Hydrogen-Bonded Molecular Ribbons as Templates for the Synthesis of Modified Mineral Phases**

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The remarkable structural diversity and mechanical strength of mineral phases associated with living organisms ("biominerals") has prompted substantial effort towards synthetically reproducing the conditions under which such materials are created.[1] Since it is known that this involves the participation of biomacromolecules as templates, a number of ingenious means of presenting an organized array of polar functions to a crystallization medium have been developed, such as nucleation at the surfaces of proteins and glycoproteins,[2] bacterial filaments,[3] micelles,[4] vesicles,[5] polymers,[6] organic crystal faces,[7] inorganic particles[8] and monolayers at the air–water interface,[9] on gold,[10] or on silicon substrates.[11] Crystal growth has also been examined in structured three-dimensional media such as microemulsions,[12] foam lamellae,[13] and reverse micelles.[14] All of these approaches have resulted in the production of ionic solids in which some degree of control over size, morphology, texture, crystallographic orientation, and/or polymorph selection has been exercised. Since the principle in operation is one of epitaxial correspondence between the mineral lattice and the template, the better the design of the template in terms of spatial definition, the greater the likelihood of developing a working model for the targeted synthesis of a specific crystalline phase.

The prospect therefore of combining two well-established organizational principles, that is surfactant monolayer assembly with that of the hydrogen bonding "molecular ribbon",[15] and their application to biomimetic crystal synthesis, was an attractive one. The overall concept is well supported in literature precedent, both in the preparation of hydrogen-bonding aggregates at the air–water interface,[16] and in the ability of Langmuir monolayers to influence crystal growth.[9] The experiment consists of the following: A monolayer is cast at the air–water interface from the amphiphile *N*,*N*′-dioctadecyltriazine-2,4,6-triamine (**1**)[17] whose polar headgroup doubles as a constituent of the molecular ribbon. Its counterpart, cyanuric acid derivative **2**,[18] is dissolved in the aqueous subphase and binds to the monolayer by hydrogen-bonding recognition. The resulting assembly has the organizational characteristics shown in Figure 1. Compound **2** possesses a tailgroup R terminated by an ionophoric functionality (carboxy, amino, or phosphate group), and is represented by the unshaded pips in the view normal to the surface (Figure 1, top). The shaded pips are the surfactant component **1**. The spatial interval between like components along the hydrogen-bonded ribbon axis is fixed at 9.5 Å.[15] In the second dimension however, individual ribbons associate at the van der Waals separation of about 4.5 Å, governed by the closest approach of the hydrocarbon chains to each other.[19] The intercomponent distance here is more flexible due to the absence of strong interactions in this dimension, and can vary from the minimum of 4.5 Å (at superimposition of the headgroups) to a maximum of 6.5 Å (where like components are completely "out-of-phase" with each other).

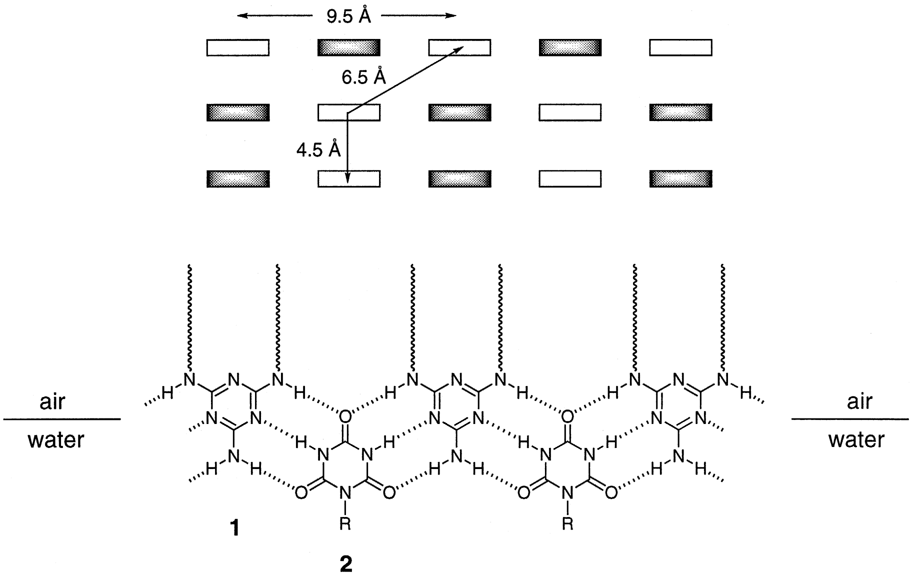

Figure 1. Representations of the melamine–cyanuric acid monolayer normal (top) and parallel (bottom) to the air–water interface. R = $CH_2CH_2CO_2H$, $CH_2CH_2CH_2OPO_3H_2$, $CH_2CH_2CH_2NH_2$.

