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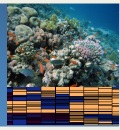

Royal Holloway University of London

The State of the Art in Carbonate Numerical Stratigraphic Forward Modelling

Peter Burgess
Dept. Earth Sciences,
Royal Holloway University of London, UK

With contributions from Chris Jenkins, Donald Potts, Rick Sarg and Dave Budd

CARBONATE FOCUSED RESEARCH GROUP

Group aim:

- To identify and address grand challenges for fundamental research on ancient and recent carbonate systems

To be achieved by:

- Creation of next generation of numerical carbonate process models under the umbrella of the CSDMS initiative
- Creation of supporting carbonate systems databases

Assuming that:

- Open-source numerical models and associated quantitative datasets can be state-of-the-art repositories for our knowledge of how carbonate systems work
- Models can be useful experimental tools applied to develop and enhance carbonate knowledge.

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CARBONATE FOCUSED RESEARCH GROUP

Peter Burgess, (Chair) Royal Holloway University of London
Andrew Barnett, BG Group
David Budd, University of Colorado
Govert Buijs, ConocoPhillips
Bob Demicco, Binghamton University
Carl Drummond, Indiana University-Purdue University Fort Wayne
Evan Franseen, University of Kansas
Ned Frost, ConocoPhillips
Xavier Janson, University of Texas at Austin
Chris Jenkins, University of Colorado
Gareth Jones, Chevron Energy Technology Company
Albert Kettner, CSDMS, INSTAAR, University of Colorado
H. Richard Lane, U.S. National Science Foundation
Patrick Lehmann, ExxonMobil Exploration Company
Mingliang Liu Auburn, University, School of Forestry and Wildlife Sciences
William A. Morgan, ConocoPhillips
Mohamad Mehdi Nasr Azadani, University of California at Santa Barbara
Gene Rankey, University of Kansas
Bernhard Riegl, Nova Southeastern University, National Coral Reef Institute
Rick Sarg, Colorado School of Mines
Fiona Whitaker, University of Bristol
Bruce Wilkinson, Syracuse University

N=22

- Issues: platforms & prediction, complexity and heterogeneity
  - Platform types and facies prediction
  - Origins of heterogeneity in carbonates
  - Other issues…
- Review of current models
  - Depositional models
  - Diagenetic models
- New modelling directions
  - Cellular automata
  - Population modelling
- C-FRG research plans

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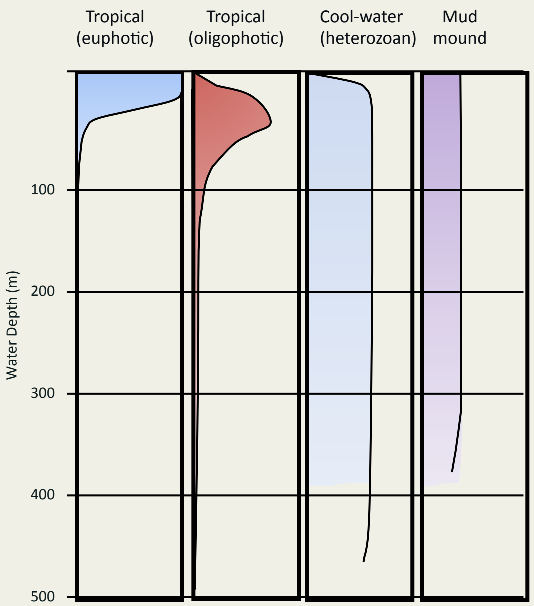
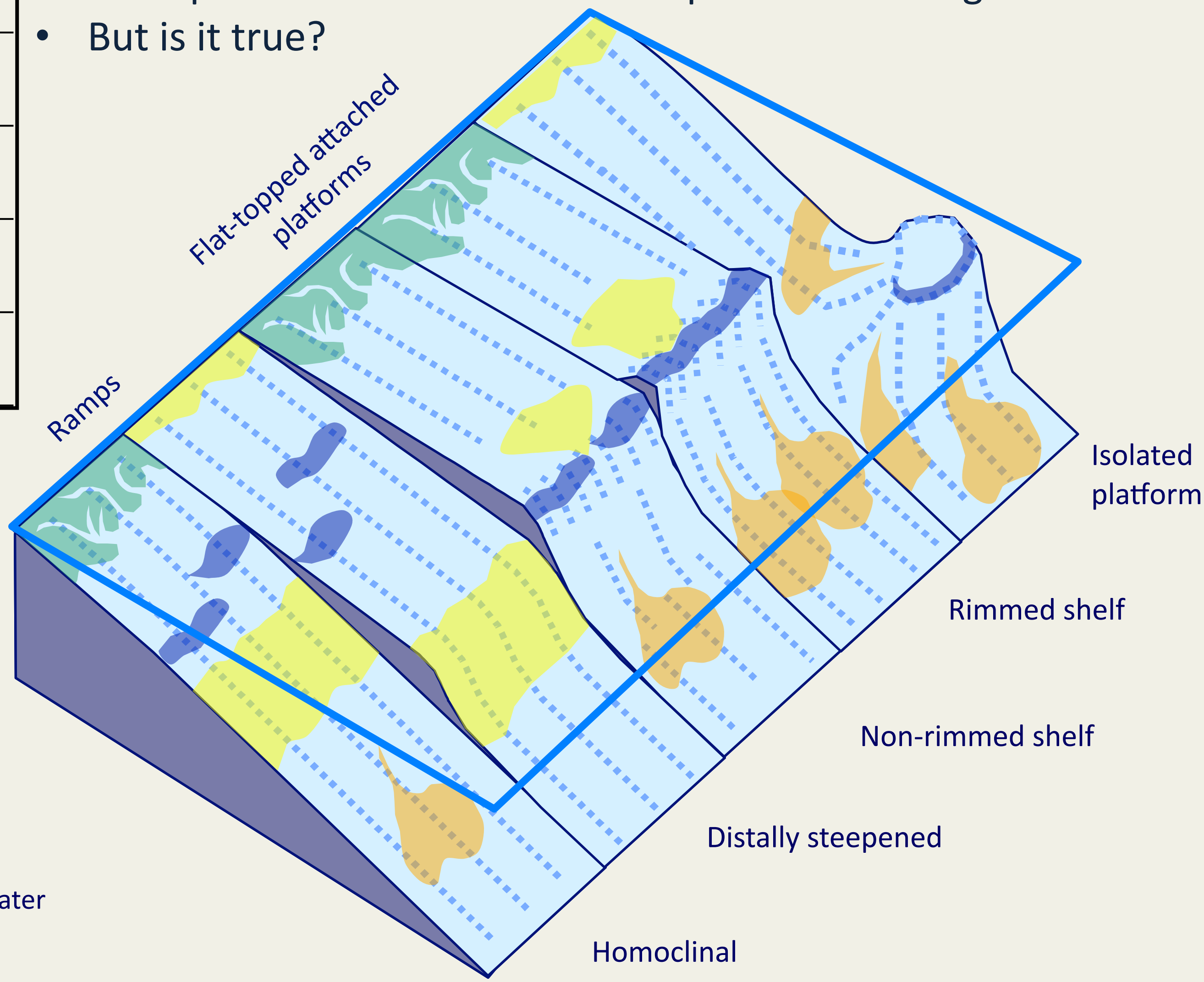
PLATFORM TYPE & FACIES PREDICTION



- Standard paradigm: carbonate factory type, represented by carbonate production profile , controls platform architecture
- Most predictions of facies and sequence strat hinge on this
- But is it true?



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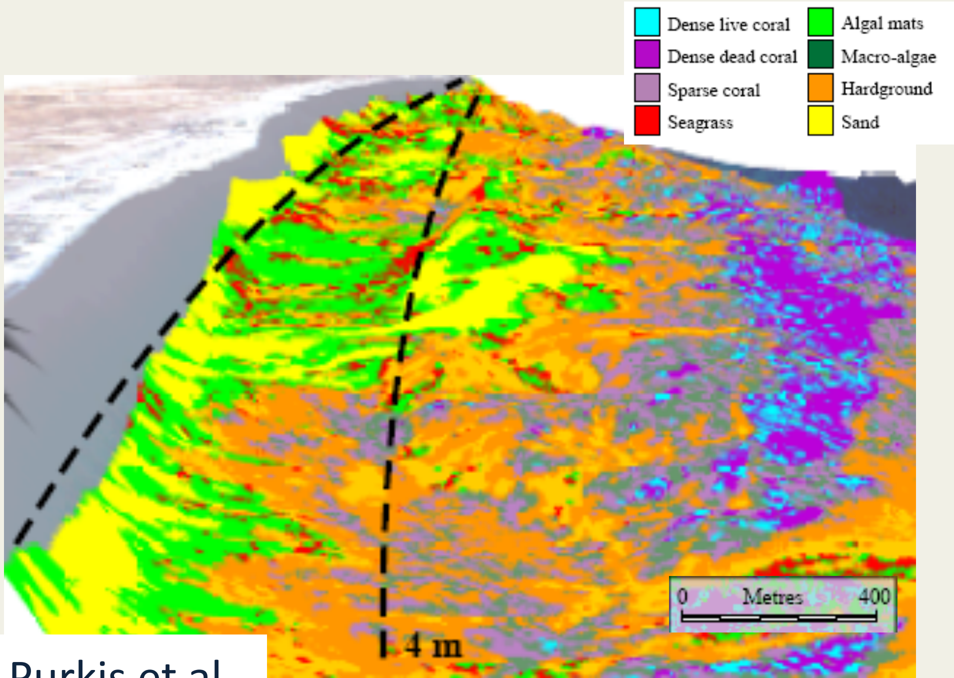
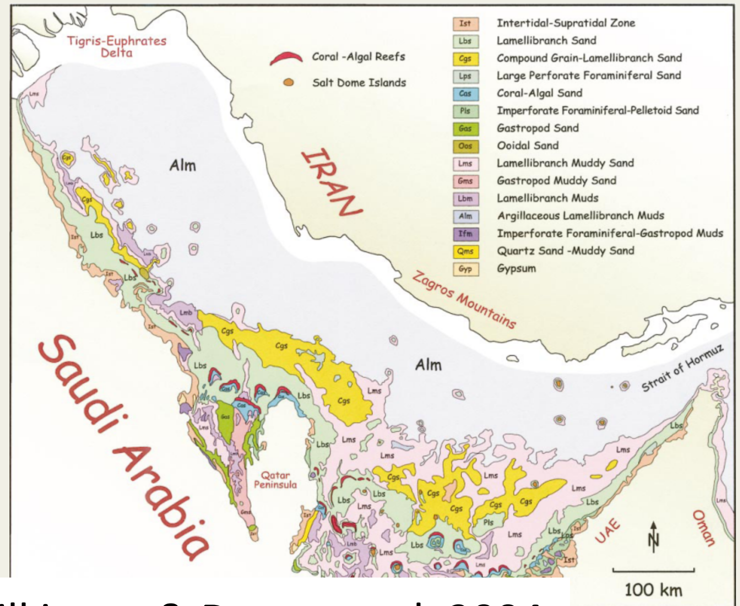
ORIGINS OF HETEROGENEITY

