7. Explain why geothermal energy is not truly a renewable energy source.
8. The internal heat flow of roughly what area of average continental surface (in km^2) would be needed to match a 2000 MW power station? (i) 5, (ii) 50, (iii) 500, (iv) 5000, (v) 50,000.
9. Explain why caves seem cool on hot days but warm on cold ones.
10. Explain, with sketches, how temperature varies with depth below ground due to daily and annual temperature variations.
11. Why does it sometimes take millions of years for the temperature profile in the Earth to return to equilibrium following a disturbance to it?
12. A thick layer of clay overlies granite, and the thermal conductivity of the clay is half that of the granite. If the temperature gradient in the granite is 16°C/km, the gradient in the clay, assuming thermal equilibrium, would be (in °C/km): (i) 4°, (ii) 8°, (iii), 12°, (iv) 16°, (v) 20°, (vi) 24°, (vii) 25°, (viii) 32°.

SUBPART I.8

Subsurface Geophysics

Well logging differs from most other geophysical methods, not only in being carried out down a borehole, but in relating the physical quantities measured more specifically to geological properties of interest, such as lithology, porosity, and fluid composition.

chapter 18

Well Logging and Other Subsurface Geophysics

The geophysical methods described so far in this book have nearly all investigated the subsurface using measurements made at the surface. This chapter describes measurements made underground, mainly in boreholes but also in mines and tunnels. The main advantages compared to surface measurements are much increased detail and close correlation with geological observations at precisely known depths; the disadvantages are the cost of boreholes and often the limited volume surveyed.

The most important application is in the exploration, evaluation, and production of oil and gas, by providing information on porosity, permeability, fluid content, and saturation of the formations penetrated by a borehole. Other applications are in mineral exploration and evaluation, and in hydrogeology. Subsurface measurements between holes or between holes and the surface may be combined to deduce the intervening geology.

Most of the geophysical principles used are the same as those used to 'look down' from the surface, described in the preceding chapters, but instruments and measurements have to be adapted to 'look sideways or upwards' in the special conditions of the subsurface, particularly the confined space of a borehole, where they also have to overcome the alterations produced in the surrounding formation by the drilling.

18.1 Introduction

Thousands of holes are drilled every year throughout the world, ranging from a few metres deep for engineering purposes, to over 14 km in the Kola Peninsula of northeast Russia, drilled to investigate the crust at depth. Most important economically are those for hydrocarbon exploration and extraction, which commonly reach depths of a few kilometres.

Their primary purpose is to provide samples of the subsurface or to extract fluids (oil, gas, water), but boreholes are expensive and the interpretation of data from them can be misleading: For example, a hole may be very close to a fault. Therefore, their value is considerably enhanced by also carrying out subsurface geophysical surveys in them to determine the properties of the rocks surrounding the borehole.

Compared to surface geophysical surveys, borehole surveys may offer deeper penetration, but their main advantage is greater detail, for measurements are made within formations of interest and can be compared with the geological information obtained from the same hole. Just as surface surveys 'look down' at the subsurface, so surveys in near-vertical boreholes through gently dipping strata can 'look sideways' and so can investigate beyond the immediate zone surrounding the borehole that, as we shall see shortly, has been affected by the drilling process, so providing some types of information that are not available even from cores taken from the hole.

18.2 Drilling and its effects on the formations

The physical properties of the geological formations in the vicinity of a borehole are often affected by the drilling process, so this will be described briefly. Drilling is usually done using a rotating bit that grinds away the formations to produce cuttings from shales, sand from unconsolidated sandstones, or chips up to a few millimetres in size from solid rock. The bit is fitted to the bottom of the drill stem, which typically consists of 10-m lengths of steel pipe screwed together. The bit may be turned by rotating the whole drill string of 10-m pipes from its top, but more commonly nowadays the bit is turned by the mud being pumped through a turbine just behind the bit. Turbine drilling allows much greater control of drilling direction. Down through the drill stem is pumped drilling fluid, usually termed **mud;** this has several functions: To cool and lubricate the bit, to carry the chips up to the surface, to stabilise the wall of the borehole, and – by its weight – to prevent any high-pressure gas encountered from blasting out of the hole. Therefore, it is not common or garden mud, but a mixture of ingredients formulated to produce the required rheological properties such as density and viscosity. Usually these solids are made into a thick liquid using freshwater, but sometimes salty water or oil are used. The nature of this base affects the physical properties of the mud (principally electrical conductivity), which have to be measured for they affect the geophysical measurements, both because the measuring instruments are immersed in it and because the mud penetrates the surrounding rocks and modifies their properties.

Because a permeable formation such as sandstone acts as a fine filter, a layer made up of the solids in the mud is deposited on the sides of the hole as **mudcake** (Fig. 18.1). The formation is invaded by the liquid of the mud, the **mud filtrate,** to a distance that depends on the porosity of the formation and characteristics of the mud. Nearest to the hole is the **flushed zone,** in which the fluids are entirely mud filtrate (apart from some residual fluid that cannot be removed); next is the **transition zone,** with decreasing replacement until at a sufficient distance is the **uninvaded zone,** quite unaffected by the drilling. In very permeable and porous formations the mudcake builds up quickly and forms a barrier to further invasion. In less-permeable, low-porosity formations the buildup is slow and invasion can be very deep.

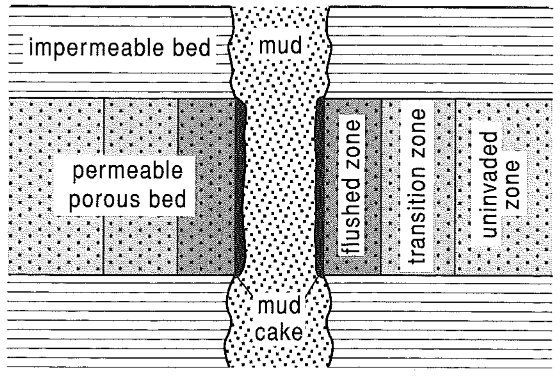


Figure 18.1 Effect of drilling mud.

These radial zones and the fluids in them are identified by subscripts, for example ρ_m, ρ_{mc}, ρ_{mf}, ρ_{xo}, ρ_i, ρ_t, ρ_g, ρ_w, and ρ_s refer to resistivities of mud, mudcake, mud-filtrate, flushed zone, invaded zone, uninvaded zone, gas, water, and adjacent bed respectively. (An oddity is that *o* is usually used for oil except in resistivity, where ρ_o is the resistivity of formation 100% saturated with water.)

Before hydrocarbons are extracted, holes are cased with steel piping, which is cemented to the wall of the hole, and as this provides an additional obstacle to measuring the properties of the surrounding rock, most measurements are taken in the **open hole** before casing. However, measurements are sometimes taken in a **cased hole,** either because the walls are unstable and the topmost part of the hole (where the pressure of the mud is low) has had to be cased, or because they are needed after extraction has begun. The diameter of the casing is reduced downwards in steps, with that at the bottom of a hole used for producing hydrocarbons commonly 120 mm, though a deep hole can start as a metre across at its top.

Later, the casing of a hole that is to produce is perforated where it passes through formations containing hydrocarbons, to allow their extraction. To facilitate precise location of the perforating gun down the hole, the collars where the lengths of drill pipe screw together are sometimes 'marked' by radioactive 'bullets', which can be located later by the γ ray logging tool (Section 18.5.4).

18.3 Sources of information from a borehole: Logs

The variation of a property down a borehole is recorded against depth as a **log** (e.g., Fig. 18.2). The most obvious log is a description of extracted cores, to provide information of lithology, microfossils, permeability, porosity, and fluids. These logs are used for geological correlation between different wells across an oil field and for the quantitative interpretation of the geophysical logs. The ideal, of course, would be to obtain continuous core, but this is very slow and expensive, for it requires the drill string to be withdrawn for each 10-m length of core; therefore, it is done only for formations of special interest, usually potential oil-producing formations when they can be identified in advance. After drilling, samples may be obtained by **sidewall sampling.** Samples of fluids are also taken with a **formation tester,** for identification and measurement of their properties, to aid interpretation of some of the geophysical measurements. As well as being very expensive, cores do not provide all the required information, which is obtained in other ways.

The first log to be obtained is the **drilling time log,** which records the rate of drilling progress, because this depends upon the nature of the formation. The chips carried to the surface are filtered from the mud and examined to provide the **mud log.** This gives an imperfect record of the formations penetrated by the drill below, because chips travel to the surface at rates that depend on their size and density, so chips of different formations may become mixed, while soft formations that wash out or soluble ones like salt may not yield any chips at all.

Geophysical measurements are made by sophisticated instruments suspended by a wire, as they are pulled to the surface by a winch fitted with a depth counter. The instruments are called **sondes** or **tools,** and the measurements they produce are known variously as **wire-line logs, geophysical well logs,** or simply **well logs.** Figure 18.2 illustrates a typical arrangement, and also shows logs for SP (self-potential) and resistivity, with scales increasing to the left and right respectively. Well logging is sometimes carried out during drilling – which has therefore to be interrupted for a few hours – as well as at its completion, and also before and after casing, and – in the case of a production well – at subsequent intervals.

18.4 Geophysical well logging in the oil industry

In Section 7.10.1 it was explained how a hydrocarbon trap often consists of a porous reservoir rock containing the oil or gas, which is prevented from leaking to the surface by an impervious cap rock. Oil accumulations occur in such reservoirs, and well logs have particular importance for their identification and evaluation, but the most important properties of the rocks of a reservoir – such as porosity, hydrocarbon saturation, and permeability – are not simply related to the quantities that can be measured by geophysical tools, such as electrical resistivity or self-potential. Consequently, many different measurements are usually made and combined to estimate the quantities of interest, as well as making allowance for the changes produced by drilling. This section describes the main reservoir properties with an outline of how they relate to the physical properties that are measured. To simplify the discussion, the porous reservoir rock will usually be taken to be a sandstone and the impervious cap rock as shale.

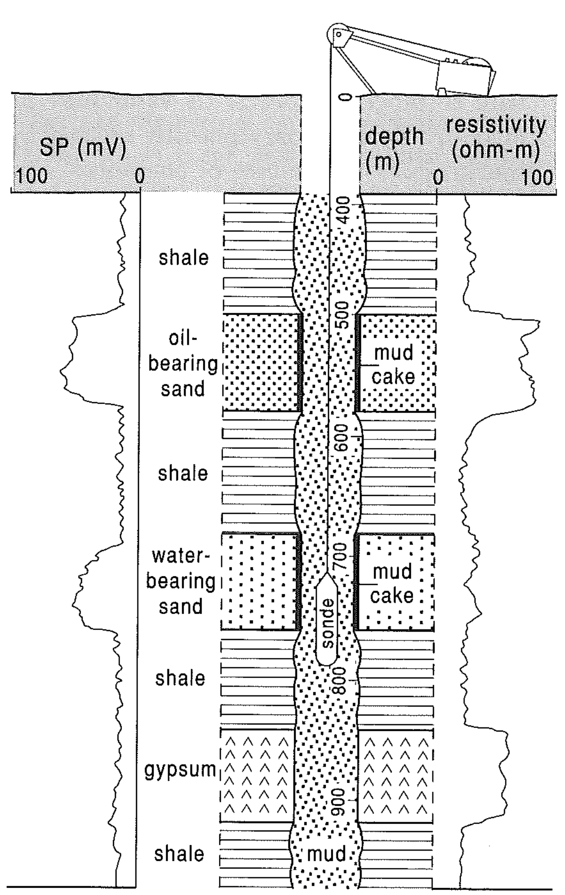


Figure 18.2 A typical well-logging arrangement and two logs.

(i) The **porosity,** ϕ, is the fraction of the rock that is occupied by pore space. It is usually the primary or matrix porosity of sandstones due to the spaces between the grains, but its value will be decreased by any shale content (shaliness) of the sands, for the shale will tend to block the pores. Its value may be increased by secondary porosity created by fractures or – in the case of limestones – by solution.

