WHAT DO WE KNOW ABOUT DIAGENESIS

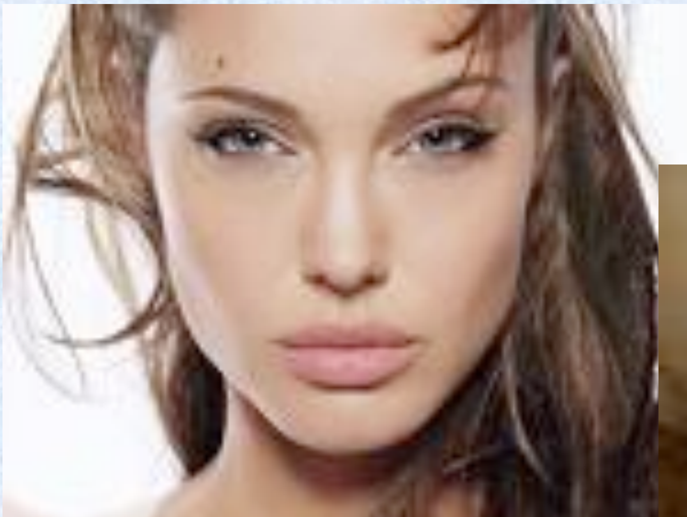
1. ***Generalities relevant to a systems approach***

2. *Diagenetic processes that affect sediment dynamics*

3. *Key post-depositional alterations through time and stratigraphic space*

David A. Budd
University of Colorado

The True Facesof Diagenesis



DIAGENESIS

- Physical and chemical alteration of sediment and rock in response to changes in its physiochemical regime.
    - Δ fluid flow
    - Δ fluid chemistry (new fluid, reactions within ambient fluid)
    - Δ effective stress
    - Δ temperature
- In carbonates, begins with deposition and extends throughout a rock's history

Carbonate Diagenesis Today

Broad Consensus On

- What diagenetic processes occur in various diagenetic settings
- The conditions that drive most of those processes
- The features that allow us to recognize those processes, conditions, and/or settings
- *Diagenesis is are complex & non-linear with many types of interactions and feedbacks*

Carbonate Diagenesis Today

Less Consensus / Knowledge On

- Microbial influences (catalysis, template)

Lateral spatial patterns in diagenetic products (at scale between one thin section and "regional" patterns)

Presence or absence of self-organization and/or scale invariance (hard to evaluate due to location, scales of analysis, & overprinting of diagenetic processes)

- Strength of the linkages (feedbacks) between processes

Thresholds at which changes might "cascade"

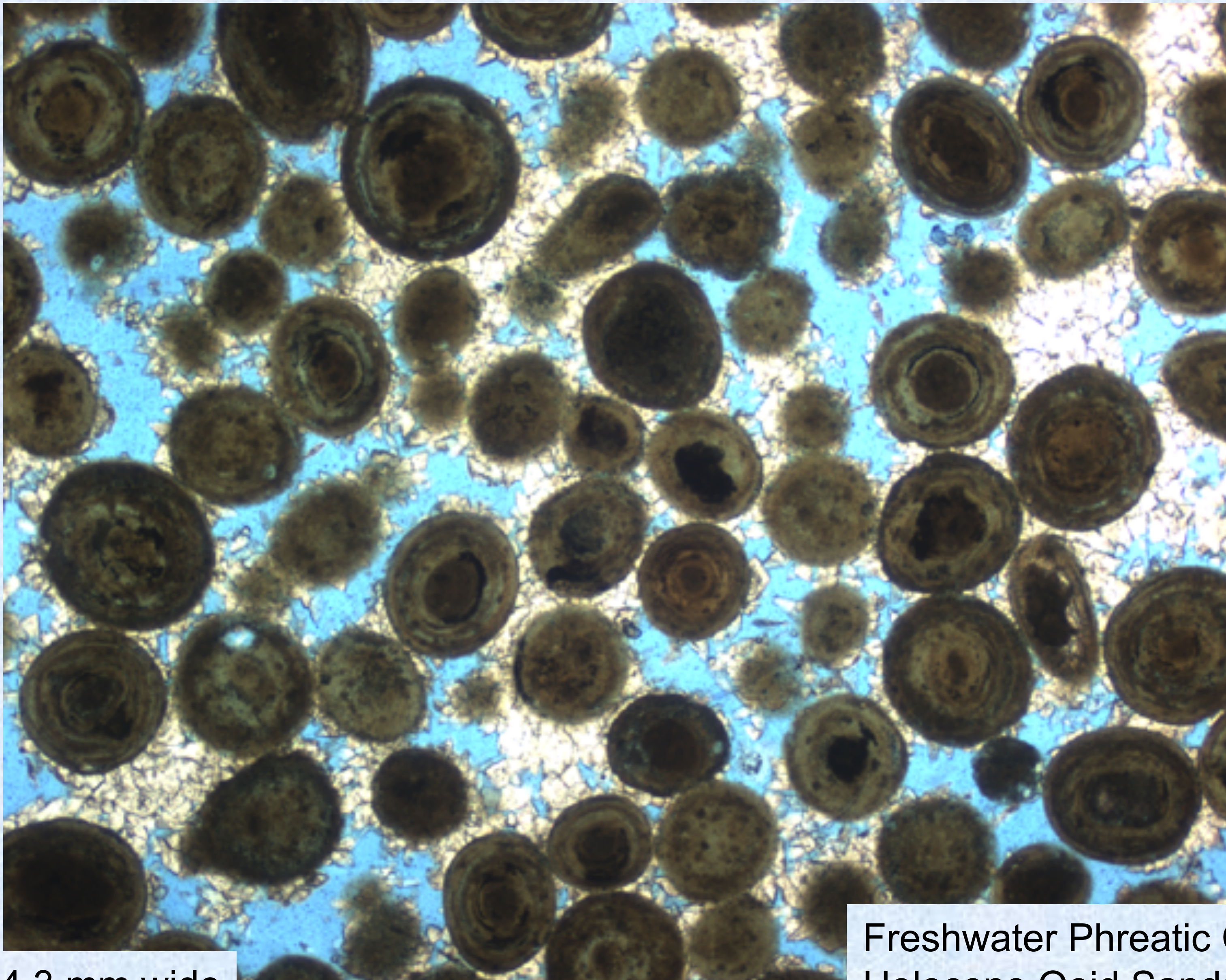
Unexplored Spatial Patterns

ates

Carbonate nodules at -3m horizon in channel bar sandstone, Cretaceous Frontier Fm., WY (Lee et al, 2007) revealed by GPR

FOV is 80 m wide

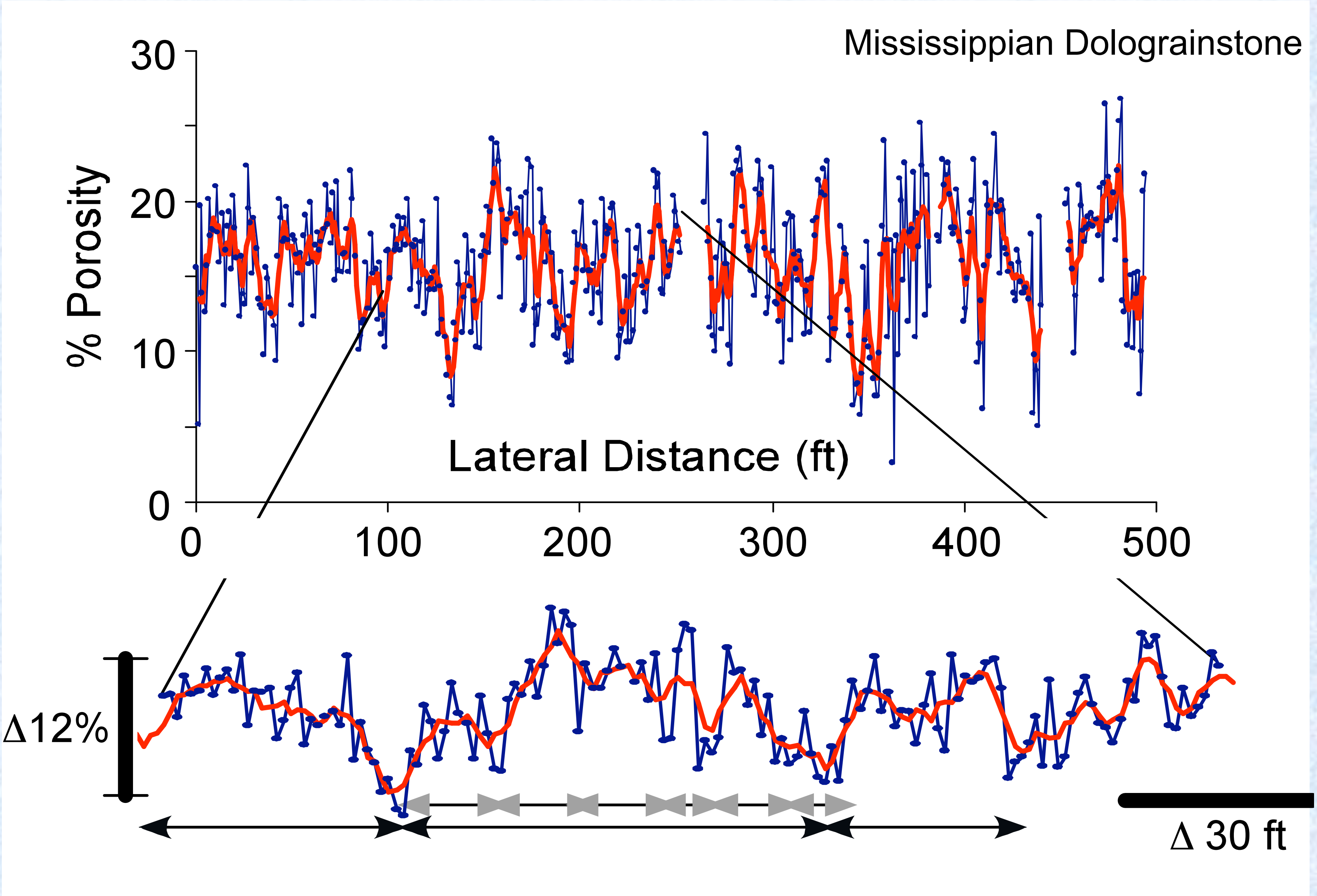
Unexplored Spatial Patterns



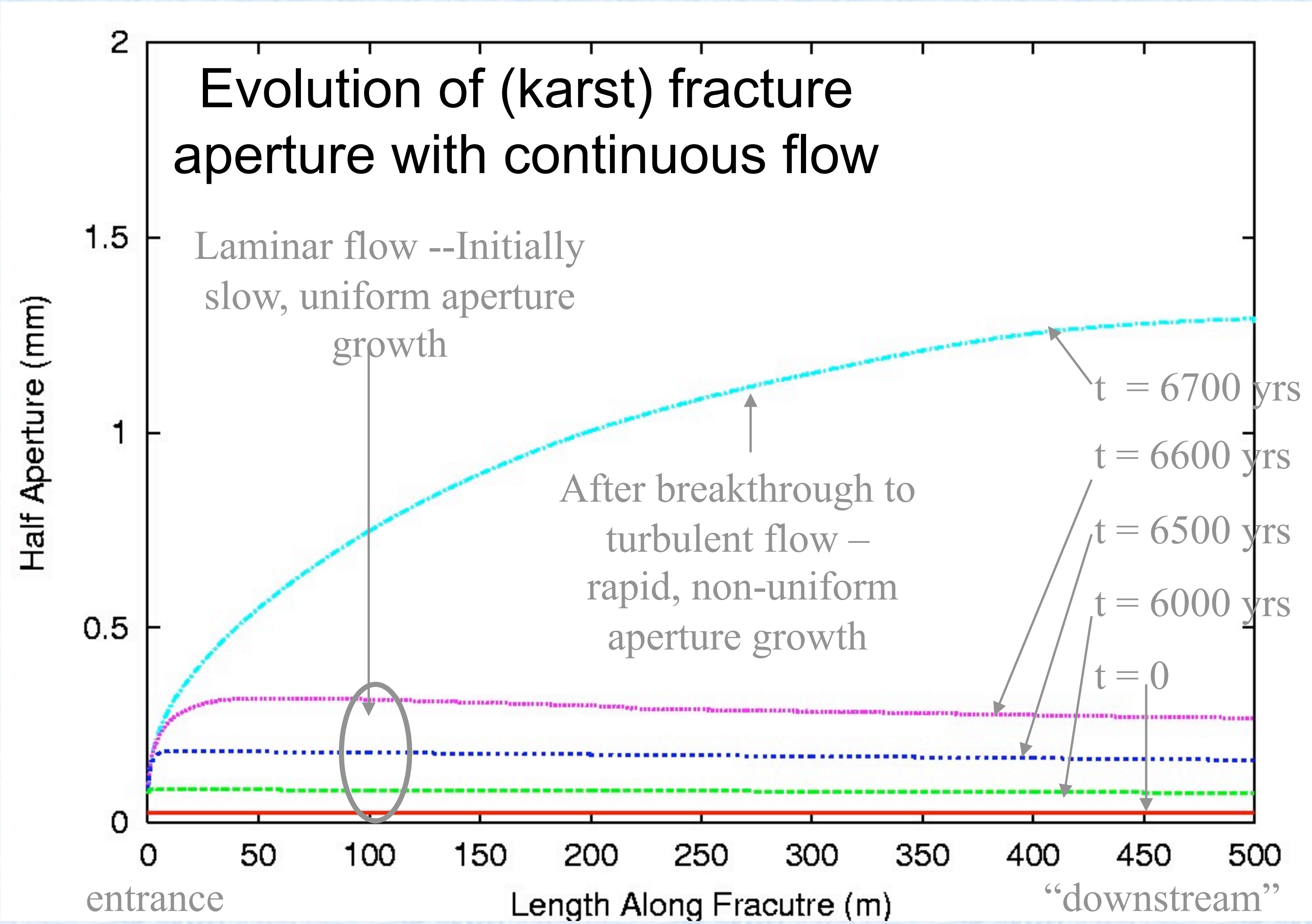
FOV is 4.3 mm wide

Freshwater Phreatic Cements,
Holocene Ooid Sands

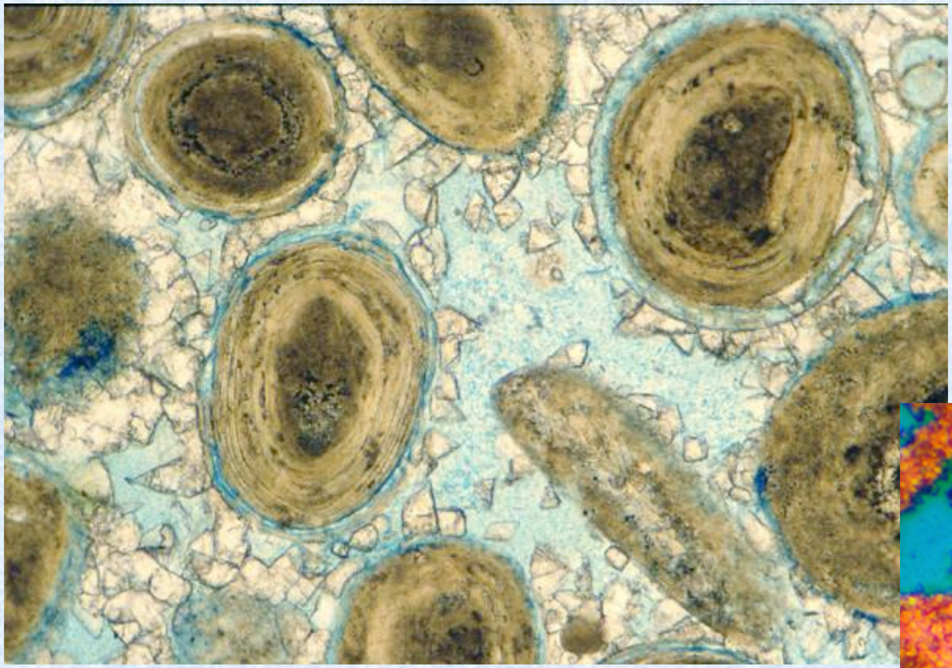
Unexplored Spatial Patterns



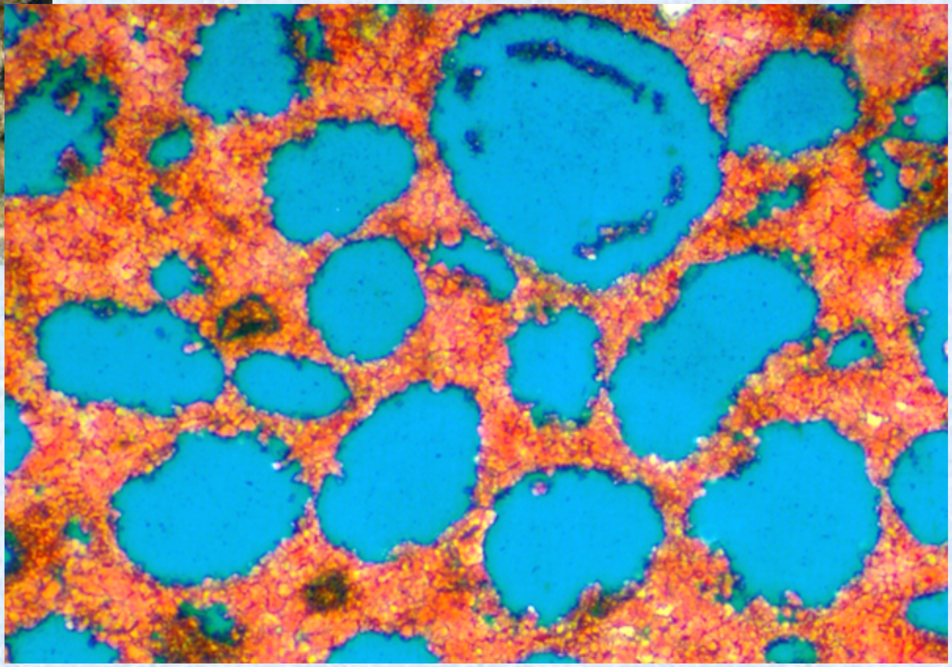
Thresholds to Diagenetic Cascading?



Thresholds to Diagenetic Cascading?



Holocene, Schooner Cays, Bhms



Permian (Scholle & Ulmer Scholle, 2003

Carbonate Diagenesis Today

Diagenesis is complex & non-linear with many types of interactions and feedbacks,

but lots of uncertainty as to the comprehensive nature of diagenesis as a SYSTEM.

What is important from a CSDMS point of view?

CSDMS Vision - Tools That

- Predict the erosion, transport, and deposition of sediment and solutes in landscapes and their sedimentary basins
- Address the challenging problems of surface-dynamic systems: self-organization, localization, thresholds, strong linkages, scale invariance, and interwoven biology & geochemistry.
- Can be applied to when the earth was abiotic, hotter or colder, when the moon was closer, the oceans more saline or stratified, sea levels rapidly changing, etc
- Are valuable to those working on modern environmental applications, future global warming scenarios, natural disaster mitigation efforts, natural hazard efforts, reservoir characterization, oil exploration, and national security.

