

# Emergence of growth and form in crystals and corals

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# Overview

- Abiotic growth and form of crystals
- Growth and form in biomineralisation
- Biomineralization in the scleractinian coral *Acropora*.
- The organic matrix in biomineralization
- Modelling calcification physiology in the confined space in corals
- Modelling growth and form of corals and crystal growth
- Quantifying complex-shaped branching growth forms

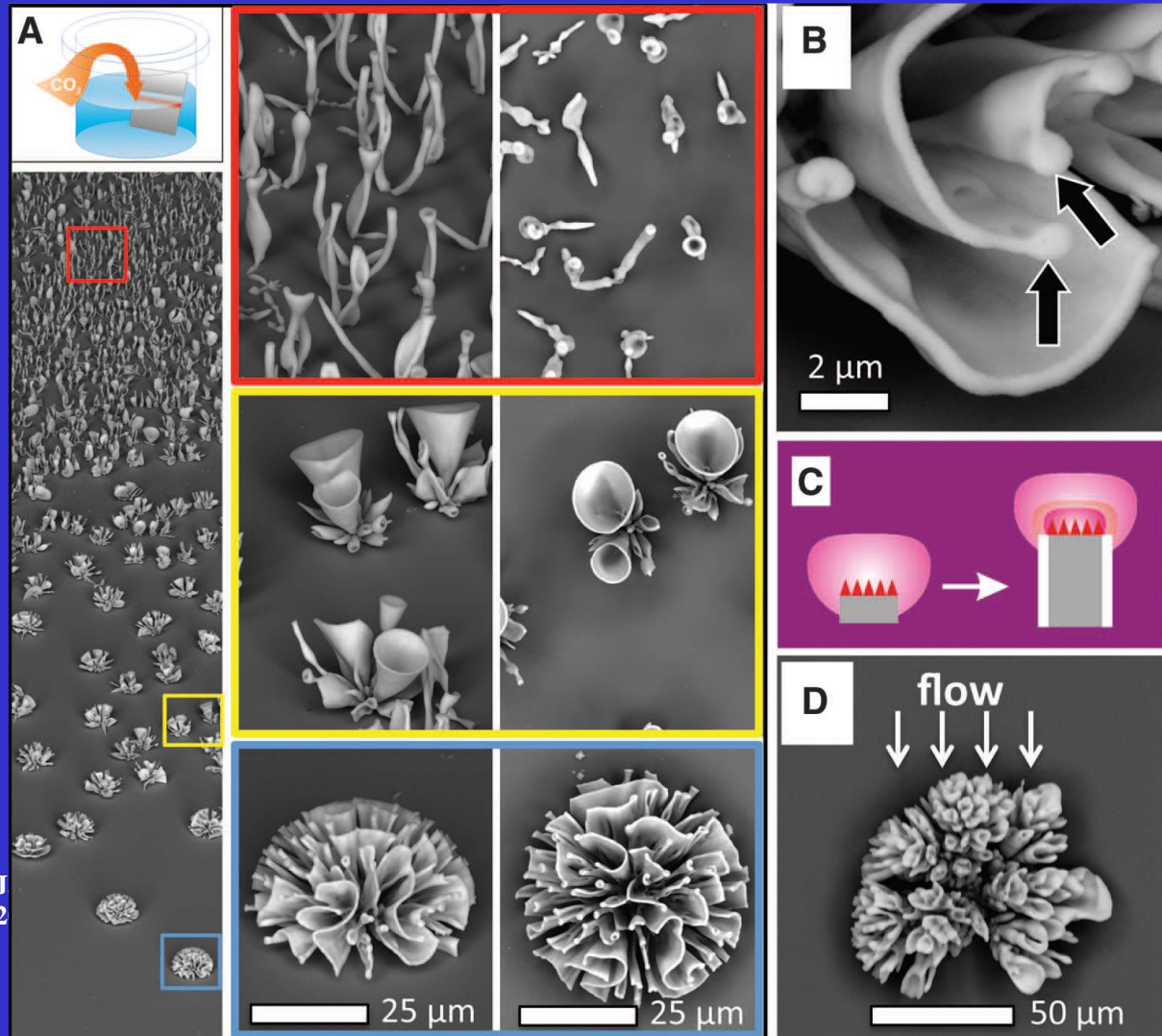
# Abiotic growth and form in crystals



Noorduyn et al,  
Science 20138



Leduc, The mechanism of  
life, 1911



# Growth and form in biomineralization

## On concretions, spicules, and specular skeletons

(Ch IX, D'Arcy Thompson, 1917)

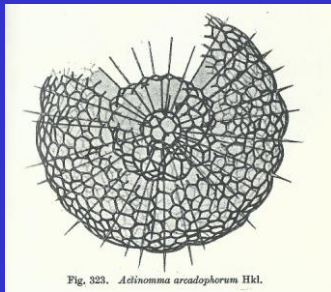


Fig. 323. *Actinomma arcadophorum* Hkl.

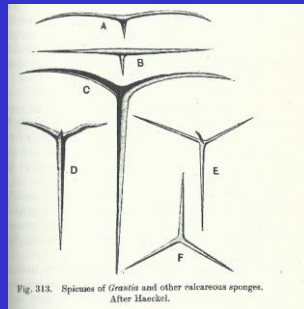


Fig. 313. Spicules of *Grania* and other calcareous sponges. After Haeckel.



Fig. 320. Arenaceous Foraminifera: *Astrochelis laevide* and *cretaria*. From Brady's *Challenger Monograph*.

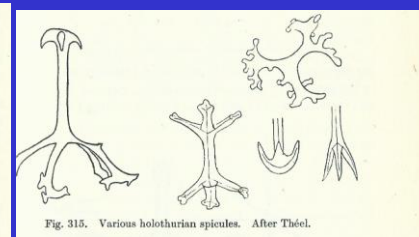


Fig. 315. Various holothurian spicules. After Théel.

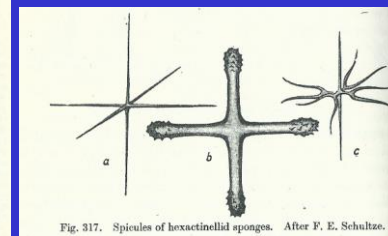


Fig. 317. Spicules of hexactinellid sponges. After F. E. Schultz.

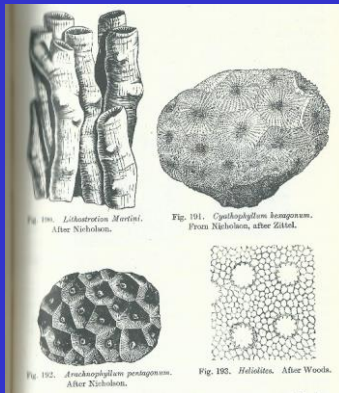


Fig. 188. *Lichastrea Morten*. After Nicholson.

Fig. 191. *Cyathophylax hamptoni*. From Nicholson, after Zittel.

Fig. 192. *Arachnophylax penagosum*. After Nicholson.

Fig. 193. *Heliolites*. After Woods.

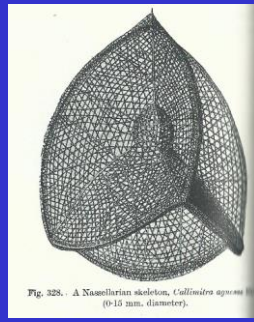


Fig. 228. A Nassariid sponge skeleton, *Callispira agrostis* (0.15 mm. diameter).

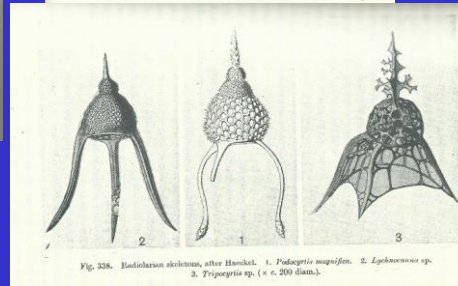


Fig. 338. Radiolarian skeletons, after Haeckel. 1. *Podocetrus magniflor*. 2. *Lophoceros* sp. 2. *Tripocetus* sp. (x c. 200 diam.).

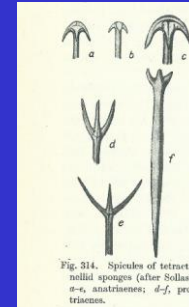
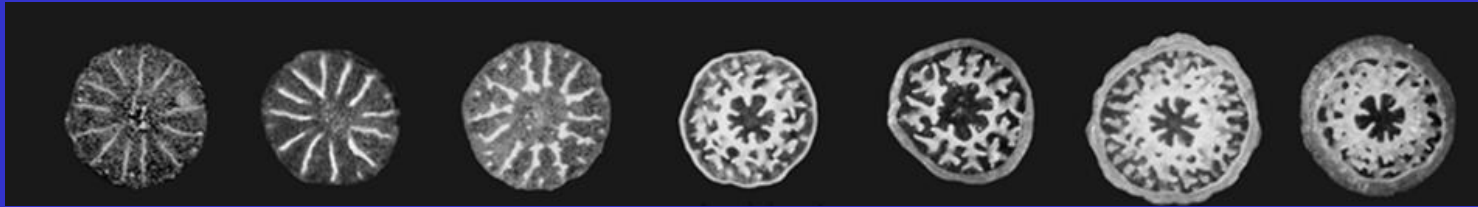


Fig. 314. Spicules of tetractinellid sponges (after Sollas). a-c, anastrisomes; d-f, pentactines.

