Diagenetic Evolution of Porosity in Carbonates during Burial*

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Abstract

The diagenetic evolution of porosity and permeability in carbonates is complex and involves a number of independent factors. Carbonate sediments start with 40-80% porosity and generally lose porosity with time and burial (Schmoker and Halley, 1982); however, there are many factors that cause higher and lower porosity in carbonates of the same age and burial depth. Alteration of carbonate sediments during shallow burial is common and includes diagenesis in seawater shortly after deposition, freshwater diagenesis during subaerial exposure, and dolomitization in hypersaline waters. Marine (seawater) diagenesis varies with depth and carbonate saturation as is shown on Enewetak Atoll. Aragonite and Mg-calcite cementation dominate in shallow seawater; however, aragonite is dissolved, and radiaxial calcite precipitates in moderately deep seawater. In even deeper seawater, calcite dissolves and dolomite precipitates. Freshwater (meteoric) diagenesis and dolomitization commonly rearrange and decrease porosity, but they also impart strength to the rock that reduces porosity loss during deeper burial. Pennsylvanian limestones in west Texas show that prolonged subaerial exposure progressively decreases matrix porosity but increases conduit porosity (fractures and vugs), and hence, formation permeability. Reflux dolomitization is commonly associated with carbonates in arid climates, like the Permian of the Permian Basin. The porosity and permeability of reflux dolomites varies according to position in the dolomitizing system with less porosity and permeability in proximal parts of the dolomitizing system. Dolomitization decreases rate of porosity loss with burial (Schmoker and Halley, 1982), allowing some porous dolomite reservoirs like the Smackover of south Alabama at depths of 16,000-18,000 feet. Deep burial dissolution increasing porosity is the exception, rather than the rule. In summary, unlike quartzose sandstones, a complex array of diagenetic factors generally affect the ultimate porosity, permeability, and production of carbonate reservoirs.

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Diagenetic Evolution of Porosity in Carbonates during Burial

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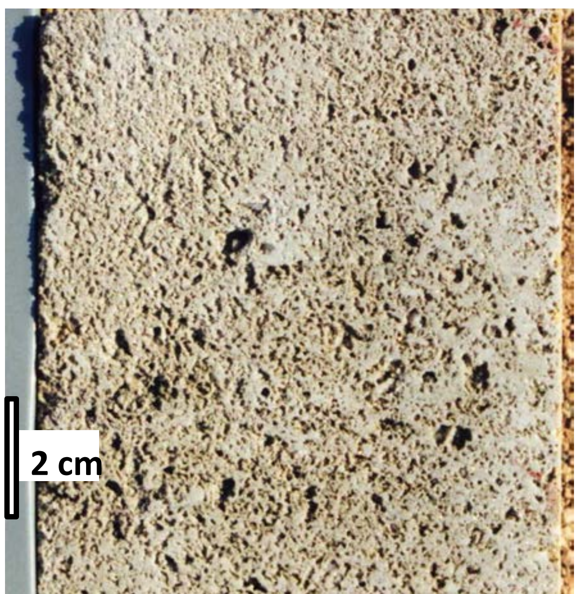
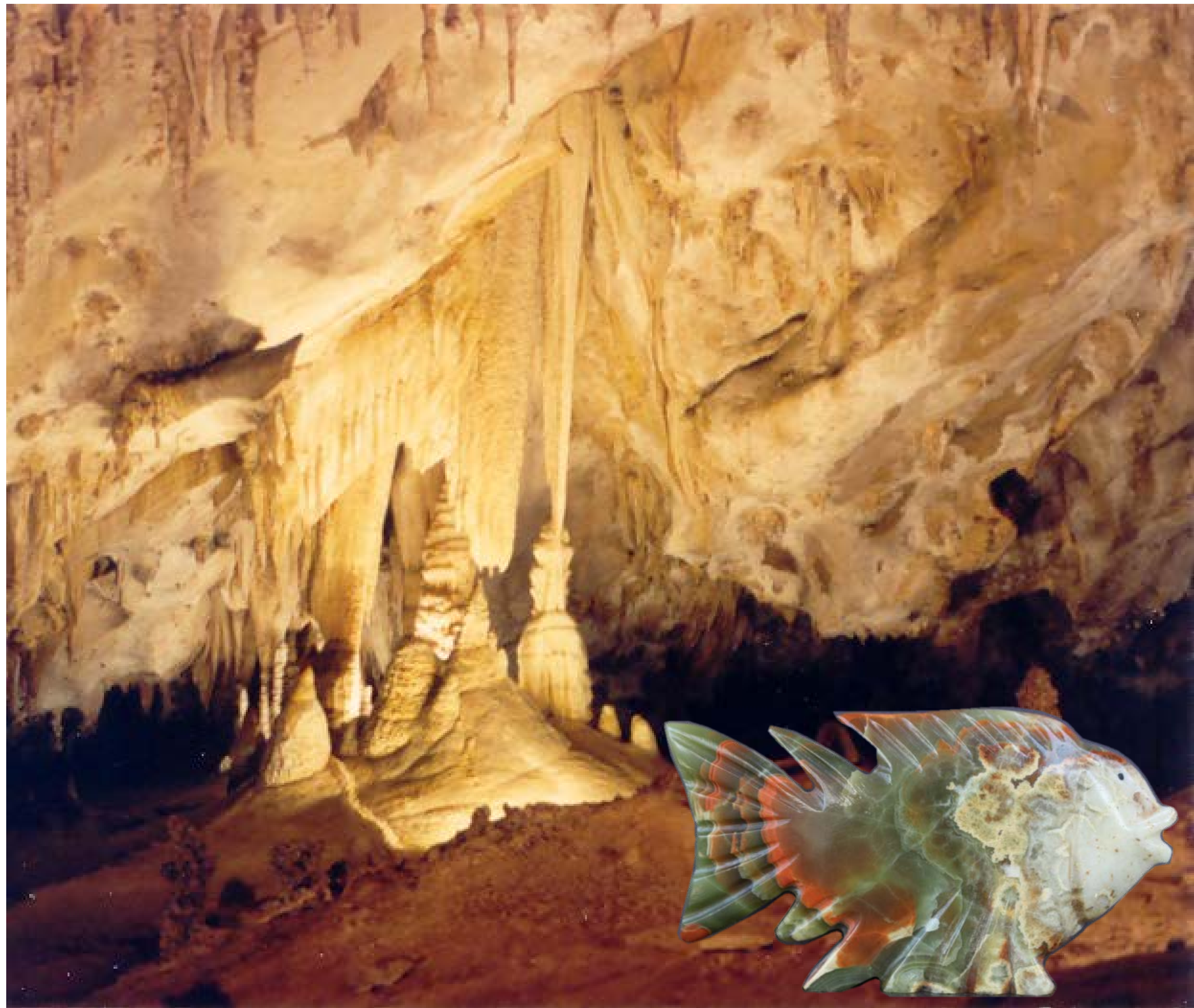




Controls on Carbonate Porosity

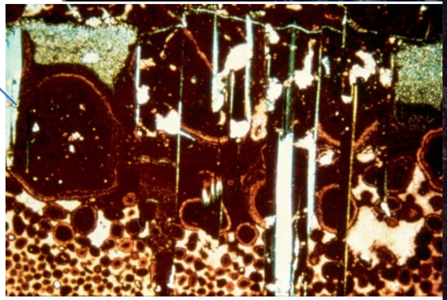
Depositional Sediments

+

Near Surface Diagenesis

+

Deep Burial Diagenesis



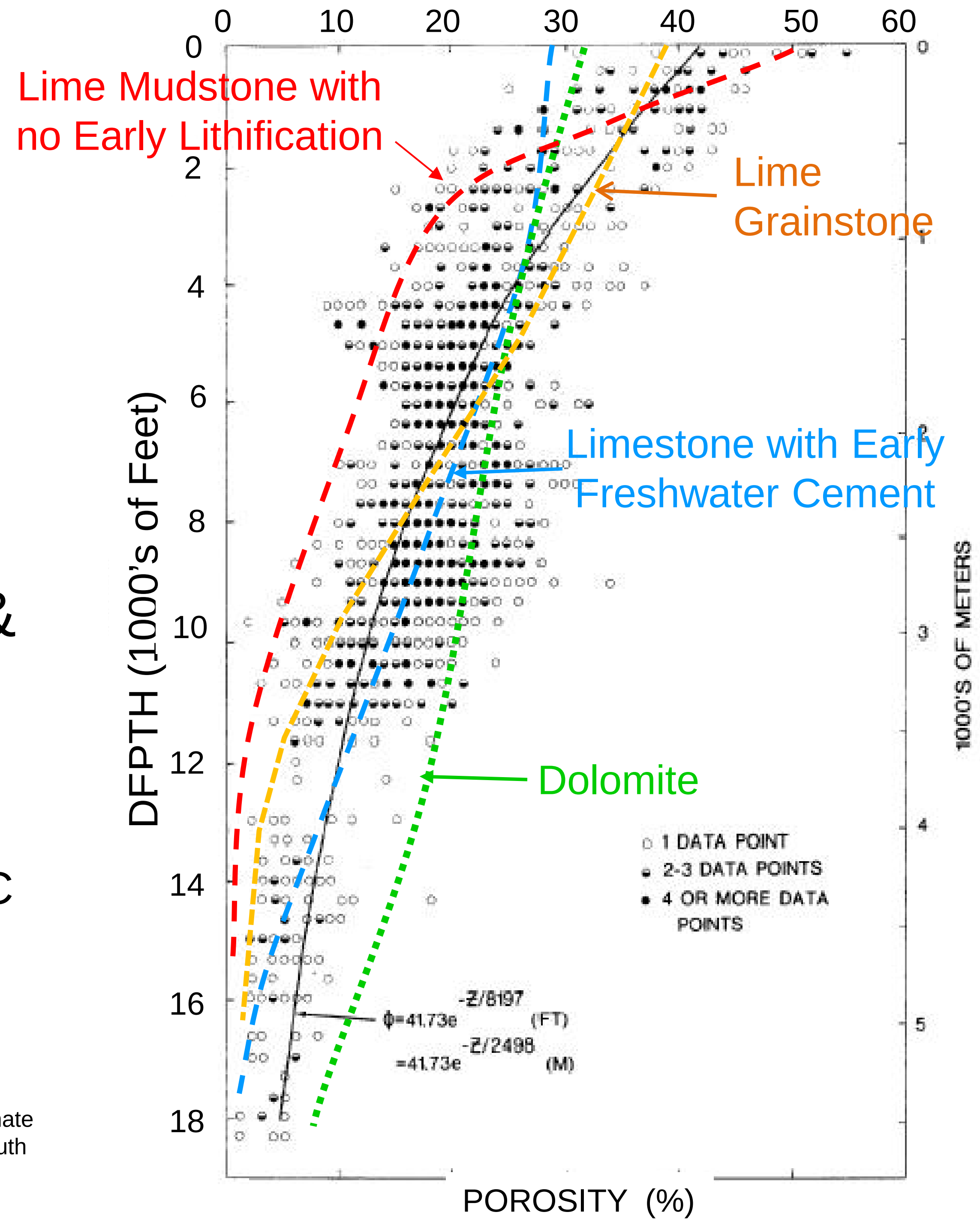
Reservoir Carbonate Porosity and Permeability

EVOLUTION OF POROSITY

- Modern carbonate sediments have porosities of 40% (grainstones) to 80% micritic carbonates (Enos & Swatsky, 1981)
- Carbonate reservoirs have 3-35% porosity
- Most nearsurface diagenetic processes decrease and/or rearrange porosity, but make more rigid
  - Submarine,
  - Subaerial exposure->meteoric diagenesis
  - Dolomitization
- Carbonates generally lose porosity during deeper burial
- Burial history- depth, temperature and time spent at those depths and temperatures determines rate of porosity loss
- Grainstones may lose porosity more slowly than wackestones and mudstone during early physical compaction
- Nearsurface diagenesis may impart a petrologic strength that reduces porosity loss during burial
- Dolomites lose porosity more slowly with burial than most limestones

POROSITY GENERALLY DECREASES WITH DEPTH
With much variation related to deposition & early diagenesis

SOUTH FLORIDA
PLEISTOCENE TO JURASSIC
CARBONATES



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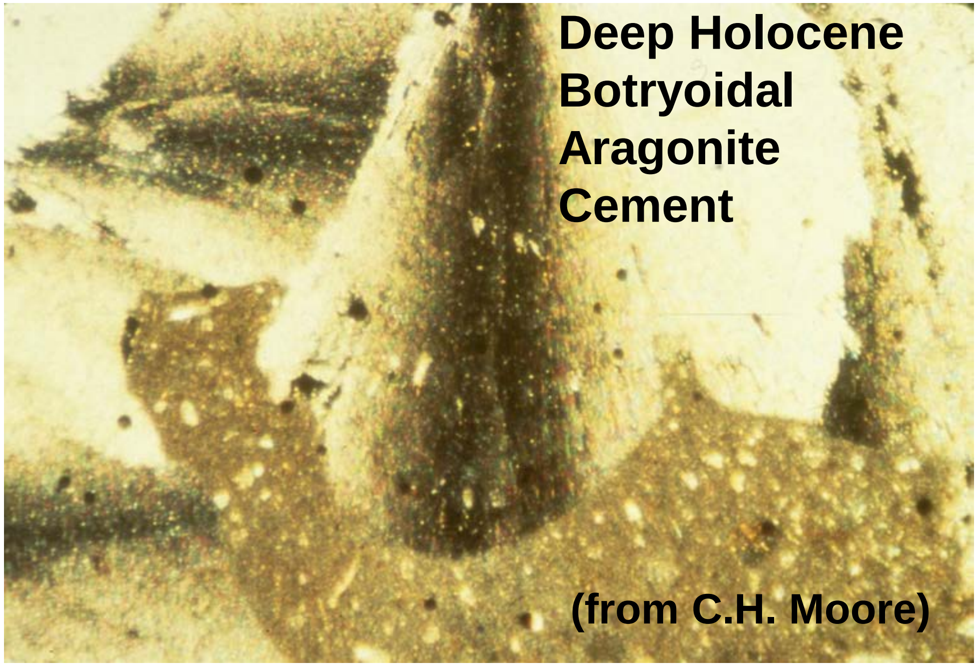
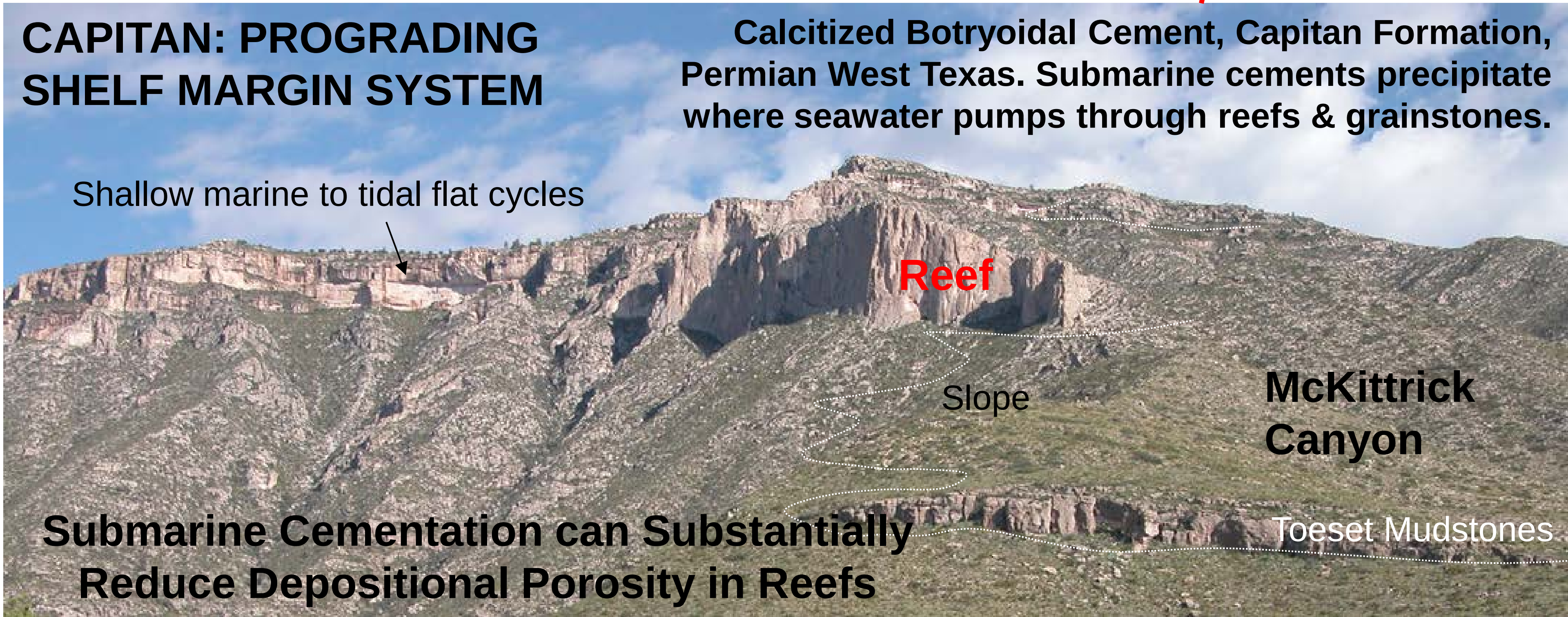
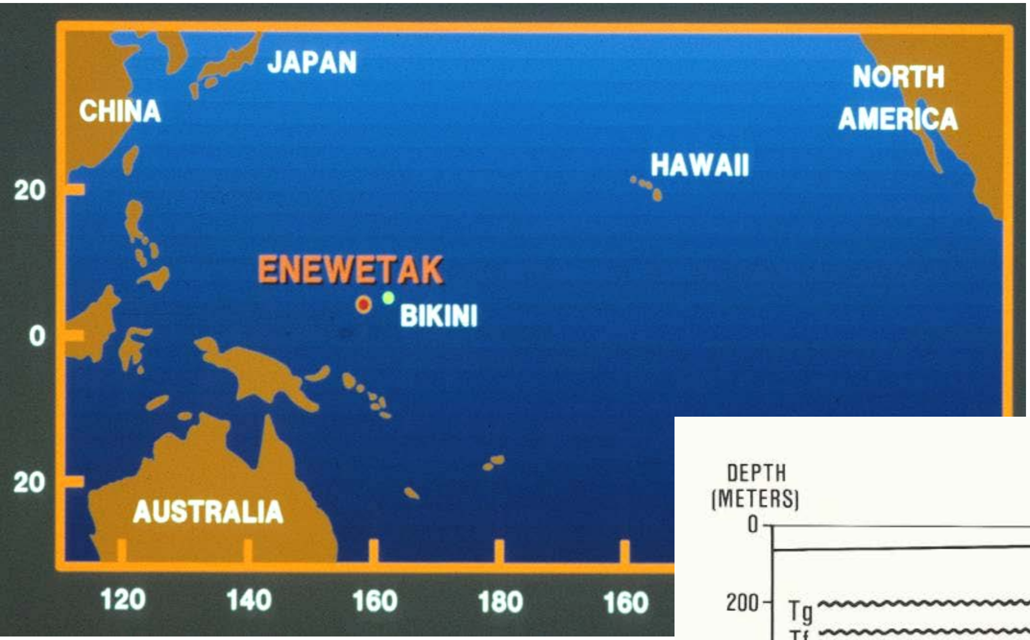
Diagenetic Evolution of Porosity in Carbonates during Burial

