During uplift and erosion (exhumation, unloading) the rocks will be subjected to extension, and extensional fractures will be produced. The porosity will not increase significantly but the extensional fractures will increase the permeability and thus improve the reservoir properties. Unfortunately the cap rock may also fracture during unloading, causing leakage from the reservoir.

To understand the properties of reservoir rock we need to integrate what we know about the sedimentology (depositional environments) of reservoir rocks, sediment composition (provenance), diagenesis and the structural geology.

Prior to drilling exploration wells, nearly all our knowledge about a reservoir is based on geophysical data. Even after data has been acquired from exploration wells, and also from production wells, prediction of the reservoir properties continues to be mostly based on geophysical methods and extrapolation between wells.

Geophysical methods including 3D and 4D seismic now provide a much more detailed picture of the reservoir than only 10–20 years ago. The methods for detecting fluid contacts, not only gas/water contacts but also oil/water contacts, from seismic data have improved greatly.

1.13 Carbonate Reservoirs

Reefs stand up as positive structures and may be draped by mud and form a stratigraphic trap determined by the size of the reef structure.

Carbonate reefs, and other carbonate deposits which can be reservoirs, form in a wide range of environments but all require clear water without much clay sedimentation. Reefs are deposited in high energy environments along coastlines exposed to high wave energy. The Bahamas carbonate platform has well-developed reefs on the exposed eastern side but not on the more protected western side. Coral reefs also require warm water (>20°C) and do not form where cold water is upwelling, e.g. along the coast of West Africa.

Reefs build up on the seafloor and may be buried beneath mud during transgressions. The reef then becomes a perfect stratigraphic trap, often with good permeability both vertically and horizontally.

Reefs can form long continuous barriers as in Australia (Great Barrier Reef). In the US much oil was found by following Jurassic and Cretaceous reef trends around the Gulf of Mexico.

High energy beach deposits on carbonate banks may consist of well-sorted carbonate sand (grainstones). Ooid sands (ooliths) are formed as beach and shoreface deposits and may have limited vertical thickness, reflecting the wave base. They may however stack up and form thicker sequences of such rocks. Ooids may also be transported from the shelf into deeper water as turbidites and other slope deposits, but the sorting and reservoir quality is then reduced.

Ooids are rather stable mechanically during burial, but at 2–3 km porosity may be strongly reduced by cementation in the intergranular pore space. The calcite cement may be derived by dissolution along stylolites. Stylolites have a thin layer of clay and other minerals that are not soluble and may present a barrier during oil migration and production.

Carbonate muds are very fine grained and do not have high enough primary porosity and permeability to form reservoir rocks, but may gain porosity and permeability by fracturing and become fractured reservoirs. They can also have mouldic porosity from dissolved aragonite fossils.

1.14 Drilling for Oil and Gas

Drilling for oil is a costly process, especially offshore. The object of a well is to prove the presence of, or produce, oil or gas. Sometimes wells are also drilled to inject water, chemicals or steam into the reservoir during production. Even a well which fails to find hydrocarbons (a dry well) is still of great value, because of the information it provides about the rocks in the area. This information forms part of the basis for the geological maps and profiles which are used in further exploration for oil and can be sold or exchanged for data from other companies. This is the reason why oil companies wish to keep the geological results of oil drilling confidential for some years after a well has been completed.

The first well in a new area is called a *wildcat* well, while *appraisal* wells are drilled to estimate the extension of an oil field. They may also become *production* wells. Stratigraphic wells are drilled mainly to obtain stratigraphical information from the basin.

Oil drilling used to be carried out largely on land, but now offshore drilling takes place not only on our continental shelves, but also in deep water (1–3 km). This type of drilling is many times more costly than drilling in shallow water or on land. This has led to increased efforts to gain maximum information from wells. The cost of analysing samples and logs is small in relation to the cost of drilling the well. We shall not go very deeply into the technical aspects of drilling for oil here, but merely look briefly at some of the most important principles.

When drilling commences at the surface, the diameter of the well may be 20"–30" (50–75 cm), but decreases downwards to 3"–6" (7–15 cm) at great depths. Normally a roller bit is used, which crushes the rock into small pieces (about 2–5 mm) called cuttings. Core samples are only taken when drilling through especially important rock strata (usually reservoir rocks) where large intact samples are needed for detailed examination. A circular diamond core drill bit must then be used. This takes time and costs a lot more per running metre, as the entire drill string has to be recovered to get each core section to the surface. Only the most critical sections are therefore cored.

Drilling mud is pumped down through the drill string into the well during drilling. This mud has several functions. When one drills several hundred or a 1,000 m down into rock, one encounters water, gas or oil which may be under high pressure. The drilling mud acts as a counterweight to prevent the uncontrolled gush of water or petroleum into the well and up to the surface in a blow-out. The pressure exerted by the drilling mud must exceed the pressure of oil and water in the surrounding formation. Heavy minerals such as barytes are frequently added to increase density; the main components of drilling mud are montmorillonite (smectite) containing clays, with a large number of different additives. The drilling mud also serves to cool the drill bit, and cuttings are brought back to the surface suspended in the circulating mud. The cuttings are then washed out from the drilling mud onto a sieve (shale shaker) and the mud can be used again.

