Biomineralization & Biominerals

“It’s a hard life”

Maria Isabel López Fierro

Literature Review

Chair: Marc A. Meyers
Joanna McKittrick
Jan Talbot

mage credit: Out Of The Blue Aquaculture Ltd

Outline

- Introduction & History
- Basic Biomineralization Principles
  - Saturation, Nucleation, Growth, & Organic Matrix
- Biominerals & Biomineralization Models
  - Calcium Carbonate
    - Shells: Nacre
  - Silica


Sponge Spicule

Image credit: http://www.choijinhyuk.com

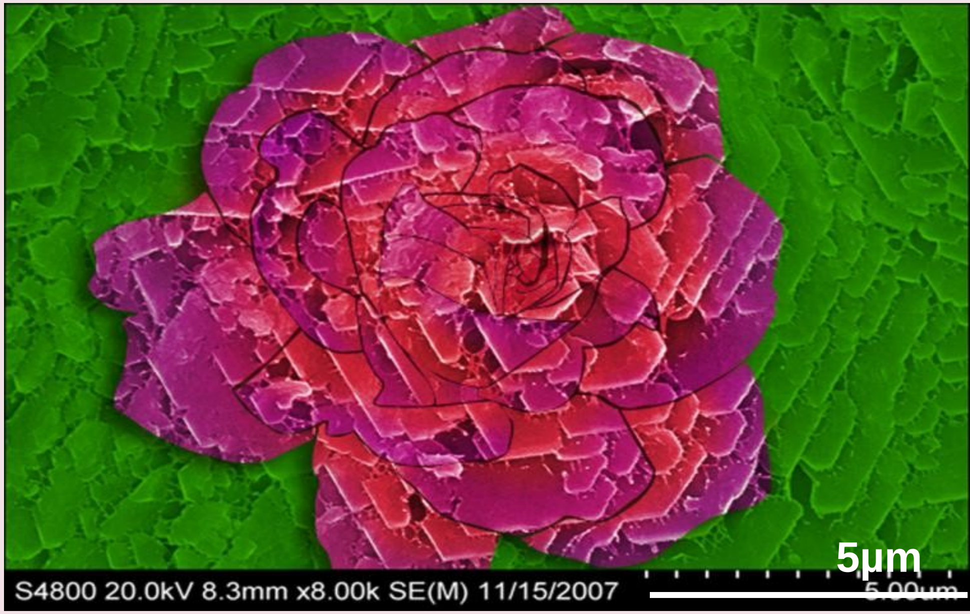

Bleached Coral

Image credit: jroy.abenaza.com

Introduction & History of Biomineralization

Introduction: The Process

- Biomineralization is the process by which living form and influence the precipitation of minerals.
- No single or ‘grand’ mechanism.
- Combination of efforts from cells, producing organic and inorganic



·Crystals from the inner shell layer of the Eastern oyster onto a metal implant.

·sheets converge forming a“rosette” structure.

·Organic matrix appears like “glue.”

Image credit: http://www.scienceasart.org

Skinner and Jahren (2003)

Introduction: Why mineralize?

Evolution of Biomineralization has provided organisms with a strong building material.

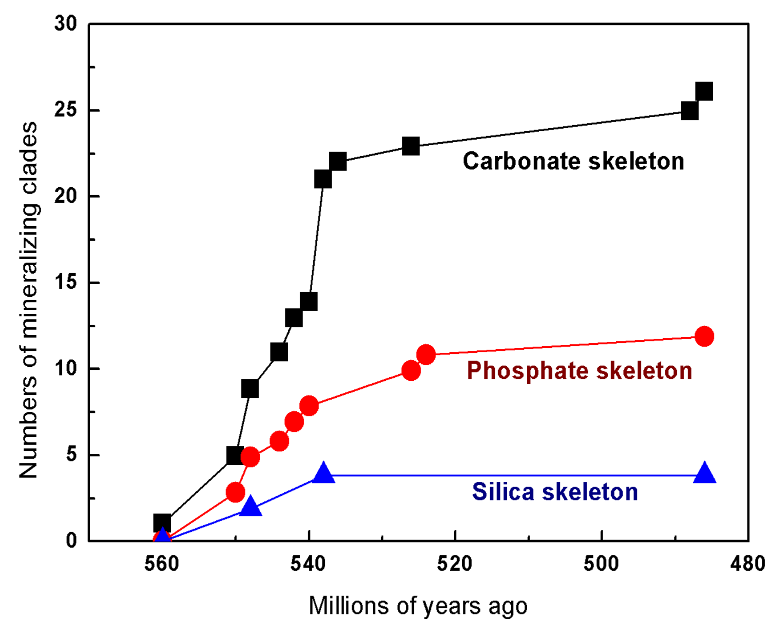
- **Minerals are stiff and brittle (& cheap energy wise)**
- **Organic materials are soft and pliable**

<u>Functions include</u>:

- Strength & Integrity
- Protection.
- Mobility
- Storage - Biominerals are ion reservoir for cellular functions.
- Cutting and grinding
- Buoyancy
- Optical, magnetic and gravity sensing

History of biominerals

- First biomineralization evidence from microbial stromatolites - 3500M years ago
  - Not controlled deposition of inorganic solids
- 560M years ago - organisms from different phyla evolved the ability to form different minerals.
- To date there are 64+

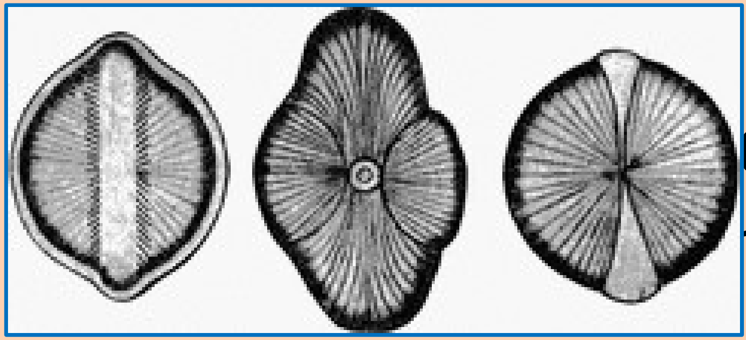


Runnegar and Bengtson (1992)

History of the field

- First books on biomineralization:
  - **D’Arcy Thompson (1917) on Growth and Form**
  - **W. J. Schmidt (1924) Die Bausteine Des Tierkörpers Im Polarisierten Lichte**
  - **A. P. Vinogradov (1953) the Elementary Chemical Composition of Marine Organisms**

- changed from “calcification”
n”



CaCO3 structures

The picture is taken from the book of D’Arcy Thompson who discusses mineral growth in the presence of proteins.

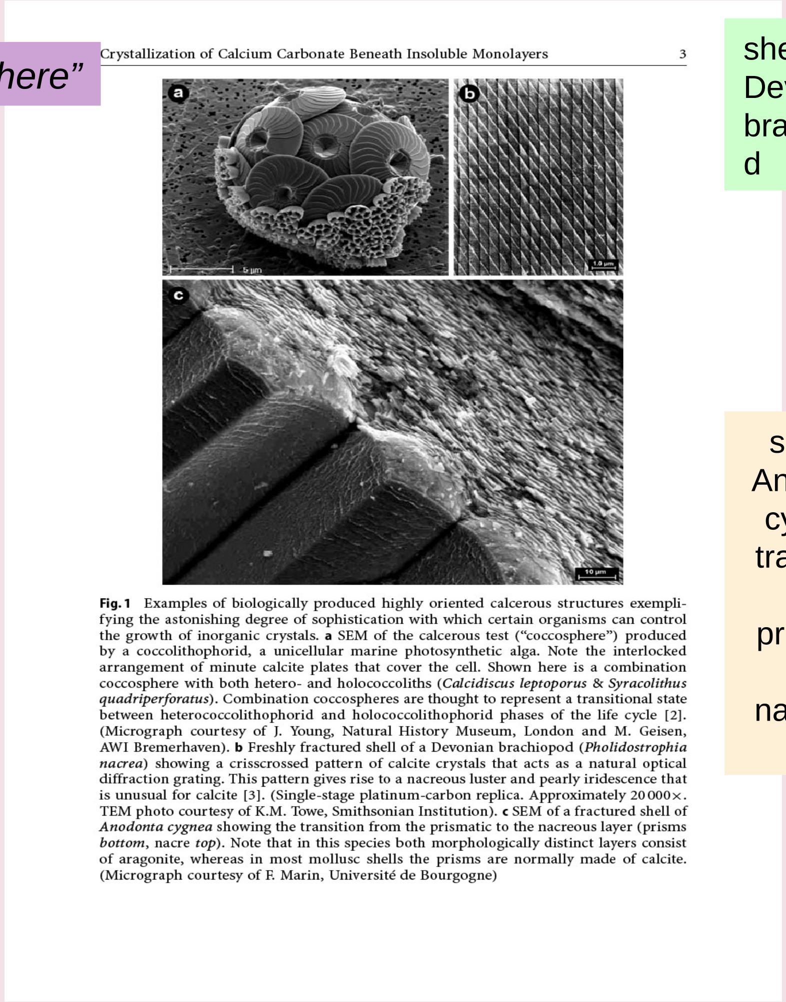
- Saturation, Nucleation, Growth, & Organic Matrix

Basic Biomineralization Principles

Basic biomineralization principles

- Composites composed of organic and inorganic compounds
- The products are:
  - Created and maintained during life.
  - Upon death they may retain some of the original characteristics.

“coccosphere”



Crystallization of Calcium Carbonate Beneath Insoluble Monolayers 3

Fig. 1 Examples of biologically produced highly oriented calcerous structures exemplifying the astonishing degree of sophistication with which certain organisms can control the growth of inorganic crystals. **a** SEM of the calcerous test (“coccosphere”) produced by a coccolithophorid, a unicellular marine photosynthetic alga. Note the interlocked arrangement of minute calcite plates that cover the cell. Shown here is a combination coccosphere with both hetero- and holococcoliths (*Calcidiscus leptoporus* & *Syracolithus quadriperforatus*). Combination coccospheres are thought to represent a transitional state between heterococcolithophorid and holococcolithophorid phases of the life cycle [2]. (Micrograph courtesy of J. Young, Natural History Museum, London and M. Geisen, AWI Bremerhaven). **b** Freshly fractured shell of a Devonian brachiopod (*Pholidostrophia nacrea*) showing a crisscrossed pattern of calcite crystals that acts as a natural optical diffraction grating. This pattern gives rise to a nacreous luster and pearly iridescence that is unusual for calcite [3]. (Single-stage platinum-carbon replica. Approximately 20 000×. TEM photo courtesy of K.M. Towe, Smithsonian Institution). **c** SEM of a fractured shell of *Anodonta cygnea* showing the transition from the prismatic to the nacreous layer (prisms *bottom*, nacre *top*). Note that in this species both morphologically distinct layers consist of aragonite, whereas in most mollusc shells the prisms are normally made of calcite. (Micrograph courtesy of F. Marin, Université de Bourgogne)

shell of a Devonian brachiopod

shell of Anodonta cygnea; transition from prismatic to nacreous layer

Calcerous structures showing the degree of control on the growth of inorganic crystals

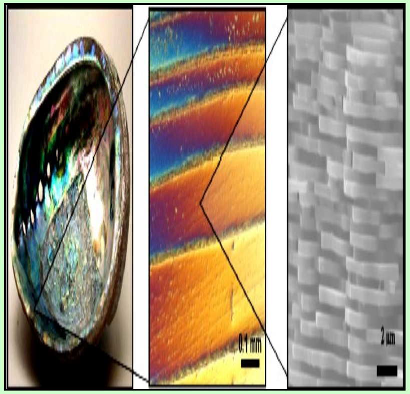
Fricke and Volkmer (2007)

Basic biomineralization principles

- Starts with an amorphous mineral phase
- The main processes are nucleation and crystal growth; they depend on:
  - Level of supersaturation of the medium
  - Molecular interactions between biomineral and organic macromolecules

Organic matrix play the most important role in biomineralization

Aragonite tiles



Aragonite crystals

Mann (1991)

Fluid Saturation

- Crystals only form from solutions with relevant ions if concentrations exceeds solubility product constant.
- Thermodynamic product of all the activities of the ions in a solution in equilibrium with a pure solid.