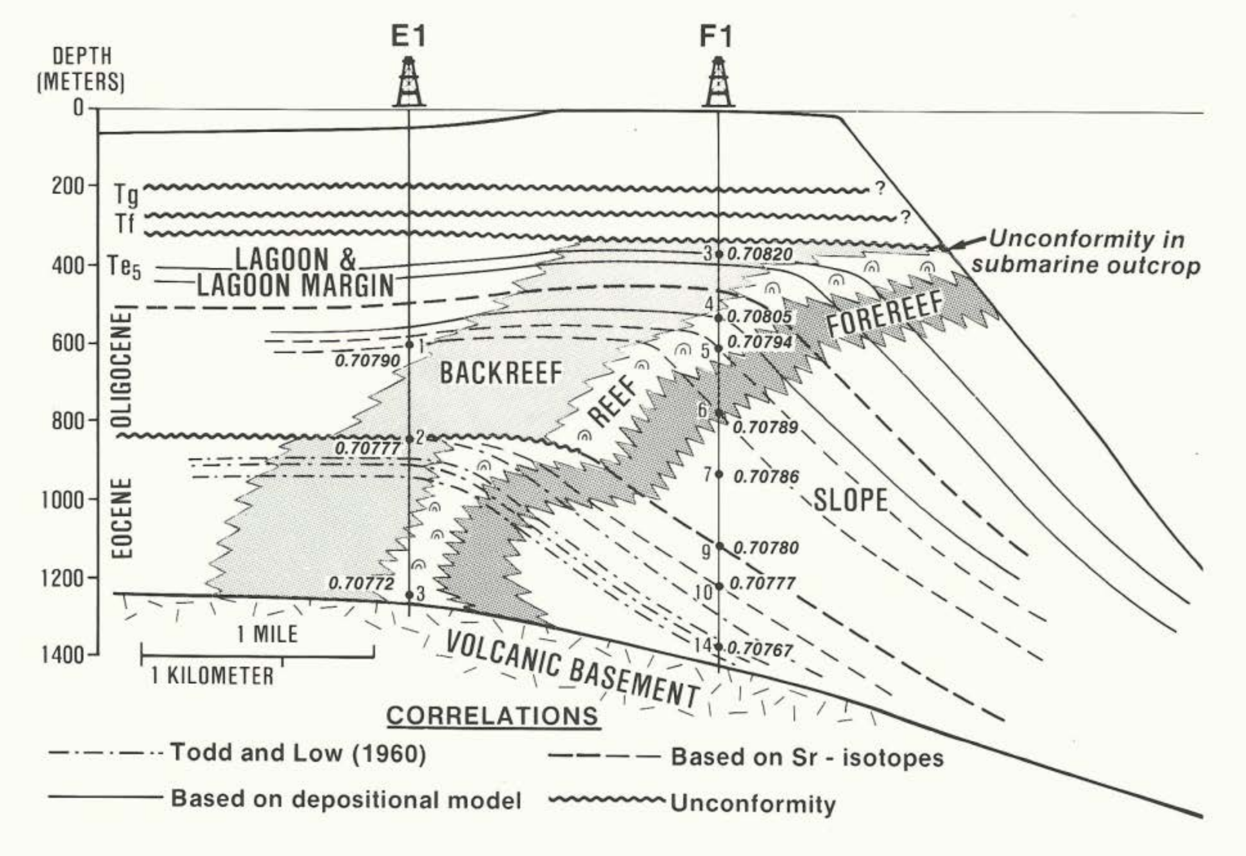
- Introduction
- Marine Diagenesis - Enewetak
- Freshwater Diagenesis – Pennsylvanian, West Texas
- Dolomitization – Permian, West Texas
- Deep Burial – Florida/ South Alabama


Deep Holocene
Botryoidal
Aragonite
Cement
(from C.H. Moore)


CAPITAN: PROGRADING
SHELF MARGIN SYSTEM
Calcitized Botryoidal Cement, Capitan Formation,
Permian West Texas. Submarine cements precipitate
where seawater pumps through reefs & grainstones.
Shallow marine to tidal flat cycles
Reef
Slope
McKittrick
Canyon
Toeset Mudstones
Submarine Cementation can Substantially
Reduce Depositional Porosity in Reefs

DEEP MARINE DIAGENESIS, ENEWETAK ATOLL





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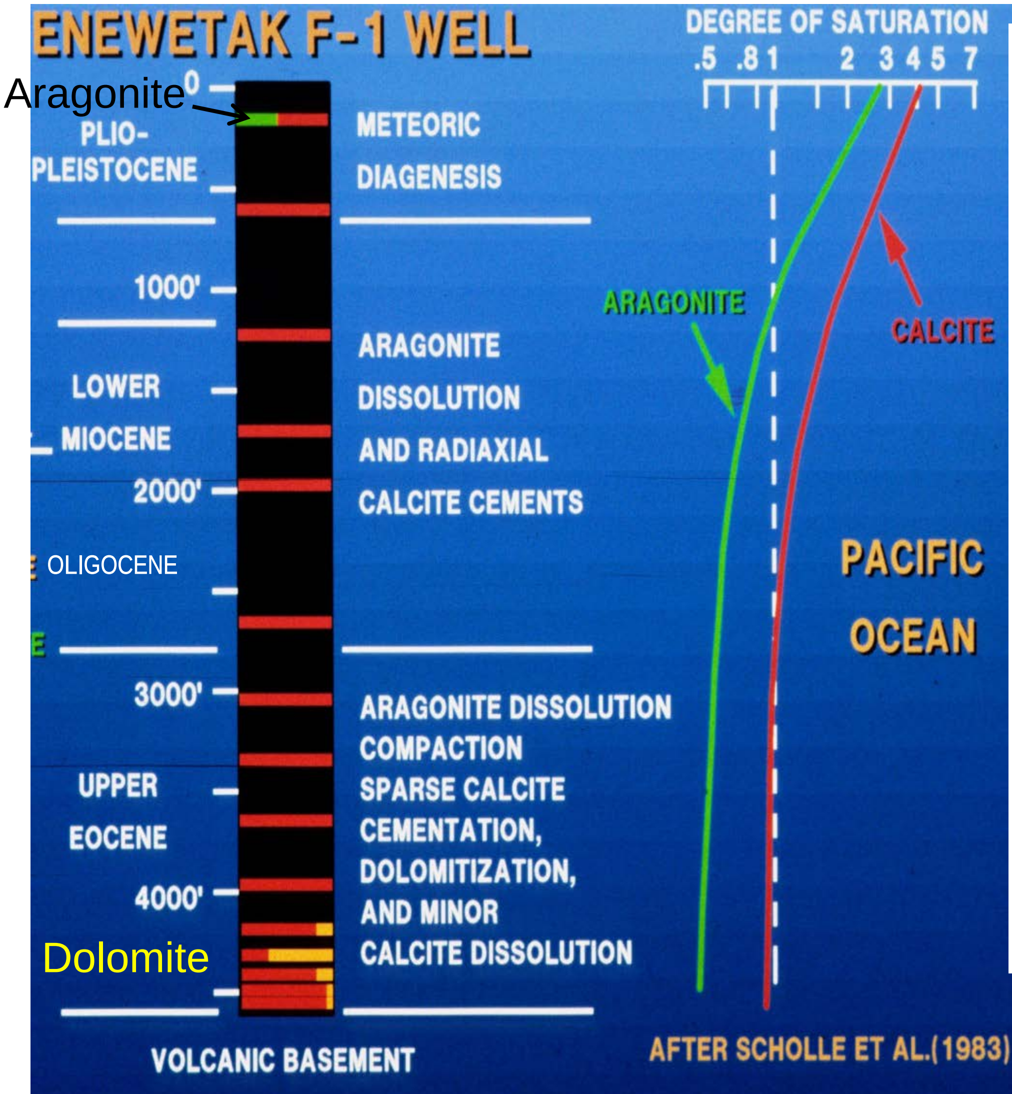
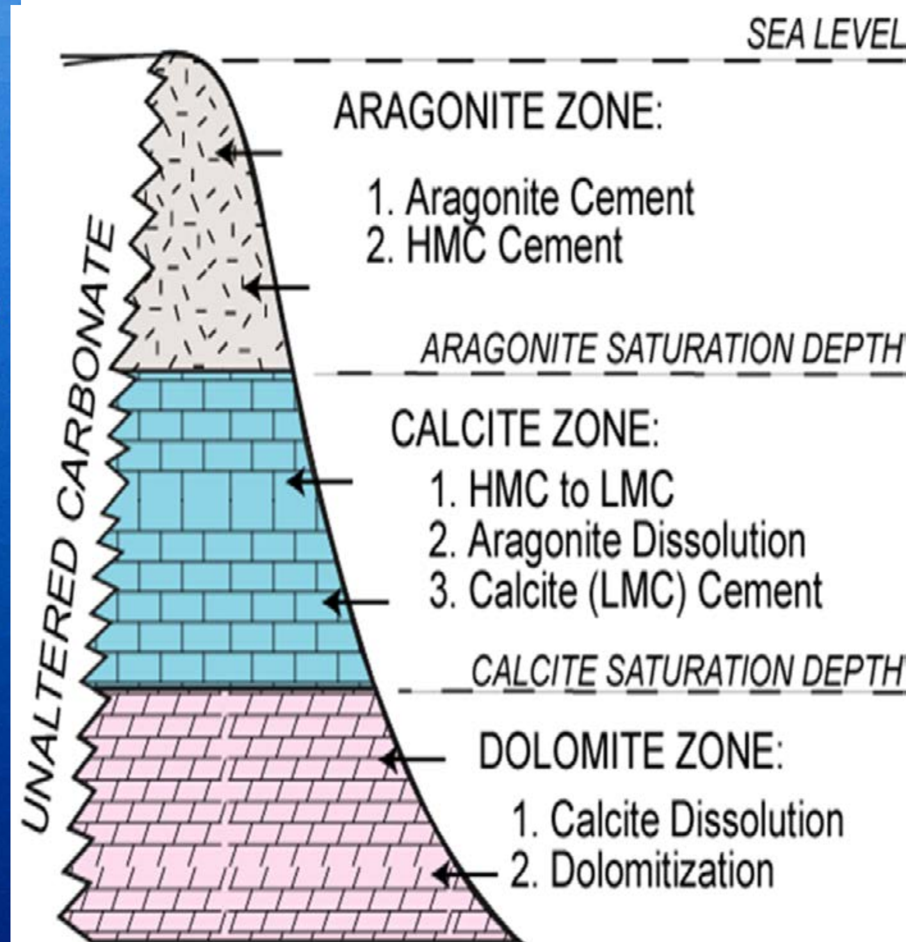
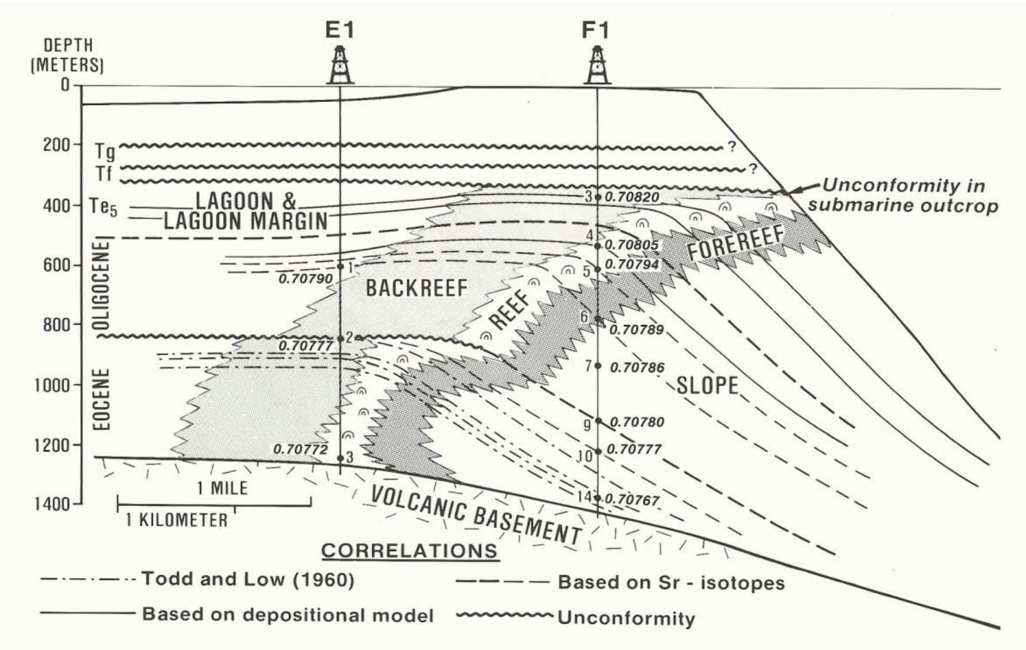
Carbonate Saturation decreases with depth in modern oceans because more CO_2 can be held in solution allowing more carbonate to be held in seawater

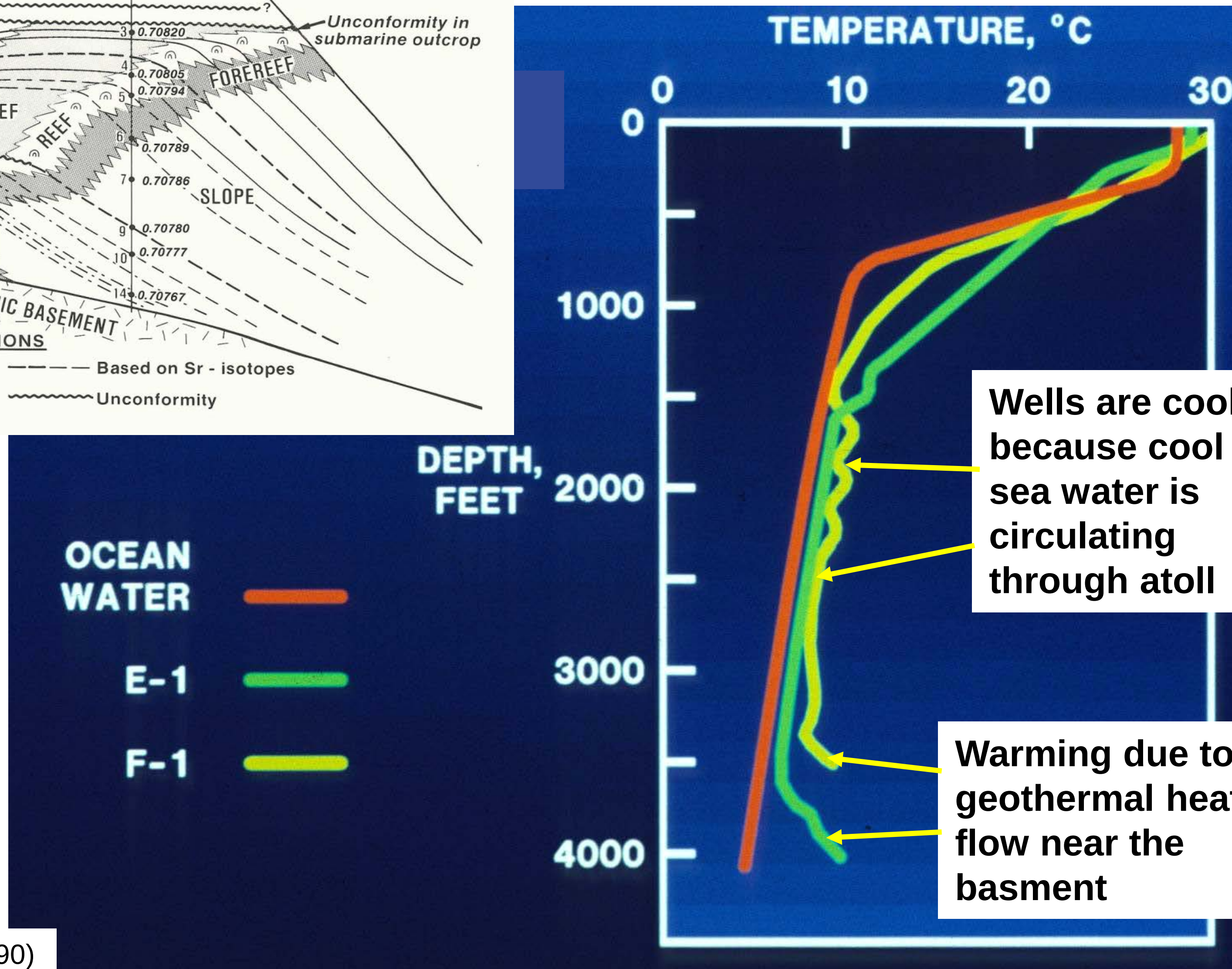




(from Saller and Koepnick, 1990)

TEMPERATURE PROFILES FROM ENEWETAK WELLS INDICATE CIRCULATION OF SEAWATER THROUGH THE ATOLL





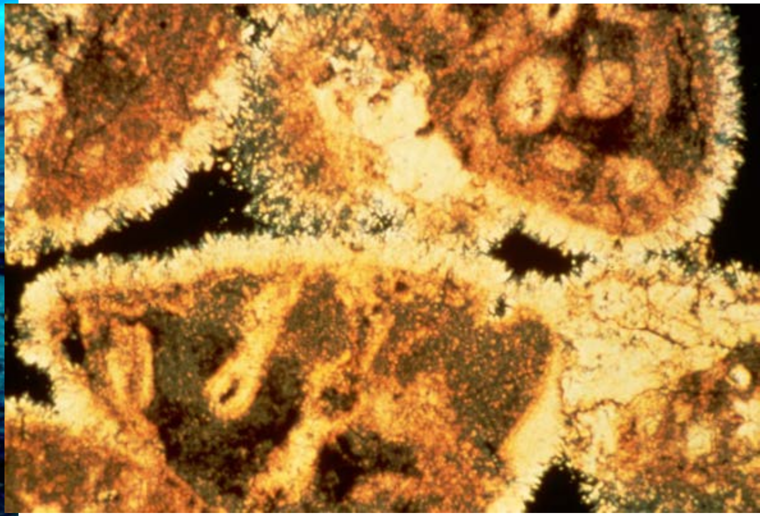
Wells are cool because cool sea water is circulating through atoll

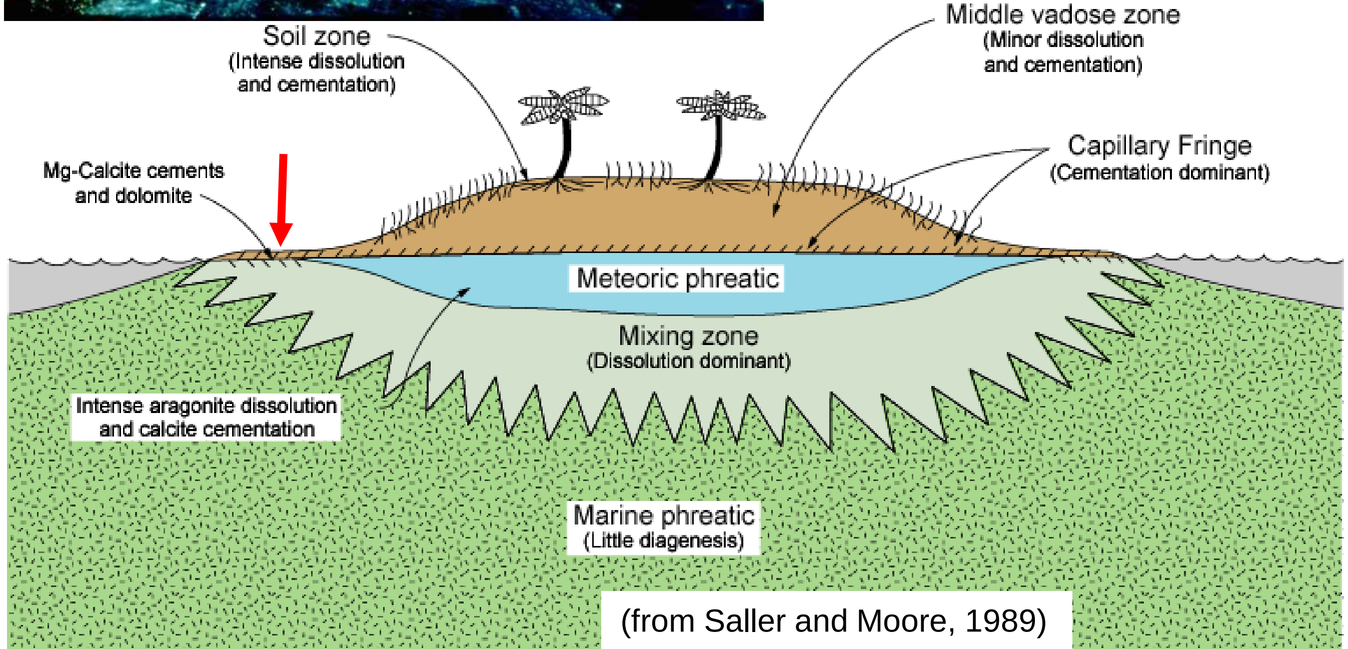
Warming due to geothermal heat flow near the basment

(from Saller and Koepnick, 1990)

Beachrock on Enewetak is Marine Cemented Grainstones that has Cemented WW II Artifacts

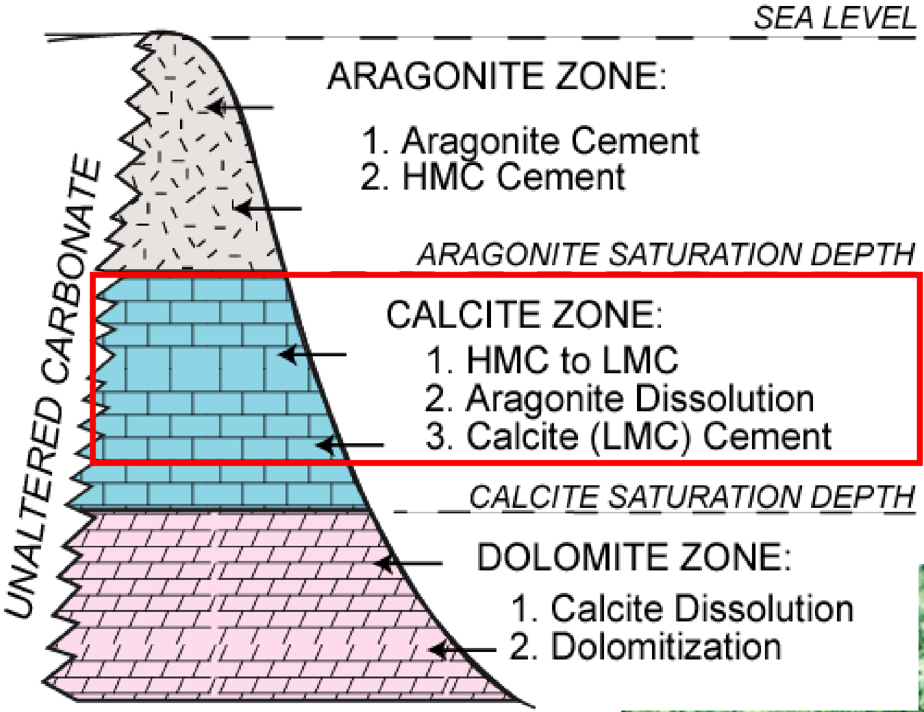
(from C.H. Moore, 1970s)





