Sequence Stratigraphy of Classic Carbonate Outcrops in West Texas and Southeast New Mexico and Application to Subsurface Reservoirs*

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Abstract

West Texas and southeast New Mexico contain many classic carbonate exposures with large vertical and lateral extents that allow delineation of major sequence stratigraphic relationships. Sequence stratigraphic relationships help to predict geometries, facies, and early diagenesis in analogous systems in the subsurface. Isolated carbonate buildups are present in Mississippian and Pennsylvanian outcrops in the Sacramento Mountains, and they grew during transgressions when accommodation (relative sea level rise) was greater than or approximately equal to carbonate sediment production. Drowned isolated buildups are commonly excellent carbonate reservoirs throughout the world, including the nearby Horseshoe Atoll.

Ramp carbonates of the Permian San Andres Formation are exposed along the western side of the Guadalupe Mountains. The San Andres has a thick lower transgressive systems tract (TST) overlain by a prograding highstand systems tract (HST). Major hydrocarbon reservoirs occur in similar sequences in the subsurface. Reservoirs are commonly shelf-crest grainstones and adjacent packstones in the HST of the upper San Andres with structures created by differential compaction over packstone-grainstone buildups in the TST of the lower San Andres.

The Capitan Formation is part of a classic carbonate shelf dominated by progradation in a 2nd order HST. Most major carbonate depositional environments occur in this system. The same stratigraphic interval occurs in the subsurface. The structural configuration of the prograding margin is dominated by basinward dip caused by differential compaction associated with the progradation. As a result, the fractured Capitan reef is generally structurally low and wet. Hydrocarbons occur in backreef carbonates and shelfal sandstones with updip, landward seals formed by impermeable lagoonal evaporites.

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Sequence Stratigraphy of Classic Carbonate Outcrops in west Texas & southeast New Mexico & Application to Subsurface Reservoirs

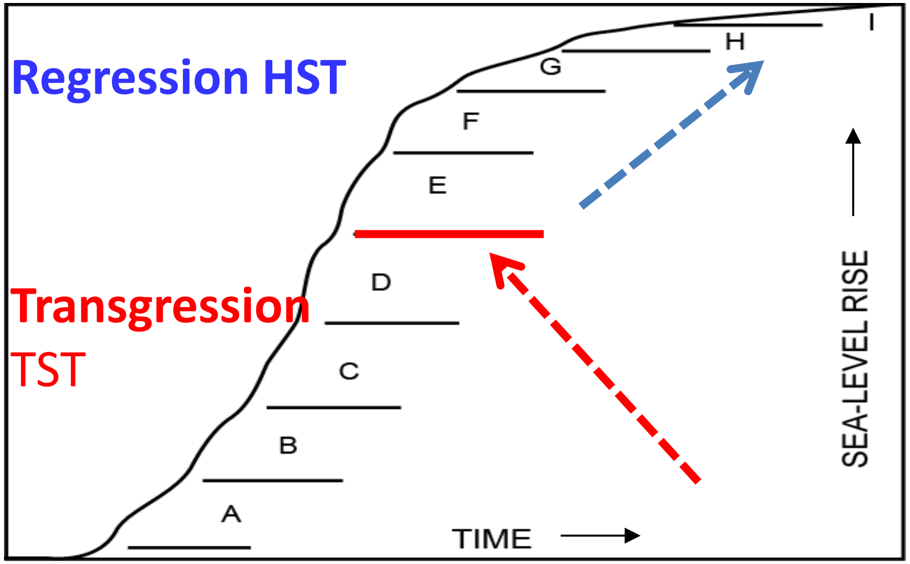
Art Saller (arthur.saller@cobaltintl.com)

Classic Carbonate outcrops in west Texas and southeast New Mexico

- Outcrops provide large, continuous exposures
  - 5-20 miles x >1000 ft (10-30 km x 300 m);
  - Field-scale and seismic scale
  - Minimal structural deformation
- Illustrate the architecture & sequence stratigraphy of the three main types of carbonate systems
  - Isolated buildups
  - Ramps
  - Shelves
- Observe all major carbonate/evaporite depositional environments
- Provide insights/analogs/visualization for the subsurface exploration and oil fields

CARBONATE SEQUENCE STRATIGRAPHIC MODEL

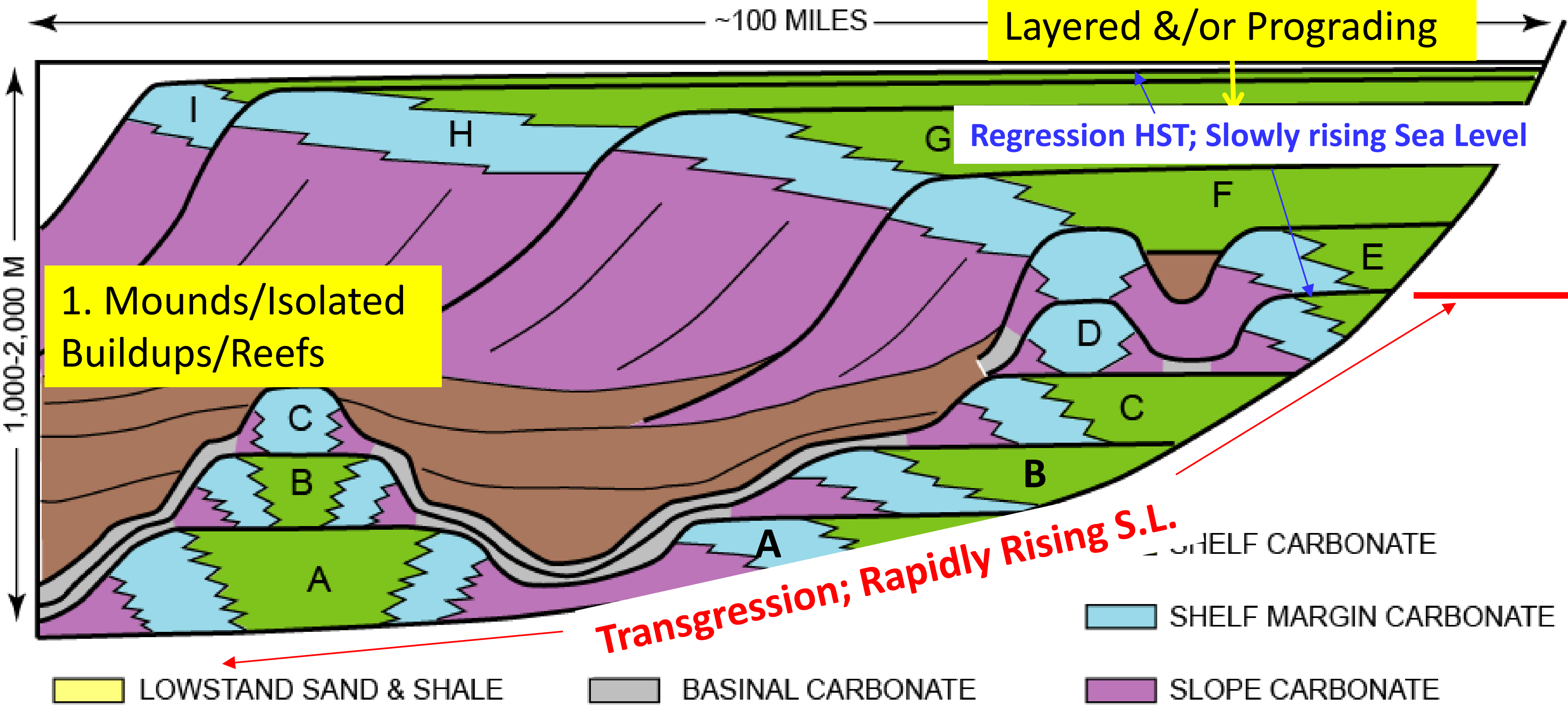
From Greenlee, S.M., and P.J. Lehmann, 1993, Stratigraphic framework of productive carbonate buildups, *in* R.G. Loucks and J.F. Sarg, eds., Carbonate sequence stratigraphy: recent developments and advancements: AAPG Memoir 57, p. 43-62.



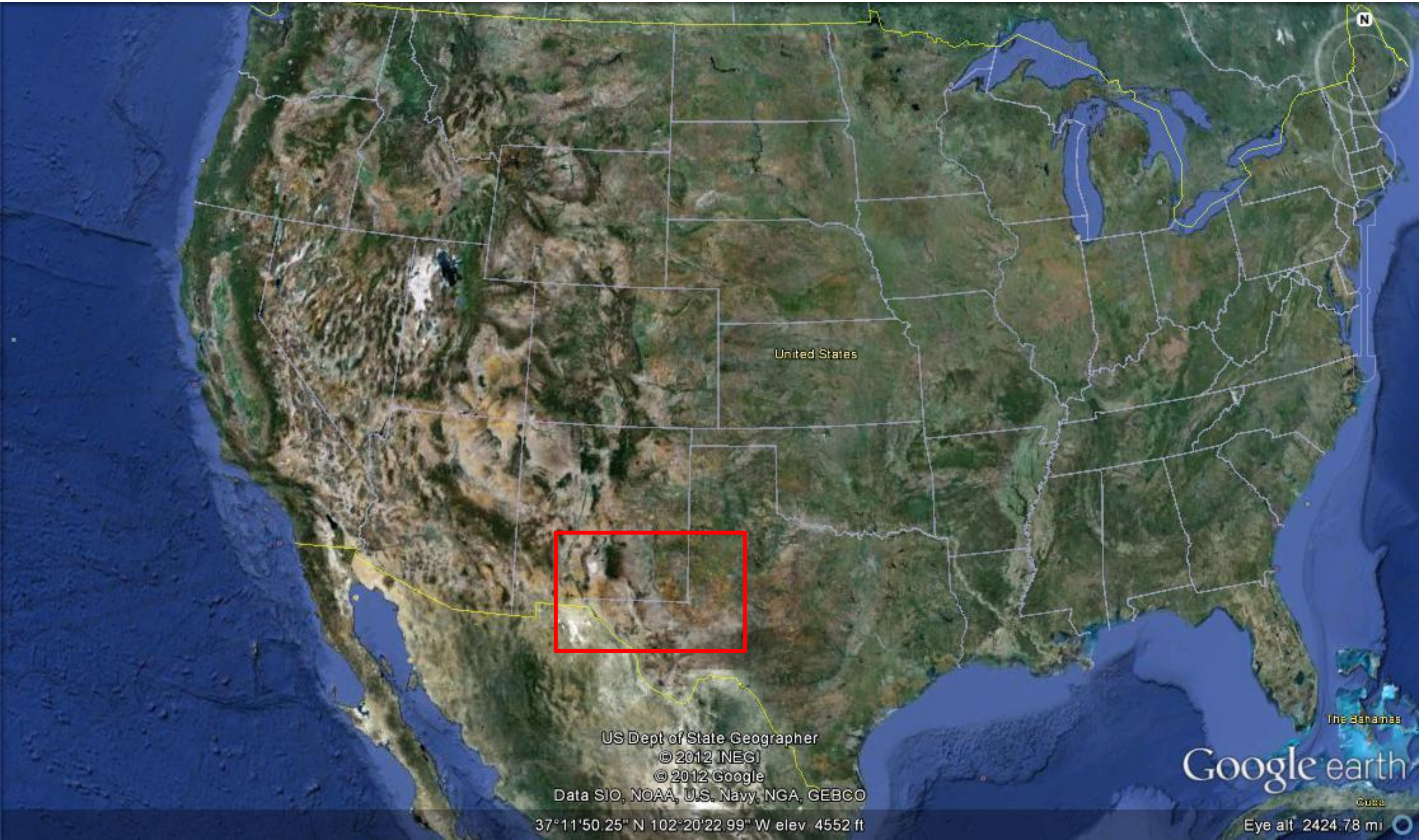
3 Main Carbonate Depositional Systems

2. Ramps
3. Shelves

Layered &/or Prograding



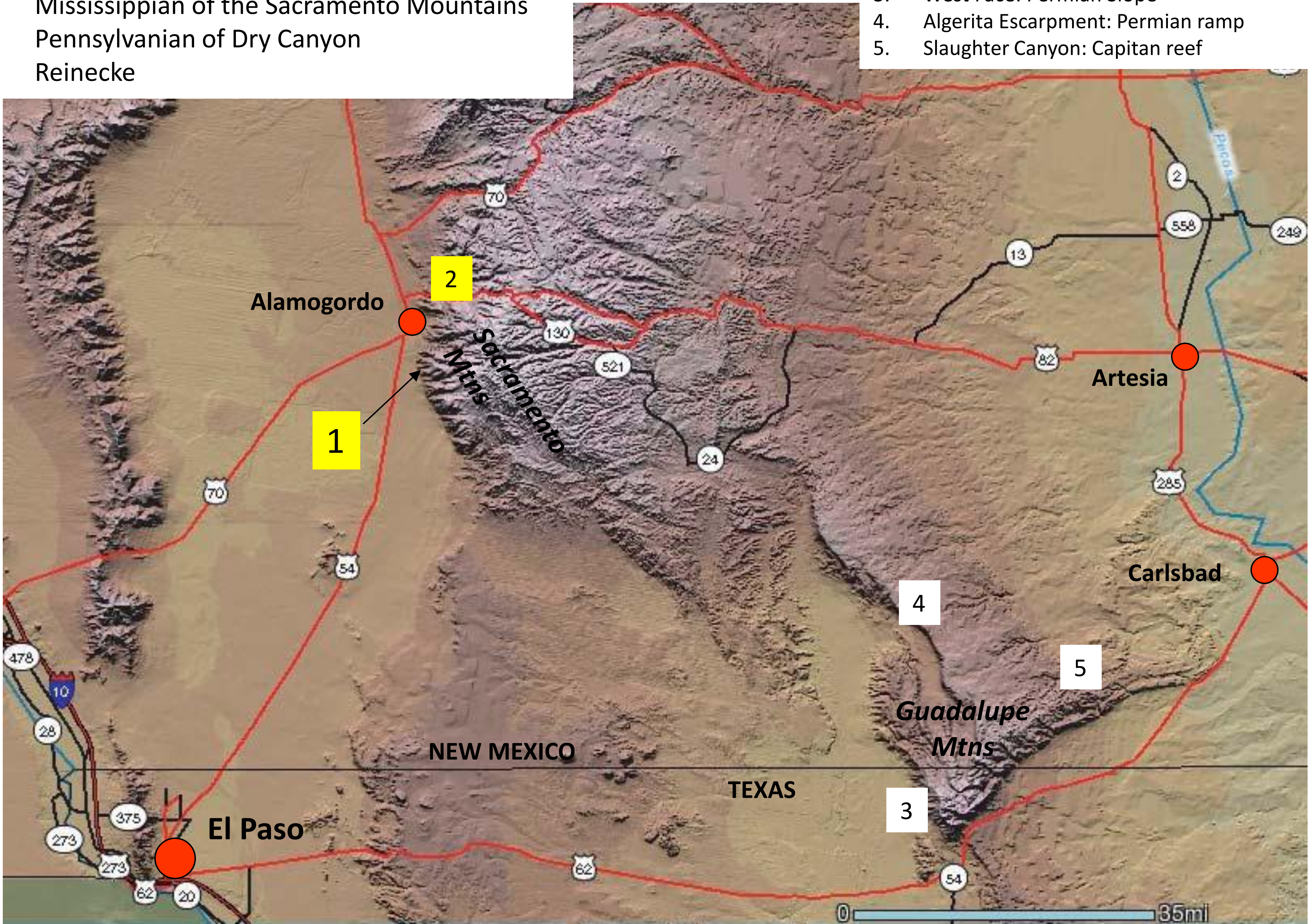
Sequence Stratigraphy of Classic Carbonate outcrops in west Texas and SE New Mexico



