Subsurface Stratigraphy and Sedimentology

Techniques for the investigation of geology below the surface have mainly been developed to satisfy the needs of the hydrocarbon industries. Exploration for coal, oil and gas has resulted in the development of a branch of geology concerned with the analysis of stratigraphy, sedimentology and structure in the subsurface. The methods principally involve geophysical techniques such as creating seismic reflection profiles and the measurement of the properties of layers in the subsurface using instruments lowered down boreholes. Core and drill cuttings are also used to sample the rocks that have been drilled. Subsurface exploration has provided a wealth of information in some areas by oil companies and has led to a better understanding of the stratigraphy of sedimentary basins. In particular knowledge of the geology of offshore areas on continental shelves has been greatly increased as a result of these activities. The concepts and application of sequence stratigraphy grew from subsurface studies and were later transferred to outcrop geology.

22.1 INTRODUCTION TO SUBSURFACE STRATIGRAPHY AND SEDIMENTOLOGY

Geologists usually learn the principles of sedimentology and stratigraphy from outcrop relationships in the field, but many will work with subsurface data if they are employed as professional geoscientists. The exploitation of mineral resources started with miners finding layers of coal or beds rich in minerals at the surface and then following them underground by tunnelling. Modern exploration, particularly for hydrocarbons, involves using a range of techniques for finding out what is below the surface. In some cases this will be direct sampling of what is down below by drilling a hole and bringing pieces of rock back to the surface, but most exploration uses less direct means of investigating the strata hundreds or thousands of metres below ground. These approaches involve making measurements of the physical properties of the rocks and are hence referred to as geophysical techniques.

Surveys of the regional variations in the Earth’s magnetic field and measurements of gravity, which varies with the density of the rock below ground, are sometimes used as very general indicators of the
nature of the subsurface. However, the first detailed approach in subsurface exploration is usually to create seismic reflection profiles across an area. These provide information about stratigraphic and structural relationships in the strata and also give some indication of the lithologies present. Analysis of these data helps to target locations where boreholes are drilled to take cores or make further geophysical measurements of the properties of the strata. The objective is to build up a picture of the subsurface geology, including an indication of the distribution of different facies and the large-scale stratal relationships. The principles of sedimentology and stratigraphy discussed in previous chapters of this book are applied in the same way, but using mainly geophysical data instead of the outcrop studies described in Chapter 5.

22.2 SEISMIC REFLECTION DATA

The underlying principle behind this very widely used technique in subsurface analysis is that there are variations in the acoustic properties of rocks that can be picked up by generating a series of artificial shock waves and then recording the returning waves. A sound wave is partially reflected when it encounters a boundary between two materials of different density and sonic velocity (the speed of sound in the material). The product of the density and sonic velocity of a material is the acoustic impedance of that material. A strong reflection of sound waves occurs when there is a strong contrast between the acoustic impedance of one material and another. In geological terms there is a strong reflection of the sound waves at the contact between two rocks that have different acoustic properties, such as a limestone and a mudstone. In general, crystalline or well-cemented rocks have a higher sonic velocity than clay-rich or porous lithologies.

The time taken for a sound wave to reach a reflector and return to the surface can be recorded: this is called the two-way time (TWT) and it can then be related to depth of the reflector at that point. The strength of the reflection is governed by the contrast in the acoustic properties at the boundary between the two rock units. By recording multiple sound waves reaching multiple reflectors across an area an image of the subsurface can be generated and subsequently interpreted in terms of geological structures and stratigraphy.

22.2.1 Acquisition of seismic reflection data

Seismic reflection profiling can be carried out on land or at sea. Marine surveys are generally more straightforward because the ship can follow a course optimised for the data collection, whereas land-based surveys are restricted by topography, access and land use. The source of the energy at the surface is provided by a number of different mechanisms. On land, explosives may be used but it is now more common to use a vibroseis set-up, a vehicle or group of vehicles that vibrate at the surface at an appropriate frequency to generate shock waves. At sea the sound energy is provided by an airgun, a device that builds up and releases compressed air with explosive force: it is usual to have multiple airguns forming an array, releasing energy every 10 to 20 seconds. The horizontal spacing of the points where the energy is released (the shot points) is usually 12.5 or 25 m.

