

**Fig. 1.1** Transformation of solar energy to fossil fuels by photosynthesis. Only a small fraction of the solar energy is used for photosynthesis and most of the produced organic matter is

oxidised. As a result very little organic matter is buried and stored in sedimentary rocks and very little of this is concentrated enough to become a potential source rock

Phosphorus (P) and nitrogen (N) are the most important nutrients, though the supply of iron can also be limiting for alga production. It is this process of photosynthesis, which started 4 billion years ago, that has built up an atmosphere rich in oxygen while accumulating reduced carbon in sedimentary rocks as oil, gas and coal. Most of the carbon is nevertheless finely divided within sedimentary rocks, for example shales and limestones, in concentrations too low to generate significant oil and gas.

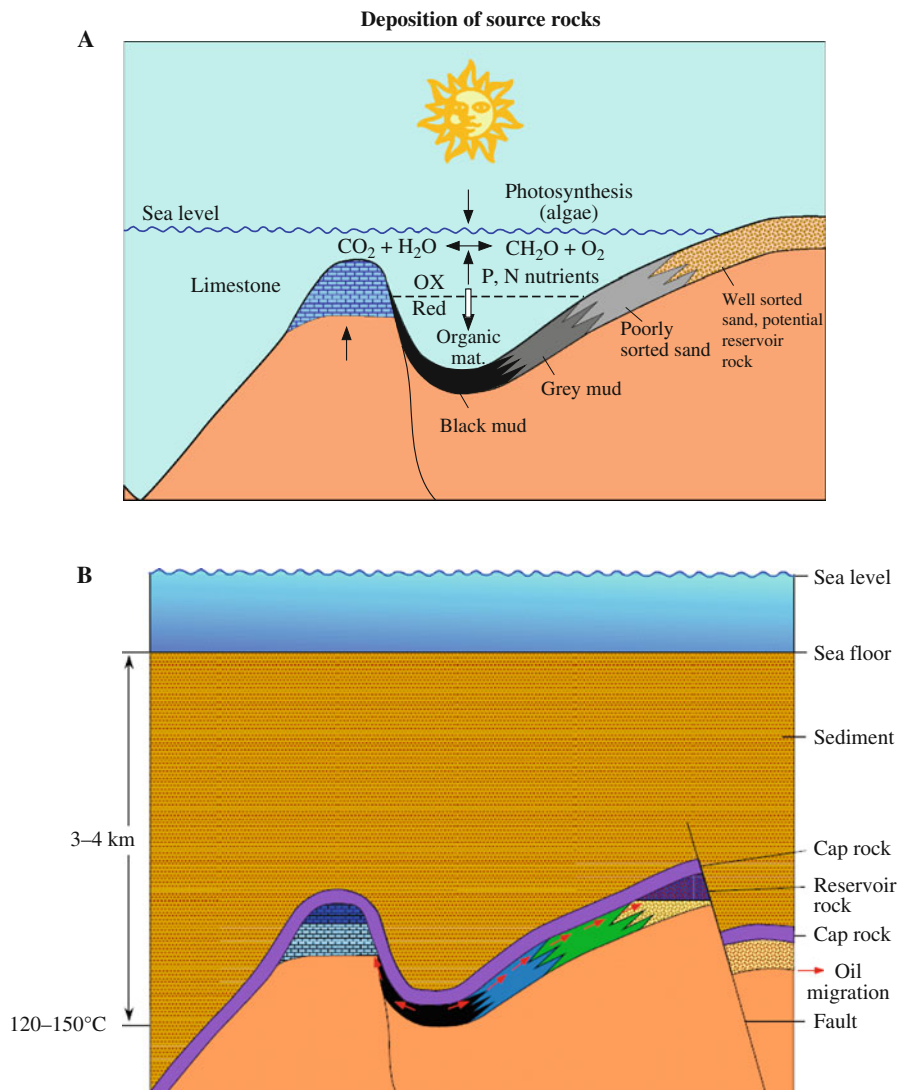
Energy stored by photosynthesis can be used directly by organisms for respiration. This is the opposite process, breaking carbohydrates down into carbon dioxide and water again, so that the organisms gain energy.

This occurs in organisms at night when there is no light to drive photosynthesis. Also when we

burn hydrocarbons, e.g. while driving a car, energy is obtained by oxidation, again essentially reversing the photosynthesis equation quoted above. Oxidation of 100 g glucose releases 375 kcal of energy. Carbohydrates that are produced but not consumed by respiration can be stored as glucose, cellulose or starch in the cell walls. Photosynthesis is also the biochemical source for the synthesis of lipids and proteins. Proteins are large, complex molecules built up of condensed amino acids (e.g. glycine ( $\text{H}_2\text{NCH}_2\text{—COOH}$ )).

