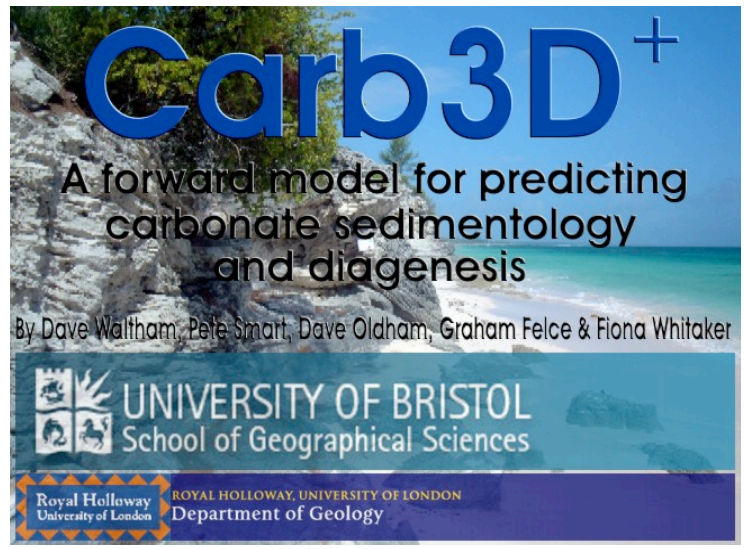
Forward Modelling of Carbonate Sedimentology and Diagenesis: Current Status and Issues

Peter Smart and Fiona Whitaker

Bristol Carbonates Consortium



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Outline:

- **Carbonate Sedimentology**
  - Accomodation and sea level cycles
  - Wind waves and facies template models
  - Sediment production
  - Sediment transport
  - Hydrodynamics and timescale issues
  - Prediction of porosity

- **Carbonate Diagenesis**
  - The hydrozones concept and common links to extrinsic controls
  - Prediction of hydrozones (hydraulic conductivity and up-scaling issues)
  - Diagenesis by hydrozone template (parameterisation issues)
  - Carbonate budgets
  - Coupled groundwater flow and geochemical models (RTM)
  - Problems of RTM

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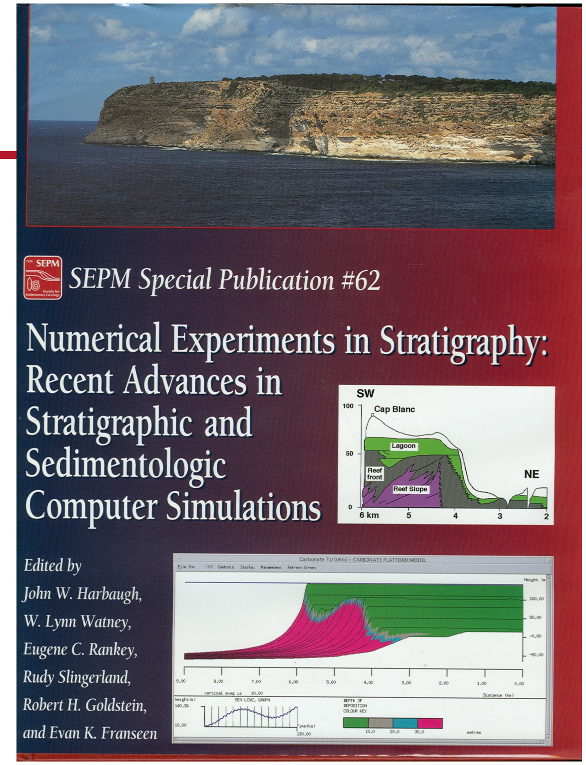
Focus on Carbonate Developments since 1999

- **Sedimentological Models**
  - DIONISOS (Granjeon and Joseph, 1999)
  - CSM Carbsim (Taizhong Duan,2000)
  - REPRO (Hussner et al, 2001)
  - ?? (Burgess et al, 2001)
  - SedTec 2000 (Boylan et al, 2002)*
  - CARBONATE 3D (Warrlich et al, 2002)*
  - SIMSAFADIM (Bitzer and Salas, 2002)
  - FUZZYREEF (Parcell, 2003)
  - TAWIC+? (Quinquerez et al, 2004)
  - CARBONATE GPM (Hill et al in prep)

- **Diagenetic (Reactive Transport) Models**
  - PHAST (Parkhurst et al, 2004)
  - TOUGHREACT (Xu et al, 2004)
  - GEOCHEMISTS WORKBENCH (Bethke, 2007)
  - + others in house

- **Sedimentological and Diagenetic Models**
  - CARB3D+ (Paterson et al, 2006)*
  - FACIES 3D (Matsuda et al, 2004)

  - BASIN 2 (Bethke et al, 2007)



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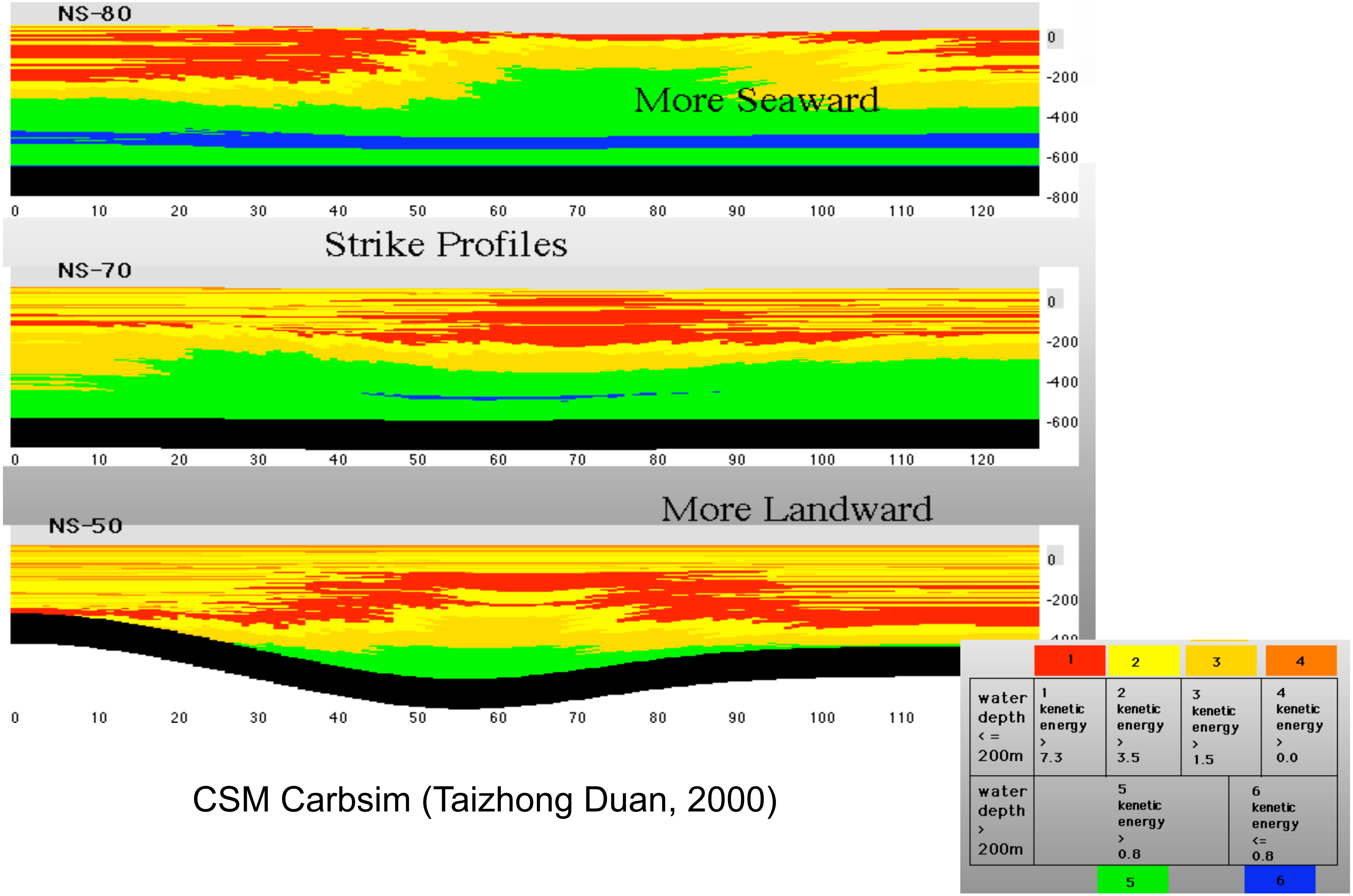
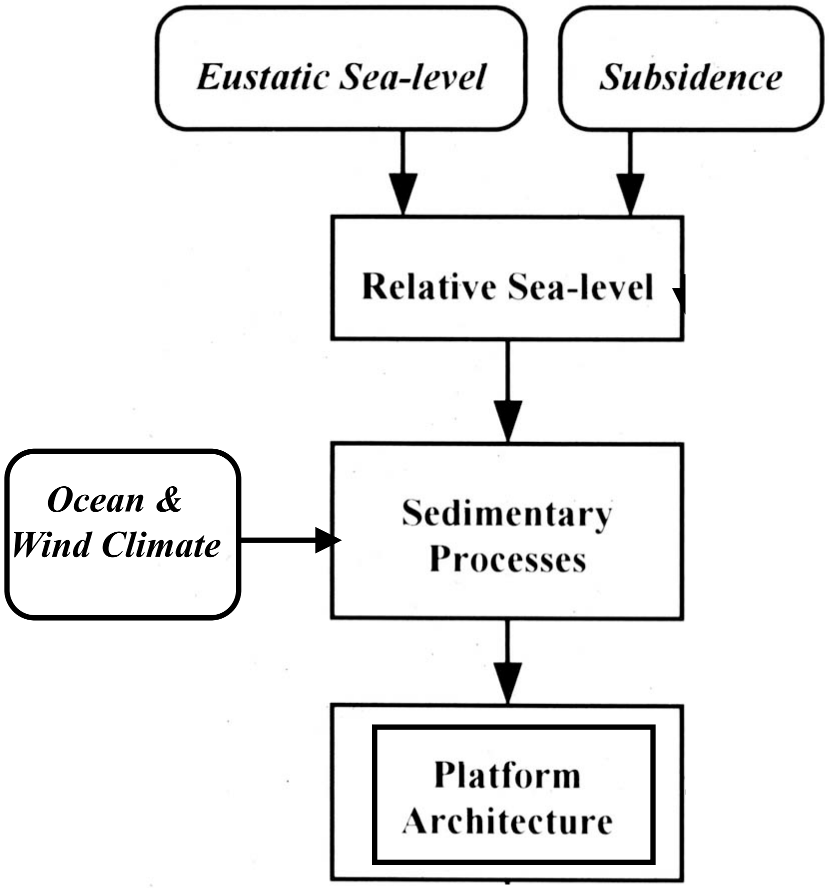
Why the move to 3D?

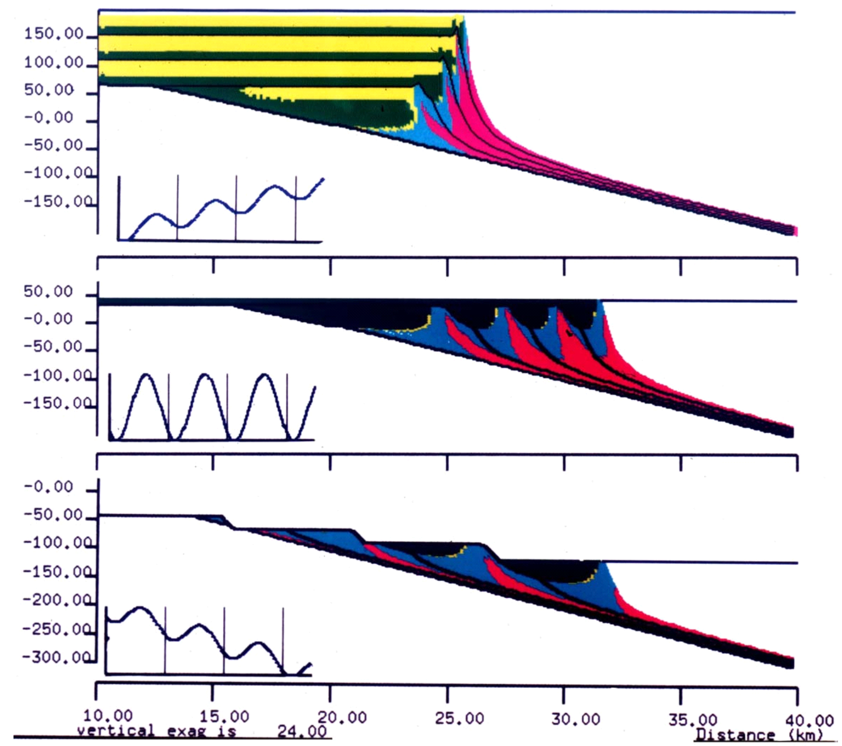


CSM Carbsim (Taizhong Duan, 2000)

Model Fundamentals : Sea level + Subsidence = Accommodation, Hydrodynamic Environment and Sedimentary Processes > Sediments



Relative Sea Level Change



Extrinsic Controls

Model Components

Model Output

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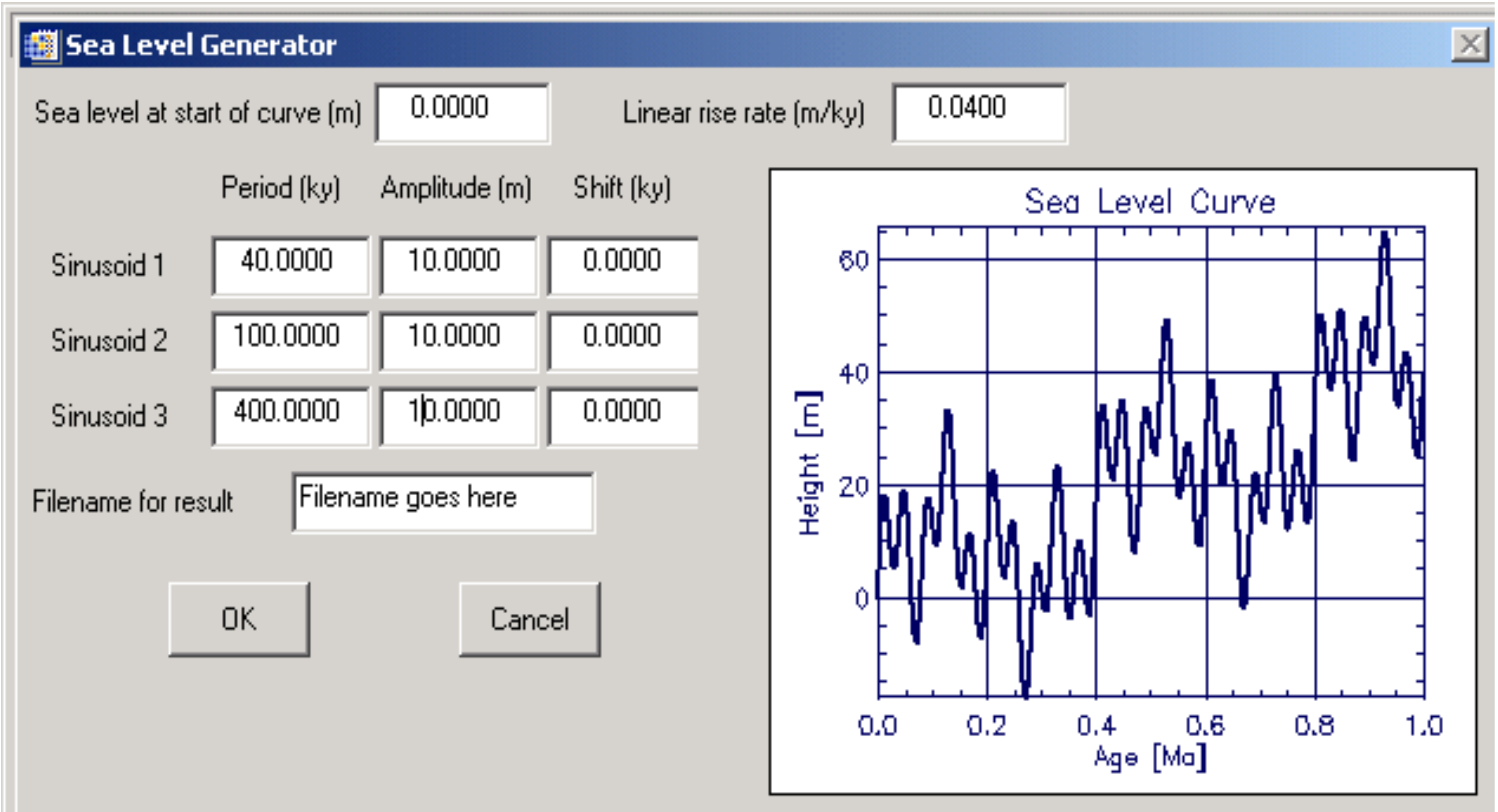
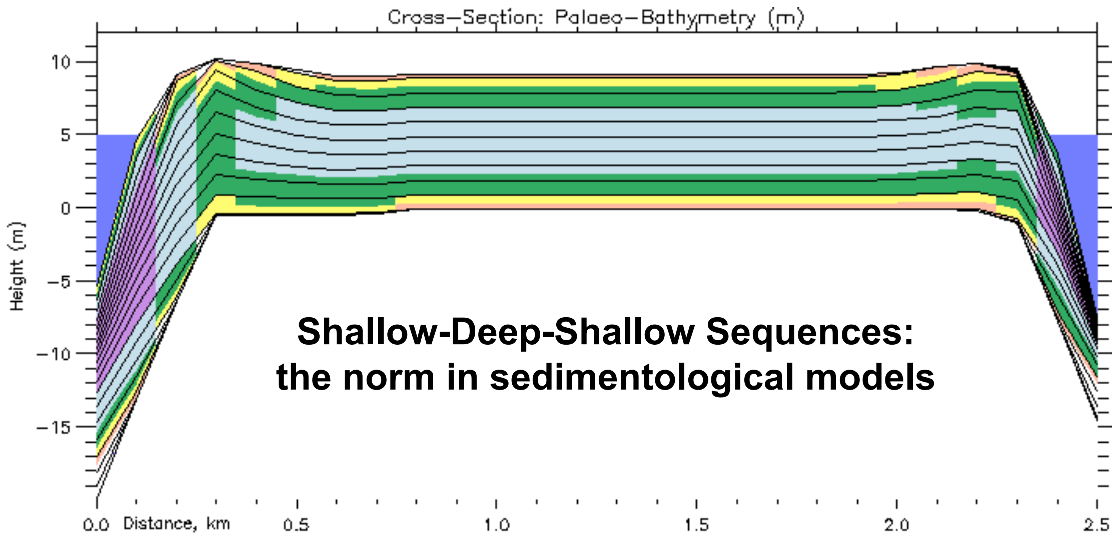
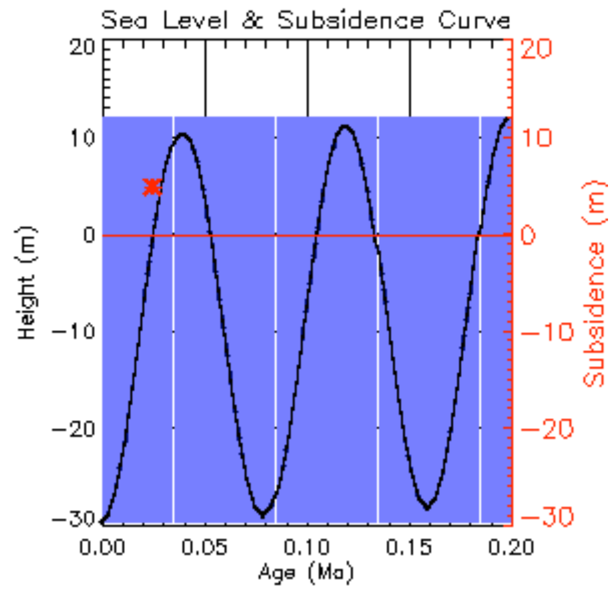
CARB3D+ symmetric sea level generator

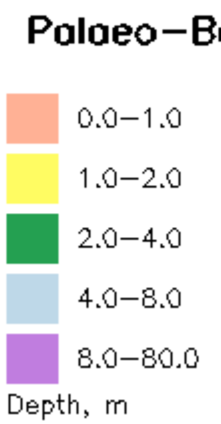


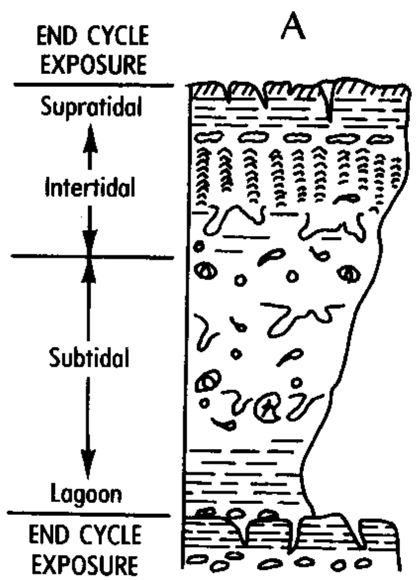
Symmetric cycles give symmetric sequences



Shallow-Deep-Shallow Sequences:
the norm in sedimentological models







Shallowing Upwards Sequences:
the norm in the geological record

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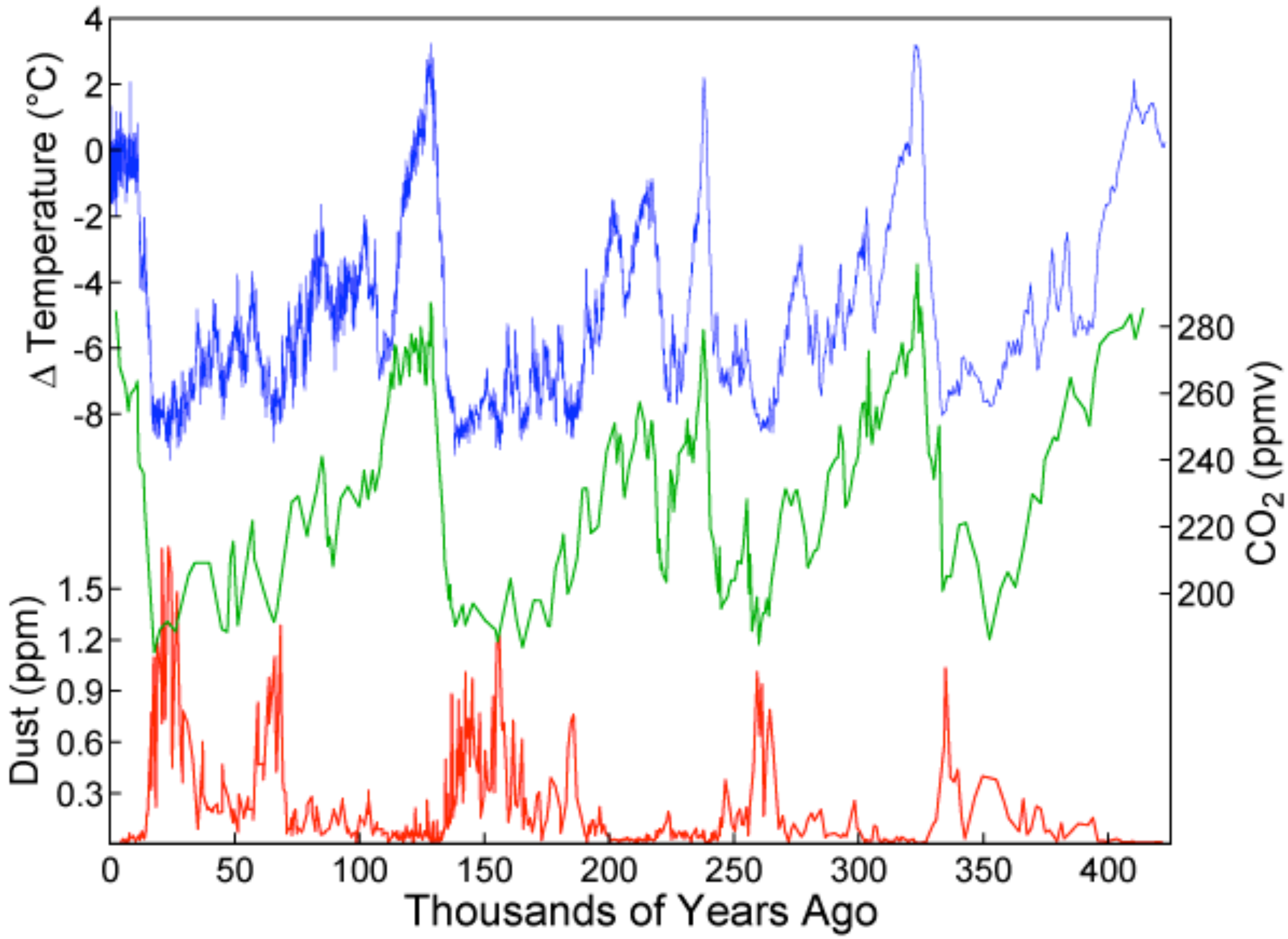
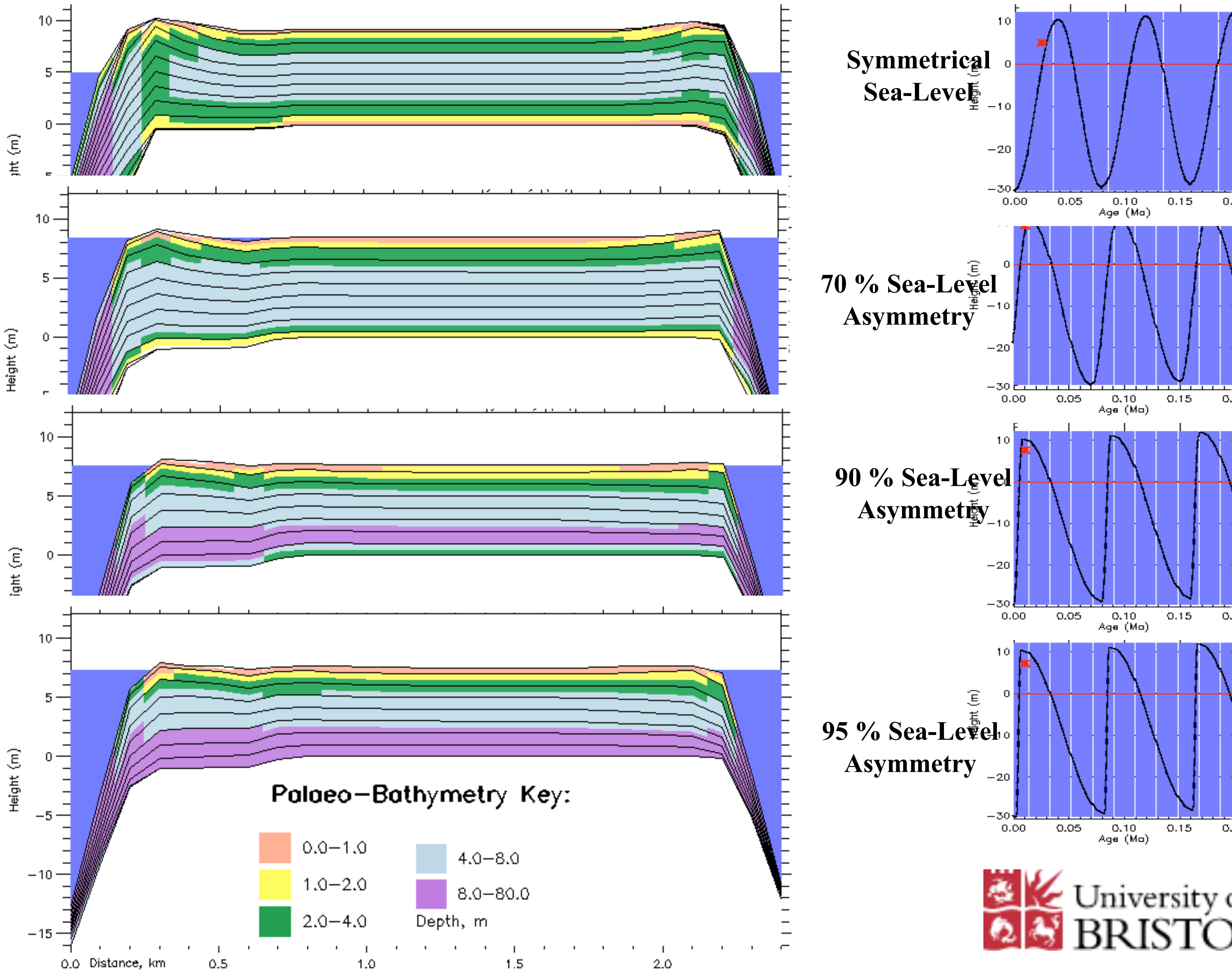
Icehouse (and other?) sea levels are highly asymmetric, so why don't we use them in modelling?



Vostok Ice Core

Shallowing Upward Sequences result from asymmetric sea level curves



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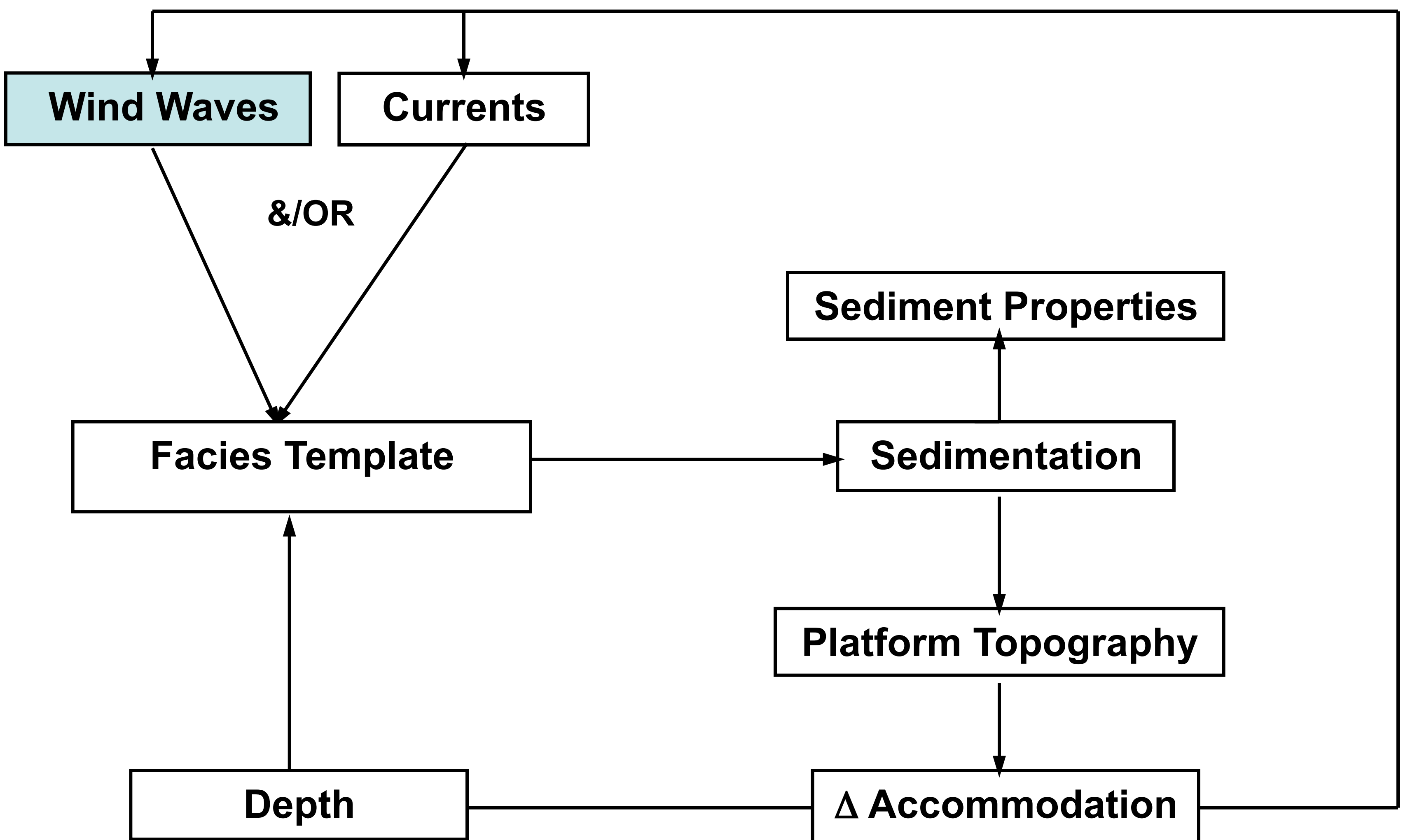
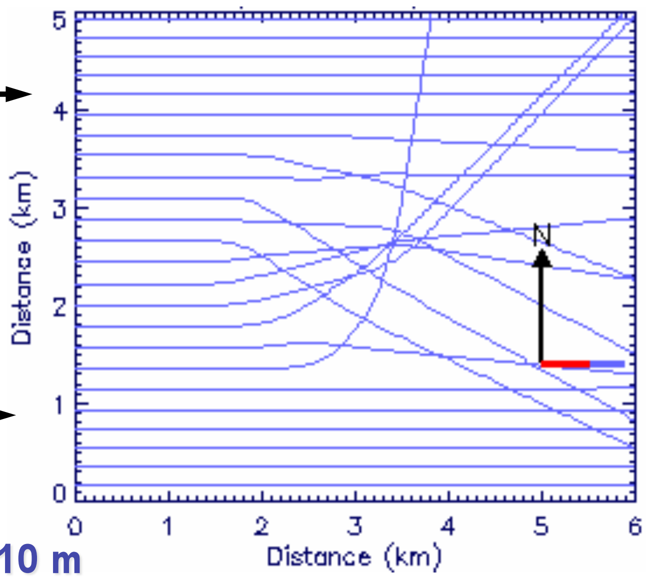
Facies Template Sedimentology

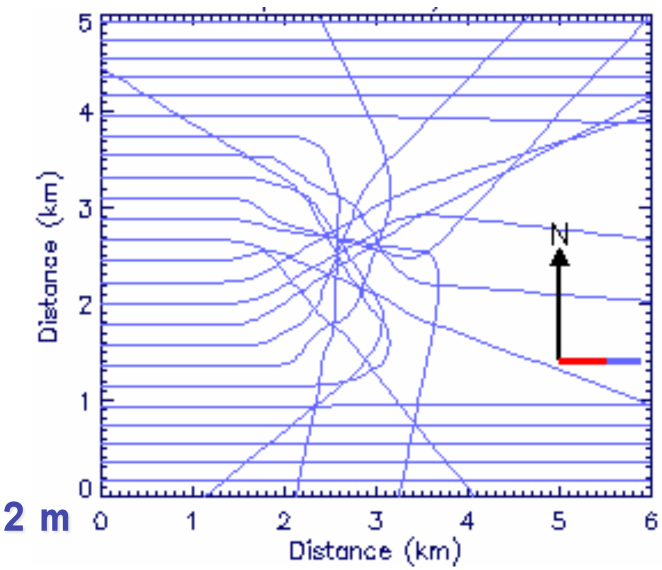


Wind generated waves and wave refraction: CARB3D+

Free Ocean Wind-waves

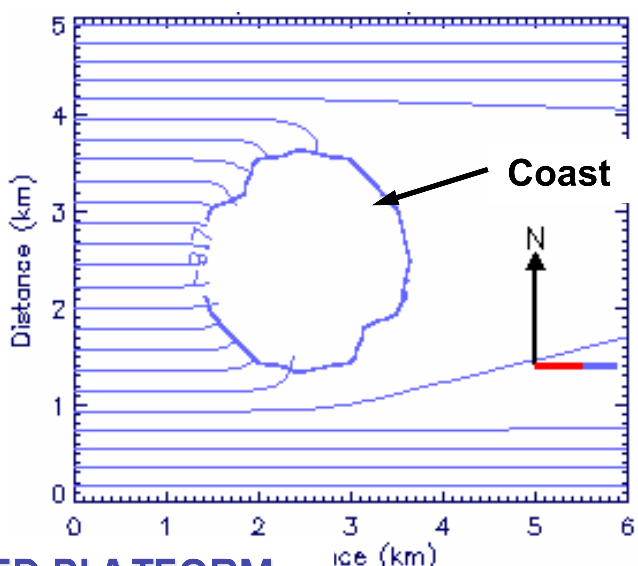


DEPTH 10 m



DEPTH 2 m

Free Ocean Wind-waves



EXPOSED PLATFORM

Wave Ray Paths

Wind Direction

Wind (red) & current direction-to indicators

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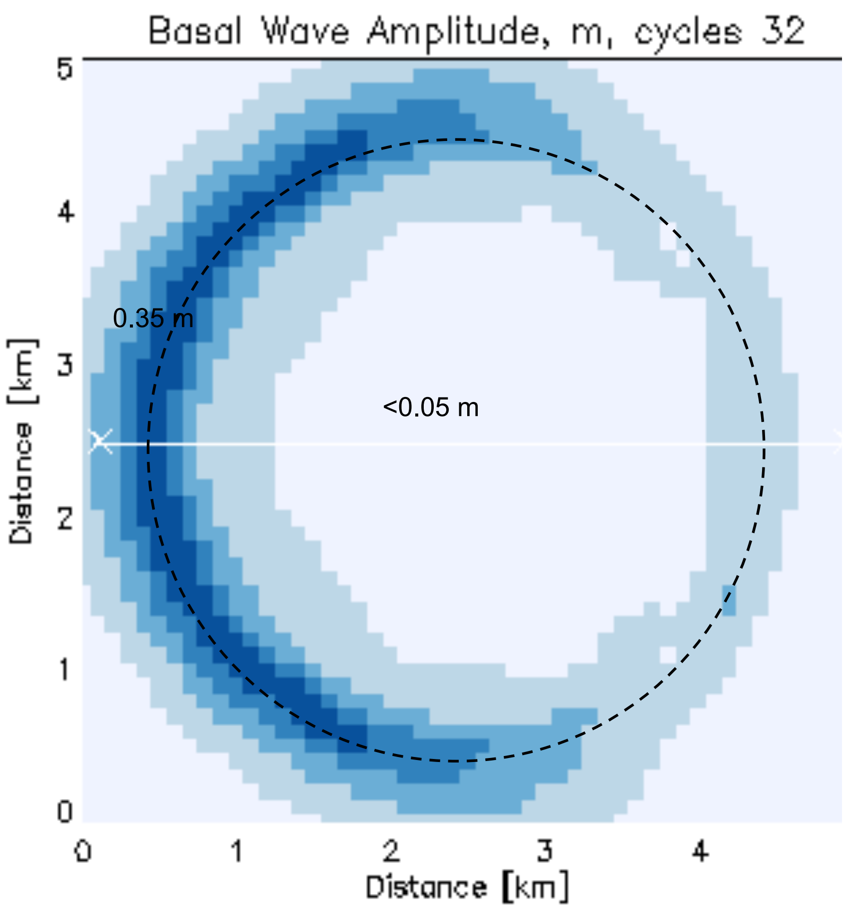
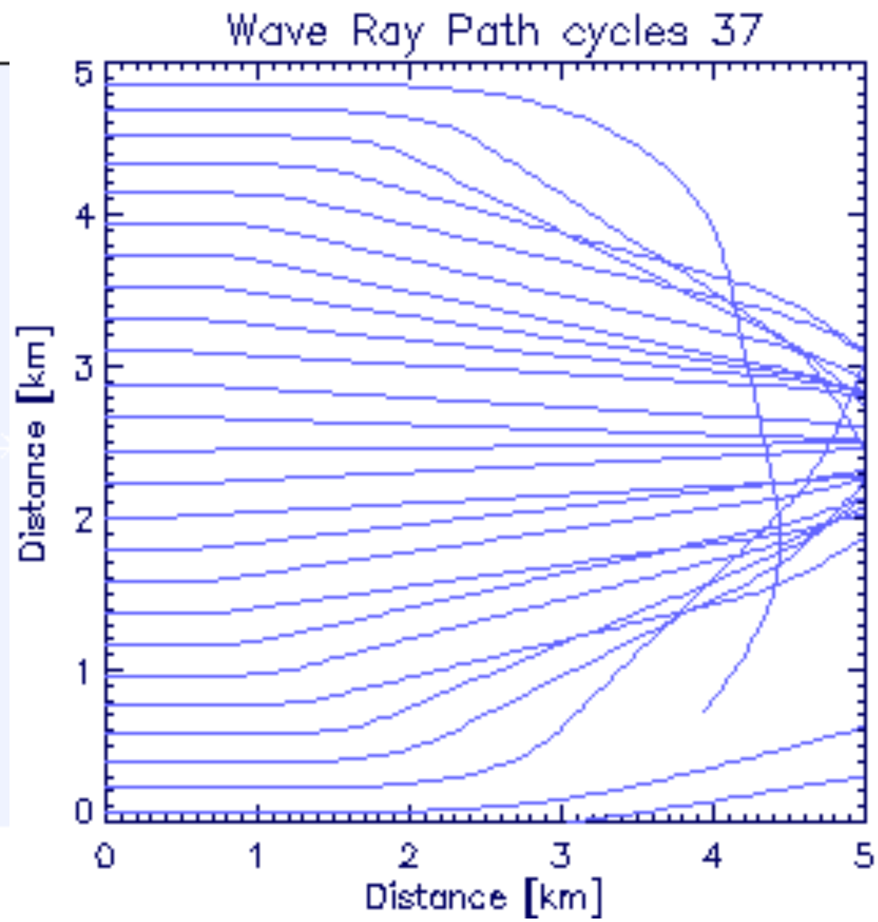
Distribution of wave energy: CARB3D+

Friction factor 5





Wind →

Water depth 10 m

Wind Speed 10 m/s

KEY: Darker is higher amplitude

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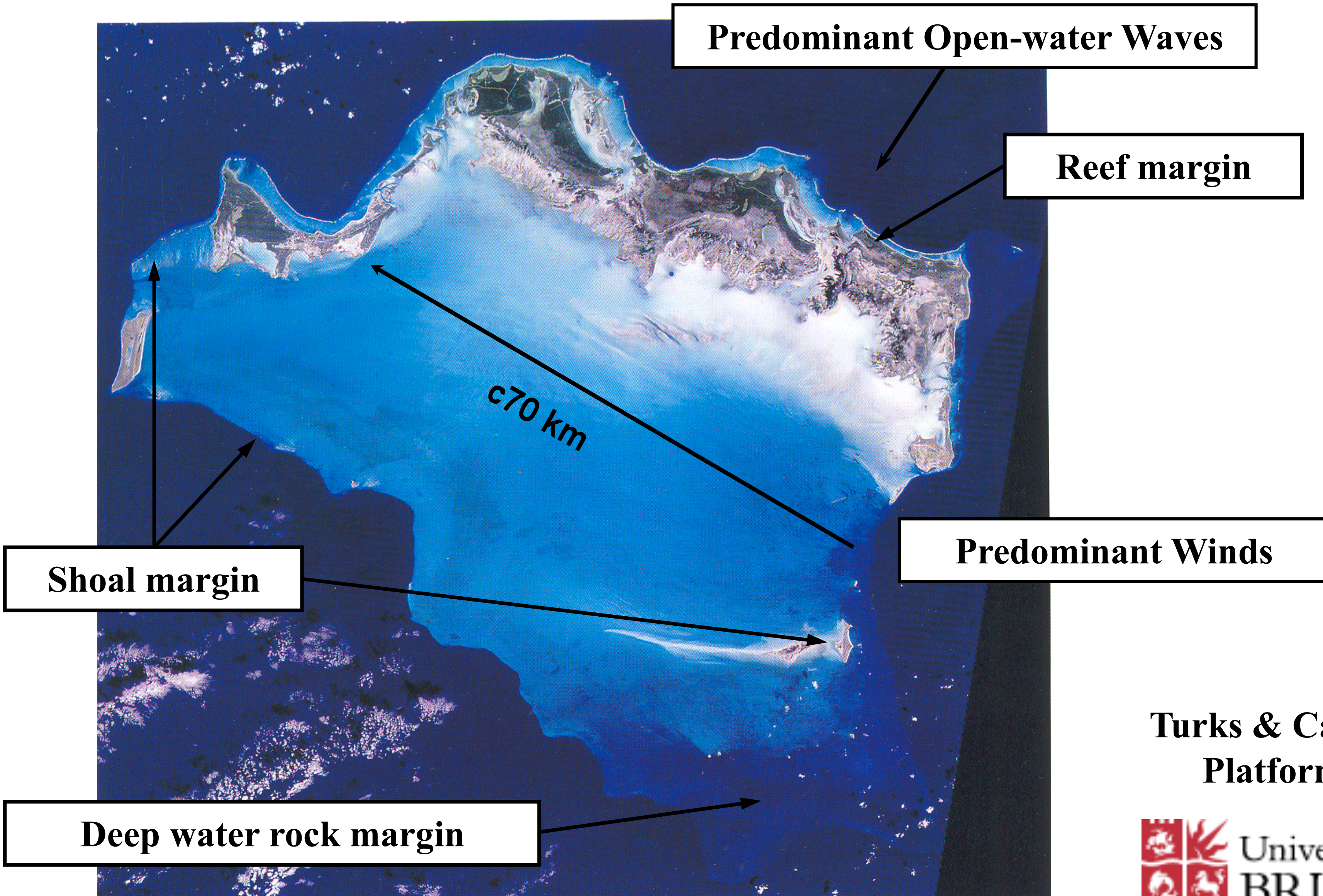
Wave propagation, long shallow fetch on platform top with wind reinforcement balancing energy loss?



Turks & Caicos Platform

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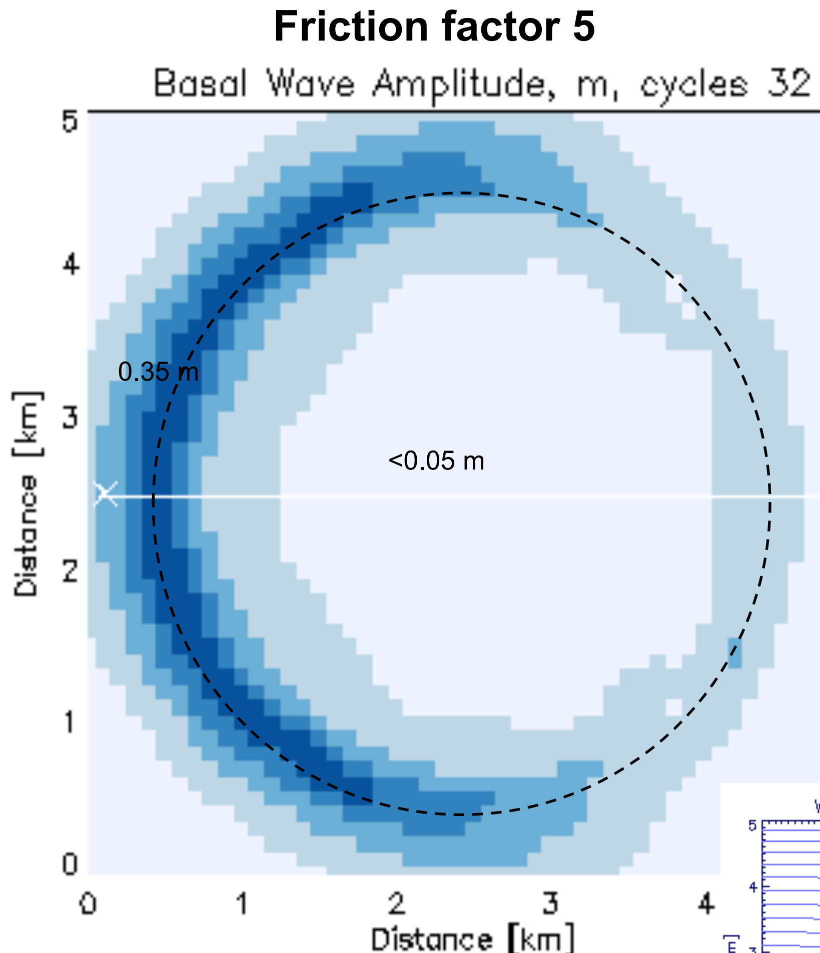
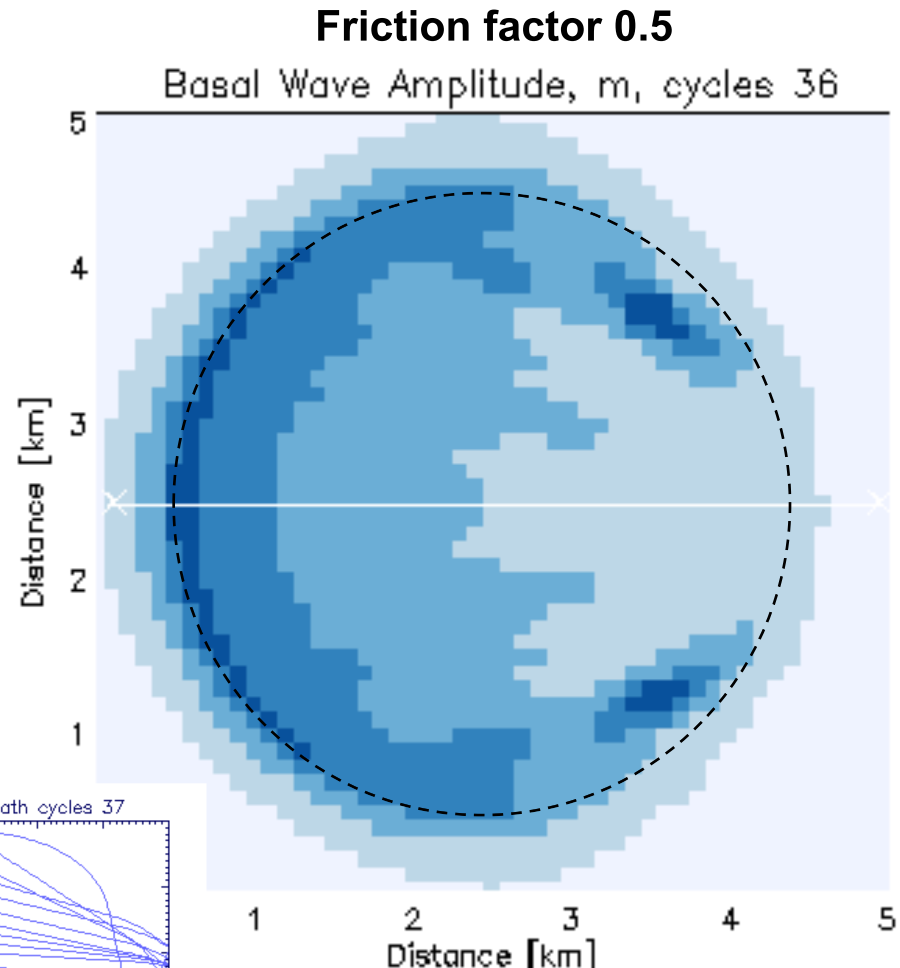
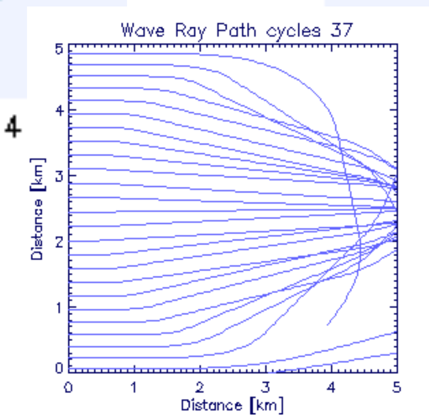
Effect of friction factor on wave energy in platform interior: CARB3D +







Water depth 10 m

Wind Speed 10 m/s

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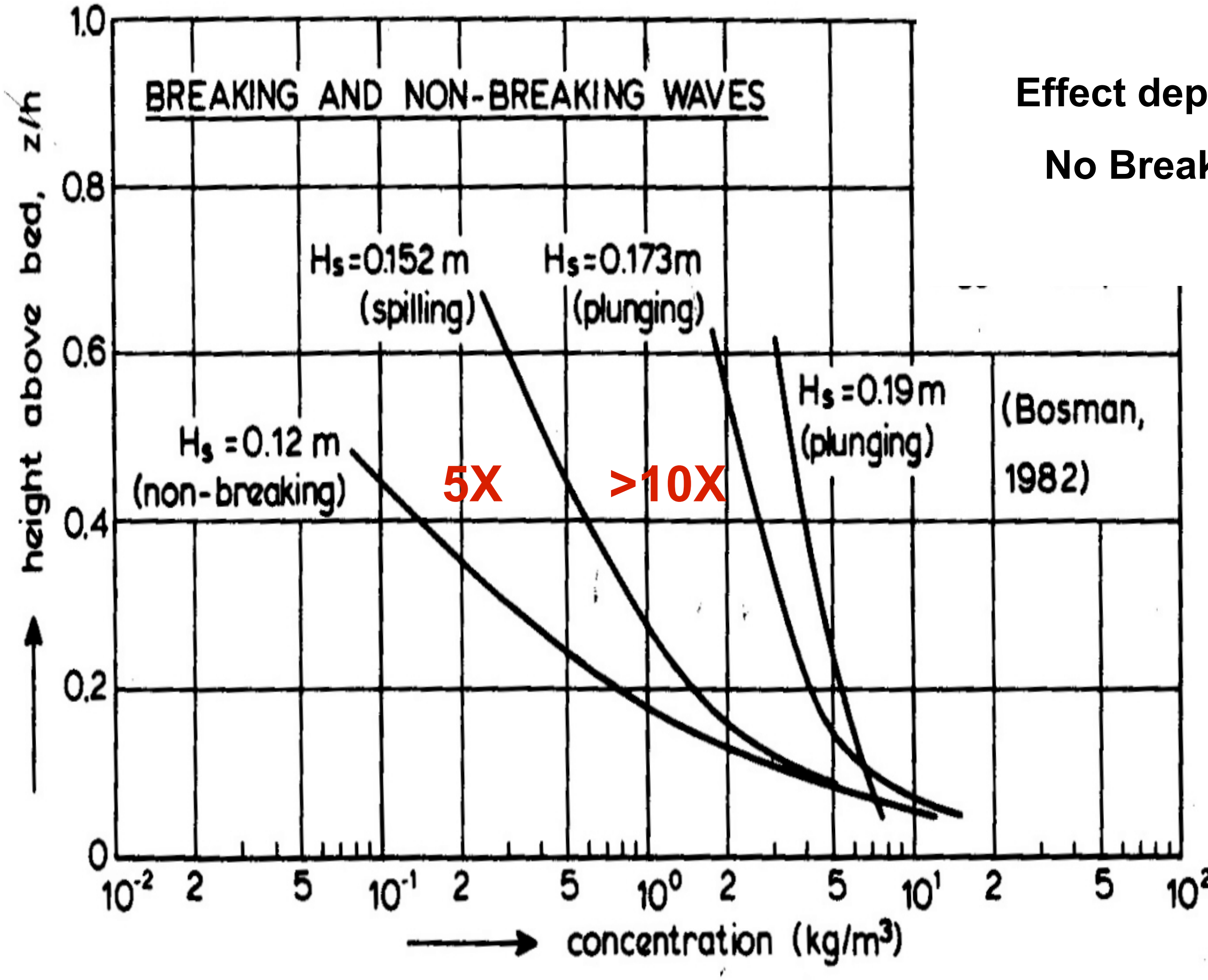
Breaking waves should entrain more sediment