The returning sound waves are detected by receivers: these are essentially microphones that are referred to as geophones on land and hydrophones at sea. The pattern of these receivers depends on whether the survey is two-dimensional, a 2-D survey, or three-dimensional, a 3-D survey. For 2-D surveys a single string of receivers is spread out along a line spaced 12.5 to 25 m apart: in marine surveys this is called a streamer and it may be 3 to 12 km long. The returning sound waves are recorded along one vertical plane, producing a single profile that may be many tens of kilometres in length. For 3-D surveys a series of 6 to 12 parallel streamers, each about 100 m apart, are towed behind the ship to create an array of receivers arranged in a grid pattern (Fig. 22.1). These record the reflected sound waves in a 3-D volume of rock in the subsurface and a 3-D survey may cover tens of square kilometres in a series of parallel swathes.

In the initial stages of exploration in an area a series of widely-spaced 2-D survey lines are shot to provide a general picture of the structure and stratigraphy of the region. 3-D surveys are more expensive to acquire and are usually used in the later stages of exploration to provide more detailed information about the exploration target.
22.2.2 Processing of seismic reflection data

The signals generated by each reflection from one burst of energy are very weak. However, each reflection point in the subsurface will generate multiple return signals recorded at many different receivers from successive shots. These signals can be merged in a process called stacking, which greatly enhances the signal strength. Another processing technique is also used to allow for the fact that the reflected sound waves do not come back to the surface along a vertical pathway. Migration of the data is a process of adjusting the time taken for the return from each reflection point to take account of the longer, oblique pathway the sound wave has taken on its journey. An important component of the processing involves converting the vertical scale of the data from two-way time to depth in metres. This depth conversion requires information about the acoustic characteristics (sonic velocity) of all the stratigraphic units from the surface down to the chosen limits of interpretation of the profile. The sonic velocity of the layers varies with lithology (22.4.1) and depth, becoming higher as more compacted lithologies are encountered at greater depth. Values for the sonic velocity of the stratigraphic units can be obtained from measurements made in boreholes and these can be used to convert the two-way time into a true thickness for that interval. If carried out in a series of steps for each unit a pattern of reflectors can be presented scaled to depth below surface.

After the processing is carried out, the results from a seismic reflection survey can be presented as an image that appears to be a series of dark lines on a white background when presented as a 2-D profile (Fig. 22.2) (colours are often used in profiles generated from 3-D surveys). These images are built up of a series of closely spaced vertical traces, each of which is a record of the acoustic impedance contrasts that generated reflections. The peaks on the right-hand side of each trace representing high contrasts are filled in black, and when these traces are put next to each other, lines of strong impedance contrast, reflectors, show as black lines on the profile. The data from 3-D surveys are also combined into images built up from closely spaced vertical traces in a 3-D volume of rock.

The data collected in the course of a single 3-D seismic reflection survey run to hundreds of gigabytes, and the processing of the raw data into a form that can be readily interpreted in terms of the subsurface geology requires significant amounts of computer processing power. An important factor in the
development of more sophisticated data acquisition and processing techniques in recent years has been the availability of more powerful computers able to store, handle and rapidly process data volumes on these scales.

22.2.3 Visualisation of seismic reflection data

2-D profiles are presented as black and white paper copy, typically rolls of paper a metre or more wide and many metres long. These will show a horizontal scale in metres and kilometres, marked with the shot points of the survey. The vertical scale will be in milliseconds of two-way time (TWT ms) unless a depth conversion has been carried out prior to printing. The patterns of reflectors can be visually assessed and interpreted in terms of structures and stratigraphy as described below. If a series of lines has been shot to form a grid pattern, cross-cutting lines are matched up and a correlation between all of the lines in the grid is carried out.

The scope for visualisation of data from a 3-D survey is much greater and has expanded as computing technology has advanced. 2-D profiles can be extracted from the data and presented on-screen in any orientation, vertically, obliquely or horizontally. It is also possible to create three-dimensional images that can be perspective images on the screen or using 3-D projection technology to generate a virtual three-dimensional effect. These latter visualisation techniques allow the interpreter to 'move' through the volume of data as if they were moving through the volume of rock and view the geology from different perspectives, angles and at different scales.

22.2.4 Interpretation of seismic reflection data

At a first glance there is a lot in common between a seismic reflection profile and a cross-section compiled from surface outcrop data. Layers looking like beds of rock may be seen on the profile, unconformities, folds and faults may be picked out and contrasts in the detailed pattern of the reflectors suggest that different rocks may be identified on a seismic reflection profile. Although all these features can indeed be related to stratigraphic and structural features seen in rocks, comparison and interpretation must be carried out with caution because there are important differences too.

