Table 5.1. *Resistivities of minerals*

		Resistivity (Ωm)	
Mineral	Formula	Range	Average
Bismuthinite	Bi_2S_3	$18-570$	
Covellite	CuS	$3 \times 10^{-7}-8 \times 10^{-5}$	2×10^{-5}
Chalcocite	CU_2S	$3 \times 10^{-5}-0.6$	10^{-4}
Chalcopyrite	$CuFeS_2$	$1.2 \times 10^{-5}-0.3$	4×10^{-3}
Bornite	Cu_5FeS_4	$2.5 \times 10^{-5}-0.5$	3×10^{-3}
Pyrite	FeS_2	$2.9 \times 10^{-5}-1.5$	3×10^{-1}
Pyrrhotite	Fe_nS_m	$6.5 \times 10^{-6}-5 \times 10^{-2}$	10^{-4}
Cinnabar	HgS		2×10^{7}
Molybdenite	MoS_2	$10^{-3}-10^{6}$	10
Galena	PbS	$3 \times 10^{-5}-3 \times 10^{2}$	2×10^{-3}
Millerite	NiS		3×10^{-7}
Stannite	Cu_2FeSnS_2	$10^{-3}-6 \times 10^{3}$	
Stibnite	Sb_2S_3	$10^{5}-10^{12}$	5×10^{6}
Sphalerite	ZnS	$1.5-10^{7}$	10^{2}
Cobaltite	$CoAsS$	$3.5 \times 10^{-4}-10^{-1}$	
Arsenopyrite	$FeAsS$	$2 \times 10^{-5}-15$	10^{-3}
Niccolite	$NiAs$	$10^{-7}-2 \times 10^{-3}$	2×10^{-5}
Bauxite	$Al_2O_3 \cdot nH_2O$	$2 \times 10^{2}-6 \times 10^{3}$	
Cuprite	Cu_2O	$10^{-3}-300$	30
Chromite	$FeCr_2O_4$	$1-10^{6}$	
Specularite	Fe_2O_3		6×10^{-3}
Hematite	Fe_2O_3	$3.5 \times 10^{-3}-10^{7}$	
Limonite	$2Fe_2O_3 \cdot 3H_2O$	$10^{3}-10^{7}$	
Magnetite	Fe_3O_4	$5 \times 10^{-5}-5.7 \times 10^{3}$	
Ilmenite	$FeTiO_3$	$10^{-3}-50$	
Wolframite	Fe, Mn, WO_4	$10-10^{5}$	
Pyrolusite	MnO_2	$5 \times 10^{-3}-10$	
Quartz	SiO_2	$4 \times 10^{10}-2 \times 10^{14}$	
Cassiterite	SnO_2	$4 \times 10^{-4}-10^{4}$	0.2
Rutile	TiO_2	$30-1000$	500
Uraninite (pitchblende)	UO_2	$1-200$	
Anhydrite	$CaSO_4$		10^{9}
Calcite	$CaCO_3$		2×10^{12}
Fluorite	CaF_2		8×10^{13}
Siderite	$Fe_2(CO_3)_3$		70
Rock salt	$NaCl$	$30-10^{13}$	
Sylvite	KCl	$10^{11}-10^{12}$	
Diamond	C	$10-10^{14}$	
Serpentine		$2 \times 10^{2}-3 \times 10^{3}$	
Hornblende		$2 \times 10^{2}-10^{6}$	
Mica		$9 \times 10^{2}-10^{14}$	
Biotite		$2 \times 10^{2}-10^{6}$	
Bitum. coal		$0.6-10^{5}$	
Anthracite		$10^{-3}-2 \times 10^{5}$	
Lignite		$9-200$	
Fire clay			30
Meteoric waters		$30-10^{3}$	
Surface waters (ign. rocks)		$0.1-3 \times 10^{3}$	
Surface waters (sediments)		$10-100$	
Soil waters			100
Natural waters (ign. rocks)		$0.5-150$	9
Natural waters (sediments)		$1-100$	3
Sea water			0.2
Saline waters, 3%			0.15
Saline waters, 20%			0.05

ers or none at all. Under the influence of an external varying electric field, the atomic electrons are displaced slightly with respect to their nuclei; this slight relative separation of negative and positive charges is known as dielectric polarization of the material and it produces a current known as the *displacement current*.

