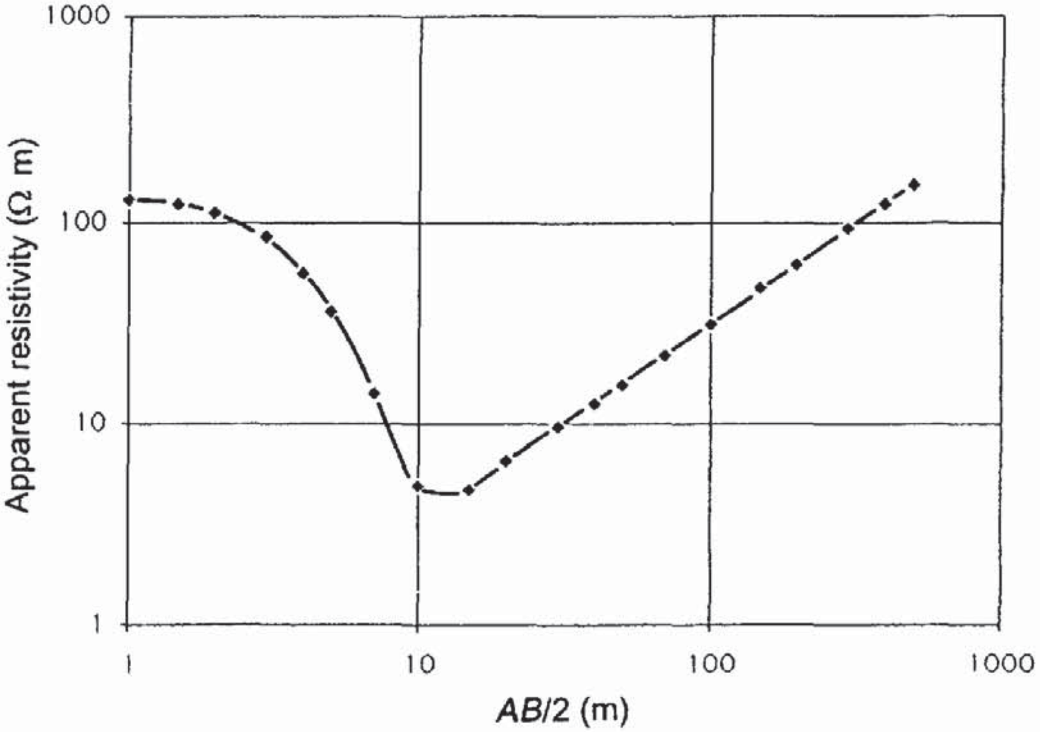


Figure 7.16 A vertical electrical sounding (VES) showing apparent resistivity as a function of current electrode half-separation ($AB/2$)

than one-fifth of the current-electrode half-spacing (a). The current electrodes are placed at progressively larger distances. When the measured voltage between P_1 and P_2 falls to very low values (owing to the progressively decreasing potential gradient with increasing current electrode separation), the potential electrodes are spaced more widely apart (spacing b_2). The measurements are continued and the potential electrode separation increased again as necessary until the VES is completed. The tangible effects of so moving the potential electrodes is discussed at the end of Section 7.4.4. A VES using the Schlumberger array takes up less space than either of the two Wenner methods and requires less physical movement of electrodes than the normal Wenner array, unless multicore cables are used.

The dipole–dipole array is seldom used for vertical sounding as large and powerful electrical generators are normally required. Once the dipole length has been chosen – i.e. the distance between the two current electrodes and between the two potential electrodes – the distance between the two dipoles is then increased progressively (Figure 7.17C) to produce the sounding. The square array is rarely used for large-scale soundings as its setting out is very cumbersome (Figure 7.17E). The main advantage of the electrode configuration is the simplicity of the method when setting out small grids. In small-scale surveys investigating the three-dimensional extent of sub-surface targets, such as in archaeology, the square sides are of the order of only a few metres.

