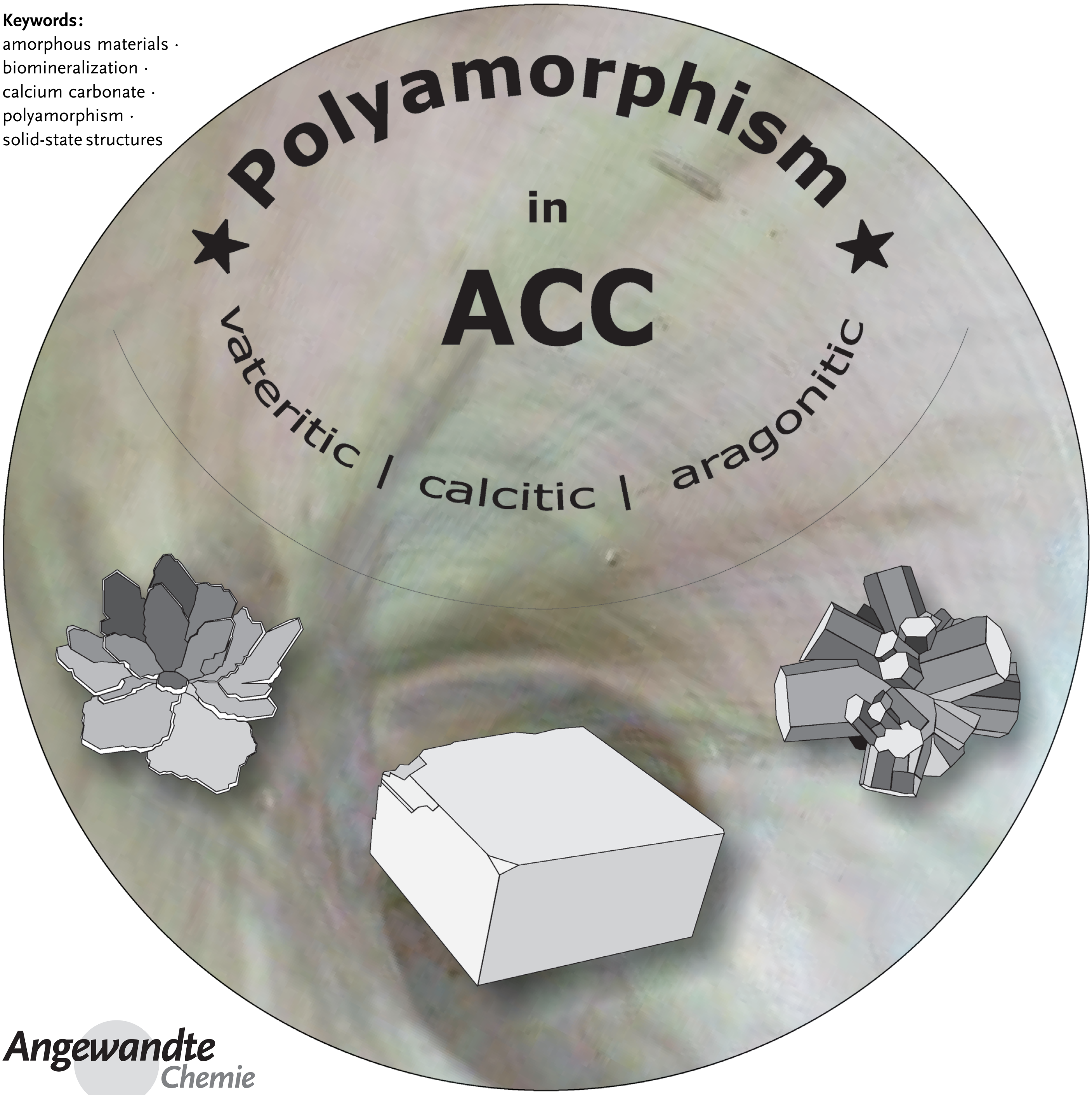
DOI: 10.1002/anie.201203125

Biomineral Polyamorphism

Calcium Carbonate Polyamorphism and Its Role in Biomineralization: How Many Amorphous Calcium Carbonates Are There?

Julyan H. E. Cartwright, Antonio G. Checa, Julian D. Gale, Denis Gebauer,* and C. Ignacio Sainz-Díaz*

Keywords:
amorphous materials ·
biomineralization ·
calcium carbonate ·
polyamorphism ·
solid-state structures



Although the polymorphism of calcium carbonate is well known, and its polymorphs—calcite, aragonite, and vaterite—have been highly studied in the context of biomineralization, polyamorphism is a much more recently discovered phenomenon, and the existence of more than one amorphous phase of calcium carbonate in biominerals has only very recently been understood. Here we summarize what is known about polyamorphism in calcium carbonate as well as what is understood about the role of amorphous calcium carbonate in biominerals. We show that consideration of the amorphous forms of calcium carbonate within the physical notion of polyamorphism leads to new insights when it comes to the mechanisms by which polymorphic structures can evolve in the first place. This not only has implications for our understanding of biomineralization, but also of the means by which crystallization may be controlled in medical, pharmaceutical, and industrial contexts.

From the Contents

1. Introduction

Calcium carbonate is one of the materials that has been found to possess more than one amorphous state, a phenomenon termed amorphous polymorphism, or polyamorphism.[1–4] While polymorphism—the possession of more than one crystalline phase—is a long-studied phenomenon, polyamorphism is a much more recently discovered occurrence. The term was introduced in 1980 by the Ukrainian physicist Leo Samoylovich Palatnik, who wrote: “*by analogy with the phenomenon of polymorphism, well known for crystalline materials, we will refer to the phenomenon of the existence of several such varieties of the amorphous state of the same substance as polyamorphism*”.[5,6]

The majority of research on polyamorphism to date relates to water, where three ice polyamorphs, termed LDA, HDA, and VHDA (low-density amorphous, high-density amorphous, and very-high-density amorphous, respectively) have been identified (Figure 1).[7–9] Apart from ice, polyamorphism has also been studied in silicon.[10] While the majority of systems that exhibit polyamorphism possess strongly directional interactions, such as covalent or hydrogen bonding, it has also been shown to occur in metallic alloys.[11] Even materials held together predominantly by van der Waals interactions—such as fullerites (C_{60} infused with small molecules or inert gases)—form orientational glasses that exhibit polyamorphic transitions.[12] Furthermore, polyamorphism can also occur in the liquid state, with the liquid being a dynamic version of an amorphous solid state; such liquid polyamorphism is seen in phosphorus[13] and triphenyl phosphite.[14]

In fact, liquid polyamorphism constitutes the ideal, while solid polyamorphism is its poor relation, in the sense that liquids are in thermodynamic equilibrium, while glasses, or amorphous phases, are not, as they are metastable in regard to crystals. It is for this reason that only liquid–liquid polyamorphism might appear on a traditional phase diagram, as opposed to Figure 1. If we think of the concept of thermodynamically ideal polyamorphism, the closest to this ideal is the coexistence of two stable liquids (e.g. phosphorus),[13] and there are successive conceptual steps away from that ideal that still enter within a broader appreciation of polyamorphism: a first-order phase transition between metastable liquids (e.g., silicon),[10] a metastable liquid to glass transition (e.g., triphenyl phosphite),[14] two amorphous solids separated by an abrupt transition (e.g., ice),[7–9] and lastly two amorphous solids which undergo a gradual transition between them. It remains to be determined exactly where calcium carbonate polyamorphism lies on this scale.

A simple physical mechanism has been proposed as a generic explanation for the phenomenon of solid and liquid polyamorphism: the existence of a double well—or, more generically, of two characteristic length scales—in the intermolecular potential energy hypersurface of a polyamorphic substance.[15–18]

---

[*] Dr. J. H. E. Cartwright,[+] Dr. C. I. Sainz-Díaz[+]
Instituto Andaluz de Ciencias de la Tierra
CSIC-Universidad de Granada
E-18100 Armilla, Granada (Spain)
E-mail: julyan.cartwright@csic.es
Homepage: http://www.lec.csic.es/~julyan
Prof. A. G. Checa[+]
Departamento de Estratigrafía y Paleontología
Universidad de Granada
E-18071 Granada (Spain)
Prof. J. D. Gale[+]
Nanochemistry Research Institute
Department of Chemistry, Curtin University
P.O. Box U1987, WA 6845 Perth (Australia)
Dr. D. Gebauer[+]
Department of Chemistry, Physical Chemistry
University of Konstanz
78457 Konstanz (Germany)
E-mail: Denis.Gebauer@uni-konstanz.de
Homepage: http://cms.uni-konstanz.de/gebauer

[+] All authors contributed equally to this work and are listed in alphabetical order.

