also be eaten by burrowing organisms which live in the top portion of the sediments. The activity of these organisms contributes to reducing the organic content of the sediments because most of the organic matter is digested when the sediment is eaten. Bioturbation also stirs up the sediments, exposing them more to the oxygen-bearing bottom water. However, if the bottom water is stagnant, the lack of oxygen and the toxicity of H_2S will exclude most life forms. The resultant lack of bioturbation will thus preserve more organic matter in the sediment together with perfect, undisturbed, lamination. Stagnant, or anoxic, conditions are defined by an oxygen content of <0.5 ml/l water. Sulphate-reducing bacteria, however, can use a good deal of organic matter and precipitate sulphides (e.g. FeS_2). If the sediments contain insufficient soluble iron or other metals which could precipitate sulphides, more sulphur will be incorporated in the organic matter and will eventually be enriched in the oil derived from such source beds.

Except where the water is completely stagnant, slow sedimentation rates will result in each sediment layer spending longer in the bioturbation and microbiological breakdown zones, and consequently less organic matter will be preserved in the sediment. Rapid sedimentation leads to more of the deposited organic matter being preserved but from the outset it will be highly diluted with mineral grains. Consequently an intermediate sedimentation rate in relation to organic production (10–100 mm/1,000 years) results in the best source rocks.

As we have seen, the net accumulation of organic matter in sediments is not so much a function of the total productivity, but rather of the relationship between productivity and biogenic breakdown and oxidation. In areas with powerful traction currents, most organic matter will be oxidised. An important source of oxygen-rich water in the deep ocean is the cold surface water which sinks to the bottom of the ocean in polar regions and flows along the ocean floor towards equatorial regions. This flow balances the surface flow to higher latitudes like the Gulf Stream in the Atlantic.

These bottom flows are of considerable magnitude during glacial periods, when large amounts of cold water are sinking near ice sheet peripheries. In warm periods, for example during the Cretaceous, the poles were probably ice-free and there was much less cold surface water available to sink down and drive the ocean conveyor system. The deeper parts of the Atlantic experienced stagnant bottom conditions during such periods.

Limited water circulation in semi-enclosed marine basins due to restricted outflow over a shallow threshold is a common cause of stagnant water bodies (Fig. 1.2a). The Black Sea is a good example. In response to an abundant freshwater supply from rivers and a relatively low evaporation rate, a low salinity surface layer leads to density stratification in the water column and a consequent reduction in circulation. In basins with little precipitation and where there is net evaporation, the surface water will have higher salinity and density than the water below it, and will sink down. This circulation brings with it oxygen from the surface and can give oxidising bottom conditions with little chance for organic matter to survive to form source rocks.

Lakes or semi-enclosed marine basins often have a temperature- or salinity-induced density stratification so that oxygenated surface water does not mix with water in the deeper part of the basin. This leads to anoxic conditions and a high degree of preservation of the organic matter produced in the surface waters. This aspect is therefore of considerable interest in exploration for petroleum in freshwater basins, particularly in Africa and China. The open oceans have normally had oxygenated water, but during the Cretaceous most of the Atlantic Ocean is believed to have been stagnant during so-called “anoxic events”, and substantial amounts of black shale were deposited in the deeper parts of the ocean during these periods.

1.5 Early Diagenesis of Organic Matter

Microbiological breakdown of organic matter in sediments is due to the activity of bacteria, fungi, protozoa, etc. and under oxidising conditions these are extremely effective. However, the porewater quickly becomes reducing if the oxygen is not replenished. In relatively coarse-grained sediments (sand), oxygen may diffuse to depths of 5–20 cm below the seabed, while in clay and fine-grained carbonate mud the boundary between oxidising and reducing water (redox boundary) may be a few millimetres below the seafloor. The pores in the sediments here are so small that water circulation and diffusion are insufficient to replace the original oxygen in the porewater as it gets used up by oxidation of organic matter. Clay-rich sediments soon become a relatively closed system, and the downward diffusion of oxygen from the seabed is very slow in fine-grained sediments.