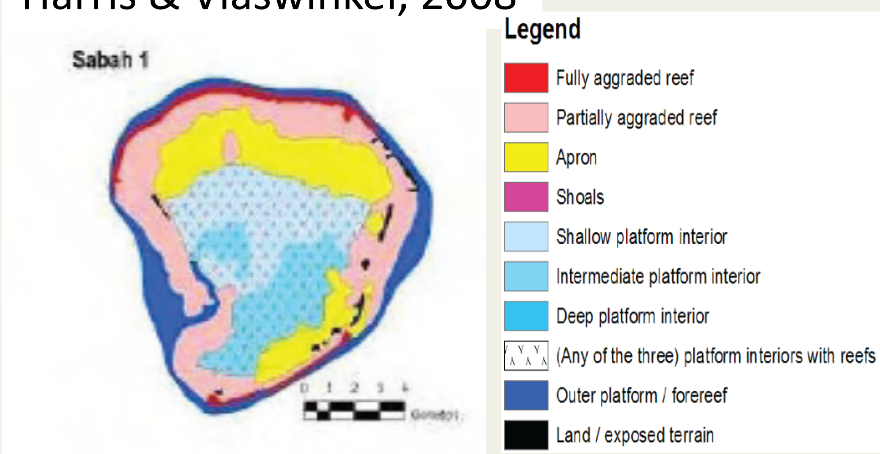


Purkis et al.



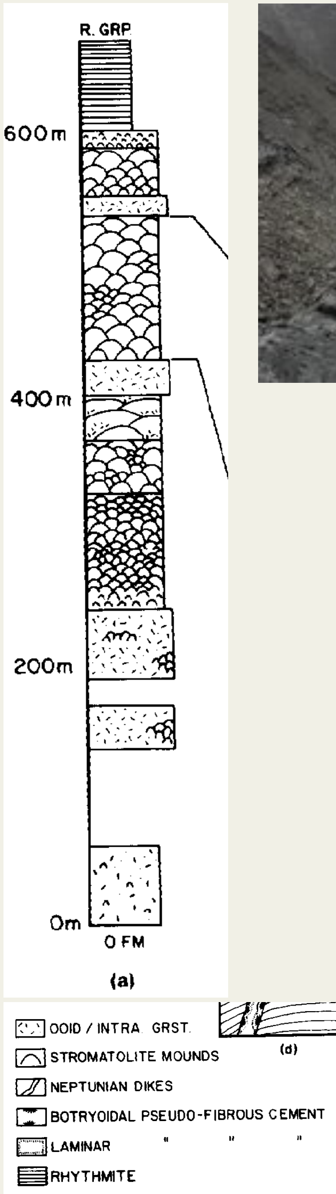
Wilkinson & Drummond, 2004

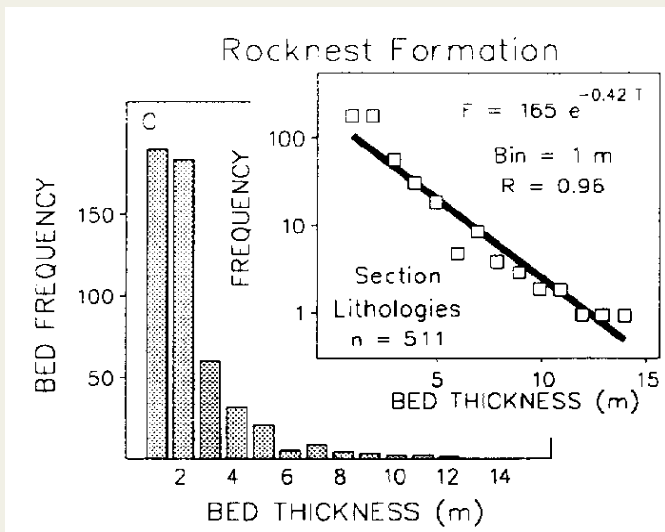
Harris & Vlaswinkel, 2008



- Planform heterogeneity observed in modern systems across a wide range of scales
- Limited statistical understanding of spatial distributions at different scales
- **Understanding of the responsible processes is even more limited, especially the link with vertical stacking**

ORIGINS OF HETEROGENEITY





Wilkinson et al, 1996, JSR, 66, p.1065-1068

Logged section from Grotzinger, 1986, JSP, 56, 813-847

- Vertical stacking in strata also shows significant heterogeneity
- Many carbonates strata exhibit exponential thickness frequency distributions
- Which means lots more thin beds than thick beds
- What does this mean in terms of depositional processes?

- Issues: platforms & prediction, complexity and heterogeneity
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OTHER ISSUES

- Ocean acidification
- Shoreline change on island nations
- Reefs, shallow and deep, and their change in response to past and future climate change
- Tsunami records

- Issues: platforms & prediction, complexity and heterogeneity
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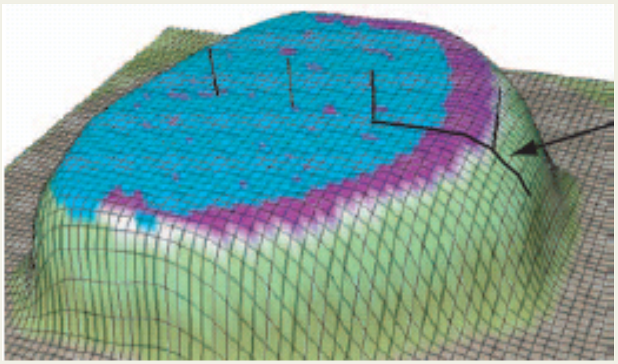
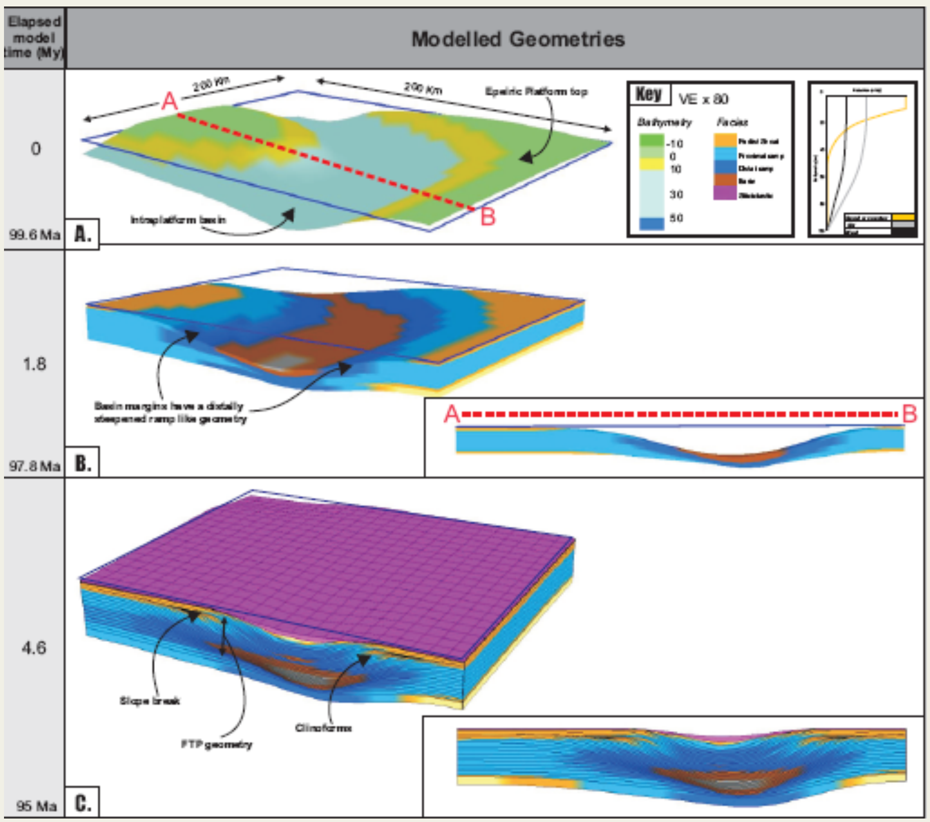
DEPOSITIONAL MODELS: DIONISOS





Summary

Spatial dimensions: 3D

Process dimensions: 1-2D

Scale: Whole platform and more

Lithologies: Multiple, user-defined linked to production curves

Transport is diffusional so ability to make fine-scale heterogeneity is rather limited

USP: Large scale, very flexible and often very fast to run

Refs:

Bassant and Harris, 2008

Williams, 2010, unpublished PhD thesis

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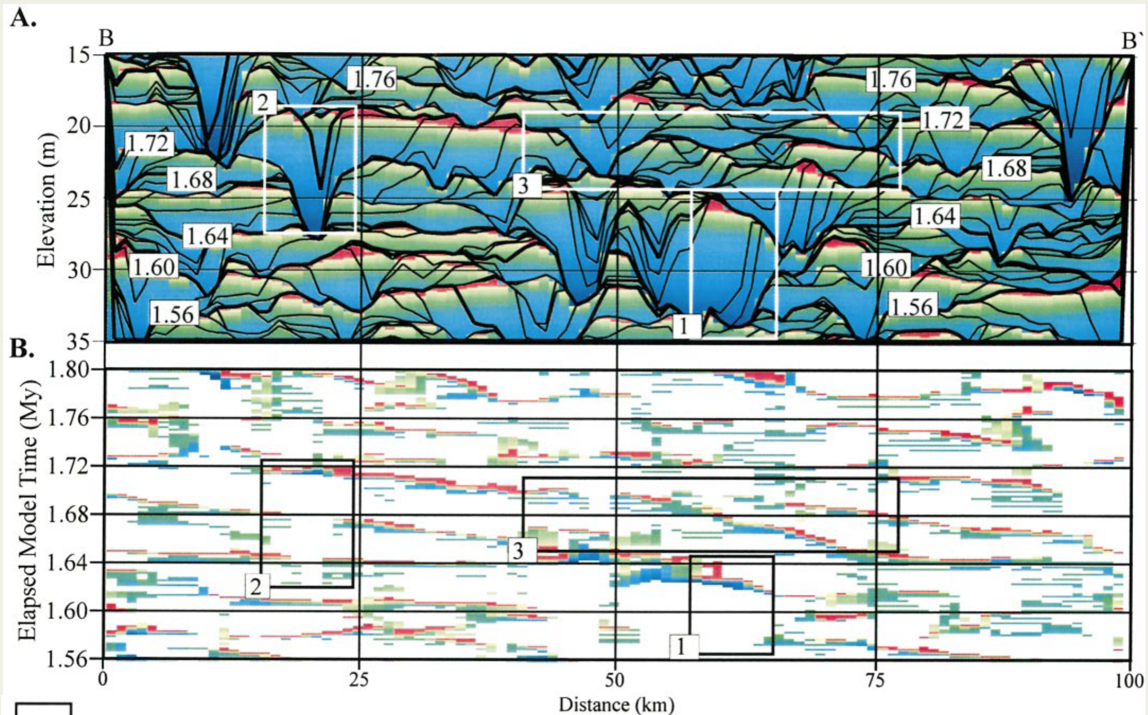
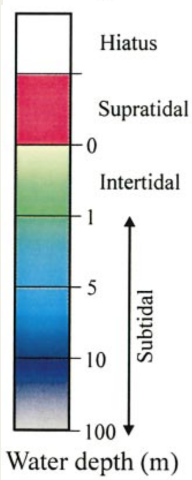
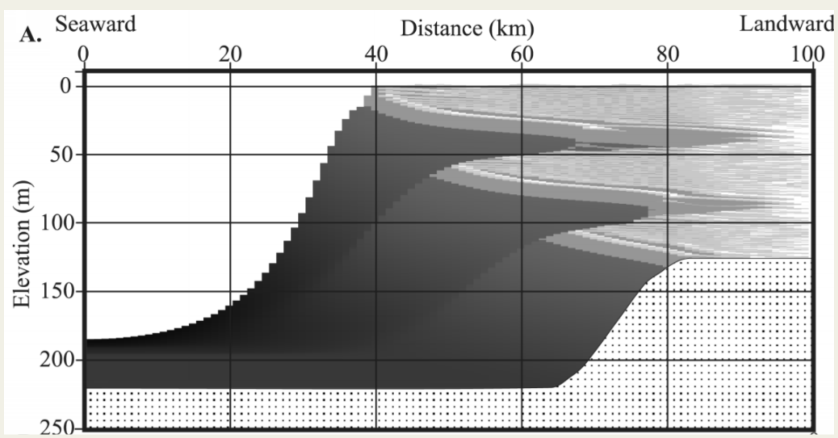
DEPOSITIONAL MODELS: CYCLOPATH







Summary

Spatial dimensions: 3D

Process dimensions: 1-2D production, 2D transport

Scale : Platform architecture & platform interior

Lithology: very basic, water-depth classification only

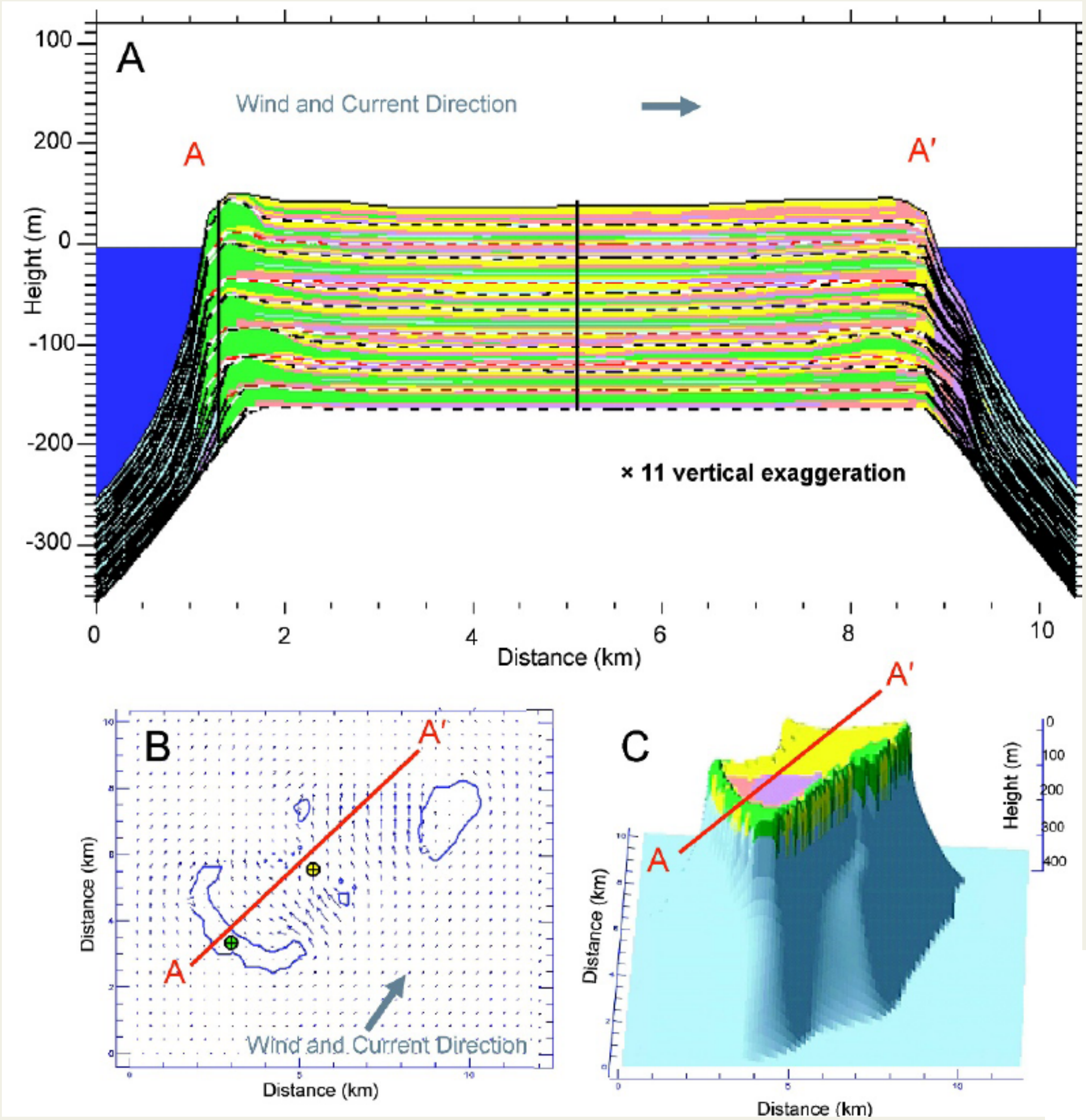
Heterogeneity: some, but limited by poor lithology representation

USP: consideration of autocyclic processes, detailed statistical analysis of results

Refs:

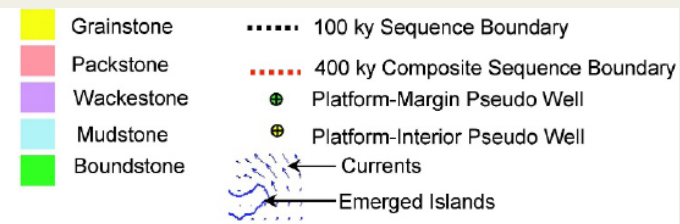
Burgess et al 2001,
Burgess, 2001,
Barnet et al 2002,
Burgess and Wright 2003,
Burgess and Emery 2004
Burgess, 2006

DEPOSITIONAL MODELS: CARB3D+



Summary
Spatial dimensions: 3D
Process dimensions: 1-2D?
Scale: Whole platform
Lithologies: Multiple, realistic
Heterogeneity – definitely, but mostly externally forced? And possible issues with numerical artefacts?
USP: good wave and current model, plus link to diagenetic processes