(from Saller and Moore, 1989)

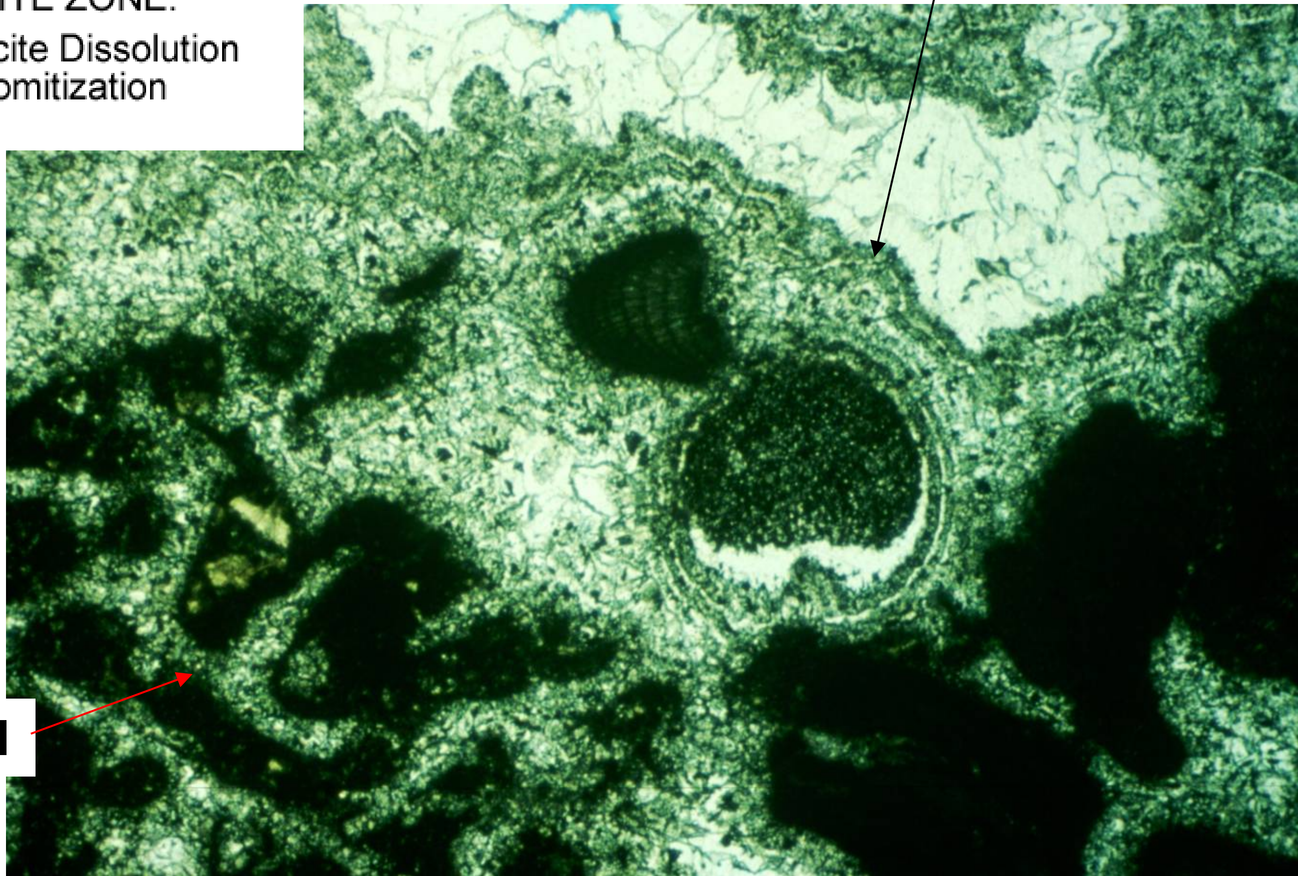
CALCITE ZONE



(Saller and Koepnick, 1990)

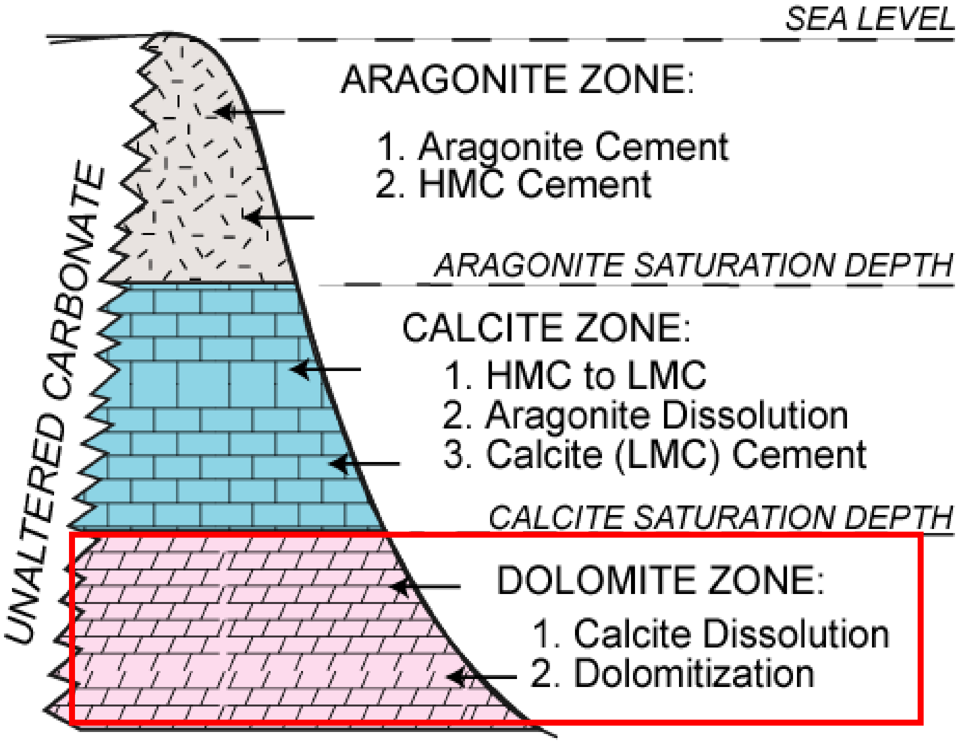
Equant, Marine Calcite Cement

Oligocene, Enewatak
~2000 feet



Dissolved, cemented Coral

Calcite Dissolution & Dolomitization by deep seawater, Eocene, Enewetak ~ 4200' Deep



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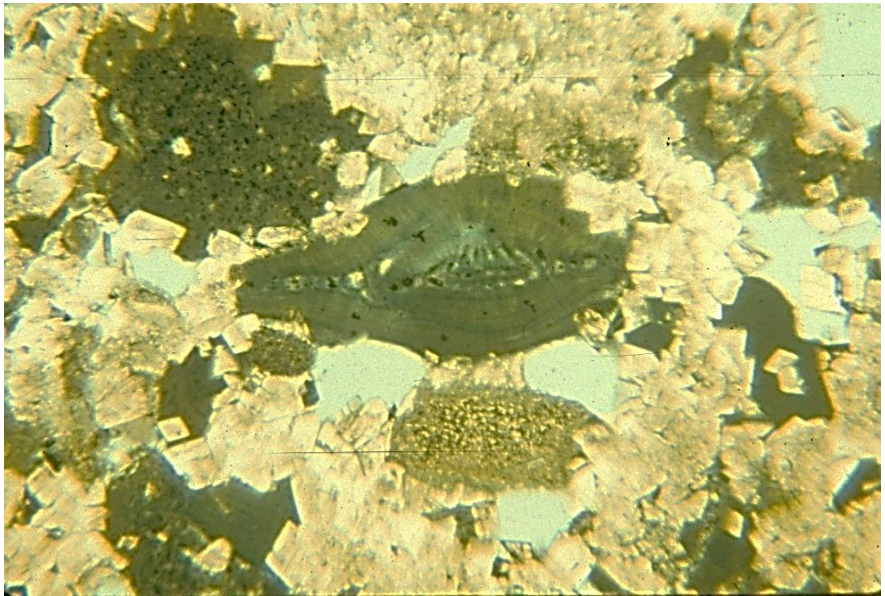
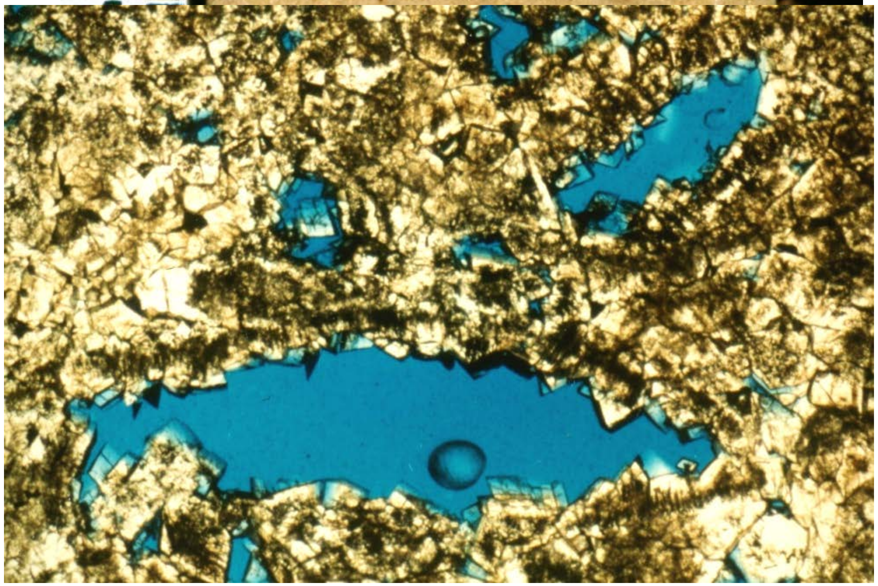
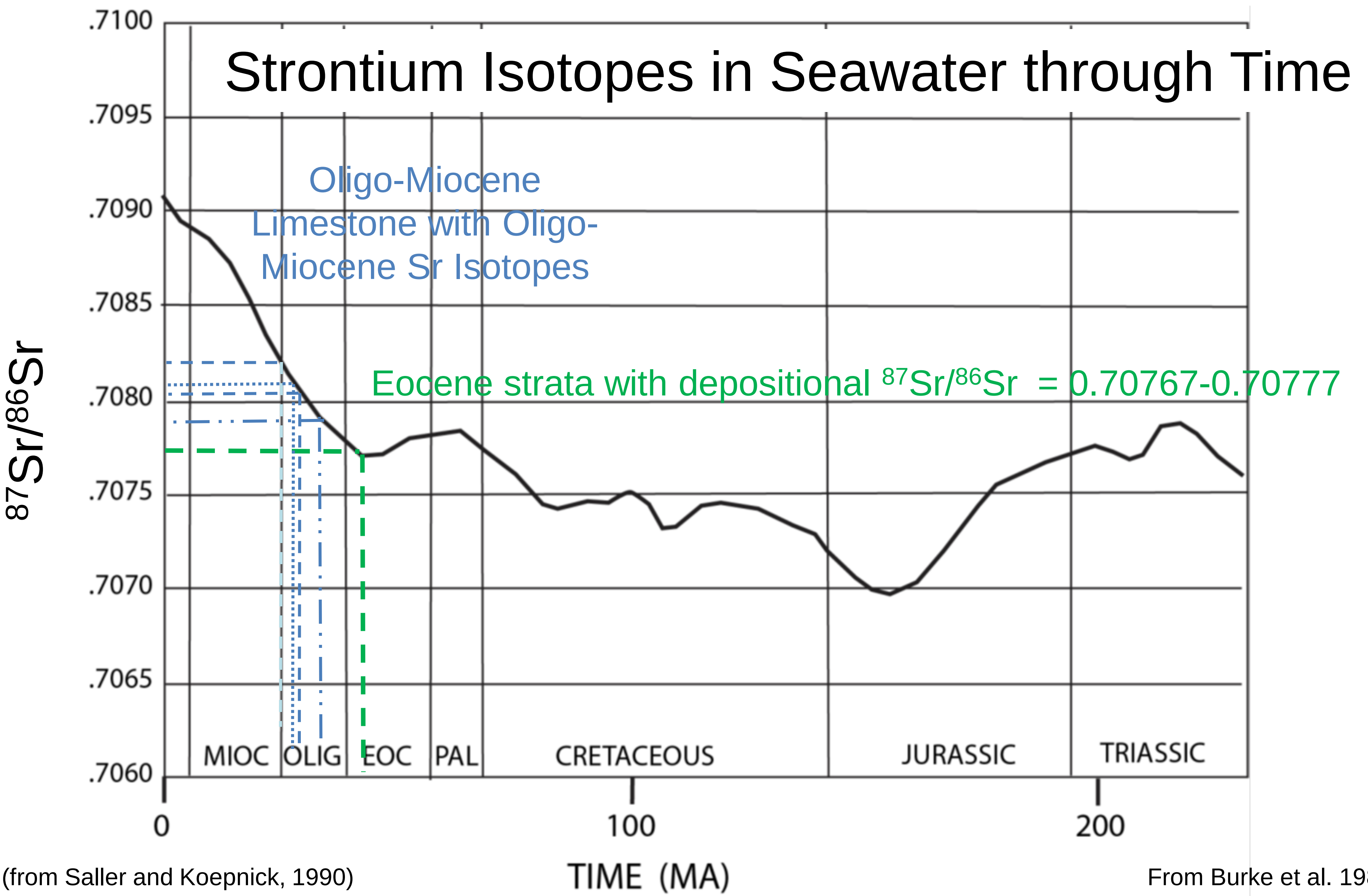


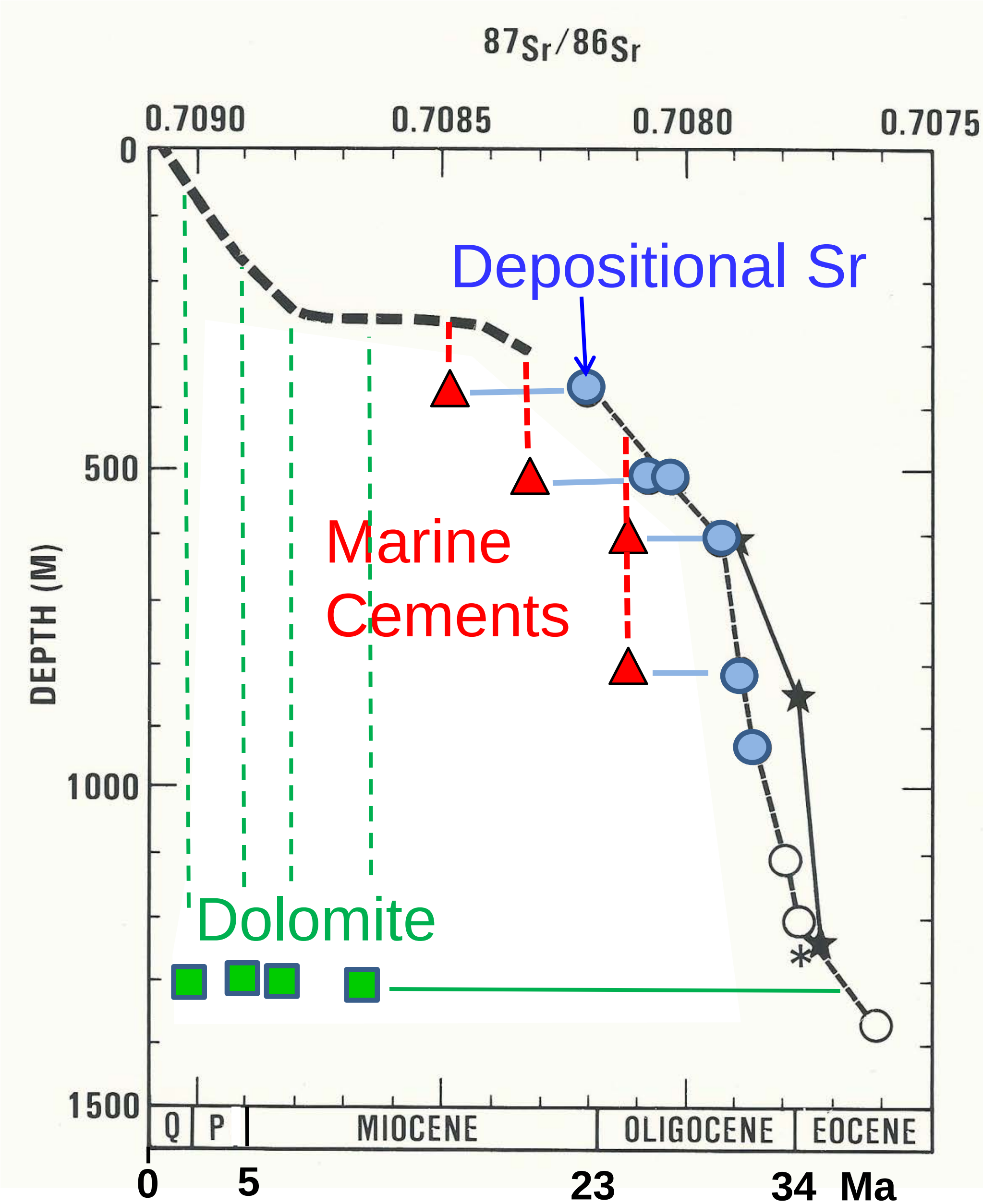


Strontium isotopes (87/86) in marine carbonates vary though time & can be used for dating & as a tracer



(from Saller and Koepnick, 1990)

From Burke et al. 1982

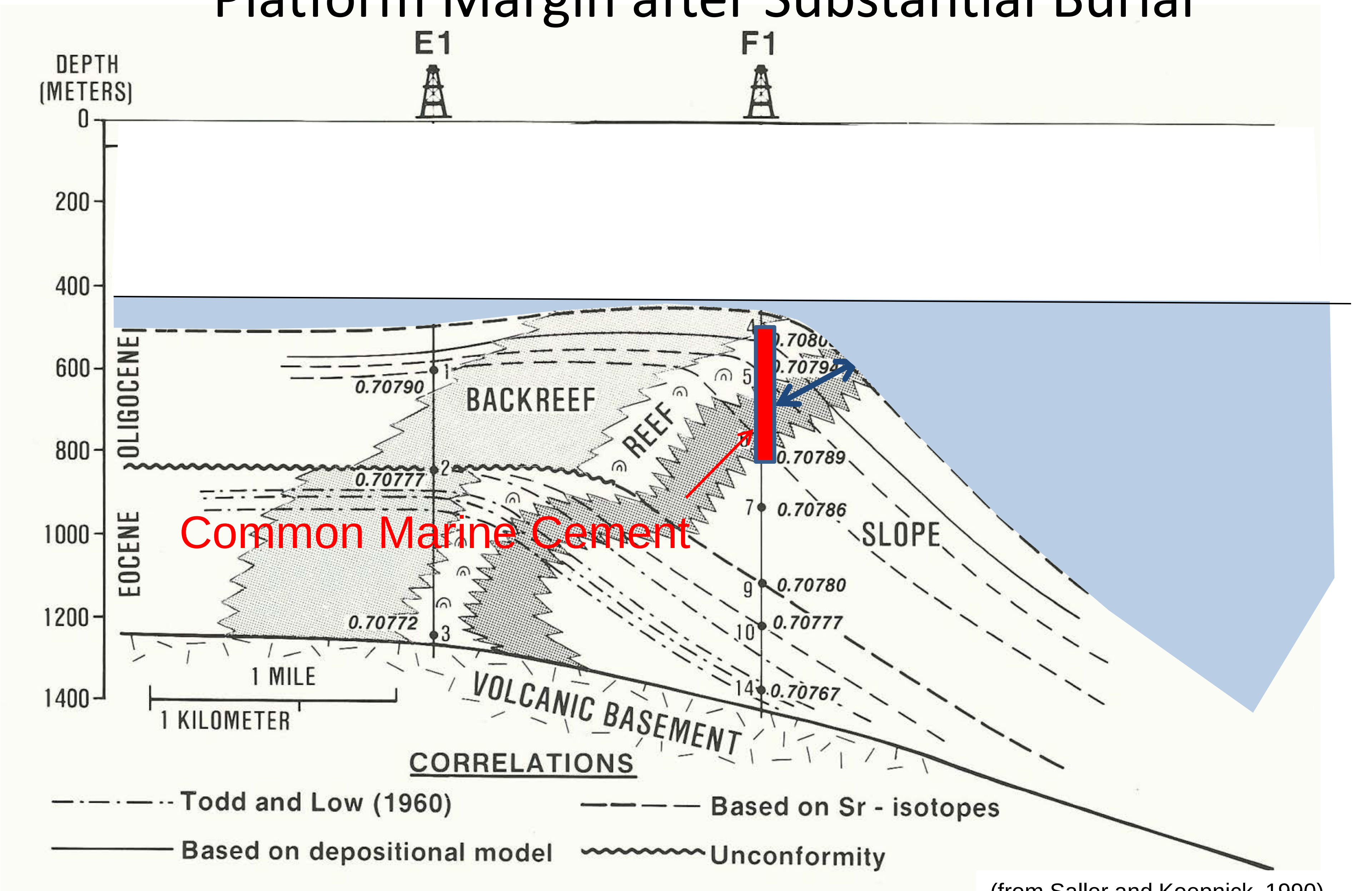


(from Saller and Koepnick, 1990)