(b) Electronic conduction. The *electrical resistivity* of a cylindrical solid of length L and cross section A, having resistance R between the end faces, is given by

$$\rho = RA/L \tag{5.5}$$

If A is in square meters, L in meters, and R in ohms, the resistivity unit is the ohm-meter (Ωm). For dimensions in centimeters the unit becomes the ohm-centimeter (Ωcm): 1 Ωm = 100 Ωcm.

The resistance R is given in terms of the voltage V applied across the ends of the cylinder and the resultant current I flowing through it, by Ohm's law:

$$R = V/I$$

where R is in ohms and the units of V and I are volts and amperes.

The reciprocal of resistivity is the *conductivity* σ, where the units are siemens per meter (S/m). Then

$$\sigma = 1/\rho = L/RA = (I/A)/(V/L) = J/E \tag{5.6}$$

where J is the current density (A/m^2) and E is the electric field (V/m).

(c) Electrolytic conduction. Because most rocks are poor conductors, their resistivities would be extremely large were it not for the fact that they are usually porous and the pores are filled with fluids, mainly water. As a result the rocks are *electrolytic conductors*, whose effective resistivity may be defined as in Equation (5.5), where the propagation of current is by ionic conduction – by molecules having an excess or deficiency of electrons. Hence the resistivity varies with the mobility, concentration, and degree of dissociation of the ions; the latter depends on the dielectric constant of the solvent. As mentioned previously, the current flow is not only slow compared to ohmic conduction, but represents an actual transport of material, usually resulting in chemical transformation.

The conductivity of a porous rock varies with the volume and arrangement of the pores and even more with the conductivity and amount of contained water. According to the empirical formula due to Archie (1942),

$$\rho_e = a\phi^{-m}S^{-n}\rho_W \tag{5.7}$$

where ϕ is the fractional pore volume (porosity), S is the fraction of the pores containing water, ρ_W is the resistivity of water, $n \approx 2$, and a, m are constants, $0.5 \le a \le 2.5$, $1.3 \le m \le 2.5$. For example, suppose $S = 1$, $a = 1.5$, and $m = 2$, then $\rho_e/\rho_W = 1.5/\phi^2$ and for values of $\phi = 0.01, 0.1, 0.3, 0.5$, ρ_e/ρ_W becomes 1.5×10^4, 150, 17, and 6, respectively.

Water conductivity varies considerably (see Table 5.1), depending on the amount and conductivity of dissolved chlorides, sulfates, and other minerals present.

The geometrical arrangement of the interstices in the rock has a less pronounced effect, but may make the resistivity anisotropic, that is, having different magnitudes for current flow in different directions. Anisotropy is characteristic of stratified rock that is generally more conductive in the bedding plane. The anisotropy effect depends on the ratio of maximum to minimum resistivity, may be as large as 2 in some graphitic slates, and varies from 1 to 1.2 in rocks such as limestone, shale, and rhyolite.

As an example, consider the layered formation shown in Figure 5.1, having resistivities ρ_1 and ρ_2 whose respective fractional volumes are v and $1 - v$. Here the resistivity in the horizontal direction – a stack of beds effectively in parallel – is

$$\rho_h = \rho_1\rho_2/\{\rho_1(1 - v) + \rho_2 v\} \tag{5.8}$$

In the vertical direction, the beds are in series so that

$$\rho_v = \rho_1 v + \rho_2(1 - v) \tag{5.9}$$

Then the ratio is

$$\frac{\rho_v}{\rho_h} = (1 - 2v + 2v^2) + \left(\frac{\rho_1}{\rho_2} + \frac{\rho_2}{\rho_1}\right)v(1 - v)$$

If $v \ll 1$ and $\rho_2/\rho_1 \gg 1$, this simplifies to

$$\frac{\rho_v}{\rho_h} \approx 1 + \frac{\rho_2}{\rho_1}v \tag{5.10}$$

If the layer of resistivity ρ_1 is for water-saturated beds, this ratio might be quite large.