# Biominingalization in the scleractinian coral *Acropora*



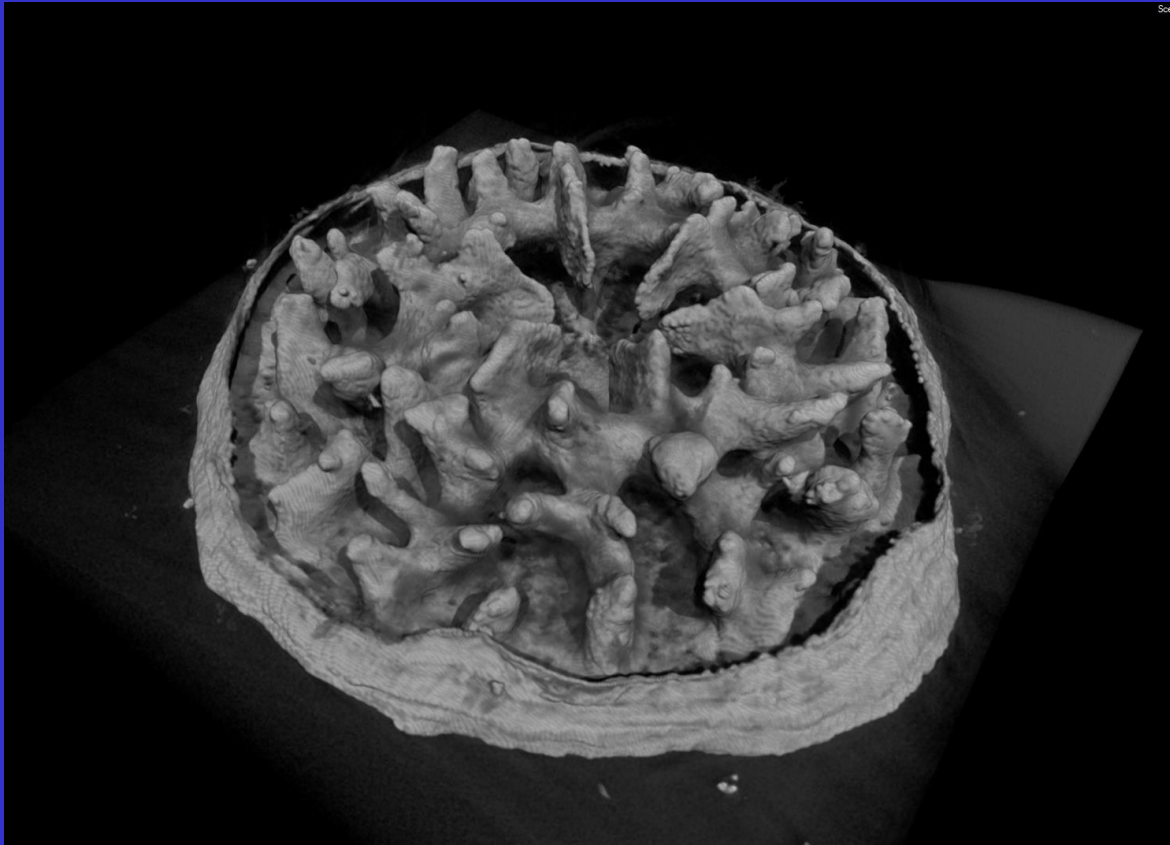
Development larval Skeleton in the coral *Acropora millepora* (Miin et al, unpublished)



The scleractinian coral *Acropora millepora*  
(Great Barrier Reef Australia)

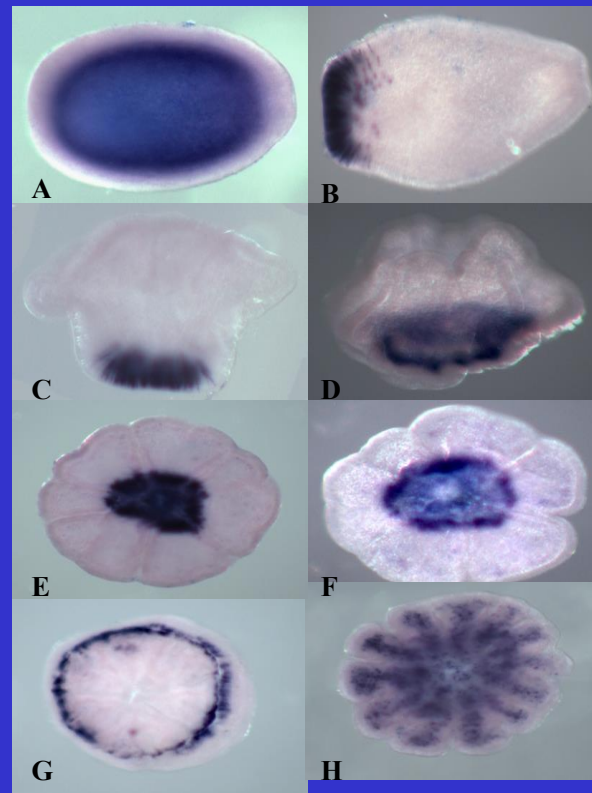
# Biom mineralization in the scleractinian coral *Acropora*

Micro CT scan of a larval skeleton of  
the scleractinian coral *Acropora millepora*



# Biominingeralization in the scleractinian coral *Acropora*

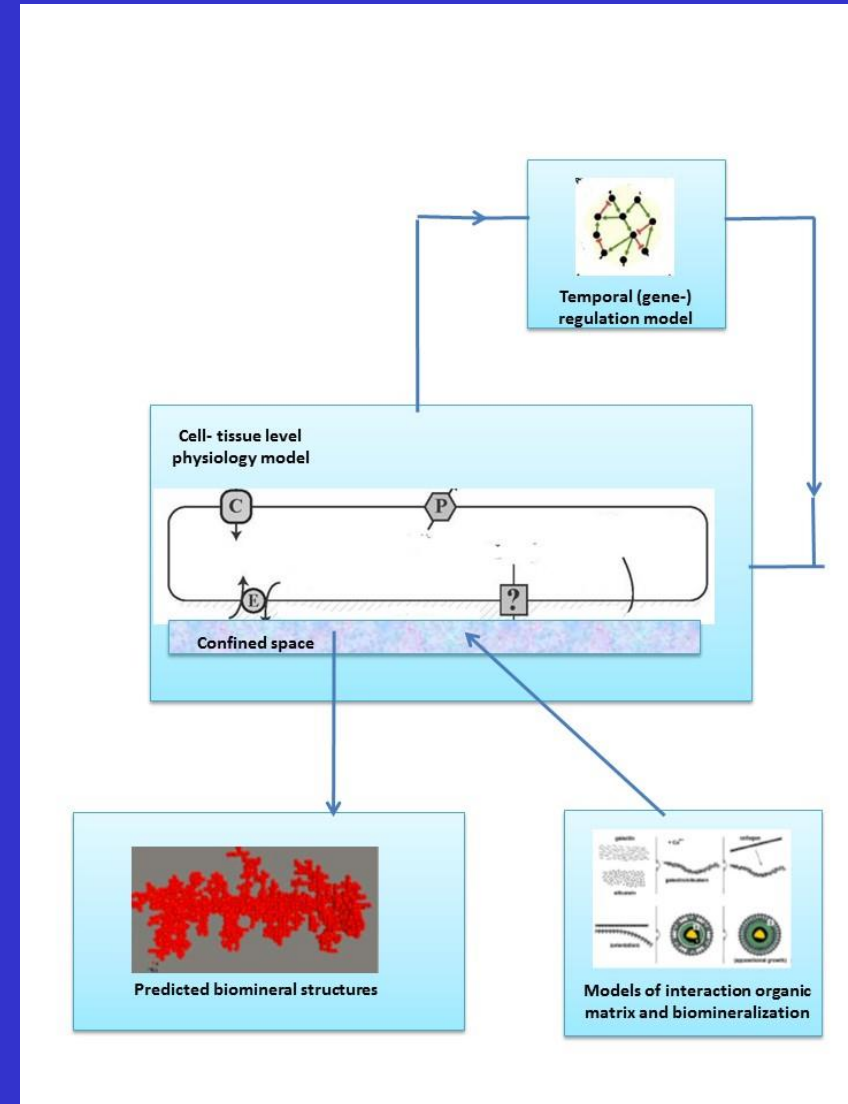
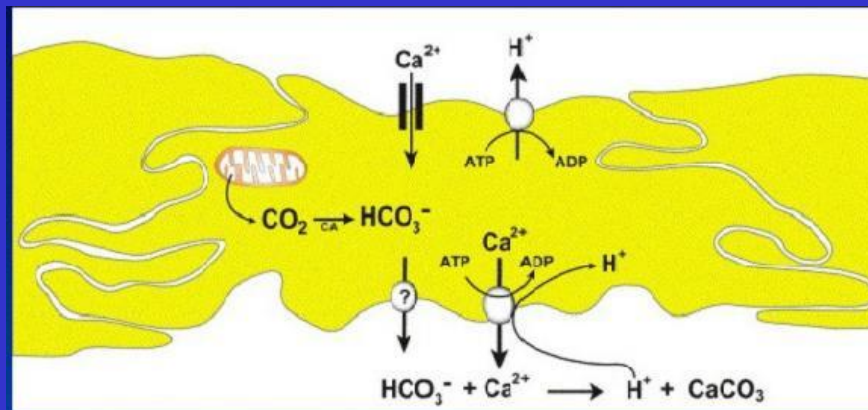
Spatio-temporal gene expression in the coral *Acropora millepora*  
(6-12 folded symmetry)