We saw in Section 12.2.1 that most rocks are electrically conducting only because the pore spaces contain water (except at shallow depths). Thus porosity and electrical resistivity (or conductivity) are related; however, conductivity also depends on the fraction of the porosity that contains water – rather than hydrocarbons, which are insulating – the salt content of the water, and the temperature. Porosity affects other physical properties of the rocks, notably density and seismic velocity, so it can be measured indirectly, while the fluid that fills the pores can also be detected because – whether water, oil, or gas – it is rich in hydrogen. Density, seismic velocity, and hydrogen content can be measured in boreholes, although they too partly depend on other rock characteristics, such as lithology, what the fluid is, and the shale content or shaliness. However, by combining the results of various logs porosity can be estimated.

(ii) The **hydrocarbon saturation,** S_{hc}, the fraction of the pore volume occupied by hydrocarbons. The greater its value the less the **water saturation,** S_w – the fraction occupied by water – as $S_w(1 - S_{hc})$, and so the higher the resistivity of the formation, for hydrocarbons are electrically insulating.

(iii) The **permeability,** k, is a measure of the ease with which fluids can pass through a bed. In general, it depends strongly on porosity but cannot be reliably estimated from it. Fine-grained rocks of high porosity usually have low permeability, while some rocks such as limestone of low porosity may have high permeabilities due to fractures.

Permeability can be measured directly in the laboratory on samples of rock but not as such in boreholes; instead, it is estimated from the porosity after comparing the values of porosity and permeability of a number of samples from the same formation. The practical unit of permeability is the millidarcy, abbreviated to md, and high-permeability rocks are in the range 10 to 100 md. (A material has a permeability of 1 darcy when a fluid of one centipoise viscosity moves at 1 cm/sec under a pressure gradient of 1 atmosphere/cm.)

(iv) The thickness of the permeable formations, from which any hydrocarbons will be extracted, can be estimated from the logs, for most show a change at the junction with impermeable beds, as illustrated in Figure 18.2.

These are the most important quantities that need to be known about a reservoir. Ultimately, what needs to be deduced is the amount of hydrocarbons present and the ease with which they can be extracted. The amount depends on the volume of the reservoir times the fraction of it that is hydrocarbons. In turn, the volume is found from the average of its thickness measured at a number of places over the extent of the field times the area of the field, while the fraction is the product of the porosity, ϕ, and hydrocarbon saturation, S_{hc}.

(v) But not all of the hydrocarbon in a formation, particularly oil, can be extracted, for some adheres to the grains. This **residual hydrocarbon saturation** can be measured before the hydrocarbons are extracted, for it is the amount remaining in the flushed zone, which can be estimated from its resistivity, ρ_{xo}.

The above quantities are determined from measurements of resistivity, SP, and so on. Other quantities, such as temperature, are also needed because they affect resistivity, while further logs are needed when holes have had to be cased, to improve the estimates. Thus many different types of logs are in use, with a selection employed in any given hole, and their results are combined.

The sections that follow describe the most common geophysical logs developed for use by the hydrocarbon industry, as well as some physical ones like the calliper log. How they are combined to give quantities needed for hydrocarbon exploration and extraction will be explained where appropriate. Some of these logs are useful outside the oil industry, so some other applications will be pointed out in Sections 18.6 and 18.7.

18.5 The most commonly used logs

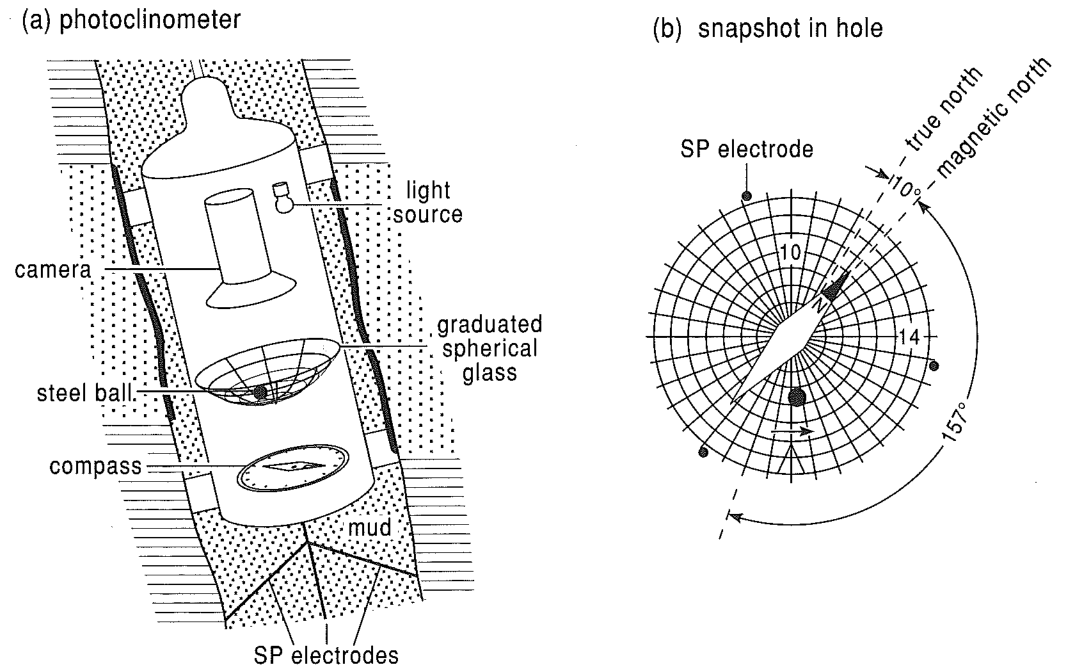
18.5.1 The measurement of strata dip, borehole inclination, and diameter

Geophysical measurements in boreholes are used to estimate properties of reservoir rocks away from the borehole, and as some of these depend on the dip of the strata, the inclination of the borehole, and its diameter at the point of measurement, these quantities need to be measured.

Though the regional dip of a particular interface can sometimes be obtained from its positions in three or more boreholes not in a straight line, in practice there are seldom enough suitable boreholes to allow for variations in dip, and there may also be doubt whether major discontinuities occur between them. Instead, a **dipmeter** is used to determine the dip of strata within a single borehole by recording the value of the SP (spontaneous potential) value at three electrodes 120° apart (Fig. 18.3), each relative to an electrode at the surface.

The method relies on formations having different potentials (how these are produced is explained in the next section) so that if the formation boundary is not perpendicular to the hole the electrodes record changes at different depths of the tool in the hole. The orientation of the tool and the deviation of the hole from the vertical must also both be known, and these are measured by a **photoclinometer** (Fig. 18.3a), which is run at the same time as the dipmeter. This has guides to keep its axis parallel to that of the hole. A steel ball rolling in a concave graduated glass dish shows the inclination by the distance of the ball from the centre. Below the dish is a compass to measure orientation. A camera with a flash, operated from the surface, takes photographs at intervals to show the compass needle, the ball, and the three dipmeter electrodes (Fig. 18.3b).

The diameter of the hole varies with the lithology. For example, in a sand–shale sequence, mudcake builds up on the permeable sands, reducing the diameter, as shown in Figure 18.2; in contrast, the diameter in the shale is increased because the vigorous flow of drill mud washes it away, so the presence of mudcake is a good indicator of high permeability. The thickness of the mudcake also needs to be known for interpreting the results of several of the geophysical logs to be described, for measurements of the properties of the surrounding rock have to be made through it. The diameter of the hole is also needed for calculating the amount of cement needed to fix the casing.


(a) photoclinometer

(b) snapshot in hole

Figure 18.3 The photoclinometer with dipmeter electrodes.

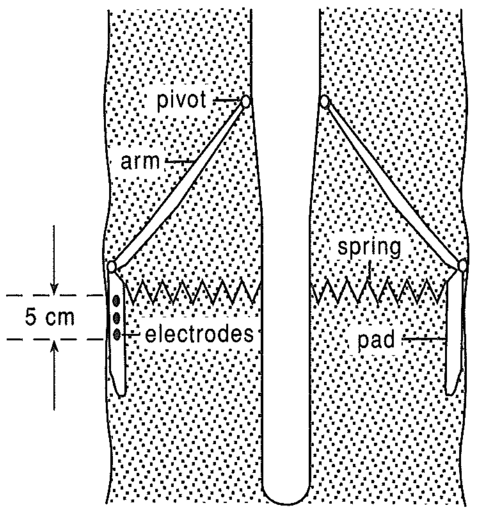


Figure 18.4 The calliper log with microlog electrodes.

The **calliper log** measures the diameter using a calliper sprung lightly against the sides of the hole (Fig. 18.4), and their extent is converted by an electromechanical device into an electrical signal suitable for recording. Due to subsurface stresses, holes are seldom circular in section, so the tool usually has more than one calliper. Sometimes an arm of the calliper log includes electrodes for the microlog described in Section 18.5.3.

18.5.2 The self-potential, SP, log

The **SP log** has two important uses, in addition to revealing the dip. One is that it indicates the positions of permeable formations, as already shown in Figure 18.2. The second use is to measure ρ_w, the resistivity of the formation fluid, needed to help calculate S_{hc}, the fraction of the pore space occupied by hydrocarbons.

Self-potential, as described in Section 13.2.1, was mainly of interest in connection with minerals that are electronic conductors, such as massive sulphides and graphite. Self-potential in oil wells arises in quite a different way, where there are adjacent formations with different concentrations of electrolyte such as a shale–sand contact (Fig. 18.5). This is because shale has a sheetlike structure with negative oxygen ions at the edges, which repel the negative ions of the salts dissolved in the water, so allowing positive but not negative ions to pass through. Because the formation water in the uninvaded sands has a much higher concentration of salts than the water normally used to make up the drilling fluid, ions tend to flow between them to equalise the concentrations, but because negative ions are unable to pass through the shale, the current flows in elliptical paths as shown. The associated potential difference (p.d.) is less than 100 mV, considerably smaller than the p.d.'s that can be generated by sulphides.

The reading of the SP log does not change abruptly at the contact but varies either side over a distance that depends on the ratio of the resistivity of the uninvaded formation to that of the mud, ρ_t/ρ_m, as comparison of columns (i) and (ii) of Figure 18.6 reveals. The position of the contact is given by the point of inflection shown by the dashed lines. The SP only reaches a constant value in sufficiently thick beds, and this value is called the static SP, or **SSP.** The cleaner the sand the greater the SSP, so the actual value is important, for the presence of shale within the sand reduces its porosity and its permeability, both of which adversely affect its value as a reservoir. The percentage of shale within the sand is roughly equal to the value of the SSP of the formation expressed as a percentage of the SSP of clean sand. How the value of the SSP is involved in the calculation of the water saturation, S_w, is explained in Box 18.1.

The second use of SSP is to determine ρ_w, the resistivity of the formation fluid, using the formula

$$\text{static self-potential,}\quad \text{SSP} = -K\log\frac{\rho_{\text{mf}}}{\rho_w} \qquad \text{Eq. 18.1}$$

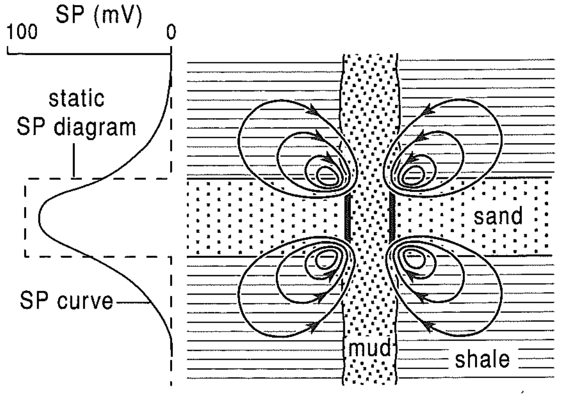


Figure 18.5 Origin of SPs in an oil well.

