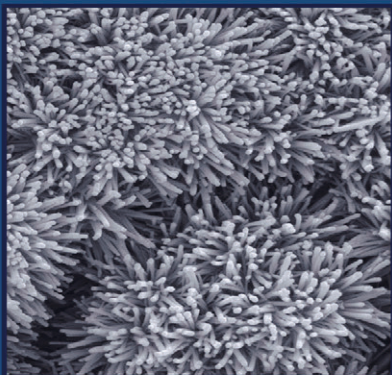


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Fundamentals and Applications

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*Conrado Aparicio and
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Preface

Bone, tooth enamel, nacre, coral, mollusk shells, stems of horsetail grass, diatom cell walls, etc., are examples of biominerals formed through biomineralization processes that result in hierarchical structures with unique and, in many cases, outstanding properties. The processes that occur to obtain the exact composition, size, shape, and spatial distribution of the minerals and organic components in these biological materials are controlled by living organisms, from prokaryotes to humans. Control of these processes is exerted via cell-orchestrated production and release of organic materials that interact with inorganic components, inside or outside of the organism that produced them. A biomineralization process is therefore essentially defined by the direct or indirect control of the process by the living organisms and the mediation of the process by organic molecular templates, such as proteins and other biomacromolecules. In many instances, the crystals and structures formed through the biomineralization process incorporate organic macromolecules. This is accomplished as biomineralization processes follow bottom-up strategies that organize defects and matter in such a way that the formed hybrid biomaterials display specific and unique surface, optical, chemical, and mechanical properties that exceed those of their individual counterparts.

The description and understanding of biomineralization and related processes, as well as the assessment of the structure–property relationships in biominerals, have been topics of intense research for many years. In the last 20 years, scientists and engineers have made significant advances in the field not only to the aforementioned understanding of mechanisms of formation, structure, and properties of the biominerals but also to the development of new characterization techniques. As a result of this, we know that key aspects of the process of biomineralization are the interactions at the organic–inorganic interface, the hydration states of the minerals at different stages of mineral formation, the properties of the aqueous solution in which the process is taking place, and the fact that biomineralization occurs at ambient or near-ambient conditions through the formation of precursor transient phases. However, much is still to be investigated and discerned about these sophisticated and elegant mechanisms of mineral formation, which keeps the field open as a hot topic for research with intense discussion and passionate dedication to validate new hypotheses. For instance, the role of organic molecules in polymorph selection, that of lipids and sugars in biomineralization, or of the organic matrix in the structure of some biominerals at different scales are areas that are still not fully understood.

The main motivation for most researchers to understand biomineralization is that it is regarded as a paradigm for the development of new routes for the synthesis of new functional materials with structural precision at different dimensional levels.

The examples that one can find in Nature can lead to the development of biomimetic processes and/or structures that incorporate at least some of the exceptional properties of the biological materials which inspired them. Many different synthetic materials can benefit from this approach, namely optical materials, materials for storage of energy, magnetic and electric sensors, micropatterned surfaces, and biomaterials for implants and scaffolds in biomedical applications. The latter is undoubtedly a field that has drawn much inspiration from the natural processes of biomineralization to either obtain or modify synthetic materials to mimic human body mineralized tissues from a physicochemical, mechanical, and biological perspectives.

Biomaterials, synthetic and natural biopolymers, bioceramics, and biocomposites have been mineralized most often with calcium phosphate minerals, i.e. the inorganic component of hard tissues in the human body, following synthetic routes that mimic in full or in part natural biomineralization processes and that, in the best-case scenario, result in structures closely resembling those found in Nature. The goal is to produce materials that will be implanted to substitute and/or regenerate bone, dentin or teeth enamel with exceptional ability to perform these functions. Cells and tissues that interact with these biomaterials are responsive to the specific physical, chemical, and mechanical properties of the biomimetic mineralized constructs. The minerals obtained can be formed in any of a series of configurations depending on the selected biomaterial, the route of implantation, and/or the clinical strategy to restore tissue and organ functions. Examples of the different approaches are: the development of calcium phosphate coatings on flat surfaces, micro- and nanofibers, or scaffolds; the intrafibrillar mineralization of scaffolds; mold infiltration at different scales; and bulk, solid-liquid mixture, or solution preparation of calcium phosphate-based materials.

In this book, leading experts in their fields have provided detailed chapters on a range of subjects directly related to the processes of biomineralization, and the design, development, and use of biomineral-based or biomineralized biomaterials. The subjects covered are divided into two parts. Part 1 explores the fundamentals of biomineralization, with an emphasis on describing and discussing new theories about the process of mineralization of hard tissues. Part 2 focuses on the wide range of biomaterials—ceramics, hydrogels, metals, collagen, etc.—that have been mineralized using inspiration from our fundamental knowledge of biomineralization.