The cuttings are continuously analysed on the drilling platform by a geologist who logs the composition of the cuttings, making a preliminary description of the rocks which are being drilled, and their mineralogy. Samples of cuttings are usually taken every 10–30 ft drilled. More detailed analyses are carried out in the laboratory. The cuttings are often poorly washed and need extra cleaning to get rid of the drilling mud; in weakly indurated mudstones it may be difficult to separate the drilling mud from the soft cuttings. Organic additions to drilling mud may cause problems when analysing cuttings, and sometimes oil-based rather than water-based drilling mud is used, which confuses analyses for oil. The fossil content of the rock fragments, largely microfossils, is used to determine the age of the strata (see Biostratigraphy).

Not all the cuttings which come up with the drilling mud have necessarily come from precisely the strata being drilled through at that time. There may also be contamination due to the *caving in* of overlying strata into the rising drilling mud. This means we can find material from younger rocks with a different composition mixed in with the formation being drilled, together with younger fossils. This demands considerable care when making stratigraphic interpretations based on microfossils identified in cuttings. The safest way is to register the first occurrences of a species when proceeding downwards from the top in the well. The last occurrence of a fossil may be the result of cave-ins from younger strata.

Since the pressure of the drilling mud is being monitored and adjusted to prevent oil and gas from penetrating into the well, significant oil and gas occurrences may be drilled through without being registered. This should be detected on the logs but it may be advisable to carry out special tests in the most promising strata to find out if there is petroleum present, and in what quantities.

As drilling proceeds, the well is lined with steel casing to prevent rock and loose sediment falling into it, but prior to casing, each section of the well has to be logged with different logging tools which require physical contact with the wall of the well. Radioactive logs, however, can also be run after the casing has been installed. It is useful to note when the different casings are installed, because that limits the strata which could have "caved in" and contaminated the cuttings. If the well is going to produce oil, a production pipe is used and installed running through the petroleum-bearing strata. It is then perforated by shooting holes in the steel casing (in the oil column) so that petroleum can flow into the well.

For an oil field to be capable of full production, several wells are normally required.

Up to 1990–1995 most of the exploration wells and production wells were nearly vertical. Horizontal barriers due to changes in facies or faults could then be critical barriers during production. It was difficult to produce oil from thin sandstones or carbonate beds because of vertical flow of water from below or gas from above. Onshore this could be compensated for by having a dense well spacing but offshore that would be too expensive. Horizontal drilling has revolutionised oil production.

It is now possible to follow thin oil columns laterally and to make complex wells to drain different compartments in the reservoir. Large oil fields with thin oil columns like the Troll field in the North Sea would have been difficult to produce without horizontal drilling. Horizontal and deviated wells may extend 8–9 km from the drilling platform, enabling production from relatively small reservoir compartments away from the platform.

Earlier, geophysics was used mainly to define structures but the quality of the seismic data was not good enough to provide much detail. 3D seismic based on 50 m line spacing allows the construction of a three-dimensional cube of geophysicial data, which provides much more detailed information.

By repeating seismic surveys during production at 2–5 year intervals, the effect of changes in the fluid composition on the seismic data can be seen, thus adding the time dimension to 3D seismics. 4D seismics has made it possible to follow the depletion of an oil or gas field by monitoring the GWC and often also the OWC during production. By this means, parts of a reservoir that have not been drained by the production wells can be detected. If the isolated reservoir compartments are large it may be economic to drill additional wells to drain them.

1.15 Oil Reserves – How Long Will Conventional Oil Last?

In the last 40–50 years we have had a discussion about how long the oil reserves will last and the famous geologist M. King Hubbert predicted in 1956 that oil production would peak in the United States between 1965 and 1970, and later Colin Campbell predicted that world production would peak in 2007 (see the Peak Oil movement). There is, however, a great deal of uncertainty in the estimation of reserves since this will depend on advancements in exploration technology as well as production efficiency.

The price of oil and taxation policies will also determine which type of oil accumulations can be exploited economically and thus reckoned as reserves.

At present the world reserves are estimated to be 1.2×10^{12} bbl $\left(2 \times 10^{11}\mathrm{m}^3\right)$ and nearly 60% of this is located in the Middle East. Europe has only got 1% and the whole of Asia about 3%.

Canada had up to recently very small reserves but after the heavy oil and tar sand in Alberta was included it has now nearly 15% and is second only to Saudi Arabia.

If oil shales were to be included, however, the USA would be the country with the largest reserves.

The world consumes about 85 million bbl/day $\left(85 \times 10^6\,\mathrm{bbl/day}\right)$; the US consumption $\left(20.7 \times 10^6\,\mathrm{bbl/day}\right)$ makes up nearly 25% of that.

The most important producers are Saudi Arabia (10.2×10^6 bbl/day) and Russia (9.9×10^6 bbl/day). The US is also a major producer (7.5×10^6 bbl/day) but this is still only about 37% of the country's consumption.