Am Galaxin-like

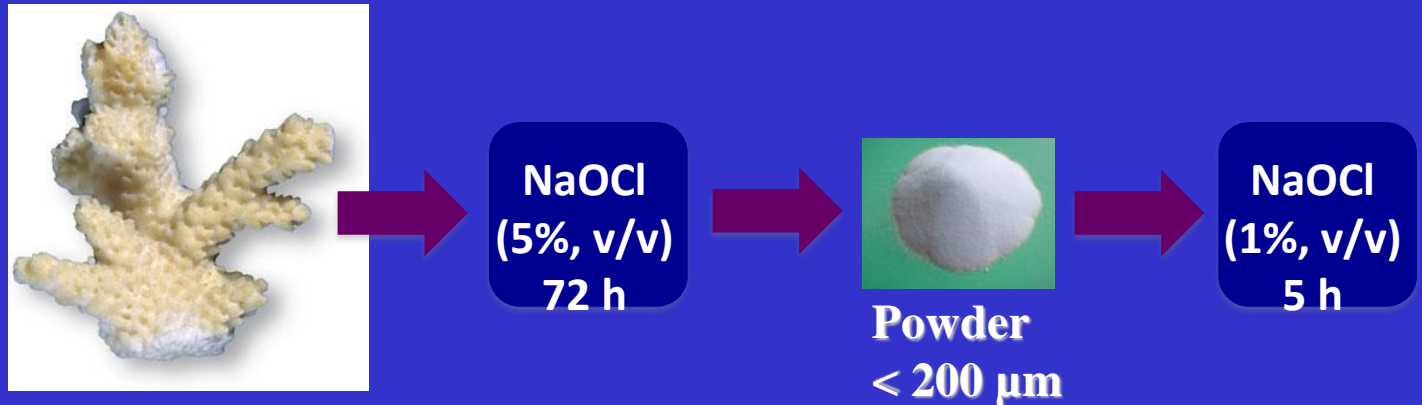
# Biom mineralization in the scleractinian coral *Acropora*

biomineralization in a confined space

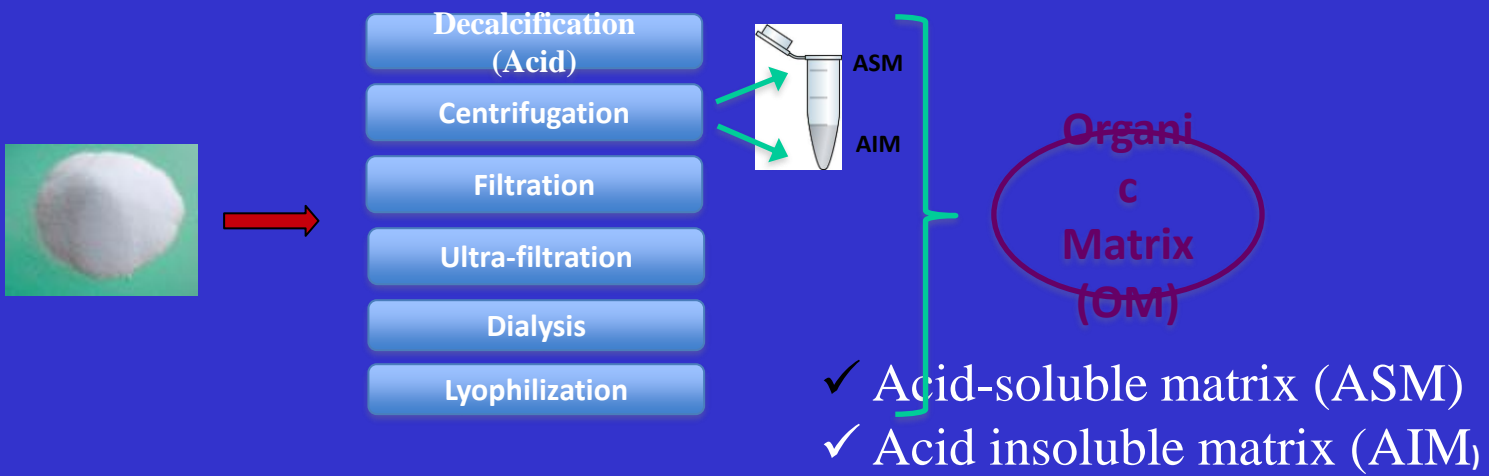


# Organic matrix extraction in the scleractinian coral *Acropora*

*millepora* (Ramos-Silva et al., Molec. Biol. Evol., 2013)

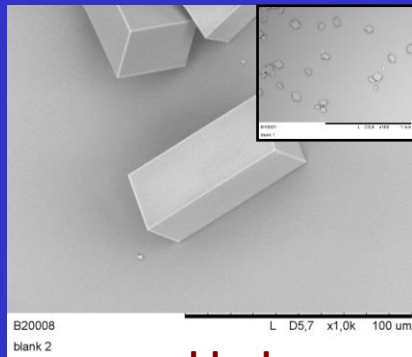


The organic matrix extraction:

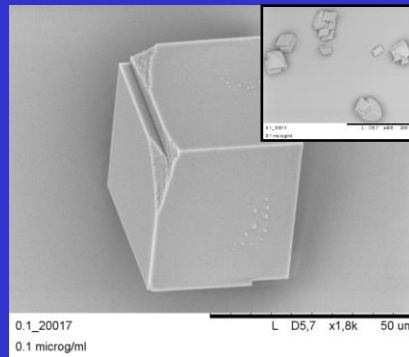


# Organic matrix extraction in the scleractinian coral *Acropora millepora*

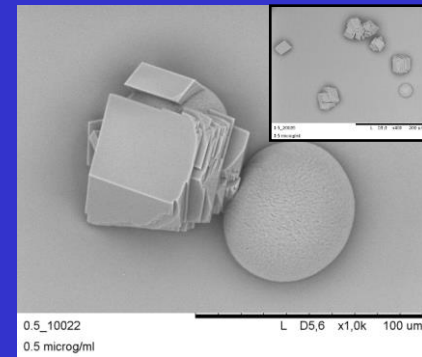
*In vitro* interaction of Acid Soluble Matrix with  $\text{CaCO}_3$   
(Ramos-Silva et al., Molec. Biol. Evol., 2013)



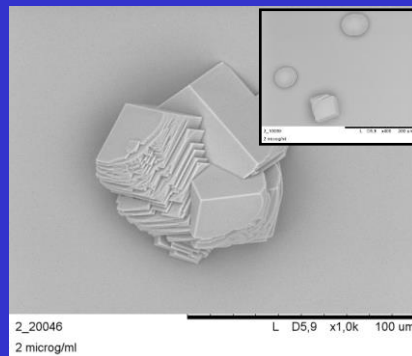
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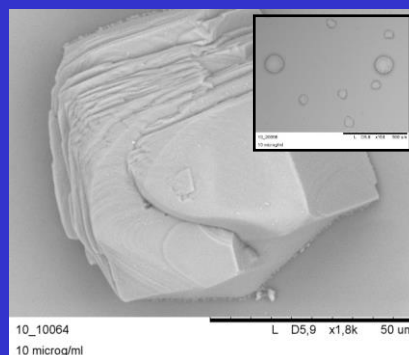
**0.1**