Diagenetic alterations that affect concurrent & subsequent sediment dynamics

Post-depositional alterations that affect rock properties through time and stratigraphic space

Alterations that affect sediment dynamics

Sea Floor Precipitation

- hardgrounds, reefs, slopes

Sediment Dissolution

Karstification of Exposed Depositional Surfaces

- surface denudation (epikarst)
- generation of new land surface topography

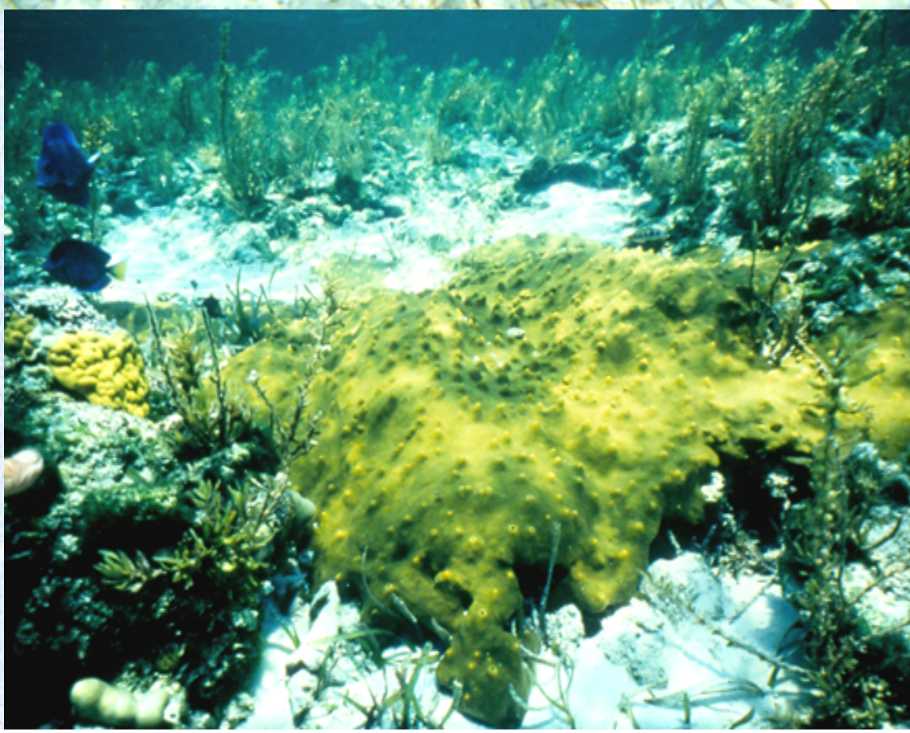
(karren, dolines, sinks)

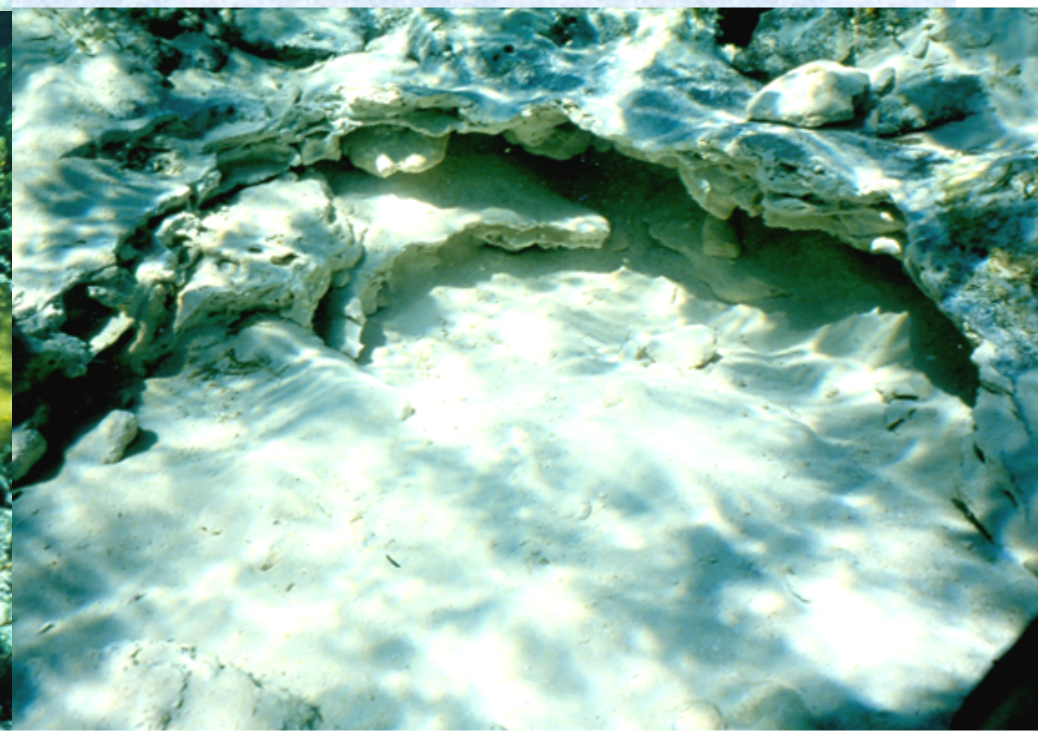
Linkages to Hardground Cementation

Even minimal cementation can stabilize sediment

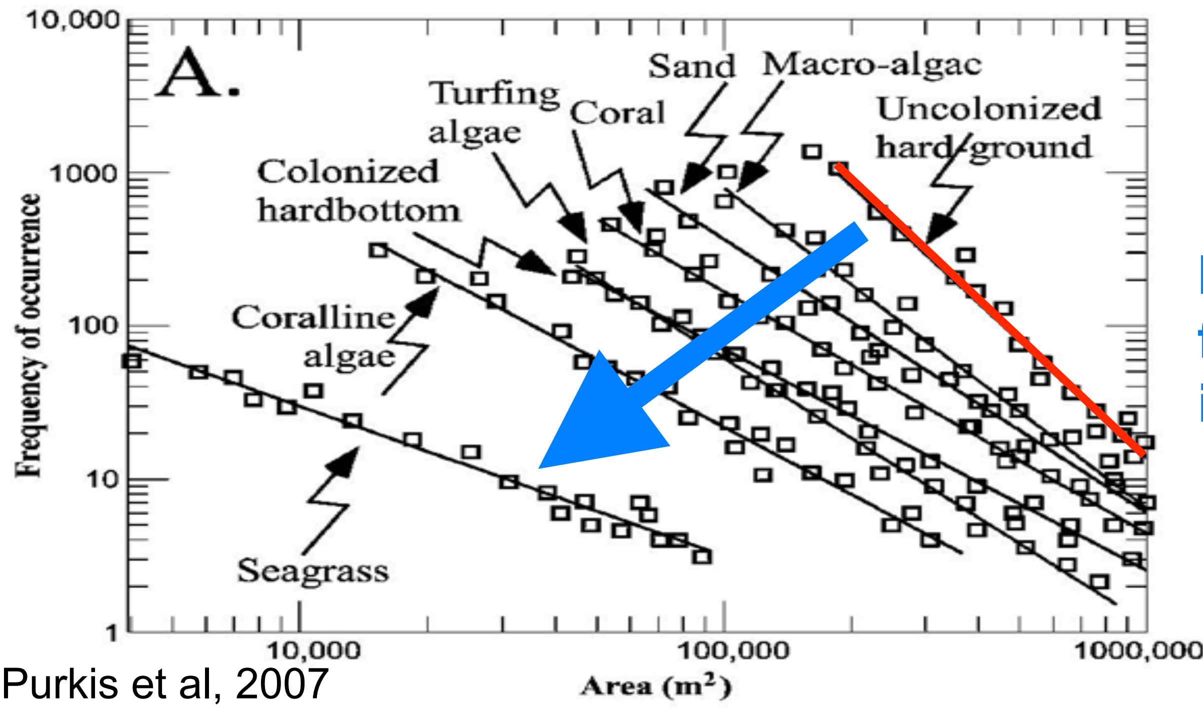
Hardgrounds can become surfaces for biohermal development

Multiple or thick cemented layers can become permeability barriers to later fluid flow.



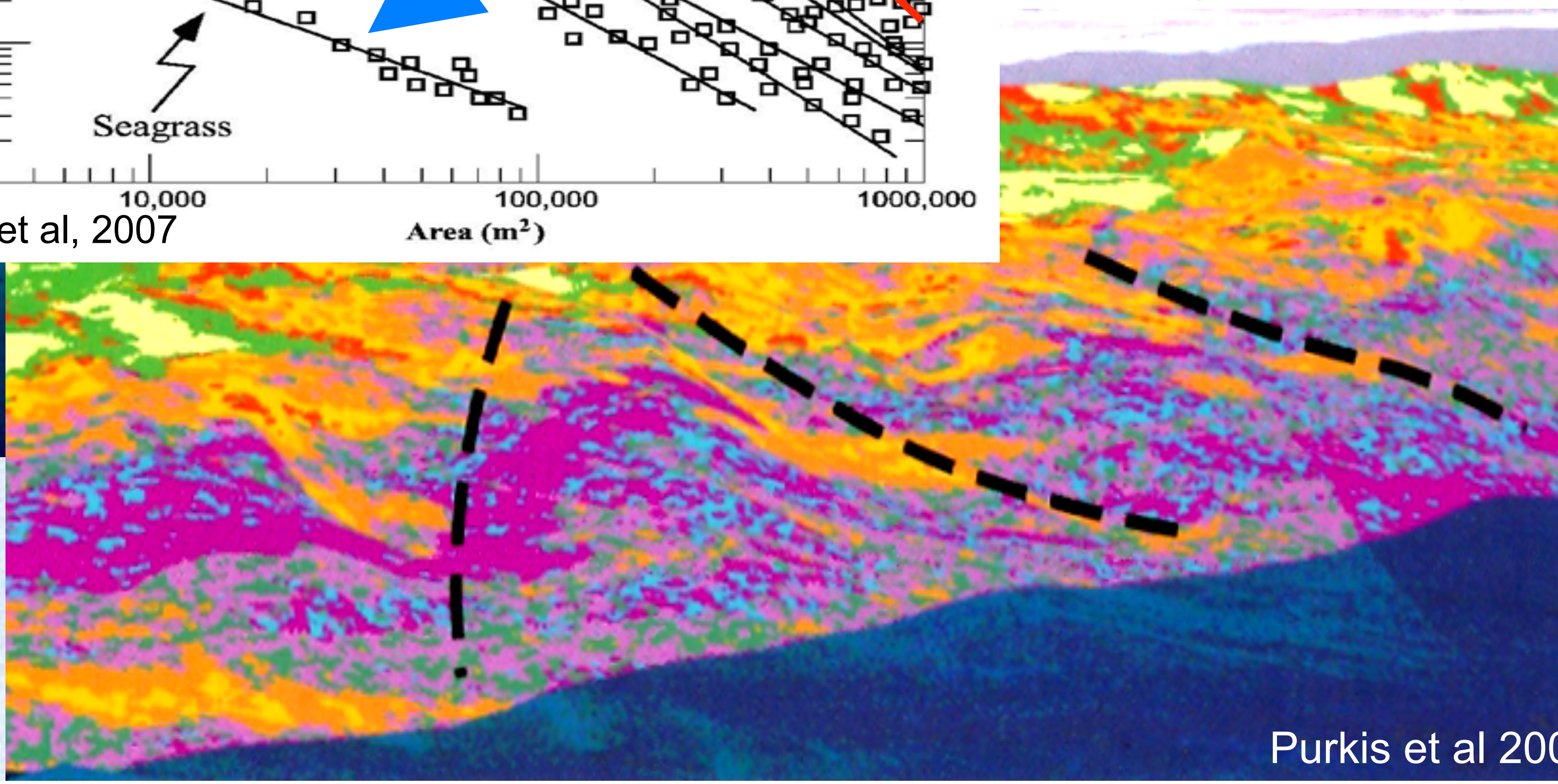


Spatial distribution of hardgrounds



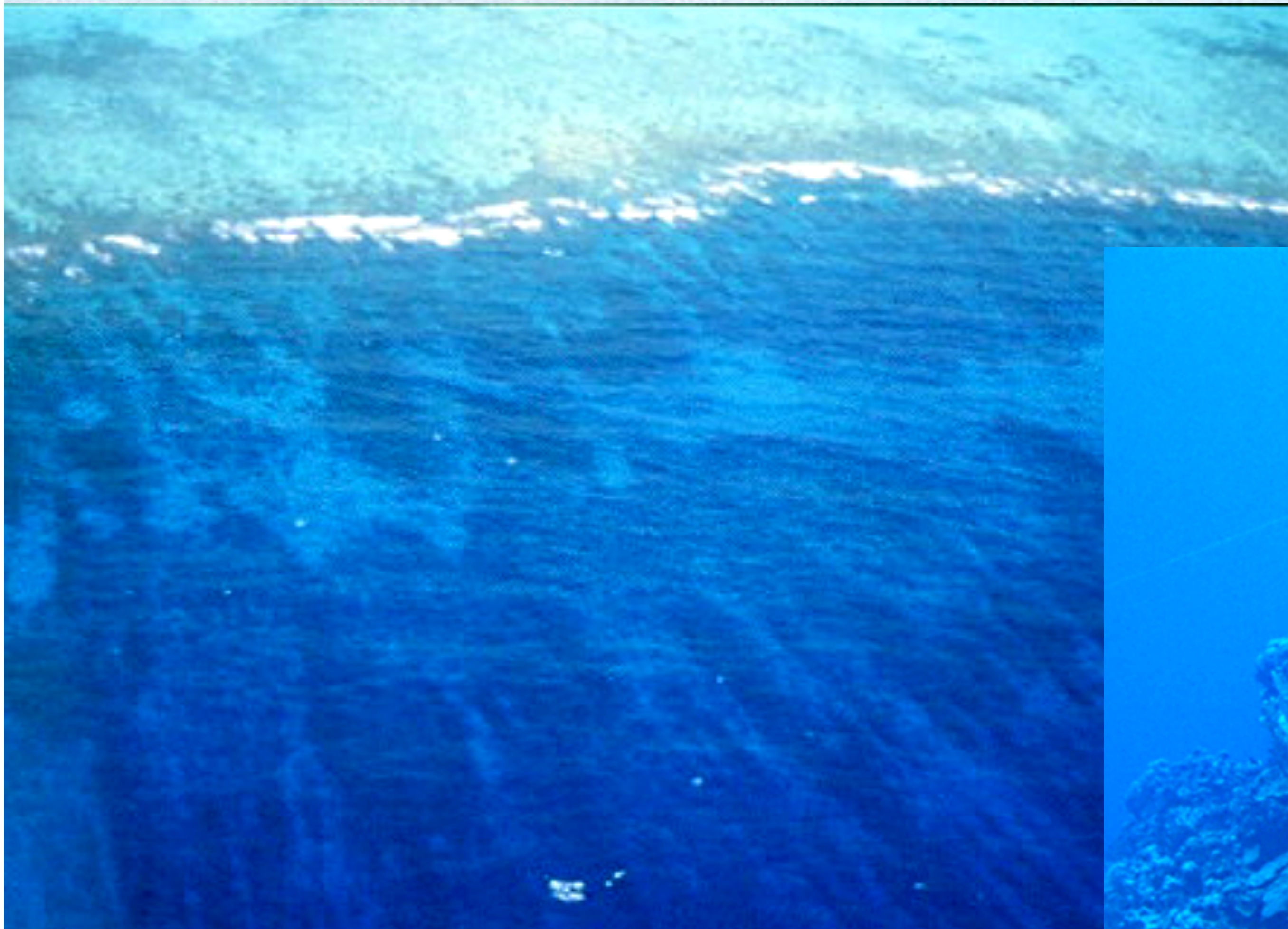
Purkis et al, 2007

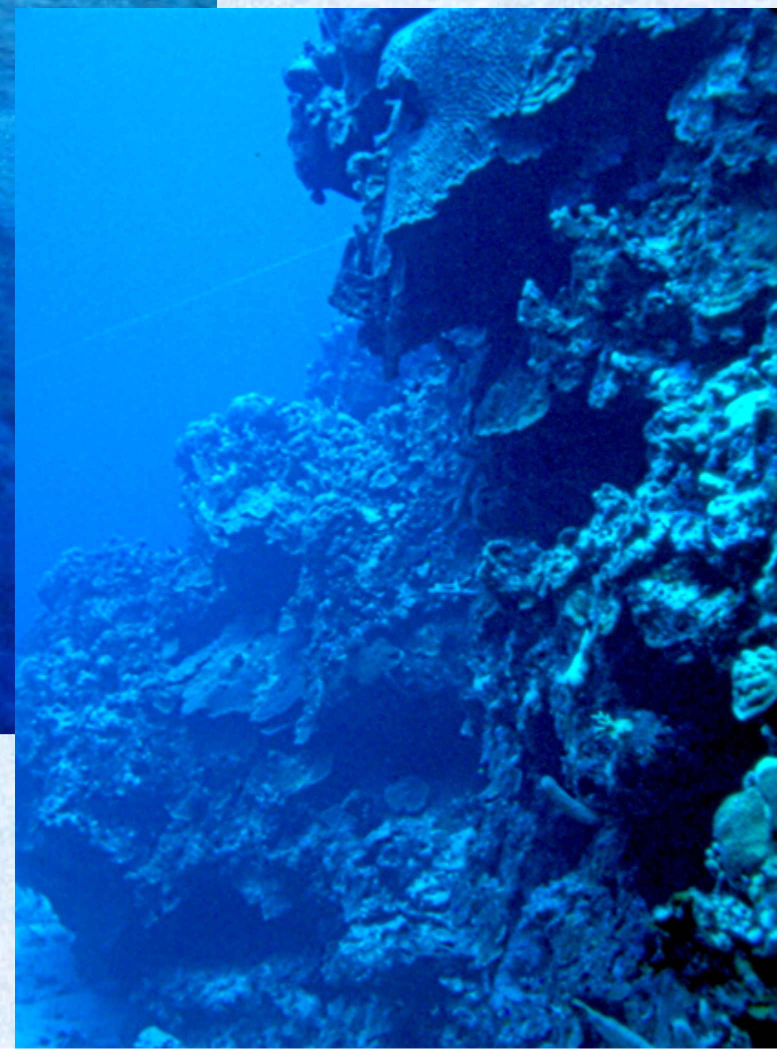
Increasing landscape fragmentation; increasing complexity



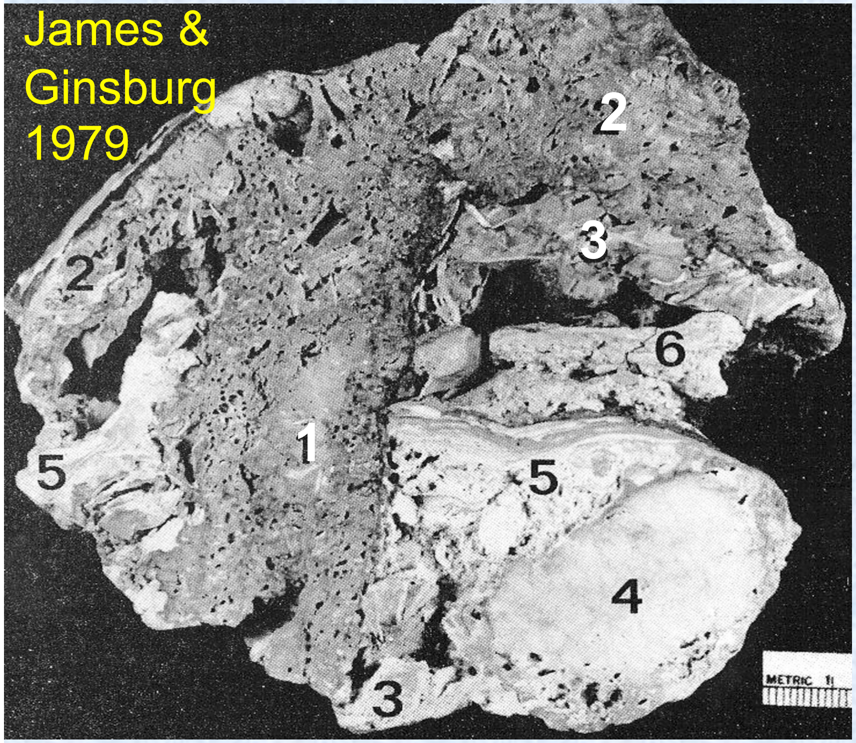
Purkis et al 2005

Reef Cementation



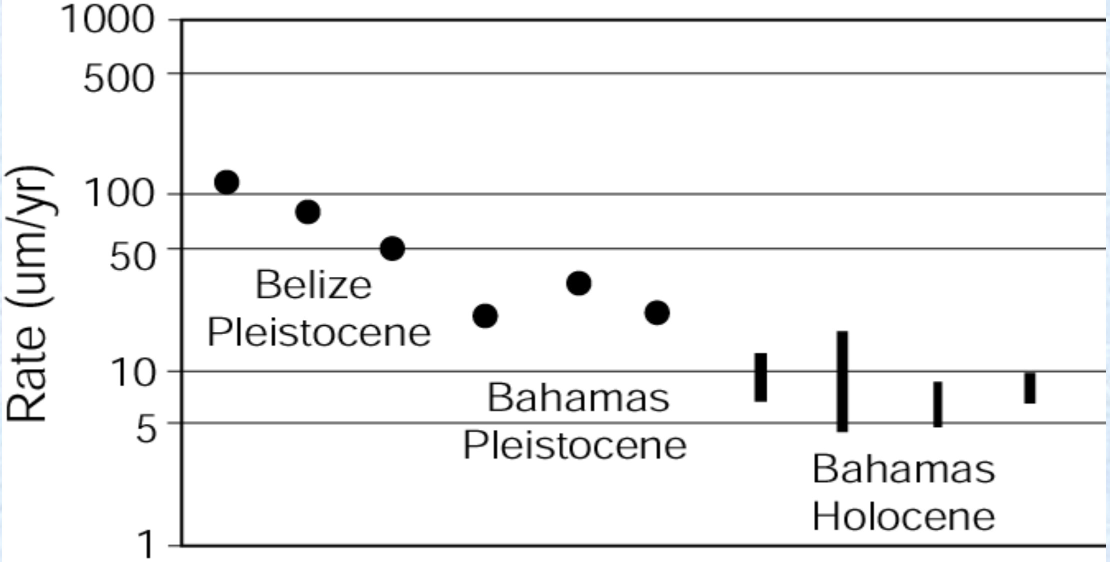


Integral component of reef construction, with potential feedbacks to (and from) biota, reef geomorphology, and nature of the eventual sedimentary accumulation



Reef Cementation – Multigenerational and fast!