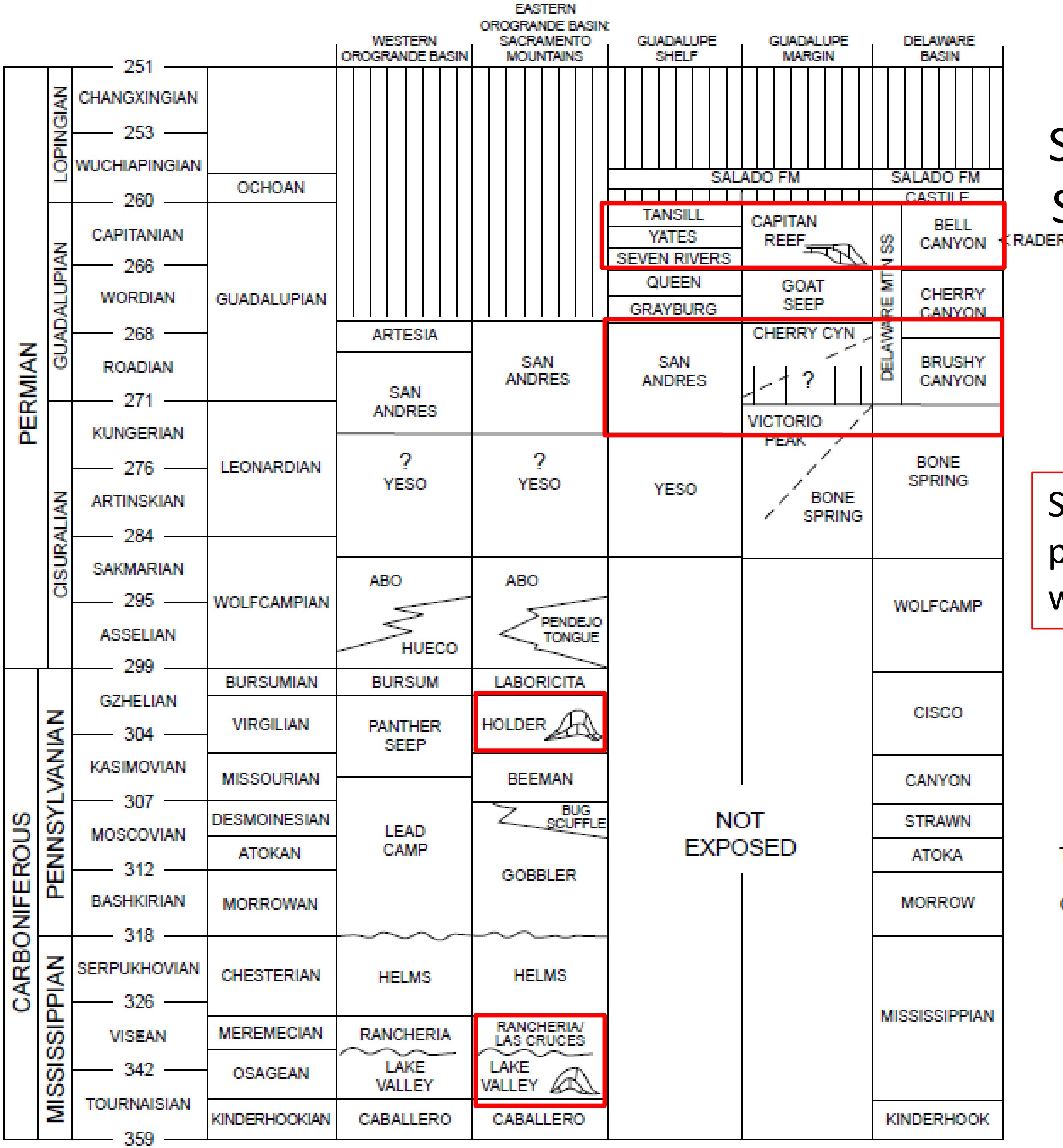
1. Mounds/Isolated Buildups/Reefs

- Mississippian of the Sacramento Mountains
- Pennsylvanian of Dry Canyon
- Reinecke

1. Sacramento Mtns: Mississippian
2. Dry Canyon: Pennsylvanian mounds
3. West Face: Permian Slope
4. Algerita Escarpment: Permian ramp
5. Slaughter Canyon: Capitan reef



CHRONO-STRATIGRAPHY FOR SACRAMENTO AND GUADALUPE MOUNTAINS



Systems shown in this presentation are shown with red rectangles

COMPILED FROM MULTIPLE SOURCES

TIME SCALE OF GRADSTEIN ET AL., 2004

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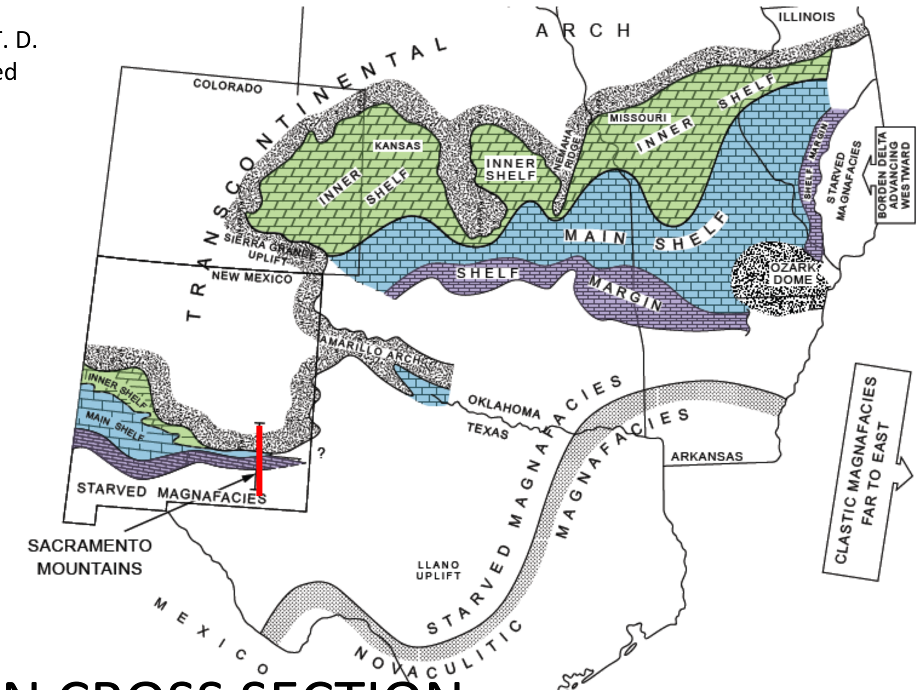
PALEOGEOGRAPHIC SETTING OF MISSISSIPPIAN MOUNDS



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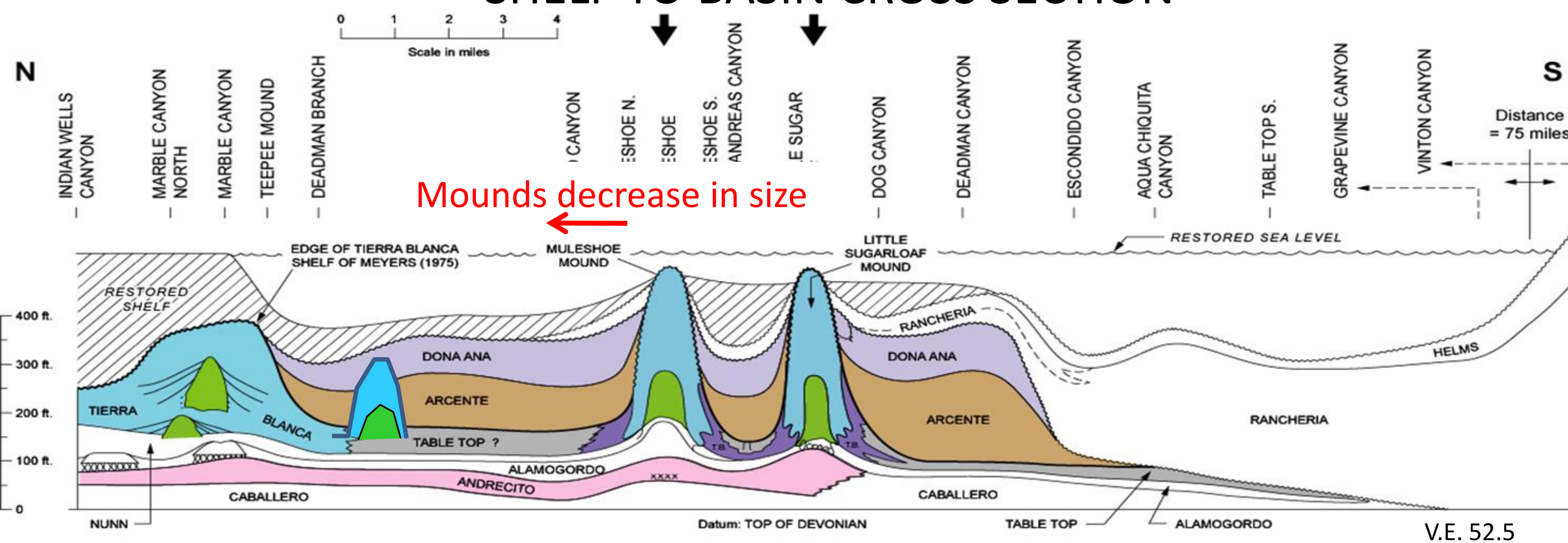
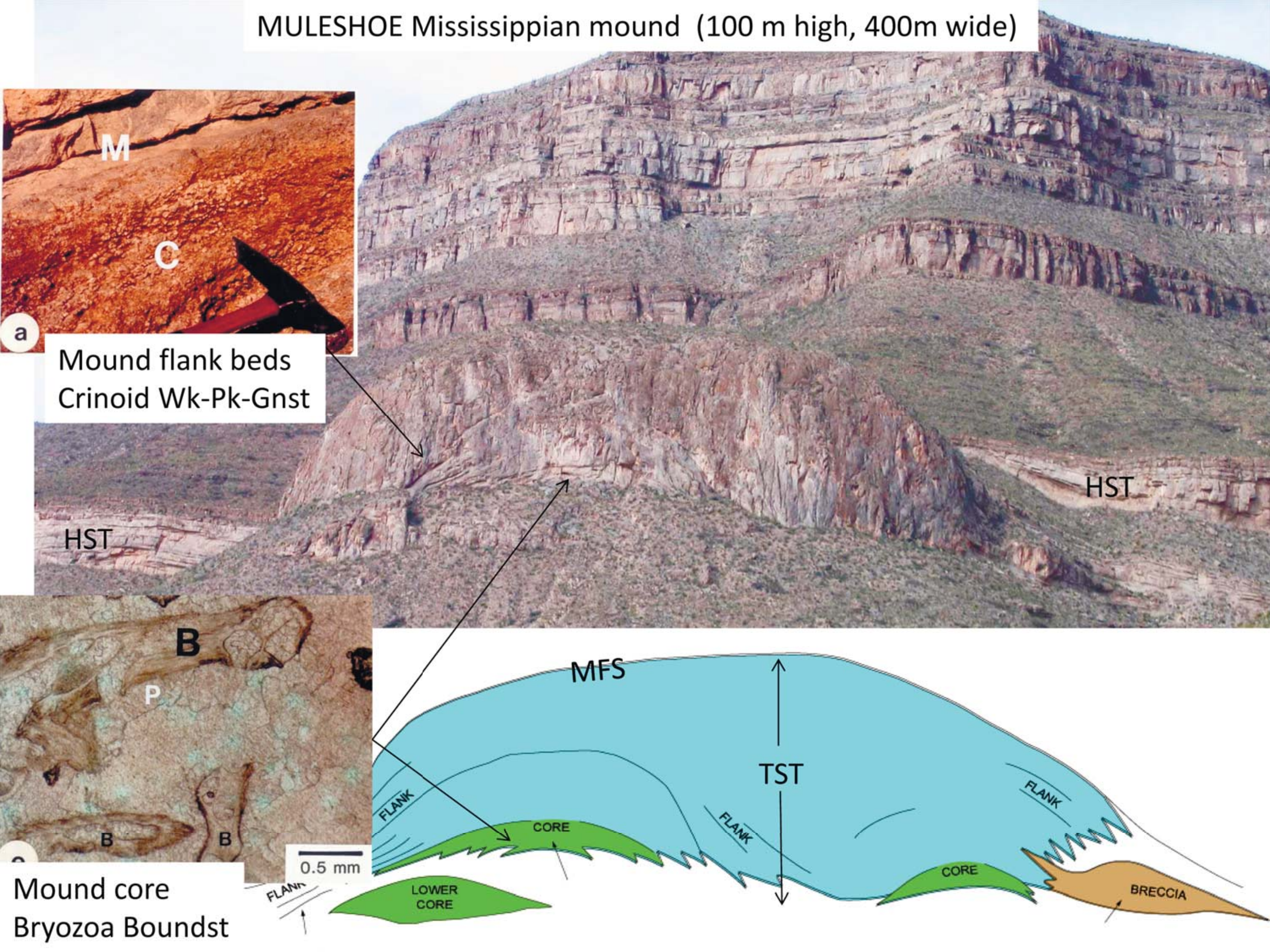
SHELF TO BASIN CROSS SECTION