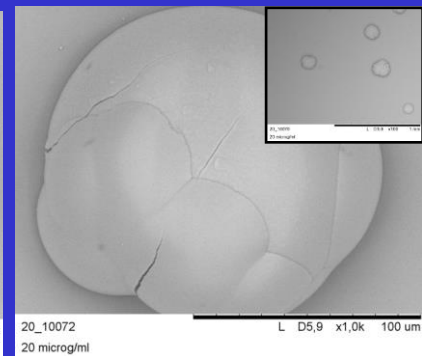
**0.5**



**2.0**



**10**

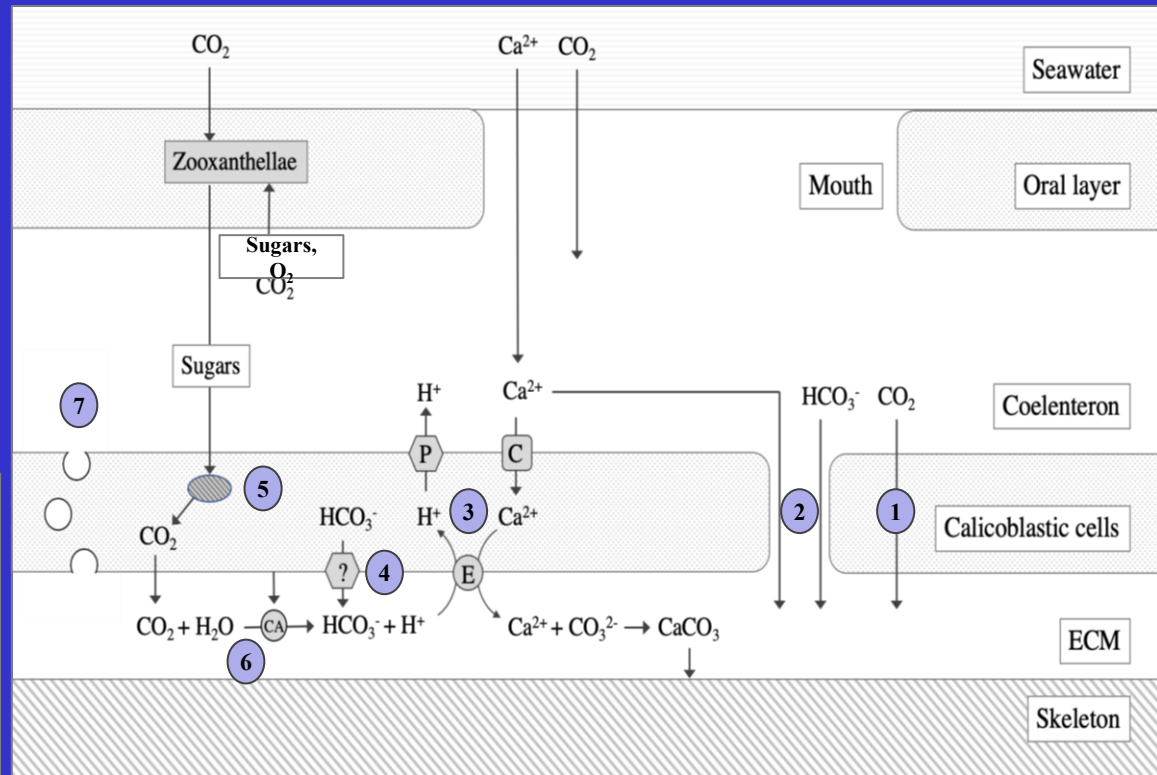
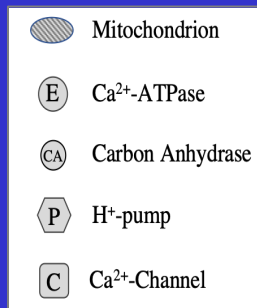


**20**

# Modelling calcification physiology in the confined space in corals: existing hypotheses

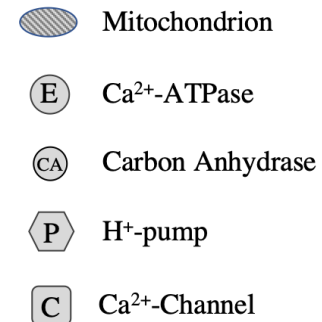
(Willard et al., J. Theor. Biol. Accepted for pub.)

- 1. Diffusion of CO<sub>2</sub>
- 2. Paracellular transport
- 3. Transcellular transport using ion-transporters 1 2 3 4 5
- 4. HCO<sub>3</sub><sup>-</sup> Transporter 5 6
- 5. Respiration 5
- 6. Carbonic Anhydrase 1 7 8
- 7. Vesicles 9



# Modelling calcification physiology in the confined space in corals: Light Enhanced Calcification

(Willard et al., J. Theor. Biol. Accepted for pub.)

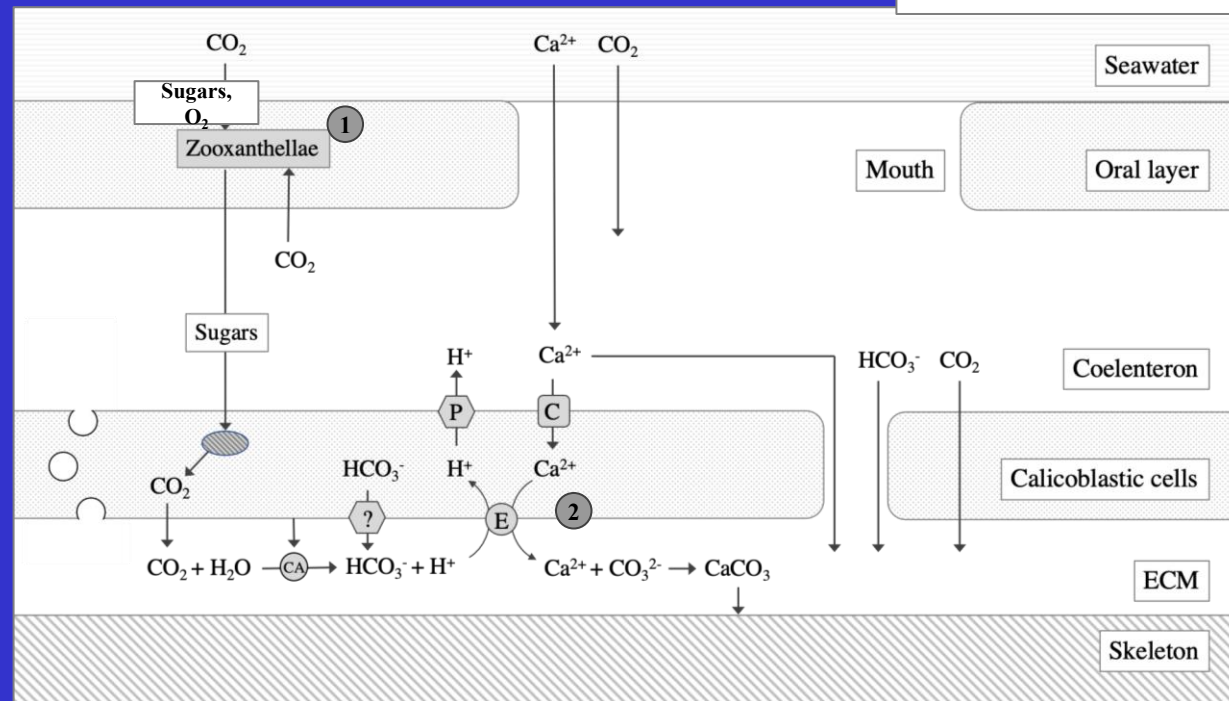


Calcification rate is known to increase in light conditions<sup>1 2 4</sup>

## 1. Photosynthesis in zooxanthellae

- 1a. More DIC available due to increased metabolism<sup>1 3</sup>
- 1b. More energy available in Calicoblastic cells for active transport and excreting OM<sup>1 2 3</sup>

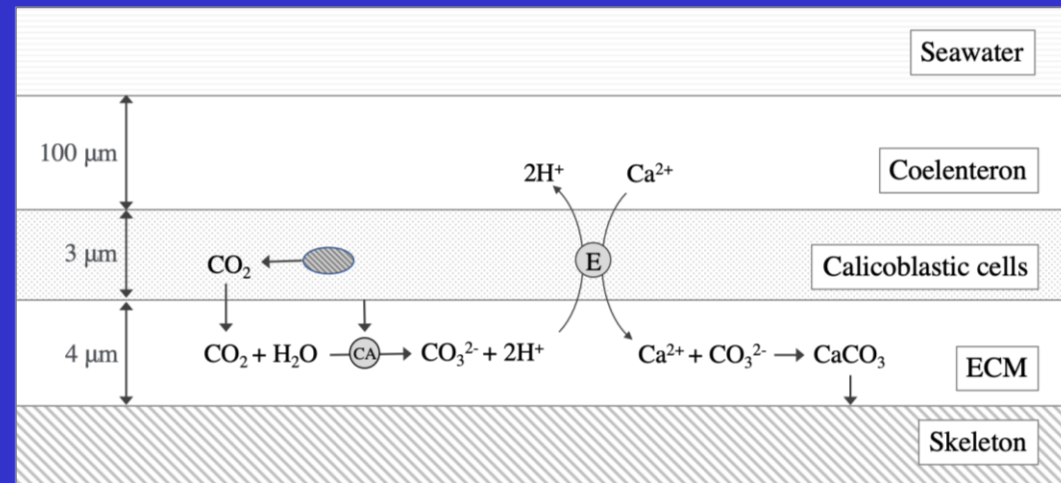
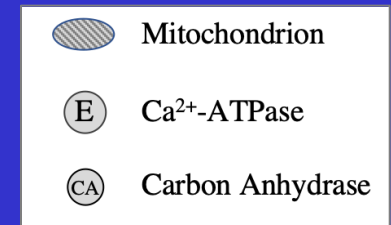
## 2. Ca<sup>2+</sup>-ATPase light sensitive<sup>2</sup>



# Modelling calcification physiology in the confined space in corals: Light computational model

(Willard et al., J. Theor. Biol. Accepted for pub.)

- Spatial Reaction-Diffusion model
  - Including  $\text{CO}_2$ -chemistry based on the system of Zeebe (2001)
- Simple topology
  - Cell membranes only permeable by  $\text{CO}_2$
  - Calcification at skeleton boundary
  - Seawater constant concentrations



# Modelling calcification physiology in the confined space in corals: computational model

(Willard et al., J. Theor. Biol. Accepted for pub.)

