Chapter 8
Spontaneous (self) potential methods

8.1 INTRODUCTION

The *self-potential* or *spontaneous polarisation* (SP) method was devised in 1830 by Robert Fox who used copper-plate electrodes connected to a galvanometer to detect underground copper sulphide deposits in Cornwall, England. The method has been used since 1920 as a secondary tool in base metal exploration, characteristically to detect the presence of *massive* ore bodies, in contrast to the induced polarization method (see Chapter 9) which is used predominantly to investigate *disseminated* ore bodies. In recent years, the SP method has been extended to groundwater and geothermal investigations, and can also be used as an aid to geological mapping, for example, to delineate shear zones and near-surface faults.

The SP method ranks as the cheapest of the surface geophysical methods in terms of equipment necessary and amongst the simplest to operate in the field. Although the phenomenon of self-potentials is utilised more extensively in borehole well logging than in surface applications, the down-hole techniques will not be discussed further here.

8.2   OCCURRENCE OF SELF-POTENTIALS

The SP method is passive, i.e. differences in natural ground potentials are measured between any two points on the ground surface. The potentials measured can range from less than a millivolt (mV) to over one volt, and the sign (positive or negative) of the potential is an important diagnostic factor in the interpretation of SP anomalies, as described later.

Self-potentials are generated by a number of natural sources (next section), although the exact physical processes by which some are caused are still unclear. A summary of the common types of SP anomaly are listed in Table 8.1 with their respective geological sources. In addition to compositional variations, the geometry of geological structures can also create SP anomalies, and so the sources listed should only be used as a guide.

Table 8.1   Types of SP anomalies and their geological sources

Source	Type of anomaly
Mineral potentials	
Sulphide ore bodies (pyrite, chalcopyrite, pyrrhotite, sphalerite, galena) Graphite ore bodies Magnetite + other electronically conducting minerals Coal Manganese	Negative ≈ hundreds of mV
Quartz veins Pegmatites	Positive ≈ tens of mV
Background potentials	
Fluid streaming, geochemical reactions, etc.	Positive +/− negative ⩽ 100 mV
Bioelectric (plants, trees)	Negative, ⩽ 300 mV or so
Groundwater movement	Positive or negative, up to hundreds of mV
Topography	Negative, up to 2 V

Natural ground potentials consist of two components, one of which is constant and unidirectional and the other fluctuates with time. The constant component is due primarily to electrochemical processes, and the variable component is caused by a variety of different processes ranging from alternating currents induced by thunderstorms and by variations in the Earth's magnetic field, to the effects of heavy rainfall. In mineral exploration, components of the SP are called the *mineral potential* and the *background potential*, respectively. This terminology belies the usefulness of the so-called 'background' potentials as these can be used in geothermal and hydrogeological investigations as the main measured anomaly. The processes by which some of these potentials are generated are discussed briefly in the next section.

8.3 ORIGIN OF SELF-POTENTIALS

The common factor among the various processes thought to be responsible for self-potentials is groundwater. The potentials are generated by the flow of water, by water acting as an electrolyte and as a solvent of different minerals, and so on. The types of potentials are listed in Table 8.2 (with their alternative names where appropriate) and their mathematical definitions are given in Box 8.1. There are three ways of conducting electricity through rocks: by dielectric, electrolytic and electronic (ohmic) conduction. The electrical conductivity (σ, the inverse of resistivity) of porous rocks therefore depends on their porosity (and the arrangement of the pores) and on the mobility of water (or other fluids) to pass through the pore spaces (hence dependent upon ionic mobilities and solution concentrations, viscosity (η), temperature and pressure).

Table 8.2 Types of electrical potentials

Electrokinetic (electrofiltration) (electromechnical) (streaming)		Variable with time
Diffusion potential Liquid-junction	Electrochemical potentials	
Nernst potential (Shale)		
Mineral potential		Constant

8.3.1   Electrokinetic potentials

An electrokinetic potential (E_k) forms as a result of an electrolyte flowing through a capillary or a porous medium, the potential being measured across the ends of the capillary (see Ahmad 1961). The potentials arising from this process are alternatively referred to as *electrofiltration, electromechanical* or *streaming* potentials.