An in-depth analysis of the structure of hydrogen-bonding molecular ribbons at the air–water interface was recently published by Kunitake et al.,[20] in which it was demonstrated that components related to **1** and **2** self-associate in a 1:1 ratio to form stable, well-defined monolayer assemblies. For this reason, discussion of the physical properties of our monolayer and the synthesis of the template components is deferred until the work is presented in full.[21]

The ensembles of polar functionalities produced by the association of **1** and **2** have been evaluated for their effect on the nucleation of calcium carbonate, the preliminary results of

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Table 1. Data for nucleation experiments.[a]

Tailgroup (R) in **2**	Molar ratio **1**:**2**[b] ([**2**])	$CaCO_3$ polymorph[c]	Orientation[d]	Mean size [μm ± s.d]	Nucleation density [crystals mm^{-2}]	Induction time
control	–	calcite	dendritic, intergrown {10.4} rhombs	30 (10)	> 300	> 4 h
$(CH_2)_3OH$	up to 1:10000 (20.6 mM)	calcite	discrete, nonoriented {10.4} rhombs	68 (24)	20	3 h
$(CH_2)_2CO_2H$	1:750 (1.55 mM)	calcite	<01.2>	79 (23)	12	< 1 h
$(CH_2)_3OPO_3H_2$	1:500 (1.03 mM)	calcite	[001]	59 (15)	17	< 1 h
$(CH_2)_3NH_3^+Cl^-$	1:1000 (2.06 mM)	vaterite	<11.0> and [001]	204 (45)	2	< 1 h

[a] Standard calcium hydrogen carbonate solution prepared as described by Kitano (Y. Kitano, *Bull. Chem. Soc. Jpn.* **1962**, *35*, 1980); $T = 20\,^{\circ}C$; pH 6.5. [b] Minimum ratio necessary to provide a sufficient concentration of the soluble component in bulk solution to promote nucleation within the stated induction time. Higher ratios had little advantageous effect. Crystallization in the presence of the stated concentrations of **2** without **1** resemble the control study. [c] By powder X-ray diffraction. [d] Crystallographic orientation at the monolayer/subphase interface.

which are presented in Table 1. Thus, when an assembly incorporating the soluble component **2** with $R = CH_2CH_2CO_2H$ is organized at the surface of a supersaturated aqueous calcium hydrogen carbonate solution, oriented nucleation of habit-modified calcite is observed. The crystals are distinguished by the occurrence of a single triangular facet truncating the vertex of three intersecting {10.4} faces (Figure 2b). This unique face was resolved to be of the negative rhomohedral {01.2} form and its development here indicates that nucleation occurred through this lattice plane.[22] This contrasts with previous work in which monolayers of long-chain carboxylate surfactants induced the orientation of calcite on the <10.0> axis.[23] The climax morphology of the mature crystals arises from the development of the stable {10.4} faces as the <01.2> oriented crystallites grow along the [001], <11.0>, and <10.0> axes.