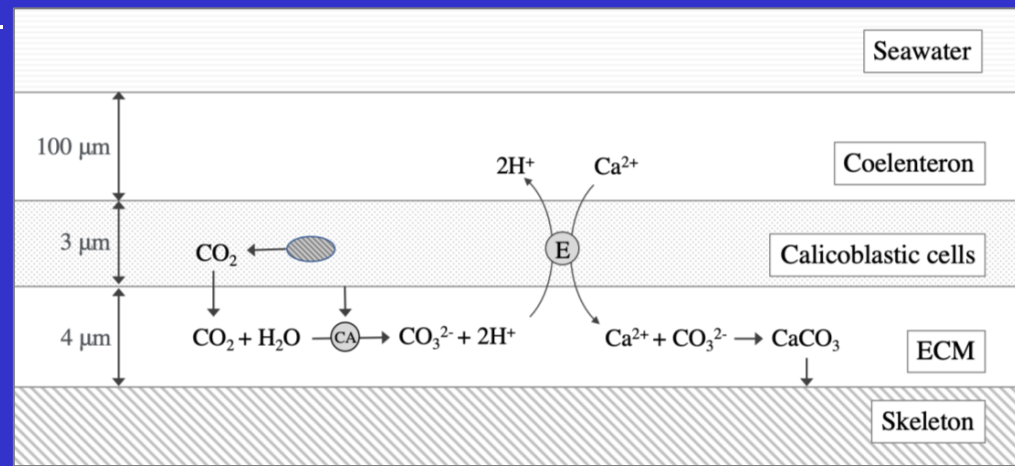
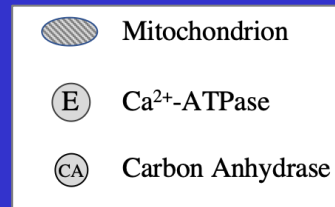
Chemical composition ECM is controlled by

- Respiration in Calicoblastic cells <sup>5</sup>
- Ion transport of  $\text{Ca}^{2+}$ -ATPase <sup>1 2 3 4 5</sup>
  - Modelled as flux over Calicoblastic cells

$$J_{\text{ex}} = J_{\text{ex}}^{\text{max}} \frac{[\text{H}^+]^2 [\text{Ca}^{2+}]_{\text{cell}}}{K_{\text{ex}} + [\text{H}^+]^2 [\text{Ca}^{2+}]_{\text{cell}}}$$

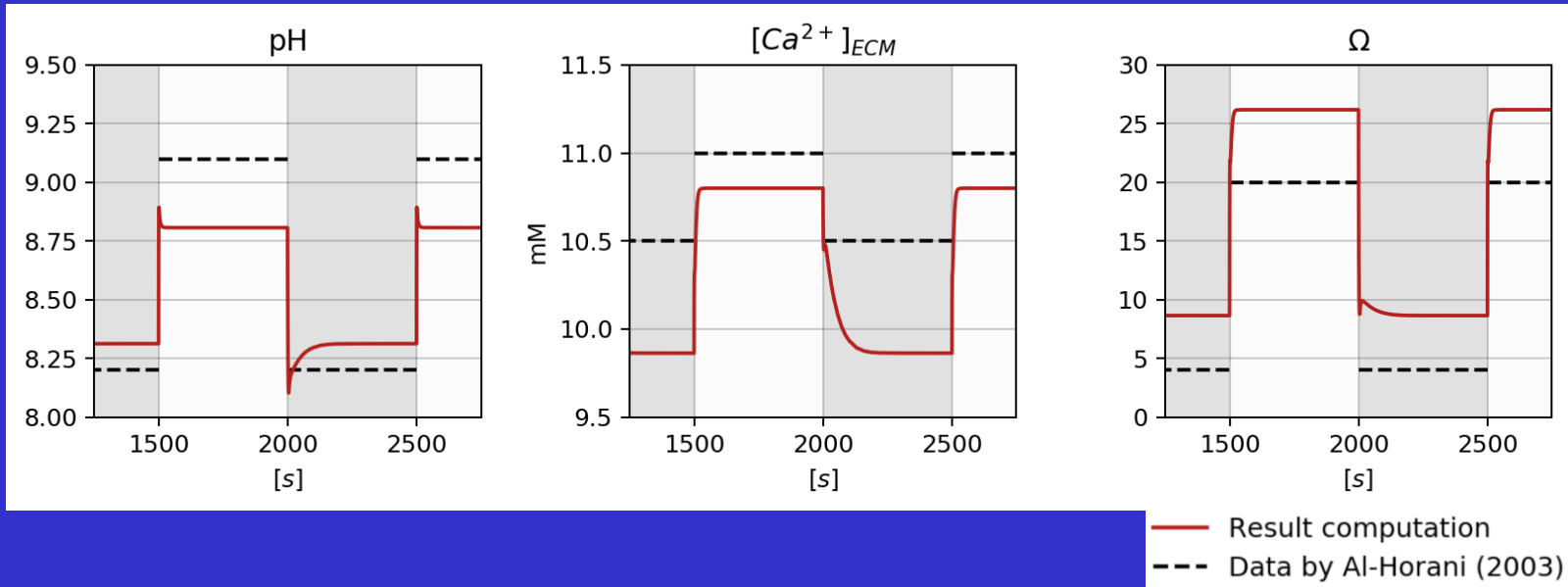
- Carbonic Anhydrase <sup>1 7 8</sup>

$$V_{\text{CA}} = E(\text{CA})_{\text{tot}} k_{\text{cat}} \frac{[\text{CO}_2]}{K_{\text{CA}} + [\text{CO}_2]}$$

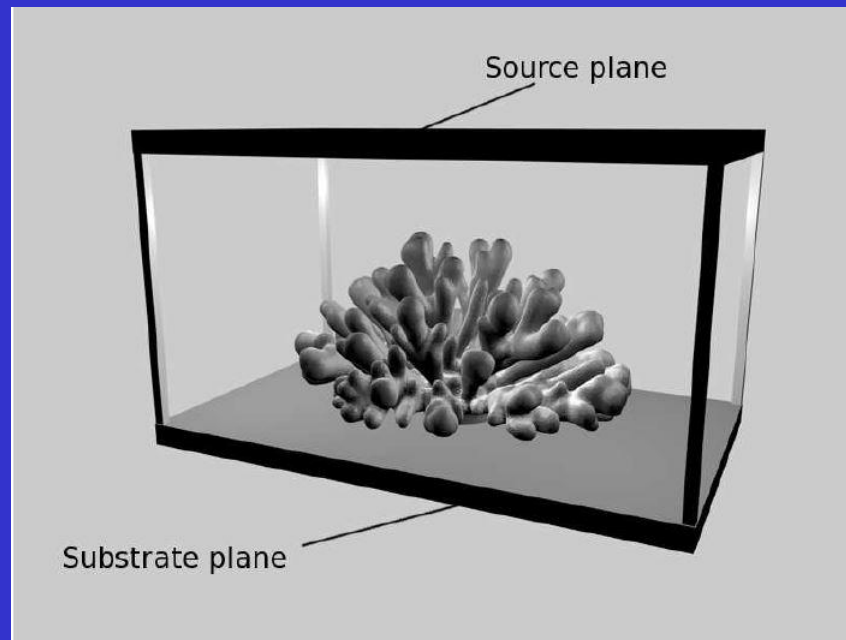


# Modelling calcification physiology in the confined space in corals: computational model vs experiments

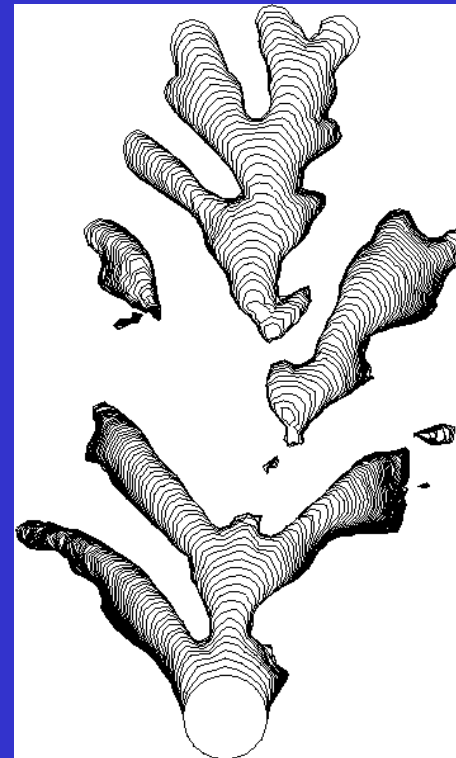
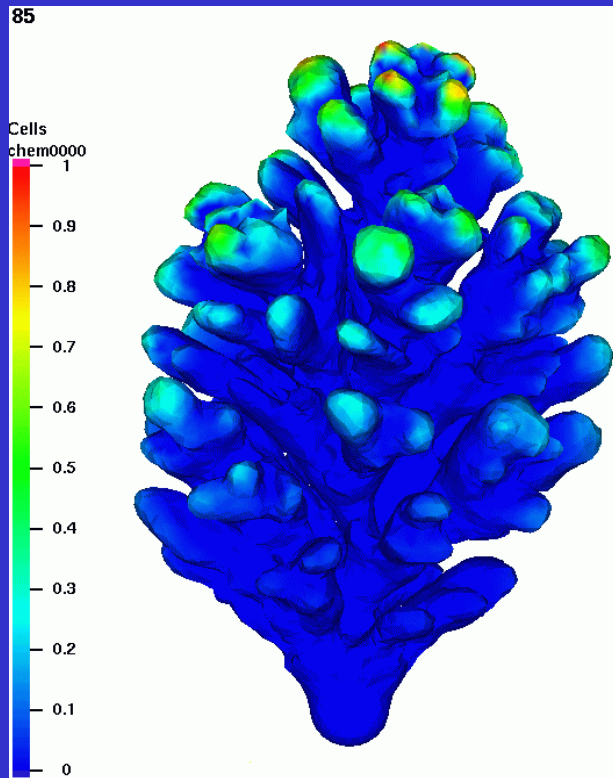
(Willard et al., J. Theor. Biol. Accepted for pub.)