Aerobic breakdown is therefore much more effective in coarse-grained sediments than in fine-grained ones. In anaerobic transformation bacteria use organic matter, e.g. short carbohydrate chains. Cellulose is broken down by fungi, and finally by bacteria. The end products are methane (CH_4) and carbon dioxide (CO_2). Methane, however, is the only hydrocarbon produced in any quantity at low temperatures by bacteria close to the surface of the sediment. Gas occurring at shallow depths (shallow gas) therefore consists largely of methane (dry gas) unless there has been addition from much deeper strata. Biogenic gas may form commercial accumulations, as in Western Siberia and also in the shallow part of the North Sea basin. The presence of abundant shallow gas may represent a hazard in the form of blowouts and fire during drilling. Gas occurring at shallow depth may also have a deeper source generated from a gas-prone source rock (coaly sediments) or by cracking of oil, but such gas has a very different isotopic signature than biogenic gas.

1.6 Kerogen

As organic material becomes buried by the accumulation of overlying sediments, water is gradually expelled during compaction.

Complex organic compounds like proteins are broken down into amino acids, and carbohydrates into simpler sugar compounds. These are able to recombine to make larger compounds, for example by amino acids reacting with carbohydrates (melanoid reaction). As this type of polymerisation proceeds, the proportion of simpler soluble organic compounds diminishes at depths of a few tens of metres down in the sediment. It is these newly-formed complex organic structures which are called kerogen.

Kerogen is a collective name for organic material that is insoluble in organic solvents, water or oxidising acids. The portion of the organic material soluble in organic solvents is called bitumen, which is essentially oil in a solid state.

Kerogen consists of very large molecules and is a kind of polymer. When it has been exposed to sufficient time and temperature these large molecules will crack into smaller molecules, mostly petroleum. When the temperature is about 100°C a long period of geological time is required. In rapidly subsiding basins the exposure time is shorter and oil generation may only start at about 140–150°C. In the North Sea basin the "oil window" may typically be between 130 and140°C.

1.7 Migration of Petroleum

Petroleum migrates from low permeability source rocks into high permeability reservoir rocks from which the petroleum can be produced (Fig. 1.2b).

The main driving force for petroleum migration is buoyancy because it is less dense than water. The forces acting against migration are the capillary forces and the resistance to flow though rocks with low permeabilities

Migration of oil and gas will therefore nearly always have an upwards component.

We distinguish between *primary migration*, which is the flow of petroleum out of the source rock and *secondary migration*, which is the continued flow from the source rock to the reservoir rock or up to the surface (Fig. 1.4).

Oil and gas may also migrate (leak) from the reservoir to a higher trap or to the surface. Hydrocarbons are relatively insoluble in water and will therefore migrate as a separate phase. Solubility varies from as little as 24 ppm for methane to 1,800 ppm for benzene. Other compounds, such as pentane, are even less soluble (2–3 ppm). However, solubility increases markedly with pressure. Many hydrocarbons have solubilities of less than 1 ppm in water

It is difficult to envisage oil being dissolved in water and transported in an aqueous solution, both because of the solubility and the low flow rates. It would also be difficult to explain how the oil would come out of solution in the reservoirs (traps).

Gas, in particularly methane, has a fairly high solubility in water, especially under high pressure. If methane-saturated water rises to lower pressures, large quantities of methane can bubble out of a solution.

It is therefore necessary to assume that oil is mostly transported as a separate phase. Oil is lighter than

