Organic templating of inorganic materials
Bone-mimetic materials

Last time: interfacial biomineralization and biomimetic inorganic chemistry

Today: biological strategies for inorganic templating by organic materials
Biomimetic organic template materials
Bone-mimetic materials

Reading:

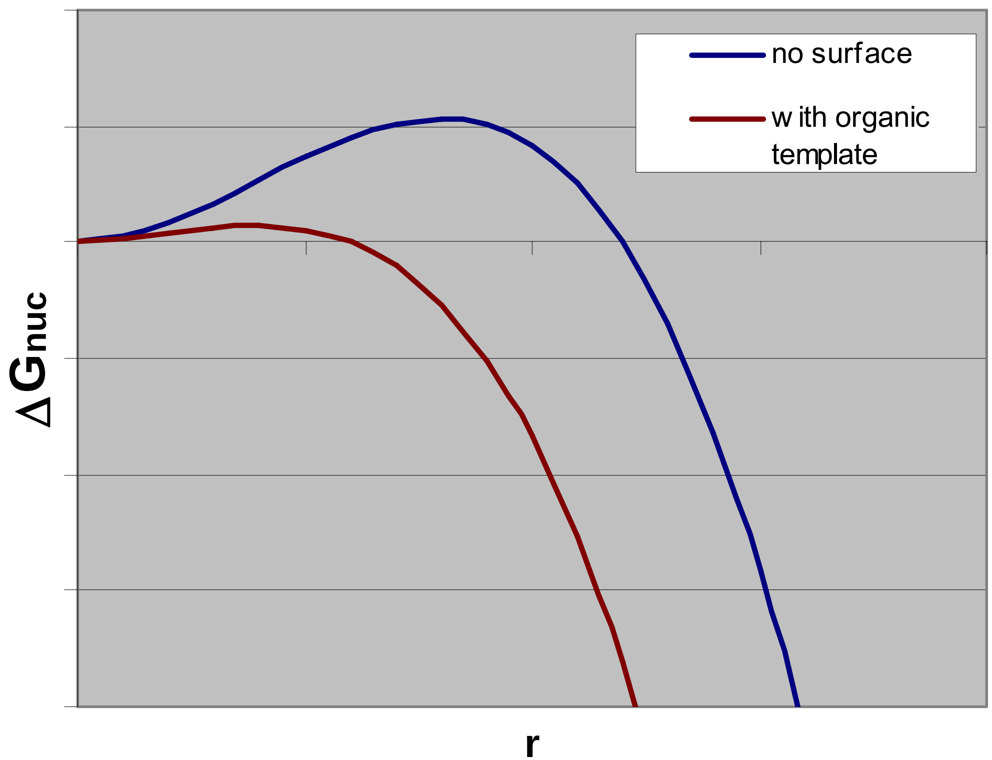
S. Mann, 'Biomineralization: Principles and Concepts of Bioinorganic Materials Chemistry,' Ch. 6, pp. 89-102 (2001)

Supplementary Reading:

Excerpt from Allen and Thomas 'The Structure of Materials'- pp. 135-138 on Miller indices to describe crystal planes

ANNOUNCEMENTS:

Last time



- High affinity between ions and organic surface groups lowers the free energy barrier to nucleation
- (shown left is effect of 50% reduction in surface energy)

Controlled nucleation and growth vs. preferential nucleation and growth

- Organic templates can preferentially nucleate inorganics without ordering or aligning the crystals

- Templated crystal growth requires both recognition of individual molecules and a larger underlying lattice to drive ordered nucleation

    - Obtaining periodicity in organic templates:

Charge distribution effects on templated nucleation

Table removed due to copyright reasons.
Please see: Table 1 in Mann, et al. 1993.

