Chapter 7

Electrical resistivity methods

7.1 INTRODUCTION

Electrical resistivity methods were developed in the early 1900s but have become very much more widely used since the 1970s, due primarily to the availability of computers to process and analyse the data. These techniques are used extensively in the search for suitable groundwater sources and also to monitor types of groundwater pollution; in engineering surveys to locate sub-surface cavities, faults and fissures, permafrost, mineshafts, etc.; and in archaeology for mapping out the areal extent of remnants of buried foundations of ancient buildings, amongst many other applications. Electrical resistivity methods are also used extensively in downhole logging. For the purposes of this chapter, applications will be confined to the use of direct current (or very-low-frequency alternating current) methods.

Electrical resistivity is a fundamental and diagnostic physical property that can be determined by a wide variety of techniques, including electromagnetic induction. These methods will be discussed in their respective chapters. That there are alternative techniques for the determination of the same property is extremely useful as some methods are more directly applicable or more practicable in some circumstances than others. Furthermore, the approaches used to determine electrical resistivity may be quite distinct – for example, ground contact methods compared with airborne induction techniques. Mutually consistent but independent interpretations give the interpreter greater confidence that the derived model is a good approximation of the sub-surface. If conflicting interpretations result, then it is necessary to go back and check each and every stage of the data acquisition, processing and interpretation in order to locate the problem. After all, the same ground with the same physical properties should give rise to the same model irrespective of which method is used to obtain it.

7.2 BASIC PRINCIPLES

7.2.1 True resistivity

Consider an electrically uniform cube of side lenght L through which a current (I) is passing (Figure 7.1). The material within the cube resists the conduction of electricity through it, resulting in a potential drop (V) between opposite faces. The resistance (R) is proportional to the length (L) of the resistive material and inversely proportional to the cross-sectional area (A) (Box 7.1); the constant of proportionality is the 'true' *resistivity* (symbol: ρ). According to Ohm's Law (Box 7.1) the ratio of the potential drop to the applied current (V/I) also defines the resistance (R) of the cube and these two expressions can be combined (Box 7.2) to form the product of a resistance (Ω) and