Effect depends upon break type

No Break<Spilling <Plunging

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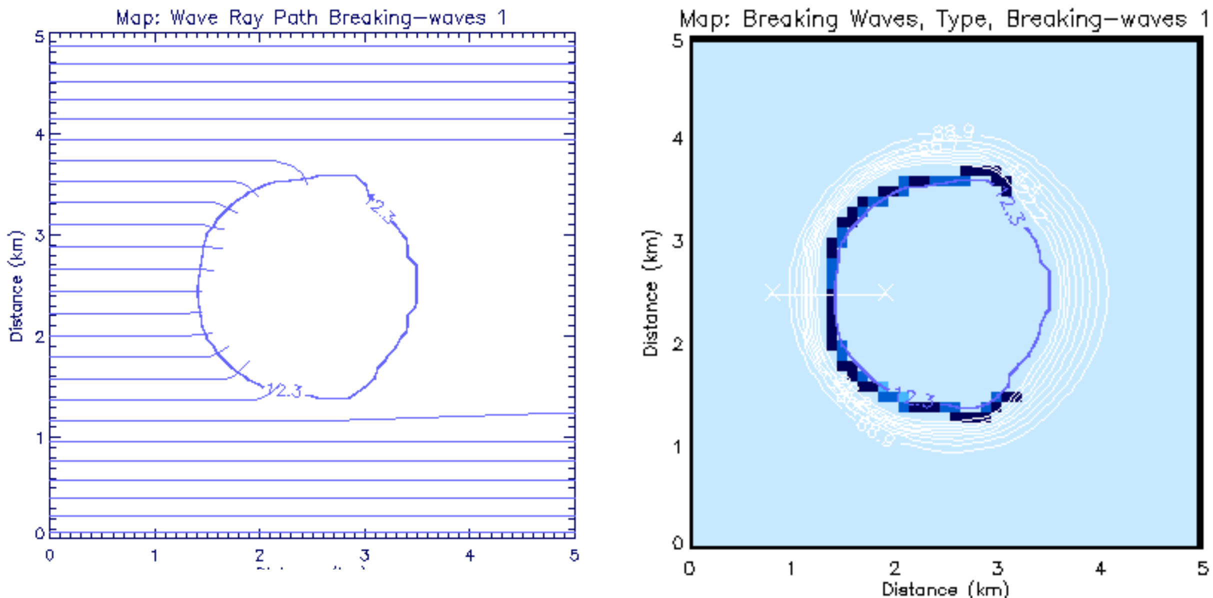
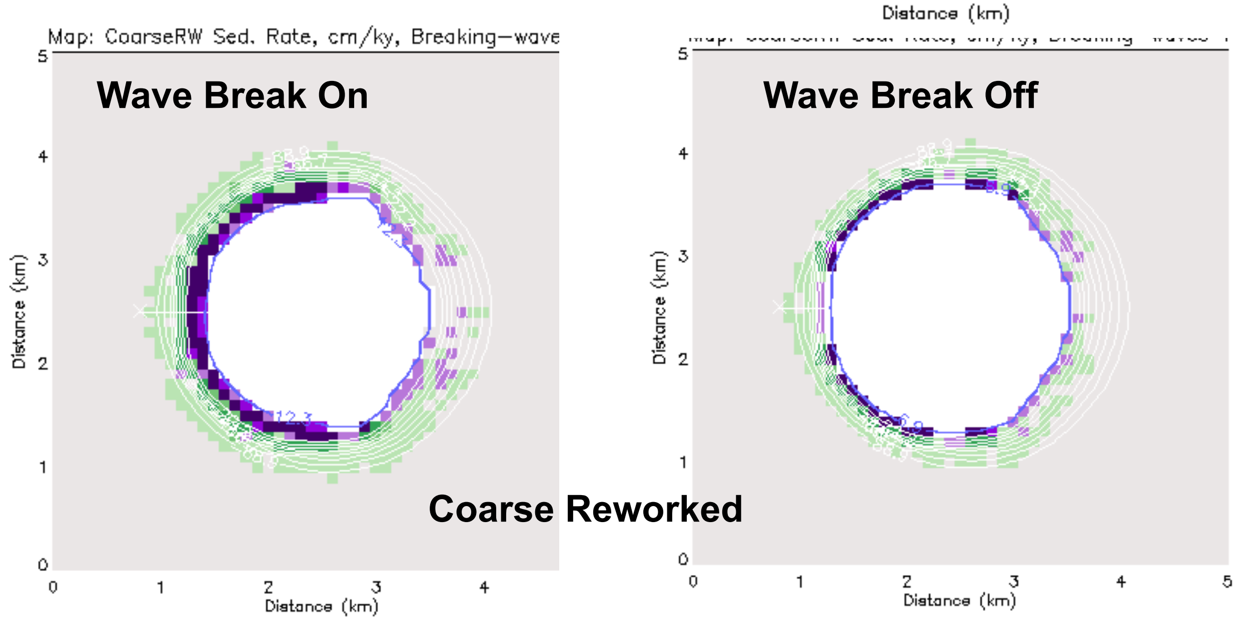
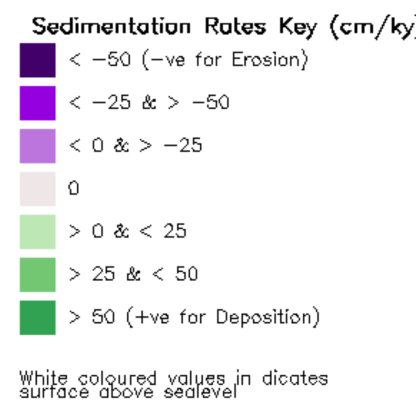
Enhanced sediment entrainment: CARB3D+







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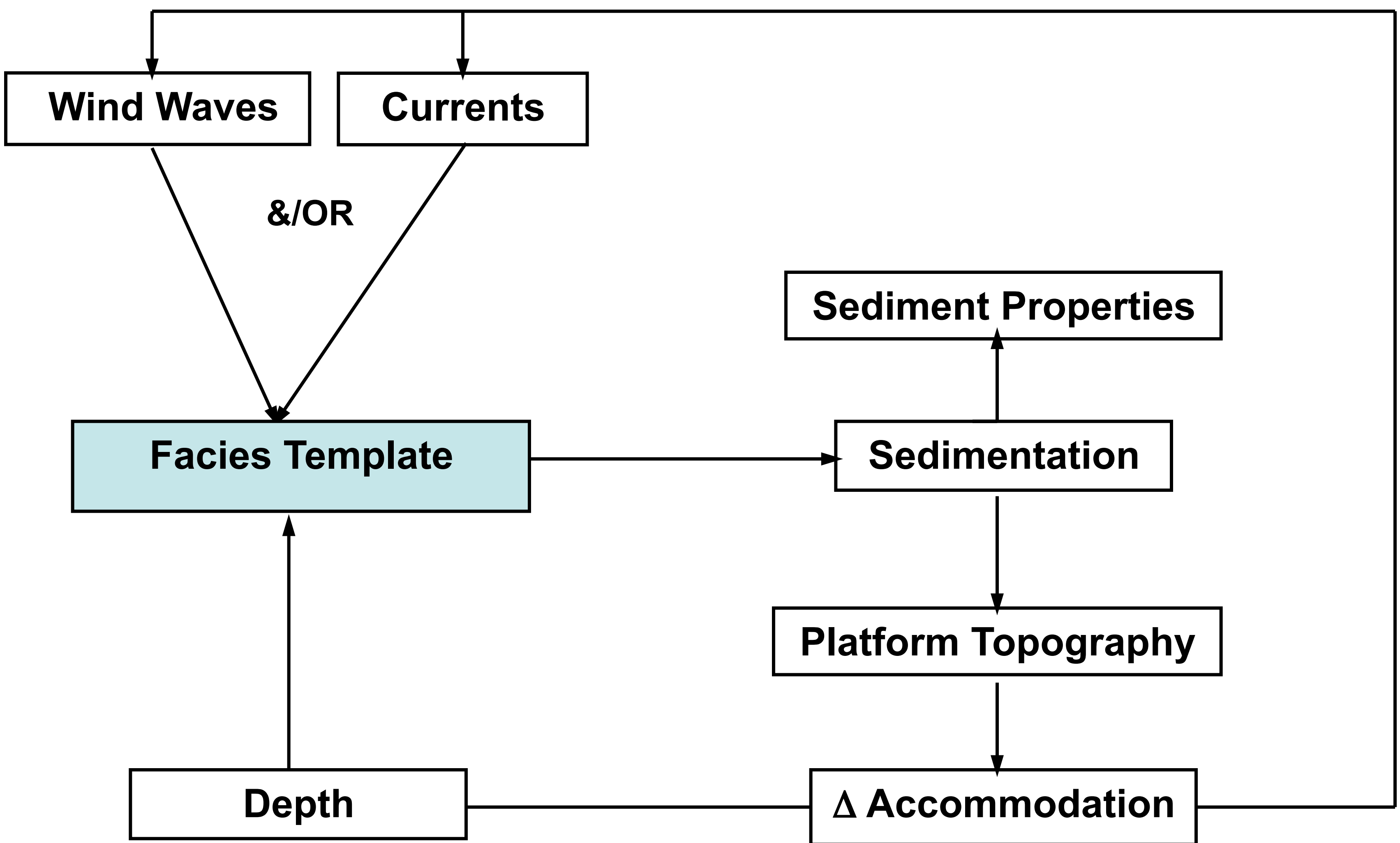
Facies Template Sedimentology



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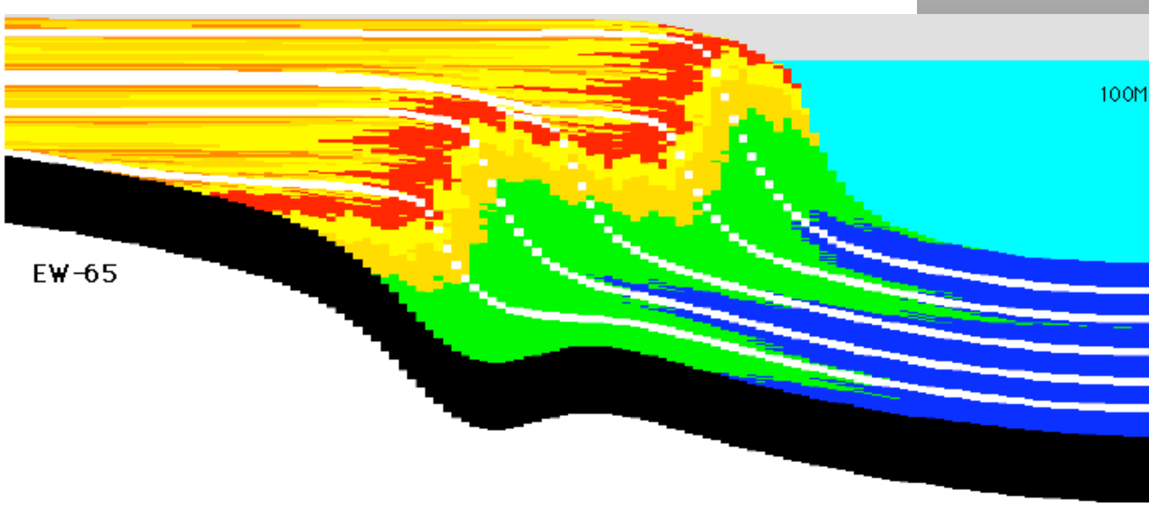
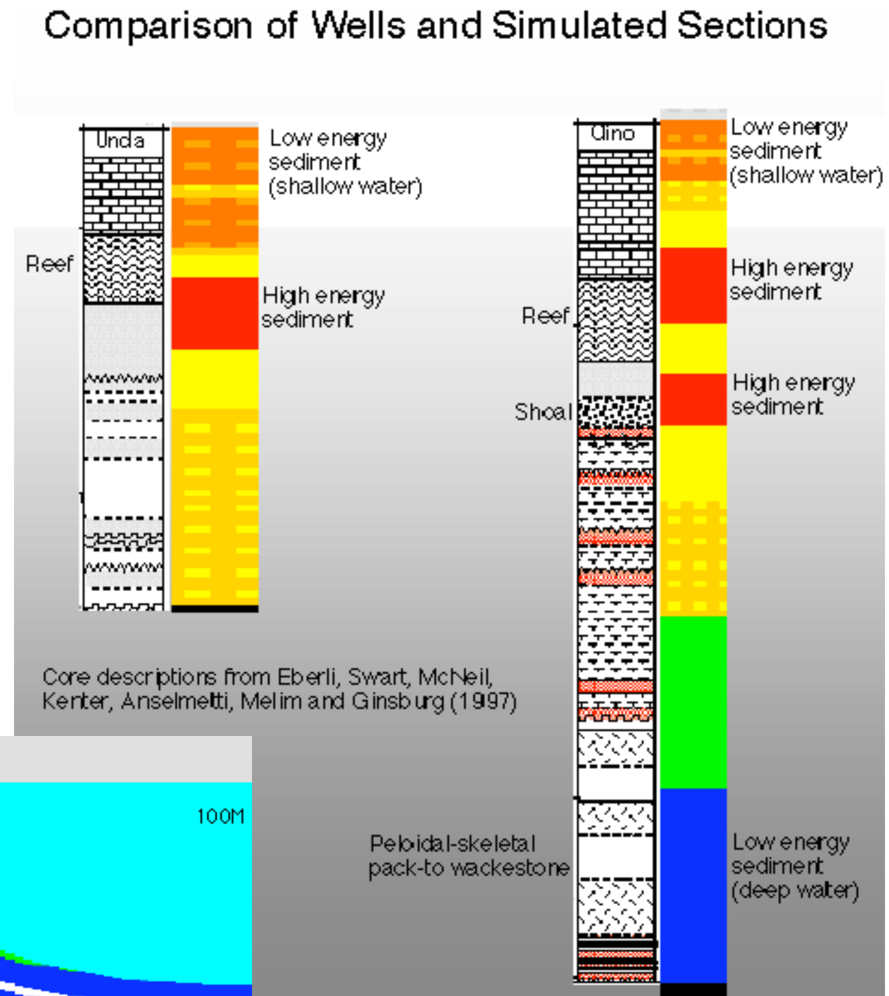
Facies template models: Need to convert wave energy to actual facies

CSM Carbsim

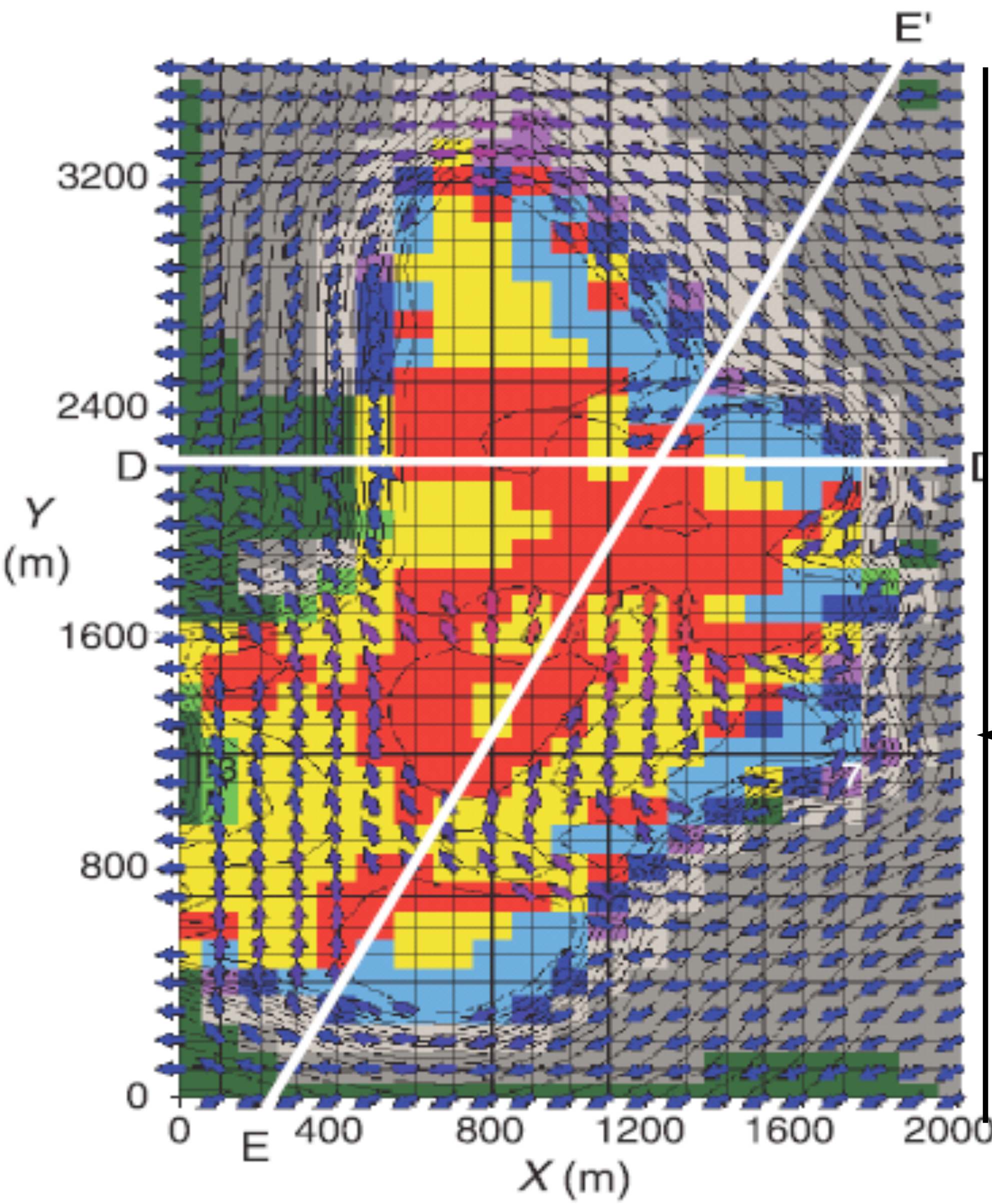
Taizhong Duan (2000)

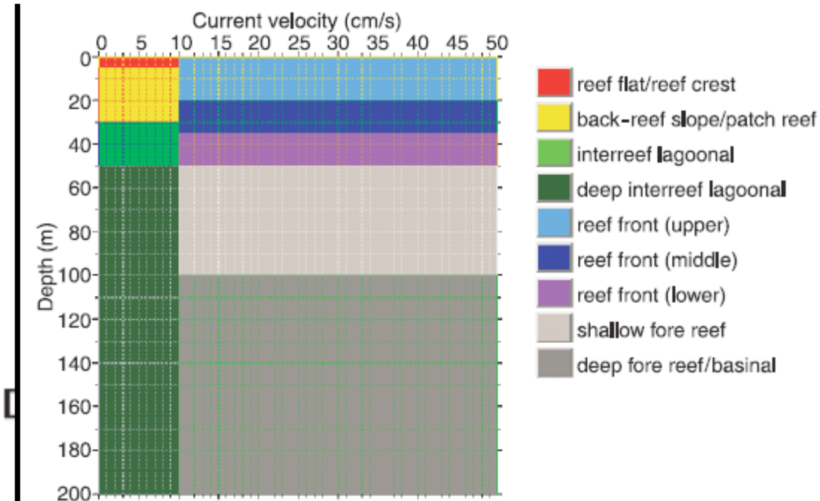
	1	2	3	4
water depth <= 200m	1 kenetic energy > 7.3	2 kenetic energy > 3.5	3 kenetic energy > 1.5	4 kenetic energy > 0.0
water depth > 200m	5 kenetic energy > 0.8		6 kenetic energy <= 0.8	
	5		6	





FACIES 3D: a facies template model based on currents





Specified Current Boundary

Late Miocene Walio Field, Iryan Jaya

Matsuda et al (2004)

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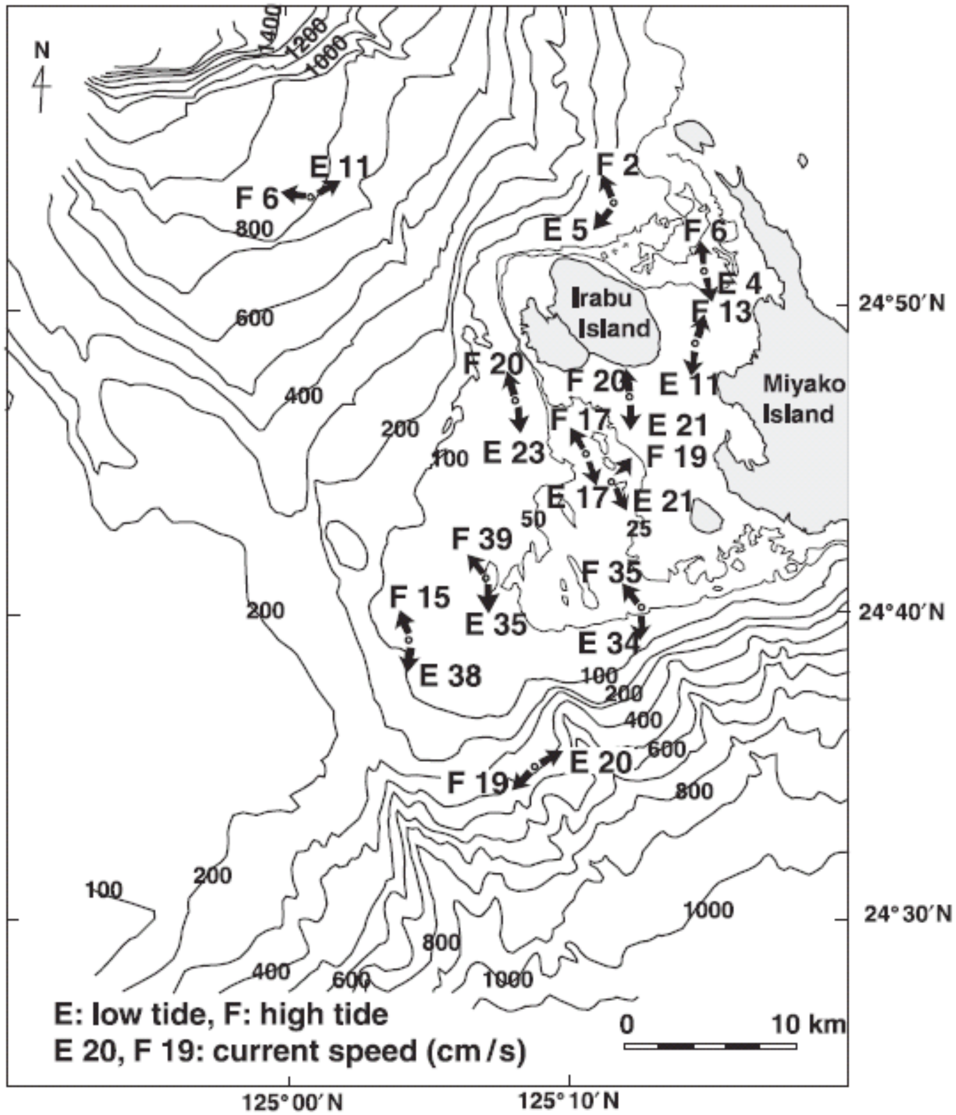
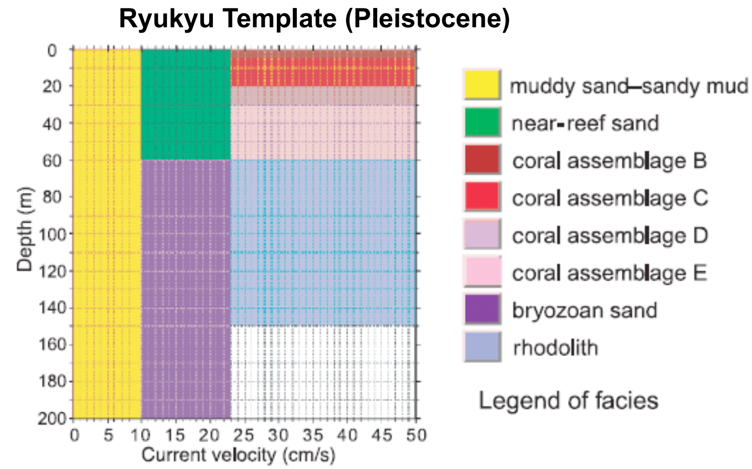
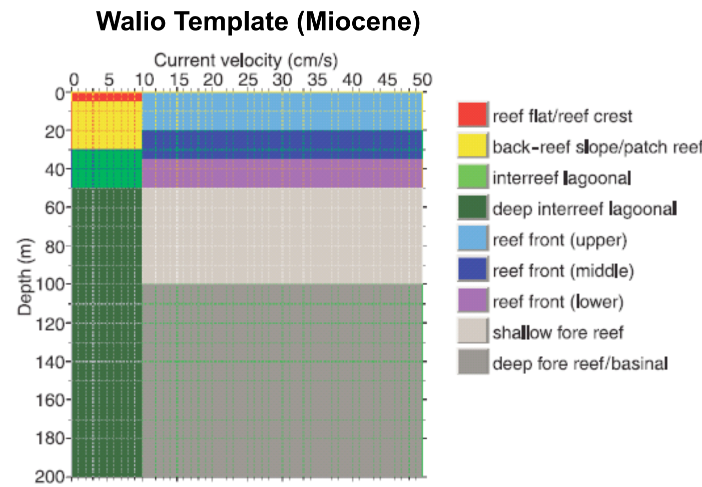
Calibration issues: Tidal or unidirectional currents?



Miyako Island tidal current calibration (Tsuji et al 1994)





Facies selected how?

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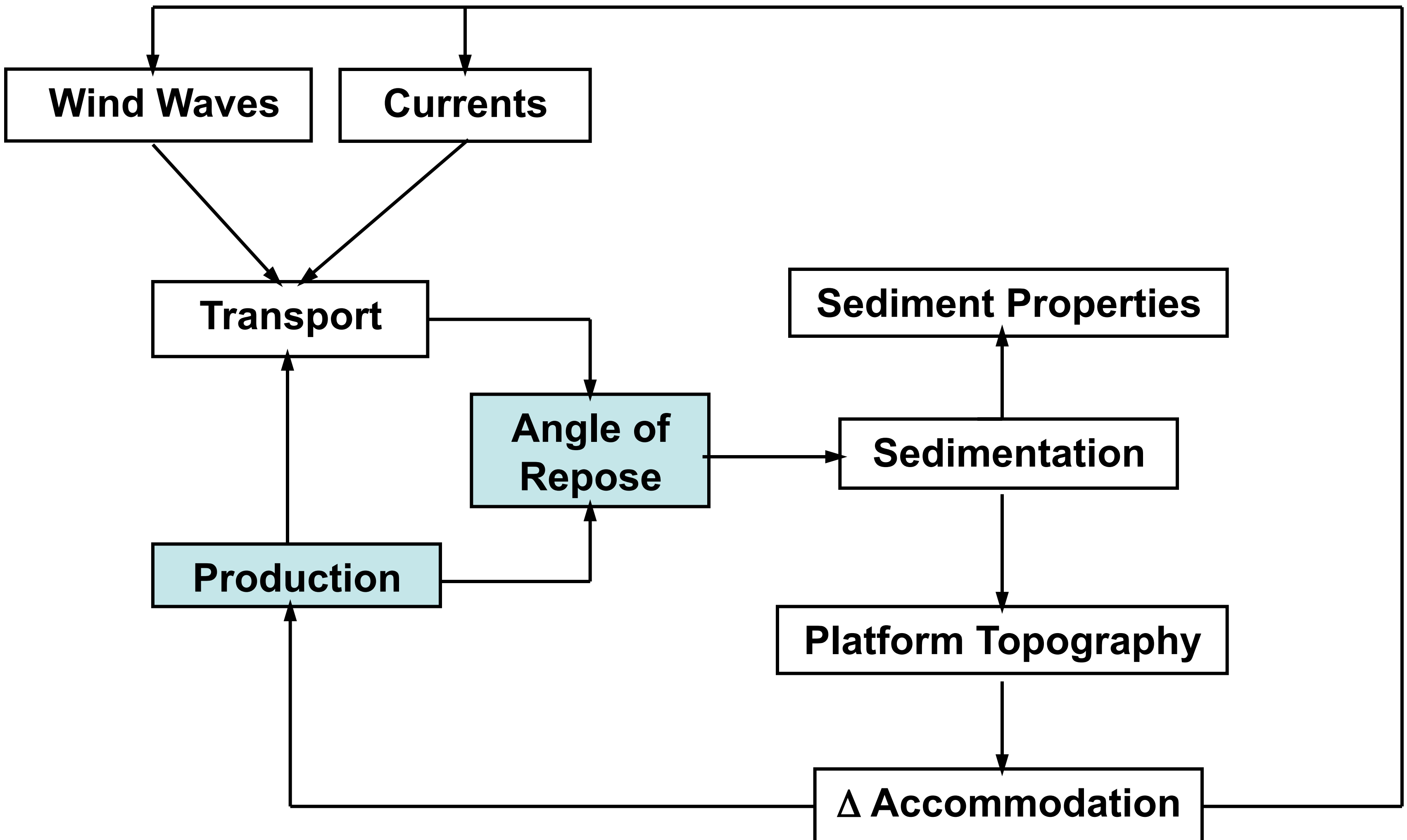
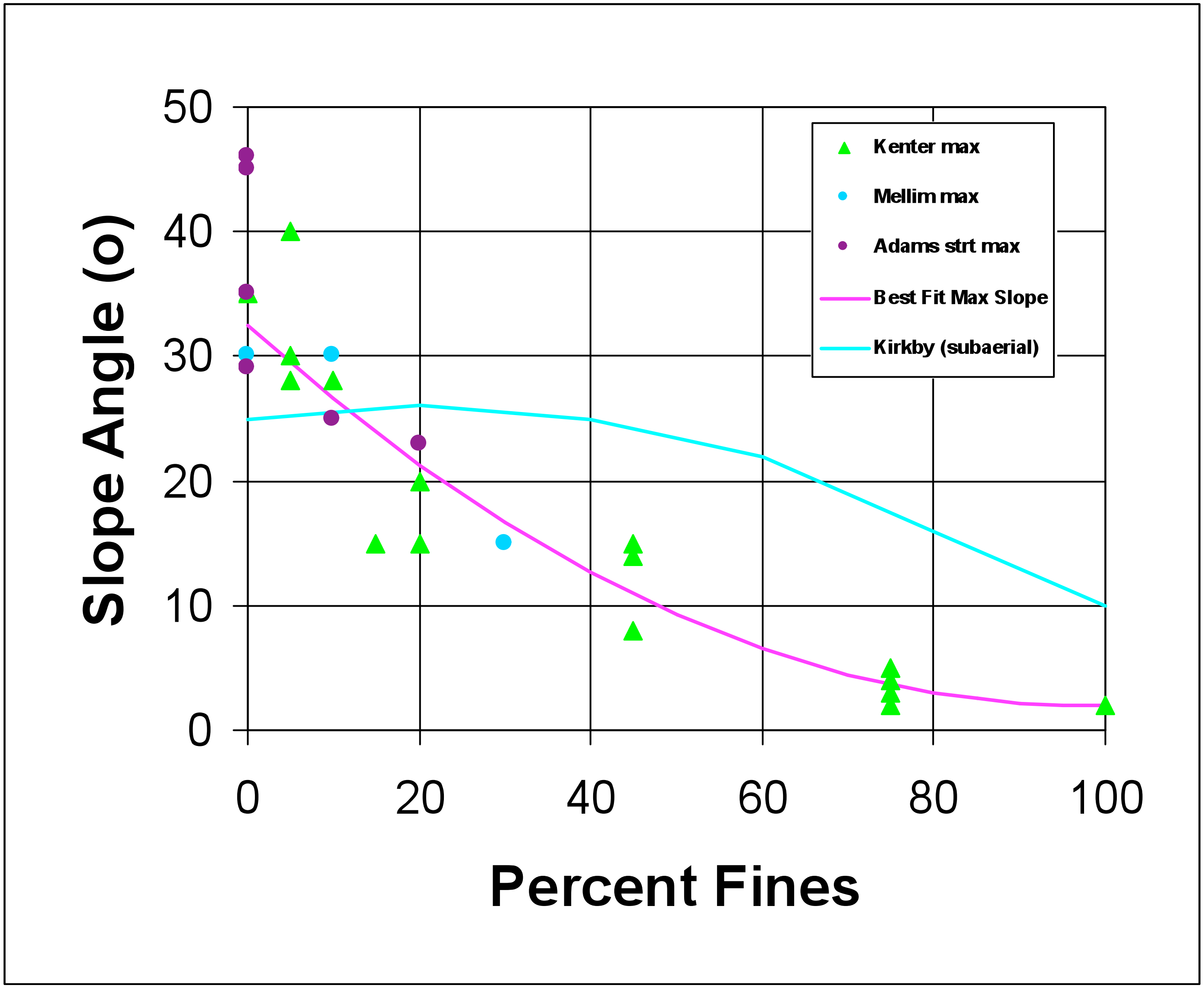
Sediment production and transport models: Carbonate Production



CARB3D+ structure

Angle of repose slopes: empirical calibration v fully explicit process specification CARB3D+



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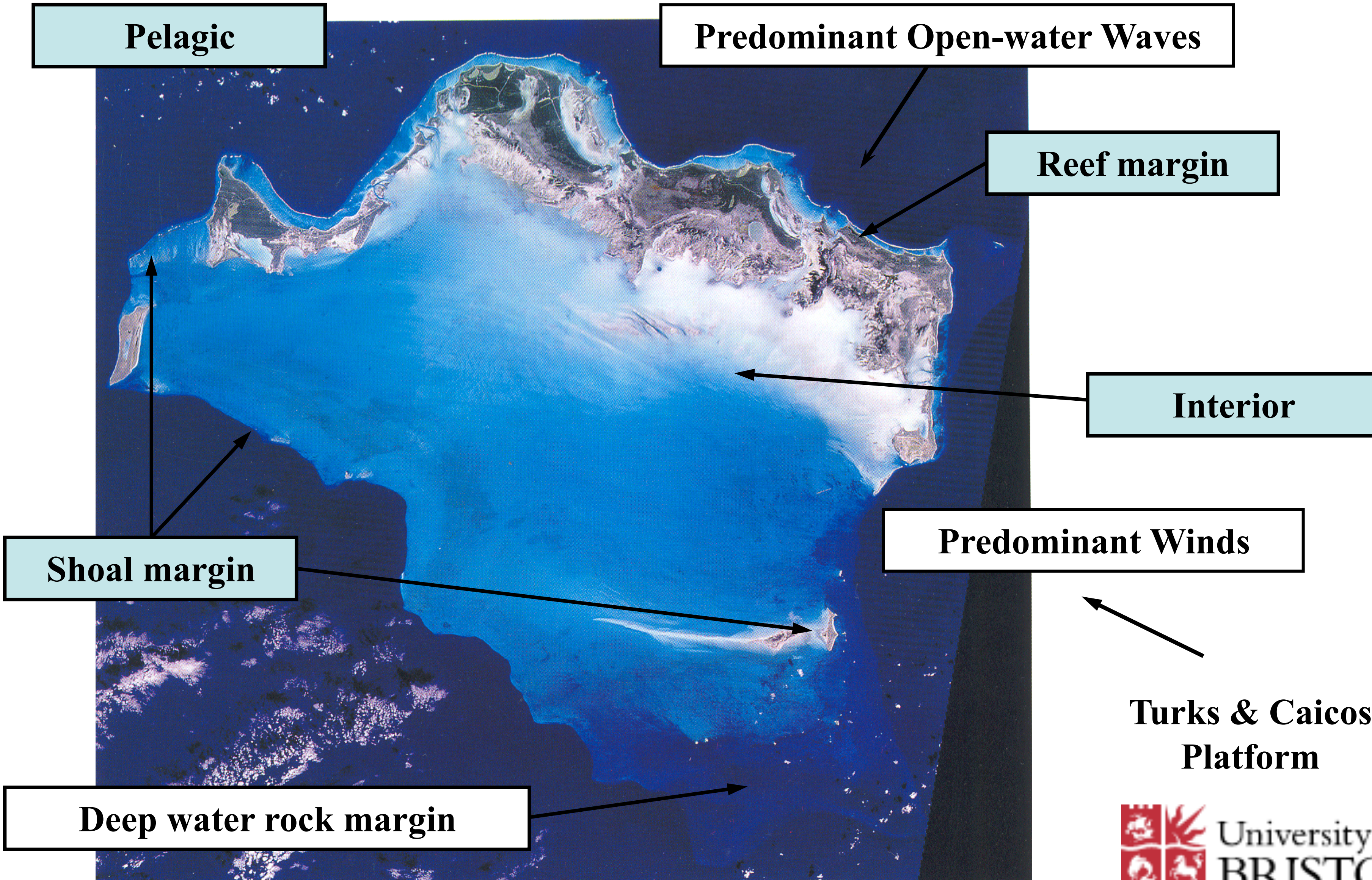
How many factories? CARB3D+ bank margin sediment production by reef and margin (shoal) + interior & pelagic factories



Turks & Caicos Platform

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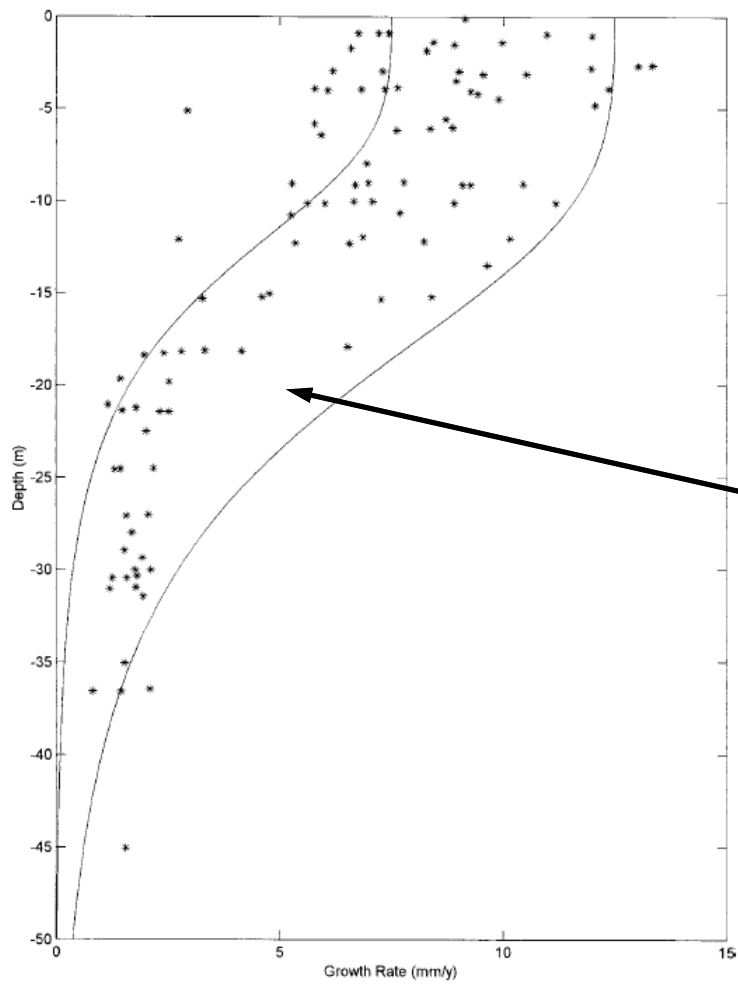
Environmental dependence of production: We know lots.
Eg. Depth (light + suspended sediments etc) reduction of carbonate production with depth: coral *Montrastrea annularis*



Exponential light attenuation with depth according to Beer –Lambert law
+
suspended sediment, competition etc

Bosscher and Schlager (1992)

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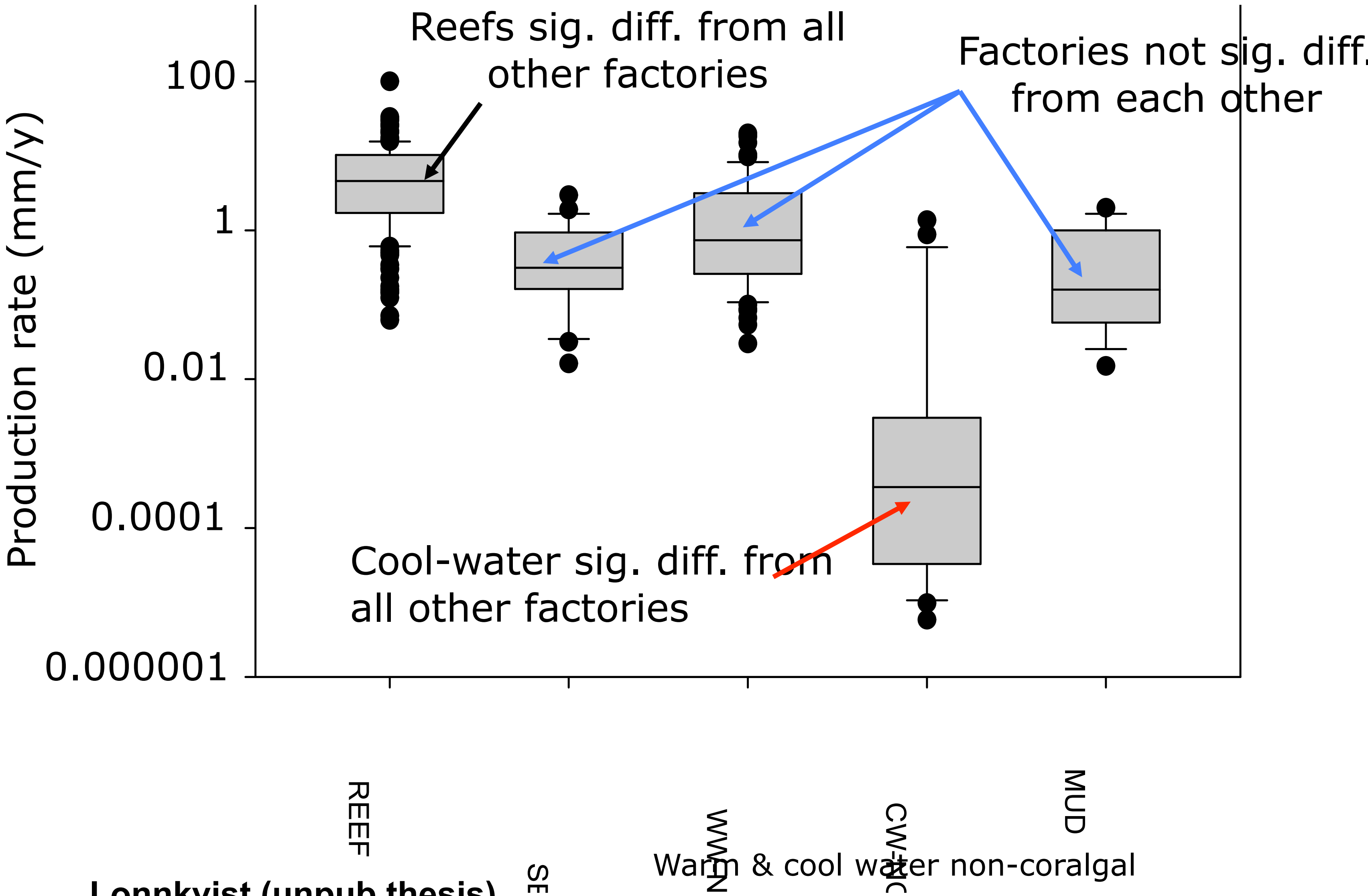
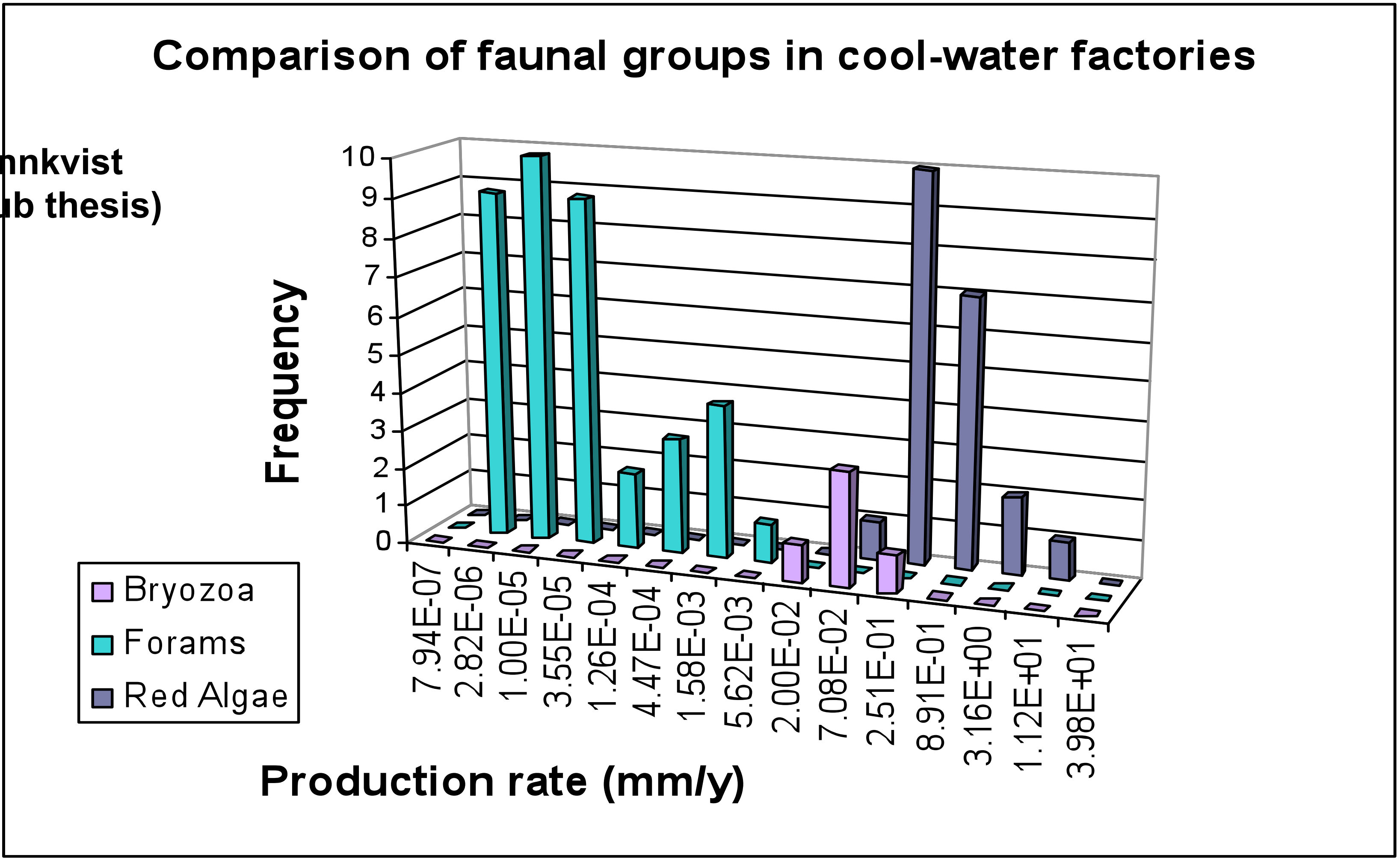
We also have good factory production rate data (Although as accommodation is usually limiting this is not so critical)



Lonnkvist (unpub thesis)

But are individual species rates and dependencies representative of factories? How do we model changes in community structure in past?

Lonnkvist (unpub thesis)



Competition between groups & factories?

SIMSAFADIM

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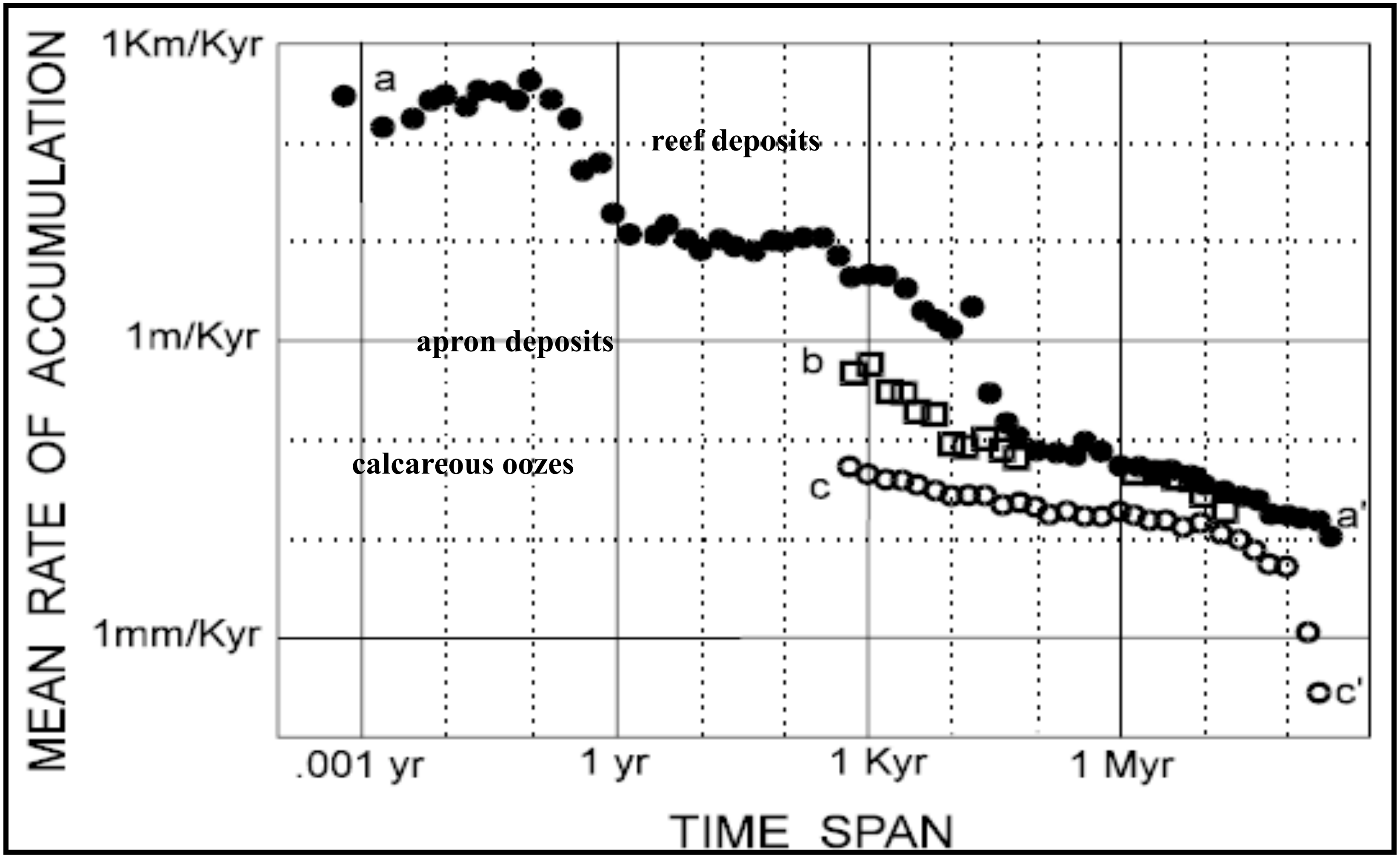
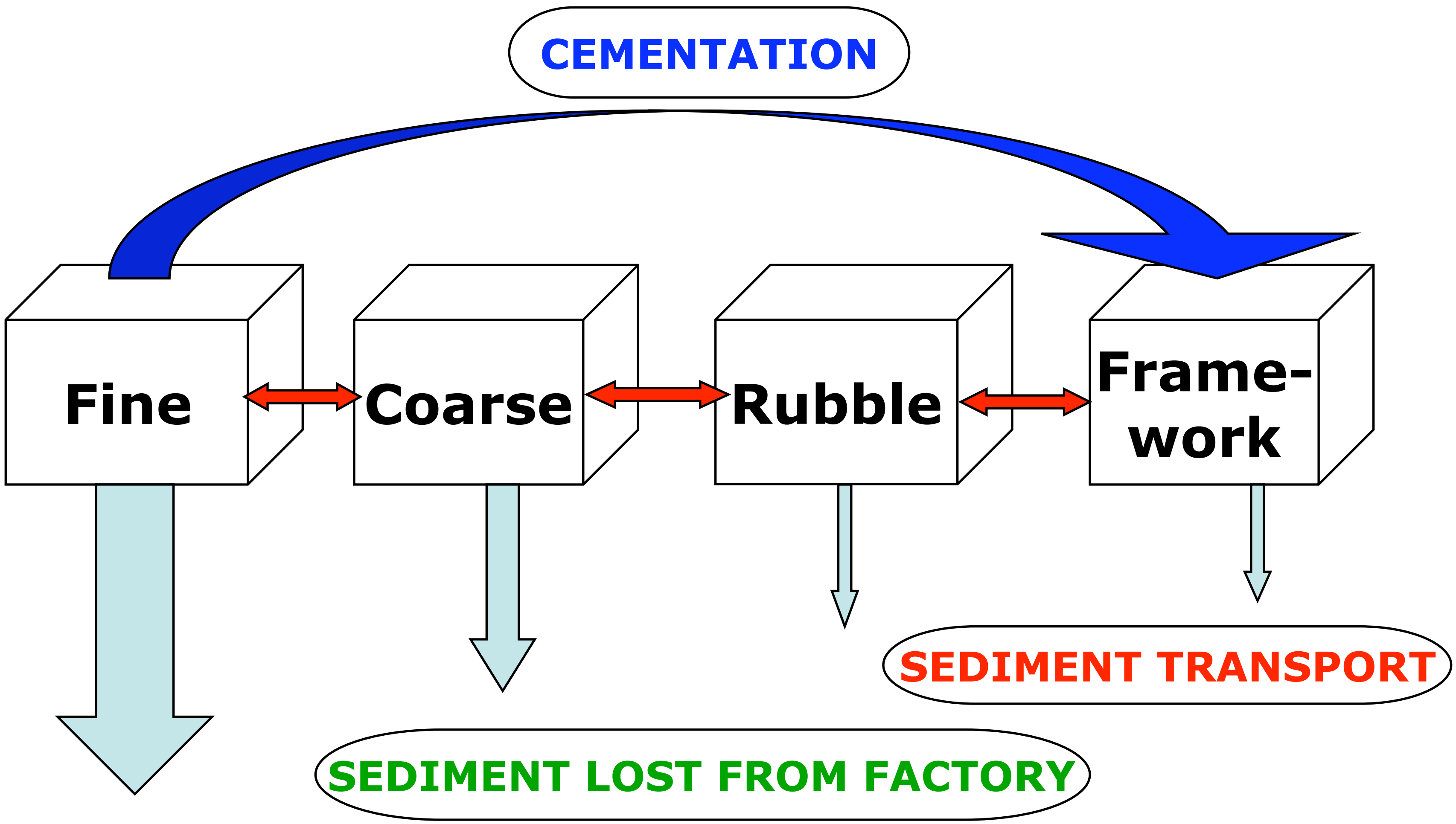
In any case do short term measurements represent long-term rates? And do models account for some of these effects especially non-deposition & platform exposure (oozes v reefs)?

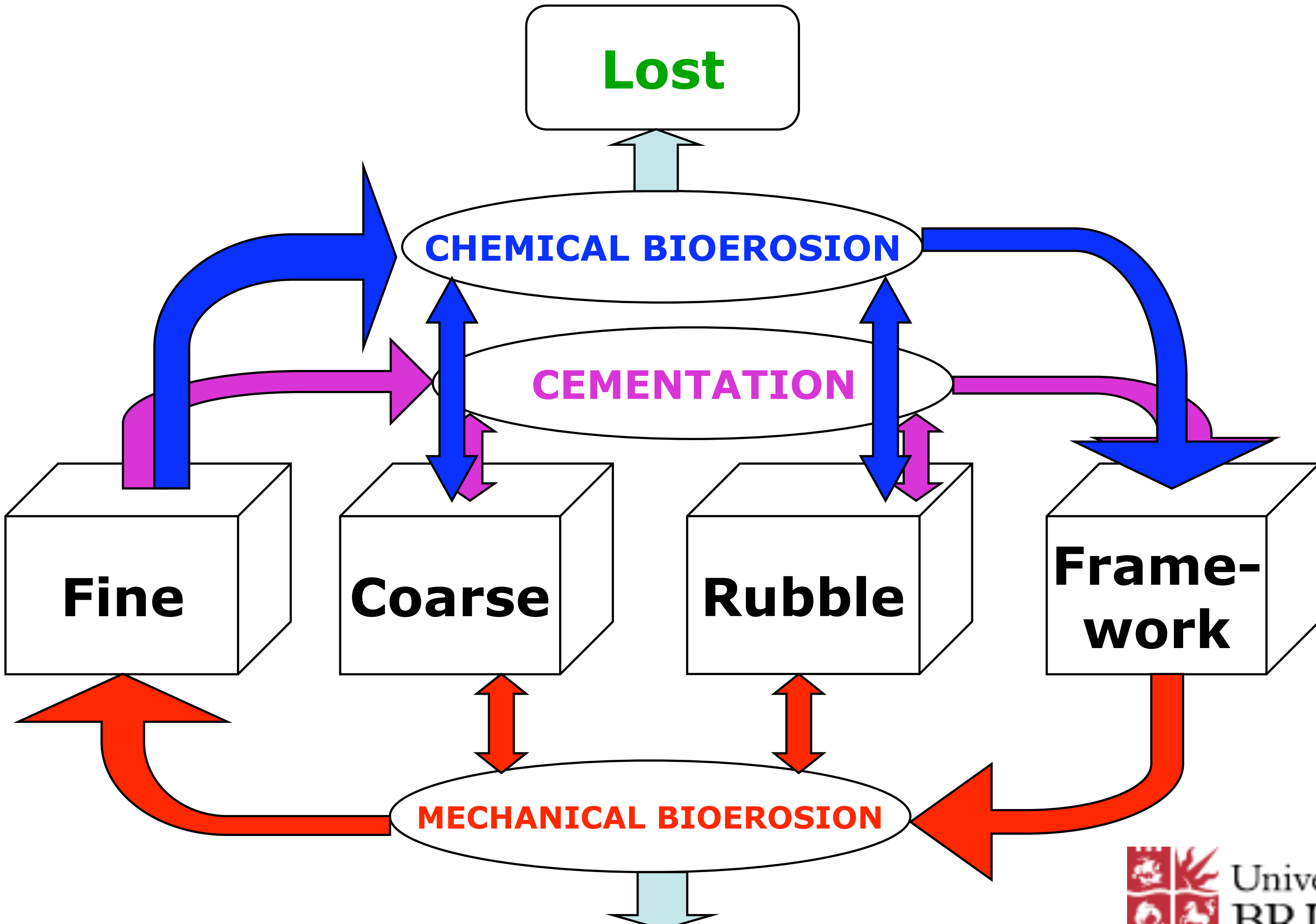


Sadler (1999)

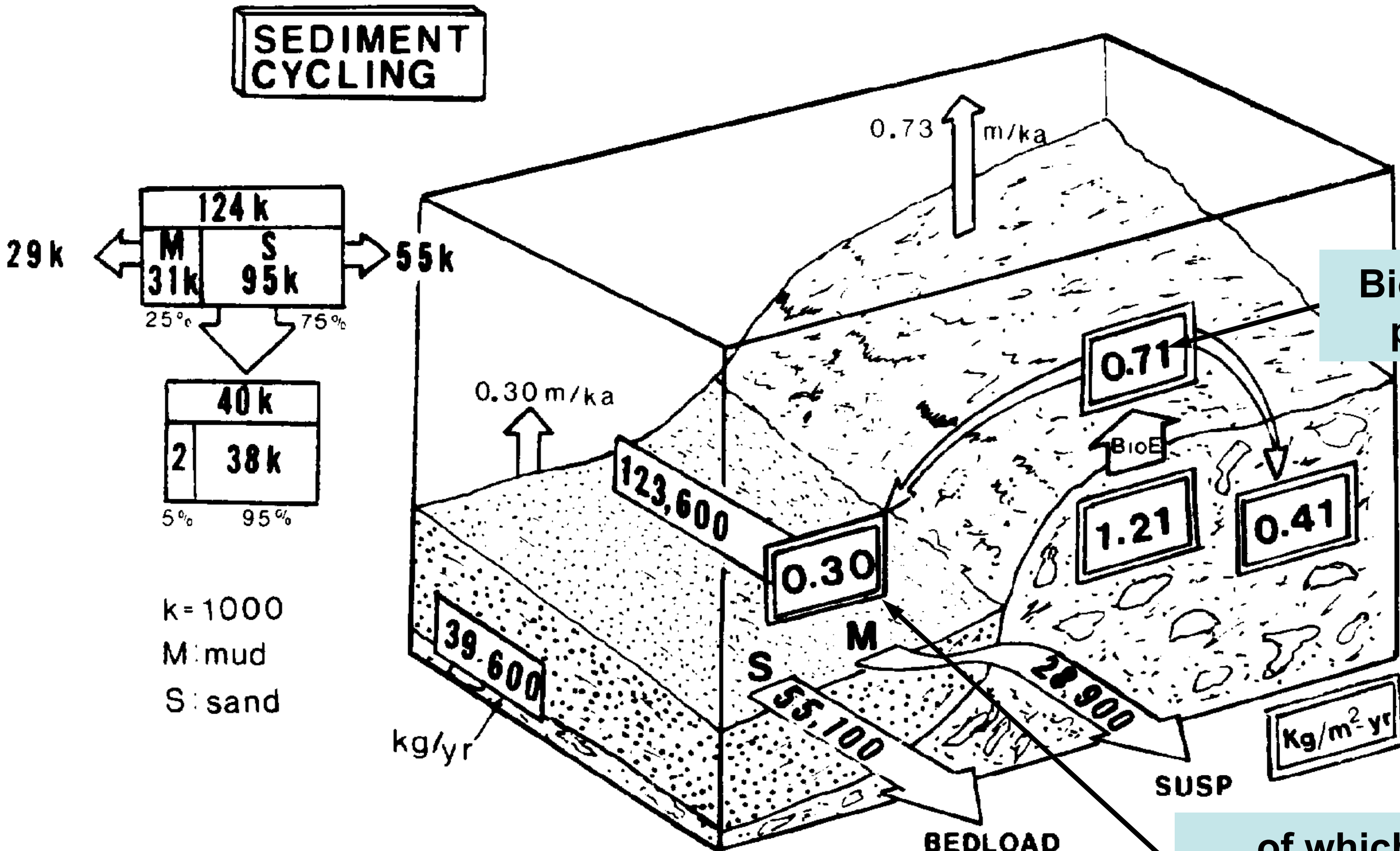
2 key issues affecting sediment availability for transport: cementation



2 key issues affecting sediment availability for transport: cementation and conversely bio-erosion (and geochemical loss of carbonate?)