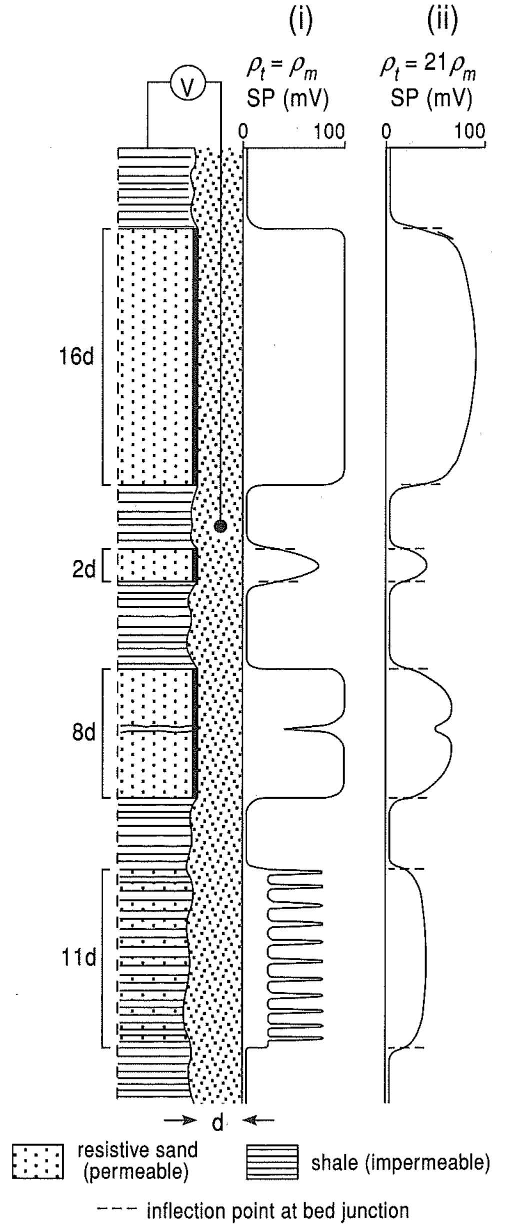


Figure 18.6 Variation of SP log with bed thickness.

where ρ_{mf} is the resistivity of the mud filtrate determined from a sample in a laboratory and K is a coefficient that depends on temperature, an average value being 71 at 25°C. Here ρ_w is not important in itself but is needed to determine the saturation, S_w, the proportion of the pore space occupied by water, using the equation

$$\text{saturation,}\quad S_w = \sqrt{\frac{F\rho_w}{\rho_t}} \qquad \text{Eq. 18.2}$$

where F is the **formation resistivity factor,** defined as the ratio ρ_o/ρ_w; ρ_o is the resistivity when the formation is 100% saturated with water, and ρ_t is the true or uninvaded **formation resistivity,** measured using one of the deep resistivity tools described in the next section.

18.5.3 Resistivity logs

The **resistivity log** is used to determine the fraction of the pore space that is occupied by water, called the water saturation, S_w (in turn used to calculate S_{hc}, the fraction that is hydrocarbons, using $S_{\text{hc}} = 1 - S_w$). This is possible because the resistivity of sediments, ρ_t, depends on the amount of water in their pores. However, resistivity also depends on the resistivity, ρ_w, of the water in the pores (which depends on the salt content) and what volume of the rock is pore space (i.e., its porosity, ϕ), and these have to be taken into account.

A further complication is that some rocks, particularly shale, have quite a low resistivity though they contain little water. However, using the SP log in addition to the resistivity one can distinguish such rocks (see Fig. 18.2) from porous ones containing water. Thus shales and water-bearing sands both have low resistivity, but whereas the sands show a high SP deflection due to their high permeability, shales show a low SP. Oil-bearing sands differ from both these rocks by having high SP and high resistivity. Other rocks that have low porosity, such as gypsum, have high resistivity and low SP. This simple example illustrates how the value of logs is enhanced by combining their results.

In Chapter 12 we saw how electrical resistivity variations beneath the ground may be measured using a four-electrode array on the surface, and in Chapter 14 how its inverse, conductivity, may be obtained by inductive methods. Both can be adapted to measure variation of resistivity down a borehole. In surface resistivity methods, electrodes are put into the ground to make contact; in boreholes, contact is through the mud, which therefore must be conducting. An example is the lateral sonde shown in Figure 18.7, which includes two potential electrodes, M and N, and a current electrode, A, the second current electrode, B, being on the surface.

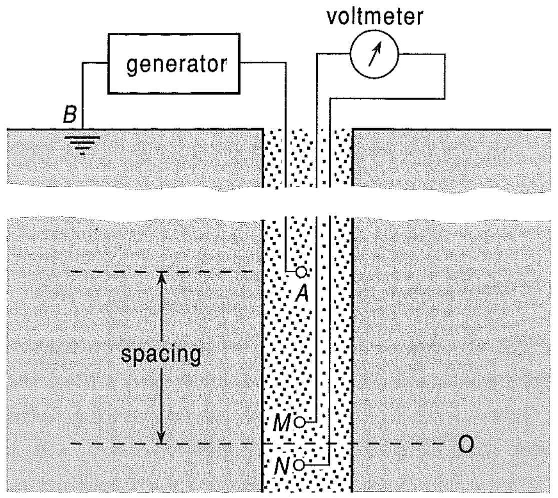
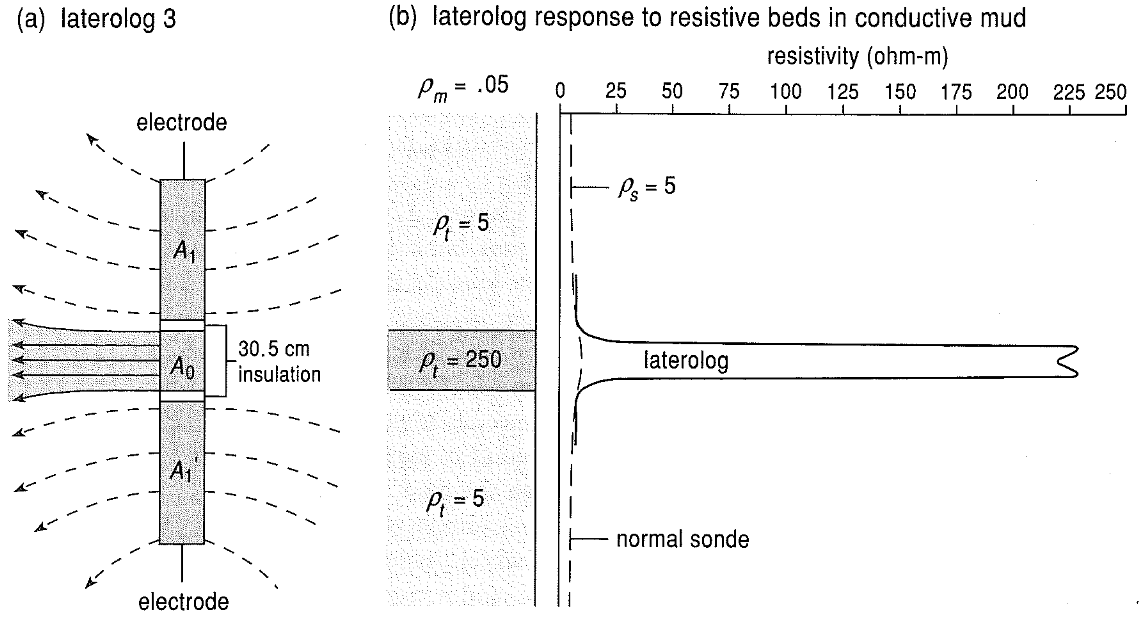


Figure 18.7 The lateral sonde.

Determining the important quantity S_w (water saturation) requires measuring the true formation resistivity, ρ_t (i.e., the resistivity in the uninvaded zone), but the electrodes in the hole are separated from it by, successively, mud, mudcake, the flushed zone, and the transition zone, which have differing resistivities. In principle, this could be solved by using a 'sideways' version of vertical electric sounding, VES, but this would be valid only provided the electrodes were not near a change of lithology and would be time-consuming to carry out. The requirement is for a tool with a large radius of investigation and fine vertical resolution. This cannot be met by a single tool. Resistivity and conductivity tools have been developed with different radii of investigation in a variety of geological situations, and combination tools have been developed in which more than one kind of log is obtained at the same time.

A related drawback for this purpose of the arrays described in Chapter 12 is that, if the mud is much less resistive than the formation, little current would penetrate beyond the mud unless the electrodes were far apart, which, as was just pointed out, would probably place them within a different lithology. This situation could occur in offshore drilling, where salty muds are used. To overcome this problem, extra electrodes are used to concentrate or 'focus' the current sideways through the mud into the formation. Such sondes are known as **laterologs**, the simplest being the laterolog 3, which employs three electrodes (Fig. 18.8a). The current electrode, A_0, is at the centre of the sonde, with symmetrically to either side electrodes A_1 and A_1', which are maintained at the same potential as the central electrode A_0 to prevent the current flowing towards them (current can only flow from higher to lower potential), thus driving it into the formation. (A current and a potential electrode at the surface make up the usual four electrodes.)


(a) laterolog 3

(b) laterolog response to resistive beds in conductive mud

Figure 18.8 The laterolog 3.

To maintain the three electrodes at the same potential requires that the current be varied depending on the apparent resistivity of the formation the sonde is in, and so the current can be calibrated in units of resistivity, ohm-m.

The great advantage of the laterolog compared to an unfocussed sonde in high-resistivity formations is illustrated in Figure 18.8b. The formation resistivity is 250 ohm-m, whereas that of the mud is only 0.05 ohm-m. The laterolog gives over 90% of the correct value, whereas the unfocussed sonde gives less than 10%. Modern laterologs include different electrodes to give deep and shallow penetration into the walls of the borehole, and so allow ρ_t and ρ_i to be determined.

To measure the resistivities of the various zones between the sonde and the uninvaded zone, needed for correction, requires microresistivity sondes with electrode separations considerably smaller than those of the sondes for deep penetration described so far. An example is the **microlog**, in which the electrodes are mounted close together and make contact with the mudcake through button-shaped electrodes mounted flush with the surface of a rubber pad; this is pressed against the side of the hole by springs and so is unaffected by the mud. Figure 18.4 shows a version in which the microlog electrodes are built into one of the pads of the calliper logging tool. It contains 3 electrodes about 2.5 cm apart in a vertical line. They can be connected in two combinations, together with an electrode at the surface, to give logs from which ρ_{mc} and ρ_{xo} may be estimated. If ρ_{mf} is known from mud samples and the residual oil saturation is known or assumed, then the formation factor, F, and hence the porosity, ϕ, may be estimated for a nonshaly sand.

An important use of the microlog is to determine the exact location of formation boundaries, especially with thin beds or in conducting muds when the SP log is not very precise (Fig. 18.8). Its response in mudcake is affected by fluids that leak out of the formation next to the hole, with oil giving a higher resistivity than water. The log can therefore reveal the boundary between oil and water in a permeable formation.

The microlog is run with the springs extended on the way up but is also run on the way down with the springs collapsed to give a mud log that shows the variation of mud resistivity with depth. This can be used to identify levels at which fluids – such as oil or water – are entering the hole, for they will have resistivities different from that of the mud. This is useful for the identification of fluid-bearing permeable formations and oil-water interfaces.

Resistivity sondes require that the hole contains a conducting fluid to allow electrical contact with the formation. The **induction log** was introduced for those holes that do not meet this requirement (i.e., if they were drilled with air or an oil-based mud, or if they are dry or – as some old wells – lined with concrete or bakelite). The induction logging sonde has transmitting and receiving coils like the Slingram system used for surface surveys (Section 14.2.1), but these are arranged with their axes along the borehole (Fig. 18.9). The strength of the currents they induce – 'eddy currents' – depends on the resistivity of the surrounding rocks. In practice, the sonde has additional coils to produce focussing analogous to the extra electrodes of the laterolog so that different depths of penetration can be selected. The induction sonde has the greatest penetration of any resistivity tool, up to 5 m or more from the borehole. It is therefore best suited for the determination of ρ_t and so is routinely used in water-filled holes as well as the special holes mentioned above.

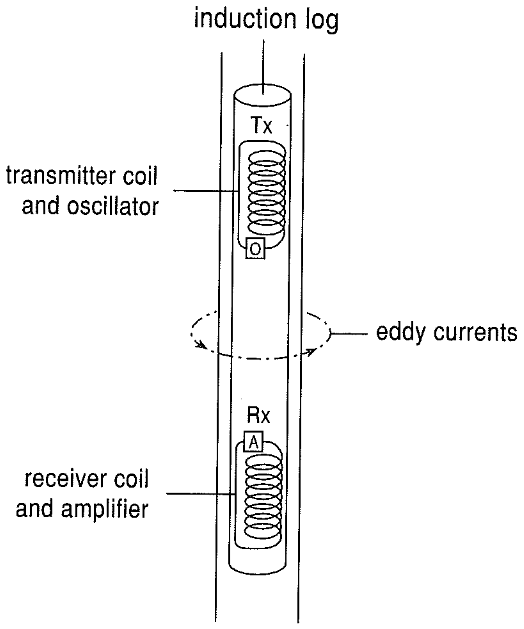


Figure 18.9 The induction log.