Marine Calcite Cements & Dolomites have distinctly younger Sr indicating precipitation after substantial burial by seawater circulating through the margin of the atoll

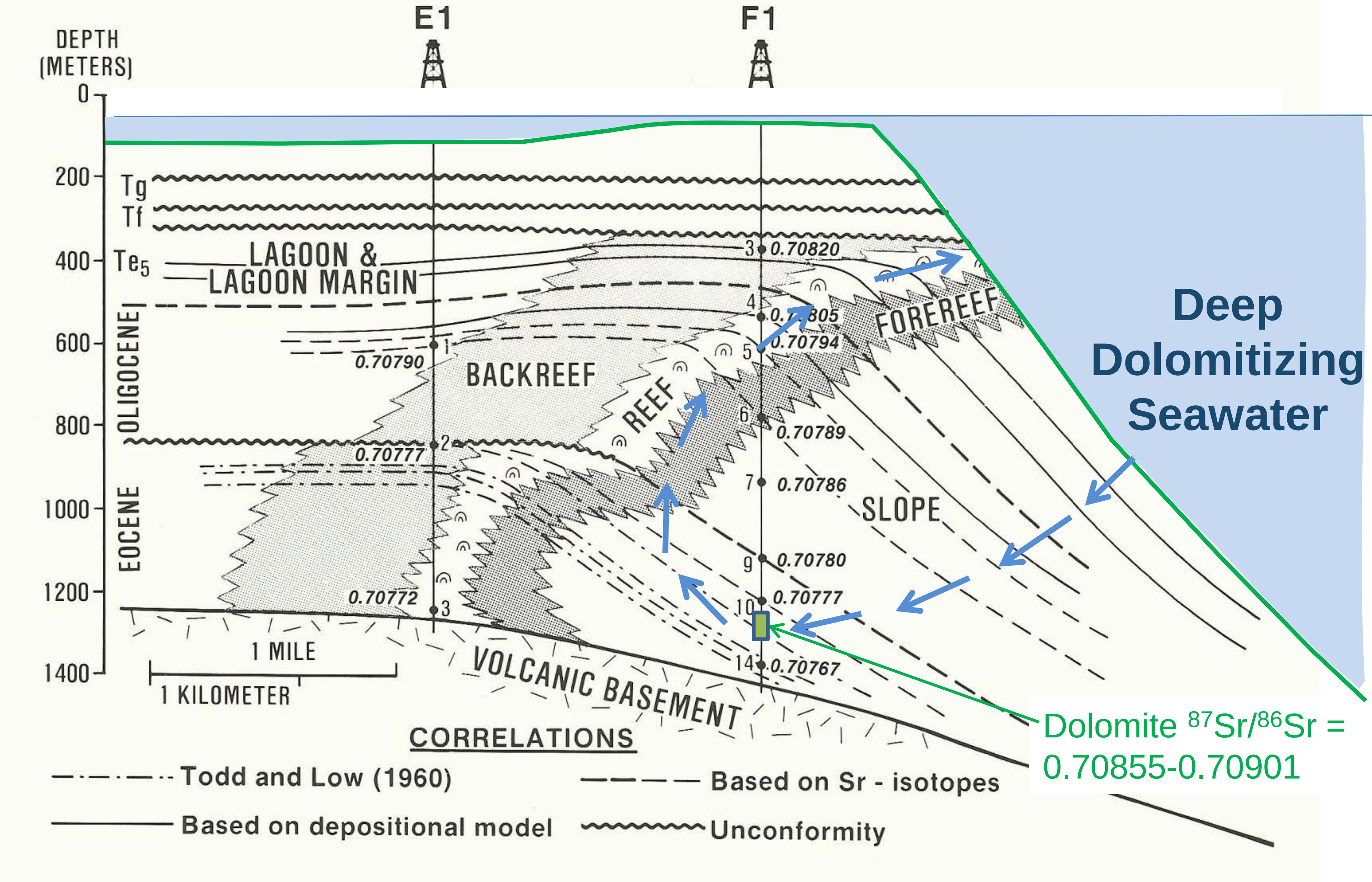
from Halley et al., 1986

Radiaxial Marine Cement Circulate into the Platform Margin after Substantial Burial



(from Saller and Koepnick, 1990)

Dolomitization by Deep Seawater after Substantial Burial



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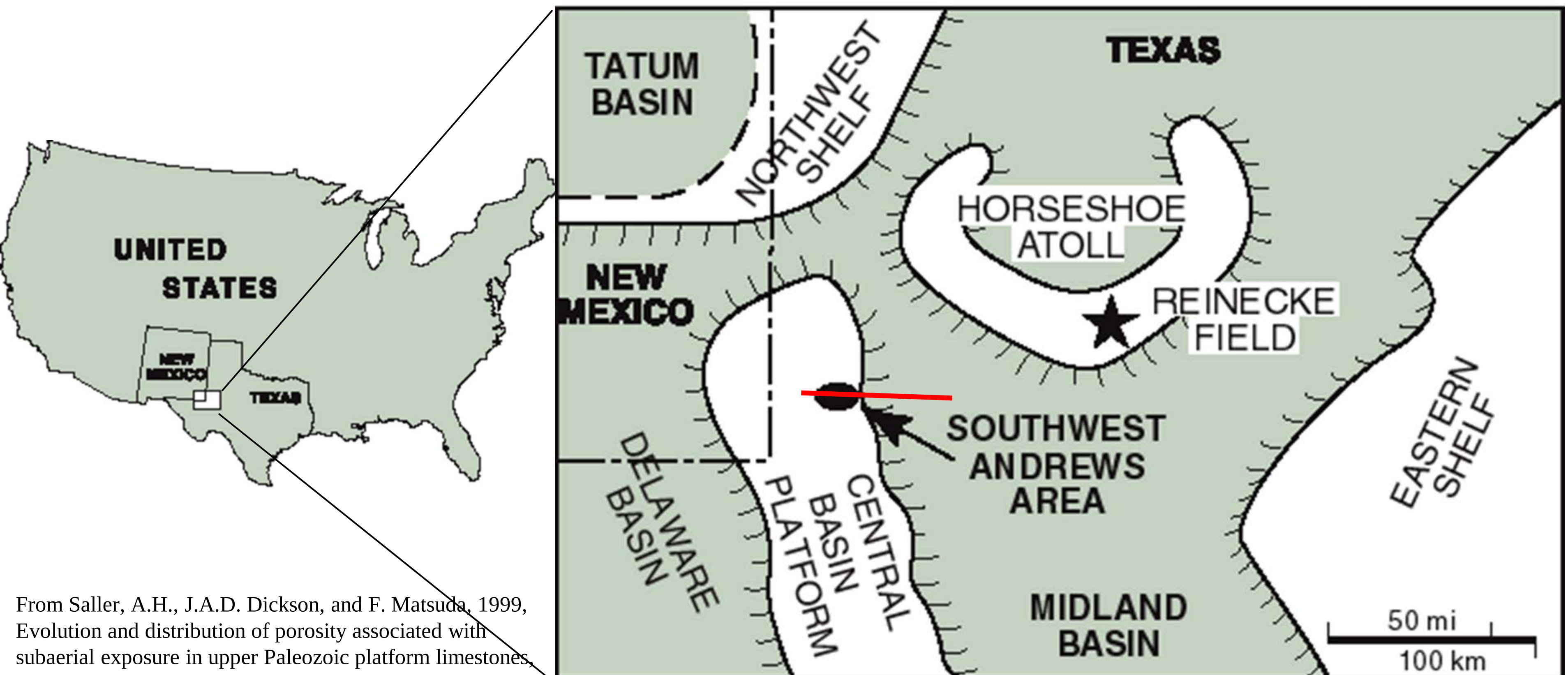
- Burial – Florida/ South Alabama

Pennsylvanian Carbonate Cycles in Southwest Andrews Area in West Texas show the Effect of Duration of Exposure on Porosity in Carbonates

UPPER PENNSYLVANIAN PALEOGEOGRAPHY



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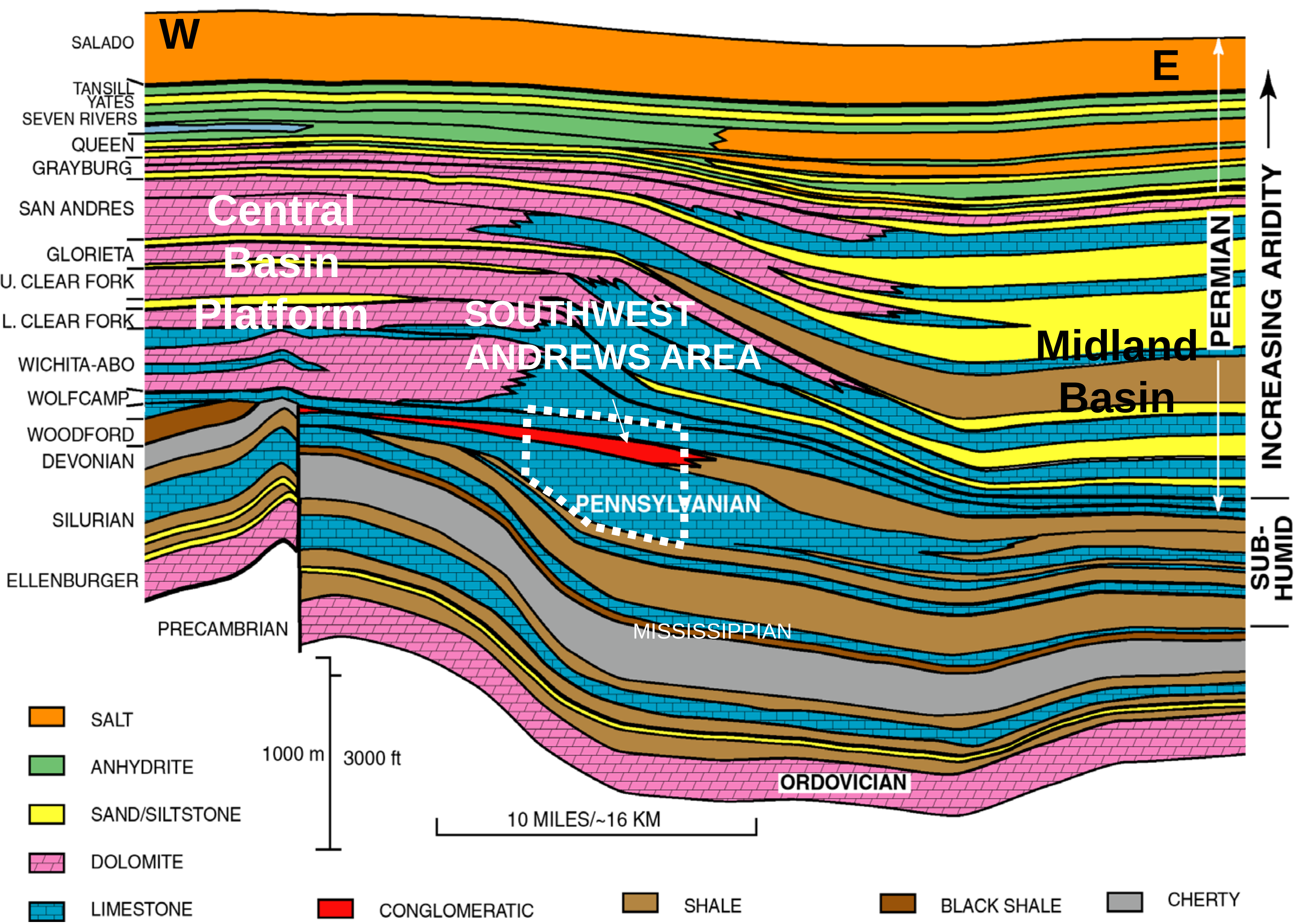

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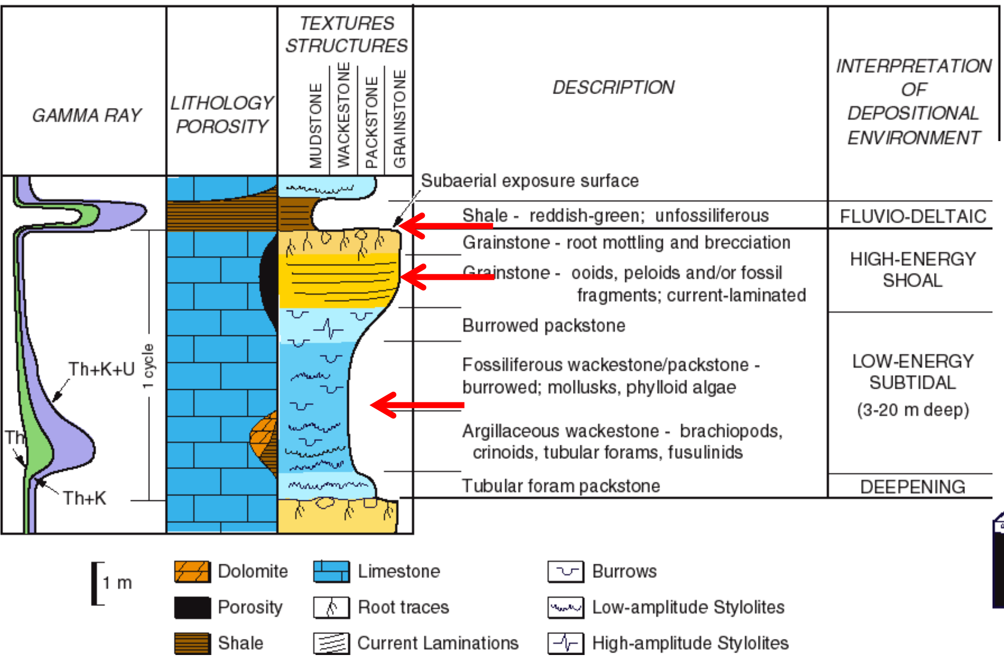
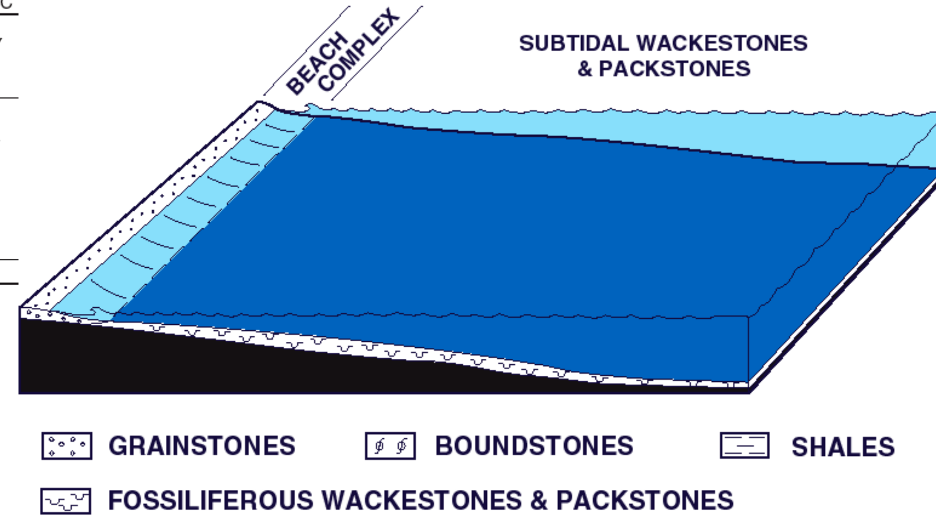
Alternate between deposition & subaerial exposure

TYPICAL SOUTHWEST ANDREWS CYCLE

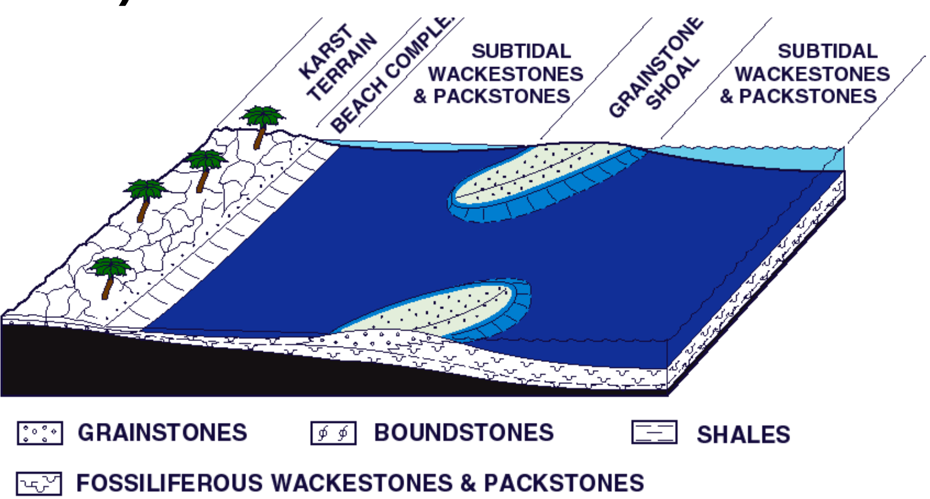


~90 cycles: Frequency ~110 ky

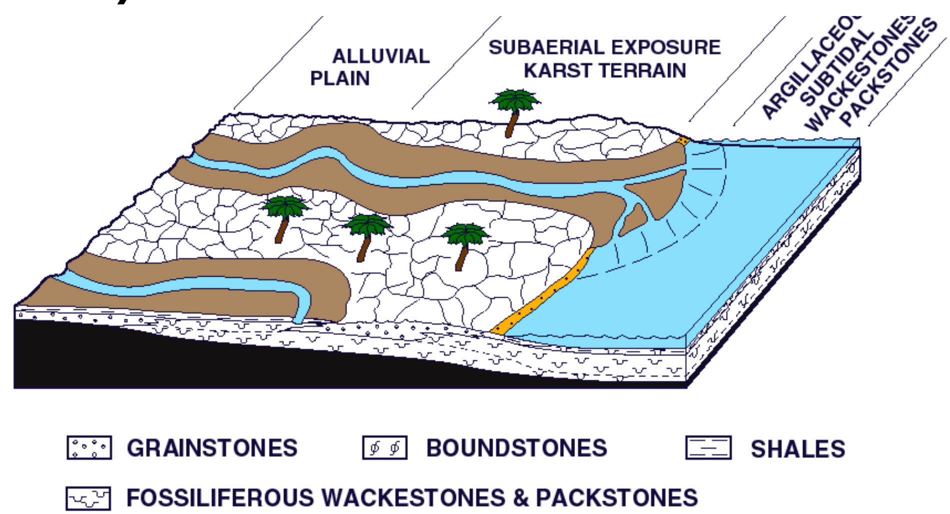
A) INITIAL FLOODING OF SHELF



B) DEVELOPMENT OF SHOALS



C) SEA LEVEL DROP & EXPOSURE



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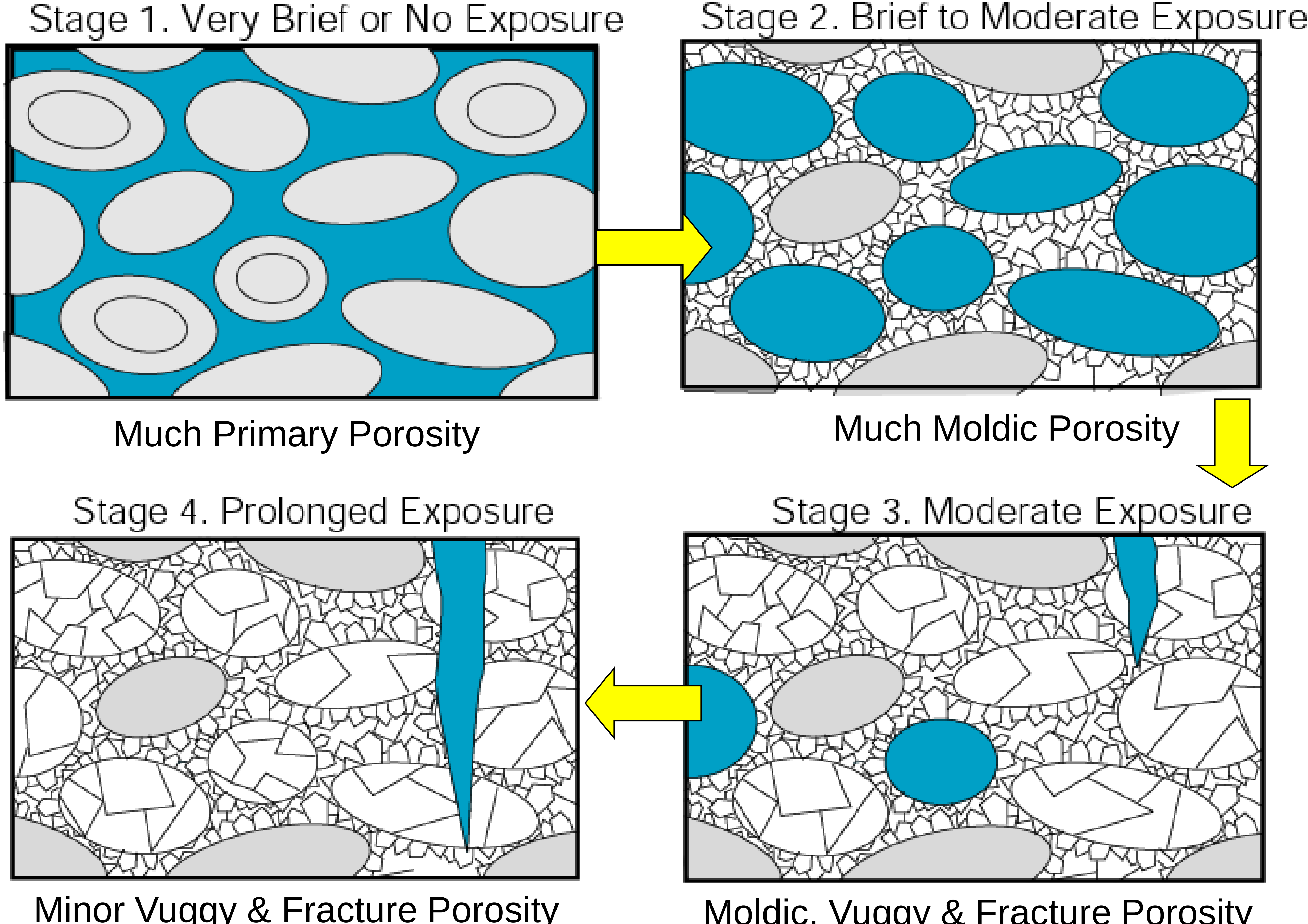
EVOLUTION OF POROSITY DURING SUBAERIAL EXPOSURE