Box 8.1   Electrical potentials

Electrokinetic:

$$E_k = \frac{\varepsilon\mu C_E \delta P}{4\pi\eta}$$

where: ε, μ and η are the dielectric constant, resistivity and dynamic viscosity of the electrolyte respectively; δP is the pressure difference; and C_E is the electrofiltration coupling coefficient.

Diffusion potential:

$$E_d = -\frac{RT(I_a - I_c)}{nF(I_a + I_c)}\ln(C_1/C_2)$$

where: I_a and I_c are the mobilities of the anions ($+$ve) and cations ($-$ve) respectively; R is the Universal Gas Constant ($8.314\,\mathrm{J\,K^{-1}\,mol^{-1}}$); T is absolute temperatue (K); n is ionic valence; F is Faraday's Consant ($96\,487\,\mathrm{C\,mol^{-1}}$); C_1 and C_2 are the solution concentrations.

Nernst potential:

$$E_N = -\frac{RT}{nF}\ln(C_1/C_2)$$

when $I_a = I_c$ in the diffusion potential equation.

According to Helmholtz's law, the flow of electric current is related to the hydraulic gradient and a quantity known as the electrofiltration coupling (or streaming potential) coefficient (C_E), which takes into account the physical and electrical properties of the electrolyte and of the network through the medium through which the electrolyte has passed. It is also important that the water flows parallel to either a geological boundary (Fitterman 1978, 1979a) or to its free surface (i.e. the water table).

Graphs of electrokinetic potentials obtained for different geological situations with characteristic values of C_E for each geological unit are given in Figure 8.1A (Schiavone and Quarto 1984). The potentials

Figure 8.1 (*opposite*) (A) Idealised electrofilteration SP profiles and maps for the following models (from Schiavone and Quarto 1984): (i) a vertical boundary with upwelling on the right; (ii) pumping from a well (injection into the well would produce the opposite sense of anomaly); (iii) horizontal boundary flow. Interfaces are marked by a contrast in streaming potential coefficients (C_1 and C_2). (B) Example of the SP anomaly produced by pumping from a well (after Semonov 1980)

(A)

(i)

(ii)

(iii)

⟶ Direction of water flow

C_1, C_2 Streaming-potential coefficients

(B)