First, there is a question of scale. In dealing with outcrop, a geologist is accustomed to looking at beds centimetres to metres thick and features tens to hundreds of metres across are considered large scale. The vertical resolution on a seismic reflection profile is related to the wavelength of the sound waves and the best resolution that can be achieved is about 15 m, so the units defined by reflectors are packages of beds, not individual beds. Sound waves reflected from deeper in the succession have lower energy so there is also a decrease in resolution with depth and detail can be much more clearly seen in shallower strata than in rocks buried a few thousand metres below ground.

Second, a contact between two rock units will not show up on a seismic profile if there is no acoustic impedance contrast between them. The boundary between a thick sandstone and a conglomerate body might be easily recognised in outcrop, but if they have the same acoustic properties the contact between the two would not be imaged as a reflector. The clearest reflectors are generated by the contacts between beds of contrasting properties, such as a mudstone and a well-cemented limestone, a basalt lava and a sandstone or a bed of halite overlain by anhydrite.

Third, processing techniques that attempt to convert the geometries imaged on the profile into the true subsurface relationships become less effective with
increasing depth. The relative horizontal positions of reflectors are distorted such that the true location is not correctly shown, and the angular relationships are also not accurate. The interpretation of both stratigraphic and structural geometries on seismic reflection profiles must therefore be carried out with care and an awareness of these potential distortions.

22.2.5 Stratigraphic relationships on seismic profiles

By tracing reflectors across profiles it is possible to recognise stratigraphic relationships (Fig. 22.3) that are on the scale of hundreds of metres to kilometres. When traced and marked these form a framework for the interpretation of the whole succession of rocks imaged on the profile.

Continuous reflectors

A well-defined reflector marks a boundary between two layers of different acoustic impedance and for this to be continuous over kilometres it must mark a change in lithological characteristics of the same extent. Changes in lithology in a sedimentary succession result from changes in depositional environment and a widespread change in depositional environment can result from events such as a change in sea level or sediment supply. For example, a sea-level rise may cause sandy, shallow-water deposits to be replaced by muddy, deeper-water sediments over a wide area. A similar widespread change may occur when a carbonate shelf environment receives an influx of mud and the lithology deposited changes from limestone to mudstone. In deeper water the progradation of a sandy submarine fan lobe over muddier turbidites may also mark a change in depositional style over a wide area. Continuous reflectors therefore may be seen as markers that indicate a significant, widespread change in deposition in the basin. For this reason, prominent reflectors are often considered to represent time-lines, isochronous surfaces, within a basin-fill succession, although care should be exercised in making this assumption where there are complex stratigraphic relationships or where reflectors merge. Changes in depositional environment usually occur over a period of time because events such as transgressions that result in retrogradation of facies (23.1.6) do not occur instantaneously.

Clinoforms

Inclined surfaces bounding stratigraphic packages on seismic reflection profiles are referred to as clinoforms (Mitchum et al. 1977) and they form a pattern that indicates a progradational geometry of packages of sediment building out into deeper water. Depositional slopes of a few degrees occur at delta fronts (especially sandy or gravelly delta: 12.4.4), on the edges of clastic shelves and in carbonate environments, a fore-reef slope may be 25° or more. The angle of the clinoform seen on a seismic reflection profile may not always represent the true depositional geometry, and the angle may be enhanced by compaction in some instances. Sandstone has a much lower initial porosity than mudstone and therefore compacts to a lesser degree on burial, so units that grade from sandstone to mudstone would tend to taper distally upon compaction, resulting in inclined surfaces on a large scale.

Unconformities

An unconformity surface will not be represented by a reflector unless there is a consistent change in lithology across it to create an acoustic impedance contrast. In many cases, an unconformity may be identified on a seismic reflection profile by the presence of reflector terminations, the points at which relatively continuous reflectors end (Mitchum et al. 1977). Some terminations are not related to unconformities (see below) but result from the shapes of the stratigraphic packages. The breaks in the sedimentary record represented by unconformities are also often considered to be time-lines within the stratigraphy, but an unconformity may actually represent a series of events over a period of time. There may be a long
time period between the erosion and subsequent deposition above the erosion surface and deposition may not occur across the whole unconformity at one time (see ‘onlap’ below).