1 – Original Coral Plate
2 – Surrounding Halimeda wackestone (cemented)
3 – Boring in cemented mudstone that is filled w/ cemented sediment
4 – 2nd cavity in fill of the 1st has a cemented coral fragment at its base
5 – laminated sediment that partially fills 2nd cavity; capped by iron oxide crust
6 – final grainstone fill of cavity (cemented)

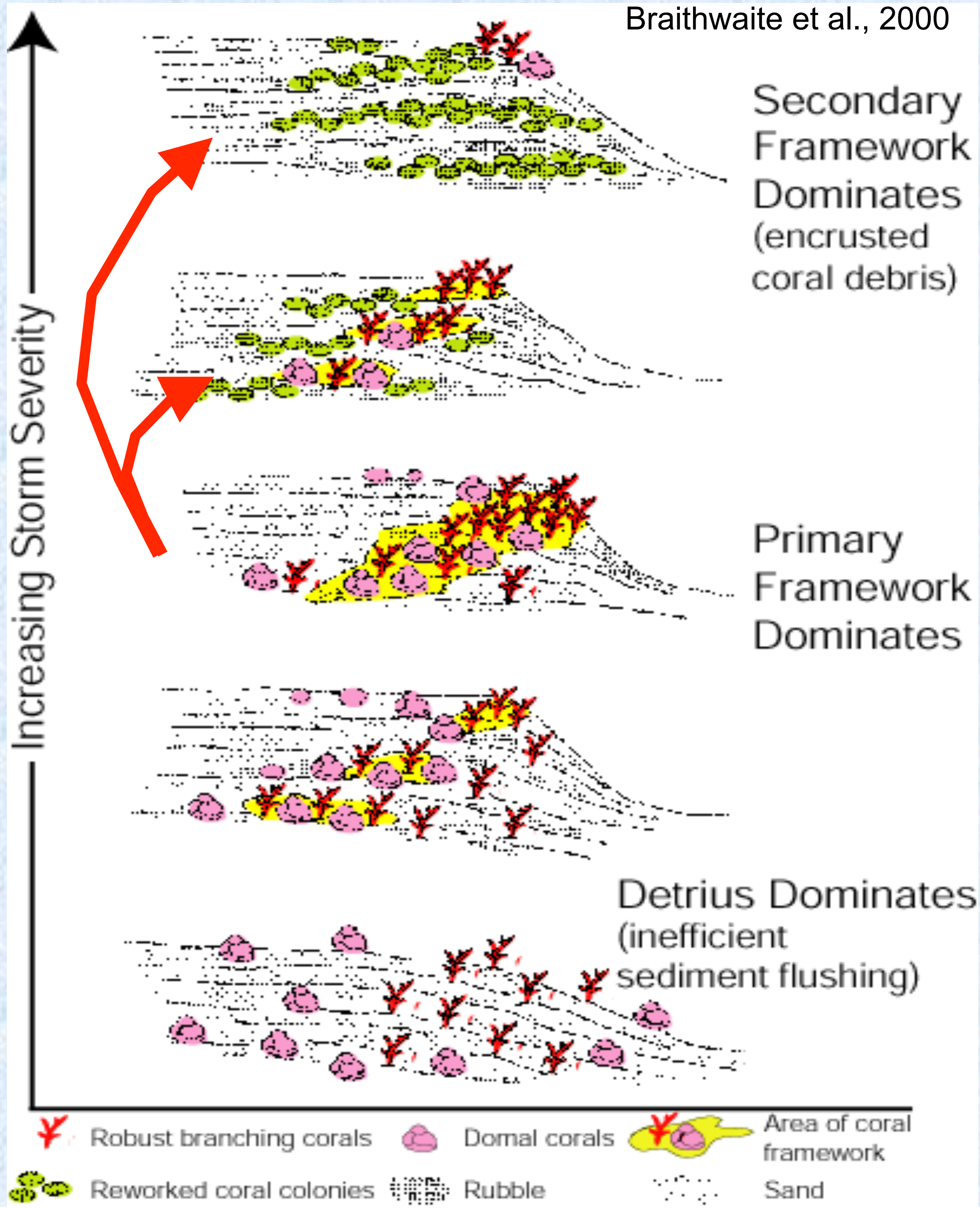


Grammer et al., 1999

Marine cementation could exhibit rapid responses (positive or negative) to changes in biogeochemical drivers of cementation

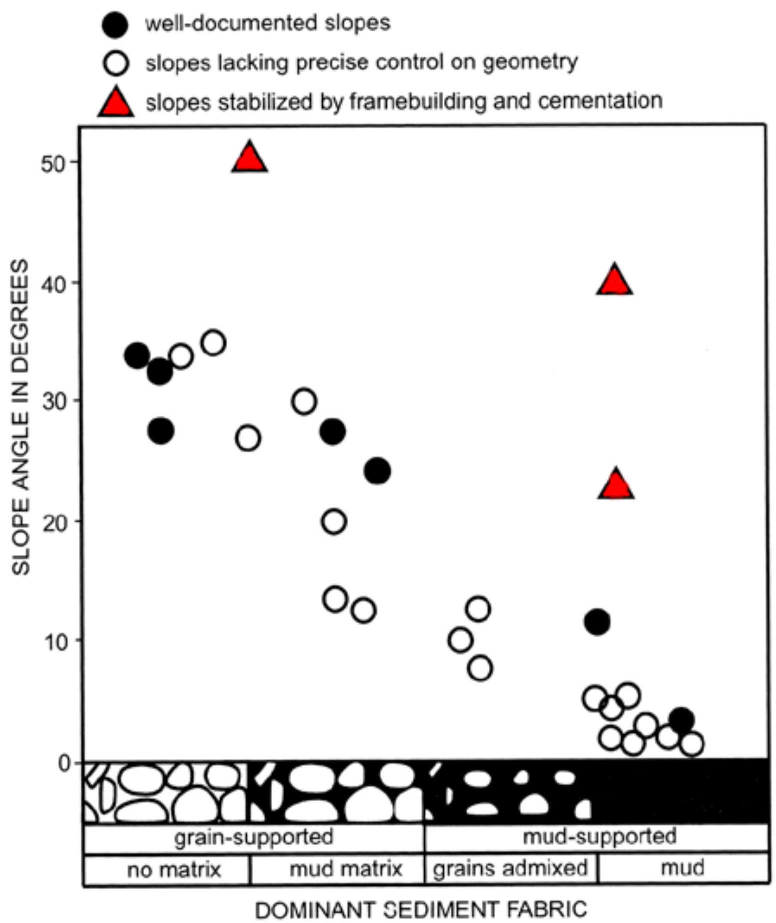
Fair-weather hydrodynamic energy and severe storms affect the ratio of framework to detrital facies

Did higher carbonate saturation states & more cementation determine ultimate reef accumulation patterns in the past?

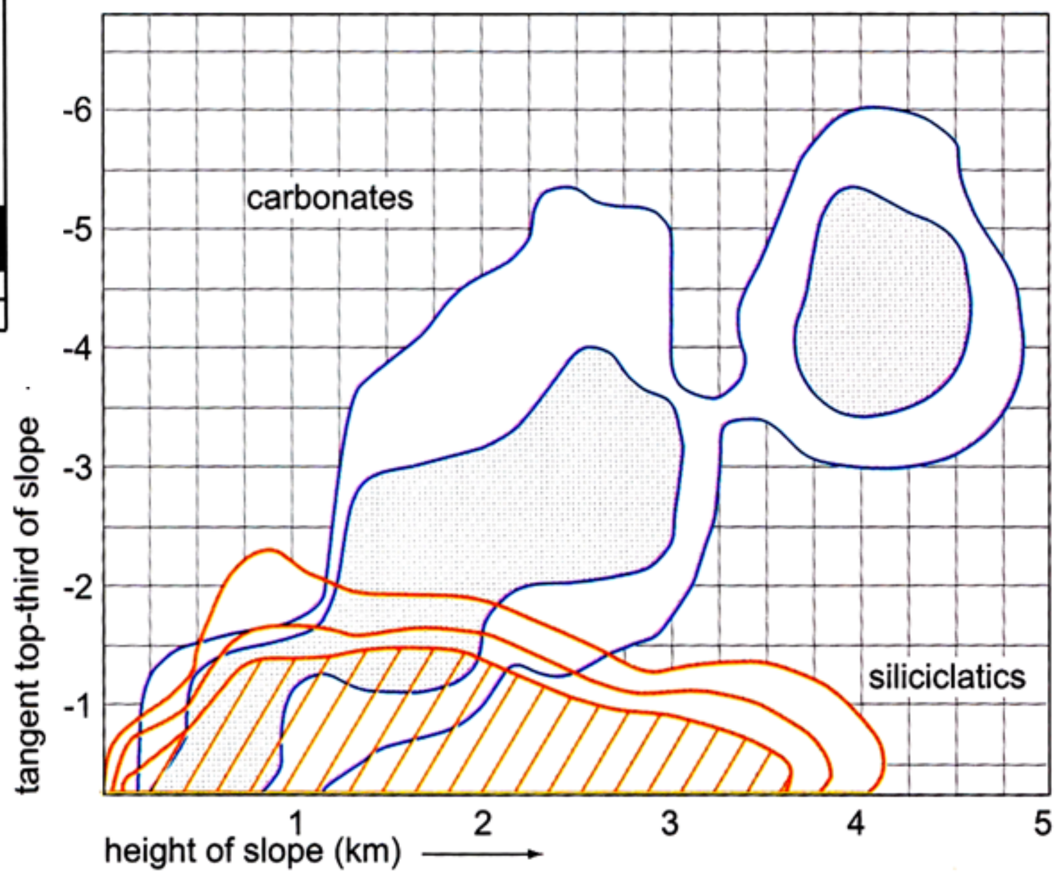


Slope Cementation

Strong linkages between marine cementation on slopes and slope shape -- and hence platform geometry.



Kenter 1990



Schlager 1989

Sediment Dissolution

Dissolution of sediment was long considered negligible

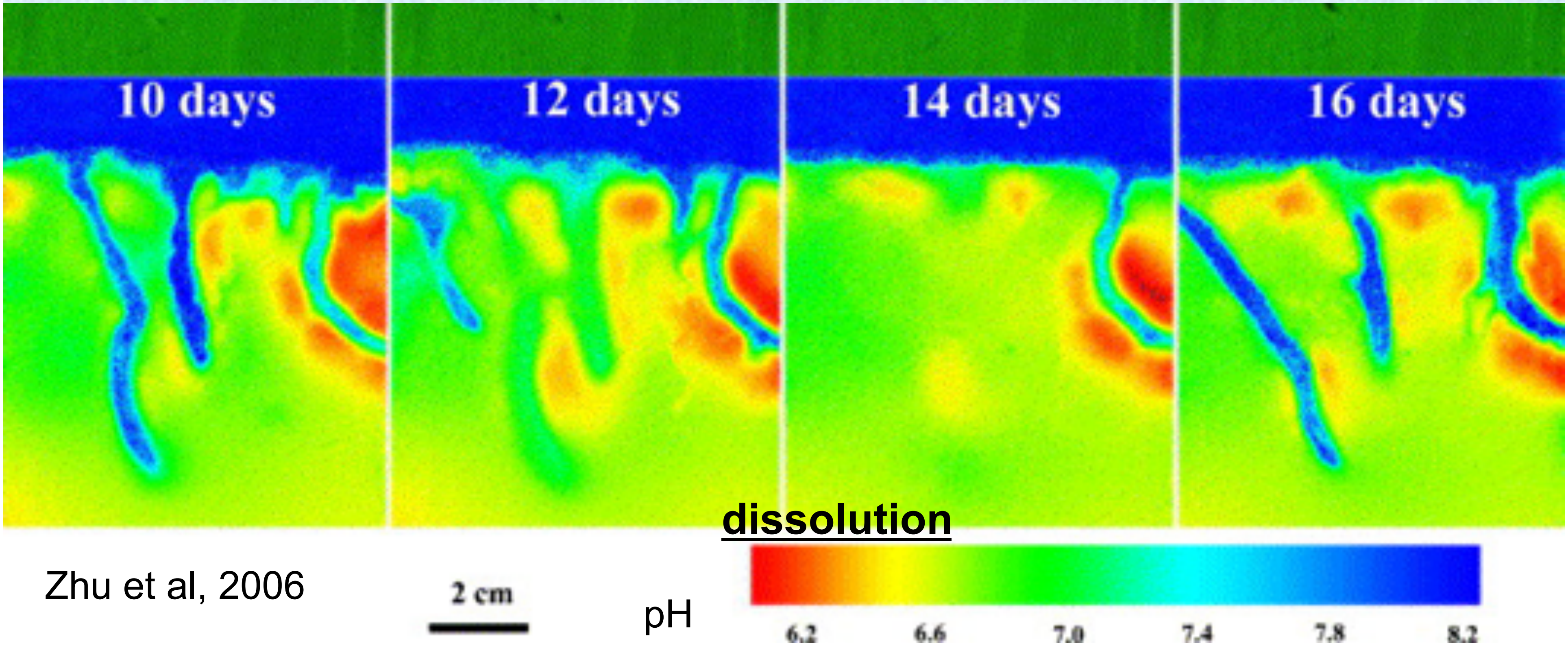
Since early 1990s, sediment dissolution has been documented
- reaction zone to 10’s cm below sediment/water interface
- 0% to >50% of bulk production affected

Affected by
- microbial oxidation of organic matter
- sulphate reduction & oxidation of resultant H2S as it migrates upward
- metastability of aragonite in cool-water settings
- carbonate mineralogies and crystal sizes
- diffusive & advective flux rates (bioirrigation beneficial)

Implication of sediment dissolution to modeling carbonate deposition

- if using sediment production functions, one should seemingly consider dissolution

- but if using net accumulation rates conditioned by modern data, dissolution is accounted for



Zhu et al, 2006

Key linkages if including cementation & dissolution in seascape

Carbonate saturation of seawater (not a constant plus variability from the micro to macro environment)

On-bank seawater fluxes

Wave & tidal energies (fluid fluxes)

Organic matter content of sediments

Bioturbation

Sediment mineralogies, initial petrophysical attributes

But we don’t really know spatial patterns by which to evaluate model outcomes

Alterations that affect concurrent & subsequent sediment dynamics

Sea Floor Precipitation

- hardgrounds, reefs, slopes

Sediment Dissolution

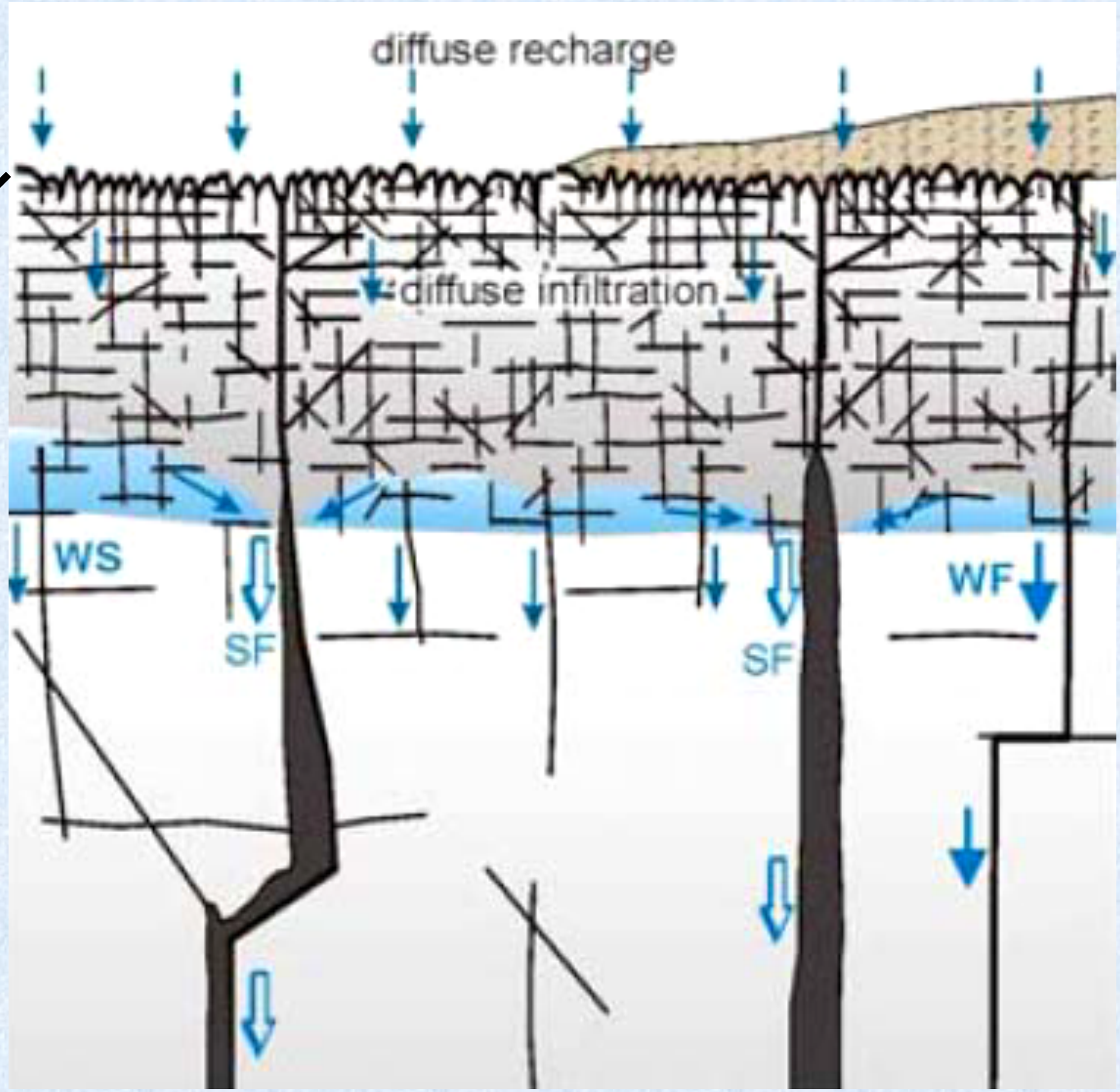
Karstification of Exposed Depositional Surfaces