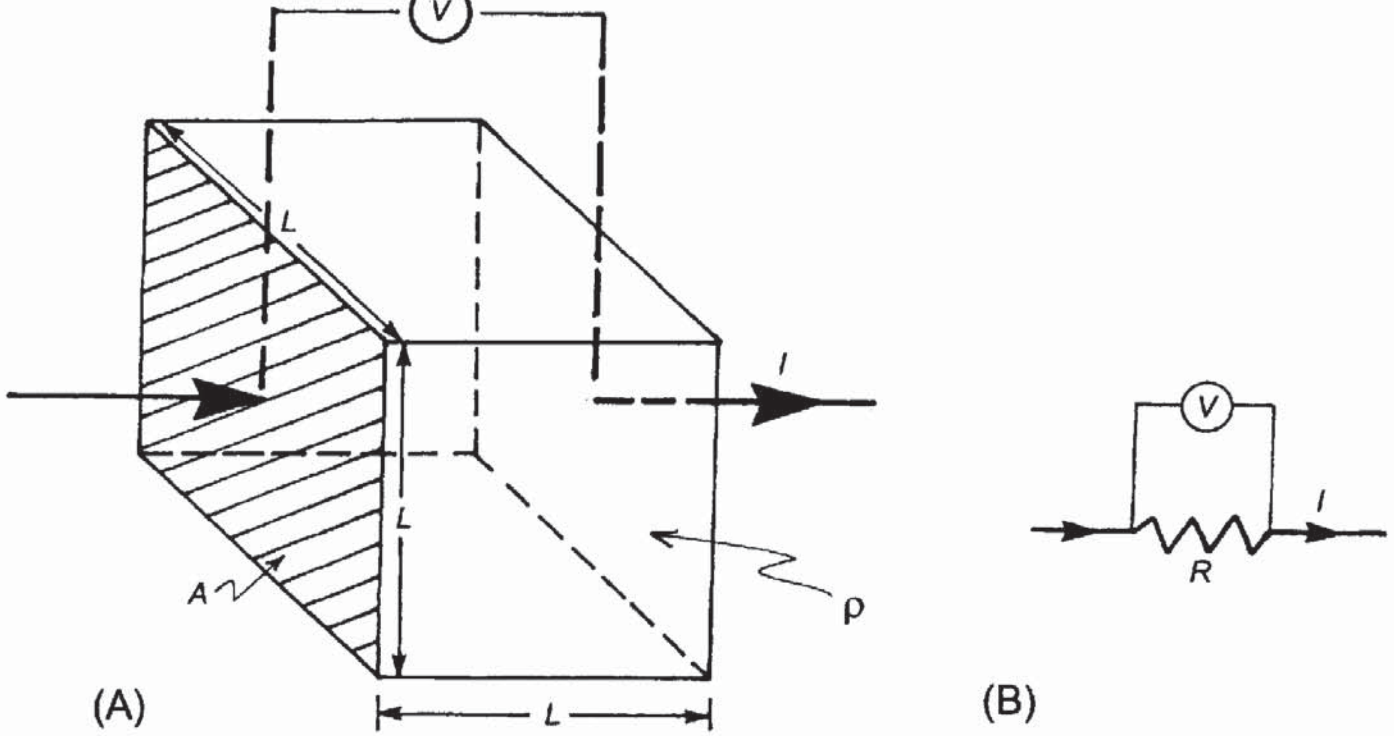

Figure 7.1 (A) Basic definition of resistivity across a homogeneous block of side length L with an applied current I and potential drop between opposite faces of V. (B) The electrical circuit equivalent, where R is a resistor

a distance (area/length; metres); hence the units of resistivity are ohm-metres (Ω m). The inverse of resistivity ($1/\rho$) is conductivity (σ) which has units of siemens/metre (S/m) which are equivalent to mhos/metre ($\Omega^{-1}\,\mathrm{m}^{-1}$). It should be noted that Ohm's Law applies in the vast majority of geophysical cases unless high current densities (J) occur, in which case the linearity of the law may break down.

If two media are present within the resistive cube, each with its own resistivity (ρ_1 and ρ_2), then both proportion of each medium and their geometric form within the cube (Figure 7.2) become important considerations. The formerly isotropic cube will now exhibit variations in electrical properties with the direction of measurement (known as *anisotropy*); a platey structure results in a marked anisotropy, for example. A lower resistivity is usually obtained when measured parallel to limitations in phyllitic shales and slates compared with that at right-angles to the laminations. The presence and orientation of elongate brine pockets (with high conductivity) strongly influence the resistivity of sea ice (Timco 1979). The amount of anisotropy is described by the *anisotropy coefficient*, which is the ratio of maximum to minimum resistivity and which generally lies in the range 1–2. Thus it is important to have some idea of the form of electrical conductors with a rock unit. Detailed discussions of anisotropy have been given, for example, by Maillet (1947), Grant and West (1965) and Telford *et al.* (1990) (see also Section 7.3.3).

Box 7.1 True resistivity (see Figure 7.1)

Resistance (R) is proportional to length (L) divided by area (A):

$$R \propto L/A.$$

This can be written as $R = \rho L/A$, where ρ is the true resistivity.

Ohm's Law

For an electrical circuit, Ohm's Law gives $R = V/I$, where V and I are the potential difference across a resistor and the current passing through it, respectively.

This can be written alternatively in terms of the electric field strength ($\boldsymbol{E}$; volts/m) and current density ($\boldsymbol{J}$; amps/m^2) as:

$$\rho = \boldsymbol{E}/\boldsymbol{J}\,(\Omega\,\mathrm{m})$$

Box 7.2 Resistivity

$$\rho = \frac{VA}{IL}\,(\Omega/\mathrm{m})$$

There are three ways in which electric current can be conducted through a rock: electrolytic, electronic (ohmic) and dielectric conduction. *Electrolytic conduction* occurs by the relatively slow movement of ions within an electrolyte and depends upon the type of ion, ionic concentration and mobility, etc. *Electronic conduction* is the process by which metals, for example, allow electrons to move rapidly, so carrying the charge. *Dielectric conduction* occurs in very weakly conducting materials (or insulators) when an external alternating current is applied, so causing atomic electrons to be shifted slightly with respect to their nuclie. In most rocks, conduction is by way of