We need more careful sediment budget studies like this one, and to use the results from them.



Bio-erosion c60% production…..

….of which 25% is exported

Cane Bay Reef Hubbard et al (1990)

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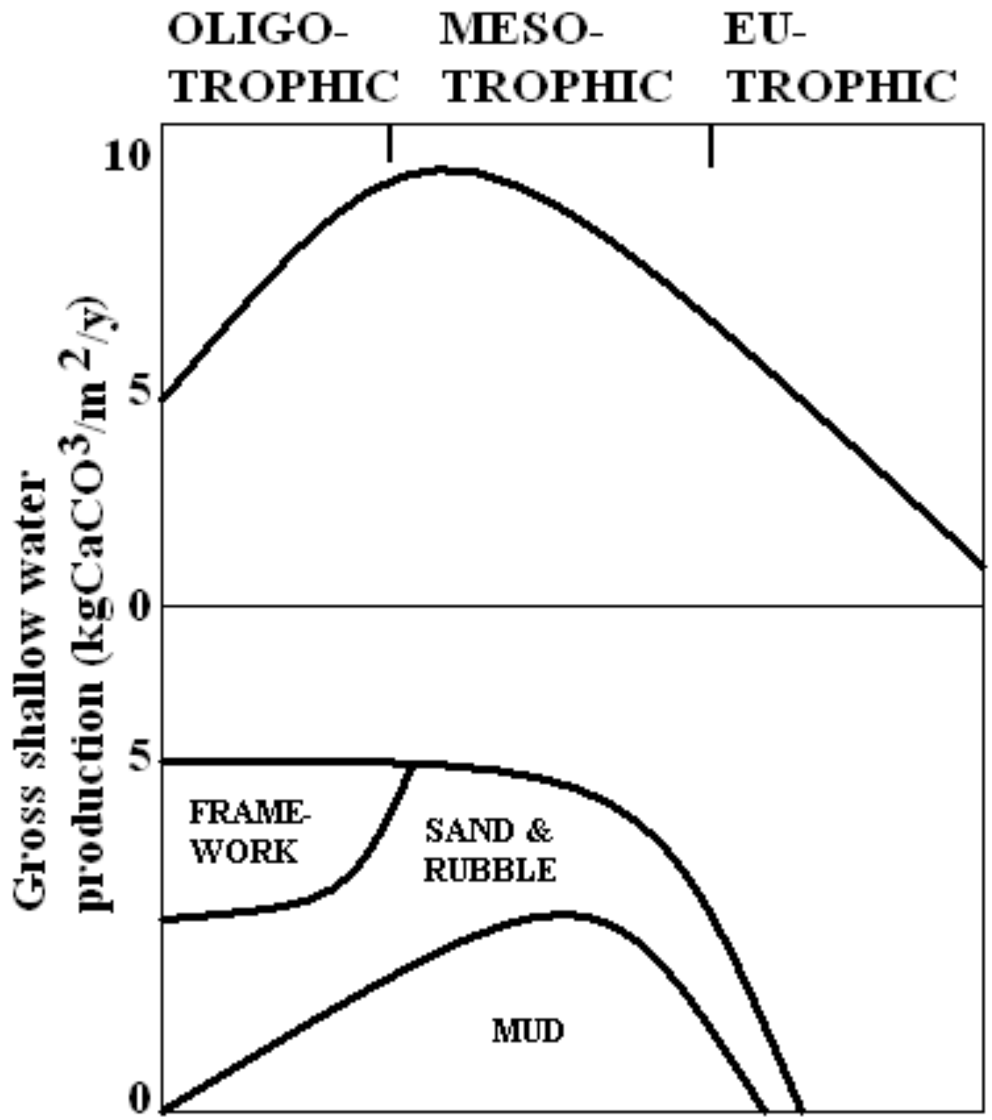
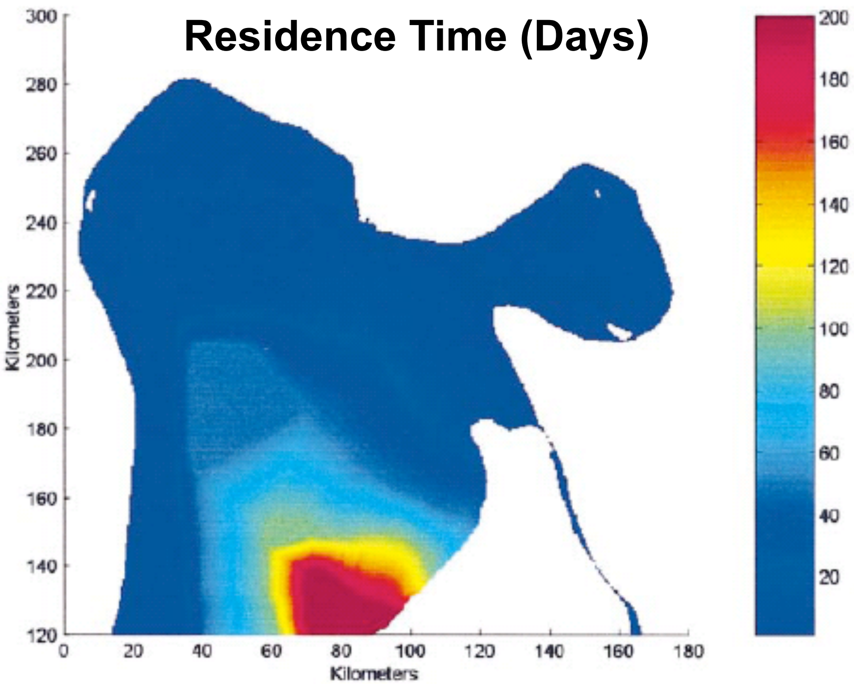
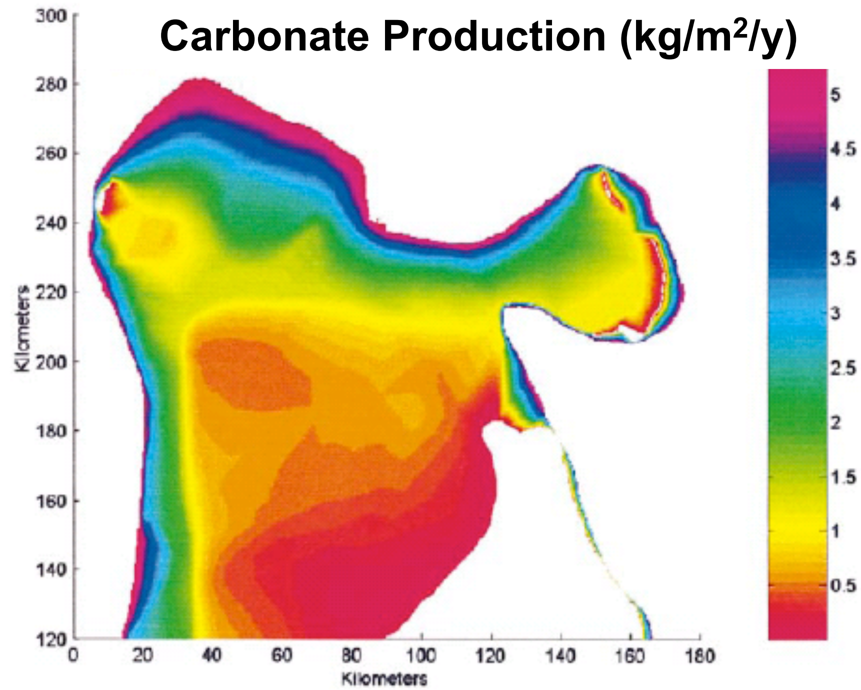
We need to be able to incorporate controls on bio-erosion into models: eg nutrients

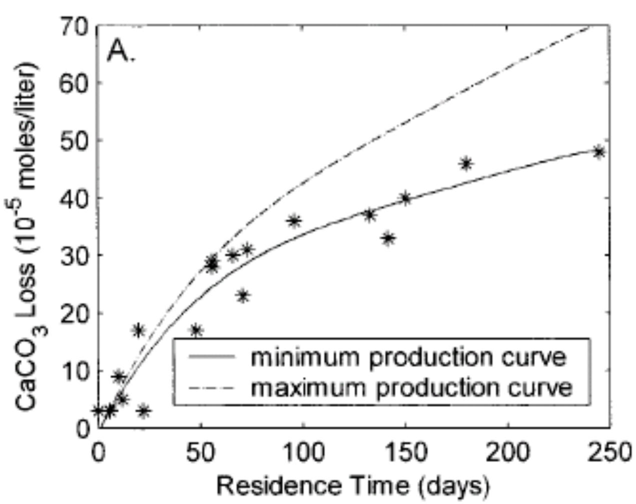


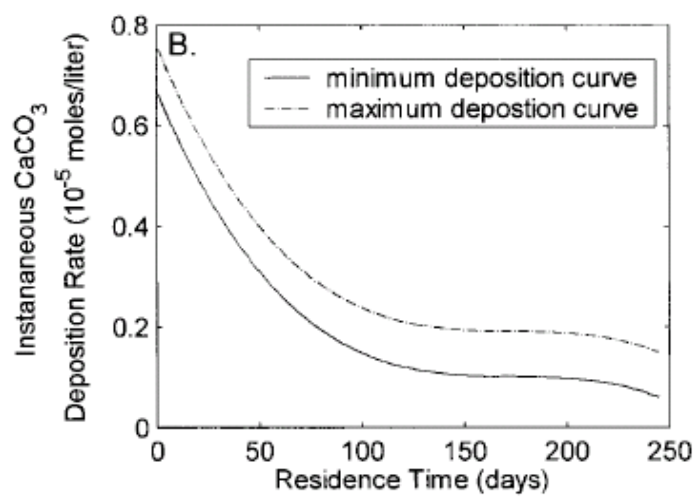
Hallcock et al

Carbonate production rates: dependence on carbonate avialability. Residence time & carbonate exhaustion, Great Bahama Bank









Demicco & Hardie (2002) after Broecker & Takahashi (1966)

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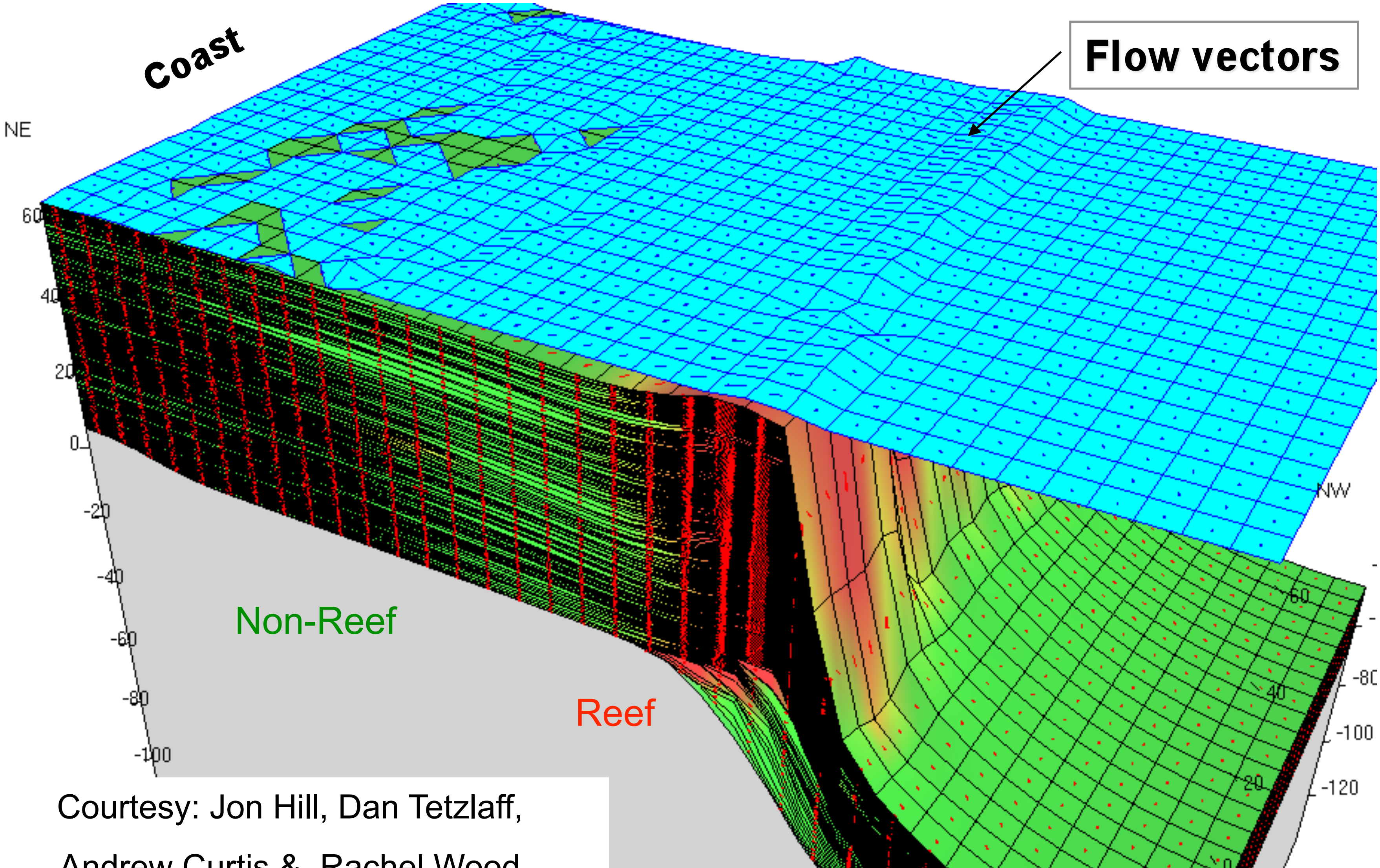
Carbonate GPM (Geological Process Modeller)



Courtesy: Jon Hill, Dan Tetzlaff, Andrew Curtis & Rachel Wood

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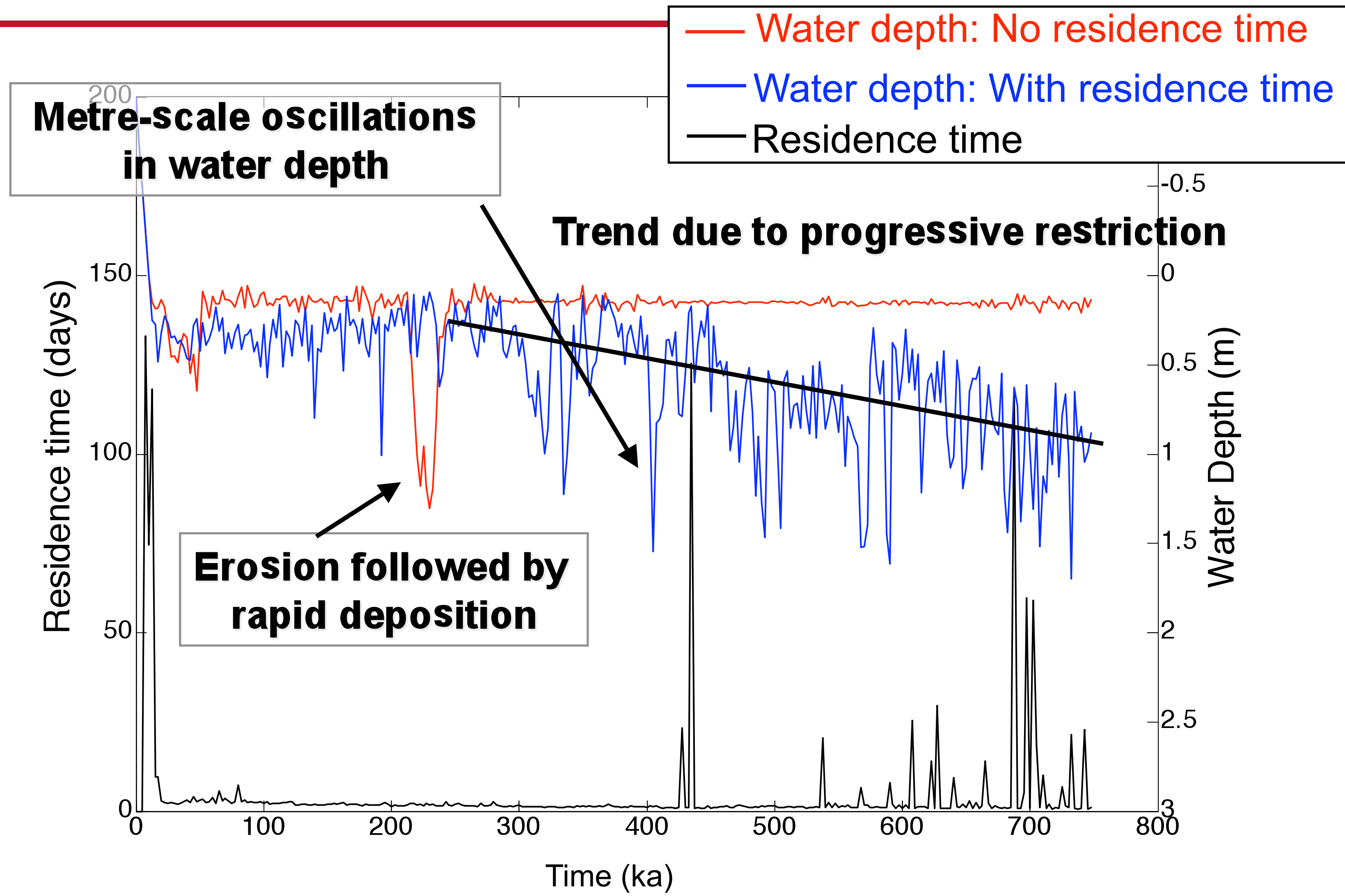
Schlumberger

Carbonate GPM: Water depth history (central lagoon)



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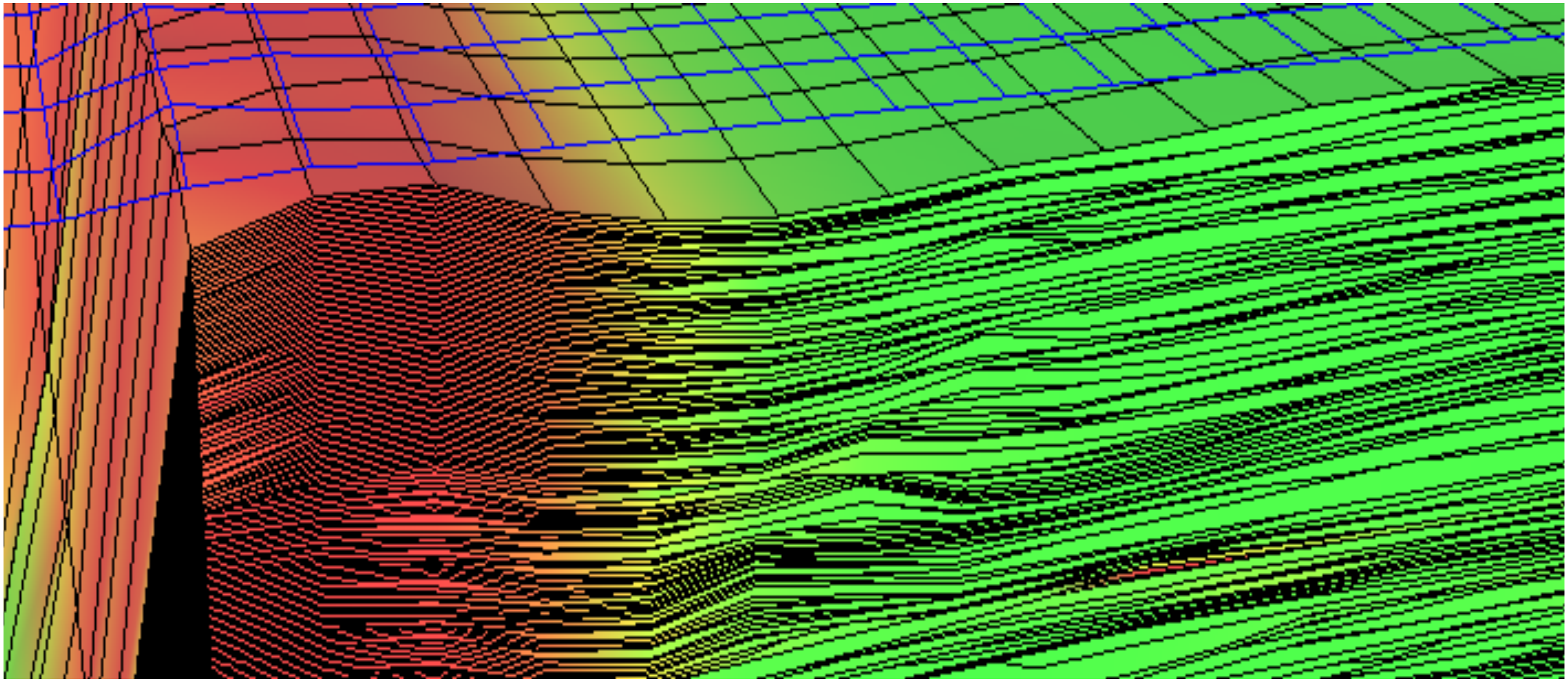
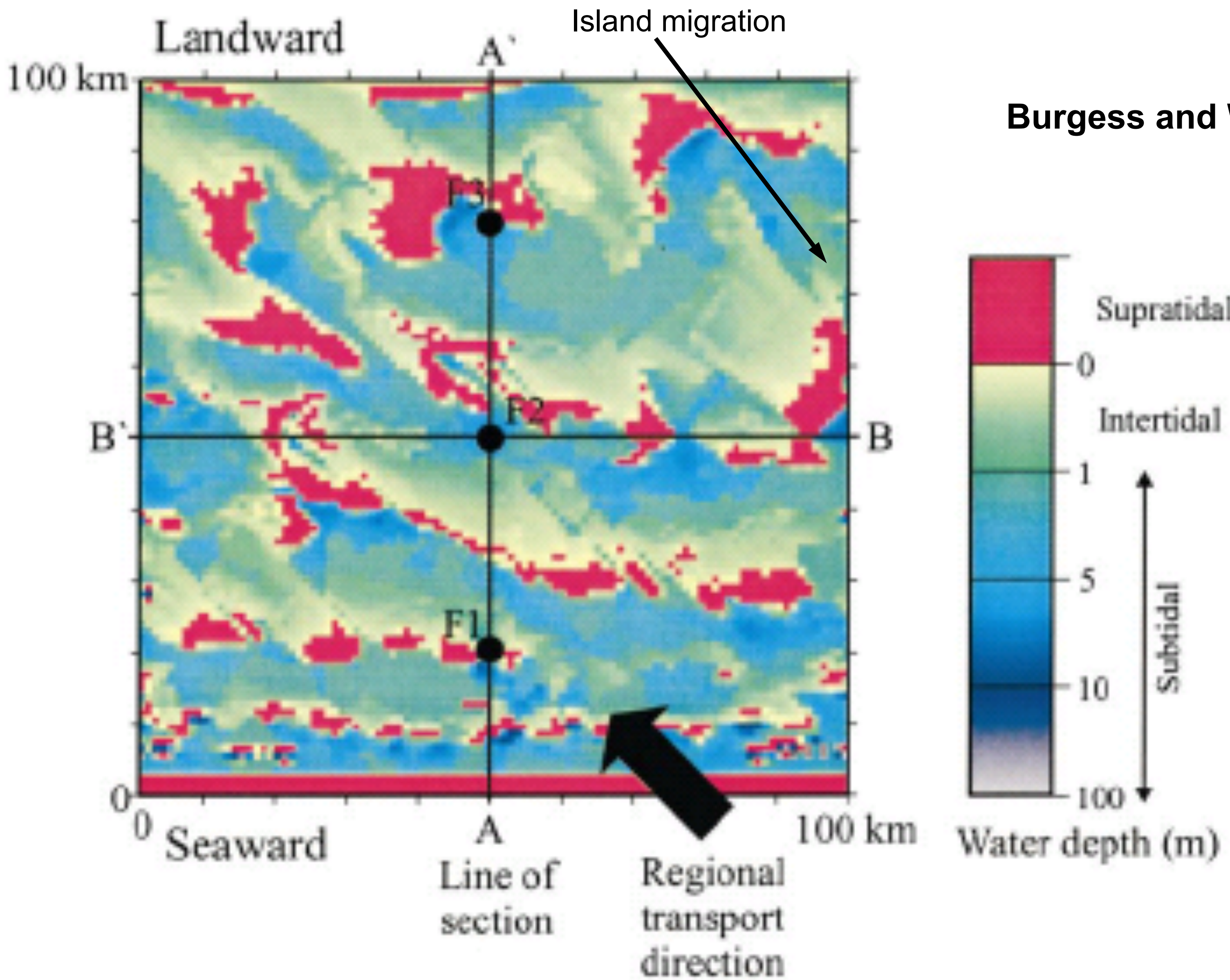
Carbonate GPM: Detail of structure in lagoon sediments

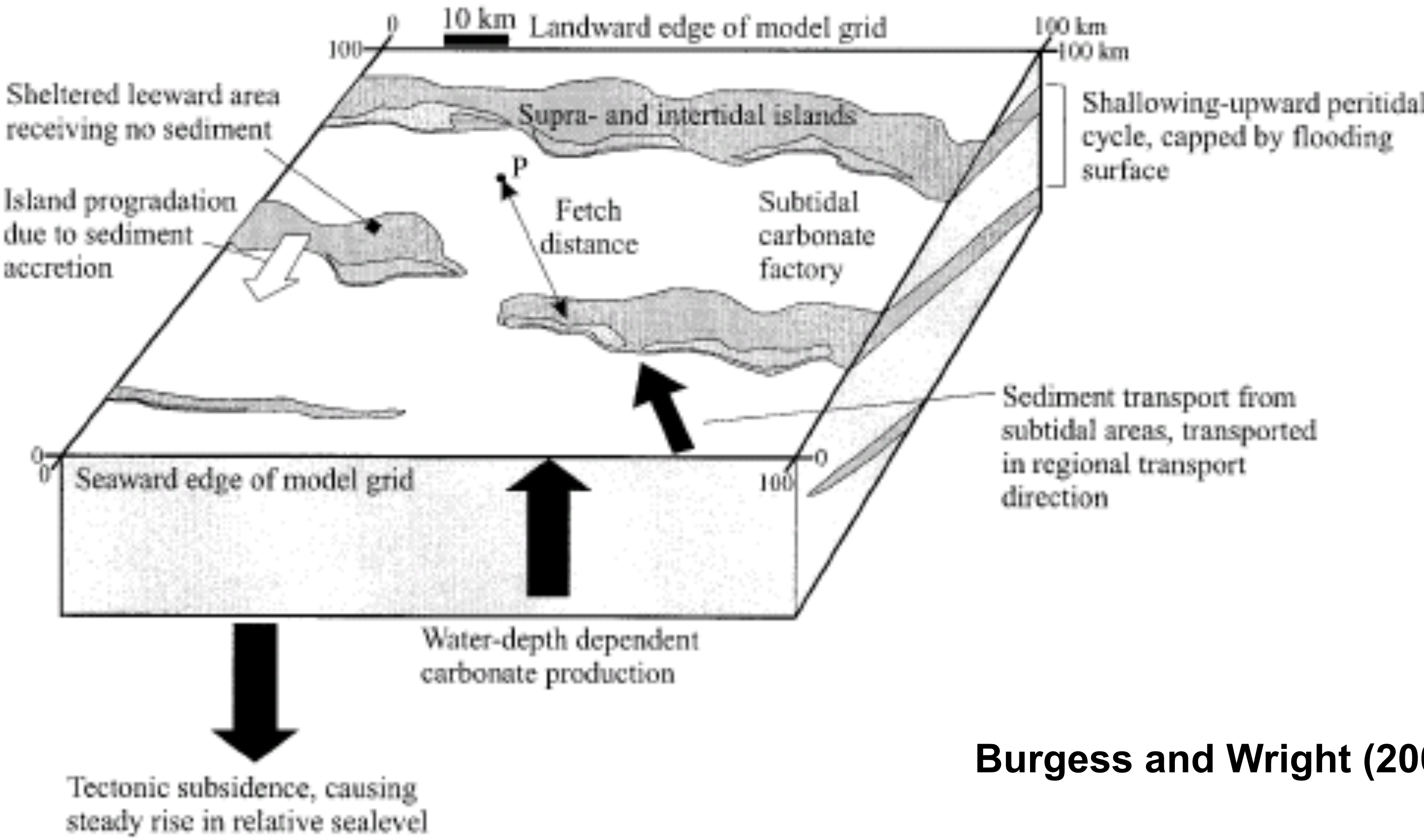


Complex palimpsest of facies or lateral uniformity?

Burgess and Wright (2003)



Are models for simulating real examples or for testing ideas or both?



Burgess and Wright (2003)

What else does model development do? Formalise existing knowledge and identify areas for further research

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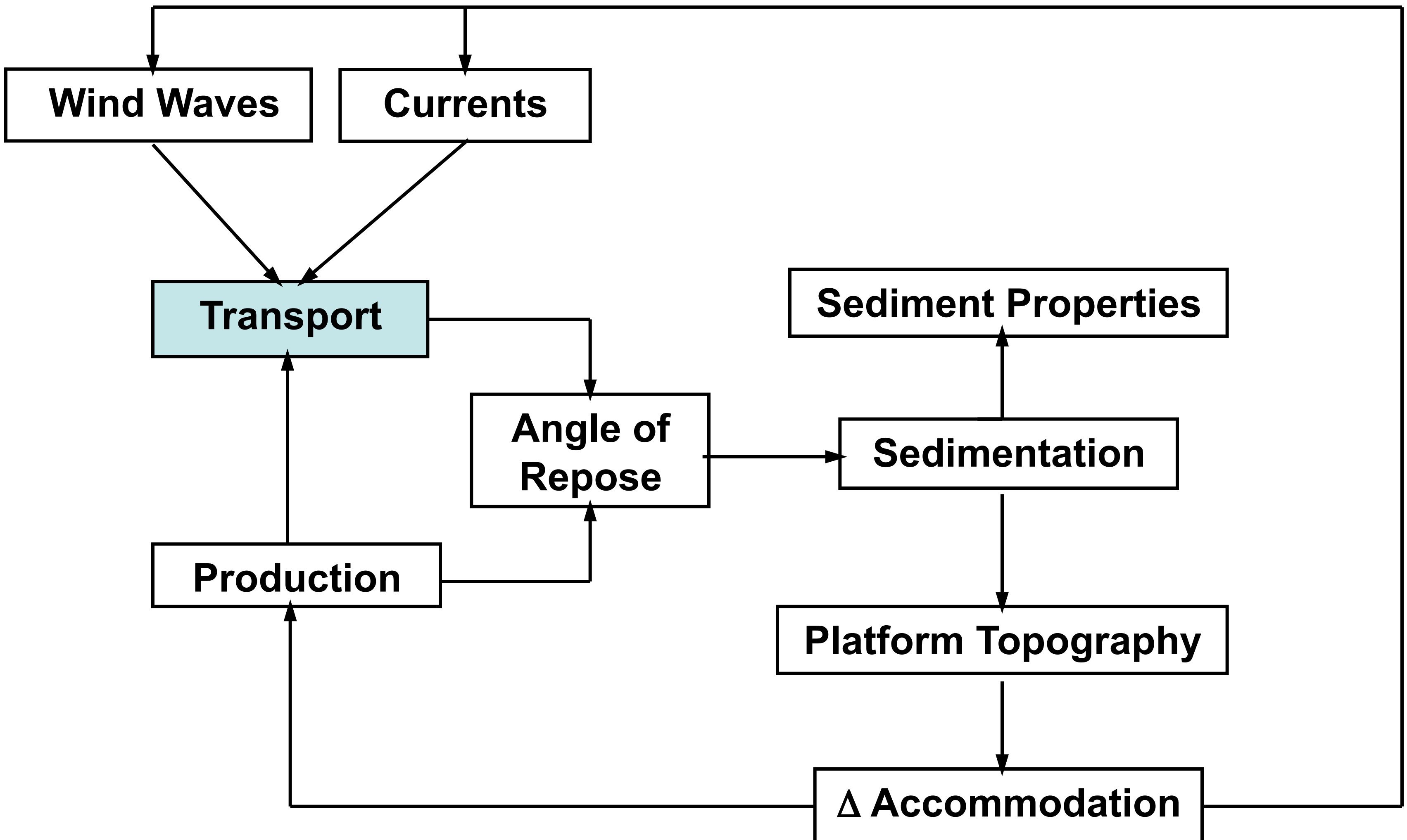
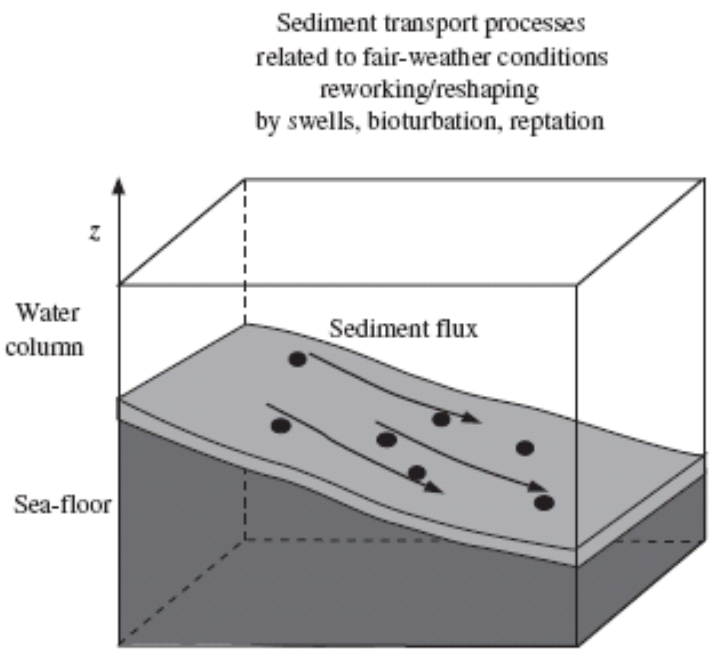
Sediment production and transport models: Sediment Transport



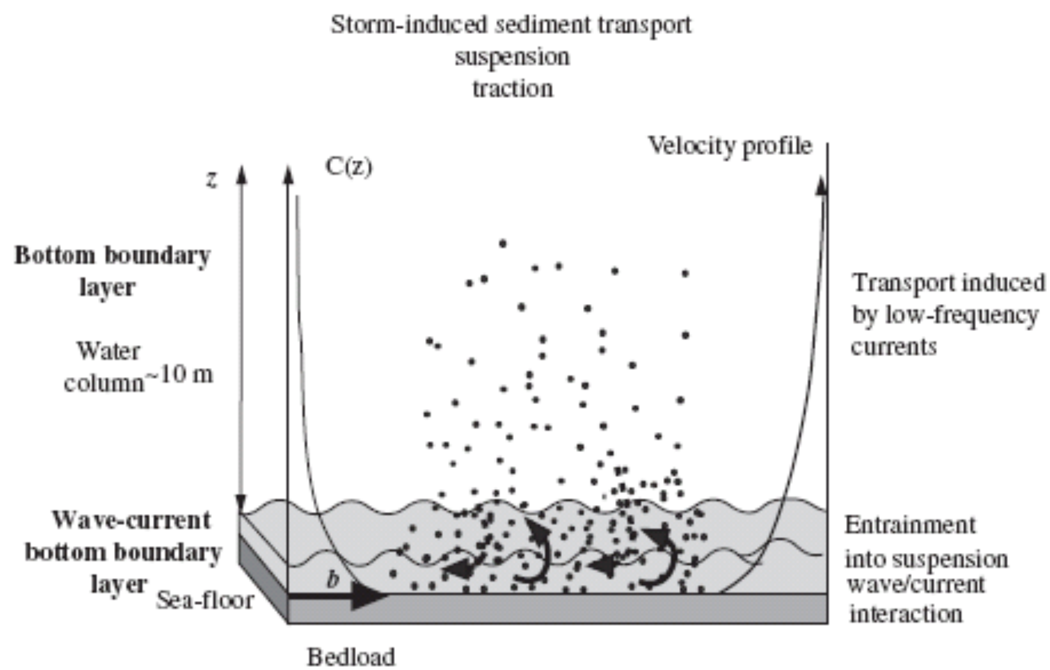
CARB3D+ structure

Sediment Transport: 2 basic models

Diffusive Model



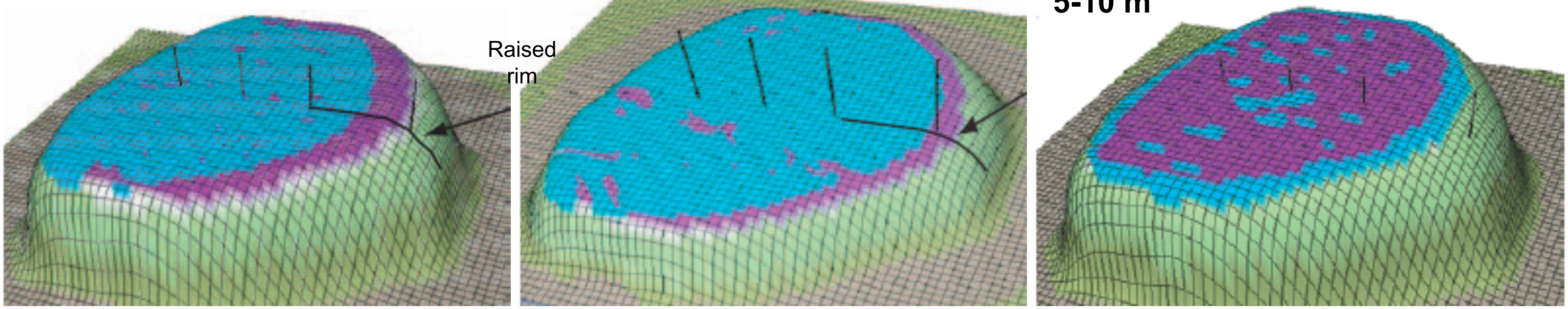
Advective Model

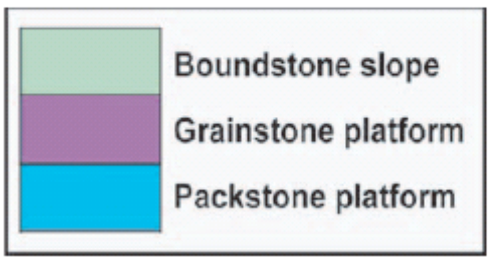


From Quinquerez et al, 2004

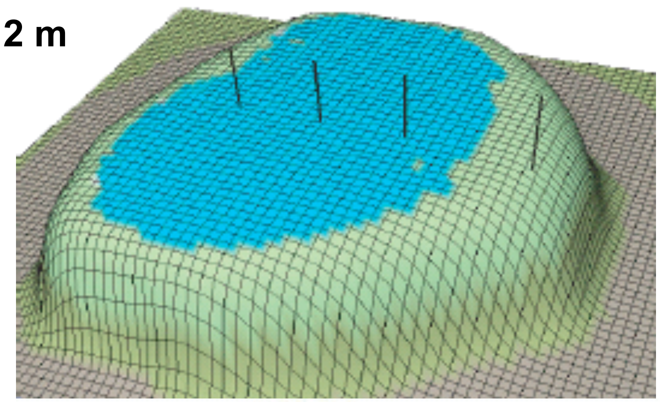
Dionisos a diffusion-based model:
effect of increasing water depth on platform facies

2-5 m 4-8 m 5-10 m

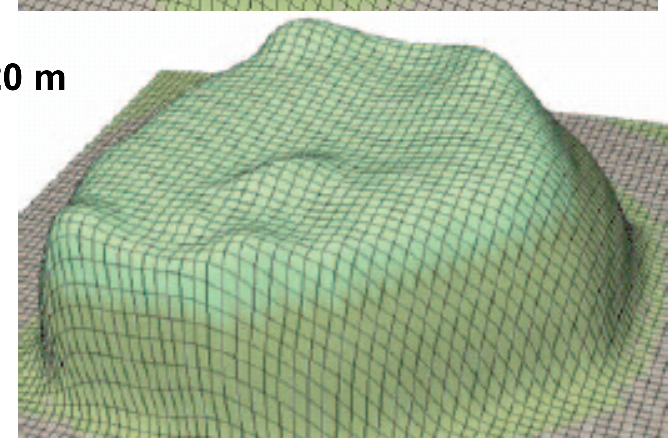




5-12 m



10-20 m



Transport proportional to slope

Mathematically efficient

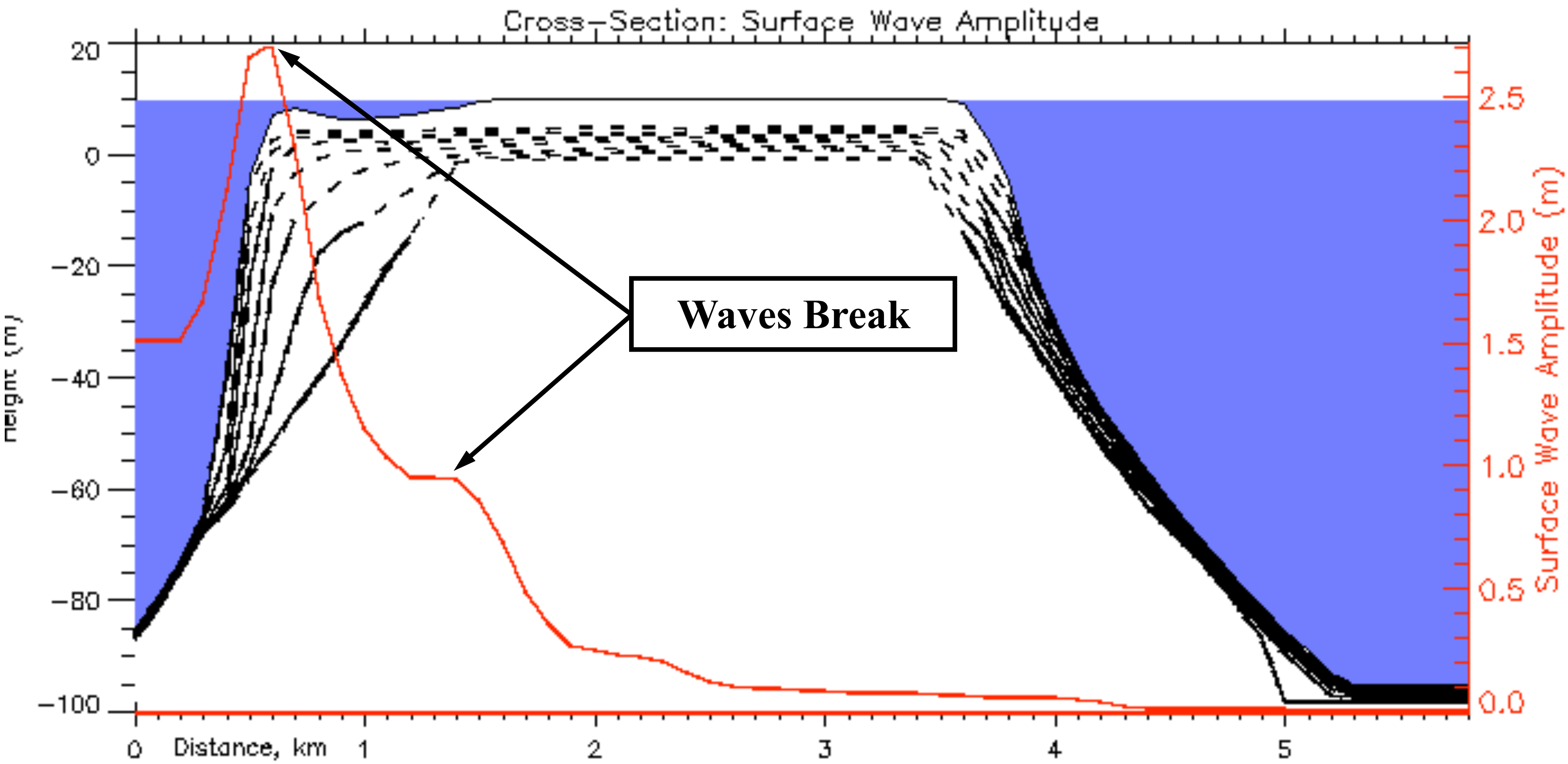
Diffusion lengths must be calibrated (up to 9!)

Very flexible sediment sources and
environmental dependence

Chevron

After Bassant and Harris (in press)

CARB3D+ Sedimentology: Advective sediment transport
Suspension of sediment by wind generated waves



Active suspension

No suspension; deposition occurs

Wave Amplitude: Windspeed 10 m/s

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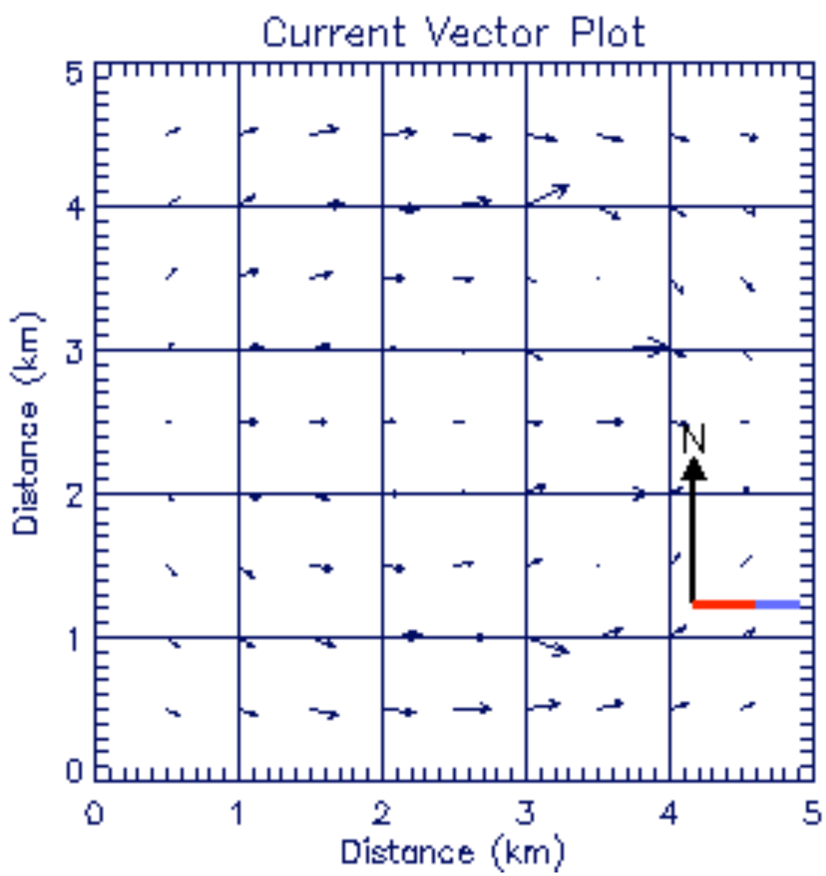
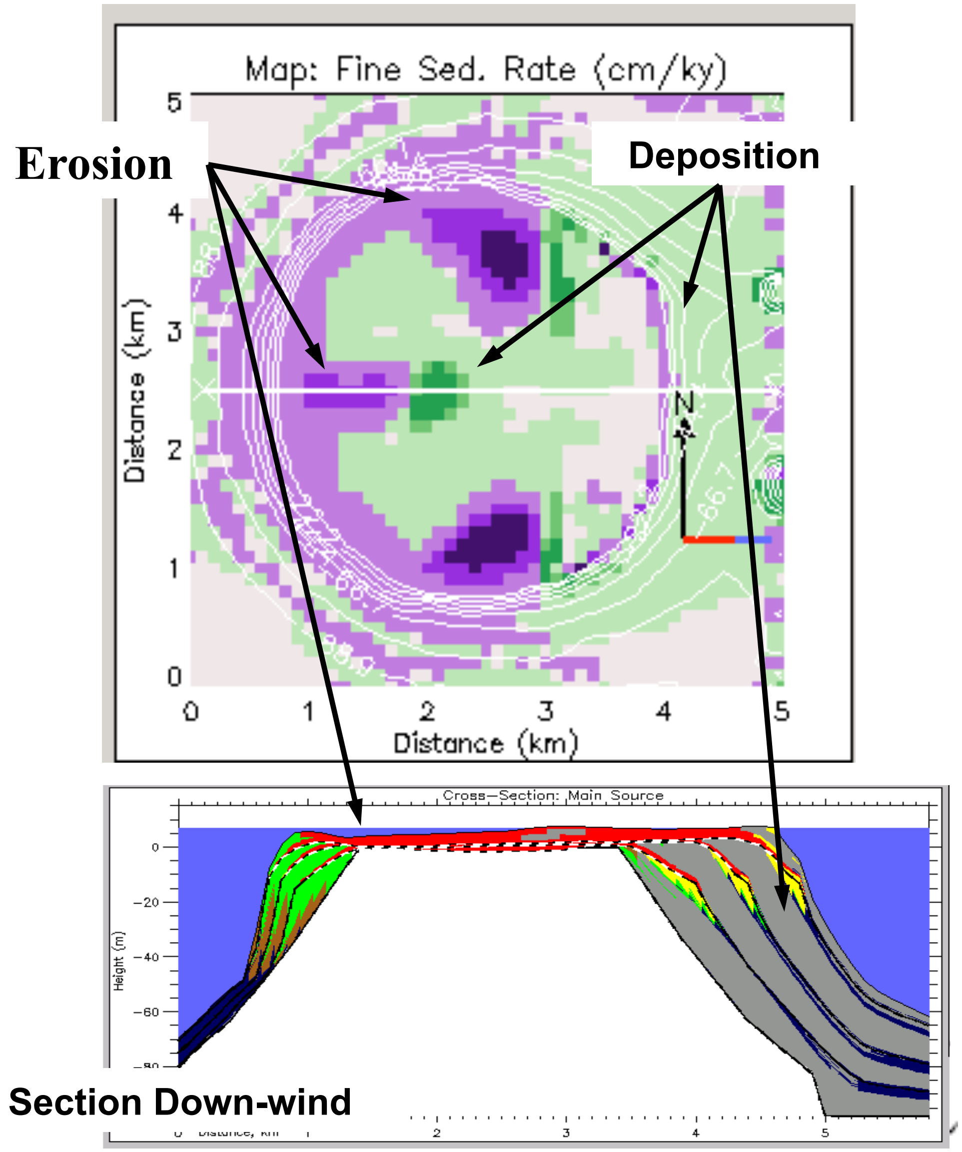
CARB3D$^+$ Sedimentology :

Sediment transport by 2D (depth averaged) potential flow currents

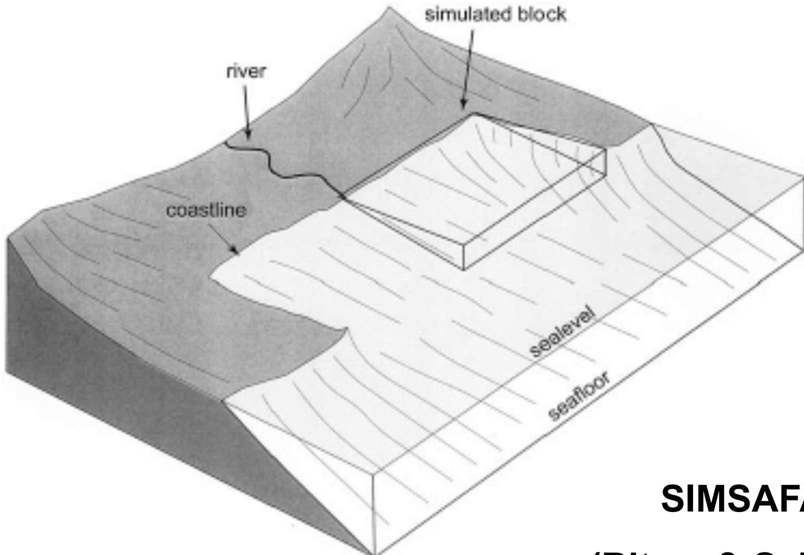


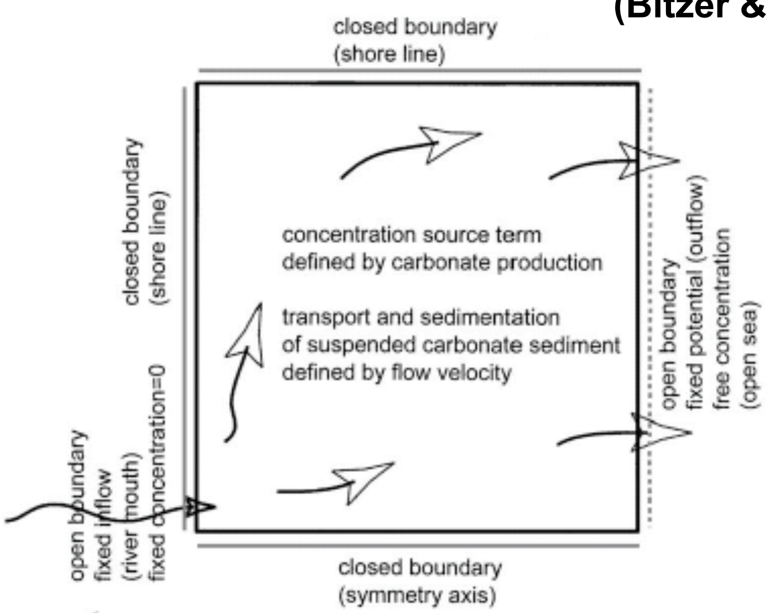
Current Direction

Wind Direction



Externally specified depth averaged currents:
What is the drive and where does the water go to?



