9 Limestones are Biological Sediments

Most limestones are directly or indirectly influenced and controlled by biological processes. The present chapter deals with the formation of carbonates by microbes and benthic encrusting organisms, and with the destructive role of micro- and macroborers. Knowledge of constructive and degrading processes is essential in evaluating carbonate budgets.

9.1 Microbial Carbonates and Stromatolites

Microbes encompass bacteria, fungi, small algae and protozoans. Bacteria comprise two major groups - Archaeabacteria and Eubacteria, now respectively called Archaea and Bacteria (including Cyanobacteria).

The sedimentologically important Cyanobacteria (Sect. 10.2.1.1) are aerobic phototrophs, living in shallow-water and using sunlight as energy. Cyanobacterial calcification is associated with the photosynthetic uptake of CO$_2$ and/or HCO$_3^-$ that raises alkalinity (Pentecost and Riding 1986; Merz-Preiss 1999) and leads to calcification of the mucilaginous sheaths. Present day, intense cyanobacteria calcification appears to be essentially a freshwater phenomenon and is rare in modern subtidal environments, by contrast to ancient cyanobacteria which occupied tidal and subtidal environments.

Many other bacteria are anaerobic heterotrophs and take their energy from the decomposition of organic material to inorganic components by redox processes. These bacteria can occupy lighted and shallow as well as dark and deep-water settings, and are responsible for ammonification, denitrification, sulfate reduction, anaerobic sulphide reduction and methanogenesis processes. These processes can lead to HCO$_3^-$ concentration and increasing alkalinity favoring fine-grained CaCO$_3$ precipitation (Knorre and Krumbein 2000) in the form of micrite.

Microbial CaCO$_3$ precipitation is triggered by various processes associated with (a) bacteria and small algae, (b) extracellular polymeric substances (EPS; accumulating outside the cells to form a protective and adhesive matrix that attaches microbes to the substrate), (c) biofilms (submillimetric veneers of bacterial communities in an EPS matrix), (d) microbial mats (millimeter-sized complex layers composed of filamentous cyanobacterial algae and diatoms, and able to trap sediment), and (e) organomineralization (precipitation of CaCO$_3$ in association with nonliving macromolecules independent of organic activity). See Riding (1991, 2000), Van Gemen (1993), and Riding and Awramik (2000) for further explanations.

The eminent role of bacteria and other microbes in the formation of carbonate rocks was summarized in Sect. 4.1.2 and is discussed in the following paragraphs which also cover controls and the terminology of microbial carbonates, and examine the importance of stromatolites.

9.1.1 Bacterial Contribution to Carbonate Precipitation

Microbial precipitation of calcium carbonates played a vital role in the development of Proterozoic and Phanerozoic carbonate platforms and reefs. The importance of bacteria and cyanobacteria in the formation of fine-grained carbonates in natural aquatic environments has long been a matter of discussion, starting with the research of Drew (1911, 1913) and Black (1933) on the action of denitrifying bacteria in tropical and temperate seas, followed by observations on calcium carbonate precipitation in seawater and freshwater environments (Pentecost 1985). Reviews discussing this topic have been published by Cohen et al. (1984) and Jones (1985). Many researchers have demonstrated that life processes of marine bacteria and the decomposition of organic matter by bacteria cause physicochemical changes in the microenvironment that can result in calcium carbonate precipitation. This has been proved in laboratory experiments and observed in various modern carbonate-producing environments (soils, freshwa-
ter and marine realms, particularly in lagoons; Castanier et al. 1989; Chafetz et al. 1991; Folk 1993; Arenas et al. 1993; summary by Buczynski and Chafetz 1993). Experiments indicate that bacteria trigger the precipitation of aragonite and calcite, exhibiting distinct morphologies that seem to be limited to bacterial contribution. The size of individual crystals, spheres and rods ranges between 0.1 and 0.4 μm; that of crystal aggregates between 5 and 100 μm. Comparable morphologies have been observed in laboratory cultures and in modern carbonate sediments. Because most bacteria except for cyanobacteria, are indifferent to light, bacterially-controlled carbonate precipitation is not restricted to shallow environments, but also occurs in deeper subtidal settings, various cryptic habitats and in deep restricted basins. A strong microbial contribution of microbes to the formation of ‘mud mounds’ is advocated by many authors (e.g. Pratt 1982; Lees and Miller 1985; see Sect. 16.2.2).

**Biological versus environmental controls:** The main processes of microbial carbonate formation are (1) trapping (agglutination) of sedimentary particles, (2) biomineralization (calcification) of organic tissues, and (3) mineralization (superficial precipitation of minerals on organisms and/or sediment). Fine-grained carbonate is trapped and produced within microbial mats, occurring under a wide range of environmental conditions in nonmarine and marine sites.

The mats are dominated by various phototrophic, chemotrophic and heterotrophic microorganisms (cyanobacteria dominating in the top layer; colorless sulfur bacteria, purple sulfur bacteria, and sulfate-reducing bacteria harboring the underlying layers). Other numerically less important groups are nitrifying and denitrifying bacteria and methanogenic bacteria. The activity of aerobic heterotrophic organisms leads to oxygen depletion. Fermentative organisms provide growth substrates for sulfate-reducing bacteria. The vertically laminated structures develop as a result of microbial growth and activity sediment trapping and binding in the organic matrix, and sedimentation (Van Gernerden 1993).

The shape and macrofabric of microbial carbonates are strongly influenced by variations in the depositional environment. Important controlling environmental parameters are the grain size of the substrate, the penetration of light, sedimentation and erosion rates, and grazing pressure (Walter 1976). Sedimentation and microbial mat composition are sensitive to water movement and light, respectively, and change with water depth. This is reflected in the morphology, texture and microfabrics. Examples were described from various shelf to basin traverses (Precambrian: Hoffman 1974; Late Devonian: Playford et al. 1976; Late Jurassic: Leinfelder 1993; Tertiary: Braga et al. 1995).

### 9.1.2 How to Recognize Microbial Carbonates?

Increasingly more authors support the idea of a strong microbial impact on the formation of Paleozoic and Mesozoic limestones, using external appearance, internal fabrics and geochemical signatures as evidence (see Faacies, vol. 29, 1993). Box 9.1 lists some criteria which are commonly used as evidence for a bacterial contribution to the formation of limestones.

### 9.1.3 Describing and Classifying Benthic Microbial Carbonates

Microbial carbonates are recorded by specific textures occurring within a wide range of scales. Common features are dense autochthonous micrites, micro- to mega-scaled laminated fabrics (e.g. stromatolites), millimeter- to centimeter-sized micritic crusts, non-laminated micritic and peloidal structures, and limestones exhibiting tiny tubelike microfossils referred to as remains of cyanobacteria.

#### 9.1.3.1 Terminology and Descriptive Criteria

*Microbial carbonates* are carbonate deposits produced or localized by benthic microbial communities (Riding 1990) living in marine, marginal-marine, freshwater and terrestrial environments. The complex associations of bacteria, cyanobacteria (cyanophytes, blue-greens) and algae embrace photosynthetic prokaryotes, eukaryotic microalgae and chemosynthetic prokaryotes. In addition, encrusting invertebrates (e.g. foraminifers) may be of some importance (Sect. 9.2).

Communities creating microbial carbonates are termed *microbial mats* (Gerdes and Krumbein 1987) or algal mats, reflecting the densely interlayered and intertwined orientations of the filamentous and coccolid cells involved and the resulting biolamellated sedimentary structures.

*Biolaminites* characterized by organic-rich laminae and microbial mats are an essential criterion of microbially induced sedimentary structures (Noffke et al.