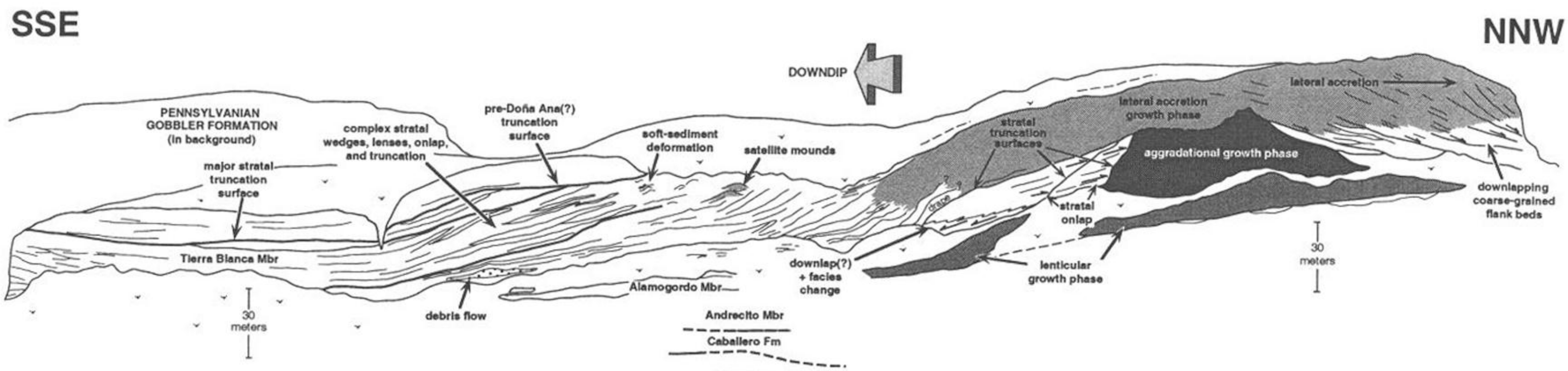


DISTRIBUTION OF THE MIDDLE MISSISSIPPIAN DEPOSITIONAL PACKAGE IN THE SOUTHERN SACRAMENTO MOUNTAINS, NEW MEXICO


MULESHOE Mississippian mound (100 m high, 400m wide)
M
C
a
Mound flank beds
Crinoid Wk-Pk-Gnst
HST
HST
B
P
B
B
0.5 mm
Mound core
Bryozoa Boundst
MFS
TST
FLANK
FLANK
FLANK
CORE
CORE
LOWER CORE
BRECCIA

Southwest Side of Deadman Branch of Alamo Canyon

Transitional mound (intermediate sized) with common prograding crinoidal beds



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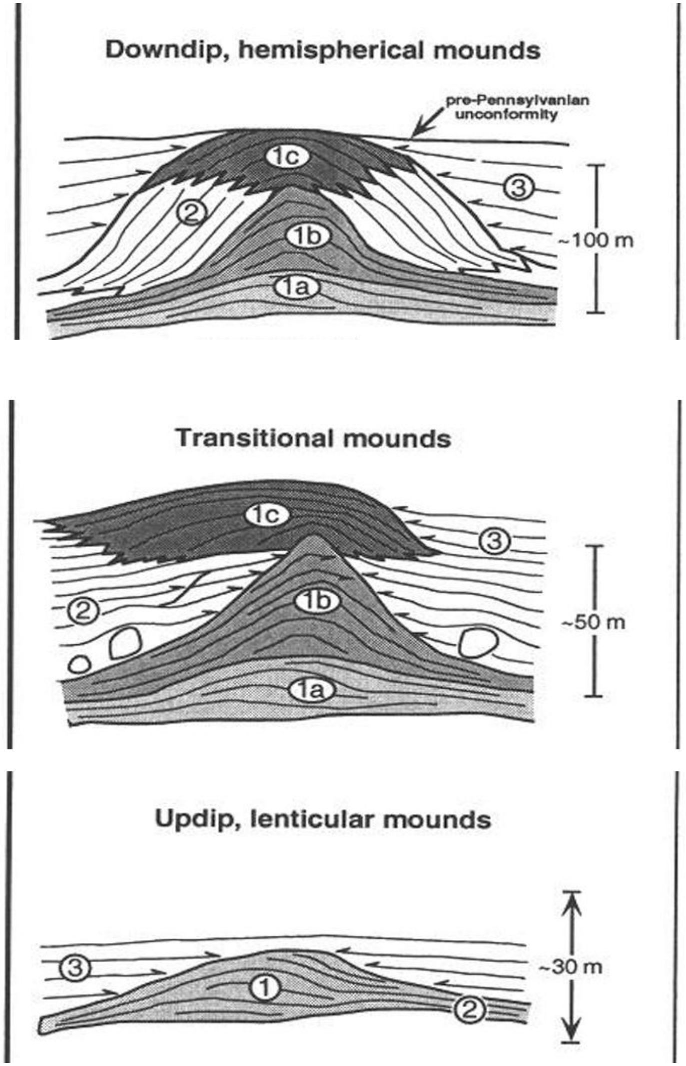
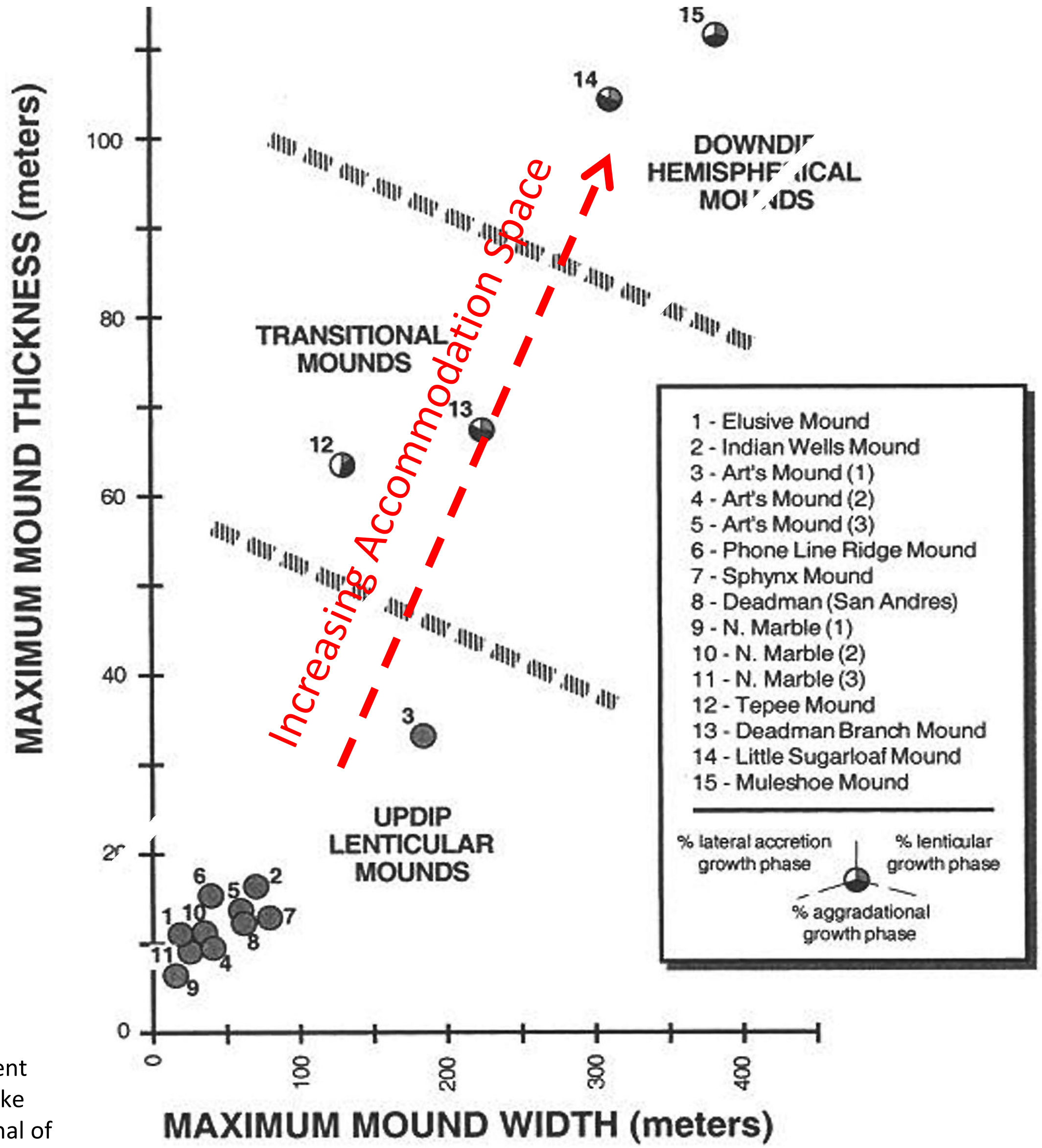
Mounds grow during times of general transgression:

Size of mounds & buildups depend on accommodation space





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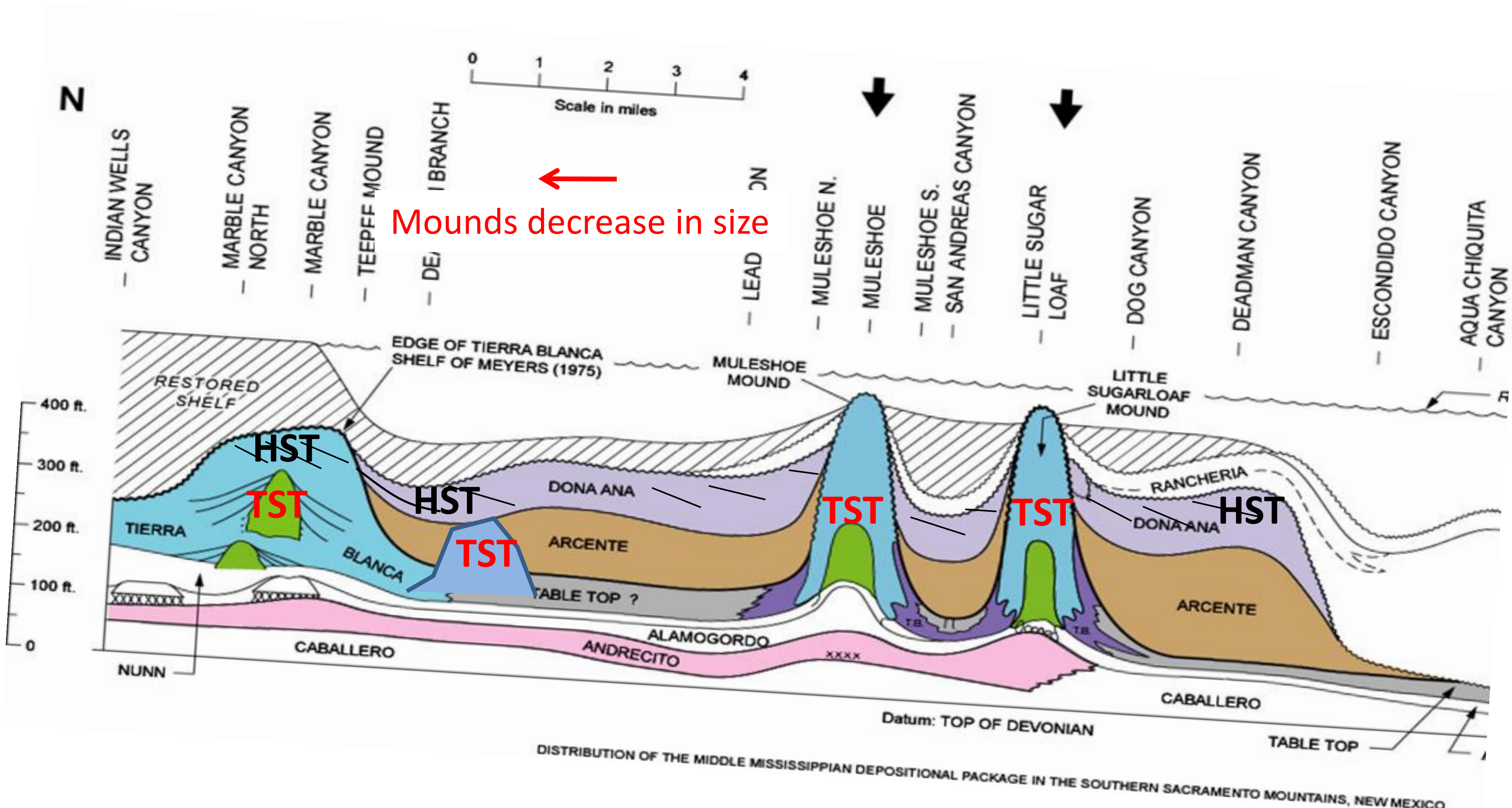

