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Introduction

The aim of this book is to explain how controlled-source electromagnetic (CSEM) methods can be used to locate resistivity variations in the top few kilometres of the Earth's crust. Applications include the search for hydrocarbons and the search for hot brine. Hydrocarbons increase the resistivity of reservoir rocks; hot brine, which is useful for geothermal purposes, reduces the resistivity of an aquifer relative to the rocks above and below. This chapter begins with Ohm's law and resistivity and proceeds to a brief discussion of resistivity of rocks, how layering introduces anisotropy, and the effect of replacing normal pore fluid with hydrocarbons in sandstone reservoirs. Hydrocarbons can increase the rock resistivity by orders of magnitude, while the P-wave velocity is hardly affected. This is demonstrated with laboratory measurements and logs from a North Sea well. As an introduction to CSEM data, acoustic propagation in water from an impulsive monopole seismic source is compared with electromagnetic propagation from an impulsive point dipole current source also in water. The effect of a buried resistor on the response is then illustrated for the simple case of a dipole source and a line of dipole receivers over a one-dimensional Earth. The effect of a buried conductor is illustrated using an identical source–receiver configuration. How subsurface resistivities may be obtained from CSEM data is not obvious. An outline of the procedure for finding the resistivities by inversion is presented, including constraints imposed by borehole and seismic data. This is followed by an outline of the book.

1.1 Ohm's Law and Resistivity

If a potential difference V volts is maintained across the ends of an electrical conductor by an external source, such as a battery, a current I amps flows in the conductor. The ratio of the voltage V to the current I is a constant R, known as the resistance of the conductor, which has units of ohms. This relationship is known as Ohm's law and is usually expressed as

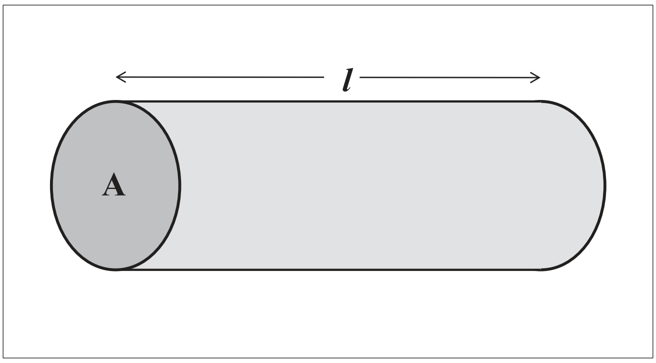

Figure 1.1 Cylindrical conductor of length l and cross-sectional area A.

$$V = IR \tag{1.1}$$

Figure 1.1 shows a cylindrical conductor of length l m and cross-sectional area A m^2. The resistance R of the conductor is proportional to its length and inversely proportional to its cross-sectional area, expressed as

$$R = \rho \frac{l}{A}. \tag{1.2}$$

The constant of proportionality ρ in equation 1.2 is a physical property of the material of the conductor, known as its resistivity, which has units of ohm-m. The reciprocal of resistivity is conductivity σ,

$$\sigma = \frac{1}{\rho}, \tag{1.3}$$

which has SI units of S m^{-1}.

1.2 Resistivity of Rocks

In metallic conductors the current flows by means of moving electrons. In other conductors the flow is by the movement of charged objects or ions. Positive ions move towards the negative potential and negative ions move towards the positive potential. By convention, the direction of current flow is taken to be the direction of flow of positively charged objects. Electrons are negatively charged, so they move towards the positive potential and thus in the opposite direction to the flow of current.

Rocks are composed of minerals that form a solid matrix that contains pores. The fraction of rock volume occupied by pore space is the porosity ϕ. The pores are full of fluids. The solid matrix is normally extremely resistive, as there are very few charged objects or ions free to move and conduct electricity. The fluid in the pores, on the other hand, contains ions and can therefore conduct electricity. Normally the fluid is salt water and the conductivity of the rock depends on the concentration of salt in the water, the fraction of the pore space that contains salt water and the freedom of movement of the ions between pores.