Macroscopic modelling of growth and form of corals:  
Simulation setup. A growing object bounded by the simulation box  
with a source plane on the top and the substrate plane at the bottom

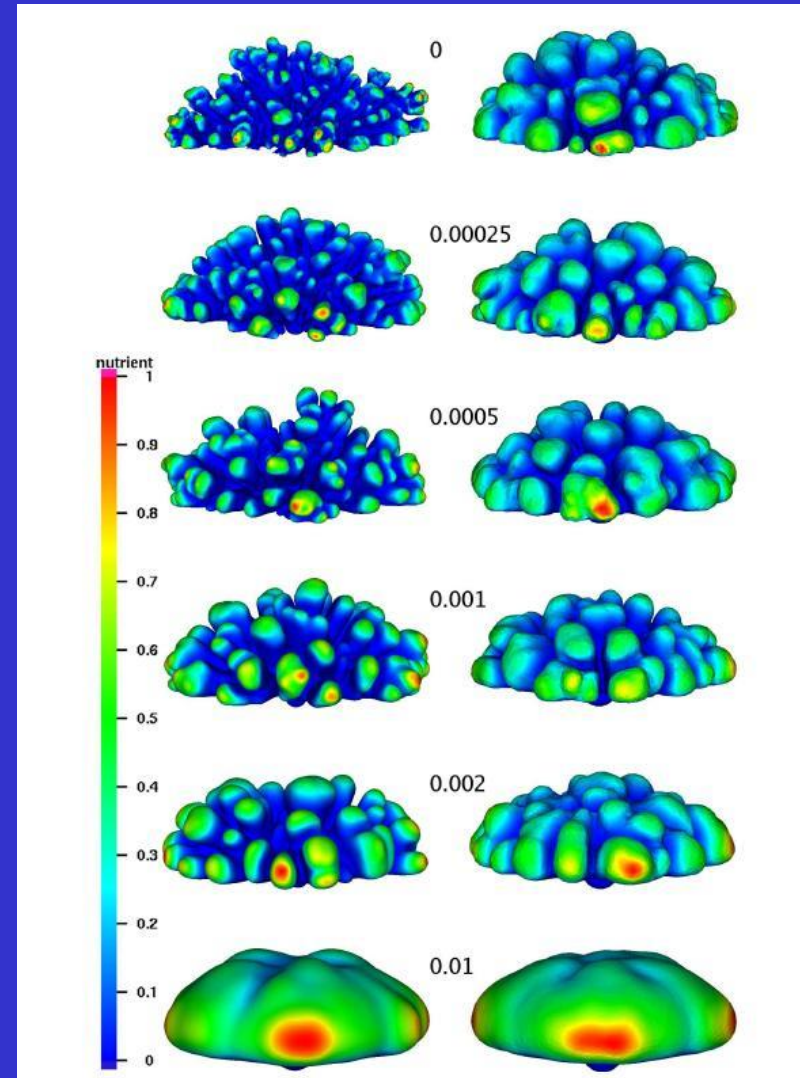


# Macroscopic modelling of growth and form of corals: Simulated accretive growth: layered deposition of material (diffusion limited growth)



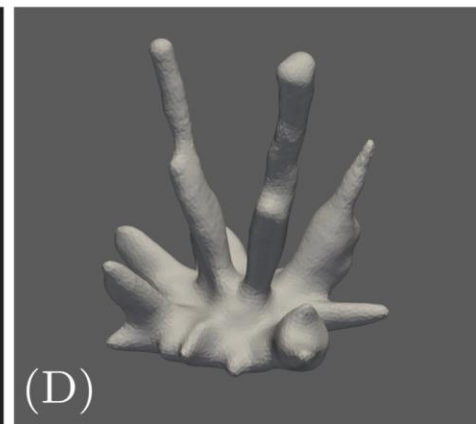
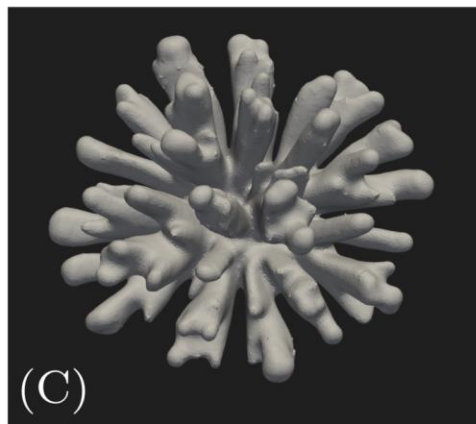
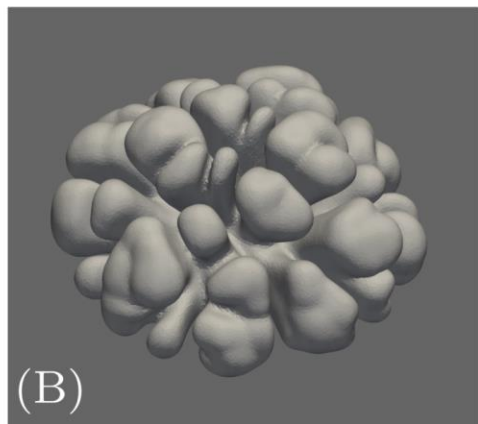
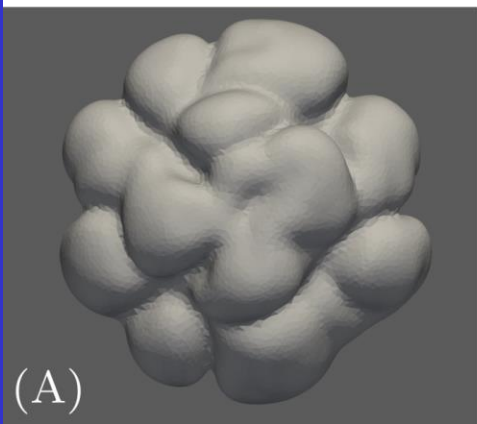
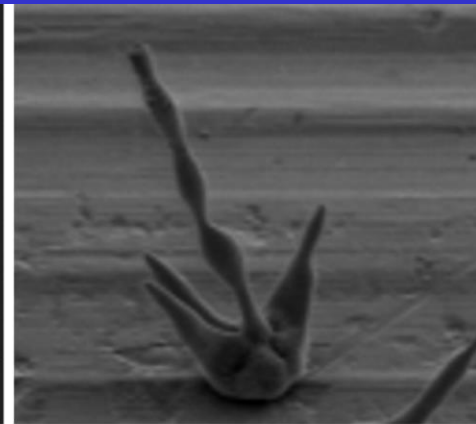
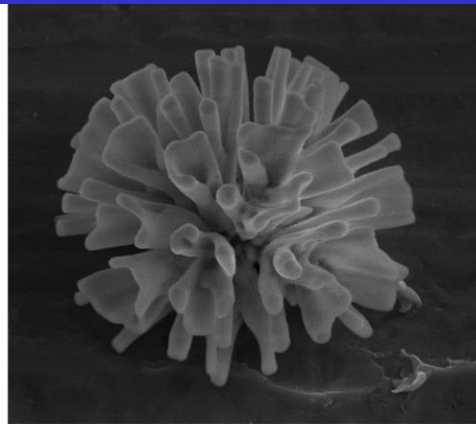
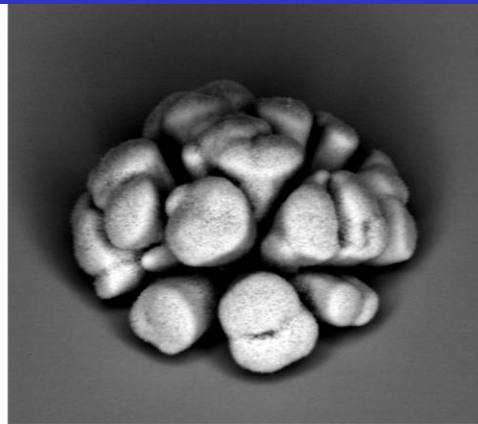
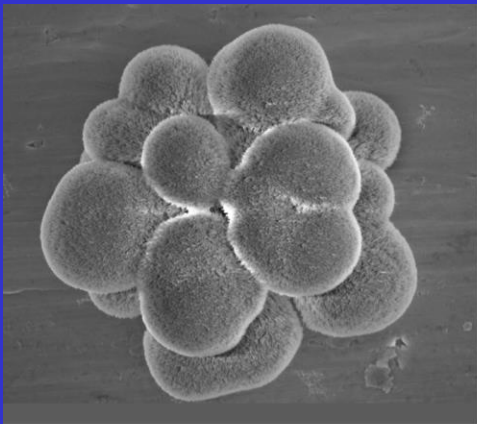
# Macroscopic modelling of growth and form of corals: Simulated diffusion limited accretive growth (Kaandorp, ISRN biomath., 2013)

Diffusion  
limited growth +  
surface  
diffusion: from  
top to bottom  
amount of  
surface diffusion  
is increased



# Macroscopic modelling of growth and form of crystals

Comparison of real and simulated  $\text{BaCO}_3$   $\text{SiO}_2$  crystals



(A)