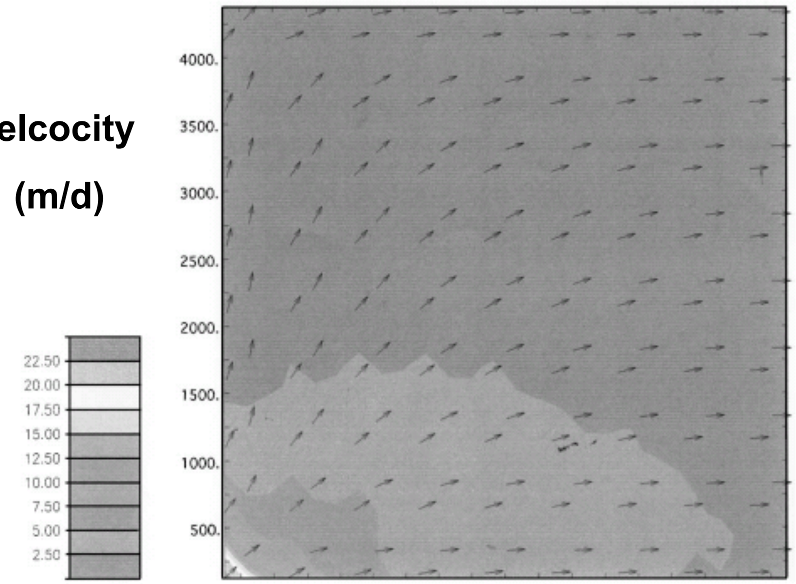


SIMSAFADIM

(Bitzer & Salas, 2002)

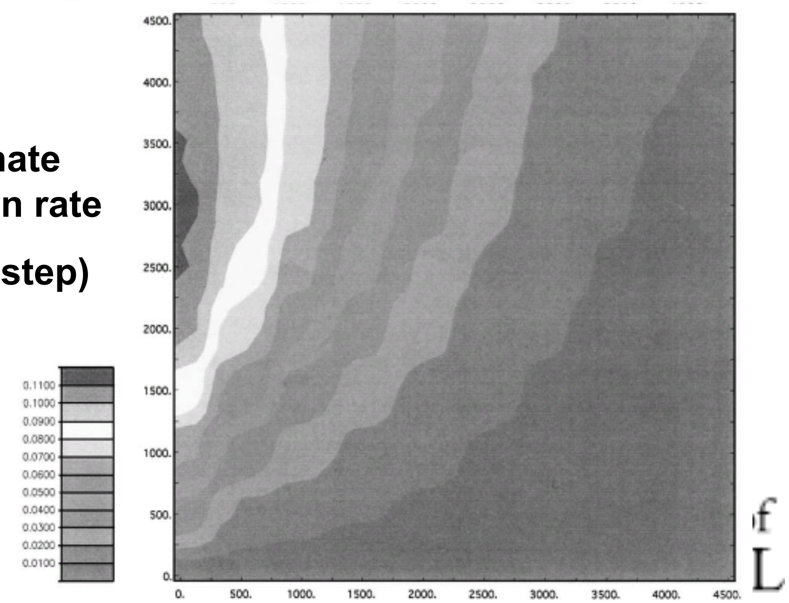
Velcocity

(m/d)

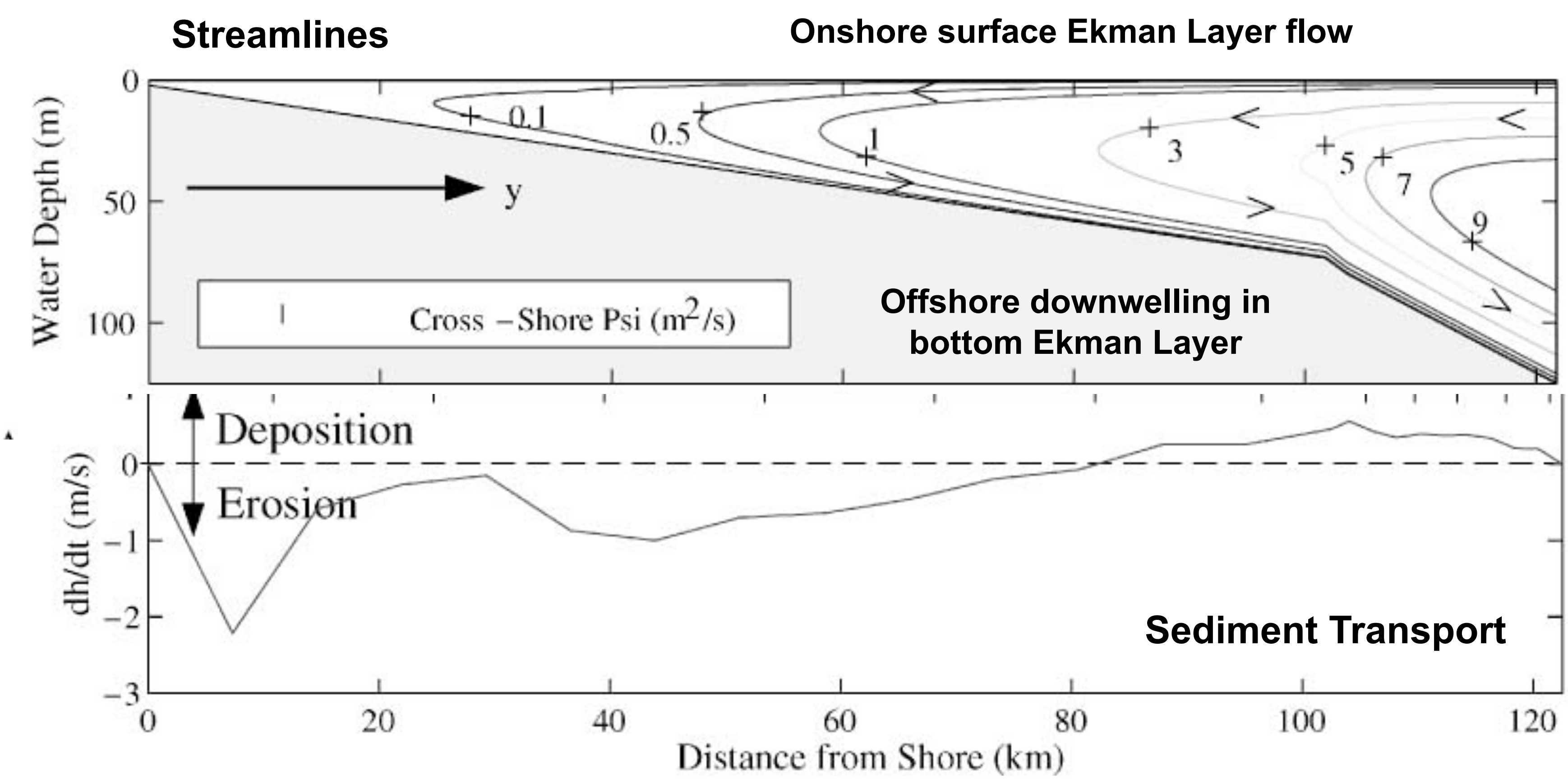


Carbonate deposition rate

(m/time step)



What about entrainment by currents? Depth averaged or 2D (3D) currents? Bi-directional wind driven circulation STORMSED 1.0



Coopman & Flemmings (2001): STORMSED 1.0 (2D)

'Large Storm' (20 m/s wind parallel to coast):

based on Mid-Atlantic continental shelf

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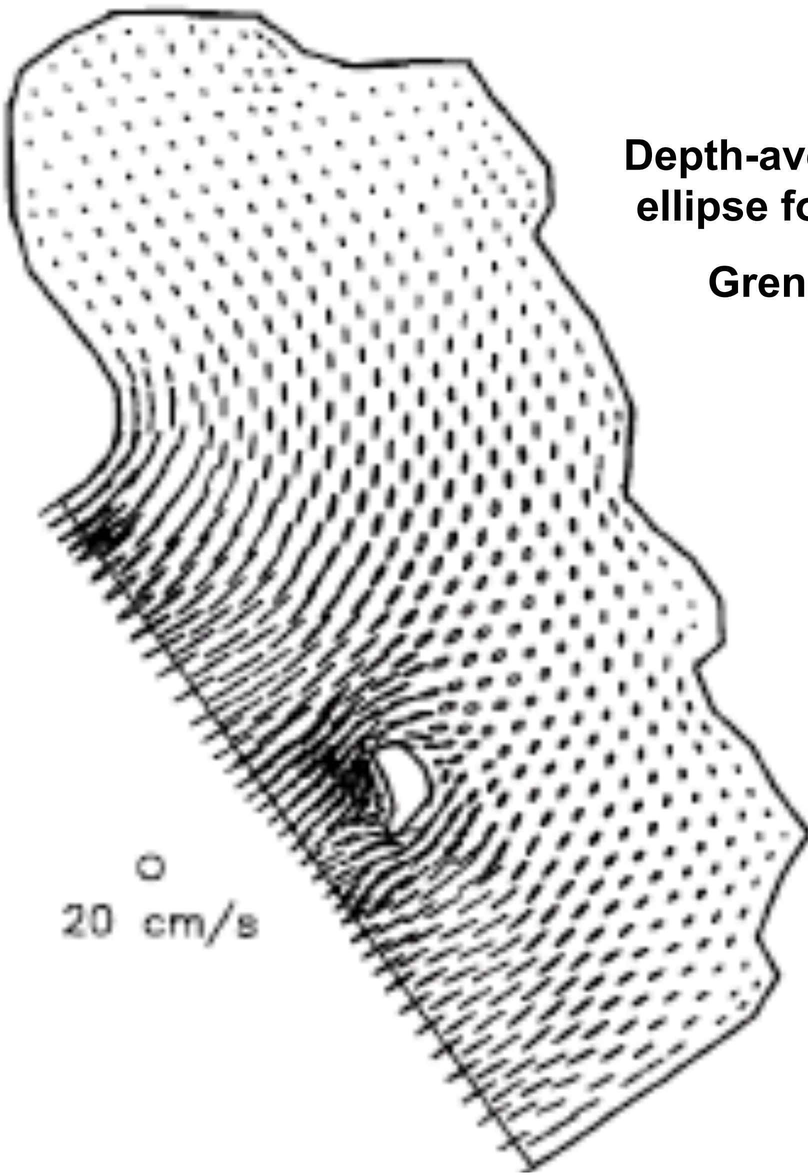
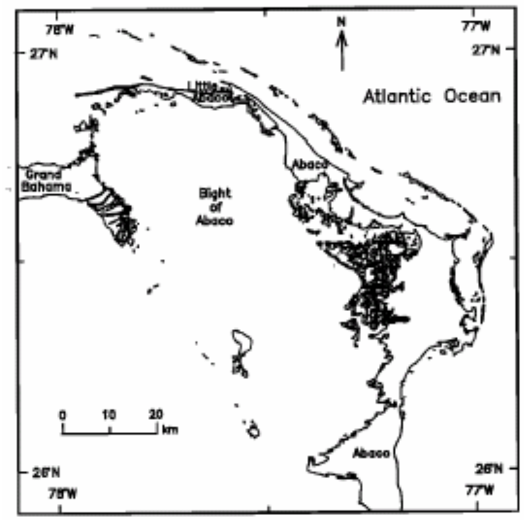
What about tidal currents (which we can also do well), don't we need them too?



Depth-averaged M2 current ellipse for Bight of Abaco.

Grenier et al (1995)



Bathymetry

Computational Mesh

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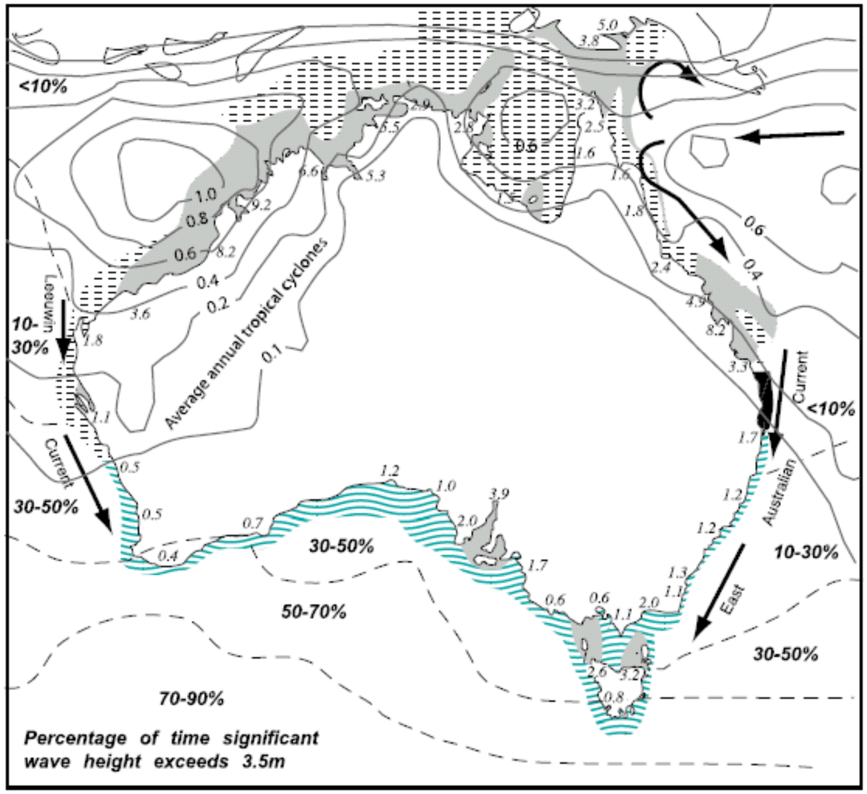
Need to develop criteria for separating different modes of sediment transport + Timescales

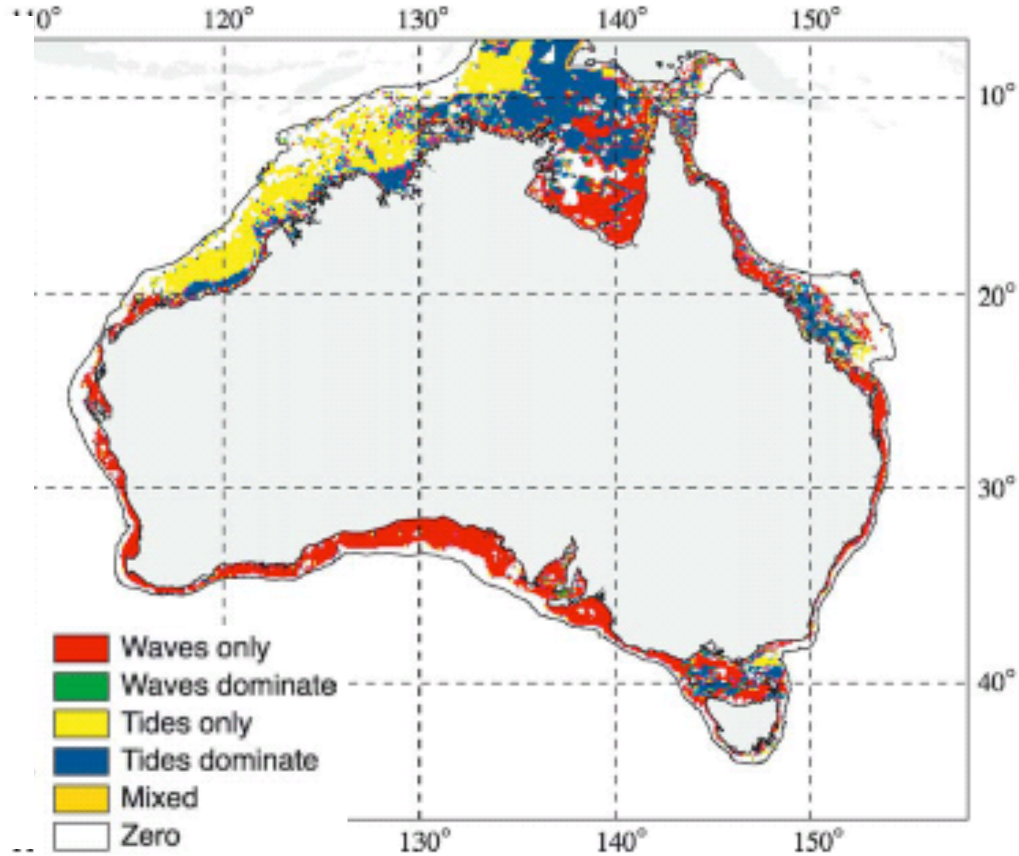


Tropical cyclones 54%%

Tidal currents 17%

Intruding ocean currents 1%

Temperate storms & swell 28%



Dominant process from ratio of wave & tidal exceedance for actual sediment size

Porter-Smith et al (2004)

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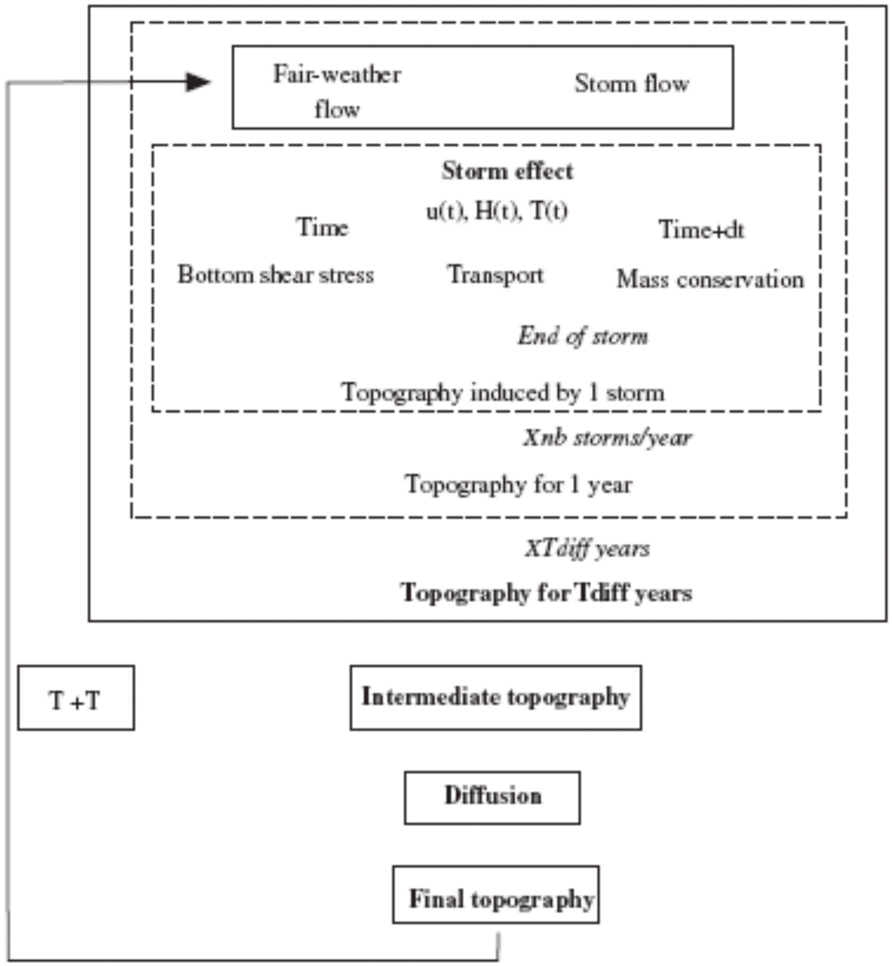
Sediment transport timescales: scaling of storm condition advection and magnitude /frequency response



Individual storm (5 parts)

Advective Model

Sum storms for year

Sum storms for n year timestep

Modify storm transport by fair-weather processes

Diffusive Model

Quinquerez et al, 2004

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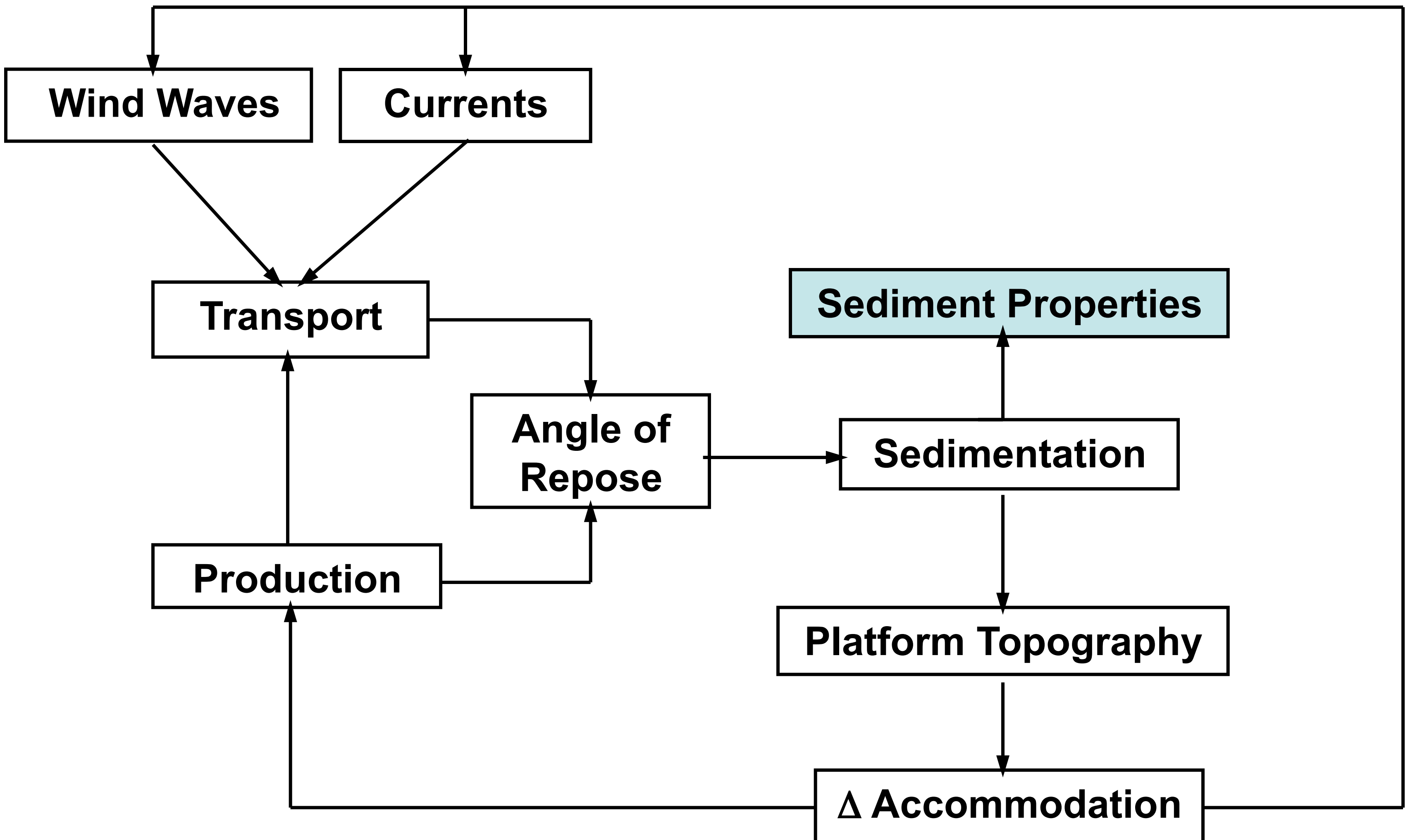
Sediment Properties



CARB3D+ structure

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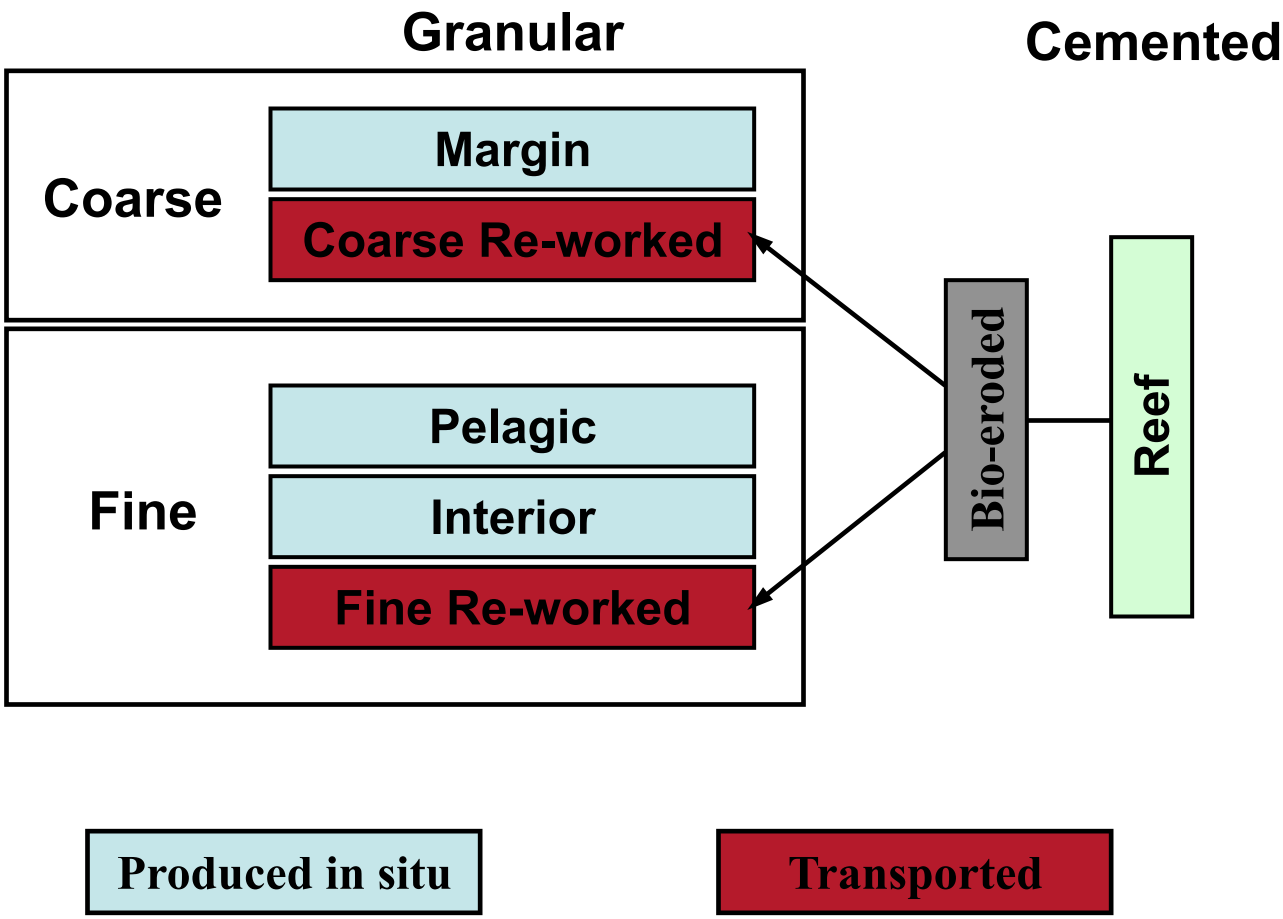
How many grain sizes?
CARB3D+ Sedimentology : 2 Grain sizes + boundstones



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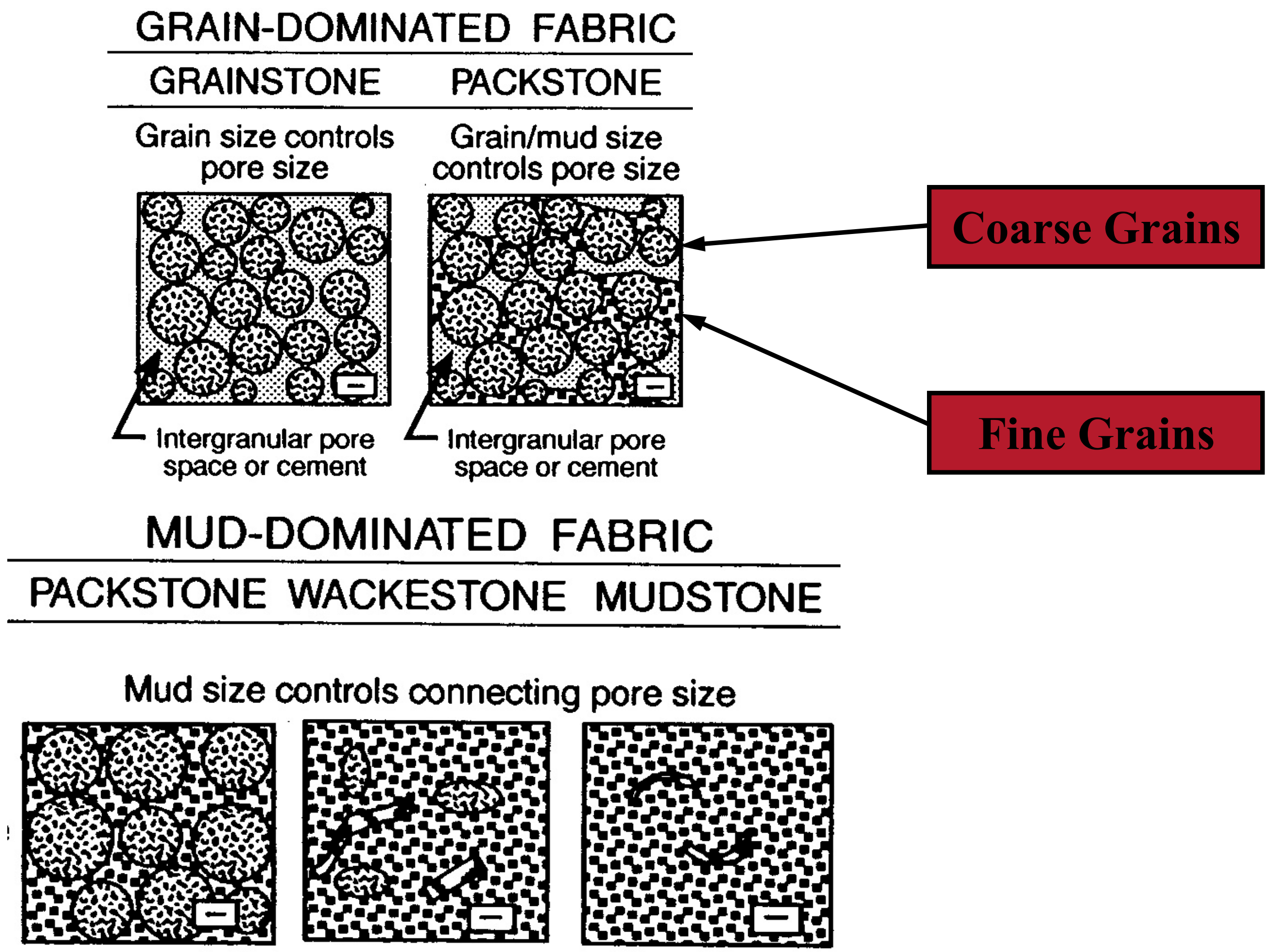
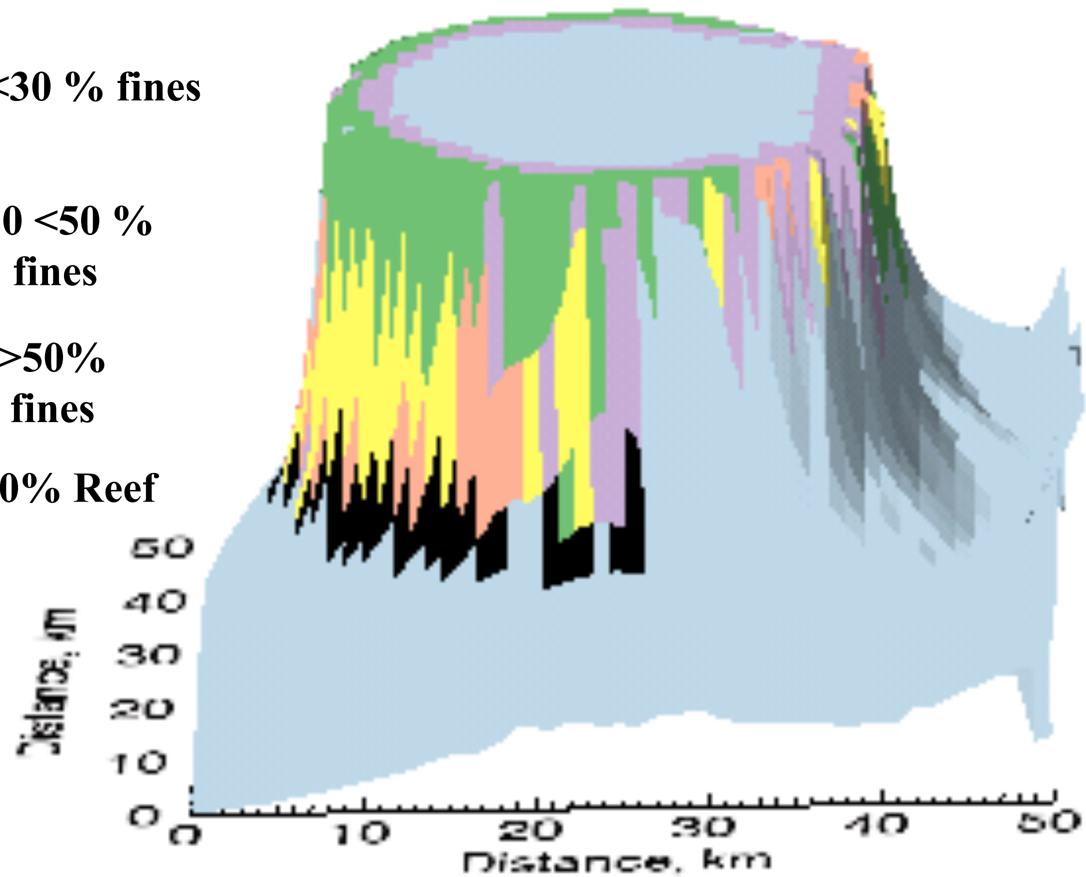
CARB3D+ Sedimentology:
The 2 component concept (coarse and fine grains)



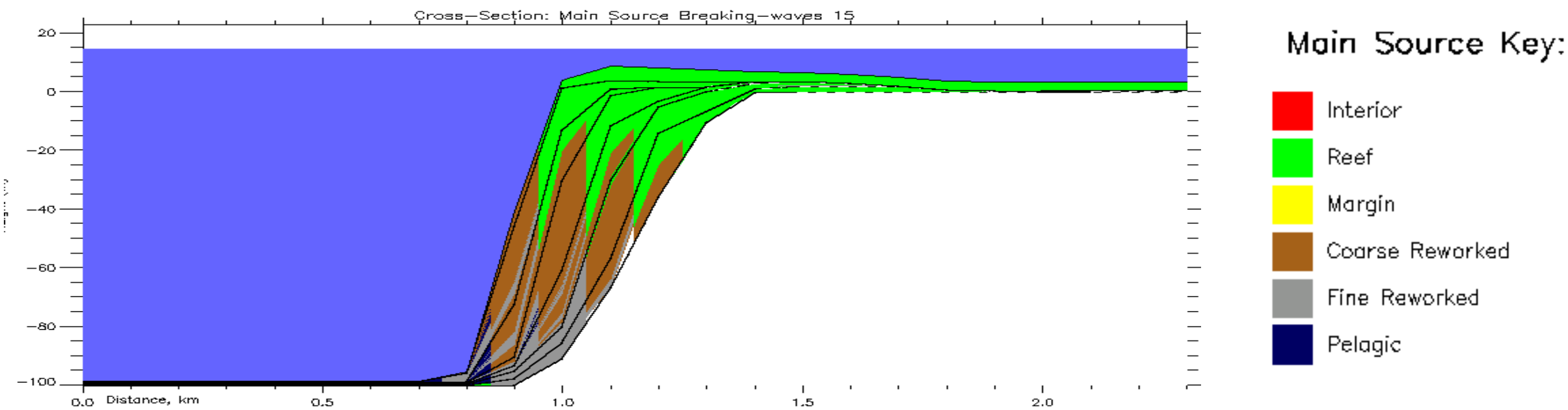
Lucia (1995)

CARB3D$^+$ sedimentology:
The 2 component concept, facies

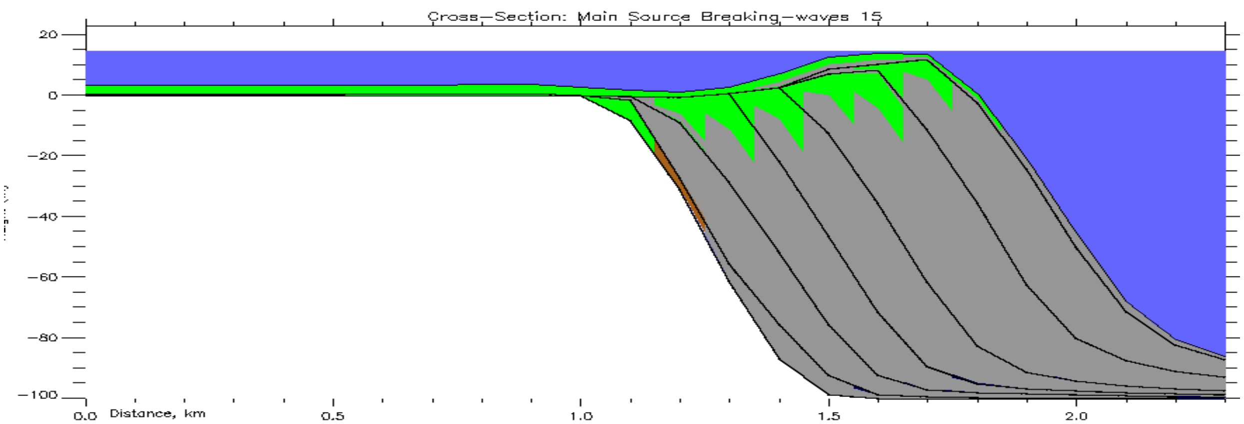
CARB3D$^+$ Facies Key	Dunham (1962) Class	Percent Fines
	Grainstone	<10% fines
	Packestone	>10 <30 % fines
	Wackestone	>30 <50 % fines
	Mudstone	>50% fines
	Boundstone	>50% Reef

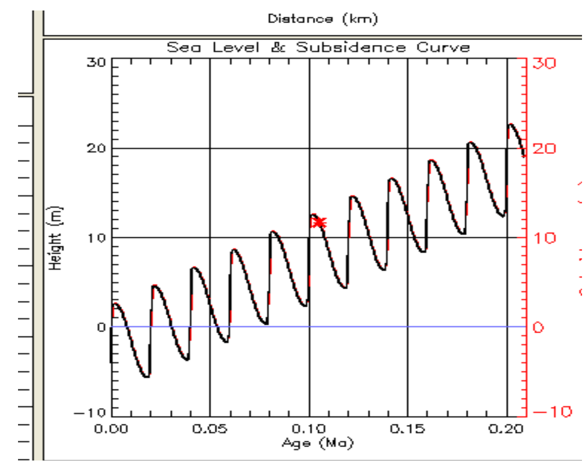


CARB3D+:Coarse fraction moves as bedload, fine as suspended load



Windward Margin Progrades over Coarse Reworked Slope Debris





Leeward Margin Progrades Over Fines Transported by Current

All Sediment is from reef on windward margin only

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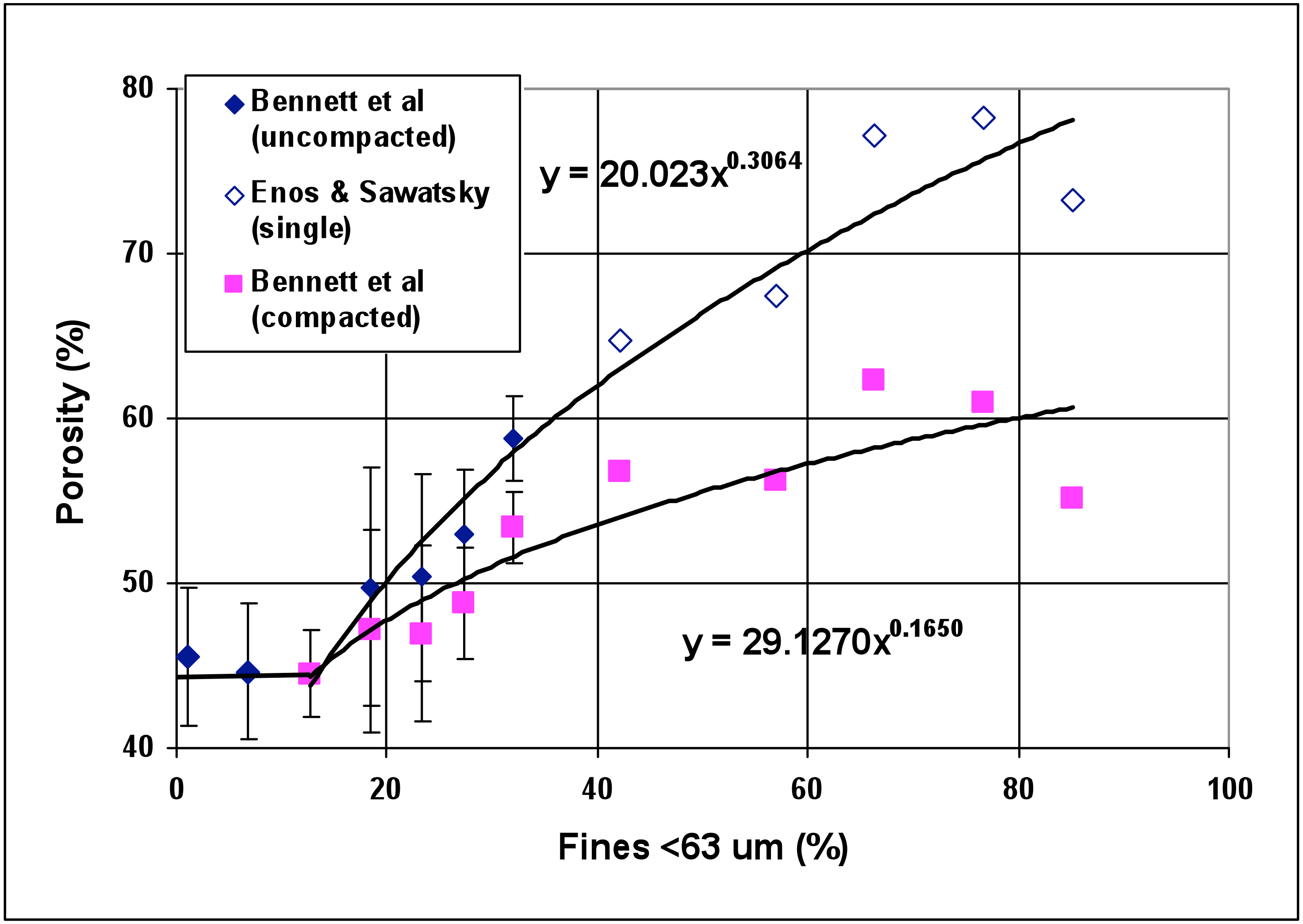
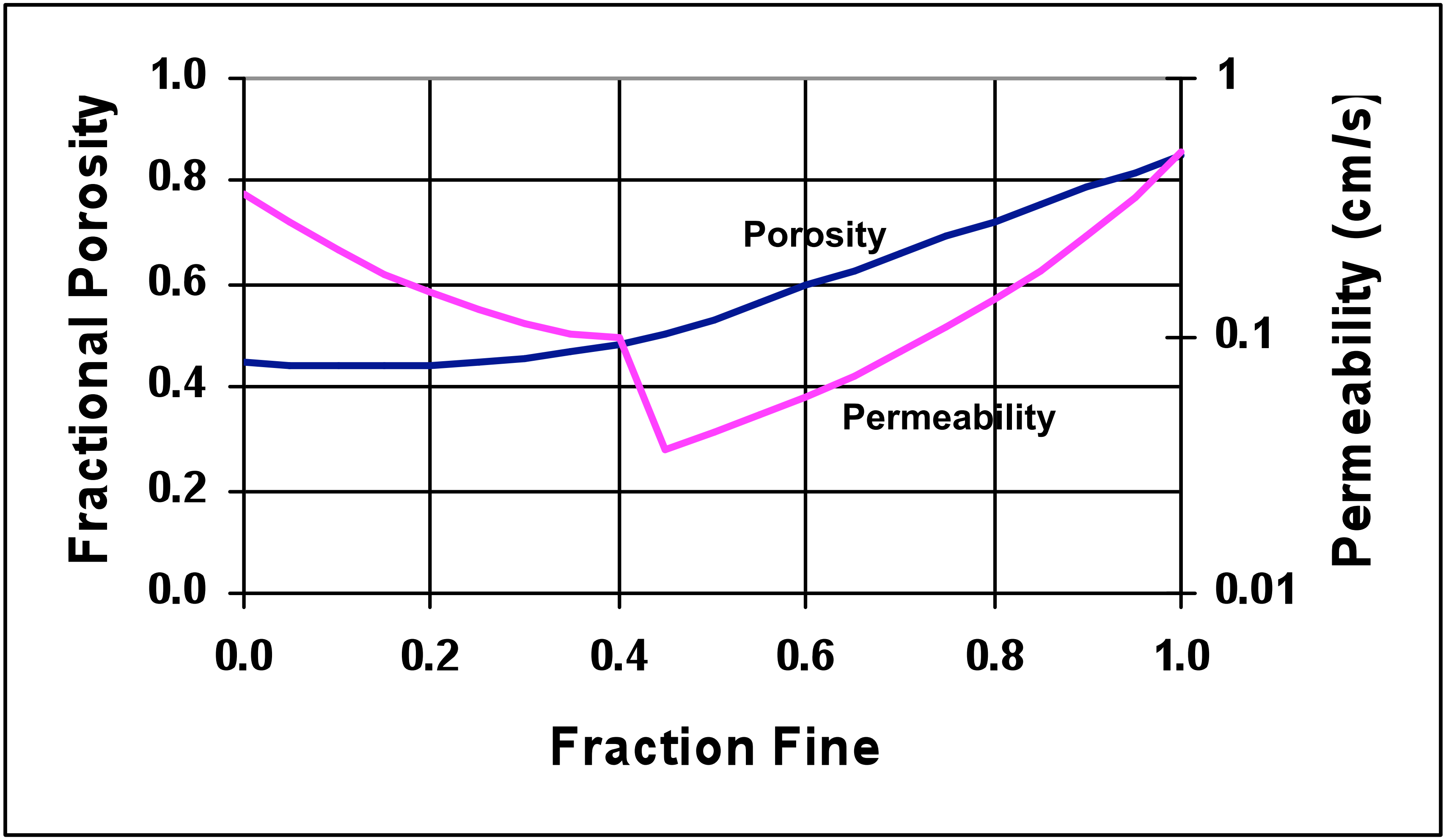
Prediction of depositional porosity: CARB3D+



Depositional Porosity, an alternative model

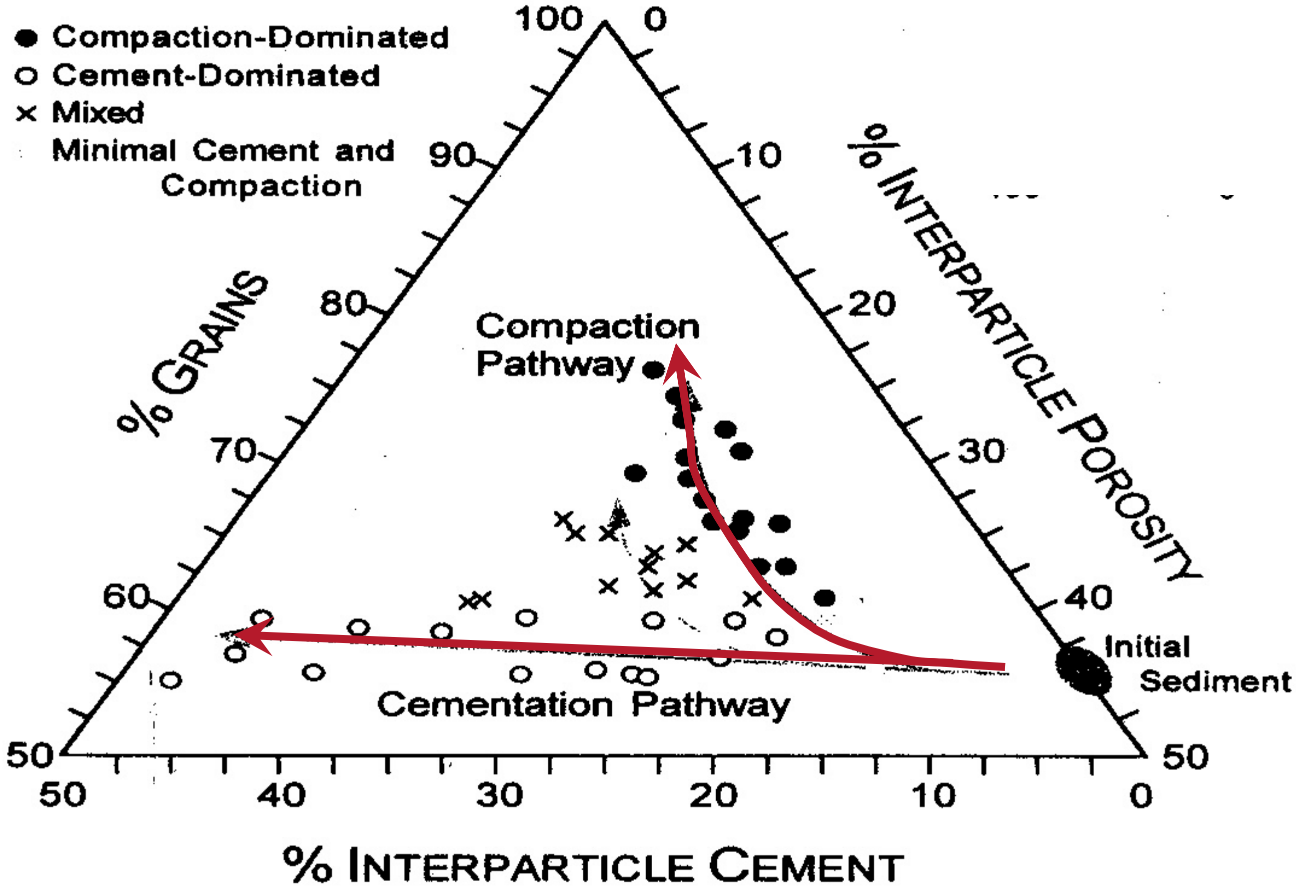


Koltermann & Gorelick (1995): 0.063 and 0.5 mm grainsize mix

CARB3D^{+}: Compaction is grain size dependent

0% fines → 100% fines

Cementation and compaction



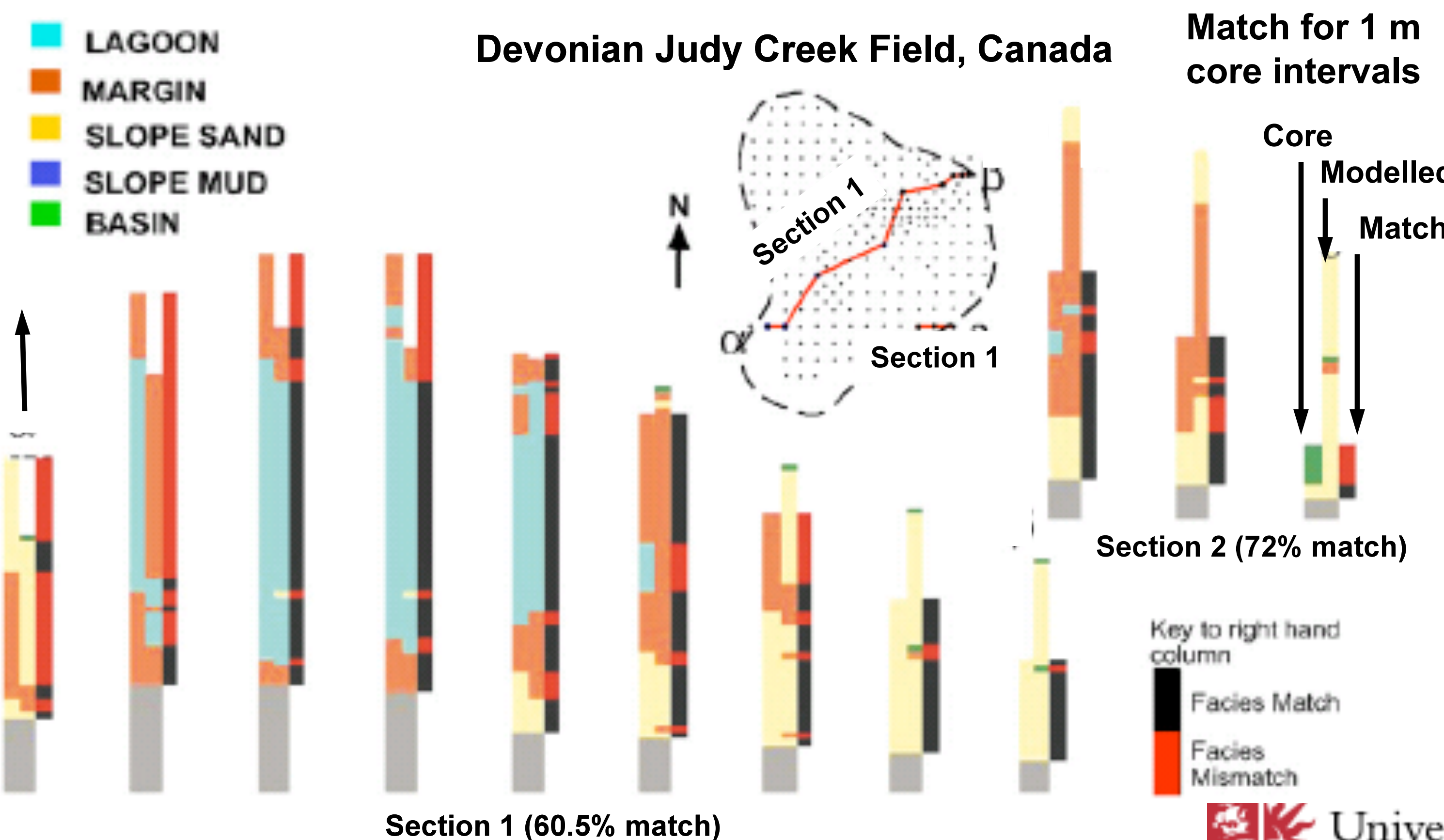
Budd (2002)

Data handling: digital rocks and facies comparator

Facies name	Field-based facies		Digital facies				
	Description	Depositional environment	Platform margin (%)	Coarse reworked (%)	Pelagic + fine reworked + platform interior (%)	Coarse clastic (%)	Fine clastic (%)
Grainstone–boundstone	Coral–microbial patch reefs and interbedded	Normal marine mod-high energy.	20–100	0–50	0–40	0–10	0–20

Digital facies defined from % model components to match field facies

Devonian Judy Creek Field, Canada



Boylan et al (2002) & Warrlich et al (2008)

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Some Conclusions on Modelling of Carbonate Sedimentology:

- **Existing models are improving:**
  - Strong hydrodynamic base (waves and currents)
  - Coupling of storm and fair-weather conditions
  - More flexible specification of carbonate factories
  - Budgeting of carbonate
  - Slope transport
  - Flexible GUI and output

- **Issues for the future:**
  - Focus on dominant sediment entrainment and transport processes
  - More sophisticated ‘competition’ between carbonate factories
  - Development of more sophisticated facies (spatial variability)
  - Consideration of role of bio-erosion and cementation on sediment mobility
  - Improved prediction of porosity
  - Improved simulation of compaction (especially role of cementation)

- **All are possible, but we must be parsimonious to achieve realistic run times**

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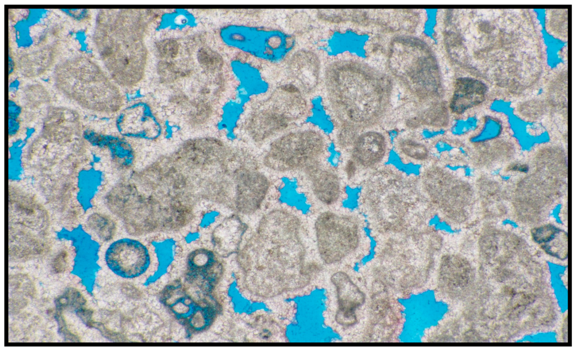
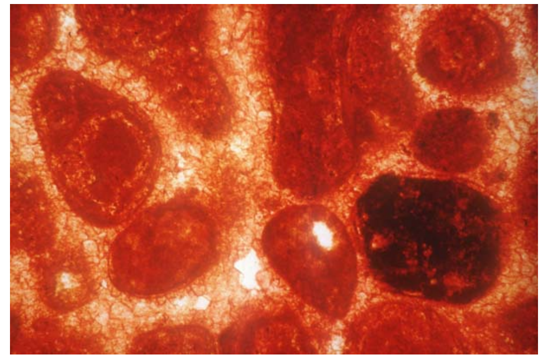
Why is diagenesis important?
Practical as well as intellectual drive

