Chapter 3
Biomineralization

Abstract Usually during biomineralization, organisms gather the precursors (such as ions of metals) essential to formation of biominerals directly in their natural environments. Marine invertebrates both fossil and recent represent amazing sources of biominerals which mostly arose at the early stages of evolution. Consequently broad diversity of hypothesis and speculations concerning the mechanisms of biomineralization of amorphous and crystalline phases within biominerals has been established during last 50 years of intensive research. The organic matrix has a fundamental role in biomineralization, and is inspiration for biomimetics, bioengineering and for the oncoming nanotechnologies. This chapter includes the list of most recent references related to the modern trends in biomineralization.

Biomineralogy is an interdisciplinary research field dealing with phenomena of biomineralization, demineralization, and remineralization, which have been naturally occurring since life began. The best way to understand the basic principles of biomineralization on both molecular and nano level lies through multidisciplinary experience, knowledge and sophisticated technologies by a coherent synergetic collaboration of biologists, chemists, physicians, and materials scientists.

Usually during biomineralization, organisms gather the precursors (such as ions of metals) (Currie et al. 2006) essential to form the biominerals directly in their natural environments (water, soil, food). After their transfer into organisms (or cells), precursors are stored (mostly within special organelles, or vesicles) and, finally, turned into biominerals.

In accordance with classical nucleation theory (Volmer 1939; Nancollas 1982), the minerals crystallization begins from the precursor's ions, which form small clusters of crystals during dynamic process of growth and disintegration, adequately to their ionic complementarity. After reaching the critical size, abovementioned clusters evolve into stable forms. Although in opposite to classic theory of nucleation, it was proved that formation of the calcium carbonate crystals begin from a transient amorphous phase of the precursor, in biomimetic as well as biological systems (see for review Nudelman and Sommerdijk 2012; De Yoreo et al. 2015). Hence, the discovery of formation of the calcitic spicules by sea urchin from amorphous calcium carbonate phase was described in 1997 (Weiner et al. 2009). Since this year it was

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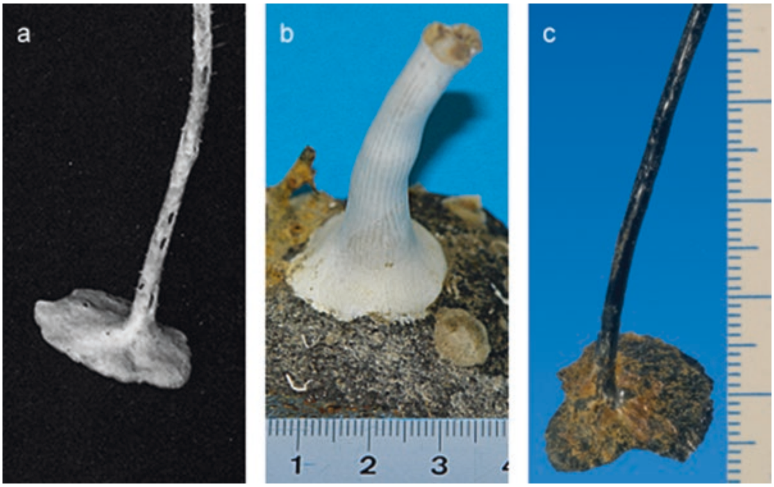

Fig. 3.1 The foot-like structures of Glass sponge *Walteria leucarti* (**a**) octocoral of *Isidella* sp. (**b**), and the black coral (*Antipatharia*) show similar behaviour with respect to their attachment to hard substrata, however differ in mechanisms of this phenomenon

reported that other animals are able to use this strategy for both calcite as well as aragonite. Nowadays, it was shown that the bone mineral matrix of vertebrate origin can be composed from amorphous calcium carbonate as a precursor phase (Weiner 2006). Papers by Politi et al. 2004, 2008; Beniash et al. 2006 confirmed this strategy. Currently, the major challenge is related to understanding the detailed manner of the formation of the primary unstable phases, as well as the mechanism of their temporary stabilization, followed by destabilization and the final formation of the crystalline products (Weiner et al. 2009). So called nanoscopic prenucleation clusters may play a crucial role being in conflict to the rules of classical nucleation theory for calcium carbonates (Pouget et al. 2009; Walker et al. 2017). Interaction between intracrystalline biomolecules leads to anisotropic distortion of crystal lattices in biological aragonite and calcite (Pokroy et al. 2004, 2007). Diverse biomineralizing systems contain diverse set of pathways (Lakes 1993; Mann 1993; Mann 1995; Aizenberg et al. 2005; Meyers et al. 2006; Fratzl 2007; Pouget et al. 2007; Dey et al. 2010; De Yoreo et al. 2013; Boskey and Villarreal-Ramirez 2016) which are dependent from both the reaction dynamics as well as complexity of the free-energy landscapes (Cartwright et al. 2012; De Yoreo et al. 2015; Jiang et al. 2018).

