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

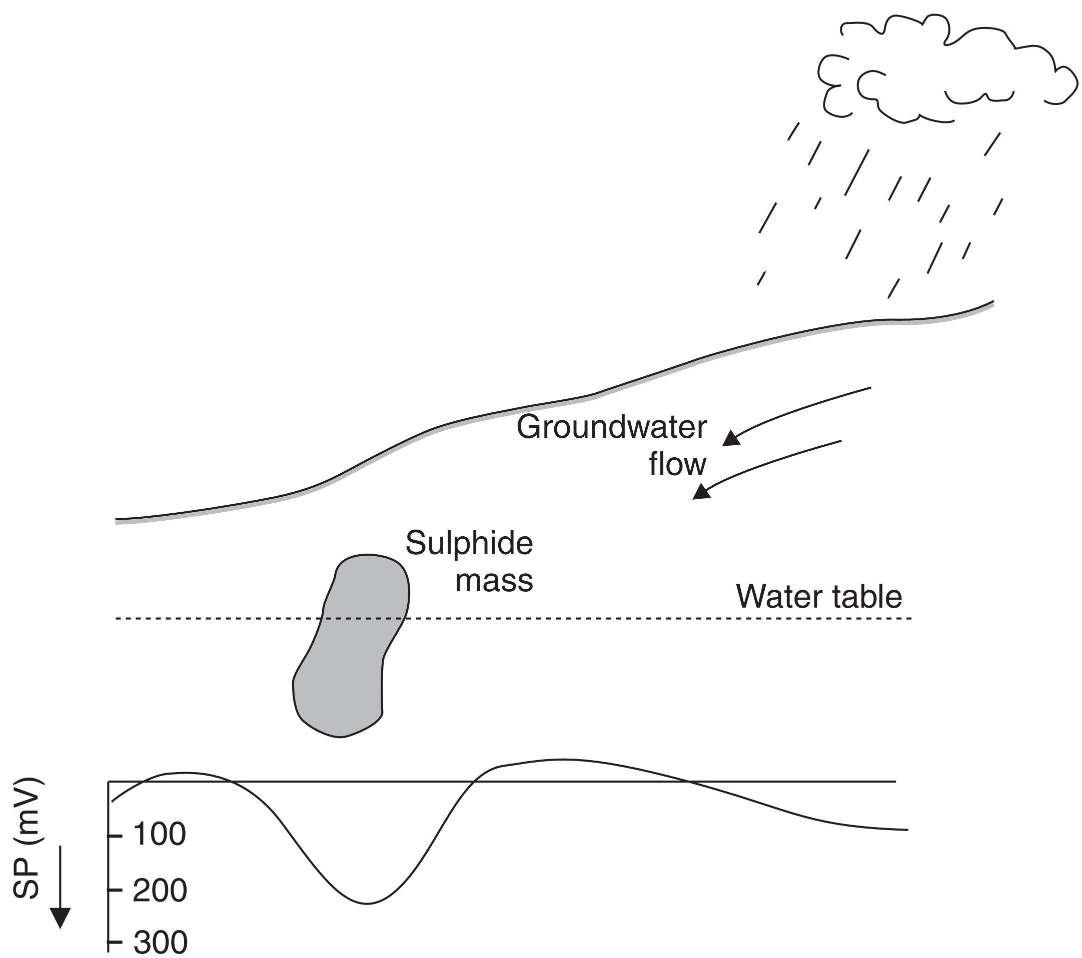

Figure 7.1 *Sources of SP effects. The sulphide mass straddling the water table concentrates the flow of oxidation–reduction currents, producing a negative anomaly at the surface. The downslope flow of groundwater after rain produces a temporary SP, in this case inversely correlated with topography.*