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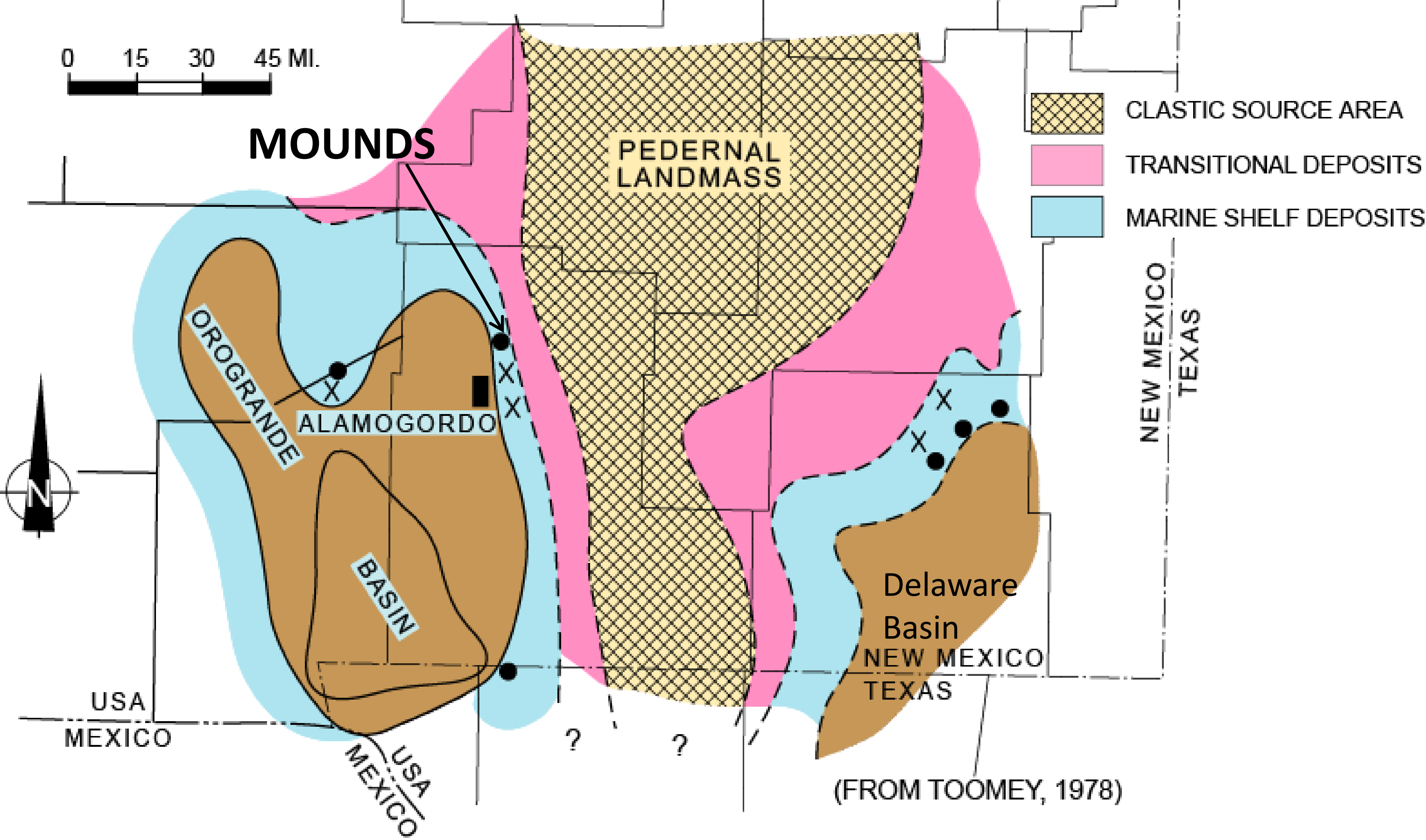
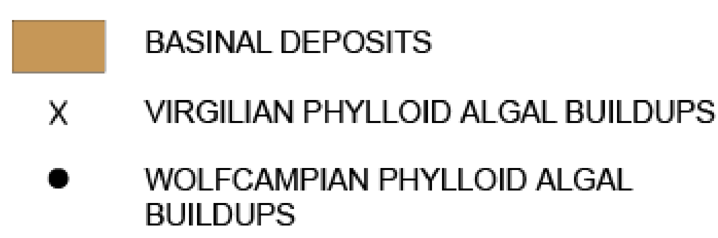
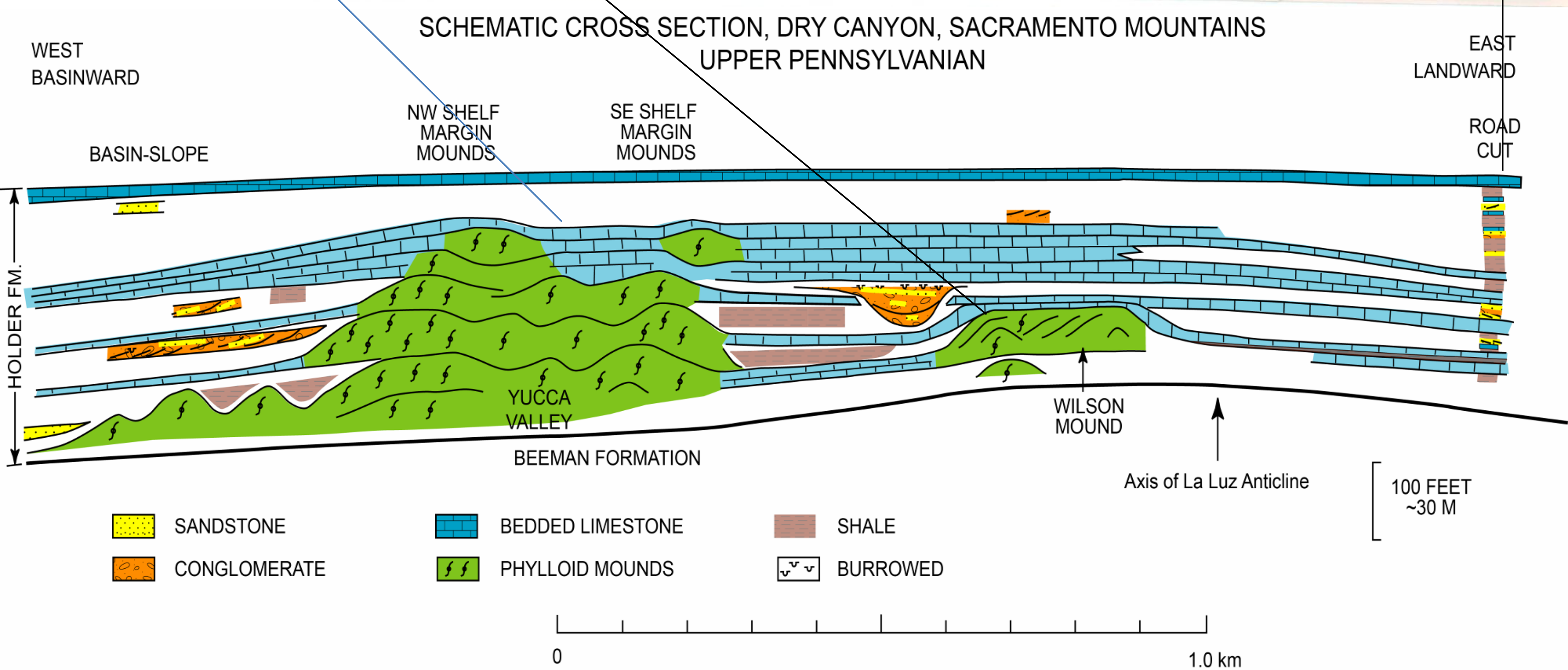


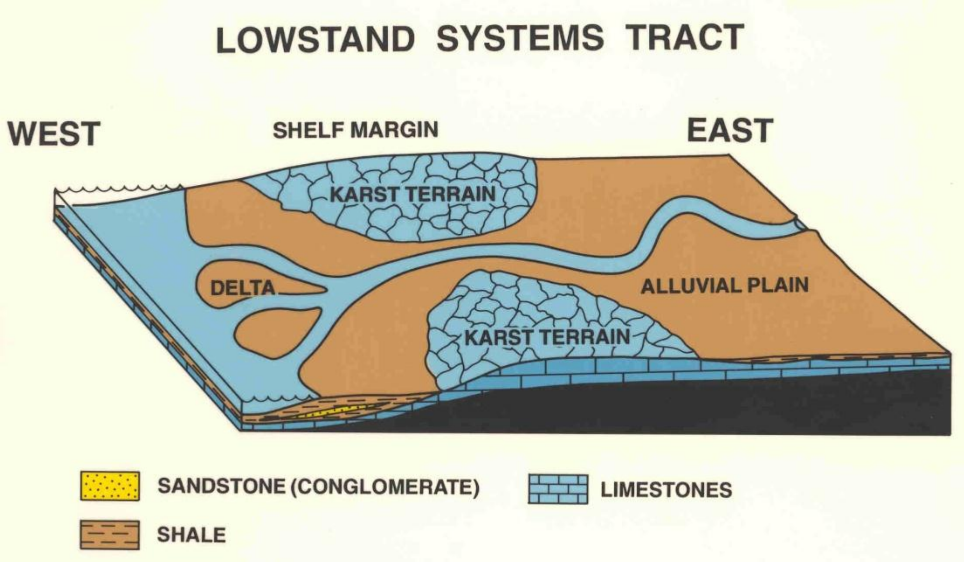
UPPER PENNSYLVANIAN PALEOGEOGRAPHY OF THE OROGRANDE BASIN



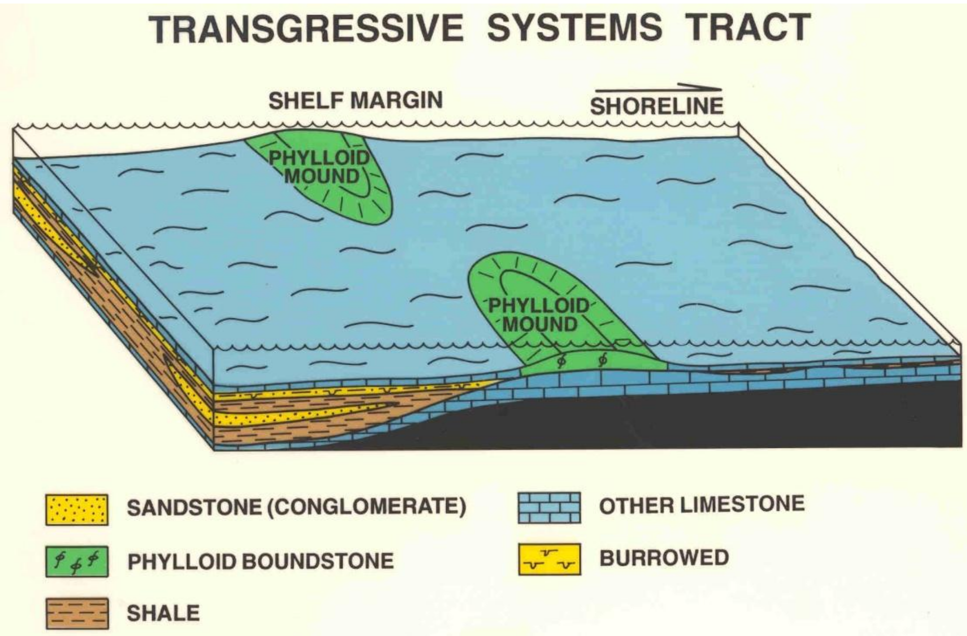
HOLDER FORMATION, DRY CANYON

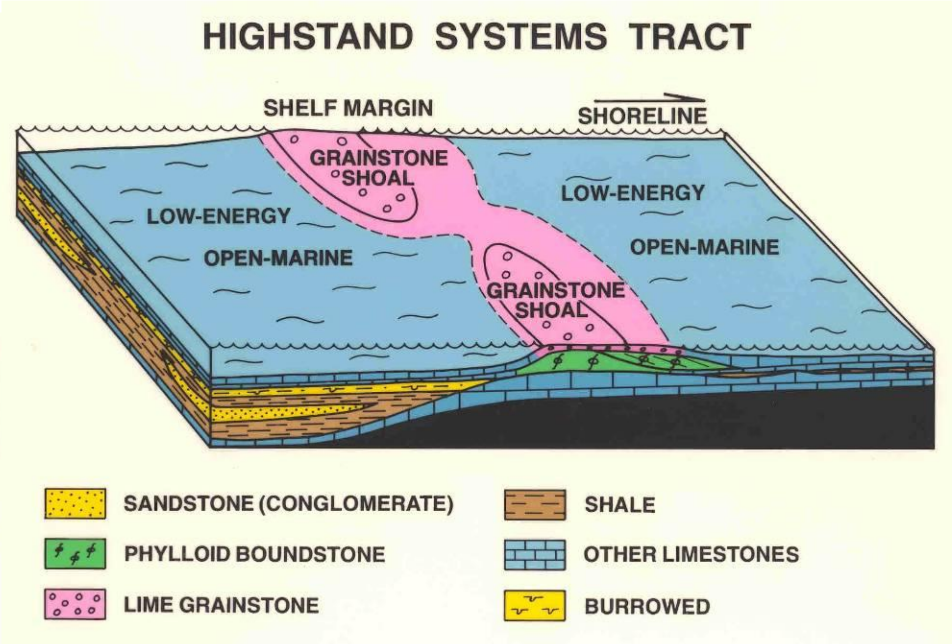


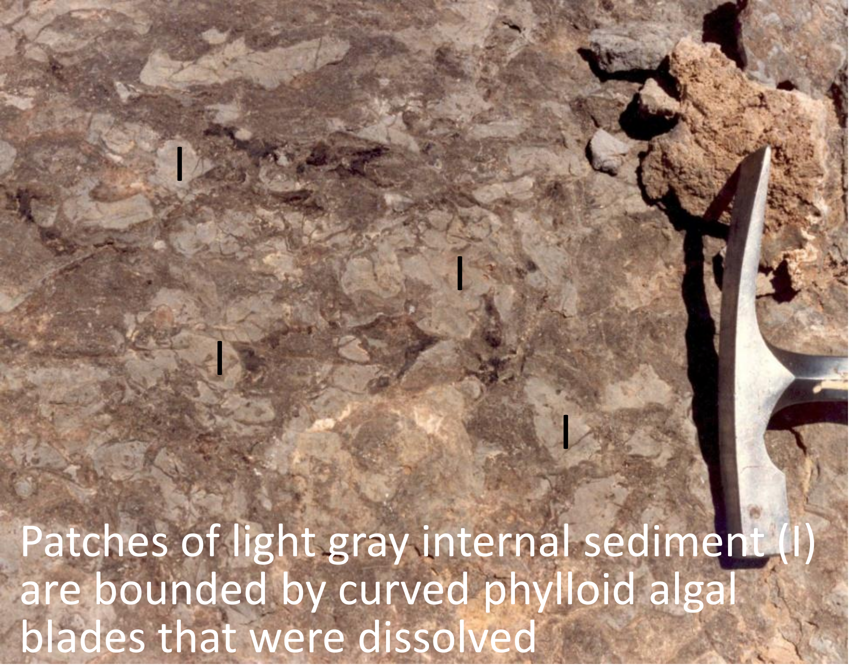
Sedimentation in a humid climate



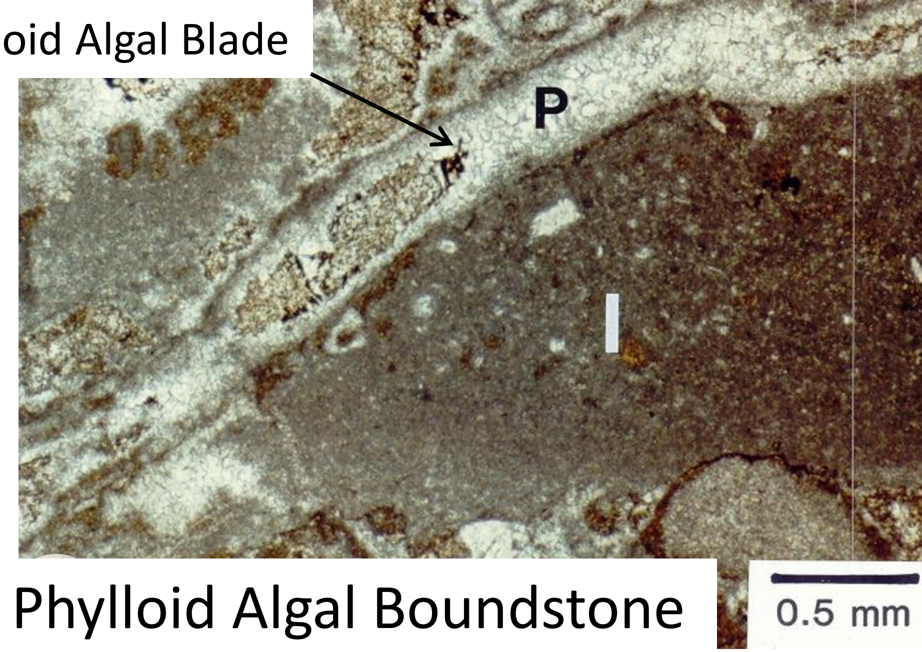
Depositional cycles/ sequences (110 ky frequency; 50-100 m amplitudes) can be divided into 3 main parts related to sea level rises and falls