**Erosional truncation**

If the surface of truncation is at a high angle to the orientation of the layers it intersects, erosional truncations are relatively easy to recognise (Fig. 22.3). They are assumed to result from the removal of packages of beds by subaerial or submarine erosion and are most distinct where the underlying layers have been uplifted and tilted prior to erosion. A truncation surface caused by the incision of a river valley into shelf strata following a sea-level fall may also be recognised, but only if the incision is several tens of metres and therefore enough to be resolved on seismic profiles. Low-angle erosional truncations may be difficult to identify.

**Onlap**

This relationship forms where there is a clear topography at the edge of or within the basin. Reflectors indicate that stratal packages are banked up against this topography, with the younger layers successively covering more of the underlying unit and sometimes covering it completely. Geometries of this type may form by the drowning of topography. Onlap relationships are an example of an unconformity representing multiple events through time: erosion may still be continuing at the upper part of the underlying unit, while deposition occurs further down dip on the surface, and deposition above this unconformity is clearly later at the top than at the bottom.

**Downlap**

This term is used to describe inclined surfaces that terminate downwards against a horizontal surface. This geometrical relationship is rarely seen in the smaller scale of outcrop because steeply inclined bedding surfaces are uncommon, although fore-reef slopes (15.3.2) and Gilbert-type deltas (12.4.4) are notable exceptions. Downlap surfaces seen on some seismic reflection profiles may be due to a merging of reflectors at the base of a clinoform slope where thicker sandstone beds pass distally into thinner mudrock units.

**Toplap**

Inclined reflectors that have upper surfaces that terminate against a horizontal surface create a pattern that is described as toplap (Fig. 22.3). This relationship occurs where there is a succession of packages of sediment that prograde basinwards, without any aggradation.

**Offlap**

This relationship refers to a pattern of reflectors, rather than a reflector termination. Offlap is a pattern of stratal packages that build upwards and outwards into the basin (Fig. 22.3).

**22.2.6 Structural features on seismic reflection profiles**

A fault surface is not often seen on a seismic line as a distinct reflector. Even if there is an acoustic impedance contrast across the fault, steeply dipping structures are poorly imaged by conventional seismic surveys because the reflected sound waves return to the surface at a high angle and are not picked up by the recording array. Faults are normally recognised by the displacement of continuous reflectors. If distinctive individual reflectors can be recognised on both sides of the fault, the direction and amount of displacement can be determined. Folds can be identified on seismic profiles although steep limbs are poorly imaged for the same reasons as discussed for steep fault surfaces. The angles of bedding or faults imaged on seismic reflection profiles are not always the true geometries and should be interpreted with caution.

**22.2.7 Seismic facies**

The character of patterns of reflectors on seismic reflection profiles can be used to make a preliminary interpretation of rock type and depositional facies (Mitchum et al. 1977; Friedman et al. 1992). For example, continuous reflectors suggest an environment that is relatively stable with periodic changes, such as a shelf affected by sea-level changes or a deep basin with periodic progradation of submarine fan lobes. In continental environments lateral facies patterns tend to be complex as rivers change course
and widespread surfaces are less common so a discontinuous reflector pattern results. Some lithologies are characterised by an absence of parallel reflectors. For example, salt and other evaporites tend to have a ‘chaotic’ pattern (random reflectors) or ‘transparent’ pattern (lacking internal reflectors). A basement of metamorphic or igneous rocks generally lacks regular reflectors. The geometry of units bounded by reflectors can also give an indication of the depositional setting. Estuarine or fluvial deposits may be underlain by an erosional truncation and confined to a valley fill. Large reefs may be picked out by their morphology and chaotic to transparent internal reflectors.

The character of some units on a profile may give some indication of the lithology and facies but interpretation of the layers in terms of a stratigraphy of rock units can be carried out with any confidence only if the succession imaged has been drilled. The seismic facies can then be related to the rock units encountered in the borehole.

22.2.8 Interpretation of three-dimensional data

Cubes of 3-D seismic reflection data and the computing power to manipulate and analyse these data have made it possible to take interpretations much further than is possible using 2-D profiles alone. For example, horizontal slicing techniques have made it possible to recognise and determine the shape of erosional features such as fluvial and estuarine palaeovalleys, and positive features such as reefs. Similarly, the depth of the basement can be shown as a map if the contact between the basement and the basin fill has been identified across the area. Variations in the thickness of a particular unit can also be shown as a map from information about the position of the top and bottom of that unit within the data cube.