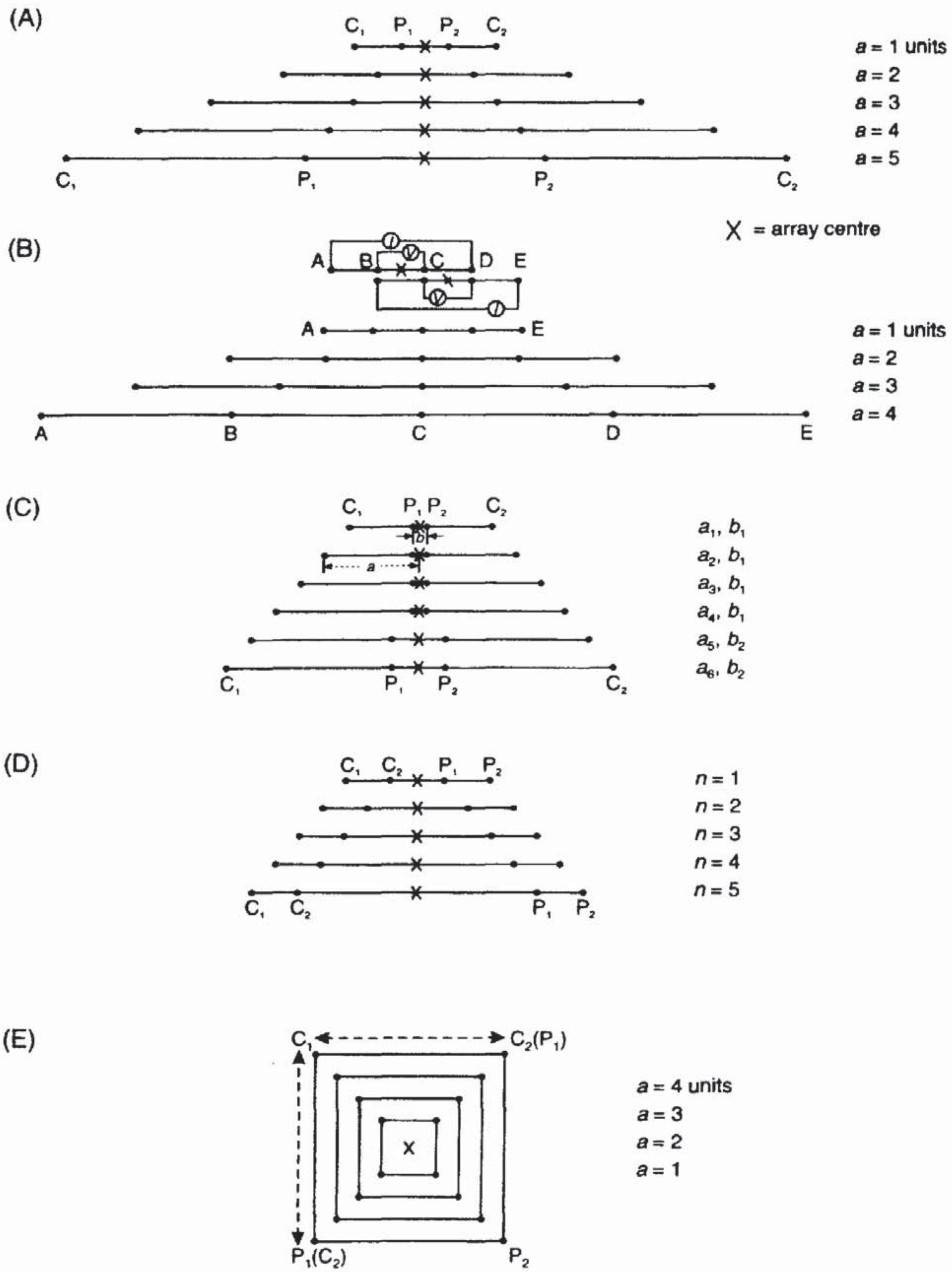


Figure 7.17 Expanded arrays (with successive positions displaced for clarity) for: (A) Wenner, (B) offset Wenner, (C) Schlumberger, (D) dipole–dipole and (E) square arrays

7.4.2 Automated array scanning

In 1981 Barker published details of the offset Wenner array using multicore cables and multiple electrodes for VES investigations. In 1985, Griffiths and Turnbull produced details of a multiple electrode array for use with CST. This theme was developed by van Overmeeren and Ritsema (1988) for hydrogeological applications and by Noel and Walker (1990) for archaeological surveys. For deeper sounding, where multicore cabling would become prohibitively heavy, the cable is wound into 50 m sections on its own drum with an addressable electronic switching unit and power supply mounted in the hub of each cable reel. The switching units are controlled by a laptop computer which can switch any electrode to either of two current or two potential cables which connect the entire array of drum reels. This system is known as the *microprocessor-controlled-resistivity traversing system* (Griffths *et al.* 1990).

In van Overmeeren and Ritsema's *continuous vertical electrical sounding* (CVES) system, an array of multiples of 40 electrodes is connected to a microprocessor by a multicore cable. Usiing software control, discrete sets of four electrodes can be selected in a variety of electrode configurations and separations and a measurement of the resistance made for each. Instead of using one cable layout for just one VES, the extended electrode array can be used for a number of VES, each one offset by one electrode spacing. If the first VES is conducted with its centre between electrodes 15 and 16, for example, the next VES will be centred between electrodes 16 and 17, then 17 and 18, 18 and 19, and so on. A field curve is produced for each sounding along the array and interpreted by computer methods (see Section 7.5.3) to produce a geo-electric model of true layer resistivities and thickness for each VES curve. When each model is displayed adjacent to its neighbour, a panel of models is produced (Figure 7.18) in which the various resistivity horizons can be delimited. It is clear from Figure 7.18D that the CVES interpretation is closest to the known physical model compared with those for either the tripotential alpha or beta/gamma ratio sections (Shown in Figure 7.18B and C respectively). This particular method requires special equipment and associated computer software, but it highlights a novel application of both field method and data analysis to improve the resolution of shallow resistivity surveys.

In sub-surface imaging (SSI), typically 50 electrodes are laid out in two strings of 25, with electrodes connected by a multicore cable to a switching box and resistance meter. The whole data acquisition procedure is software-controlled from a laptop computer. Similar products have been produced, such as the LUND Automatic Imaging System (ABEM), and MacOhm 21 (DAP-21) Imaging System (OYO), and the Sting/Swift (Advanced Geosciences Inc.), among others.