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

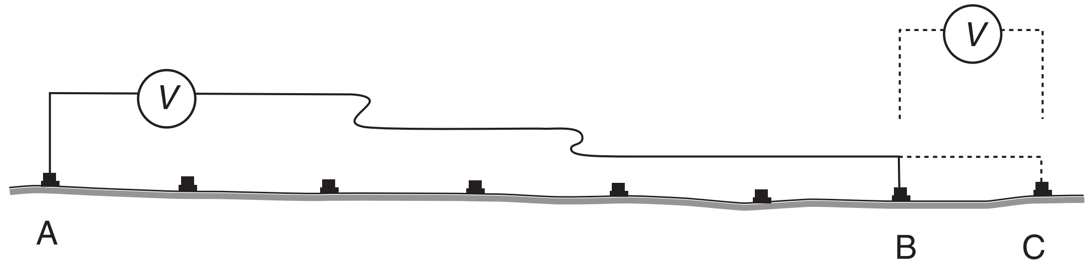

Figure 7.2 *Moving base in an SP survey. The value at the new base (B) relative to A is measured directly and also indirectly by measurements of the voltage at the field point C relative to both bases. The two estimates of the voltage difference between A and B are then averaged.*

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

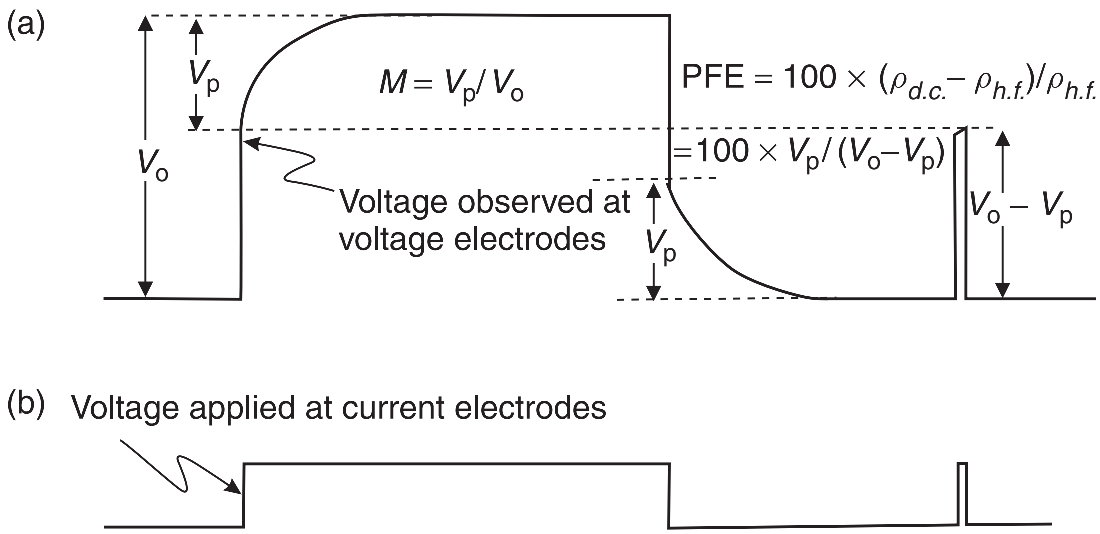

Figure 7.3 *Ground response to a square-wave signal and to a spike impulse. The ratio of* V_o *to* V_p *is seldom more than a few percent. Input voltage waveform is for reference only. In practice its amplitude will be many times greater than the measured voltage, the exact values depending on the array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