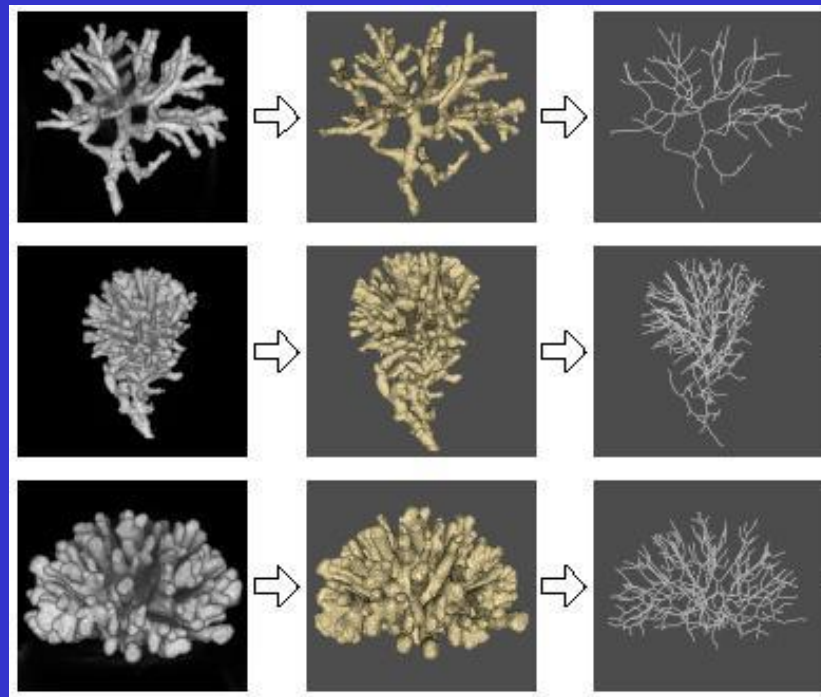
(B)

(C)

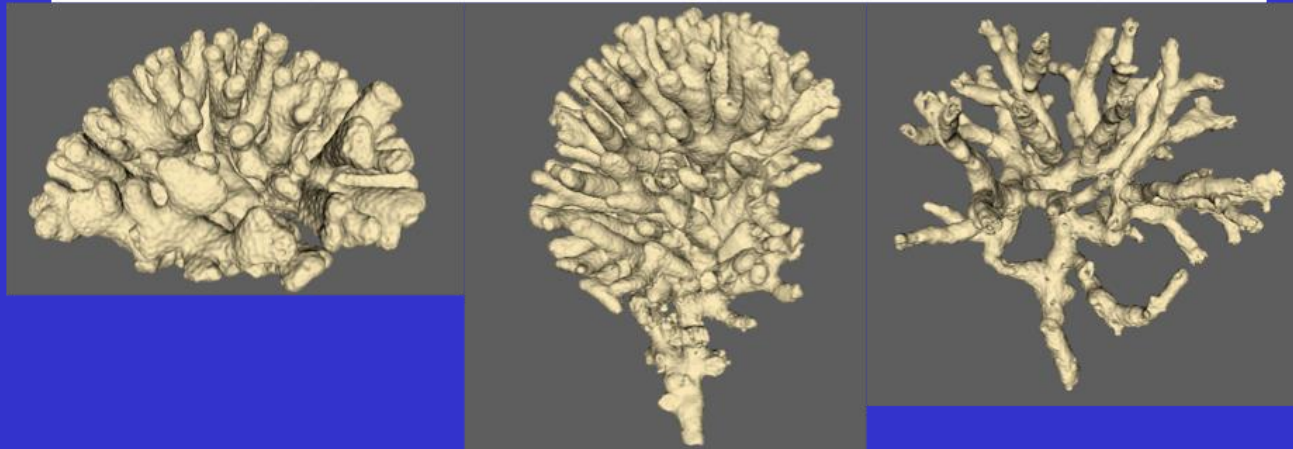
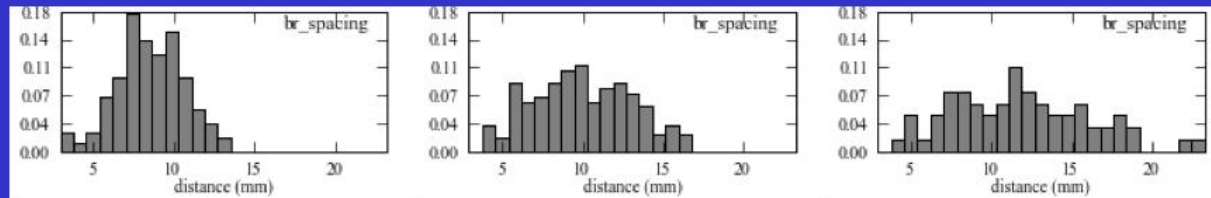
(D)

# Quantifying complex-shaped branching growth forms

Morphological Skeleton in a 3D images of the coral *Madracis mirabilis* (K. Kruszynski et al., Coral Reefs 2007)

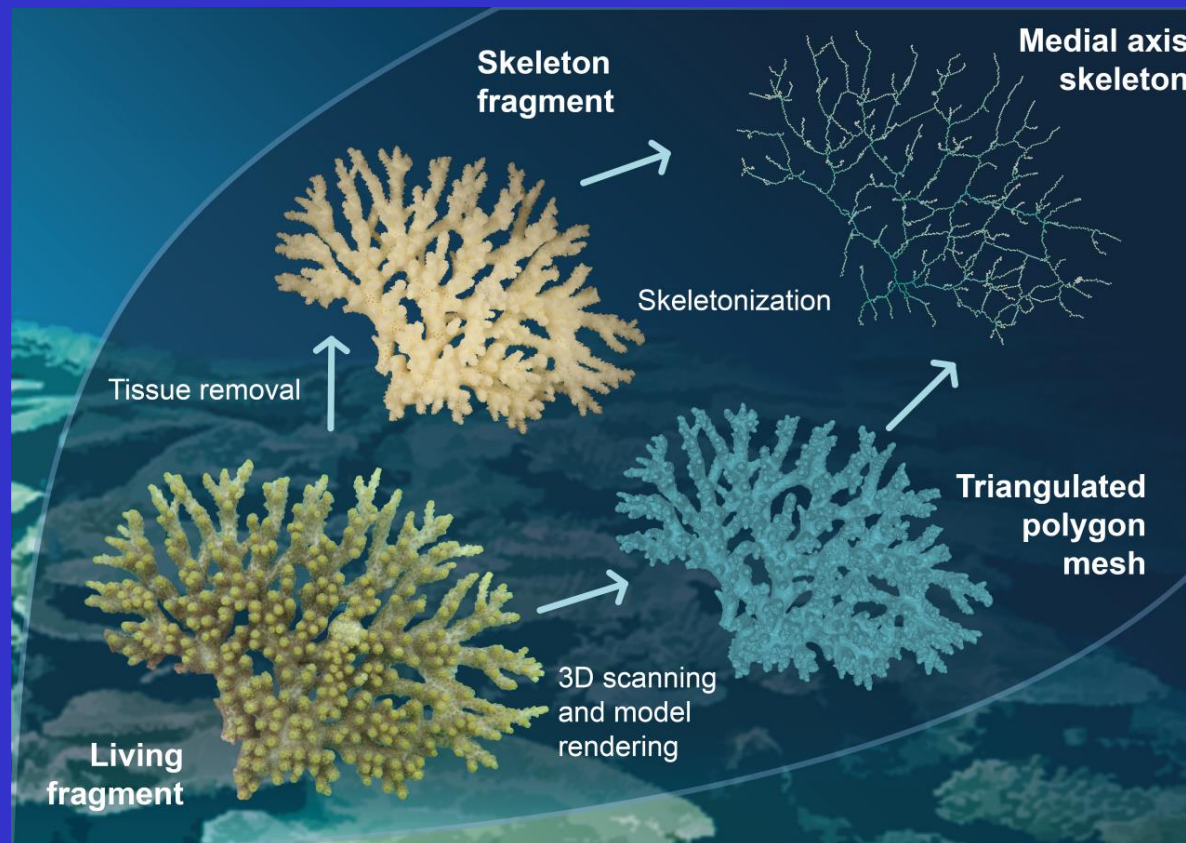


# Quantifying complex-shaped branching growth forms: Coral Morphometrics



# Quantifying complex-shaped branching growth forms: Coral Morphometrics

(Ramirez-Portilla et al., Frontiers in Mar. Sci, 2022)



# Conclusions and Open Questions

- 1. We do know the organic matrix involved in biomineralization in *Acropora millepora*, but we don't what this organic matrix is doing..
- 2. We have initial model available of the confined space (the Extra Cellular matrix in *Acropora*), many details are still missing here
- 3. We have initial models how gene regulation is controlling body plan formation in a sea anemone
- 4. How do we couple 1., 2. and 3.?
- 5. We have developed macroscopical models of growth and form of corals, we can capture some growth forms of corals. In these models levels 1-4 are still missing
- 6. We have developed macroscopical models of growth and form of the  $\text{BaCO}_3$  crystals, we can capture some growth forms, but not all
- 7. Can we go from abiotic growth models towards growth models including biomineralization?