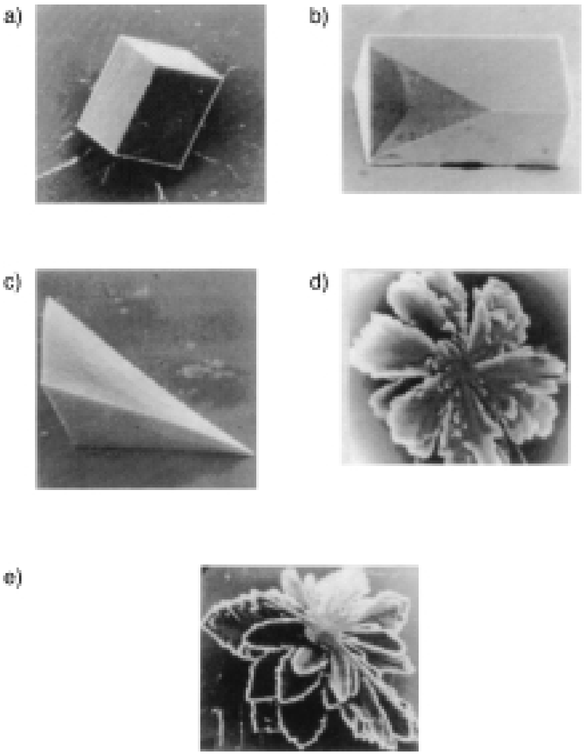

Figure 2. a) Calcite control crystal, 1 cm = 5 μm; b) {01.2}-oriented calcite grown under monolayer **1**·**2** ($R = CH_2CH_2CO_2H$), 1 cm = 5 μm; c) [001]-oriented calcite grown under monolayer **1**·**2** ($R = CH_2CH_2CH_2OPO_3H_2$), 1 cm = 15 μm; d) [001]-oriented vaterite and e) <11.0> oriented vaterite, both grown under monolayer **1**·**2** ($R = CH_2CH_2CH_2NH_3^+Cl^-$), 1 cm = 25 μm.

As predicted, the crystallographic orientation and morphology could be altered by employing a solution component **2** with a different tailgroup. In the case where $R = CH_2CH_2CH_2OPO_3H_2$, calcite nucleation in [001] orientation was favored. Pyramidal evolution from a triangular (001) basal face was observed, terminating at an apex formed by the intersection of three {10.4} faces (Figure 2c).

In both of the above examples, the achievement of oriented nucleation can be rationalized by invoking a stereochemical correspondence between the monolayer template and the relevant crystal face. In the case of <01.2>-oriented calcite, the carboxylate functions of the template coincide with lattice positions occupied by carbonate groups. Unlike the {10.4} face, which is neutral, calcite <01.2> consists of segregated layers of calcium and carbonate ions. The stabilization of this high-energy, homoatomic face is proposed to be the result of charge neutralization coupled with ligand binding of the calcium by the carboxylate group of **2** ($R = CH_2CH_2CO_2H$), with the 5.0 × 9.8 Å 75/105° rhomboidal carbonate array in calcite (Figure 3a) commensurate with a 4.7 × 9.5 Å 75/105° template assembly. The question arises as to why the {01.2} face is selected in preference to the other homoatomic facets, the (001), in which an appropriate lattice match also exists (vide infra). Here, however, the full effect of stereochemical homology between the mineral lattice and the template is realized: The carbonate anions are tilted by about 64° out of the crystal plane in {01.2}, whereas they lie parallel to the (001) face. This means that the carboxylate tailgroups of **2**, with their twofold axes approximately perpendicular to the aqueous surface due to the conformational requirements of the chain, are a much closer steric match to the {01.2} calcite face.[24]

In the case of the (001)-oriented calcite, four in-plane carbonate anions occupy the corners of a 60/120° rhomboid of dimensions 5.0 × 10.0 Å (Figure 3b) in the unique (001) face. A mimetic register of phosphate groups with their C_3 axes also aligned to [001] is presented by **2** ($R = CH_2CH_2CH_2OPO_3H_2$) which displays closely matching dimensions (5.2 × 9.5 Å). This favors nucleation on (001) and rapid growth along the

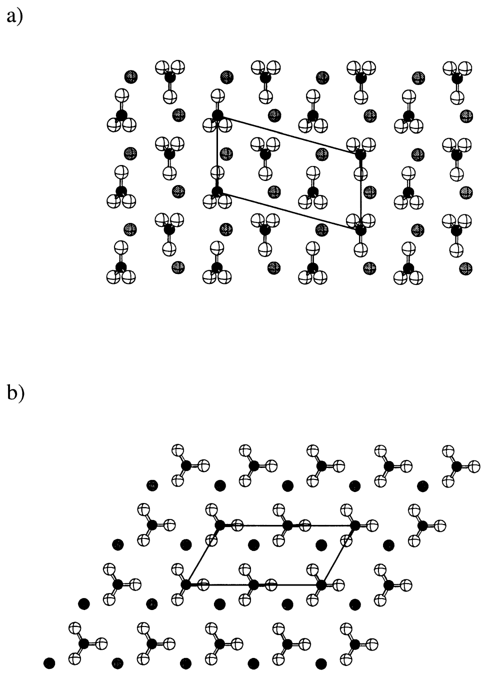

Figure 3. a) View of calcite normal to the (012) face; b) view of calcite normal to the (001) face.