(*f*C+) (*f*A-)

Ksp=[C+] [A-]

Ksp } solubility product constant
[C+],[A-] } Ion Concentration
***f*C+,*f*A- } Square of mean activity coefficient of ions**

- Product constant is specific for particular arrangement of ions.
  - Calcite 4.7x10-9 Kmol2m-3

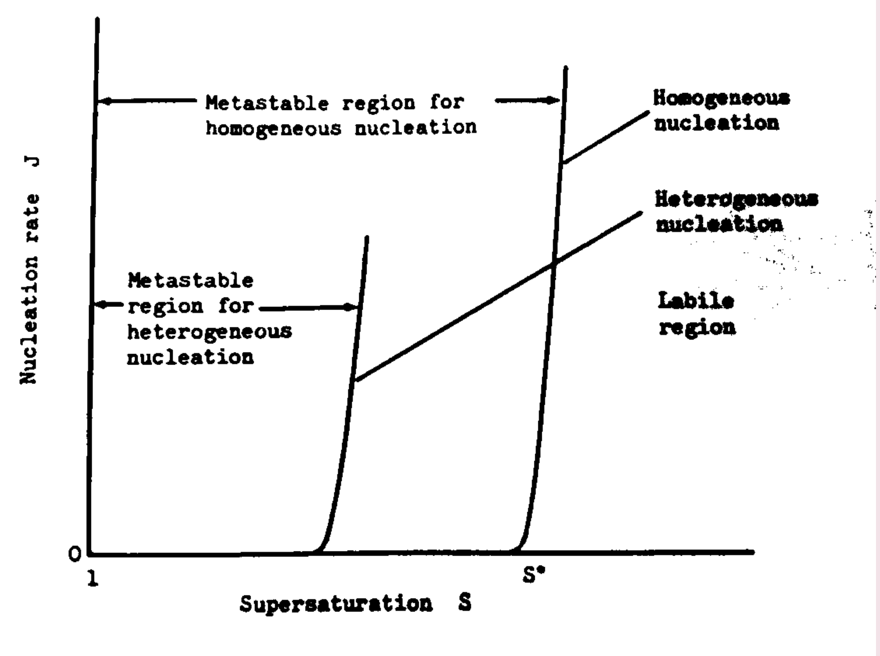
Mann (1983)

Nucleation: Level Of Saturation

The number of nuclei formed within a volume is a function of level of saturation.

- Below S* - Nucleation rate is low
- At a range where nucleation is possible the solution is metastable
- Above S* (or by seeding) - rate is increased

ration of the solution and the rate of crystal nucleation. (From Garside, 1982.)



Garside (1982); Mann (1983)

Crystal Nucleation

- When the expenditure of the interfacial energy (ΔGi) is balanced by the energy released in the formation of bonds in the aggregate (ΔGvol) a stable nucleus is attained.

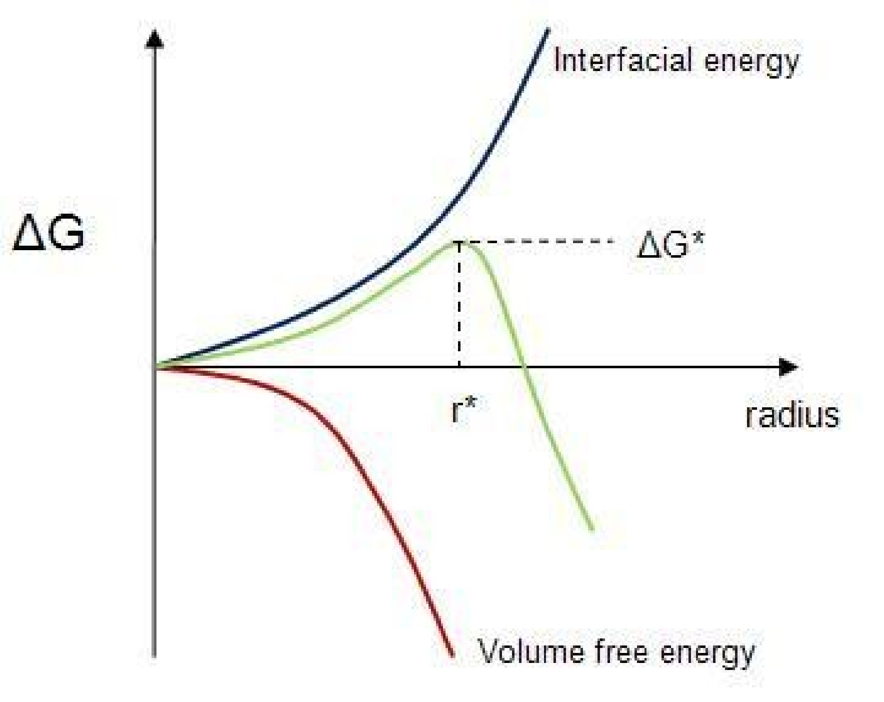
$$\Delta G = \Delta Gi + \Delta Gvol$$

Free Energy Change

Energy loss due to surface tension

Negative free energy released by bond formation

ΔG* free energy of nucleus at maximum



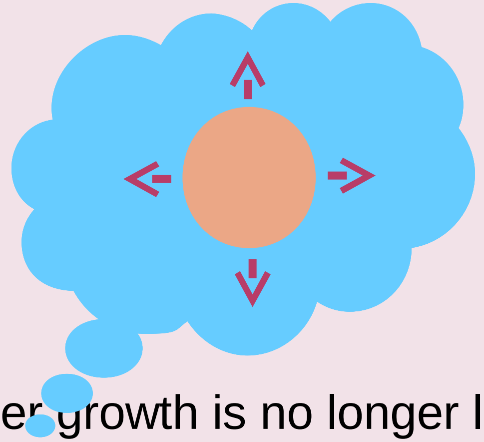
Free energy of nucleation as a function of cluster size (Image credit: wikipedia –JuliyaK)

Simkiss and Wilbur (1989); Mann (2001)

Nucleation: Homogeneous

- As concentration increases ions associate into small unstable clusters that dissociate if they don’t reach a critical size, r=r*
- It costs energy to add molecules until r* is reached

Energy released by formation is too small so cluster dissociates



Cluster growth is no longer limited by nucleation but by reaction kinetics and diffusion.

Critical Size ~ 10-1000 ions

Simkiss and Wilbur (1989)

Nucleation: Biological Systems

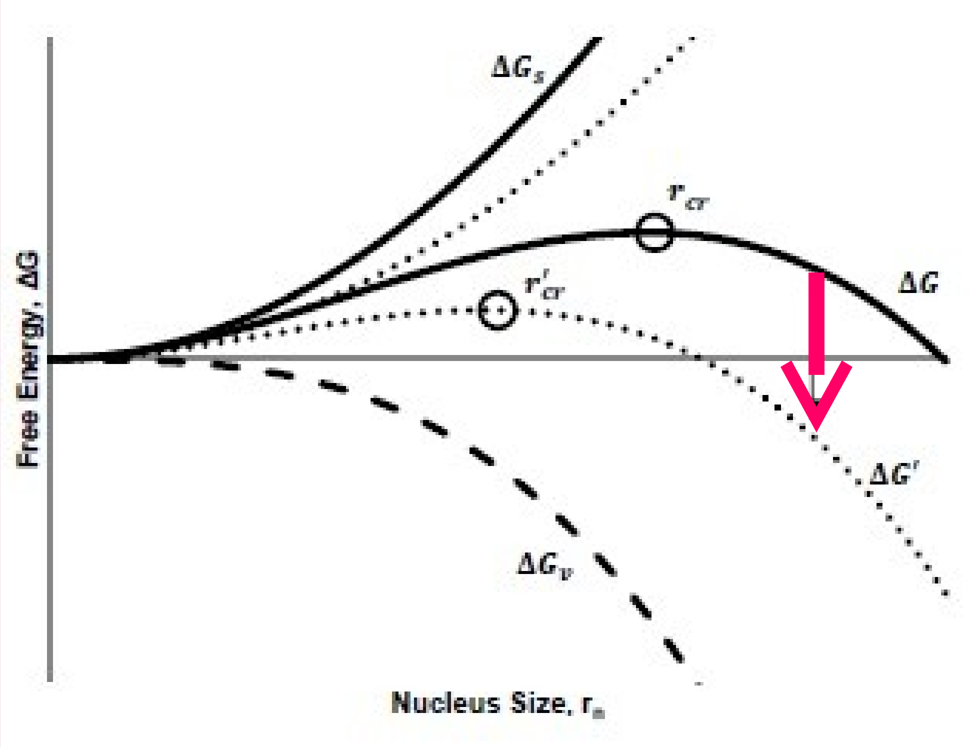
- In biological systems, the site of mineral deposition is isolated from the environment.
- Size of that site must limit diffusion into/out of the system.
- Ion supply (or removal) occurs by two means:
  - Active pumping associated with organelles near the sites of mineralization.

The effect of the organic substrate is to lower the activation energy of nucleation by lowering the interfacial energy.

Simkiss and Wilbur (1989)

Heterogeneous Nucleation

- In biominerals other molecules, ions, external bodies and surfaces are always present.
- Mineral is deposited on existing surfaces.
- Process can continue at lower saturation levels.
- Requires less energy



Primed values indicate parameters associated with a lowered free energy barrier due to heterogeneous nucleation

(image credit: Porter (2010))

Simkiss and Wilbur (1989)

Growth: [1] ‘Kinks’

- Growth occurs by addition of ions to the crystals.
- Addition of ions is not consistent - dislocations & steps form.
- Minute crystals form on a smooth face, edge, step– or- a

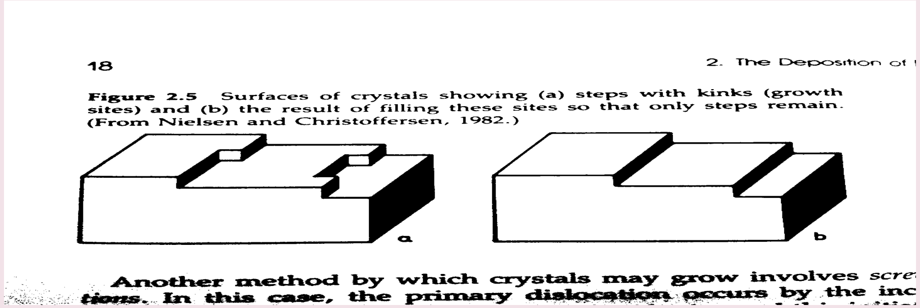

18 2. The Deposition of

Figure 2.5 Surfaces of crystals showing (a) steps with kinks (growth sites) and (b) the result of filling these sites so that only steps remain. (From Nielsen and Christoffersen, 1982.)

Another method by which crystals may grow involves *scre*
tions. In this case, the primary dislocation occurs by the inc

Surfaces of crystals showing (a) steps with kinks (growth sites) and (b) the result of fllling these sites so that only steps remain.
(image credit: Nielsen and Christoffersen, 1982)

Burton et al. (1951); Nielsen and Christoffersen (1982)

Growth: [2] ‘Screw Dislocation’

- Primary dislocation occurs by inclusion of foreign ions or mismatches in surface lattice which initiates a step.
- Growth takes a spiral course – leads to a growth

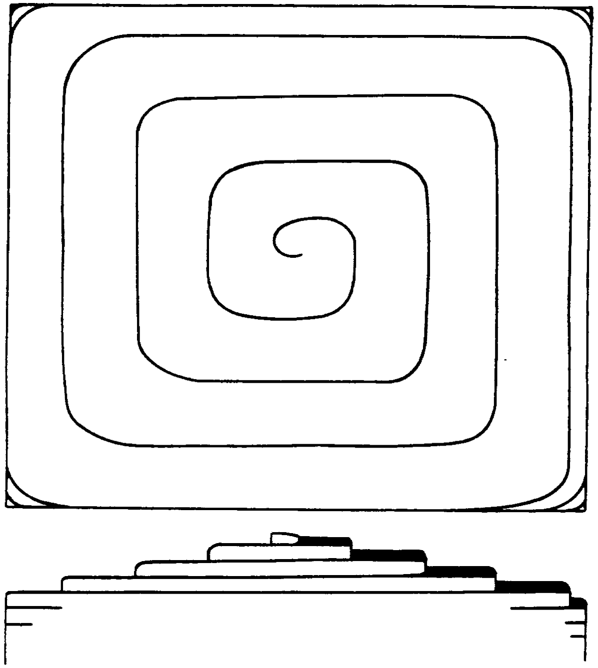


Figure 5. Schematic of a screw dislocation for the BCF model.

Growth pyramid due to a single screw dislocation

Burton et al. (1951); Simkiss and Wilbur (1989)

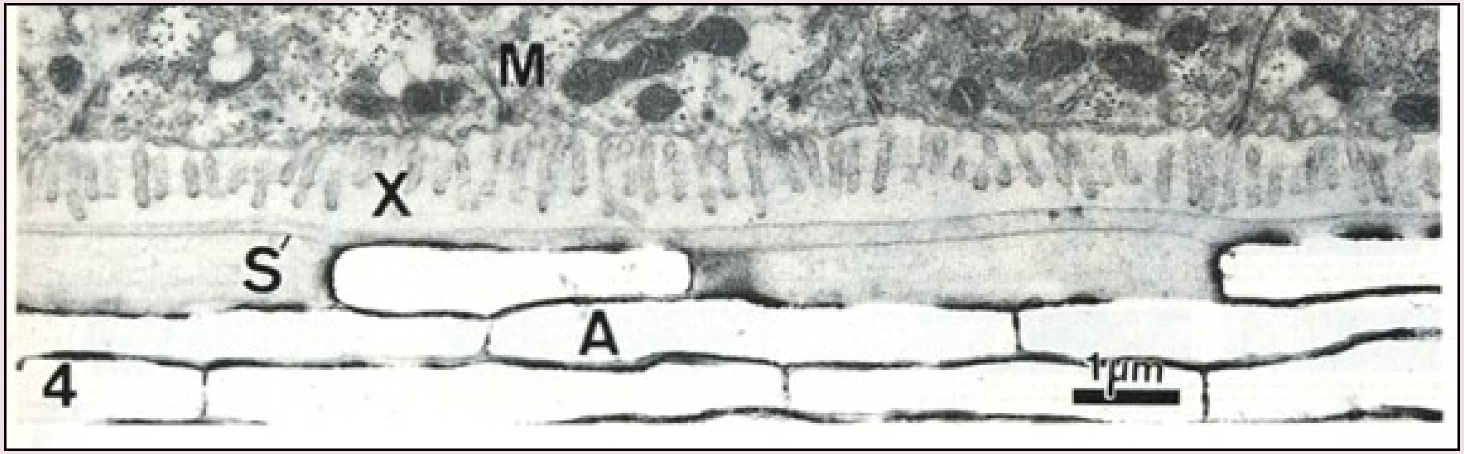
Crystal Growth Modifiers

- Rate Supply of Ions
- Rate of Diffusion
- Adsorption
- Integration
- Inhibitors

Control of Mineralization: Organic Matrix

Biominerals have functional structures and shapes.
e.g. curved teeth and light baskets.