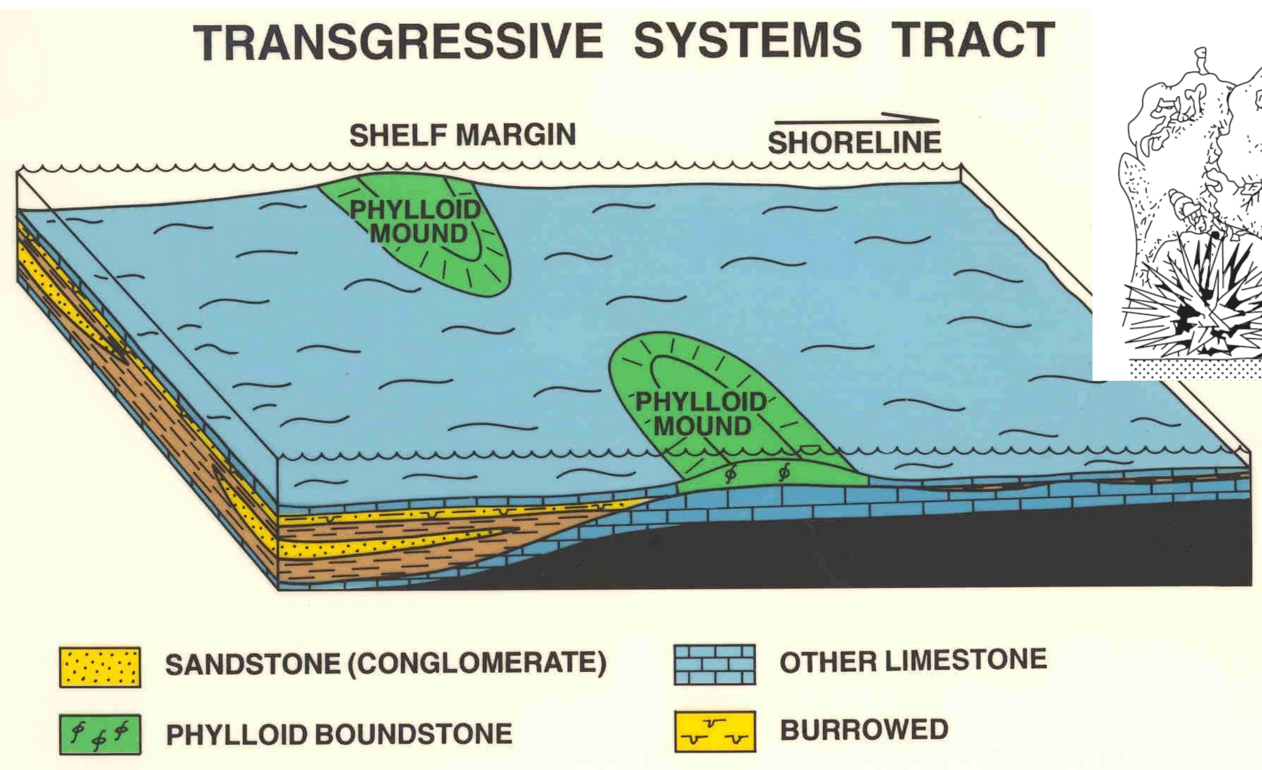


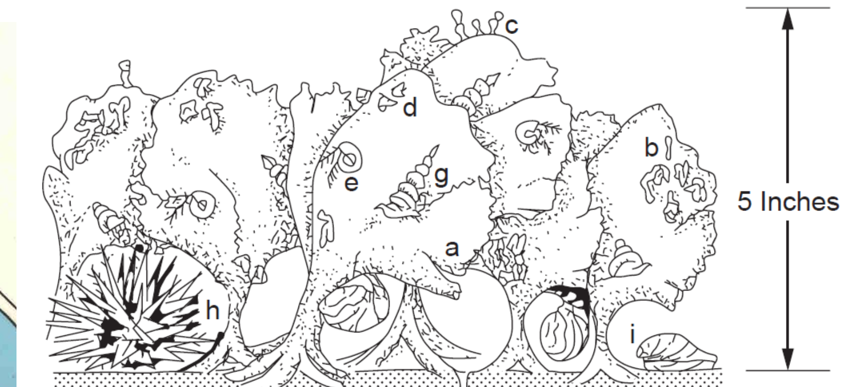


Patches of light gray internal sediment (I) are bounded by curved phylloid algal blades that were dissolved



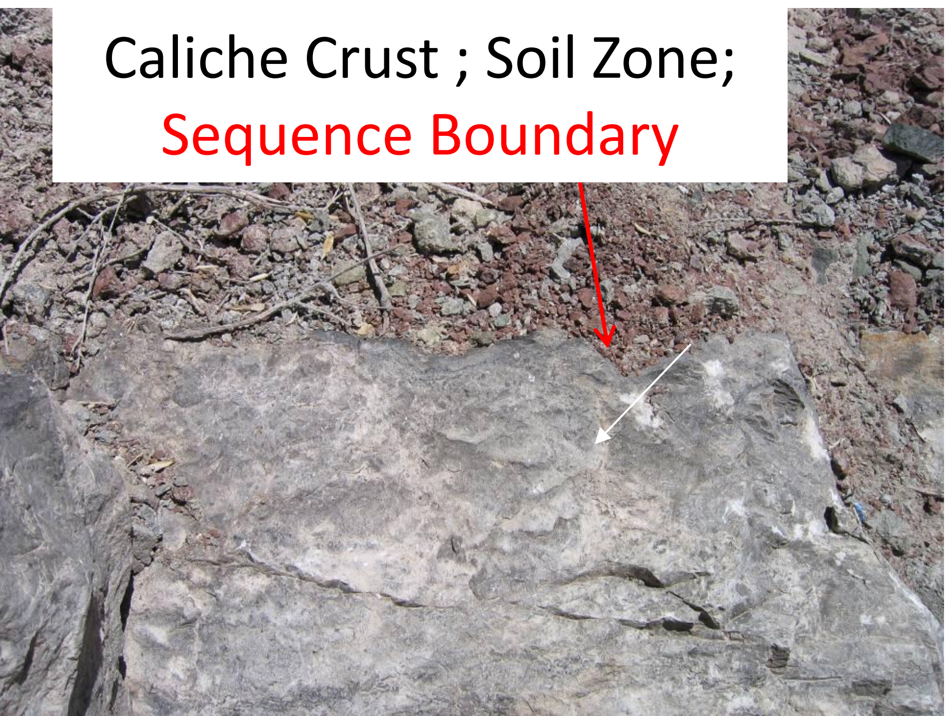
Phylloid Algal Boundstone

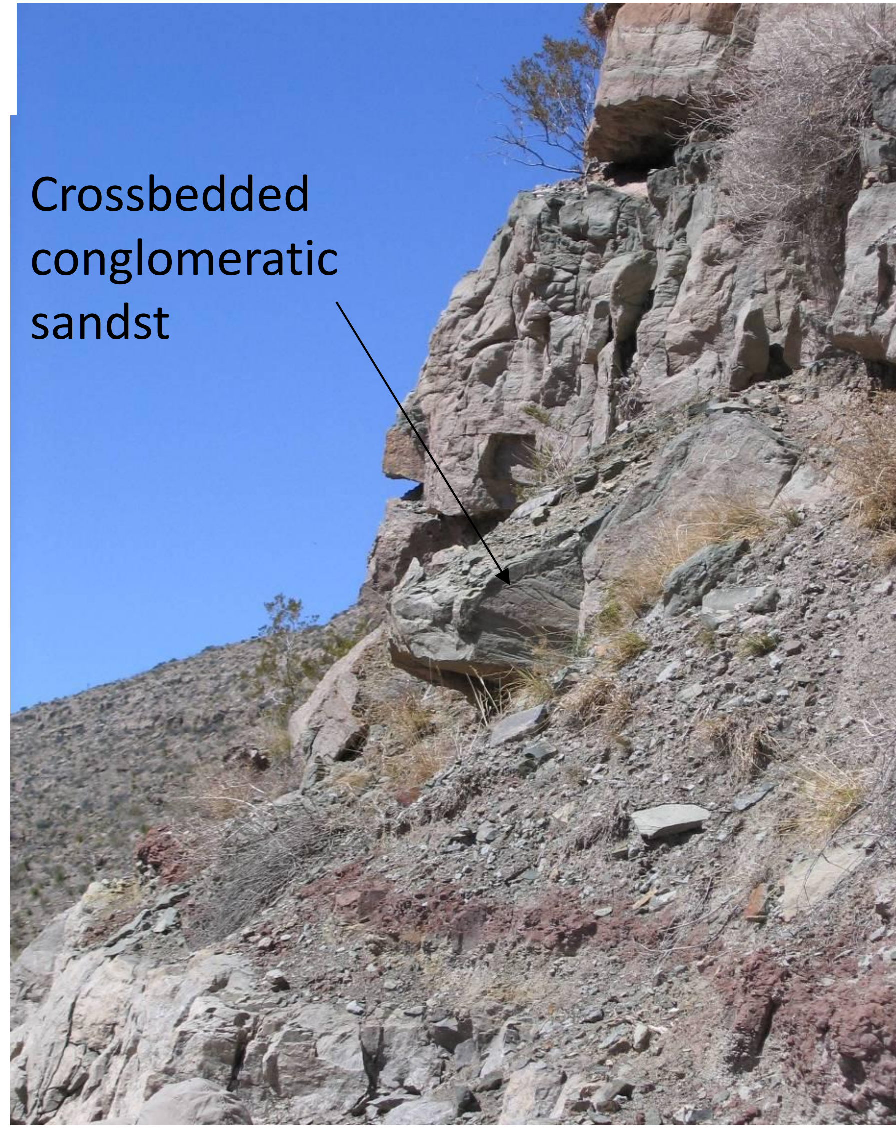




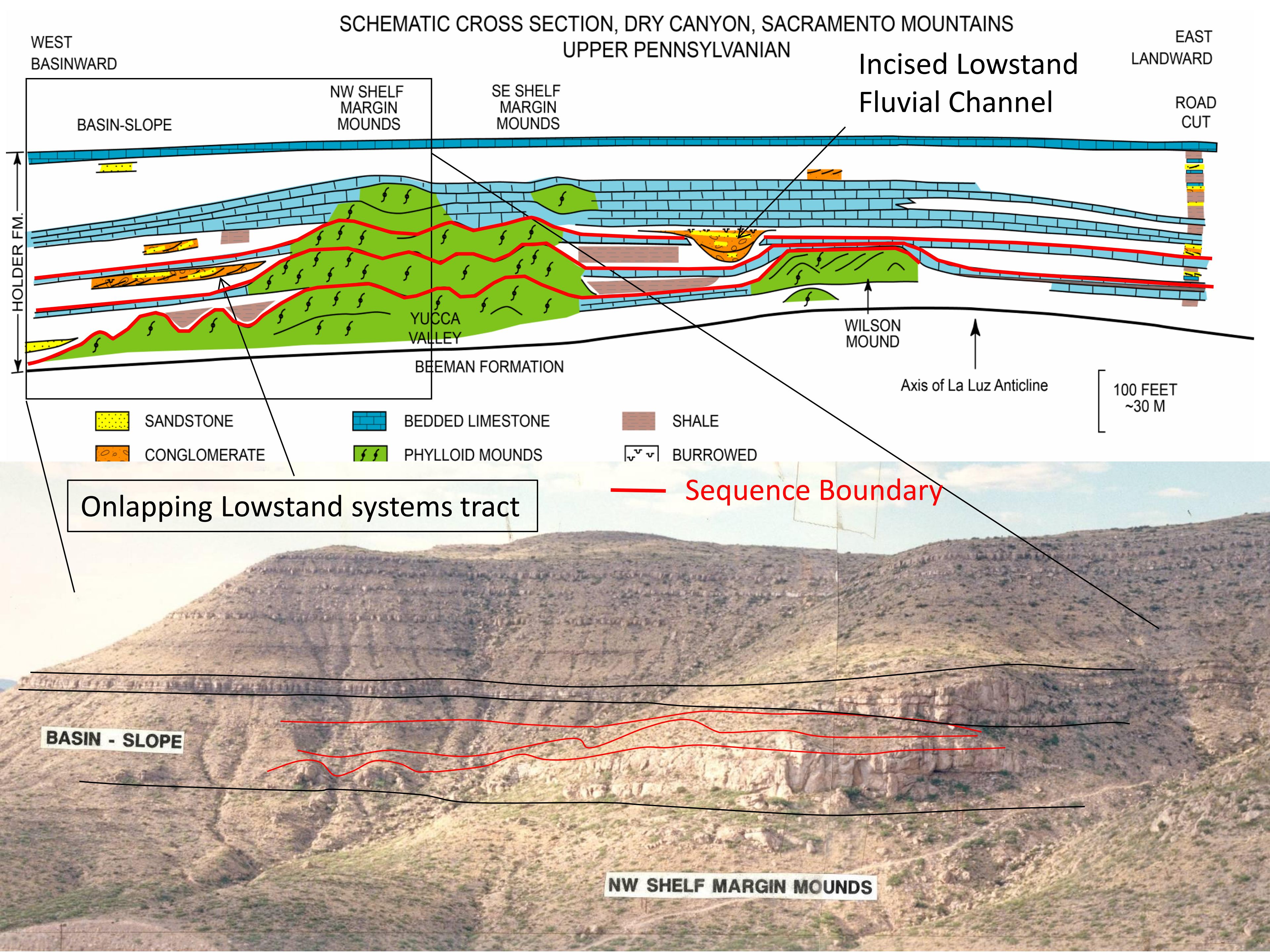
Fusulinid Wacke-Packstone; Deeper water, Off-Mound Facies, near Max Flood Surface

