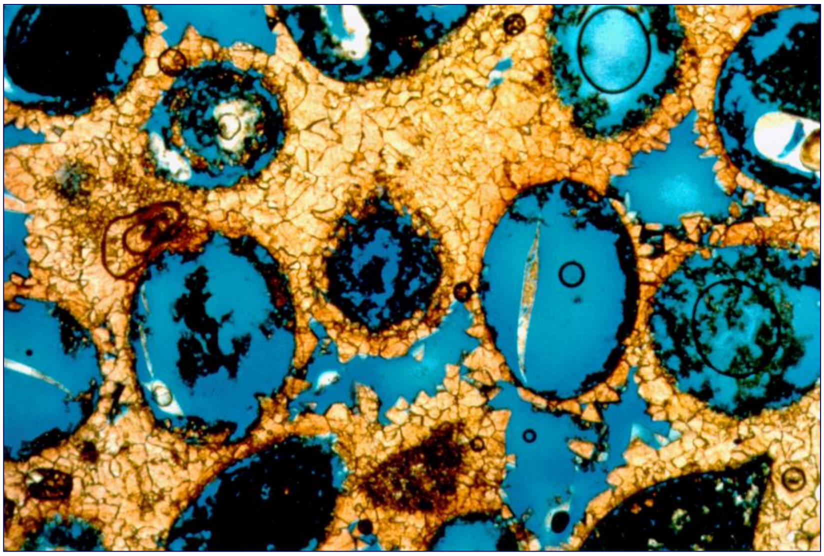
Carbonate Diagenesis: Pore Types

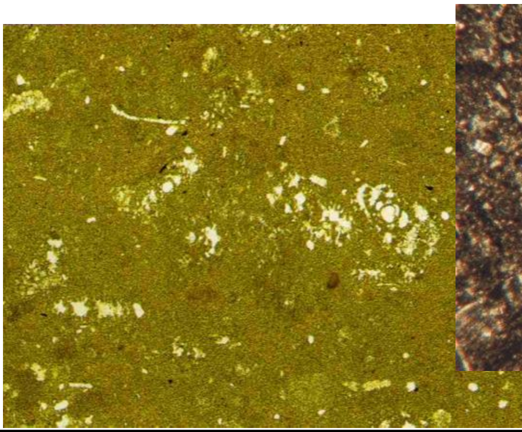


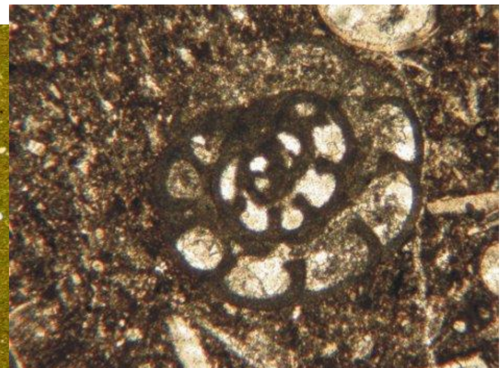
- Carbonates capable of ~ syndepositional cement (not predictable properties during burial compaction)!
- *Carbonates are extremely prone to diagenetic modification: reactions are also commonly reversible!!*

Recent, Marine Cemented Foreshore Strata - "Beachrock", Grand Cayman Island

Inden & Moore, 1983 (AAPG Memoir 33)

- Carbonates may show early recrystallization, generally of the fine grained elements first (e.g., micrite)
- The change of one mineral into another form of the same mineral (or one of a similar composition) is referred to as neomorphism - a type of replacement
- Where this change is accompanied by an increase in crystal size, this is called Aggrading Neomorphism (e.g., micrite to microspar 4-15 micron size)





Carbonate Pore Types

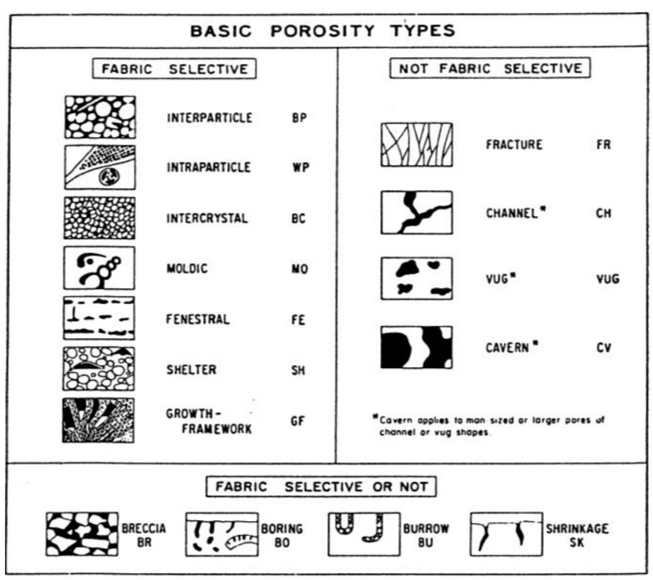
A major control on rock properties

Non-predictable relationships

Commonly multiple types (different influences on fluid flow)

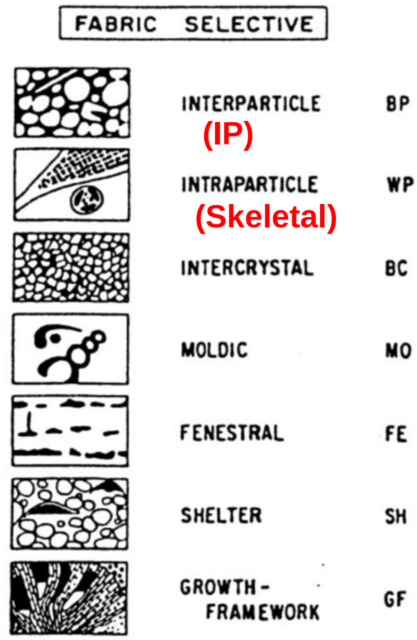
Types change through diagenesis (inversion is common)

Philip W. Choquette and Lloyd C. Pray



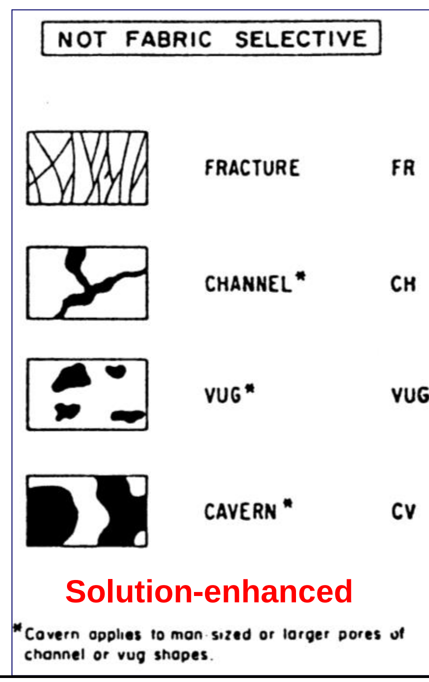
Carbonate Pore Types

- A major control on rock properties
- Non-predictable relationships
- Commonly multiple types (different influence on fluid flow)
- Types change through diagenesis (inversion common)

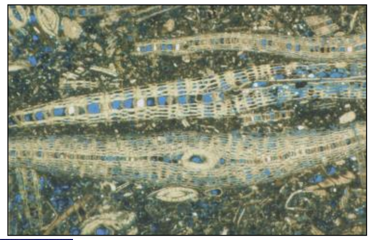


Carbonate Pore Types

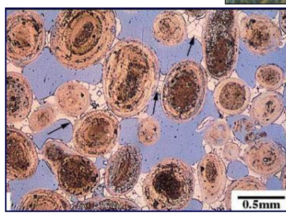
- A major control on rock properties
- Non-predictable relationships
- Commonly multiple types (different influence on fluid flow)
- Types change through diagenesis (inversion common)

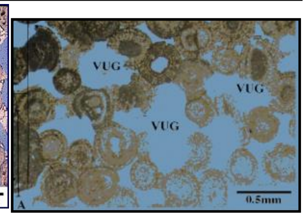


Pore types

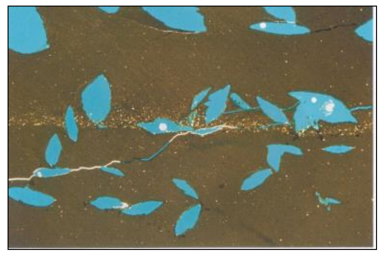


Primary
- Between (Inter) Particle (BP)
- Within (Intra) Particle (WP)
- Intercrystal
- Fenestral
- Shelter
- Growth Framework





Secondary
- Moldic (macro- and micro- Mo)
- Vuggy (V): Cavern or Breccia
- Fracture (F)
- Between Crystal (BC)
- Solution Enhanced…

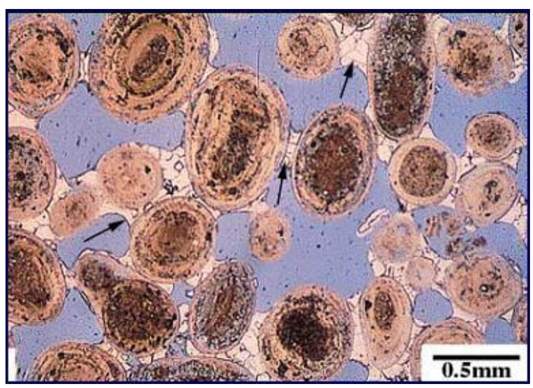


Pore Types

Interparticle

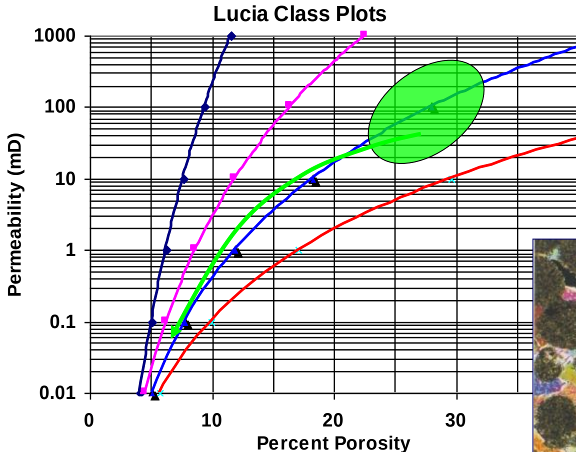
(Between Particle) (BP)