In addition to providing information about geometrical relationships, 3-D data can be used to provide information about spatial variations of the rock or fluid properties. One example of this is that a single reflector can be traced through the cube and its intensity mapped: variations in the intensity can be related to lithological changes, such as a sandstone bed being more muddy in one part of the area and hence showing less of a contrast with an overlying mudrock unit. An assessment of the fluid present can also be made because the acoustic properties of a bed depend on both the lithology and the fluid present in pore spaces: areas where gas fills the pore spaces can be distinguished from oil- or water-bearing rocks using this approach.

The possibilities offered by the manipulation of 3-D seismic data cubes are considerable, but the interpretations ultimately require corroboration by lithological data from boreholes (see below). However, these techniques make it possible to consider stratal units in three-dimensions in a way that is rarely, if ever, possible from outcrop data alone. This has greatly improved the understanding of large-scale stratigraphy and structure of sedimentary basins.

22.3 BOREHOLE STRATIGRAPHY AND SEDIMENTOLOGY

The interpretation of seismic reflection profiles provides a model for the stratigraphic and structural relationships that may exist in the subsurface. Data from these sources can provide some indicators of the lithologies in the subsurface, but a full geological picture can be obtained only by the addition of information on lithology and facies. This can be provided by drilling boreholes through the succession and either taking samples of the rocks and/or using geophysical tools to take detailed measurements of the rock properties. When a borehole is drilled there are a number of ways of collecting information from the subsurface, and these are briefly described below.

22.3.1 Borehole cuttings

In the course of drilling a deep borehole, a fluid is pumped down to the drill bit to lubricate it, remove the rock that has been cut (cuttings) and to counteract formation fluid pressures in the subsurface. Due to the weight of rocks above, fluids (water, oil and gas) trapped in porous and permeable strata will be under pressure, and without something to counteract that pressure they would rush to the surface up the borehole. The drilling fluid is therefore usually a ‘mud’, made up of a mixture of water or oil and powdered material, which gives the fluid a higher density: powdered barite (BaSO₄) is often used because this mineral has a density of 4.48. The density of the drilling mud is varied to balance the pressure in the formations in the subsurface.

The drilling mud is recirculated by being pumped down the inside of the drill string (pipe) and
returning up the outside: because it is a dense, viscous fluid, it will bring the cuttings with it as it reaches the surface. The cuttings are filtered from the mud with a sieve and washed to provide a record of the strata that have been drilled. These cuttings are typically 1–5 mm in diameter and are sieved out of the drilling mud at the surface. Recording the lithology of these drill chips (mud-logging) provides information about the rock types of the strata that have been penetrated by the borehole, but details such as sedimentary structures are not preserved. Microfossils such as foraminifera, nanofossils and palynomorphs (20.5.3) can be recovered from cuttings and used in biostratigraphic analysis. There is usually a degree of mixing of material from different layers as the fluid returns up the borehole, so it is the depth at which a lithology or fossil first appears that is most significant.

22.3.2 Core

A drill bit can be designed such that it cuts an annulus of rock away leaving a cylinder in the centre, a core, that can be brought up to the surface. Where coring is being carried out the drilling is halted and the section of core is brought up to the surface in a sleeve inside the hollow drill string. As each section of core is brought to the surface it is placed in a box, which is labelled to show the depth interval it was recovered from. Recovery is often incomplete, with only part of the succession drilled preserved, and the core may be broken up during drilling. The core is then usually cut vertically to provide a smooth-surfaced slab of rock that is typically 90 mm to 150 mm across, depending on the width of the borehole being drilled. Cores cut in this way provide a considerable amount of detail of the lithologies present, the small-scale sedimentary structures, body and trace fossils.

In exploration for oil and gas and in the development of fields for hydrocarbon production, cores are cut through ‘target horizons’, that is, parts of the succession that have been identified from the interpretation of seismic interpretation as likely source rocks, or, more importantly, reservoir bodies. Core is usually only cut and recovered through these parts of the stratigraphy; the rest of the succession has to be interpreted on the basis of geophysical wireline logs (22.4). However, continuous cores may be cut through successions that cannot be interpreted satisfactorily using geophysical information alone, as can occur when the properties of the rock units do not allow differentiation between different lithologies using wireline logging tools.