- Organic Matrix acts as a meditator of mineralization and as a crystal modifier.



In many invertebrates this organic matrix is secreted by epithelial cells contiguous to the site of mineral deposition

Image credit: Nakahara (1991)

Simkiss and Wilbur (1989)

Control of Mineralization: Organic Matrix

- Different organic constituents have different functions:
  1. <u>Anionic groups</u>: concentrate Ca++ on specific sites & induce supersaturation for nucleation.
  2. <u>Soluble matrix proteins</u>: inhibit mineral deposition and control mineralization.
  3. <u>Matrix proteins</u>: favor growth of particular isomorphs.
  4. <u>Soluble matrix proteins that are overgrown by mineral</u>: influence the strength of the crystal.

Simkiss and Wilbur (1989)

- Calcium Carbonate, Silica, Hydroxyapatite

Biominerals

Biominerals

Table modified from: *Lowenstam and Weiner (1989)*

Carbonates	
Calcite	CaCO3
Mg-Calcite	(MgxCa1-x)CO3
Aragonite	CaCO3
Vaterite	CaCO3
Monohydrocalcite	CaCO3·H2O
Protodolomite	CaMg(CO3) 2
Hydrocerussite	Pb3 (CO3) 2(OH) 2
Amorphous Calcium Carbonate	CaCO3·H2O or CaCO3

Phosphates	
Octacalcium phosphate	Ca8H2(PO4)6
Brushite	CaHPO4·2H2O
Francolite	Ca10(PO4)6F2
Carbonated-hydroxyapatite	Ca5(PO4,CO3)3(OH)
Whitlockite	Ca18H2(Mg,Fe)2+2(PO4)14
Struvite	Mg(NH4)(PO4)·6H2O
Vivianite	Fe3+2(PO4)2·8H2O
Amorphous Calcium Phosphate	Variable
Amorphous Calcium Pyrophosphate	Ca2P2O7·2H2O

Oxides	
Magnetite	Fe3O4
Amorphous limenite	Fe+2TiO3
Amorphous Iron Oxide	Fe2O3
Amorphous Manganese Oxide	Mn3O4

Sulfates	
Gypsum	CaSO42H2O
Barite	BaSO4
Celestite	SrSO4
Jarosite	KFe3+3(SO4)2(OH)6

Hydrated Silica	
Amorphous Silica	SiO2·nH2O

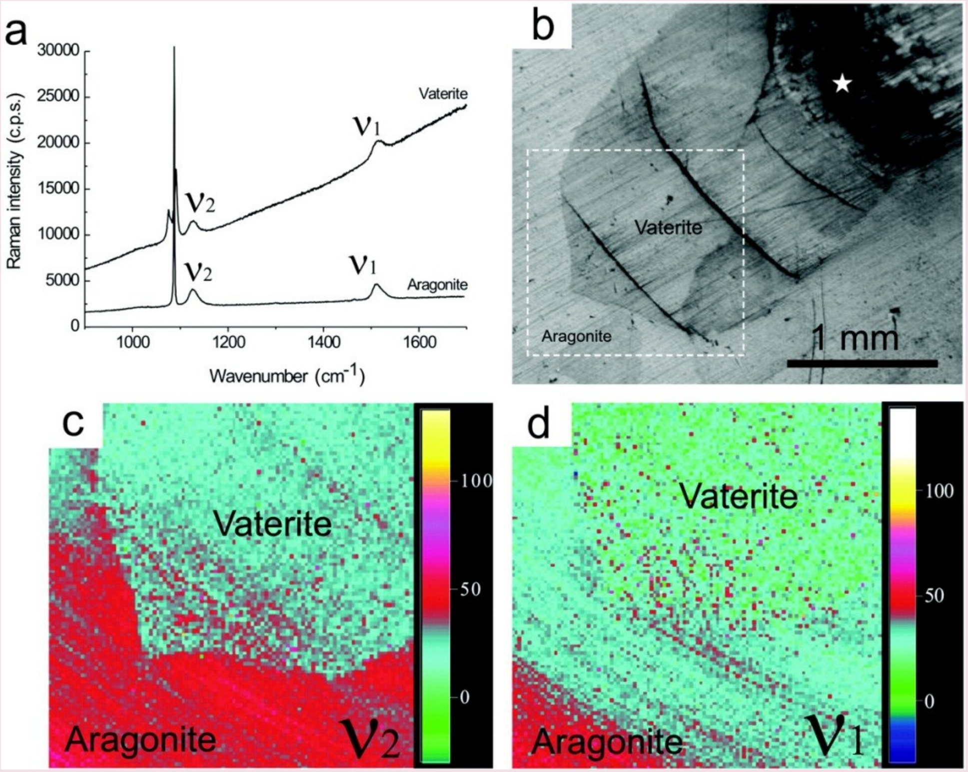
Fluorides	
Fluorite	CaF2
Hieratite	K2SiF6

- Calcium is exceedingly widespread & the most common constituent in skeletal system
- (e.g. bones and shells)

Calcium Carbonate

Calcium Carbonate: Abundant!

- Calcite – Most stable CaCO3 at ambient conditions.
- Aragonite – At superstaturated aqueous solutions containing Mg2+ at a molar ratio Mg/Ca >4 (seawater).
- Vaterite – metastable



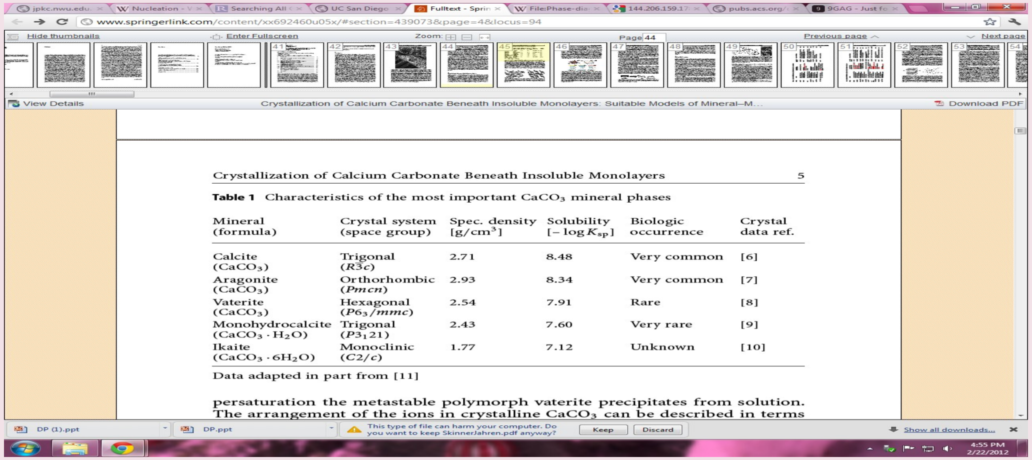
(image credit: gsminmag.highwire.org)

Lowenstam and Weiner (1989)

Fricke and Volkmer (2007)

Calcium Carbonate

- Calcite has a trigonal structure
- Aragonite has the orthorhombic structure.
- Minerals are not isolated in living organisms. - They are connected with organic materials, forming complex hierarchically structured composites.



Crystallization of Calcium Carbonate Beneath Insoluble Monolayers 5

Table 1 Characteristics of the most important $CaCO_3$ mineral phases

Mineral (formula)	Crystal system (space group)	Spec. density [g/cm³]	Solubility [$-\log K_{sp}$]	Biologic occurrence	Crystal data ref.
Calcite ($CaCO_3$)	Trigonal ($R\bar{3}c$)	2.71	8.48	Very common	[6]
Aragonite ($CaCO_3$)	Orthorhombic ($Pmcn$)	2.93	8.34	Very common	[7]
Vaterite ($CaCO_3$)	Hexagonal ($P6_3/mmc$)	2.54	7.91	Rare	[8]
Monohydrocalcite ($CaCO_3 \cdot H_2O$)	Trigonal ($P3_121$)	2.43	7.60	Very rare	[9]
Ikaite ($CaCO_3 \cdot 6H_2O$)	Monoclinic ($C2/c$)	1.77	7.12	Unknown	[10]

Data adapted in part from [11]

persaturation the metastable polymorph vaterite precipitates from solution. The arrangement of the ions in crystalline $CaCO_3$ can be described in terms

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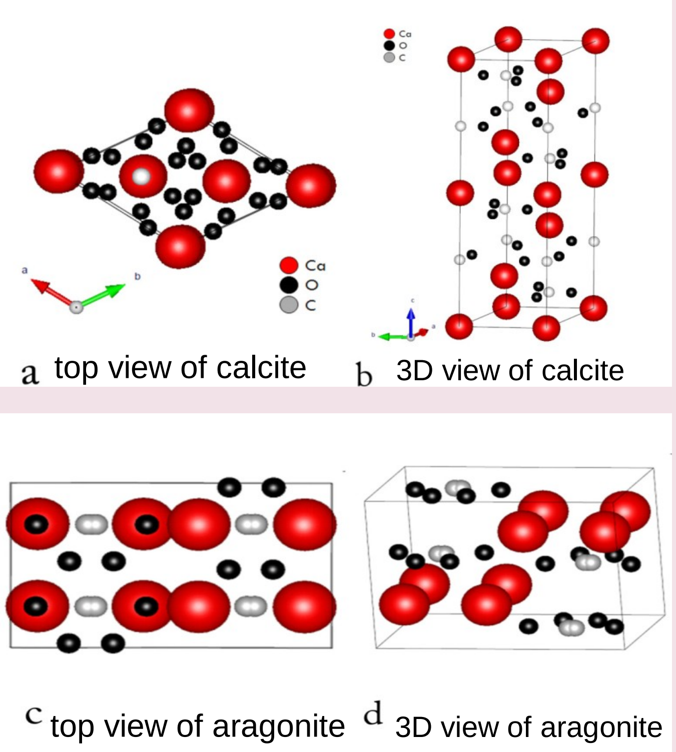


a top view of calcite b 3D view of calcite

c top view of aragonite d 3D view of aragonite

Comparison of the calcite and aragonite unit cells.

Large spheres depict the calcium ions
Small darker spheres depict the oxygen ions
Small lighter spheres show the carbon ions.

(Image: Lopez (2011))

Fricke and Volkmer (2007)

Calcium Carbonate: Organism Examples

- Mollusc shells
- Foraminifera
- Coccolithophores
- Calcareous Sponge spicules
- Corals
- Echinoderms


Santa Barbara Maritime Museum

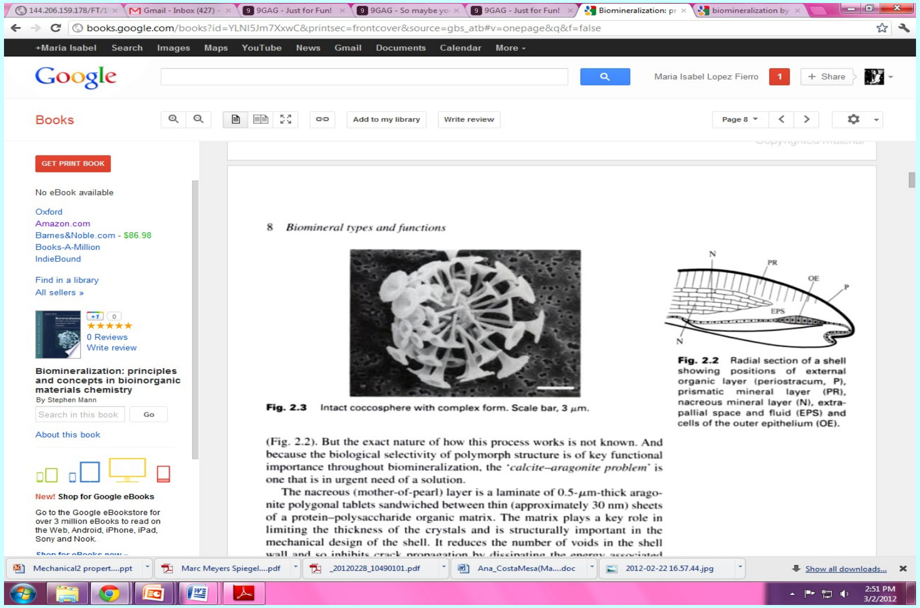

Echinoderms

http://www.photolib.noaa.gov


newscom.com

Calcium Carbonate: Shells

- Shells vary in size and morphology
- The structure is separated in each part of the shell.
- The prismatic layer consists of large calcite crystals
- The nacre region is a plate like aragonite crystals
- Switching of polymorphs is achieved by the outer epithelium (OE)
- OE is separated from the inner shell surface by a space filled with aqueous solution (extrapallaial space)



8 *Biomineral types and functions*

Fig. 2.3 Intact coccosphere with complex form. Scale bar, 3 μm.