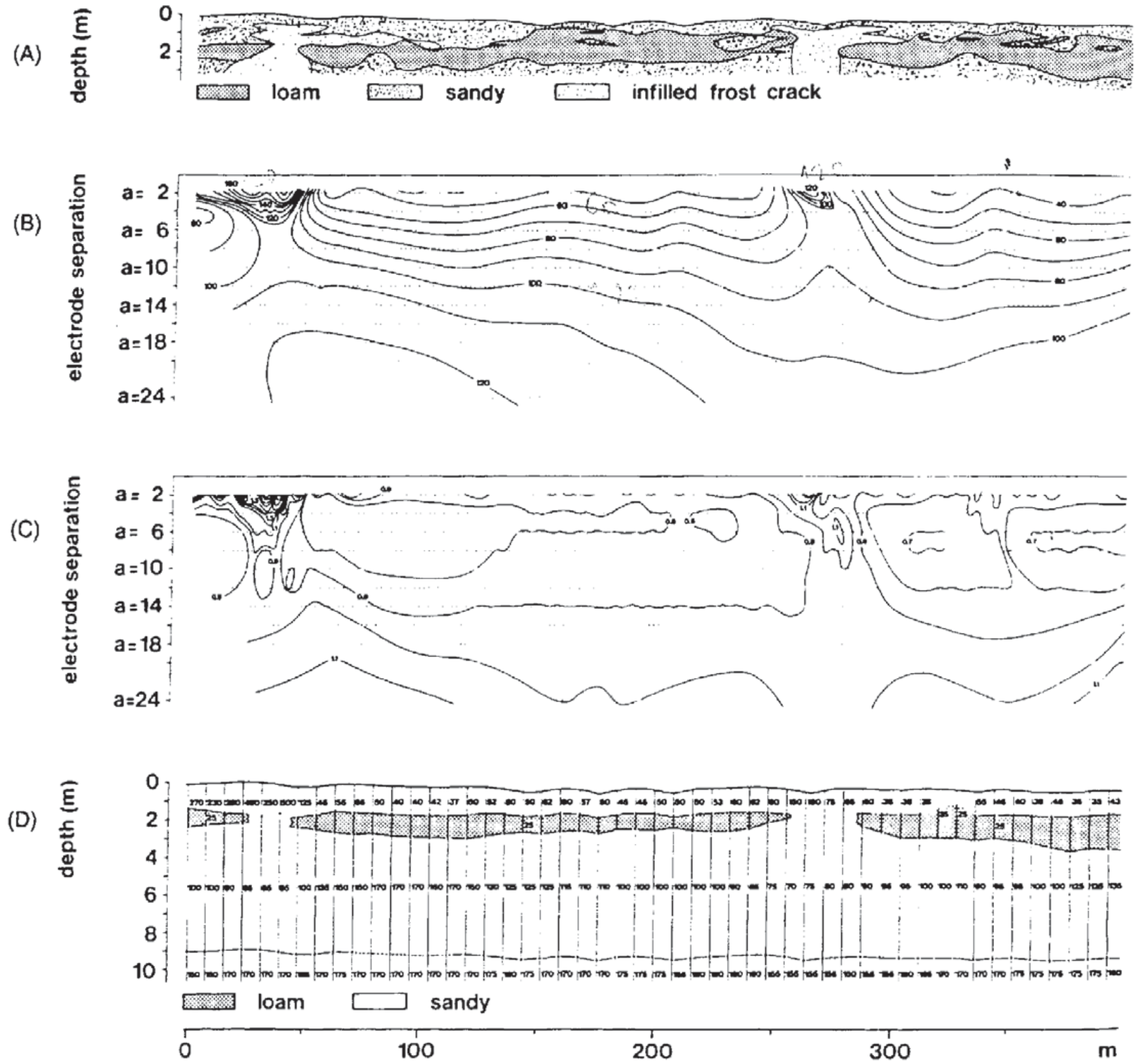


Figure 7.18 High-resolution soil survey using a scanned array. (A) Soil section determined by shallow hand-drilling. Pseudo-sections obtained using (B) Wenner tripotential alpha and (C) beta/gamma arrays. (D) Continuous vertical electrical sounding results with true resistivities indicated. From van Overmeeren and Ritsema (1988), by permission

As with van Overmeeren and Ritsema's CVES method, a discrete set of four electrodes with the shortest electrode spacing ($n = 1$; see Figure 7.19) is addressed and a value of apparent resistivity obtained. Successive sets of four electrodes are addressed, shifting each time by one electrode separation laterally. Once the entire array has been scanned, the electrode separation is doubled ($n = 2$), and the process repeated until the appropriate number of levels has been scanned. The values of apparent resistivity obtained from each measurement are plotted on a pseudo-section (Figure 7.19) and contoured. The methods of interpretation are described in more detail in Section 7.5.6. There are considerable advantages in using SSI or equivalent

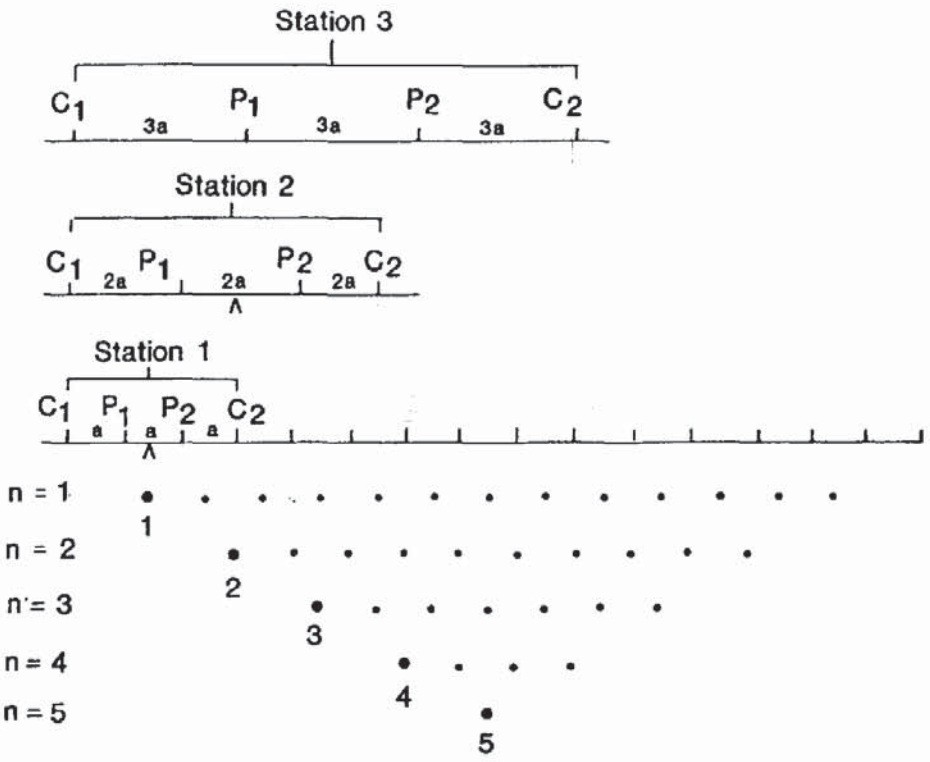


Figure 7.19 Example of the measurement sequence for building up a resistivity pseudo-section. Courtesy of Campus Geophysical Instruments Ltd.