Dried phytoplankton contains 45–55% carbon, 4.5–9% nitrogen, 0.6–3.3% phosphorus and up to 25% of both silica and carbonate.

Planktonic algae are the main contributors to the organic matter which gives rise to petroleum. Among the most important are diatoms, which have amorphous silica (opal A) shells.



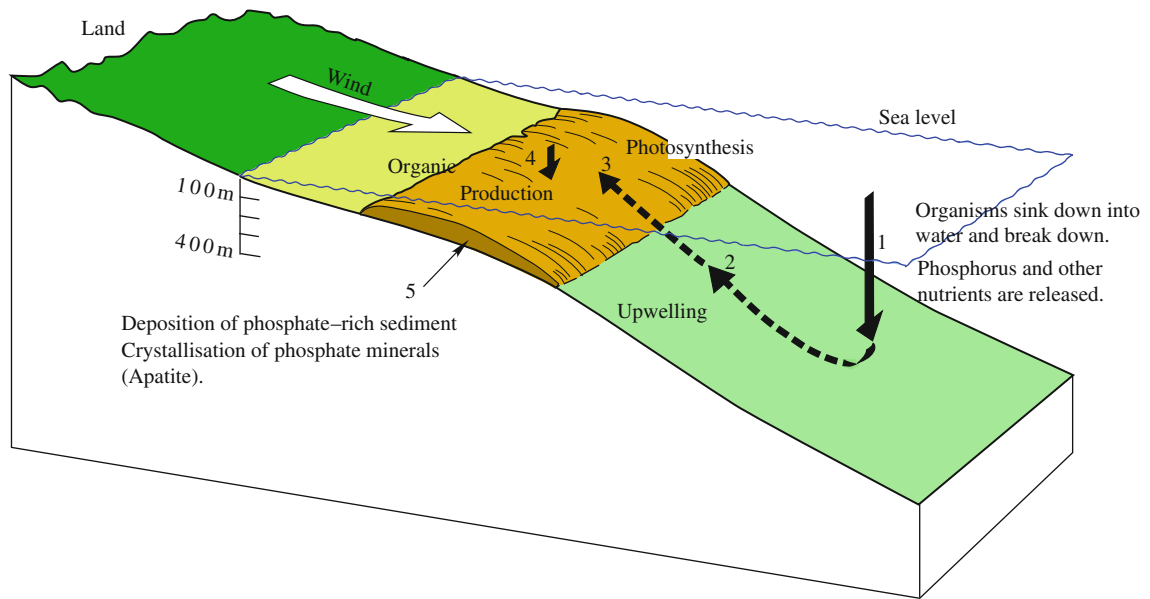
**Fig. 1.2** (a) Depositional environments for potential source and reservoir rocks. Depressions on the sea floor with little water circulation provide the best setting for organic matter to be accumulated before it is oxidised. (b) Migration of petroleum from

source rocks into reservoir rocks after burial and maturation. The carbonate trap (e.g. a reef) is a stratigraphic trap, while the sandstone forms a structural trap bounded by a fault

Diatoms are most abundant in the higher latitudes and are also found in brackish and fresh water. Blue-green algae (cyanobacteria) which live on the bottom in shallow areas, also contribute to the organic material in sediments.

In coastal swamps, and particularly on deltas, we have extensive production of organic matter in the form of plants and trees which may avoid being oxidised by sinking into mud or bog. The residues of these higher land plants may form peat, which with deeper burial

may be converted into lignite and bituminous coal. But such deposits are also a potential source of gas and oil. Plant matter, including wood, also floats down rivers and is deposited when it sinks to the bottom, usually in a nearshore deltaic environment. When the trees rot they release  $\text{CO}_2$  and consume as much oxygen as the plant produced during the whole period when it was growing. There is thus no net contribution of oxygen to the atmosphere. This also applies to the bulk of the tropical rainforests. Where trees and plants sink into



**Fig. 1.3** Upwelling of water rich in nutrients on a continental margin with deposition of organic-rich mud

Trophic level 1	Trophic level 2	Trophic level 3	Trophic level 4
1,000 kg	100 kg	10 kg	1 kg
Phytoplankton	Zooplankton	Crustaceans	Fish

black mud, preventing them from being oxidised, there is a net contribution of oxygen to the atmosphere and a corresponding reduction of CO<sub>2</sub> in the atmosphere.

All animal plankton (zooplankton) live on plant plankton, and in turn are eaten by higher organisms in the food chain. At each step in the food chain, which we call a trophic level, the amount of organic matter (the biomass) is reduced to 10%.

Ninety percent of the production of organic matter is therefore from algae. This is why algae and to some extent zooplankton account for the bulk of the organic material which can be transformed into oil. Larger animals such as dinosaurs are totally irrelevant as sources of oil.