The book starts with two chapters that provide the most basic knowledge on the processes of biomineralization. Basic introductions to crystals and biominerals as well as methods for their characterization are provided. The main goal of these two chapters is complementary describing the increasingly better understood nonclassical pathways for nucleation and crystallization of biominerals and how organic templates participate in this process and control crystal polymorphism in Nature. A selection of different natural biomineralized structures and tissues are introduced to exemplify the aforementioned topics.

The rest of the first part of the book focuses on describing the biominerals and the biomineralization processes that form natural human tissues. These are the main mineralized structures that are both mimicked and targeted to be restored by the biomaterials covered in the second part of the book. The chapter introducing the

physical chemistry of biological apatites opens this section, including a discussion on bone mineral precursors and transient mineral phases. The properties of bone mineral apatites are correlated with the mineral-ion reservoir function of bone and the interactions between apatite nanocrystals and the organic constituents of the extracellular matrix. Then, the next two chapters provide an excellent overview of the biological and biochemical mechanisms of the traditional and newly described processes of mineralization of bone, tooth enamel, and dentin. Embryogenic and histological considerations for the formation of these tissues are also introduced, as well as the pathological processes associated with their mineralization.

The last chapter in the first part of the book is unique in that it presents a critical analysis on the understanding of the physicochemical mechanisms involved in the intrafibrillar mineralization of collagen with hydroxyapatite using a biomimetic system that induces a nonclassical transient precursor crystallization process. The in-depth, critical, and somewhat controversial discussion is valuable, among other considerations, to better analyze how the processes described in the two previous chapters can be studied, interpreted, and utilized by mimicking them to explore applications such as those presented in the second part of the book.

The second part opens with a chapter on the relevance of ion substitution in biological and synthetic apatites. As a matter of fact, one of the most remarkable distinctive features of biological apatites is the presence of foreign ions, which play an essential role in the functional behavior of mineralized tissues. For this reason, ionic substitution is being explored as a strategy to develop synthetic apatites with enhanced performance, in an approach that conceives the synthetic material as a bioinorganic controlled release system. The chapter reviews the main characteristics of biological apatites derived from the presence of foreign ions, followed by a description of the structural and chemical modifications induced by ionic substitution in synthetic apatites.

This following block of four chapters introduce biomimetic approaches to mineralize different generic types of materials—polymers/hydrogels, ceramics, metals, and surfaces. Each of them introduces a thorough description of the different biomimetic mineralization approaches pursued to advance the functions of the materials to be used in biomedical applications. The rationale for the route of mineralization and/or the consensus mechanism by which the biomineralization is achieved are also discussed. The authors complement the chapters with a more detailed presentation of their research contribution to the subject of interest.

The final four chapters of the book cover specific biomineralized biomaterials and biomineral delivery strategies to treat hard body tissues. This block of content introduces the most advanced approaches to apply inspiration in biomineralization to develop new generations of biomaterials to substitute, repair, engineer, and regenerate enamel, dentin, and bone. The first and second of these chapters provide comprehensive information on strategies to facilitate dentin remineralization, both for products on the market and for those currently under research and development; and how to use and modify glasses and polymers to promote biomineralization to substitute and regenerate bone, respectively. The evolution of biomimetic approaches for the development of calcium phosphate-based bone substitute scaffolds is addressed in

the next chapter, with particular emphasis on the development of complex inorganic forms, inspired by naturally occurring architectures. Finally, the last chapter provides an insight into the different strategies used for the development of mineralized fibrous scaffolds, which aim to mimic the native extracellular matrix of mineralized tissues, and have great potential for tissue engineering applications. Again, as in the preceding chapters, the authors complement and illustrate the information with a review of the most relevant research contributions to the subject of interest.

It is clear from the contents presented in this book that our knowledge of the processes of biomineralization and the structure–property relations of the biominerals formed constitute a broad and versatile field that provides continuous inspiration to scientists and engineers to design, develop, or improve the performance of biomaterials for tissue repair and regeneration.

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Part One

Fundamentals

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Shaping it up: Design and engineering of biominerals and crystalline materials from the bottom up

1

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1.1 Introduction

*Humpty Dumpty sat on a wall,
Humpty Dumpty had a great fall,
All the King's horses and all the King's men,
[Finally re-crystallized] Humpty together again.*

Unknown

We can search Nature's abyss and find that we are, in fact, surrounded by crystalline-based materials. From the CaCO_3 spines of sea urchins that populate the tide pools at the shoreline to the silica granules found in the body plans of sea sponges occupying the vast seas, these biogenic crystals have been sources of mineral that create geological landmarks such as cliffs and seafloors for eons of time. More impressively, each organism that produces these crystalline materials has its own "toolkit" of organic molecules that are tailored to create the structures and functions that allow these organisms to propagate onward into the future. The biological control and regulation involved in the formation and growth of these materials are also flexible enough to enable for additional revision as well as continued evolution, when making new biological mineral components.