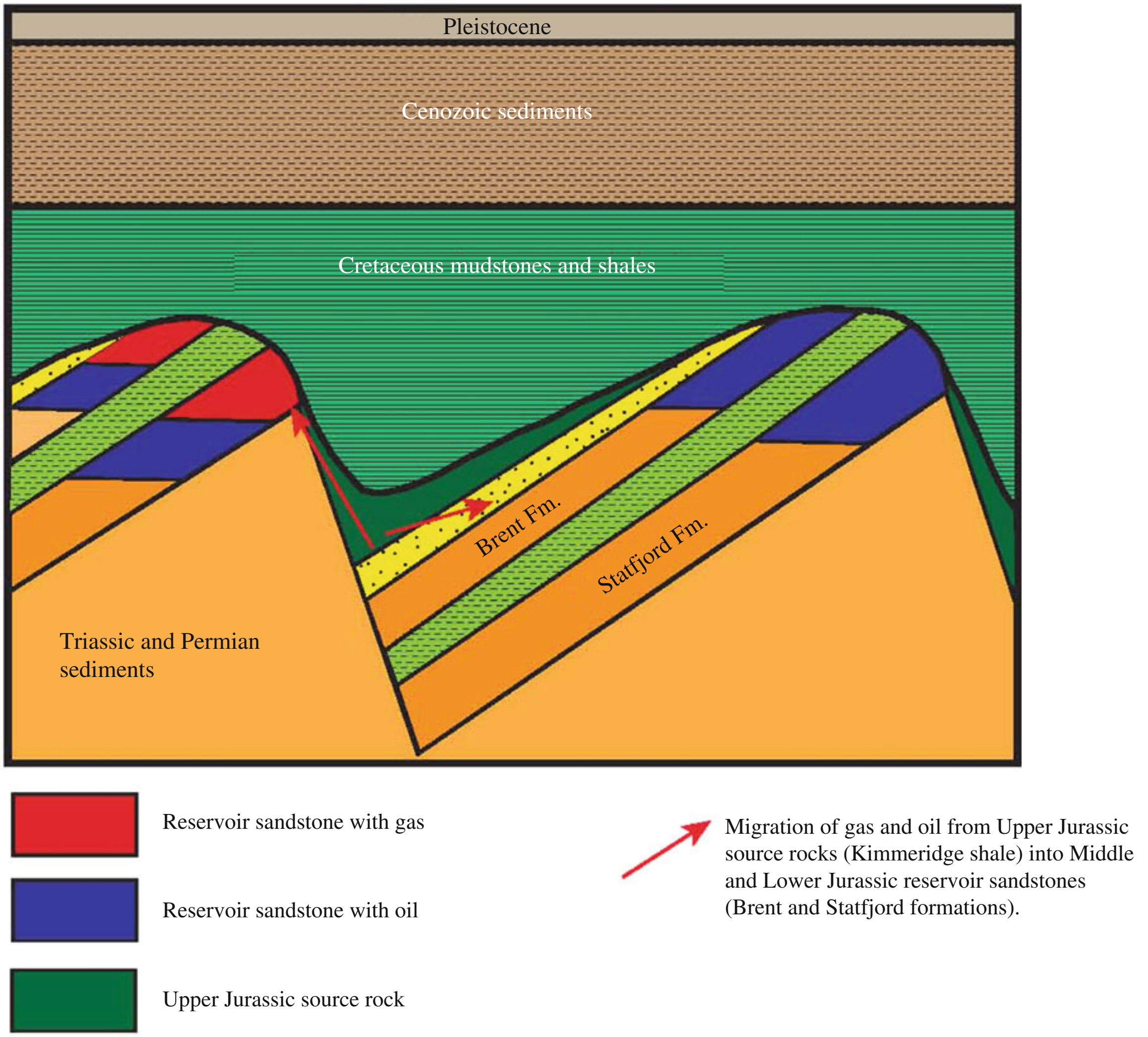

Fig. 1.4 Schematic illustration of primary migration (expulsion) of petroleum from a source rock and secondary migration into a reservoir (trap). This example is from the northern North Sea where rifting in Upper Jurassic time produced good conditions for the formation of a source rock and also traps on the uplifted fault blocks

water, and oil droplets would be able to move through the pores in the rocks but the caplliary restance is high for separate oil drops in a water-wet rock (Fig. 1.5). In order to pass through the narrow passage between pores (pore throat), the oil droplets must overcome the capillary forces. When the pores are sufficiently small in a fine-grained sediment, these forces will act as a barrier to further migration of oil. The small gas molecules, however, can diffuse through extremely small pores and thus escape from shales which form tight seals for oil.

Oil can therefore not migrate as small discrete droplets, but moves as a continuous string of oil where most of the pores are filled with oil rather than water (highly oil-saturated). The pressure in the oil phase at the top is then a function of the height of the oil-saturated column (string) and the density difference between oil and water.

The rate of migration is a function of the rate of petroleum generation in the source rocks. This is a function of the temperature integrated over time (Fig. 1.6).