In contrast to oil and gas exploration, coal and mineral exploration normally involves taking a complete core through the section drilled. The width of the core that is cut is smaller, often just 40 mm, and the core is not split vertically (Fig. 22.4). The small size
22.2.3 Core logging

The procedure for recording the details of the sedimentary rocks in a core is very similar to making a graphic sedimentary log of a succession exposed in the field. Core logging sheets are similar in format to field logging sheets (Fig. 5.3), and the same types of information are recorded (lithology, bed thickness, bed boundaries, sedimentary structures, biogenic structures, and so on). The scale is usually 1:20 or 1:50. In some ways recording information about strata from core is easier than field description. If the core recovery is good then there will be an almost complete record of the succession, including the finer grained lithologies. Weathering of mudrocks in the field usually means that they are less well preserved than the coarser beds, but in core this tends to be less of a problem, although weaker, finer grained beds will often break up more during the drilling. The main limitations are those imposed by the width of the core. It is not possible to see the lateral geometry of the beds and recognise features such as channels easily, and only parts of larger scale sedimentary structures are preserved. On the other hand, the details of ripple-scale features may be more easily seen on the smooth, cut surface of a core. Palaeocurrent data can be recorded from sedimentary structures only if the orientation of the core has been recorded during the drilling process, and this is not always possible. The other, not insignificant, difference between core and outcrop is that the geologist can carry out the recording of data in the relative comfort of a core store, although it is unlikely to be such an interesting environment to work in as a field location in an exotic place.

Not all cores pass through the strata at right angles to the bedding. If the strata are tilted then a vertical drill core will cut through the beds at an angle, so all bed boundaries and sedimentary structures observed in the core will be inclined. During the development phase of oil and gas extraction, drilling is often directed along pathways (directional drilling) that can be at any angle, including horizontal. Interpretation of inclined and near-horizontal cores therefore requires information about the angle of the well.

22.4 GEOPHYSICAL LOGGING

There is a wide range of instruments, geophysical logging tools, that are lowered down a borehole to record the physical and chemical properties of the rocks. These instruments are mounted on a device called a sonde that is lowered down the drill hole (on a wireline) once the drill string has been removed. Data from these instruments are recorded at the surface as the sonde passes up through the formations (Fig. 22.5). An alternative technique is to fix a sonde mounted with logging instruments behind the drill bit and record data as drilling proceeds.

The tools can be broadly divided into those that are concerned with the petrophysics of the formations, that is, the physical properties of the rocks and the fluids that they contain, and geological tools that provide sedimentological information. The interpretation of all the data is usually referred to as formation evaluation – the determination of the nature and properties of formations in the subsurface. A brief introduction to some of the tools is provided below (see also Fig. 22.6), while further details are provided

![Fig. 22.5 Geophysical instruments are normally mounted on a sonde that passes through formations on the end of a wireline.](image-url)
in specialist texts such as Rider (2002). Many of these tools are now used in combinations and provide an integrated output that indicates parameters such as sand:mud ratio, porosity, permeability and hydrocarbon saturation.

22.4.1 Petrophysical logging tools

Caliper log

The width of the borehole is initially determined by the size of the drill bit used, but it can vary depending on the nature of the lithology and the permeability of the formation (Fig. 22.7). The borehole wall may cave in where there are less indurated lithologies such as mudrocks, and this can be seen as an anomalously wide interval of the hole. The caliper log can also detect parts of the borehole where the diameter is reduced by the accumulation of a mud cake on the inside: mud cakes are made up of the solid suspension in the drilling mud and form where there is a porous and permeable bed that allows the drilling fluid to penetrate, leaving the mud filtered out on the borehole wall.

Gamma-ray log

This records the natural gamma radioactivity in the rocks that comes from the decay of isotopes of potassium, uranium and thorium. The main use of this tool is to distinguish between mudrocks, which generally have a high potassium content and hence high natural radioactivity, and sandstone and limestone, both

![Diagram of caliper log and gamma-ray log showing the determination of lithology and porosity.](image-url)
of which normally have a lower natural radioactivity. The gamma-ray log is often used to determine the 'sand: shale ratio' in a clastic succession (note that for petrophysical purposes, all mudrocks are called 'shales'). However, it should be noted that mica, feldspar, glauconite and some heavy minerals are also radioactive, and sandstones rich in any of these cannot always be distinguished from mudstones using this tool. Organic-rich rocks can also be detected with this tool because uranium is often naturally associated with organic matter. Mudrocks with high organic contents are sometimes referred to as 'hot shales' because of their high natural radioactivity. The spectral gamma-ray log records the radioactivity due to potassium, thorium and uranium separately, allowing the signal due to clay minerals to be separated from radioactivity associated with organic matter.