Caliche Crust ; Soil Zone; Sequence Boundary



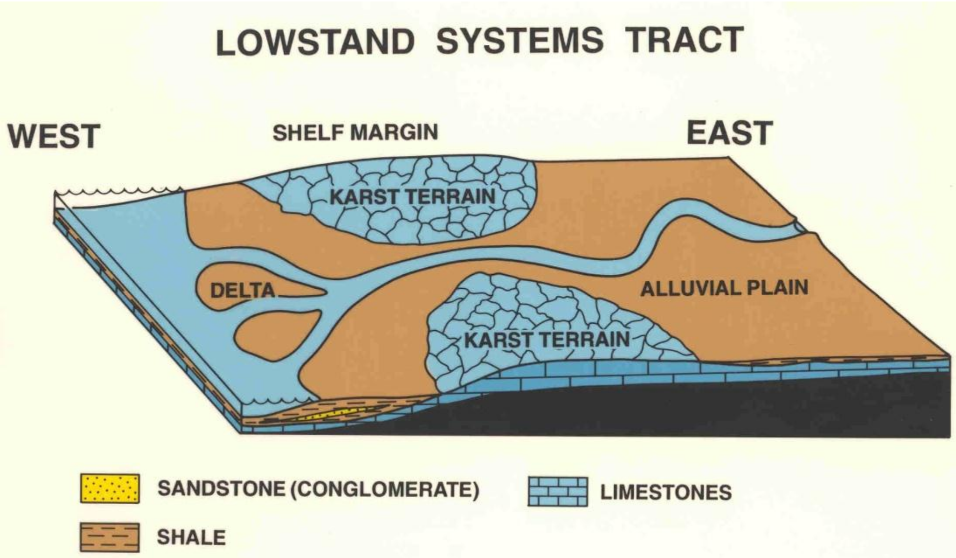


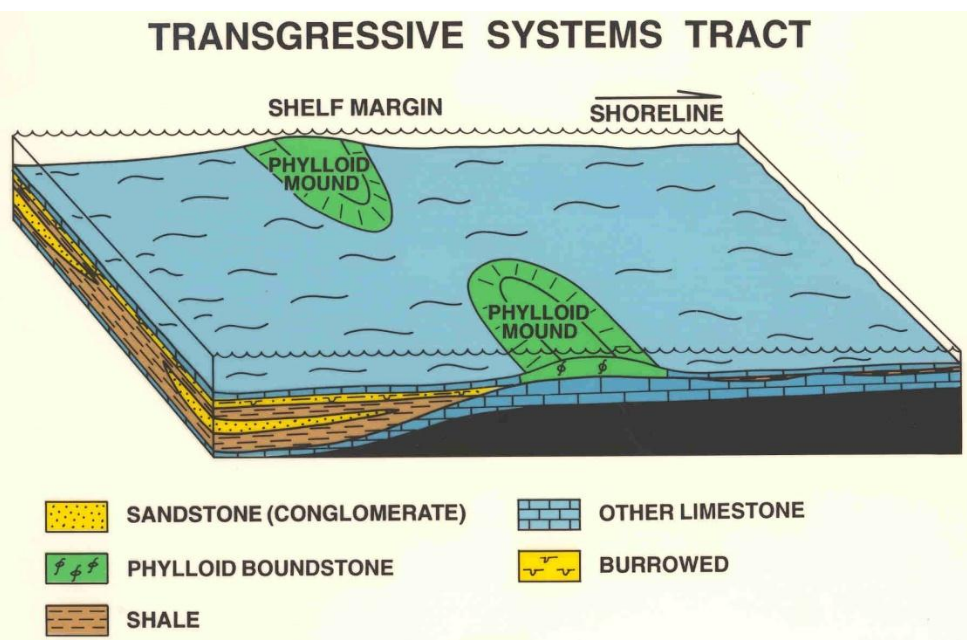
Red Shale, Crossbedded Conglomeratic Sandstones (fluvial) Deposited during Lowstands of Sea Level

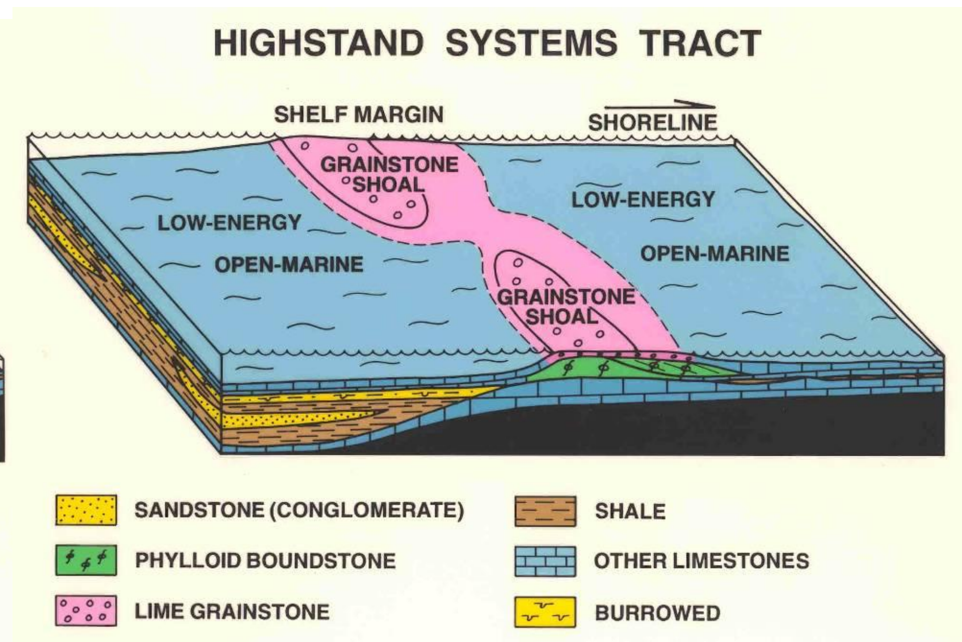

SCHEMATIC CROSS SECTION, DRY CANYON, SACRAMENTO MOUNTAINS
UPPER PENNSYLVANIAN
WEST
BASINWARD
EAST
LANDWARD
Incised Lowstand Fluvial Channel
BASIN-SLOPE
NW SHELF MARGIN MOUNDS
SE SHELF MARGIN MOUNDS
ROAD CUT
HOLDER FM.
YUCCA VALLEY
BEEMAN FORMATION
WILSON MOUND
Axis of La Luz Anticline
100 FEET
~30 M
SANDSTONE
CONGLOMERATE
BEDDED LIMESTONE
PHYLLOID MOUNDS
SHALE
BURROWED
Onlapping Lowstand systems tract
Sequence Boundary
BASIN - SLOPE
NW SHELF MARGIN MOUNDS

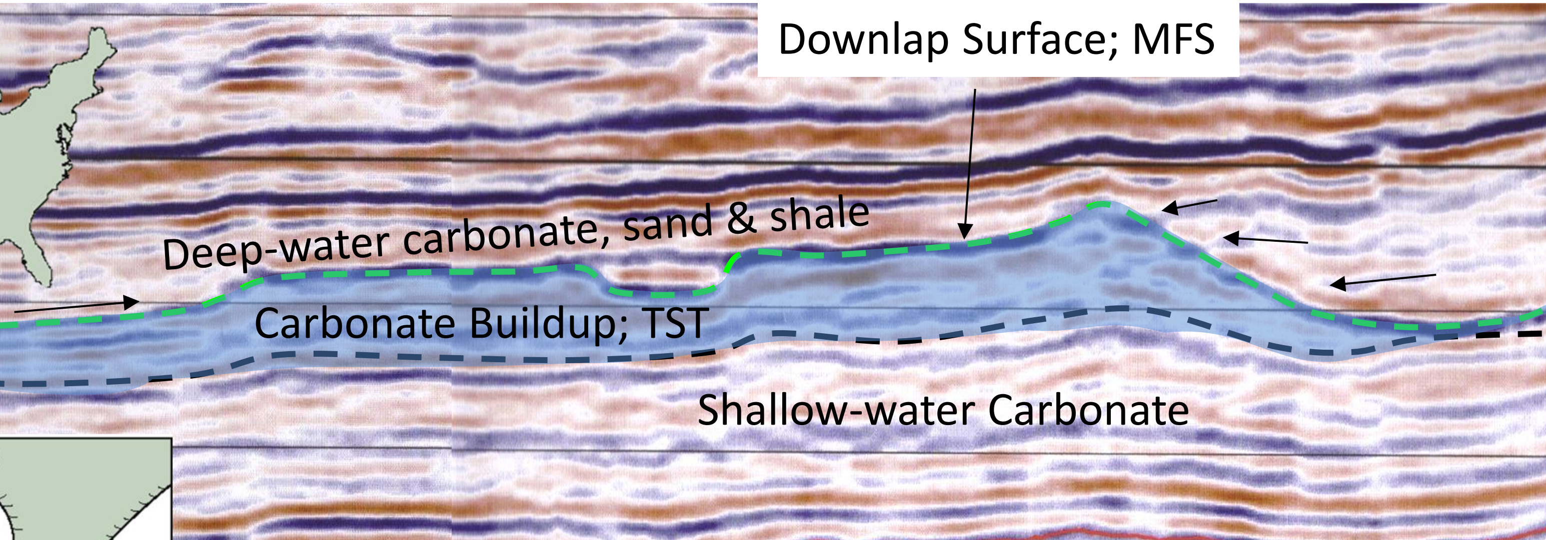
Sedimentation in a humid climate

Depositional cycles/ sequences (110 ky frequency; 50-100 m amplitudes) can be divided into 3 main parts related to sea level rises and falls









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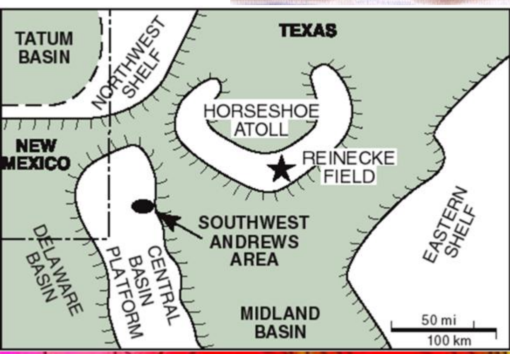
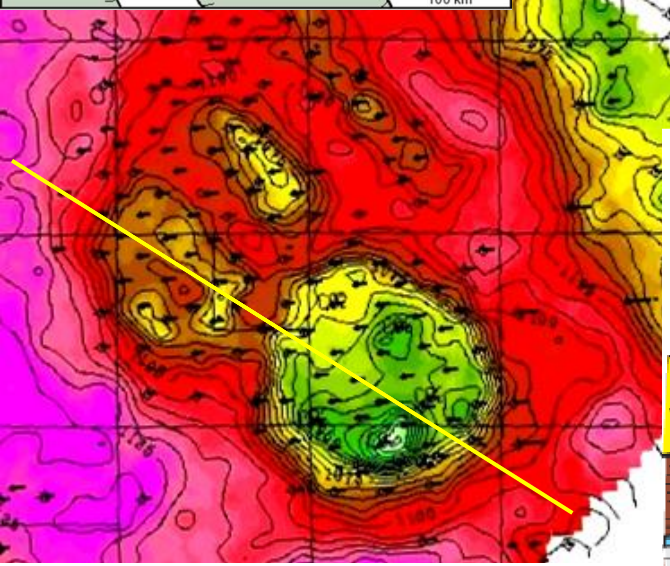
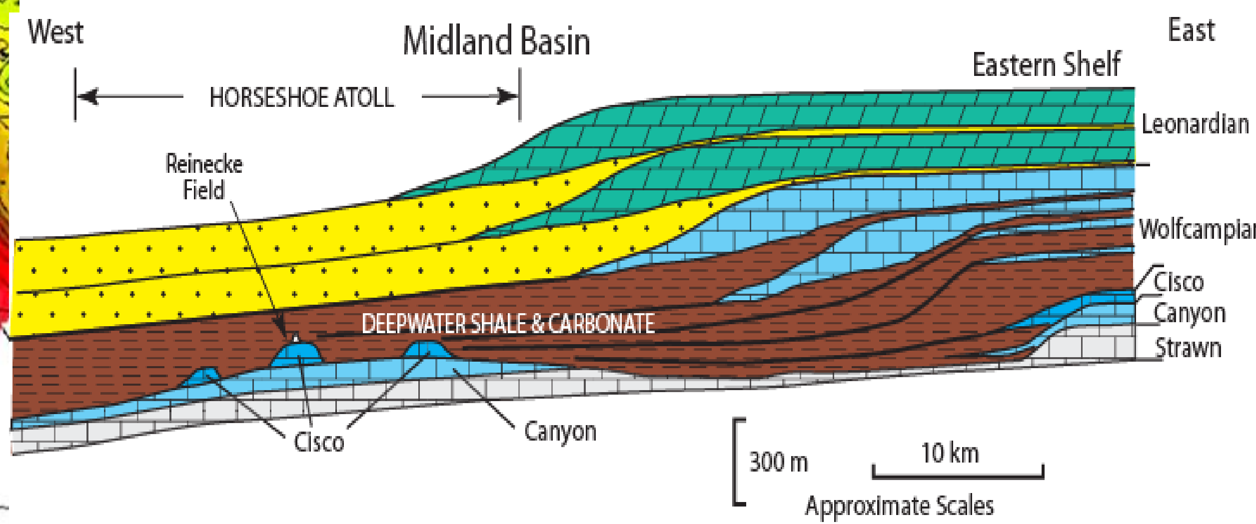