- surface denudation (epikarst)
- creates topography on landscape

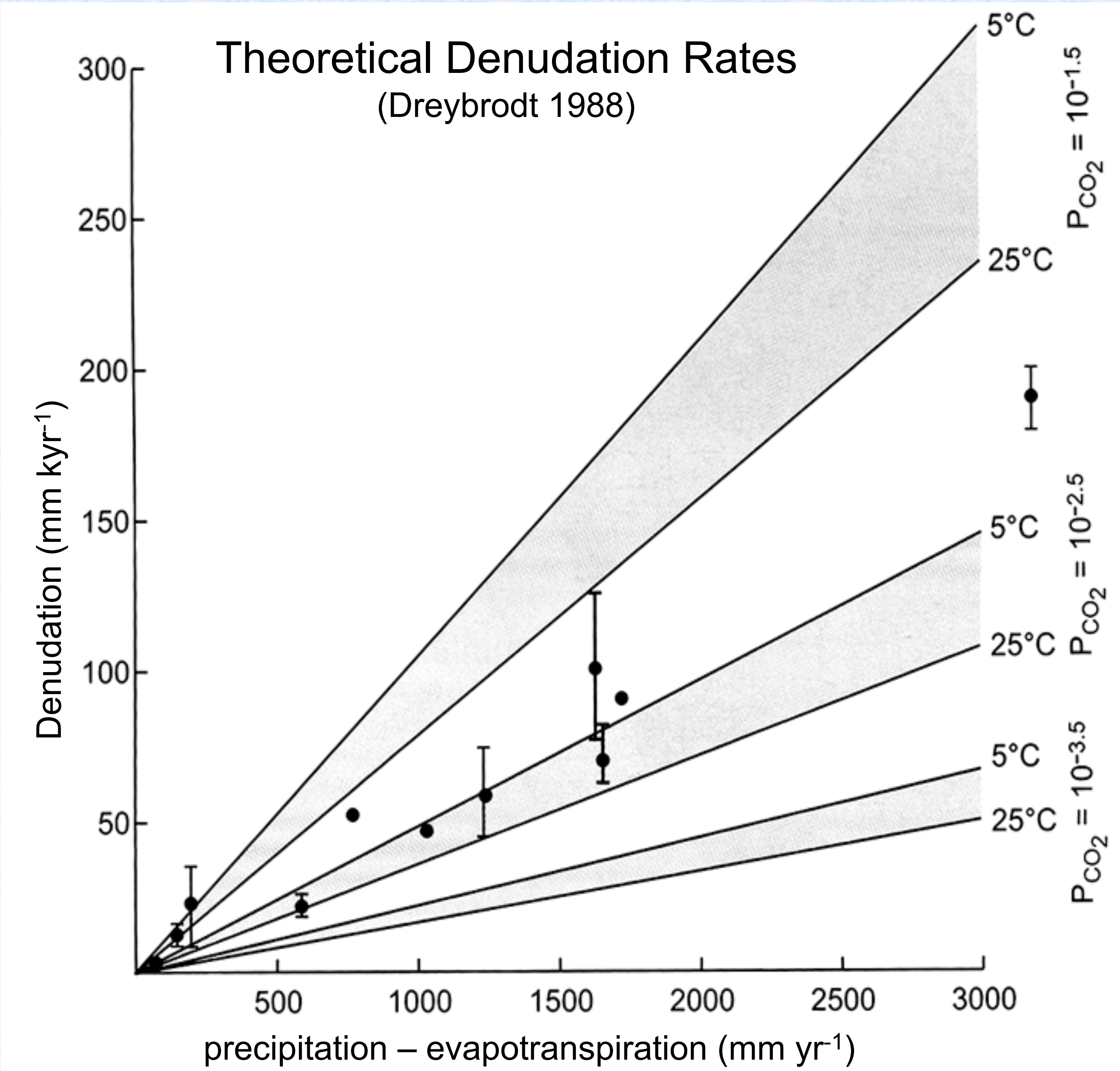
Epikarst zone – interface between soil and rock,

between the land surface and the vadose zone

Zone of denudation



Klimchouk, 2004



Observed and theoretical rates of surface karst denudation dependent on climate, soil zone PCO2, and time.

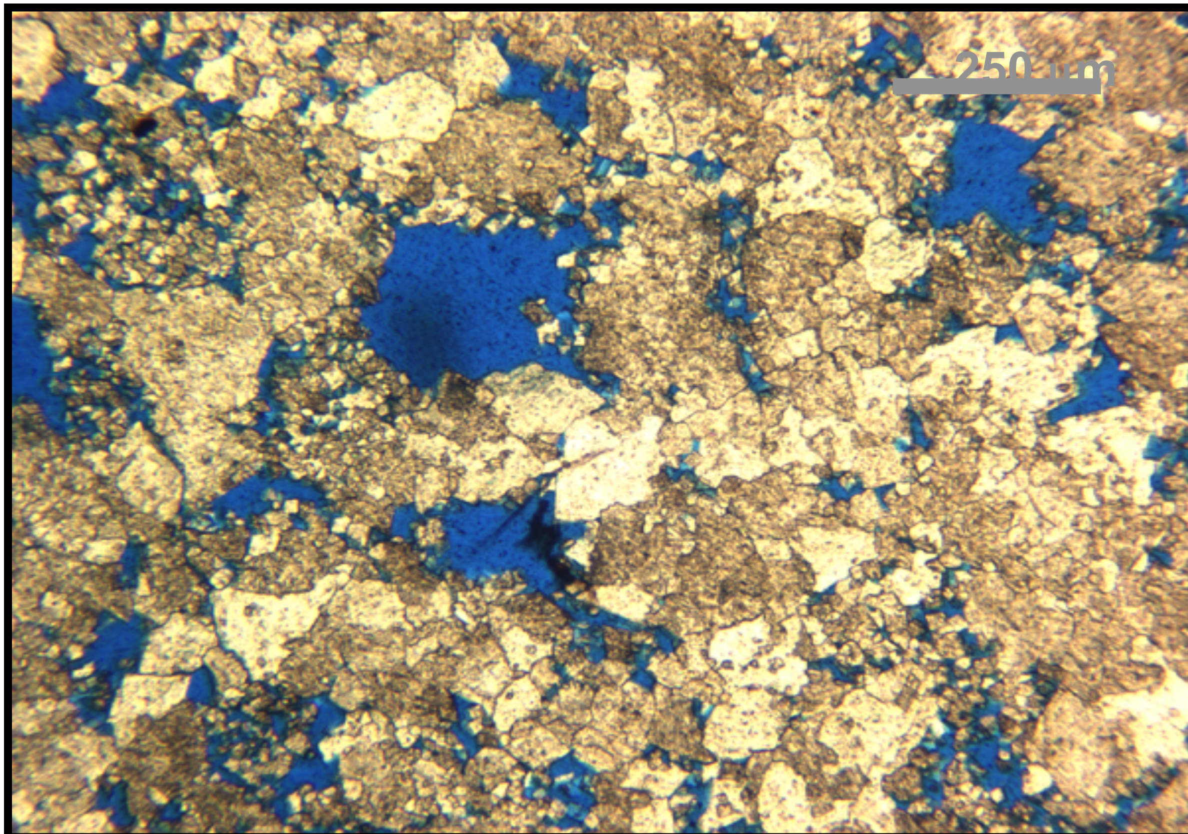
Magnitude of the process:

20 to 100 cm per 10,000 yr

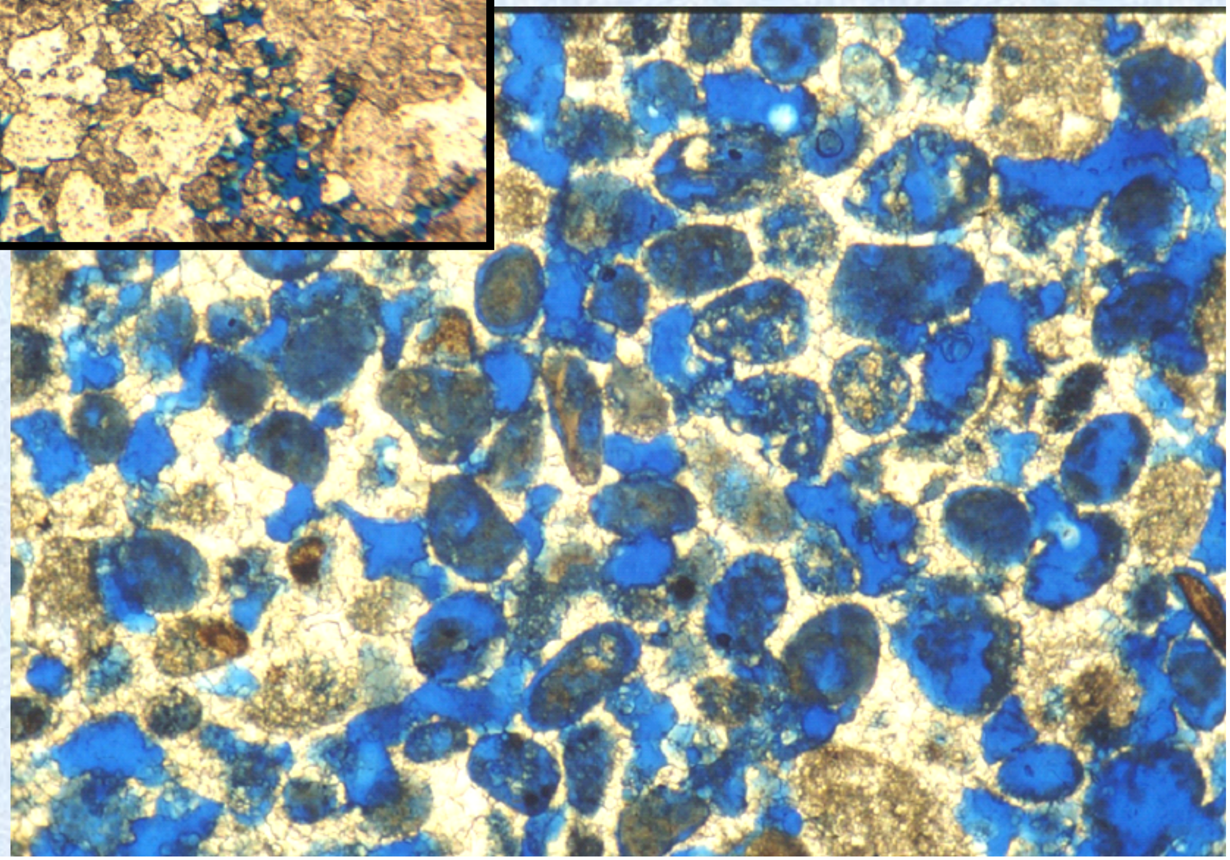
Post-depositional alterations through time and stratigraphic space

Mass transfers that:

- Change mineralogies
- Alter rock fabrics & textures
- Restructure, and generally reduce, porosity and permeability



Mississippian
Dolostone



Pleistocene
Rock

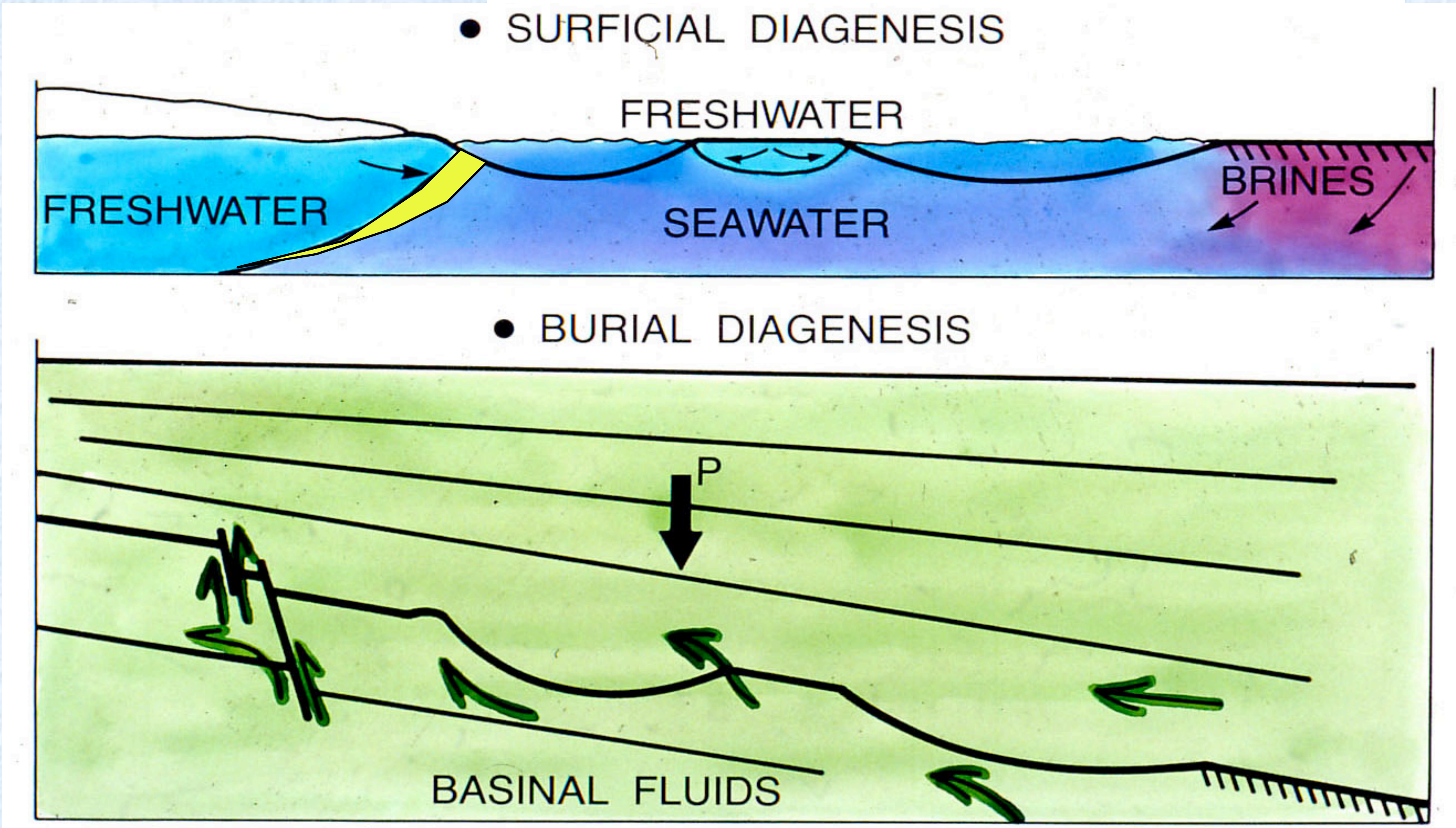
Known Diagenetic Processes

- Dissolution
- Cementation
- Recrystallization
- Replacement
- Fracturing
- Mechanical Compaction
- Chemical Compaction

Known from the land surface upon exposure to the deep subsurface

Known from 10s of meters & ~300 m below the surface and downward

Diagenesis historically viewed in terms of hydrochemical regimes that generate internally consistent process-response dynamics



Known driving mechanisms for alteration

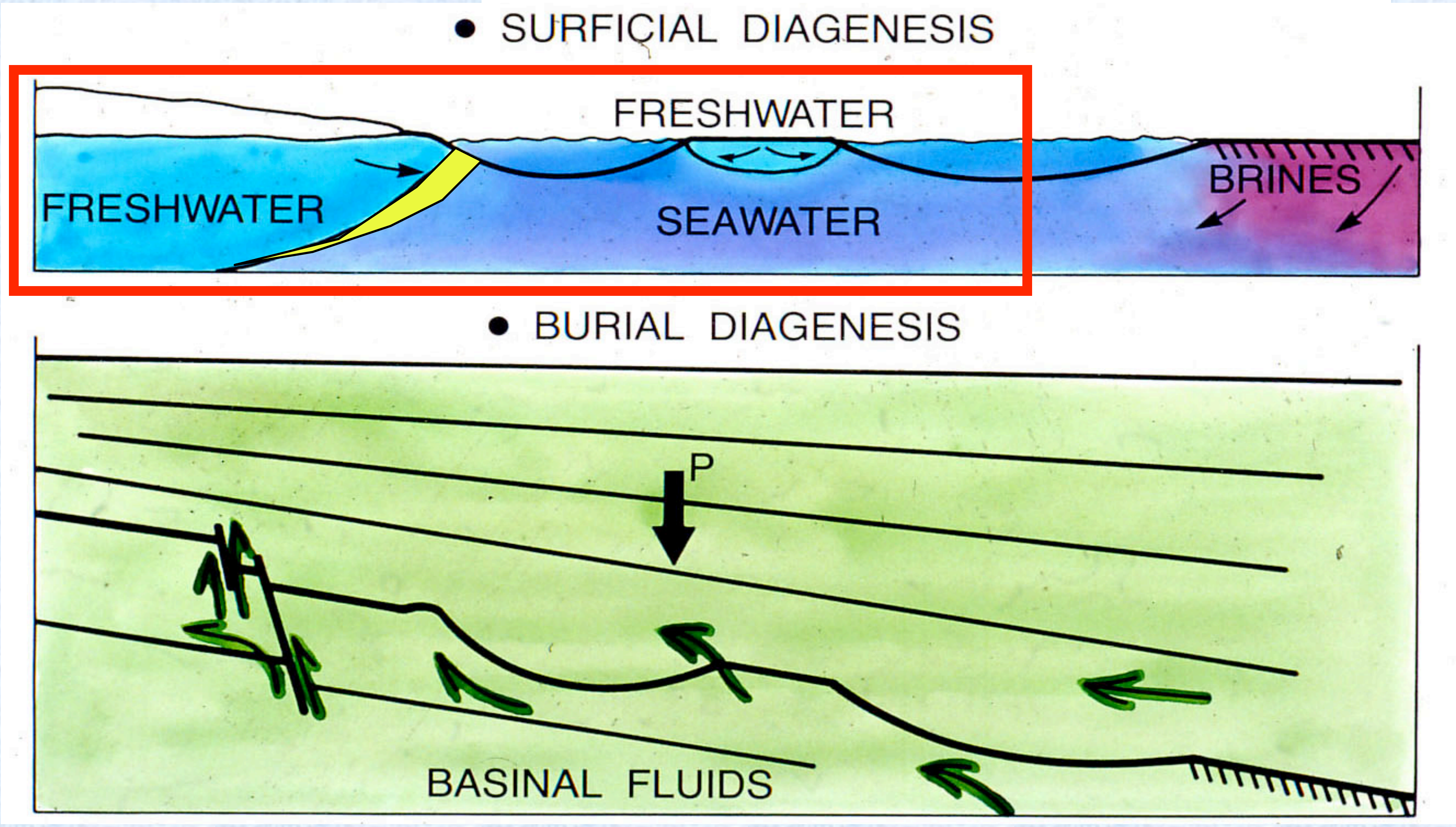
- Mineralogical stabilization (aragonite→calcite; high Mg calcite→calcite; metastable dolomite→dolomite)
- Mineralogical disequilibrium (generated by fluid fluxes)
- CO_2 effects (CO_2 charging, degassing, effervescence)
- Microbial mediated reactions (generate acid)
- Common ion effects (anhydrite dissolution; dedolomitization, calcite ppt)
- Organic diagenesis (oxidation, decarboxylation)
- Evaporation
- Fluid mixing effects (freshwater-seawater, freshwater-freshwater, brine-brine)
- Dehydration reactions (gypsum→anhydrite, smectite→illite, opalA→quartz)
- Lithostatic load (mechnical compaction)
- Effective stress (chemical compaction)
- Tectonic stress
- Ostwald ripening
- Heat flux

And of course kinetics must be considered [1]