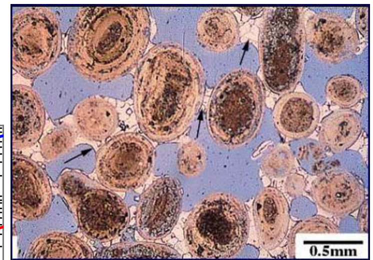
- Reflects Primary Fabric
- Best developed in well-sorted carbonate sands
- Commonly cemented early
- Predictable degradation with burial, if not cemented
- Most akin to siliciclastic sandstones

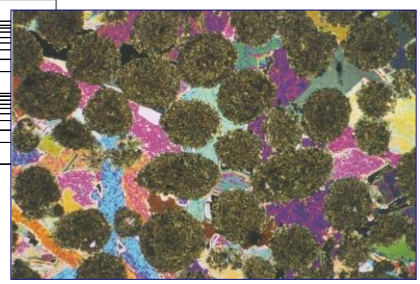


Pore Types

Interparticle (Between Particle) (BP)



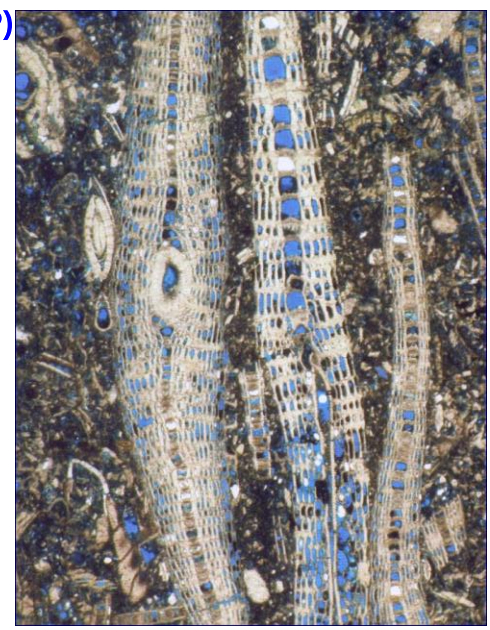




Typical case:
High P
High K

Pore Types: Intraparticle

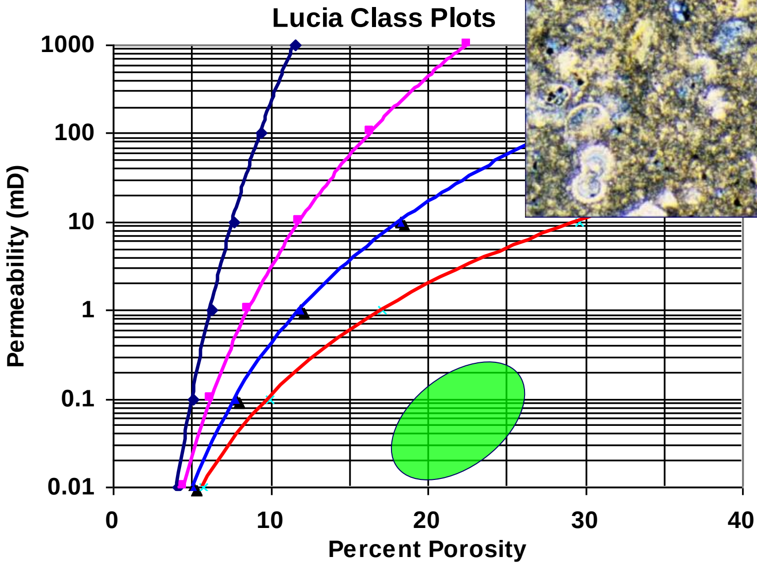
(Within Particle-Skeletal) (WP)

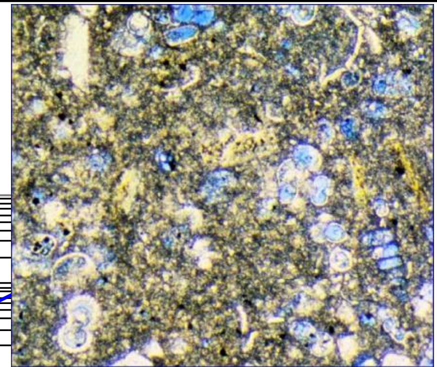


- Primary pore type
- Can be excellent, but needs a mechanism to connect the pores (e.g., solution enhancement)
- Best when there are abundant, large allochems with similar pore structure
- Pores tend to be isolated in mud-dominated units

Pore Types: Intraparticle

Within Particle-Skeletal (WP)



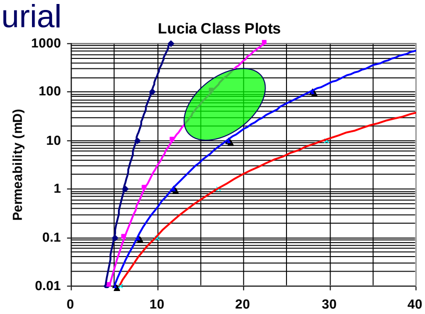


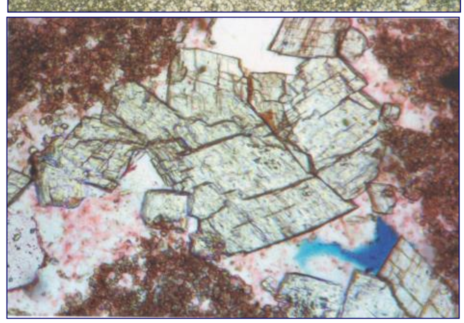
Typical case:
High P
Low K

Pore Types: Intercrystal

(Between Crystal) (BC)

- Similar character as BP, but *generally* secondary origin (esp. fine sucrosic dolomite)
- Properties strongly dependent on crystal size
- Important pore type with deep burial

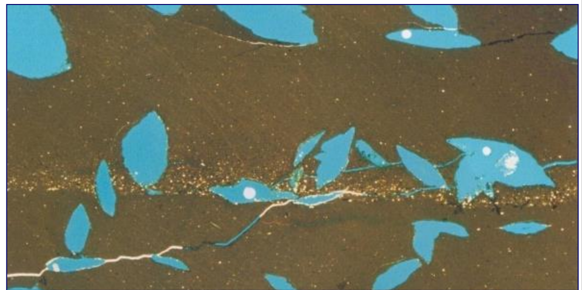


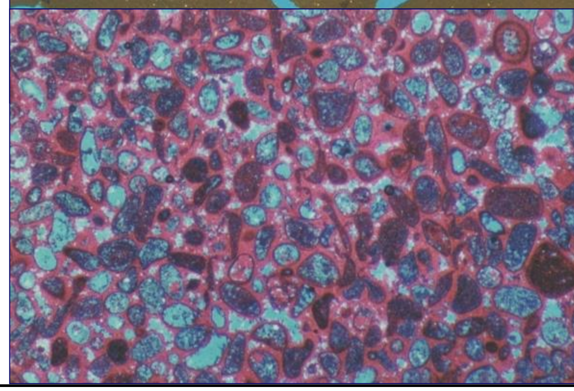


Typical case:
High effective P
High K

Pore Types
Moldic (Mo) Pores

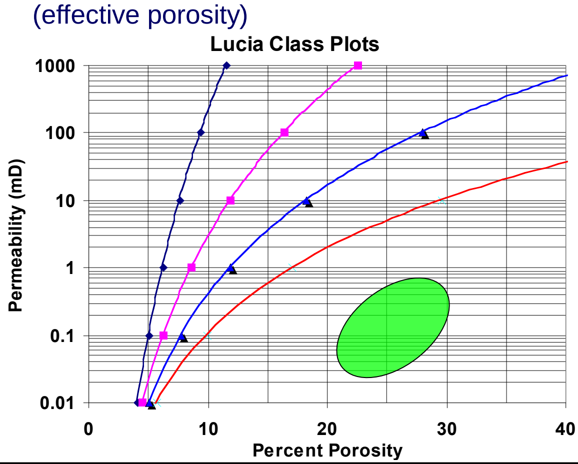
- Secondary pore type, fabric selective
- Dissolution of unstable grains/allochems (esp. aragonitic)
- May have high porosity, but generally poor permeability
- Excellent reservoir character when pores connected

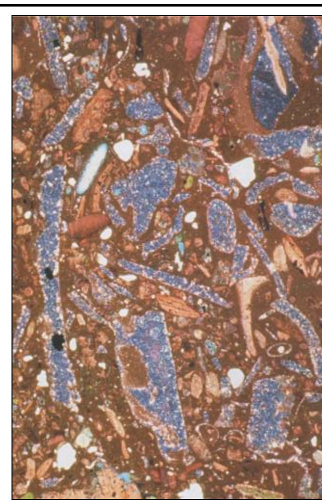




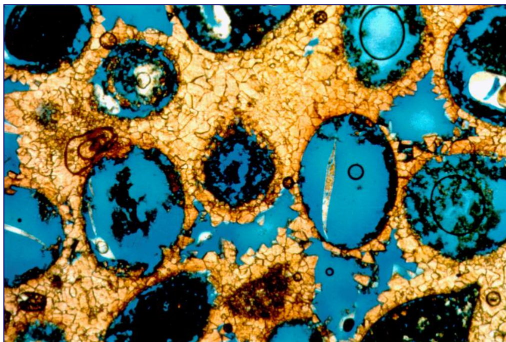
Pore Types
Moldic (Mo) Pores

- Dissolution of unstable grains / allochems
- May have high porosity, but poor permeability
- Excellent reservoir when pores connected (effective porosity)



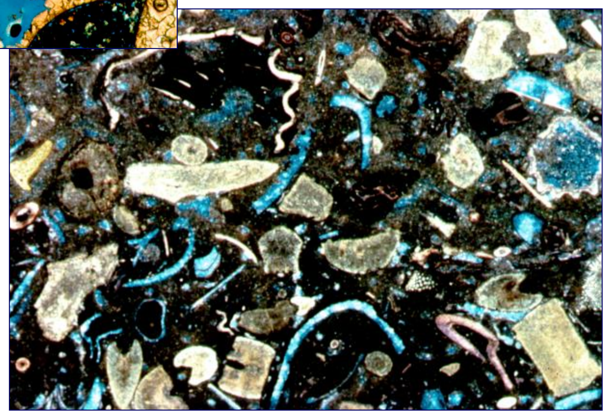


Typical case:
High ineffective P
Low K



Oomoldic and Skelmoldic Porosity

Moldic porosity is not diagnostic of any one particular diagenetic environment.