BOX 18.1 Determination of hydrocarbon saturation S_{hc}

The determination of S_{hc} is based on the assumption that the pore space is saturated with fluids – water, hydrocarbons, or a mixture. The fraction of the pore space that is water, S_w, can be deduced from measurements of electrical resistivity, because the larger the fraction the lower the resistivity. However, resistivity also depends on the porosity of the rock – a rock with very low porosity will have a comparatively high resistivity even if the pores are full of water – and on the resistivity of the water in the pores:

$$\text{water saturation,} \quad S_w = \sqrt{\frac{\rho_0}{\rho_t}} \qquad \text{Eq. 1}$$

where ρ_t is the formation resistivity as it actually is, while ρ_o is the value it would have if the pores were entirely filled with water, rather than partly with hydrocarbons. ρ_o of course depends on ρ_w, the resistivity of the water in the pores, which is deduced from the self-potential log. They are related by

$$\frac{\rho_0}{\rho_w} = F, \text{ the formation factor} \qquad \text{Eq. 2}$$

F is less than 1 because the pores make up only a fraction of the rock – the porosity, ϕ, and F is related to it by

$$F = \frac{a}{\phi^m} \qquad \text{Eq. 3}$$

where a and m are constants that depend on the rock type; for sandstones, their average values are 0.62 and 2.15 for a and m respectively. Equations 2 and 3 can be combined to give

$$S_w = \sqrt{\frac{0.62 \times \rho_w}{\phi^{2.15} \times \rho_t}} \qquad \text{Eq. 4}$$

This is a rearrangement of Archie's Law (Eq. 12.3) with $a = 0.62$, $m = 2.15$, and $n = 2$.

As explained in Section 18.5.2, the SP arises because the concentrations of electrolytes in the mud and sand fluids are different, with the result that the fluids have different electrical resistivities, and the SP is related to them by Eq. 18.1:

$$\text{static self-potential,} \quad \text{SSP} = -K \log \frac{\rho_{mf}}{\rho_w} \qquad \text{Eq. 5}$$

Here ρ_w is found from the value of SSP, using the equation and inserting the value of ρ_{mf}, the resistivity of the mud filtrate, which is measured in the laboratory on a sample, while K has a value that depends on the temperature (it is 71 at the typical temperature of 25°C). The determination of ρ_t is described in Section 18.5.3.

Finally, S_{hc} is found using $S_{hc} = 1 - S_w$.

Measuring resistivity is important because it depends on porosity and the fraction of the pore space occupied by hydrocarbons, S_{hc}, two quantities that are needed for estimating the quantity of hydrocarbons in a reservoir. In the simplest case of a shale cap rock over a sandstone containing only water and hydrocarbons, the crucial logs in the hydrocarbon industry are resistivity and/or induction logs, together with the calliper log of Section 18.5.1. Under ideal conditions they enable the extent of permeable beds and the hydrocarbon saturation to be determined (Box 18.1). However, conditions are rarely this simple. Reservoir formations are seldom clean, as pore spaces may be partially blocked with shale, there may be fractures in addition to the matrix porosity, the matrix may be unknown or a mixture of lithologies, and it is not known whether any hydrocarbon present is oil or gas. These all affect the reservoir resistivity. Some of these unknowns can be determined by logs involving the use of natural and induced radioactivity and of seismic velocity.

As mentioned earlier, S_{hc}, the hydrocarbon saturation, is only one factor that determines the resistivity reading, so to deduce it requires combining the results of several logs. This is described in Box 18.1.

18.5.4 Radioactivity logs

These logs involve the use of radioactivity (Section 15.12.1) and are mainly used to identify lithologies and to help deduce density and porosity, particularly when a hole is cased, for – unlike the electrical logs – they will function with steel casing in place.

Radioactivity logs belong to two groups. Those of one group passively measure the natural γ ray radioactivity of the formations, while those of the other measure the activity induced by strong radioactive sources in the sondes.

The simple **natural γ ray log** of the first group gives the total natural γ ray activity, which is due mainly to potassium (K), thorium (Th), and uranium (U), as explained in Section 16.2.1. Of lithologies commonly present, usually shales have the highest activity; sands are intermediate; limestones, dolomite, and quartz are low; while anhydrite, salt, coal, and chert are least active. Occasionally, potash beds, ash bands, and radioactive ores with higher activity than shales may be encountered. As shales are the most radioactive common sediments, the tool was first used primarily for identifying them, and it is therefore often referred to as the 'shale log', for the calculation of shale content is an important use of the log, even when an SP log is available. Figure 18.10 shows how well the two logs agree in an open-hole (uncased) shale–sand sequence. Radioactivity is measured in API (American Petroleum Institute) units defined by the activity of specially made concrete in a well in Houston, Texas, where radioactivity logging equipment is calibrated. However, it should be interpreted with care, for not all shales are radioactive, and not all radioactive formations are shales. Although the γ ray activity of shales varies widely on a worldwide basis, it tends to be constant in a particular field. It is therefore used to estimate shale content, assuming the maximum value on the log means 100% shale and the minimum value means no shale.

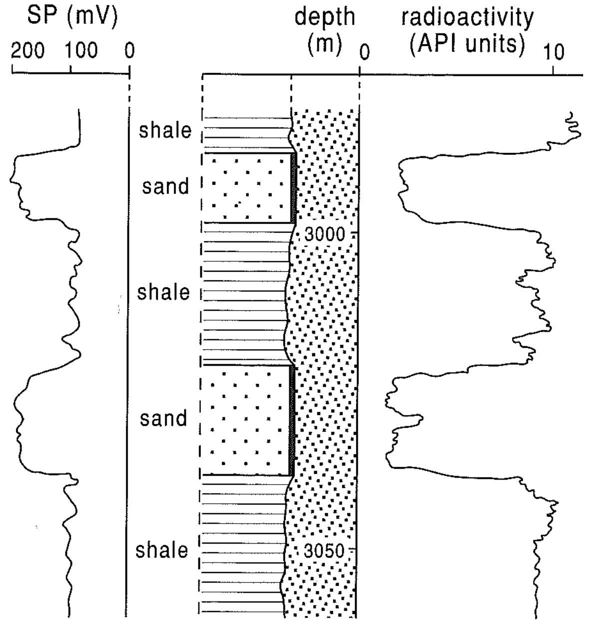


Figure 18.10 γ ray and SP logs in a sand–shale sequence.

The log has other uses, which include monitoring the injection of cement behind the casing, by including a radioactive tracer in the cement. Another is to monitor depth precisely, as mentioned earlier: Radioactive 'bullets' incorporated into the collars at joints in the casing produce sharp signals in the log. Depth can be measured more precisely this way than by using the wire-line winch counter, because of stretching of the wire. The natural γ ray log is usually run together with other logs in combination tools.

The **spectral γ ray log** is the borehole equivalent to the γ ray spectrometer described in Section 16.2.1. It differs from the simple γ ray log in recording separately the activities of K, Th, and U, so allowing more precise identification of shales, for these differ from other rocks in their relative proportions of the three elements. The proportions of U and Th may also be used to identify depositional environments of the formations, for uranium is concentrated in marine sediments and thorium in terrestrial ones, as explained in Sections 15.12.1 and 16.2.3. The thorium count is used in preference to the total count for estimating shale content, for potassium and uranium are more common in other rock types.

The radioactive logging devices that contain a radioactive source are of two main types: One is the **gamma–gamma** (γ–γ), or **formation density, log** (Fig. 18.11). It has a strong source of γ rays (e.g., ^{137}Cs) at one end of the tool; at the other is a scintillometer (described in Section 16.2.1). The scintillometer is shielded so that it cannot receive rays directly from the source, so only γ rays that result from scattering from the surrounding rock are counted. Most rocks of interest in oil wells have densities in the range 2 to 3 Mg/m^3, and in this range the count decreases exponentially with density (Fig. 18.12), allowing the instrument to be calibrated directly in density.

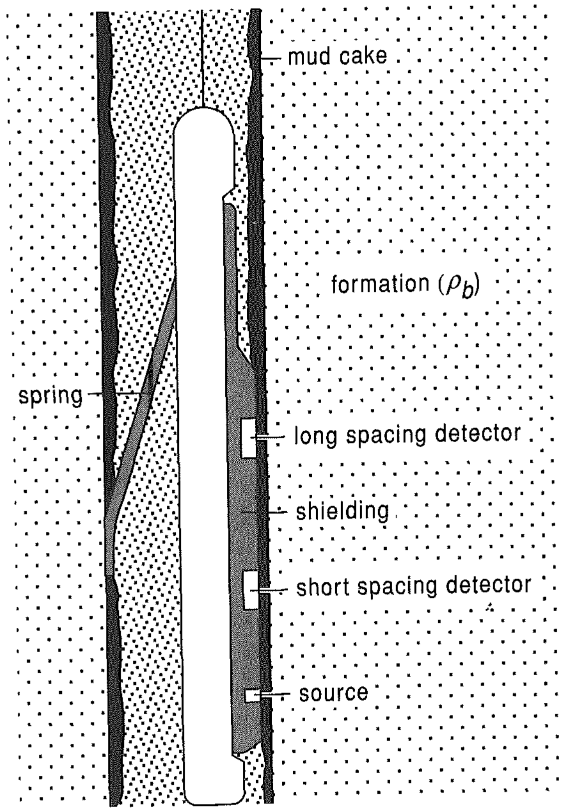


Figure 18.11 The γ–γ, or formation density, logger.

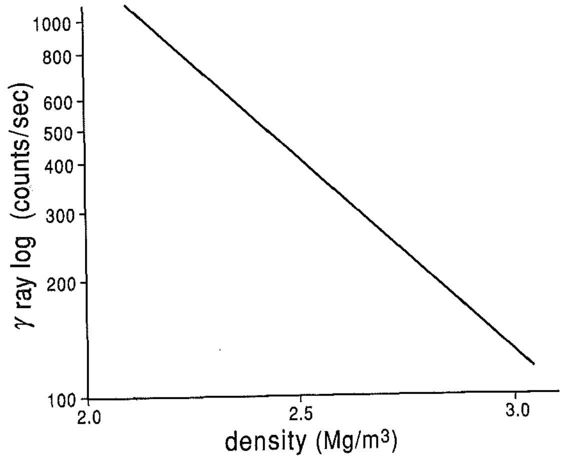


Figure 18.12 Relation between density logger count and density.

Some γ rays are also absorbed or scattered by the mud and mudcake between the tool and the formation, affecting the reading. To reduce this, the tool is held against the side of the hole by a strong spring to scrape through the mudcake as it is pulled up the hole. However, this may not be totally effective, so the thickness of any remaining mudcake is measured by having two detectors placed at different distances from the source; these are affected differently by the mudcake, so comparing their readings allows a correction to be made.

The bulk density of a porous rock, ρ_b, depends on the density of the matrix, ρ_{ma}, the porosity, ϕ, and the density of the fluid in the pores, ρ_f:

$$\phi = \frac{(\rho_{\text{ma}} - \rho_b)}{(\rho_{\text{ma}} - \rho_f)} \qquad \text{Eq. 18.3}$$

The values of density obtained from the log are also used in the interpretation of surface gravity and seismic data, as both of these depend on density (Chapter 8 and Box 4.1). It is also useful, sometimes combined with other logs, for recognising fractures, in compaction studies, and – as demonstrated below – in the identification of lithology.