(d) Dielectric conduction. The mechanism of dielectric conduction – the displacement current – was described briefly at the beginning of this section, where it was pointed out that the displacement current flows only in nonconductors when the external electric field changes with time. The significant parameter in dielectric conduction is the *dielectric constant* k, sometimes called the *specific inductive*

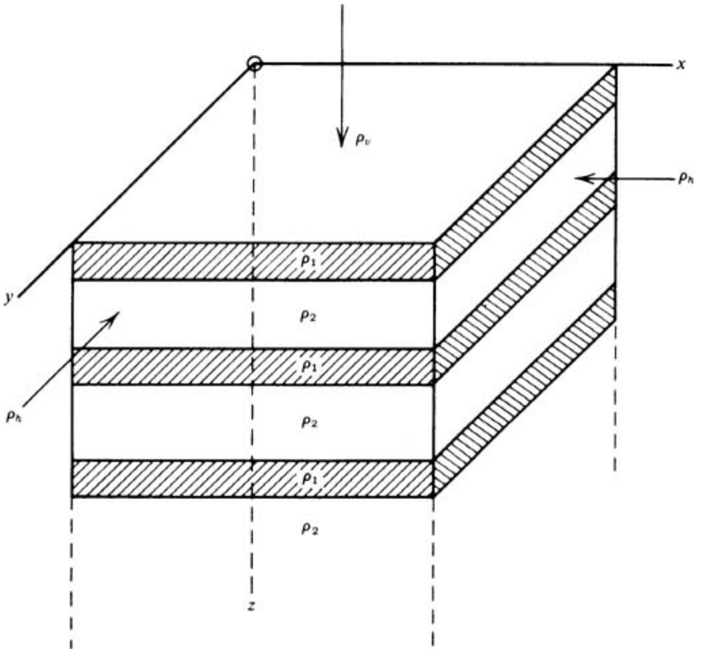

Figure 5.1. Anisotropic resistivity as a result of horizontal bedding.

capacity of the medium. In analogy with magnetic quantities M, H, k, B, and μ (§3.2.1) we have an electrostatic set: *electric polarization* (*electric dipole moment/unit volume*) P, *electric field strength* E, *electric susceptibility* η, *electric displacement* (*flux/unit area*) D, and *dielectric constant* k. In electrostatic units, the relations between these are

$$P = \eta E \qquad D = E + 4\pi P = E(1 + 4\pi\eta) = kE \tag{5.11}$$

whereas in mks units,

$$P = \eta E \qquad D = \varepsilon_0 E + P = E(\varepsilon_0 + \eta) = \varepsilon E \tag{5.12}$$

and the dielectric constant $k = 1 + \eta/\varepsilon_0 = \varepsilon/\varepsilon_0$.

In electrostatic units, P, E and D are volts per centimeter and η and k are dimensionless. In mks units ε, ε_0, and η are in farads per meter, P, D are in coulombs per square meter, E is in volts per meter, and k is again dimensionless and the same in either system.

The dielectric constant is similar to the conductivity in porous formations in that it varies with the amount of water present (note that water has a very large dielectric constant; see Table 5.5). We shall see in Section 6.2.3 that displacement currents are of secondary importance in earth materials because electrical prospecting methods generally employ low frequencies.

5.2.3. Magnetic Permeability

Where EM sources are employed, the voltage induced in a subsurface conductor varies not only with the rate of change of magnetic field, but also with the magnetic permeability of the conductor. From Maxwell's equation,

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

we see that currents induced in the ground are enhanced by the factor μ. Practically, however, the permeability rarely is appreciably greater than unity, except for a few magnetic minerals (§5.4.3); consequently it is of no particular significance in electrical work, except when Fe_2O_3 is present in large concentration.

5.2.4. Polarization Potentials

Where a steady current is passed through an electrolytic conductor containing mineral particles it is possible, as described in Section 5.3.1, to determine the effective resistivity. If a current is suddenly switched on or off in a circuit containing an electrolyte, a finite time elapses before the potential increases to a fixed value or drops to zero. The delayed buildup or decay of current is characteristic of electrolytic conduction, and is due to accumulation of ions at interfaces between the electrolyte and mineral particles. As a result, a potential opposing