methods. With multicore cable and many electrodes, the entire array can be established by one person. The acquisition of apparent resistivity data is controlled entirely by the software whose parameters are selected at the outset. By changing the inter-electrode spacing between electrodes, the vertical and horizontal resolutions can be specified to meet the objectives of the survey. For example, the horizontal resolution is defined by the inter-electrode spacing, and the vertical resolution by half the spacing. For example, using a 2 m inter-electrode spacing, the horizontal and vertical resolutions are 2 m and 1 m, respectively, for the pseudo-section display. Whether sub-surface features can be resolved at a comparable scale is determined also by the lateral and vertical variations in true resistivity.

7.4.3 Constant-separation traversing (CST)

Constant-separation traversing uses a manul electrode array, usually the Wenner configuration for ease of operation, in which the electrode separation is kept fixed. The entire array is moved along a profile and values of apparent resistivity determined at discrete intervals along the profile. For example, a Wenner spacing of say 10 m is used with perhaps 12 electrodes deployed at any one time at 5 m intervals. Alternate electrodes are used for any one measurement (Figure 7.20) and instead of uprooting the entire sets of electrodes, the connections are moved quickly and efficiently to the next electrode along the line, i.e. 5 m down along the traverse. This provides a CST profile with

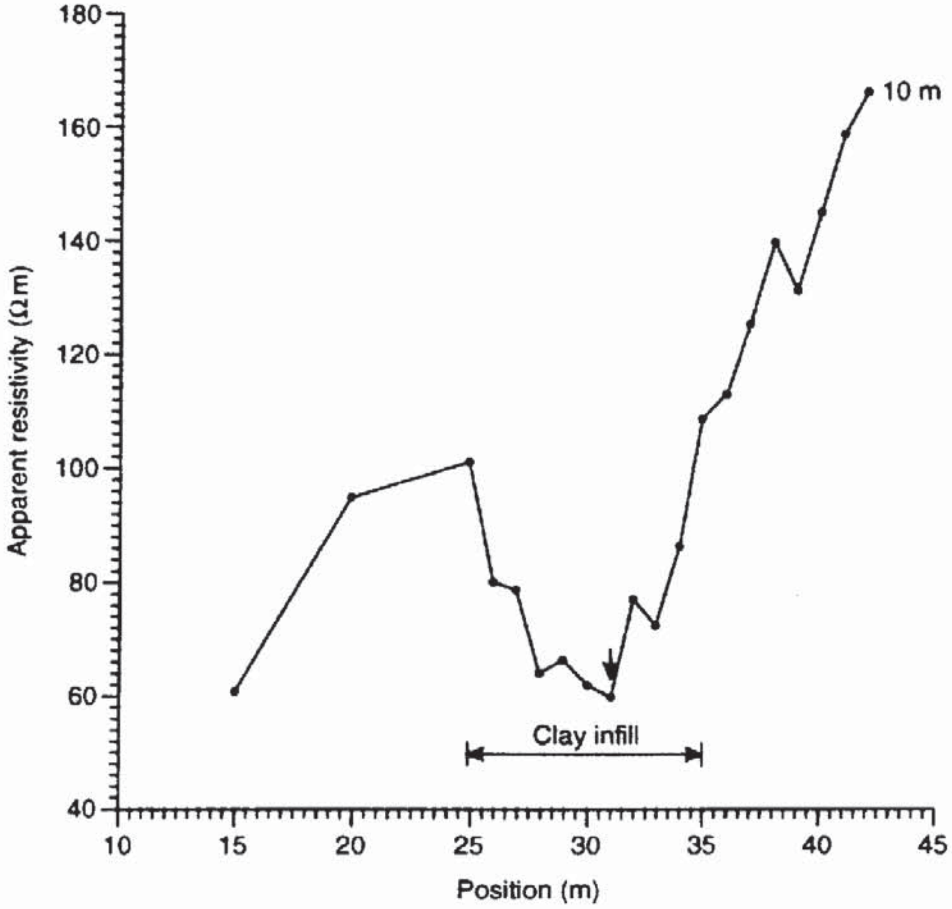


Figure 7.20 A constant-separation traverse using a Wenner array with 10 m electrode spacing over a clay-filled solution feature (position arrowed) in limestone

electrode separation of 10 m and station interval of 5 m. The values of apparent resistivity are plotted on a linear graph as a function of distances along the profile (Figure 7.20). Variations in the magnitude of apparent resistivity highlight anomalous areas along the traverse.

Sörensen (1994) has described a 'pulled array continuous electrical profiling' technique (PA–CEP). An array of heavy steel electrodes, each weighing 10–20 kg, is towed behind a vehicle containing all the measuring equipment. Measurements are made continuously. It is reported that 10–15 line kilometres of profiling can be achieved in a day. The quality of results is reported to be comparable to that of fixed arrays with the same electrode geometry.

7.4.4 Field problems

In order for the electrical resistivity method to work using a collinear array, the internal resistance of the potential measuring circuit must be far higher than the ground resistance between the potential electrodes. If it is not, the potential circuit provides a low-resistance alternative route for current flow and the resistance measured is completely meaningless. Most commercial resistivity equipment has an input resistance of at least 1 MΩ, which is adequate in most cases.

In the case of temperature glacier ice, which itself has a resistivity of up to 120 MΩ m, a substantially higher input resistance is required (preferably of the order of $10^{14}\,\Omega$).