Resistivity logs
Resistivity logging tools are a range of instruments that are used to measure the electrical conductivity of the rocks and their pore fluids by passing an electrical
current from one part of the sonde, through the rocks of the borehole wall measuring the current at another part of the sonde. Most minerals are poor conductors, with the exception of clay minerals that have charged ions in their structures (2.4.3). The resistivity measurements provide information about the composition of the pore fluids because hydrocarbons and fresh water are poor electrical conductors but saline groundwater is a good conductor of electricity. Resistivity logging tools are usually configured so that they are able to measure the resistivity at different distances into the formation away from the borehole wall. A microresistivity tool records the properties at the borehole wall, a ‘shallow’ log measures a short distance into the formation and a ‘deep’ log records the current that has passed through the formation well away from the borehole (these are sometimes called laterologs). Comparison of readings at different distances from the borehole wall can provide an indication of how far the drilling mud has penetrated into the formation and this gives a measure of the formation permeability. Induction logs are resistivity tools that indirectly generate and measure the electrical properties by the process of induction of a current.

**Sonic log**

The velocity of sound waves in the formation is determined by using a tool that comprises a pulsing sound source and receiver microphone that records how long it has taken for the sound to pass through the rock near the borehole. The sonic velocity is dependent upon two factors. First, lithologies composed of high-density material transmit sound faster than low-density rocks: for example, coal is a low-density material, basalt is high-density, and sandstones and limestones have intermediate densities. Second, if the rock is porous, the bulk density of the formation will be reduced, and hence the sonic velocity, so if the lithology is known, the porosity can be calculated, or vice versa. The velocities determined by this tool can be used for depth conversion of seismic reflection profiles.

**Density logs**

These tools operate by emitting gamma radiation and detecting the proportion of the radiation that returns to detectors on the tool. The amount of radiation returned is proportional to the electron density of the material bombarded and this is in turn proportional to the overall density of the formation. If the lithology is known, the porosity can be calculated as density decreases with increased porosity. The application of this tool is therefore very similar to that of the sonic logging tool.

**Neutron logs**

In this instance the tool has a source that emits neutrons and a detector that measures the energy of returning neutrons. Neutrons lose energy by colliding with a particle of similar mass, a hydrogen nucleus, so this logging tool effectively measures the hydrogen concentration of the formation. Hydrogen is mostly present in the pore spaces in the rock filled by formation fluids, oil or water (which have approximately the same hydrogen ion concentration) so the neutron log provides a measure of the porosity of the formation. However, clay minerals contain hydrogen ions as part of the mineral structure, so this tool does not provide a reliable indicator of the porosity in mudrocks or muddy sandstones or limestones.

**Electromagnetic propagation log**

The dielectric properties of the formation fluids are measured with this tool. It consists of microwave transmitters that propagate a pulse of electromagnetic energy through the formation and measures the attenuation of the wave with receivers. The measurements are related to the dielectric constant of the formation, which is in turn determined by the amount of water present. The tool therefore can be used to distinguish between oil and water in porous formations.

**Nuclear magnetic resonance logs**

Conventional porosity determination techniques do not provide information about the size of the pore spaces or how easily the fluid can be removed from those pores. Fluids that are bound to the surface of grains by capillary action cannot easily be removed and are therefore not producible fluids, and if pore spaces are small more fluid will be bound into the formation. The nuclear magnetic resonance (NMR) tool works by producing a strong magnetic field that polarises hydrogen nuclei in water and hydrocarbons.
When the field is switched off the hydrogen nuclei relax to their previous state, but the rate at which they do so, the relaxation time, increases if they interact with grain surfaces. Measurement of the electromagnetic ‘echo’ produced during the relaxation period can thus be used as a measure of how much of the fluid is ‘free’ and how much of it is close to, and bound on to, grain surfaces. The tool operates by producing a pulsed magnetic field and measuring the echo many times a second.