Dictating crystal polymorph via lattice matching

Calcium carbonate ($CaCO_3$) crystal structures

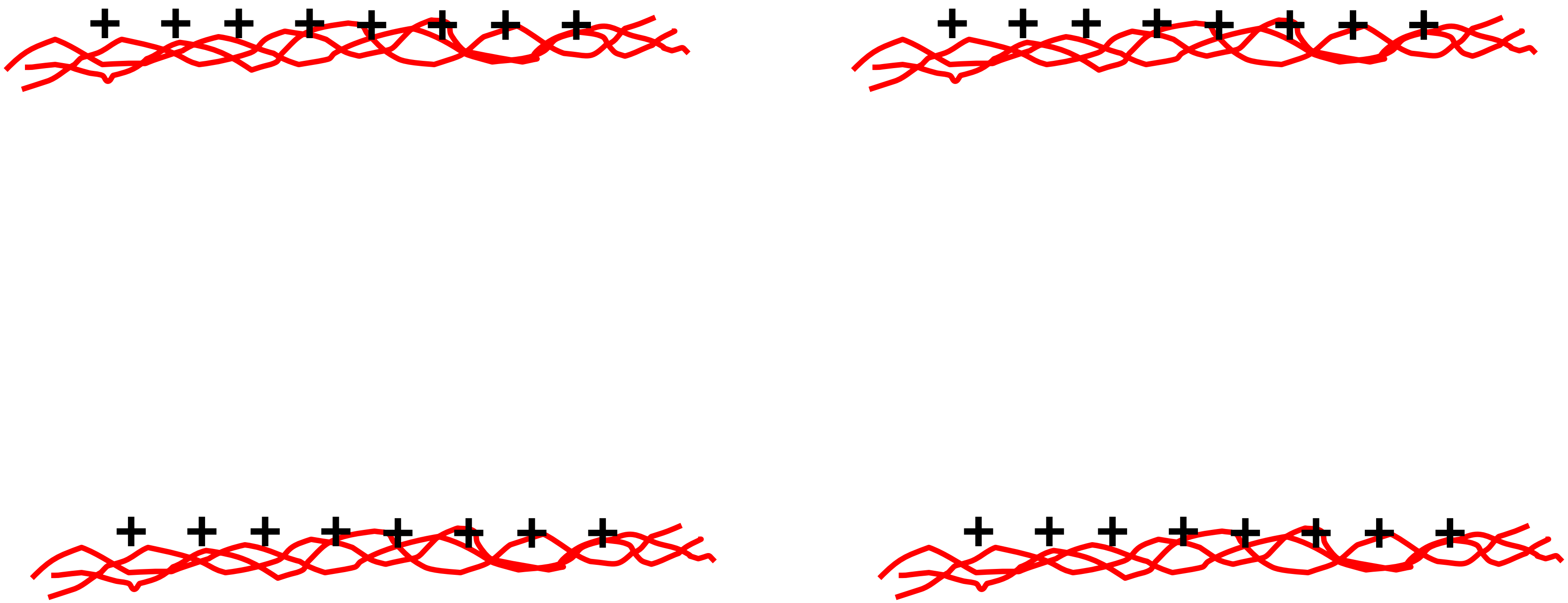
calcite

aragonite

Images removed due to copyright reasons.
Please see: http://ruby.coloarado.edu/~smyth/min/minerals.html

Charge distribution effects on templated nucleation

2 mechanisms of surface-mediated nucleation:



Example of organic templating: nacre

Plate-like aragonite ($CaCO_3$) crystals form the inner layer of seashells:

Figure removed for copyright reasons.
Please see: Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry.* New York, NY: Oxford University Press, 2001.

Figure removed for copyright reasons.
Please see: Figure 6.38 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry.* New York, NY: Oxford University Press, 2001.

Figure removed for copyright reasons.
Please see: Figure 6.39 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry*. New York, NY: Oxford University Press, 2001.

Building artificial nacre

Images removed for copyright reasons.
Please see: Tang, Z.Y., N. A. Kotov, S. Magonov, and B. Ozturk. "Nanostructured Artificial Nacre." *Nature Materials* 2 (2003): 413-U8.