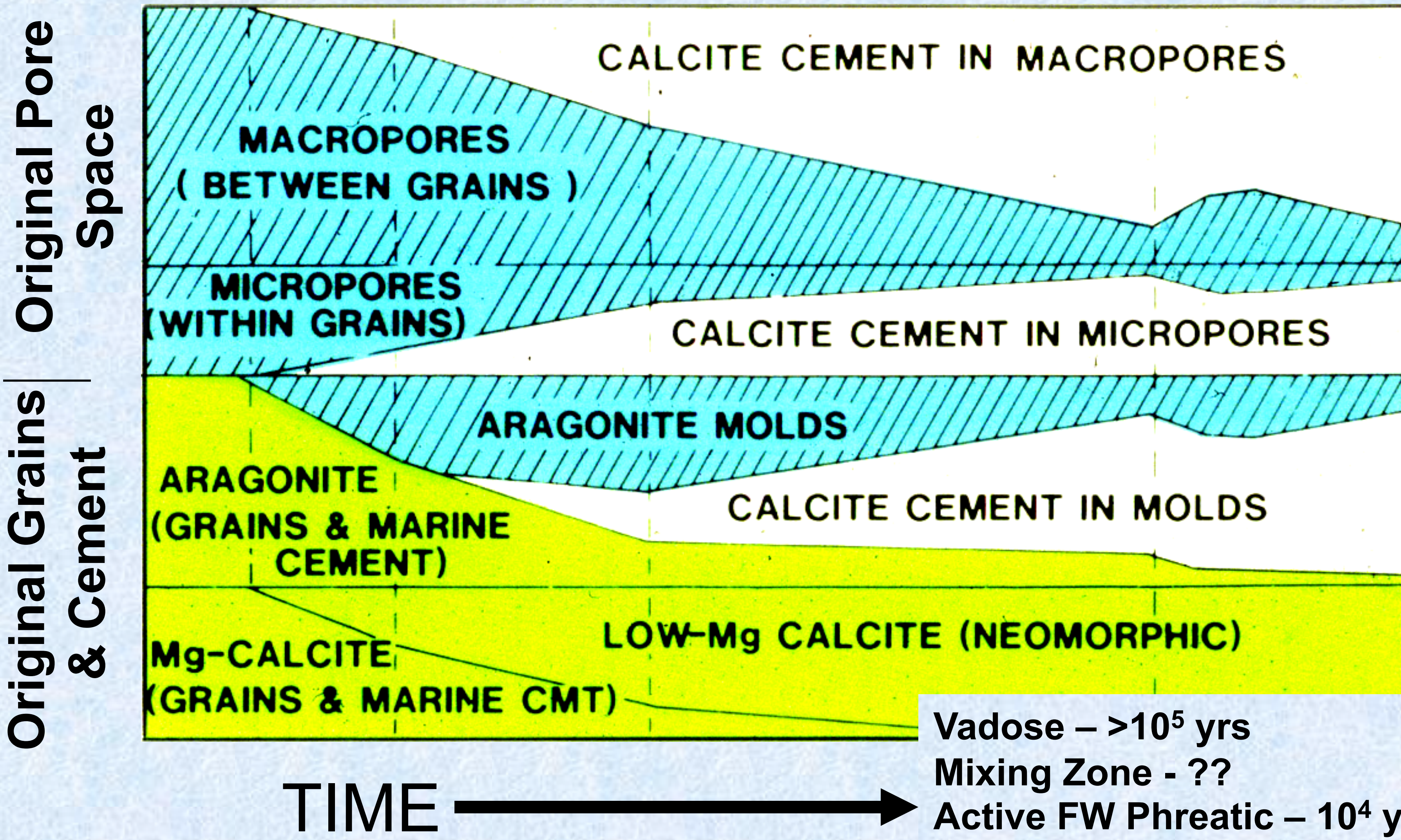
- Nucleation energies
- Reactive surface area (grain size, crystal size)
- Surface-control or transport-controlled reactions
- Crystal-surface contamination & cation-complexing (foreign ion effects, Mg-hydration, PO_4, SO_4)
- Reaction rates near & far from equilibrium
- Microbial effects (mediation, catalysis, …
- Temperature
- Fluid flow rates (relative to reaction rates)

1 – Assuming thermodynamics are also known, but see “dolomite”

Diagenesis historically viewed in terms of hydrochemical regimes that generate internally consistent process-response dynamics

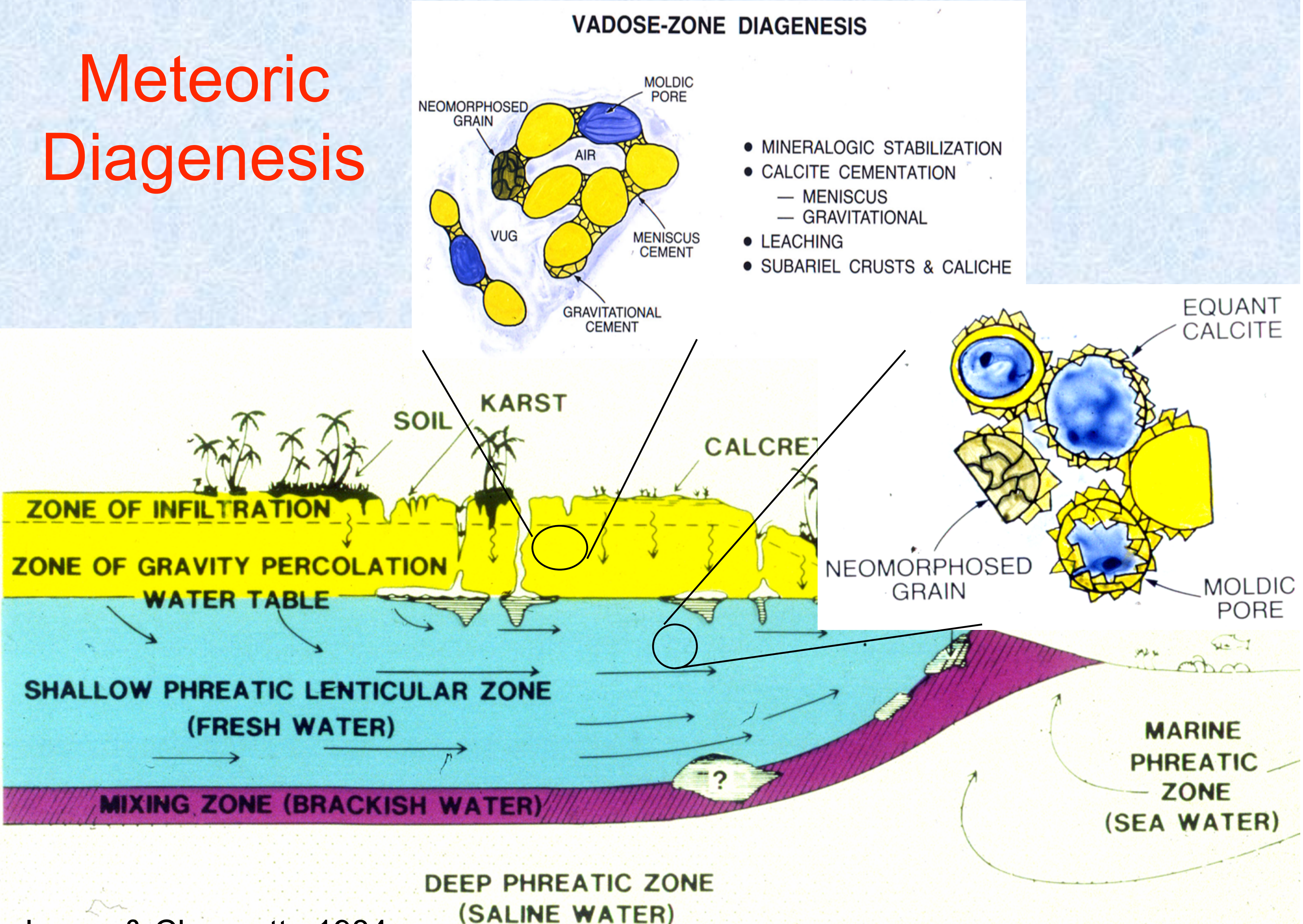


Mineralogical Stabilization

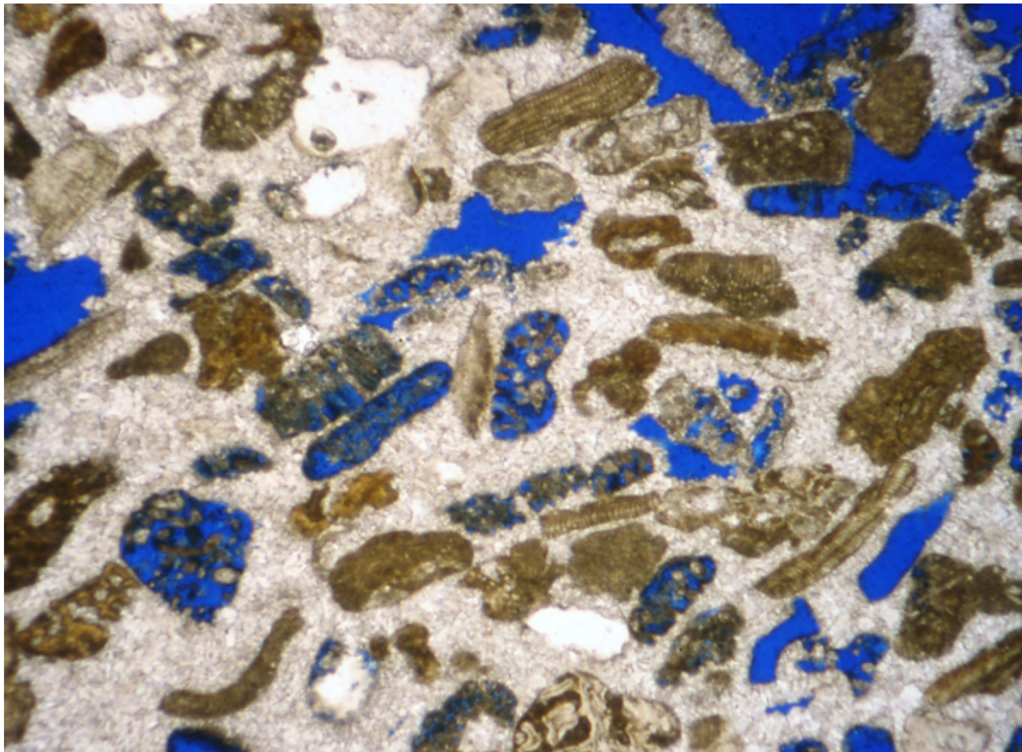
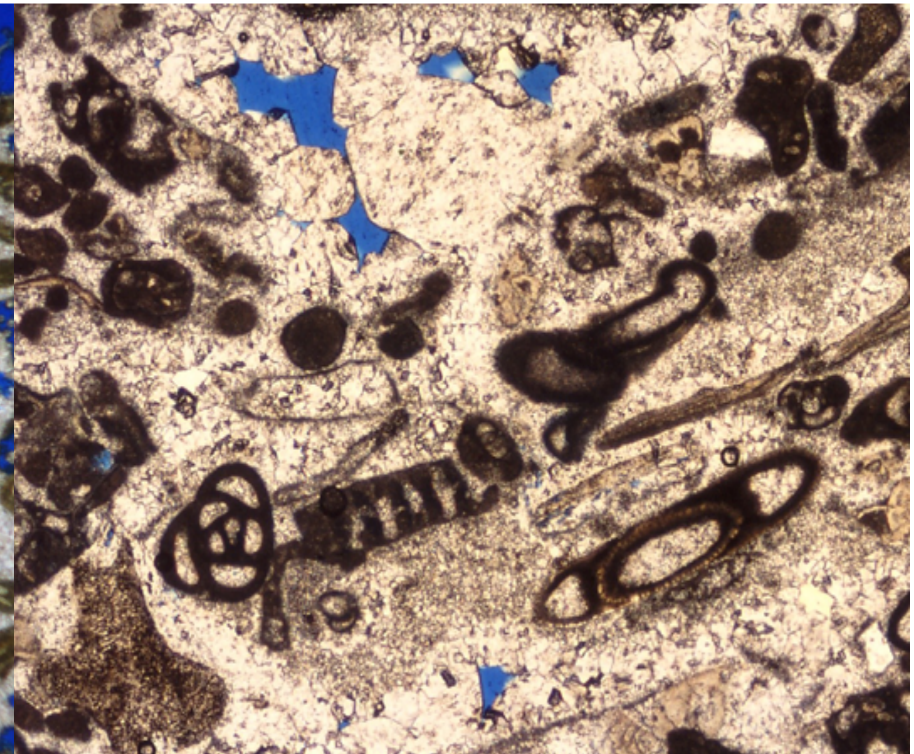
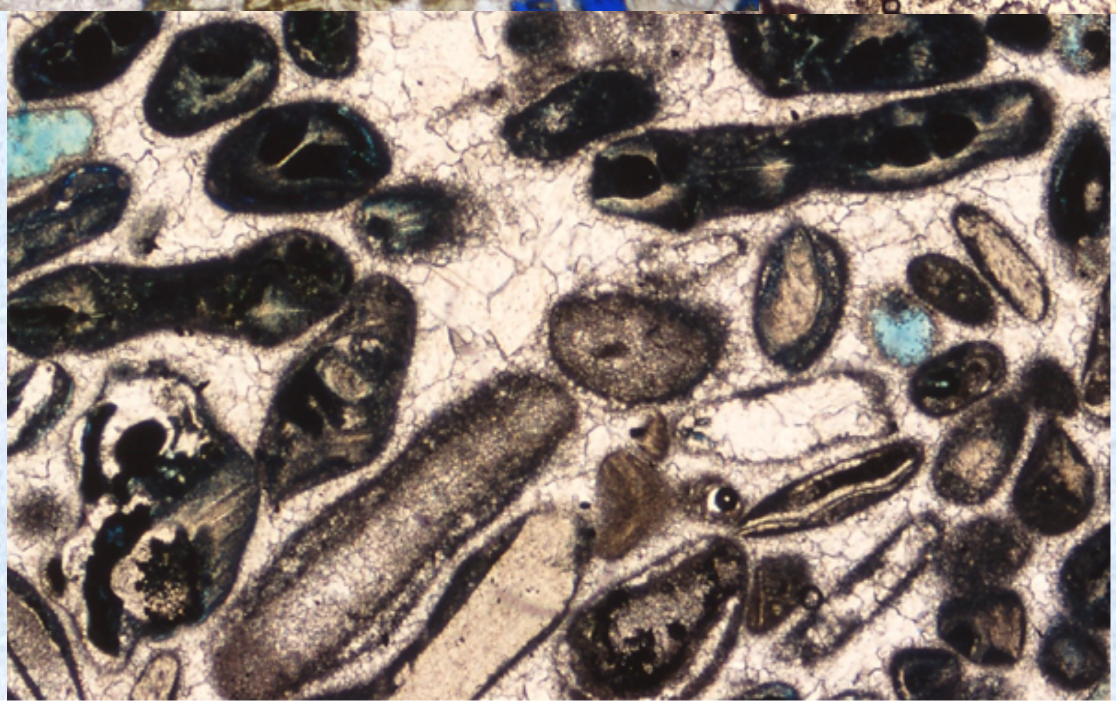


Vadose – >10^5 yrs
Mixing Zone - ??
Active FW Phreatic – 10^4 yrs
Seawater Phreatic – > 10^6 yrs