Refs:
Peterson et al 2006
Peterson et al 2008



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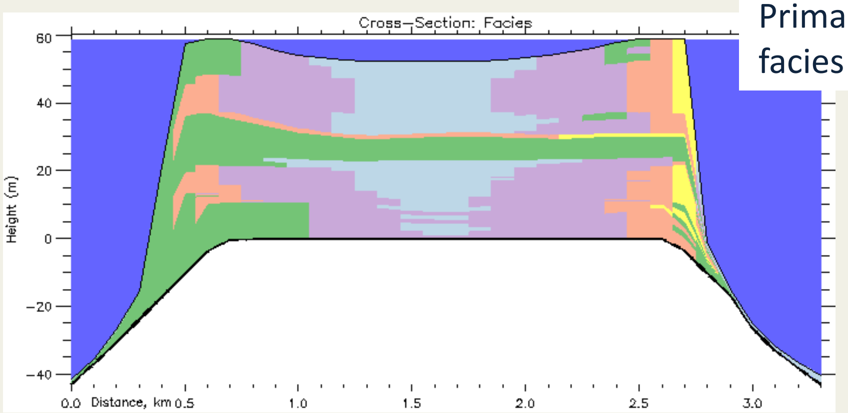
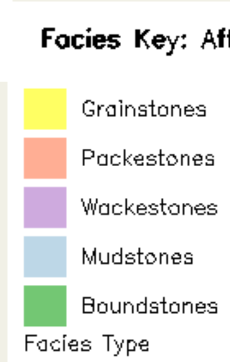
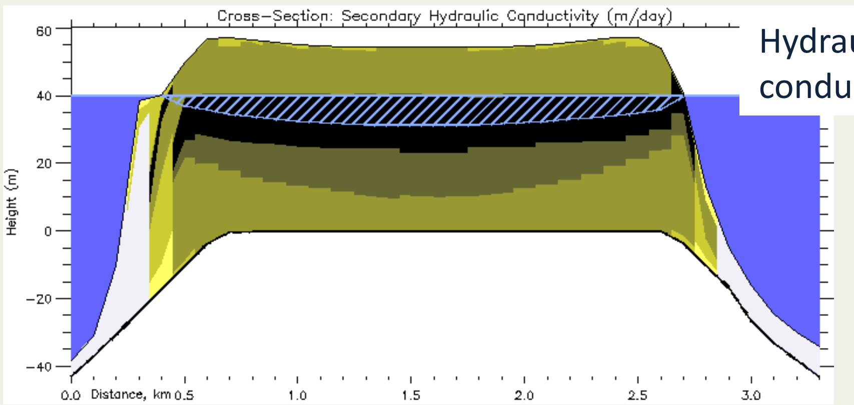
DIAGENETIC MODELS: CARB 3D+

Primary facies

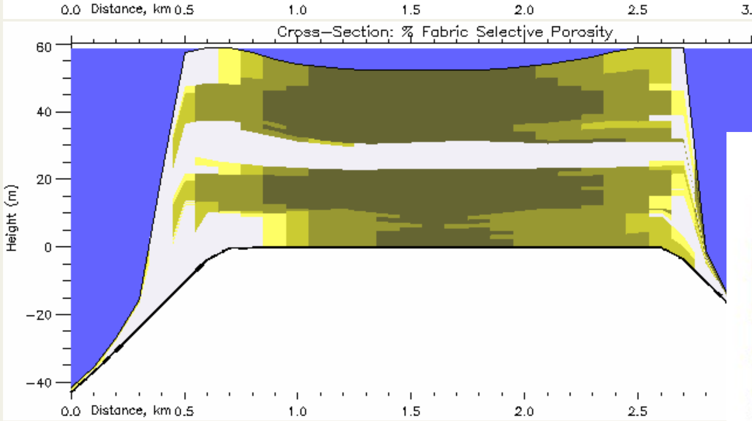


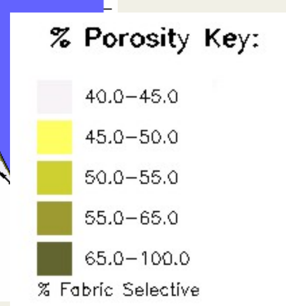


Hydraulic conductivity



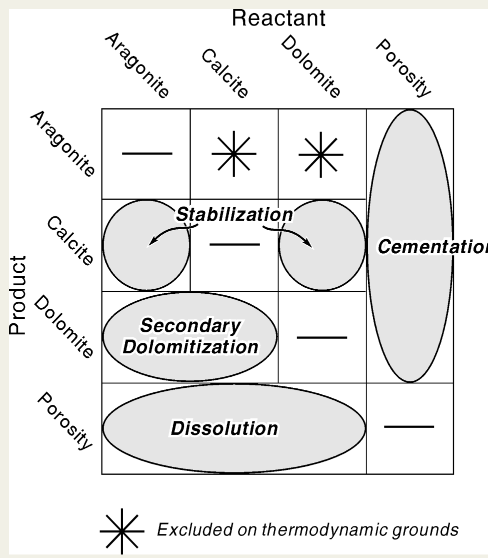
Porosity





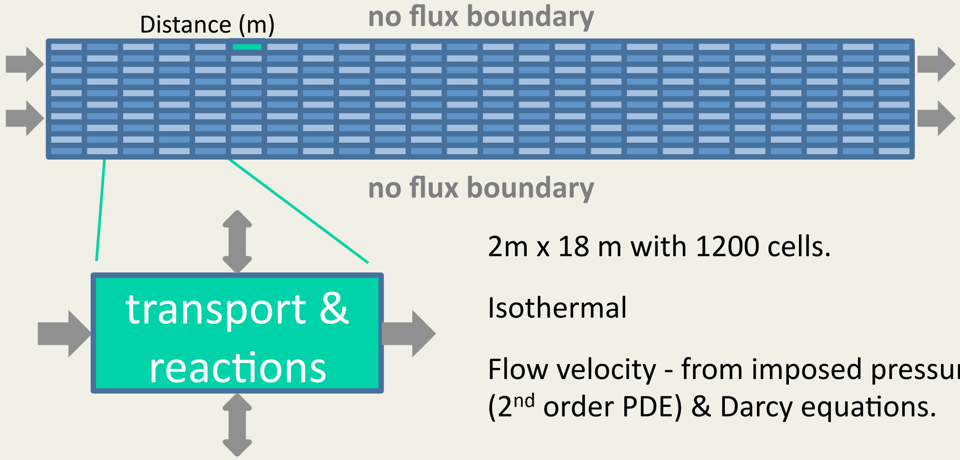
Summary
Spatial dimensions: 3D
Process dimensions: 1-2D?
Scale: Whole platform
Lithologies: Multiple, realistic
Diagenetic model: hybrid parametric

Refs:
Peterson et al 2006
Peterson et al 2008



DIAGENETIC MODELS: RT MODEL OF SO BEDS

Reaction-transport modeling of bed-scale dolomitization to assess pattern formation using **Sym.8 simulator**



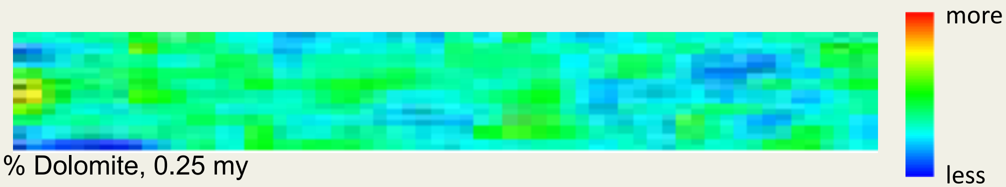
2m x 18 m with 1200 cells.

Isothermal

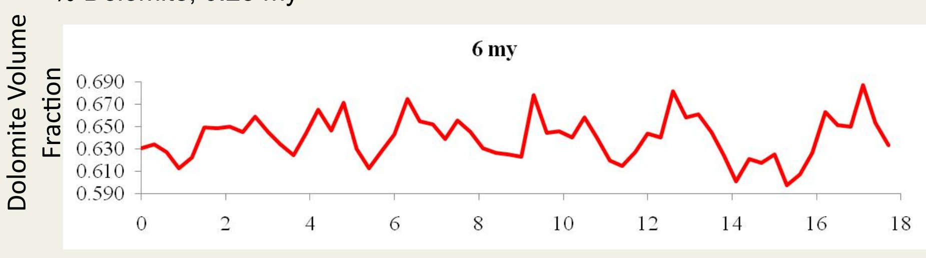
Flow velocity - from imposed pressure gradient (2^{nd} order PDE) & Darcy equations.

Fluid - Mississippian seawater evaporated to near halite saturation, 4x modern atm CO_2

Grids centered in 30 cm x 10 cm cells



% Dolomite, 0.25 my



Summary

Spatial dimensions: 2D

Process dimensions: 1-2D?

Scale: Small-scale bed stacking

Lithologies: Realistic depiction of bed-scale dolomitization

Refs:

Budd, 2010, pers. comm.

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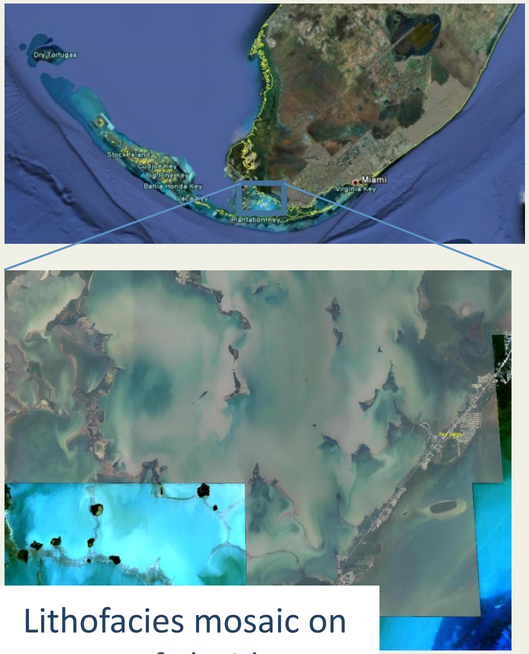
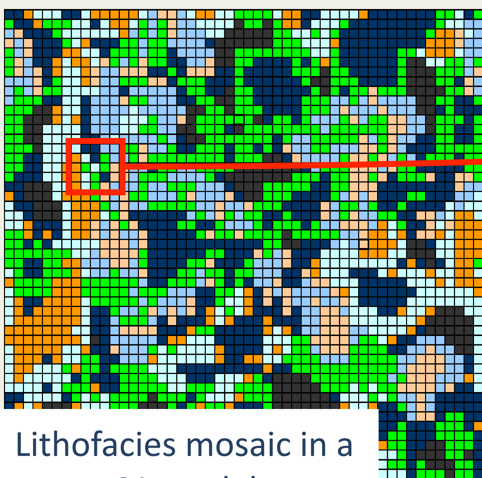
CELLULAR AUTOMATA



Lithofacies mosaic on a map of Florida Bay

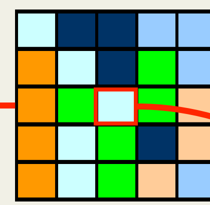
- Rule-based deterministic models
- Each cell evolves through time according to very simple rules based on contents of neighbouring cells
- Combine with subsidence, sea-level, sediment production etc to make a model of carbonate accumulation ...

