Aragonite and high-Mg calcite are metastable minerals in the marine environment. They precipitate because low-Mg calcite, which is the thermodynamically stable calcium carbonate phase, fails to precipitate. This is probably due to the poisoning (inhibiting) effect of sulphate on calcite precipitation (Kastner 1984). During burial both aragonite and high-Mg calcite dissolve and are replaced by low-Mg calcite, but we do not know how fast this reaction is in marine sediments. This thermodynamic drive for dissolution and compaction is almost independent of stress. The dissolution of aragonite fossils or cements may cause grain framework to collapse, whereas high-Mg calcite is replaced by calcite that retains much of the original texture so that the grain framework is conserved.

The solubility of carbonate grains is also a function of effective stress and thus burial depth. Pressure solution will often be concentrated at particular horizons where there has been some enrichment of clay particles which increases the rate of solution. Stylolites, which are surfaces where a considerable amount of solution has taken place, will then form. The horizon will be enriched with finely divided silicate minerals and other insoluble material in the limestones (Fig. 5.53). Where carbonate, usually calcite, is dissolved due to pressure solution, the dissolved material tends to be precipitated in the neighbouring pore spaces. When the pores between stylolites are filled with cement, dissolution along the stylolite ceases. Stylolites may have a relief from 1–2 mm up to several tens of centimetres and a spacing of typically 1–5 cm. As the rate of solution along the surface varies, a very irregular relief develops which may be taken as a minimum measure of the thickness of the carbonate layer dissolved.

**Fig. 5.53** Cross-section of a stylolite. The *dark colour* is due to insoluble material within the limestone (such as clay minerals, pyrite and organic matter) which is concentrated in the seam. The amplitude (the distance between top and bottom) may be taken as a minimum measure of the thickness of the dissolved carbonate layer

The carbonate dissolved at grain contacts and along stylolites is transported to the adjacent sediments by diffusion. Here the carbonate will usually re-precipitate in the pores, with a possible reduction in porosity of up to about 20%. Investigation of interbedded layers of limestone and dolostone show that the former is more susceptible to pressure dissolution than the latter. Dolostone usually has a strong framework of interconnected dolomite rhombs. Stylolites are therefore especially well developed in carbonates that are almost exclusively calcitic. Some late diagenetic dolomite rhombs may precipitate along developing stylolite surfaces as a result of a dynamic system with pressure gradients on a microscopic scale.

$CO_2$ and organic acids generated from decomposing organic matter are rapidly neutralised. The pH decreases with depth because of the increasing amounts of $CO_2$ that can be dissolved in the porewater as the pressure increases. The solubility of calcite increases with increasing pressure but at normal hydrostatic pressure gradients temperature is the overriding factor determining the solubility gradients. Calcite precipitates only very locally during upwards flow, where there are abrupt pressure drops.

Compaction-driven flow is normally directed upwards and since the solubility then is reduced, dissolution rather than precipitation will occur. The capacity of compaction-driven porewater to transport carbonate is in any case rather limited because of the low solubility gradients and moderate fluid fluxes at greater depth. During burial diagenesis the loss of porosity depends both on the mechanical compaction and on pressure solution. Both are functions of the effective stress.

### 5.7.7 Classification of Carbonate Rocks

Early petrologists often subdivided limestones according to the size of the dominant mechanically deposited grains: Calcilutite (grains <63 μm), calcarenite (grains between 63 μm and 2 mm) and calcirudite (grains >2 mm). Later Folk's (1959, 1962) classification was widely accepted because of its applicability to a wide range of carbonate rock types and the ease with which its terms could be utilised and understood. Folk's classification is based on the idea that, in principle, the sedimentation of carbonate sediments is comparable to that of terrigenous material. However, today most workers prefer to use the classification by Dunham (1962) because it is not based on the composition of the matrix but on the nature of the framework, which is more applicable in revealing the depositional processes.