Fig. 2.2 Radial section of a shell showing positions of external organic layer (periostracum, P), prismatic mineral layer (PR), nacreous mineral layer (N), extra-pallial space and fluid (EPS) and cells of the outer epithelium (OE).

(Fig. 2.2). But the exact nature of how this process works is not known. And because the biological selectivity of polymorph structure is of key functional importance throughout biomineralization, the '*calcite–aragonite problem*' is one that is in urgent need of a solution.

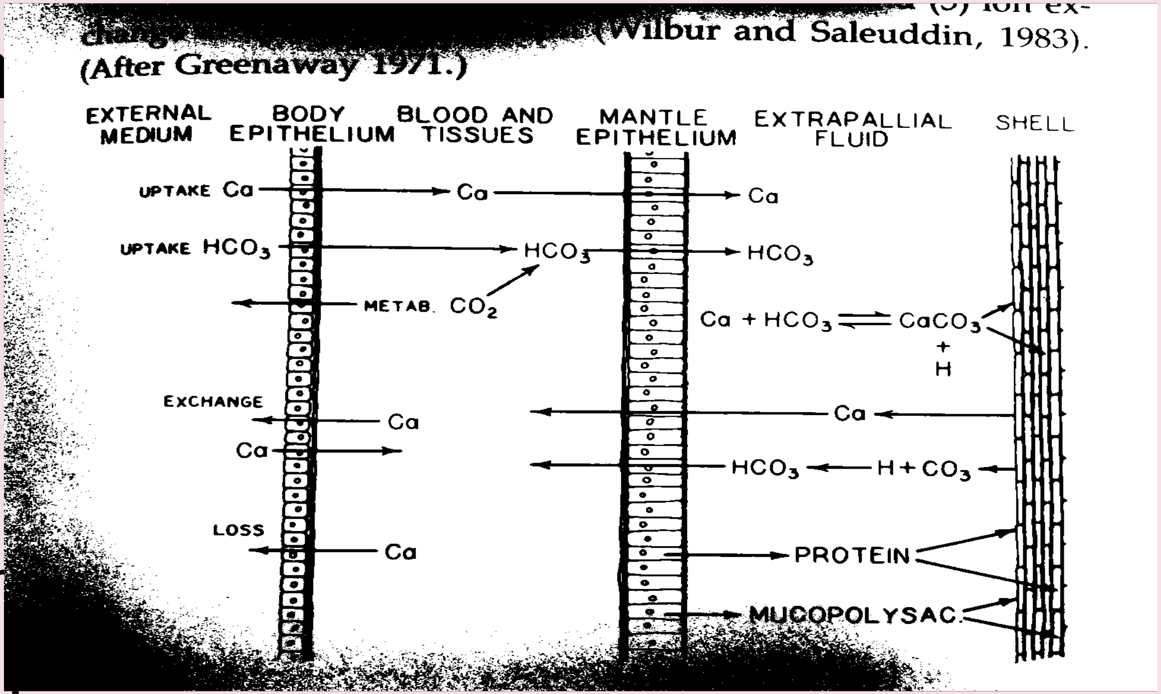
The nacreous (mother-of-pearl) layer is a laminate of 0.5-μm-thick aragonite polygonal tablets sandwiched between thin (approximately 30 nm) sheets of a protein–polysaccharide organic matrix. The matrix plays a key role in limiting the thickness of the crystals and is structurally important in the mechanical design of the shell. It reduces the number of voids in the shell

(**P**) Periostracum (image Credit:
(**PR**)Prismatic Layer
(**N**)Nacreous Layer
(**EPS**) Extrapallial Space
(**OE**) Outer Epithelium

Simkiss and Wilbur (1989)

Shells: Calcium Carbonate

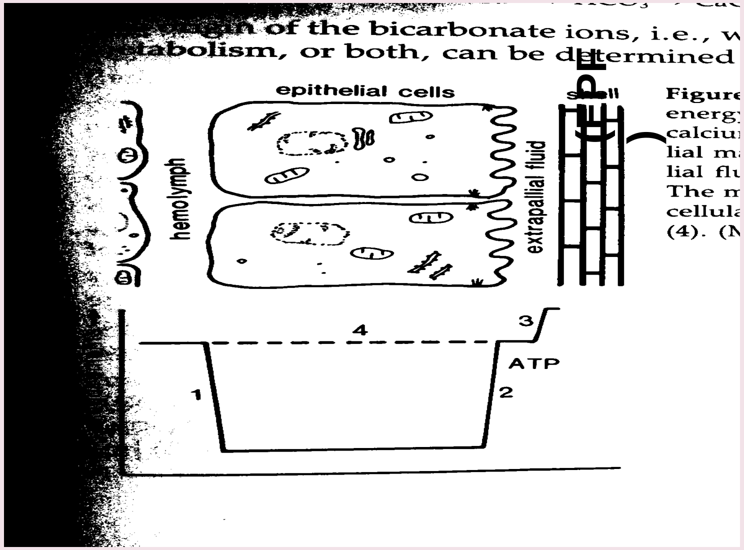
- Six Compartmen
  - Outer medium
  - Body epithelium
  - Blood & Tissues
  - Mantle epitheliur
  - Extrapallaiai fluid
  - Shell
- Ion movement bidirectional

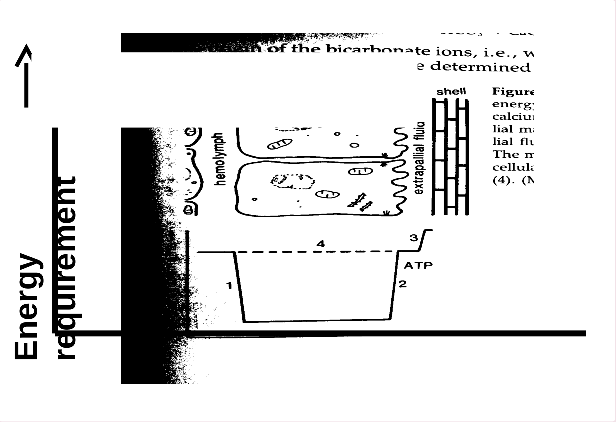


Wilbur and Saleuddin (1983)

Energy Requirement: From hemolymph to EPF

- Ca++ enters epithelial cells from hemolymph (1)
- To pass EPF, energy is supplied by ATP (2)
- Crystal formation requires more energy to raise ion activities above solubility





*Adenosine triphosphate (ATP)

Simkiss (1976); Simkiss and Wilbur (1989)

Nacre Formation

- Each structure regardless of complexity is formed directly by a single layer of epithelial cells.
    - Cells are involved in movement of minerals ions to the site of deposition and in the secretion of organic matter that will become the matrix of the deposit.

This epithelial layer of the mantle is ideal for experimental studies as it is separated from the mineral it deposits!

Simkiss and Wilbur (1989)

Formation induced by Organic Matrix

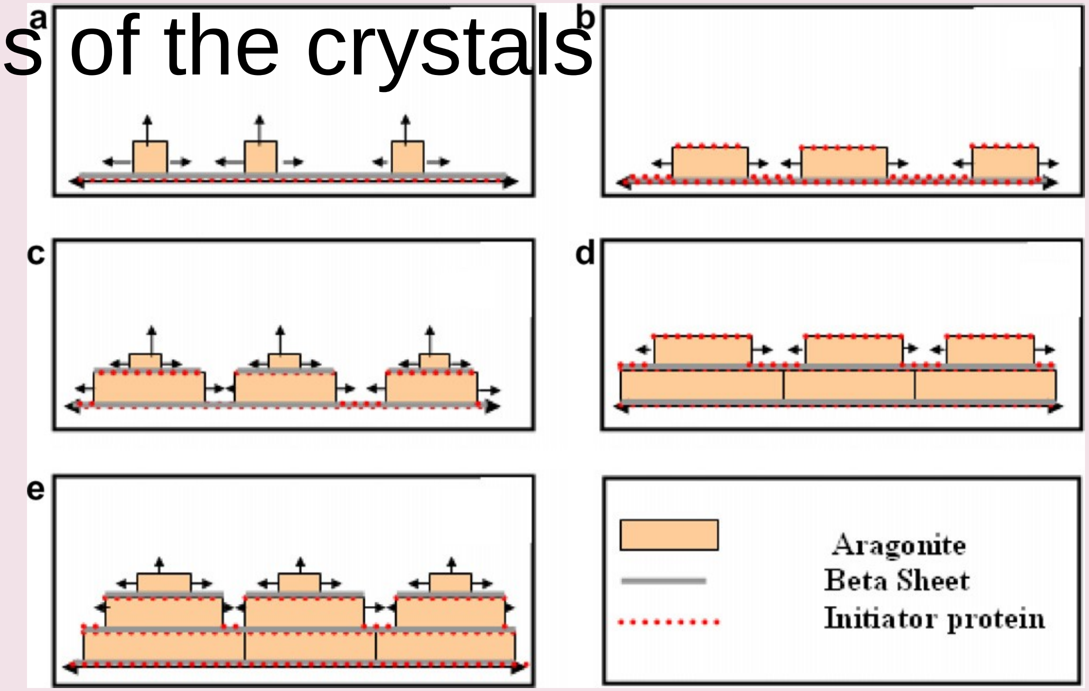
- Secretion of the sheet covering many stacks of crystals can have an effect in terminating growth in thickness of the crystals

(a,b) Crystal nucleation & protein deposition causing the arrest of crystallographic growth in the “c” direction;

(c) Second growth spurt after deposition of beta sheet and nucleation;

(d) First aragonite plates are butted together while growth of second layer continues in “a, b” direction;

(e) Nucleation of third layer as second layer growth continues in “a” direction

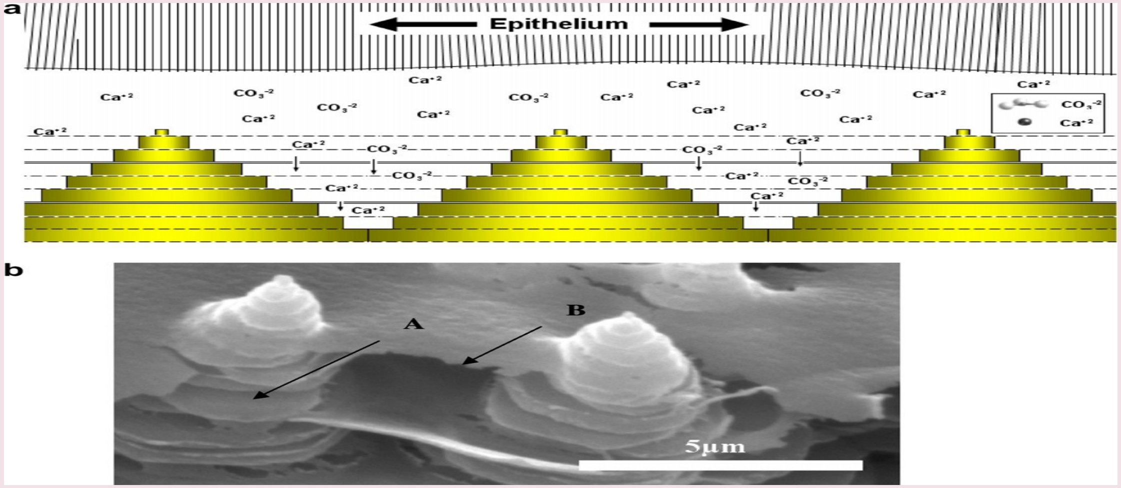


Meyers et al. (2008).