[001] and < 11.0 > directions which determines the evolution of the unique pyramidal morphology.[25]

The use of a soluble molecular ribbon component incorporating an amine functionality ($R = CH_2CH_2CH_2NH_2$) resulted in the observation of the metastable $CaCO_3$ polymorph, vaterite. Morphological analysis revealed two distinct crystal populations; one group oriented on the [001] axis (Figure 2 d) and the other aligned with the < 11.0 > axis perpendicular to the template (Figure 2 e). The proportion of < 11.0 > -oriented crystals was significantly greater than the [001]-oriented form (< 11.0 > :[001] = 18:1). In this case, it is more appropriate to reserve comment on the reasons for the selection of this polymorph, since no definitive crystal structure of vaterite exists.[26] However, vaterite crystals displaying these distinct morphologies and specific orientations have been reported in earlier related work with simple amine surfactant monolayers (e.g. octadecylamine).[23]

On the basis of these results it can be assumed that the failure of the soluble component terminated by a hydroxy group (**2**, $R = CH_2CH_2CH_2OH$) to influence the growth of calcium carbonate relates in the first instance to its neutrality under the conditions of the assay, and second to the absence of any meaningful congruity with the ionic lattice.

Thus we have been able to demonstrate a transfer of information from a self-organized surface assembly to the nascent inorganic phase which develops from the crystallization medium. Hydrogen bonding and the hydrophobic effect work together to produce a hybrid assembly in which noncovalent aggregates pack into a monolayer at the air–water interface, directing an array of potential nucleating functions into the aqueous subphase. The basic concept is firmly grounded in work by Kunitake, Ringsdorf, and coworkers,[16] and the combination of order and mobility in this system is highly relevant to its application as a "biomimetic" mineral template.

Most importantly, the morphology and crystallographic orientation of the resulting inorganic solid can be modeled against a reciprocal geometric and functional register in the template, indicating that a systematic approach to the targeted production of specific crystalline phases can be developed. The advantages of the system described here over standard amphiphile monolayers are the following: First, systematic variation of the chemical identity of the ionophoric functions of the template is a simple matter of altering the tailgroup of the solution component **2**, without regard to whether such functionality at the end of a hydrocarbon chain would be capable of producing a stable monolayer. Second, the spatial distribution of ionophores in the monolayer is unique and more flexible than the hexagonal closest-packed arrangement of simple monolayers. Finally, the **1**·**2** monolayer does not require external compression to function as a template for crystal nucleation, whereas surfactant monolayers often do. This allows the practical extension of template-mediated crystallization to a wider range of media and removes the requirement for a dedicated Langmuir trough.

With these principles now established, there is clearly scope for modification of the above system. Most simply, the ionophoric functionality of component **2** can be further varied, as can the length of the hydrocarbon spacer between the functionality and the headgroup and/or the inorganic phase under investigation, giving new mineral–template conjugates whose analysis will also contribute to resolving the fundamentals of targeted crystal synthesis. Perhaps most interestingly, it has been shown that mixed cyanuric acid/melamine lipid systems related to **1** and **2** self-organize into disklike aggregates formed from bilayers of hydrogen-bonding ribbons,[27] leaving open the potential for extending this work into a third dimension.

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[21] In the present work, studies of ribbon assembly at the air–water interface and on a range of subphases reflecting the composition of the crystallization media confirm the auto-assembly of a robust monolayer with a structure commensurate with the model presented in Figure 1.

[22] The preferred orientation of the inorganic particles was confirmed by an analysis of the crystallographic ultrastructure of immature crystallites harvested 60 min after the induction of template assembly using established techniques for the collection and analysis of crystals which mitigate against any disruption of their alignment relative to the template.[23] In the present case, all crystals produced single-crystal electron diffraction patterns corresponding to the <01.2> zone of calcite, thereby confirming the morphological assignment.

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Interanionic O–H $\cdots$ O Interactions: The Charge Density Point of View**

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Interanion $^{\delta-}$O–H $\cdots$ O$^{\delta-}$ interactions in the solid state have been the subject of recent scientific discussion. On the basis of in vacuo calculations on isolated anions and on the global repulsion between a pair of them, Braga et al.[1] suggested that the H $\cdots$ O "contacts" should be regarded as pseudo hydrogen bonds, in spite of the very short O $\cdots$ O and H $\cdots$ O distances.[2–5] In their view, the conformation adopted by two anions in the solid state minimizes the repulsion[6] but does not produce a chemical bond, and the stability of the crystal structure is due only to cation–anion attractions (the overall effect was called a tugboat effect). If confirmed, this hypothesis would have far-reaching implications for the understanding of hydrogen bonds (HB) and intermolecular

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