Pore Types

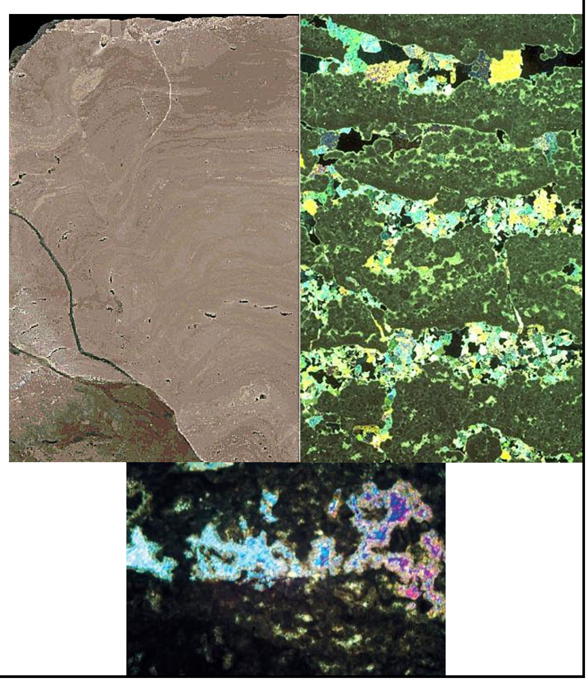
Fenestral (FE) Pores

- Fenestral Pores: cavities from trapped gas bubbles, commonly associated with organic-rich, lagoonal muds

- Primary pore type and fabric selective

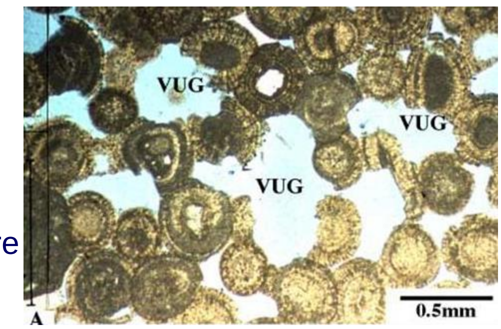
- Pores lens-shaped, poorly connected, but commonly associated with dolomitization and intercrystal porosity

- May be filled early on by gypsum or calcite

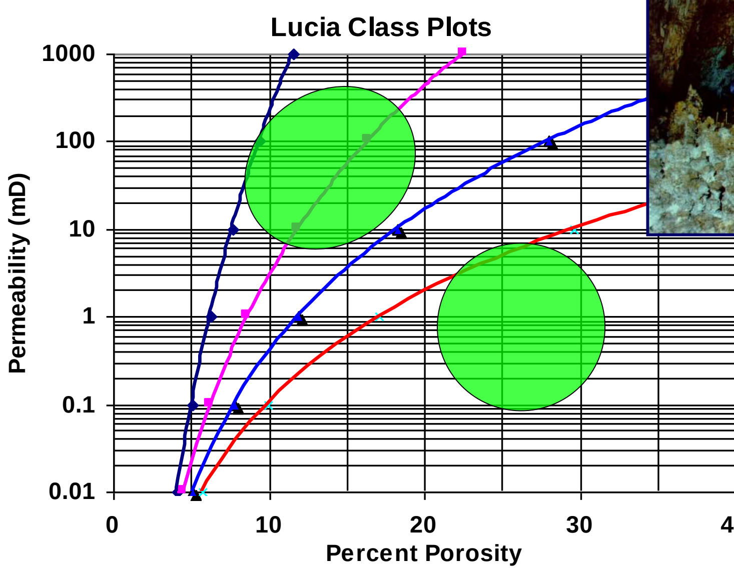


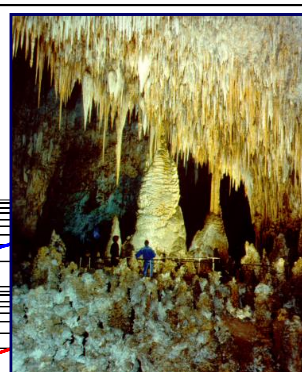
Pore Types
Vug (V) - Cavern

- Secondary pore type, not fabric selective
- Commonly begins as a mold, then enlarges due to carbonate dissolution
- Allochem-sized to arena-sized "pores"
- If large, generally collapse with progressive burial (forming fracture /breccia porosity)
- Commonly connect other pore types!



Pore Types
Vug (V) - Cavern





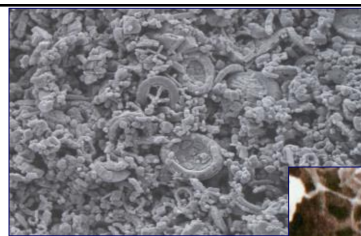
Typical case:
Low P
High K

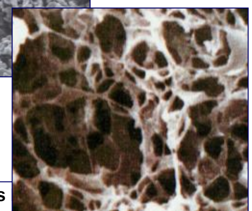
through

High P
Mod K

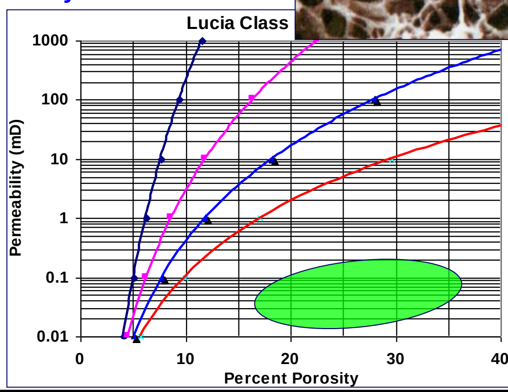
Pore Types
Microporosity (μM)

- Not visible in core, possibly visible in thin section
- Both primary and secondary; may be fabric selective or not selective
- Includes micro-BP and micromoldic
- Excellent porosity, but generally low permeability (bound H_20)
- Chalks/'chalky' porosity



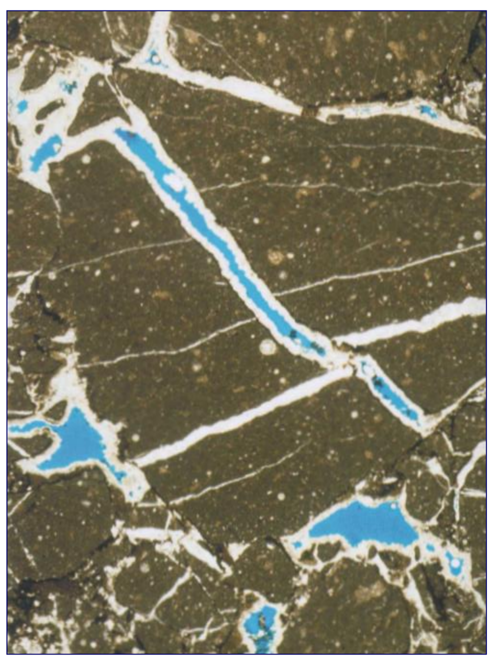


Typical case:
High P
Very low K



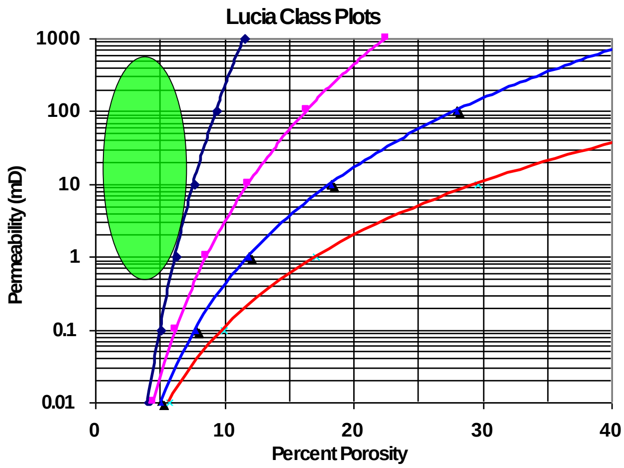
Pore Types
Fracture (F)

- Secondary Pore Type
- Generally non-fabric selective
- Typically associated with burial / compaction or tectonic stress
- Commonly multiple generations, some filled with cement
- Important influence on flow properties of reservoir



Pore Types
Fracture (F)

- Difficult to verify in core/cuttings/seismic
- need high-end wireline logs

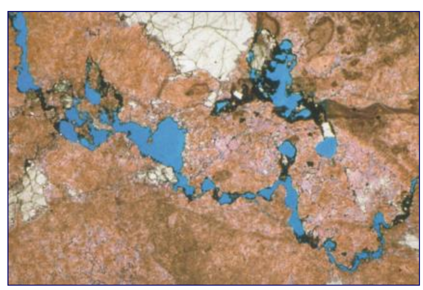


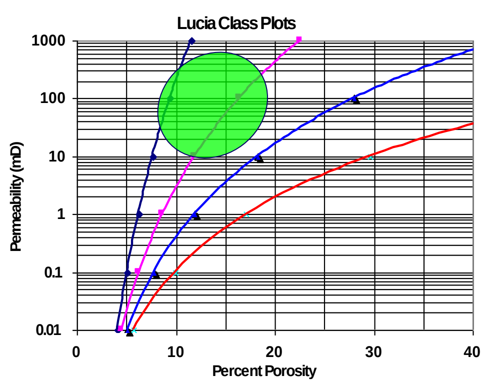
Typical case:
Low P (negligible effect
Very high K

Pore Types: Any may be Solution Enhanced!

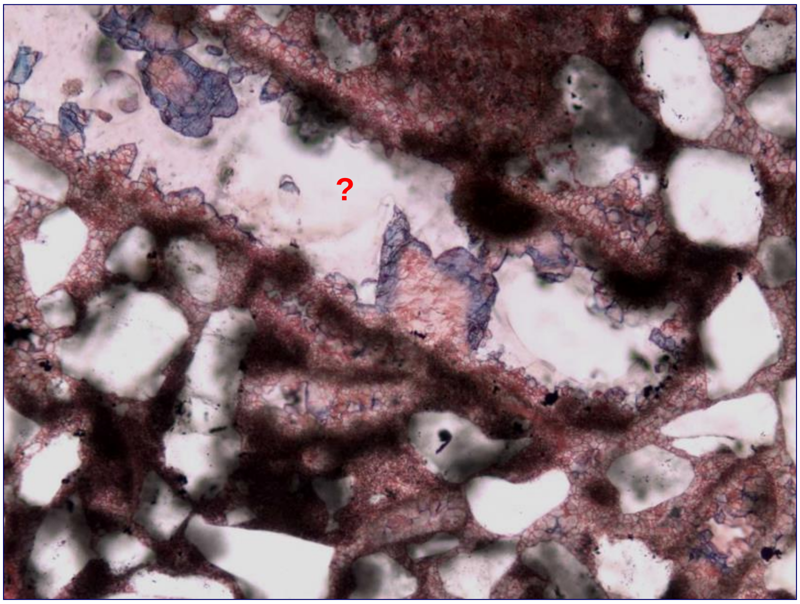
- Secondary Pore Type
- May be associated with exposure surfaces or compaction elements
- Commonly associated with vugs
- Typically important flow conduits that connect other pore types (best reservoir properties)
- May concentrate fluid flow to excessive degree (sweep issues)