In this Review we discuss the occurrence of polyamorphism in calcium carbonate, a mineral that is well known both for its polymorphism and also for its importance in biomineralization (that is, in mineral structures formed by biological systems). We believe that it is timely to examine polyamorphism in calcium carbonate from the point of view of biominerals, since on the one hand amorphous calcium carbonate (ACC) is increasingly acknowledged to be playing an important role in biomineralization (Section 2) and, on the other, it is becoming increasingly clear that there is not just one form of ACC, but that polyamorphs exist (Section 3). In addition, new insights into both ACC and the highly amorphous precursor species have recently come to light from molecular dynamics simulations (Section 4). We also highlight several open problems and challenges to be addressed (Section 5).

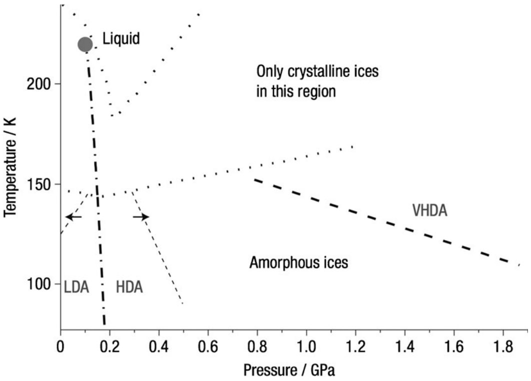
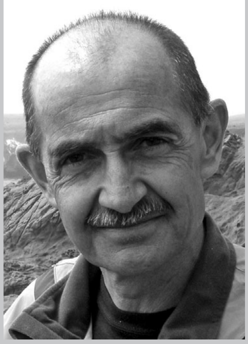


Figure 1. Polyamorphism in ice: the polyamorphism "phase diagram" of water. Dotted lines: top: minimum crystallization temperature of (super)cooled water; bottom: maximum crystallization temperature of amorphous forms of ice.[19] Filled gray circle: proposed second critical point of water and (below, dot-dashed) proposed line of first-order transitions in (inaccessible) water,[19,20] continuing into the estimated equilibrium phase boundary between LDA and HDA.[21,22] The arrows show the observed low- to high-density transition at 0.35 GPa, and reverse transition at 0.05 GPa back to LDA, at 130–140 K, crossing the upstroke and downstroke lines (thin dashed lines) found by Mishima.[21] (On compression, LDA remains metastable up to the upstroke line, and, on decompression, HDA remains metastable down to the downstroke line.) Thick dashed line: approximate *P-T* boundary for the formation of VHDA. Reproduced from Ref. [23] with permission. Copyright 2006 Macmillan Publishers.

2. Amorphous Calcium Carbonate in Biomineralization

The notion that many organisms produce amorphous minerals such as silica, calcium phosphate, or calcium

Julyan Cartwright is a physicist interested in the emergence of structure and pattern in nature. He has been studying mechanisms and processes of pattern formation, self-organization, and self-assembly both in ice and in biomineralization, and has found that these questions intersect in the polyamorphism of calcium carbonate.



Antonio Checa received his PhD in Geology in 1984 from the University of Granada, and since 2000 he has been Full Professor of Paleontology at the same university. His main research interests are the constructional morphology and biomineralization of the shells of molluscs. His interests include the nanostructure and crystallography of biocrystals, the distribution of the intracrystalline and extracrystalline organic components, and the evolution of the different types of exoskeletons since the emergence of molluscs, some 540 million years ago.

Julian Gale obtained his BA and DPhil from the University of Oxford, after which he was a postdoctoral research associate at the Royal Institution of Great Britain in collaboration with ICI Chemicals and Polymers. Following the award of a Royal Society University Research Fellowship, he moved to Imperial College London. In 2003 he moved to Curtin University in Western Australia, where he is currently an ARC Professorial Fellow and John Curtin Distinguished Professor. His research interests include the development and application of computational techniques to problems in materials chemistry, geochemistry, and mineralogy.

Denis Gebauer obtained his PhD in Physical Chemistry from the University of Potsdam (Germany), working at the Max-Planck-Institute of Colloids and Interfaces. After a two-year postdoctoral stay at the University of Stockholm (Sweden), he returned to Germany and started his Habilitation at the University of Konstanz in 2011. His research interests include concepts of nucleation and crystallization as well as biomineralization and materials chemistry in general. He is one of the awardees of the Heinz Maier-Leibnitz Prizes 2012.

Ignacio Sainz-Díaz obtained his PhD from the University of Alcalá de Henares (Madrid, Spain). After several years in research centers of chemical industry and European centers, he moved to a CSIC (Higher Council of Scientific Researches) Institute at Granada (Spain). Since 2004 he has been a senior researcher at the Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR). His research interests include organic–inorganic interatomic interactions in crystals, as well as crystal growth, biomineralization, and spectroscopy.

carbonate (ACC) has a long history, but it was not until the late 1960s that the first transient amorphous phase was identified in chiton teeth.[24] Since then there has been increasing evidence that biominerals, both in vertebrates and invertebrates, are formed from the corresponding amorphous precursor (see reviews in Refs. [25–27]). Calcium carbonate is, by far, the material most commonly employed by invertebrates for the construction of hard structures. These occur as granules, spicules, shells, and additional structures, and can be made of either of the two main calcium carbonate biominerals, aragonite or calcite as well as, more rarely, vaterite.

According to Addadi et al.,[28] the first mention of biogenic ACC was made in the early 20th century, although the first detailed studies involving high-resolution techniques began in the 1990s. Since then, ACC has been widely recognized in many groups of organisms (see the review by Addadi et al.).[28] In some of them, ACC is used as a structural component (e.g. plant cystoliths,[29] calcitic sponge spicules,[30–32] ascidian spicules),[31–33] or as a reservoir for the future availability of calcium carbonate (earthworms,[34–36] arthropods).[22–26,37–41] In other groups (e.g., molluscs[42–48] and sea urchins),[49–57] ACC is used as a precursor for the formation of crystalline calcium carbonate. The study of the two latter groups is particularly intensive due to the intrinsic general interest in processes involving the crystallization of ACC.

It is a matter of debate how such a metastable phase as ACC becomes stabilized, either transitorily or permanently. There have been proposals that macromolecules, water, membranes, and ionic components could perform this role.[58] Aizenberg et al.[30,31,33] found significant differences in the amino acid impurities of ACC and calcite from ascidian and calcitic sponge spicules, and proposed that macromolecules, in cooperation with Mg^{2+} ions, were responsible for the stabilization of ACC. This view was later taken by other authors to explain the stabilization of ACC in crustaceans,[38] sea urchin larval[53] and adult[49,57] spines, and earthworms.[34,35] More recently, the role of low-molecular-weight metabolites (inorganic phosphates, phosphoenol pyruvates, citrates …) has been demonstrated for the stabilization of the ACC of crustaceans.[41,59]

Beniash et al.[50] were the first to propose the transformation of ACC into another crystalline phase (magnesium-rich calcite in the larval spicules of the sea urchin). This interpretation was later reinforced by the detection of granules of ACC in spiculogenic cells, which could subsequently be transported to the mineralization site.[49] Similarly, the transformation of ACC into aragonite has been reported by Hasse et al.[42] and Marxen et al.[44] in the gastropod *Biomphalaria*, by Weiss et al.[43] in larval bivalves (although Kudo et al.[60] did not find ACC in the larval shell of a *Crassostrea*), and by Jacob et al.[47] in freshwater cultured pearls. All these authors observed how the ratio of crystalline calcium carbonate to ACC increased during the growth of the structures. This alone does not imply transformation of ACC into crystalline calcium carbonate, because direct deposition of the latter might occur in more advanced growth stages.