Water level before pumping

Monitoring borehole

Water table during pumping

Exploitation borehole

tend to increase in positiveness with the direction of water flow as the electric charge flows in the opposite direction. Consequently, negative charge flows uphill and can result in spectacular SP anomalies on topographic highs. Gay (1967) reported a potential of $-1842\,mV$ measured on a mountain top near Hualgayoc, Peru (mineralisation: *alunite); Nayak (1981) measured a value of $-1940\,mV$ on a hill of unmineralised quartzites in Shillong, India; Corwin and Hoover (1979) reported a value of $-2693\,mV$ on the peak of Adagdak Volcano, Adak Island, Alaska. This topographic effect requires a correction to be applied (see Section 8.5) particularly where slope angles exceed $20°$.
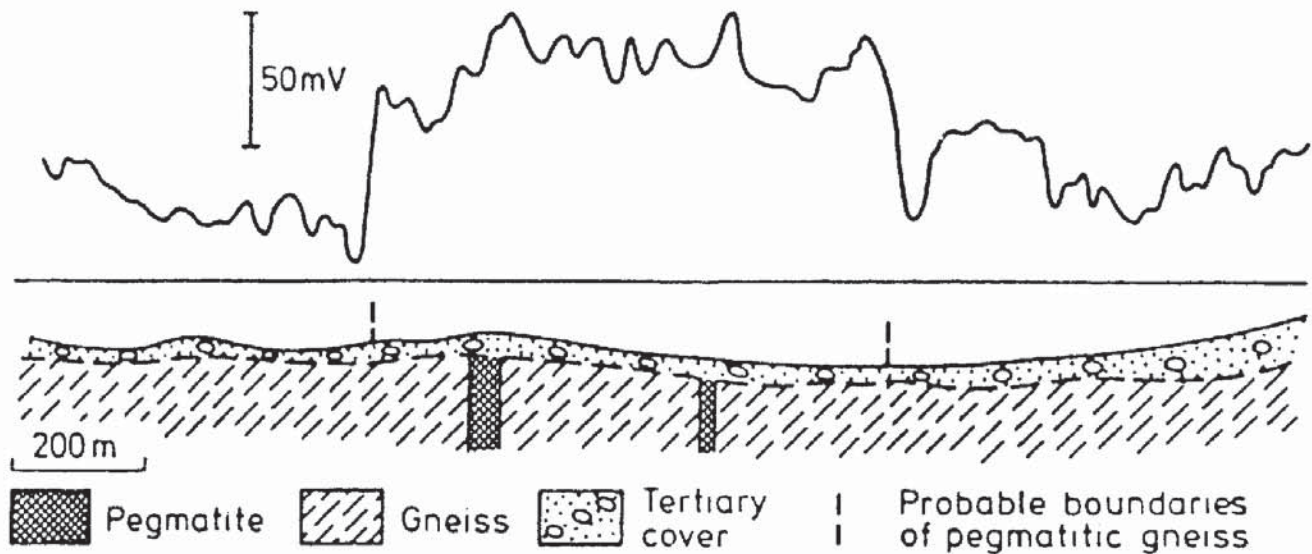
Superimposed on the topographic flow generation of self-potentials can be potentials of the order of $5\,mV$ which are caused by the brief but rapid percolation of water such as from heavy rainfall (Fournier 1989). Variation in soil moisture content may also produce locally variable SP signals (Corwin and Hoover 1979) with the electrode in the wetter soil often becoming increasingly positive (Poldini 1939). The small but measurable SP anomaly lasts only as long as the water flow. Potentials of the order of tens of millivolts can be induced artificially through pumping groundwater (Semenov 1980). The hydraulic gradient is increased by water abstraction, thereby increasing the rate of water flow towards the borehole; hence a positive anomaly is observed (Figure 8.1B).

A further factor that needs to be taken into account is *thermoelectric coupling*, which is the production of a potential difference across a rock sample throughout which a temperature gradient is maintained. The effect may be caused by differential thermal diffusion of ions in the pore fluid and of electrons and donor ions in the rock matrix (Corwin and Hoover 1979), a process called the *Soret Effect* (Heikes and Ure 1961).

8.3.2   Electrochemical potentials

Transient background *diffusion (or liquid-junction) potentials* (E_d) up to tens of millivolts may be due to the differences in the mobilities of electrolytes having different concentrations within groundwater. For this mechanism to explain the continued occurrence of background potentials, a source capable of maintaining imbalances in the electrolytic concentrations is needed, otherwise the concentrations differences will disappear with time by diffusion.

The *Nernst (shale) potential* (E_N) occurs when there is a potential difference between two electrodes immersed in a homogeneous solution and at which the concentrations of the solutions are locally different. It can be seen from Box 8.1 that the form of the equation for the Nernst potential is a special case of that for the diffusion potential and can easily be combined to form the *electrochemical potential*. For a solution of sodium chloride (NaCl) at $25°C$ with a ratio of concen-

Figure 8.2 An SP profile across pegmatite dykes in gneiss. From Semenov (1980), by permission

trations of 5:1, the electrochemical potential is about $\pm 50\,mV$. The Nernst potential is of particular importance in well logging, in which case it is referred to as the *shale potential*. It can also be seen from Box 8.1 that the electrochemical potential is directly dependent upon the concentration differences (C_1/C_2) and temperature. The higher the temperature and the greater the concentration differences, the larger the electrochemical potential will be. For this reason, the measurement of self-potentials is important in the exploration for geothermal resources (e.g. Corwin and Hoover 1979) where the temperatures are obviously elevated and the concentrations of salts within the groundwater are also likely to be high (see also Section 8.6.3).