Typical case:
Low P
High K



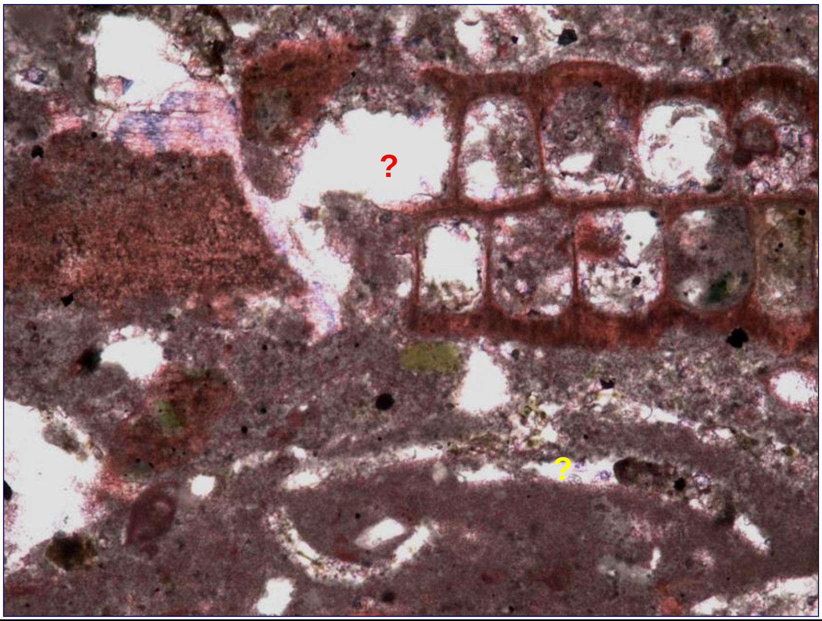


Carbonate Pore Types

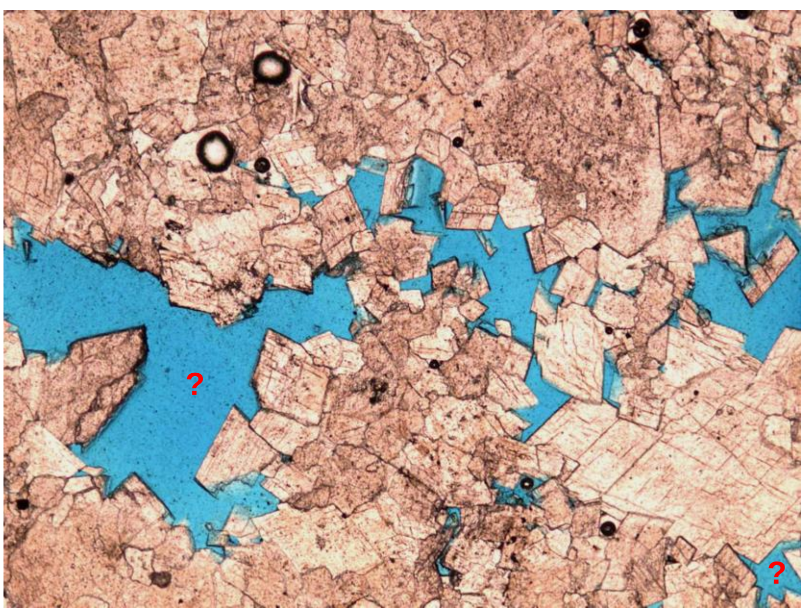


Carbonate Pore Types

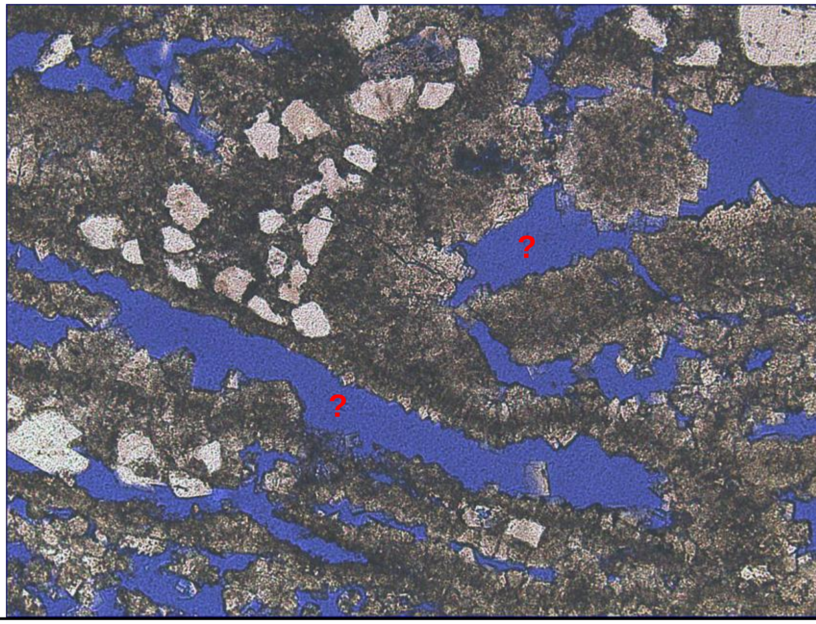
Carbonate Pore Types



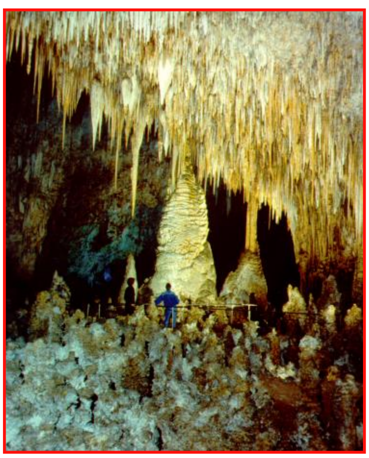
Carbonate Pore Types



Carbonate Pore Types



Diagenetic Processes: Dissolution



Dissolution = cement source!

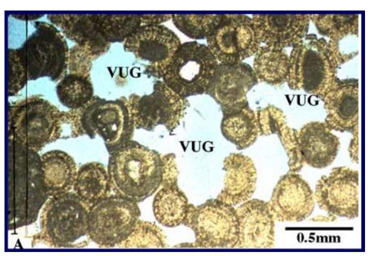
Pore fluids undersaturated relative to host rock

Any stage of burial history

Porosity enhancement:
- moldic (<1 mm) to cavernous (100s m)

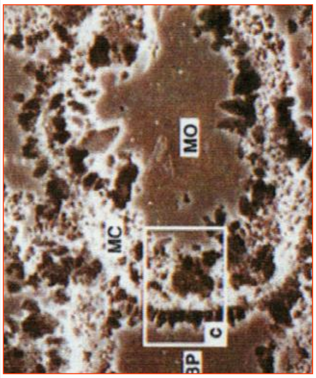
Permeability enhancement:
- dependent on vug connectivity

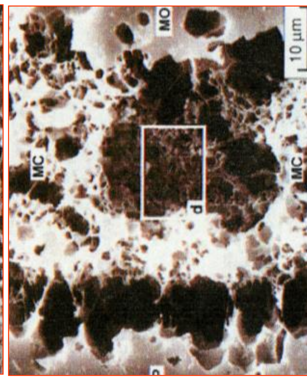
Early: fabric selective: more likely vugs unconnected
Late: non-fabric selective: more likely vugs connected



Moore, 2001

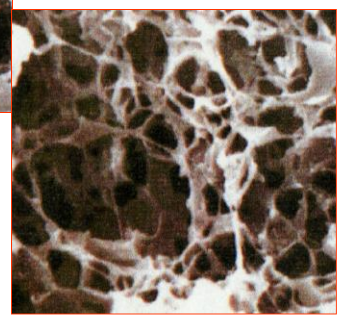
Diagenetic Processes: Microporosity





Pores < 10 micrometers

Microporous grains
Microporous matrix
Microporous cements

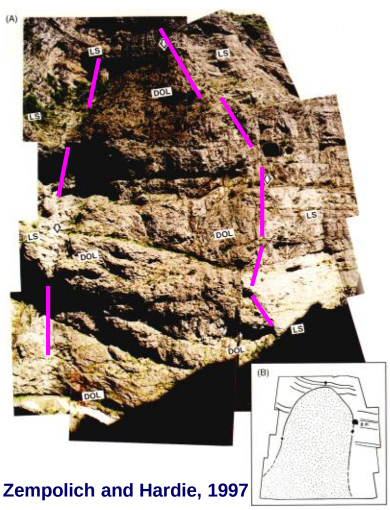


Mechanisms:
Leaching and incomplete mineral stabilization
Crystal growth contact inhibition

Rocks: Abundant bound water in micropores

Cantrell and Hagerty, 2002

Diagenetic Process: Dolomitization



Zempolich and Hardie, 1997

$2(CaCO_3) + Mg^{2+} \rightarrow CaMg(CO3)_2 + Ca^{2+}$

Most by replacement - direct precipitation rare

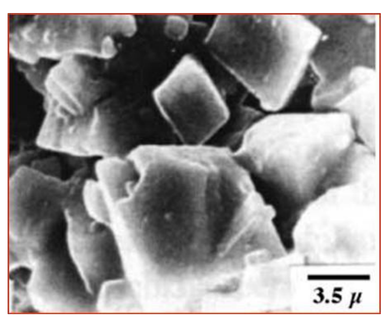
Requires a source of Mg^{2+} ions

Requires an efficient flow mechanism

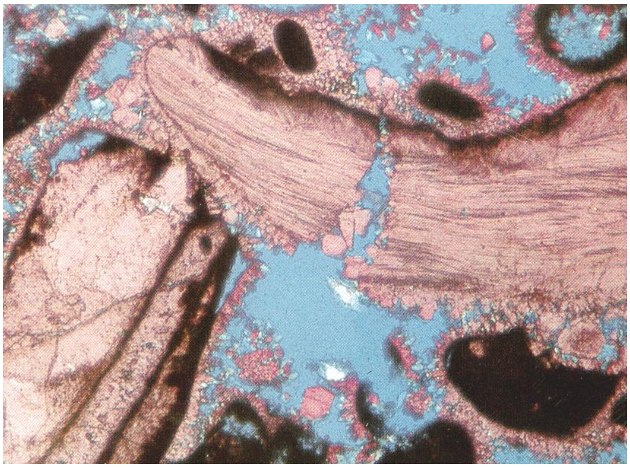
Substantial kinetic barriers

Diverse range of models, environments, fluids

DOES NOT ALWAYS INCREASE POROSITY
Variable effect on rocks
Resistive to compaction (cf. limestone)