Some examples of the spatial, temporal control and precision involved in the regulation of crystal formation and growth can be witnessed through parallels with the basic premise of an embryo in biology. A mineral crystal forms from a nucleation event where a cation and anion pair bonds and creates a nuclei for crystal growth; an embryo forms from the union of female and male gamete cells and cellular developmental processes enable it to grow into an organism (Figure 1.1). In a similar fashion, the pathway a crystal nuclei will take will depend on its chemical and physical environments to determine its trajectory to becoming a fully fledged crystal with specific properties (i.e., polymorph, orientation, lattice spacings, and size) such as the path of crystal growth it will take and whether it will become one crystal polymorph versus another polymorph. Many of these environments can be controlled by biological macromolecules—proteins, lipids, and carbohydrates, as well as nucleic acids (Burke et al., 2000; Fantner et al., 2005; Vos et al., 2007; Knapp et al., 2012; Rao et al., 2014; Chow et al., 2014; Figure 1.2). By taking the simple scenario whereby the presence

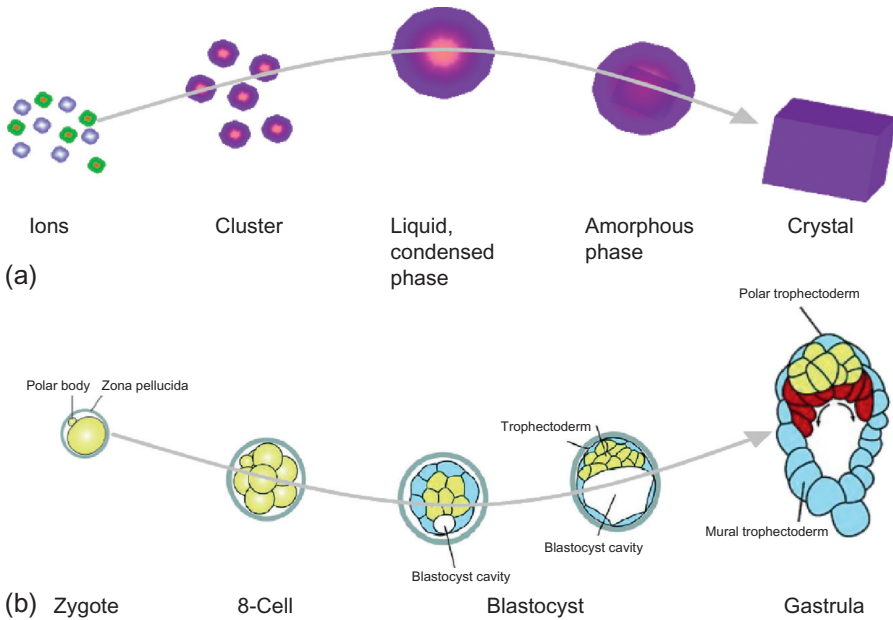


Figure 1.1 Processes of crystallization and embryogenesis compared. (a) Ion pair bonding occurs to initiate nucleation and, subsequently, crystal growth. (b) Sperm and egg cells join to form a zygote that will undergo various stages of growth and development.

Adapted from (a) Cölfen and Antonietti (2008) and (b) Beddington and Robertson (1999).

of biomolecules like nucleic acids, such as deoxyribonucleic acid (DNA), the carboxyl acid group ($-\text{COOH}$) can alter the bulk pH of solutions such that the local supersaturation of ion concentrations are slightly altered to induce a specific polymorph of a mineral (Xu et al., 2008; Figure 1.2). The presence of these molecules has been studied to a great degree and sheds light on how these molecules affect liquid–liquid as well as liquid–solid interfaces in crystal formation as well as the final crystalline product too (Li et al., 2012; Gebauer et al., 2008; Bewernitz et al., 2012; Gower, 2008; Burke et al., 2000; Lu et al., 2005).

It may seem surprising to the reader that such “minor” alterations in the chemical environment, in this case a slight decrease of pH, can inflict such a dramatic outcome in crystallization. The pH, an indicator of the number of H^+ ions in solution, more precisely related to the log of the concentration of H^+ ions, inhibits the kinetics of the anion and thus affects the local supersaturations of the ion pairs involved in crystallization (Figure 1.3). By varying the pH in a crystallizing solution, whether it be lower (more H^+ ions) or higher (more OH^- groups), the cation and anion pair will be obstructed by the additional H^+ or OH^- ions in solution. As a result, the association and dissociation constants, respectively, will be affected above or below the pK of the cation and anion bonding pair (Figure 1.3). Thus, the degree and controls required to keep crystallization in biology in check necessitate regulatory schemes that can handle large amounts of ions as well as various potentials created by the ions.

In biology, regulation comes in the form of compartmentalization such that sensitive elements are localized and surrounded by protective membranes in order to create a