### 5.7.8 Folk (1959, 1962) Classification

Disregarding admixture of terrigenous material, Folk (1959, 1962) distinguished between three basic components of limestones:

1. Sediment grains (allochems). The principal allochems are: skeletal grains, ooids, peloids and fragments of carbonate rocks (intraclasts or extraclasts).
2. Microcrystalline lime mud (micrite) comprising clay-size particles (grain size <4 µm). In modern carbonate environments such as the Bahamas most of the mud consists of micron-sized needles of aragonite produced by green algae like *Halimeda* and *Penicillus*. These are transported as clay fraction material.
3. Sparry calcite cement (sparite) which is carbonate crystals that have been diagenetically precipitated in the pore space after deposition. While the carbonate mud and some of the grains have a brown stain due to organic material, the cement stands out as clear and transparent in thin section.

Almost all carbonate deposits contain more than one type of material, and Folk's classification is based on the relative proportions of the three endmembers: allochems, microcrystalline lime mud and sparry calcite cement (Fig. 5.54). Allochems represent the framework of the rock making up the bulk of most limestones. The matrix between the allochems may consist of lime mud if there is little bottom current. In limestones this mud may have recrystallised into small calcite crystals (microcrystalline mud), which is called *micrite* and is thus an indicator of a low-energy environment.

Deposits consisting of well-sorted allochems have primary porosity which may be filled with cement during diagenesis. The cement is precipitated from aqueous solutions and consists of clear, transparent crystals (spar) which are easy to distinguish from micrite, which tends to be brownish because of the organic content. *Sparite* is thus a term for well-sorted carbonate sand, originally with high primary porosity, which has later been filled with calcite cement (spar). As such it normally represents a high-energy environment. Thus the relative proportions of micrite and sparry calcite cement indicate the degree of "sorting" or current strength of the environment during deposition.

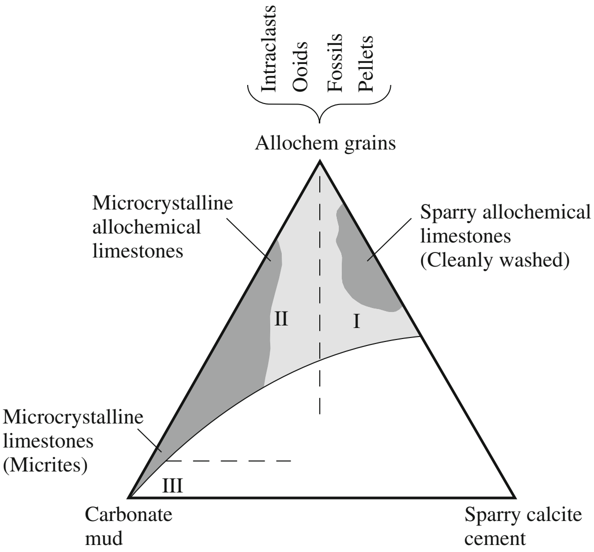

**Fig. 5.54** Triangular diagram showing the three major textural types of limestones. *Shaded areas* depict the most commonly encountered limestones. *I*. The limestones consist chiefly of allochemical constituents cemented by sparry calcite. The relative proportions of sparry calcite cement and allochems varies within rather restricted limits depending on the packing and shape of the allochems, which are important factors for the pore volume. *II*. These limestones also consist of a considerable proportion of allochems, but in these cases the currents were not strong enough or persistent enough to winnow away the micrite. In these deposits the restriction of packing imposes a certain maximum on the amount of allochems, but there is no minimum. Therefore the content of allochems may vary from about 80% down to almost nothing in clean carbonate mud. *III*. Limestones consisting almost entirely of micrite with little or no allochems or sparry calcite (modified from Folk 1962)

As illustrated in Fig. 5.55 there are two parts to the rock name classification. The first part is contributed by the abbreviated allochems' name based on the dominating type of allochem. The second part reflects the void-filling material (micrite or sparry