Montmorillonite structures

Images removed for copyright reasons.

Please see: http://www.wwnorton.com/college/chemistry/chemconnections/Rain/pages/minerals.html

Building artificial nacre

Images removed for copyright reasons.
Please see: Tang, Z. Y., N. A. Kotov, S. Magonov, and B. Ozturk. “Nanostructured Artificial Nacre.” *Nature Materials* 2 (2003): 413-U8.

Mechanical properties of the biomimetic composite

Graphs removed for copyright reasons.
Please see: Tang, Z. Y., N. A. Kotov, S. Magonov, and B. Ozturk. "Nanostructured Artificial Nacre." *Nature Materials* 2 (2003): 413-U8.

Table removed for copyright reasons.
Please see: Table 1 in Tang, Z.Y., N. A. Kotov, S. Magonov, and B. Ozturk. "Nanostructured Artificial Nacre." *Nature Materials* 2 (2003): 413-U8.

biomimetic nucleation of crystals with synthetic patterned organic surfaces

Image removed due to copyright reasons.

Please see: Aizenberg, J. "Patterned Crystallization of Calcite in Vivro and in Vitro." *Journal of Crystal Growth* 211 (2000): 143-148.

Figure removed due to copyright reasons.

Please see: Figure 2 in Aizenberg, J. "Patterned Crystallization of Calcite in Vivro and in Vitro." *Journal of Crystal Growth* 211 (2000): 143-148.

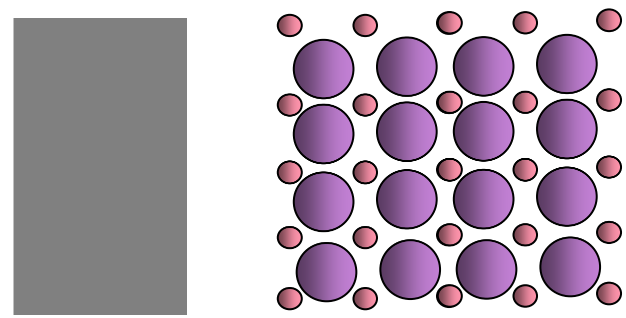
Figure removed due to copyright reasons.
Please see: Figure 4 in Aizenberg, J. "Patterned Crystallization of Calcite in Vivro and in Vitro."
Journal of Crystal Growth 211 (2000): 143-148.

Strategies to augment bone-biomaterial integration

Introduction of HA-nucleating charged groups on degradable polymer surfaces:

HA growth on hydrolyzed PLGA films
after 7 days:

Image removed due to copyright reasons.
Please see: Murphy, W. L., and D. J. Mooney. "Bioinspired Growth of Crystalline Carbonate Apatite on Biodegradable Ploymer Substrata." *Journal of the Americal Chemical Society* 124 (2001): 1910-1917.



Structure of bone

Functions of organic components in bone:

1. Template formation of HA crystals at physiological concentrations of ions
2. Provide strength by forming an organic-inorganic composite

Bone as an example of organic templated-inorganic growth: Mineralization in human bone

Crystallization of HA:

- Thermodynamically most stable form of Ca phosphate
- Does not spontaneously crystallize in physiologic Ca/HPO4 concentrations
    - Forms metastable solutions well above the solubility product levels

Figure removed due to copyright reasons.
Please see: Figure 6 in Busch, S., U. Schwarz, and R. Kniep. "Morphogenesis and Structure of Human Teeth in Relation to Biomimetically Grown Fluorapatite-Gelatine Composites." *Chemistry of Materials* 13 (2001): 3260-3271.

2-component model of bone organic matrix

Figure removed for copyright reasons.
Please see: Figure 6.4 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry*. New York, NY: Oxford University Press, 2001.