- Total porosity generally decreases with duration of subaerial exposure
- Dissolution at the surface lowers the surface, & that $CaCO_3$ moves down and can precipitate calcite in the shallow subsurface decreasing porosity
- Systematic changes in porosity, pore types & permeability occur during exposure
- Initially primary pores are filled as secondary pores (esp. moldic porosity) are created during early diagenesis
- Later, moldic pores are filled as vugs and fractures are created (Φ less, K more)
- Prolonged exposure results in fractures & cavernous porosity with high K, but low Φ



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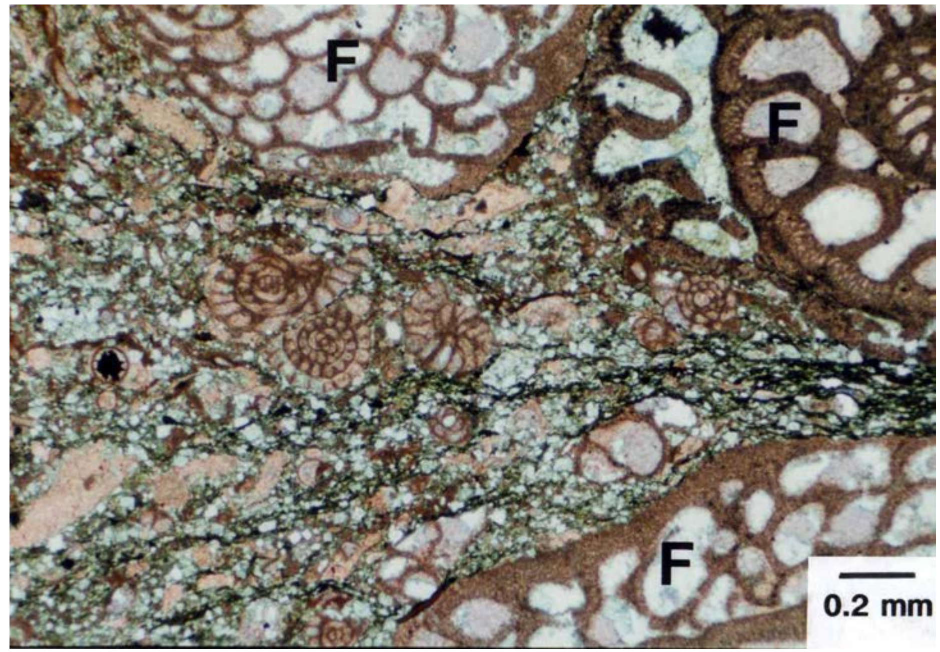
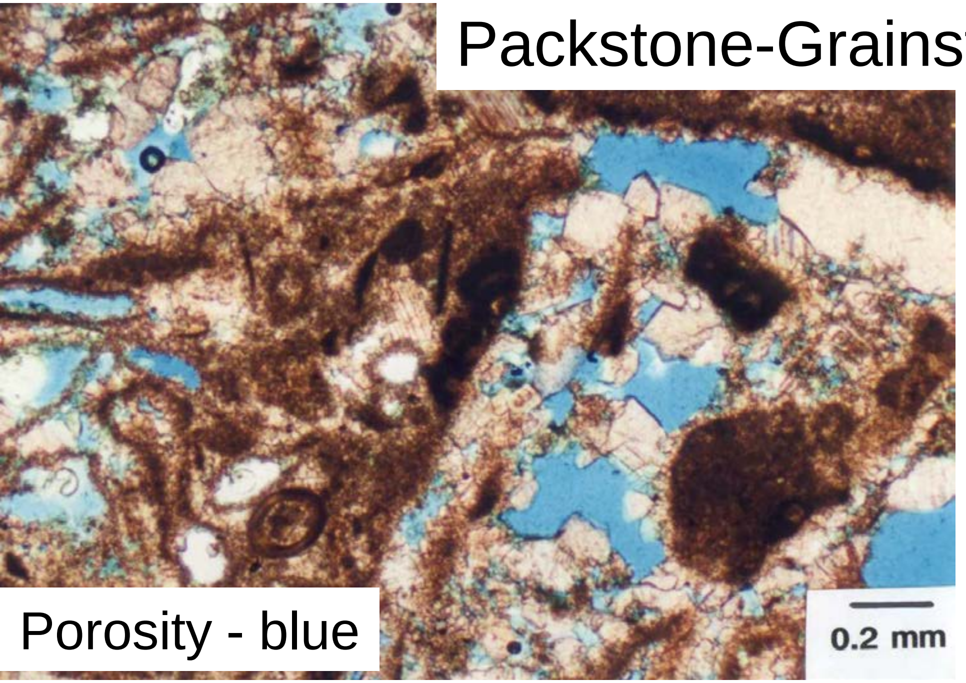
SOUTHWEST ANDREWS: NO SUBAERIAL EXPOSURE

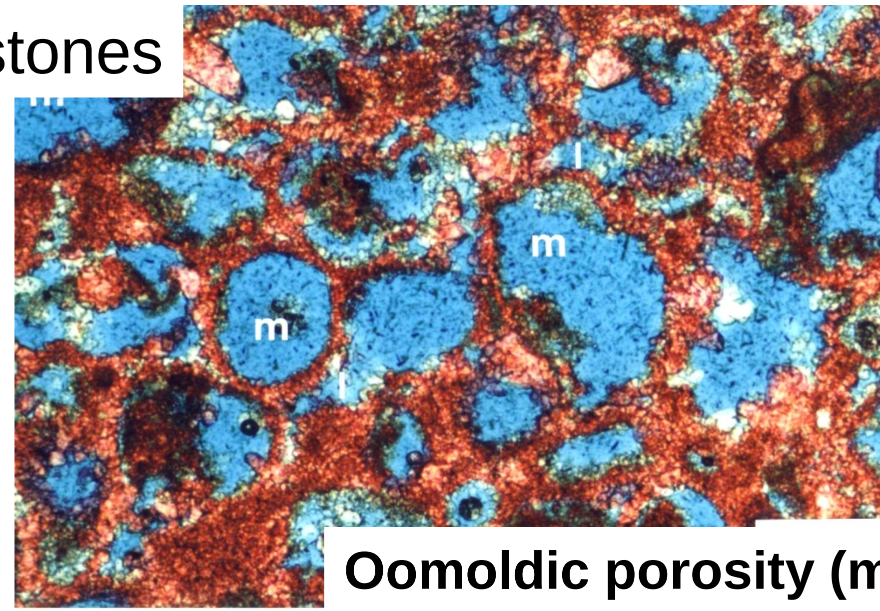


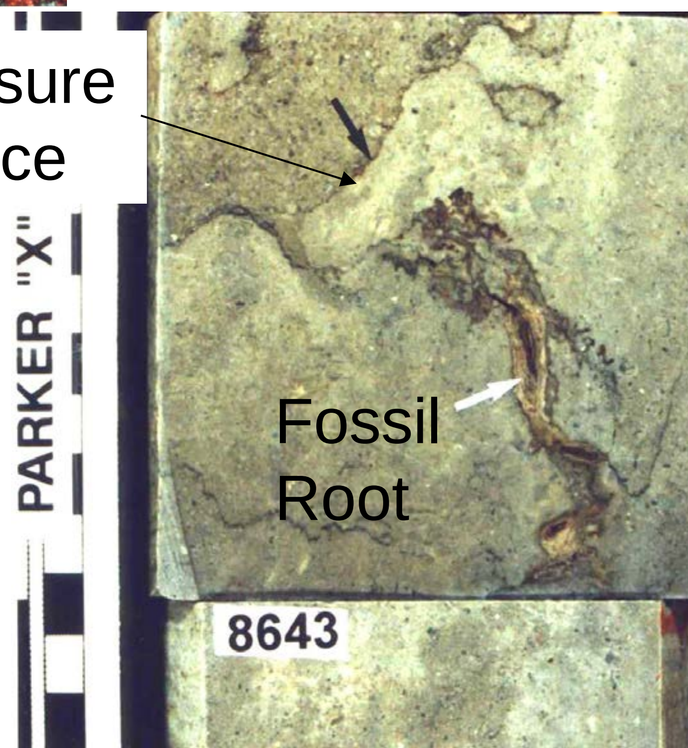
Compaction reduces porosity in initially porous micritic sediment with no early lithification

SOUTHWEST ANDREWS: BRIEF SUBAERIAL EXPOSURE

Packstone-Grainstones

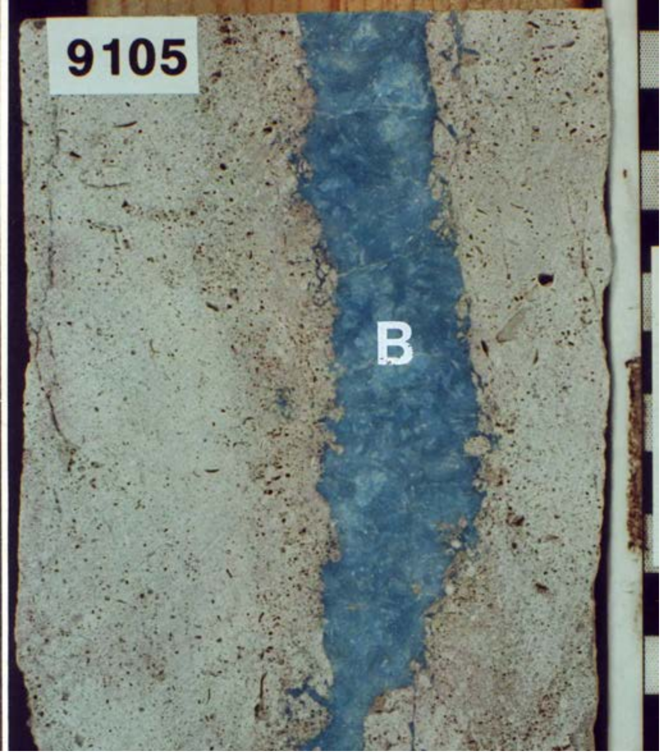






Porosity ~15%
Permeability ~1 mD

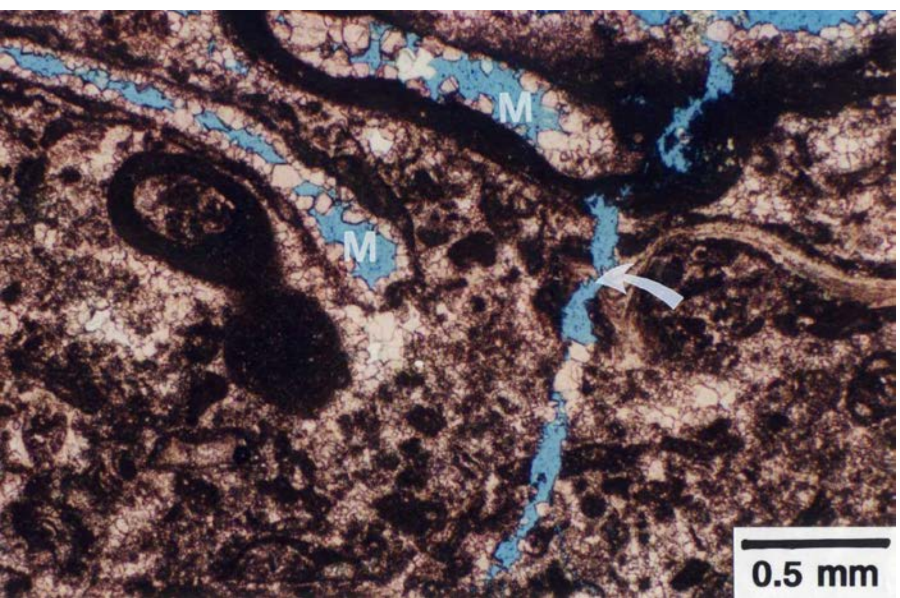
Brief subaerial exposure (10-30K years?) in grainstones causes dissolution that creates pores (mainly moldic), and cemention that fills pores and lithifies the rock

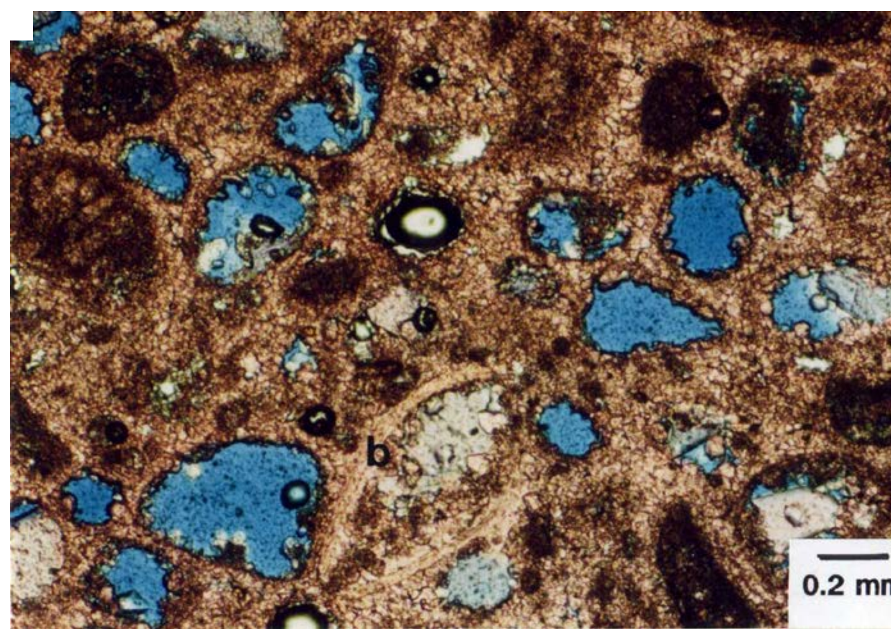


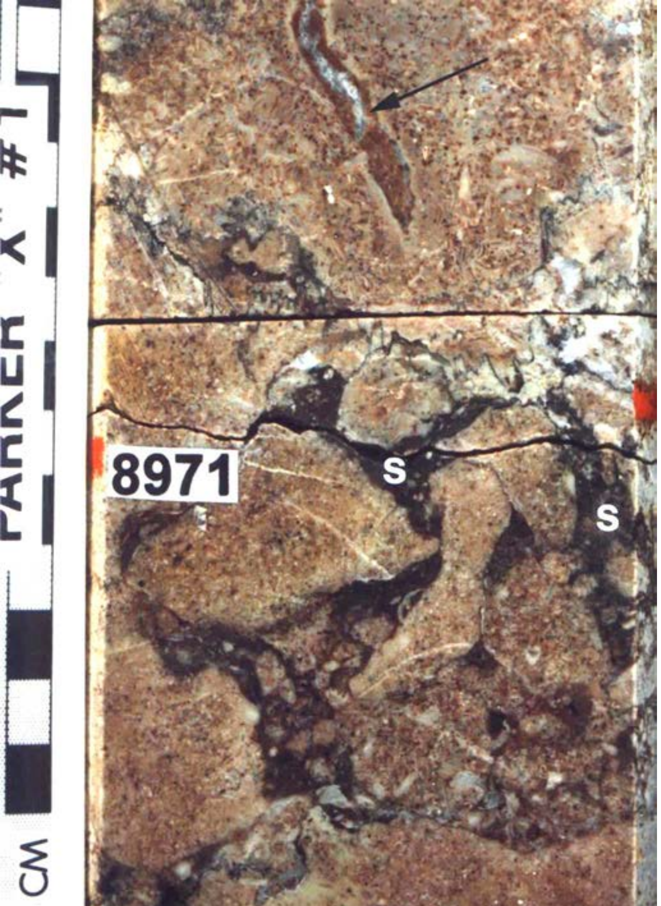
SOUTHWEST ANDREWS

Moderate subaerial exposure (30-60K years?) causes dissolution of some conduit pores and more cementation resulting in decreased porosity, but increased permeability