Electrical resistivity soundings on glaciers are complicated by the fact that ice does not conduct electricity electronically but by the movement of protons within the ice lattice and this causes substantial polarisation problems at the electrode–ice contact. Consequently, special techniques are required in order to obtain the relevant resistivity data (Reynolds 1982).

Perhaps the largest source of field problems is the electrode contact resistance. Resistivity methods rely on being able to apply current into the ground. If the resistance of the current electrodes becomes anomalously high, the applied current may fall to zero and the measurement will fail. High contact resistances are particularly common when the surface material into which the electrodes are implanted consists of dry sand, boulders, gravel, frozen ground, ice or laterite. If the high resistance can be overcome (and it is not always possible), there are two methods that are commonly used. One is to wet the current electrodes with water or saline solution, sometimes mixed with bentonite. The second method is to use multiple electrodes. Two or three extra electrodes can be connected to one end of the current-carrying cable so that the electrodes act as resistances in parallel. The total resistance of the multiple electrode is thus less than the resistance of any one electrode (see Figure 7.21 and Box 7.12). However, if this method is used, the extra electrodes must be implanted at right-angles to the line of the array rather than along the direction of the profile. If the extra electrodes are in the line of the array, the geometric factor may be altered as the inter-electrode separation (C_1–P_1–P_2–C_2) is effectively changed. By planting the electrodes at right-angles to the line of the array, the inter-electrode separation is barely affected. This problem is only acute when the current electrode separation is small. Once the current electrodes are sufficiently far apart, minor anomalies in positioning are insignificant. This also applies when laying out the survey line to start with.

Box 7.12 Resistances in parallel

Total resistance of multiple electrodes is R_T:

$$1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \cdots 1/R_n = \sum_{i=1}^{n} (1/R_i).$$

For example, if $r_1 = r_2 = 0.2R$ and $r_3 = r_4 = 0.5R$, then:

$$1/R_T = 1/0.2R + 1/0.2R + 1/0.5R + 1/0.5R + 1/R = 15/R.$$

Thus $R_T = R/15$, and R_T is much less than the lowest individual resistance ($= R/5$).

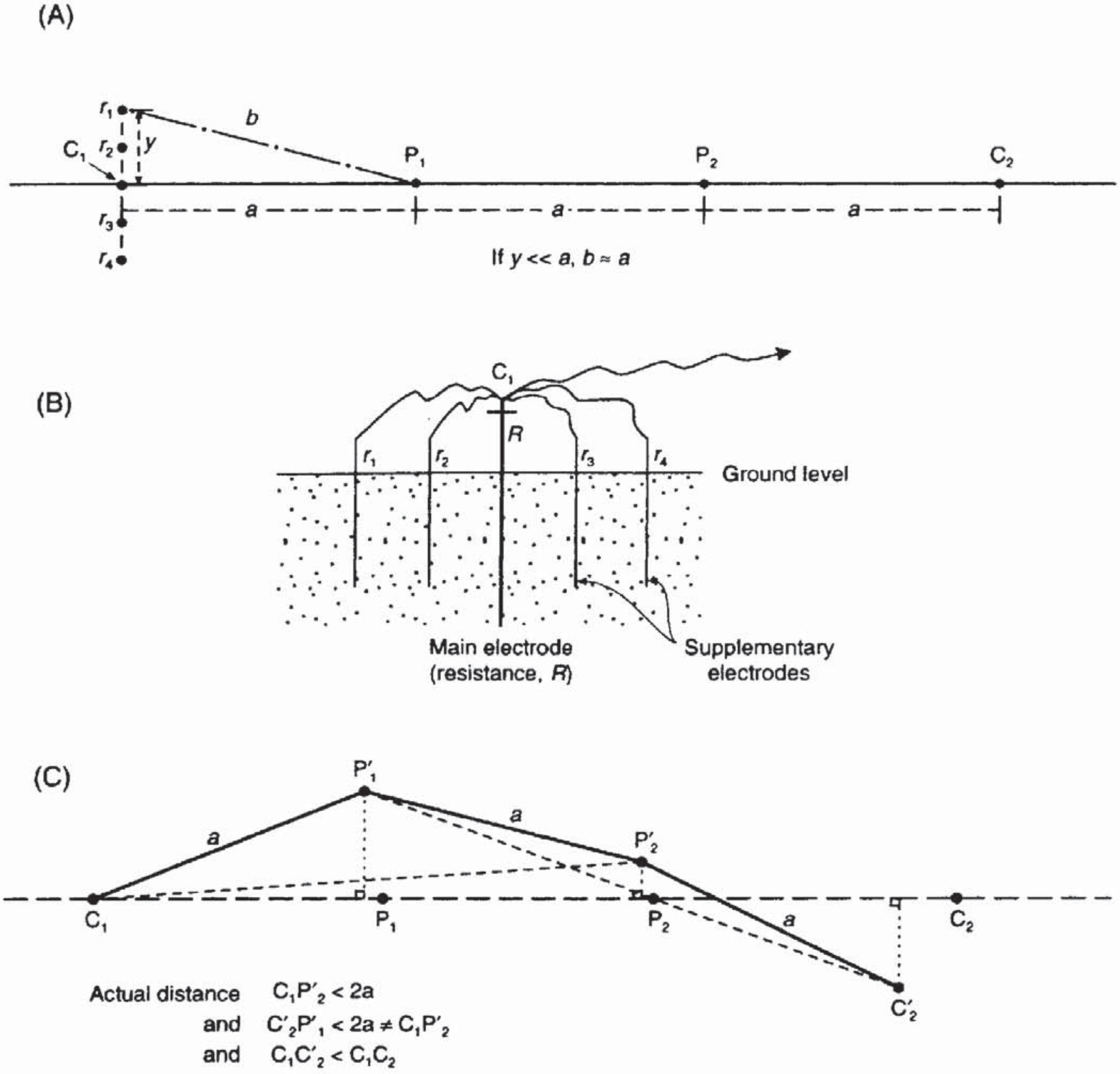


Figure 7.21 (A) Supplementary electrodes planted in a straight line at right-angles to the main electrode have minimal effect on the geometric factor as long as the offset $y \uparrow a$. (B) Any number of additional electrodes act as parallel resistances and reduce the electrode contact resistance. (C) An out-of-line electrode array will give rise to erroneous ρ_a values unless the appropriate geometric factor is used. Shortened C_1C_2 produces elevated ΔV between P_1 and P_2 and needs to be compensated for by a reduced value of the geometric factor.

