hypersaline or brackish water. Recent green algae are abundant in depths of 5–10 m, but may range down to 100 m and also extend into lagoons and mangrove swamps. Some species can grow on firm substrates, but most grow in sand or mud. They generally prefer environments with only moderate wave energy. The calcareous green algae are major producers of small aragonite crystals which form lime mud. The presence of green algae therefore ensures that lime mud is deposited in the lagoons.

5.4.2.2 Mineralogy

The skeletal material in living algae is either calcite or aragonite, never mixtures of these two minerals in the same species. The extent of calcification is highly variable and may be only partial in some groups while other groups have a pervasive calcification of the whole plant body. In recent calcareous algae, the precipitated calcite (usually high-Mg calcite) or aragonite consists of small crystals (<4 μm). The same is assumed to apply to pre-Quaternary species too. The preservation of the plant bodies depends on the extent of calcification, with the most calcified parts selectively preserved in the fossil record.

Modern red algae deposit either aragonite or high-Mg calcite with a Mg content up to about 30 mol% $MgCO_3$. The skeletal elements in green algae consist only of aragonite. This primary difference in their skeletal composition is an important preservation factor. The solubility of skeletal aragonite in pure water is about twice that of low-Mg calcite, whereas the solubility of skeletal high-Mg calcite is up to 10 times that of low-Mg calcite. Hence, the fine-grained aragonite skeleton of the green algae is replaced by sparry calcite, whereas coralline red algae with a primary calcitic composition of varying magnesium content show different degrees of alteration (often partial dissolution).

5.4.2.3 Geological Range

Calcareous green algae first appeared in the Cambrian, which led to the production of large amounts of lime mud. These algae are still an important factor in modern shallow-water carbonate sedimentation. Red calcareous algae also evolved in the Cambrian. In Recent marine environments they are commonly encountered both in cold and warm water deposits within the photic zone, although most of them live in fairly shallow water (<25 m).

5.4.2.4 Significance for Petroleum Geology

Red algae, particularly those with erect growth forms, may form primary framework porosity in reefs. The algae are susceptible to neomorphic replacement and develop secondary porosity when exposed to extensive freshwater dissolution.

Red algae are common associates of many oil and gas producing reefs, notably stromatoporoid and coral reefs. This includes the Middle Silurian pinnacle reefs (stromatoporoid-coralgal reefs) in the Michigan Basin of southeastern Michigan, USA, the Upper Palaeocene Intisar "D" Field (coralgal reef) in Libya, the Miocene coralgal reefs in the Salwati Basin of Irian Jaya, Indonesia and the Miocene Central Luconia Fields of offshore Sarawak, Malaysia.

Calcareous green algae may form important source rocks for oil.

5.4.3 Coccolithophores

Coccolithophores are an example of free-floating algae with carbonate shells. They are single-celled, microscopic (5–20 μm) plants belonging to the golden-brown algae. A coccolithophore is generally spheroidal or ovoidal and is covered with an external calcareous skeleton (coccosphere) (Fig. 5.10). The coccosphere is composed of a variable number of small (a few μm), commonly round to oval, calcareous plates (coccoliths). The coccoliths are made of tiny, platy low-Mg calcite crystals (0.25–1 μm) with a flattened rhombic form, and are stacked in an imbricate fashion that produces a spiral pattern. The coccolithophores usually disaggregate after death and accumulate as individual coccoliths, sometimes forming extensive chalk deposits.