Porosity ~10%; Permeability ~10 mD

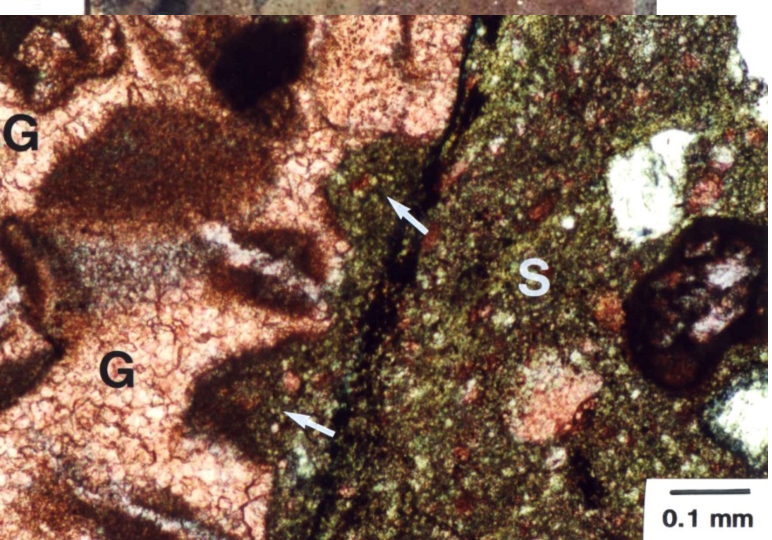


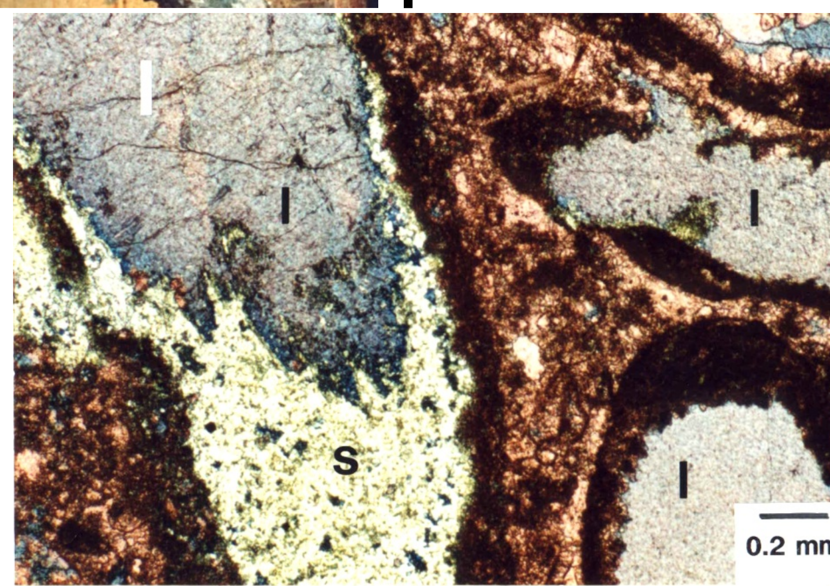


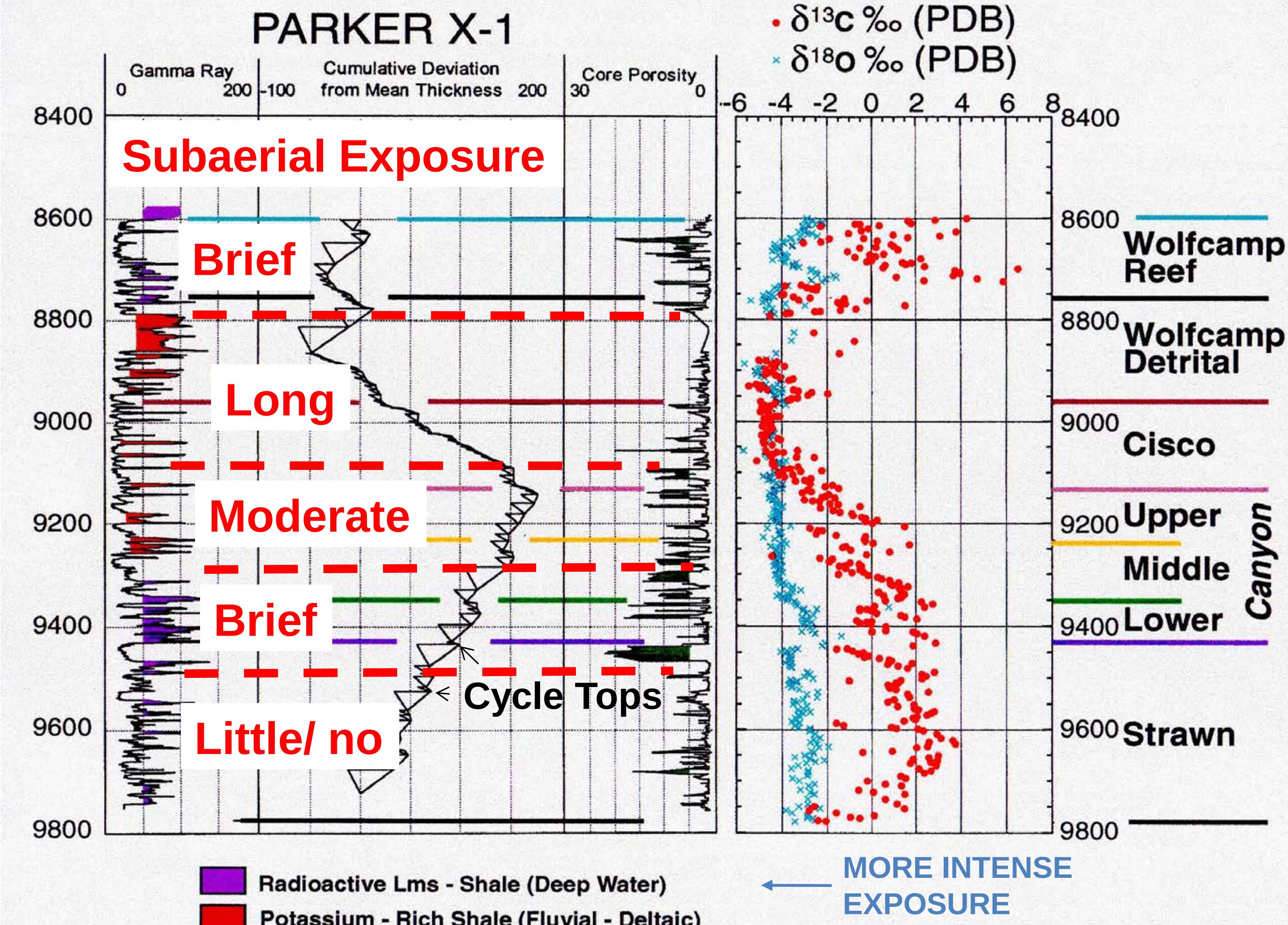


SW ANDREWS: PROLONGED EXPOSURE IN/NEAR SOIL ZONE

Shaley material (s) fills between breccia clasts. Iron-rich burial cements fill other pores.







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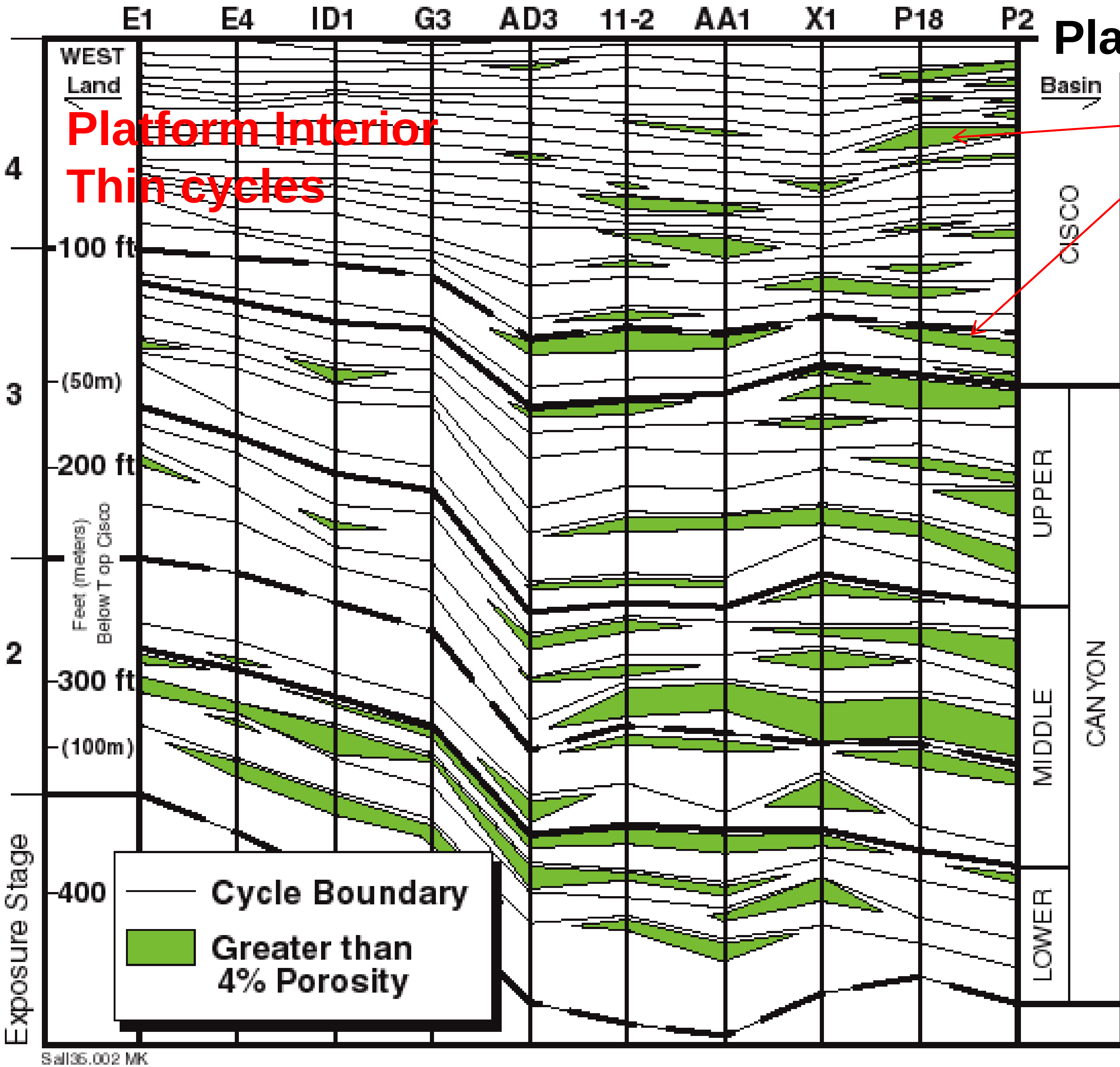
Platform Margin



Grainstones

POROSITY: UPPER PENN. SW ANDREWS

Thinner cycle = Longer Exposure

From Saller, A.H., J.A.D. Dickson, and F. Matsuda, 1999, Evolution and distribution of porosity associated with subaerial exposure in upper Paleozoic platform limestones, west Texas: *AAPG Bulletin*, v. 83, p. 1835-1854

Prolonged exposure fills most matrix pores, but creates caves that continually form and collapse.

Total Porosity in Mature Karst Areas is commonly <3%.

Sediment around collapse cave clasts

Diagenetic Evolution of Porosity in Carbonates during Burial

- Introduction
- Marine Diagenesis - Enewetak
- Freshwater Diagenesis – Pennsylvanian, West Texas
- Dolomitization – Permian, West Texas
- Burial – Florida/ South Alabama

EFFECT OF DOLOMITIZATION ON POROSITY DEPENDS ON:

(A) Input of Ions,

(B) Position in System/Saturation

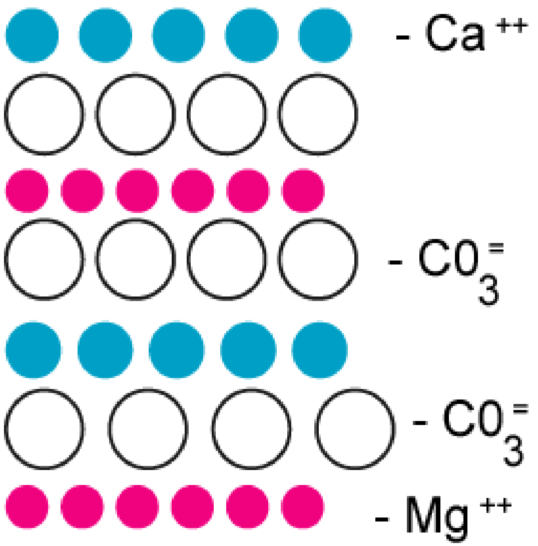
(C) Volume of Brines Flowing Through

(1) $2CaCO_3 + Mg^{2+}$ ----> $CaMg(CO_3)_2 + Ca^{2+}$

Solid volume decreases by 12%

Dolomitization creates porosity

DOLOMITE STRUCTURE (SCHEMATIC)

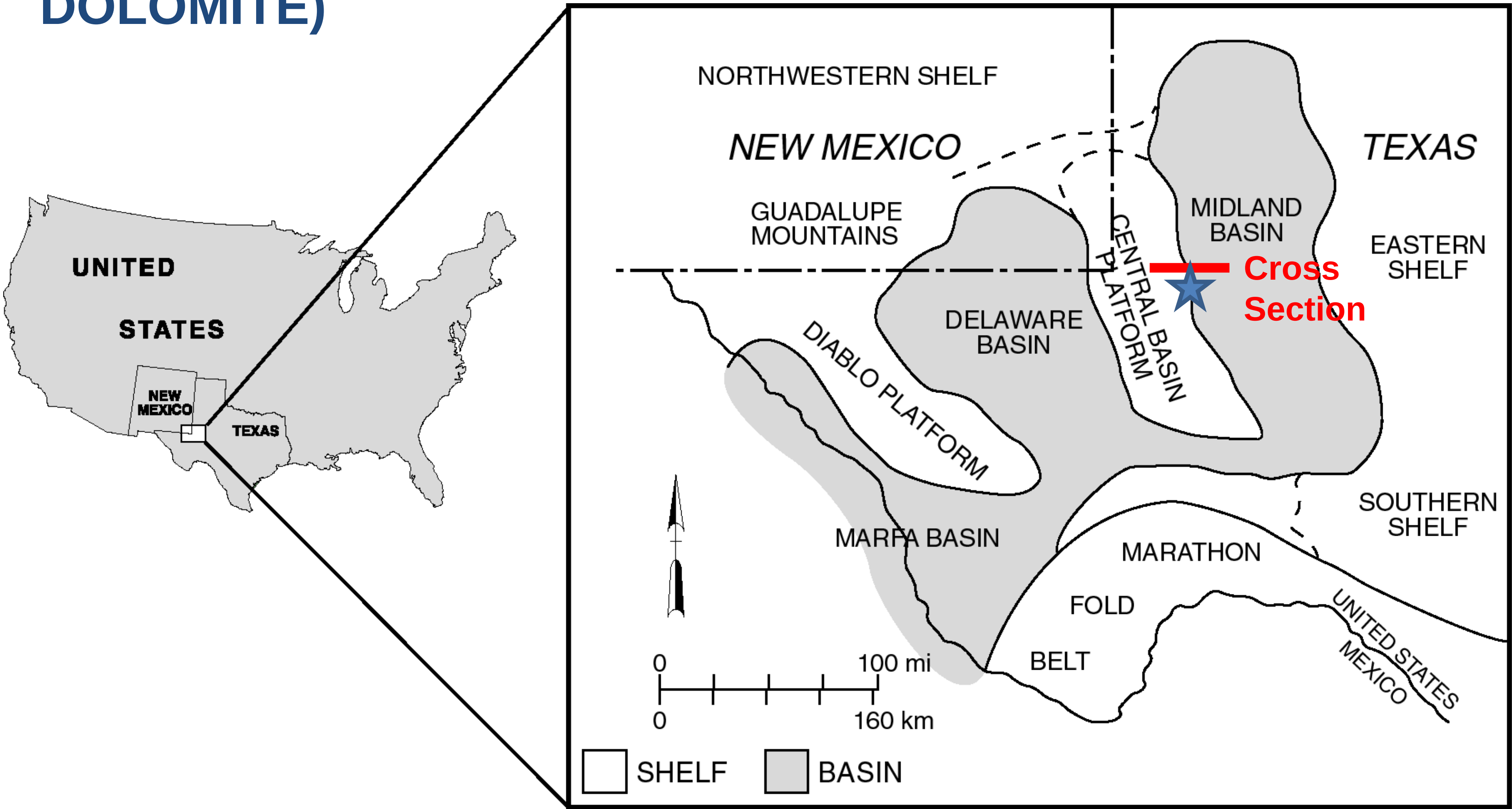


(2) Except when it doesn't

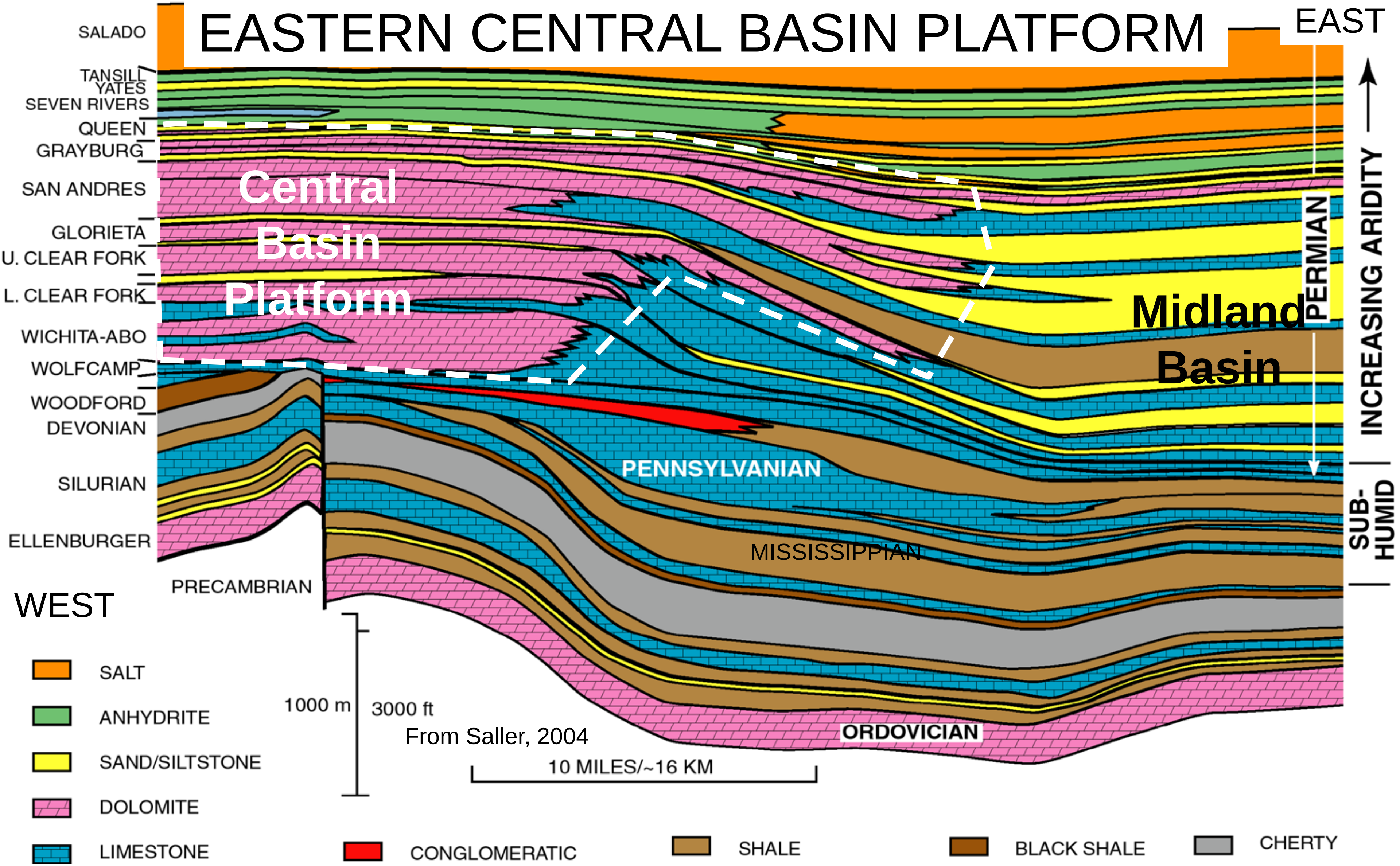
$CaCO_3 + Mg^{2+} + CO_3^{2-}$ ----> $CaMg(CO_3)_2$

Solid volume increases by 75%

Dolomitization is common in platform interiors in arid climates. Permian of west Texas is a classic example. Most of this dolomitization is probably related to evaporated seawater formed in lagoons. That evaporated seawater is dense, moves down and dolomitizes. (REFLUX DOLOMITE)



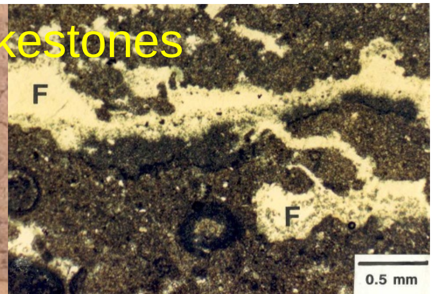
EASTERN CENTRAL BASIN PLATFORM



Preferential Dolomitization of Platform/ Shelf Tops of Middle-Upper Permian Carbonates (Arid Climate)

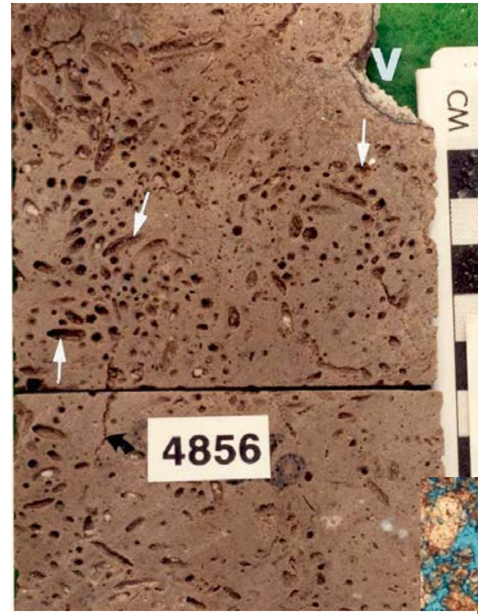
From Saller, A.H., 2004, Palaeozoic dolomite reservoirs in the Permian Basin, SW USA: stratigraphic distribution, porosity, permeability and production, *in* C.J.R. Braithwaite, G. Rizzi, and G. Darke, eds., The geometry and petrogenesis of dolomite hydrocarbon reservoirs: Geological Society of London, Special Publication 235, p. 309-323.