Meteoric Diagenesis



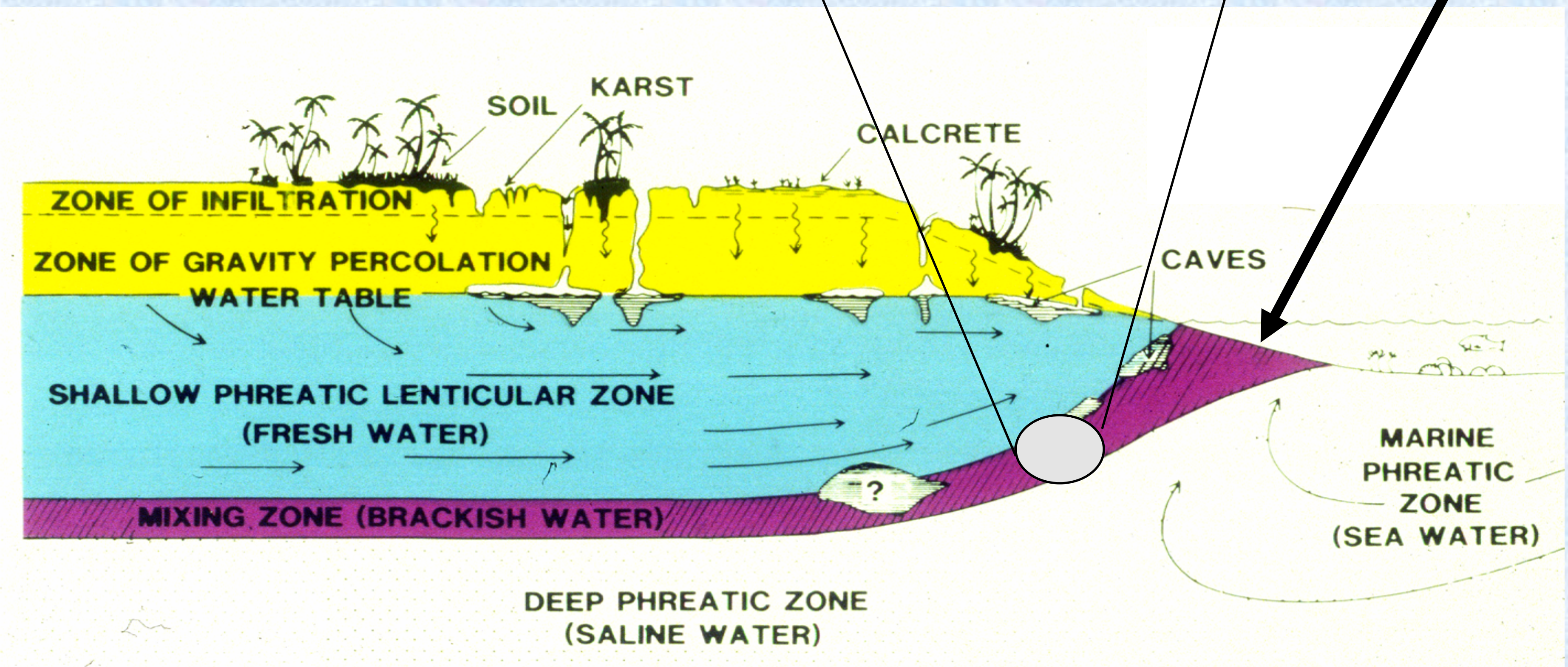
James & Choquette 1984

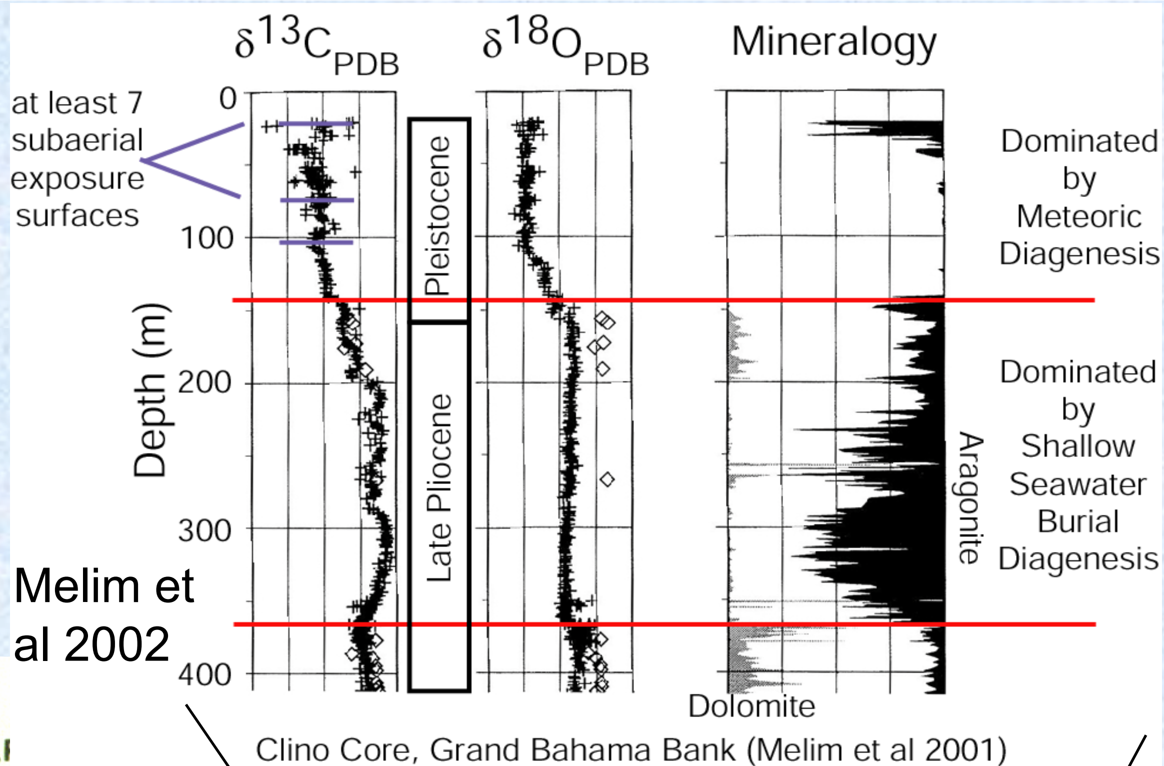
Mixing Zone Diagenesis

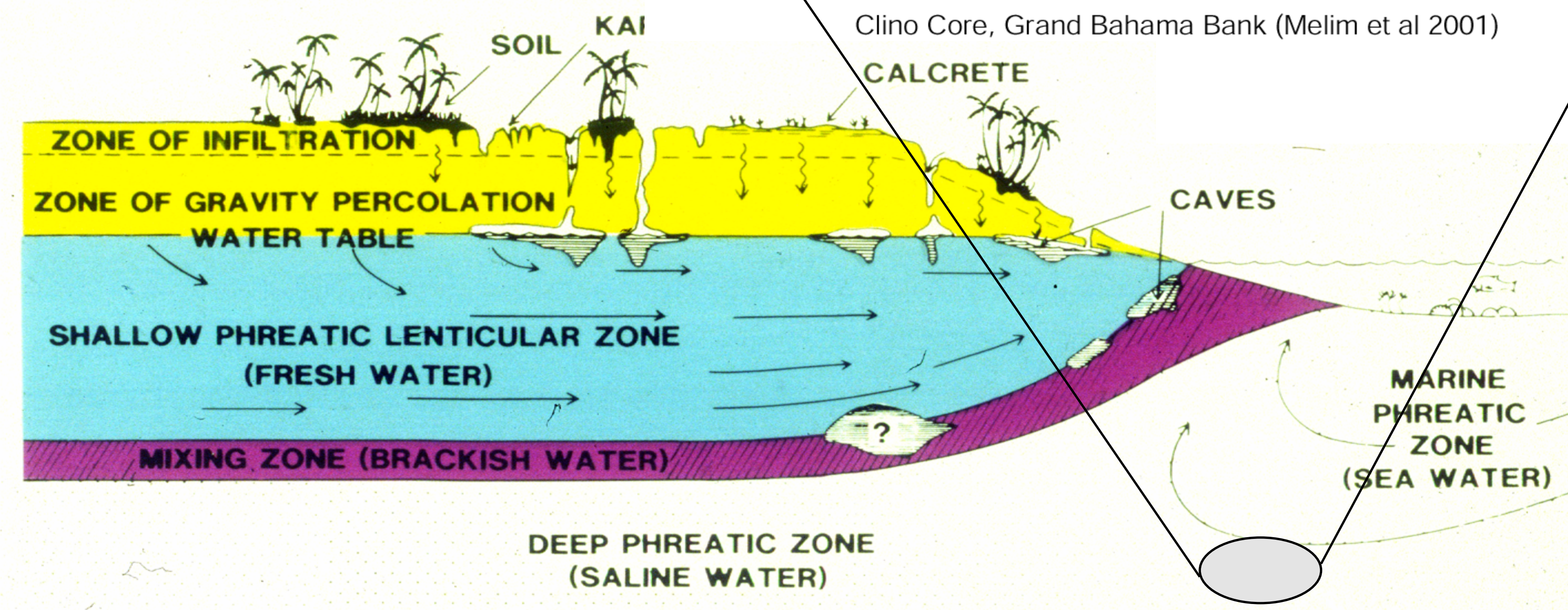
Dominated by dissolution.

But cementation also noted in hydrochemistry of some modern upper mixing zones (20-30% SW) & implicated in fluid inclusion data from some ancient cements (0-90% SW).