# Acknowledgements

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**Paula Ramos-Silva**



**Helena Willard**



**Inge Bieger**



**Catalina Ramirez**



**Wim Noorduyn**

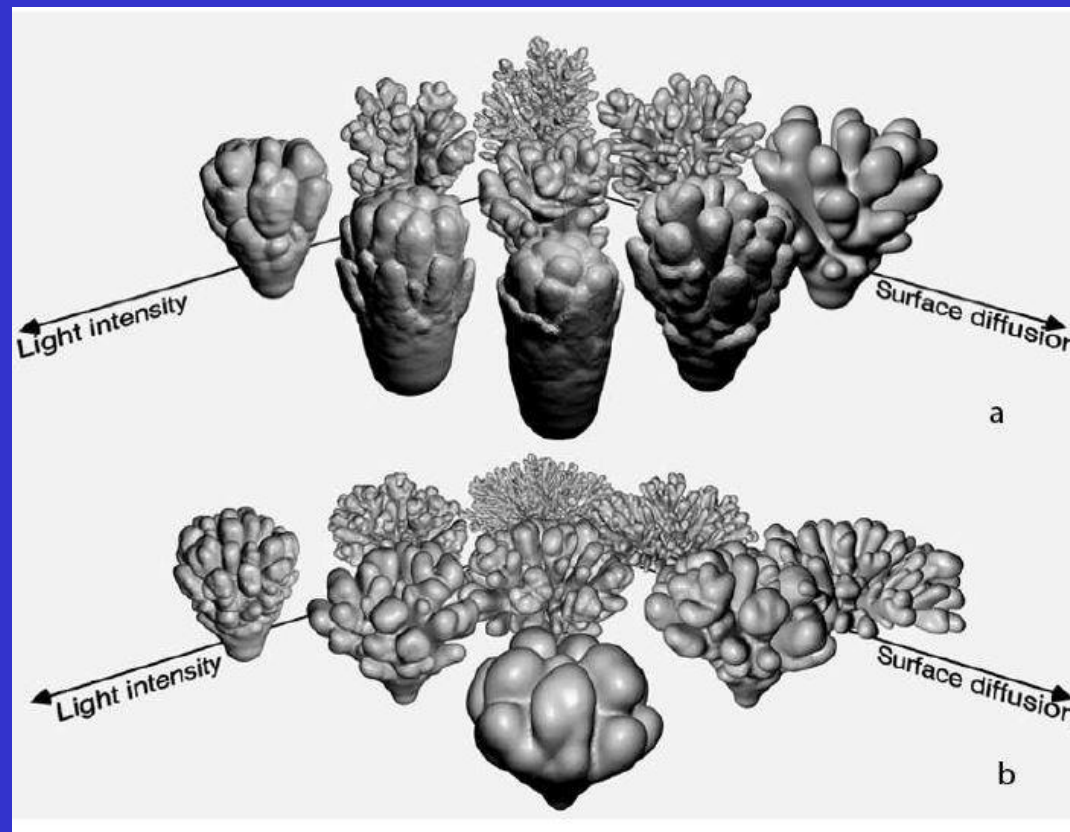


**Wouter Meering**



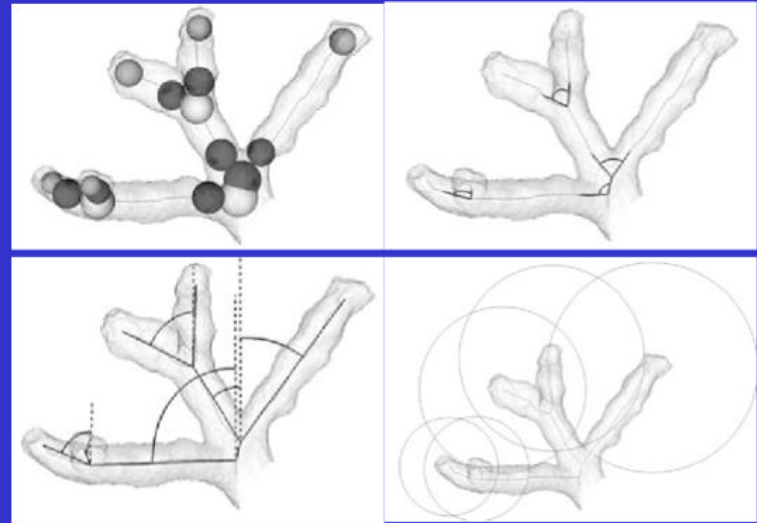
**Maud Bremer**

# Simulated Morphospace (Filatov et al, Proc Roy Soc B, 2010)

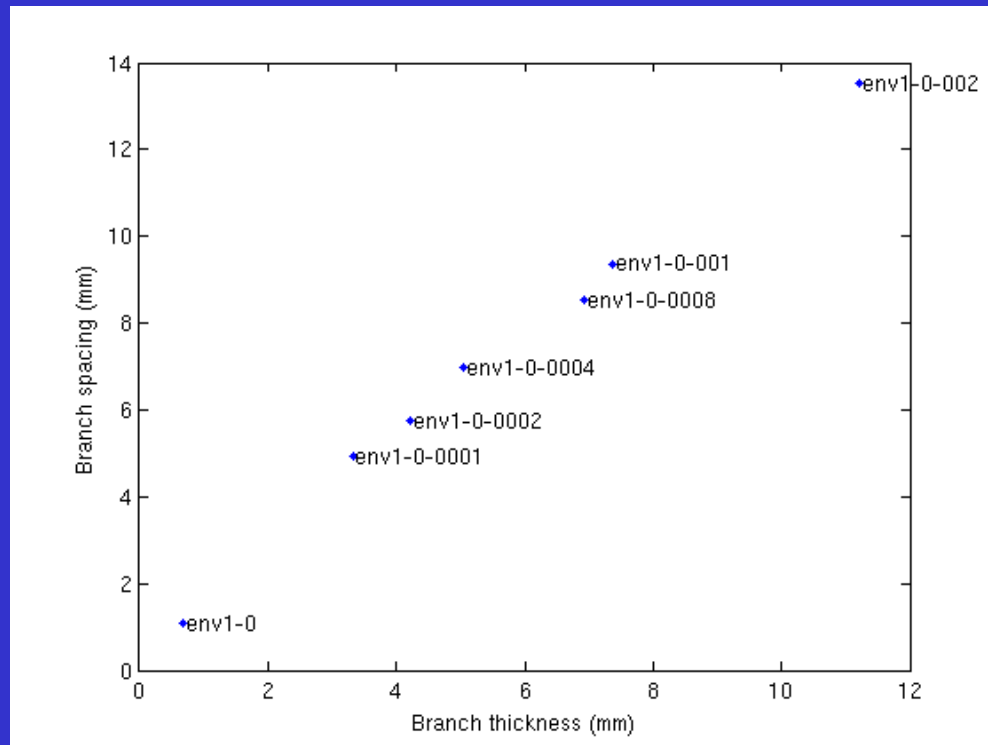


# Coral Morphometrics

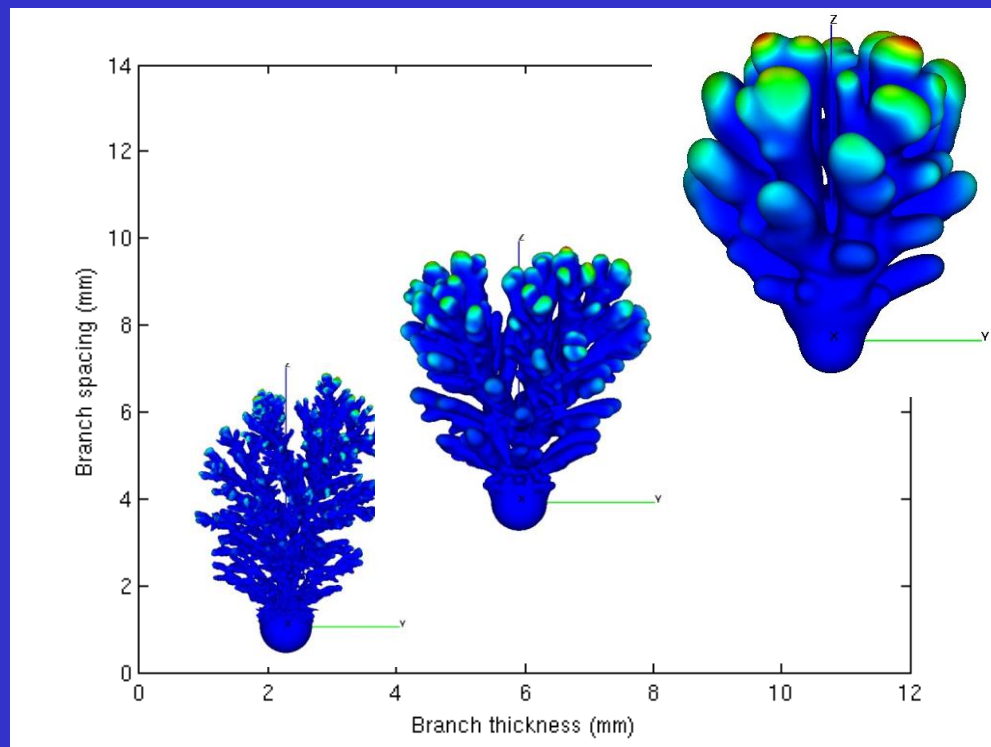
- ◆ Branch thickness
- ◆ Branching angle
- ◆ Branch spacing



# Comparison of simulated forms



# Comparison of simulated forms



# Quantitative comparison simulated and real growth forms *Madracis* sp.