The first direct evidence was obtained concurrently in two distant groups of invertebrates. Politi et al.[52] showed by differential etching how the ACC of the regenerating sea urchin spine occurs in a 100–200 nm thick outer layer (Figure 2 A) and deposits preferentially at the tip, which is where the growth rate is the fastest (see also Seto et al.).[57] They also imaged the transformation of ACC into calcite under irradiation by transmission electron microscopy (TEM). Simultaneously, Nassif et al.[45] found a 3–5 nm ACC layer coating the surface of mature nacre tablets. A similar, although thicker and more continuous, amorphous front was found in the prismatic calcitic layer of the pearl

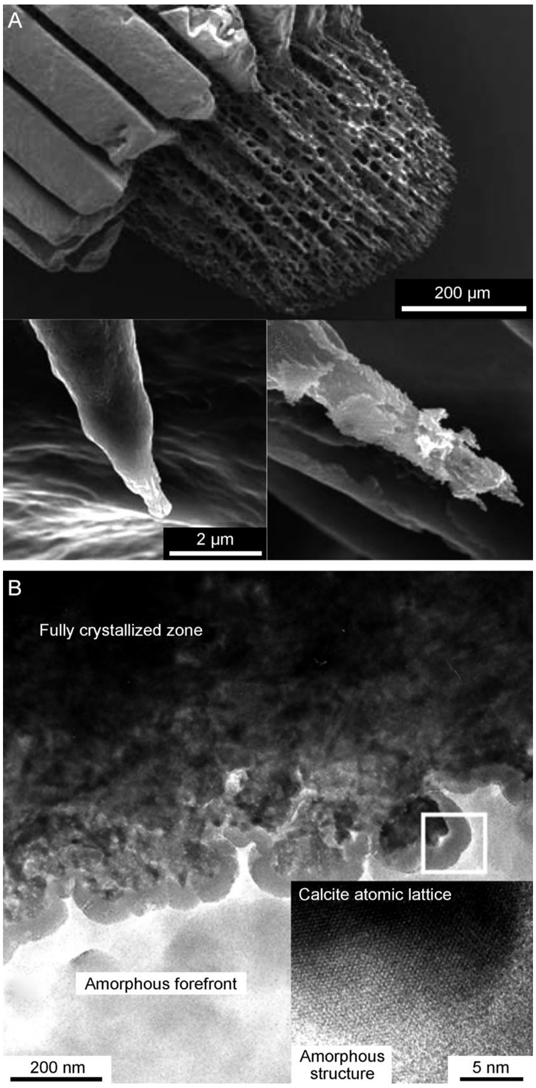


Figure 2. Evidence of ACC surrounding a regenerating sea urchin spine (A) and a growing calcitic prism of a bivalve (B). A) Regenerating spine of the sea urchin *Paracentrotus lividus*. Lower left: view of a freshly formed microspine after 4 days of regeneration. Lower right: view of a similar microspine etched in water; dissolution of ACC has occurred in the external layer. Reproduced from Ref. [52] with permission. Copyright 2004 AAAS. B) Growing front of a prism of the outer calcitic layer of the bivalve *Pinctada margaritifera* showing the contact between the crystalline interior and the amorphous cortex. Reproduced from Ref. [46] with kind permission of the Mineralogical Society. Copyright 2008 GeoScienceWorld.

oyster[46] (Figure 2B). Since all these structures grow by the addition of material at the growth front, the only possibility is that the ACC cortex transforms into the corresponding crystalline phase. Transformation of ACC into crystalline calcium carbonate immediately raises the interesting issue of how this transition takes place. During the study of the formation of the spicules of the sea urchin embryo, Beniash et al.[49] found that ACC contains significant amounts of water that are released during the crystallization process. Later studies on this structure as well as on sea urchin spines[52,53,55] and teeth[56] made it clear that stabilized biogenic ACCs typically contain structural water, while transient biogenic ACCs are in general anhydrous (see Section 4). Biomineralization proceeds in three stages: a) formation of hydrated ACC, which rapidly transforms into b) short-lived anhydrous ACC, which changes into c) calcite (see the review by Addadi et al.[28]). According to experimental data,[61] this sequence is energetically downhill.

Nudelmann et al.[62] first suggested that calcitic prisms of a bivalve grow by precipitation of ACC particles (50–100 nm diameter), which subsequently crystallize epitaxially upon contact with the crystalline surface. Politi et al.[55] were the first to propose that short-lived anhydrous ACC of sea urchin larvae transforms into calcite by secondary nucleation, in which crystallization of ACC stimulates the transformation of the contacting domains. In this process, the two phases (ordered and disordered) are both solid and in contact with each other, and the transformation involves a solid-state transformation.[63] The crystallographic orientation is determined by that of the central initial crystal of the larval skeleton. The secondary nucleation hypothesis is supported by experiments, whereby the use of Langmuir monolayers as model systems has led to the solid-state transformation of ACC into vaterite being observed.[64]

Distinct short-range order has been observed in ACC. The first evidence came from ACC of the aragonitic freshwater snail *Biomphalaria glabrata*, which was found to have a short-range order similar to aragonite.[42,44] Other orders relating to aragonite[28] and calcite[28,53,58] were found in aragonitic larval molluscs and in calcitic sea urchin structures, respectively. Monohydrocalcite-like ACC has also been referred to in a series of other organisms.[65] Therefore, the statement of Addadi et al.[28] that biogenic ACC is structurally not one mineral phase, but a family of phases that appear to be genetically controlled in different species and phyla, makes sense. Belcher et al.[66] and Falini et al.[67] demonstrated concurrently that polymorph secretion is controlled by the macromolecules associated with either the calcitic or aragonitic shell layers. The same macromolecules could also control the short-range order of ACC, if we consider the structural relationship between polyamorphs and polymorphs.

3. Protocrystalline Amorphous Versions—or Polyamorphs—of Calcium Carbonate

Apart from biogenic specimens, synthetically prepared ACCs can also exhibit distinct short-range structures. Short-range structures resembling vaterite and aragonite may be obtained in the presence of poly(aspartic acid) and magnesium ions, respectively.[69] Additives can stabilize ACC, which is unstable at ambient conditions, but additive-free stabilized ACC can be isolated from aqueous environments if it is precipitated at high supersaturation.[70–73] However, such ACCs show no distinct short-range order.[74,75] These observations may imply that additives induce short-range structuring in ACC and thus that distinct local order would be an extrinsic feature of ACC. This notion is in accord with the observation of structuring in biogenic ACC, since this always contains bio(macro)molecules as well, and could hence be under genetic control as speculated by Addadi et al.[28] However, it is now evident that distinct short-range structural features are intrinsic to ACC if it is precipitated from a moderate level of supersaturation. The earliest evidence of distinct structures in additive-free synthetic specimens was reported by Günther et al.,[76] who found calcite-like short-range structures in ACC synthesized at 0 °C.