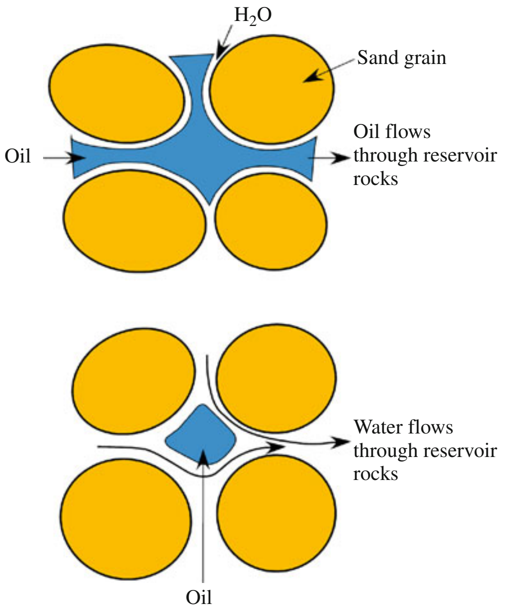

Fig. 1.5 Most sandstones are oil-wet and have a thin layer of water around the grains. A continuous oil phase will flow easily if the permeability is relatively high and the pore throats between the pores are relatively wide. Isolated droplets of oil will, however, be prevented from moving by capillary forces

The temperature history is a function of the burial depth and the geothermal gradients.

Deep burial over long time will cause all oil to be decomposed (cracked) into gas.

The degree of alteration of organic matter can be measured in different ways. Plant material is altered from a dull material to a material which becomes more shiny with increasing temperature. This can be quantified by measuring the amount of light reflected from a piece of plant material (vitrinite) under the microscope. A vitrinite reflectivity of 1.2 indicates that the source has generated much of the oil that can be generated. We will say that the source rock is in the middle of the "oil window" (Fig. 1.7). Values below 0.7–0.8. are found in source rocks which have not been heated enough (immature source rocks).

Vitrinite reflectivities close to 2.0 and above indicate that the source rock has generated all the oil and can generate only gas.

The Upper Jurassic Kimmeridge shale (Fig. 1.8) is the main source rock for the North Sea basin but it is not mature at its outcrop at Kimmeridge Bay in Dorset, south England.

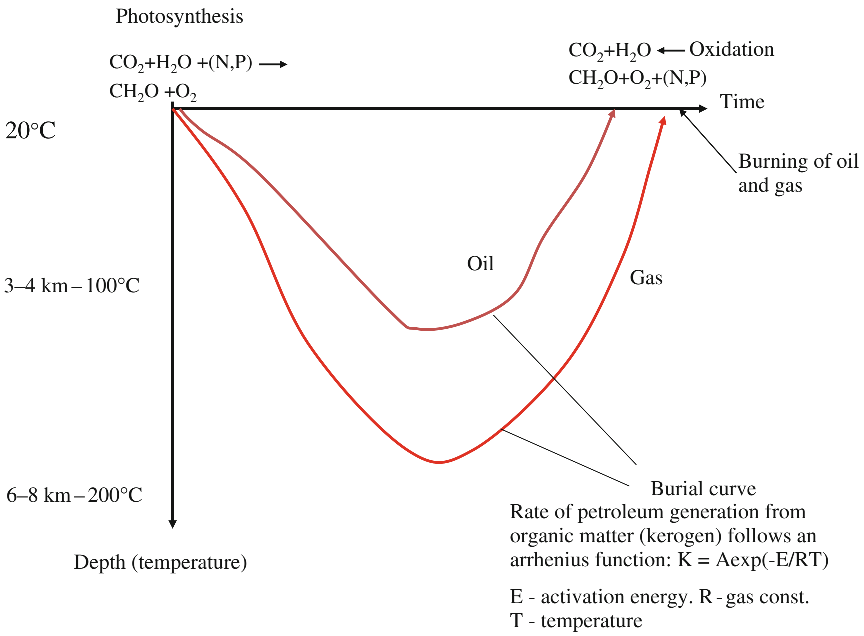

Fig. 1.6 Burial curve for source rocks determining the transformation of kerogen to oil and gas depending on time and temperature (burial depth)