2-component model of bone organic matrix

Human bone framework macromolecules:

Staggered arrangement of tropocollagen (triple helices) maximizes interfilament cross-links:

Figure removed for copyright reasons.

Please see: Figure 6.11 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry*. New York, NY: Oxford University Press, 2001.

Mineralization in human bone

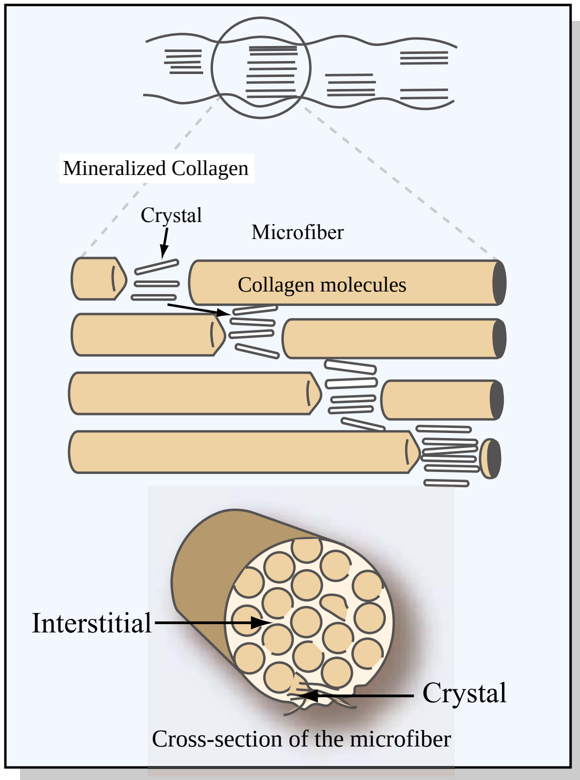


Figure by MIT OCW.

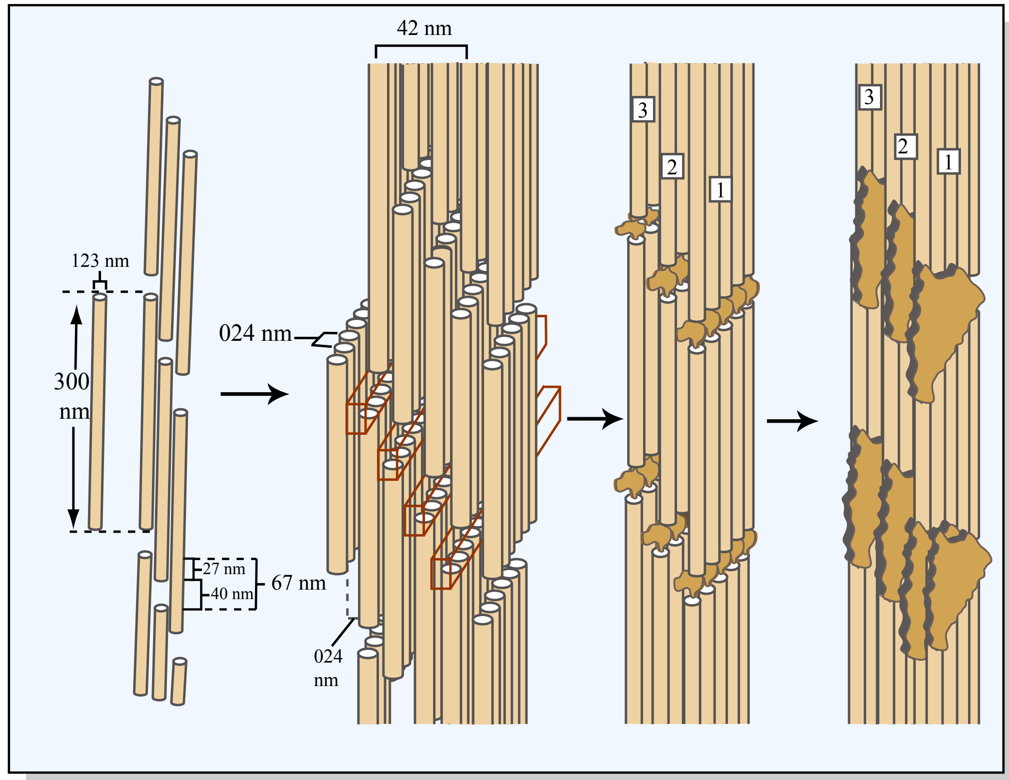


Figure by MIT OCW.