Cellular Automata Rules				
Distance	Min Neighbours	Max neighbours	Min trigger	Max trigger
2	4	10	6	10



Lithofacies mosaic in a CA model

- Hiatus/no deposition
- Primary producer lithotope 1
- Primary producer lithotope 2
- Primary producer lithotope 3
- Byproduct lithotope 1
- Byproduct lithotope 2
- Erosion



- What happens next to this cell?
- 4 same-lithotope neighbours
- So persists into next timestep

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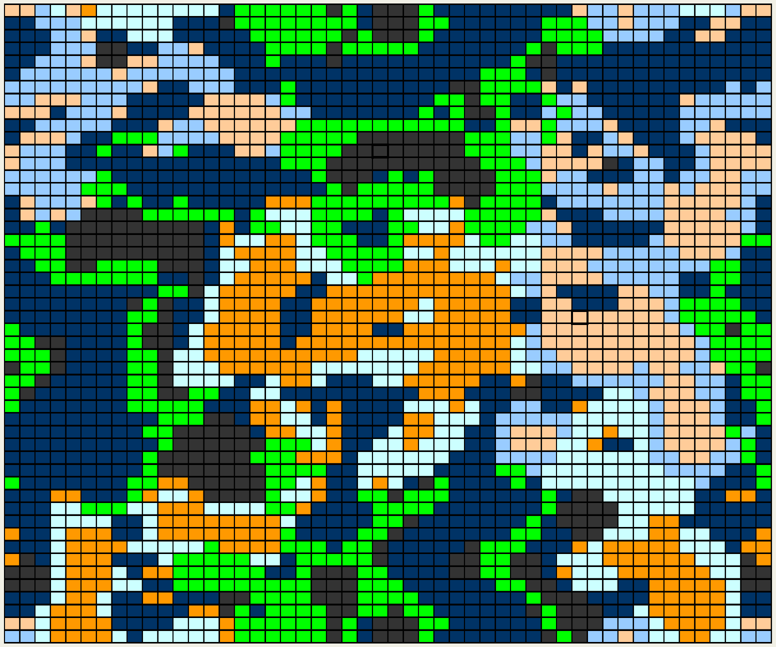
CELLULAR AUTOMATA

Lithotope mosaic map



Lithotope/process
- Hiatus/no deposition
- Primary producer lithotope 1
- Primary producer lithotope 2
- Primary producer lithotope 3
- Byproduct lithotope 1
- Byproduct lithotope 2
- Erosion

- Animation from “patches” initial condition
- Each cell evolves through time according to very simple rules based on contents of neighbouring cells
- 20 time steps=20 ky
- Lateral migration of facies
- Increasing lateral heterogeneity/spatial entropy

- Even this simple model leads to complicated results

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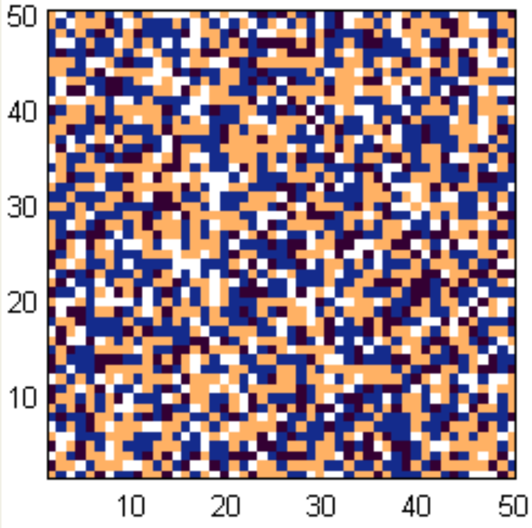
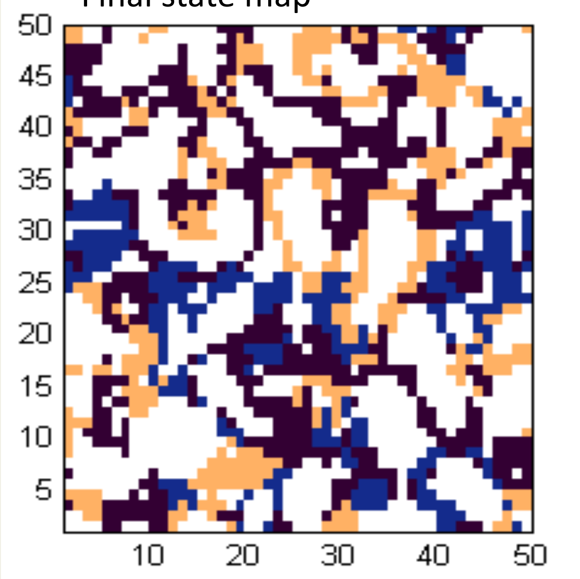
Initial state map



Final state map

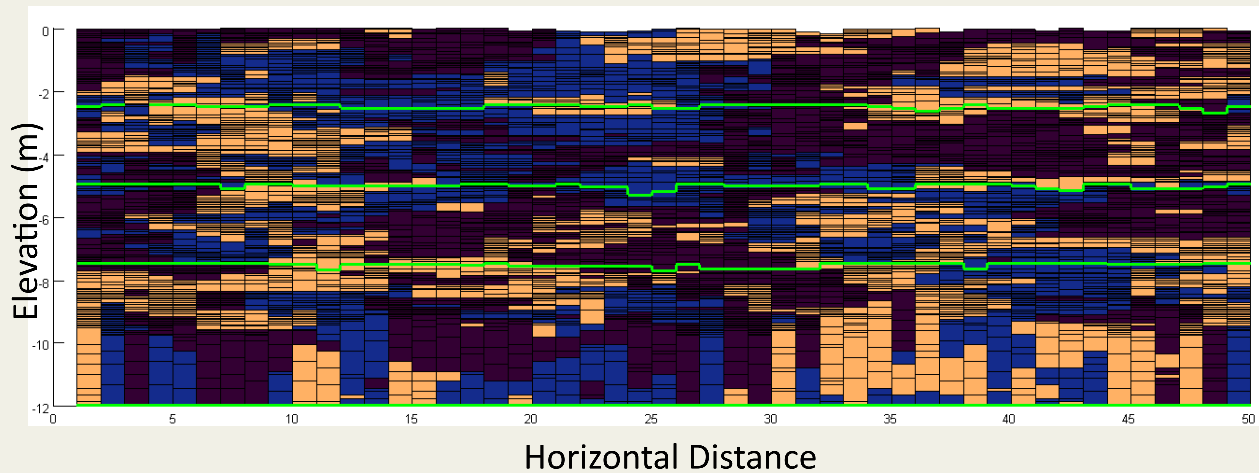


CarboCAT

- **3D cellular automata model desgined to model platform interior heterogeneity, constrained by lithofacies thickness distributions**
- Multiple facies calculated by cellular automata
- Simple sediment transport algorithms
- Depth-dependent sediment production rate
- Subsidence
- Eustatic sea-level oscillations

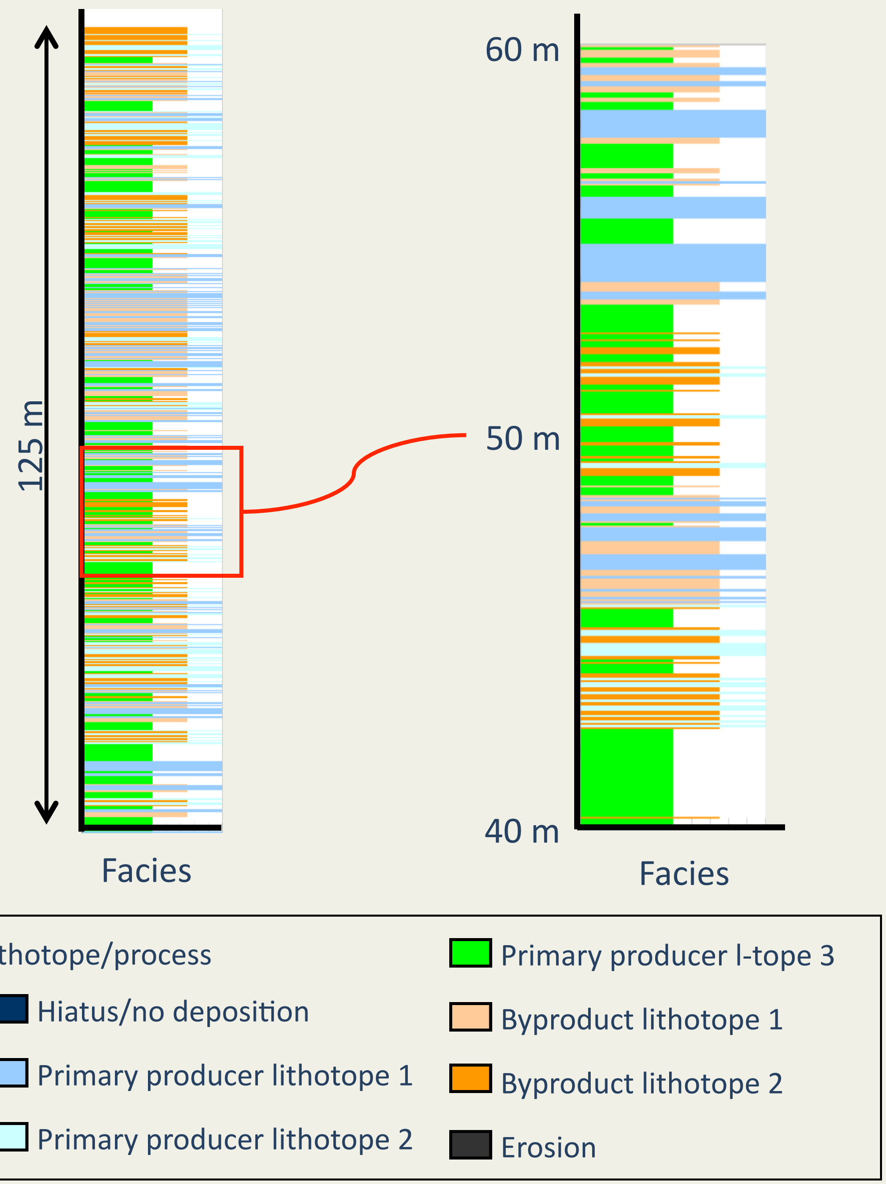
Cellular Automata Rules				
Distance	Min Neighbours	Max neighbours	Min trigger	Max trigger
2	4	10	6	10