Additive-free ACC that is precipitated from equilibrated, slightly supersaturated (metastable) solutions of calcium carbonate by means of a sudden change to a medium that only weakly solvates calcium carbonate (e.g. a "quench" in ethanol) exhibits distinct short-range order.[68] The structuring depends on the pH value, that is at $\mathrm{pH} \approx 8.75$ and $\mathrm{pH} \approx 9.80$ ACCs with short-range structures related to calcite and vaterite, respectively, are obtained (Figure 3). The pH dependency of different structures of ACC was suggested in an earlier study, with two different solubilities of ACCs identified (ACCI and ACCII).[77] Solubilities directly correlate with the thermodynamic stability of the respective phases (and can reflect the size, because Gibbs–Thomson effects become important at the nanoscale, or the presence of impurities). The more stable ACC (ACCI) resembles the short-range structure of calcite, which is the more stable crystalline polymorph, while the less stable ACC (ACCII), on the other hand, is related to the least stable anhydrous crystalline polymorph, vaterite.[68] Consequently, the notion of protocrystalline structuring in ACC has been introduced, namely ACCI and ACCII are proto-calcite ACC (pc-ACC) and proto-vaterite ACC (pv-ACC), respectively.[68]

Interestingly, the different stabilities of ACC reflect different, pH-dependent stabilities of prenucleation clusters.[77] The more stable prenucleation clusters correspondingly yield the more stable pc-ACC upon nucleation. Since nucleation appears to proceed by aggregation of the prenucleation clusters,[77,79–81] this strongly suggests that distinct structures are also present in prenucleation clusters.[82] This is evidence that the different structures in ACC are intrinsic and can depend on intensive parameters during the early stages of crystallization. Moreover, this mechanism may rationalize why no distinct structures may be obtained in ACC if it is precipitated from very high levels of supersaturation; in this case, ACC is precipitated virtually instantaneously, and protocrystalline structuring in prenucleation clusters (and with it, in ACC) cannot equilibrate according to a given set of intensive variables. On the other hand, interactions with additives may stabilize certain protocrystalline structures in ACC, which are successively developed. Recent modeling studies indicate that chainlike and highly dynamic structures

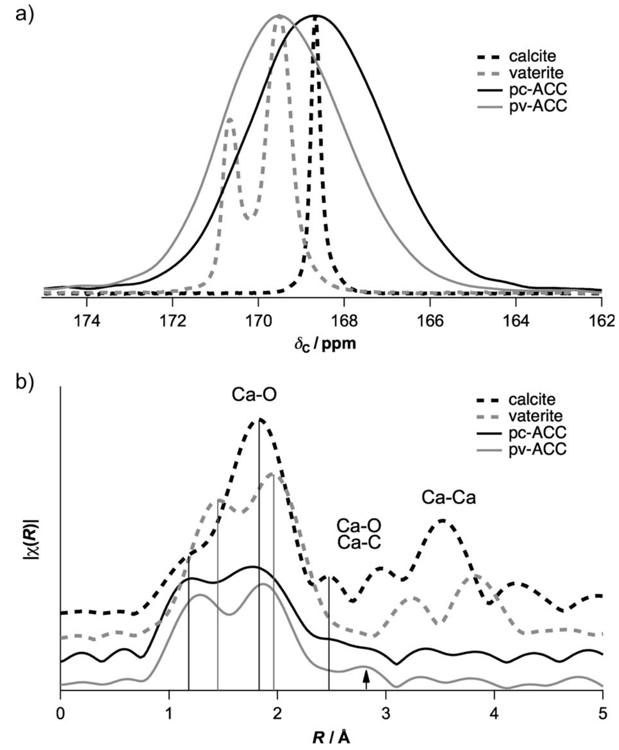


Figure 3. Spectra of calcite, vaterite, proto-calcite ACC (pc-ACC), and proto-vaterite ACC (pv-ACC). a) ^{13}C solid-state NMR spectra recorded by single pulses at a magnetic field of 9.4 T and a magic-angle-spinning (MAS) rate of 8.0 kHz. b) Fourier transform of calcium *K*-edge EXAFS plotted as a function of distance *R*; the expected species assignments for the first three coordination shells are indicated. The black arrow marks a peak that may relate to the coordination of structural water. The vertical lines are a guide to the eye. The data show that pc-ACC and pv-ACC relate on average to the structure of calcite and vaterite, respectively, within the short-range structure. Adapted from Ref. [68].

in prenucleation clusters may be the basic principle behind protocrystalline structuring in intermediate ACC (see Section 4).[78]

Despite the above, the protocrystalline structures of additive-free amorphous intermediates do not necessarily predetermine the outcome of the amorphous to crystalline phase transition—proto-calcite ACC does not always transform into calcite,[68] while unambiguous transformations have also been reported.[76] Since additive-containing and biogenic protostructured ACCs can transform in an unambiguous manner, it appears that additives may specifically interact with the protostructures during the amorphous to crystalline phase transitions, and in this way control polymorph selection.[83] However, there are also exceptions to this rule; for example, the “aragonitic” ACC in the freshwater snail *Biomphalaria glabrata* can apparently transform into minor amounts of vaterite in adult animals.[42] The detailed mechanisms underlying additive–mineral interactions throughout the different stages of crystallization (prenucleation, nucleation, postnucleation) remain as yet unknown (see Section 5).

4. Simulation of the Amorphous Phases and “Protocrystalline Structures”

Determining structural models for amorphous calcium carbonate is a challenging prospect experimentally. Recently, it has been possible to arrive at two different sample atomic configurations based on the use of Reverse Monte Carlo (RMC) simulations to fit to the pair distribution function data for ACC.[72] It should be noted that here ACC was precipitated from very high levels of supersaturation and consequently did not exhibit distinct protostructural features (see Section 3). While this result is suggestive of a possible heterogeneous distribution of water within ACC when the stoichiometry is close to that of monohydrocalcite, there remain uncertainties as to how representative these configurations may be. Indeed, a recent study based on solid-state ^{43}Ca NMR spectroscopy in combination with molecular dynamics computer simulations[84] suggests that the RMC-based structure of Goodwin et al.[72] changes during the simulations, which may lead to a reduced heterogeneity.

An alternative approach that complements experimental studies is to exploit atomistic simulation techniques and, in particular, molecular dynamics to provide structural insights into ACC. Quigley and Rodger[85] have used metadynamics, a form of bias acceleration, to estimate the relative free energies of amorphous and crystalline nanoparticles of calcium carbonate. Although the underlying force field fails to capture the correct relative stability of the crystalline polymorphs, this study demonstrates that it is possible to overcome the limited timescales accessible to molecular dynamics that would normally prevent phase transformations from being observed.

Raiteri and Gale[86] have taken an alternative approach to the study of amorphous nanoparticles by quenching clusters that have been melted in vacuo and subsequently annealing them in an aqueous environment. Here, a range of cluster dimensions have been probed, from ion pairs through to clusters with diameters approaching 4 nm, while also varying the water content. Although no clear evidence for polyamorphism was observed, there are indications of size-dependent structural inhomogeneity. In particular, the thermodynamically favored water content was found to increase as the particles grow. Combined with the hindered diffusion of water within ACC, it is probable that this will lead to radial variations in composition, with the outer shell being wetter than the inner core. Furthermore, by optimizing the water content, the free energy of ACC nanoparticles can remain lower than that of crystalline calcite nanoparticles at small sizes, thereby leading to ACC being stable, rather than metastable. However, as particles agglomerate or grow they will rapidly become metastable with respect to calcite and aragonite.

Aside from the structure of ACC, molecular dynamics simulations can also play a role in understanding the nature of prenucleation species, as identified experimentally. Recently Demichelis et al.[78] have shown that calcium and carbonate ions rapidly aggregate in solution to form stable clusters. These precursors have an unusual and very dynamic structure consisting of chains of alternating cations and anions.

Remarkably the system can adopt configurations in which the ions form rings as well as branched and linear chains that all possess the same free energy to within the ambient thermal energy. This new type of species has been labeled a dynamically ordered liquidlike oxyanion polymer (DOLLOP), and has been suggested to represent the structural form of prenucleation clusters.[78] Although the behavior of DOLLOP is not formally polyamorphism, as there is no phase boundary, these structures represent disordered clusters, but with different topologies that can interconvert (Figure 4). If these species, which are in equilibrium with the solution, can reach a critical size it appears that they undergo a subtle change in structure that causes larger clusters to appear that are more stable than the initial DOLLOP form. However, it remains unclear what exactly happens at the point of nucleation, that is, how the DOLLOPs grow to reach a critical size; this process could in principle be based on either ion-by-ion growth or on aggregation of individual DOLLOPs. Experimental observations[77,79–81] point towards the latter pathway. Thus, the structural change in larger DOLLOPs, which can exhibit different interconverting topologies at smaller sizes, may be related to the protocrystalline structures observed experimentally, thereby laying the foundation for polyamorphic ACC.