Second role of the organic component in bone: strengthening the inorganic matrix

	HA + protein	HA alone
Relative Tensile strength:		
Relative Modulus:		

Proteins which regulate growth of hydroxyapatite *in vivo*

Image removed due to copyright restrictions.
Please see in Flade, et al. *Chem Mater* 13 (2001): 3596.

Structural hierarchy in bone

‘plywood’ arrangement of mineralized collagen sheets

Figure removed for copyright reasons.
Please see: Figure 8.1 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry*. New York, NY: Oxford University Press, 2001.

Image removed due to copyright restrictions.
Please see Figure 2 in S. Weiner, W. Traub, and H. D. Wagner. *J Struct Biol* 126 (1999): 241.

Assembly of the superstructure

Figure removed for copyright reasons.
Please see: Figure 8.2 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry*. New York, NY: Oxford University Press, 2001.

Figure removed for copyright reasons.
Please see: Figure 8.3 in Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry*. New York, NY: Oxford University Press, 2001.

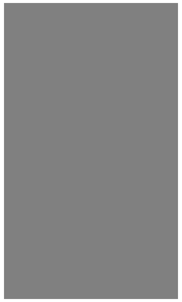
Mimicking bone structure/organic-templated assembly

Issues in bone tissue engineering relevant to biomimetic materials synthesis

Solid metal implants used for bone replacement (e.g., Ti hip implants):

- Do no match mechanical props of natural bone (much stiffer than bone)
  - Drives stress shielding and subsequent bone resorption
- Do not integrate with surrounding tissue
  - Failure of implant-tissue adhesion can lead to loosening of implants

Image removed due to copyright reasons.
Please see: Trident® System at
http://www.stryker.com/jointreplacements/sites/trident/patient/pat_tech.php



Strategies to augment bone-biomaterial integration

Introduction of HA-nucleating charged groups on degradable polymer surfaces:

Graph removed due to copyright reasons.
Please see: Murphy, W. L. and D. J. Mooney. "Bioinspired growth of crystalline carbonate apatite on biodegradable ploymer substrata." *Journal of the Americal Chemical Society* 124 (2002): 1910-1917.

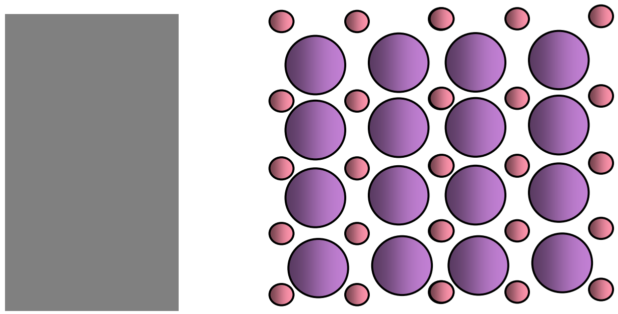
Image removed due to copyright reasons.
Please see: Murphy, W. L., and D. J. Mooney. “Bioinspired Growth of Crystalline Carbonate Apatite on Biodegradable Ploymer Substrata.” *Journal of the Americal Chemical Society* 124 (2002): 1910-1917.