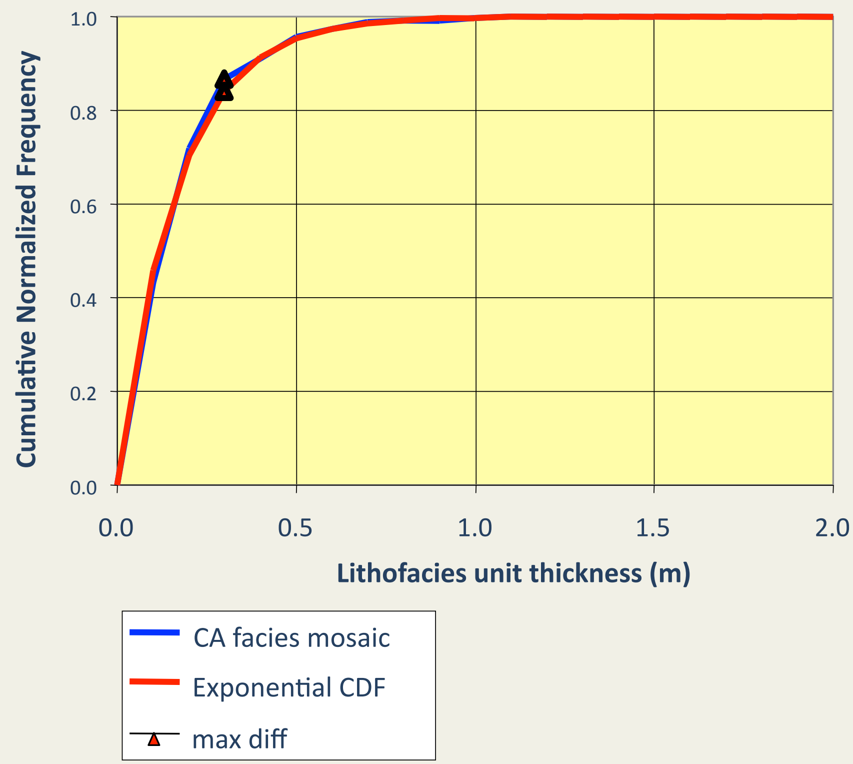
Cross section



CELLULAR AUTOMATA

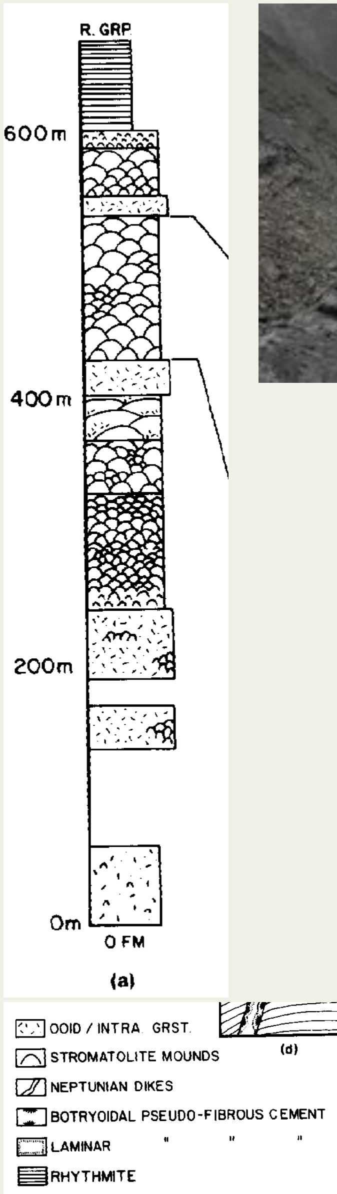
Vertical sections from middle of model grid …

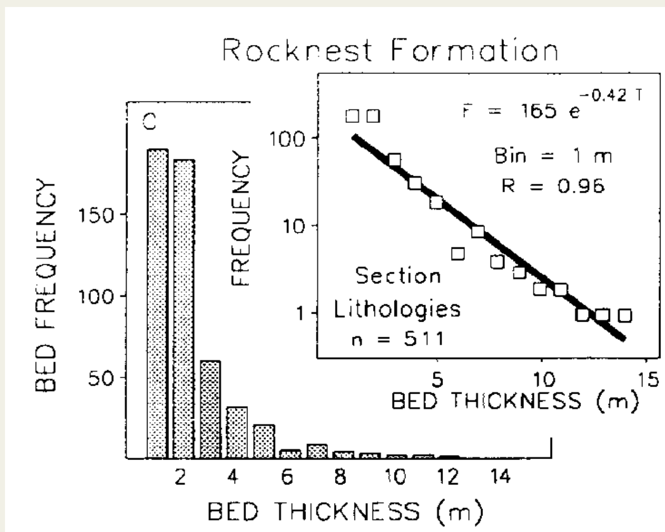




- CarboCAT can generate a good fit with exponential curve
- Reproduces one important aspect of carbonate strata

ORIGINS OF HETEROGENEITY





Wilkinson et al, 1996, JSR, 66, p.1065-1068

Logged section from Grotzinger, 1986, JSP, 56, 813-847

- Vertical stacking in strata also shows significant heterogeneity
- Many carbonates strata exhibit exponential thickness frequency distributions
- <u>Which means lots more thin beds than thick beds</u>
- What does this mean in terms of depositional processes?

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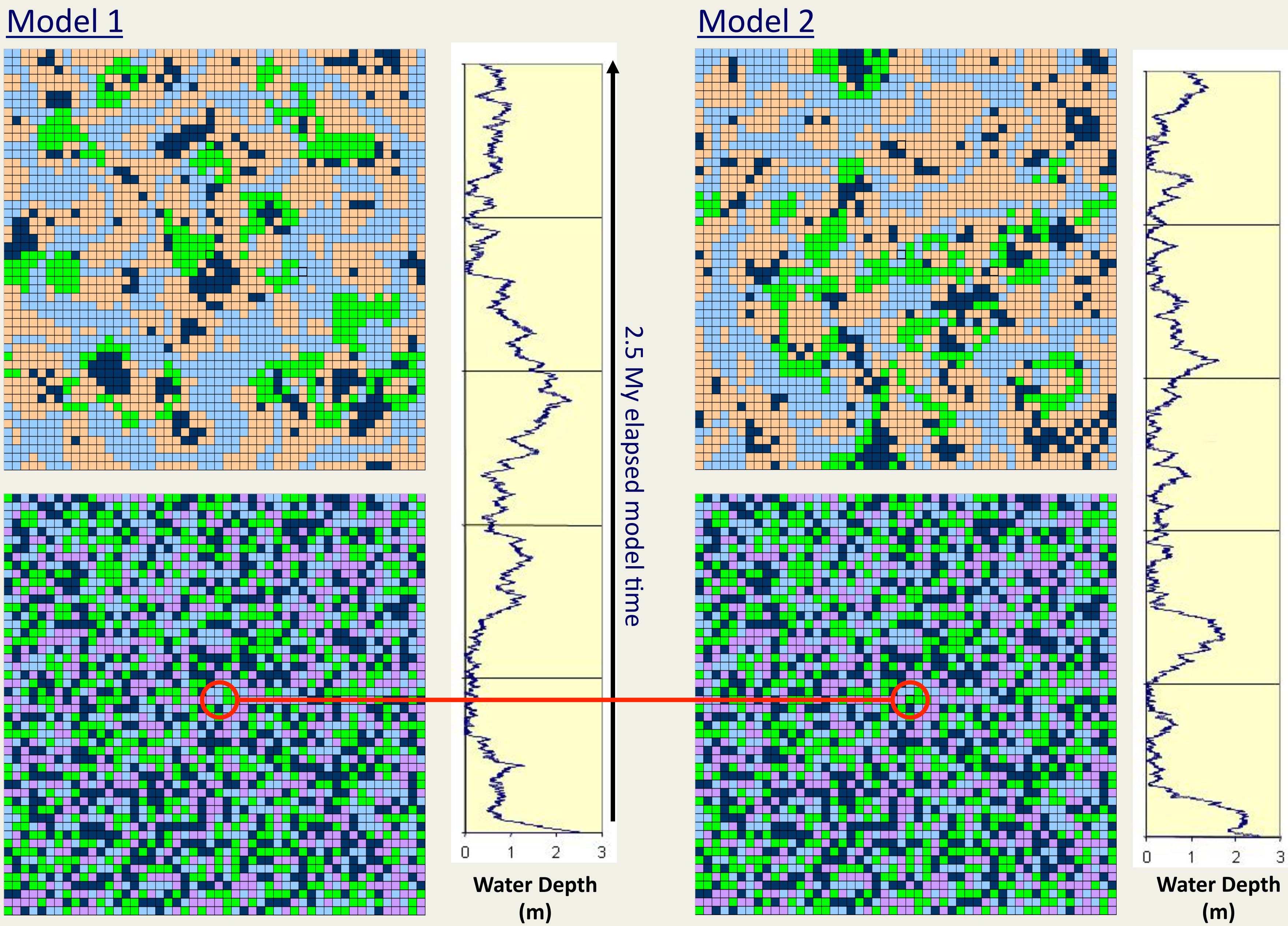
CELLULAR AUTOMATA