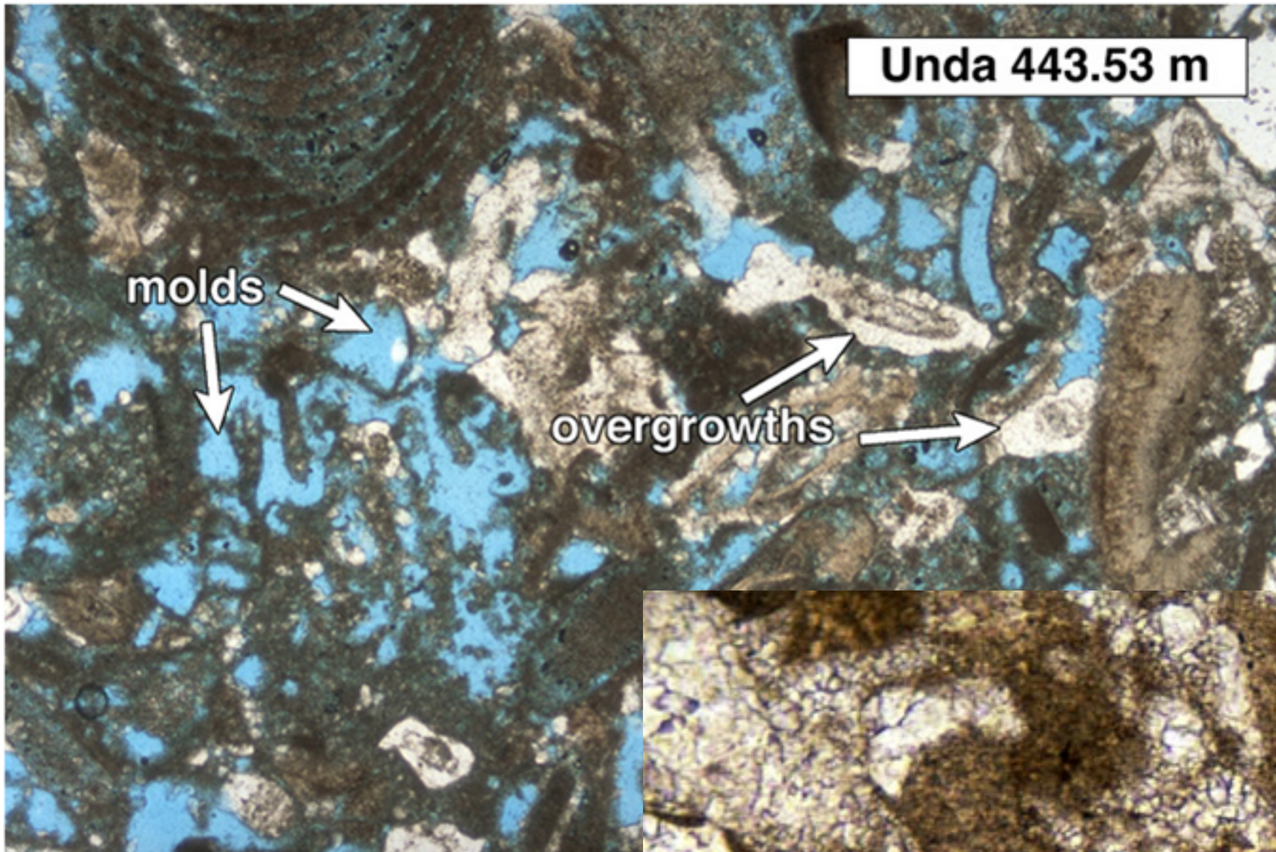


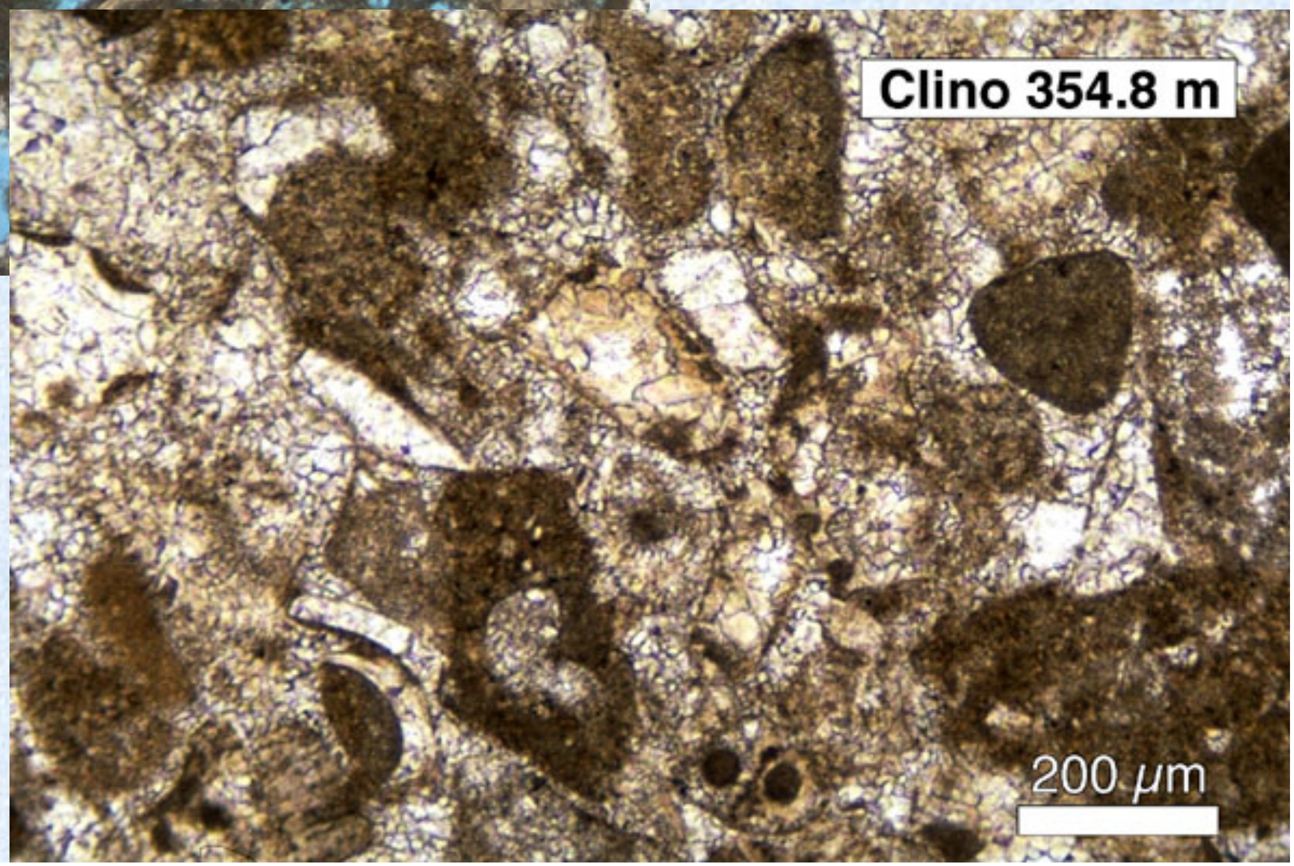
“Shallow” Seawater Burial Diagenesis





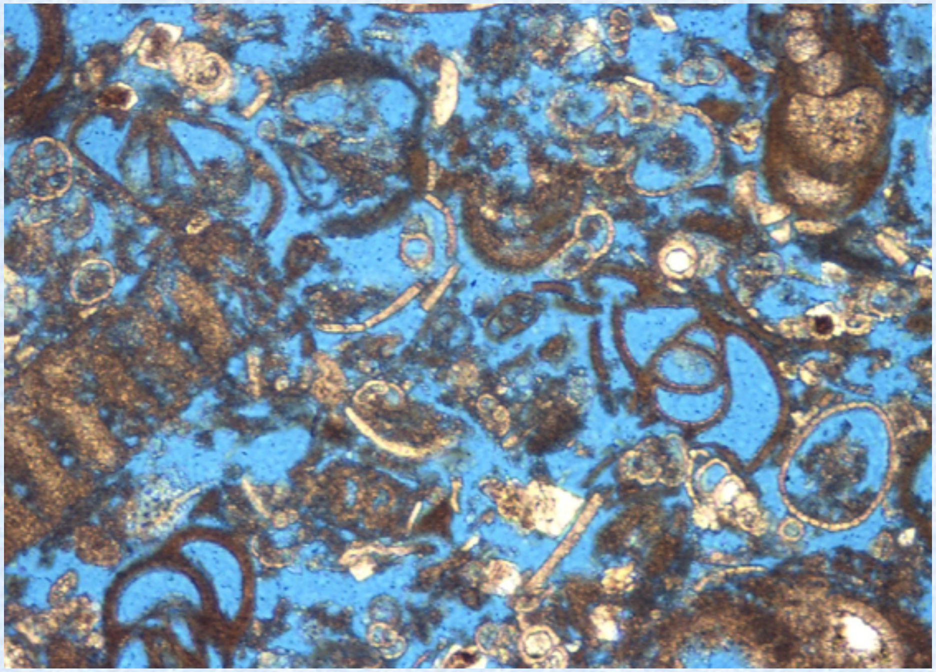
Seawater Burial Diagenesis



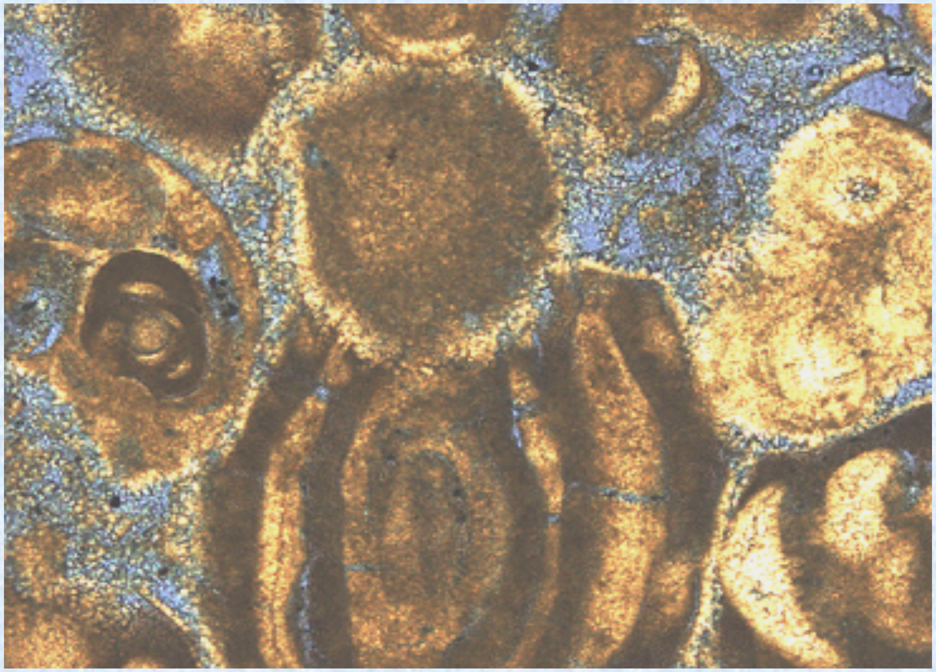


Melim et al 2001

Seawater Burial Diagenesis

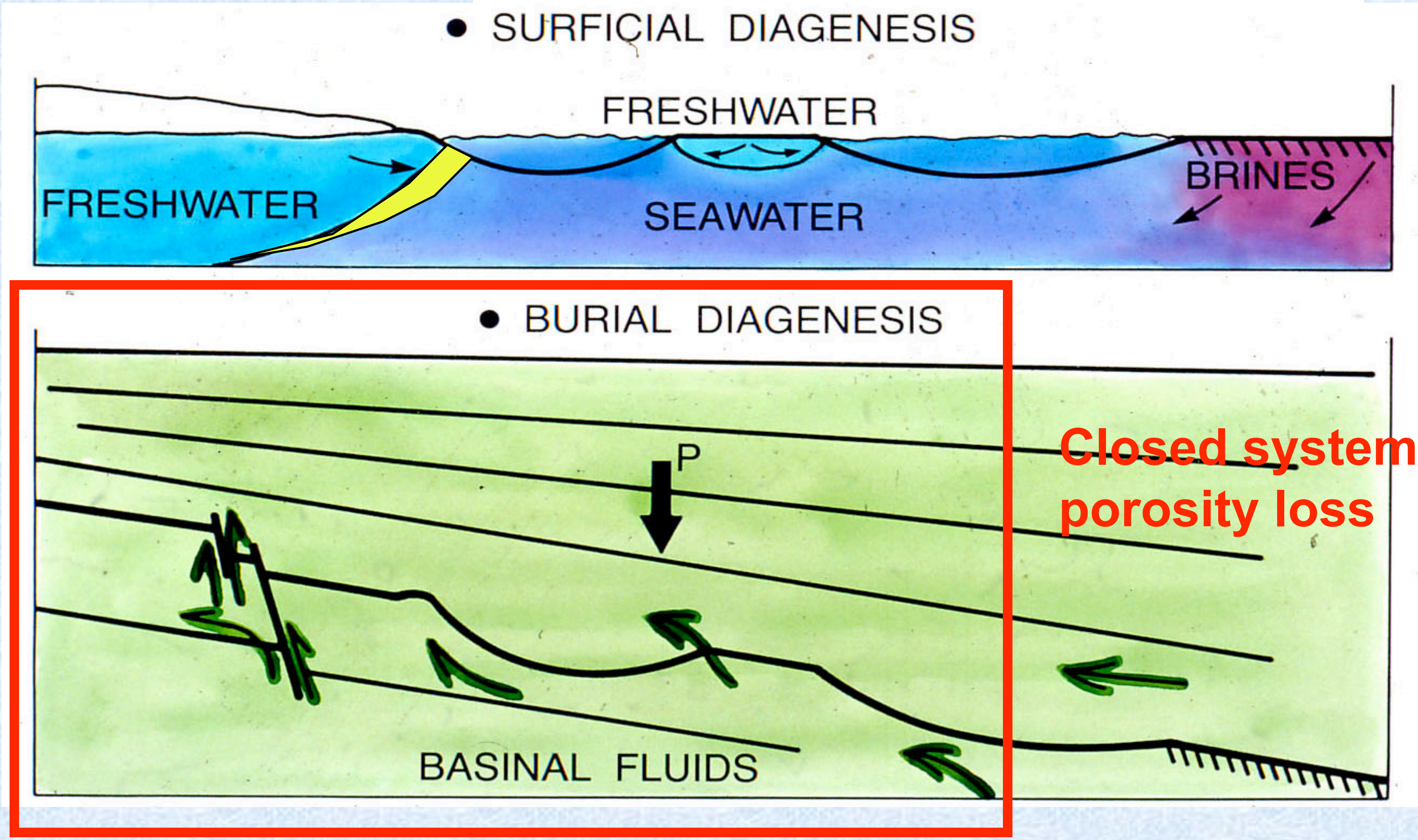


Eocene, Avon Park Fm, 140 m



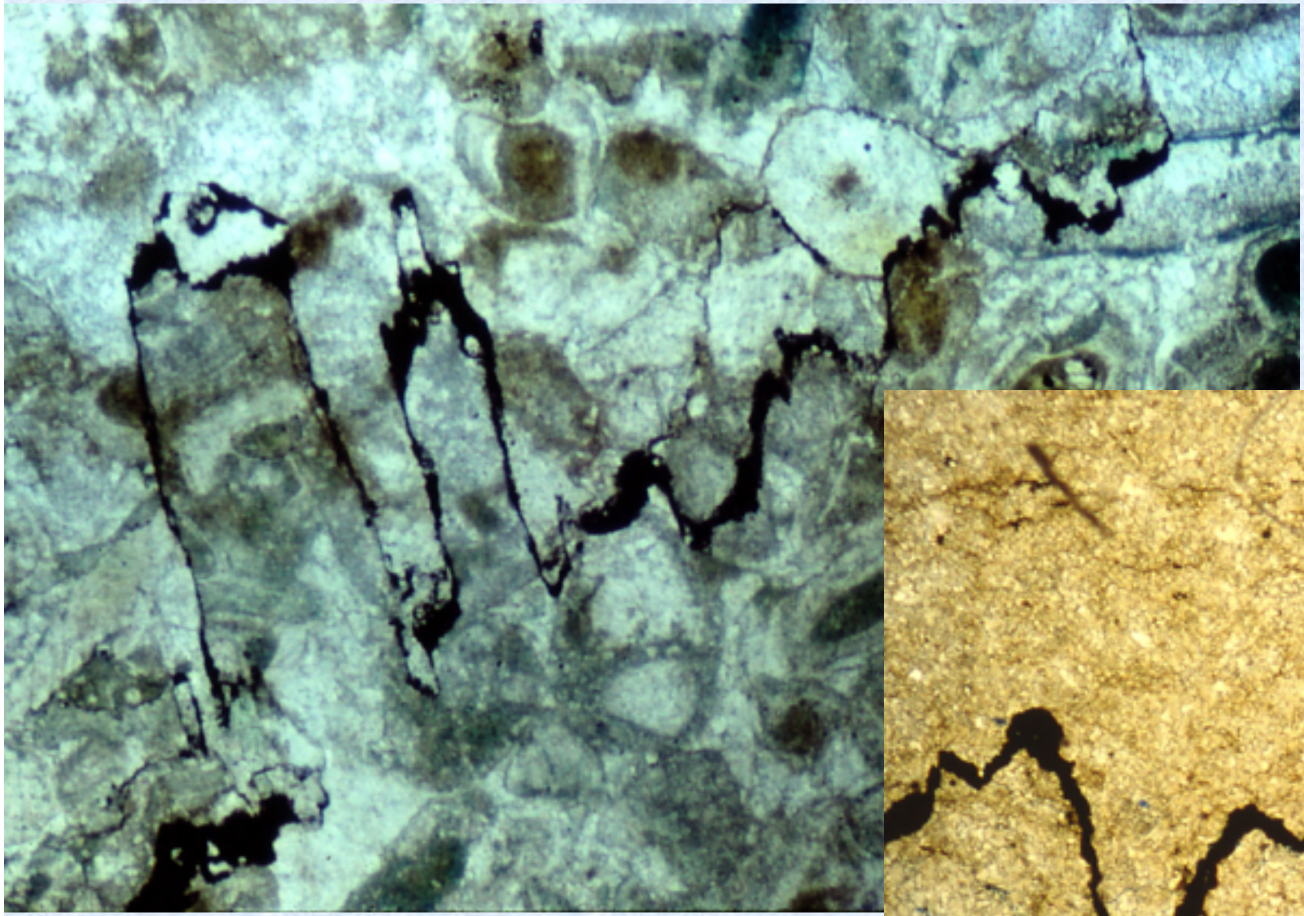
Eocene, Avon Park Fm, 390 m

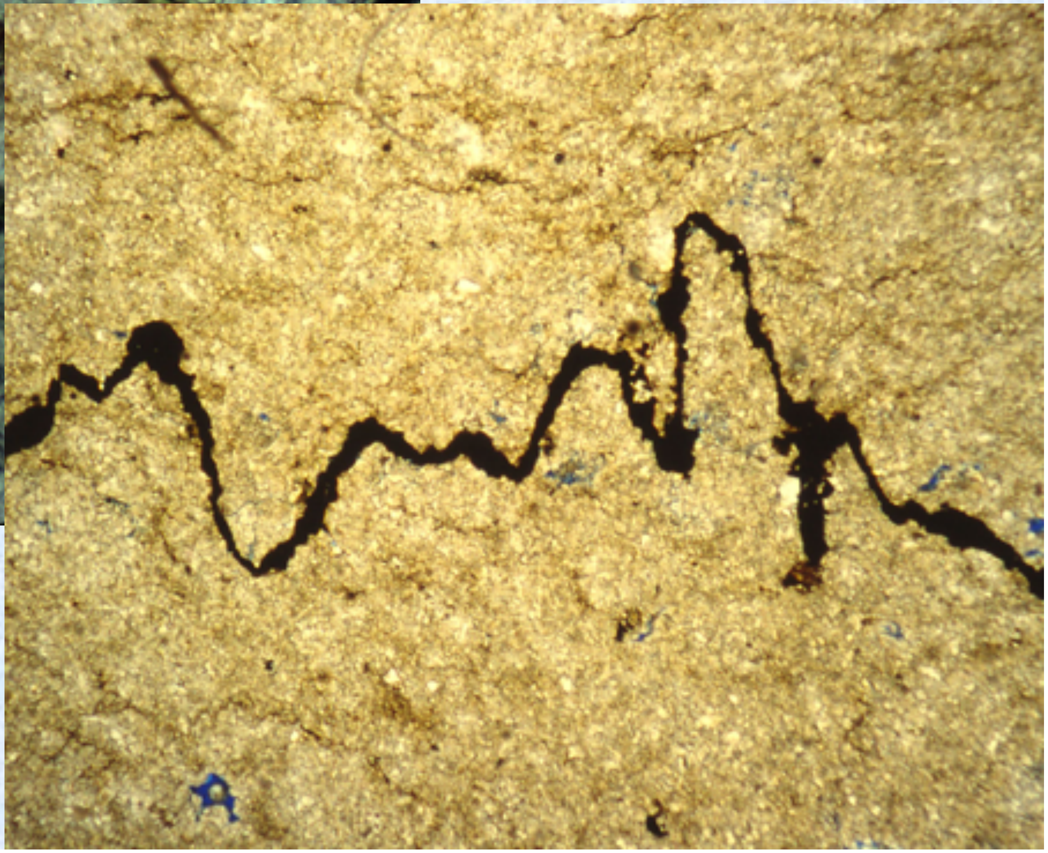
Diagenesis historically viewed in terms of hydrochemical regimes that generate internally consistent process-response dynamics



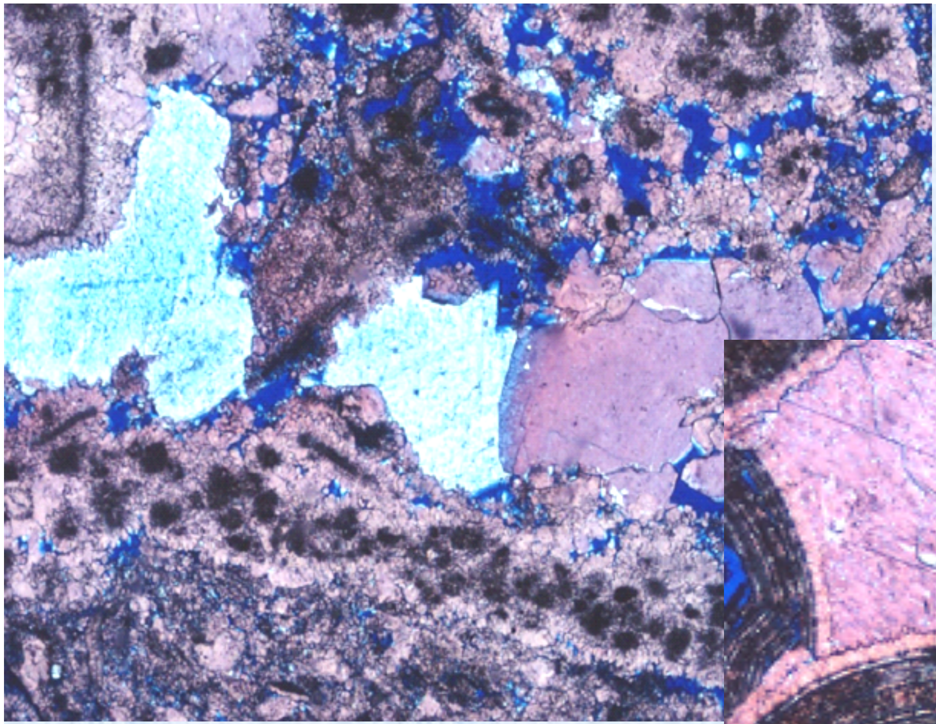
Closed system porosity loss

Pressure Solution

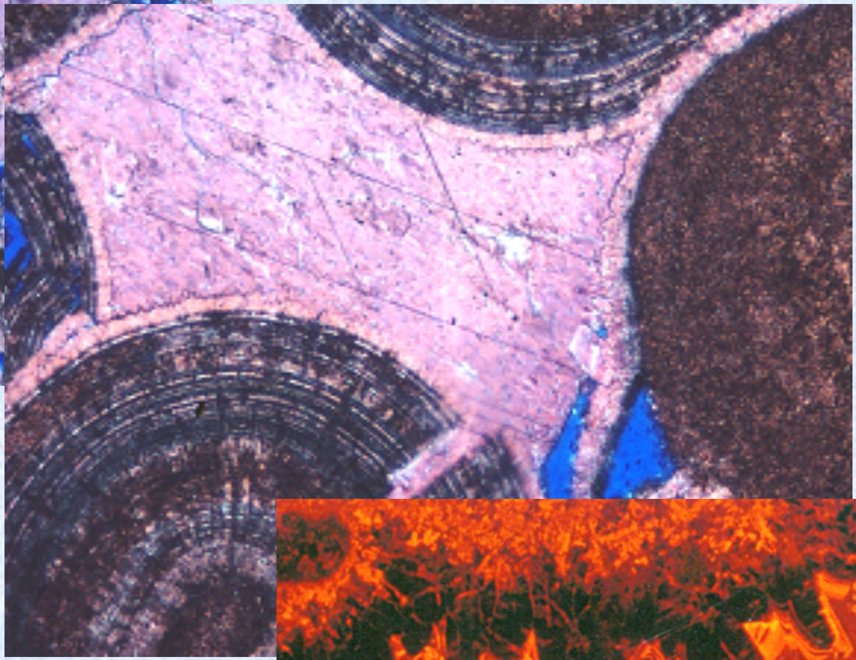




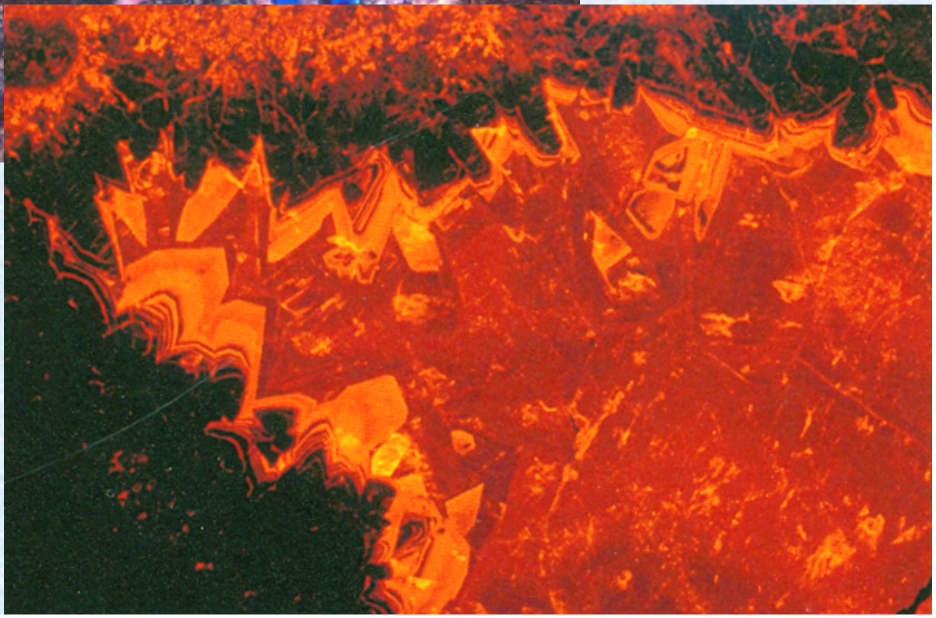
Deep Burial Cement



Pennsylvanian, Paradox Basin

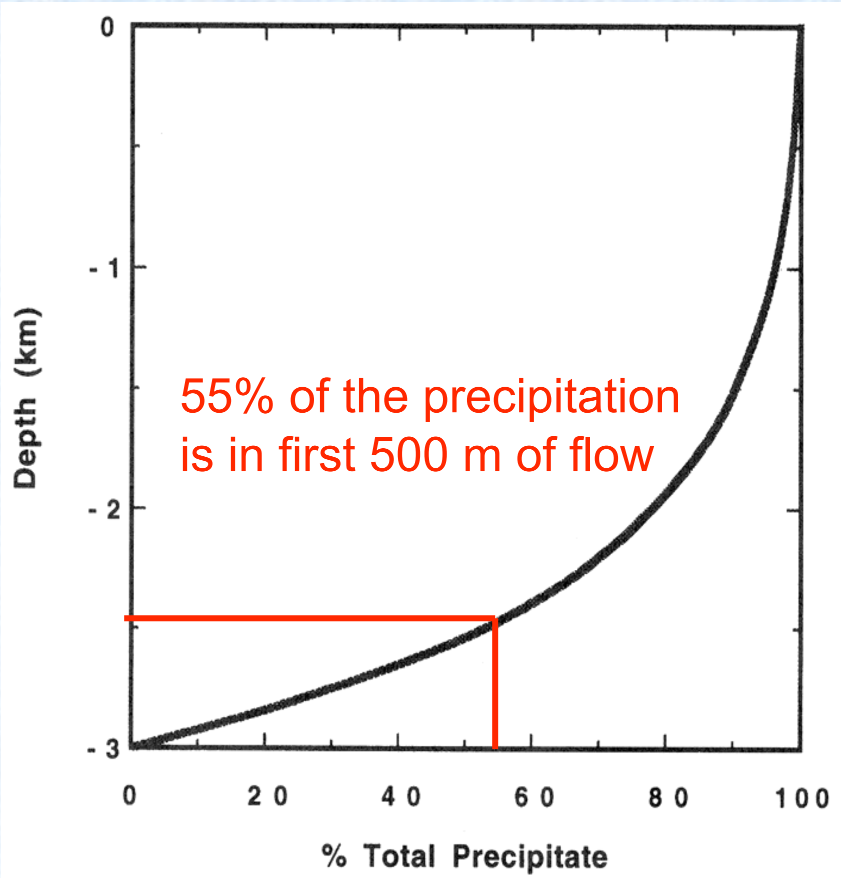


Jurassic, Smackover Fm.

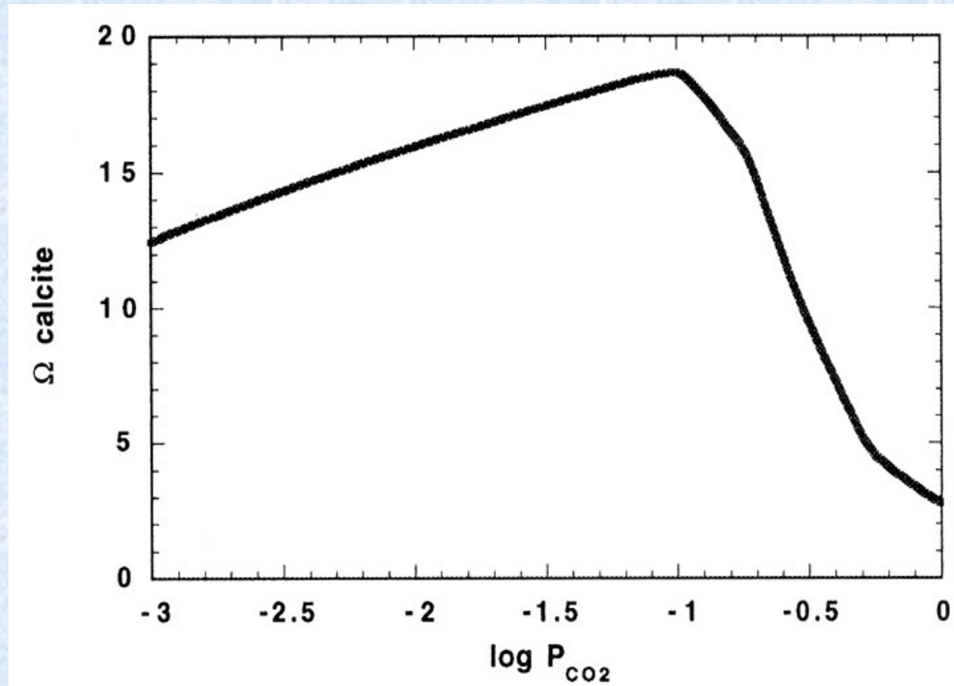


L. Cambrian, Labrador

Where calcite precipitates as 200,000 mgL^{-1} brine migrates from 100°C & 300 bars to STP



Supersaturation of a 200,000 mgL^{-1} brine at 100°C if pressure drops from 600 bars to 300 bars