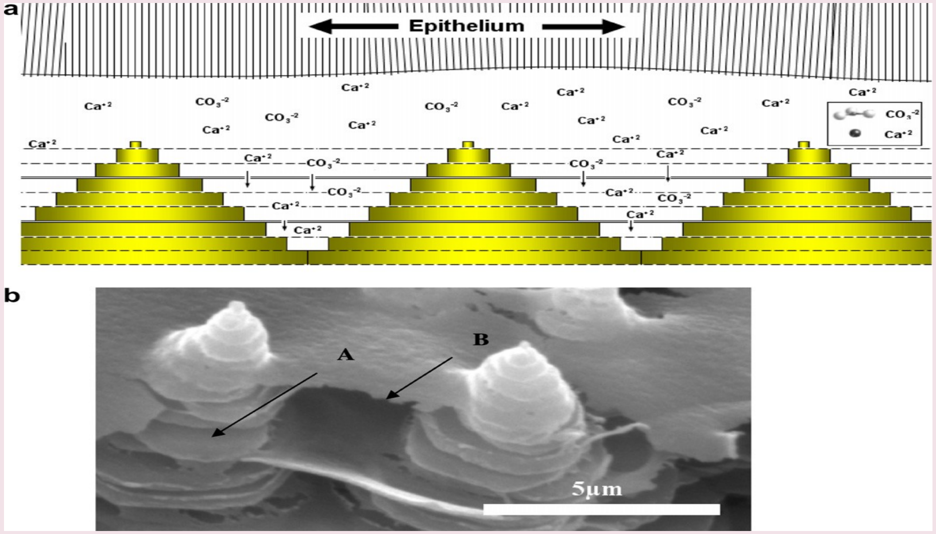
Lin (2008)

Nacre: Formation

Growth Of Nacreous Tiles by Terraced Cone Mechanism



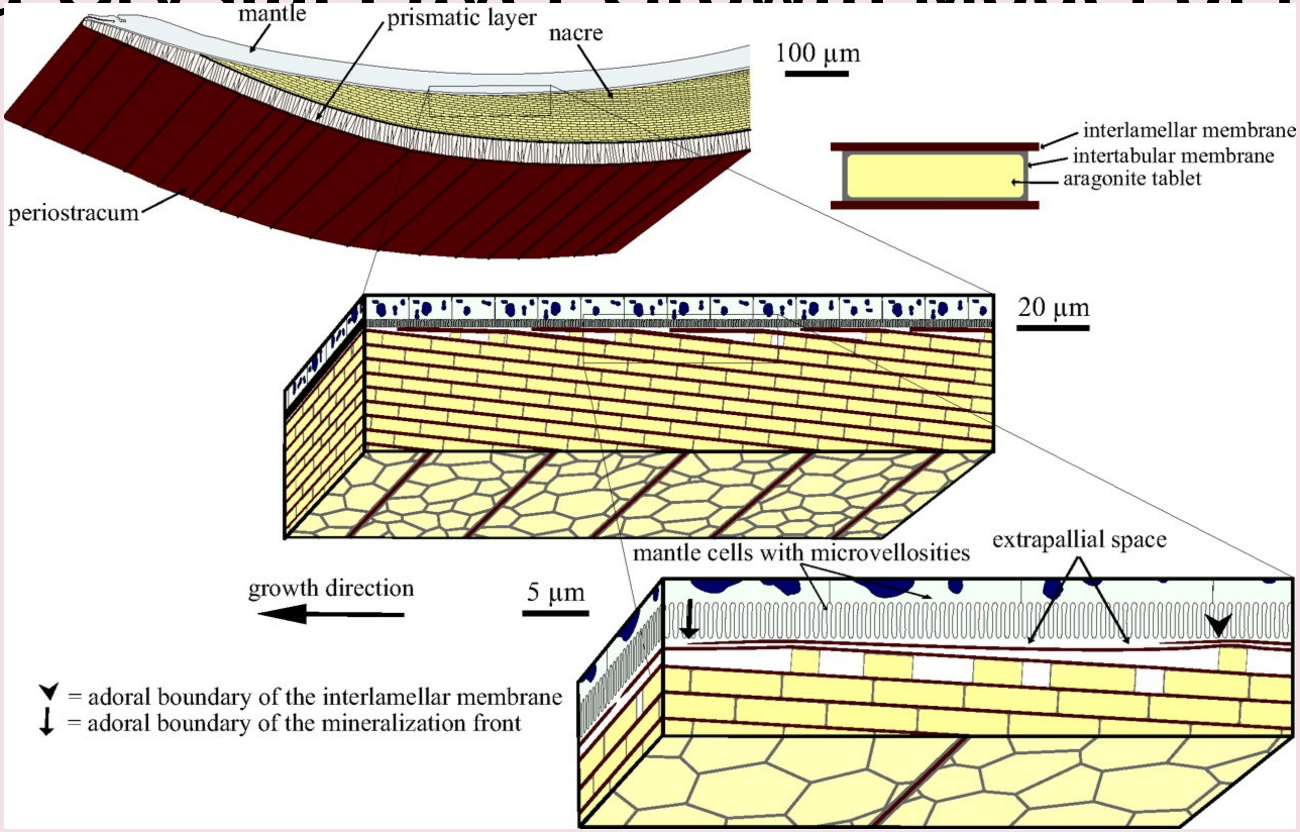
Schematic of growth mechanism showing intercalation of mineral and organic layers

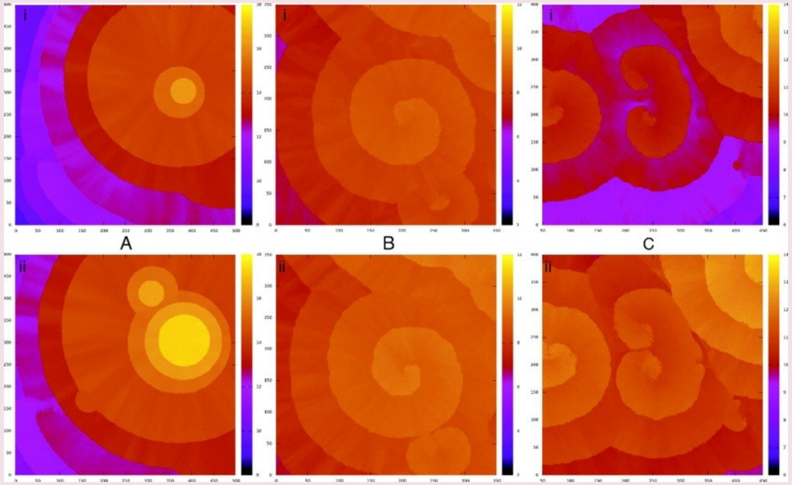


SEM of arrested growth showing partially grown tiles (arrow A) and organic layer (arrow B).

Lin, A.Y.L, Chen P.-Y., and Meyers, M.A. (2008)

Liquid-Crystal Layer Growth Model of Nacre



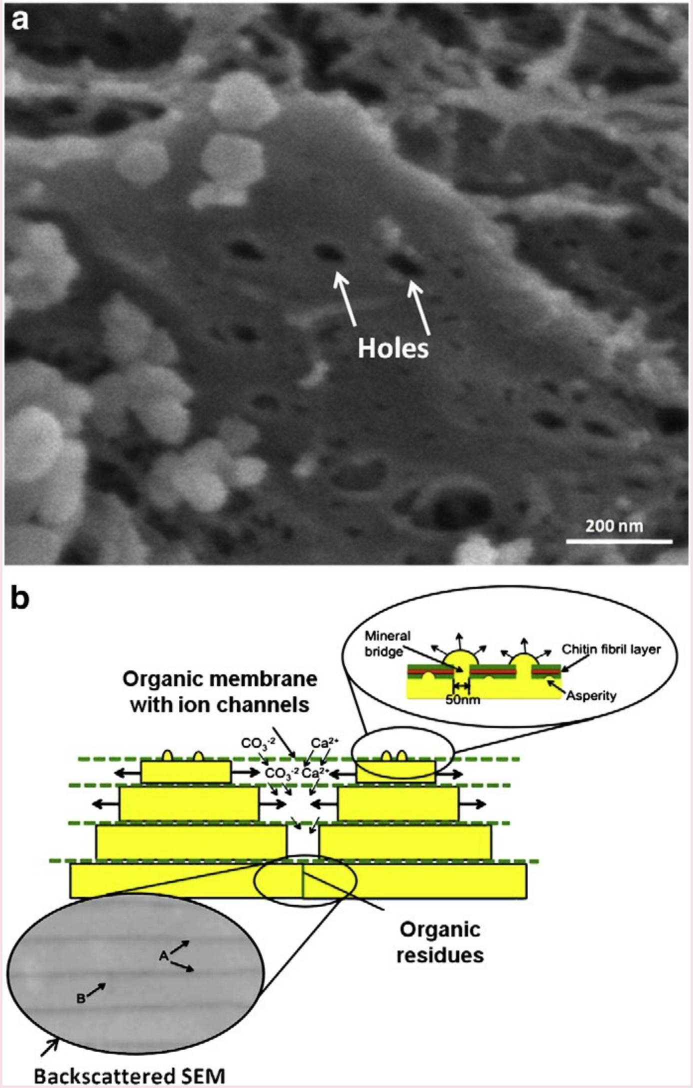


Checa et al. (2011)

Formation Through nacre Mineral bridge

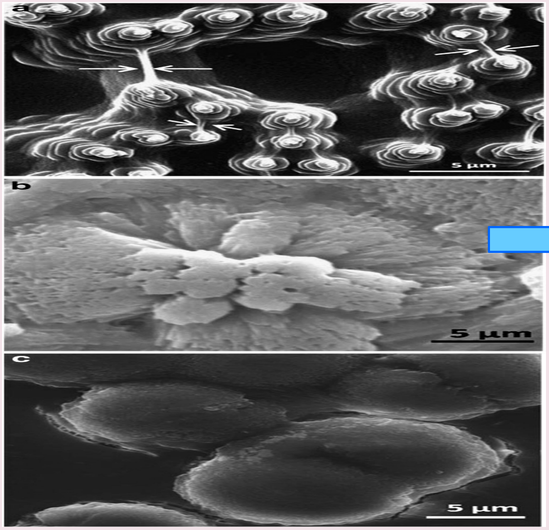
- Holes in the matrix exist between mineral layers
- Nucleation event for a given stack of crystals occurs once.

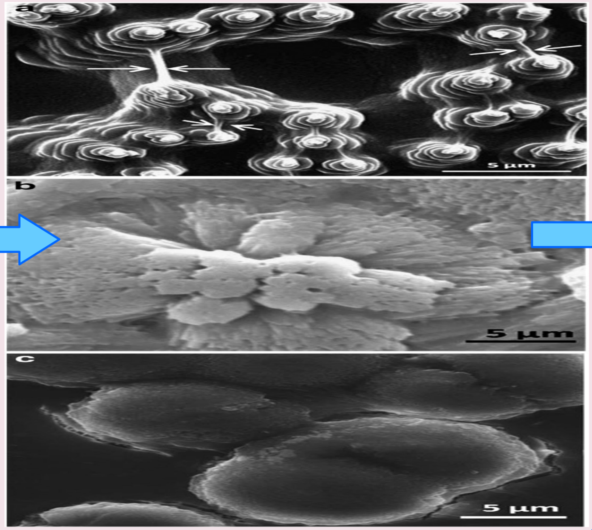
This model has been supported further by observations of 3-D coherence between crystals in a given stack using electron diffraction

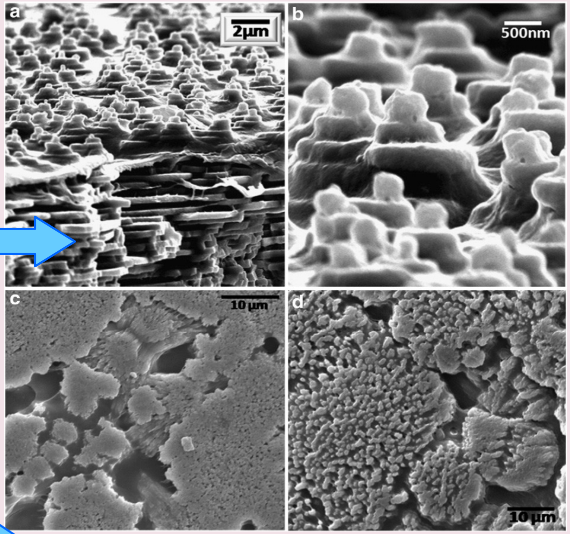


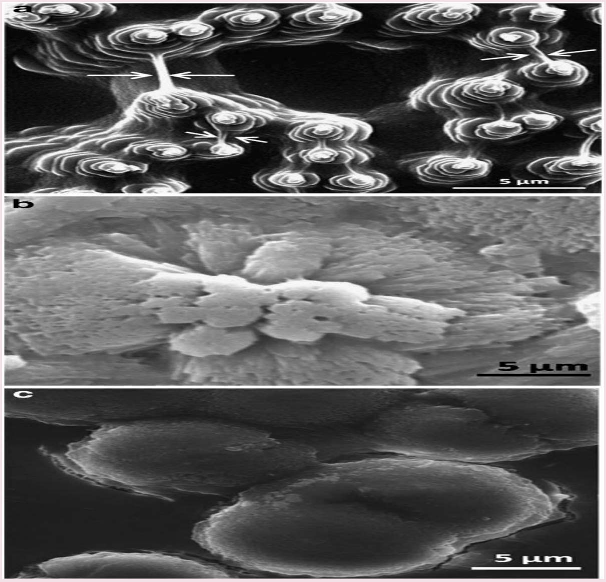
Lin et al. (2005); Lopez et al. (2010); Checa et al. (2011)