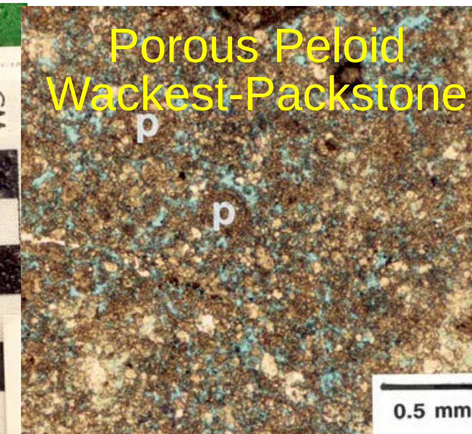
PLATFORM INTERIOR



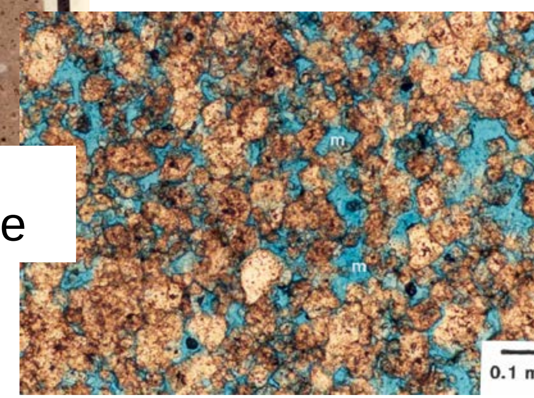
Nonporous Fusulinid Wackestone

POROUS PLATFORM MARGIN

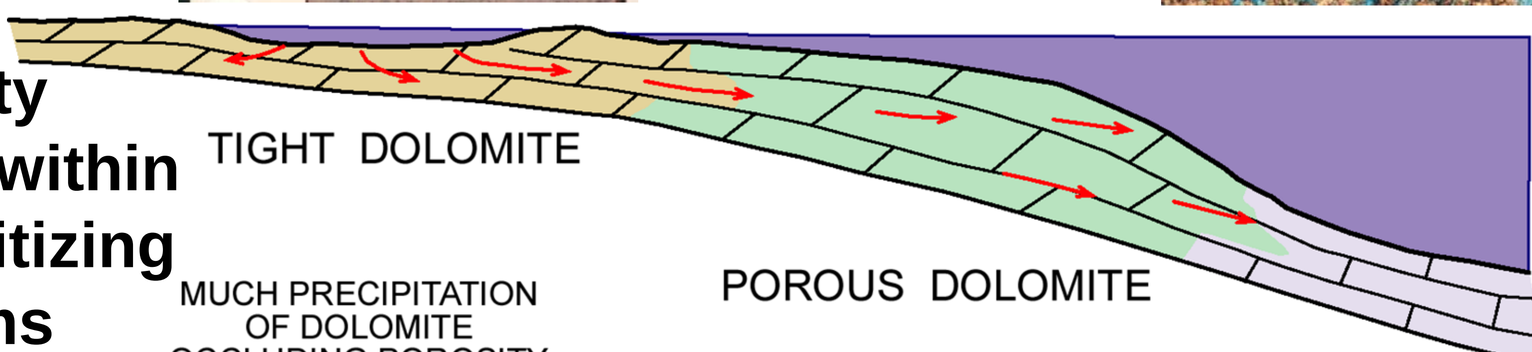




Porous Fusulinid Wackest-Packstone



Porosity varies within Dolomitizing Systems

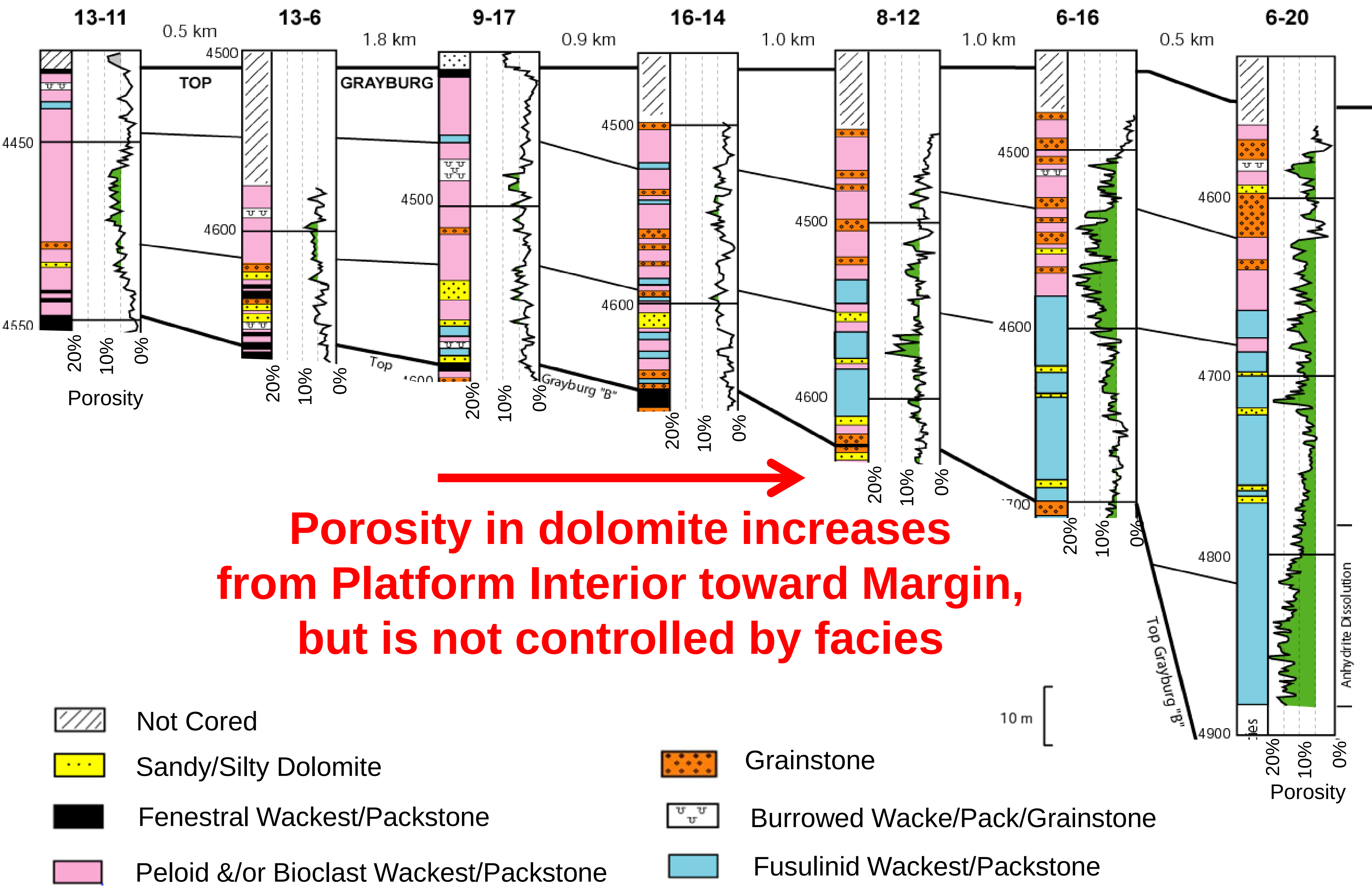


From Saller, A.H. and N. Henderson, 1998, Distribution of porosity and permeability in platform dolomites: insight from the Permian of west Texas: *AAPG Bulletin*, v. 82, p. 1528-1550.

South Cowden Field

West
Platform Interior

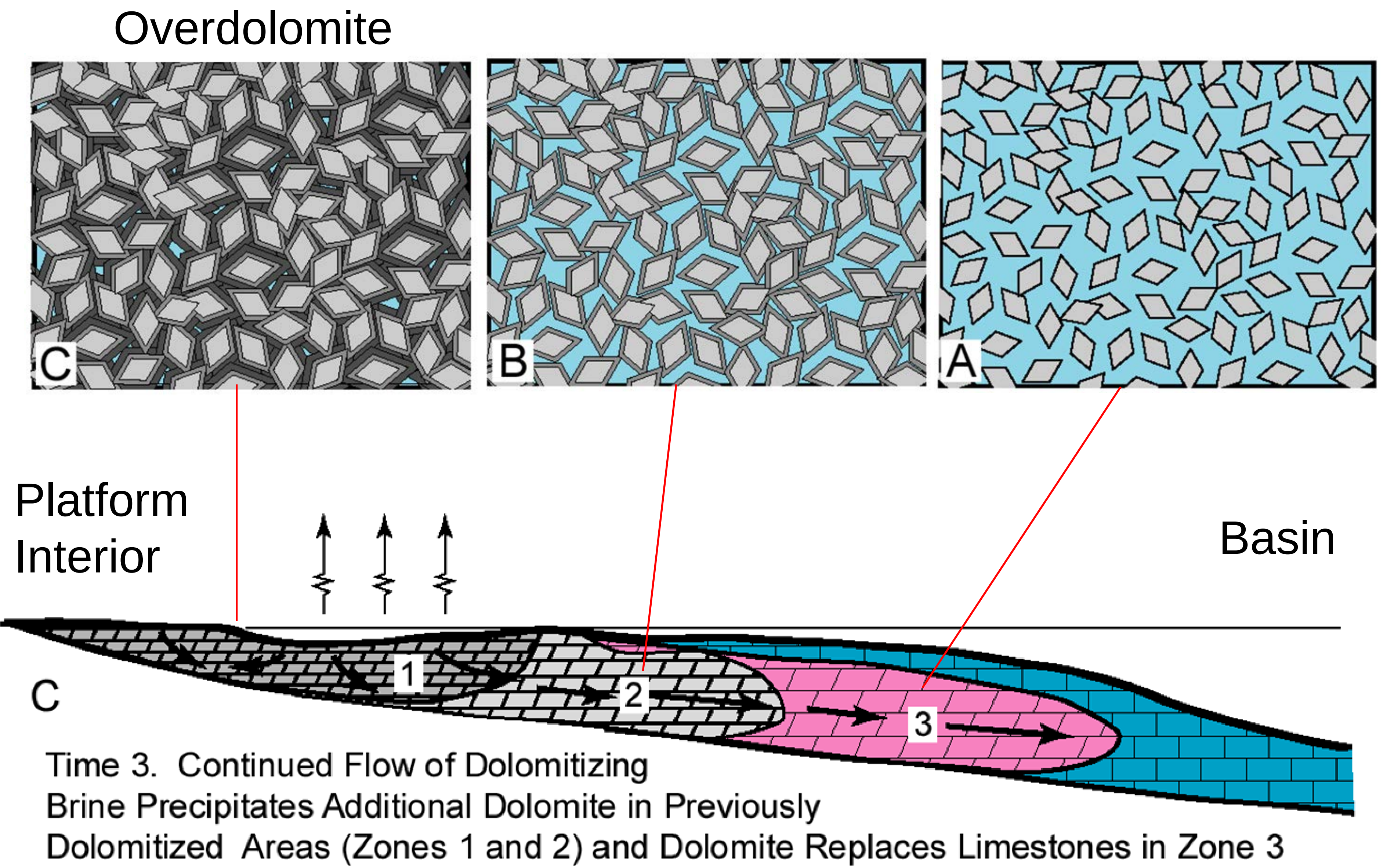
East
Platform Margin



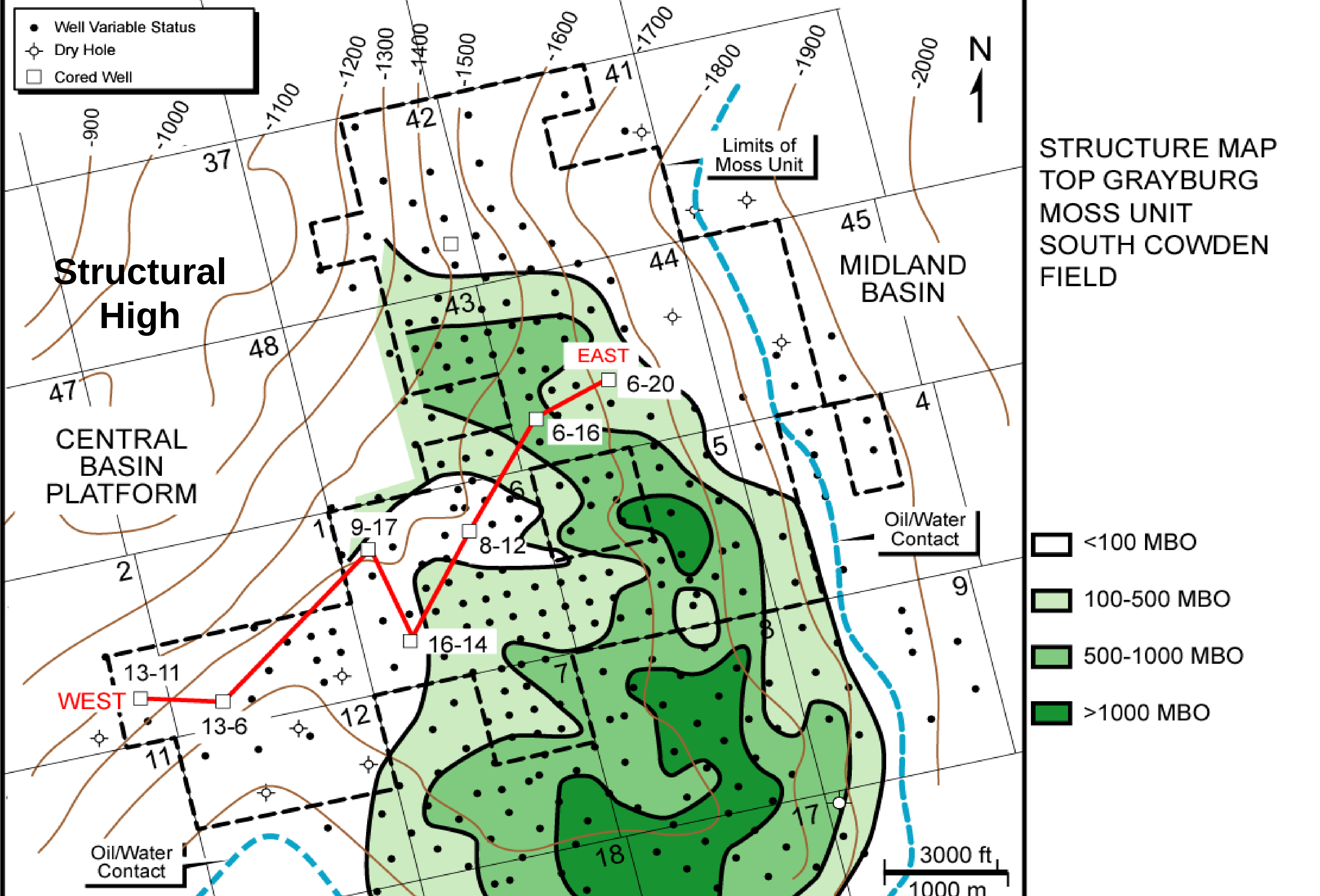
Porosity in dolomite increases from Platform Interior toward Margin, but is not controlled by facies

From Saller & Henderson, 1998

STAGE/DURATION OF DOLOMITIZATION AFFECTS POROSITY



From Saller, A.H., 2004, Palaeozoic dolomite reservoirs in the Permian Basin, SW USA: stratigraphic distribution, porosity, permeability and production, *in* C.J.R. Braithwaite, G. Rizzi, and G. Darke, eds., The geometry and petrogenesis of dolomite hydrocarbon reservoirs: Geological Society of London, Special Publication 235, p. 309-323.



STRUCTURE MAP
TOP GRAYBURG
MOSS UNIT
SOUTH COWDEN
FIELD

Highest Oil Production occurred where high porosity platform margin dolomites are above the oil/water contact

From Saller & Henderson, 1998

Diagenetic Evolution of Porosity in Carbonates during Burial

- Introduction
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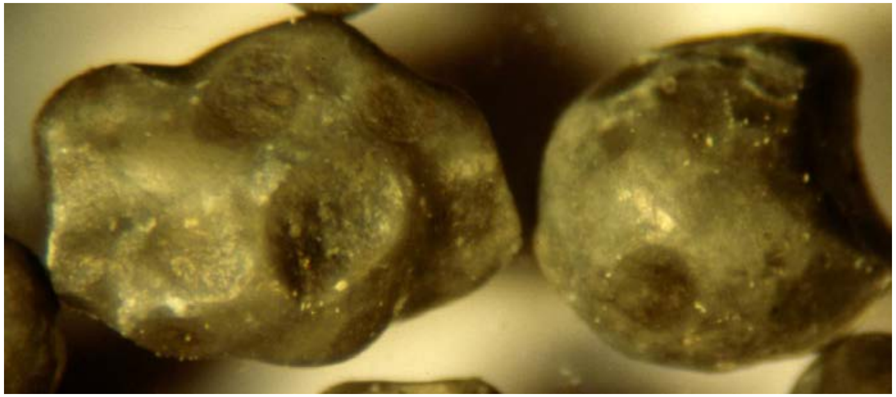
- Dolomitization – Permian, West Texas
- Deep Burial – Florida/ South Alabama

LOSS OF POROSITY WITH DEEPER BURIAL

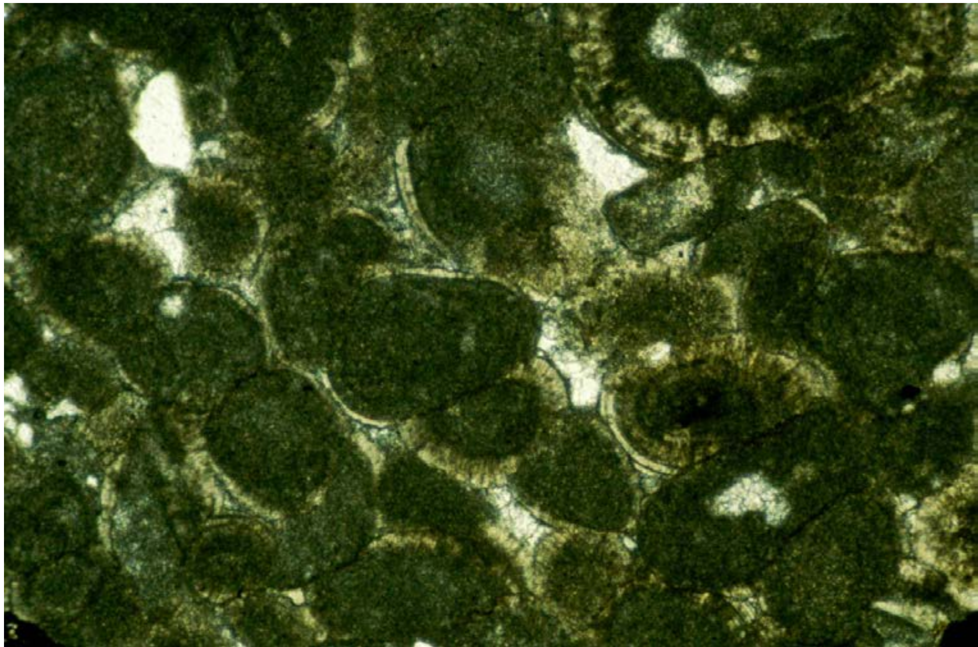
- Physical (plastic) compaction
- Chemical compaction (pressure solution)
- Cementation

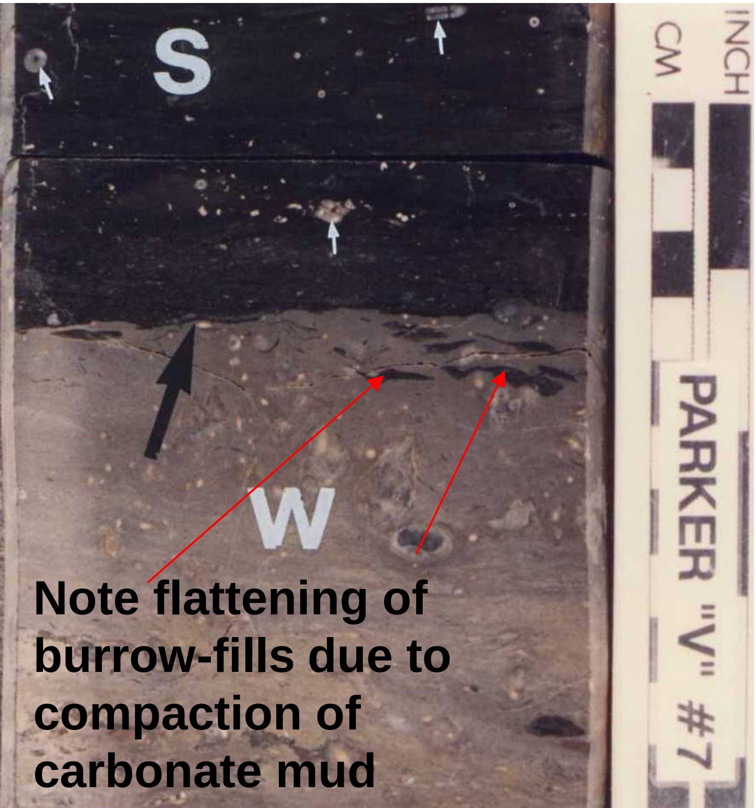
- Physical (plastic) compaction
  - Carbonate muds start with ~80% porosity (Enos & Swatsky, 1981)
  - Without early lithification, they will compact until they have no effective porosity

Grainstone will also compact, but more slowly



Ooid Grainstone; Jurassic Smackover Fm; ~10,000 feet deep; Plastic Deformation & Grain-to-Grain Pressure Solution