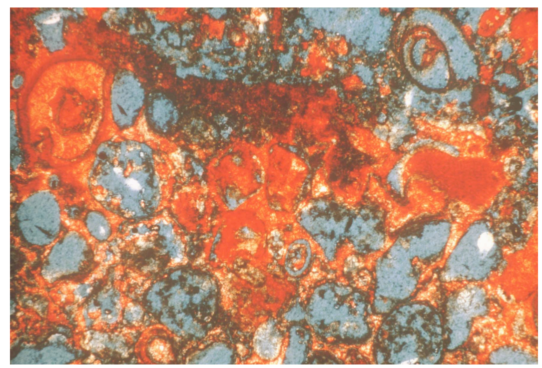
Ooid Grainstone



Diagenesis

Cemented Grainstone – low porosity





Dissolved Grainstone – high porosity

There is no simple relationship between facies and poro-perm characteristics

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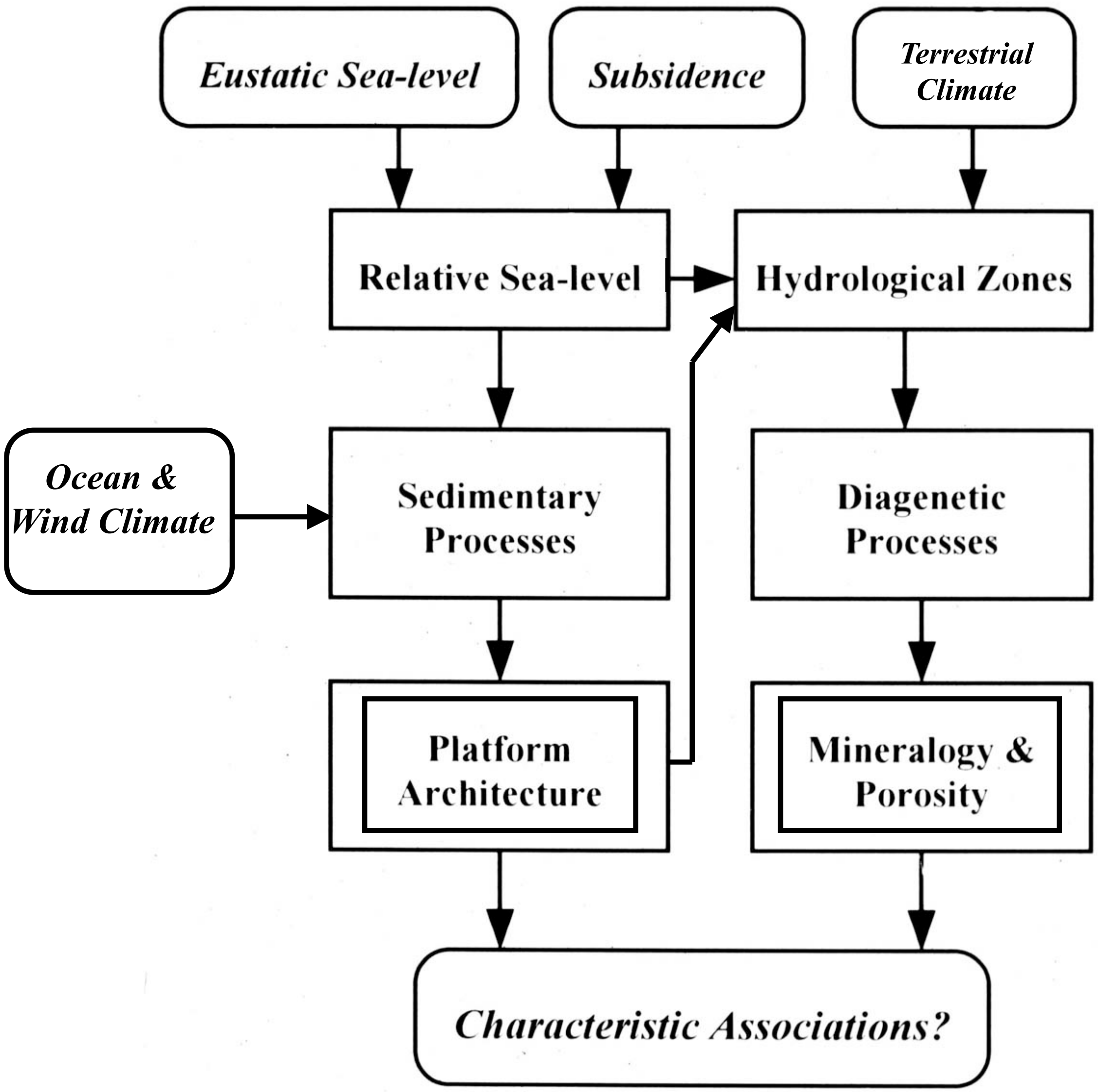
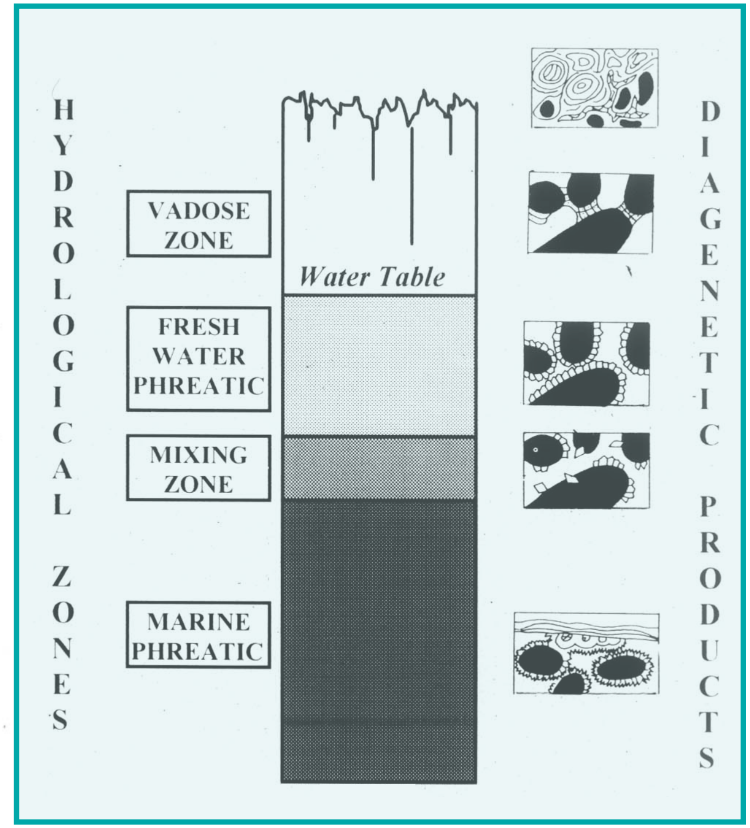
The conceptual base:
Common extrinsic controls on sedimentology and diagenesis



Hydrozones Concept



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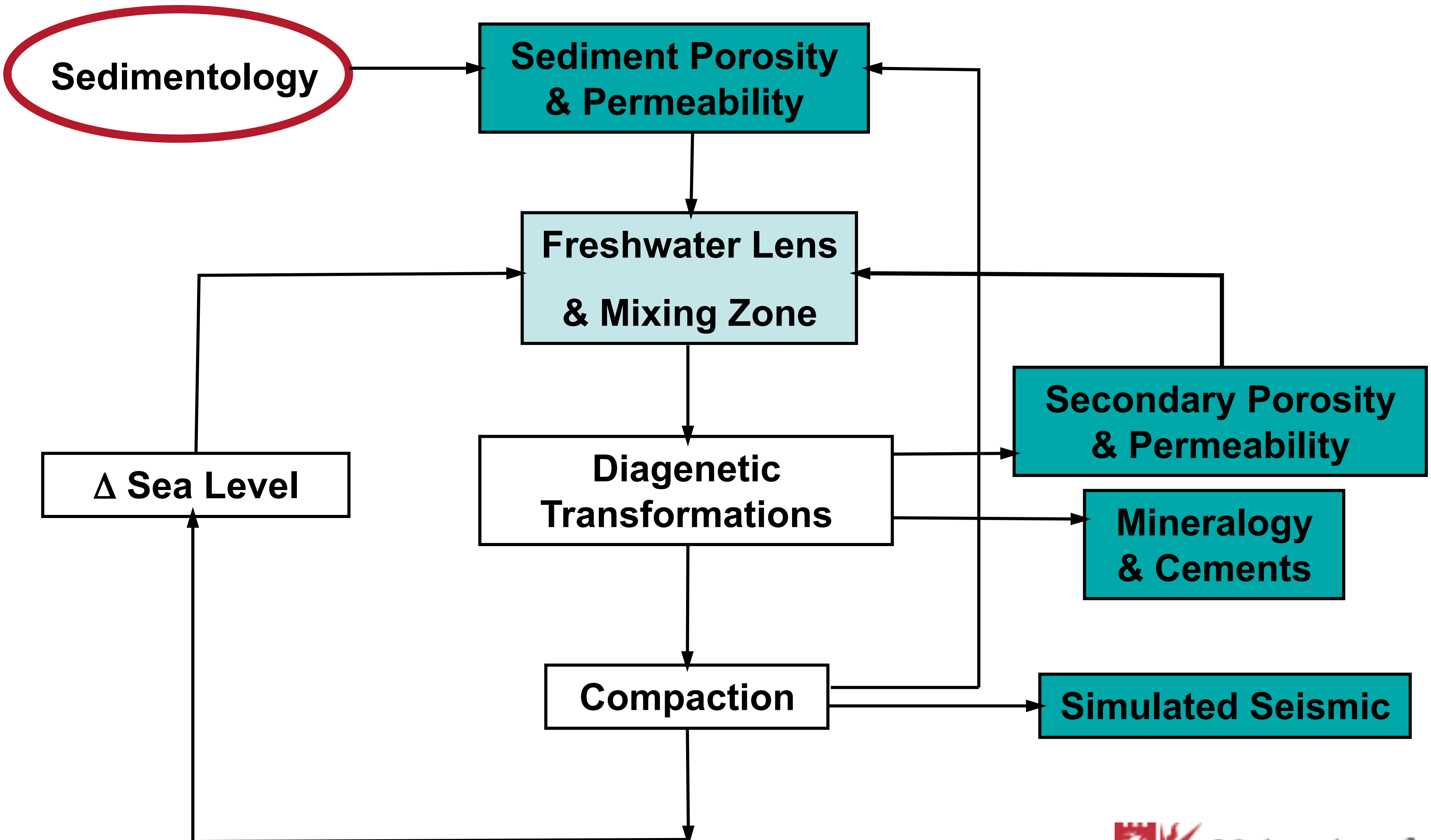
CARB3D+ Diagenesis Components:

Hydrozones



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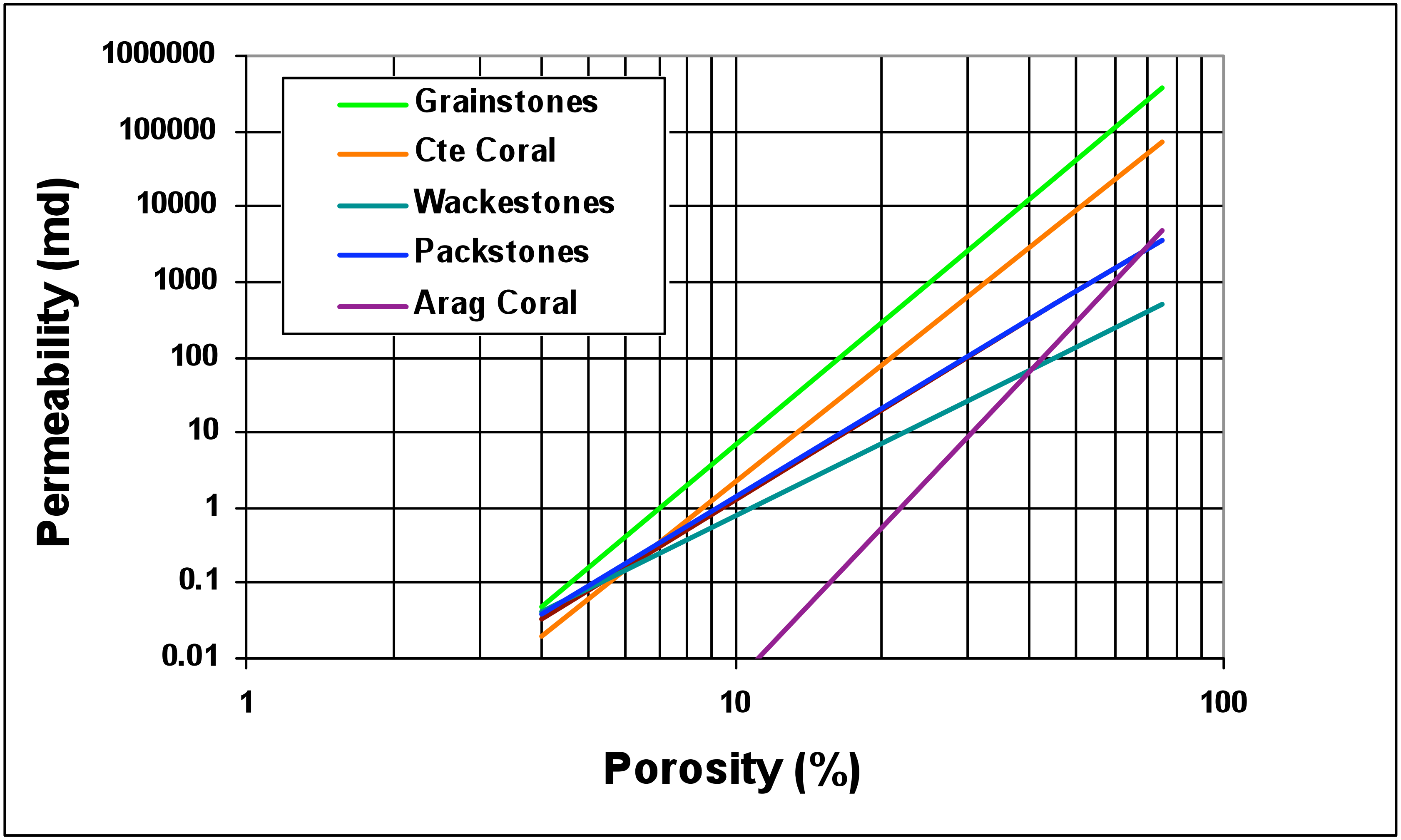
CARB3D+ Diagenesis :
Depositional porosity to permeability based on facies



Empirical poro-perm relationships from published data

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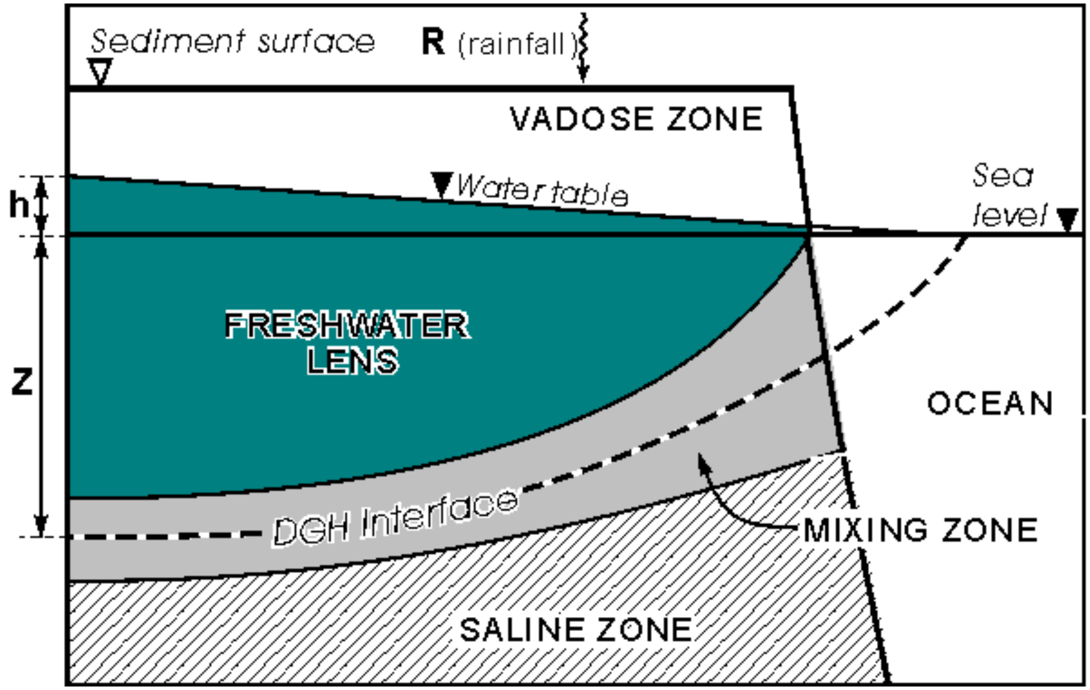
CARB3D+ Diagenesis :
3D depth-averaged freshwater lens model

$$K\,(1+\alpha)\,\nabla.(\,h\,\nabla h\,) = R$$



Where:

K **= hydraulic conductivity,**

$\alpha = \Delta\rho/\rho$ **density diff sea & freshwater / density of fresh water**

h **= lens top height above sea level,**

R **= recharge**

Fetter (1972)

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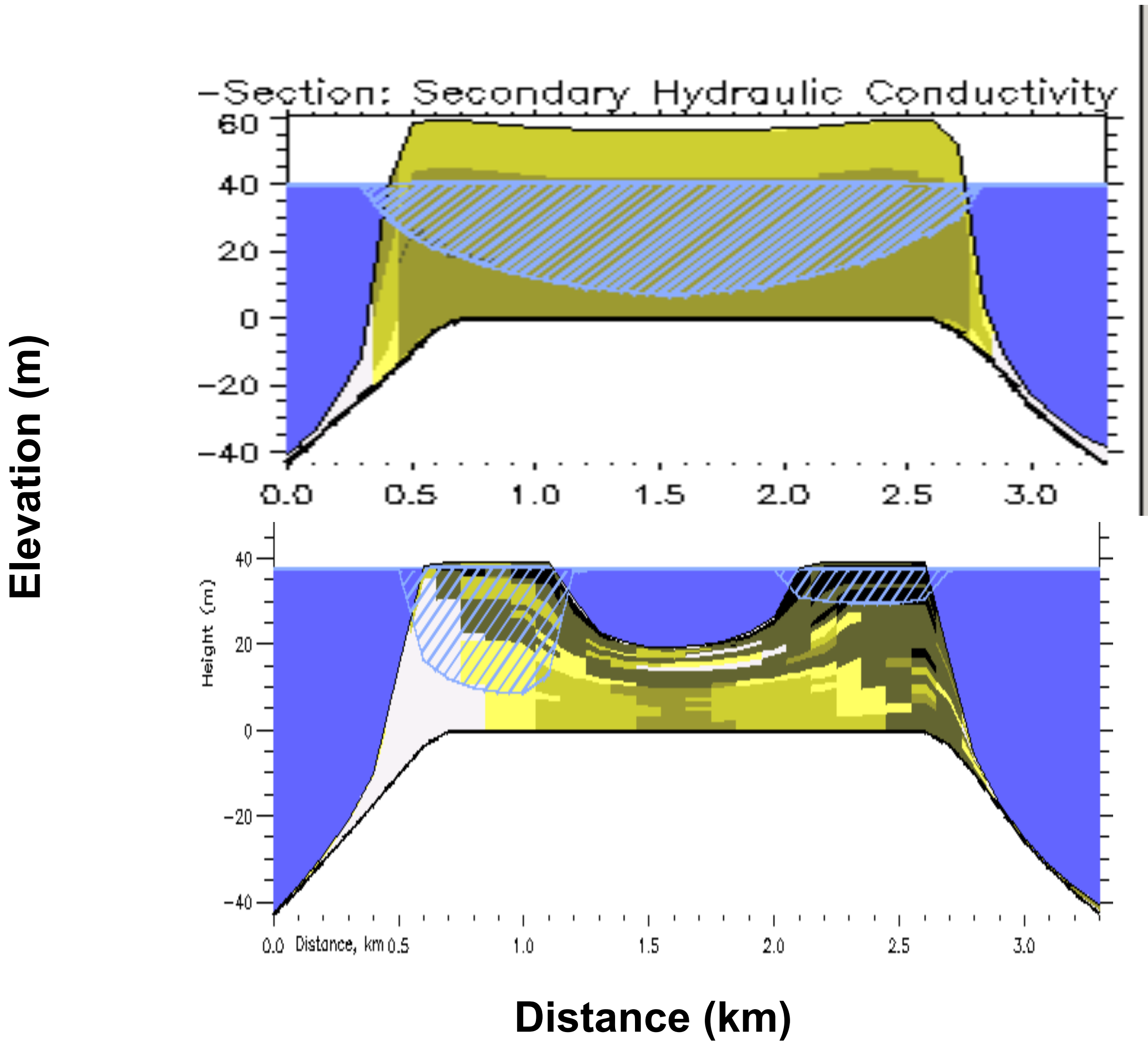
CARB3D+ Diagenesis:
3D depth-averaged freshwater lens model



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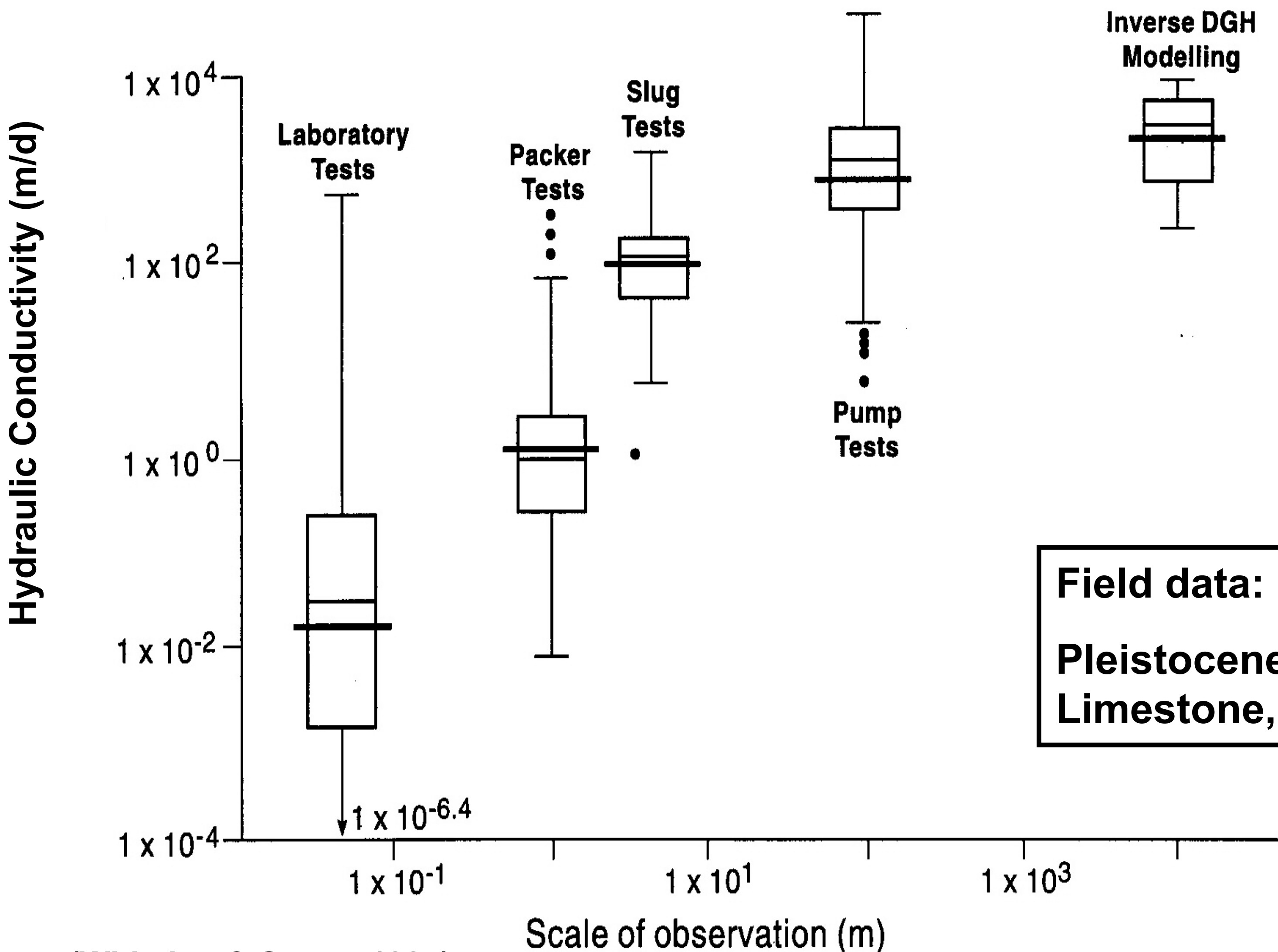
CARB3D⁺ Diagenesis:
Up-scaling of permeability



Field data:

Pleistocene Lucayan Limestone, Bahamas

(Whitaker & Smart, 1997)

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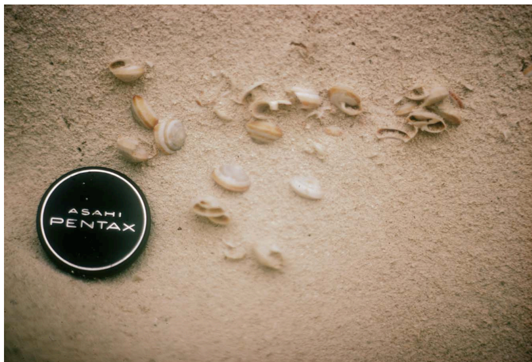
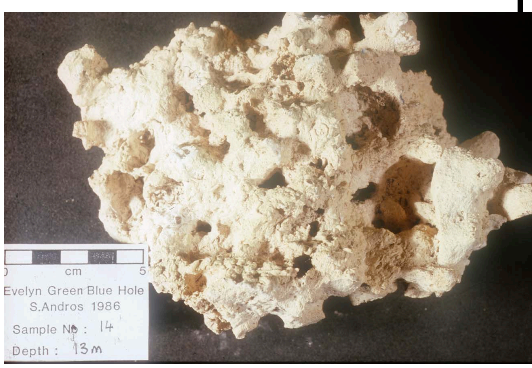
CARB3D⁺ Diagenesis:
Up-scaling of permeability using dissolutional porosity





Porosity		Permeability (Hydraulic Conductivity)
Fabric Selective (Depositional)	→	Matrix
Non-fabric Selective (Dissolutional)	→	Secondary

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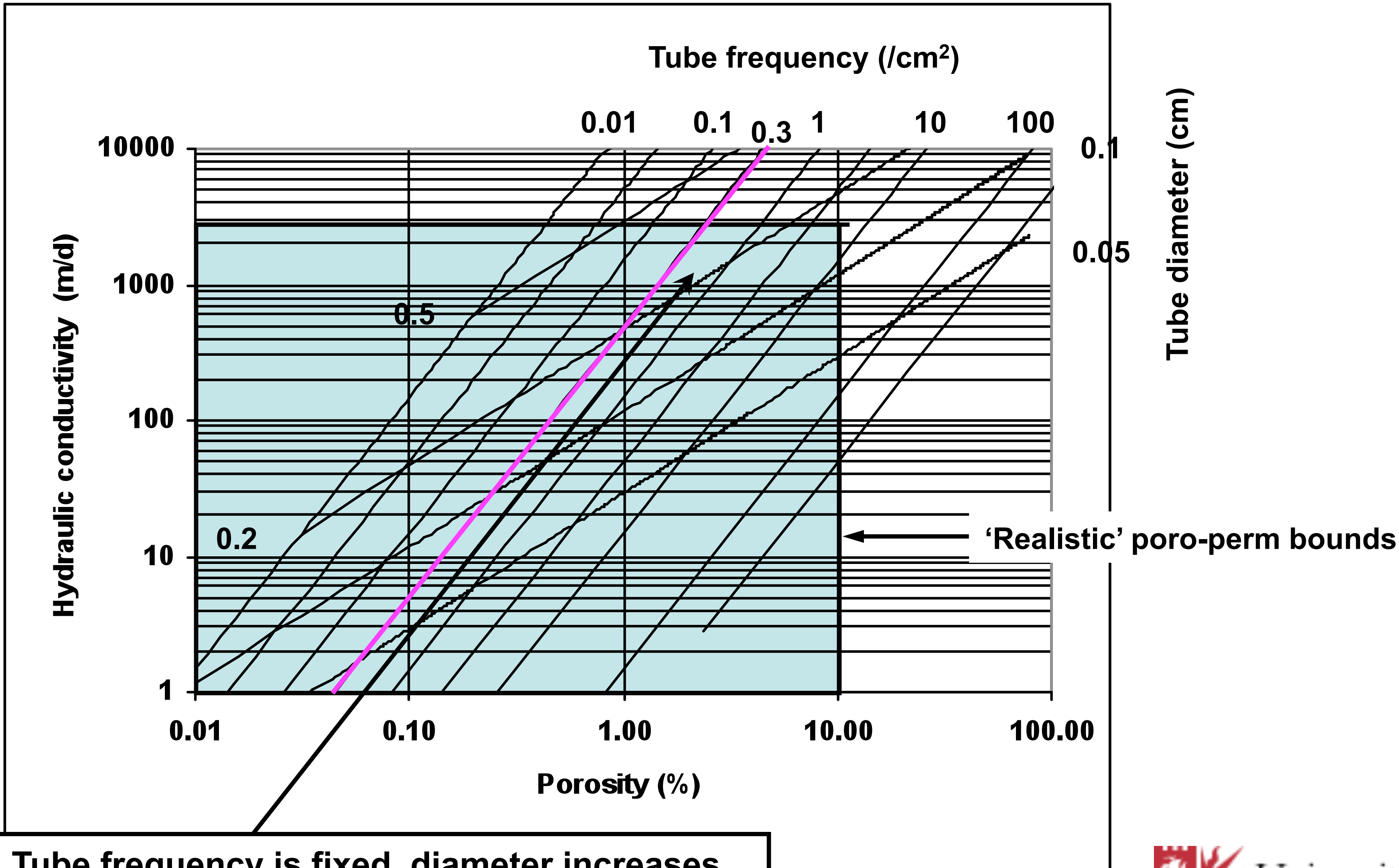
CARB3D+ Diagenesis:
Up-scaling of permeability using Kozeny-Carmen model



Tube frequency is fixed, diameter increases with progressive dissolution

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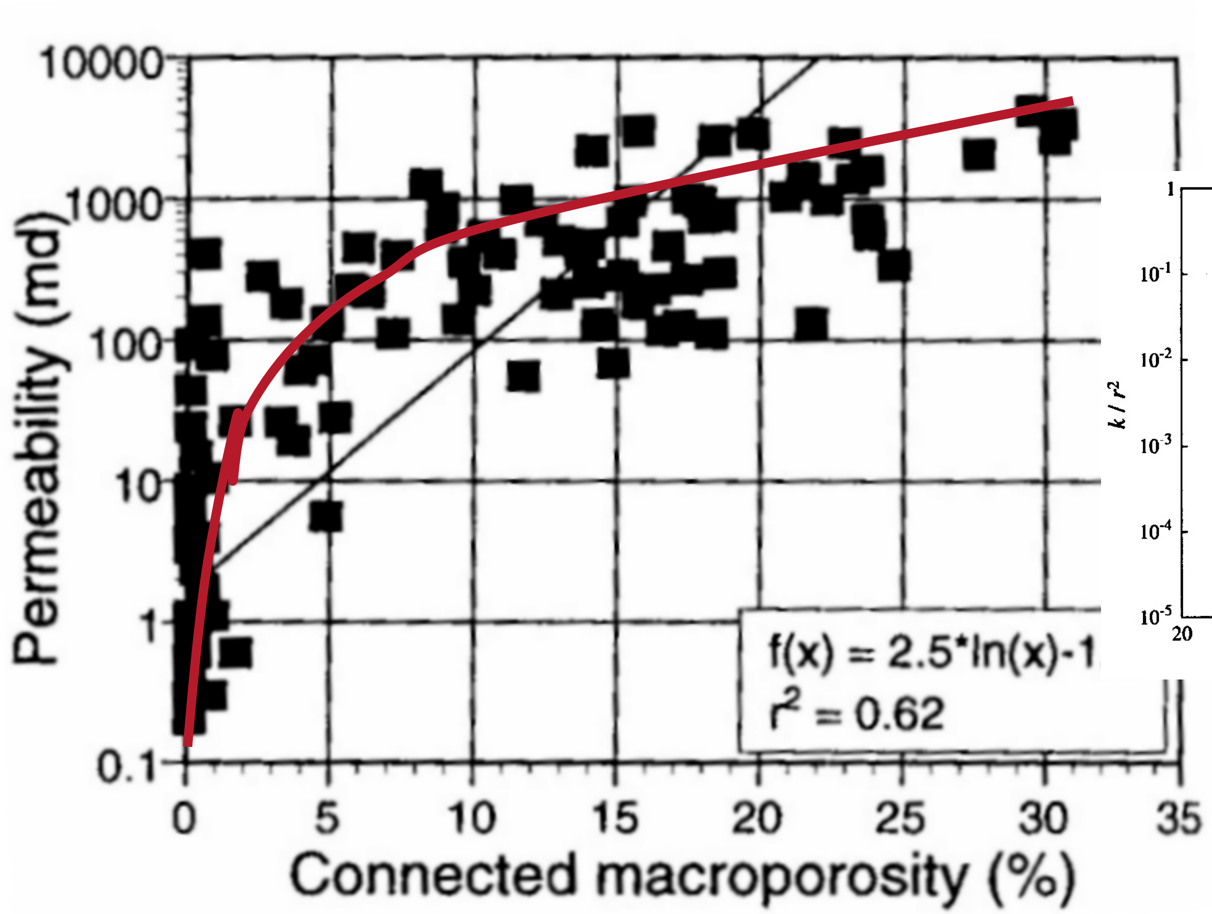
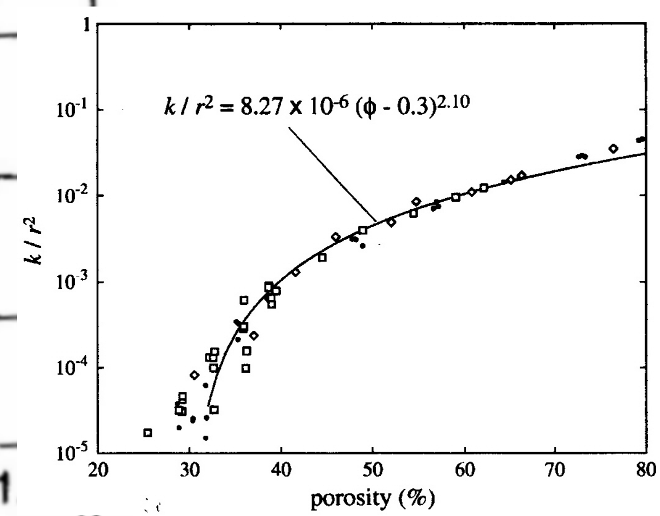
CARB3D+ Diagenesis:
Alternative model non-fabric selective porosity to permeability



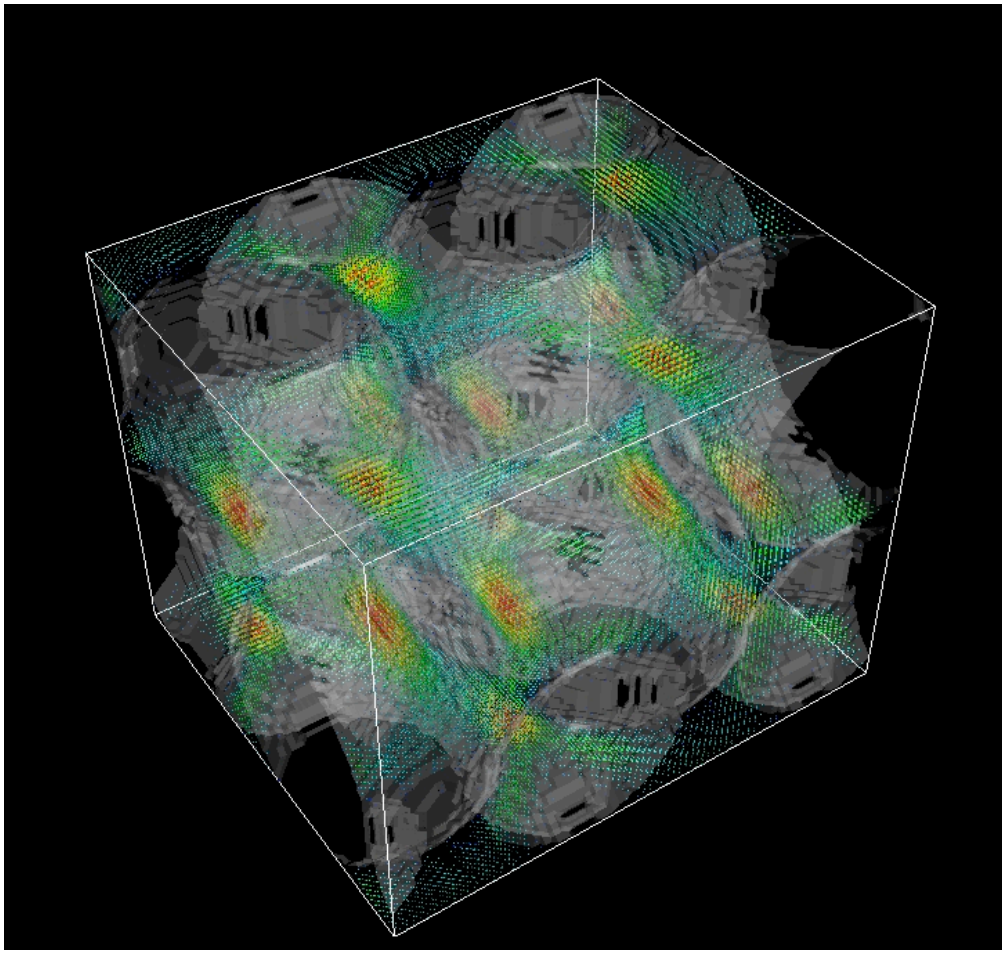
Blowers et al model

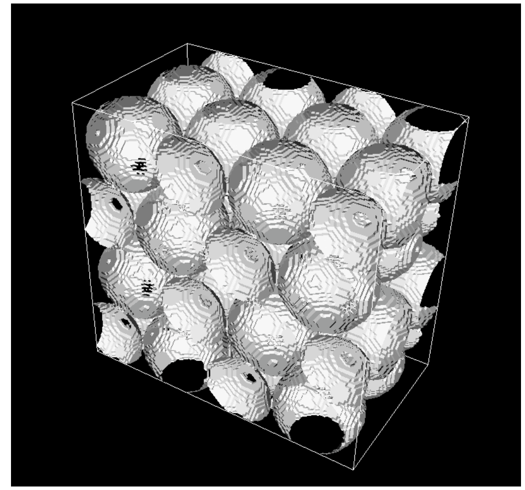


Clino & Unda data, Mellim et al (2001)

CARB3D+ Diagenesis:
Alternative model non-fabric selective porosity to permeability

- Use of lattice-Boltzmann model for predicting permeability of vuggy carbonates





(Felce et al., in prep)

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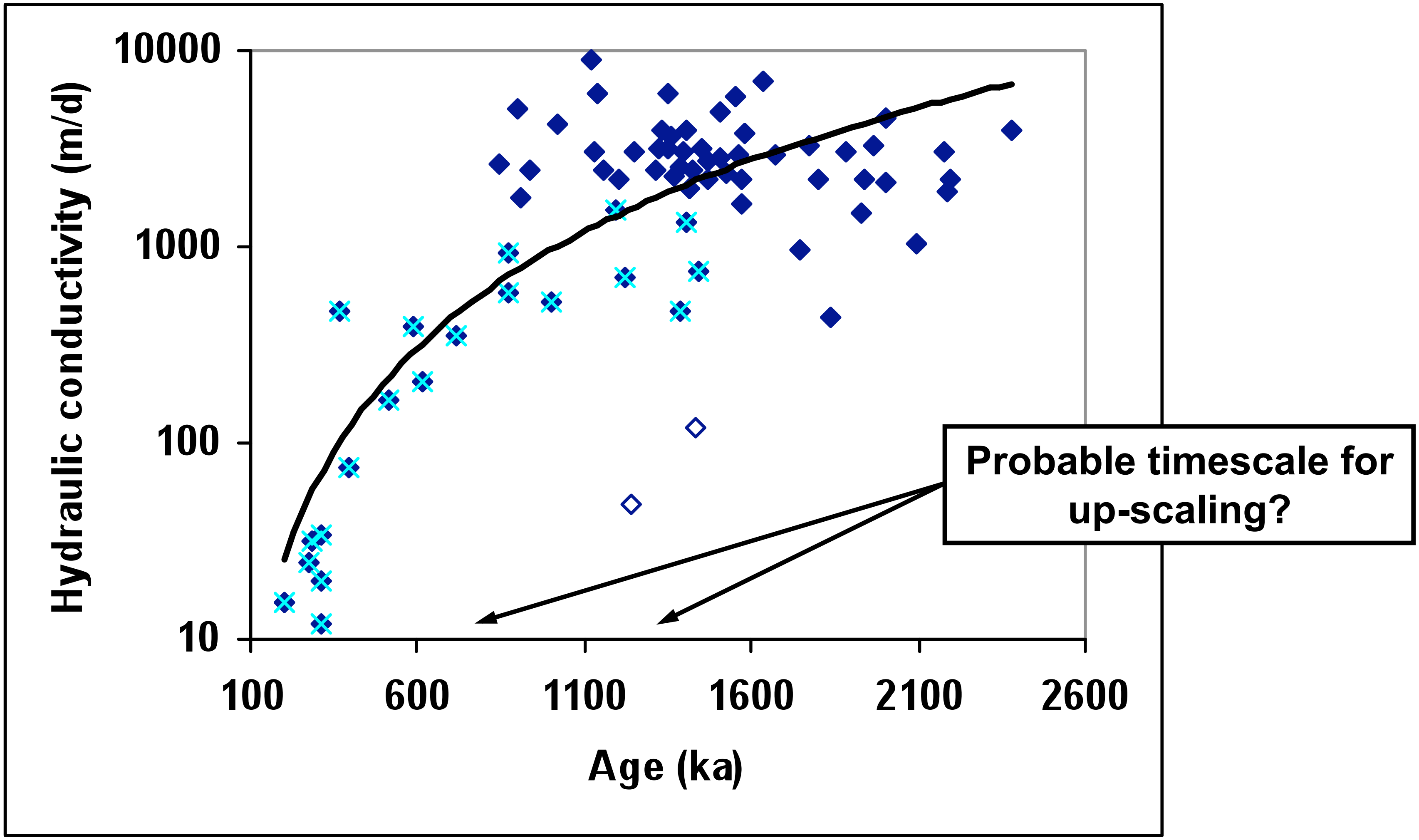
CARB3D+ Diagenesis:
Up-scaling of permeability using dissolutional porosity



Lucayan Limestone, Grand Bahama

(depth/age conversion)

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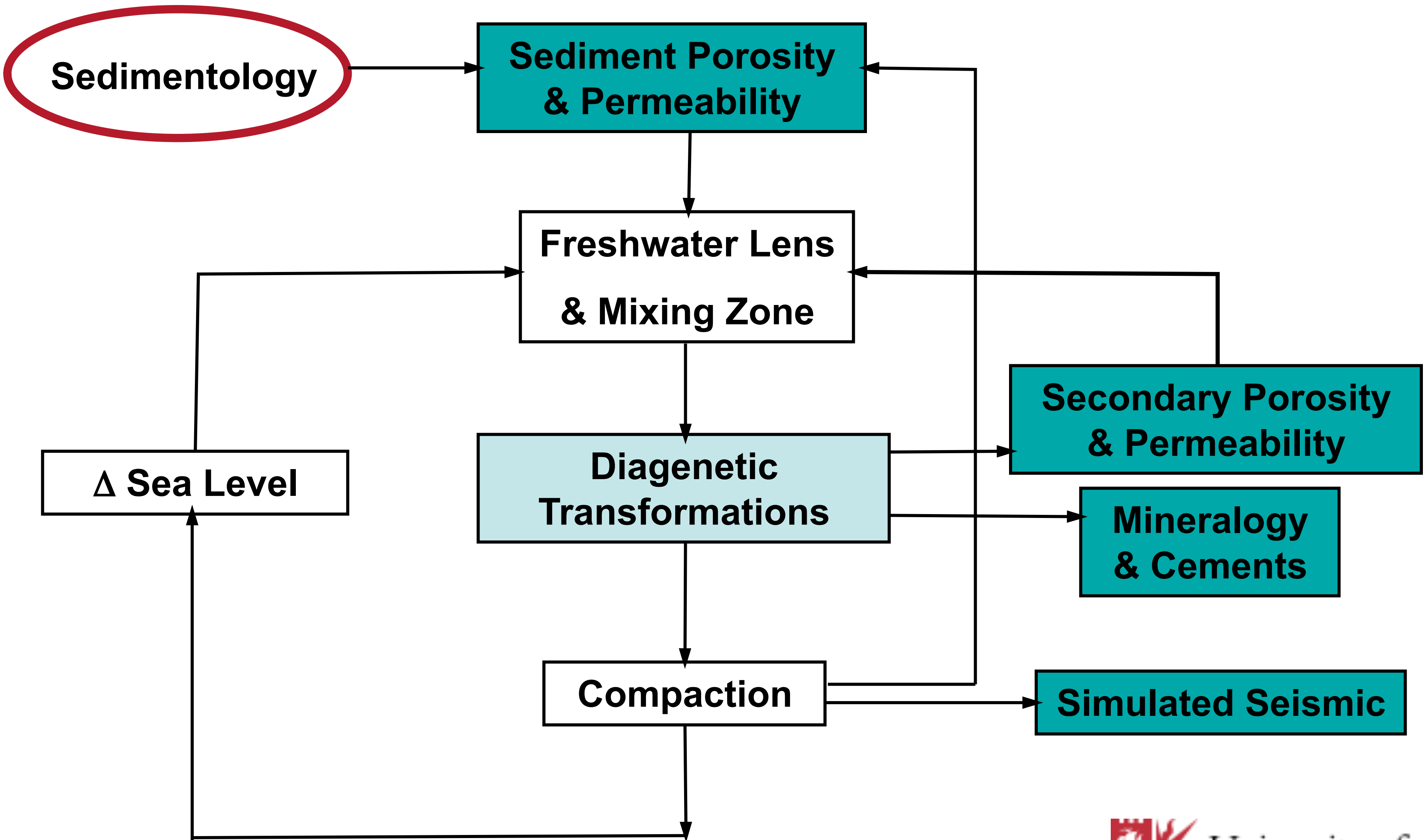
CARB3D+ Diagenesis Components:

Diagenetic Transformations



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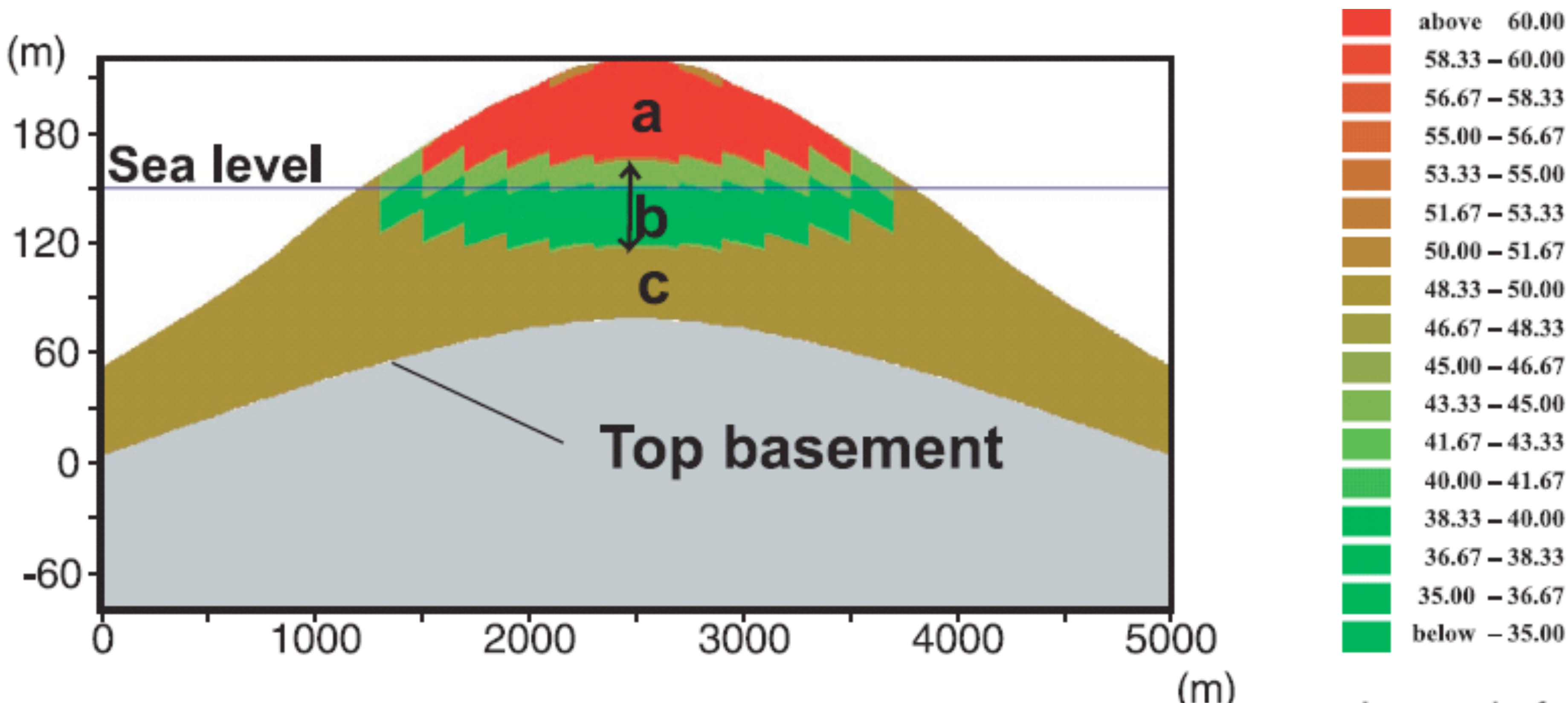
Hydrozone diagenesis template: Facies-3D



Legend of porosity (%)

Porosity Change:

a) Vadose +0.198 %/ka

b) FWL -0.536 %/ka

(No mixing zone hydrozone)

c) Marine 0 %/ka

Matsuda et al (2004)

Vacher 2D model and k???

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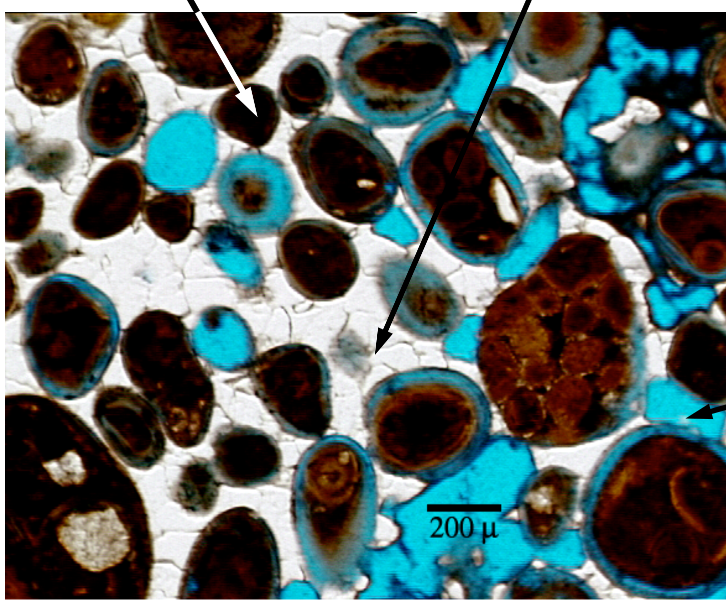
CARB3D: Mineralogical Components

Mineral Phase

Grains	Cement
Aragonite	Aragonite
Calcite	Calcite
Dolomite	Dolomite



Pleistocene ooid grainstone, West Caicos

Porosity

(Primary and Secondary)

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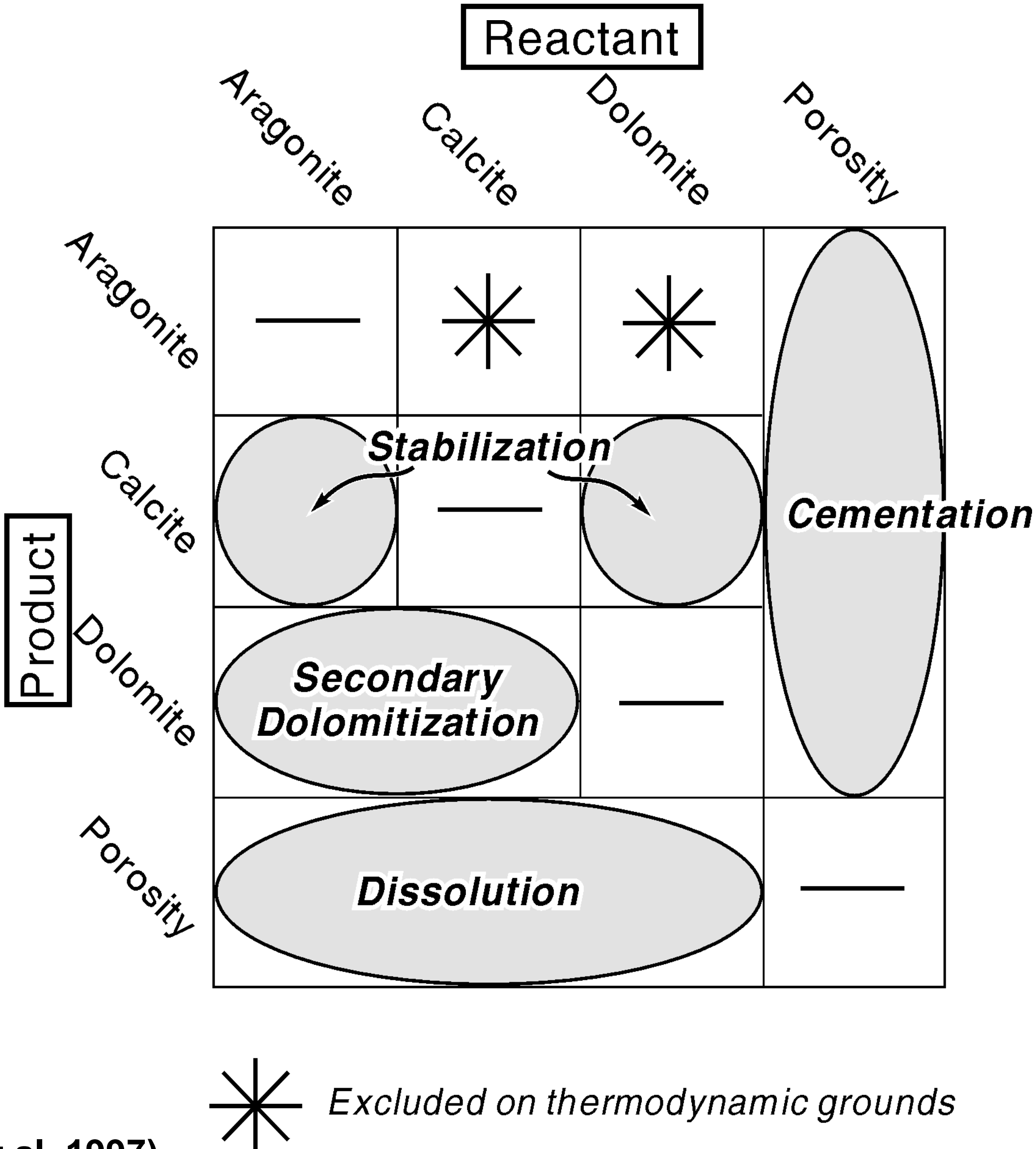
CARB2D Diagenesis:
Diagenetic transformations for each hydrozone



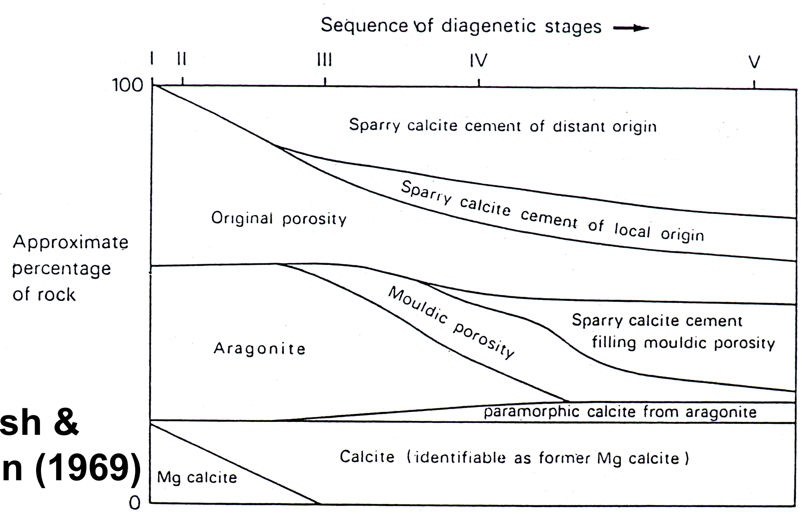
(Whitaker et al, 1997)

CARB3D+ V2.0 Diagenesis:
What determines the extent of diagenetic modification?