Ideally, a VES array should be expanded along a straight line. If it curves significantly and/or erratically (Figure 7.21C), and no correction is made, cusps may occur in the data owing to inaccurate geometric factors being used to calculate apparent resistivity values. Cusps in VES field curves are particularly difficult to resolve if their cause is unknown. Even if the apparent resistivity values have been calculated correctly with appropriately modified geometric factors, ambiguities may arise in the field curve which it may not be possible to model or interpret. In the case of CST data, if the correct geometric factors are used to derive the apparent resistivities, the CST profile may be interpreted normally. It always pays to keep adequate field notes in addition to recording the geophysical data so that appropriate corrections can be made with recourse to the correct information rather than to a rather hazy recollection of what may have been done in the field.

The presence of pipes, sand lenses or other localised features, which are insignificant in relation to the main geological target, can degrade the quality of the field data and thus reduce the effectiveness of any interpretation. If a conductive clay lens is present, for example, then when a current is applied from some distance away from it, the lines of equipotential are distorted around the lens and the current flow lines

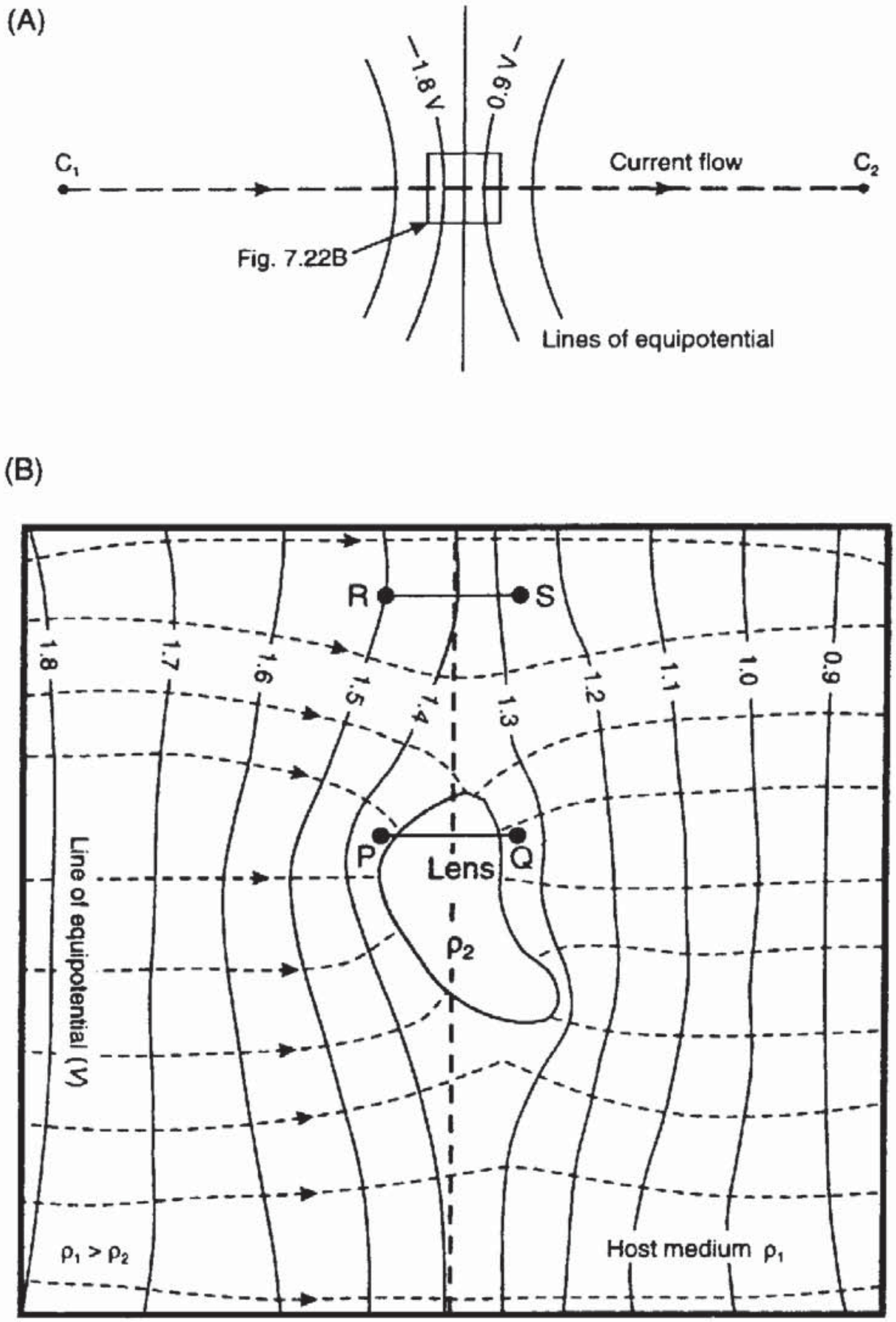


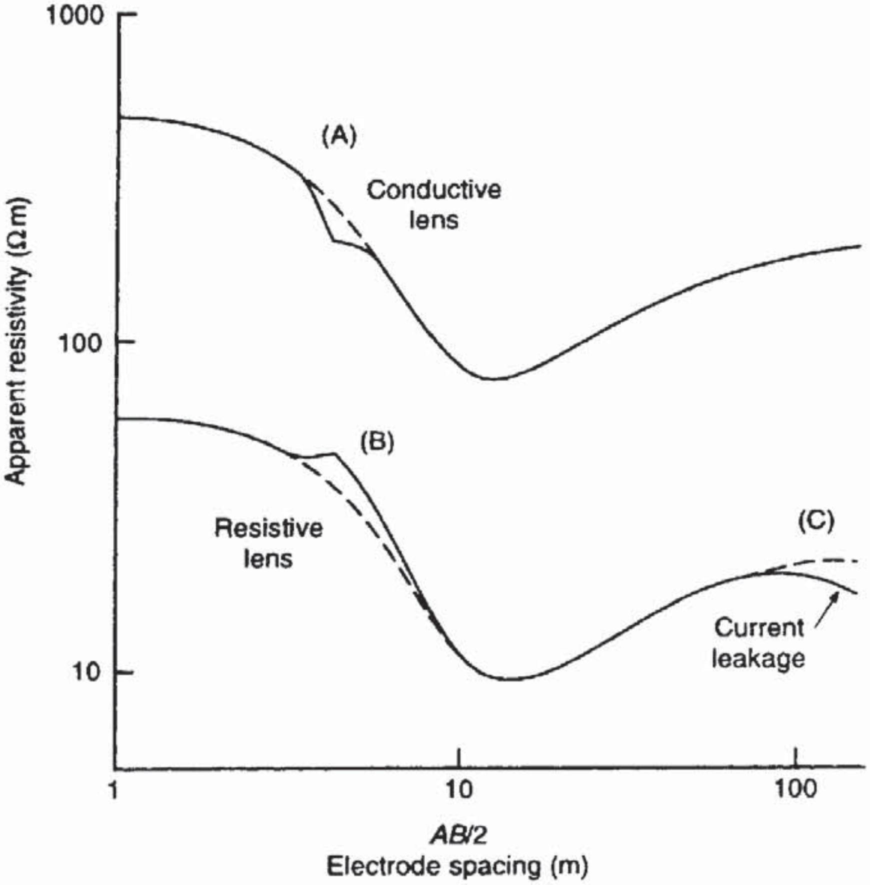
Figure 7.22 Distortion of current flow lines and equipotentials around an anomalous feature. The boxed area in (A) is enlarged to show detail in (B). The magnitude of equipotentials is for illustrative purposes only