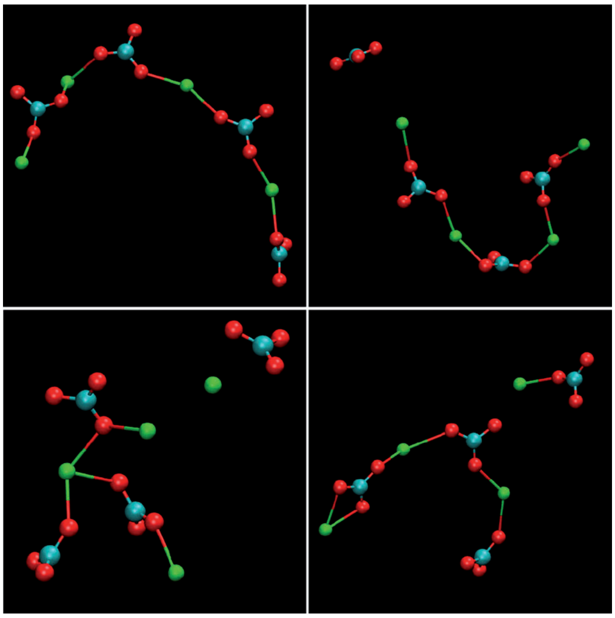


Figure 4. Structures of the prenucleation clusters formed from four formula units. Structures shown represent the configurations of four separate clusters after 1 ns of simulation under the experimental conditions ([Ca] = 0.4 mM, [HCO_3^-] = 10 mM, pH 10); Ca green, C blue, and O red. Note that the surrounding water has been hidden for clarity. Reproduced from Ref. [78] with permission. Copyright 2011 Macmillan Publishers.

5. Open Questions, Challenges, and Conclusions

There are many gaps in our knowledge on the polyamorphism of calcium carbonates, especially when it comes to understanding what is occurring at the atomic scale. The presence of strong electrostatic interactions between carbonate anions and calcium cations, and the hydrogen bonds arising from the presence of water molecules, must be the key to understanding the phase transitions between glassy forms, and also between amorphous and crystalline forms. Similar cases have been studied, such as in the polyamorphism of ice,[87] and in the transformation of carbonate to carbonic acid,[88] where several polyamorphs have been detected. It is often assumed that each amorphous form yields one specific crystalline form of carbonate, however, this is not necessarily the case, but instead depends on the nucleation and crystallization conditions. One of the main challenges in calcium carbonate polyamorphism is the lack of a structural model that describes these glassy phases. Such a model would allow us to study the atomic arrangements of different crystallographic long-range ordered structures or different disordered structures, as well as the role of water and/or protein molecules in influencing the mechanism of the amorphous/crystal-phase transition. The knowledge of a structural model for these amorphous phases would help in understanding the role of additives in biocrystallization processes and the interactions occurring during the amorphous–crystalline phase transition. Various techniques used in the characterization of crystalline forms of carbonates have also been used to distinguish between the amorphous phases, such as infrared spectroscopy, X-ray diffraction, extended X-ray absorption fine structure (EXAFS), and synchrotron X-ray total scattering methods. However, only indirect information related to the atomic structure has so far been obtained.[72]

EXAFS analyses of glassy calcium carbonates have found average coordination numbers for Ca^{2+} ions lower than those existing in the crystal forms (6 for calcite and vaterite, and 9 for aragonite).[74] Calcium *K*-edge EXAFS experiments along with Reverse Monte Carlo simulations have found different Ca distributions, while NMR and IR spectroscopic studies have found different water molecule environments within the amorphous carbonate structure.[72] However, no clear differences between the atomic structures of the possible amorphous phases have yet been detected. Indeed, it remains uncertain as to how homogeneous the composition, and therefore the structure, of partially hydrated ACC actually is.

Taking all of the above into account, we can conclude that the polyamorphism of calcium carbonate is rather extensive (Figure 5). To begin with, there are hydrous and anhydrous ACCs, which have been observed to correspond to stabilized and transient ACCs in biogenic specimens, respectively.[28] The water content in ACC can vary, but with stoichiometric or near-stoichiometric $CaCO_3 \cdot H_2O$ predominating.[26] From the point of view of polyamorphism, a varying water content in distinct forms of ACCs would be regarded as pseudo-polyamorphism (cf. pseudo-polymorphism in the crystalline case). However, a thorough discussion is difficult, as it depends on the understanding of the actual structural role of water (see Section 4). For example, there might be regions of polyamorphic ACC with the same composition separated by different wet regions. Dehydration of water-containing ACCs to generate anhydrous ACC, and subsequent crystallization, follows a downhill energetic pathway,[61] at least at larger

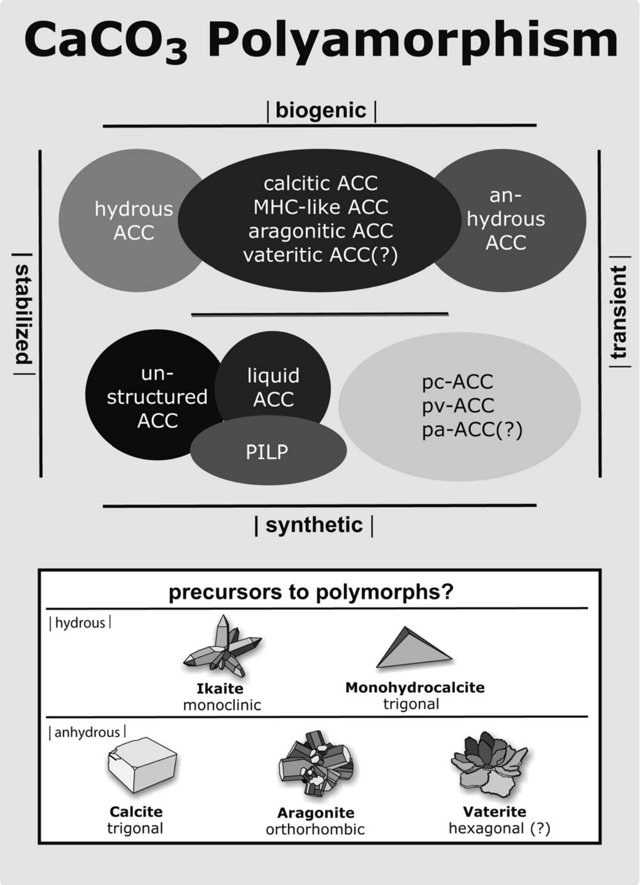


Figure 5. Overview of calcium carbonate polyamorphism and polymorphism (inset). For explanations see text.

particle sizes, which might indicate that transient biogenic ACCs are actually formed from stabilized hydrous precursors during biologically induced crystallization. In addition to the varying water content, biogenic ACCs can exhibit distinct short-range structural features, which can be related to calcite[28,53,58] (calcitic ACC), aragonite[28,42,44] (aragonitic ACC), or monohydrocalcite[65] (MHC-like ACC). Biogenic vateritic ACC, however, has not yet been reported with certainty (Figure 5). The ACC in sternal deposits of *Porcellio scaber* may be related to vaterite or monohydrocalcite on the basis of the oxygen–calcium distance within the first coordination shell, as determined by means of EXAFS, although IR data suggest a structural relationship to aragonite.[89] Moreover, it is important to realize that there are only a few examples of biogenic vaterite (see Section 2), although the mechanism of formation has not yet been studied in detail. Future studies may possibly lead to the unambiguous identification of a biogenic vaterite-like intermediate of ACC. Following our considerations above, the differently structured biogenic ACCs may exhibit varying states of hydration, depending on their biological function (storage or transient forms that are about to crystallize).

