deltas with oolite banks in the shallowest parts (<2 m). In addition to oolites there are grains of bioclastic material. Tidal deltas of this sort would form good oil reservoirs because of the high primary porosity, and in the Mesozoic series we find similar reservoir rocks. Shoreface deposits are not as well sorted as we would normally expect as they consist of fine sand and lime mud. This is possibly because the shoreline is stabilised by plants which bind the sediments.

Gastropods are particularly important in the lagoons and the intertidal environment. On the beach, shrimps and crabs burrow and disturb the lamination in the sediments. The lagoons are surrounded by swamps with bushes and mangroves, or algal flats. Landward of the algal mat facies, which is most typically developed at the high water mark, the sabkha facies continues. The degree of evaporation is higher here in the supratidal zone and dilution with seawater rarer. The sulphates, especially gypsum or anhydrite, are precipitated within the sediment near the groundwater table. The sabkha flats pass landwards into drier areas dominated by aeolian sand.

The facies distribution we have just described, from the open marine lagoon to the supratidal environment, will form a characteristic vertical sequence in the event of relative sea level fall and progradation. Periods with transgressions and subsequent regressive outbuilding will result in a series of sequences (cycles), starting with shallow marine (subtidal) sediments and culminating with evaporites (anhydrite) at the top. These cycles are also found in the Mesozoic and the impervious anhydrite beds forms an ideal cap rock above oil reservoir rocks. Carbonate sand facies, pellet facies, and particularly oolites, make good reservoir rocks, while the marine muds are source rocks.

5.7.3.4 Evaporite Basins

In ocean areas with normal salinity, practically all carbonate deposition is through biological precipitation. This is because the biological precipitation is rather efficient so the sea water does not become saturated with respect to the most common carbonate minerals like aragonite and calcite. In areas with somewhat higher salinity, however, for example in the Persian Gulf, there may also be chemical precipitation of calcium carbonate. This is because there are fewer organisms to precipitate carbonate and because of evaporation concentrating the sea water. Here too this precipitation may nevertheless be linked to biological factors. Periods with algal blooms in the surface waters involve photosynthesis and consumption of CO_2. This raises the pH, creating oversaturation and thus favourable conditions for chemical precipitation, i.e. a high degree of oversaturation.

Carbonates make up only a small percentage of the salt precipitated when seawater evaporates to dryness. However, they are among the least soluble of the common salts in restricted ocean basins where the salinity is too low for the more soluble salts to precipitate (e.g. NaCl). Carbonates together with sulphates like gypsum or anhydrite often form thick evaporite sequences. In highly saline basins with more intense evaporation and restricted circulation, the water will become enriched in Mg^{2+} and dolomite will form, perhaps also magnesite.

5.7.3.5 Carbonate Turbidites on Slopes Skirting Carbonate Platforms

Carbonate sand and mud which is stirred up during storms over shallow water may be transported over the shelf edge to continue downslope as turbidites or debris flows. Carbonate platforms may rise 2–3 km above the surrounding seafloor and the slope may be very steep (20–30°) because of the hard and stable carbonate rocks.

5.7.3.6 Pelagic Carbonate

Pelagic carbonate deposits consist largely of planktonic organisms (coccolithophores, foraminifera, pteropods etc.) which live in the upper part of the water column, sinking to the bottom when they die. How clean the carbonate deposits are depends on how much other biological sedimentation there is, e.g. from siliceous organisms like diatoms and radiolaria, and how rapidly clastic sedimentation takes place. Therefore, carbonate sediments commonly become concentrated on top of submarine highs where the siliciclastic sedimentation rates are low. This is often observed on seismic lines where the reflections become stronger on the top of submarine positive tectonic structures.