Sometimes the pores also contain hydrocarbons as solid, liquid, gas or a combination of phases. When hydrocarbons are present there are usually three fluid phases: salt water, hydrocarbon liquid and hydrocarbon gas – normally methane. The hydrocarbons are not ionised and so they are not conductors of electricity. It follows that the presence of hydrocarbons increases the resistivity of the rock. The greater the fluid fraction, or saturation, of hydrocarbons, the greater is the resistivity of the rock. As shown in the following, the effect of replacing salt water by hydrocarbons can increase the resistivity by orders of magnitude.

1.3 Resistivity Anisotropy

Very often rocks are layered, as indicated in Figure 1.2. A current flowing vertically through the sequence of layers sees resistances in series, with the resistance of the stack of layers being

$$R_v = \frac{l}{L^2} \sum_{j=1}^{n} \rho_j h_j. \tag{1.4}$$

In the horizontal direction the resistance of the jth layer is $R_j = \rho_j / h_j$ and the horizontal resistance R_h is given by

$$\frac{1}{R_h} = \sum_{j=1}^{n} \frac{1}{R_j}. \tag{1.5}$$

Resistors in parallel offer less resistance than the same resistors in series, so $R_h < R_v$. The scale of Figure 1.2 is arbitrary. It could be metres or millimetres. The point is that layering, and rock heterogeneity in general, gives rise to resistive anisotropy which is normally very important. The ratio R_v/R_h is often greater than 2, sometimes much greater.

1.4 Effect of Hydrocarbons on Resistivity: Archie's Law

In 1942 Gustavus E. Archie of Shell published results of laboratory experiments on Gulf Coast reservoir rock core samples in what has become a classic paper in rock physics. Archie (1942) found that the resistivity ρ_0 of a reservoir rock sample

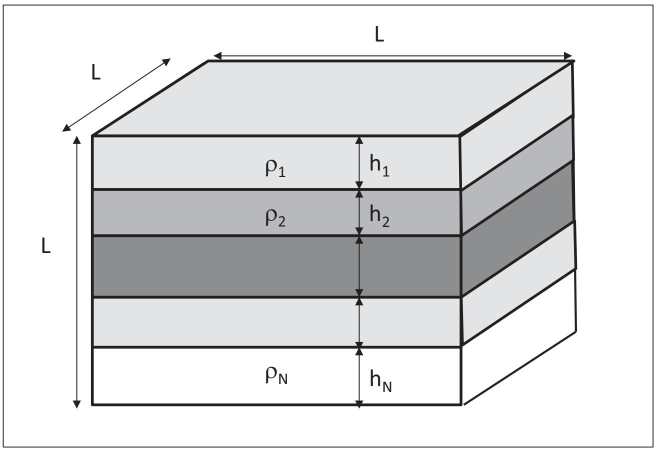

Figure 1.2 Horizontally layered cube of rock: resistivity varying with depth.

saturated with salt water was always related to the resistivity of the water ρ_w by a constant factor, which he called the formation factor F:

$$F = \frac{\rho_0}{\rho_w}. \tag{1.6}$$

This formula implies that the electricity flows only through the salt water. It is a consequence that the rock matrix has zero conductivity. Archie also found a power-law relation between this formation factor and the porosity ϕ:

$$F = \frac{1}{\phi^m}, \tag{1.7}$$

where the exponent m depends on the rock. Archie then combined these findings with work that had been published by Wyckoff and Botset (1936), Jakosky and Hopper (1937), Martin et al. (1938) and Leverett (1939). These researchers had established that displacing varying amounts of conducting water from water-saturated sand with non-conducting oil or carbon dioxide increases the resistivity of the rock. Specifically, the water saturation S_w, the fraction of pore space filled with water, is related to the rock resistivity ρ_t as