It remains a matter of debate as to how, in terms of polyamorphism, the "prestructured" biogenic ACCs relate to synthetic proto-structured ACCs (proto-calcite ACC (pc-ACC), proto-vaterite (pv-ACC),[68] and possibly proto-aragonite (pa-ACC), which has not yet been obtained; Figure 5). On the one hand, the origin of distinct short-range structures may also be based on prenucleation clusters and DOLLOP, as outlined in Sections 3 and 4, in the biogenic case. On the other hand, structural characterizations by means of EXAFS show that biogenic species of ACC can have coordination numbers commensurate with crystalline species,[90] as opposed to the low coordination of $N=2$ in the synthetic protostructured ACCs.[68] While comparably low coordination numbers can also be found in biogenic ACCs,[65] this observation may in the end relate to the high uncertainty surrounding the determination of reliable coordination numbers by means of EXAFS.[91] Calcium–oxygen distances derived from EXAFS may also be used as a diagnostic test for different structures, because of their higher accuracy compared to the coordination numbers obtained from this technique. However, additional experimental characterization is required. Different techniques may provide contradictory evidence, as in the case of ACC in the sternal deposits of *Porcellio scaber*,[89] because of small differences that may lie within experimental error. While this underlines that different techniques should be combined for structural characterizations of ACC, an alternative explanation could be that bio(macro)molecules incorporated in biogenic phases of ACC could stabilize amorphous states that are already much closer to crystalline states, but which have originated from less-ordered, although proto-structured, ACCs with lower coordination numbers. This could also be true for distinctly structured ACCs obtained by utilizing different additives in vitro.[69]

Additive-containing ACCs that do not relate to crystalline polymorphs can be synthesized in vitro, notably the polymer-induced-liquid precursors (PILP)[26,92] and liquid ACC,[93] which may also be stabilized in the absence of additives if the contact with an extrinsic surface, and thereby heterogeneous nucleation, is reduced through levitation in droplets.[94] These phases differ from the ACCs discussed above as they are regarded as liquid forms of calcium carbonate—that can even form micrometer-sized droplets—rather than solid particles. Structural details of these phases, however, remain unknown, while the results of Wolf et al.[93,94] imply that small amounts of certain polymers stabilize, rather than "induce", this liquid intermediate, which is believed to form first upon nucleation through a liquid/liquid phase separation. Thus, these phases represent a precursor to the solid forms of ACCs discussed above, and they can not be strictly considered polyamorphs of calcium carbonate. Recent results indicate that a neutral pH value with a dominating fraction of bicarbonate ions is essential when it comes to observing liquid forms of calcium carbonate in the absence of polymers.[95]

Last but not least, additive-free ACC that does not resemble any crystalline polymorph can be obtained from high levels of supersaturation (denoted as "unstructured" in Figure 5),[70–75] and stabilized without the help of additives. It may be speculated that, indeed, the high degree of structural disorder of this metastable phase leads to an intrinsic kinetic stabilization against crystallization.

Another open question related with ACC and carbonate crystallization is to understand the effect of the presence of

Mg^{2+} ions on the formation of calcium carbonates and dolomites. Natural dolomite (calcium-magnesium carbonate) was formed at low temperature, but it is not yet possible to synthesize it in the laboratory at low temperature. Dove and co-workers suggest that alternative crystallization pathways from amorphous precursors may explain the occurrence of dolomites,[96,97] although the definitive formation mechanism of dolomite deposits still largely remains a conundrum; taking all of the above into account, it can be speculated that dolomites may have a biomineral origin. This amorphous calcium-magnesium carbonate can be stabilized by the presence of inorganic or organic additives that can also modulate the formation of different polyamorphs. The presence of Mg^{2+} ions can favor environments with high water content, or cations with a low coordination number[72] can stabilize some atomic arrangements that can be considered as amorphous phases. An understanding of the role of amorphous carbonate in dolomite formation could change previous interpretations of the origin of many dolomites.[98] It is known that the presence of Mg^{2+} ions induces the formation of aragonite without incorporation of the Mg^{2+} ions in the crystal lattice. The Mg^{2+} ions probably favor the proto-aragonite ACC phase.[69] We should also not forget the presence of organic molecules during the biomineralization process; these organic additives can have carboxylate functional groups that can modulate the biogenic ACC to form a specific amorphous phase (see above). This organic matter with carboxylate groups can facilitate the ordering of the ACC atoms to nucleate a specific polymorph of crystalline carbonate. This effect can be combined also with that of Mg^{2+} ions, thereby leading to a change in the amorphous precursor phase or the nucleation of the crystalline form.

Polyamorphism has been reported for titania (TiO_2) when either nanoparticulate anatase[99,100] or nanoribbons of TiO_2-B[101] are amorphized under pressure. Although the nature of the polyamorphism is far from clear in this case, it is apparent that a critical dimension on the nanoscale is important for this phenomenon to be observed. Given that calcium carbonate is proposed to form by agglomeration of nanoparticles of ACC, it remains an open question as to whether the presence of a length scale in the nanometer regime may more generally be important for polyamorphism.

Perhaps it is not surprising that determining structural models for polyamorphic calcium carbonate is challenging when the details of the structure for even the crystalline (Figure 5, inset), but disordered, phase vaterite are still open to debate. Although it is widely accepted that vaterite has on average hexagonal symmetry, the arrangement of the carbonate groups within the structure is still a matter for discussion. While the carbonates are often believed to be disordered by rotation about the *c*-axis of the hexagonal cell, recent ab initio calculations[102] have indicated that most of the existing ordered structure models are dynamically unstable and that the carbonate groups also undergo subtle rotations about axes that also lie in the *ab* plane. This demonstrates that, even for vaterite, there are two mechanisms for disorder with different length scales, thereby supporting the hypothesis that underpins models of polyamorphism. Indeed, in this case there may be several minima within multiple basins on the potential energy hypersurface on an extended length scale, rather than simply a double well. For ACC, the situation for carbonates is further compounded by disordering of all the species, thereby leading to the possibility of even more distinct structural length scales for this material.

Our hope is that this Review will contribute to bringing together research being carried out into biogenic and synthetic ACC polyamorphism, so that a future review will be able to display a graphic such as Figure 1 for calcium carbonate. Understanding calcium carbonate polyamorphism from these different perspectives will contribute to comprehending the generalized crystallography of structures beyond crystals at the intersection between crystallography, materials science, and biology.[103]

J.H.E.C., A.G.C., and C.I.S.D. acknowledge funding provided by projects CGL2010-20748-CO2-01 and FIS2010-22322-C02-02 of the Spanish Ministerio de Ciencia e Innovación, and J.H.E.C., A.G.C., D.G., and C.I.S.D. acknowledge funding provided by the European COST Action TD0903. J.D.G. thanks the Australian Research Council for a Professorial Fellowship and funding from the Discovery program. D.G. thanks Helmut Cölfen for his support.

Received: April 23, 2012
Revised: June 8, 2012

---

[1] P. H. Poole, T. Grande, F. Sciortino, H. E. Stanley, C. A. Angell, *Comp. Mater. Sci.* **1995**, *4*, 373–382.
[2] P. F. McMillan, M. Wilson, M. C. Wilding, D. Daisenberger, M. Mezouar, G. Neville Greaves, *J. Phys. Condens. Matter* **2007**, *19*, 415101.
[3] T. Loerting, V. V. Brazhkin, T. Morishita, *Adv. Chem. Phys.* **2009**, *143*, 29–82.
[4] M. C. Wilding, M. Wilson, P. F. McMillan, *Chem. Soc. Rev.* **2006**, *35*, 964–986.
[5] L. S. Palatnik, Y. A. Bykovskiĭ, P. A. Panchekha, A. G. Dudoladov, V. I. Verchenko, S. V. Marun'ko, *Sov. Phys. Dokl.* **1980**, *25*, 770–772.
[6] L. S. Palatnik, Y. A. Bykovskiĭ, P. A. Panchekha, A. G. Dudoladov, V. I. Verchenko, S. V. Marun'ko, *Dokl. Akad. Nauk SSSR* **1980**, *254*, 632–635.
[7] T. Bartels-Rausch, V. Bergeron, J. H. E. Cartwright, R. Escribano, J. L. Finney, H. Grothe, P. J. Gutiérrez, J. Haapala, W. F. Kuhs, J. B. C. Pettersson, et al., *Rev. Mod. Phys.* **2012**, *84*, 885–944.
[8] O. Mishima, *Proc. Jpn. Acad. Ser. B* **2010**, *86*, 165–175.
[9] T. Loerting, N. Giovambattista, *J. Phys. Condens. Matter* **2006**, *18*, R919–R977.
[10] S. K. Deb, M. Wilding, M. Somayazulu, P. F. McMillan, *Nature* **2001**, *414*, 528–530.
[11] H. W. Sheng, H. Z. Liu, Y. Q. Cheng, J. Wen, P. L. Lee, W. K. Luo, S. D. Shastri, E. Ma, *Nat. Mater.* **2007**, *6*, 192–197.
[12] A. N. Aleksandrovskii, A. V. Dolbin, V. B. Esel'son, V. G. Gavrilko, V. G. Manzhelii, A. S. Bakai, D. Cassidy, G. E. Gadd, S. Moricca, B. Sundqvist, *Low Temp. Phys.* **2005**, *31*, 429–444.
[13] Y. Katayama, T. Mizutani, W. Utsumi, O. Shimomura, M. Yamakata, K.-I. Funakoshi, *Nature* **2000**, *403*, 170–173.
[14] R. Kurita, H. Tanaka, *Science* **2004**, *306*, 845–848.

