

Gast Lecture

Deciphering the physical basis of biomineralization through the lens of mineral assembly

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Over the course of Earth history, organisms have developed the ability to produce single crystal and composite materials with remarkable properties that fulfil specific functional needs. Using biologically mediated crystallization strategies, aqueous solutes are organized into mineralized structures with nanoscale to macroscopic dimensionalities. Although biomineral compositions and morphologies are signatures that may be used to decipher environments of prosperity and decline, most current interpretations lack an understanding of fundamental processes.

Recently, the biomineralization activities of marine microorganisms have emerged as particularly important owing to the use of biomineral products as paleoclimate indicators. In addition to providing critical information on crystal growth history, the minor and trace elements contained in biominerals also behave as impurities to regulate their properties and formation rates. We can begin to unravel this complexity by recognizing that mineralization is, above all, a thermodynamic phase transition. Using integrated approaches, we are investigating the kinetics and thermodynamics of CaCO₃ growth as a simple model system to decipher mechanisms of biomineral formation. Our focus is to understand the surface processes that govern growth of nanoscale structures, their chemical compositions, and how these growth structures interact to yield complex mineralized morphologies.

By combining in situ AFM studies of growth that use characterized solution chemistries with molecular modeling and surface spectroscopy, we link observations of nanoscale growth mechanisms with quantitative kinetic and thermodynamic information. We have established growth thermodynamics for the CaCO₃-NaCl and now the CaCO₃-synthetic seawater systems to show how key inorganic impurities affect mineralization through complex ion-specific mechanisms.

We also show how simple amino acids affect growth by modifying the energetics of step edges to produce mirror-imaged growth structures that reflect the chirality of bioactive compounds. In new work, we are investigating the interactions of simple peptides with the calcite surface as a simple model system for understanding roles of the more complex matrix proteins in mineralization.

A central theme that has emerged from our studies is the importance of steps. Existing crystal growth models have proposed that stereochemical recognition of impurities for particular faces causes stabilization of those faces while largely ignoring the roles of step-edge structures and their specificities for reaction. Our findings demonstrate that morphological evolution is defined by nanoscale impurity-step interactions.