$$S_w^n = \frac{\rho_0}{\rho_t}, \tag{1.8}$$

in which n is known as the saturation exponent. Eliminating the formation factor F from equations 1.6 and 1.7 results in an expression for ρ_0, which may be substituted in equation 1.8 to give:

$$S_w^n = \frac{1}{\phi^m}\frac{\rho_w}{\rho_t}. \tag{1.9}$$

This is Archie's law. The formation factor in equation 1.7 has subsequently been modified by multiplying the right-hand side by a factor a, known as the 'tortuosity factor'. This then leads to the generalised form of Archie's law:

$$S_w^n = \frac{a}{\phi^m}\frac{\rho_w}{\rho_t}. \tag{1.10}$$

As Rider (1996: 56) puts it, 'When S_w is not 100% there are hydrocarbons present.' Water saturation S_w and hydrocarbon saturation S_{hc} are related as

$$S_w = 1 - S_{hc}. \tag{1.11}$$

The saturation exponent n is normally 2; m, known as the cementation factor, is closely related to the shape of the grains, or texture, of the rock (Rider, 1996), and is normally about 2. Rider (1996: 57) says the most frequently used formula for the formation factor F is with $a = 0.62$ and $m = 2.15$, which is the best average for sandstones.

Archie's law works well on clean, uniform sandstones. It works less well when clay is present in the sandstone, as Archie was well aware. Clay minerals can choke the narrowest pore throats in the rock matrix; they are also electrically conductive. The conductivity of the clay invalidates equation 1.6, because the rock matrix is no longer a perfect insulator. Further, the choking effect at pore throats decreases the permeability and impedes the flow of charged objects. Many attempts have been made to find formulae to include the presence of clay (e.g. De Witte, 1957; Bussian, 1983) and to account for the variations in connectivity between pores (e.g. Wyllie and Rose, 1950).

For the interpretation of well logs, Archie's law is indispensable. For the interpretation of electromagnetic data, which sample much larger rock volumes and thus a large range of heterogeneities, Archie's law should be regarded as a guide.

Figure 1.3, redrawn from Wilt and Alumbaugh (1998), shows the variation of resistivity with brine saturation for a real sandstone with porosity 0.3. As the brine saturation decreases, and hydrocarbon saturation increases, the resistivity increases exponentially. These are real measurements and the variation of resistivity with saturation is according to Archie's law. On the same graph is shown the corresponding effect of variation in P-wave velocity with brine saturation. There is a small decrease in P-wave velocity for substantial decrease in brine saturation. Comparing the two curves, it is clear that the resistivity is much more sensitive than the P-wave velocity to variations in brine saturation and thus to the presence of hydrocarbons.

1.5 Example Well Logs: P-Wave Velocity and Resistivity

Figure 1.4 shows a resistivity log (in black) and a sonic log (in grey) from well 9/23B-7 in the North Sea Harding field. Harding is a medium-size oil and gas field

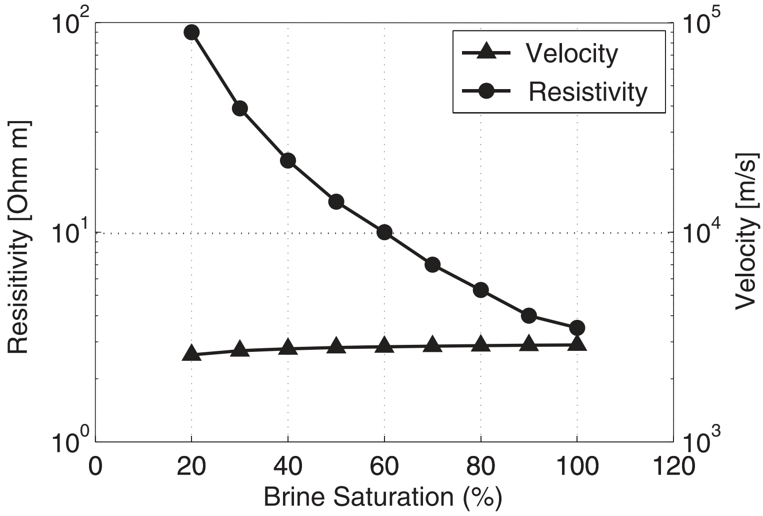

Figure 1.3 Resistivity and P-wave velocity as a function of brine saturation for a porous sandstone (redrawn from Wilt and Alumbaugh, 1998).