CARB3D⁺ Hydrozone Residence Times

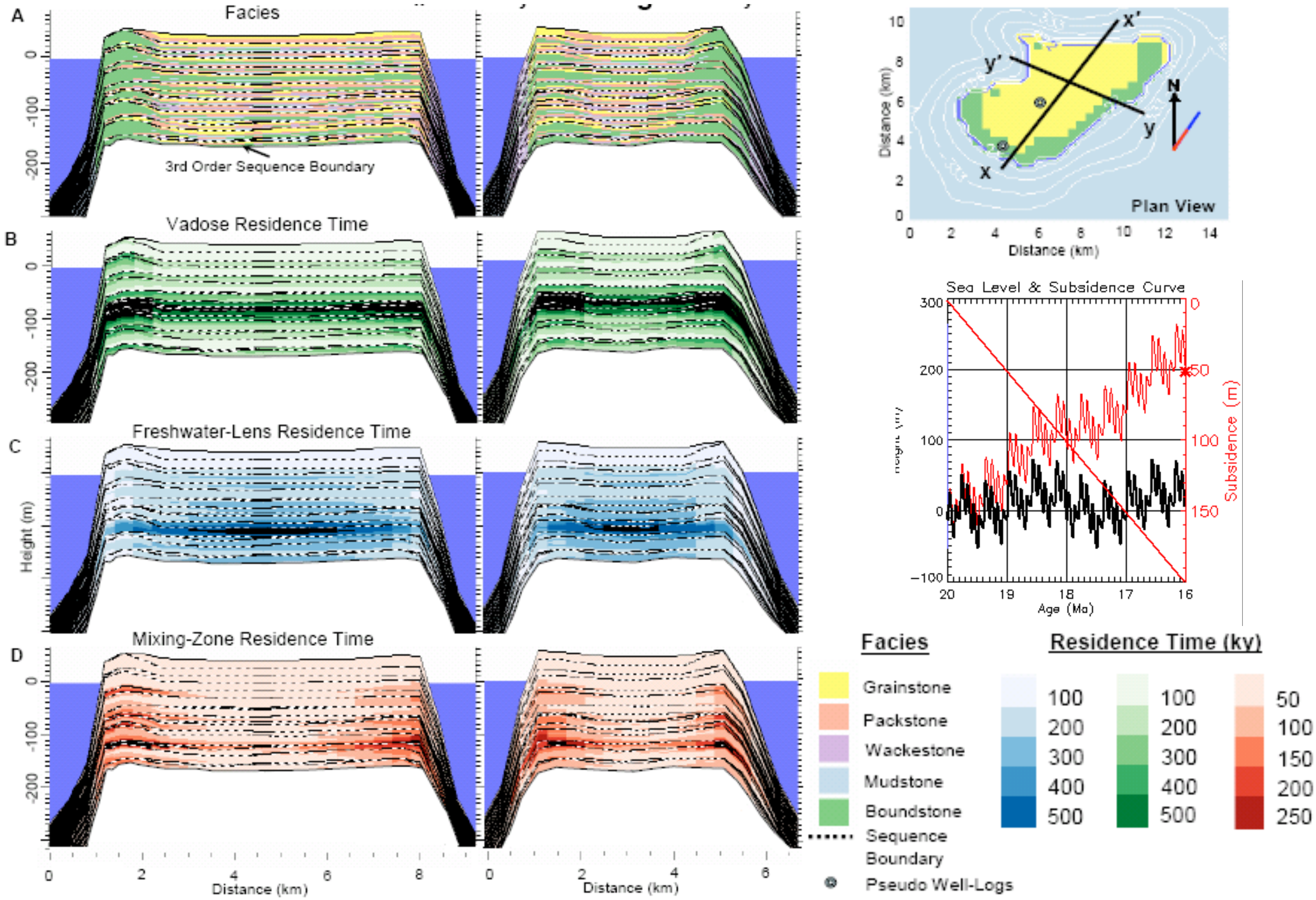
1) Total Diagenesis = $\text{Rate}_{\text{Diagenesis}}$ x Time Acting

Geological, Field Process & Modelling Studies

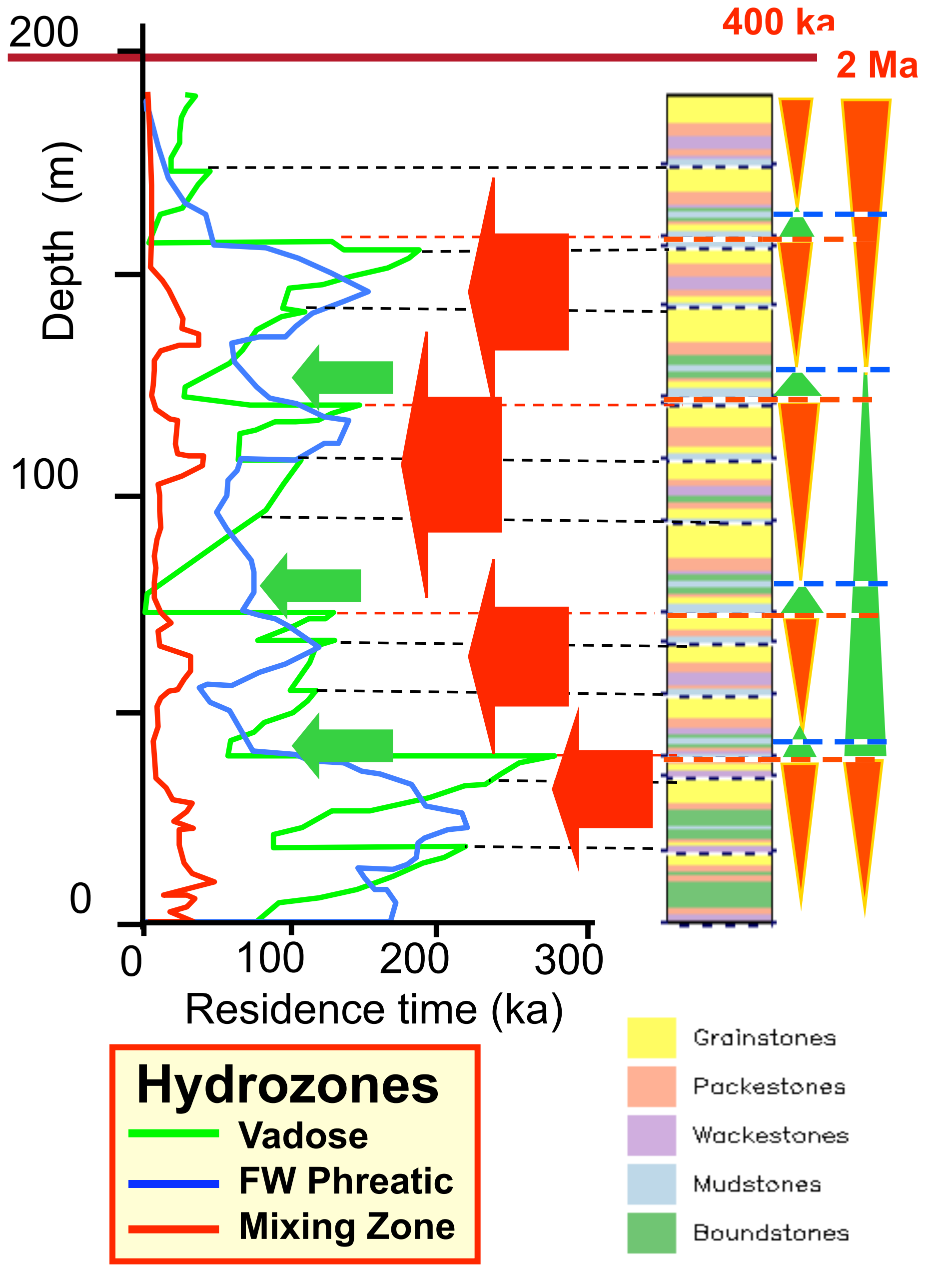


Gavish & Freidman (1969)

Paterson et al (2008) hydrozone residence times



CARB3D+ Diagenesis:
Link between hydrozone residence times and sequence types



➢ 3rd and 4th Order Transgressive System Tract (TST) have Minimum Meteoric Alteration

➢ 3rd and 4th Order (Highstand System Track) HST have Maximum Meteoric Alteration

= HSTs
= TSTs
= SBs
= MFS

(Paterson et al, 2008)

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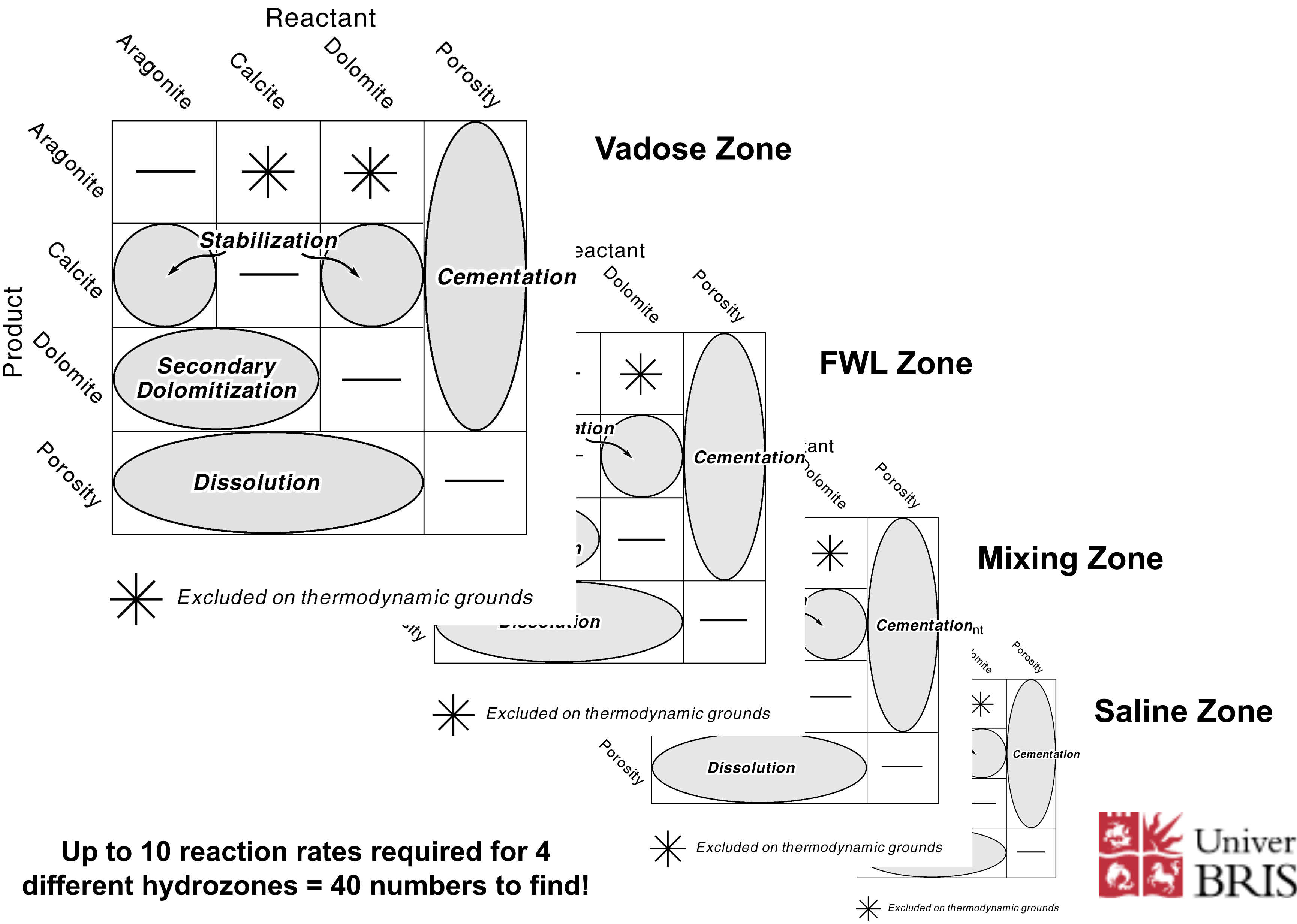
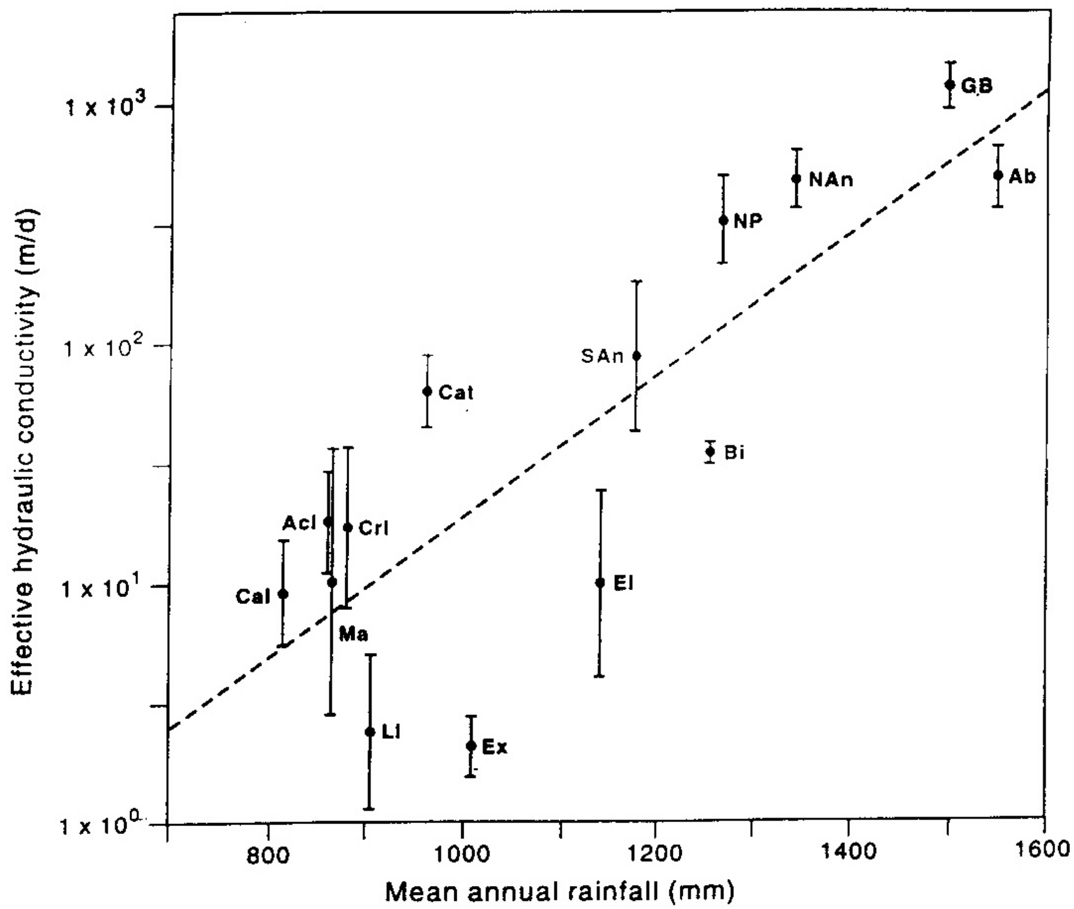
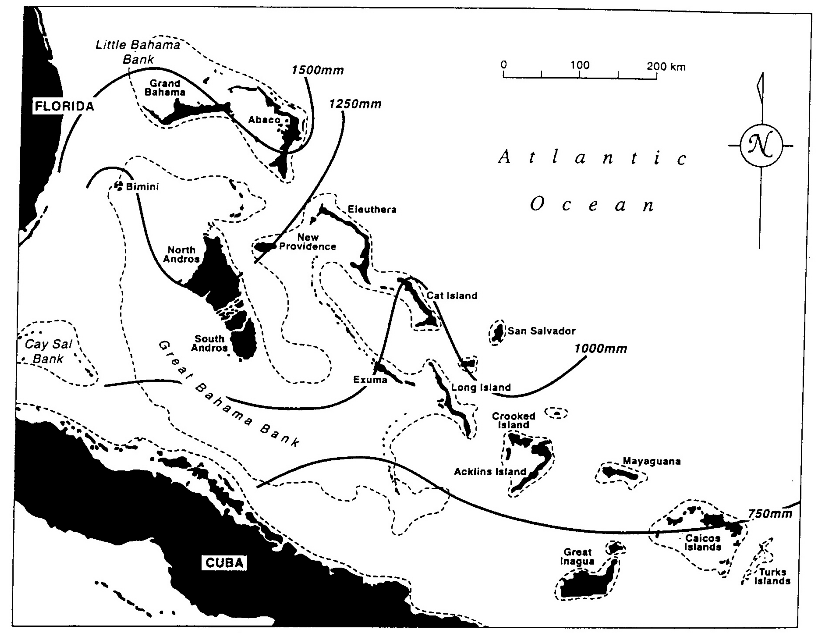
CARB3D+ V2.0 Diagenetic rates parameterization overload
Need to reduce and simplify



Up to 10 reaction rates required for 4 different hydrozones = 40 numbers to find!

CARB3D+ V2.0 Diagenetic rates parameterisation
eg Using climate parameters such mean annual rainfall





Bahamas rainfall

Whitaker & Smart (1997)

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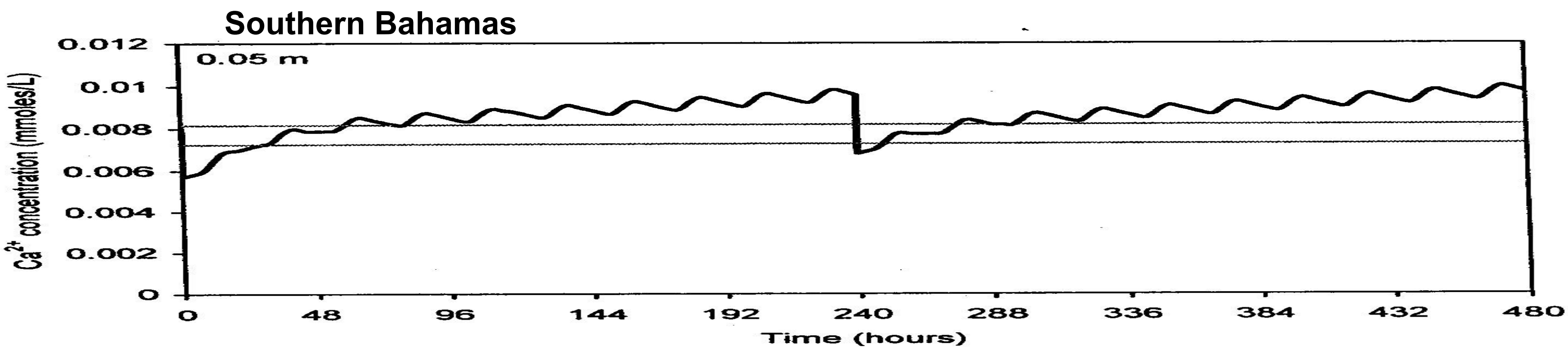
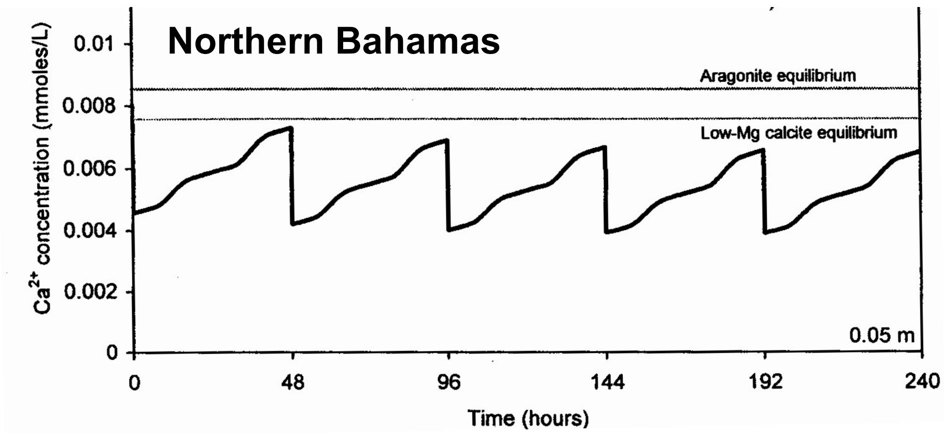
But remember as for sediment transport, diagenetic transformations occur as a cumulative result of many individual events in time





Calcium concentrations in 0.05 m pore waters in relation to carbonate saturation

Ranson (Unpublished dissertation)

Simulation conditions

Variable	Northern Bahamas	Southern Bahamas
Temperature	24° C	27° C
Base temperature	20° C	23° C
Storm frequency	48 hours	240 hours
Storm duration	10 minutes	5 minutes
Storm intensity	40 mm/h	20 mm/h
Evapotranspiration	3.8 mm/day	4.7 mm/day

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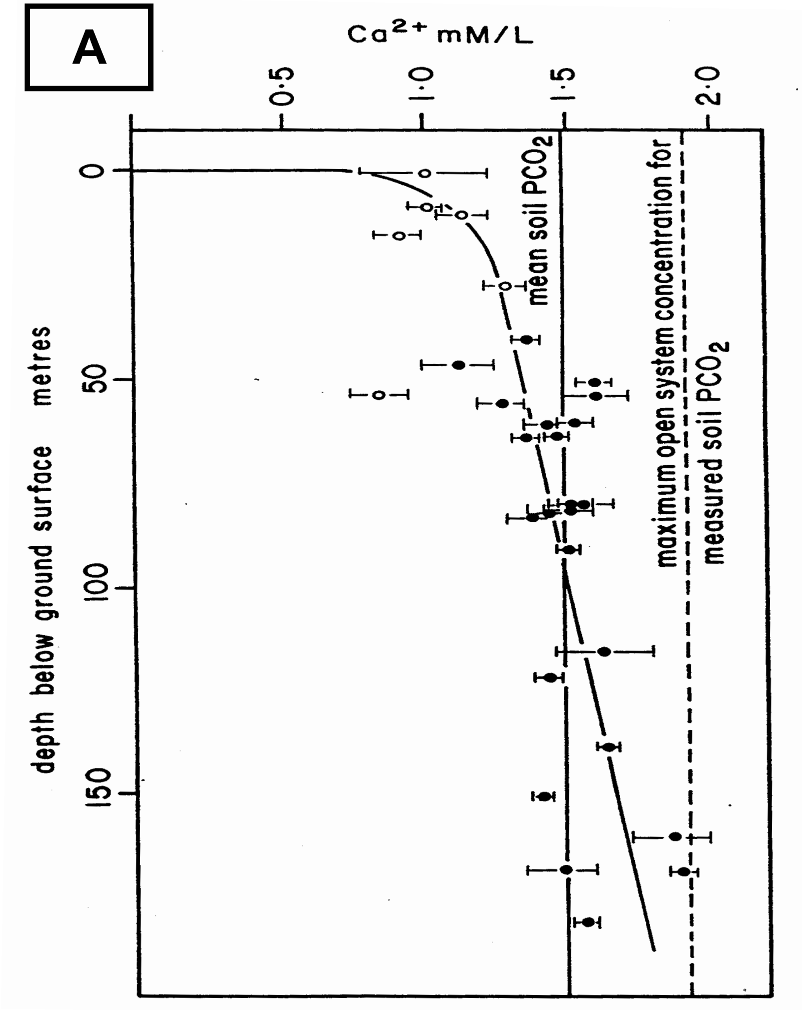
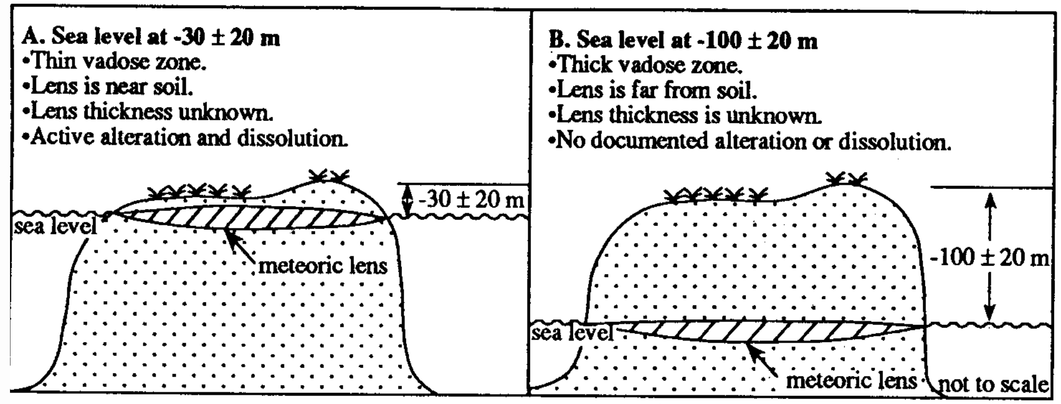
CARB3D+ V2.0 Diagenesis rates are uniform with depth (A), have no feedback between zones (B) and are not dependent on grain size (C)

A



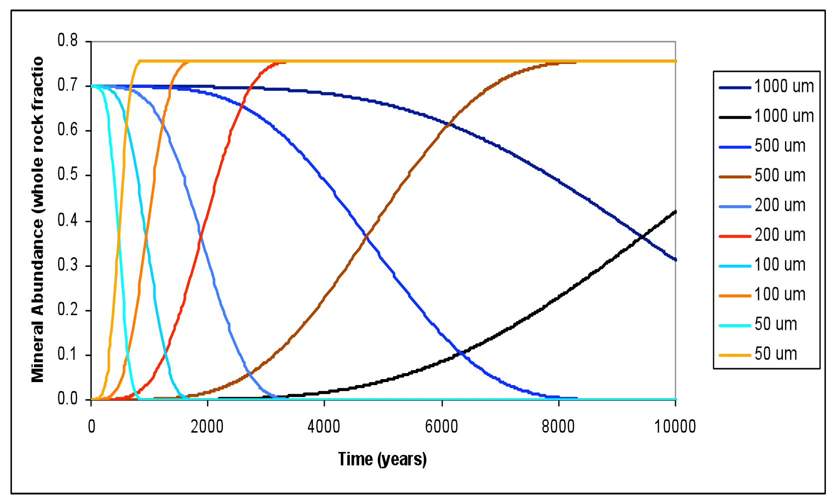
Depth dependence of vadose dissolution, karstified Paleozoic Limestone, UK (Smart & Freiderich 1980)

B



Melim et al (1995) inactive deep meteoric lens model

C

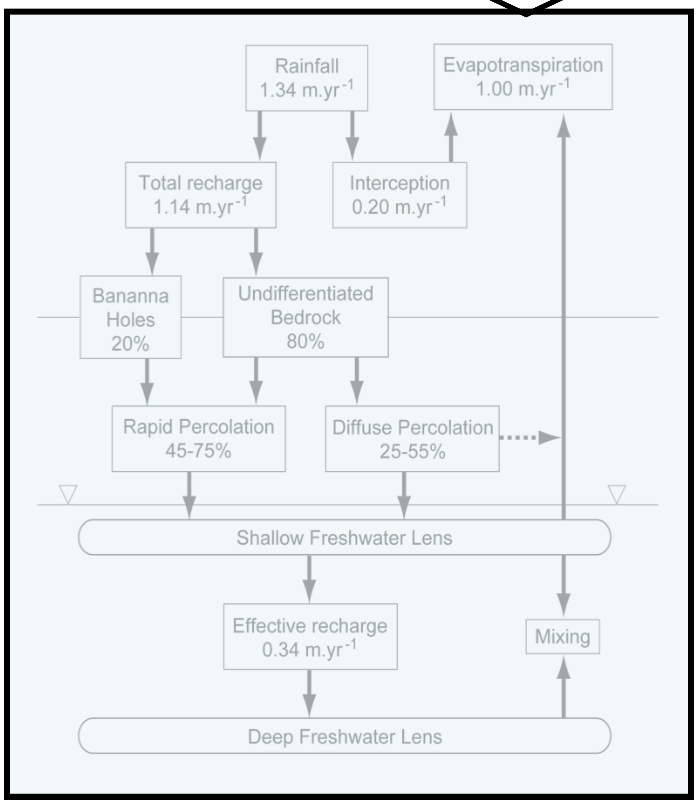


Dependence of A to C stabilisation on grain size (Whitaker & Smart in prep)

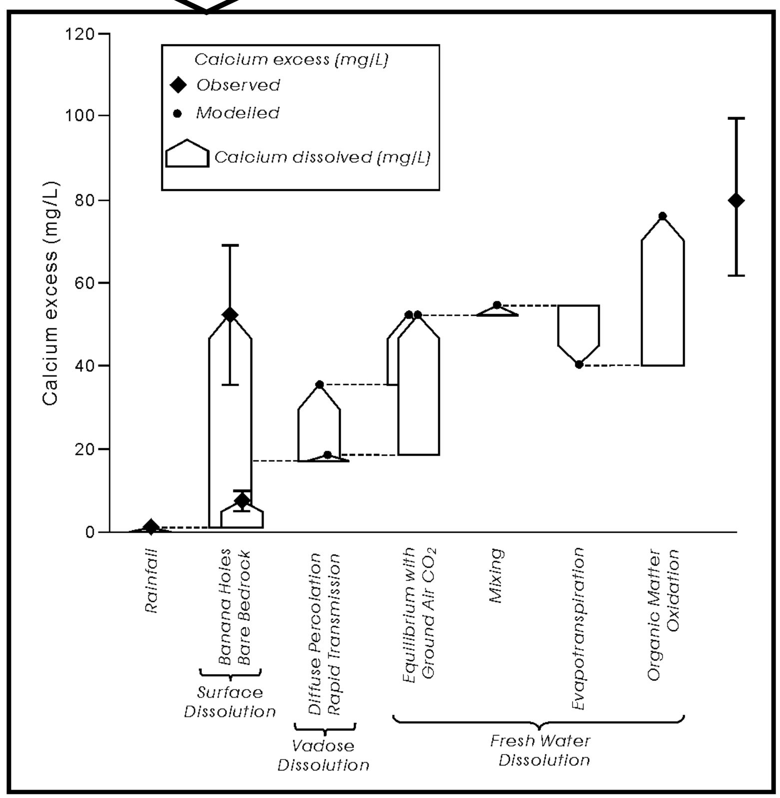
CARB3D+ Diagenesis: uniform hydrozones template (V2.0 top) and (STEP1) sequential carbonate budget approach (V3.0 below)…then

Total Diagenesis = $\text{Rate}_{\text{Diagenesis}}$ x Time Acting (V2.0)

$\text{Rate}_{\text{Diagenesis}}$ = Flux H_20 x Reactant Concentration (V3.0)



(Whitaker & Smart, 2006 a and b)



Northern Bahamas field data: Water & Ca budgets

……distribute reactions along the flow path (Step 2)

Total Diagenesis = Rate$_{\text{Diagenesis}}$ x Time Acting

Rate$_{\text{Diagenesis}}$ = Flux H_20 x Reactant Concentration

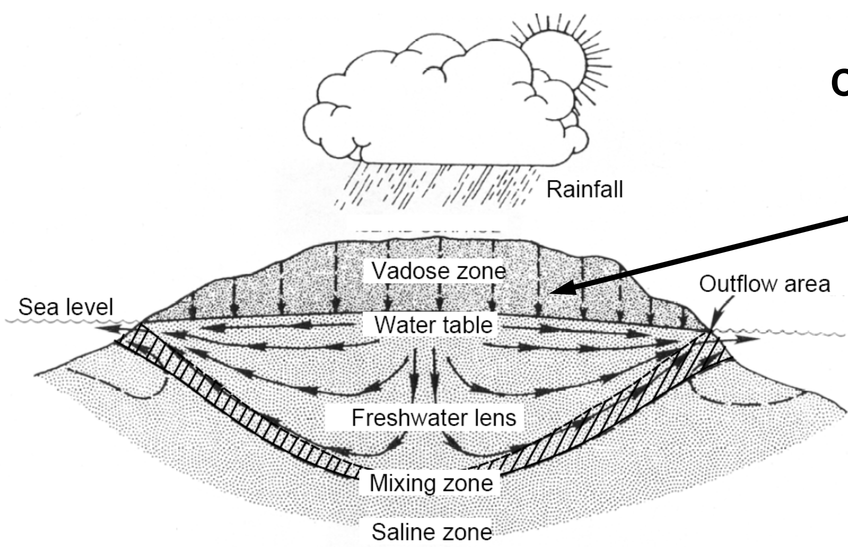
Reactant Concentration = f (degree of saturation, time, surface area)

Chemical reaction rate

+

Groundwater velocity and flow path

Rock property



After Craig (1987)

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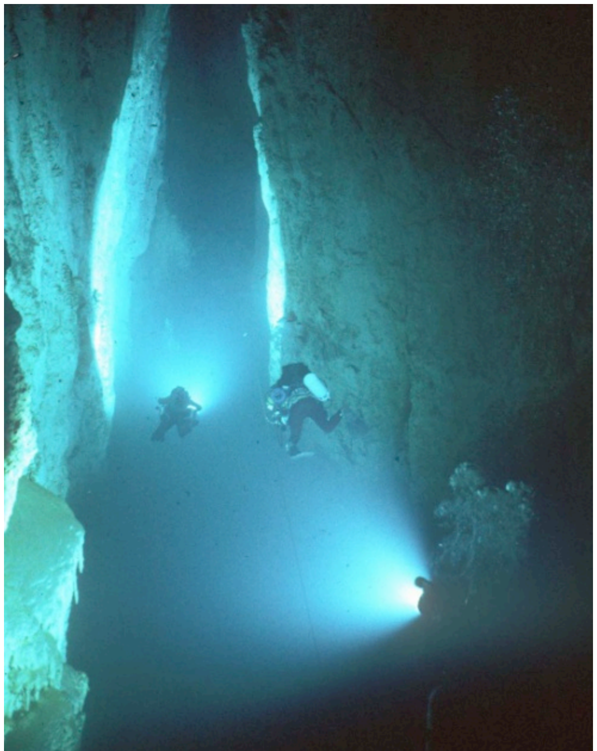
Field sampling along the flowpath:
We try hard but….

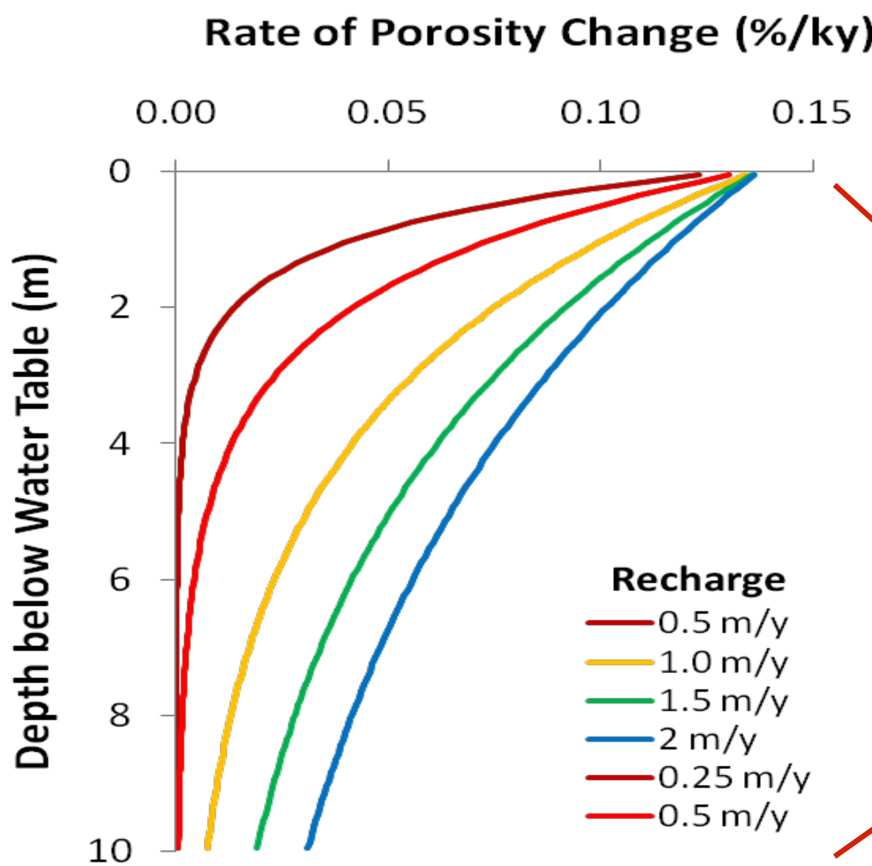


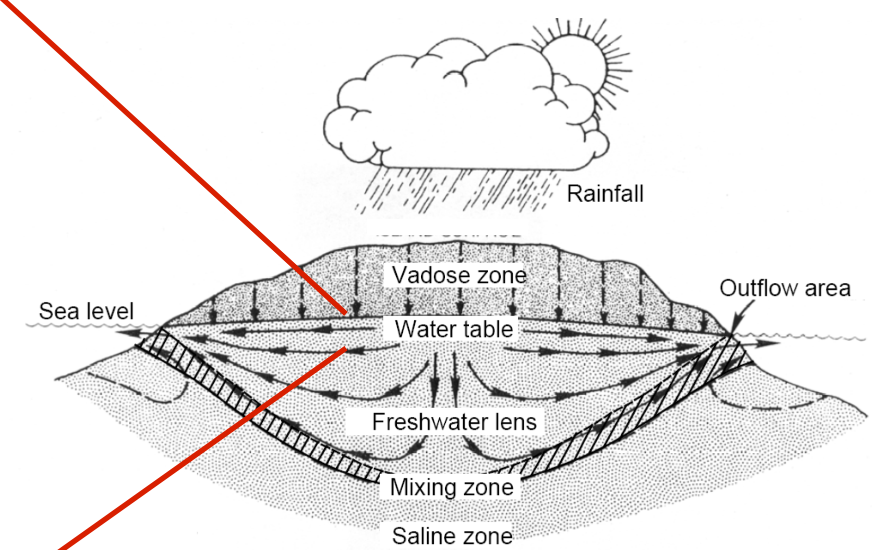
North and South Andros Blue-holes,

exploration, geochemical and hydrological sampling

Shell & Amoco

Reactive Transport Models:
reach the parts that other research techniques don't!





Depth dependence of fresh water lens dissolution, non-karstified Pleistocene Limestone from RTM

(Whitaker and Smart in prep)

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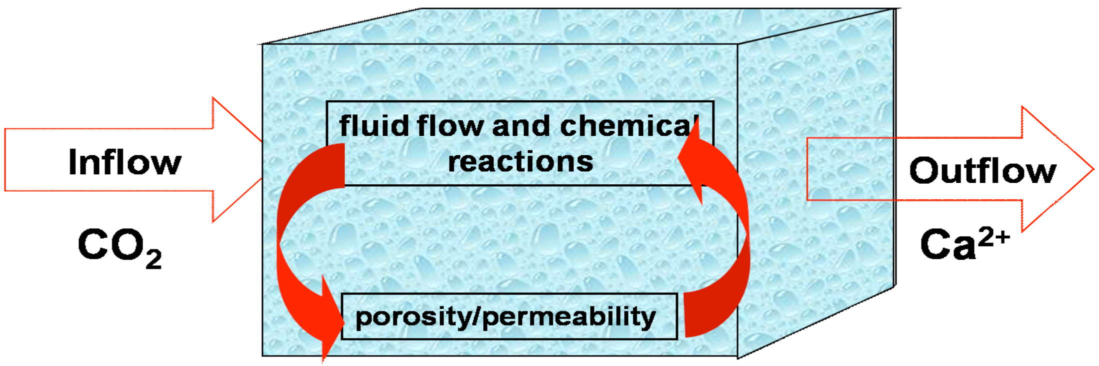
Reactive Transport Models: Integrate transport and geochemical reactions including reaction kinetics



Calcite Dissolution: $CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$

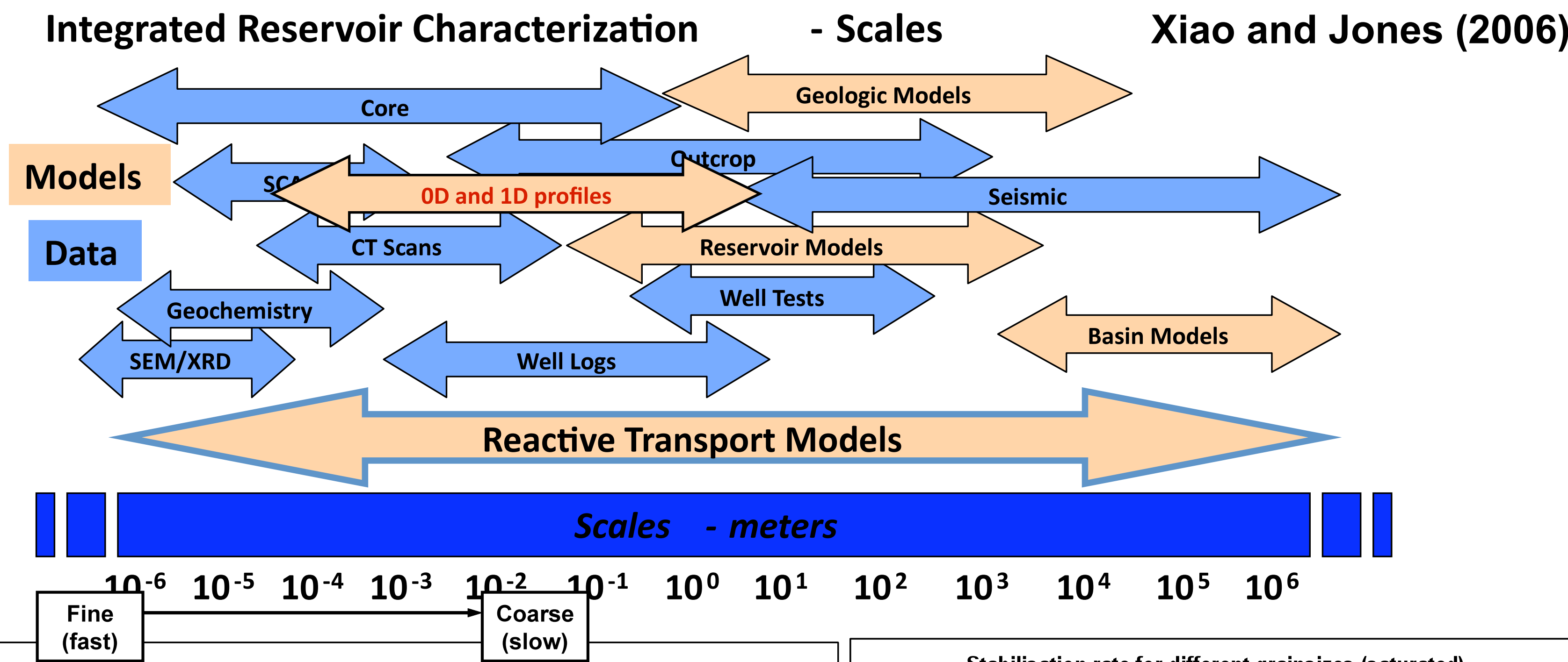
$$\frac{\partial}{\partial t}(\phi C_i) = \underbrace{\underbrace{\frac{1}{\phi}\frac{\partial}{\partial x}\left(\phi D \frac{\partial C_i}{\partial x}\right)}_{\text{Diffusion \& Dispersion}} - \underbrace{q\frac{\partial C_i}{\partial x}}_{\text{Advection}}}_{\text{Transport}} + \underbrace{\phi \sum_k \left(\frac{\partial C_i}{\partial t}\right)_k}_{\text{Reaction}}$$

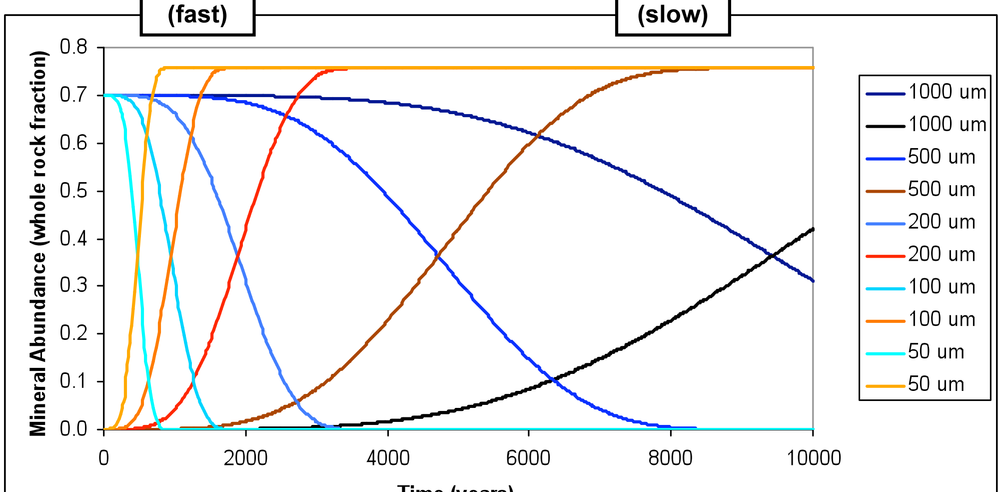
$$\frac{\partial C_{calcite}}{\partial t} = S\, A\, e^{-\frac{E_a}{RT}} \left(\frac{Q}{K_{eq}} - 1\right)^{2.26}$$

Surface Area — Kinetics — Saturation Index

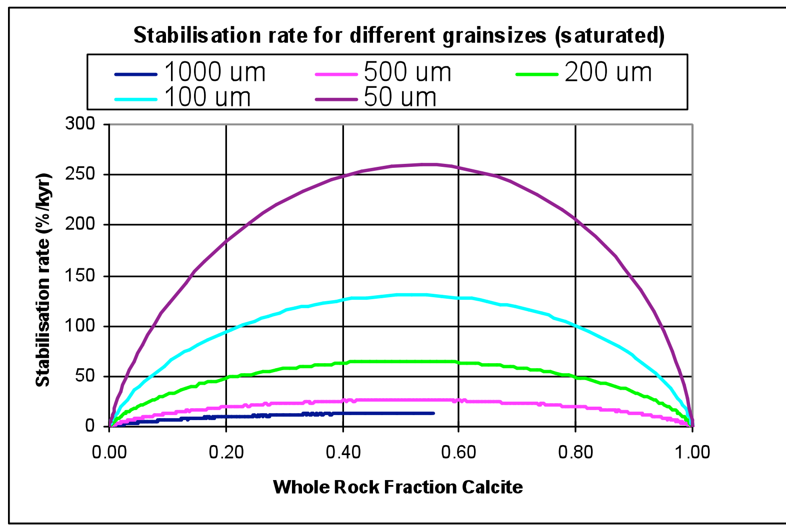
After Xiao and Jones (2006)

RTM is applicable across a great range of scales

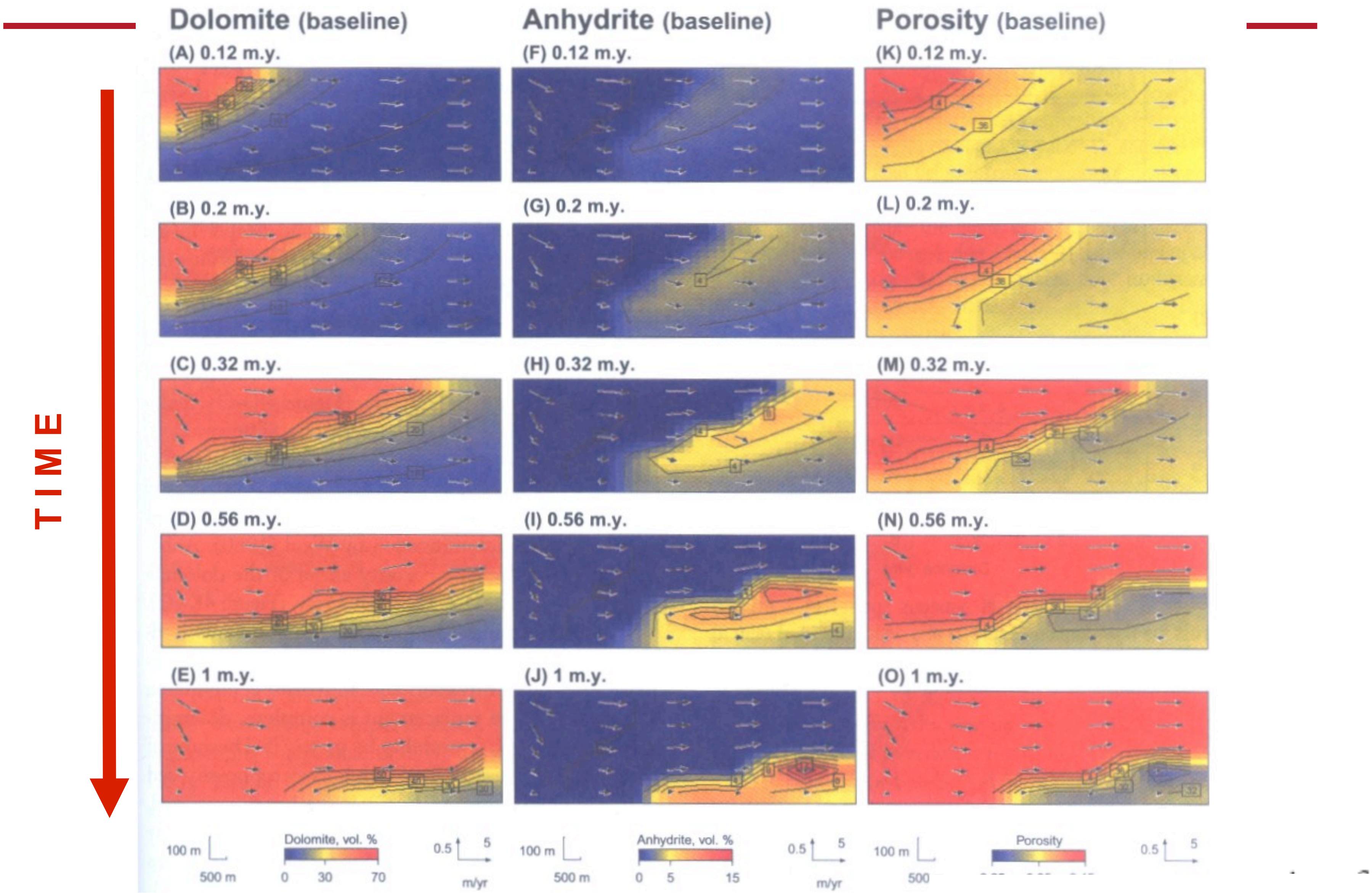




(Whitaker and Smart in prep)



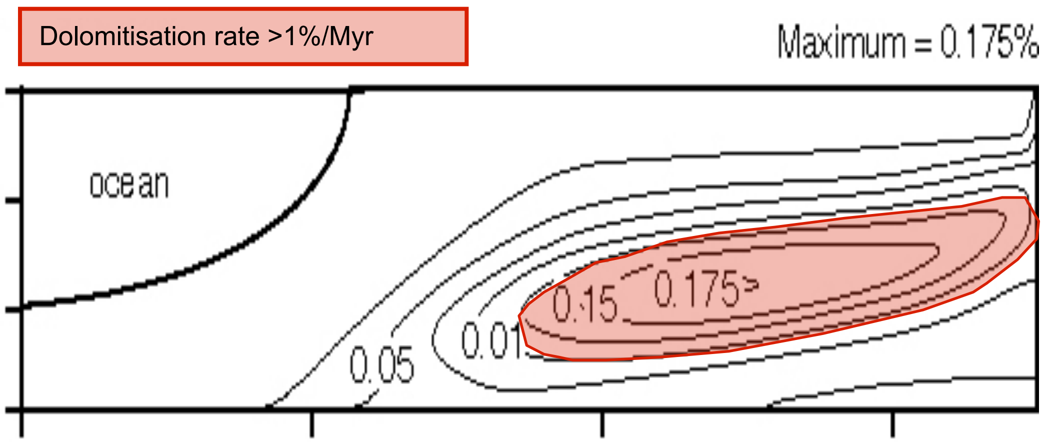
RTM give great results: Reflux dolomitisation



Jones & Xiao (2005)

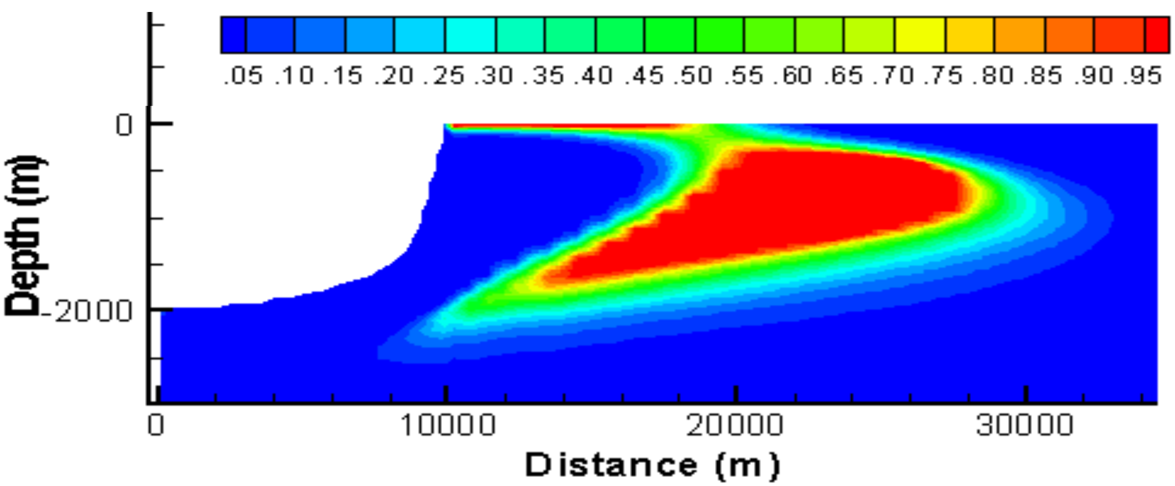
BUT>>>>RTM Issues:

Challenging to parameterise, slow and cumbersome to run



100 ky

Wilson et al (2001)



15 My

Whitaker & Xiao (2007)

Geothermal convection and dolomitisation

Non-linearities in the system as a function of dolomite surface area

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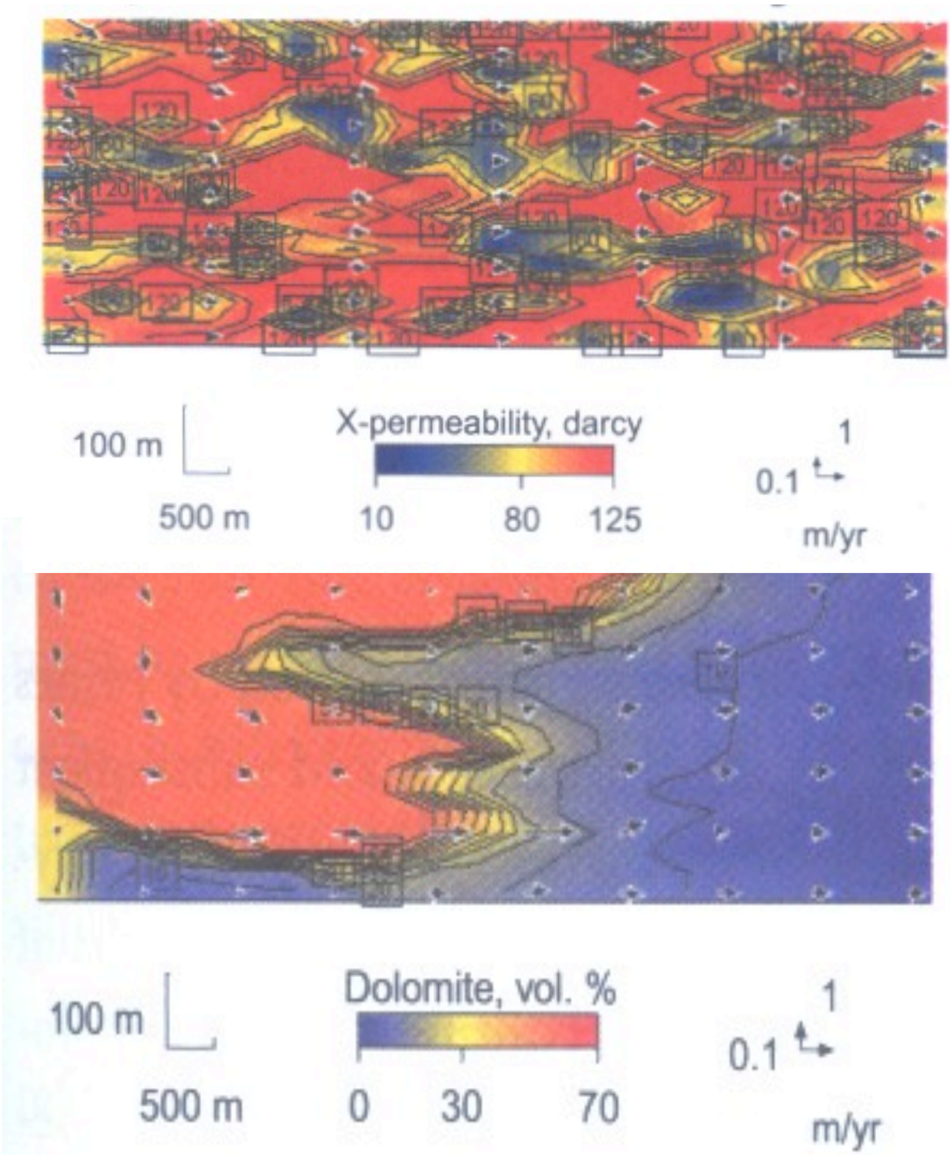
RTM Issues:

Need to better model heterogeneous permeability systems



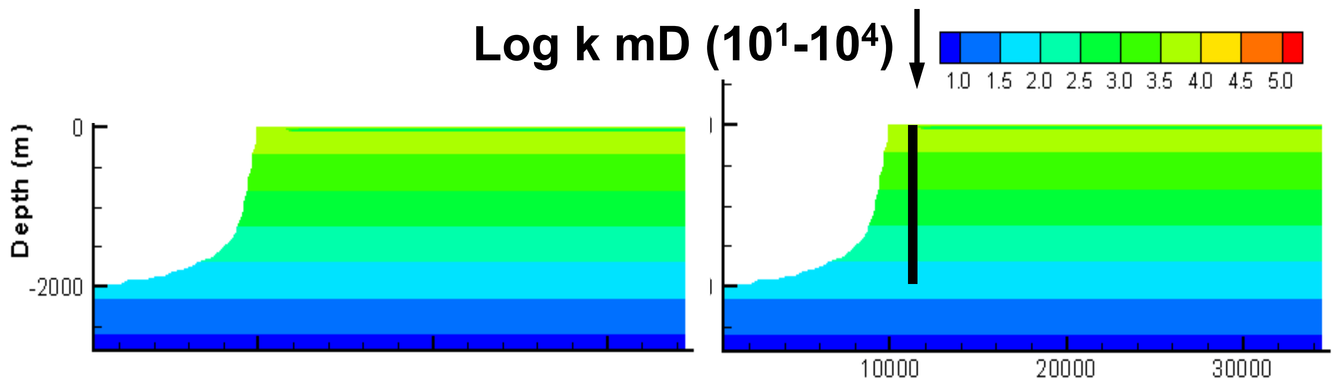
Reflux dolomitisation with spatially random variation in porosity and permeability