22.4.2 Geological logging tools

Dipmeter log

The sonde for this tool has four or six separate devices for measuring the resistivity at the borehole wall. They are arranged around the sonde so that if there is a difference in the resistivity on different sides of the borehole, this will be detected. If the layering in the formations is inclined due to a tectonic tilt or cross-stratification it is possible to detect the degree and direction of the tilt by comparing the readings of the different, horizontal resistivity devices. Hence this tool has the potential to measure the sedimentary or tectonic dip of layering.

Microimaging tools

These tools, often called borehole scanners, are also resistivity devices and use a large number of small receiving devices to provide an image of the resistivity of the whole borehole wall. If there are fine-scale contrasts in electrical properties, for instance where there are fine alternations of clay and sand, it is possible to image sedimentary structures as well as fractures in the rock. The images generated superficially resemble a photograph of the borehole wall, but is in fact a ‘map’ of variations in the resistivity.

Ultrasonic imaging logs

High-resolution measurements of the acoustic properties of the formations in the borehole walls are made by a rotating transmitter that emits an ultrasonic pulse and then records the reflected pulse with a receiver. The main use of this tool is to detect how uneven the borehole wall is, and this can be related to both lithology and the presence of fractures.

22.4.3 Sedimentological interpretation of wireline logs

It is common for the interpretation of subsurface formations to be based very largely on wireline log data, with only a limited amount of core information being available. Modern systems often provide a large amount of ‘automatic’ interpretation of the data, but there is nevertheless a requirement for sedimentological interpretation based on an understanding of sedimentary processes and facies analysis.

Certain lithologies have very distinctive log responses that allow them to be readily distinguished in a stratigraphic succession. Coal, for example, has a low density that makes it easily recognisable in a succession of higher density sandstones and mudstones (Fig. 22.6). A bed of halite may also be picked out from a succession of other evaporite deposits and limestones because it is also relatively low density. Igneous rocks such as basalt lavas have markedly higher densities than other strata. Organic-rich mudrocks have high natural gamma radioactivity that allows them to be distinguished from other beds, especially if a spectral gamma-ray tool is used to pick out the high uranium content. However, many common lithologies cannot easily be separated from each other using these tools, including quartz sandstone and limestone, which have similar densities, natural radioactivity and electrical properties. Information from cuttings and core is therefore often an essential component of any lithological analysis.

The gamma-ray log is the most useful tool for subsurface facies analysis as it can be used to pick out trends in lithologies (Fig. 22.8). An increase in gamma value upwards suggests that the formation is becoming more clay-rich upwards, and this may be interpreted as a fining-up trend, such as a channel fill in a fluvial, tidal or submarine fan environment. A coarsening-up pattern, as seen in prograding clastic shorelines, shoaling carbonate successions and submarine fan lobes may be recorded as a decrease in natural gamma radiation upwards. A drawback of using these trends is that they are not unique to particular depositional settings and other information will be required to identify individual environments. Borehole imaging tools (scanners) provide centimetre-scale detail of the beds in the borehole and can allow sedimentary structures such as cross-bedding, horizontal laminae, wave and ripple lamination to be recognised. Detailed facies analysis can therefore be
carried out using these tools, although patterns are not always easy to interpret and the most reliable interpretations can be made if there is also some core with which to make comparisons.

22.5 SUBSURFACE FACIES AND BASIN ANALYSIS

From the foregoing it should be apparent that a combination of information from the interpretation of seismic reflection data, core, cuttings and wireline logging tools can be used to carry out a full stratigraphic and sedimentary analysis of a subsurface succession of rocks. The vast majority of oil and gas reserves are to be found in the subsurface, so, from an economic point of view, the techniques described in this chapter are fundamental to exploiting those reserves. The principles of interpretation of sedimentary facies and the application of stratigraphic principles are the same whether the data are collected from below ground or from outcrops. Seismic reflection data provide information about large-scale structural and stratigraphic relationships which, with the advent of 3-D seismic cubes of data, offer a more complete image of the geology than scattered outcrops at the surface. Although data from boreholes may be scattered and one-dimensional, they provide a record of the sedimentary history that is more complete than is available from surface exposures, and seismic reflection data can be used to help correlate. Further description of these techniques is beyond the scope of this book and the reader is referred to the books and articles listed below for more detailed information.

FURTHER READING