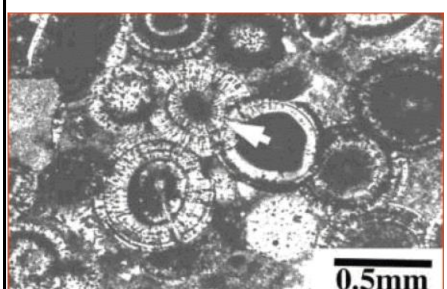


Diagenetic Processes: Mechanical Compaction



Begins shortly after burial with dewatering
Contemporaneous with early cementation
Rotation, repacking and fracturing of grains
Negative impact on porosity of rocks

Diagenetic Processes: Chemical Compaction



Moore, 2001

(Pressure Dissolution)

Starts ~ 300 m; Stylolites ~ 600 m

Sutured grain contacts

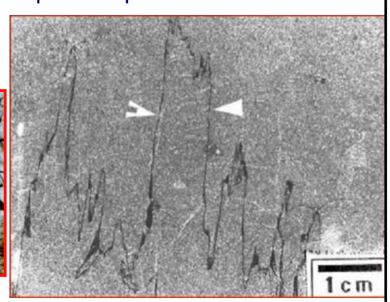
Dissolution seams - **Stylolites**: Most cases show about 25% reduction of section, but has been estimated to reach 90%! Estimated by concentration of insoluble material along stylolite surface

Syntaxial and poikilotopic cement fabrics

Major Negative impact on rocks

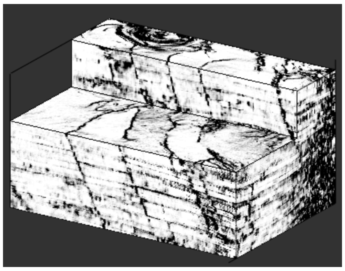
Syntaxial

Poikilotopic



Moore, 2001

Diagenetic Processes: Fracturing



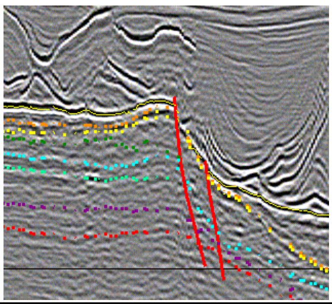
Many carbonates are fractured….

Mineralogy and early cementation = brittle

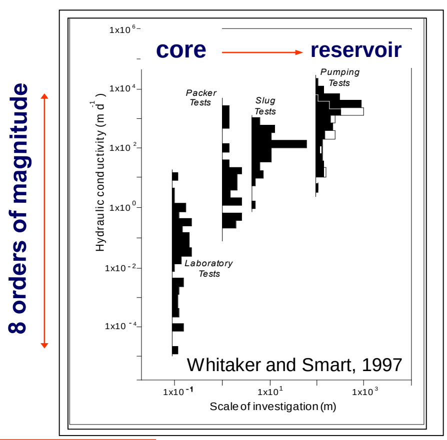
Can occur throughout burial history

Mechanisms: Differential compaction, faulting, solution collapse, salt movement, hydraulic fracturing

Major effect on rocks, especially permeability

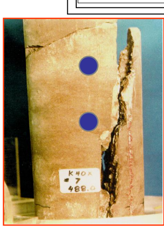


Diagenetic Processes: Fractures and "Excess" Permeability

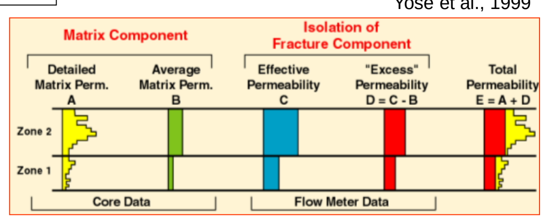


Core plugs used to measure matrix permeability tend to underestimate reservoir scale permeabilities

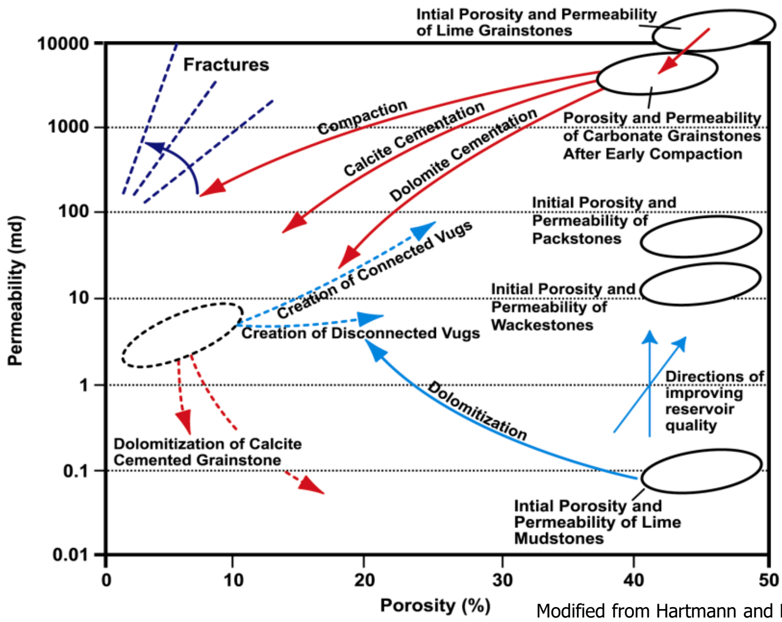
The "excess" permeability can be many orders of magnitude greater than that of the matrix!!



Yose et al., 1999



Diagenetic Processes: Impact on Reservoir Quality



Modified from Hartmann and Beaumont, 1999

Cement Distribution Summary

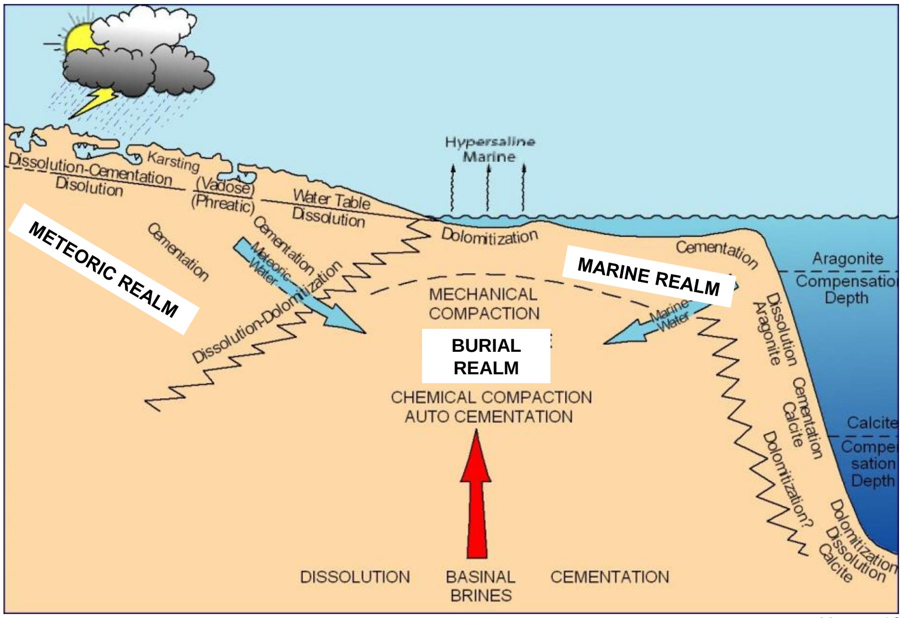
Siliciclastics

- Strongly dependent on provenance/maturity of host rock
- General trends can be related to burial depth (zeolites v. early, calcite early, silica intermediate, albite deep)

Carbonates

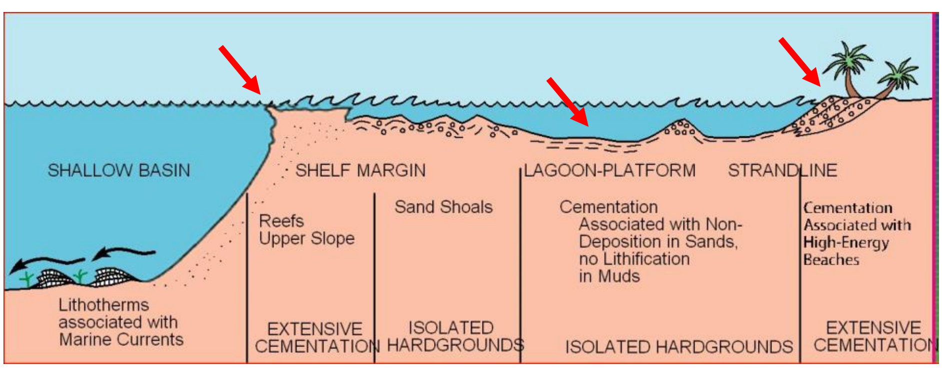
If early, commonly mainly related to eustatic processes and water table (especially peritidal and shelf margin)

- Facies/Allochem specific
- Burial alteration commonly concentrated along faults and fractures (fluid conduits)



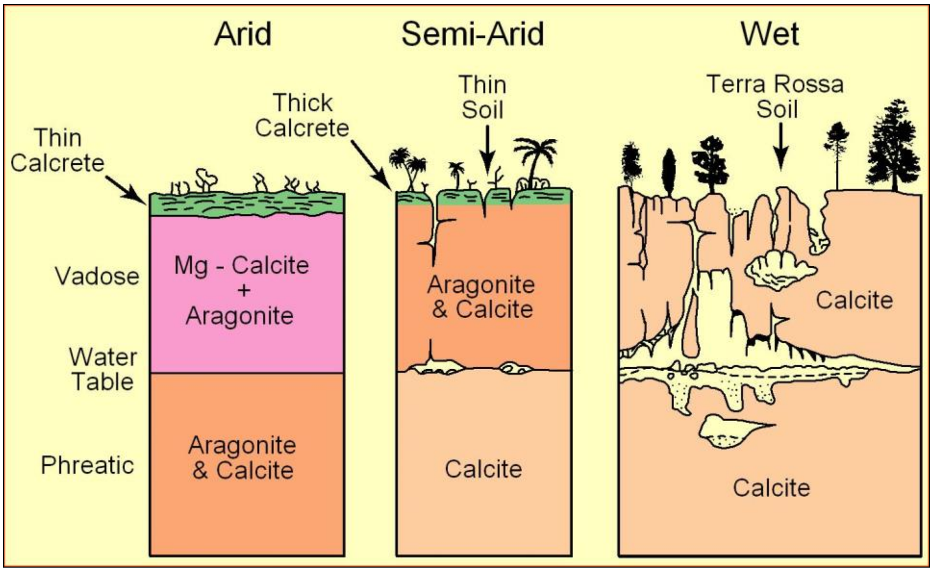
Moore, 1989

Shallow Marine Environment: Distribution of Cementation



Moore, 1989

Meteoric Environment: Effect of Climate

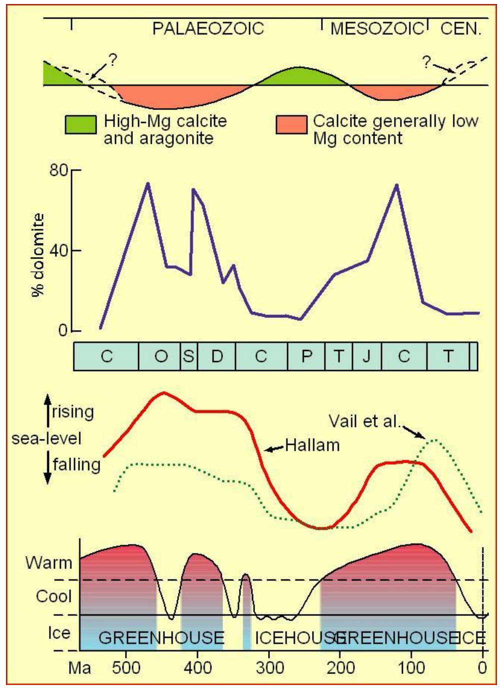


James and Choquette, 1984

Blue Hole (Sinkhole)