Taking into consideration the biological environments, the process of biomineralization is divided into an intercellular, extracellular or intracellular process (Subburaman et al. 2006). The knowledge about the mechanisms of selection, localization, and concentration of these elements by organism is achieved by evaluation of the biologically controlled biomineralization. It was accepted as a fact that the organic matter has a significant role in the formation and growing of crystals, as well as is important to the formation of the mineralized tissue biomechanical features (Weiner 1984). Corresponding organic matter in several mineralized tissues, is able to create two- or three-dimensional templates on which (or into) the crystalline phase is formed. Therefore, the oriented adhesion - one of the most important biomineralization mechanisms - is responsible for the structure formation and development of the characteristic physicochemical features of biological matrixes (Li et al. 2012; (see also Fig. 3.1). From this view especially those biomineralizing organisms (biomineralizers) which are able to produce structures where the organic component of the biomineral possesses properties of crystals and the inorganic part remains amorphous, are of crucial scientific interest. Typical examples of such biomineralizers include broad variety of unicellular and multicellular organisms which produce amorphous biosilica (see for review Wysokowski et al. 2018).

It is well recognized that, especially in calcified tissues, the crystal growth and orientation are influenced by a distinctive assemblage of special glycoproteins and acidic proteins, or both (see for overview Veis and Dorvee 2013; Chen et al. 2014; Branson et al. 2016; Polowczyk et al. 2016; Deymier et al. 2017; Kim et al. 2018; Jiang et al. 2017; Xu et al. 2018).

One of the fundamental questions formulated by Stephen Mann is "*why some organisms utilize, for example, silica rather than calcium carbonate as a structural material is unknown*" (Mann 1995).

The reason for corresponding selection may be based on the atomic and molecular features of the inorganic phases. Predestination to insert Ca and not Ba into biominerals producing protozoans as *Acantharia*, *Remanella* and *Loxodes* (Karyorelictida) has been studied previously (Rieder et al. 1982; Fenchel and Finlay 1984, 1986). This phenomenon is based on ability of these protists possess a specialized system that distinguish the light elements from the IIa group of the periodic system. For organisms, the incorporation of Ba from fresh water is easier than from seawater, due to a fact that the ratio of Sr to Ba is 5:1, and 400:l in seawater (Rieder et al. 1982).

In this group of elements there is a great difference between the ionic radius. The radius increases proportionally with mass of the ion. Therefore, it is assumed that there is one general mechanism of the recognition of ions, which has not been changed during evolution significantly. This manner may apply the various ions radius. Thus, some related organisms could not differentiate between the elements such as *Loxodes* or *Remanella.* Other specimens from the Karyorelictida order, like *Trachelocerca* or *Geleia,* modify the naturally occurring ratio of Ca:Sr:Ba to a large extent, although they could not discern as well against the lighter elements.

Although, good discrimination of elements from the IIa group is reported in all protozoa tested except of one *Trachelocerca* species which is able to embed Mn.

Why are Ba and Sr embedded towards above-mentioned unicellular creatures? Why do they not embed calcium (exclude *Prorodon),* that they can achieve without difficulty? The authors suggested that *Remanella* as well as *Loxodes* embedded Sr or Ba due to their mass (higher than Ca,) and thus these minerals are more beneficial for a mechanoreceptor. However, other question has to be clarified, why is Sr embedded in acantharia, and while Ba, Sr or Ca are incorporated in *Trachelocerca and Geleia?*

Any explanation was found for the *Trachelocerca* species derived from island Sylt in Germany that embeds Ba, Sr, Ca and probably small amount of Mn, while other specimens found in northern Italy absorbs Sr, Mn and Ca. It is still not specified which manganese compounds are incorporated into the animal. Probably, in this case different incorporation mechanism occurs, another than this one that incorporate Sr, Ca, and/or Ba (Rieder et al. 1982).

The question about the ability of organisms to select cations is also related to phenomenon known as "*multiphase biomineralization*" proposed by us for the first time in 2010 (Ehrlich et al. 2010). We found that organic matrices (i.e. chitin) template the formation of both amorphous (silica) and crystalline (aragonite) phases in skeletal fibres of selected demosponges of the Verongiida order (Ehrlich et al. 2010). Multiphase biomineralization occurs in skeletal formations of diverse marine invertebrates including radula in molluscs (Rinkevich 1993; Brooker et al. 2003), shells in brachiopods (Schmahl et al. 2004a, b, 2008; Merkel et al. 2007; Goetz et al. 2009), as well as teeth of copepods (Miller et al. 1990; Becker et al. 2005; Michels et al. 2012, 2015; Michels and Gorb 2015).

3.1 Conclusion

The literature on biomineralization is amazing. A general principles of biomineralization that addresses diverse levels of this phenomenon has been proposed by Nancollas (1982), Lowenstam and Weiner (1989), Mann (1995, 2001), Simkiss and Wilbur (1989), Addadi and Weiner (1992), Addadi et al. (2002), Cölfen and Mann (2003) and the excellent overall sources of information on this and related topics have been provided by Bäuerlein (2007), Meyers et al. (2006), Weiner (2006), Estroff (2008), Cölfen (2010), De Yoreo et al. (2015), Niu et al. (2013), Smeets et al. (2017), and Wood et al. (2017). Nowadays attention is paid on biomineralization of viruses (Wang et al. 2018), in foraminiferans (Tyszka et al. 2019), in sponges (Voigt et al. 2017), in corals (Mass et al. 2017), in plants (He et al. 2014), fungi (Li and Gadd 2017) as well as to biophysical (Rao and Cölfen 2016), medical (Kim et al. 2018; Götz et al. 2019) and diverse practical (Ramesh et al. 2017; Evans 2019) aspects of this phenomenon.

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