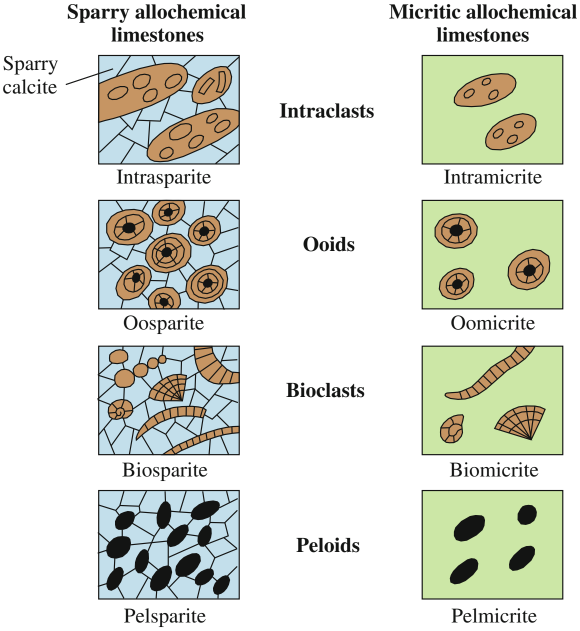

**Fig. 5.55** Somewhat simplified schematic representation of the constituents that form the basis for Folk's classification of carbonate rocks (modified from Tucker and Wright 1990)

calcite). Biosparite, for example, means that the carbonate rock is dominated by fossil fragments without any matrix, but cemented with sparry calcite cement. Oomicrites and pelmicrites are sediments consisting of oolites or pellets with a carbonate mud matrix. Intrasparite consists of carbonate fragments eroded inside a basin to form well-sorted carbonate deposits. Sediments with a considerable percentage of grains larger than 1.0 mm are called rudites. A coarse-grained bioclastic sparite would thus be classified as biosparrudite.

If the allochems are found in a matrix of carbonate mud (micrite) the rock is termed biomicrite, oomicrite, intramicrite or pelmicrite. These sediments represent low-energy environments where neither currents nor wave action separate the mud from the grains. Micrites normally have to have low porosity and permeability to be reservoir rocks. While the carbonate mud may initially have high porosity this is strongly reduced by mechanical and chemical compaction. Micrites may, however, become tectonically fractured, thus increasing their porosity and particularly their permeability. Secondary porosity due to dissolution of aragonite and high-Mg calcite fossils may also improve the reservoir quality of micrites.

Carbonate sediments deposited in environments with sufficient wave or current energy to separate the grains from the muddy matrix can be well-sorted with an initial pore space of about 40% between the grains (or even more if the skeletal material shows irregular growth forms). These sparry deposits are potential reservoir rocks if they only become partly cemented with calcite spar. The presence of petroleum may retard the precipitation of carbonate cement.

### 5.7.9 *Dunham (1962) Classification*

Working for Shell Oil, Dunham (1962) developed a classification which was more oriented to the needs of the oil industry, and this simple classification has become the most widely used today. His classification is also based on the depositional texture of the limestone, but the fundamental criterion is not the composition on the matrix as in the Folk (1959, 1962) classification, but the nature of the framework (whether it is mud-supported or grain-supported), see Fig. 5.56. Mud is defined as carbonate particles with a grain size <20 μm.

Mud-supported deposits imply deposition in a low energy environment. Limestones with very few grains (<10%) floating in a mud matrix are classified as mudstones. Mudstones with more than 10% grains, but still mud-supported, are classified as wackestones. Grain-supported limestones indicate deposition in a high energy environment. They are classified as packstones or grainstones, the former having a mud matrix, the latter a greater or lesser amount of calcite cement in the intergranular pores. The term boundstone is used where the fabric indicates that the original components are bound together during deposition (e.g. as in reefs). It is equivalent to the term biolithite in the classification of Folk (1959).