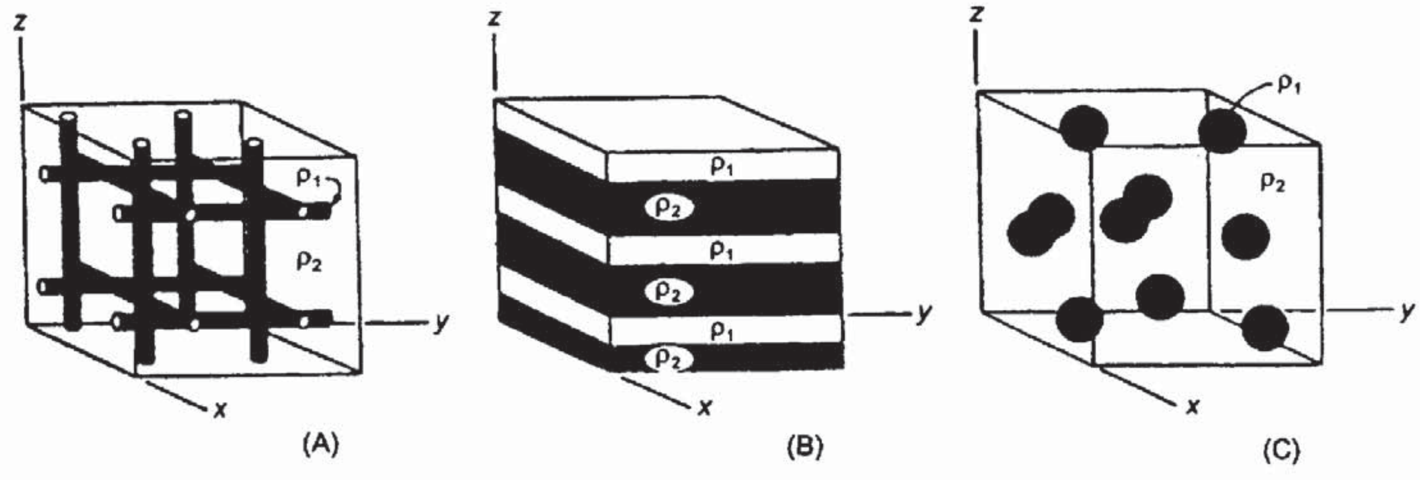

Figure 7.2 Three extreme structures involving two materials with true resistivities ρ_1 and ρ_2. After Grant and West (1965), by permission

pore fluids acting as electrolytes with the actual mineral grains contributing very little to the overall conductivity of the rock (except where those grains are themselves good electronic conductors). At the frequencies used in electrical resistivity surveying dielectric conduction can be disregarded. However, it does become important in 'spectral induced polarisation' and in 'complex resistivity' measurements (see Chapter 9).

The resistivity of geological materials exhibits one of the largest ranges of all physical properties, from $1.6 \times 10^{-8}\ \Omega\,\mathrm{m}$ for native silver to $10^{16}\ \Omega\,\mathrm{m}$ for pure sulphur. Igneous rocks tend to have the highest resistivities; sedimentary rocks tend to be most conductive, largely due to their high pore fluid content; and metamorphic rocks have intermediate but overlapping resistivities. The age of a rock also is an important consideration: a Quaternary volcanic rock may have a resistivity in the range 10–200 Ω m while that of an equivalent rock but Precambrian in age may be an order of magnitude greater. This is a consequence of the older rock having far longer to be exposed to secondary infilling of interstices by mineralisation, compaction decreasing the porosity and permeability, etc.

In sedimentary rocks, the resistivity of the interstitial fluid is probably more important than that of the host rock. Indeed, Archie (1942) developed an empirical formula (Box 7.3) for the effective resistivity of a rock formation which takes into account the porosity (ϕ), the fraction (s) of the pores containing water, and the resistivity of the water (ρ_w). Archie's Law is used predominantly in borehole logging. Korvin (1982) has proposed a theoretical basis to account for Archie's Law. Saline groundwater may have a resistivity as low as 0.05 Ω m and some groundwater and glacial meltwater can have resistivities in excess of 1000 Ω m.

Resistivities of some common minerals and rocks are listed in Table 7.1, while more extensive lists have been given by Telford *et al.* (1990).

Box 7.3 Archie's Law

$$\rho = a\phi^{-m}s^{-n}\rho_w$$

where ρ and ρ_w are the effective rock resistivity, and the resistivity of the pore water, respectively; ϕ is the porosity; s is the volume fraction of pores with water; a, m and n are constants where $0.5 \leqslant a \leqslant 2.5$, $1.3 \leqslant m \leqslant 2.5$, and $n \approx 2$.
The ratio ρ/ρ_w is known as the Formation Factor (F).

Some minerals such as pyrite, galena and magnetite are commonly poor conductors in massive form yet their individual crystals have high conductivities. Hematite and sphalerite, when pure, are virtual insulators, but when combined with impurities they can become very