[15] O. Mishima, H. E. Stanley, *Nature* **1998**, *392*, 164–168.
[16] G. Franzese, G. Malescio, A. Skibinsky, S. V. Buldyrev, H. E. Stanley, *Nature* **2001**, *409*, 692–695.
[17] Z. Yan, S. V. Buldyrev, N. Giovambattista, H. E. Stanley, *Phys. Rev. Lett.* **2005**, *95*, 130604.
[18] P. Vilaseca, G. Franzese, *J. Non-Cryst. Solids* **2011**, *357*, 419–426.
[19] P. G. Debenedetti, *J. Phys. Condens. Matter* **2003**, *15*, R1669–R1726.
[20] P. H. Poole, F. Sciortino, U. Essmann, H. E. Stanley, *Nature* **1992**, *360*, 324–328.
[21] O. Mishima, *J. Chem. Phys.* **1994**, *100*, 5910.
[22] E. Whalley, D. D. Klug, Y. P. Handa, *Nature* **1989**, *342*, 782–783.
[23] R. J. Nelmes, J. S. Loveday, T. Strässle, C. L. Bull, M. Guthrie, G. Hamel, S. Klotz, *Nat. Phys.* **2006**, *2*, 414–418.
[24] K. M. Towe, H. A. Lowenstam, *J. Ultrastruct. Res.* **1967**, *17*, 1–13.
[25] S. Weiner, J. Mahamid, Y. Politi, Y. Ma, L. Addadi, *Front. Mater. Sci. Chin.* **2009**, *3*, 104–108.
[26] L. B. Gower, *Chem. Rev.* **2008**, *108*, 4551–4627.
[27] P. U. P. A. Gilbert, F. H. Wilt, *Molecular Biomineralization: Aquatic Organisms Forming Extraordinary Materials* (Ed.: W. E. G. Müller), Springer, New York, **2011**, pp. 199–223.
[28] L. Addadi, S. Raz, S. Weiner, *Adv. Mater.* **2003**, *15*, 959–970.
[29] H. Setoguchi, M. Okazaki, S. Suga, *Origin, Evolution, and Modern Aspects of Biomineralization in Plants and Animals* (Ed.: R. E. Crick), Plenum, New York, **1989**, pp. 409–418.
[30] J. Aizenberg, G. Lambert, L. Addadi, S. Weiner, *Adv. Mater.* **1996**, *8*, 222–226.
[31] J. Aizenberg, S. Weiner, L. Addadi, *Connect. Tissue Res.* **2003**, *44*, 20–25.
[32] I. Sethmann, R. Hinrichs, G. Wörheide, A. Putnis, *J. Inorg. Biochem.* **2006**, *100*, 88–96.
[33] J. Aizenberg, G. Lambert, S. Weiner, L. Addadi, *J. Am. Chem. Soc.* **2002**, *124*, 32–39.
[34] M. J. I. Briones, E. López, J. Méndez, J. B. Rodríguez, L. Gago-Duport, *Mineral. Mag.* **2008**, *72*, 227–231.
[35] L. Gago-Duport, M. J. I. Briones, J. B. Rodríguez, B. Covelo, *J. Struct. Biol.* **2008**, *162*, 422–435.
[36] M. R. Lee, M. E. Hodson, G. N. Langworthy, *Mineral. Mag.* **2008**, *72*, 257–261.
[37] A. Ziegler, *J. Struct. Biol.* **1994**, *112*, 110–116.
[38] S. Raz, O. Testeniere, A. Hecker, S. Weiner, G. Luquet, *Biol. Bull.* **2002**, *203*, 269–274.
[39] R. Dillaman, S. Hequembourg, M. Gay, *J. Morphol.* **2005**, *263*, 356–374.
[40] A. Ziegler, H. Fabritius, M. Hagedorn, *Micron* **2005**, *36*, 137–153.
[41] A. Akiva-Tal, S. Kababya, Y. S. Balazs, L. Glazer, A. Berman, A. Sagi, A. Schmidt, *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 14763–14768.
[42] B. Hasse, H. Ehrenberg, J. C. Marxen, W. Becker, M. Epple, *Chem. Eur. J.* **2000**, *6*, 3679–3685.
[43] I. M. Weiss, N. Tuross, L. Addadi, S. Weiner, *J. Exp. Zool.* **2002**, *293*, 478–491.
[44] J. C. Marxen, W. Becker, D. Finke, B. Hasse, M. Epple, *J. Mollus. Stud.* **2003**, *69*, 113–121.
[45] N. Nassif, N. Pinna, N. Gehrke, M. Antonietti, C. Jäger, H. Cölfen, *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 12653–12655.
[46] A. Baronnet, J. P. Cuif, Y. Dauphin, B. Farre, J. Nouet, *Mineral. Mag.* **2008**, *72*, 617–626.
[47] D. E. Jacob, A. L. Soldati, R. Wirth, J. Huth, U. Wehrmeister, W. Hofmeister, *Geochim. Cosmochim. Acta* **2008**, *72*, 5401–5415.
[48] D. E. Jacob, R. Wirth, A. L. Soldati, U. Wehrmeister, A. Schreiber, *J. Struct. Biol.* **2011**, *173*, 241–249.
[49] E. Beniash, L. Addadi, S. Weiner, *J. Struct. Biol.* **1999**, *125*, 50–62.
[50] E. Beniash, J. Aizenberg, L. Addadi, S. Weiner, *Proc. R. Soc. London Ser. B* **1997**, *264*, 461–465.
[51] F. H. Wilt, *Zool. Sci.* **2002**, *19*, 253–261.
[52] Y. Politi, T. Arad, E. Klein, S. Weiner, L. Addadi, *Science* **2004**, *306*, 1161–1164.
[53] S. Raz, P. C. Hamilton, F. H. Wilt, S. Weiner, L. Addadi, *Adv. Funct. Mater.* **2003**, *13*, 480–486.
[54] Y. R. Ma, S. Weiner, L. Addadi, *Adv. Funct. Mater.* **2007**, *17*, 2693–2700.
[55] Y. Politi, R. A. Metzler, M. Abrecht, B. Gilbert, F. H. Wilt, I. Sagi, L. Addadi, S. Weiner, P. U. P. A. Gilbert, *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 17362–17366.
[56] C. E. Killian, R. A. Metzler, Y. U. T. Gong, I. C. Olson, J. Aizenberg, Y. Politi, F. H. Wilt, A. Scholl, A. Young, A. Doran, et al., *J. Am. Chem. Soc.* **2009**, *131*, 18404–18409.
[57] J. Seto, Y. R. Ma, S. A. Davis, F. C. Meldrum, A. Gourrier, Y.-Y. Kim, U. Schilde, M. Sztucki, M. Burghammer, S. Maltsev, et al., *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 3699–3704.
[58] Y. Politi, Y. Levi-Kalisman, S. Raz, F. Wilt, L. Addadi, S. Weiner, I. Sagi, *Adv. Funct. Mater.* **2006**, *16*, 1289–1298.
[59] A. Sato, S. Nagasaka, K. Furihata, S. Nagata, I. Arai, K. Saruwatari, T. Kogure, S. Sakuda, H. Nagasawa, *Nat. Chem. Biol.* **2011**, *7*, 197–199.
[60] M. Kudo, J. Kameda, K. Saruwatari, N. Ozaki, K. Okano, H. Nagasawa, T. Kogure, *J. Struct. Biol.* **2010**, *169*, 1–5.
[61] A. V. Radha, T. Z. Forbes, C. E. Killian, P. U. P. A. Gilbert, A. Navrotsky, *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 16438–16443.
[62] F. Nudelman, H. H. Chen, H. A. Goldberg, S. Weiner, L. Addadi, *Faraday Discuss.* **2007**, *136*, 9–25.
[63] S. Weiner, L. Addadi, *Annu. Rev. Mater. Sci.* **2011**, *41*, 21–40.
[64] B. P. Pichon, P. H. H. Bomans, P. M. Frederik, N. A. J. M. Sommerdijk, *J. Am. Chem. Soc.* **2008**, *130*, 4034–4040.
[65] Y. Levi-Kalisman, S. Raz, S. Weiner, L. Addadi, I. Sagi, *Adv. Funct. Mater.* **2002**, *12*, 43–48.
[66] A. M. Belcher, X. H. Wu, R. J. Christensen, P. K. Hansma, G. D. Stucky, D. E. Morse, *Nature* **1996**, *381*, 56–58.
[67] G. Falini, S. Albeck, S. Weiner, L. Addadi, *Science* **1996**, *271*, 67–69.
[68] D. Gebauer, P. N. Gunawidjaja, J. Y. P. Ko, Z. Bacsik, B. Aziz, L. J. Liu, Y. F. Hu, L. Bergström, C. W. Tai, T. K. Sham, et al., *Angew. Chem.* **2010**, *122*, 9073–9075; *Angew. Chem. Int. Ed.* **2010**, *49*, 8889–8891.
[69] R. S. K. Lam, J. M. Charnock, A. Lennie, F. C. Meldrum, *CrystEngComm* **2007**, *9*, 1226–1236.
[70] J. Bolze, B. Peng, N. Dingenouts, P. Panine, T. Narayanan, M. Ballauff, *Langmuir* **2002**, *18*, 8364–8369.
[71] J. R. Clarkson, T. J. Price, C. J. Adams, *J. Chem. Soc. Faraday Trans.* **1992**, *88*, 243–249.
[72] A. L. Goodwin, F. M. Michel, B. L. Phillips, D. A. Keen, M. T. Dove, R. J. Reeder, *Chem. Mater.* **2010**, *22*, 3197–3205.
[73] Y. S. Han, G. Hadiko, M. Fuji, M. Takahashi, *J. Eur. Ceram. Soc.* **2006**, *26*, 843–847.
[74] F. M. Michel, J. MacDonald, J. Feng, B. L. Phillips, L. Ehm, C. Tarabrella, J. B. Parise, R. J. Reeder, *Chem. Mater.* **2008**, *20*, 4720–4728.
[75] H. Nebel, M. Neumann, C. Mayer, M. Epple, *Inorg. Chem.* **2008**, *47*, 7874–7879.
[76] C. Günther, A. Becker, G. Wolf, M. Epple, *Z. Anorg. Allg. Chem.* **2005**, *631*, 2830–2835.
[77] D. Gebauer, A. Völkel, H. Cölfen, *Science* **2008**, *322*, 1819–1822.
[78] R. Demichelis, P. Raiteri, J. D. Gale, D. Quigley, D. Gebauer, *Nat. Commun.* **2011**, *2*, 590.