The most important of the zooplankton which provide organic matter for petroleum are:

1. Radiolaria – silica shells, wide distribution, particularly in tropical waters.
2. Foraminifera – shells of calcium carbonate.
3. Pteropods – pelagic gastropods (snails) with a foot which has been converted into wing-shaped lobes; carbonate shells.

This is the second lowest level within the marine food chain. These zooplanktonic organisms are eaten by crustaceans which themselves are eaten by fish.

The total amount of organic matter that can be produced in the ocean is dependent on the nutrient supply from rivers, but river water does not only carry inorganic nutrients. It also contains significant amounts of organic matter, in particular humic acid compounds, lignin and similar substances formed by the breakdown of plant material which are weakly soluble in cold water. When the river water enters the sea, there is precipitation due to the increased pH and lower surface temperature in the ocean.

Other plant materials, like waxes and resins, are more chemically resistant to breakdown and are insoluble in water. Such organic particles tend to attach themselves to mineral grains and accompany sediment out into the ocean.

Most of the oil reservoirs which have been formed since the Palaeozoic have been uplifted and eroded, and over time vast quantities of oil have flowed (seeped) out onto the land or into the sea. In this sense, oil pollution is a natural process. Only a small

proportion of the petroleum that has been formed in source rocks has actually become trapped in a reservoir. One might expect this seepage to have provided a source of recycled petroleum in younger sediments, but petroleum breaks down extremely rapidly when subjected to weathering, oxidising to  $\text{CO}_2$ , and the nutrients (P, N) that were required to form the organic matter are released and may act like a fertilizer.

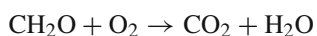
On land, evaporation will remove the lighter components while bacteria will degrade the heavier components. Fossil asphalt lakes consist of heavy substances which neither evaporate nor can be easily broken down by bacteria. In the ocean, the lighter components will dissolve quite rapidly, while the heavier asphalt fraction will sink to the bottom and be degraded and recycled.

In uplifted sedimentary basins like the Ventura Basin and the Los Angeles Basin in Southern California there are abundant natural oil seeps both onshore and offshore.

On the beaches from Santa Barbara towards Los Angeles there are many natural oil seeps.

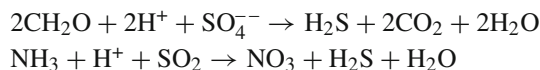
### 1.3 Breakdown of Organic Matter

Almost all (>99%) of the organic matter which is produced on land and in the oceans is broken down through direct oxidation or by means of microbiological processes. If oxygen is present, organic matter will be broken down in the following manner:

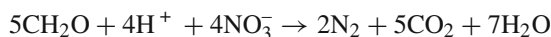


Where oxygen is available, organic matter is oxidised relatively rapidly both on land and in the sea. As organisms die, organic material suspended in seawater sinks through the water column consuming oxygen. If water circulation is restricted due to density stratification of the water column, the oxygen supply will be exhausted. Instead, the bound oxygen in sulphates or nitrates is used by sulphate-reducing and denitrifying bacteria which decompose organic material in an anoxic environment. The first few centimetres below the seabed are usually oxidised, while reducing conditions prevail 5–30 cm below the sea floor. Below this redox boundary where there is no free oxygen,

sulphate-reducing bacteria react with organic matter as indicated below:



$\text{H}_2\text{S}$  is liberated, giving stagnant water and mud a strong smell. Through denitrification we get



When the rate of accumulation of organic matter exceeds the rate of oxygen supply the redox boundary will be in the water column, separating the oxidising surface water from the reducing bottom water.

This is typical of basins separated from the deep ocean by a shallow sill, like the Black Sea and some of the deep Norwegian fjords. Fresh or brackish surface water floating on more saline water also helps to maintain a stable water stratification with little vertical mixing. Lakes may have good water stratification because warm surface water is less dense than the colder bottom water. Black mud deposited at the bottom of lakes may produce good source rocks. In cold climates, however, the water in the lakes overturns in the winter because the maximum water density is at  $4^\circ\text{C}$ , preventing the stable stratification required to form source rocks.

### 1.4 Formation of Source Rocks

All marine organic material is formed near the surface of the ocean, in the photic zone, through photosynthesis. For the most part this is algae. Some phytoplankton are broken down chemically and oxidised and some are eaten by zooplankton. Both types of plankton are eaten by higher organisms which concentrate the indigestible part of the organic matter into fecal pellets which may be incorporated into sediments. Plankton is made up of very small organisms which sink so slowly that they are in most cases almost entirely degraded (oxidised) before they reach the bottom. Pellets, on the other hand, are the size of sand grains and sink more rapidly, and this organic matter is more likely to be preserved in the sediments.

On the bottom, organic matter will be subjected to breakdown by micro-organisms (bacteria). It will