Strategies to augment bone-biomaterial integration

Introduction of HA-nucleating charged groups on degradable polymer surfaces:

HA growth on hydrolyzed PLGA films
after 7 days:

Image removed due to copyright reasons.
Please see: Murphy, W. L., and D. J. Mooney. "Bioinspired Growth of Crystalline Carbonate Apatite on Biodegradable Ploymer Substrata." *Journal of the Americal Chemical Society* 124 (2001): 1910-1917.



Strategies to augment bone-biomaterial integration

Introduction of HA-nucleating charged groups on hydrogels:

Images removed due to copyright reasons.
Please see: Song, J., E. Saiz, and C. R. Bertozzi. "A New Approach to Mineralization of Biocompatible Hydrogel Scaffolds: An Efficient Process Toward 3-Dimensional-Bonelike Composites." *Journal of the American Chemical Society* 125 (2003): 1236-1243.

Images removed due to copyright reasons.
Please see: Song, J., E. Saiz, and C. R. Bertozzi. "A New Approach to Mineralization of Biocompatible Hydrogel Scaffolds: An Efficient Process Toward 3-Dimensional-Bonelike Composites." *Journal of the American Chemical Society* 125 (2003): 1236-1243.

Strategies to augment bone-biomaterial integration

Introduction of HA-nucleating charged groups on hydrogels:

Amorphous calcium phosphate nucleated by hydrogel surface

Images removed due to copyright reasons.
Please see: Song, J., E. Saiz, and C. R. Bertozzi. "A New Approach to Mineralization of Biocompatible Hydrogel Scaffolds:
An Efficient Process Toward 3-Dimensional-Bonelike Composites." *Journal of the American Chemical Society* 125 (2003): 1236-1243.

Graph removed due to copyright reasons.
Please see: Song, J., E. Saiz, and C. R. Bertozzi. "A New Approach
to Mineralization of Biocompatible Hydrogel Scaffolds: An Efficient Process Toward 3-Dimensional-Bonelike Composites."
Journal of the American Chemical Society 125 (2003): 1236-1243.

Modifying the growing structure of HA crystals

Images removed due to copyright reasons.
Please see: Liu, Y., E. B. Hunziker, N. Randall, K. de Groot, and P. Layrolle. "Proteins Incorporated Into Tbiomimetically Prepared Calcium Phosphate Coatings Modulate their Mechanical Strength and Dissolution Rate." *Biomaterials* 24 (2003): 65-70.

Self-assembling bone-mimetic materials

Please see: Figures 1A, 1B, 1C in Hartgerink J. D., E. Beniash, and S. I. Stupp. "Peptide-Amphiphile Nanofibers: A Versatile Scaffold for the Preparation of Self-Assembling Materials." Proceedings of the National Academies of Science U.S.A. 99 (2002): 5133-8.

Mineralization of synthetic template fibers

Figures removed due to copyright reasons.
Please see: Figures 4 A, B, C, D in Hartgerink, J. D., E. Beniash, and S. I. Stupp. "Peptide-Amphiphile Nanofibers: A Versatile Scaffold for the Preparation of Self-Assembling Materials." Proceedings of the National Academies of Science U.S.A. 99 (2002): 5133-8.