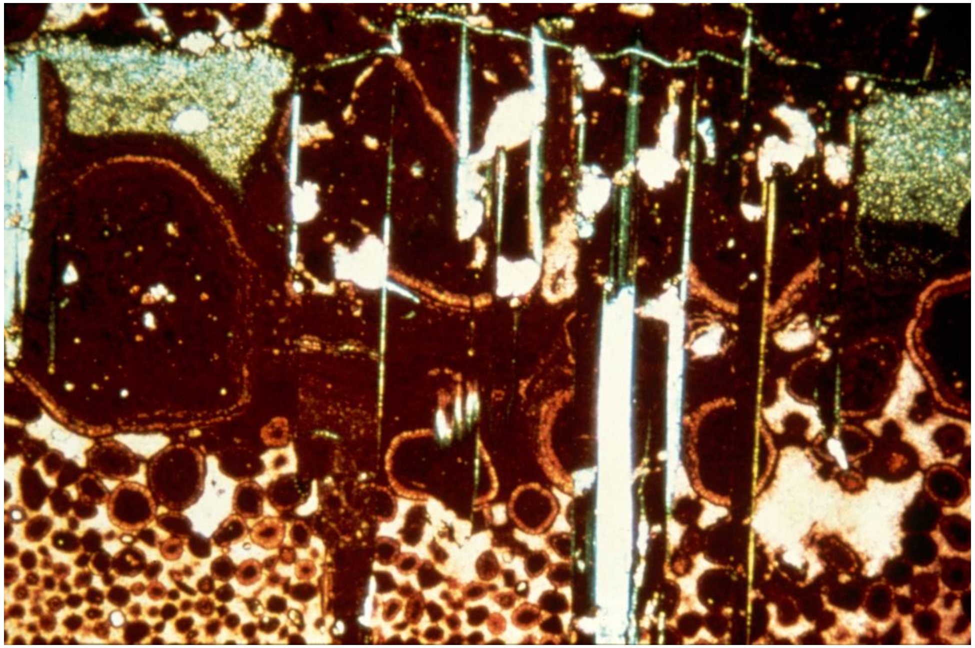


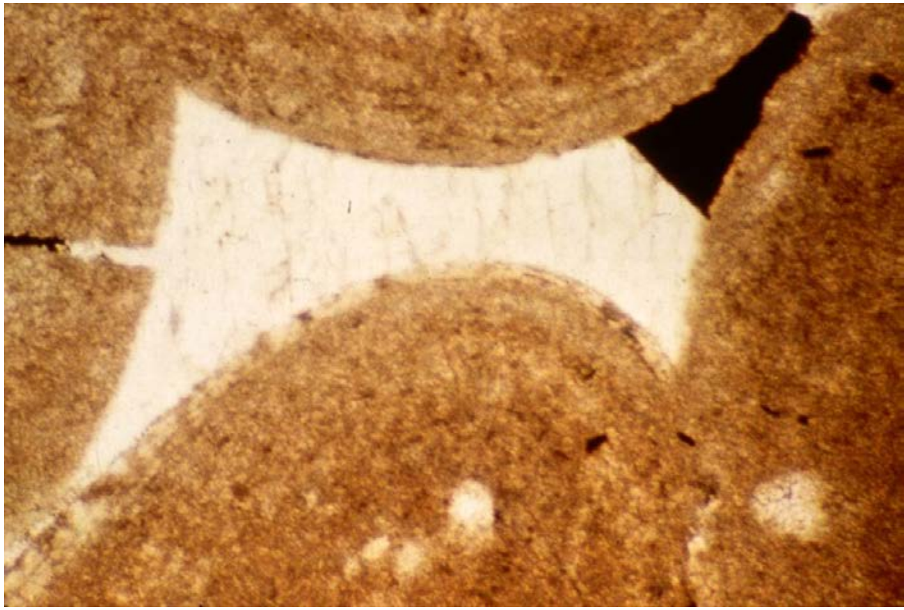
Note flattening of burrow-fills due to compaction of carbonate mud

LOSS OF POROSITY WITH BURIAL

- Physical (plastic) compaction
- Chemical compaction (pressure solution)
- Cementation

Burial cements are commonly derived from pressure solution of adjacent strata

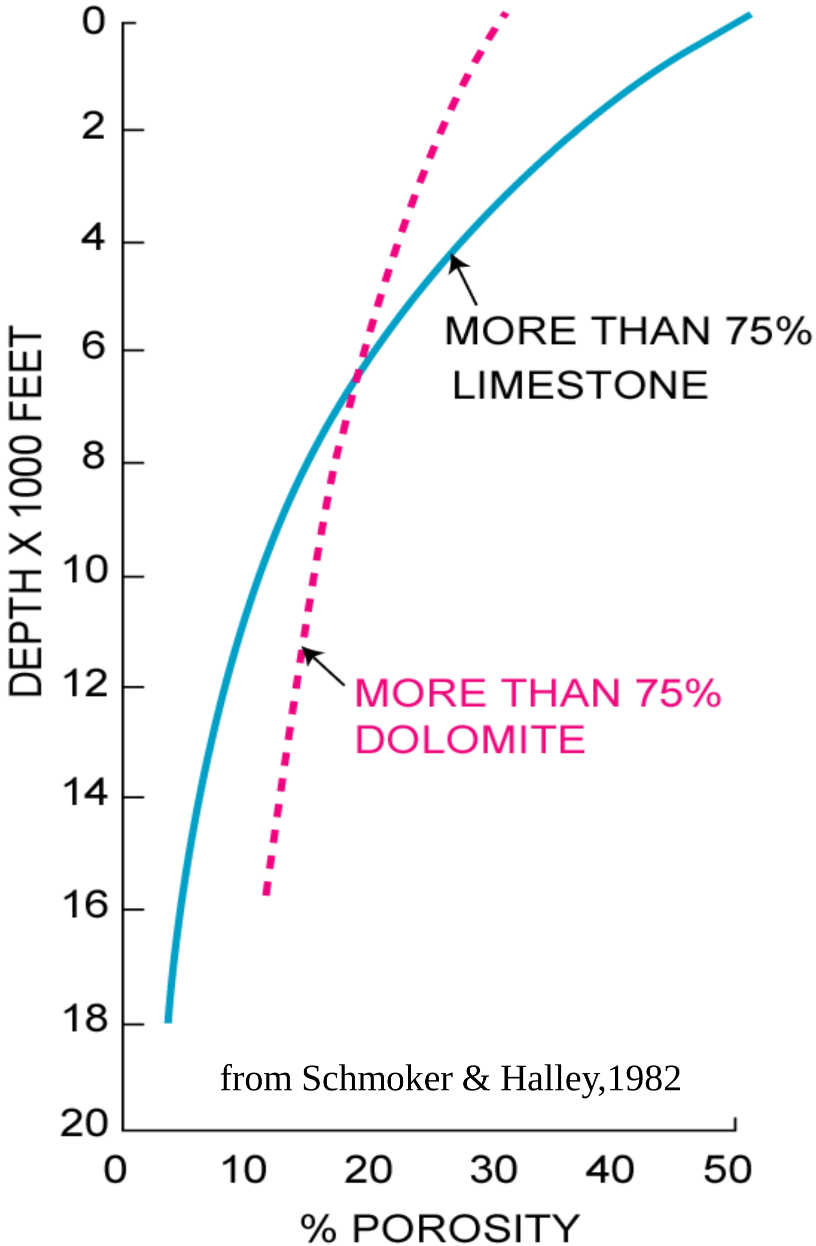


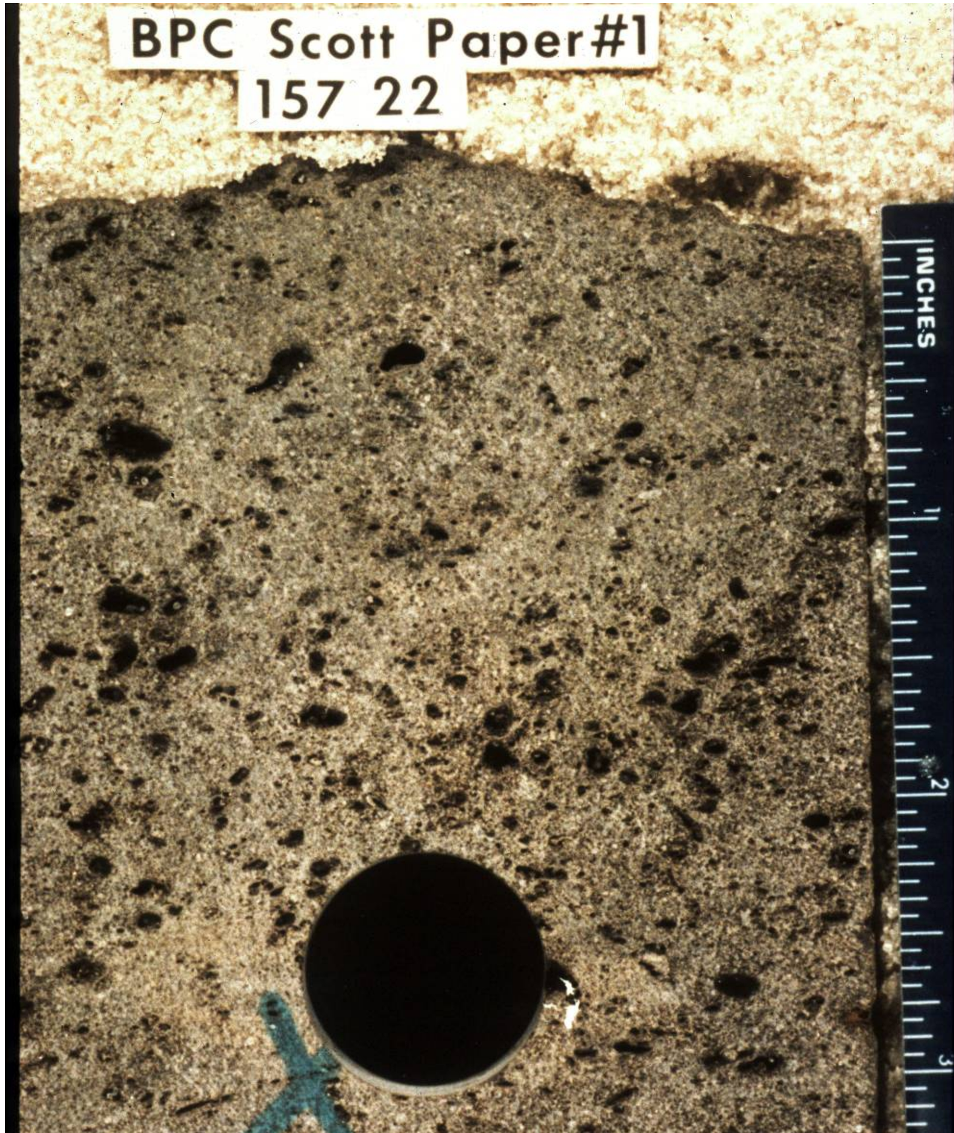


Burial Cement; Smackover ~10,000 feet **(from C.H. Moore)**

Rate of Porosity Loss Depends on Pressure, Temperature & Time

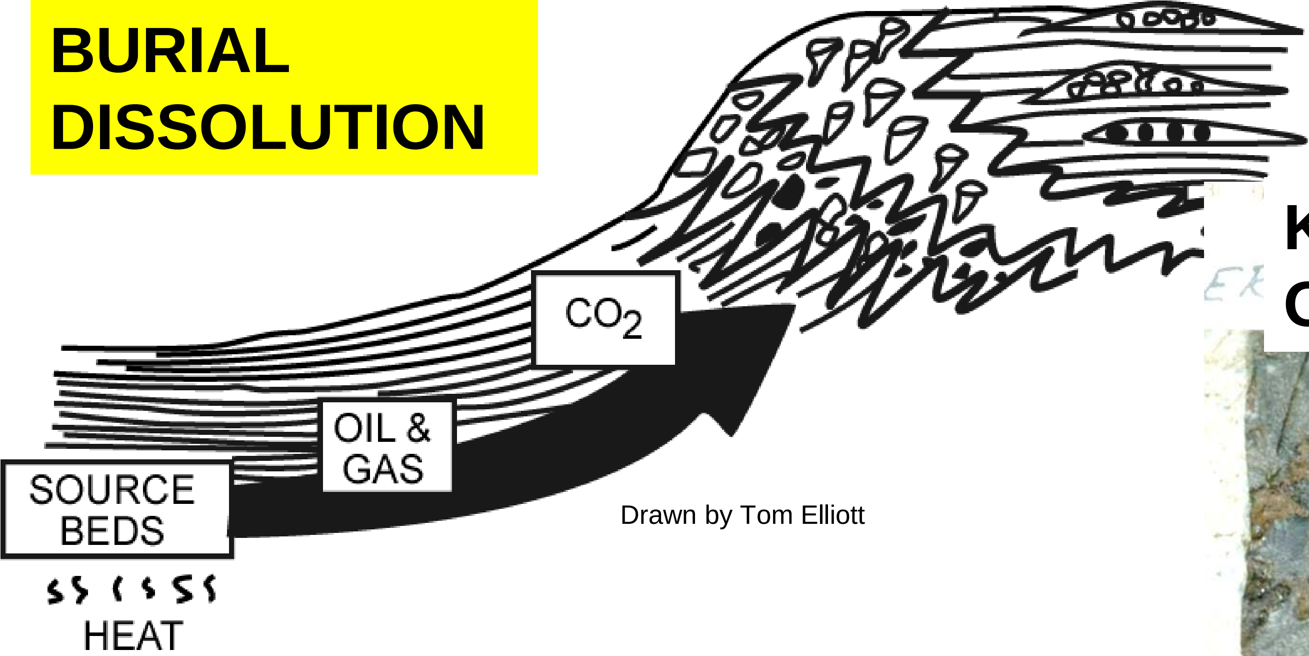
Upper Jurassic Smackover dolomite with 10-15% porosity, west Florida





Early dolomitization causes lithification that decreases porosity loss with burial

BURIAL DISSOLUTION

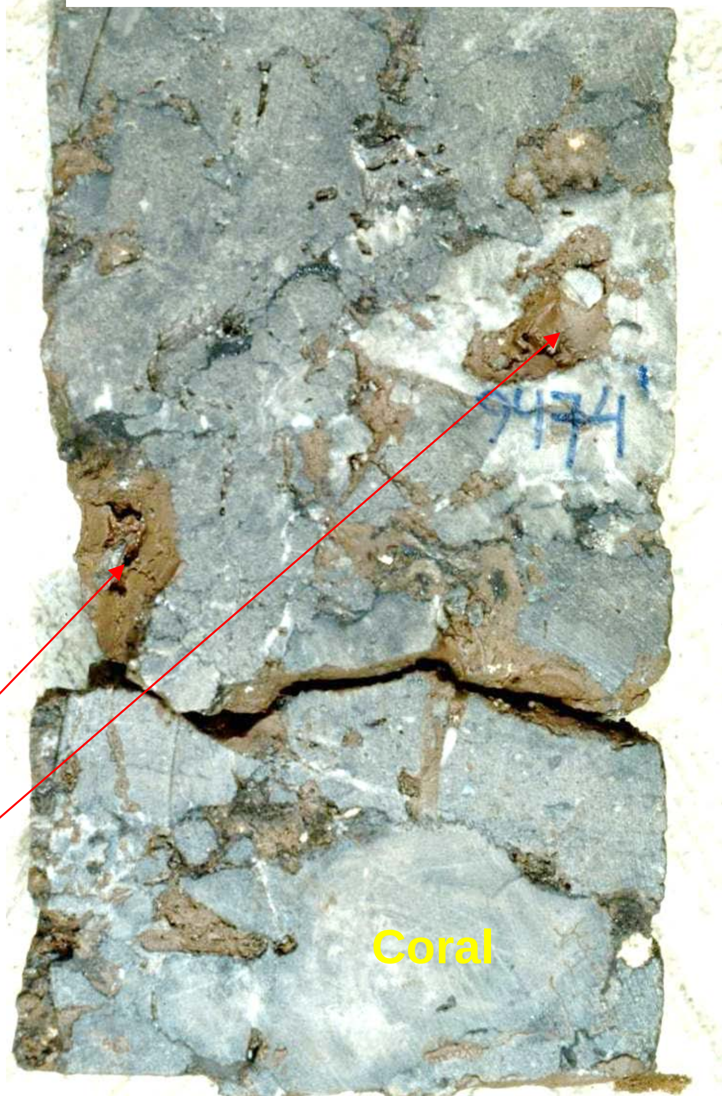


Drawn by Tom Elliott

Kerendan Platform Oligocene, Borneo

Carbonate dissolution during deep burial can create porosity.
-Acidic waters can be expelled from organic-rich shale
-Dissolution is commonly associated with "hydrothermal dolomite"

Reddish drilling mud fills vugs created during dissolution during deep burial at the margins of an Oligocene platform

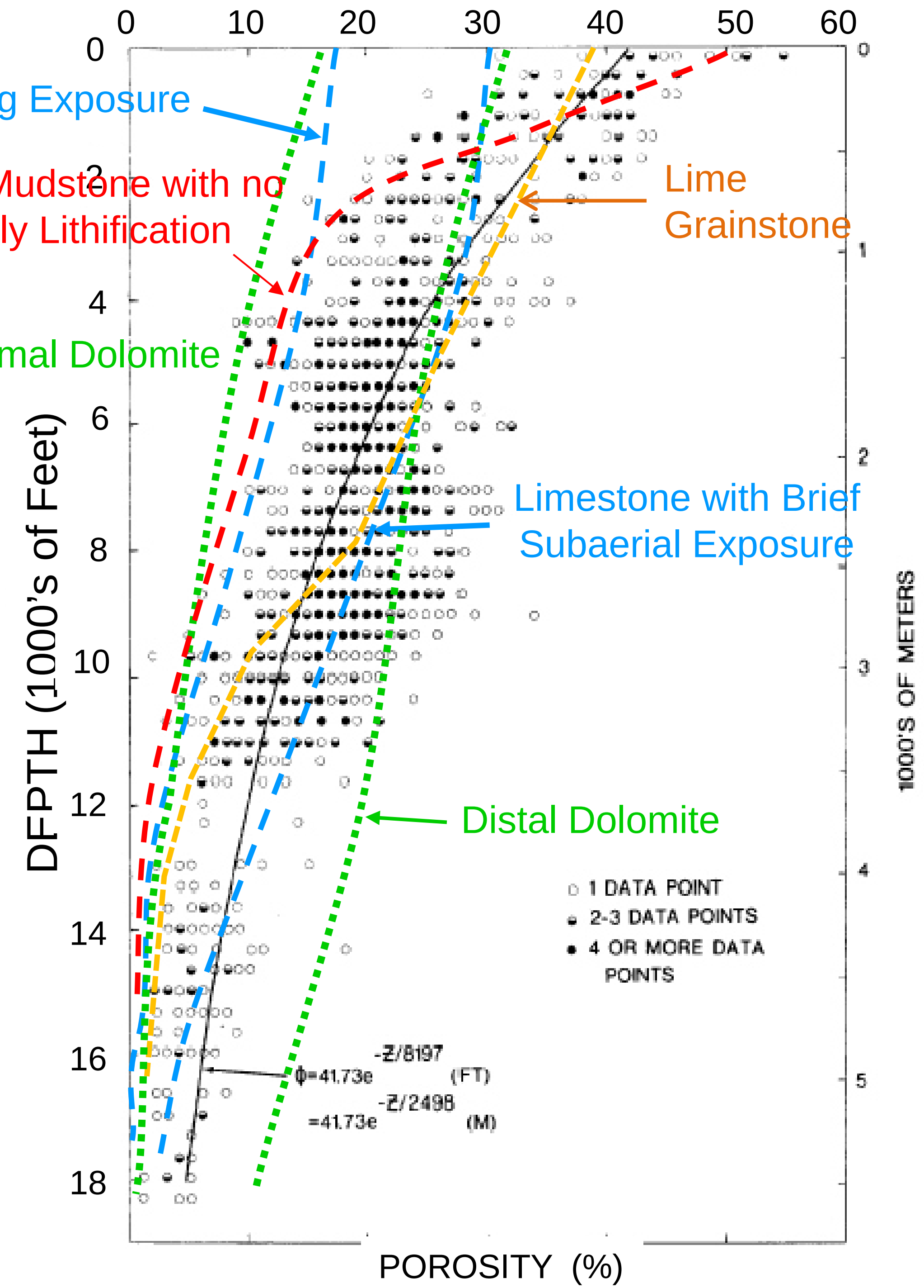


From Saller, A.H., and Suta Vijaya, 2002, Depositional and diagenetic history of the Kerendan carbonate platform, Oligocene, central Kalimantan, Indonesia: Journal of Petroleum Geology, v. 25, p. 123-150.

POROSITY GENERALLY DECREASES WITH DEPTH

With much variation related to deposition & early diagenesis, temperature, pressure, & time

SOUTH FLORIDA
PLEISTOCENE TO JURASSIC CARBONATES



From Schmoker, J.W. and R.B. Halley, 1982, Carbonate Porosity Versus Depth: A predictable Relation for South Florida: AAPG Bulletin, v.66, p.2561-2570.

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