Further electrochemical potentials are attributable to adsorption of anions on to the surface of veins of quartz and pegmatite and are known as *adsorption (or zeta) potentials*. For example, an anomaly of up to $+100\,mV$ has been measured over vertical pegmatitic dykes within gneiss (Figure 8.2) (Semanov 1980; cited by Parasnis 1986). In addition, adsorption potentials may account for the observed anomalies over clays where the solid–liquid double layer may generate a potential.

8.3.3 Mineral potentials

Of most importance in the use of SP in mineral exploration is the *mineral potential* such as that associated with massive sulphide ore bodies. Large negative anomalies can be observed particularly over pyrite and chalcopyrite and other good electronic conductors. (Mineral potentials have also been observed over sphalerite, somewhat surprisingly, as it is a poor conductor.)
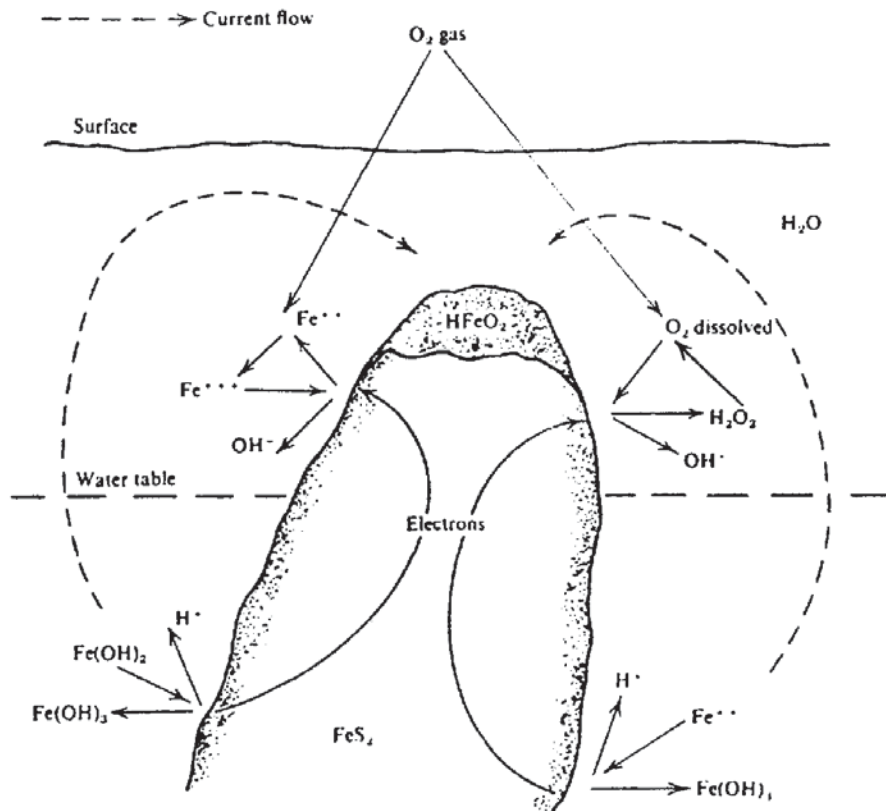
Figure 8.3 Physicochemical model proposed by Sato and Mooney (1960) to account for the self-potential process in a massive sulphide orebody. Reproduced by permission

Sato and Mooney (1960) have provided the most complete explanation of the electrochemical processes (Figure 8.3) which cause the observed self-potential anomalies, although no hypothesis is yet able to account for all the observed mineral potentials. Where a sulphide orebody straddles the water table, a cathodic electrochemical half-cell forms by the chemical reduction of the ions in the surrounding electrolyte, i.e. they gain electrons. In contrast, below the water table, an anodic electrochemical cell operates in which oxidation is dominant and ions lose electrons. The role of the massive orebody is to permit the flow of electrons from the lower half of the orebody to the upper half. The net result of this process is that the upper surface becomes negatively charged (hence the negative SP anomalies) and the lower half becomes positively charged. However, the fact that this hypothesis does not explain all the occurrences of self-potentials indicates that the actual physical processes are more complicated and not yet fully understood (Kilty 1984). This is even truer when more than one orebody is involved resulting in complex SP anomaly shapes (e.g. Becker and Telford 1965).