are focused towards the lens (Figure 7.22). The potential between P and Q (< 0.1 V) is obviously smaller than that measured between R and S (≈ 0.25 V) which are outside the field of effect of the lens. The apparent resistivity derived using this value of potential is lower than that obtained had the lens not been there, hence the occurrence of a cusp minimum (Figure 7.23A). If the lens has a higher resistivity than the host medium, the current flow lines diverge and the potential between P and Q becomes anomalously high and results in a positive cusp (Figure 7.23B).

Another feature which may occur on VES profiles is current leakage, particularly at large current electrode separations, when the array is aligned parallel to a conductive feature such as a metal pipe or a surface stream. The values of apparent resistivity become increasingly erratic owing to the voltage between the potential electrodes falling to within noise levels and tend to decrease in value (Figure 7.23C). If the position and orientation of a pipe is known, there should be no ambiguity in interpretation. There is no point in extending the VES once it is obvious current leakage is occurring.

A method of reducing the effects of these lateral inhomogeneities using the offset Wenner array has been described in Section 7.3.2. There is, however, no alternative method for the Schlumberger electrode configuration and cusps can be removed by smoothing the curve (dashed lines in Figure 7.23).

Figure 7.23 Distortion of Schlumberger VES curves due to (A) a conductive lens or pipeline, and (B) a resistive lens. After Zohdy (1974), by permission