In the deep ocean much of the pelagic carbonate production is dissolved as the particles settle through the water column. The sedimentation rate is a function of productivity in the upper water layers minus solution as the dead organisms sink towards the seafloor. The dissolution of skeletal material is due to undersaturation of $CaCO_3$ in deep ocean water because this cold water can dissolve more CO_2 than warm surface water. The combination of low temperatures and increasing hydrostatic pressure with depth involves an increase in the pCO_2 and decrease in the pH. The CO_2 is produced by respiration and decay of pelagic organisms in the deep ocean. Below the depths where the rate of dissolution is equal to the rate of sedimentation of carbonate, no carbonate sediments accumulate. This is called the carbonate compensation depth (CCD) and varies from 1–2 km in cold water at higher latitude to 4–5 km in the warm water equatorial regions.

Since the planktonic carbonate organisms are very small, pelagic carbonate deposits form a fine-grained ooze of clay- and silt-size particles, with occasional larger fossil fragments. Large areas of the South Atlantic and Pacific are covered by sediment containing more than 50% $CaCO_3$ from planktonic organisms. Foraminifera and coccolithophores form the most important deep-sea carbonate deposits. They are also important as an indication of environment, e.g. water temperature (Fig. 5.12). Coccolithophores live mainly in the photic zone. In areas of high productivity, for example in the fjords of Norway, the concentration of coccolithophores may be several millions per litre, but 50,000–500,000 is a more normal level. Although they consist of low-Mg calcite, their size makes them relatively soluble in cold water. In consequence, although production is greatest at high latitudes, it is only at lower latitudes that large quantities of coccolithophores are able to accumulate on the seafloor.

Shallow, warm seas with little other carbonate production provide particularly favourable conditions for the deposition of purer coccolith deposits. The seas of northwest Europe in Cretaceous times were a good example. The climate in the Mesozoic was undoubtedly considerably warmer than today, and northwest Europe also lay further south. Chalk forms a characteristic rock which is exposed in Denmark, South England and France, and continues under the southern and middle sections of the North Sea. It is missing in the north, possibly for palaeoclimatic reasons, although it is found in northeast Ireland. Chalk sediments were probably deposited in water depths of not more than 1–300 m, mostly below the photic zone. Since chalk is a micritic limestone, one would not expect it to form a suitable reservoir rock. The Ekofisk and associated fields are in fact the world's only major oilfield in such rocks, and the low permeability of this fine-grained lithology creates problems for production.

Pelagic calcareous algae such as coccolithophores did not become common until the late Jurassic and early Cretaceous. Consequently we do not have chalk deposits from older periods. This is an example of where the rock type is totally dependent on which organisms were precipitating carbonate. During the Palaeozoic most carbonate production took place in shallow water, as there were no planktonic calcareous algae to form deepwater pelagic carbonates.

5.7.3.7 Lakes and Inland Seas

Carbonate sedimentation in lakes depends on the rate of weathering and supply of Ca^{2+} from older calcareous sediments and calcium-bearing silicate rocks in the drainage basin. If there is an ample supply of Ca^{2+} and CO_3^{2-} also lacustrine sediments may contain considerable amounts of carbonate, and particularly at lower latitudes we find pure carbonate deposits. In cold lakes the solubility of carbonate is high and the carbonate content in the bottom sediments will mostly be limited to a few species of bivalves and gastropods. Temperate lakes often accumulate calcareous muds called marls, which in some lake sediments contain dolomite. Algae and certain higher plants often play an important role in carbonate production in lakes.

The Dead Sea is a good example of an inland sea where carbonate is precipitated chemically due to strong evaporation. In Africa and other tropical areas, lakes will be subject to seasonal evaporation to dryness, and we may find alternating layers of biogenic carbonate and chemically precipitated carbonate. Here, too, algal blooms in the surface water layer play a major role in precipitating carbonate. Thicker beds of carbonate below lake floors can be associated with longer term climate variation. In Lake Victoria, the sediments older than about 12,000 years have high carbonate content. This is because the lake nearly dried up during the last glacial period, when rainfall in the region was lower than now.