at a depth of about 1700 m below the sea floor in block 9/23B, about 320 km north-east of Aberdeen. The field has a high-quality Eocene Balder sandstone reservoir. Original oil in place was 300 million barrels. First oil production was in 1996, with gas being re-injected into the reservoir.

The measured resistivity is approximately 1 ohm-m for most of the 800–1800 m logged interval. At 1100–1150 m there are thin resistive beds with resistivities up to 200 ohm-m; the sonic log shows sharp fluctuations in the same interval. At 1570 m and 1600 m there are three more thin resistive beds with resistivities of 200 and 300 ohm-m which are correlated with slight increases in sonic velocity. Between 1630 and 1760 m the resistivity increases dramatically to as high as 1000 ohm-m. This is the Balder sandstone layer. In the same interval the sonic log shows two layers, with the upper one 1630–1700 m having a slightly lower velocity than the lower layer, 1700–1760 m. The huge increase in resistivity in this interval is caused by the replacement of brine in the sandstone by hydrocarbons.

From the sonic log there is very little indication of this hydrocarbon potential. It is the resistivity log that reveals this. This is a clear demonstration of the motive for searching for resistive reservoirs.

Suppose a potential sandstone reservoir of volume $\mathcal{V}$ has been identified using seismic data. Suppose also that the porosity ϕ of the reservoir has been estimated from an analysis of seismic attributes. The total volume of the pore space is then $\phi\mathcal{V}$. If now the resistivity ρ_t of the reservoir is known from electromagnetic survey data, the water saturation S_w can be estimated from Archie's law, equation 1.10,

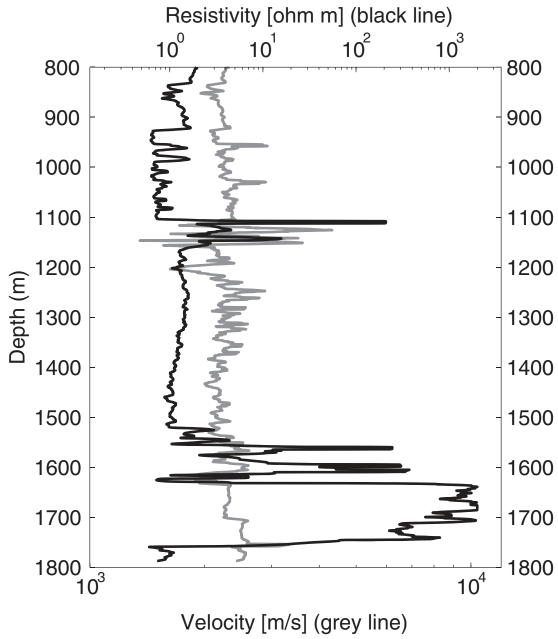

Figure 1.4 Logs from North Sea well 9/23b-7; resistivity is black; P-wave velocity is grey (redrawn from Ziolkowski et al., 2010).

and the volume of hydrocarbons is then $(1 - S_w)\phi\mathcal{V}$. Calculations like this are the motivation for using electromagnetic surveys to determine subsurface resistivity variations and rank drilling prospects already identified with seismic data.

1.6 Controlled-Source Electromagnetic Surveys

Conductivity variations in the Earth's crust and upper mantle have been investigated for decades using passive measurements of the electromagnetic field at the Earth's surface induced by natural variations in the Earth's magnetic field caused by ionospheric signals. This is the magnetotelluric (MT) method (Cagniard, 1953). MT measurements on the ocean floor suffer from attenuation of the ionospheric signals by the conducting sea water, the attenuation increasing with frequency and with the depth of the water.