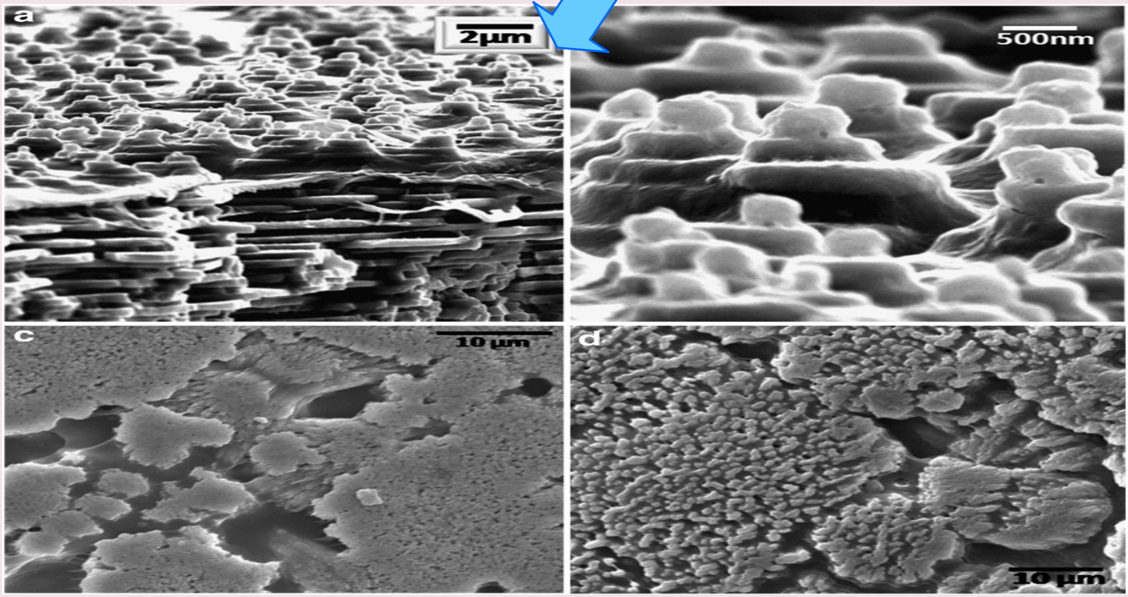
Growth of Nacre











Silica

Silica: distinctive!

- Amorphous – Odd for biominerals as it is less stable (more soluble).
- Lack of crystallinity

http://www.bentonite.us/Diatoms.htm

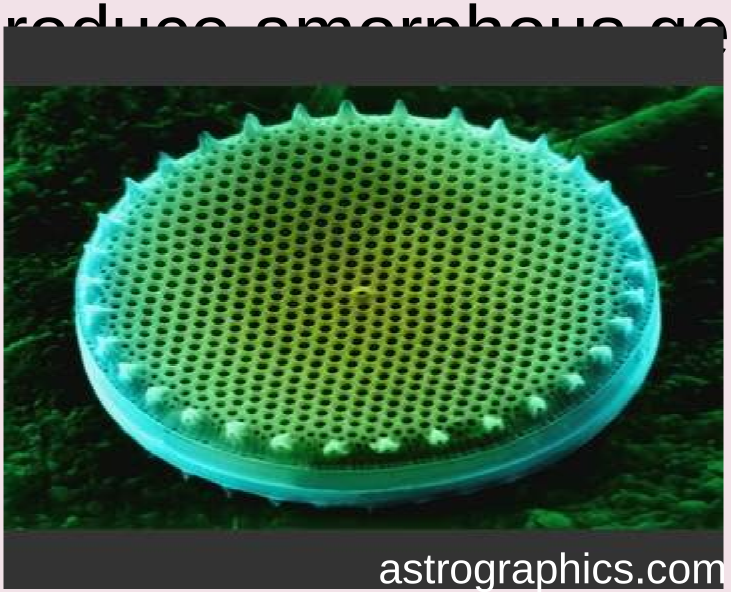
- Opal is common!
  - Common in single celled organisms
  - Small bodies within multicellular tissues (sponges)
  - Small = stronger
- Fracture planes are miss
  mol
  oss
  of strength.

Diatomos means "*cut in half*"

Addadi et al. (2003)

Silica Formation

- Deposition of silica is different from ionic minerals
  - At a neutral pH the soluble form is silicic acid
  - At >1mM the acid undergoes polycondensation reactions to produce amorphous gels or colloidal particles.



astrographics.com

Stephen Mann (2001)

Silica Formation

- Amorphous silica's structure varies based on the polymeric network of the randomly arranged siloxane centers and various layers of hydroxylation.
- These range from condensed to partially condensed centers giving a complex material

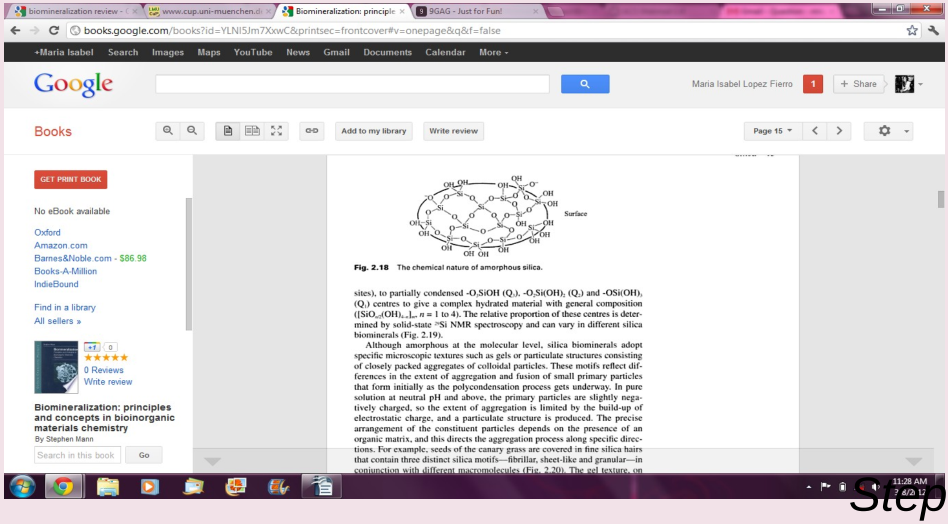


Fig. 2.18 The chemical nature of amorphous silica.

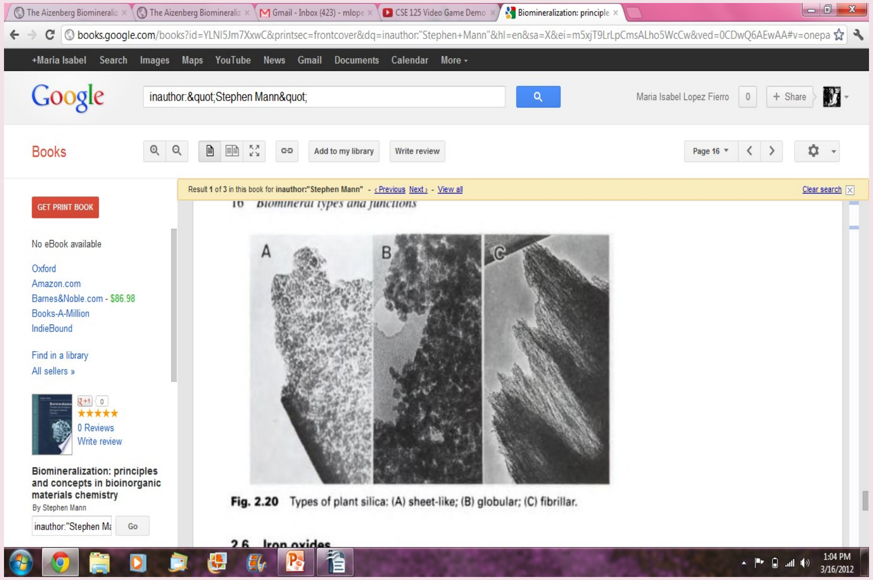
sites), to partially condensed -O_3SiOH (Q_3), -$O_2Si(OH)_2$ (Q_2) and -$OSi(OH)_3$ (Q_1) centres to give a complex hydrated material with general composition ($[SiO_{n/2}(OH)_{4-n}]_m$, $n = 1$ to 4). The relative proportion of these centres is determined by solid-state ^{29}Si NMR spectroscopy and can vary in different silica biominerals (Fig. 2.19).

Although amorphous at the molecular level, silica biominerals adopt specific microscopic textures such as gels or particulate structures consisting of closely packed aggregates of colloidal particles. These motifs reflect differences in the extent of aggregation and fusion of small primary particles that form initially as the polycondensation process gets underway. In pure solution at neutral pH and above, the primary particles are slightly negatively charged, so the extent of aggregation is limited by the build-up of electrostatic charge, and a particulate structure is produced. The precise arrangement of the constituent particles depends on the presence of an organic matrix, and this directs the aggregation process along specific directions. For example, seeds of the canary grass are covered in fine silica hairs that contain three distinct silica motifs—fibrillar, sheet-like and granular—in conjunction with different macromolecules (Fig. 2.20). The gel texture, on

Stephen Mann (2001)

Silica Formation

- Microscopic features exist due to the differences in aggregation of particles that formed during the polycondensation process.



Result 1 of 3 in this book for inauthor:"Stephen Mann" - ‹ Previous Next › - View all

Biomineralization: principles and concepts in bioinorganic materials chemistry
By Stephen Mann

16 *Biomineral types and functions*

Fig. 2.20 Types of plant silica: (A) sheet-like; (B) globular; (C) fibrillar.

2.6 Iron oxides

An example of this is seeds of the canary grass covered in fine silica hairs with 3 different morphologies

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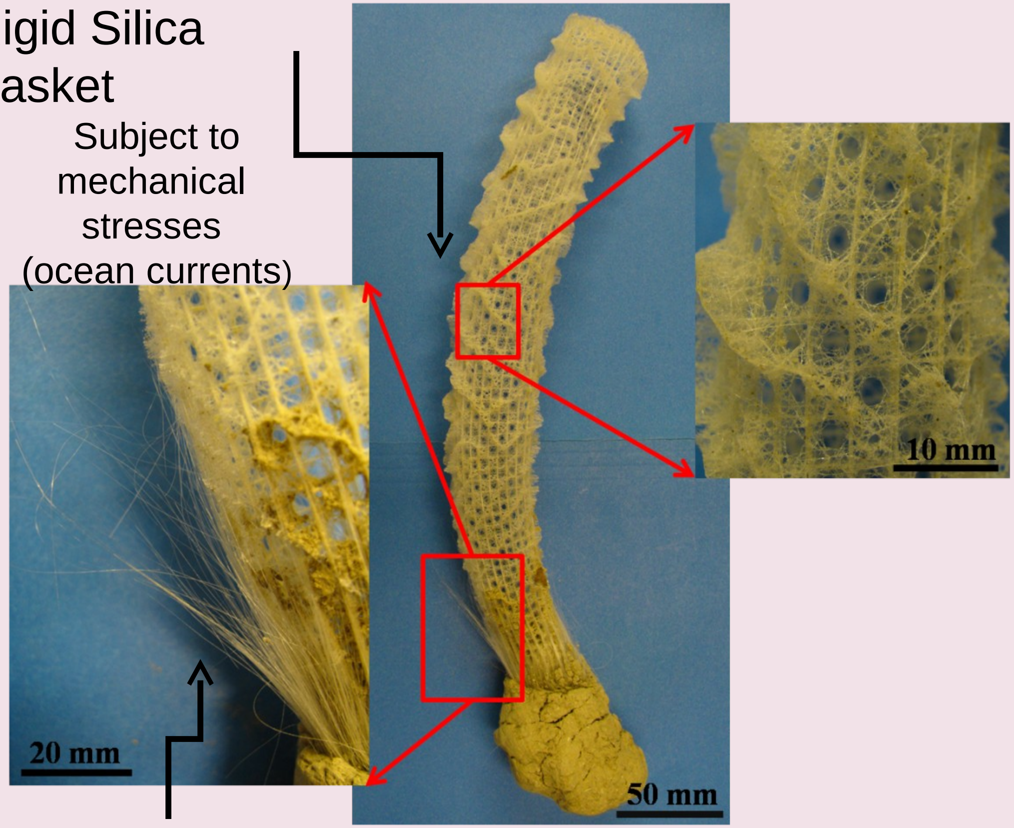
sponge spicule



Rigid Silica Basket

Subject to mechanical stresses (ocean currents)