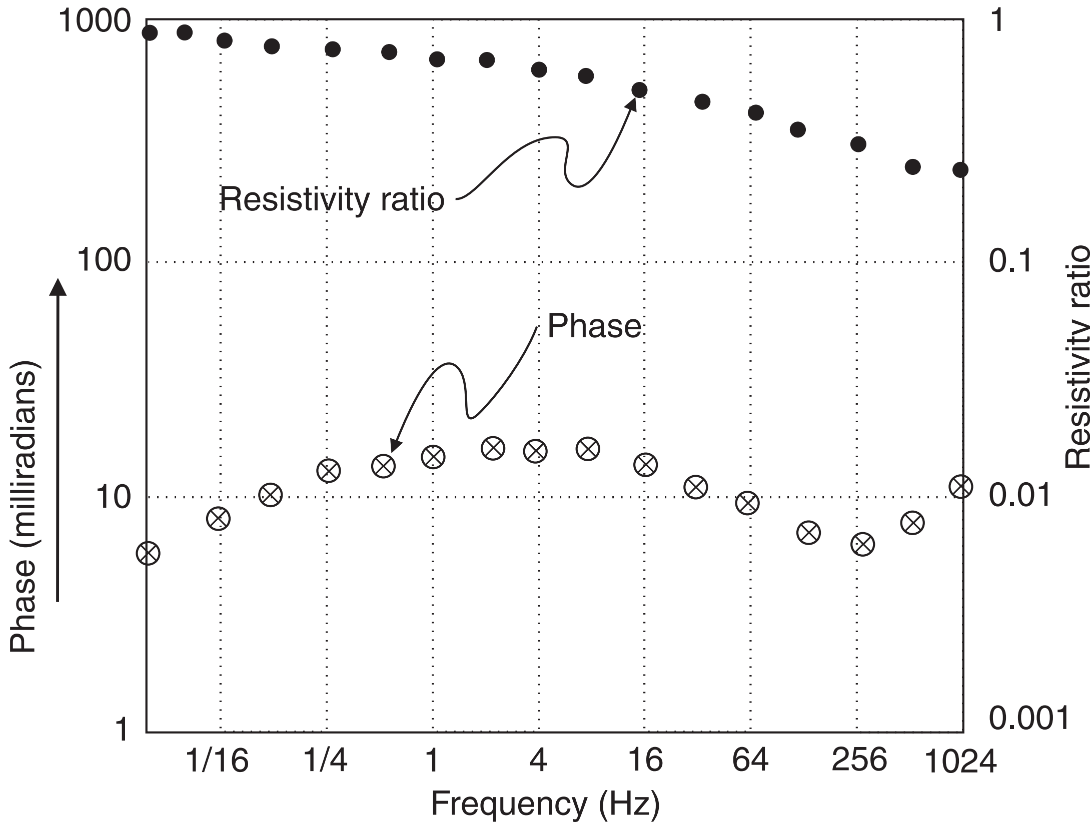

Figure 7.4 *Typical plot of IP phase and amplitude against frequency.*

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

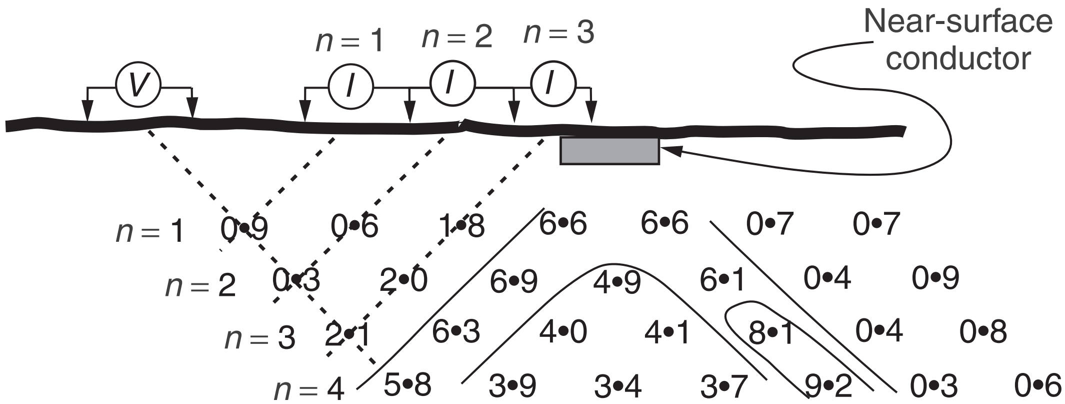

Figure 7.5 *Pseudo-section construction. The three different positions of the current dipole correspond to three different multiples of the basic spacing. Measured values (of IP or resistivity) are plotted at the intersections of lines sloping at 45° from the dipole centres. The plotting 'point' often 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.