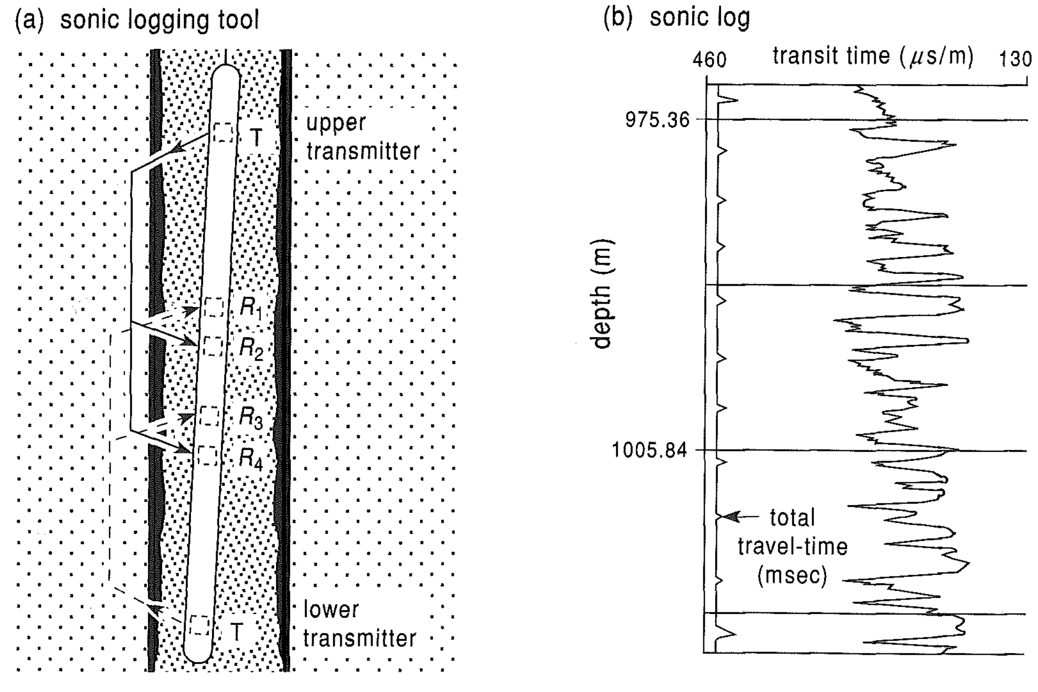
The second type, the **neutron** or **porosity logging tool**, is similar to the gamma–gamma tool in having two scintillation counters held against the side of the hole but differs in having a radioactive source (e.g., plutonium–beryllium) that bombards the formation with fast neutrons rather than γ rays. Neutrons travelling through the formation only slow down significantly when they collide with atoms of a similar mass, that is, hydrogen atoms. Once they have been slowed by repeated collisions, they are absorbed into the nucleii of the heavier atoms present and cause them to emit γ rays, some of which are recorded by the counters. The more rapidly the neutrons slow down, the nearer to the counters the γ rays are produced, resulting in a stronger signal. As hydrogen is an important component of both water and oil, which fill the pore spaces, the response increases with porosity, which is why the log is also known as the porosity log. But the tool is calibrated to give the true porosity only in clean limestones filled with water; allowances have to made for other lithologies. This can be done by combining the neutron log with the density or the sonic log, described in the next section, as their responses also depend on porosity and lithology. The tool also responds to gas, which has many fewer hydrogen atoms per unit volume (referred to as having a 'lower **hydrogen index**'), but shows a porosity that is too low. Oil and water have almost the same hydrogen index.

As the two tools, γ ray and neutron, respond to permeability and fluids in a similar way to SP and resistivity respectively, they are used to replace them in cased holes.

18.5.5 The sonic log

The **sonic log** is a record of the seismic velocity, v_p, and is mainly used in the interpretation of seismic reflection sections. Values are combined with those of the density log to calculate the variation of acoustic impedance (Section 7.8.1) down the borehole. This is then used to calculate a synthetic seismogram, which can be compared with the observed one (Section 7.8.3). This allows seismic sections for parts of the hydrocarbon field that lack boreholes to be interpreted with more accuracy. Other uses are to measure fracture porosity and help identify lithologies.

The log operates in the same way as that of a surface seismic refraction survey of a dipping interface (Section 6.4), the dip occurring if the tool is oblique to the borehole (Fig. 18.13a), with the wall rock behind the mudcake being the higher velocity dipping layer. As with a surface survey, pulses are produced at each end (alternately), and for each transmitter there are two receivers (R_1 and R_3 for the lower transmitter in Fig. 18.13a) positioned far enough along the tool that the first arrivals at both are rays refracted from the wall of the borehole (Section 6.2). Therefore, their separation divided by their difference in arrival times gives the apparent velocity in the wall rock. The upward and downward velocities (corresponding to forward and reverse in surface surveys) will differ, but as the deviation of the tool from the borehole axis is small, it is sufficient to take their average for the velocity of the wall rock. The results are not presented as a velocity but its reciprocal, the transit time, Δt, usually measured in μs/foot, for imperial units are still widely used in the oil industry (1 μs/foot = 3.281 μs/m), but shown in μs/m in Figure 18.13b. Just to the right of the depth scale is a line with ticks or pips; these show the total travel time down from the surface, so that to deduce the travel time between any two depths it is only necessary to count the number of pips between them. This can be used to calculate interval velocities (Section 7.2), which are needed for converting two-way travel-times of surface seismic waves to depths; their values are obtained more directly than those calculated from moveout; and because they operate at frequencies of 20 to 40 kHz, compared with 5 to 50 Hz for surface reflection surveys, sonic logs resolve the boundaries more precisely – 50 cm compared with 50 m (Section 7.8.2).


(a) sonic logging tool

(b) sonic log

Figure 18.13 The sonic log.

The seismic velocity can also be used to estimate the porosity, because in any particular lithology the velocity depends on porosity, following the equation

$$\phi = \frac{(\Delta t_{\text{log}} - \Delta t_{\text{ma}})}{(\Delta t_{\text{fluid}} - \Delta t_{\text{ma}})} \qquad \text{Eq. 18.4}$$

where ϕ is the porosity, Δt_{log} is the transit time from the sonic log, Δt_{ma} is the transit time in the matrix and is measured on chips recovered from the circulating drilling mud, and Δt_{fluid} is the transit time in the fluid, also measured in the laboratory on a sample.

18.5.6 The temperature log

The most important use of the **temperature log** is for making corrections to the resistivity, for this is affected by the temperature as well as by the water saturation and so on. Temperature normally increases with depth in the ground, as was explained in Section 17.1.1. Temperature in a borehole also generally changes with time as it returns towards equilibrium after the disturbance caused by drilling (Box 17.1), so resistivity logging is usually accompanied by a temperature log, which is easily done by incorporating an electrical thermometer in the sonde.

The temperature log may also indicate a change of lithology: Because different lithologies have different thermal conductivities, the same heat flux up through a column results in a higher temperature gradient in lithologies with lower conductivity, such as shale, and a lower gradient in a high-conductivity one such as salt, as follows from Eq. 17.2. Major interfaces of this kind therefore show up a kink on the temperature log. Even though the circulation of drilling mud makes the temperature almost constant down a hole, high-conductivity lithologies will return more quickly towards equilibrium – which can take months – as heat conducts in laterally from undisturbed regions, and so logs run before equilibrium is reached will still reveal the interfaces. The log also shows the location of zones containing gas at high pressure, for it cools due to its expansion into the hole.

A further use of the temperature log is to monitor the setting of cement between the casing and the walls, for this releases heat. Further, the highest temperatures occur where the cement is thickest, which is where shales have been washed out, as explained in Section 18.5.1, so the log can be used to relocate these formations, initially recognised from the resistivity log before casing, when the casing is to be perforated to allow extraction of hydrocarbons.

18.5.7 Cross plots

Well logging differs from most other geophysical methods, not only in being carried out down a borehole, but in relating the physical quantities measured to geological properties of interest, such as lithology, porosity, and fluid composition. Because of the variability of geological properties, the results of several logs have to be combined, and this can be done in several ways. For instance, we have encountered in this chapter four methods for estimating porosity, the key parameter needed for calculating the capacity of a reservoir. Which method is used depends partly on what other logs can be included in a tool (so reducing the cost) and whether the hole is cased (this prevents electrical logs being used). Generally, porosity estimates based on the formation resistivity factor *F* (Section 18.5.2 and Box 18.1) are subject to greater uncertainty than those using sonic, neutron, or density logs.

More reliable estimates can be found by using **cross plots**, in which two variables are plotted against one another (e.g., Fig. 18.14) and quantities such as porosity are read off along lines on this plot. This is particularly necessary in more complex lithologies that are formed of two minerals and for which the simple relationships between physical properties and porosity used earlier (Eqs.18.3 and 18.4) give poor results. Figure 18.14 illustrates the method for a neutron-density cross plot. Both tools are calibrated for water-filled limestone, so for this material the plot of density, ρ_b, against the neutron porosity, ϕ_n, gives a straight line called the limestone line. The position of a plot on the line indicates the porosity. Other lithologies give different lines, with porosity scales added as shown. A lithology that gives, say, values of 2.55 for ρ_b and 21 for ϕ_n plots at *p*, between the limestone and dolomite lines. A line is drawn through *p* that connects points on the two lines that have the same value of porosity, giving a value of 18%. The neutron-density cross plot has been found to give the most reliable porosity estimates. It also gives the composition of the lithology: From simple proportion of *p* along the line, it is 40% dolomite and 60% limestone, providing it consists of only these two minerals. If more than two lithologies are present, then other data (e.g., from the sonic log) have to be used. Figure 18.14 also indicates how specific minerals such as anhydrite can be identified from their position on the plot.

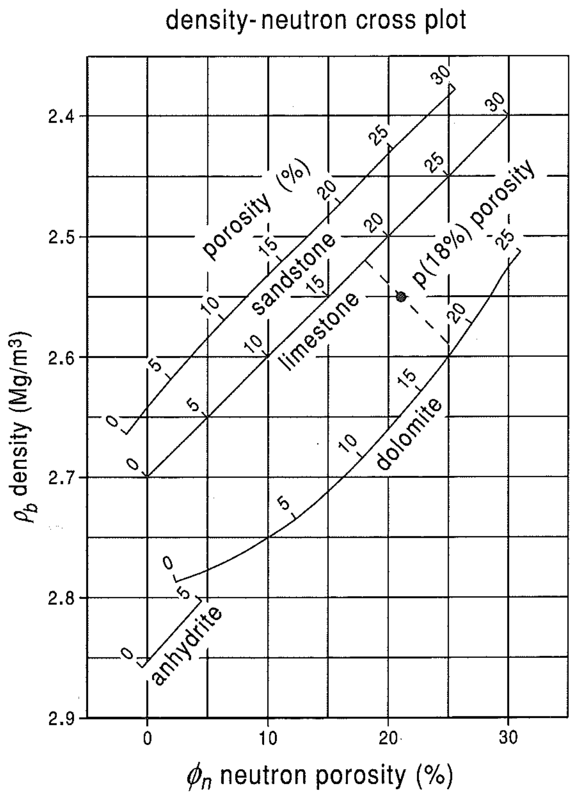


Figure 18.14 Neutron-density cross plot for estimating porosity and lithology.

Because valuable quantities can only be deduced from two or more physical measurements, a number of logs are run; often several that will function together are combined in a single tool or sonde. Common combination tools, each 10 to 20 m long, include induction, sonic and γ ray (referred to as an ISF–sonic–GR tool), and density, neutron, and γ ray (RDC–CNL–GR tool). More than one combination tool may be run successively. The cost of such sophisticated logging is extremely high, both because of the cost of the tools and operating trucks and for the interruption they cause to drilling or other operations, but they are economic because of the information they provide.

18.6 Geophysical logging outside the oil industry

Boreholes are routinely drilled for many other purposes: in mineral exploration and evaluation programs, for water location and extraction, for extracting geothermal energy, and for monitoring waste disposal sites. There are ocean and continental deep-drilling programs that aim to understand the Earth's deep crustal structure and history, and borehole logging is used to complement the information obtained from recovered core.