5.4.3.1 Ecology

Coccolithophores are most common in the photic zone of open seas, although they may also range into

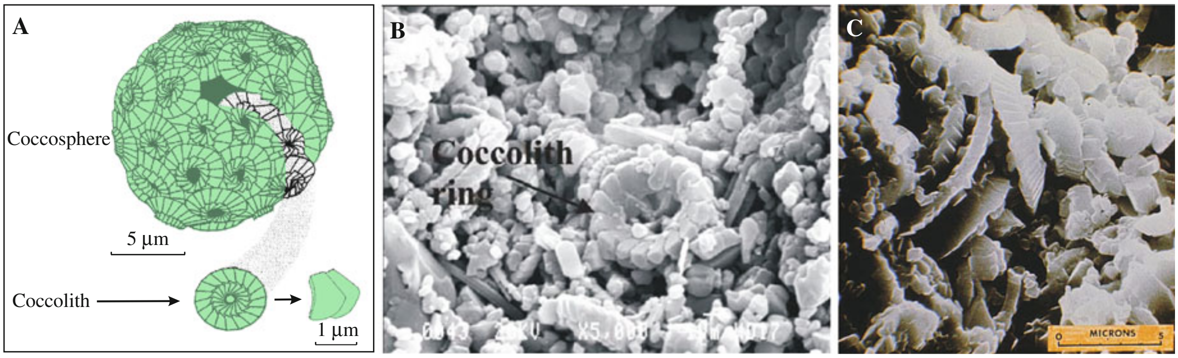

Fig. 5.10 (**a**) Skeletal structure of coccospheres and coccoliths. In this example the spheroidal coccosphere is composed of many round calcareous plates (coccoliths) which consist of tiny, platy calcite crystals stacked in an imbricate pattern. Modified from Hjuler (2001). (**b**) SEM picture of Liège chalk consisting of a mixture of coccoliths and loose platy calcite crystals. (**c**) SEM picture of Upper Cretaceous coccoliths in the Ekofisk field, North Sea. Petroleum occurs between the small plate-like coccoliths. The limestone has 32% porosity and 1 mD permeability (from Bjørlykke 1989)

nearshore lagoons. They swim freely in the surface waters (commonly the upper 100 m) of the ocean, occurring in greatest abundance in temperate zones. Coccolithophores are abundant (commonly as many as half a million individuals per litre of water) in the photic zone of modern oceans. Coccoliths are important constituents of some fairly deep basinal and distal shelf sediments.

Deep-sea drilling has shown that coccolithophores were very much more widespread during the Cretaceous and Lower Tertiary than they are today. The colder climate which began in the Miocene shifted the northern limits for coccolithophore sedimentation southwards. Many pelagic species have very specific temperature requirements and their occurrence provides an important contribution to the palaeoecology of marine sediments of various ages.

5.4.3.2 Mineralogy

The plates of the coccolithophores consist of low-Mg calcite which makes them fairly stable during diagenesis.

5.4.3.3 Geological Range

Coccolithophores range from the Triassic to Recent, but were not common before the Jurassic. They were particularly abundant in the Cretaceous and Lower Tertiary, forming thick, extensive chalks. They comprise approximately 25% of present-day calcareous oozes and up to 90% of some Cretaceous and Tertiary chalks.

5.4.3.4 Significance for the Petroleum Industry

Chalks made up of coccoliths may be extremely porous. The porosity is in the form of primary interparticle micropores and may be as high as 40–50%, even in deeply buried chalks. Although their porosity may be high, permeability is generally low (less than a few mD) because of small pore-throat diameters (generally <1 µm). Hydrocarbon-filled interparticle pores in chalks are therefore productive only in combination with some other pore type, preferably fracture pores, which increases the permeability. Fractured chalks of Maastrichtian (late Cretaceous) to Danian (early Tertiary) age form major hydrocarbon reservoirs in the Central Graben of the North Sea (Ekofisk and associated fields). These are in fact the world's only major oilfield in such rocks, but the low permeability of this fine-grained lithology creates some production problems.

5.4.4 *Calcispheres*

Calcispheres are of uncertain biological affinity, but many consider them to be algae because there is a great similarity between non-ornamented fossil calcispheres and reproductive cysts of some living green algae (dasycladacean algae). They are generally 40–200 μm in diameter and are composed of a thin (commonly 3–30 μm), well-defined calcite wall, enclosing a single spherical chamber (Fig. 5.11). The wall may be singly layered or have several concentric layers distinguishable by the alternation of uniform micritic texture with a fabric showing radial elements. The wall has radial pores, but there is no aperture. The outer surface may bear spines. The chamber is normally filled with cement or sediment.