Further Reading

1. Nanci, A. Content and distribution of noncollagenous matrix proteins in bone and cementum: Relationship to speed of formation and collagen packing density. *Journal of Structural Biology* **126**, 256-269 (1999).
2. Weiner, S., Traub, W. & Wagner, H. D. Lamellar bone: structure-function relations. *J Struct Biol* **126**, 241-55 (1999).
3. Busch, S., Schwarz, U. & Kniep, R. Morphogenesis and structure of human teeth in relation to biomimetically grown fluorapatite-gelatine composites. *Chemistry of Materials* **13**, 3260-3271 (2001).
4. Fincham, A. G., Moradian-Oldak, J. & Simmer, J. P. The structural biology of the developing dental enamel matrix. *Journal of Structural Biology* **126**, 270-299 (1999).
5. Moradian-Oldak, J., Paine, M. L., Lei, Y. P., Fincham, A. G. & Snead, M. L. Self-assembly properties of recombinant engineered amelogenin proteins analyzed by dynamic light scattering and atomic force microscopy. *Journal of Structural Biology* **131**, 27-37 (2000).
6. Liu, Y., Hunziker, E. B., Randall, N. X., de Groot, K. & Layrolle, P. Proteins incorporated into biomimetically prepared calcium phosphate coatings modulate their mechanical strength and dissolution rate. *Biomaterials* **24**, 65-70 (2003).
7. Habibovic, P., Barrere, F., van Blitterswijk, C. A., de Groot, K. & Layrolle, P. Biomimetic hydroxyapatite coating on metal implants. *Journal of the American Ceramic Society* **85**, 517-522 (2002).
8. Flade, K., Lau, C., Mertig, M. & Pompe, W. Osteocalcin-controlled dissolution-reprecipitation of calcium phosphate under biomimetic conditions. *Chemistry of Materials* **13**, 3596-3602 (2001).
9. Murphy, W. L. & Mooney, D. J. Bioinspired growth of crystalline carbonate apatite on biodegradable polymer substrata. *Journal of the American Chemical Society* **124**, 1910-1917 (2002).
10. Song, J., Saiz, E. & Bertozzi, C. R. A new approach to mineralization of biocompatible hydrogel scaffolds: An efficient process toward 3-dimensional bonelike composites. *Journal of the American Chemical Society* **125**, 1236-1243 (2003).
11. Hartgerink, J. D., Beniash, E. & Stupp, S. I. Peptide-amphiphile nanofibers: a versatile scaffold for the preparation of self-assembling materials. *Proc Natl Acad Sci U S A* **99**, 5133-8 (2002).
12. Hartgerink, J. D., Beniash, E. & Stupp, S. I. Self-assembly and mineralization of peptide-amphiphile nanofibers. *Science* **294**, 1684-8 (2001).

Further Reading

1. Mann, S. *Biomineralization: Principles and Concepts in Bioinorganic Materials Chemistry* (Oxford Univ. Press, New York, 2001).
2. Mann, S. Molecular Tectonics in Biomineralization and Biomimetic Materials Chemistry. *Nature* **365**, 499-505 (1993).
3. Tang, Z. Y., Kotov, N. A., Magonov, S. & Ozturk, B. Nanostructured artificial nacre. *Nature Materials* **2**, 413-U8 (2003).
4. Brott, L. L. et al. Ultrafast holographic nanopatterning of biocatalytically formed silica. *Nature* **413**, 291-3 (2001).
5. Aizenberg, J., Black, A. J. & Whitesides, G. M. Control of crystal nucleation by patterned self-assembled monolayers. *Nature* **398**, 495-498 (1999).
6. Aizenberg, J. Patterned crystallization of calcite in vivo and in vitro. *Journal of Crystal Growth* **211**, 143-148 (2000).
7. Whaley, S. R., English, D. S., Hu, E. L., Barbara, P. F. & Belcher, A. M. Selection of peptides with semiconductor binding specificity for directed nanocrystal assembly. *Nature* **405**, 665-8 (2000).
8. Kriven, W. M., Kwak, S. Y., Wallig, M. A. & Choy, J. H. Bio-resorbable nanoceramics for gene and drug delivery. *Mrs Bulletin* **29**, 33-37 (2004).
9. Choy, J. H., Kwak, S. Y., Park, J. S., Jeong, Y. J. & Portier, J. Intercalative nanohybrids of nucleoside monophosphates and DNA in layered metal hydroxide. *Journal of the American Chemical Society* **121**, 1399-1400 (1999).
10. Khan, A. I., Lei, L. X., Norquist, A. J. & O'Hare, D. Intercalation and controlled release of pharmaceutically active compounds from a layered double hydroxide. *Chemical Communications*, 2342-2343 (2001).