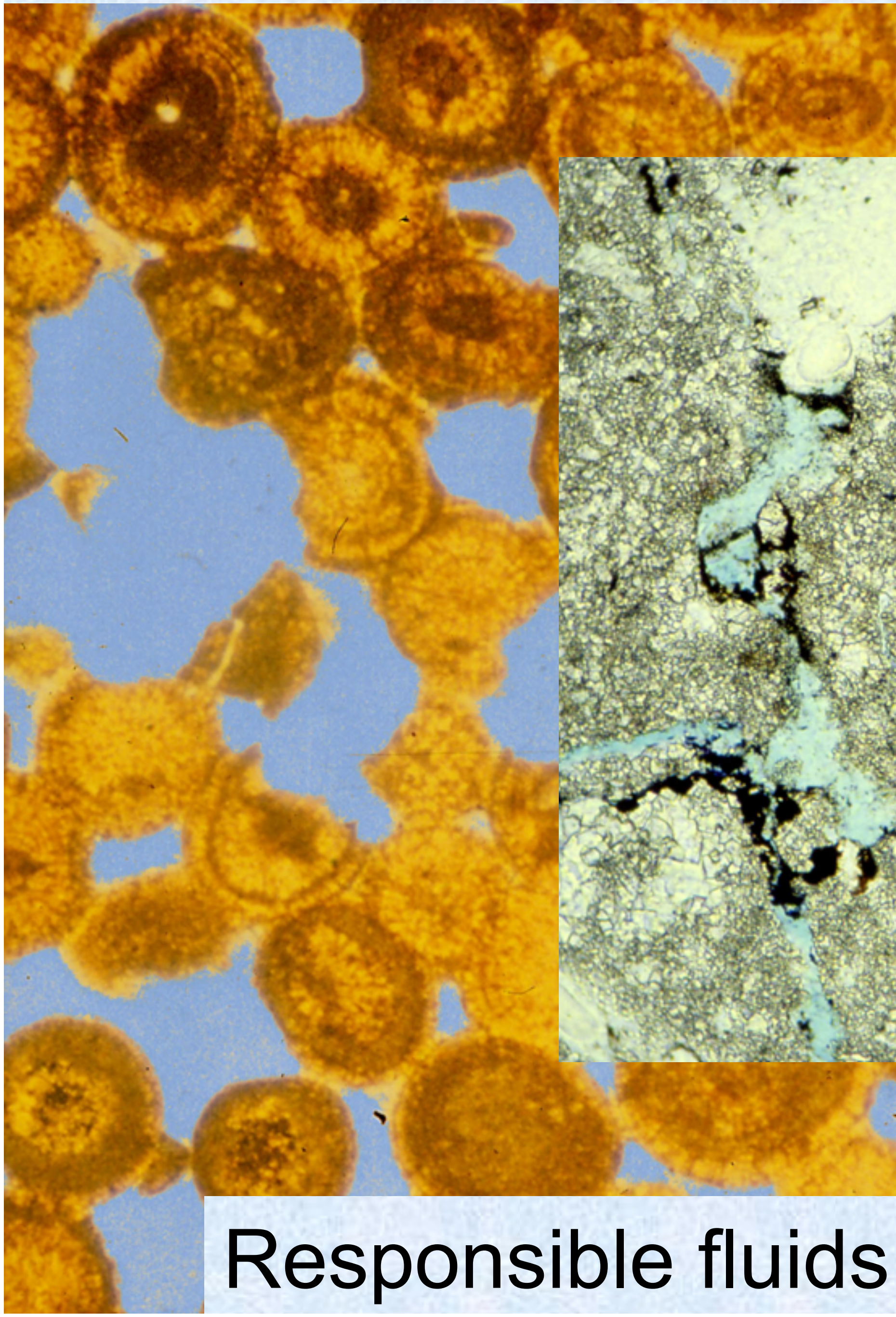


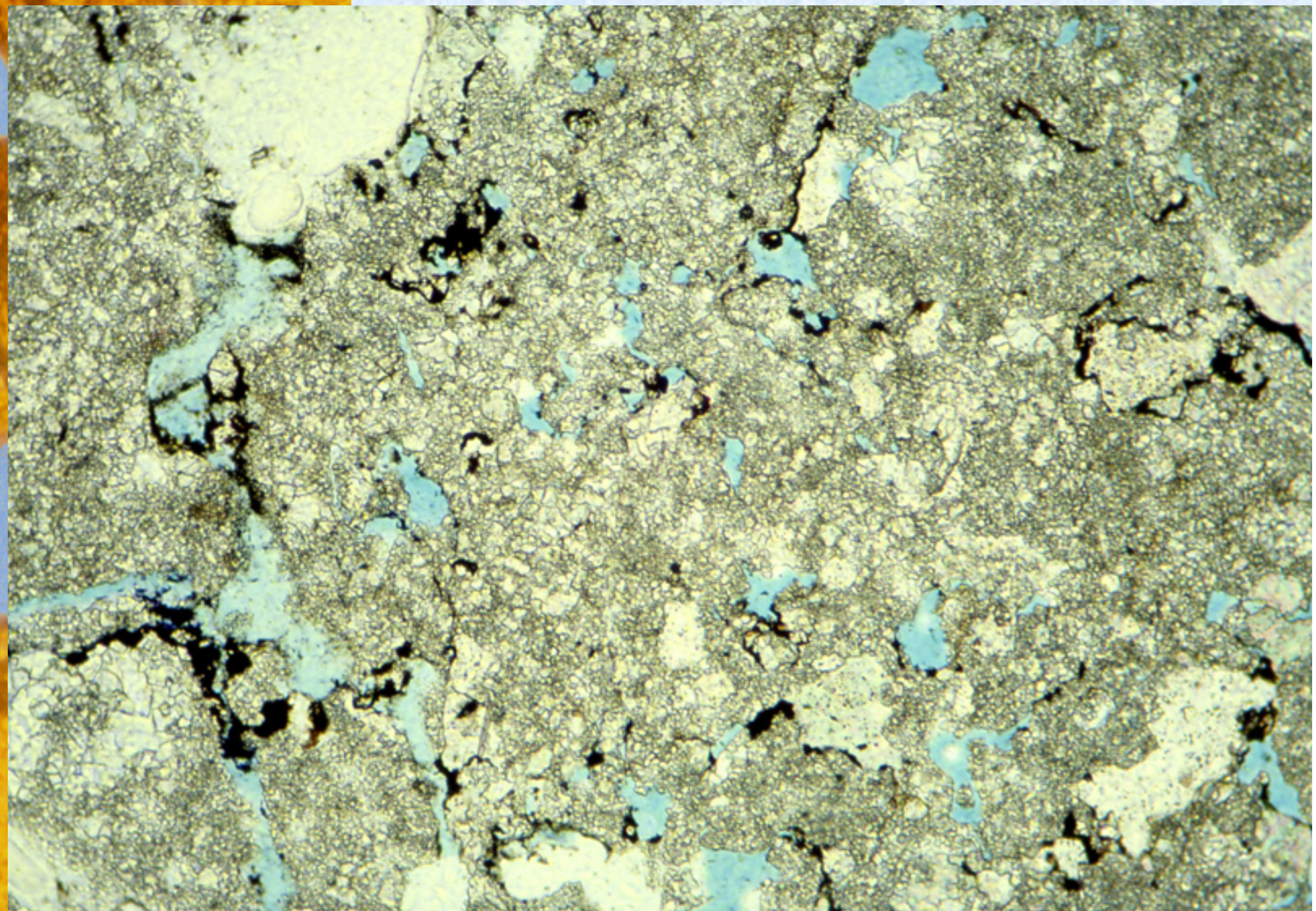
Implication

- **– deep cementation has strong linkage to abrupt vertical fluid flow**
- **- also to fluid mixing (convection cells?)**

Morse et al 1997

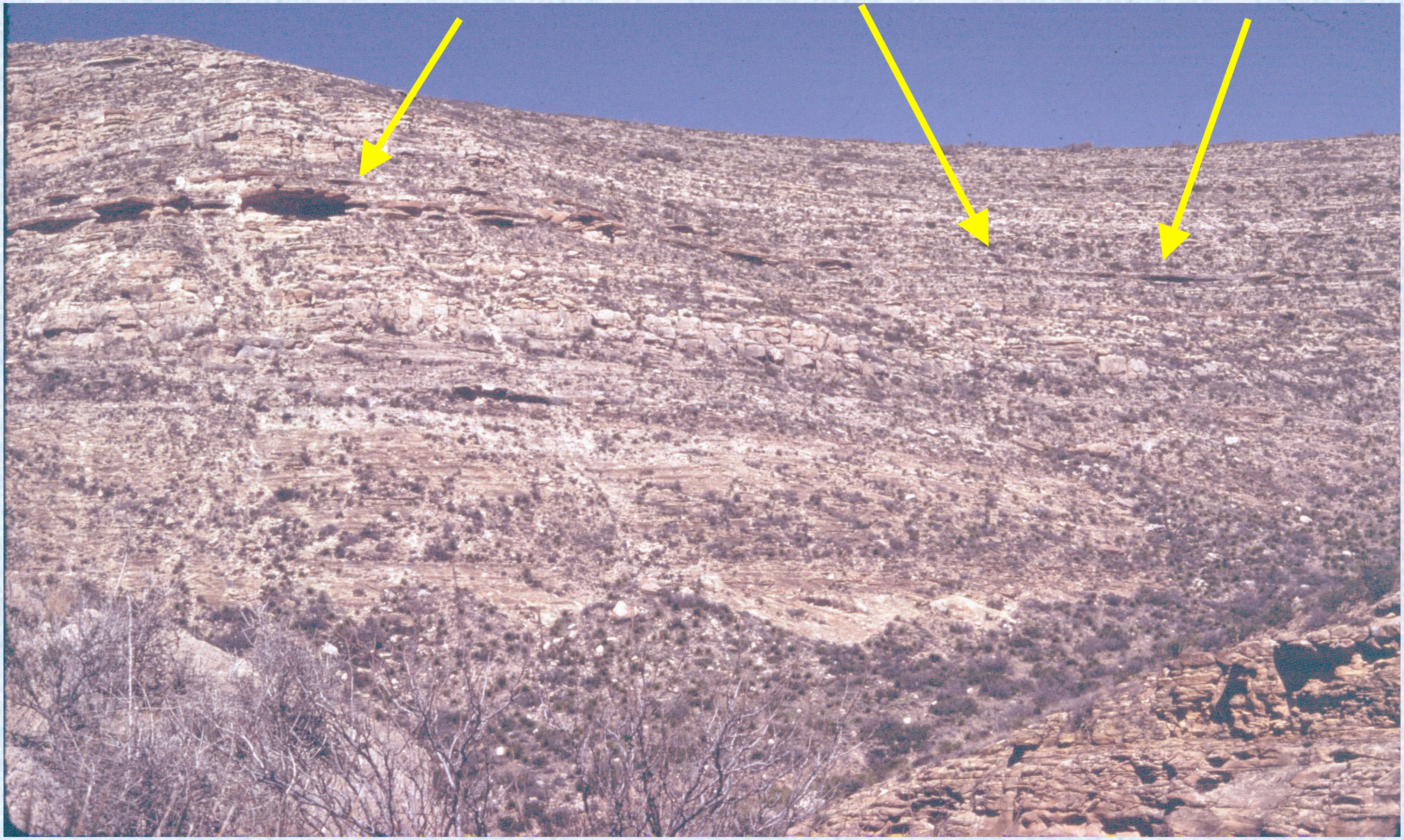
Dissolution



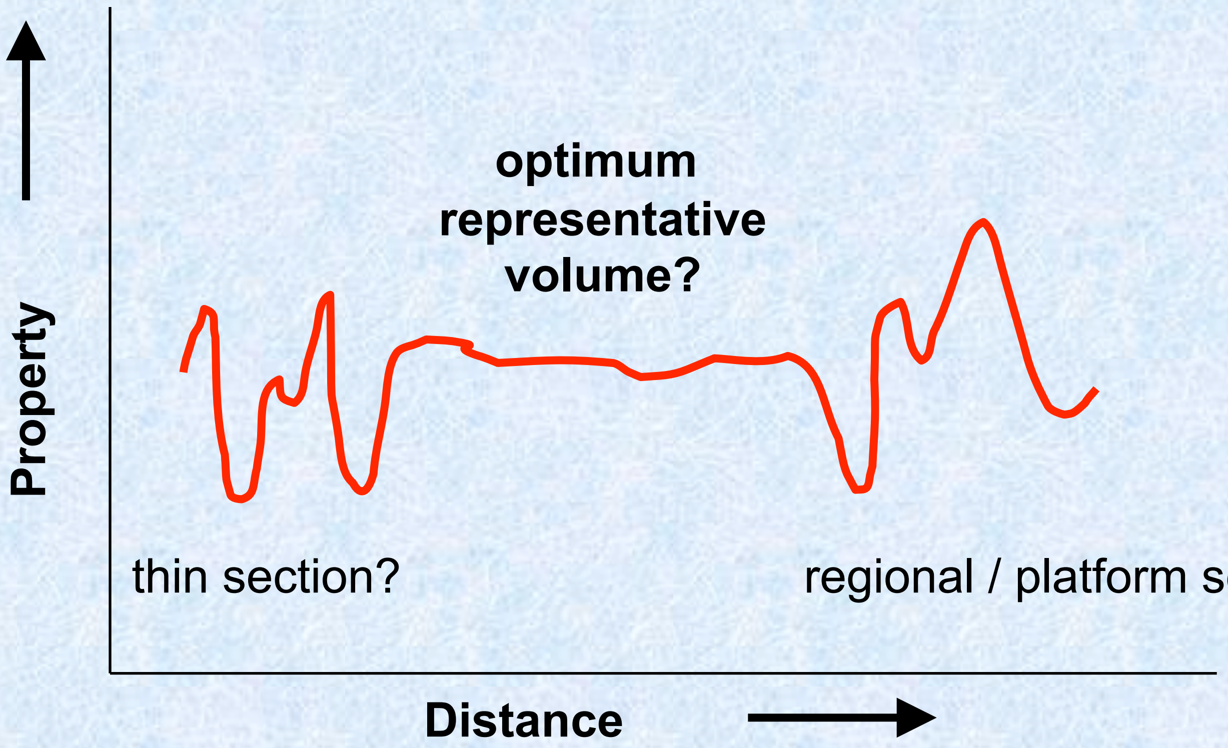


Responsible fluids / reactions still unclear.

Still unresolved for all these process – seafloor to deepest burial --- What happened "there" versus "there", or "there"?



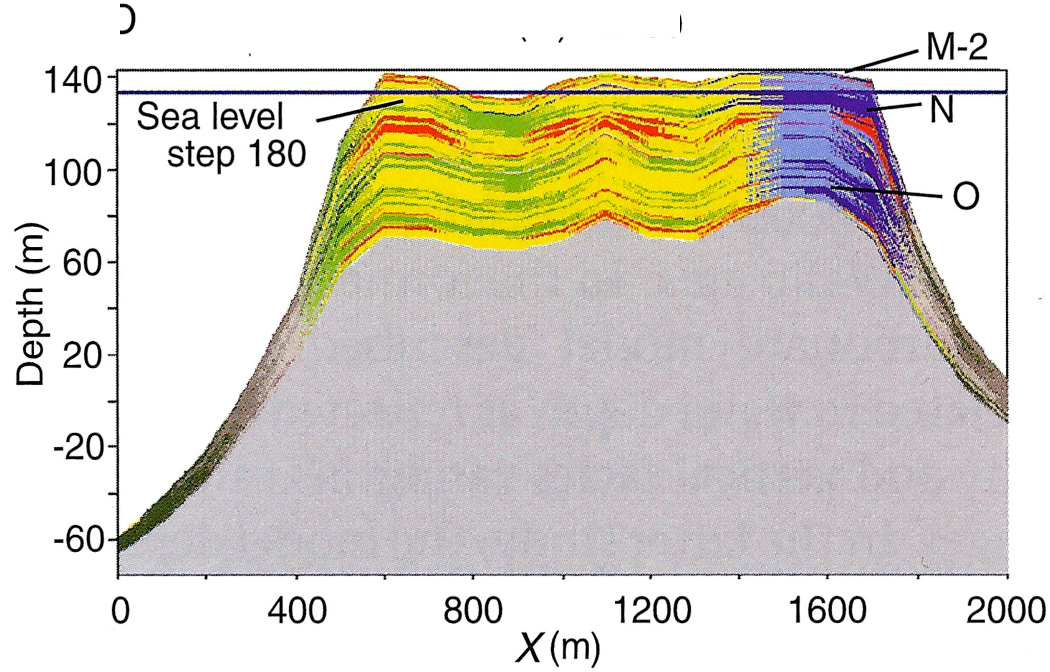
Is there an optimum scale at which to approach diagenetic modeling?



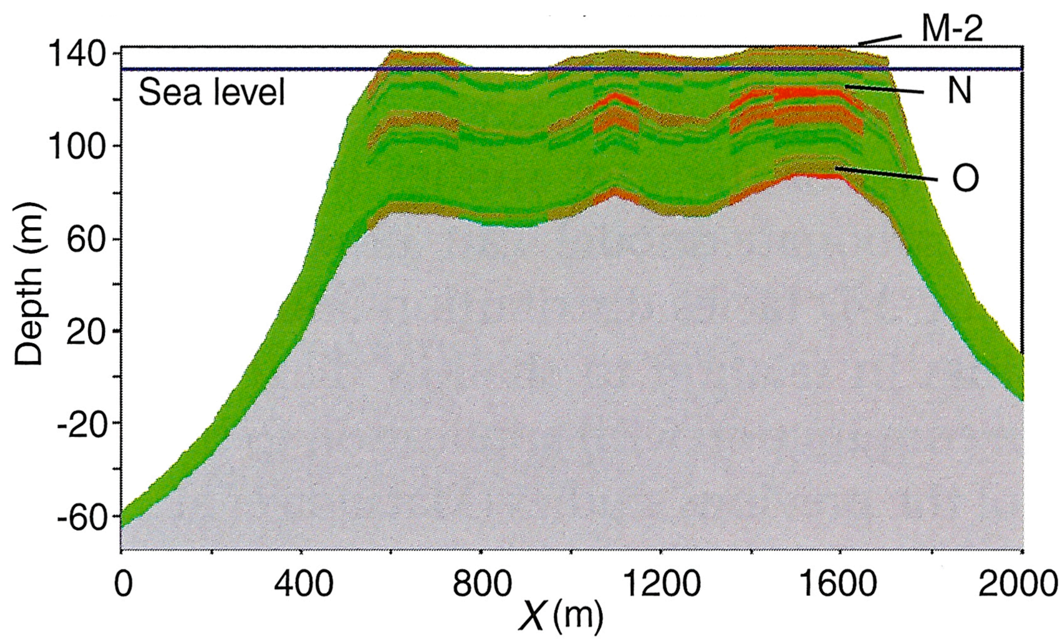
And if so, is that the scale of interest?

1 Current Modeling Approach

Coupled sediment production and sea level models to predict facies mosaics and exposure surfaces

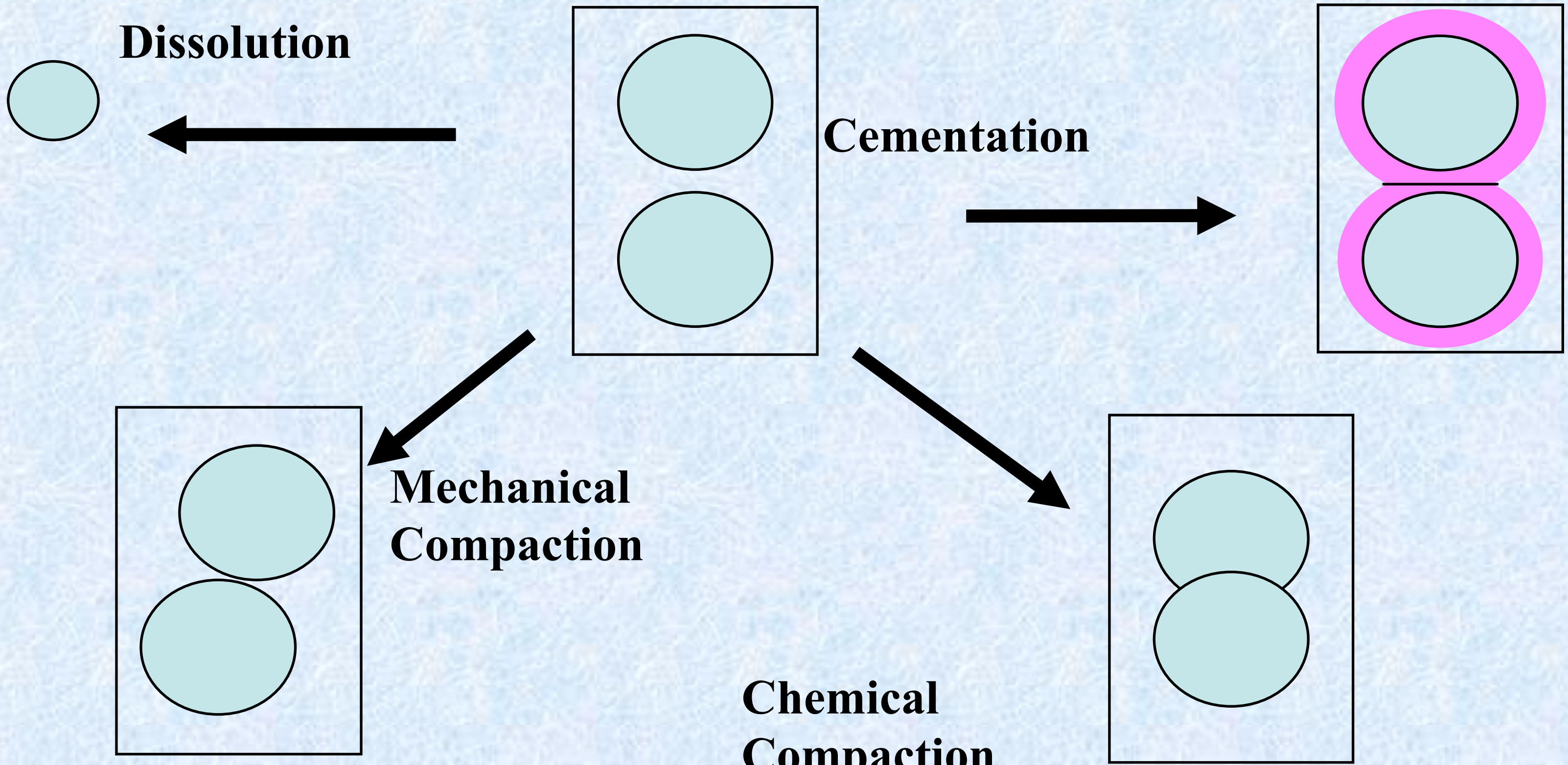


plus residence time in meteoric hydrozones, and thus diagenetic variability by inference



Matsuda et al., 2004

Can we track fabric dependent processes?



And if so, is that the scale of interest?

Summary Points

We know what diagenetic processes occur in various diagenetic settings

The conditions that drive most of those processes

The features that allow us to recognize those processes, conditions, and/or settings

---

Diagenetic systems are complex & non-linear with many types of interactions and feedbacks

But there is uncertainty regarding presence/absence of

- self-organization and/or scale invariance
- thresholds in feedback relations

Summary Points

Diagenetic alterations that affect sediment dynamics include

seafloor cementation & dissolution

denudation with exposure

There are many post-depositional alterations that can and do occur through time and stratigraphic space.

Critical questions to their modeling will be

scales of analysis (pore to regional)

linkage of reactions and transport processes through evolving temperature, pressure, & petrophysical regimes

dependence on fabric relations

And, with the exception of the "regional" and finest spatial scales, we don't really know lateral spatial patterns by which to evaluate model outcomes