18.6.1 Mineral exploration

Drilling is particularly important in mineral exploration and evaluation programs, where holes are routinely cored to detect and quantify the presence of economic minerals. Often the information is incomplete because of missing core, or misleading because of rapid lateral variation of the mineralisation, so many holes are needed to detect and assess the mineralisation. Drilling is becoming more costly as exploration targets become deeper, so there is growing interest in extending the information from holes by making geophysical measurements in them. Deeper targets may also be beyond the depth of investigation of surface geophysical exploration methods. The depth of investigation may be increased by lowering instruments down the hole closer to the ore bodies. Therefore, it is important to get as much information as possible from the boreholes, and geophysical measurements greatly increase it, by detecting and assessing mineralisation missed by the hole or cores. As the holes are much smaller than those common for oil wells (diameters are 48 to 122 mm and depths often less than 100 m) and budgets much less lavish, the logging systems are simple and more portable (Fig. 18.2) than the large truck-mounted systems required for oil wells.

Some logs are adaptations of ones already described in connection with the hydrocarbon

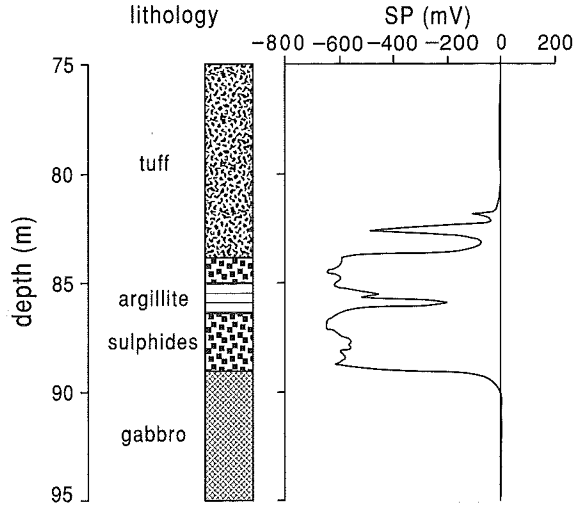


Figure 18.15 Self-potential log through a massive sulphide deposit, New Brunswick.

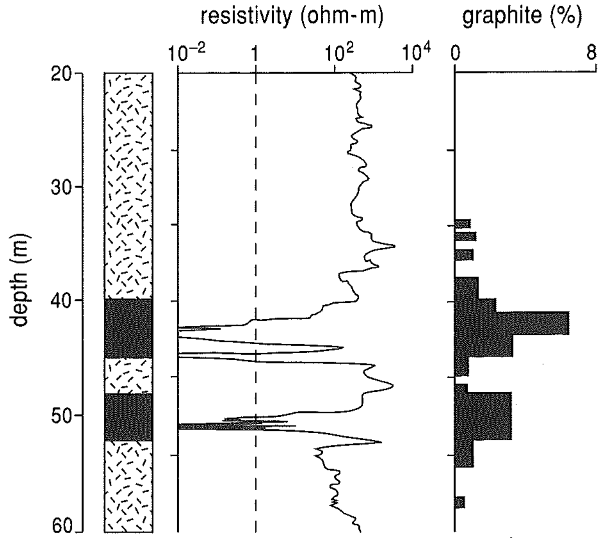


Figure 18.16 Resistivity through a graphite deposit, Canada.

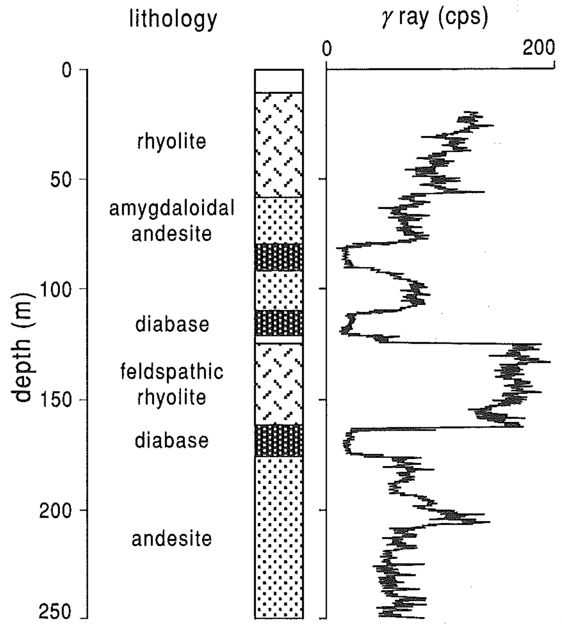


Figure 18.17 γ ray log, Buchan's Mine, Newfoundland.

industry, and some of their uses are described in the sections that follow, but others have been developed for use in mineral exploration and these are described later. The physical properties of interest are magnetic susceptibility, density, conductivity, and the IP effect of the rocks themselves, rather than resistivity, and so on related to the fluids in the pore spaces as in the hydrocarbon industry.

Figure 18.15 shows the SP log obtained through a volcanogenic sulphide deposit containing pyrite (FeS_2), galena (PbS), sphalerite (ZnS), and chalcopyrite ($CuFeS_2$). It was drilled to evaluate a surface anomaly, and continuous SP measurements were made between a nonpolarising electrode at the surface and an inert lead electrode in the hole. Large SP anomalies up to about 600 mV were observed in the mineralised zones intersected by the borehole, but smaller anomalies where there was no borehole mineralisation indicate other zones at some distance.

Figure 18.16 shows a resistivity log through a high-grade graphite deposit. The resistivity correlates strongly with the graphite content, increasing by several orders of magnitude as the content decreases. This correlation reduces the need for detailed sampling and chemical analysis of borehole samples, so illustrating the potential of logs in evaluating economic deposits.

Another example is given by Figure 18.17, which shows the γ ray response through a sequence of volcanic rocks. The rhyolitic rocks, which contain the most potassic feldspars, show higher responses than the diabase, which contains the lowest, and the andesites, with intermediate content.

We turn next to logs that are not adapta-tions of those used in the hydrocarbon industry but have been developed for mineral exploration and assessment.

18.6.2 Magnetic logs

Two kinds of magnetic measurement are made in boreholes, magnetic field and magnetic susceptibility (Section 10.6). We saw in Chapter 11 how magnetometers can be used on the ground, from the air, or from ships. Boreholes can be used to extend measurements downwards. The magnetometers used in a **magnetic field log** are fluxgates (Box 11.1) because they give continuous readings; by measuring three perpendicular components the total field can be calculated in direction as well as strength. Figure 18.18 shows the position of a borehole, BH1, that had been drilled in a surface magnetic anomaly but failed to intersect any ore. Magnetic measurements in it showed large magnetic anomalies that could not be attributed to the rocks intersected by the borehole. It was therefore deduced that all the significant sources of magnetisation lie between the borehole and the surface; a second hole, BH2, positioned as a result of this information, successfully intersected ore.

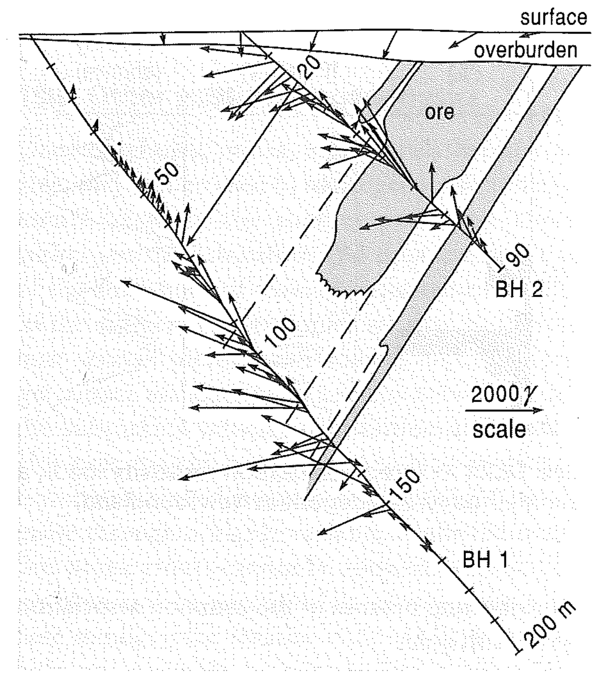


Figure 18.18 Magnetic field log near sulphide bodies in Sweden.

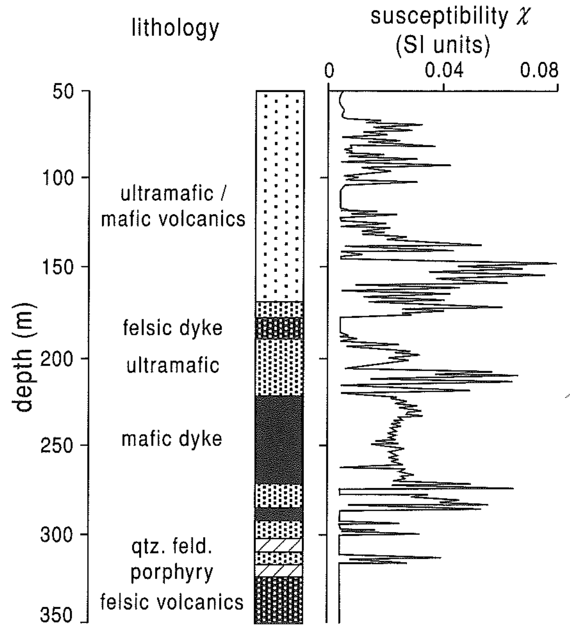


Figure 18.19 Borehole magnetic susceptibility log, nickel deposit.

Magnetic susceptibility logs can also be made continuously down a hole, using a coil system similar that in the induction logging tool (see Fig. 18.20). In fact, the two measurements can be carried out by a single instrument, the magnetic susceptibility and electrical conductivity being proportional to the in-phase and out-of-phase components respectively (Section 14.6). They can be used to identify mineralised zones through changes in susceptibility resulting from alteration of the magnetic minerals or to detect the presence of ore-bearing magnetic intrusions. Figure 18.19 shows the susceptibility logged through a nickel deposit, with high susceptibilities only in the mafic and ultramafic rocks and low in the felsics. The log may be used to quantify the nickel content more easily than by collecting samples for chemical analysis.

Another, fairly obvious, application is the estimation of the grade of iron ore deposits, for Figure 18.20 shows that there can be a strong relationship between susceptibility (measured on samples in the laboratory) and the ore grade. The figure also shows the ability of the γ ray and resistivity logs to discriminate between the shaly rocks and magnetic cherts.

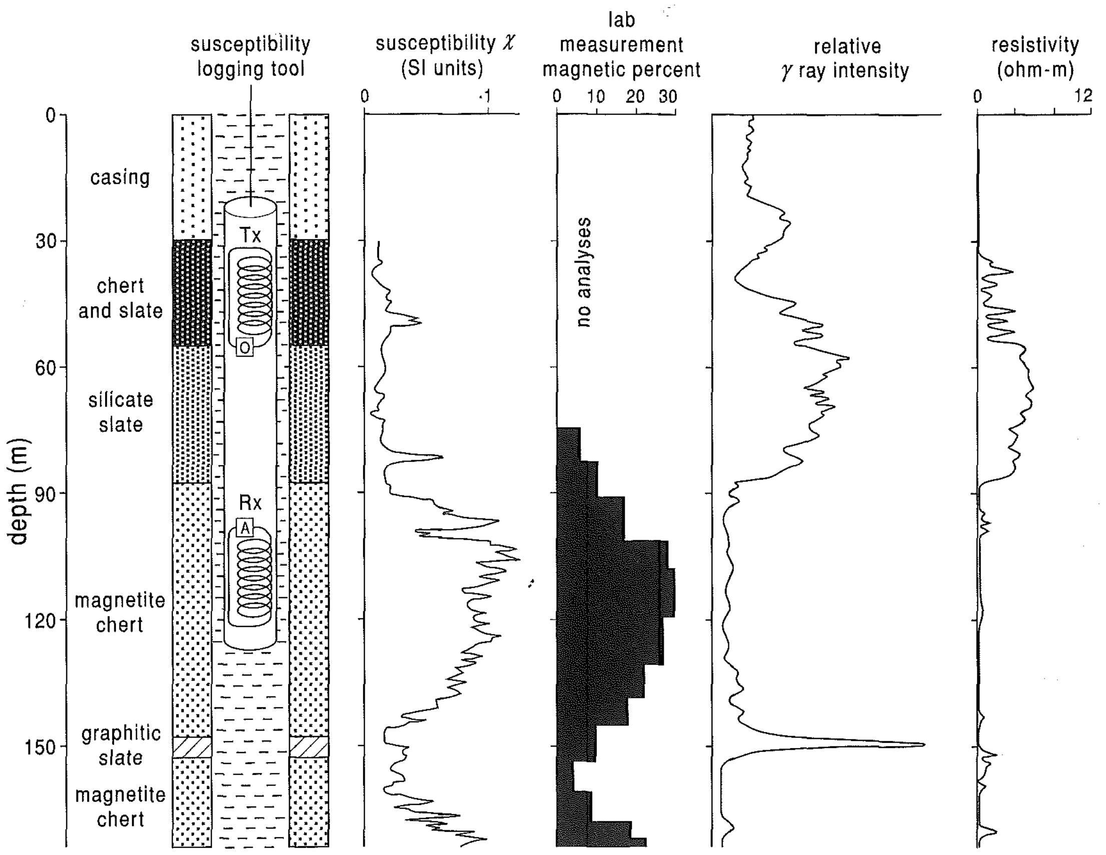


Figure 18.20 Susceptibility and other values versus iron content.