Flexible Silica Spicules

Anchor to sea floor
5-15 cm long
40-70 µm in diameter

Image Credit: Y. Wen

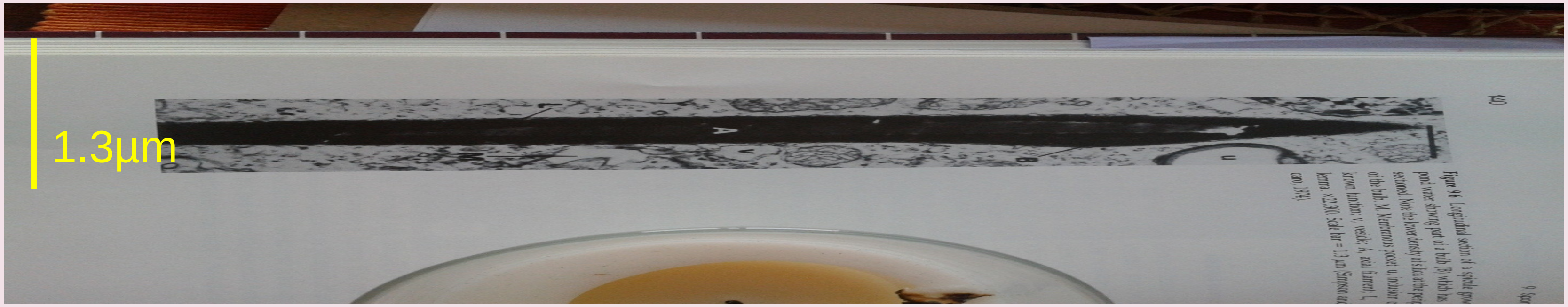
- Siliceous spicules consist of hydrated silica in a layer arrangement around an axis filament‘
- Each silica rod is composed of a central pure silica core.
- Surrounded by

Aizemberg et al (2005)

Sponge Spicule

Formed intracellularly in sclerocyte within an organelle bounded by a membrane

- 1.Axial filament formation
- 2.Mineralization gives it shape
- 3.Punctures sclerocyte
- 4. Spicule is moved to definite position



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9. Spon

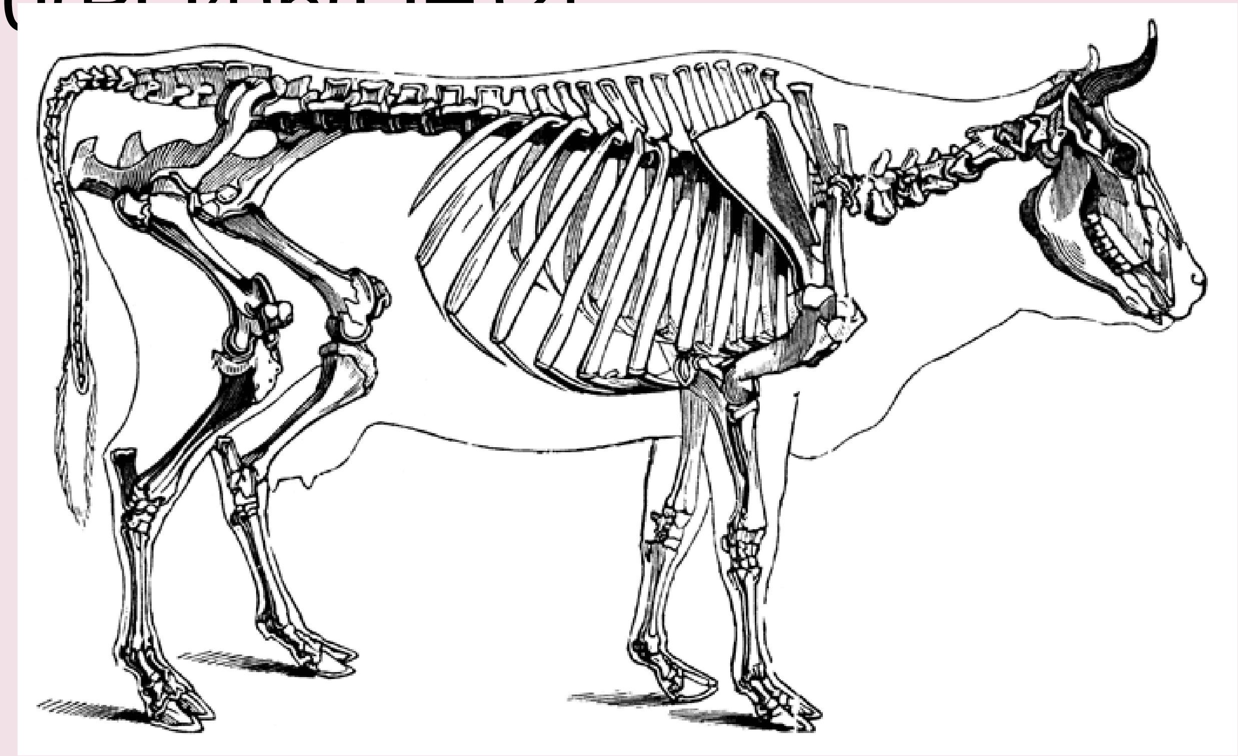
Figure 9.6 Longitudinal section of a spicule grow
pond water showing part of a bulb (B) which has
sectioned. Note the lower density of silica at the perip
of the bulb. M, Membranous pocket; u, inclusion o
known function; v, vesicle; A, axial filament; L,
lemma. ×22,300. Scale bar = 1.3 µm (Simpson and
caro, 1974).

Garrone et al. (1981); Simpson and Vacaro (1947); *Simkiss and Wilbur (1989)*

Hydroxyapatite

Hydroxyapatite

- The mineral that forms bones and teeth of vertebrates is hydroxyapatite [Ca10(PO4)6(OH)2]



S. G. Goodrich, *The Animal Kingdom Illustrated*

Hydroxyapatite

- Pure state: Monoclinic structure with Ca/P ratio of 10/6
- In most substituted forms: hexagonal structure in where molar ratio changes

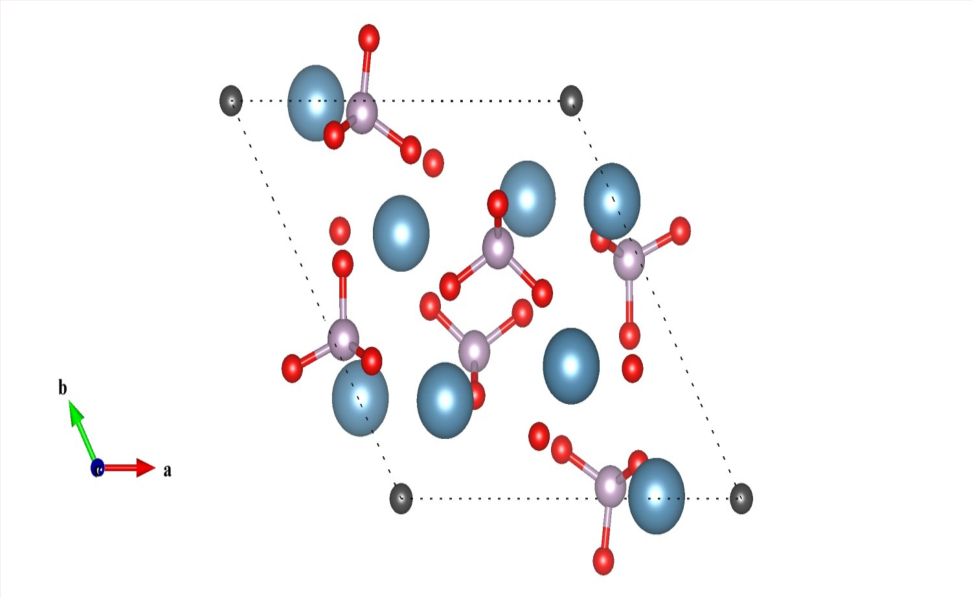
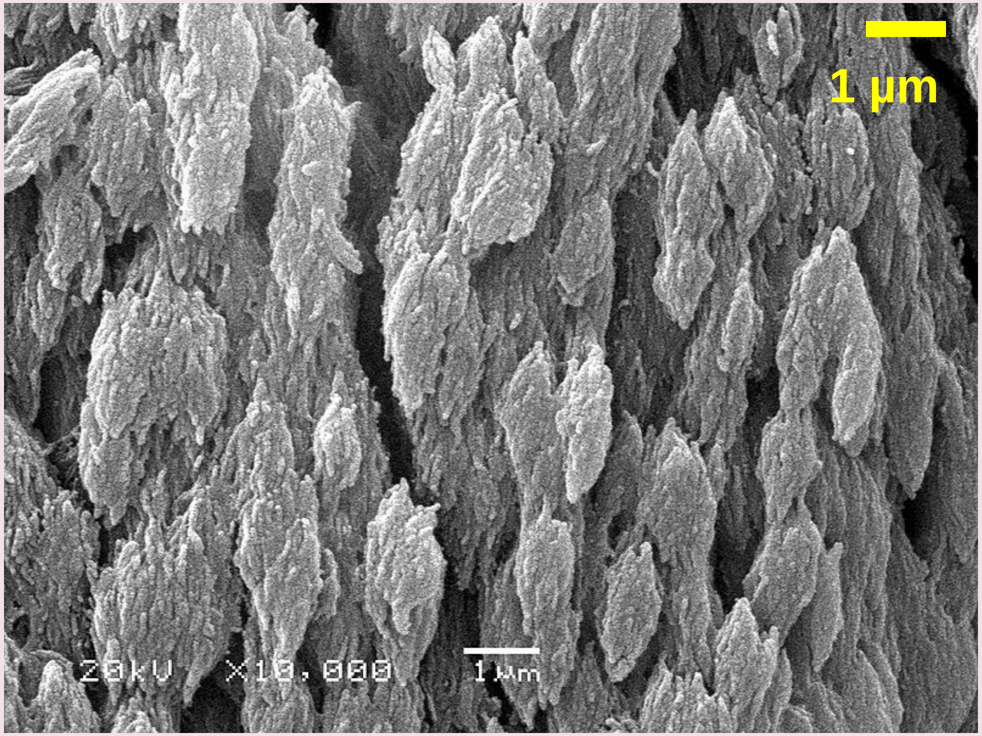


Image Credit: Michael Porter

Simkiss and Wilbur (1989)

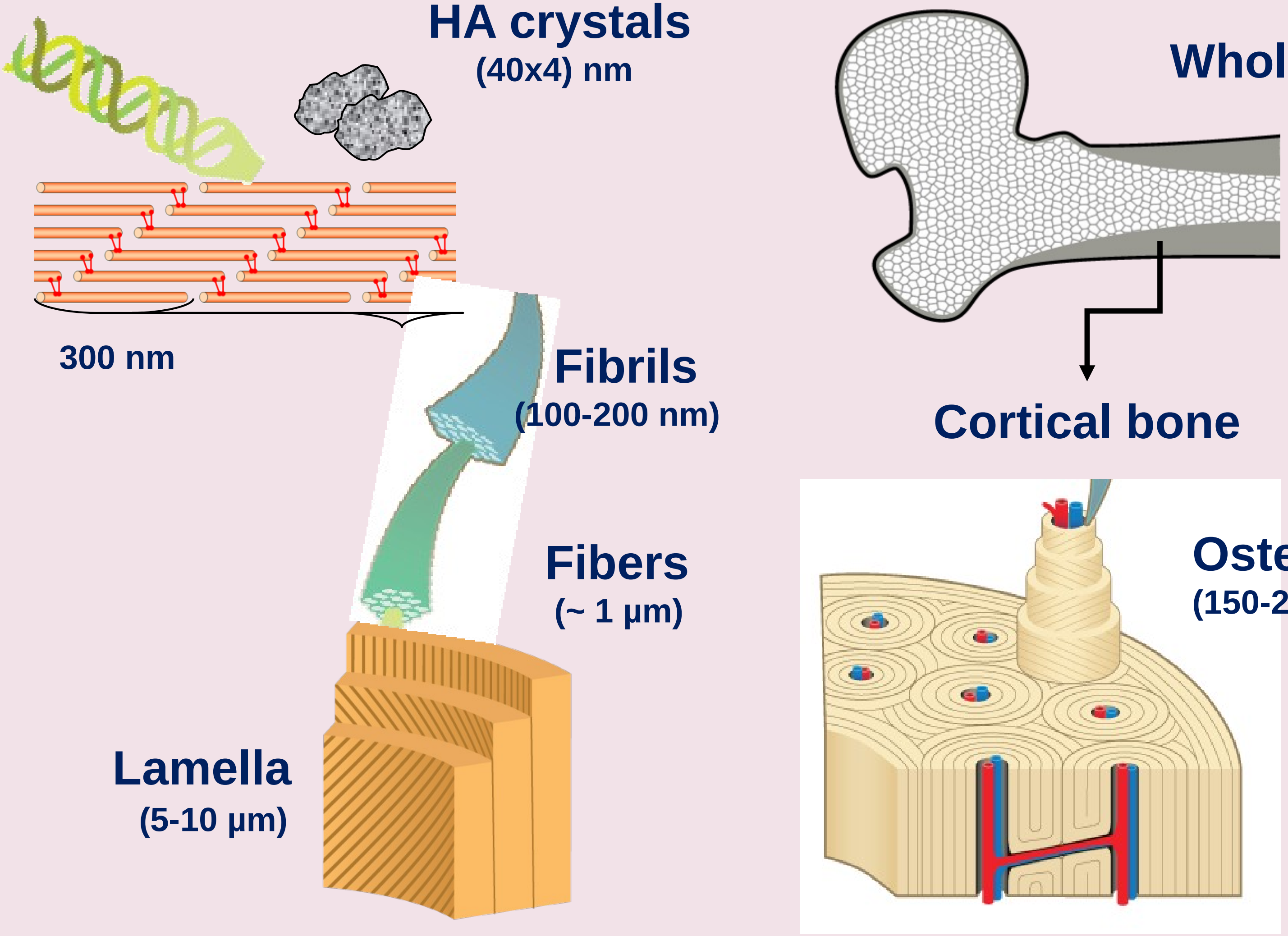
Bone Mineral

- Hard to determine solubility constant and understand formation:
  - Ion substitution affects solubility
  - Various Ca/P ratios exist