Cyclicity in Carbonates

Predictive Diagenesis: Sequence Stratigraphy, 1st Order Controls

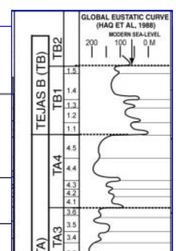


Tucker, 1993

Cyclicity in Carbonates

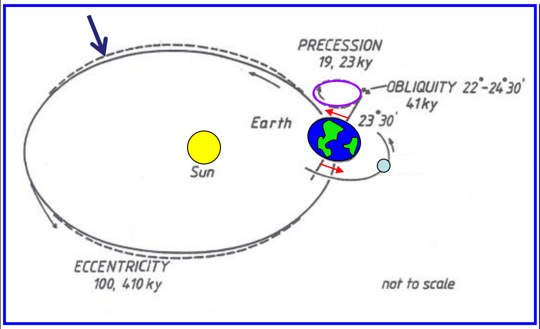
TEMPORAL ORDERS OF STRATIGRAPHIC CYCLICITY

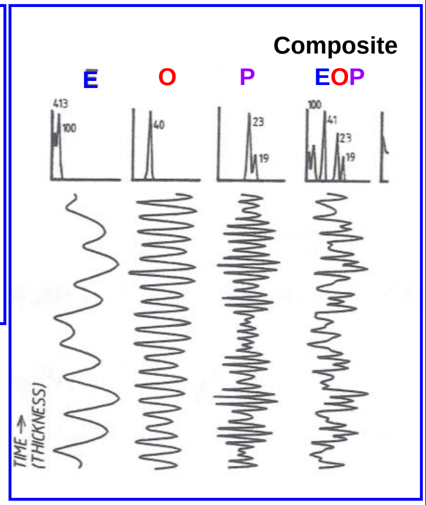
SEQUENCE STRAT. TERMINOLOGY	EUSTATIC CYCLES (ORDERS)	DURATION	AMPLITUDE (METERS)	RISE/FALL RATES (CM/100 YR)	MECHANISMS
MEGASEQUENCE	FIRST	>100 MY		<1	LONG-TERM PLATE REORGANIZATION
SUPERSEQUENCE COMPOSITE SEQUENCE	SECOND	10-100 MY	50-100	1-3	TECTONO-EUSTACY CHANGES IN OCEAN VOLUME DUE TO SEA-FLOOR SPREADING LONG TERM-CLIMATICALLY DRIVEN EUSTACY (ICEHOUSE TO GREENHOUSE FLUCTUATIONS)
SEQUENCE COMPOSITE SEQUENCE	THIRD	1-10 MY	50-100	1-10	CLIMATICALLY DRIVEN EUSTACY (GLACIAL IN ICE-HOUSE CLIMATES)
HF SEQUENCE PARASEQUENCE SET	FOURTH	0.1-1 MY	1-15	40-500	
PARASEQUENCE (HF SEQUENCE)	FIFTH	0.01-0.1 MY	1-150	60-700	



Global Trends Provide Insight into Local Sequence Stratigraphy
--- Do Not Incorporate Local Basin Controls (cf. Tectonism)

Origins of High Frequency Cyclicity in Carbonate Rocks





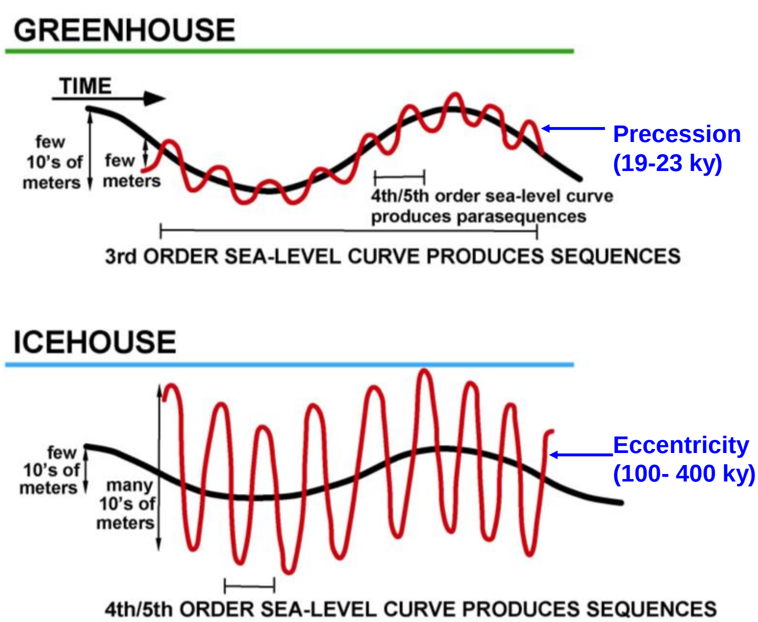
Einsele and Ricken, 1994

- Proposed by Milankovitch (1941)

- Eccentricity (Solar Orbit Path): 410 ka, 100 ka
- Obliquity (Tilt): 41 ka
- Precession (Wobble): 23, 19 ka

- Expression In Rock Record Dependent on Global Climate

Cyclic Expression of Sea-Level Amplitude in Varied Climates

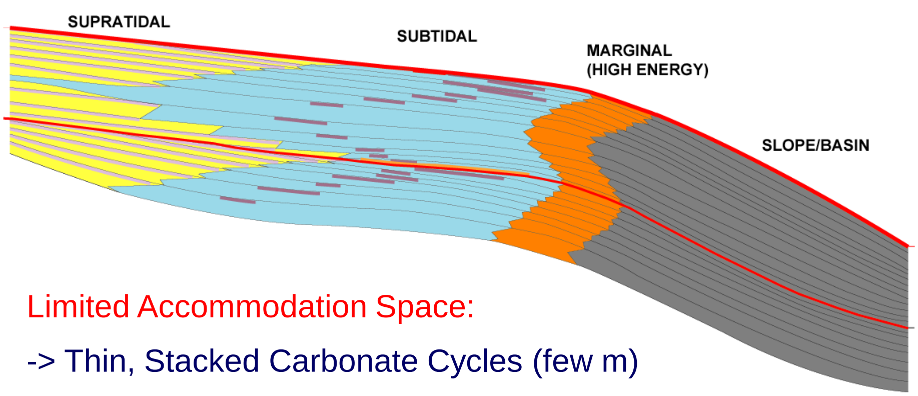


Climatic Controls on Carbonates

Greenhouse Climates:

- Limited Glaciation
- Warm Global Climate / Elevated Ocean Temperature
- Calcite-Dominated Ocean Chemistry
- Elevated Sea-Levels; Common Epeiric Seas
- Low-Amplitude Eustatic Variations (<10 m)
- Precessional Cyclicity Dominant (20-40 ka)
- Aggradational Stacking Patterns
- Examples: Mid-Cambrian, Mid-Cretaceous

Greenhouse Climates



Limited Accommodation Space:

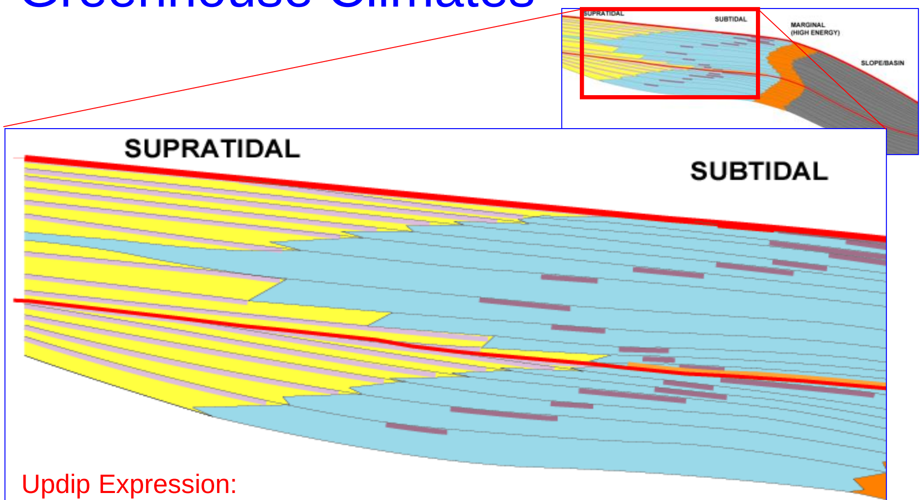
-> Thin, Stacked Carbonate Cycles (few m)

-> Strongly Aggradational Stacking Patterns

-> Subtle Vertical Facies Variations

-> Rare Buildups (on Slope)

Greenhouse Climates



Updip Expression:

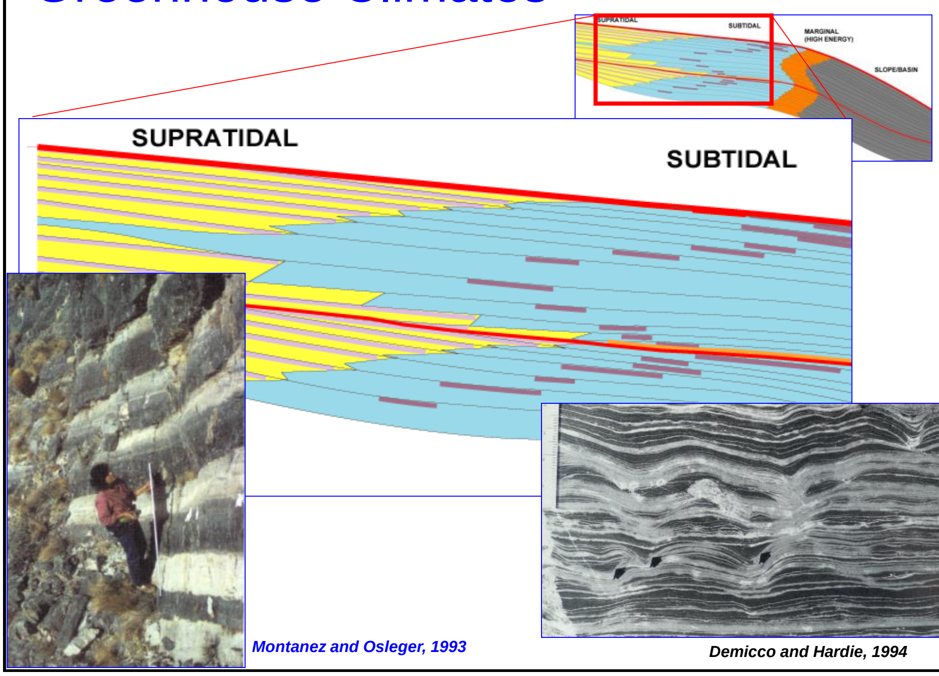
-> Well-Developed Tidal Flats; Thinly Bedded

->Common Localized Exposure Surfaces – Difficult to Correlate

-> Broad, Storm-Dominated Subtidal Belt

-> Minimal Exposure-Related Erosion

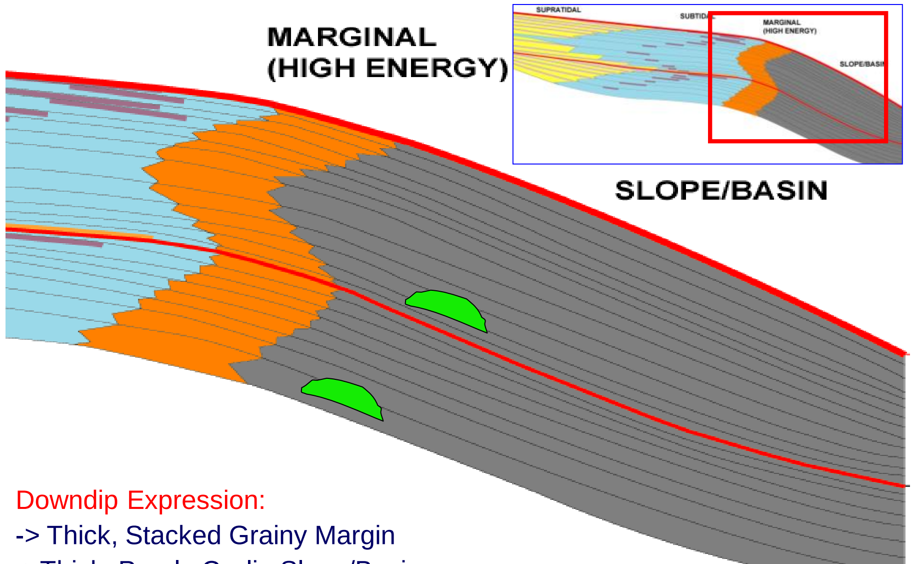
Greenhouse Climates



Montanez and Osleger, 1993

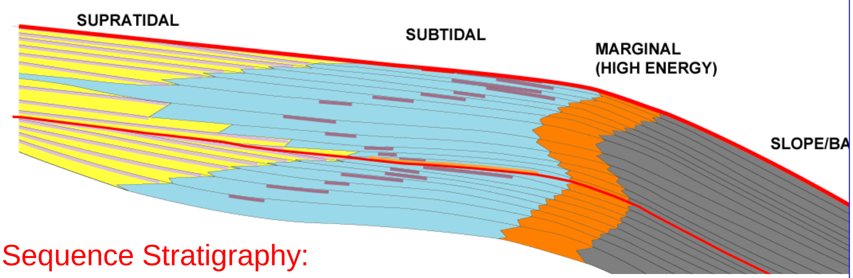
Demicco and Hardie, 1994

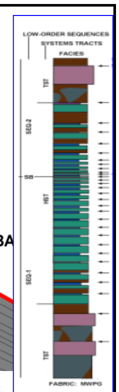
Greenhouse Climates



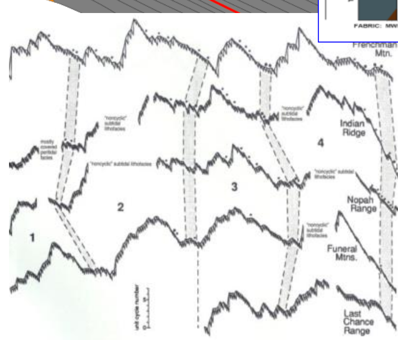
Downdip Expression:
-> Thick, Stacked Grainy Margin
->Thick, Poorly Cyclic Slope/Basin
-> Local Bioherms (Mud Mounds) on Slope (Accommodation)

Greenhouse Climates



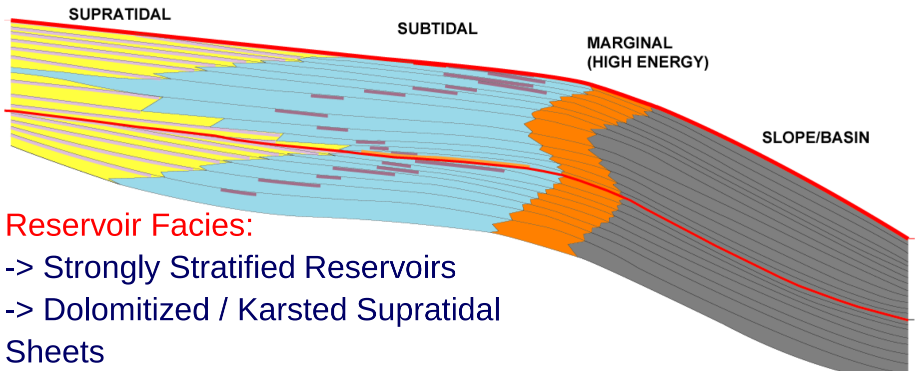


Sequence Stratigraphy:
-> Surfaces Difficult to Pick (MFS/SB)
-> Common Autocyclicity (Especially Supratidal)
-> Non-Regional Unconformities
-> Broad-Scale Stacking Patterns Well-Developed
-> Commonly Rely on Time-Subsidence Plots to Correlate (Fischer Plots)



Montanez and Osleger, 1993

Greenhouse Climates



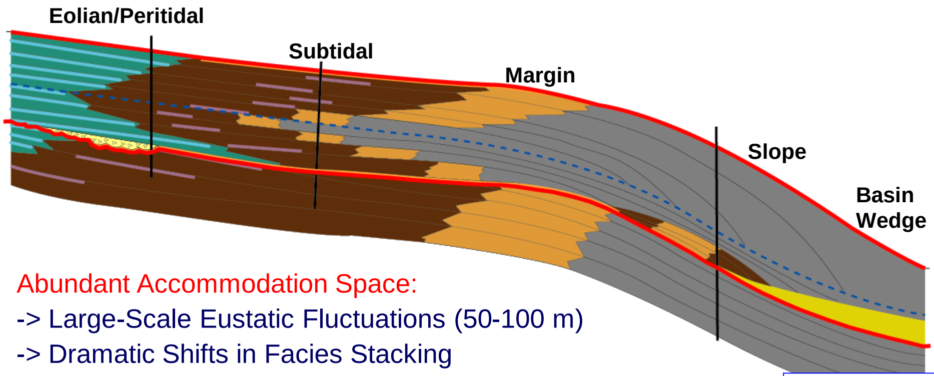
Reservoir Facies:
-> Strongly Stratified Reservoirs
-> Dolomitized / Karsted Supratidal Sheets
-> Vertically Stacked Marginal Skeletal / Ooid Sands
-> Potential Algal-Derived Source Updip
-> Well-Developed Evaporite Seals

Climatic Controls on Carbonates

Icehouse Climates:

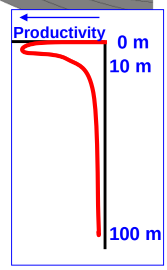
- Continental Glaciations
- Cooler Global Climate / Reduced Ocean Temperature
- Aragonite-Dominated Ocean Chemistry
- High-Amplitude Eustatic Variations (50-100 m)
- Eccentricity Driven Cyclicity (100 ka, 410 ka)
- Abrupt Vertical Depositional Facies Transitions
- Progradational Stacking Patterns Common
- Major Erosional Incision / Lowstand Wedge Development
- Extensive Diagenetic Overprinting
- Upper Carboniferous (Pennsylvanian); Pleistocene

Icehouse Climates

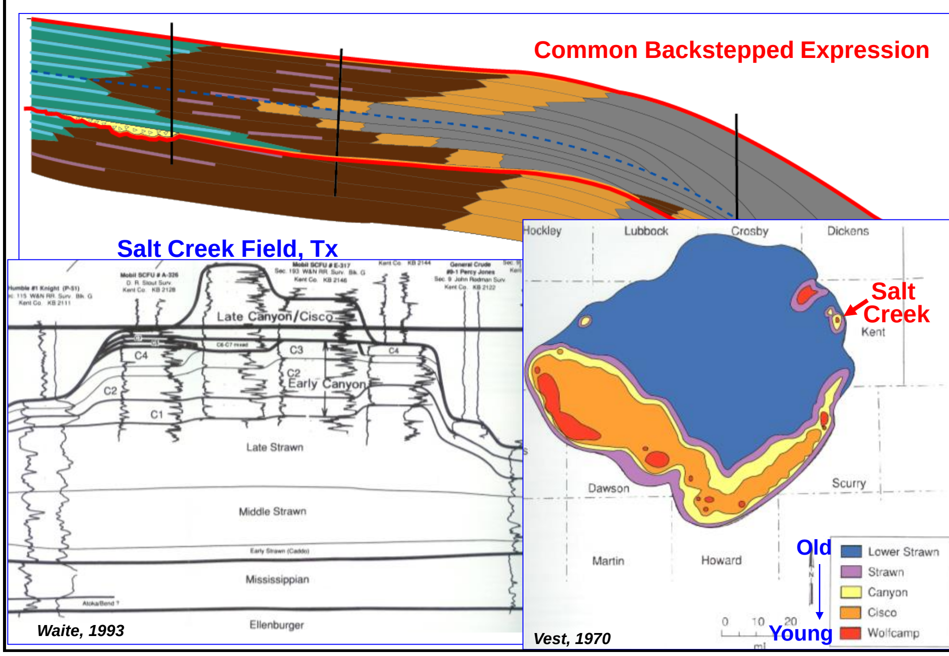


Abundant Accommodation Space:
-> Large-Scale Eustatic Fluctuations (50-100 m)
-> Dramatic Shifts in Facies Stacking
-> Common Backstepped, 'Wedding Cake' Geometry
-> Constructive Carbonate Buildups (Reefs)
-> Steep Depositional Gradients
-> Lowstand Wedges / Incision