It is not clear who first had the idea of using an active electromagnetic marine source to solve this problem. Certainly Bannister (1968), working in the US Navy Underwater Sound Laboratory at Fort Trumbull, New London, Connecticut, provided an early key step with the analysis of the responses of horizontal electric and magnetic dipoles in water. He argued that electric field measurements are preferable to magnetic measurements because the induced noise component is smaller. He showed that the sea bed conductivity may be determined by measuring only the horizontal electric field components produced by a subsurface horizontal magnetic dipole antenna or an electric dipole antenna, the configuration used today. Constable (2010) describes parallel work by the Scripps Institution of Oceanography, where Charles Cox and Jean Filloux developed the first equipment suitable for deep-water MT and CSEM soundings. In 1980, Cox proposed the use of an active man-made electromagnetic source at the sea bottom to overcome the problem caused by the attenuation of the magnetotelluric signal in deep water. According to Constable (2010), Cox appears to have been unaware of Bannister's 1968 paper and proposed the method independently. In 1981, Edwards et al. (1981) stated: 'Controlled source electromagnetic techniques are the obvious solution to this problem.' They showed theoretically that a vertical current bipole source in the water would produce detectable signals from below the sea floor in a horizontal magnetic receiver on the sea floor. The same group at Toronto had already pioneered the use of periodic pseudo-random binary sequences for CSEM survey on land (Duncan et al., 1980). Chave and Cox (1982) at Scripps showed theoretically for the marine case that 'Horizontal electric dipole sources produce much larger field amplitudes than their vertical counterparts for a given frequency range, and the horizontal electric field offers superior received signal performance.' By 1982, the horizontal electric dipole (HED) had become accepted as the preferred source.

Edwards et al. (1981) use the word *bipole*, while Chave and Cox (1982) use the word *dipole* for the same thing. The two poles of a dipole or a bipole are separated by a distance. In this book we use *dipole* whatever the distance between the poles. The meaning should be clear from the context.

1.7 Seismic and Electromagnetic Propagation

Here, we now compare seismic wave propagation with electromagnetic propagation in conducting media.

Some seismic sources, such as underground explosions and earthquakes, produce permanent displacements. That is, the displacement source time function contains a zero-frequency, or DC, component. To first order, seismic wave propagation is elastic; that is, there are no losses. The elastic waves from the source deform the media in which they propagate very slightly: the strains are usually smaller than 10^{-5}. After a seismic wave has passed through a medium, the medium returns to its original state, apart from any permanent displacement. Most man-made seismic sources, apart from explosives, do not generate permanent displacements. In fact, it is very difficult to generate very low-frequency energy (<1 Hz) with man-made seismic sources, especially in the marine environment. Measurements of seismic waves from such sources contain no DC component.

Electromagnetic waves are different from seismic waves. Electromagnetic waves in conducting media – fluids and solids – exhibit both electric and magnetic fields. The electric fields are associated with currents according to Ohm's law. The currents generate magnetic fields according to the Biot–Savart law. Changes in the magnetic fields cause changes in the electric field by Faraday's law of electromagnetic induction. Maxwell developed his famous theory of electromagnetism by starting with the experimental evidence presented by Faraday. The important point for the exploration geophysicist is that the electric and magnetic fields are related, and whenever there is current, as there must be in a conducting medium, there are losses. These losses are the principal difference between seismic and EM propagation. Another major difference is that it is very easy to create DC electromagnetic energy – for instance, simply by switching on a DC current. Whether the electromagnetic data contain DC energy or not depends only on the source time function.

Seismic waves propagate according to the wave equation, which is derived from two more fundamental equations: Newton's second law of mechanics (force equals mass times acceleration) and Hooke's law of elasticity (stress is proportional to strain). In solids there are two kinds of elastic waves: longitudinal, or P-waves, in which the particle vibration is parallel to the direction of wave propagation; and shear, or S-waves, in which the particle vibration is perpendicular to the direction of propagation. Fluids have no shear strength and therefore do not support shear waves. P-waves propagate in fluids and are known as acoustic waves.