18.6.3 The IP–resistivity log

The **IP (induced-polarisation) log** is particularly useful for detecting disseminated sulphide ores, as explained in Section 13.1. Time-domain equipment can be used with little adaptation in water-filled boreholes, using four electrodes made of lead, attached at intervals to the lowering wire to form an array. As with surface measurements, resistivity measurements are also taken, since they need no extra apparatus. Measurements are usually made with the array stationary, and as they take a few seconds are made at intervals. However, a slow-speed system has been devised to allow continuous measurements at a slow rate of ascent. Figure 18.21 shows the results of such a log in a carbonate-hosted zinc deposit. Although sphalerite itself is nonconducting, there is an IP anomaly due to the presence of pyrite, whose concentration correlates with the sphalerite, whereas the resistivity log does not reveal it so clearly. Similarly, IP logging can be used for gold prospecting because of the common association of pyrite with gold.

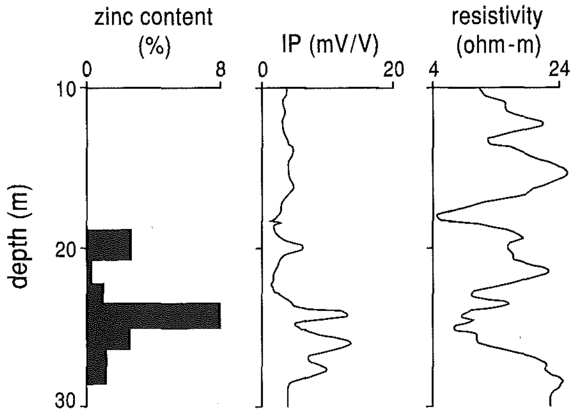


Figure 18.21 Induced-polarisation resistivity log in a carbonate-hosted zinc deposit in Newfoundland.

The above are the main logs used in connection with metallic ores. There are also nonmetallic ores sufficiently valuable to drill for, such as sulphur, evaporite, and coal. Various combinations of the tools described can be used but will not be described.

18.7 Other well-logging applications

Borehole logging is also used for a variety of other purposes. One is in water location and extraction, where – as with hydrocarbons – porosity and permeability are important. Another hydrogeological application is to measure saline contamination by exploiting the large effect it has on conductivity. The selection or monitoring of a waste disposal site provides yet another use, for the presence of fractures that could provide pathways for leachates needs to be known, and fractures can be located from their effect on a number of tools, including sonic, neutron, resistivity, and calliper ones. In assessing the potential of the subsurface for geothermal energy, temperature is obviously important, but so also is the presence of water and permeability, whether through pores or fractures. The borehole logs have been a very useful complement to the information obtained from recovered core in the ocean and continental deep-drilling programs that investigate the Earth's deep crustal structure. However, in a book of this nature it is not possible to go further into these applications.

18.8 Other subsurface geophysics

Once boreholes, mines, and tunnels become available, they can be used to make geophysical measurements between the surface and subsurface or entirely in the subsurface and thus overcome some of the limitations of making measurements confined to the surface. For example, we saw in Chapter 7 how seismic surveys with sources and detectors on the surface are extensively used to provide models of the subsurface velocity distribution and structure. However, the ability of such surveys to resolve small features is limited because observations have to be made through a highly variable weathered overburden whose effects cannot be allowed for exactly. The problem can be overcome by carrying out a **cross-hole** tomographic (Section 4.6) survey if two boreholes are available – a seismic source can be placed in one hole and detectors placed in the other and below the surface layers. By measuring the travel times and amplitudes of direct *P* and *S* waves from sources at various depths in one hole to detectors in another, it is possible to use computer-assisted tomographic (CAT) imaging techniques, similar to those used in medicine, to make a detailed section of the velocity variation between the holes. Special high-frequency sparker sources and detectors which can be clamped in the hole have been developed for such studies.

Electrical tomographic surveys can also be carried out in a similar manner using electromagnetic sources to map the conductivity distribution between boreholes in the exploration for minerals, oil, and water, as well as in environmental and crustal studies. Another subsurface seismic application is the use of reflection surveys in mines to map steeply dipping orebodies by directing the seismic energy sideways rather than vertically as in the surface surveys. The mise-à-la-masse method, in which a conducting orebody encountered in a drill hole is energised by means of a current electrode and potentials are measured on the surface or in other boreholes (Section 12.4.2), is used to determined the shape and extent of the body.

Summary

1. The most used form of subsurface geophysical surveying is well logging in boreholes. Other types of measurement are made from borehole to surface, between boreholes, and in mines and tunnels.
2. The records of the variation of various quantities down boreholes are called logs, and are of both geophysical and nongeophysical quantities.
3. Geophysical logs are made by instruments in sondes, or tools, suspended on a wire, with readings usually taken as they are pulled to the surface. Sondes often contain several instruments that can operate without mutual interference.
4. Measurements of geophysical quantities in boreholes differ from those in surface surveys in three main ways:
   (i) Measurements are made 'sideways' into the formations around the borehole.
   (ii) Instruments have to be adapted for the dimensions of a borehole and usually to operate submerged in drilling mud.

  (iii) Measurements have to take account of the changes resulting from the drilling.
5. Geophysical logging is not only cheaper than continuous coring but it provides information that cannot be obtained on cores, partly because of the alterations produced by the drilling, and reduces the need for sampling. Geophysical logs are often more valuable when combined than when used singly.
6. By far the largest and most sophisticated application of well logging is in the hydrocarbon industry, where it is used to assess the amount of hydrocarbon in a reservoir and also the ease with which it can be extracted. This requires estimating the volume of reservoir, the hydrocarbon concentration within it, and its permeability. These are calculated from the lateral and vertical extent of the reservoir formation, and from its porosity and hydrocarbon saturation. The last two cannot be *measured* directly by geophysical well logs but are *deduced* by combining the results of several geophysical and nongeophysical logs. Permeability is estimated from the porosity.
7. In hydrocarbon exploration and assessment, the most important geophysical logs from open holes with conducting mud are SP and resistivity, used in conjunction with dip, inclination, and calliper logs.
8. Self-potentials in oil wells usually result from there being different concentrations of salts in permeable sandstones, impermeable shales, and the mud. The SP logs reveal shale boundaries; as shale is a common cap rock, they therefore often reveal the boundary of the reservoir rock. The SP value attained in a sufficiently thick porous formation is called the SSP (static SP); it is used in the estimation of ρ_w, which is needed to calculate saturation.
9. The induction log also measures resistivity (or conductivity), but – unlike the resistivity log – it also functions in a dry hole or one filled with nonconducting mud.
10. Radioactivity logs belong to two groups. In one, the natural γ ray activity is measured and used to identify lithologies. In the other, γ ray activity induced by γ ray (density log) or neutron (neutron or porosity log) sources carried in the sonde are recorded. The γ ray and neutron logs are recorded together as a pair and can be used instead of the SP and resistivity logs in a cased hole.
11. The sonic log measures the seismic velocity and is used to improve interpretation of seismic reflection sections. It can also be used to estimate porosity and to improve identification of lithologies when used in a cross plot with the neutron log.
12. The temperature log is mainly needed to correct for the effects of temperature on resistivity. It is also useful to locate formation boundaries and high-pressure gas zones, and in monitoring the progress of cementing operations.
13. The most commonly used logs in mineral exploration are SP and resistivity, for they respond to most massive sulphides and graphite, but magnetic logs (field and susceptibility) are useful for magnetic ores, while IP is valuable with disseminated ores.
14. In hydrogeology, electric logs are useful in delineating aquifers, determinating their porosity, and estimating the quality of the water in them.
15. Geophysical sources and/or sensors can be used between boreholes, mines, and tunnels as well as at the surface for tomographic studies or to extend the depth of exploration.
16. You should understand these terms: drilling mud, mudcake, mud filtrate; flushed, transition and uninvaded zones; open hole, cased hole, sidewall sampling, formation tester; log, wireline log, geophysical well log, sonde, tool; reservoir rock, cap rock; porosity, permeability, hydrocarbon saturation, residual hydrocarbon saturation, hydrogen index, water saturation; SP, SSP, formation resistivity, formation resistivity factor; cross plot, cross-hole tomography.

    You should know what the following logs are and what they measure: drilling time, mud, calliper, dipmeter, clinometer, SP, IP, resistivity, laterolog, microlog, induction, natural γ ray, spectral γ ray, gamma–gamma, formation density, neutron, porosity, sonic, temperature, magnetic field, magnetic susceptibility.

Further Reading

Rider (1996) gives an excellent account of the principles and practice of well logging and their geological interpretation in hydrocarbon exploration. Baltosser and Lawrence (1970) is a good early introduction to the use of well logging outside the oil industry. Chapellier (1992) is a very readable account of the principles and uses of well logs written for engineers and hydrogeologists.

Problems

1. Give two general reasons why geophysical logging would still be needed in hydrocarbon exploration even if complete cores were available.
2. In what circumstances are radioactivity logs preferred to electrical ones?
3. What are two advantages of an induction tool over a resistivity one?
4. What are the main factors that determine the electrical resistance of a formation?
5. Explain the uses of SP logs in (a) hydrocarbon exploration and (b) mineral exploration.
6. What does the natural gamma ray log respond to, and what is it used to determine? Why is the spectral γ ray log an improvement?
7. If you suspected a lithology was dolomite, how would you confirm this and measure its composition using logs?
8. How would the signal of a neutron log in dry sand compare with that in water-saturated sand and in sand filled with gas? Explain why.
9. Why can the sonic log provide more precise estimates of seismic velocities and more precise locations of interfaces than surface seismic reflection surveys?
10. (a) The transit times for the matrix and fluid in a sandstone are known from laboratory measurements to be 180 μs/m and 656 μs/m respectively. What is the porosity of a bed for which the sonic log gives a value of 213 μs/m?
    (b) The neutron log opposite the same sandstone gave a porosity of 9.5%. What is the most likely cause of the difference?
11. Name three logs that would probably reveal the presence of shale.
12. In a sedimentary sequence of shales and sandstones, the γ–γ log gives values of 60 and 20 API units opposite a shale and a clean sandstone respectively. What is the percentage of shale by volume in a shaly sandstone for which the reading is 25 API units?
13. How are water saturation and hydrocarbon saturation related?
14. Sketch the SP and resistivity logs for the following downward succession of formations: thick sand with the water table halfway down it, thin shale, thick water-saturated sand, thick gypsum, thin water-saturated sand, thick shale, thick oil-saturated sand, shale.

Part I described a range of geophysical methods, with a number of examples provided for illustration. In reality, of course, the problem normally comes first, and then the question arises, Which methods – geophysical and others – will help to solve it? In Part II we give examples of such problems. They have been chosen to illustrate the range of problems that geophysics has helped solve, and also to involve a range of geophysical – plus other – methods. But the range of problems is not comprehensive, nor does geophysics always plays so large a role or so successfully; these are simply a variety of problems where different geophysical methods have been able to make a significant contribution.

Part II begins with a short chapter describing how appropriate geophysical methods are chosen.

chapter 19

Which Geophysical Methods to Use?

19.1 Introduction

In Part I, deciding which method to use in any of the examples given was not a problem, for they were chosen to illustrate the particular method being described, but when a geological problem is first encountered it is necessary to decide which – if any – geophysical methods to use and how best to employ them. Choosing the most suitable one or combination needs experience and perhaps some luck, but considering the following questions should narrow the choice.