[79] E. M. Pouget, P. H. H. Bomans, J. A. C. M. Goos, P. M. Frederik, G. de With, N. A. J. M. Sommerdijk, *Science* **2009**, *323*, 1455 – 1458.
[80] A. Dey, P. H. H. Bomans, F. A. Müller, J. Will, P. M. Frederik, G. de With, N. A. J. M. Sommerdijk, *Nat. Mater.* **2010**, *9*, 1010 – 1014.
[81] M. Kellermeier, D. Gebauer, E. Melero-García, M. Drechsler, Y. Talmon, L. Kienle, H. Cölfen, J. M. García-Ruiz, W. Kunz, *Adv. Funct. Mater.* **2012**, *22*, 4301 – 4311.
[82] D. Gebauer, H. Cölfen, *Nano Today* **2011**, *6*, 564 – 584.
[83] D. Gebauer, H. Cölfen, A. Verch, M. Antonietti, *Adv. Mater.* **2009**, *21*, 435 – 439.
[84] J. W. Singer, A. Ö. Yazaydin, R. J. Kirkpatrick, G. M. Bowers, *Chem. Mater.* **2012**, *24*, 1828 – 1836.
[85] D. Quigley, P. M. Rodger, *J. Chem. Phys.* **2008**, *128*, 221101.
[86] P. Raiteri, J. D. Gale, *J. Am. Chem. Soc.* **2010**, *132*, 17623 – 17634.
[87] T. Loerting, K. Winkel, M. Seidl, M. Bauer, C. Mitterdorfer, P. H. Handle, C. G. Salzmann, E. Mayer, J. L. Finney, D. T. Bowron, *Phys. Chem. Chem. Phys.* **2011**, *13*, 8783 – 8794.
[88] K. Winkel, W. Hage, T. Loerting, S. L. Price, E. Mayer, *J. Am. Chem. Soc.* **2007**, *129*, 13863 – 13871.
[89] A. Becker, U. Bismayer, M. Epple, H. Fabritius, B. Hasse, J. Shi, A. Ziegler, *Dalton Trans.* **2003**, 551 – 555.
[90] Y. Levi-Kalisman, S. Raz, S. Weiner, L. Addadi, I. Sagi, *J. Chem. Soc. Dalton Trans.* **2000**, 3977 – 3982.
[91] M. Epple, M. Panthöfer, R. Walther, H. J. Deiseroth, *Z. Kristallogr.* **2000**, *215*, 445 – 453.
[92] L. B. Gower, D. J. Odom, *J. Cryst. Growth* **2000**, *210*, 719 – 734.
[93] S. E. Wolf, J. Leiterer, V. Pipich, R. Barrea, F. Emmerling, W. Tremel, *J. Am. Chem. Soc.* **2011**, *133*, 12642 – 12649.
[94] S. E. Wolf, L. Müller, R. Barrea, C. J. Kampf, J. Leiterer, U. Panne, T. Hoffmann, F. Emmerling, W. Tremel, *Nanoscale* **2011**, *3*, 1158 – 1165.
[95] M. A. Bewernitz, D. Gebauer, H. Cölfen, L. B. Gower, *Faraday Discuss.* **2012**, DOI: 10.1039/C2FD20080E.
[96] D. Wang, A. F. Wallace, J. J. De Yoreo, P. M. Dove, *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 21511 – 21516.
[97] D. Wang, L. M. Hamm, A. J. Giuffre, T. Echigo, J. D. Rimstidt, J. J. DeYoreo, J. Grotzinger, P. M. Dove, *Faraday Discuss.* **2012**, DOI: 10.1039/c2fd20077e.
[98] S. E. Kaczmarek, D. F. Sibley, *J. Sediment. Res.* **2007**, *77*, 424 – 432.
[99] A.-M. Flank, P. Lagarde, J.-P. Itié, A. Polian, G. Hearne, *Phys. Rev. B* **2008**, *77*, 224112.
[100] D. Machon, M. Daniel, V. Pischedda, S. Daniele, P. Bouvier, S. LeFloch, *Phys. Rev. B* **2010**, *82*, 140102.
[101] Q. J. Li, B. B. Liu, L. Wang, D. M. Li, R. Liu, B. Zou, T. Cui, G. T. Zou, Y. Meng, H.-K. Mao, et al., *J. Phys. Chem. Lett.* **2010**, *1*, 309 – 314.
[102] R. Demichelis, P. Raiteri, J. D. Gale, R. Dovesi, *CrystEngComm* **2012**, *14*, 44 – 47.
[103] J. H. E. Cartwright, A. L. Mackay, *Philos. Trans. R. Soc. London Ser. A* **2012**, *370*, 2807 – 2822.