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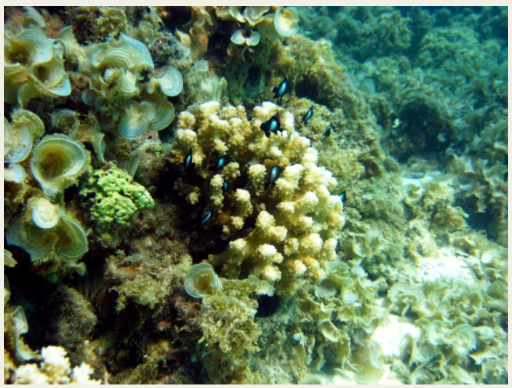
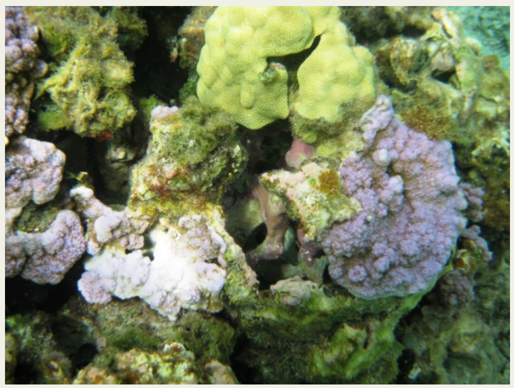
COMMUNITY MODELS




- Model spatial and temporal distribution of carbonate accumulation based on community model
- Community model encapsulates competition, positive feedbacks in occupied sites, and manipulation of local environment by organisms

Population Approach Lotka-Volterra coupled ordinary differential equations

Increase (growth):
- Growth in number of individuals
- Growth in % areal cover

Mortality:
- Day-in day-out
- Extreme events

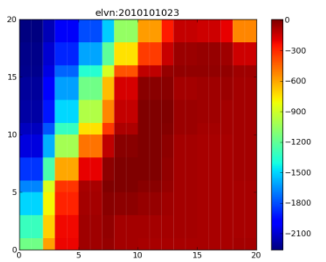
Immigration:
- Spat dispersal
- Neighbouring cell populations
- Suitable settlement substrate

$$\frac{dN_i}{dt} = RN_i\left(1 - \frac{N_i}{K_i}\right) - N_i\left(\sum_J A_{ij} N_j - M_i\right) + I_i$$

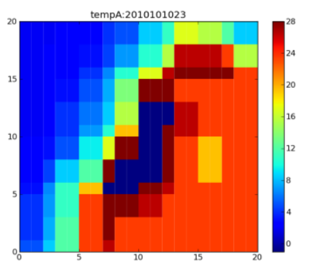
Carrying Capacity:
- Physical & trophic habitat suitability
- ?Full capacity at optimum (restricted by A,M,I of course)

Competition (antagonism):
- Space restriction and overgrowth
- Nutrient competition including light by all J against i

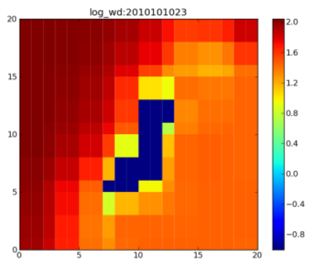
POPULATION ECOLOGY CARBONATE



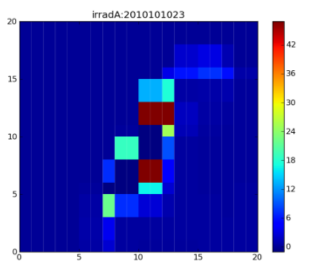
Elevation (m)



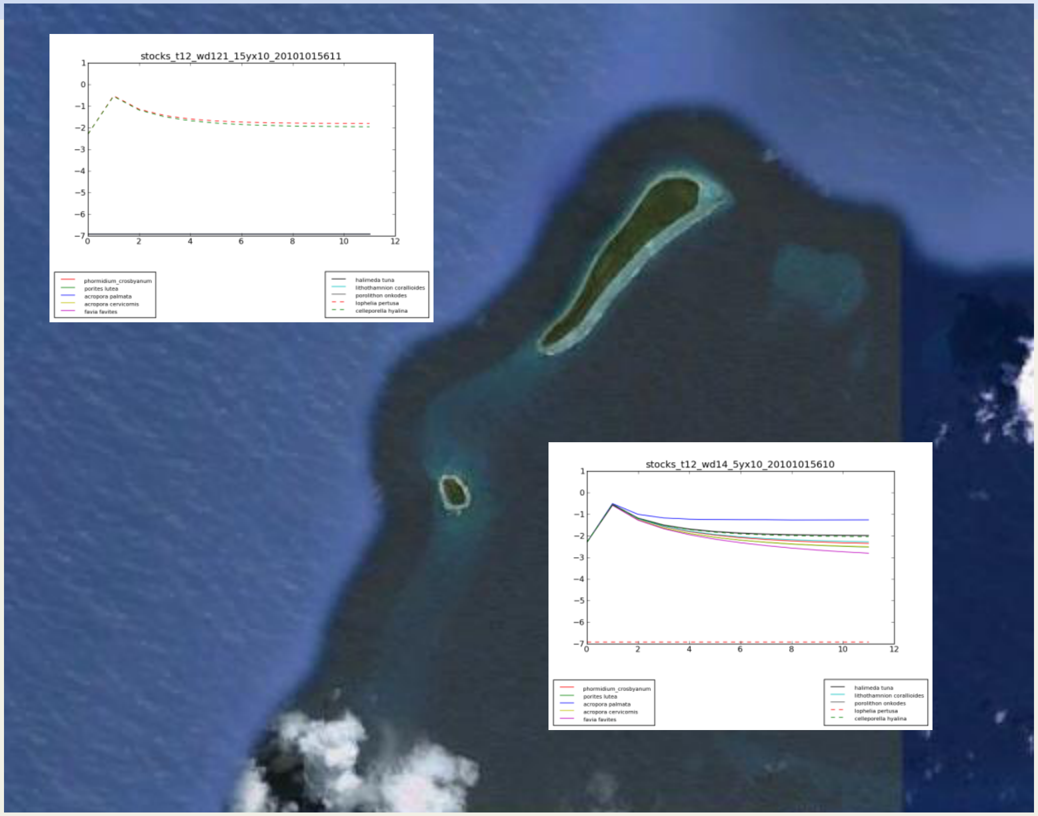
Temperature (dgC)



WD (log10 m)

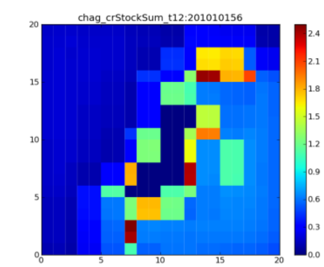


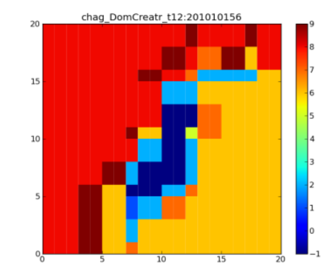
Benthic Irradiation (umol phot /m2 /s)



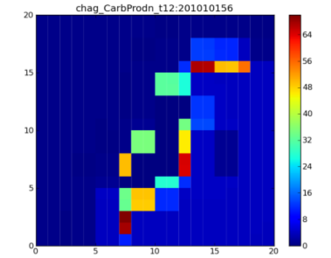
Chagos Bank 071.23E 06.35S 20*0.01dg

Total Stock (live % area)

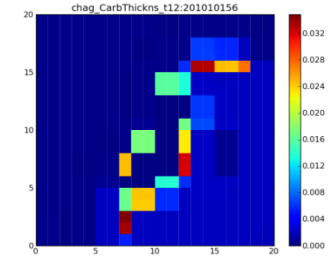




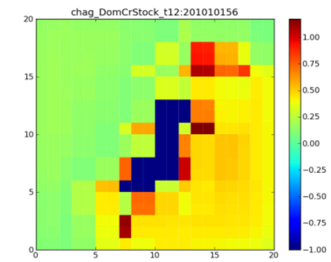
Dominant Creatures (Favia, Lithothamnion)



Carbonate production (kg/ m2/ yr)



Carbonate thickness At yr 12 (m)



Dominant Creature Stock (live % area)

CSDMS
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- Issues: platforms & prediction, complexity and heterogeneity
  - Platform types and facies prediction
  - Origins of heterogeneity in carbonates
  - Other issues…
- Review of current models
  - Depositional models
  - Diagenetic models
- New modelling directions
  - Cellular automata
  - Population modelling
- C-FRG research plans

C-FRG RESEARCH PLANS

- Focus on development of workbench module prototypes based on combined community model and cellular automata approach
- Integrate with available sediment transport modules
- Development of supporting knowledge base with rate data
- New NSF grant proposal (and EU proposal?)
- Expand group membership based on working model modules
- Testing of model against modern and ancient carbonate systems

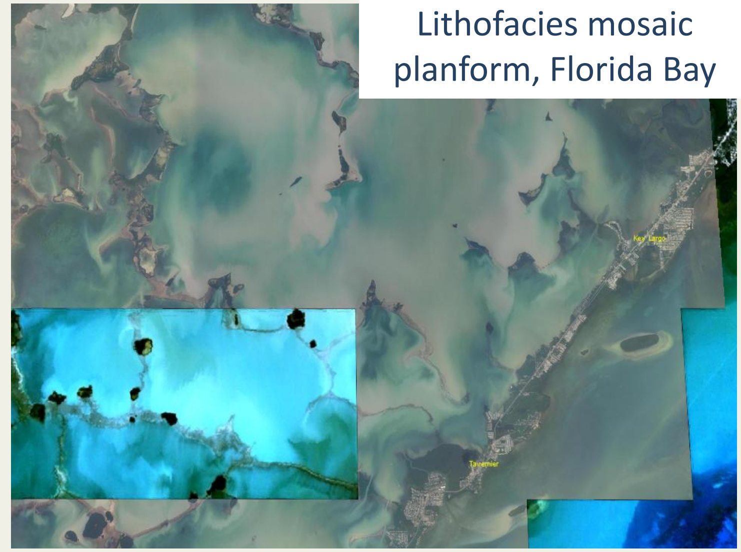
CSDMS
C-FRG

CSDMS
C-FRG

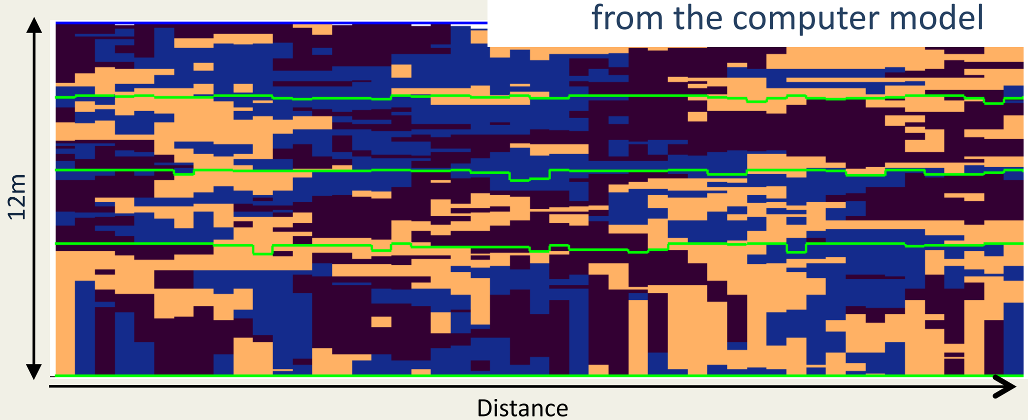
CELLULAR AUTOMATA

Mid Cretaceous carbonate strata, central Spain – also a lithofacies mosaic?