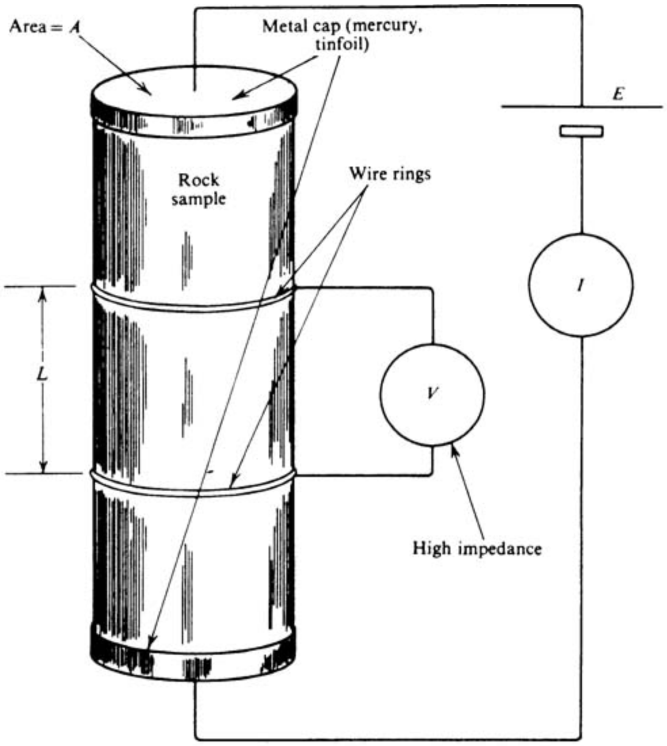

Figure 5.2. Simplified schematic of equipment for measuring resistivity of core samples.

the normal current flow is developed across the interface. A similar effect is observed at the contact between electrolytes and clay particles. These are known as *polarization potentials*; the process is called the *induced polarization effect*. Induced polarization (IP) prospecting involves these interface potentials. They will be considered in more detail in Section 9.2.

5.3. MEASUREMENT OF ELECTRICAL PROPERTIES OF ROCKS AND MINERALS

5.3.1. Laboratory Measurement of Resistivity

In order to measure directly the true resistivity of a rock, mineral, electrolyte, and so forth, it is necessary to shape the sample in some regular form, such as a cylinder, cube, or bar of regular cross section. An experimental arrangement is shown in Figure 5.2. The main difficulty is in making good electrical contact, particularly for the current electrodes. For this purpose tinfoil or mercury electrodes may be used and it is generally necessary to apply pressure to the current electrodes; sometimes the ends of the sample are dipped in soft solder. From Figure 5.2 and Equation (5.6) the resistivity is given by

$$\rho = AV/LI$$

The power source may be dc or preferably low frequency ac (400 Hz or less). The possibility of anisotropy can be checked by measuring the resistivity in two directions, provided the shape is suitable for this.

Obviously one can make these measurements in the field as well, on drill core, grab samples, even outcrop, if the electrode contact is reasonably good. Estimates of resistivity, made on samples by using an ohmmeter and merely pressing or scraping the terminals of the leads against the surface however, are not very trustworthy.

5.3.2. Measurement of Dielectric Constant

An ac bridge may also be used to measure the resistivity of soils and electrolytes. At audio frequencies any reactive component – normally capacitive – must be accounted for in order to get a good bridge balance. Consequently the measurement determines the effective capacitance, as well as resistivity, of the specimen. Since capacitance varies with the dielectric constant of the material, it is thus possible to determine the latter by substitution. The Schering capacitance bridge is suitable for this measurement in the laboratory (Hague, 1957).