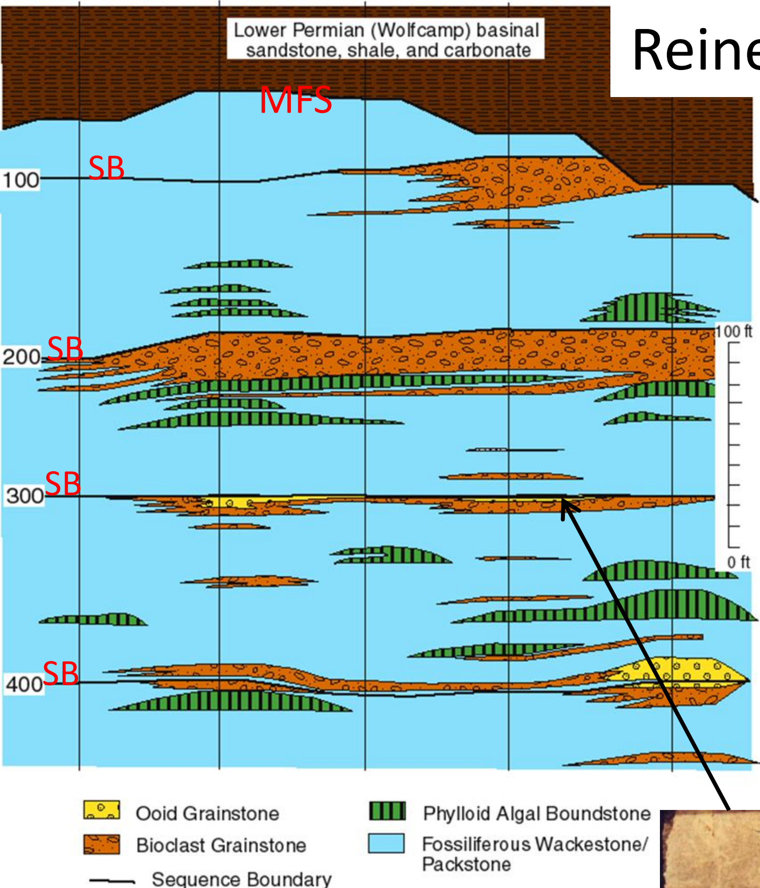
CARBONATE MOUND OIL FIELD: REINECKE FIELD, HORSESHOE ATOLL



TOP CARBONATE STRUCTURE MAP

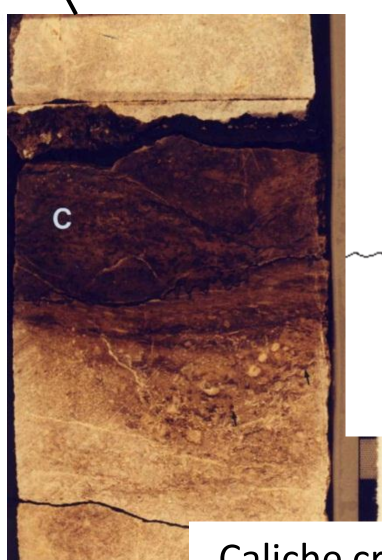


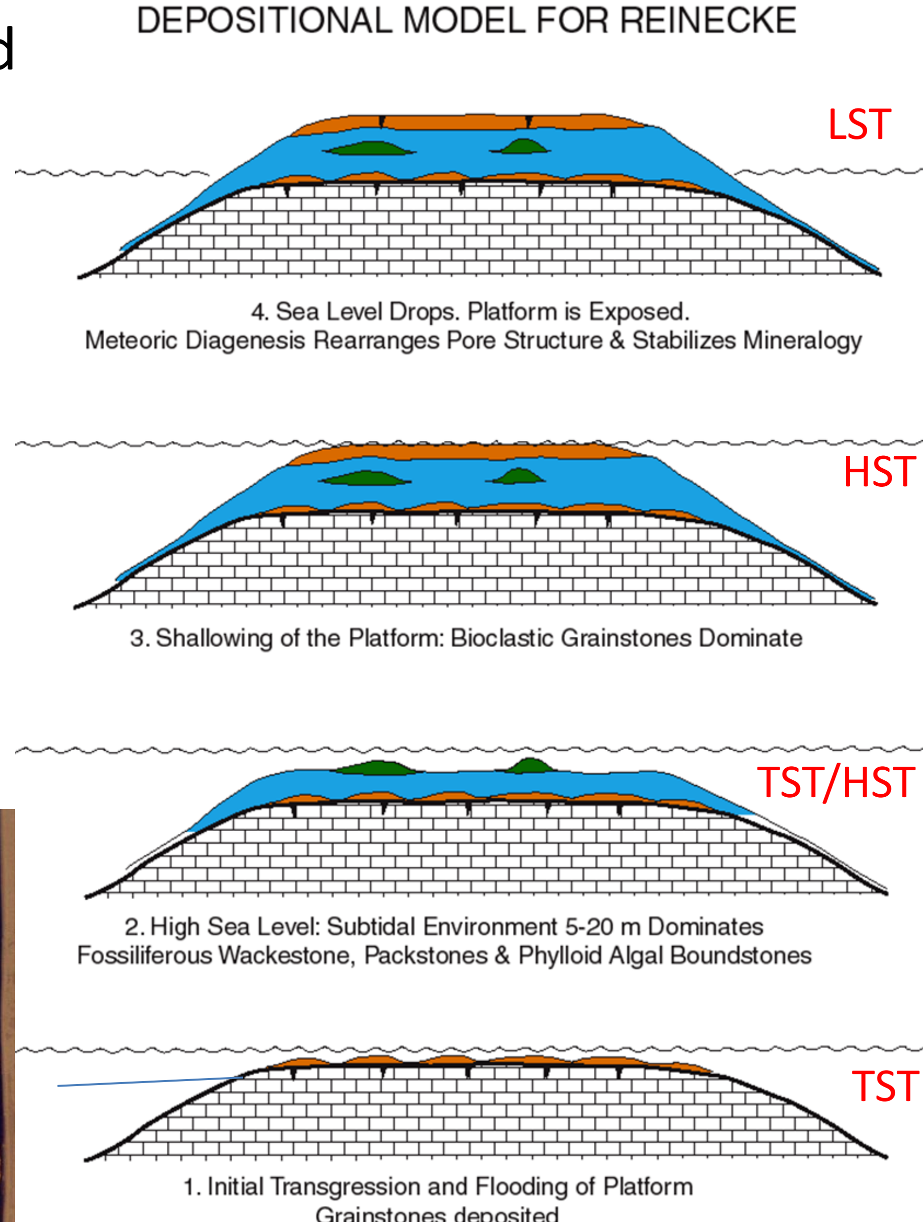
Reinecke Field



4 sequences represent 4 intervals of sea-level rise and fall during ice-house time

From Saller, A.H., A.W. Walden, S. Robertson, M. Steckel, J. Schwab, H. Hagiwara, and S. Mizohata, 1999, Reservoir characterization of a reefal carbonate for crestal CO_2 flood, Reinecke field, west Texas, *in* T.F. Hentz, ed., *Advanced Reservoir Characterization for the 21st Century:* Gulf Coast Section SEPM Foundation 19th Annual Research Conference, p. 259-268.

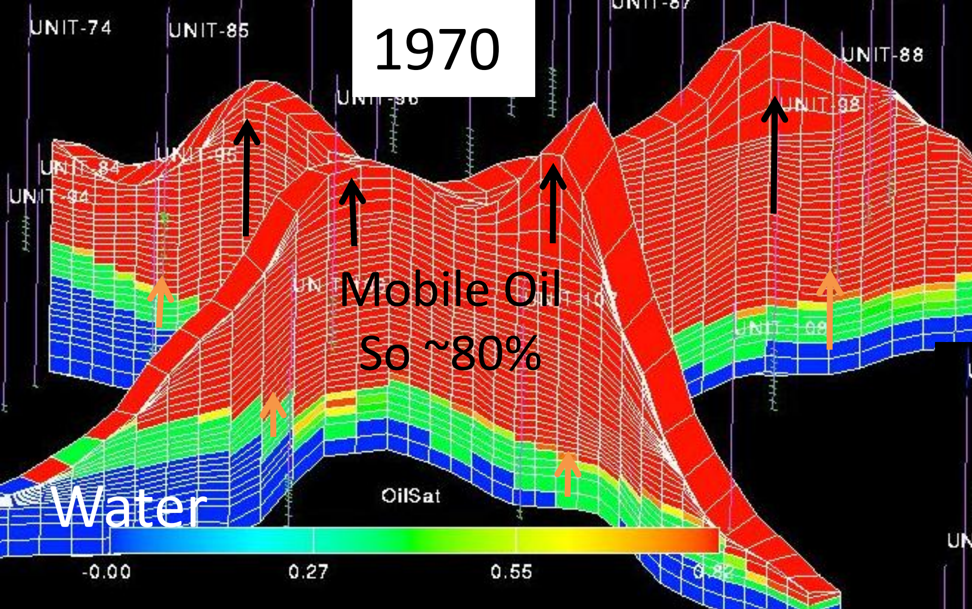


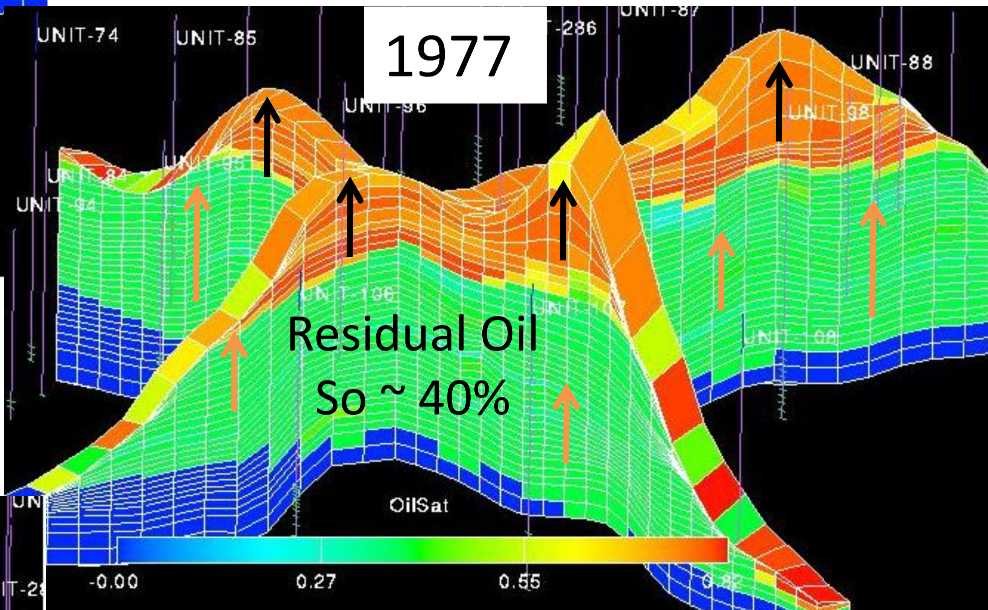


Caliche crust (soil zone) represents subaerial exposure during low sea level (sequence boundary)

Reinecke South Dome Oil Saturations from Fluid Flow Simulation

50% of OOIP recovered from primary + bottom water injection





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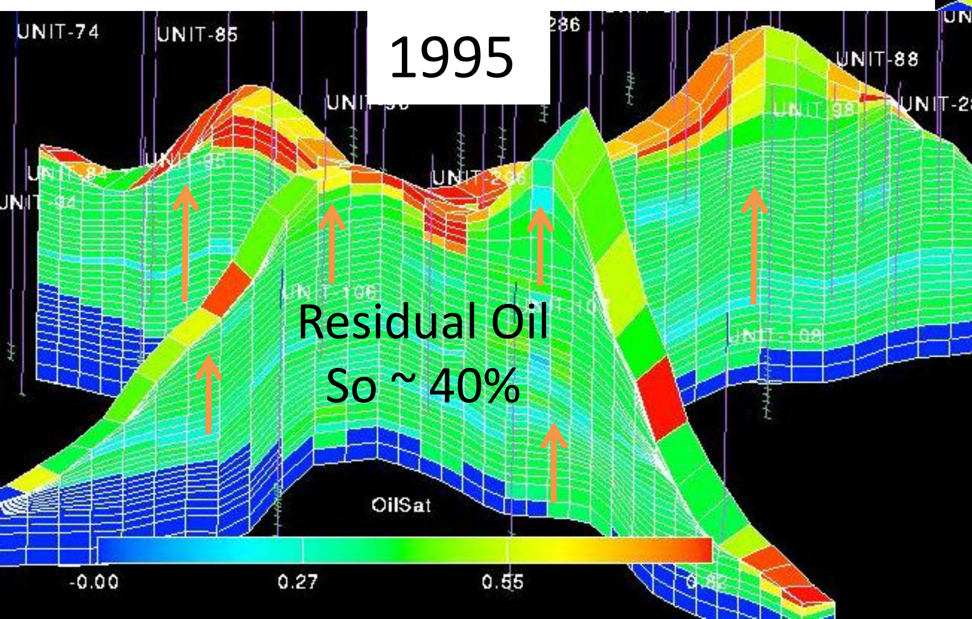
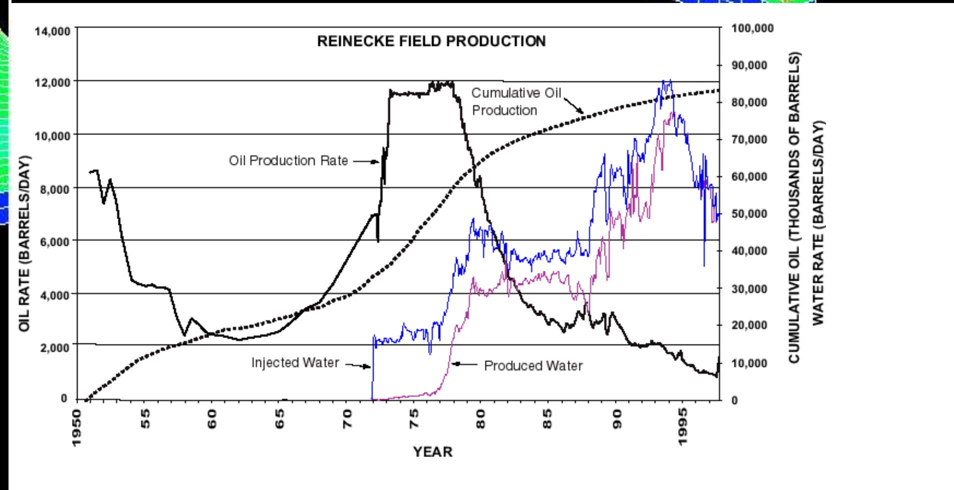
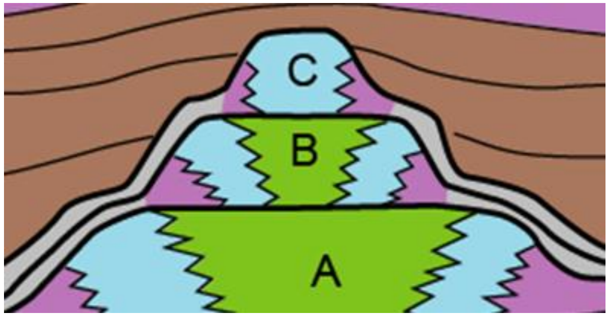
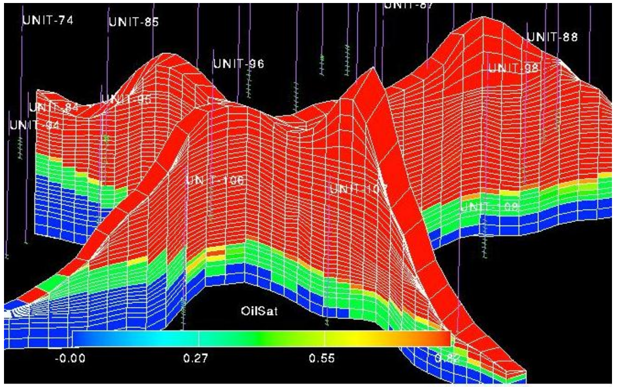