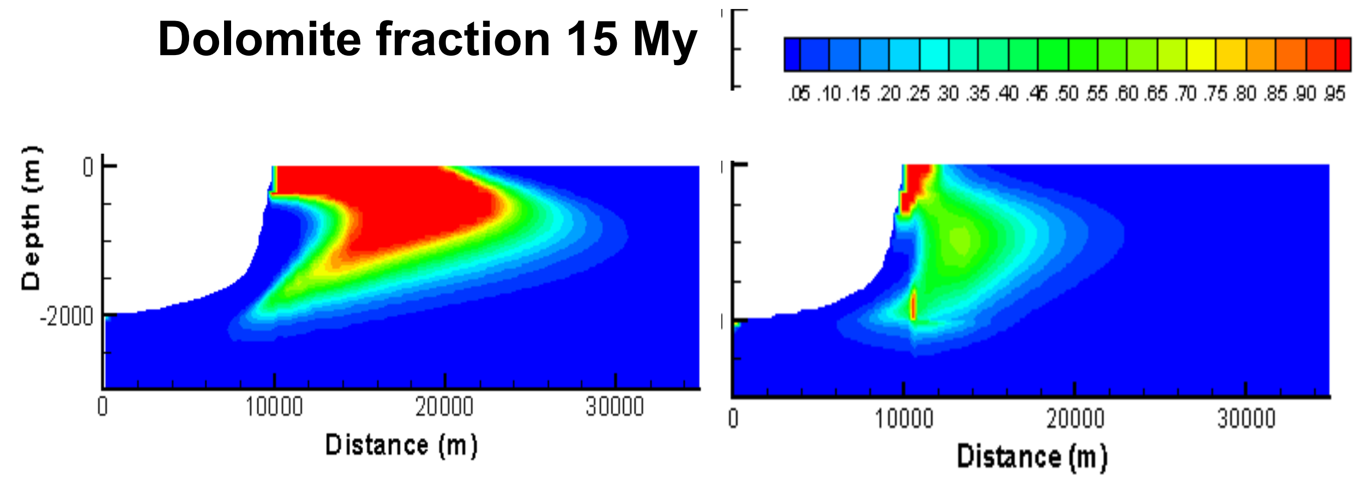
(Jones & Xiao, 2005)

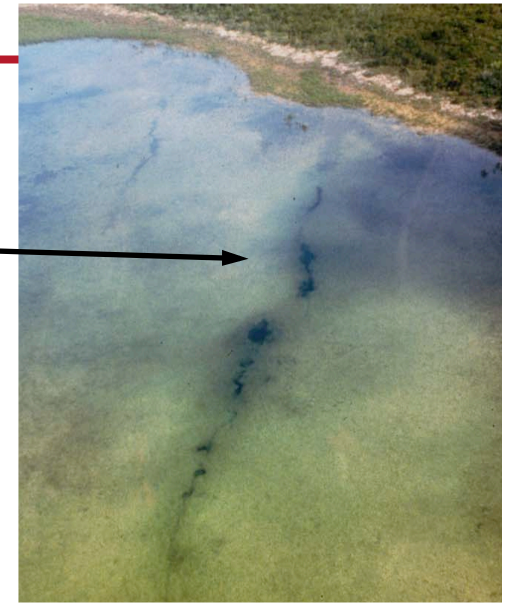
RTM Issues:
Fractures & high k routes

Unfractured Platform **Fractured Platform Margin**

Bank margin fracture







South Andros Bank Marginal Fracture

Whitaker & Xiao (2007)

Geothermal convection and dolomitisation

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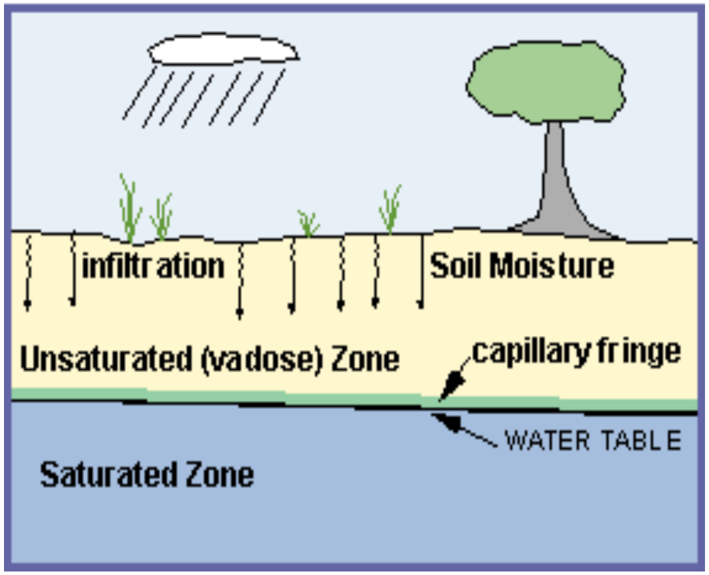
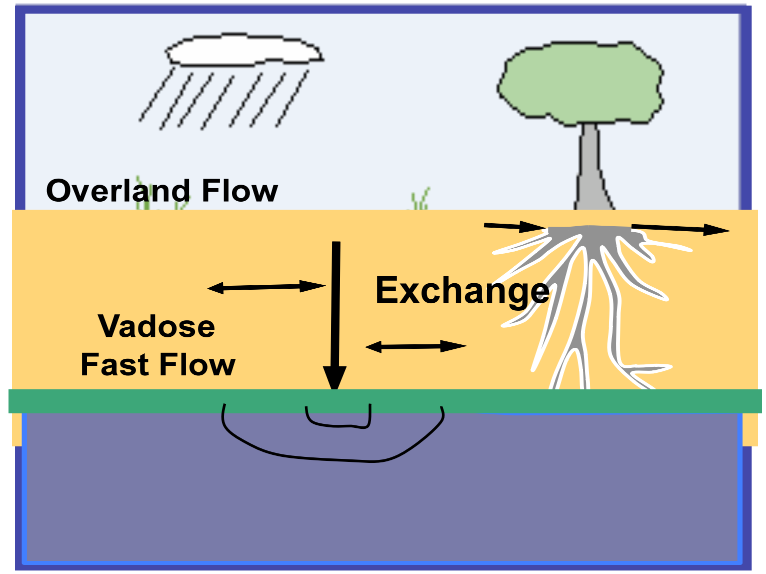
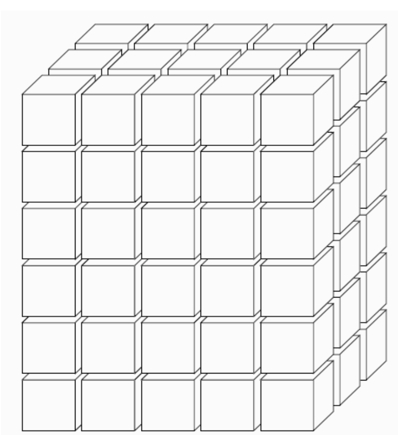
RTM Issues: Fractures & matrix, conceptual models and numeric formulations (and not just in reservoirs)

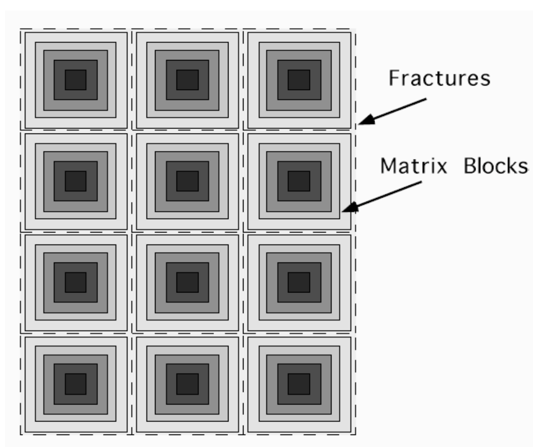




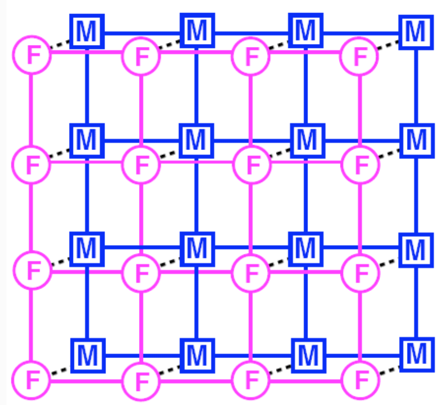
Double Porosity



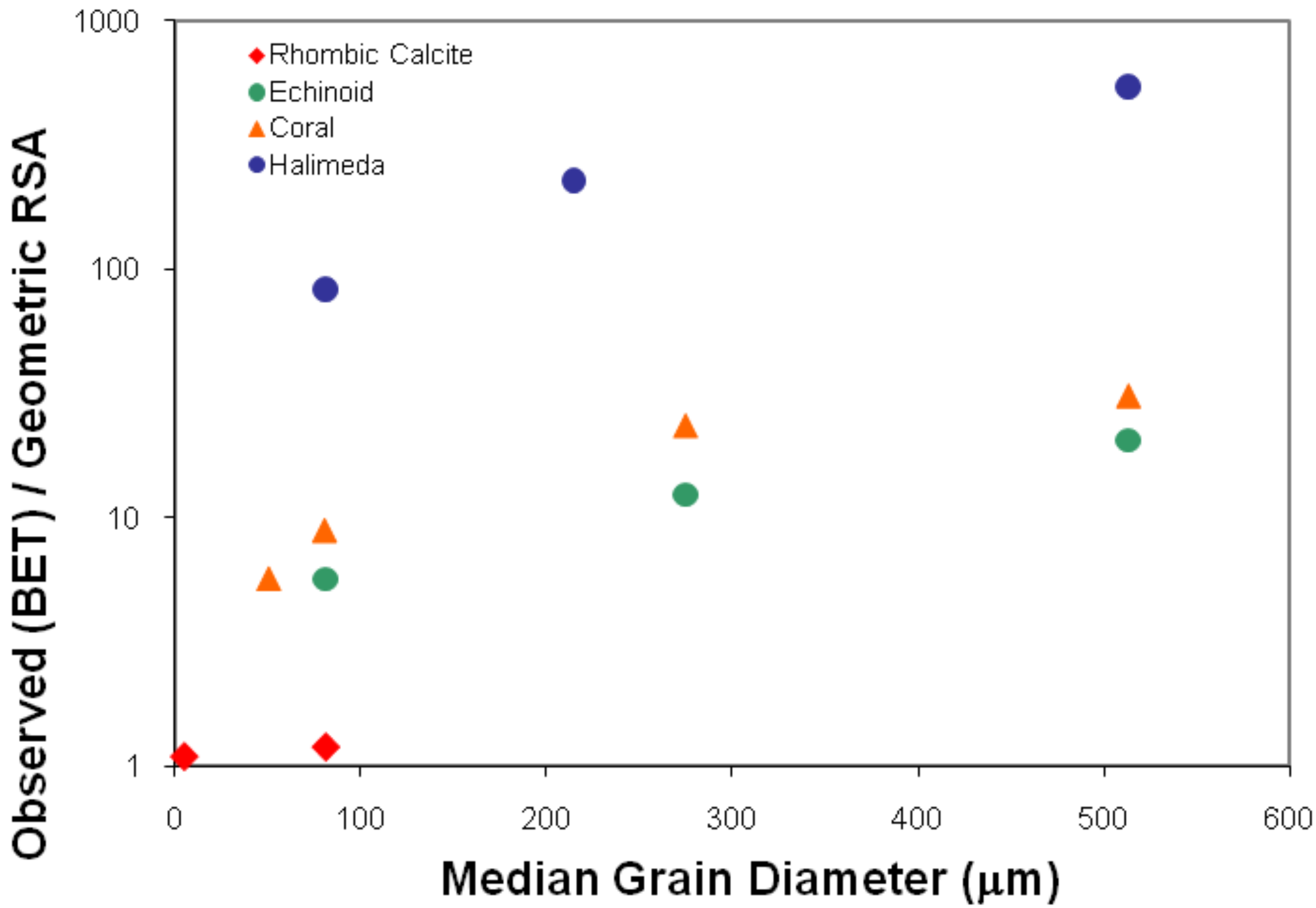
Multiple Interacting Continua



Dual Permeability



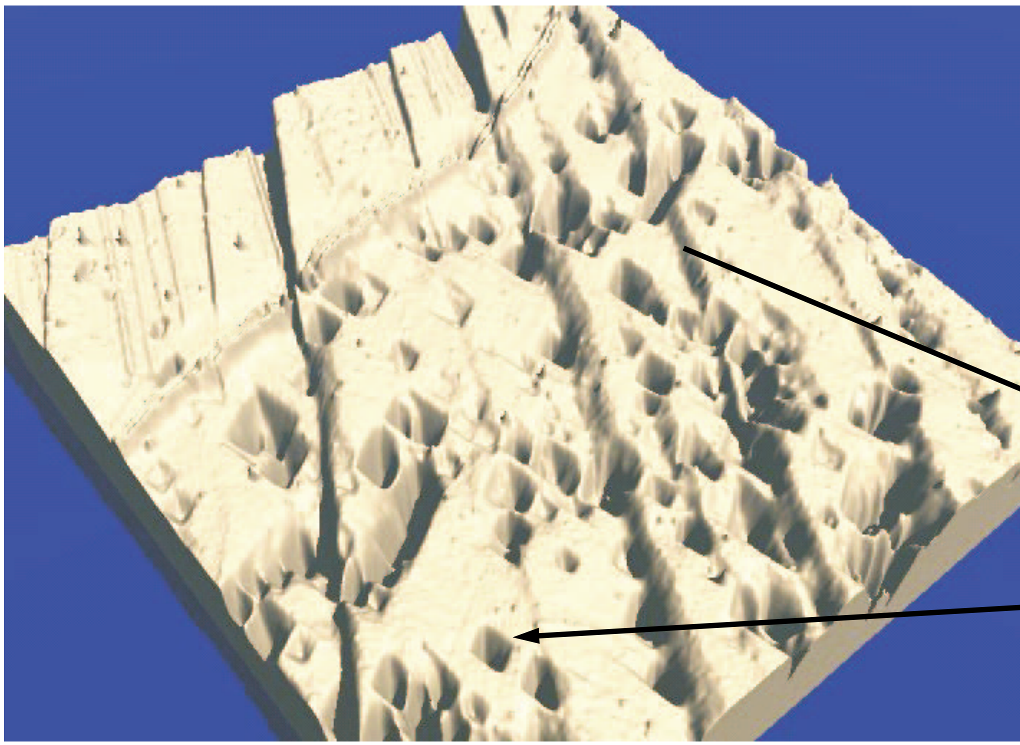
RTM Issues (geochemistry): Reactive surface area much greater for real carbonate grains than their geometric surface areas

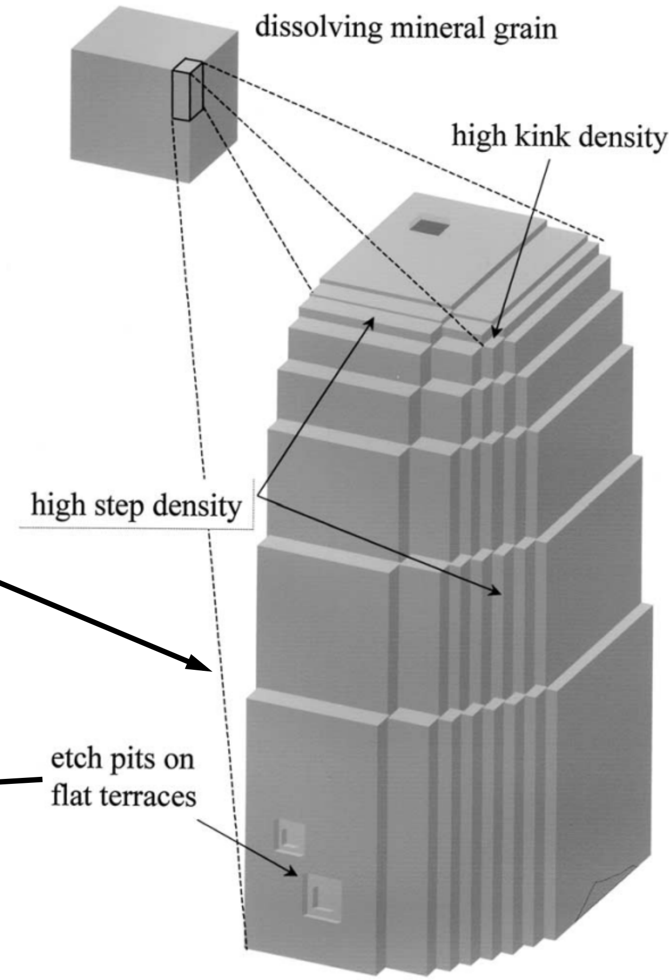


Walter and Morse (1984)

RTM Issues: Reactive surface area changes during dissolution and reaction rates vary between sites

c 1 mm





Calcite surface after dissolution

Arvidson et al (2003)

Luttge et al 2005

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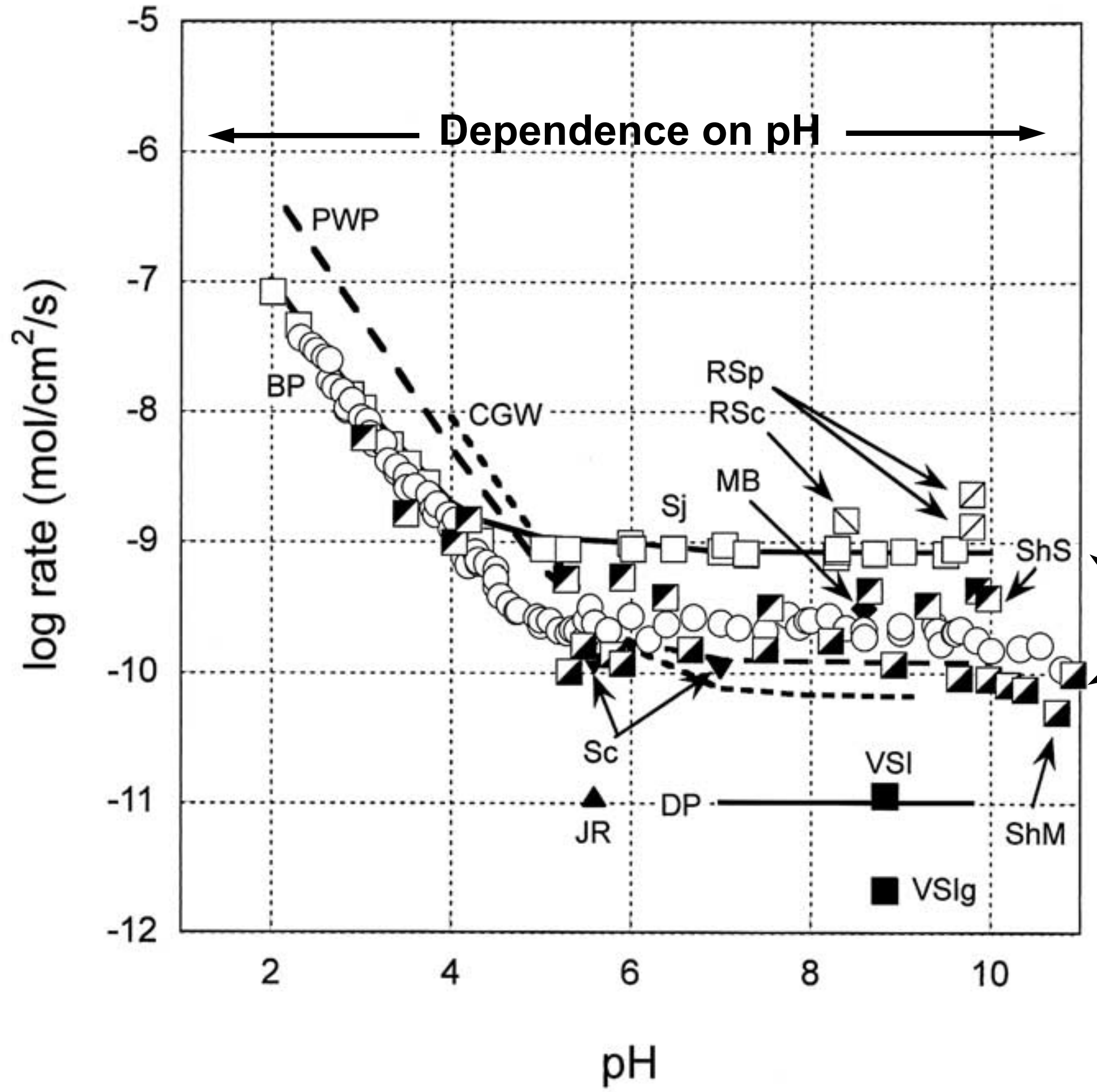
RTM Issues: Reaction constants from laboratory experiments depend on surface area, and may not be representative of natural conditions

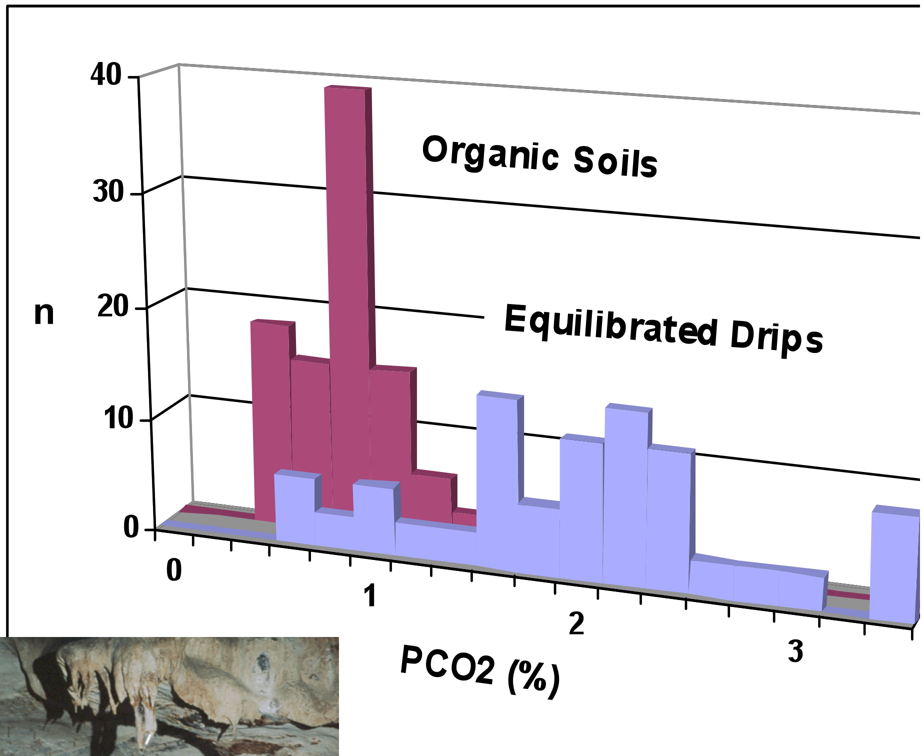


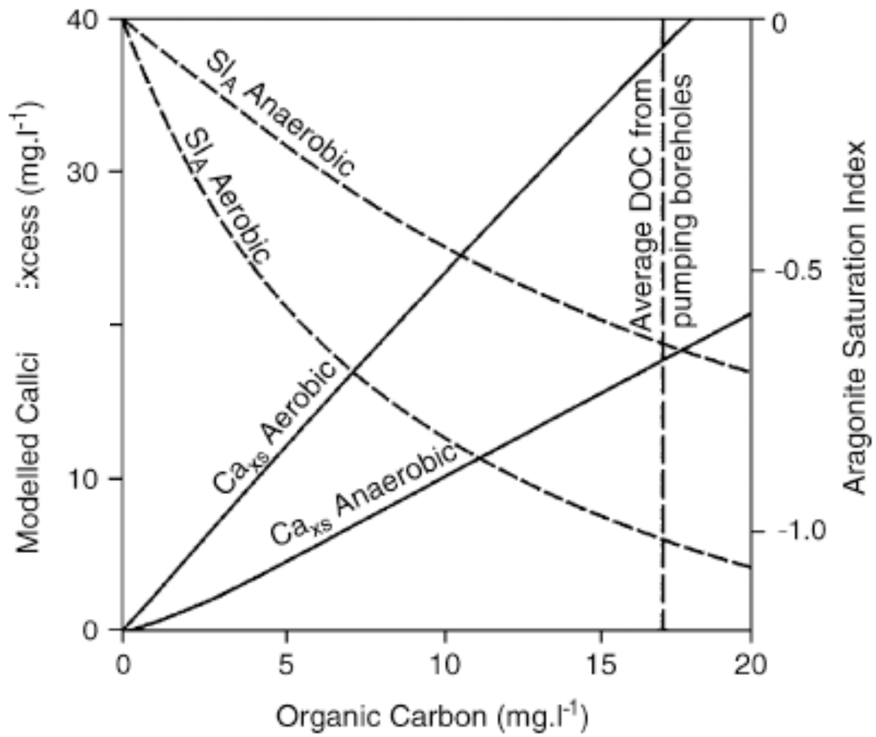
$$Rate\ constant = \left(\frac{Bulk\ reaction\ rate}{Surface\ area}\right)$$

Systematic differences between studies

Rate constants for calcite dissolution: Arvidson et al (2003)

RTM Issues: Geochemical reactions are not wholly inorganic but may be driven by organic matter oxidation



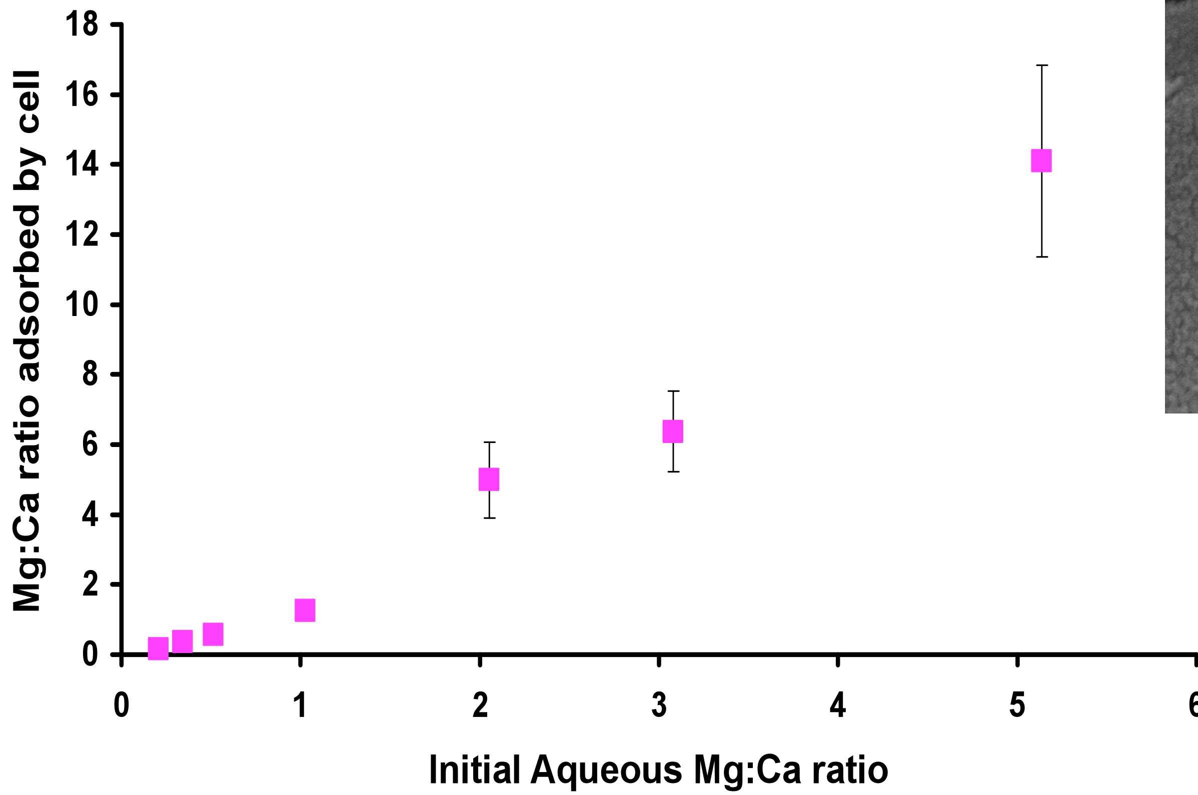


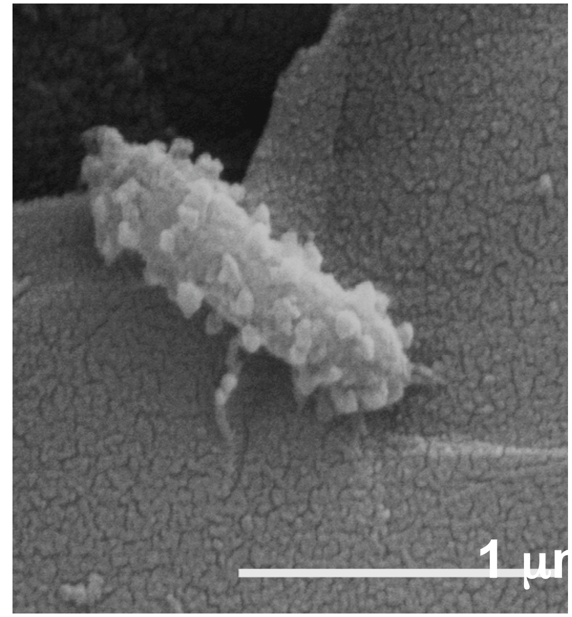
Cave drip waters, Turks and Caicos Is:

Equilibrated with much higher PCO2 than that of organic soils due to oxidation of organic matter

RTM Issues: Microbial mediation of reactions is important

Ordered dolomite precipitated on microbe, at 25 C in low Mg/Ca solution experiment (Roberts et el, 2004)





Sorption on *Methanobacterium formicicum*)
Kenward et al

Slide from Bob Goldstein

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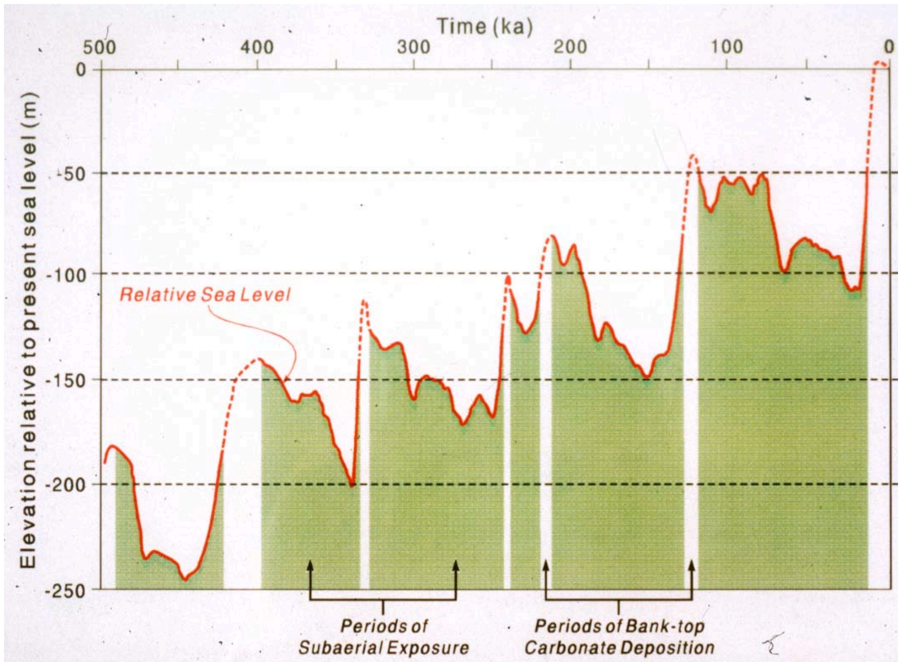
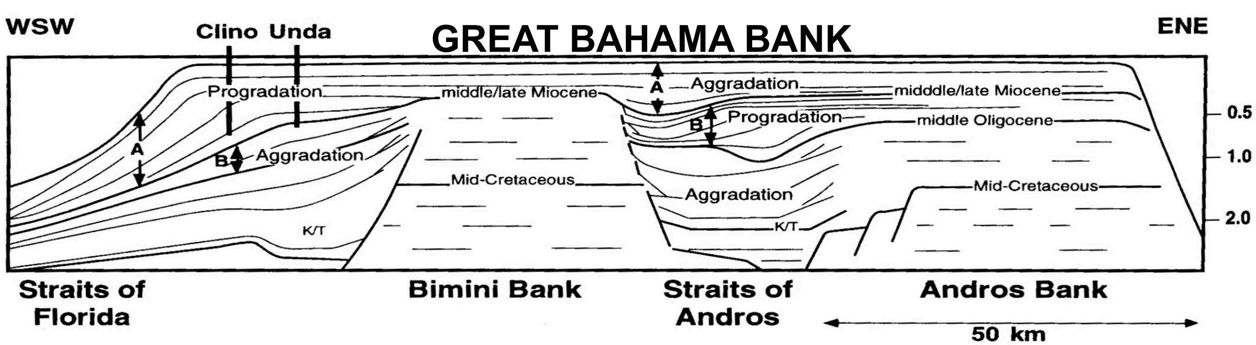
RTM Issues:
Need to consider changing boundary conditions



Whitaker et al (1997)

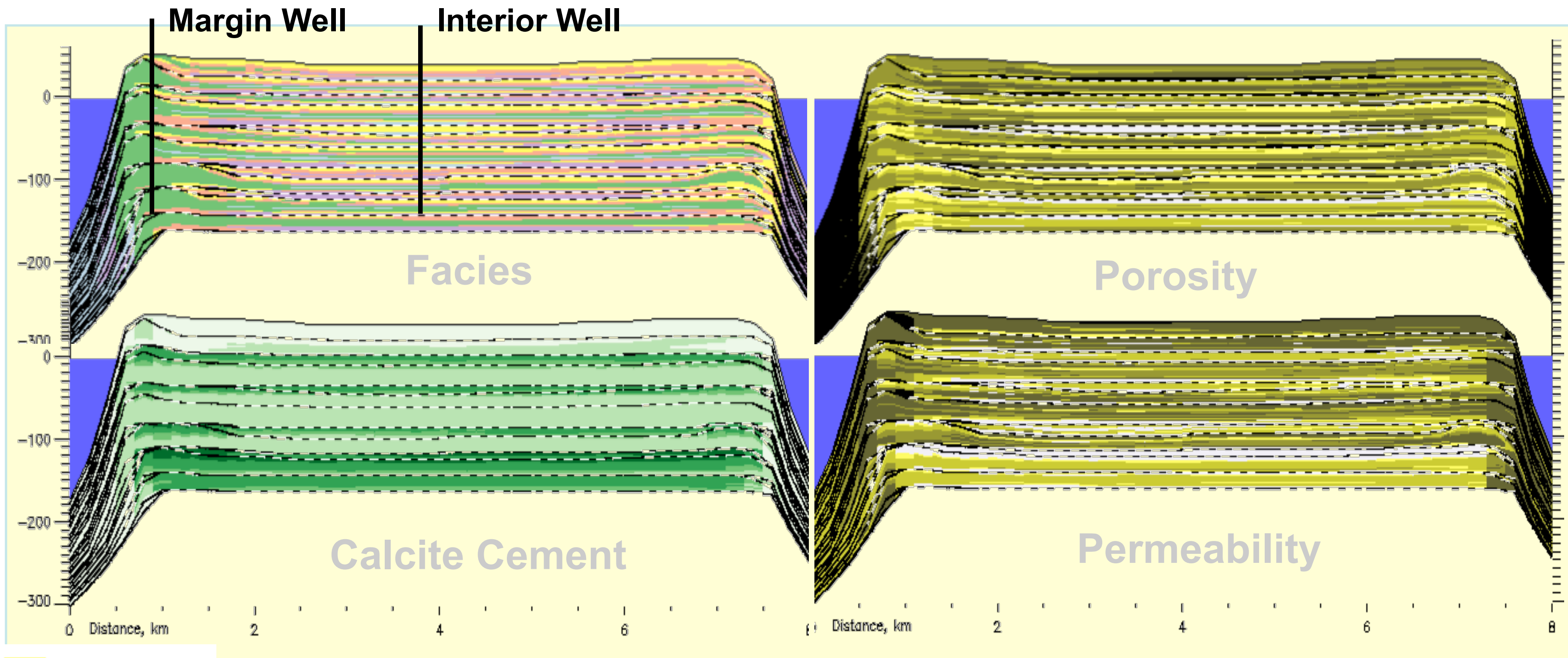
Sea level

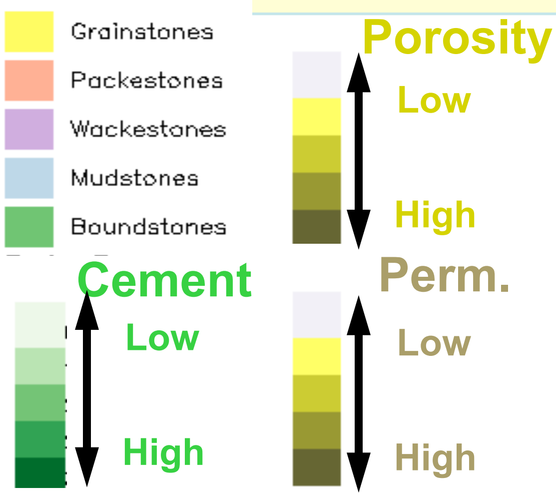
Platform geometry



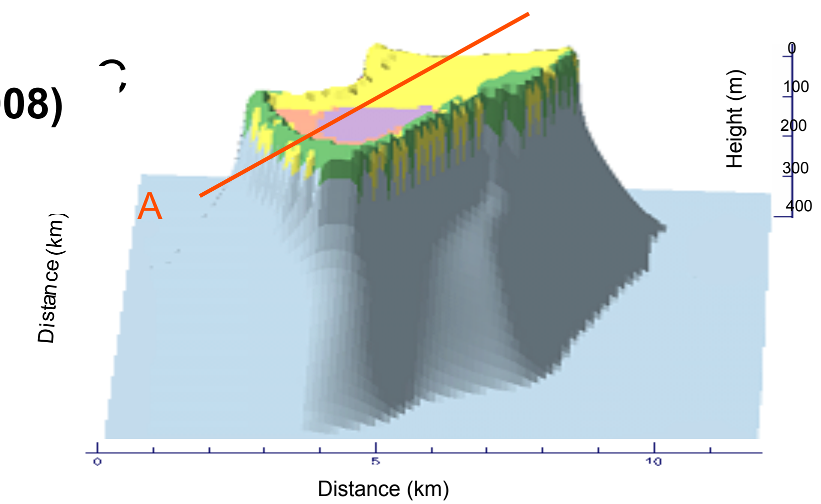
Eberli et al (2003)

In the meantime we have CARB3D+ !





Paterson et al (2008)



- **Model complexity and applicability issues:**
  - How many processes are explicitly represented?
  - How detailed or realistic are the representations?
  - What are the time and space scales at which the processes can be explicitly represented?
  - Model applicability
    - GUI & run time issues
    - Model purpose (simulator v hypothesis testing)

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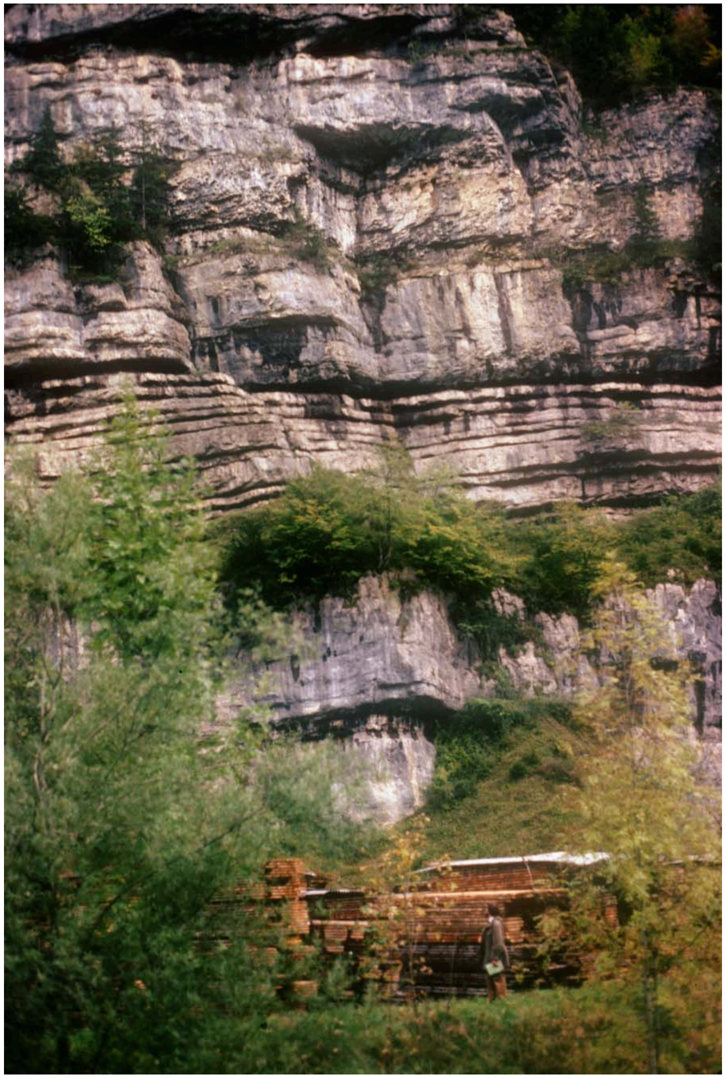
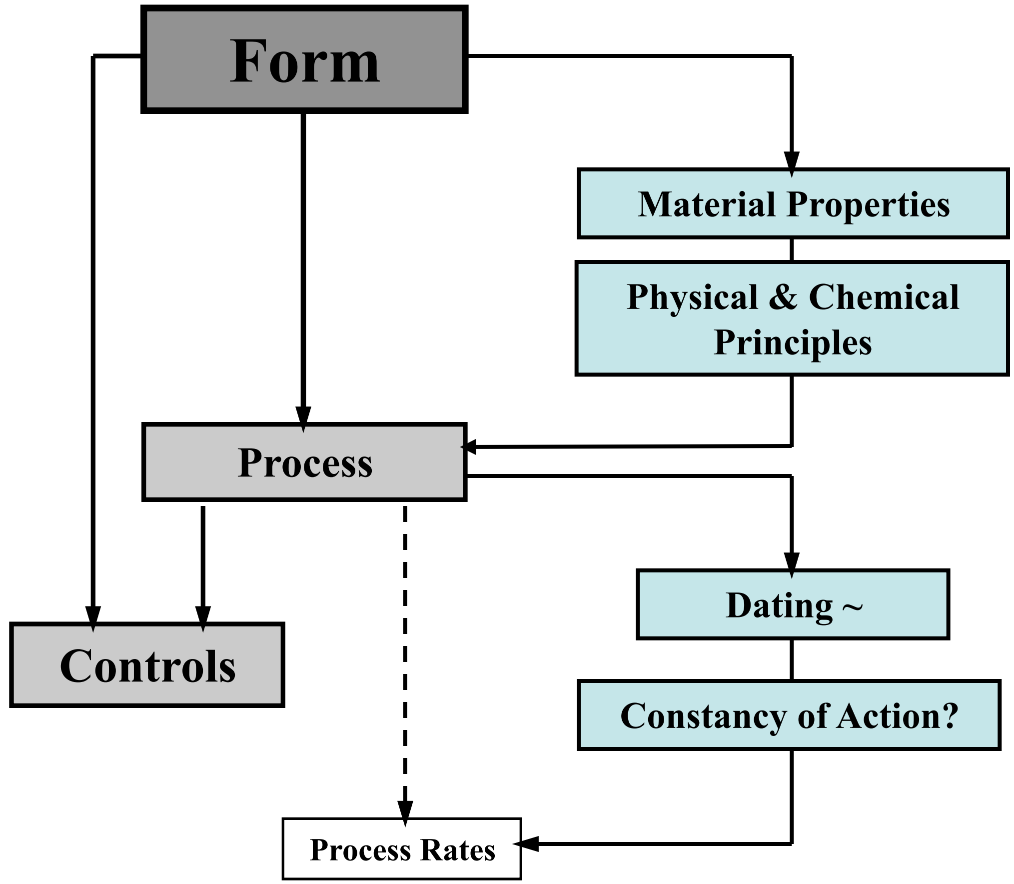
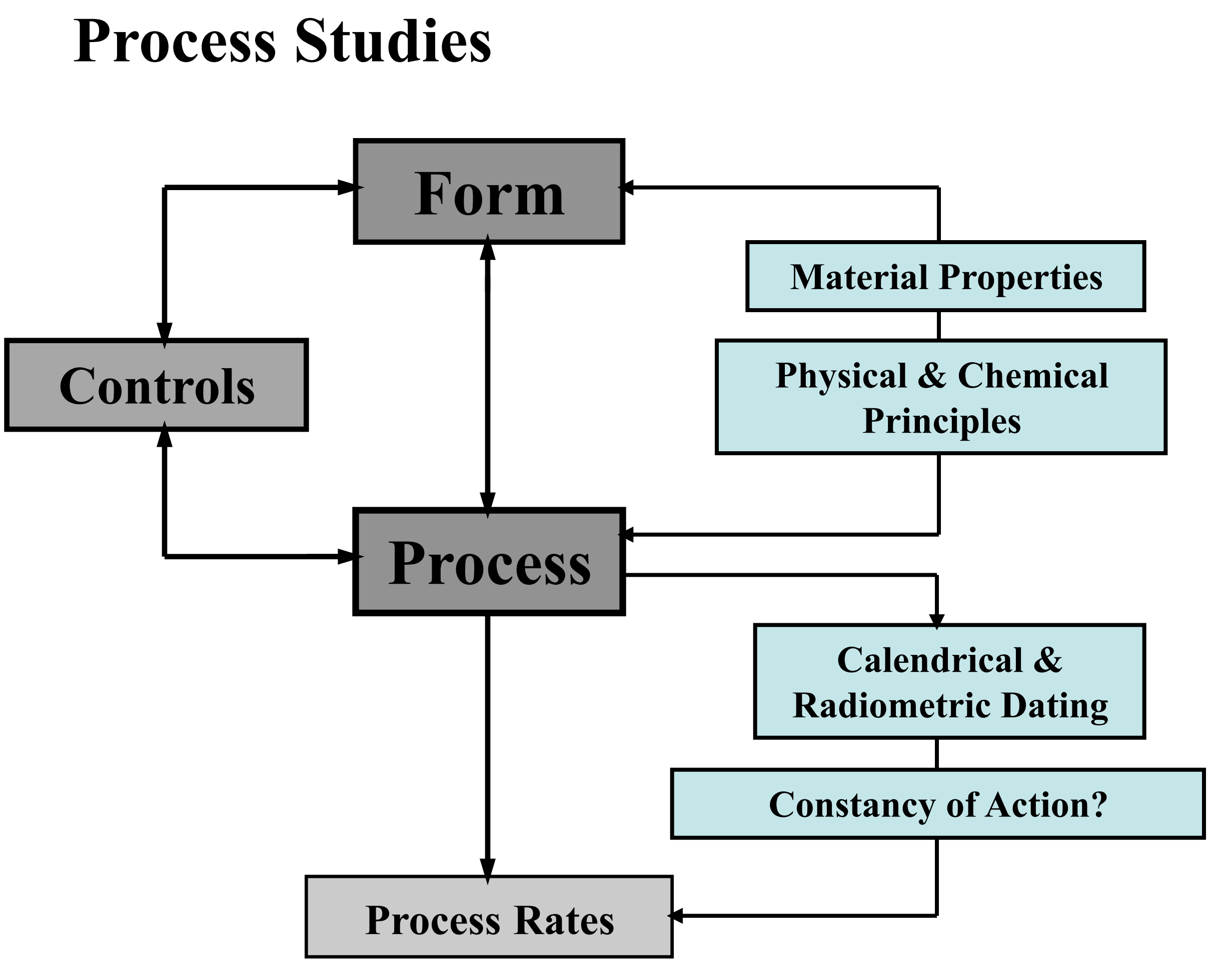
Model development & parameterisation: the rock record

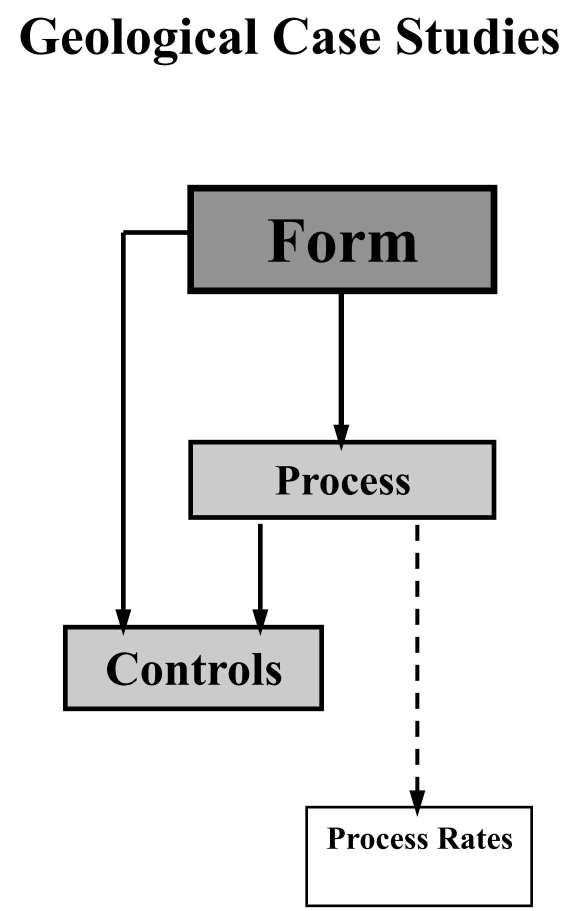




Key: Darker better known

Model development & parameterisation, a Polemic:
More process work, less geological case studies please!