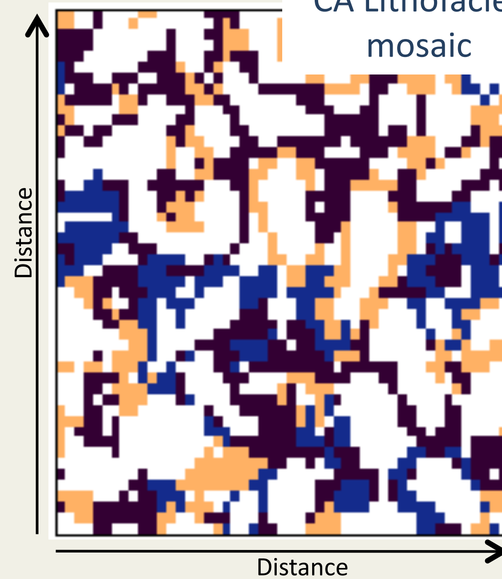
Lithofacies mosaic planform, Florida Bay



Cross-section of a lithofacies mosaic from the computer model



CA Lithofacies mosaic



POPULATION MODELS

What carbonate properties should SedGrid store and how?

The hypothetical cell: [Aa 0.05; Ag 0.90; At 0.05]
The hypothetical cemented cell: [Aa 0.05; Ag 0.80; At 0.05; Bd 0.10]

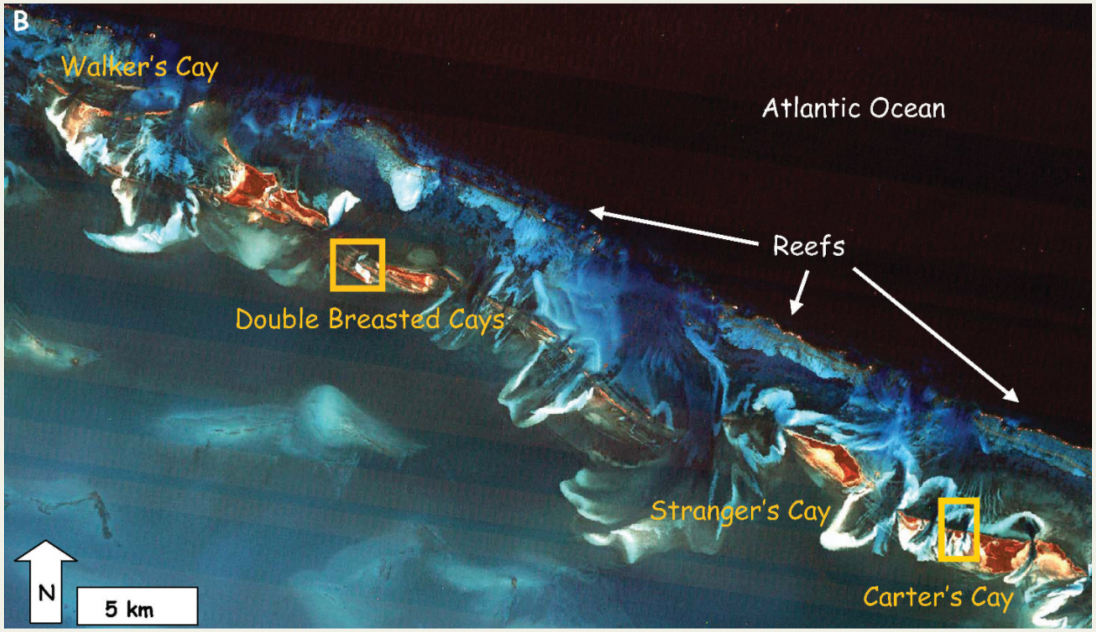
Transport dictionary	Aa	...	Ag	...	At	...	Bd	...
Transportable	Yes		Yes		No		No	
Grain size (mm)	2mm		10mm		Null		Null	
Bulk density (gcm^{-3})	2.1		2.2		Null		Null	
Grain shape??	Messy		Spherical		Null		Null	

Production dictionary	Aa	...	Ag	...	At	...	Bd	...
Name	Coral X		Grainwithnoname		Seagrass		Cement	
Hardness	Skeletal		Skeletal		Soft		Null	
Feeding habit	Filter		Mobile carnivore		Photosynth		Null	
Trophic Type	Pred, sessile		Pred, mobile		Primary		Null	
Trophic level	5		7		1		Null	
Ingestion size	Large		Large		Small		Null	
Temp range	21-27		16-27		15-27		Null	
Salinity range							Null	
Mineralogy	Aragonite		Calcite		Aragonite		Aragonite	

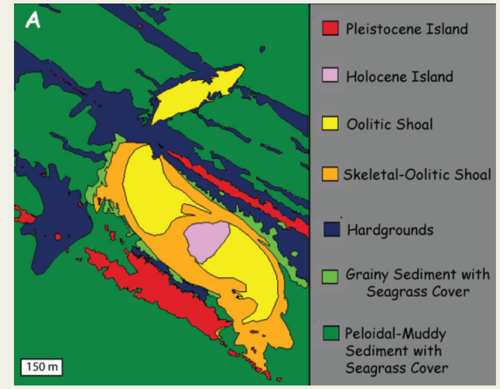
Roughness dictionary	Aa	...	Ag	...	At	...	Bd	...
Roughness	Rough		Smooth		Rough		Smooth	
Form	Upstanding						Flat	
Bafflement	Some				Lots		None	
Form drag	2.1							

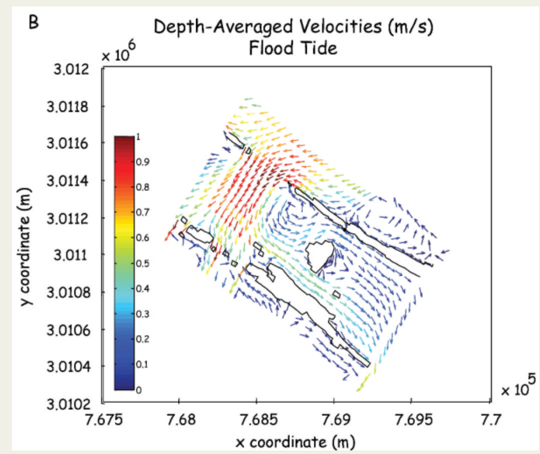
CSDMS
C-FRG

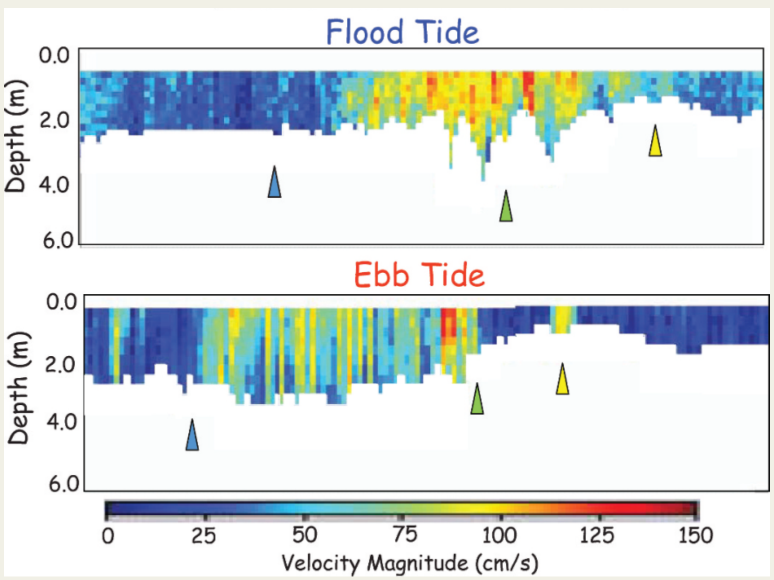
ORIGINS OF HETEROGENEITY



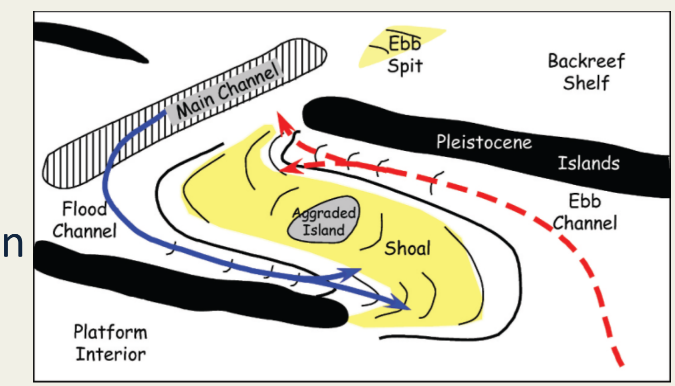
Reeder & Rankey, 2008







- Ooid factory controlled by tidal currents
- Net circular hydrodynamic pattern around the shoal – spin cycle
- Combined production and transport is the key



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