Where clay overlies a massive sulphide orebody, the mineral potential may be suppressed to the extent that no anomaly is observed (Telford *et al.* 1990). This may be a result of the adsorption potential (which tends to be positive) having the same amplitude as the mineral potential (negative polarity) and thus cancelling each other out.
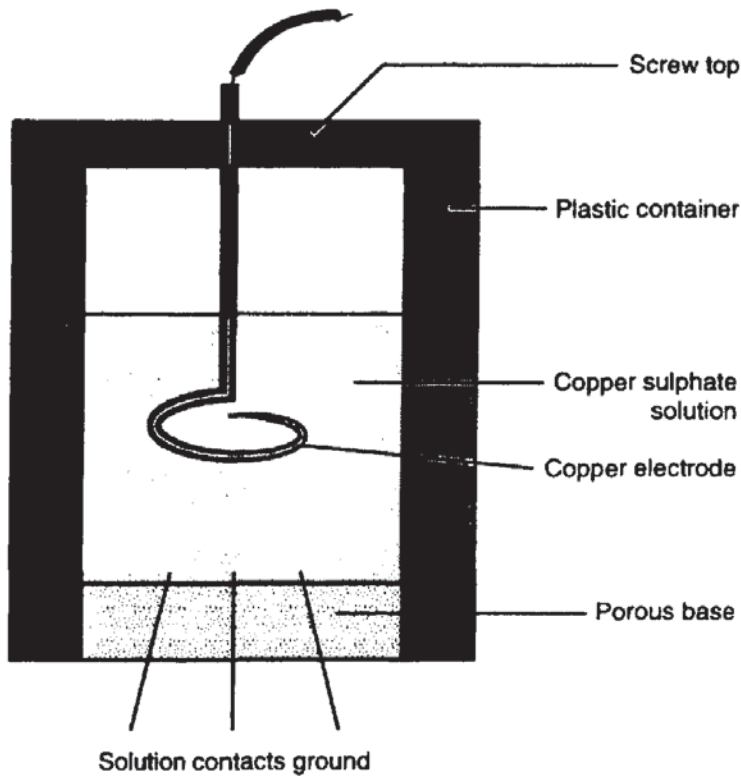
Figure 8.4 Cross-section through a porous pot electrode

- Screw top
- Plastic container
- Copper sulphate solution
- Copper electrode
- Porous base

Solution contacts ground

8.4 MEASUREMENT OF SELF-POTENTIALS

The measurement of self-potentials is very simple. Two non-polarisable porous-pot electrodes are connected to a precision multimeter with an input impedance greater than 10^8 ohms and capable of measuring to at least 1 mV. Each electrode is made up of a copper electrode dipped in a saturated solution of copper sulphate which can percolate through the porous base to the pot (Figure 8.4) in order to make electrical contact with the ground. Alternatively, a zinc electrode in saturated zinc sulphate solution or silver in silver chloride can be used.

There are two field techniques, both of which are carried out at right-angles to the suspected strike of the geological target. The *potential gradient method* uses two electrodes, at a fixed separation, typically 5 m or 10 m, between which the potential difference measured is divided by the electrode separation to give a potential gradient (mV/m). The point to which this observation applies is the midpoint between the two electrodes. The two porous pots are leap-frogged along the traverse but care has to be taken to ensure that the correct polarity of the potential is recorded. The procedure in the *potential amplitude method* is to keep one electrode fixed at a base station on unmineralised ground and to measure the potential difference (in mV) between it and the second one which is moved along the traverse. This

removes the problems of confusing polarity and accumulating errors. Care should be taken to ensure that the temperature of the electrolyte in the mobile pot does not differ significantly from that in the reference electrode, or else a potential difference will be produced. The temperature coefficient for copper–copper sulphate is about 0.5 mV/°C (about 0.25 mV/°C for silver–silver chloride electrodes).

