

Introduction: Biomineralization

Lara A. Estroff

Chem. Rev., **2008**, 108 (11), 4329-4331 • DOI: 10.1021/cr8004789 • Publication Date (Web): 12 November 2008

Downloaded from <http://pubs.acs.org> on December 24, 2008

More About This Article

Additional resources and features associated with this article are available within the HTML version:

- Supporting Information
- Access to high resolution figures
- Links to articles and content related to this article
- Copyright permission to reproduce figures and/or text from this article

[View the Full Text HTML](#)

Introduction: Biomineralization

Biomineralization is the study of biologically produced materials, such as shells, bone, and teeth, and the processes that lead to the formation of these hierarchically structured organic–inorganic composites. The mechanical, optical, and magnetic properties of these materials are exploited by the organisms for a variety of purposes. These properties are often optimized for a given function as compared to the properties of a biological materials of similar composition. Materials chemists are intrigued by the exceptional control organisms exert over the composition, crystallography, morphology, and materials properties of biominerals and the mild conditions (physiological temperature, pressure, and pH) required to form them. In recent years, therefore, the field of biomineralization has expanded to include the application of strategies adapted from biology to the production of synthetic materials. Biomineralization is by definition a multidisciplinary field that draws on researchers from biology, chemistry, geology, materials science, and beyond. In this issue, we focus on the role that chemistry, broadly defined, has played and will continue to play in the development of this growing field.

The impact of chemistry in the field of biomineralization can roughly be divided into three different areas: (1) the characterization of the crystallography, composition, and biochemistry of the biological materials; (2) the design of *in vitro* model systems to answer questions from biology such as testing hypotheses regarding the interactions between the organic matrix and the crystals and the role of biomacromolecules in controlling nucleation and growth of crystals; and (3) the development of new synthetic methods, which are based upon the biological systems, for controlling crystal morphology, polymorph, and materials properties, leading to new classes of organic–inorganic composites. All three of these approaches are highlighted in the 22 articles assembled for this issue.

The articles are arranged loosely by mineral class (e.g., carbonates, phosphates). Within each section, the articles are further organized beginning with reviews that cover fundamental aspects of biomineralization and moving to reviews that address bioinspired materials applications. The first review by Meldrum and Cölfen serves as an excellent introduction to many of these topics. Specifically, they provide an overview of recent developments in understanding crystal nucleation and growth mechanisms in both biological and synthetic systems and how these processes can be modified to form crystals with unusual morphologies, structures, and properties.



Lara A. Estroff received her B.A. with honors from Swarthmore College (1997), with a major in Chemistry and a minor in Anthropology. Before beginning her graduate studies, she spent a year at the Weizmann Institute of Science in Rehovot, Israel, as a visiting researcher in the laboratories of Profs. Lia Addadi and Steve Weiner. During this time, she was introduced to the field of biomineralization and studied chemical approaches to archeological problems. In 2003, she received her Ph.D. in Chemistry from Yale University for work done in Prof. Andrew D. Hamilton's laboratory on the design and synthesis of bioinspired organic superstructures to control the growth of inorganic crystals. After completing graduate school, she was an NIH-funded postdoctoral fellow in Prof. George M. Whiteside's laboratory at Harvard University (2003–2005). Since 2005, Dr. Estroff has been an assistant professor of Materials Science and Engineering at Cornell University. Her group focuses on bioinspired materials synthesis, in particular, the study of crystal growth mechanisms in gels and their relationships to biomineralization. In 2006, she was awarded a J.D. Watson Young Investigator's award from NYSTAR.

The next six articles focus on the carbonate biominerals, primarily calcium carbonates (both crystalline polymorphs and amorphous phases), which are the most abundantly produced and widespread minerals found in biology. The contribution by Cusack and Freer highlights the diversity of calcium carbonate producing organisms and reviews the chemico-structural relationships within these biominerals.

The processes of biomineralization are often under strict biological control and involve the interactions of a large number of biological macromolecules. In recent years, much progress has been made toward determining the sequences and solution-state structures of these biomacromolecules as well as establishing structure–function relationships for them. Evans reviews the current state of knowledge on the proteins associated with mineralization in mollusks. In Killian and Wilt's contribution, they present a molecular view of biomineralization in another class of organisms, the

echinoderms, which include sea urchins and brittle stars. In addition to proteins, polysaccharides and proteoglycans are emerging as important components in the organic matrices associated with biominerals. Arias and Fernández review what is known about this class of molecules in controlling the growth of calcium carbonate crystals in biological and synthetic systems.

In addition to the control exerted by the organisms over carbonate crystallization, the environment in which these organisms grow can also substantially influence the production of these minerals. Stanley reviews this hotly debated, and timely, topic in an article that addresses the effects of seawater chemistry (e.g., calcium-to-magnesium ratio and pH) and atmospheric carbon dioxide levels on mineralization in coccolithophores, calcareous algae, corals, and other carbonate-producing organisms.