5.4.4.1 Ecology

Many fossil calcispheres seem to owe their origin to dasycladacean algae, and as such, they provide a useful palaeo-environmental indicator. Devonian and Permian calcispheres are most common in shallow subtidal environments, especially in restricted or back-reef environments. In the Cretaceous, calcispheres are especially important in pelagic deposits such as Chalk sediments in the North Sea.

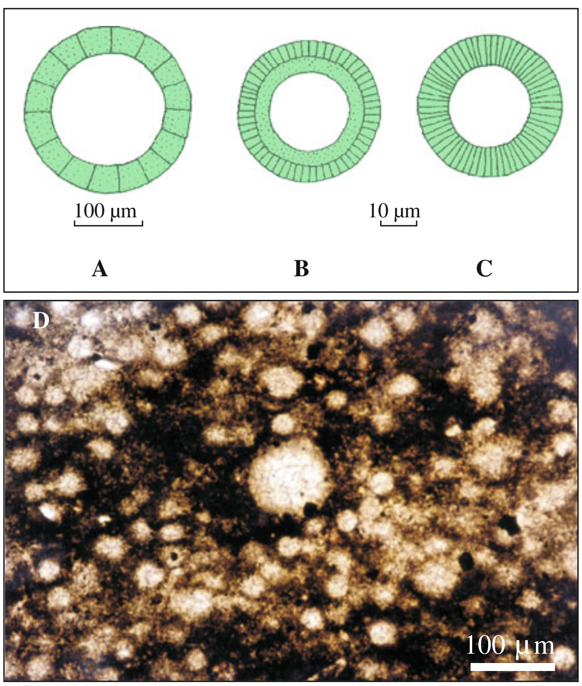

Fig. 5.11 Sections of calcispheres. In most cases, the calcitic wall consists of only one layer (**a**, **c**), but multilayered walls are also known (**b**). (**d**) Micrograph of the abundant calcispheres, partially replaced by euhedral pyrite as viewed in transmitted light, Ravnefjeld Formation (Upper Permian), East Greenland. See Nielsen and Hanken (2002). **a**, **b** and **c** are modified from Scoffin (1987)

5.4.4.2 Geological Range

Calcispheres are widely known from Upper Palaeozoic limestones, especially Devonian and Carboniferous, but also occur in older and younger strata.

Calcispheres have no particular significance for petroleum geology. However, they may be an important component improving the overall potential of a source rock.

5.4.5 Distribution of Algae in Modern and Older Carbonate Sediments

If one places a profile extending from a basin centre to a coast with reef development (Fig. 5.12), we see the following distribution of algae:

A. The sedimentation basinward consists largely of planktonic algae (coccolithophores), planktonic foraminifera and some other calcareous organisms.
B. In the reef facies we find mainly red algae which build strong, solid structures of carbonate, which in conjunction with the corals can resist waves which break against the reef. In the lagoons landward of the reef we find green algae. These have bush-shaped skeletons and can only grow where the wave energy is moderate. They are major producers of small aragonite crystals which form lime mud. The green algae therefore ensure that lime mud is deposited in the lagoon.
C. In protected parts of lagoons and in the tidal zone, the sea bed is often covered with cyanobacteria which lie like a gelatinous carpet over the sediments. These algae consist of a network of threads which hold the sediment in place and protect it against moderate currents and wave erosion. However, they may be eaten by grazing animals, e.g. snails. In high-energy nearshore environments we find red algae.

The age range and taxonomic diversity of the major calcareous algal groups are shown in Fig. 5.13.