Table 5.2. *Resistivities of various ores*

Ore	Other minerals	Gangue	ρ (Ωm)
Pyrite			
18%	2% (chalco)	80%	300
60%	5% (ZnS) + 15%	20%	0.9
95%	5% (ZnS)		1.0
Pyrrhotite			
41%		59%	2.2×10^{-4}
79%		21%	1.4×10^{-5}
95%		5%	1.4×10^{-5}
SbS_2 in quartz			$4 \times 10^3 - 3 \times 10^7$
FeAsS 60%	FeS 20%	20% SiO_2	0.39
FeAsS			$10^{-4} - 10^{-2}$
Cu_5FeS_4			3×10^{-3}
Cu_5FeS_4 40%		60% SiO_2	7×10^{-2}
Fe, Mn, WO_4	CoAsS		$10^3 - 10^7$
PbS, near massive			0.8
Fe_2O_3			0.1 – 300
Fe_2O_3, massive			2.5×10^3
Iron			
Fe_3O_4 60%			45
75% brown iron oxide		25%	$2 \times 10^4 - 8 \times 10^5$
Fe_3O_4			$5 \times 10^3 - 8 \times 10^3$
Zinc			
30%	5% PbS, 15% FeS	50%	0.75
80%	10% PbS, 10% FeS		1.7×10^3
90%	5% PbS	5%	130
Graphitic slate			0.13
Graphite, massive			$10^{-4} - 5 \times 10^{-3}$
MoS_2			$2 \times 10^2 - 4 \times 10^3$
MnO_2 colloidal ore			1.6
Cu_2S			3×10^{-2}
$CuFeS_2$			$10^{-4} - 1$
$CuFeS_2$ 90%	2% FeS	8% SiO_2	0.65
$FeCr_2O_4$			10^3

5.4. TYPICAL VALUES OF ELECTRICAL CONSTANTS OF ROCKS AND MINERALS

5.4.1. Resistivities of Rocks and Minerals

Of all the physical properties of rocks and minerals, electrical resistivity shows the greatest variation. Whereas the range in density, elastic wave velocity, and radioactive content is quite small, in magnetic susceptibility it may be as large as 10^5. However, the resistivity of metallic minerals may be as small as 10^{-5} Ωm, that of dry, close-grained rocks, like gabbro as large as 10^7 Ωm. The maximum possible range is even greater, from native silver (1.6×10^{-8} Ωm) to pure sulfur (10^{16} Ωm).

A *conductor* is usually defined as a material of resistivity less than 10^{-5} Ωm, whereas an *insulator* is one having a resistivity greater than 10^7 Ωm. Between these limits lie the *semiconductors*. The metals and graphite are all conductors; they contain a large number of free electrons whose mobility is very great. The semiconductors also carry current by mobile electrons but have fewer of them. The insulators are characterized by ionic bonding so that the valence electrons are not free to move; the charge carriers are ions that must overcome larger barrier potentials than exist either in the semiconductors or conductors.

A further difference between conductors and semiconductors is found in their respective variation with temperature. The former vary inversely with temperature and have their highest conductivities in the region of 0 K. The semiconductors, on the other hand, are practically insulators at low temperatures.

In a looser classification, rocks and minerals are considered to be good, intermediate, and poor conductors within the following ranges:

(a) Minerals of resistivity 10^{-8} to about 1 Ωm.
(b) Minerals and rocks of resistivity 1 to 10^7 Ωm.
(c) Minerals and rocks of resistivity above 10^7 Ωm.

Group (a) includes the metals, graphite, the sulfides except for sphalerite, cinnabar and stibnite, all the arsenides and sulfo-arsenides except $SbAs_2$, the antimonides except for some lead compounds, the

Table 5.3. *Resistivities of various rocks and sediments*

Rock type	Resistivity range (Ωm)
Granite porphyry	4.5×10^3 (wet) – 1.3×10^6 (dry)
Feldspar porphyry	4×10^3 (wet)
Syenite	$10^2 - 10^6$
Diorite porphyry	1.9×10^3 (wet) – 2.8×10^4 (dry)
Porphyrite	$10 - 5 \times 10^4$ (wet) – 3.3×10^3 (dry)
Carbonatized porphyry	2.5×10^3 (wet) – 6×10^4 (dry)
Quartz diorite	$2 \times 10^4 - 2 \times 10^6$ (wet) –1.8×10^5 (dry)
Porphyry (various)	$60 - 10^4$
Dacite	2×10^4 (wet)
Andesite	4.5×10^4 (wet) – 1.7×10^2 (dry)
Diabase (various)	$20 - 5 \times 10^7$
Lavas	$10^2 - 5 \times 10^4$
Gabbro	$10^3 - 10^6$
Basalt	$10 - 1.3 \times 10^7$ (dry)
Olivine norite	$10^3 - 6 \times 10^4$ (wet)
Peridotite	3×10^3 (wet) – 6.5×10^3 (dry)
Hornfels	8×10^3 (wet) – 6×10^7 (dry)
Schists (calcareous and mica)	$20 - 10^4$
Tuffs	2×10^3 (wet) – 10^5 (dry)
Graphite schist	$10 - 10^2$
Slates (various)	$6 \times 10^2 - 4 \times 10^7$
Gneiss (various)	6.8×10^4 (wet) – 3×10^6 (dry)
Marble	$10^2 - 2.5 \times 10^8$ (dry)
Skarn	2.5×10^2 (wet) – 2.5×10^8 (dry)
Quartzites (various)	$10 - 2 \times 10^8$
Consolidated shales	$20 - 2 \times 10^3$
Argillites	$10 - 8 \times 10^2$
Conglomerates	$2 \times 10^3 - 10^4$
Sandstones	$1 - 6.4 \times 10^8$
Limestones	$50 - 10^7$
Dolomite	$3.5 \times 10^2 - 5 \times 10^3$
Unconsolidated wet clay	20
Marls	3 – 70
Clays	1 – 100
Oil sands	4 – 800