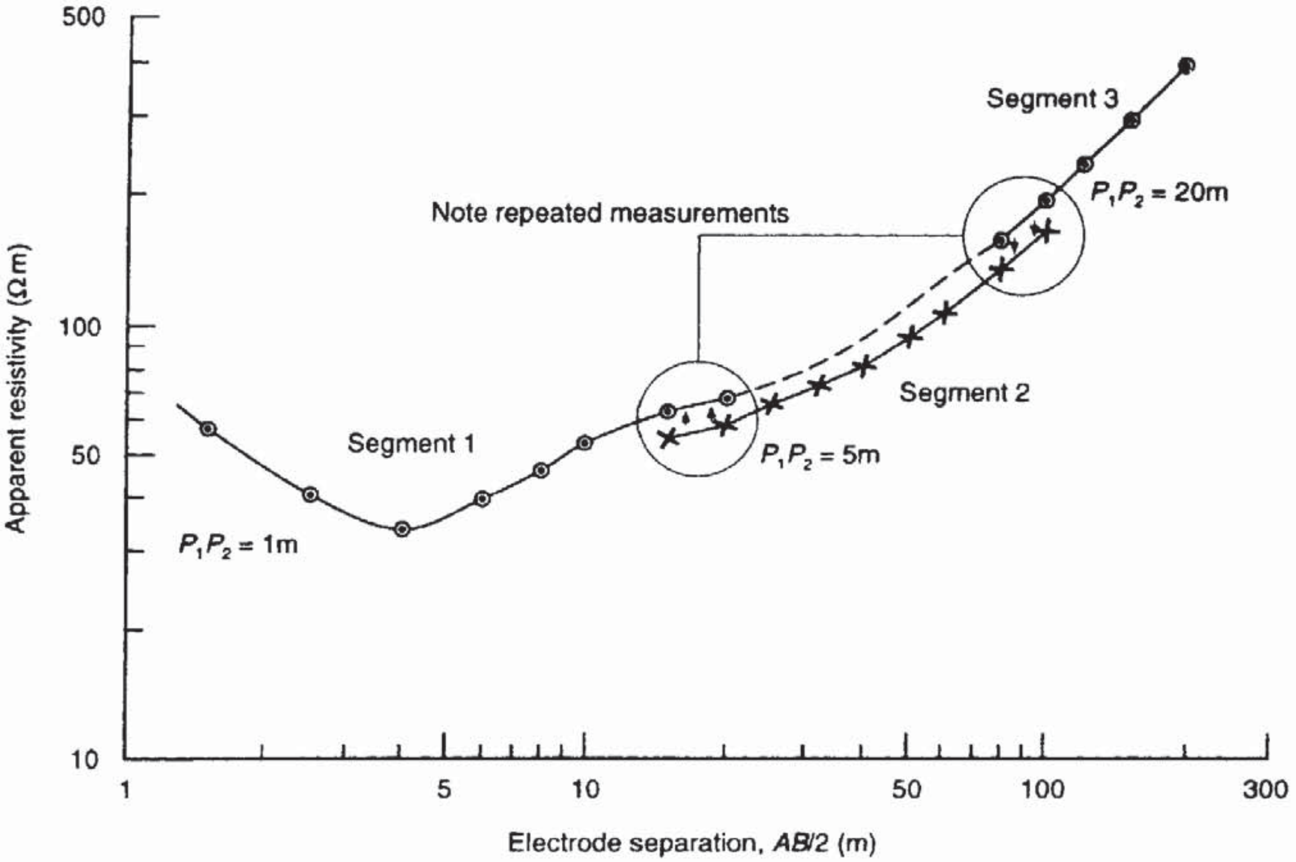


Figure 7.24 Displaced segments on a Schlumberger vertical electrical sounding curve due to different electrode resistances at P_1 and P_2 on expanding potential electrode separations; segment 3 is displaced to fit segment 2 which is in turn displaced to fit segment 1 to produce a smoothed curve

An additional but easily resolvable problem can occur with Schlumberger depth soundings. When the separation of the potential electrode pair is increased (b_1 to b_2 in Figure 7.17C), the contact resistance may change, causing a discrete step up or down of the next segment of the curve (Figure 7.24). Although the value of the apparent resistivity may change from the use of one electrode pair to another, the gradient of the change of apparent resistivity as a function of current electrode half-separation should remain the same. Consequently, the displaced segments can be restored to their correct values and the curve smoothed ready for interpretation. Segments at larger potential electrode separations should be moved to fit the previous segment obtained with a shorter electrode separation. So in Figure 7.24, segment 3 is moved down to fit segment 2 which is moved up to join on the end of segment 1. Measurements of resistance should be repeated at both potential electrode separation when crossing from one segment to the next. As all the electrodes are moved when a manual Wenner array is expanded, there is no discernible displacement of segments of the curve. Instead, the field curve may appear to have lots of cusps and blips through which a smooth curve is then drawn, usually by eye (Figure 7.25). An alternative, preferable, approach is to use the offset Wenner array (see Section 7.3.2) which improves the quality of the acquired field data (Figure 7.25).

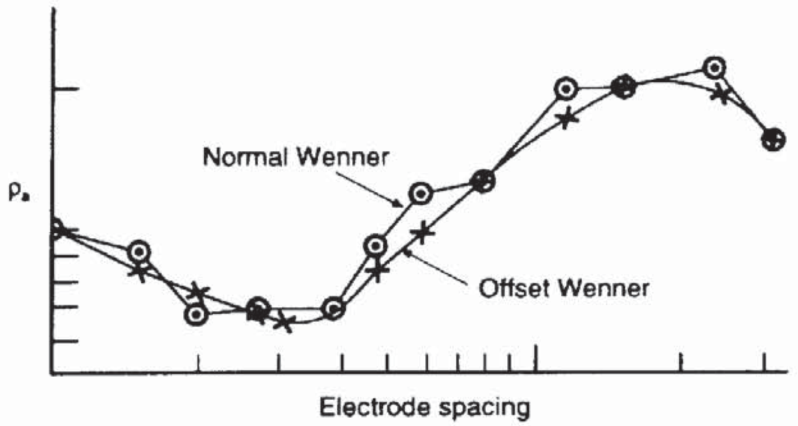


Figure 7.25 The difference in data quality that can be obtained by using an offset Wenner array in place of a normal Wenner array; the normal curve is more noisy

7.5 INTERPRETATION METHODS

Vertical sounding field curves can be interpreted qualitatively using simple curve shapes, semi-quantitatively with graphical model curves, or quantitatively with computer modelling. The last method is the most rigorous but there is a danger with computer methods to over-interpret the data. VES field curves may have subtle inflections and cusps which require the interpreter to make decisions as to how real or how significant such features are. Often a noisy field curve is smoothed to produce a graph which can then be modelled more easily. In such a case, there is little point in spending large amounts of time trying to obtain a perfect fit between computer-generated and field curves. As a general rule, depending on how sophisticated the field acquisition method is, layer thicknesses and resistivities are accurate to between 1% and 10%, with poorer accuracies arising from the cruder field techniques. Furthermore, near-surface layers tend to be modelled more accurately than those at depth, primarily because field data from shorter electrode separations tend to be more reliable than those for very large separation, owing to higher signal-to-noise ratios.

7.5.1 Qualitative approach

The first stage if any interpretation of apparent resistivity sounding curves is to note the curve shape. This can be classified simply for three electrical layers into one of four basic curve shapes (Figures 7.26A–D). These can also be combined to describe more complex field curves that may have several more layers. Note that the curve shape is dependent upon the relative thicknesses of the in-between layers (layer 2 in a 3-layer model; Figures 7.26C, D). The maximum angle of slope that the rising portion of a resistivity graph may have on a log–log graph, is 45°, given the same scales on both axes (Figure 7.26A). If the field curve rises more steeply, then this suggests error in the data or that geometric effects due to steeply inclined horizons are distorting the data.