The textures of carbonate deposits correspond in many ways to those we observe in clastic terrigenous sediments. Mudstone corresponds to clay, and wackestone and packstone correspond to greywackes. Grainstones are well-sorted sandstones with little matrix, and have many of the same properties as well-sorted quartz sandstones, both as regards primary porosity and diagenetic transformation. We distinguish between grain-supported and matrix- or mud-supported sandstones. Mud-supported sandstones will

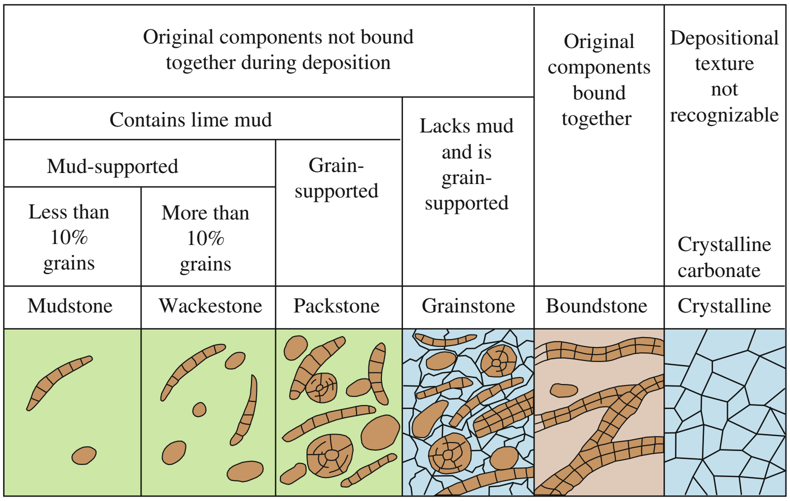

**Fig. 5.56** Dunham (1962) classified carbonate rocks according to depositional texture (modified from Tucker and Wright 1990)

be subject to compaction of the matrix between the grains, and have many of the plastic properties of fine-grained sediments (muds). The degree of compaction will depend on the proportion of grains.

Grain-supported carbonates have a framework of grains which rest upon one another. Compaction cannot take place without the grain framework being deformed. This may take place by the grains being packed more tightly through mechanically crushing due to the force exerted by the overburden, or being chemically dissolved, particularly at the contacts between grains (pressure solution). The mechanical strength of carbonate fragments from fossils may be relatively low, but that of thick-shelled fossils and ooids is high. The contacts between grains will initially be very small, for example round ooids will only have very limited areas of contact. As the overburden increases, the pressure per unit area at the contact points will be very great. Pressure solution will then occur at the contact points, so that the contact area expands and the pressure per unit area decreases.

The distinction between grain-supported and mud-supported rocks is not simply a function of the ratio of grains to mud, because carbonate grains have widely different and often highly irregular shapes. Rocks composed of spherical grains (e.g. ooids) may need a grain content of about 60% to achieve grain support, whereas rocks with highly irregular grain shapes may form a self-supporting framework with a grain content of only 20–25%.

Mudstones, wackestones and packstones would all be poor reservoir rocks because of the carbonate mud in the matrix. In the case of packstones the grains form a grain-supported fabric but the matrix is still carbonate mud. Grainstones represents well-sorted carbonate deposits with good porosity and permeability, which may serve as a good reservoir if cement precipitation is not too advanced. This is the carbonate equivalent of well-sorted siliceous sand. Boundstones are rocks bound together by organisms (fossils) as in reefs, and they may also have high porosity and permeability.

## 5.7.10 Dolomitisation

The term “dolomite” is used to designate both a mineral (Fig. 5.57) and rocks in which this mineral is the main constituent. To avoid confusion, the term “dolostone” has been introduced for the rock, but has not been widely adopted.

The mineral dolomite ($CaMg(CO_3)_2$), consists of layers of $CO_3^{2-}$ groups separated by alternating layers of $Mg^{2+}$ and $Ca^{2+}$. This is a highly organised structure (trigonal rhombohedral) and the organisation of more or less pure layers of $Mg^{2+}$ and $Ca^{2+}$ leads to high kinetic energy being required for the crystallisation of dolomite. This is particularly true at low temperatures and so far it has not been possible to synthesise low temperature dolomite (<100°C) in the laboratory.

Dolomite is in most cases not formed directly, but as a secondary mineral as a result of reactions between different forms of $CaCO_3$ and $Mg^{2+}$. The reaction

$$2CaCO_3 + Mg^{2+} = CaMg(CO_3)_2 + Ca^{2+}$$