The last two articles in the carbonate section cover the work of polymer and organic chemists toward the design of synthetic additives to control the crystallographic orientation, morphology, and polymorph of carbonate-based minerals. Sommerdijk and de With provide a thorough review of the rapidly growing field of bioinspired “designer” small molecules and interfaces (e.g., self-assembled monolayers and Langmuir monolayers) to control the nucleation, polymorphism, structure, and composition of crystals and organic–inorganic composites. In her article, Gower discusses the role of amorphous calcium carbonate precursors, which are stabilized by polyelectrolytes, in the formation of crystalline structures in both synthetic and biological systems.

After the carbonate minerals, the phosphates are the second most prevalent family of biominerals. Since our bones and teeth are both composed of carbonated apatite (an orthophosphate) crystals embedded within an organic framework, there is an emphasis in the biomedical community on such systems. We begin this section with a review by Wang and Nancollas describing the physical chemistry of the orthophosphates. A fundamental understanding of crystal growth and dissolution for this class of materials *in vitro* is essential for analyzing and modeling the biological systems.

A family of highly phosphorylated proteins is closely associated with the production of phosphate minerals *in vivo*. George and Veis review both *in vitro* and *in vivo* experiments that elucidate the role these proteins play in controlling the biomineralization of orthophosphates, such as carbonated apatite. In Omelon and Grynepas’s contribution, they discuss polyphosphates, an interesting class of biomacromolecules whose role in biomineralization is just recently becoming appreciated.

Boskey and Roy review the specialized cell-culture techniques, that have been developed to study biomineralization of bone and teeth *in vitro*. Of key importance in these studies is the identification and characterization of the mineral phase and the “biological relevance” of the mineral phase that is formed. This review addresses both of these issues and provides guidelines for designing future cell-based studies of mineralization.

The characterization, *in situ*, of the macro- and microscopic 3-D structures of biomineralized tissues is essential for understanding the spatial distribution of minerals during tissue development. Neues and Epple review the emerging field of synchrotron radiation microcomputer tomography

(μ CT) for imaging mineralized structures, at high resolution, in a nondestructive manner.

Immense attention has been paid to the development of osteoconductive and osteoinductive materials, materials that can stimulate the production of new bone *in vivo*, for use in biomedical implants for the repair of damaged hard tissues. LeGeros reviews different calcium phosphate based materials for this purpose. In the contribution from Stupp and co-workers, they present recent developments in the design of structurally complex organic templates to promote hydroxyapatite mineralization and bone repair, *in vivo*. Unlike traditional biomaterials, these newer synthetic constructs often incorporate multiple components, each with a specific biological function (e.g., chemical signals to promote both cell adhesion and mineralization).

In addition to the carbonates and the phosphates, there is a wide range of other inorganic minerals and organic crystals formed by biological organisms. We conclude this issue with a series of articles that cover some of these other systems and the techniques used to study them. Atomic force microscopy (AFM) can provide insight into the dynamics of crystallization, including the mechanisms by which small molecules and proteins can inhibit and/or modify crystal growth. Qiu and Orme review applications of AFM to study, among other systems, the crystallization of calcium oxalate, one of the main components of kidney stones. In recent years, molecular dynamics and other computational techniques have been applied to modeling crystal nucleation and growth. Harding and co-workers review how these computational techniques are applied to a range of biological and synthetic systems to provide insight into the role of the organic–inorganic interface in controlling crystallization.

The next articles cover three specific examples of different types of biominerals and the biological organisms that produce them. Hildebrand reviews the formation of amorphous silica by diatoms, with a focus on how genomics can contribute to our understanding of biomineralization processes. Faivre and Schüler examine the formation of magnetic minerals by magnetotactic bacteria and the macromolecules that are involved. The only review in this issue to address organic crystal growth in biology is by Weissbuch and Leiserowitz, who discuss the formation of hemozoin crystals by the parasite that causes malaria. In particular, they highlight the role that molecular recognition and crystal design can play in developing novel treatments for malaria by inhibiting the growth of hemozoin crystals and, thus, poisoning the parasites.

Finally, two reviews highlight bioinspired materials synthesis based upon a wide range of mineralizing systems. Brutchey and Morse focus on a protein, silicatein, which is isolated from the silica spicules of a marine sponge, to design new polymers and interfaces to control the growth of inorganic materials, including some that are important for energy production and storage. Dickerson, Sandhage, and Naik address the rapidly emerging field of protein- and peptide-directed synthesis of inorganic materials, including ceramic oxides, semiconductors, and metallic nanoparticles.

It is my hope that this issue of *Chemical Reviews* will introduce the broader chemistry community to the many facets of biomineralization. I also encourage the use of this

Thematic Issue as a “reader” for advanced undergraduate and/or graduate level courses in Biomineralization. I thank all of the authors for their thought-provoking and timely contributions and the editorial staff at *Chemical Reviews* for all of their help in preparing this issue.

Lara A. Estroff
Cornell University
Ithaca, New York

CR8004789