Key: Darker better known

Some Conclusions on Modelling of Carbonate Diagenesis:

Reactive transport models are great, but

- **Slow and complex (precludes use in coupled sedimentological modelling)**
- **For the future need to:**
  - Incorporate heterogeneity in rock properties
  - Model fracture/matrix interaction
  - Improve understanding of reactive surface area and kinetic rates
  - Include biogeochemical reactions
  - Deal with changing sea level and platform geometry

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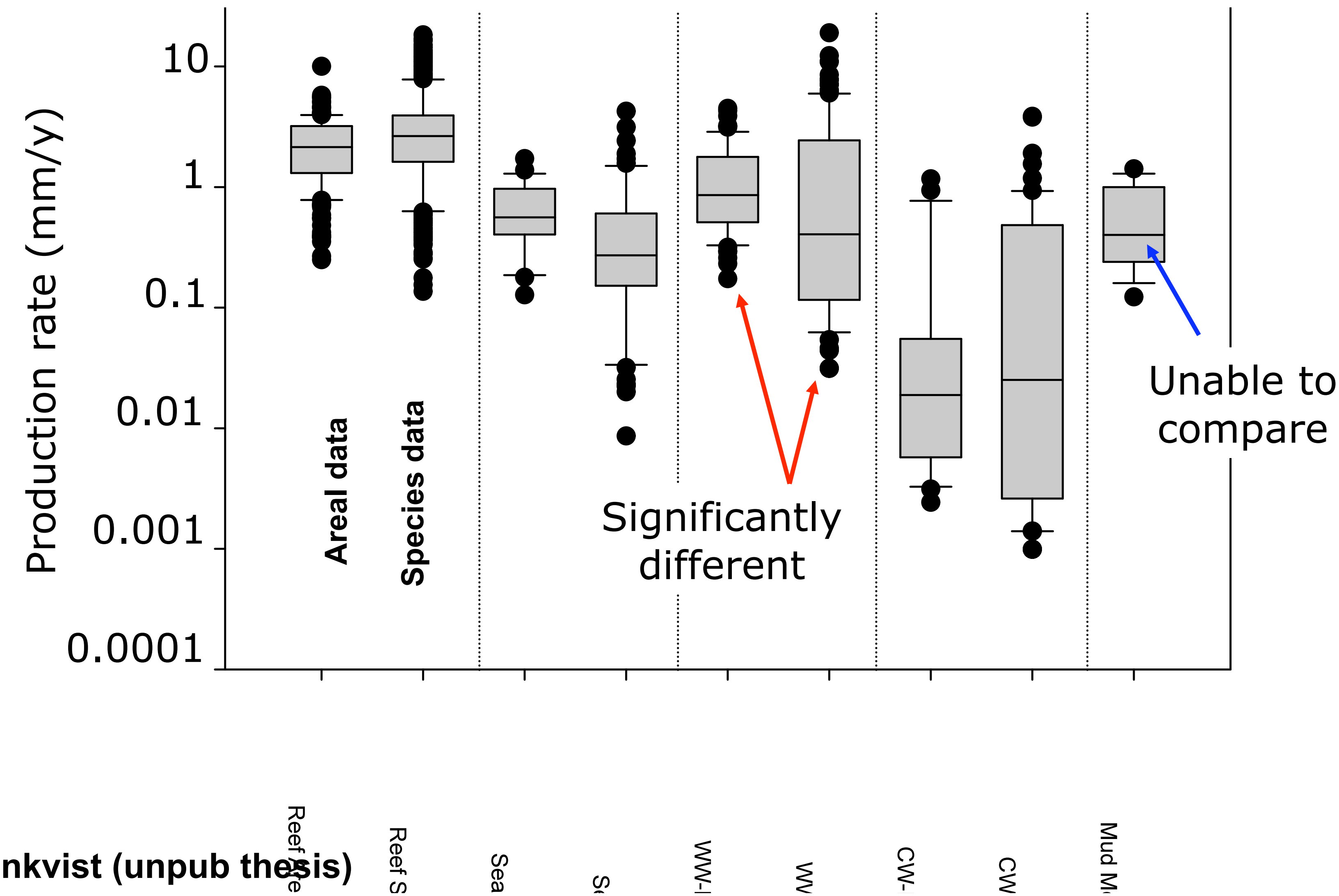
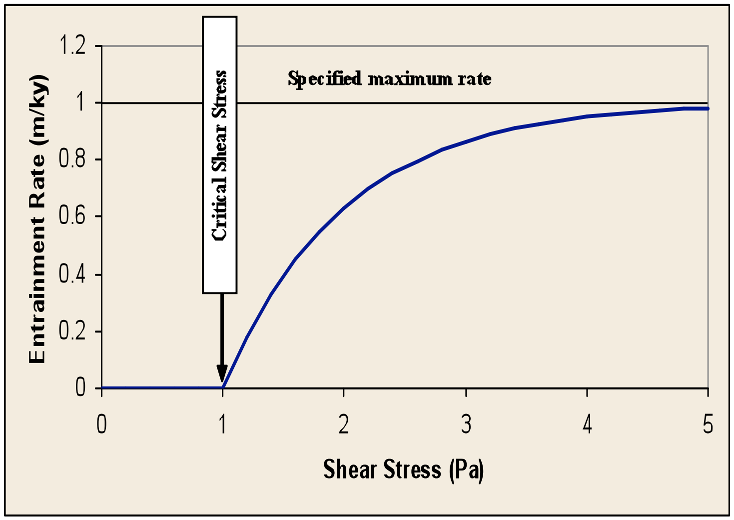
Not for warm water non-coralgal factory, but strong dependence on individual species makeup of factory (larger species ranges)



Lonnkvist (unpub thesis)

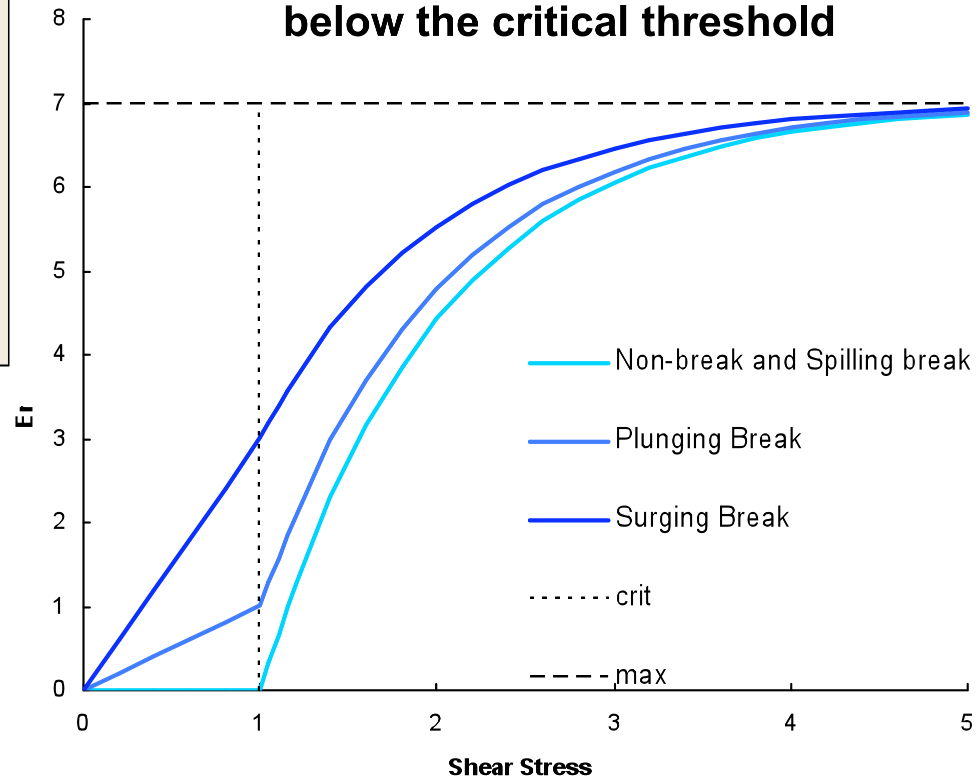
Enhanced Entrainment Model



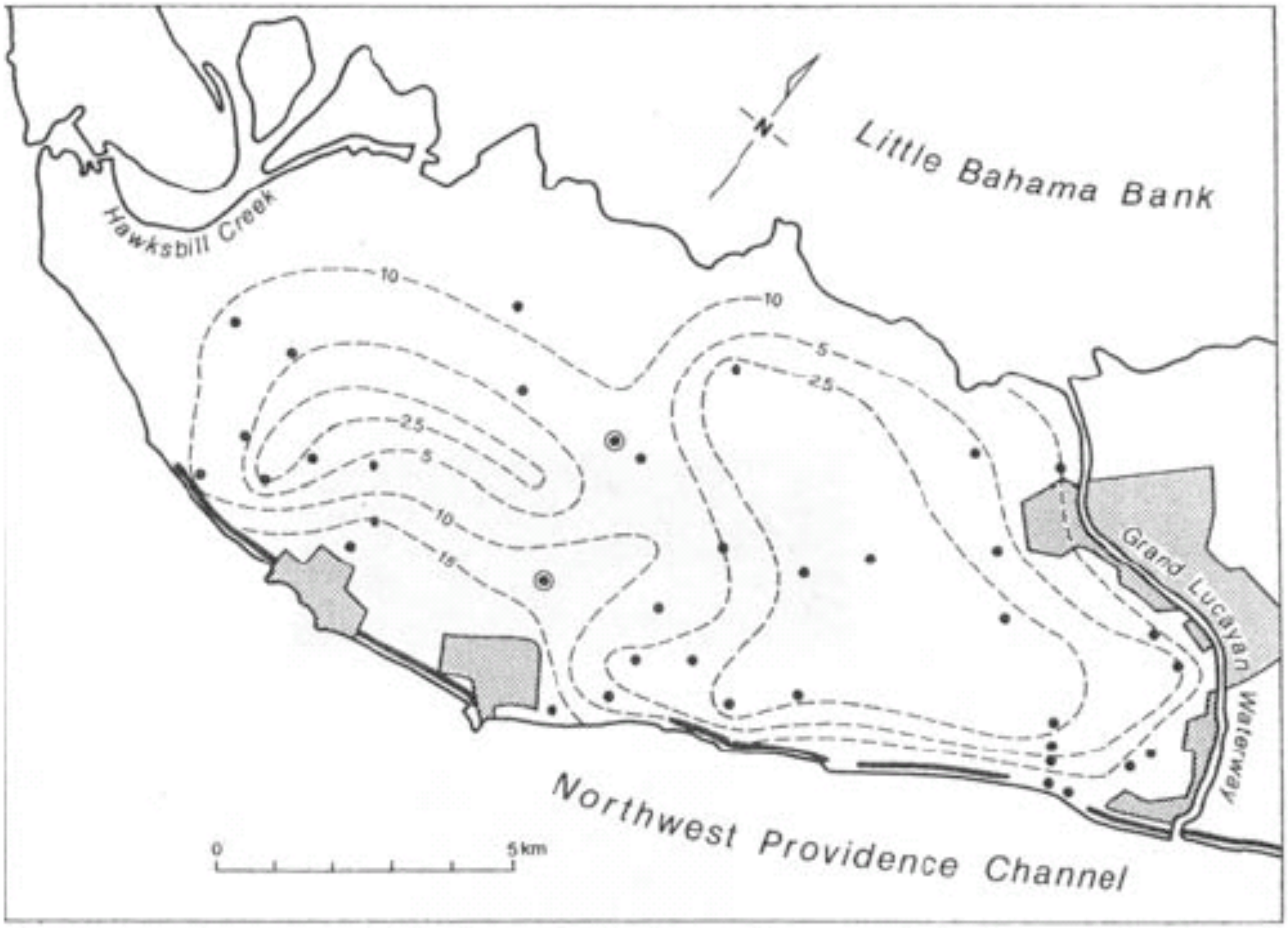
Existing Scheme

New Scheme

Entrainment enhanced both above and below the critical threshold



Limited field data for parameterisation



Mixing zone thickness, Grand Bahama

The New Mixing Zone Scheme after *Bear & Todd, 1960*

$$D_{MZ} = a\sqrt{2 D_\alpha \bar{u}\, t}$$

Where

D_{MZ} The mixing zone thickness (m)

a = A constant (normally taken as '5')

D_α = The constant of dispersion (normally taken as 0.01 cm)

u = The amplitude of the fluctuating velocity (m/day)

t = The time for the system to reach equilibrium (normally taken as 10,000 d)

$$\bar{u} = \frac{2\sqrt{2}}{\pi}\frac{kh_0}{\theta}\sqrt{\frac{\pi S}{t_0 T}}\exp\left(-x\sqrt{\frac{\pi S}{t_0 T}}\right)$$

Where

u = The amplitude of the fluctuating velocity (m/d)

k = The hydraulic conductivity of the aquifer (m/d)

h_0 = The tidal amplitude (m)

θ = The porosity of the aquifer (%)

S = The storativity of the aquifer (equals the porosity in unconfined aquifer)

t_0 = The tidal cycle (normally half a day, in d)

T = The transmissivity of the aquifer (m^2/d)

x = The distance from the coast (m)

Only Tidal Amplitude is not know (1 parameter)

There are feedbacks to evolving porpo/perm of sediments> dynamic response

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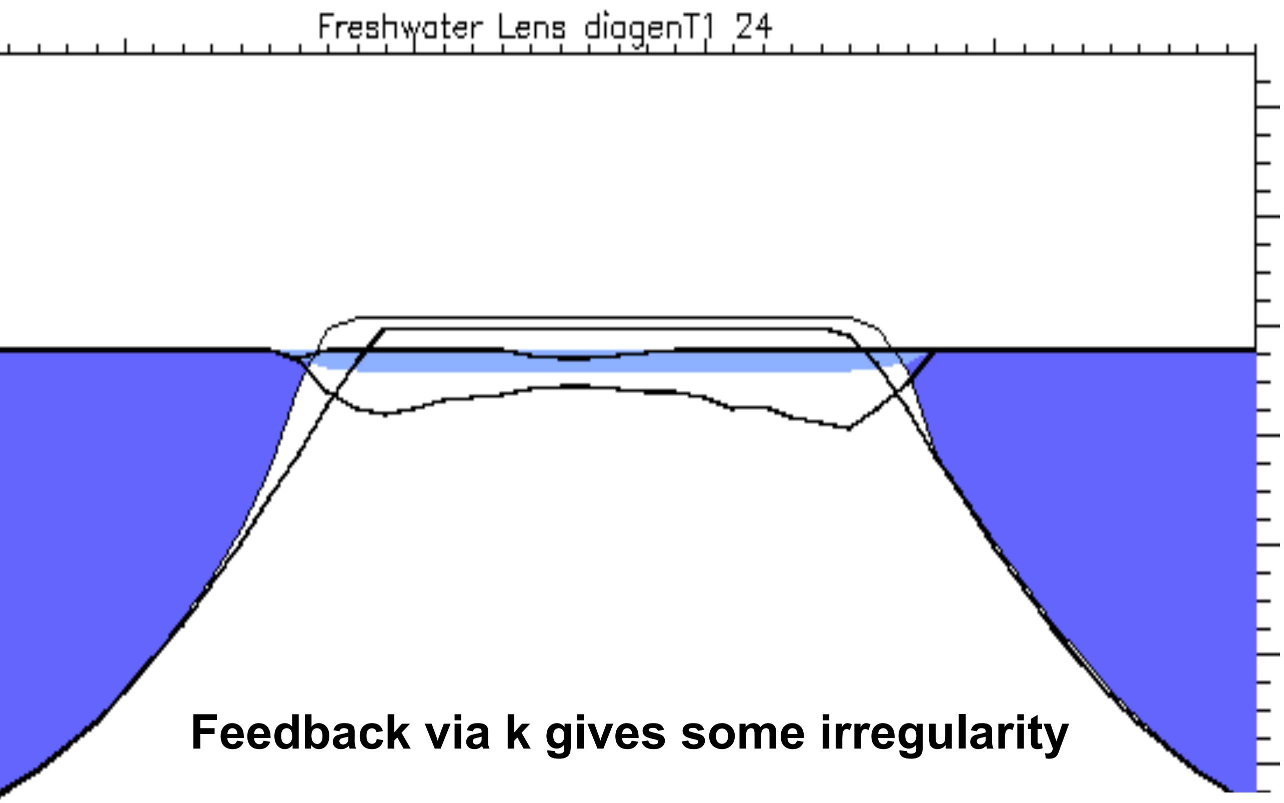
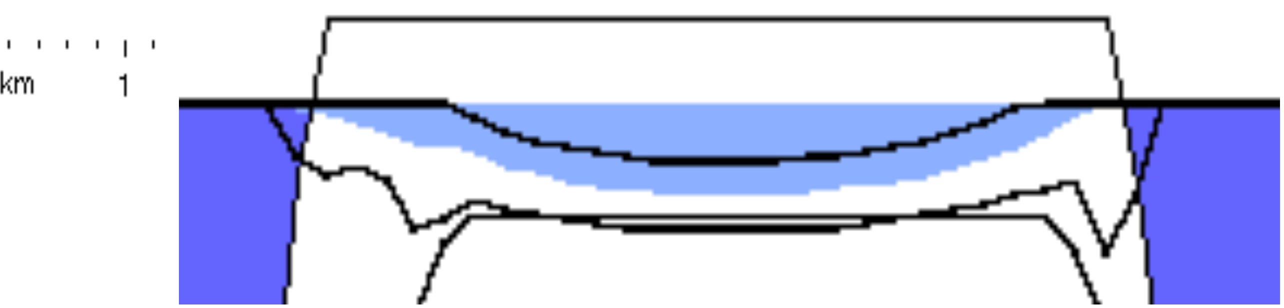
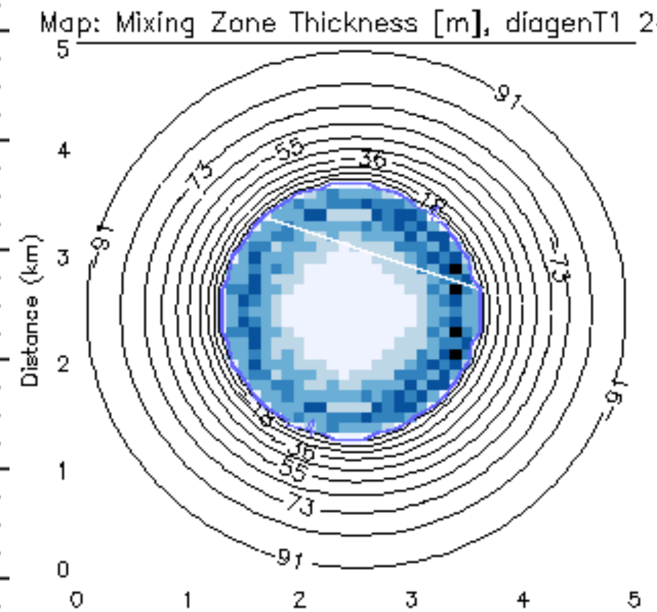
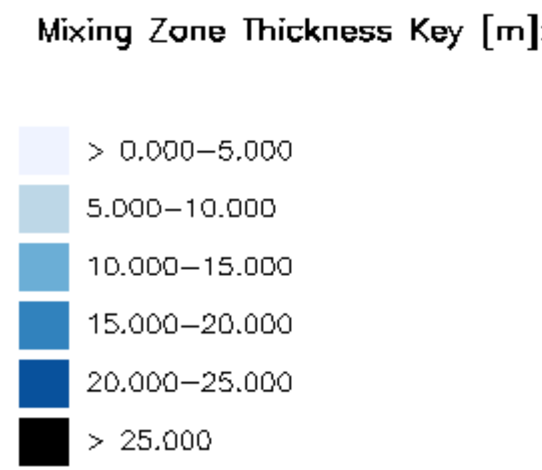


Feedback via k gives some irregularity

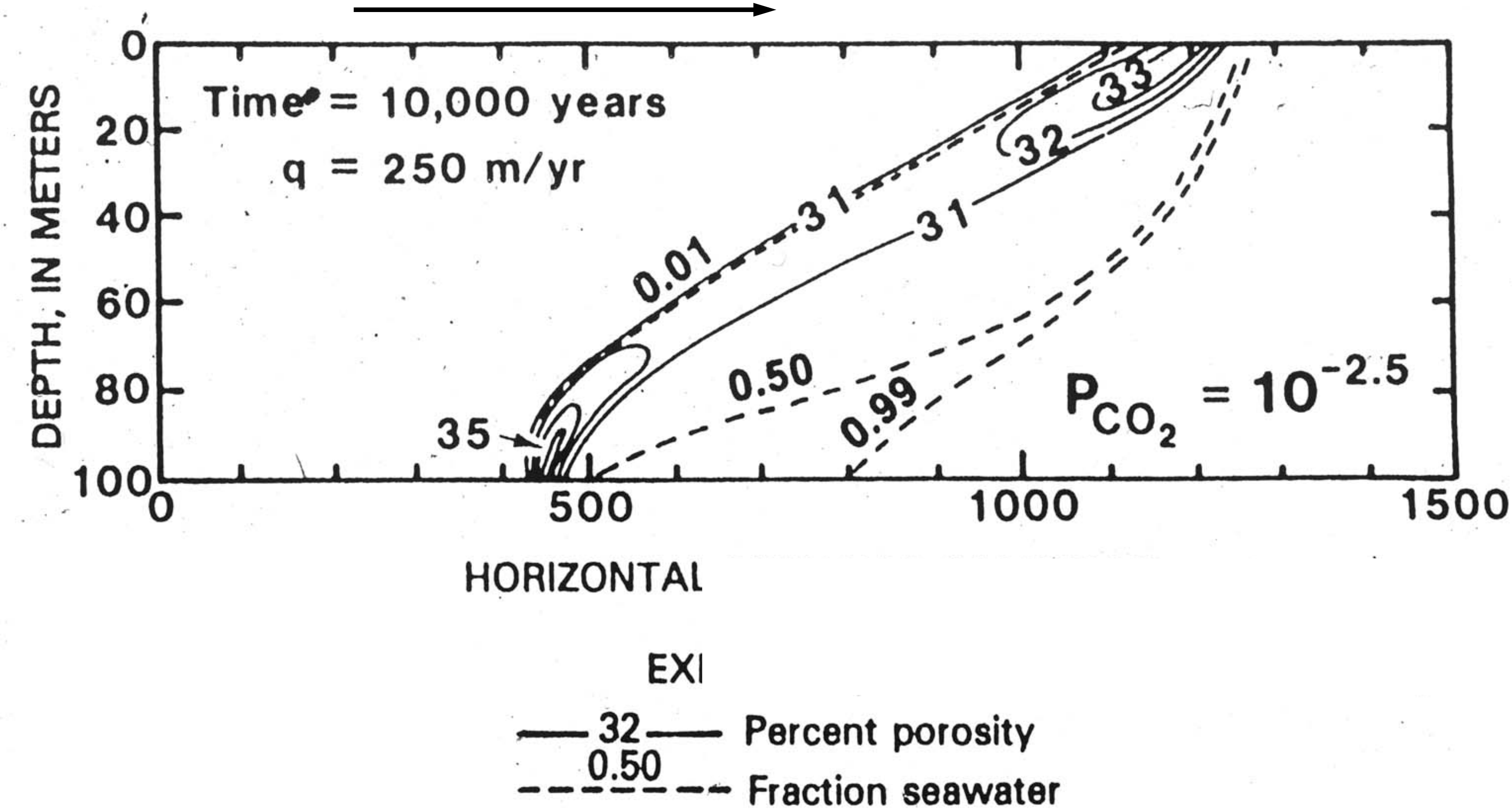






CARB3D+: externally coupled reactive transport model of mixing zone porosity generation

Freshwater Flow Direction **Sea**



Sanford and Konikow (1989)

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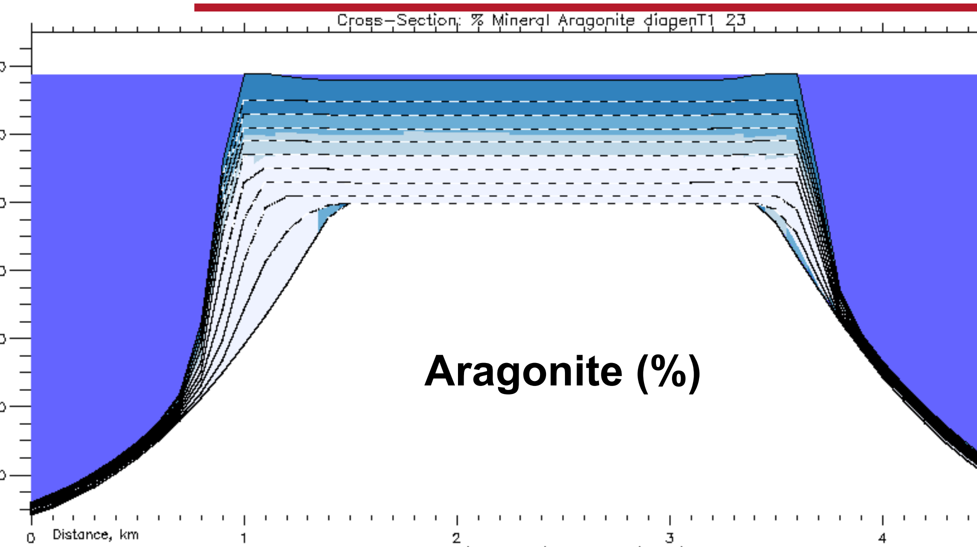
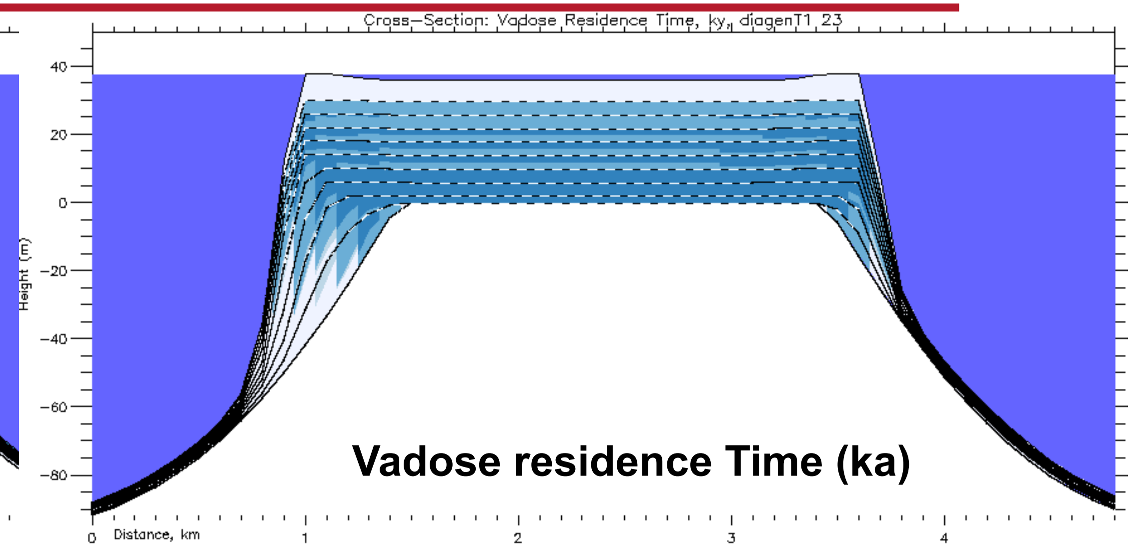
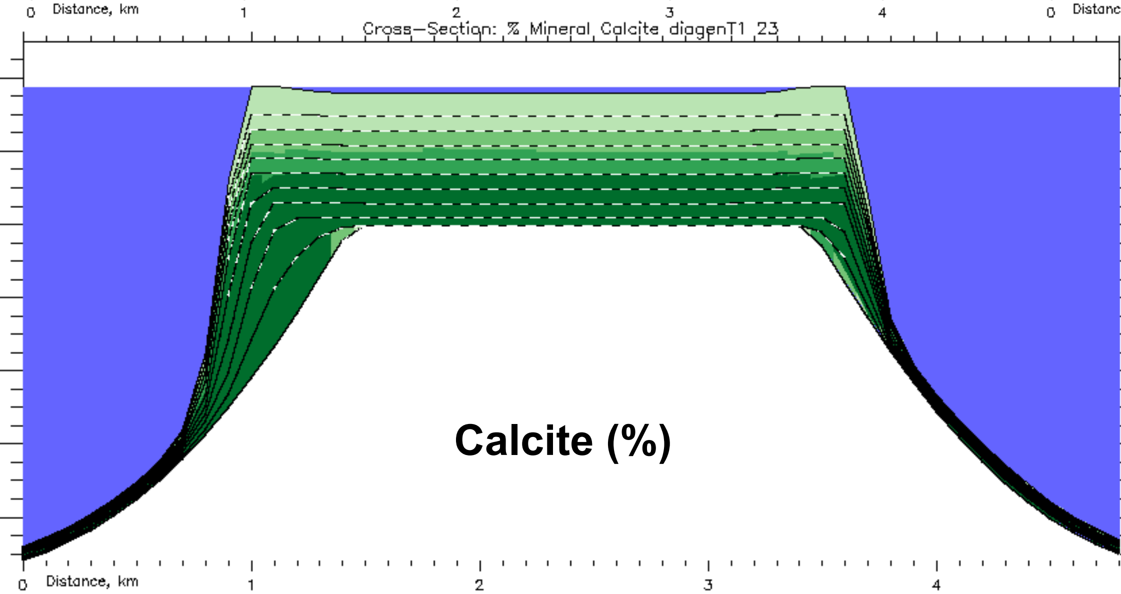
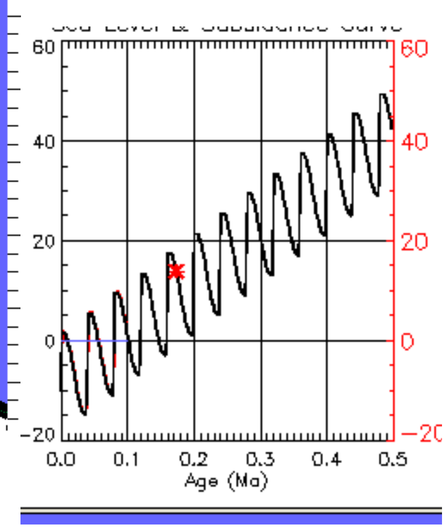
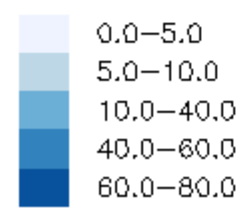
CARB3D$^+$ Diagenetic Processes: Aragonite Stabilisation> FW



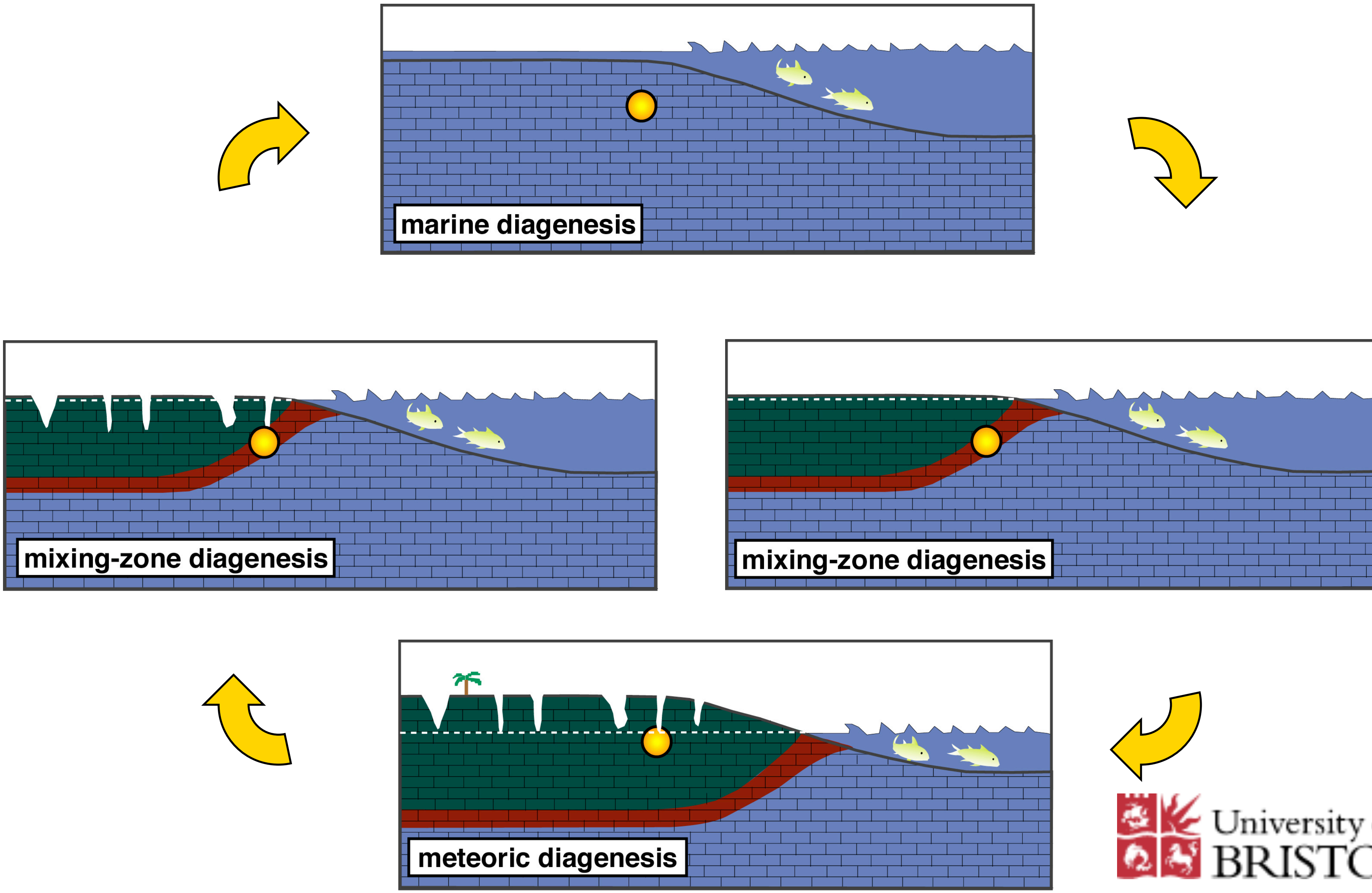








A complete diagenetic salinity cycle Gldstein slide



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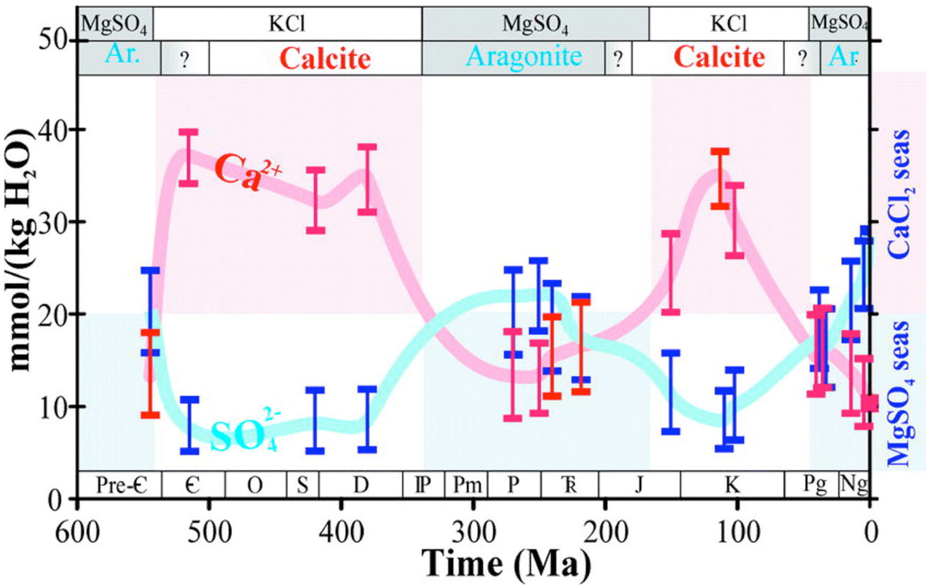
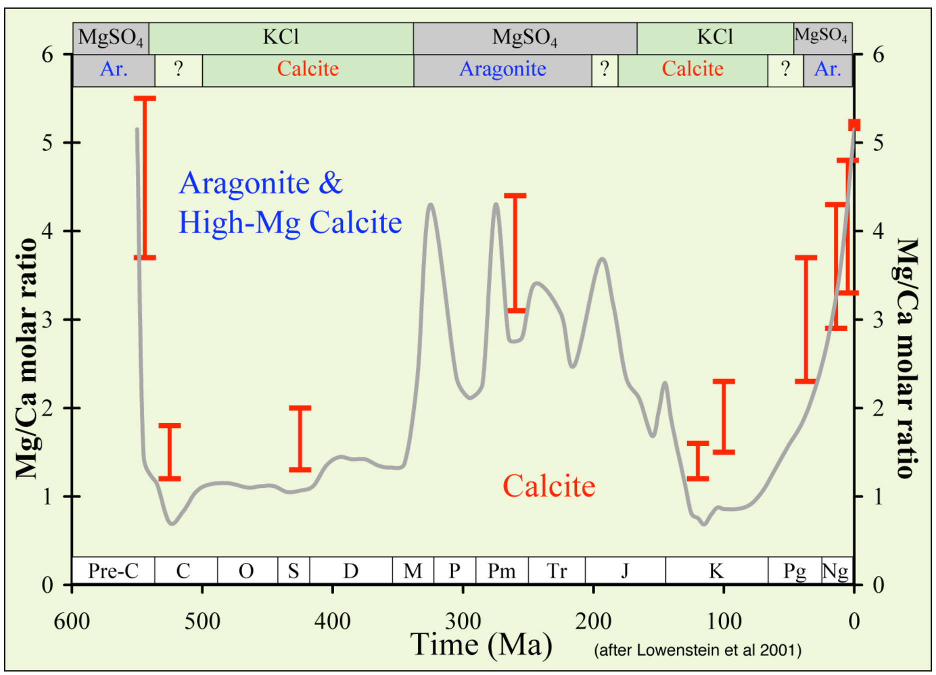
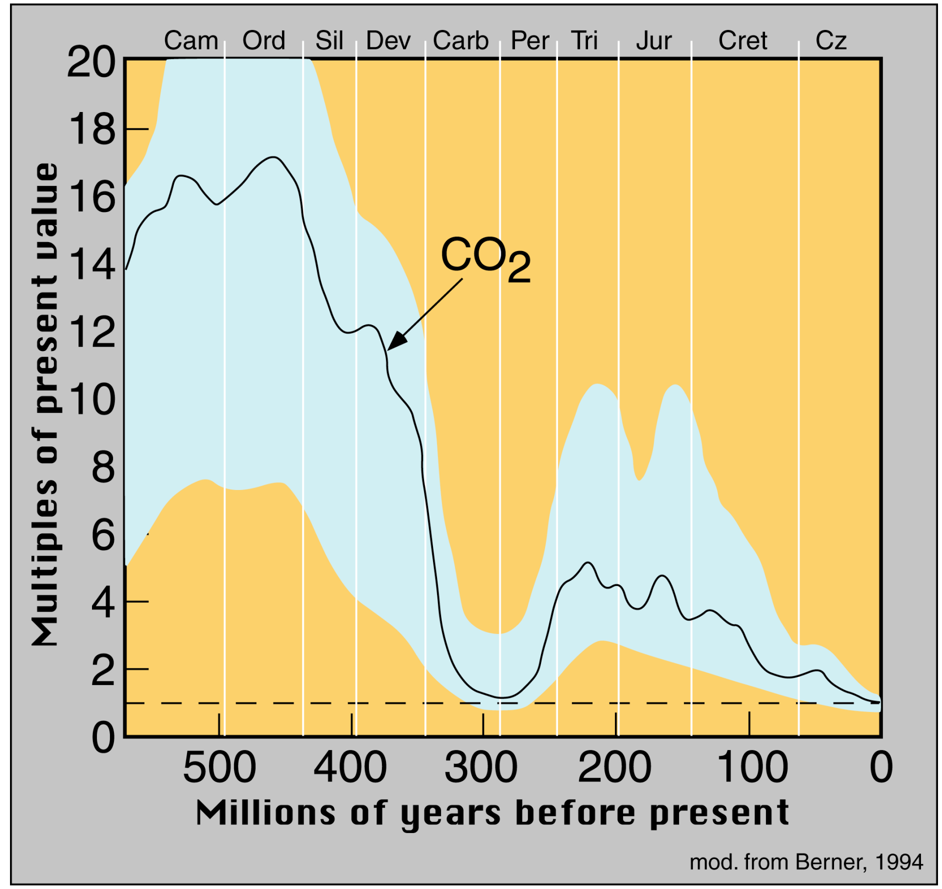
Secular variation in seawater chemistry







Goldstein slide

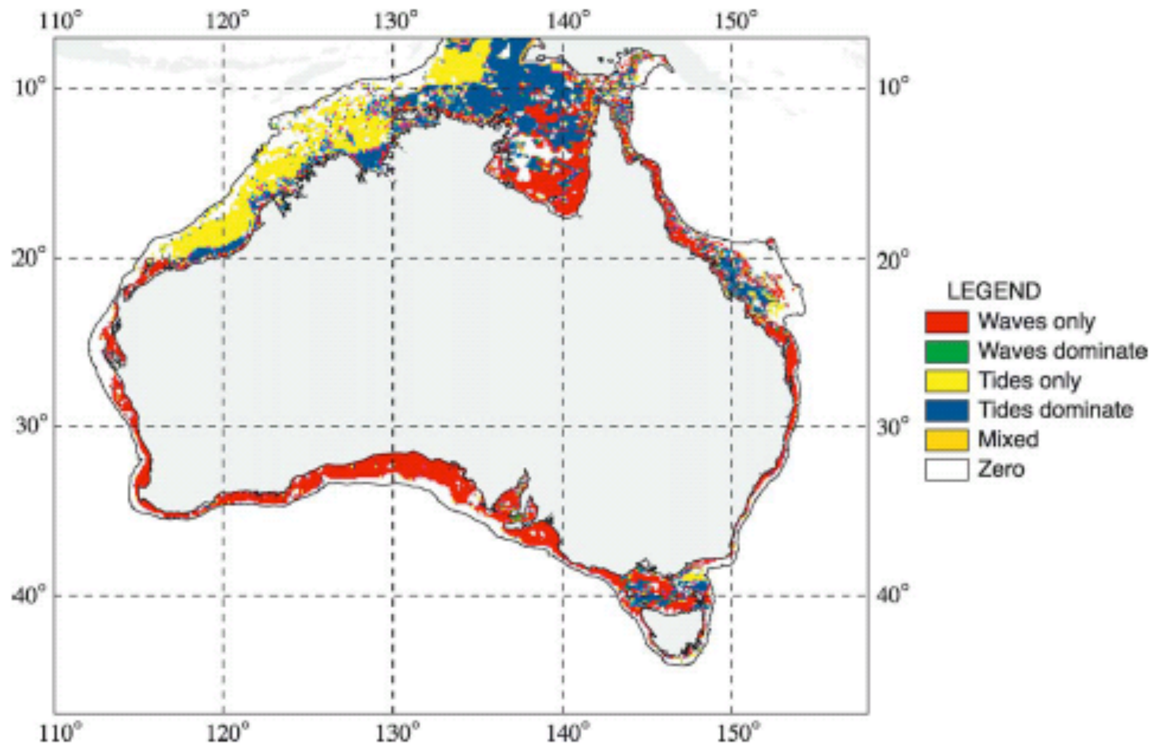


Fig. 9. Regionalisation of the Australian continental shelf for observed grain size distribution based on ratio of wave and tidal exceedance estimates.

Porter-Smith et al (2004)

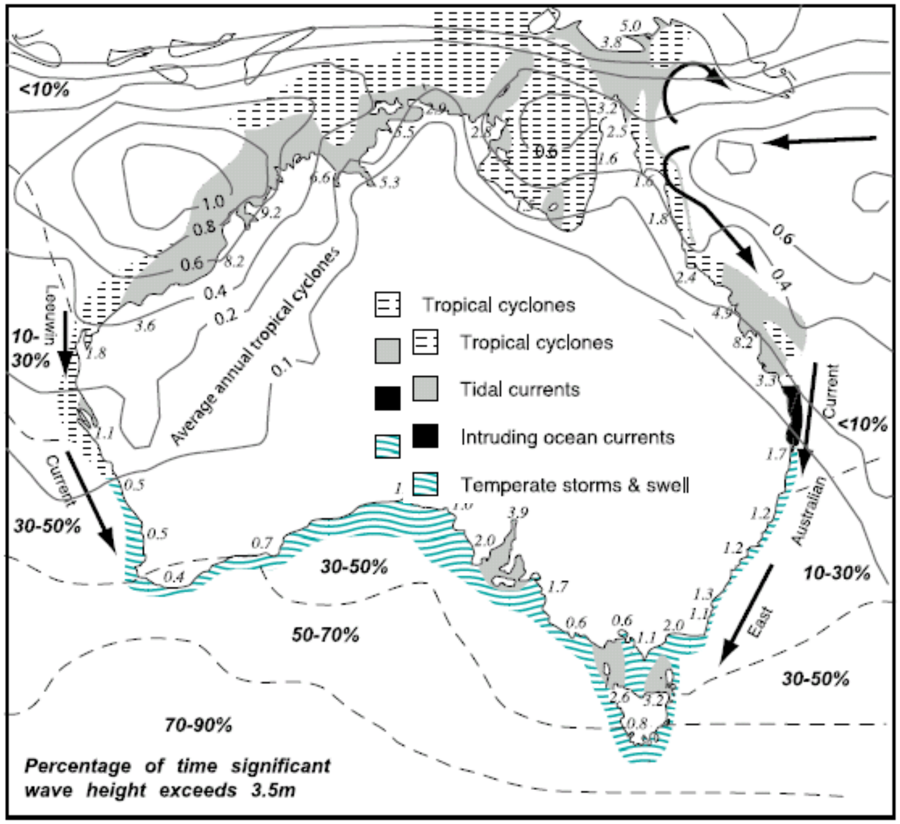
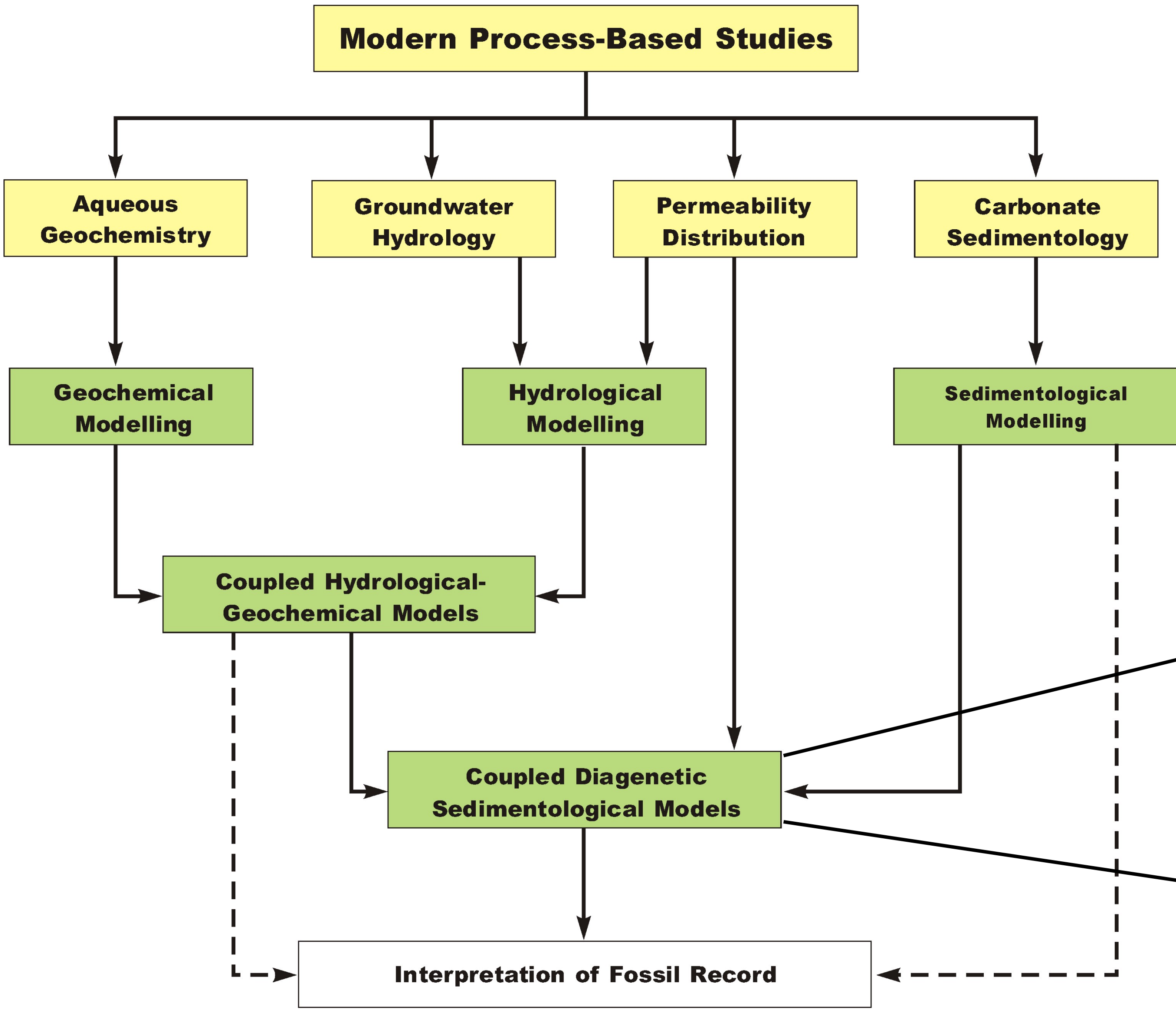
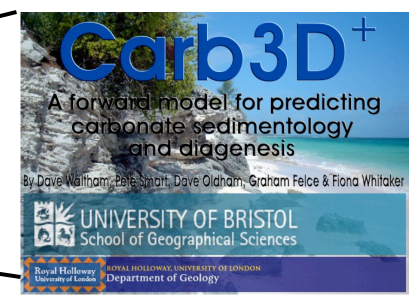


Fig. 1. Division of the Australian shelf (after Harris, 1995) into regions in which sediment transport is caused mainly by tidal currents (17.4% of the shelf area), currents derived from tropical cyclones (53.8%), ocean swell and storm generated currents (28.2%) and intruding ocean currents (0.6%). Contours representing tropical cyclone frequency are from the Bureau of Meteorology (http://www.bom.gov.au/climate/averages/climatology/tropical_cyclones/tropical_cycl.shtml) and contours for significant wave height percentage exceedence are from McMillan (1982). Mean spring tidal ranges indicated along the coastline are derived from the Australian National Tide Tables. The location and direction of flow of major ocean currents are indicated.

What do we do at Bristol?





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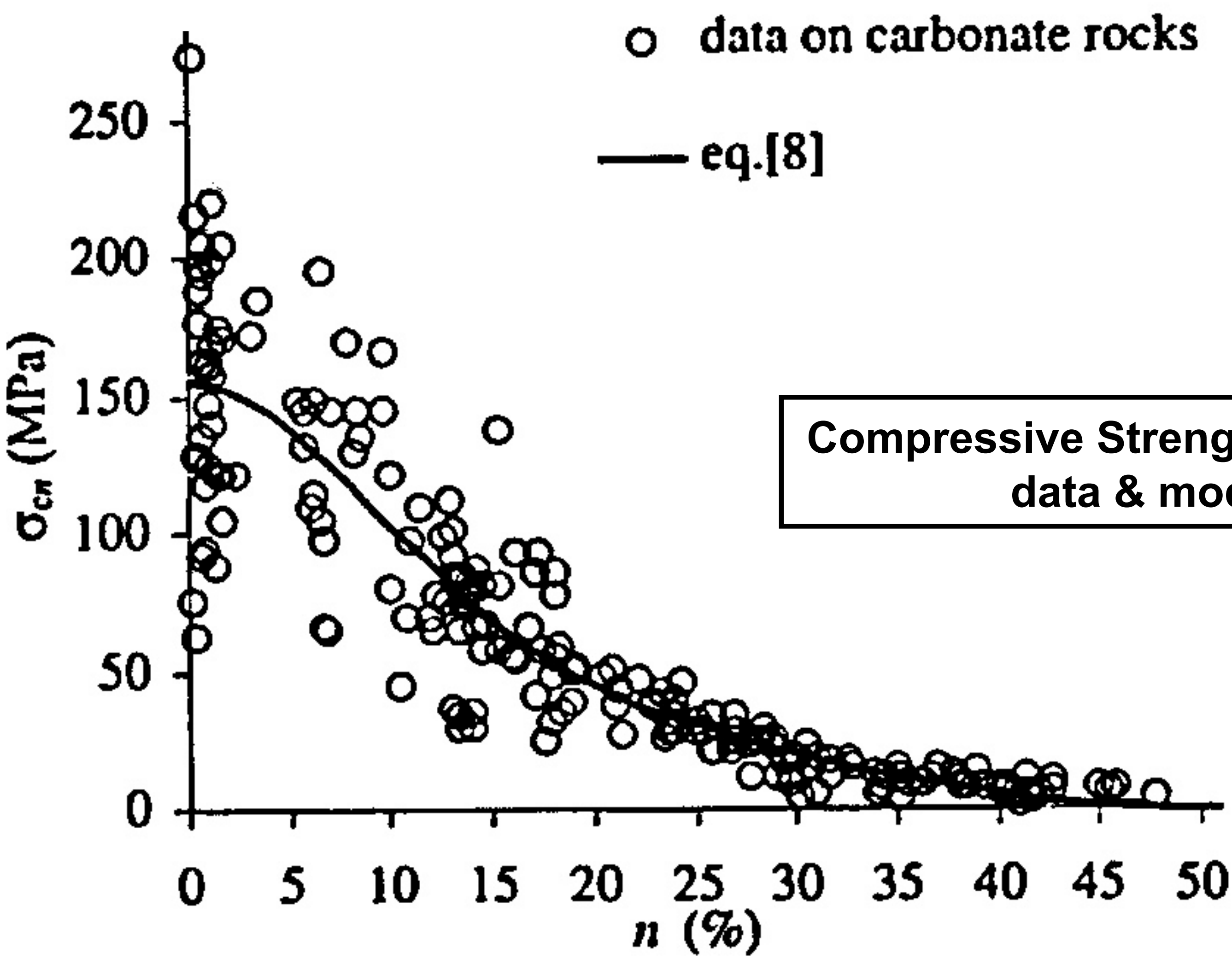
CARB3D$^+$: Cementation and compaction



Compressive Strength / Porosity data & model

Li & Aubertin (2003)

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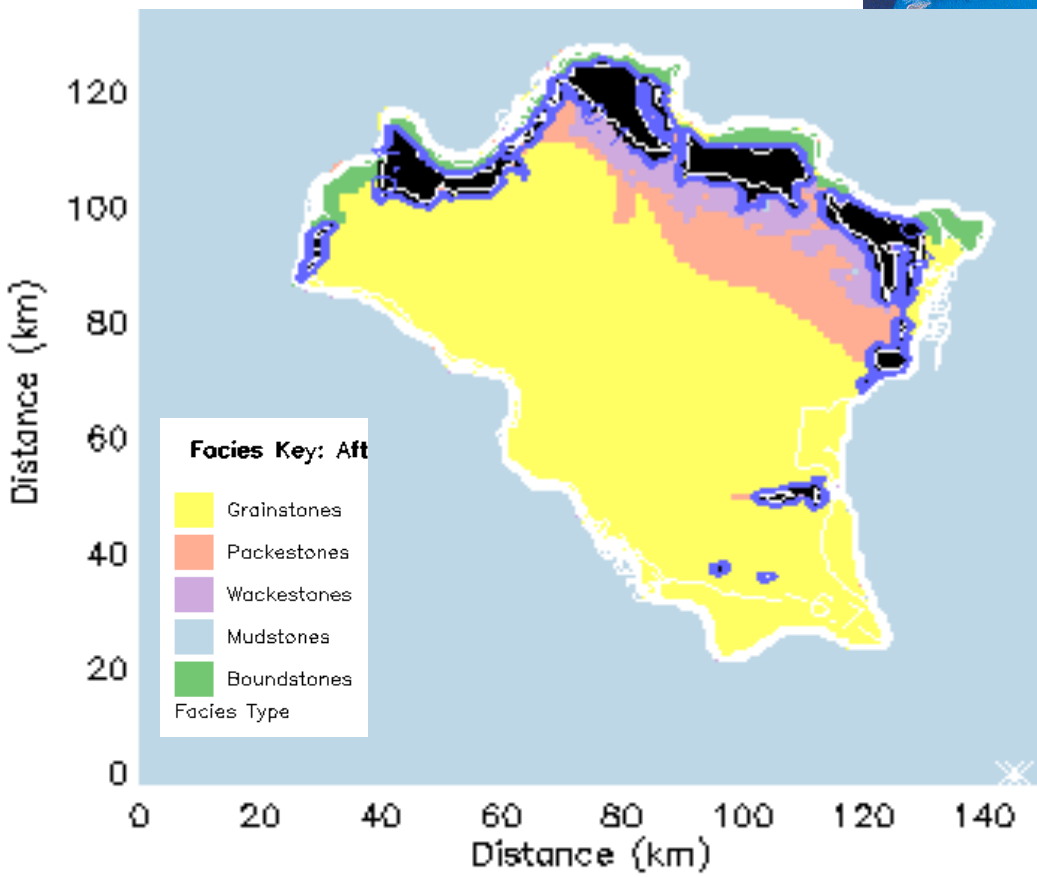
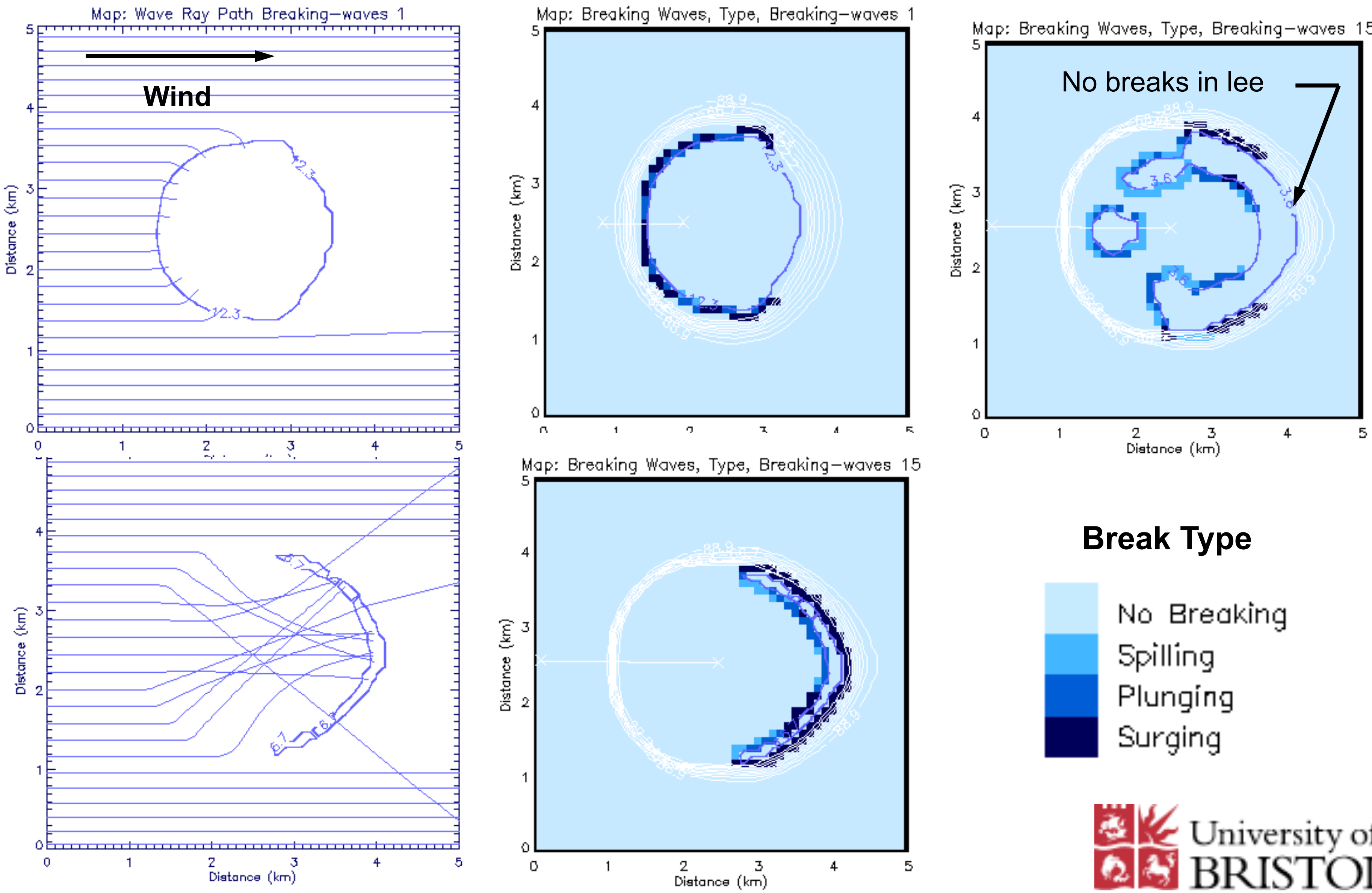
CARB3D^{+} Sedimentology: Comparison with Modern Turks & Caicos Platform



Type of break depends on sea floor gradient + wave energy: CARB3D+



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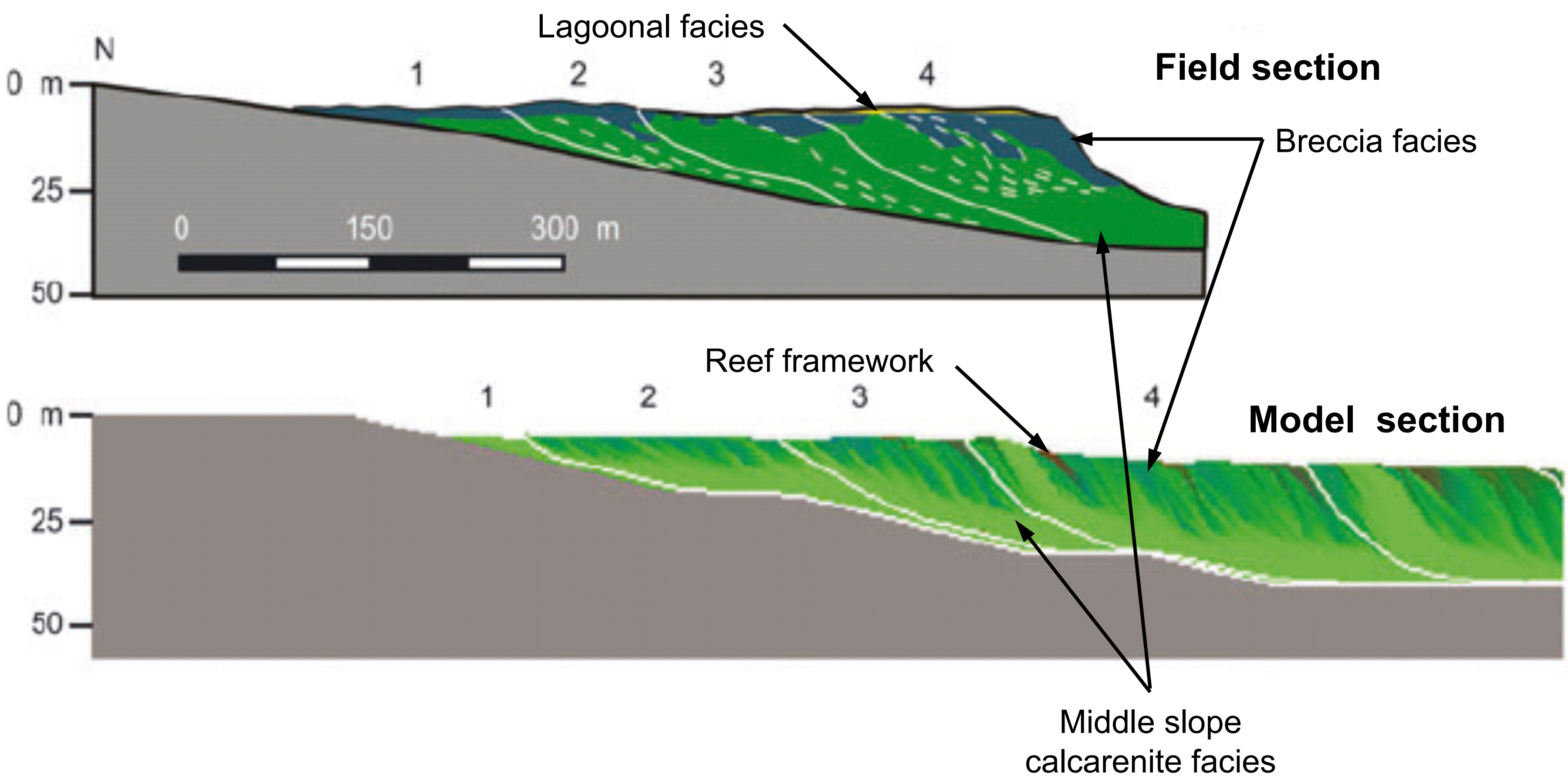
Additional sediment types: Reef derived slope breccias in REPRO



Messinian Cariatiz platform, Spain

Castell et al, 2007

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Angle of repose slopes: empirical calibration CARB3D+