(image credit: Bertazzo S, wikipedia.com)
SEM deproteined bone - cranium rat)

Bone Matrix



Collagen molecule

1.5 nm

HA crystals

(40x4) nm

300 nm

Fibrils

(100-200 nm)

Fibers

(~ 1 µm)

Lamella

(5-10 µm)

Whole bone

Cortical bone

Osteon

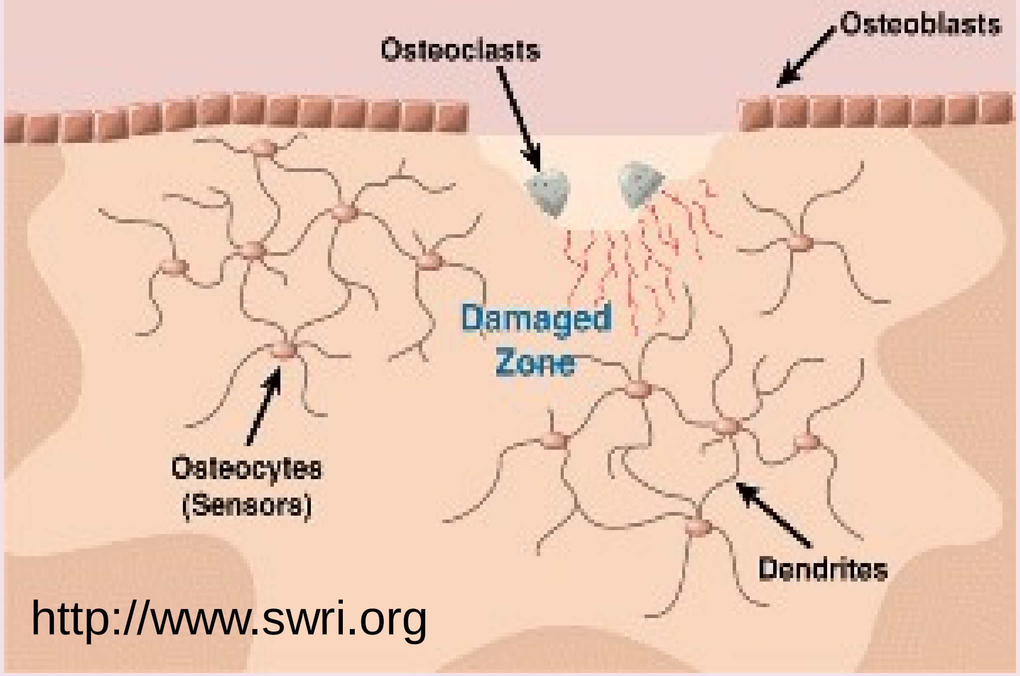
(150-250 µm)

Image Credit: Steve

Bone: Cellular interactions

Though as a “living mineral” because it undergoes continual growth, dissolution & remodeling

- 3 Main Cells associated
  - Osteoblasts (formation)
  - Osteocytes (maintaining)
  - Osteoclasts (resorption)
- Application of pressure stimulates



http://www.swri.org

Stephen Mann (2001)

Bone

- By controlling the different levels of mineral content you can control the stiffness (young's modulus).
  - E.g. a fast moving animal (deer) requires a highly elastic bone (less mineralized – 50 weight %)

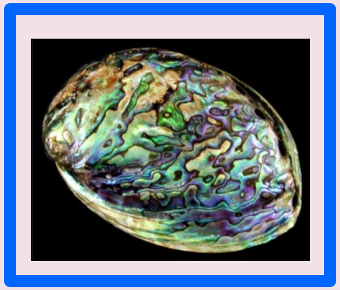

jesuspaintings.com


fish-journal.com

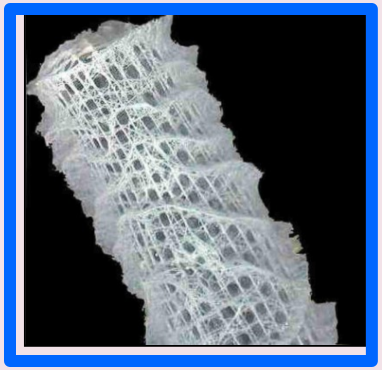
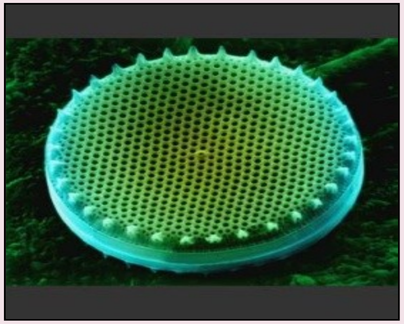
Stephen Mann (2001)

Summary

alcium carbonate
$CaCO_3$) + chitin +
rotein



morphous
lica (SiO_2)(H_2 O)n

m phosphate
oxyapatite
$PO_4)_6(OH)_2$ + collagen





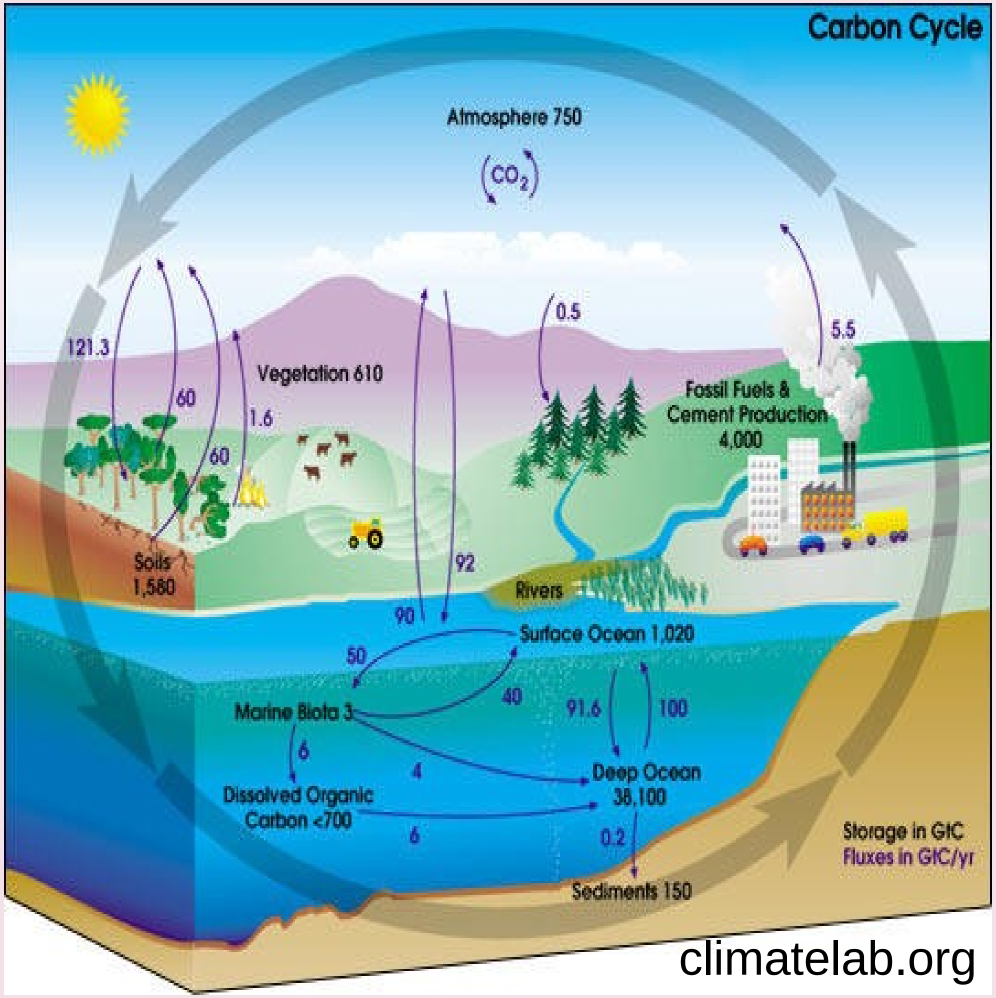

Meyers et al., 2008

- Social Impact

Why do we need to understand biomineralization?

Social Impact: Ocean Acidification

- Changes in seawater chemistry are occurring in the ocean.
- Industrial and agricultural activities is increasing amount of CO2 in the atmosphere.



climatelab.org

PMEL NOAA – Carbon Program

Social Impact: Ocean ACidification

- When CO2 is absorbed by seawater
  - Carbonate ion concentration and saturation states are lowered
  - pH level in ocean is reduced – “Ocean Acidification”
- C of
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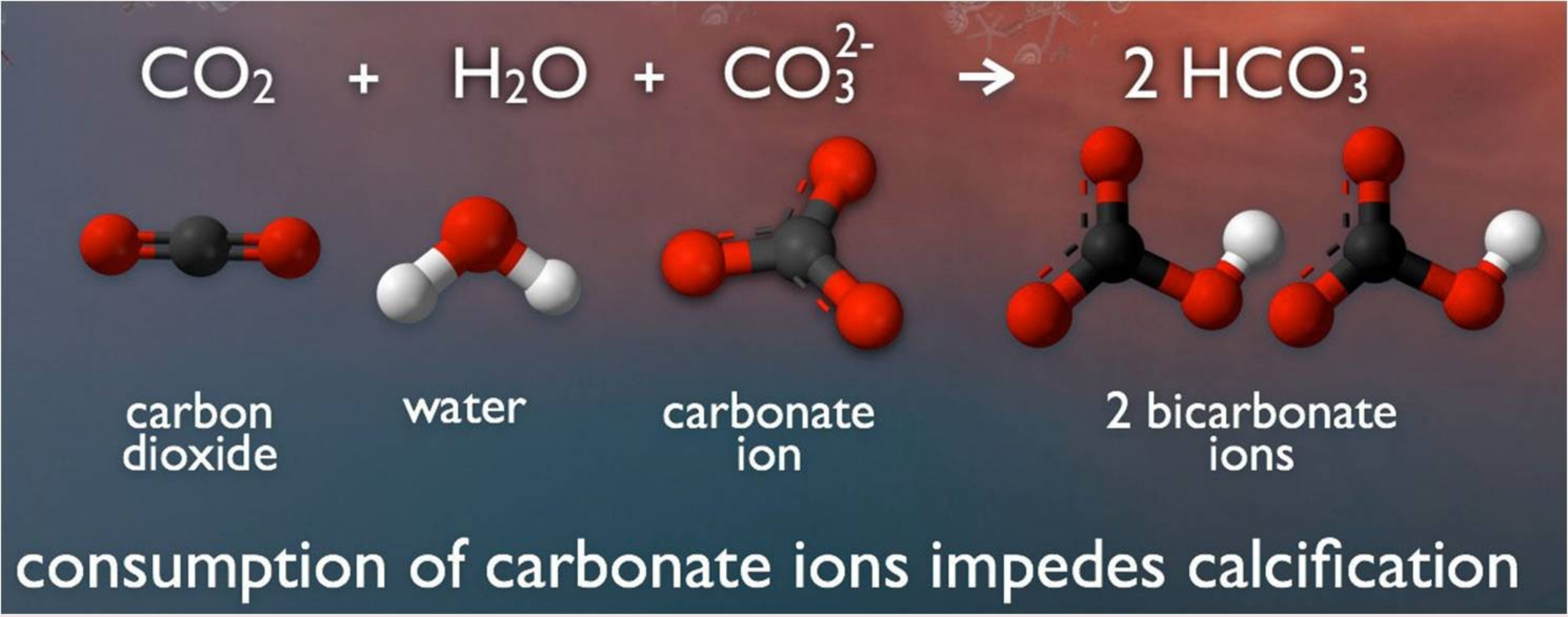

$CO_2 + H_2O + CO_3^{2-} \rightarrow 2\,HCO_3^-$

consumption of carbonate ions impedes calcification

NOAA – Carbon Program

Social Impact: Ocean Acidification

- The pH of surface ocean waters has fallen by 0.1 pH units
  - ~ a 30% increase in acidity.
- Many organisms are at risk!
- Remember that by threatening our shelled frie … !
- Th … n ou

National Geographic Images.

photos below show what happens to a pteropod’s shell when placed in sea water with pH and carbonate levels projected for the year 2100. The shell slowly dissolves after 45 days.

NOAA – Carbon Program

Summary & Conclusions

- Biomineralization is the process by which living organisms form and influence the precipitation of minerals.
  - No ‘grand’ mechanism.
  - Saturation, Nucleation Growth & Influence of Organic Matrix .
- Many Biominerals:
  - Calcium Carbonate – Abundant!
  - Silica – Distinctive!
  - Hydroxyapatite – Living!


http://geniusbeauty.com

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Thank you!