Cyclothem Stacking Patterns Common



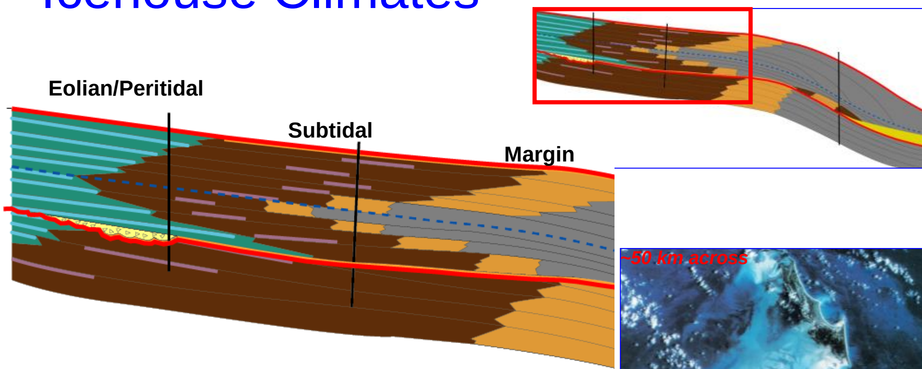
Icehouse Climates

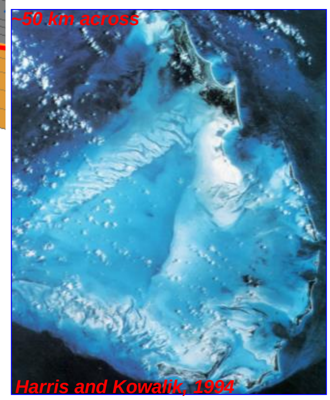


Waite, 1993

Vest, 1970

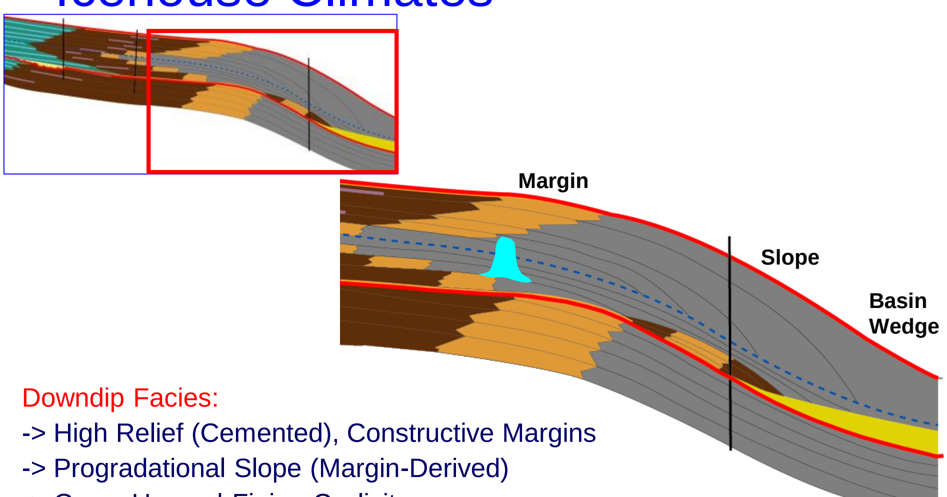
Icehouse Climates





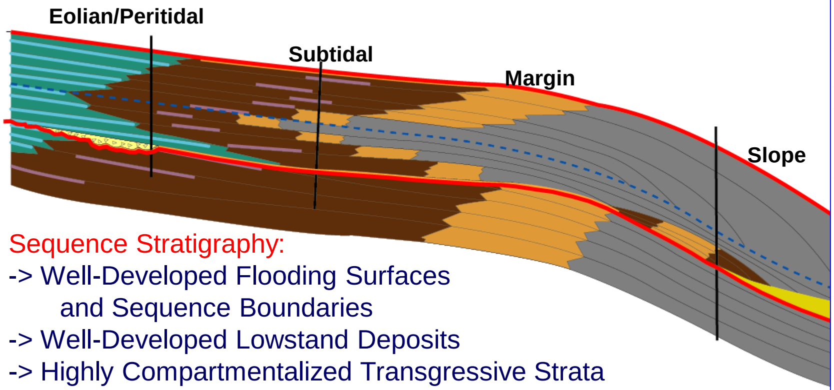
Updip Facies:
- -> Highly Compartmentalized Facies
- -> Subtidal Grainy Interiors Common
- -> Sparse, Discontinuous Peritidal
- -> Aeolian Strata
- -> Common Fluvial Incision
- -> Intense Weathering/Dissolution

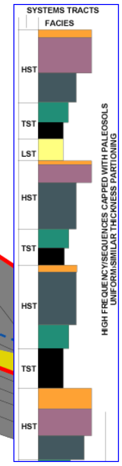
Icehouse Climates



Downdip Facies:
- -> High Relief (Cemented), Constructive Margins
- -> Progradational Slope (Margin-Derived)
- -> Gross Upward-Fining Cyclicity
- -> Siliciclastic ‘Bypass’ Wedges in Basin
- -> Margin-Derived Skeletal Debris to Slope / Basin
- -> Pinnacle Buildups May Occur on Slope / Margin

Icehouse Climates

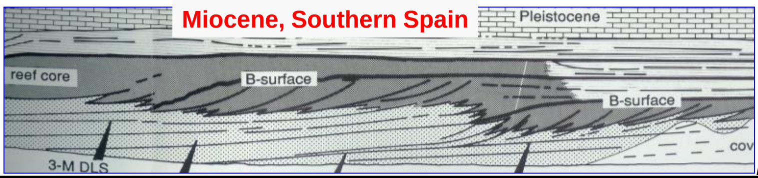




Sequence Stratigraphy:

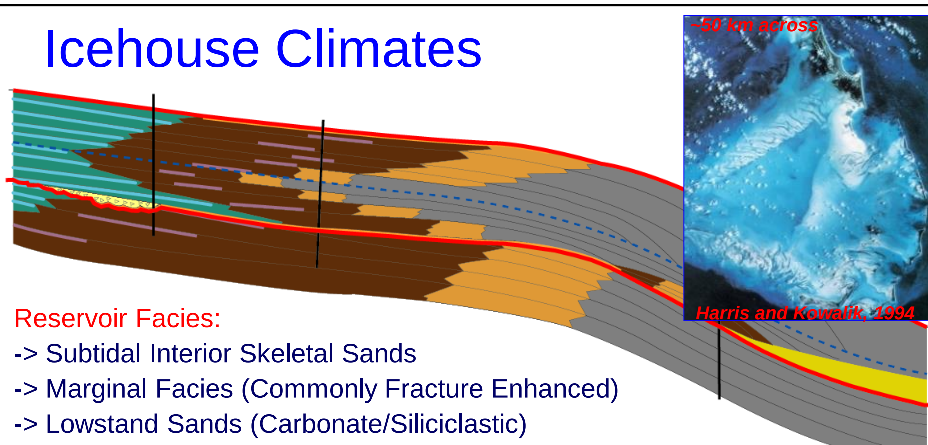
-> Well-Developed Flooding Surfaces and Sequence Boundaries
-> Well-Developed Lowstand Deposits
-> Highly Compartmentalized Transgressive Strata
-> Rapid Transgression, Gradual Prograding Highstand
-> Regional Exposure / Erosion at Sequence Boundaries
-> Extensive Meteoric Diagenetic Overprinting at Sequence Boundaries

Miocene, Southern Spain



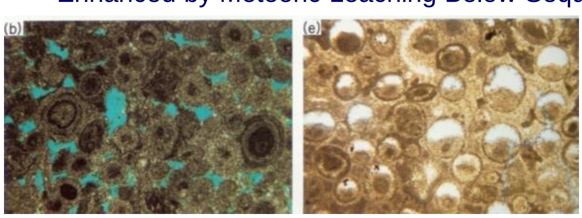
Pomar, 1993

Icehouse Climates



Reservoir Facies:

-> Subtidal Interior Skeletal Sands
-> Marginal Facies (Commonly Fracture Enhanced)
-> Lowstand Sands (Carbonate/Siliciclastic)
-> Organic-Rich Flooding Facies May Form Source and Seal
-> Enhanced by Meteoric Leaching Below Sequence Boundaries



Permian, New Mexico (2 mm across)

Hovorka et al. 1993

Climatic Controls on Carbonates

Transitional Climates:

- Minor Glaciation; Some Continental
- Variable Global Climate / Ocean Temperature
- Moderate-Amplitude Eustatic Variations (20-50 m)
- Eccentricity Driven Cyclicity (100 ka, 410 ka)
- Shingled Geometries / Lateral Shoal Migration
- Moderate Erosional Incision / Lowstand Wedges
- Regional Disconformities Cap Cycles
- Increased Meteoric Modification

Reservoir Distribution

Greenhouse Reservoirs:

- Updip, Stratified Supratidal Reservoirs (Dolomitic)
- Thick, Homogeneous Margin Sands
- Good Up-Dip Evaporite Seals
- Regional Fairways if Productive Interval Identified

Icehouse Reservoirs:

- Well-Developed Grainy Interiors
- Highly Compartmentalized Sand Shoals in TST
- Fractured Margins (Reefal)
- Downslope Clastics / Margin Debris Fans
- Flooding Surfaces Seal / Source
- Extensive Diagenetic Overprinting - Dissolution

Summary

Greenhouse:

- Warm, Stable Global Climate
- Decreased Amplitude Sea-Level Changes
- High-Frequency Variations Driven by Precession (20-40 ka)
- Aggrading Cyclic Carbonate Deposition

Icehouse:

- Cooler, Variable Global Climate
- High Amplitude Sea-Level Changes
- Eccentricity Driven Cyclicity (100 ka, 410 ka)
- Regional Erosional / Incision During Lowstands
- Progradational Stacking Patterns
- Increased Diagenetic Modification