5.7.3.8 Calcareous Tufa Deposits and Travertine

Tufa is the name of a porous and spongy calcareous deposit common in limestone areas, usually at the base of slopes where groundwater emerges at the ground surface. Accreted in thin layers which often incorporate vegetation, it can build up into deposits several metres thick. Travertine is a more massive, relatively dense and sometimes finely banded and laminated carbonate deposit associated with freshwater springs or precipitated as speleothems in caves. Both varieties are precipitated from freshwater supersaturated with respect to calcium carbonate. Groundwater flowing through carbonate rock contains CO_2 at a higher partial pressure than at the surface because of the lower ambient temperature and the higher pressure that is due to the weight of the overlying water column. The increased partial pressure of CO_2 promotes increased dissolution of calcium carbonate from the host rock. When the water flows out of the rock at the surface, or reaches a cave, it will regain equilibrium with atmospheric pressure, causing degassing of CO_2. The loss of CO_2 entails that the water may become supersaturated with regards to calcite, followed by precipitation of this mineral. This is particularly effective in summer when the water will quickly warm up once it emerges. Exposure to light will also cause biogenic precipitation (photosynthesis) by algae. Evaporation may also concentrate the carbonate sedimentation in lakes, though this depends on the rate of weathering and supply of Ca^{2+} from older calcareous sediments and calcium-bearing silicate rocks. Evaporation may also concentrate the water and lead to increased precipitation.

5.7.4 Meteoric Water Flow and Diagenesis

The introduction of meteoric water has a profound effect on carbonate sediments and their potential as reservoir rocks.

A proportion of the rainwater (meteoric water) falling on land infiltrates into the groundwater. The flow of groundwater ultimately is limited by the rate of recharge by rainwater, which determines the water table gradient. As long as the water table is above sea level the groundwater has the hydrodynamic potential to flow beneath the beach and out into the basin beneath the seafloor, floating on top of the more saline basin porewater (Fig. 5.47). The freshwater lens is floating like an iceberg in the sea. With a groundwater density of 1.00 g/cm^3 and the more saline water 1.025 g/cm^3, the ratio between the groundwater head and the depth of freshwater penetration is theoretically $1/(1.025 - 1.00) = 1/40$. A groundwater head of just 10 m can drive freshwater to a depth of up to 400 m below sea level. Shallow water carbonates deposited in coastal environments and around islands will thus in

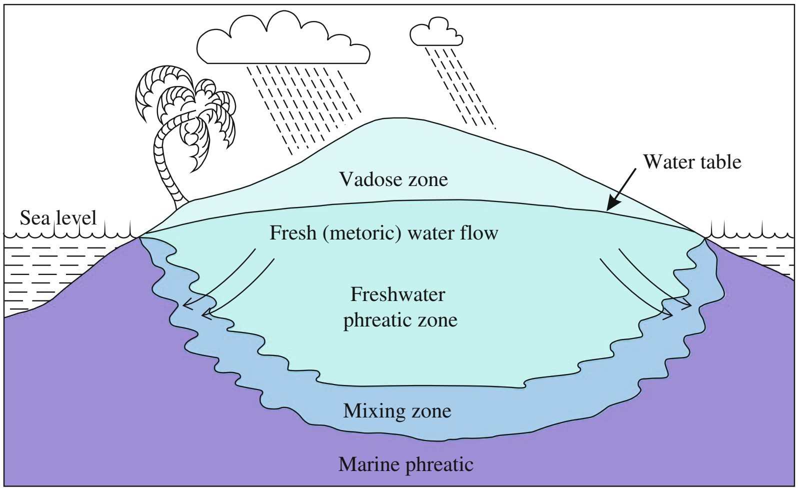

Fig. 5.47 Cross-section of an ideal permeable carbonate sand island showing the distribution of major diagenetic environments in the shallow subsurface. The vadose zone is situated near the surface above the water table, and the pore spaces are occupied by water and air. The pore spaces below the groundwater table are permanently water-saturated. The fresh interstitial waters float on the denser saline waters beneath. There is a mixing zone between the two water phases

most cases be flushed by fresh groundwater after deposition. The diagenetic effects are greatest at shallow depth where the flow rates are highest.