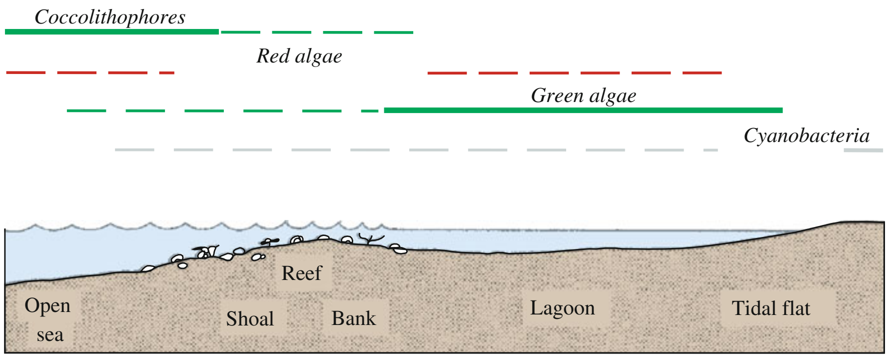

Fig. 5.12 Generalised distribution of recent skeletal and non-skeletal algae across a sediment basin in a low-latitude region (modified from Wray 1977)

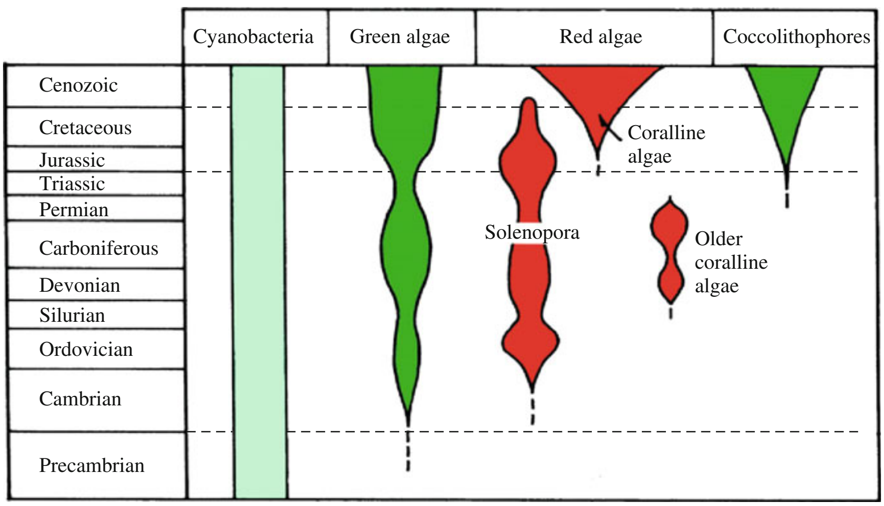

Fig. 5.13 Distribution of the important algal groups through geological time. Cyanobacteria have existed since early Precambrian times, and the oldest stromatolites known are up to about 3 billion (3×10^9) years old. Both green and red calcareous algae first appeared in the Cambrian. The evolution of calcareous green algae led to the production of large amounts of lime mud without chemical precipitation. The Solenoporaceae family (red algae), which was widely distributed in the Palaeozoic, died out during the Cretaceous. Coralline algae appeared in the Jurassic, and still exist. The evolution of the planktonic algae, mainly coccolithophores from the Triassic to present, has been a vital factor in global carbonate sedimentation (modified from Ginsburg et al. 1971)

5.5 Invertebrate Skeletal Fossils

5.5.1 Foraminifera

Foraminifera (or forams for short) are a very important group of single-celled animals that secrete chambered, calcareous or sometimes agglutinated tests. Agglutinated tests are made up of foreign particles like mineral grains and/or shell fragments such as coccoliths, small foraminifera and sponge spicules (Fig. 5.14a–c). These particles are attached by calcitic or ferruginous cement to a layer of tectin (an organic compound composed of protein and polysaccharides).

Most foraminifera have an outer carbonate shell with one or more openings (apertures). A few species have only one chamber, but most foraminifera add new chambers as they grow. The individual chambers are arranged in a specific pattern (Fig. 5.14d–g), either in a single row (uniserial) or in two or three alternating