Consider the simple case of a monopole source in water generating a spherical pressure wave $p(r,t)$ with the form

$$p(r,t) = \frac{\rho}{4\pi r} q'\left(t - \frac{r}{c}\right), \tag{1.12}$$

in which r is the distance from the source, t is time, $q(t)$ is the source time function with dimensions of volume divided by time and c is the speed of sound in water

$$c = \sqrt{\frac{K}{\varrho}}, \tag{1.13}$$

with K and ϱ the bulk modulus and density of the water. Consider also a similar simple case of an x-directed electric current impulsive dipole source in water generating a spherically spreading diffusive electric field $E_x(x,y,z,t)$ with the form

$$E_x(x, y=0, z, t) = \frac{\mu I_x \exp[-\sigma\mu r^2/(4t)]}{4\pi t^{5/2}} \sqrt{\frac{\sigma\mu}{4\pi}} \left[1 - \frac{\sigma\mu z^2}{4t}\right]. \tag{1.14}$$

The derivation of this result is given in Chapter 4 and the corresponding Green's function is given in equation 4.95. Figure 1.5(a) shows the configuration used to

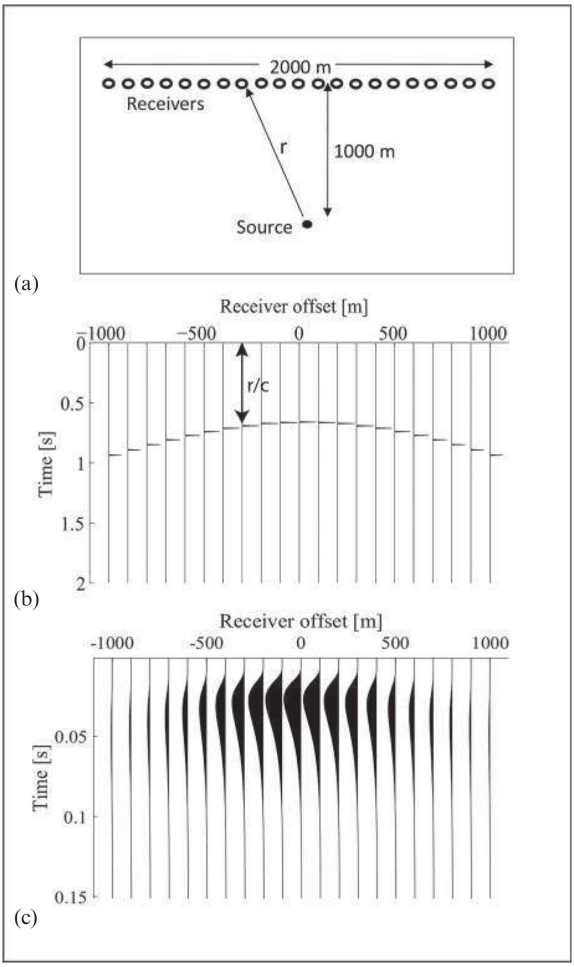

Figure 1.5 (a) Configuration of source and receivers in water of velocity 1500 m/s and resistivity 0.33 ohm-m; (b) pressure response at the receivers to an impulsive acoustic monopole at the origin; (c) *x*-component of electric field response to a *x*-directed impulsive current dipole source at the origin.

compute the whole space responses for the acoustic and electromagnetic situations. Figure 1.5(b) shows a representation of the pressure response to an impulsive compressional monopole source in an infinite body of water. The impulse is band-limited by the sampling and therefore has finite amplitude. The arrival time of the impulsive wave at a receiver is proportional to the distance r from the source, while the amplitude decays as $1/r$, as expressed in equation 1.12. Figure 1.5(c) shows the corresponding electric field response to an impulsive x-directed electric dipole source in an infinite body of water. The arrivals are not impulsive. The electric