19.2 Does the problem have geophysical expression?

Geophysical surveys do not respond to geological features as such, but to differences in physical properties, so the first requirement is that the geological situation has geophysical expression; that is, there must be some related subsurface body or structure that can be detected geophysically. For example, a granite pluton, which rose into place because of its low density, gives rise to a negative gravity anomaly (Fig. 8.16), and this may be used to locate it and estimate its size. In this example, the geophysical expression – the negative anomaly – is *directly* due to the body to be detected because its density is an intrinsic property of the granite, but sometimes geophysical expression is *indirect*. For example, a fault may be detectable by a seismic reflection survey if it has produced a vertical offset in subhorizontal layers (Fig. 7.10) but not if there are no layers or they are not offset vertically; or a concealed shaft may be directly detected by its negative gravity anomaly, but indirectly, for example, by a magnetic survey if it happens to contain ferrous objects (Section 27.2.3). The geophysical expression may be only *associated;* for example, when gold is present it is in such low concentrations that it produces no detectable change in the physical properties of the host rock, but in some areas it is associated with banded iron formations, which are magnetic, or with disseminated sulphide ores that can be detected using IP. With the wide range of geophysical techniques it is often possible, with some ingenuity, to find an indirect or associated geophysical expression, if there is no direct one.

So deciding which physical properties are likely to vary spatially as a result of the geological situation is the first step to choosing a method: A resistivity contrast suggests a resistivity or e-m survey, a density difference suggests a gravity one, and so on.

19.3 Is the variation lateral or vertical?

Though, for example, a density difference suggests that a gravity survey could be used, a gravity anomaly is produced only by a *lateral* variation of density, for a uniform horizontal sheet simply produces a constant increase or decrease in g measured at the surface; only where the sheet ends is there an anomaly (Section 8.4). This is also true for magnetic surveying.

Methods that utilise waves – seismics and GPR (ground-penetrating radar) – mostly require subhorizontal interfaces, which usually means a layered subsurface. If the waves are being reflected the interface must form a *discontinuity,* which requires that the thickness of the interface must be smaller than about a quarter-wavelength (Section 7.8.2). In some survey techniques subhorizontal interfaces may be more an *assumption* of the interpretation than a necessary requirement to get results; for example, modelling of VES (vertical electrical sounding) results usually assumes that the subsurface consists of electrically uniform horizontal layers, though these may not actually exist.

The value of tomographic methods is that they can be used whether variations are vertical or lateral or when there are no discontinuities, though resolution is usually poor and often the methods are complex to carry out.

19.4 Is the signal detectable?

Even if the above requirements have been met, the geophysical 'signal' may not be large enough to be measured with useful precision. This might be because the target is too deep: In seismic reflection, the reflections from progressively deeper boundaries become weaker as the downgoing pulse loses energy by reflections from higher layers, by absorption, and by simply spreading out. The amplitude of a gravity anomaly decreases with the depth of the causative body – as well as with decreasing density contrast with its surroundings – so there is some depth below which its anomaly is too small to be detectable.

In practice, what limits detectability is usually not that the signal has become too small to be measured but that it is submerged in the noise. In the gravity example above, the anomaly due to the granite may be within the capability of the gravimeter to measure it, but the varying thickness and density of overburden may obscure it; that is, the signal-to-noise ratio (Section 2.3) is too low. Various things can be done to improve the signal-to-noise ratio. In passive methods, such as gravity and magnetics, where the signal is generated entirely by the target, the signal itself cannot be increased, but readings can be averaged and corrections can be made with greater care. With active methods, where a signal is sent into the ground, the geophysicist has more control. In seismic reflection, for example, the size and duration of the pulse can be chosen to improve depth of penetration or resolution; in resistivity surveys the type of electrode array, the electrode separation, and the current through them can be selected for the same purpose. Even so, there is usually a trade-off between depth of penetration and resolution, and there may be no pulse or electrode setting that allows a small target at depth to be detected. In seismic reflection, two reflecting interfaces cannot be resolved if they are less than about a quarter wavelength apart, but a pulse with sufficiently high frequency may be too attenuated before it reaches the required depth to give a detectable reflection. Other ways of improving the signal-to-noise ratio are stacking and filtering. Signal-to-noise ratio needs to be considered when designing a survey, to allow the above factors to be taken into account.

Knowing the limit of detectability is particularly important if the object is to check that some feature is *not* present, so as to be sure that when no signal has been found this is because no causative body larger than some size is present. For example, suppose that for a proposed building site it is necessary to take remedial action if there are cavities in the underlying limestone more than say 5 m across at a depth less than 10 m below; the precision of measurement and correction need to be sufficient to detect the corresponding anomaly. To find whether a boundary is present, a seismic refraction line needs to be long enough for the refracted rays to be first arrivals over a significant distance. The station spacing is also important, for this must be less than the width of the anomaly, while the traverse must be long enough to extend beyond the anomaly.

19.5 Will the result be clear enough to be useful?

All geophysical methods suffer from some degree of ambiguity of interpretation, which limits what may be expected from a survey. Sometimes the ambiguity is intrinsic to the technique, as with the non-uniqueness of gravity and magnetic modelling, where, even in theory, many different bodies (with varying degrees of plausibility) could be producing the observed anomaly. Other examples are the principle of equivalence in VES, where different combinations of layer thickness and resistivity can give the same readings, and hidden and low-velocity layers in seismic refraction. It has also been pointed out that geophysical interfaces are not necessarily geological boundaries and vice versa. Ambiguity also arises, of course, from limited resolution and from errors on readings.

19.6 Is a survey practicable?

Because surveying costs time and money, measurements need to be concentrated where they will be most useful. Extensive geophysical surveys, which are likely to be expensive, may start with a reconnaissance survey (after, of course, considering the available geological and other evidence) to see if any likely targets are present, before employing more detailed surveys. As illustration, in an area where mineral veins are possibly present, the first survey could be to measure profiles across the likely strike of the veins, perhaps using an airborne e-m technique such as TEM, and then, if any significant anomalies are found, to map them in more detail using ground surveys, perhaps on a grid. Follow-up surveys need not use the same technique as the reconnaissance survey; for example, in another situation magnetic and gravity surveys with widely spaced stations may indicate the presence of a sedimentary basin and hence the possibility of hydrocarbon fields; but high-resolution seismic reflection would be used where hydrocarbon traps were likely (Section 22.4). Using more than one technique often provides complementary information, which together may reveal far more than separately, as was explained, for instance, for wire-line logging in the previous chapter.

The full consideration of all relevant factors needs great experience, far beyond the scope of this book to impart, but the chapters that follow describe a number of case studies that illustrate some of the points.

Problems

1. Basement rock is overlain by twenty to thirty metres of sand, which is beneath several metres of clay. To measure the depths to the top and base of the sand you could use which of the following methods?
    - (i) Seismic refraction.
    - (ii) Gravity.
    - (iii) Magnetics.
    - (iv) Resistivity.
    - (v) GPR.
    - (vi) Radioactivity surveying.
2. Strata seen in a sea cliff can also be seen on the beach below in a few places where it is not covered by a thin layer of sand. Which of the following methods should be considered for investigating (during low tides) the geometry of the strata below the beach?
    (i) Seismic refraction. (ii) Seismic reflection. (iii) Resistivity. (iv) Slingram. (v) GPR. (vi) Magnetic.
3. You wish to survey for normal faulting of limestone beneath an overburden of glacial deposits. Discuss whether and how each of the following techniques might be useful:
    - (a) Microgravity.
    - (b) Seismic refraction.
    - (c) Resistivity.
    - (d) γ ray survey.
    - (e) Magnetometer survey.
    - (f) Magnetic gradiometer.
    - (g) GPR.
4. A new road is to be laid across an area underlain by Carboniferous limestone that is known to contain sinkholes filled with clay. What quick and cheap site investigations would you recommend?
5. Two boreholes in a Permian sandstone produce freshwater, but a third is quite saline. Overlying sands and gravels plus faulting are thought to control the distribution of saline water, which probably has a source in evaporite deposits. How would you employ geophysical surveys to determine the extent of the saline water and the factors determining its distribution?
6. A gas pipeline is to cross an area of sedimentary rocks that is intersected by both igneous dykes and valleys eroded in the sediments. The dykes will cause difficulty when excavating the trench needed to hold the pipeline, while the valleys may contain saline water at depth that could corrode the pipe. What geophysical surveys could help reveal such features?
7. You need to locate a plastic pipe beneath a road surface. It was buried in a trench cut about a metre into granite, then infilled with limestone chippings and surfaced. Discuss which of the following it would be sensible to try:
    - (a) Microgravity.
    - (b) Seismic refraction.

(c) Resistivity.
(d) γ ray.
(e) Magnetometer.
(f) Magnetic gradiometer.
(g) GPR.
(h) Slingram e-m.

8. As the previous question except the pipe is steel.
9. What is the problem of nonuniqueness? How may it be surmounted, at least partly?
10. Which geophysical methods can be employed in aeroplanes? What are the advantages and disadvantages of doing so?

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chapter 20

Global Tectonics

In the 1960s the theories of continental drift and sea floor spreading (hitherto largely regarded with scepticism) fused to give birth to plate tectonics, the idea that the surface of the Earth consists of huge rigid pieces that move independently, with most tectonic and igneous activity taking place at their margins as a consequence of their relative movements. Plate tectonics provides a framework for much of geology, being relevant to topics as diverse as continent formation, orogenesis, earthquakes, volcanoes, past climates, and palaeontology. It has been particularly successful when applied to oceans and their margins, but less so at explaining tectonic processes within continents, where deformation extends far from the plate margins.

The success of plate tectonics posed further questions: How deep do plates extend, and what moves them? How does intracontinental tectonics relate to plate collisions? What causes the volcanism – sometimes very extensive – found far from plate margins? This has led enquiry deeper within the earth, particularly to convective flows within the mantle, and this larger framework can be termed global tectonics.

This chapter is mainly concerned with the basic concepts of plate tectonics, which were established largely by geophysical evidence, and geophysics, with its ability to investigate the deep Earth, continues to play a major part in extending our understanding of its processes.

Geophysical techniques employed: *Many geophysical techniques have played a part, but seismology, seismicity, magnetics, palaeomagnetism, gravity, radiometric dating, and heat flow have had the major roles.*

20.1 The basic concept of plate tectonics

Most geologists are familiar with the concepts of plate tectonics, but fewer know the evidence supporting the theory, in which geophysics played the major role, or how geophysics continues to help work out the details. Until the 1950s, most earth scientists thought the continents were fixed in position, with areas that have been largely constant except for flooding by shallow seas, while the oceans – largely from lack of data – were conceived rather as submerged continents. Mountain building, thrusting, and basin formation were recognised, of course, but there was no adequate theory of why they occurred.

Evidence for continental splitting provided by matching of features across oceans had been dismissed by most earth scientists, but the advent of palaeomagnetism provided new evidence that continents could move slowly or 'drift' over the globe. However, widespread acceptance did not come until a better understanding was gained of the ocean floors, and, as these were largely inaccessible to conventional geology, this was mainly acquired using geophysics. A crucial discovery – also involving magnetism – was that ocean floors are splitting apart at oceanic ridges, with continuous formation of new ocean floor. The combining of the ideas of **sea floor spreading** and **continental drift** led to the theory of **plate tectonics**, according to which the surface of the Earth is divided into a number of pieces or **plates** (Plate 2c and Fig. 20.25). The plates are more or less rigid, and relative movement between them leads, at their margins or boundaries, to most of the observed tectonic activity, including orogenies, volcanism, and seismicity (Plate 2b). Plate margins are often marked by topographic features, as Plate 2a shows; margins may be edges of continents, but not all continental edges are plate margins, for a plate may comprise both continental and adjacent oceanic areas.

What processes occur at a plate margin depend on the relative motion of the plates. There are three types of margins. Where plates move apart new plate surface is created, and these are called **divergent** or **constructive margins**; where they move together and plate is destroyed are called **convergent** or **destructive margins**. In addition, in some places plates slide past one another without construction or destruction of plate, and these are called **conservative margins**. We shall examine the evidence for the different processes that occur at these different types of margins.