Table 5.4. *Variation of rock resistivity with water content*

Rock	% H_2O	ρ (Ωm)
Siltstone	0.54	1.5×10^4
Siltstone	0.38	5.6×10^8
Coarse grain SS	0.39	9.6×10^5
Coarse grain SS	0.18	10^8
Medium grain SS	1.0	4.2×10^3
Medium grain SS	0.1	1.4×10^8
Graywacke SS	1.16	4.7×10^3
Graywacke SS	0.45	5.8×10^4
Arkosic SS	1.0	1.4×10^3
Organic limestone	11	0.6×10^3
Dolomite	1.3	6×10^3
Dolomite	0.96	8×10^3
Peridotite	0.1	3×10^3
Peridotite	0	1.8×10^7
Pyrophyllite	0.76	6×10^6
Pyrophyllite	0	10^{11}
Granite	0.31	4.4×10^3
Granite	0.19	1.8×10^6
Granite	0	10^{10}
Diorite	0.02	5.8×10^5
Diorite	0	6×10^6
Basalt	0.95	4×10^4
Basalt	0	1.3×10^8
Olivine-pyrox.	0.028	2×10^4
Olivine-pyrox.	0	5.6×10^7

tellurides, and some oxides such as magnetite, manganite, pyrolusite, and ilmenite. Most oxides, ores, and porous rocks containing water are intermediate conductors. The common rock-forming minerals, silicates, phosphates and the carbonates, nitrates, sulfates, borates, and so forth, are poor conductors.

The following tables list characteristic resistivities for various minerals and rocks. The data are from various sources, including Heiland (1940, Ch. 10), Jakosky (1950, Ch. 5), Parasnis (1956, 1966, Ch. 6), Keller (1966), and Parkhomenko (1967).

Resistivities of the various metals in pure form, from antimony to zinc, vary by only about 2 orders of magnitude. (Bi $\approx 1.2 \times 10^{-6}$ Ωm, Ag $\approx 1.6 \times 10^{-8}$ Ωm). Tellurium is an exception ($\approx 10^{-3}$ Ωm). Two other elements of common occurrence are graphite (5×10^{-7} to 10 Ωm range, $\approx 10^{-3}$ Ωm average) and sulfur (10^7–10^{16} Ωm range, $\approx 10^{14}$ Ωm average).

The variation in resistivity of particular minerals is enormous, as can be seen from Table 5.1. Among the more common minerals, pyrrhotite and graphite appear to be the most consistent good conductors, whereas pyrite, galena, and magnetite are often poor conductors in bulk form, although the individual crystals have high conductivity. Hematite and sphalerite, in pure form, are practically insulators, but when combined with impurities may have resistivities as low as 0.1 Ωm. Graphite is often the connecting link in mineral zones, which makes them good conductors.

The range of resistivities of various waters is notably smaller than for solid minerals; the actual resistivities are also lower than those of a great many minerals.

Table 5.2 from Parkhomenko (1967) lists resistivities for a variety of ores. In general it appears that pyrrhotite in massive form has the lowest resistivity, that the resistivity of zinc ores is surprisingly low (possibly due to the presence of lead and copper fractions), and that molybdenite, chromite, and iron ores have values in the range of many rocks.

Table 5.3 lists typical values for rocks and unconsolidated sediments. The ranges are quite similar to that for water, which is the controlling factor in many rocks.