China has become a major importer of oil with a consumption of 7.6×10^6 bbl/day, while their production is 3.9×10^6 bbl/day.

It is clear that consumption of oil in Asia will rise and it will be very difficult to meet this demand.

Norway's oil production was 122 million Sm^3 in 2008 and about the same amount of gas. This corresponds to 0.8×10^6 bbl or 2.1 million bbl of oil/day. However since the domestic consumption is only about 10% of this (0.22 million bbl/day), Norway is a major exporter.

It will probably be difficult to meet the demand for conventional oil in the next decades. There are, however, very large reserves of fossil fuels in terms of gas, heavy oil, tar sand and also coal. All these types of fossil fuel can be used for heating and transport. Particularly in North America there is much oil shale and also gas shale. Gas in fine-grained siltstones and shales is expected to be a major source or energy in the years to come.

In recent years coal methane and shale gas have become important sources of such energy. Gas in solid form (gas hydrates) may also represent a future source of hydrocarbons. There are, however, many environmental problems connected to the production and utilisation of these resources and this represents a great challenge, including for geoscientists.

It will probably take a long time before fossil fuels can be replaced by other sources of energy. As the demand increases, oil exploration and production will become more and more sophisticated technologically and also geologically.

A broader background in geological and engineering disciplines will also be required to reduce the environmental problems with the exploitation of fossil fuels.

Storage of carbon dioxide requires expertise from petroleum geologists.

The exploitation and burning of fossil fuels releases large amounts of CO_2 into the atmosphere which is an addition to what is part of the natural carbon cycle (Fig. 1.14). The CO_2 in the atmosphere is dissolved in seawater to H_2CO_3 and then precipitated as carbonate. Another part is taken up by plants, including algae, and may be stored as reduced carbon.

The total amounts of calcite precipitated is equal to the amounts of Ca^{++} released by weathering of silicate rocks (e.g. plagioclase) and transported into the ocean by rivers.

1.16 The Future of Petroleum Geoscience

Petroleum geoscience is geology and geophysics applied to petroleum exploration and production. In this book we will try to show the wide range of disciplines that are relevant and useful for this purpose.

Many of the disciplines in the geosciences are highly specialised and there is often too little communication between the different fields. Most researchers naturally focus on a very small area because of the requirements with respect to methods and analytical techniques, and the demands of following the literature. Petroleum geoscience requires a broad overview of substantial parts of geology and geophysics and

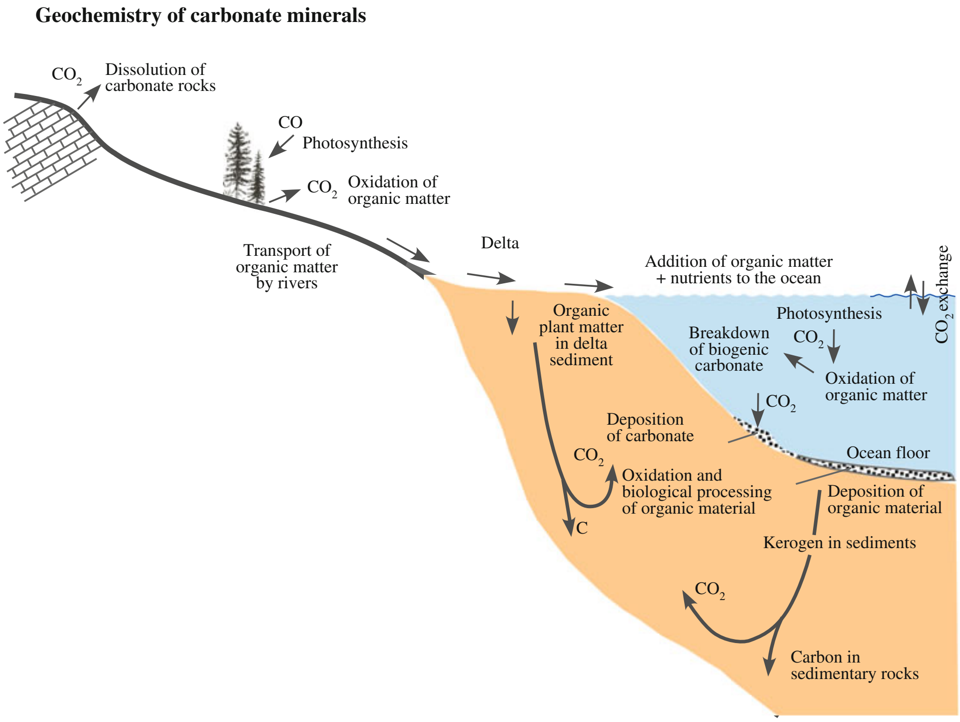

Fig. 1.14 Illustration of the carbon cycle. Carbon from organic matter and carbonate rocks are the major sinks for carbon (CO_2). The rate of precipitation of carbonate in the ocean by organisms is limited by the supply of Ca^{++} and Mg^{++} from weathering of silicate rocks brought in by rivers