As mentioned above, the self-potential consists of a static and a variable alternating component. The latter, which can have frequencies typically in the range of 5–10 Hz, is caused by atmospheric effects and its long period component may have amplitudes that are of the same order as the static mineral potential. Where this signal is present, the mineral potential can be resolved by taking measurements along the same profile at different times of the day and averaging the results. Electrical noise can also result if measurements are made too soon after heavy rain or too close to running surface water, as streaming potentials may then swamp any mineral potentials.

The maximum depth of sensitivity of the SP method is around 60–100 m, depending on the depth to the orebody and the nature of the overburden.

Self-potential measurements can also be made over water to measure streaming potentials. The porous pot electrodes are enclosed in special containers so that they can be towed through water without causing serious loss of electrolyte from the pots. This method will only work where there is little current flow (lateral of vertical) within the water column (Ogilvy *et al.* 1969); the amplitude of any SP anomaly obtained within a saline water body (resistivity 0.3–1 Ω m) tends to be very small.

8.5   CORRECTIONS TO SP DATA

Self-potentials measured over a large area (of the order of many square kilometres) may have a regional trend due to 'telluric' currents (see Section 11.5) of $\geqslant 100$ mV/km. The mineral potential may be superimposed upon this regional gradient. Thus, to interpret the anomaly due to mineralisation, its anomaly has to be isolated in much the same way as gravity residuals are obtained (see Section 2.6.1). Regional corrections must be applied before any adjustment for topography is made. However, for a local survey whose length is small in comparison with the regional wavelength, removing regional trends is usually unnecessary.

The association of negative anomalies with topographic highs has already been mentioned (Section 8.3.1). Telluric currents are also affected by changes in elevation. The combined effects are extremely hard to quantify explicitly but can be corrected for in a general manner as prescribed by Yüngül (1950) and discussed further by

Bhattacharya and Roy (1981) and Bhattacharya (1986). If the surface slope of a survey area is large ($> 20°$), the SP minimum may be well displaced from its cause and subsequent drilling may miss the orebody completely. In any attempts to correct data for either regional or topographic effects, the SP anomaly for an individual polarised body should be isolated. If the observed anomaly is due to the superposition of a number of anomalies from different geological sources (and hence with different shapes and polarities), corrections cannot be carried out and the locations of the tops of the orebodies must be taken as very approximate and alternative geophysical methods used to try to delimit the geological structure more explicitly.

It may also be necessary to make allowance for the effects of bioelectric potentials caused by vegetation. Passing from bare ground into an area of vegetation can cause a negative potential of several hundred millivolts, comparable to a mineral potential due to a sulphide orebody. Basic field observations should clarify the situation.

8.6 INTERPRETATION OF SELF-POTENTIAL ANOMALIES

SP anomalies are often interpreted qualitatively by profile shape, amplitude, polarity (positive or negative) and contour pattern (see Figure 8.1). The top of an orebody is then assumed to lie directly beneath the position of the minimum potential. If the axis of polarisation (i.e. the axis between the cathode and anode on the orebody) is inclined from the vertical, the shape of the profile will become asymmetrical with the steepest slope and positive tail both lying on the downdip side (Figure 8.5).

Complications arise when two or more geological features give rise to superimposed SP anomalies. One such example (Nayak 1981) is shown in Figure 8.6. An anomaly over graphitic phyllites is characteristically large ($-740\,mV$) owing to mineral electrochemical potentials. A second anomaly ($-650\,mV$) has been produced by electrokinetic potentials associated with water flow through permeable disintegrated conglomerates. However, if similar-sized bodies are present but with different dips, the resultant anomaly can be used to resolve between them. Consider two graphite bodies in gneiss (Figure 8.7) in two different models (Meiser 1962). The first is where the graphites dip towards each other in a synclinal structure, in which case the negative centres associated with each polarisable body are well separated, resulting in an anomaly with two negative minima. The second is where the graphite bodies dip away from each other in an anticlinal structure, in which case the two negative centres are very close together and may even combine to form one large negative minimum. The separation between the two minima is equal to the separation of the tops of the graphite bodies.