However, coastal carbonate environments are usually rather dry and while carbonate platforms may have more rainfall, the islands on them may be small compared to the size of the platform. Both these factors tend to reduce the flux of meteoric water into marine carbonate sediments, although it may still be very significant, particularly when the sedimentation rate is low. More distal and pelagic facies may avoid this flushing altogether. On land and in the nearshore parts of the basin meteoric water may also be undersaturated with respect to calcite, in which case caverns are likely to develop.

When meteoric water flows through recent carbonate sediments it will be undersaturated with respect to aragonite but become rapidly supersaturated with respect to calcite. Aragonite will therefore dissolve first and calcite will precipitate. Gradually the meteoric water will reach equilibrium with low-Mg calcite, and calcite cement in the form of large crystals (block-shaped cement) may be precipitated (Fig. 5.48). This cement is very different from marine cements precipitated from modified seawater (without sulphate).

On land, the sediments above the water table are located in the *vadose* zone, where the pores are alternately filled with water and air as a consequence of intermittent meteoric water percolation. Partial desiccation results in an unequal distribution of the porewater with it primarily held near grain contacts, by capillary forces; as a result there will be a preferential cementation of pore throats giving a rounded pore geometry. This cement type is called meniscus cement. Porewater will also collect on the underside of grains as pendant droplets and precipitate cement in this form, called pendant cement. Both meniscus cement and pendant cement are characteristic of partial cementation in the vadose zone.

At sea level lowstands, particularly in the Quaternary, marine carbonate sediments were directly exposed to freshwater that caused rapid cementation and hardening. The sea level drop of more than 100 m during the glaciations exposed and cemented all carbonate sediments that had been in the photic zone during the preceding interglacial (highstand) periods. On modern carbonate banks soft sediments are therefore limited to the Holocene (postglacial) deposits, which normally are less than 2–3 m thick.

5.7.5 Shallow-Marine Diagenesis

5.7.5.1 Introduction

Lithification is the process which transforms loose sediment into solid rock. It occurs through new minerals (cement) being precipitated in the pore spaces binding together the primary particles. To cause carbonate cement to be precipitated, we must have porewater which is oversaturated with respect to a carbonate phase.

In general diagenetic processes are driven by a progression towards more mechanically stable grain packings and more thermodynamically stable mineral assemblages. This is also the case for carbonate sediments. During progressive burial the increasing overburden stress causes denser packing of grains so that the porosity is reduced. The reduction in porosity is then a function of the effective stress that may be expressed as the compressibility of the rock. Mechanical compaction is in principle instantaneous but there is usually some additional compaction with time at the same effective stress. This is called creep.

The mechanical compaction of carbonate sand and mud follows the same principles as for terrigenous sand and clay. In the case of carbonate sediments however, chemical processes involving dissolution and cement precipitation are much more important at low temperatures. This is because the kinetics of carbonate reactions are much faster at low temperature than is the case for silicate reactions. The prediction of porosity and permeability in carbonate rocks therefore also depends to a very large extent on chemical diagenesis at shallow depth. Porosity reduction in carbonates can therefore not be predicted solely on the basis of effective stress because it also depends on the primary mineralogical composition of the grains and textural relationships.

Cement formed in a marine environment is aragonite or high-Mg calcite, which forms needle-shaped crystals. High-Mg calcite can also precipitate as micritic cement. Early marine aragonite cement may grow as evenly distributed layers of aragonite needles perpendicular to the surface of the grains. This is called isopachous fibrous cement because a layer of uniform thickness is formed (Fig. 5.49). Isopachous calcite cement may also be precipitated in meteoric (phreatic) porewater.