Table 7.1 Resistivities of common geologic materials

Material	Nominal resistivity (Ω m)
Sulphides:	
Chalcopyrite	$1.2 \times 10^{-5}-3 \times 10^{-1}$
Pyrite	$2.9 \times 10^{-5}-1.5$
Pyrrhotite	$7.5 \times 10^{-6}-5 \times 10^{-2}$
Galena	$3 \times 10^{-5}-3 \times 10^{2}$
Sphalerite	1.5×10^{7}
Oxides:	
Hematite	$3.5 \times 10^{-3}-10^{7}$
Limonite	$10^{3}-10^{7}$
Magnetite	$5 \times 10^{-5}-5.7 \times 10^{3}$
Ilmenite	$10^{-3}-5 \times 10$
Quartz	$3 \times 10^{2}-10^{6}$
Rock salt	$3 \times 10-10^{13}$
Anthracite	$10^{-3}-2 \times 10^{5}$
Lignite	$9-2 \times 10^{2}$
Granite	$3 \times 10^{2}- \times 10^{6}$
Granite (weathered)	$3 \times 10-5 \times 10^{2}$
Syenite	$10^{2}-10^{6}$
Diorite	$10^{4}-10^{5}$
Gabbro	$10^{3}-10^{6}$
Basalt	$10-1.3 \times 10^{7}$
Schists (calcareous and mica)	$20-10^{4}$
Schist (graphite)	$10-10^{2}$
Slates	$6 \times 10^{2}-4 \times 10^{7}$
Marble	$10^{2}-2.5 \times 10^{8}$
Consolidated shales	$20-2 \times 10^{3}$
Conglomerates	$2 \times 10^{3}-10^{4}$
Sandstones	$1-7.4 \times 10^{8}$
Limestones	$5 \times 10-10^{7}$
Dolomite	$3.5 \times 10^{2}-5 \times 10^{3}$
Marls	$3-7 \times 10$
Clays	$1-10^{2}$
Alluvium and sand	$10-8 \times 10^{2}$
Moraine	$10-5 \times 10^{3}$
Sherwood sandstone	100–400
Soil (40% clay)	8
Soil (20% clay)	33
Top soil	250–1700
London clay	4–20
Lias clay	10–15
Boulder clay	15–35
Clay (very dry)	50–150
Mercia mudstone	20–60
Coal measures clay	50
Middle coal measures	>100
Chalk	50–150
Coke	0.2–8
Gravel (dry)	1400
Gravel (saturated)	100
Quaternary/Recent sands	50–100

Table 7.1 (*continued*)

Material	Nominal resistivity (Ω m)
Ash	4
Colliery spoil	10–20
Pulverised fuel ash	50–100
Laterite	800–1500
Lateritic soil	120–750
Dry sandy soil	80–1050
Sand clay/clayey sand	30–215
Sand and gravel	30–225
Unsaturated landfill	30–100
Saturated landfill	15–30
Acid peat waters	100
Acid mine waters	20
Rainfall runoff	20–100
Landfill runoff	<10–50
Glacier ice (temperate)	2×10^6–1.2×10^8
Glacier ice (polar)	5×10^4–3×10^5 *
Permafrost	10^3–$>10^4$

* -10°C to -60°C, respectively; strongly temperature-dependent. Based on Telford *et al.* (1990) with additional data from McGinnis and Jensen (1971), Reynolds (1987a). Reynolds and Paren (1980, 1984) and many commercial projects.

good conductors (with resistivities as low as 0.1 Ω m). Graphite dispersed throughout a rock mass may reduce the overall resistivity of otherwise poorly conducting minerals. For rocks that have variable composition, such as sedimentary rocks with gradational facies, the resistivity will reflect the varying proportions of the constituent materials. For example, in northern Nigeria it is possible, on the basis of the interpreted resistivities, to gauge whether a near-surface material is a clayey sand or a sandy clay. Resistivities for sandy material are about 100 Ω m and decrease with increasing clay content to about 40 Ω m, around which point clay becomes the dominant constituent and the values decrease further to those more typical of clay: well-formed and almost sand-free clay has a value in the range 1–10 Ω m (Reynolds 1987a).

The objective of most mordern electrical resistivity surveys is to obtain true resistivity models for the sub-surface because it is these that have geological meaning. The methods by which field data are obtained, processed and interpreted will be discussed later.

The *apparent resistivity* is the value obtained as the product of a measured resistance (R) and a *geometric factor* (K) for a given electrode array (see Section 7.3.2), according to the expression in Box 7.2. The geometric factor takes into account the geometric spread of electrodes and contributes a term that has the unit of length (metres). Apparent resistivity (ρ_a) thus has units of ohm-metres.

7.2.2 Current flow in a homogeneous earth

For a single current electrode implanted at the surface of a homogeneous medium of resistivity ρ, current flows away radially (Figure 7.3). The voltage drop between any two points on the surface can be described by the potential gradient $(-\delta V/\delta x)$, which is negative because the potential decreases in the direction of current flow. Lines of equal voltage ('equipotentials') intersect the lines of equal current at right-angles. The current density (J) is the current (I) divided by the area over which the current is distributed (a hemisphere; $2\pi r^2$), and so the current density decreases with increasing distance from the current source. It is possible to calculate the voltage at a distance (r) from a single current point source (Box 7.4). If, however, a current sink is added, a new potential distribution occurs (Figure 7.4) and a modified expression is obtained to describe the voltage at any point (Box 7.5).

Figure 7.3 (A) Three-dimensional representation of a hemispherical equipotential shell around a point electrode on a semi-infinite, homogeneous medium. (B) Potential decay away from the point electrode