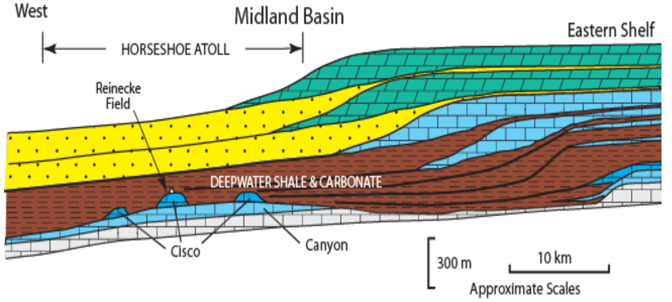


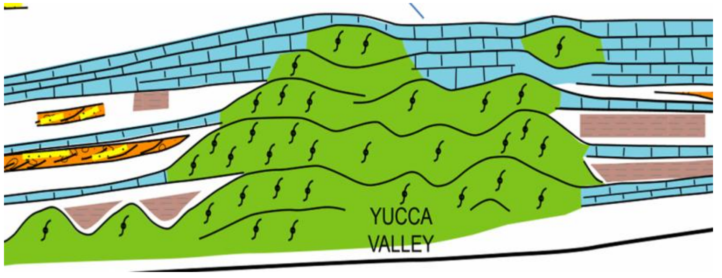
Mounds/Isolated Buildups Key Features

- Grow during transgressions when accommodation (subsidence + eustatic SL rise) >, = sediment production
- Commonly single tanks with good reservoir characteristics
- Drowning of buildups and covering by drapes of deepwater muds creates seals critical for stratigraphic traps
- Buildups onlapped by shallow marine carbonates or siliciclastics generally do not have good lateral seals



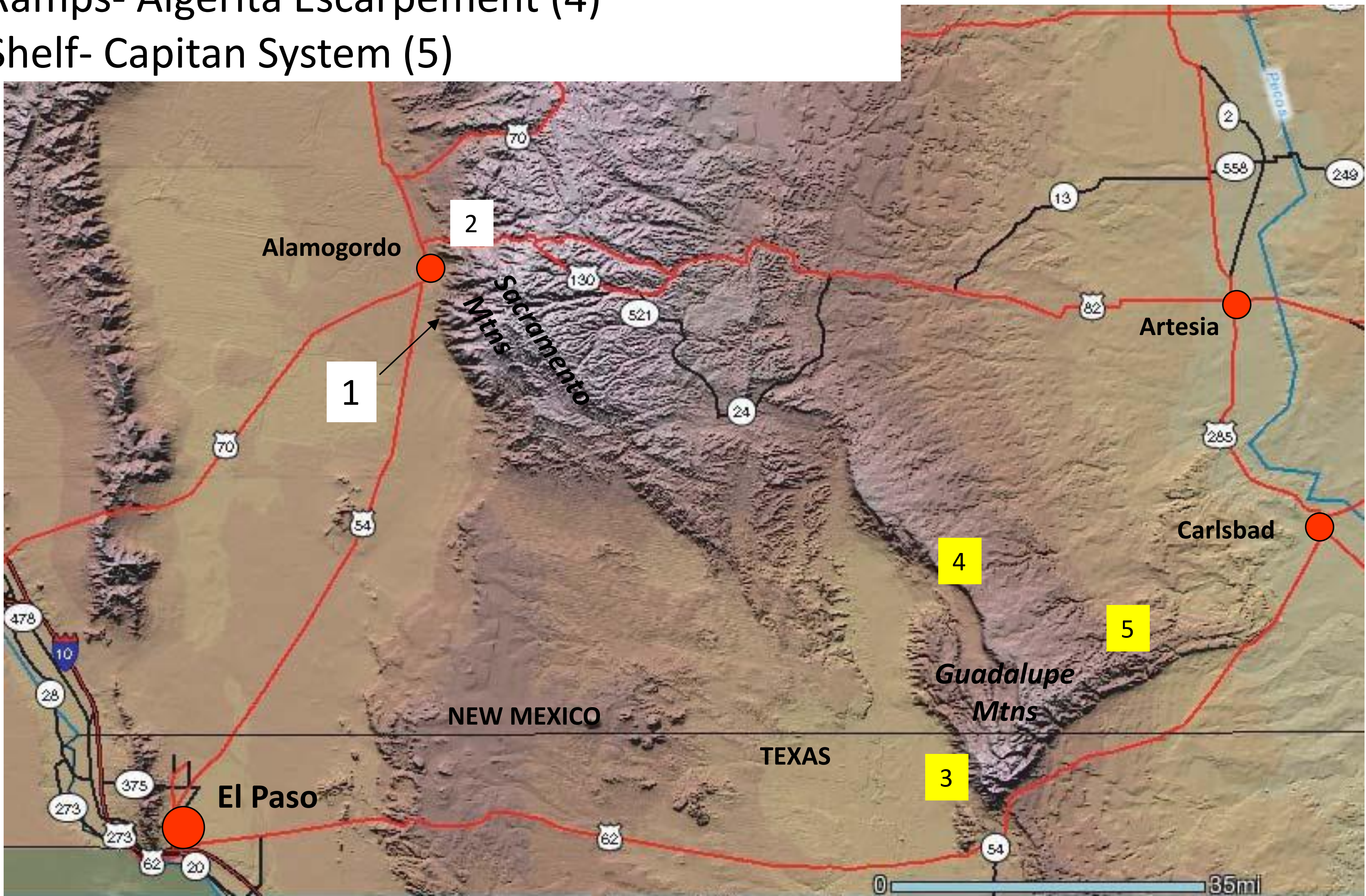






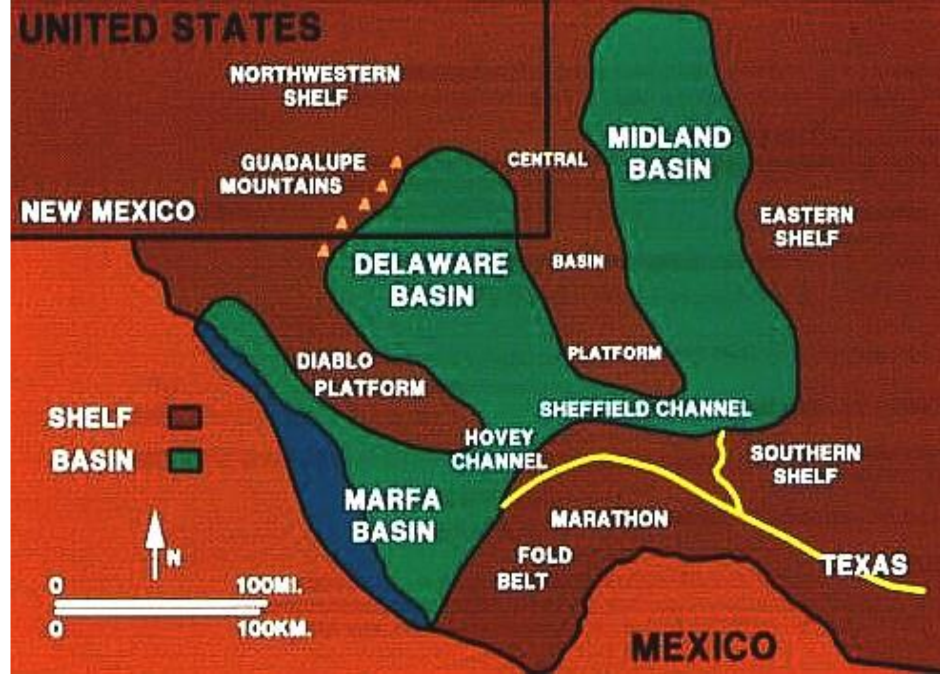
Guadalupe Mountains:
Large Scale Stratigraphy (West Face, 3)
Ramps- Algerita Escarpement (4)
Shelf- Capitan System (5)

1. Sacramento Mtns: Mississippian
2. Dry Canyon: Pennsylvanian mounds
3. West Face: Permian Slope
4. Algerita Escarpment: Permian ramp
5. Slaughter Canyon: Capitan reef



GUADALUPE MOUNTAINS

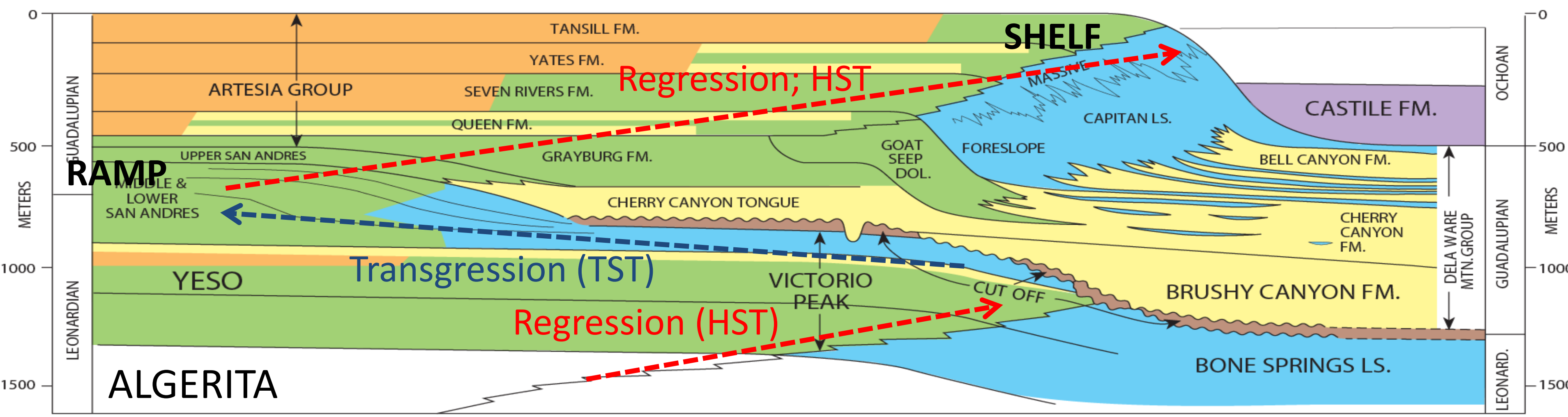
2. Ramp
3. Shelf
Layered &/or Prograding



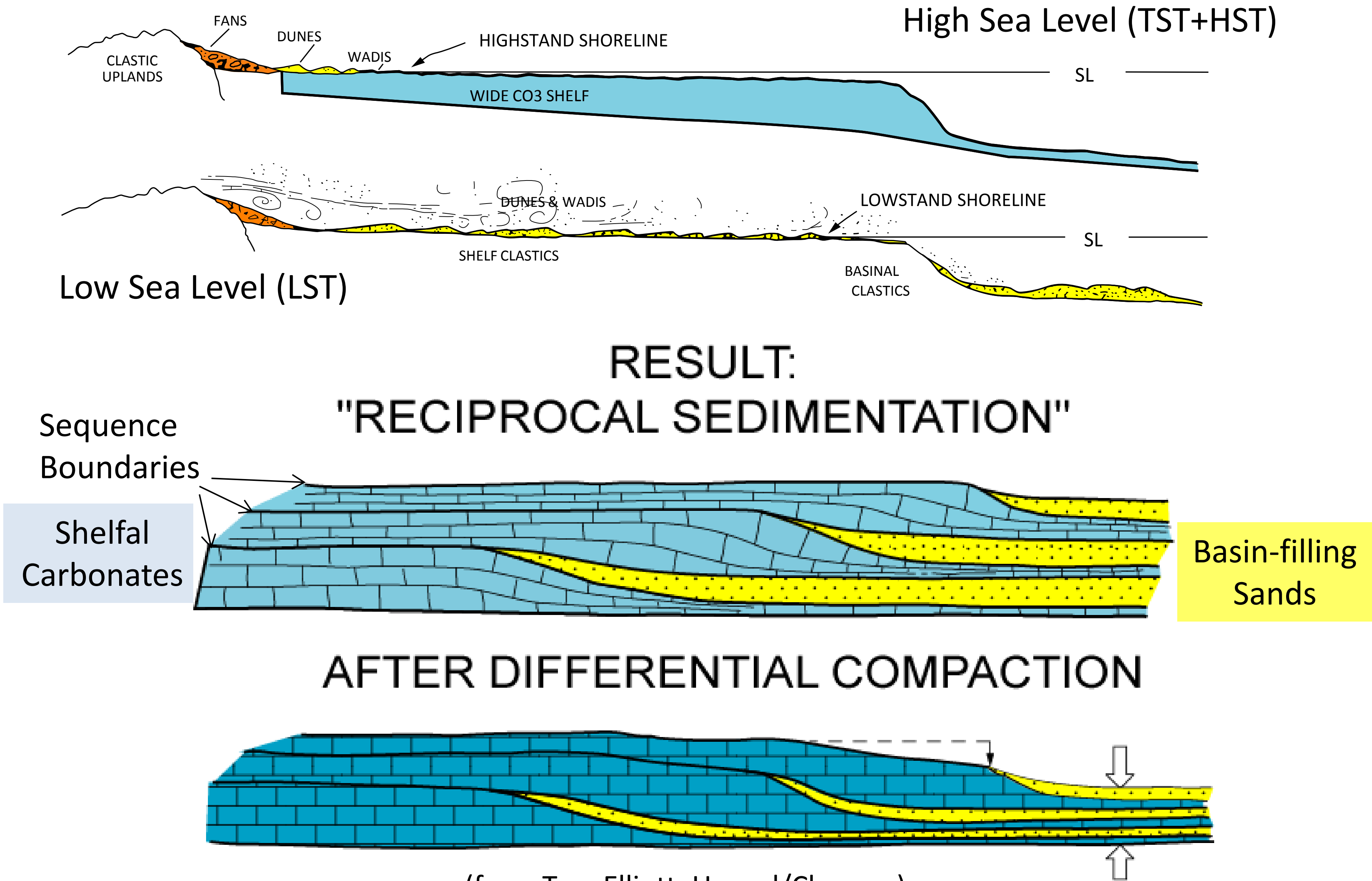
Evaporite
Dolomite
Limestone
Sandstone

WEST FACE

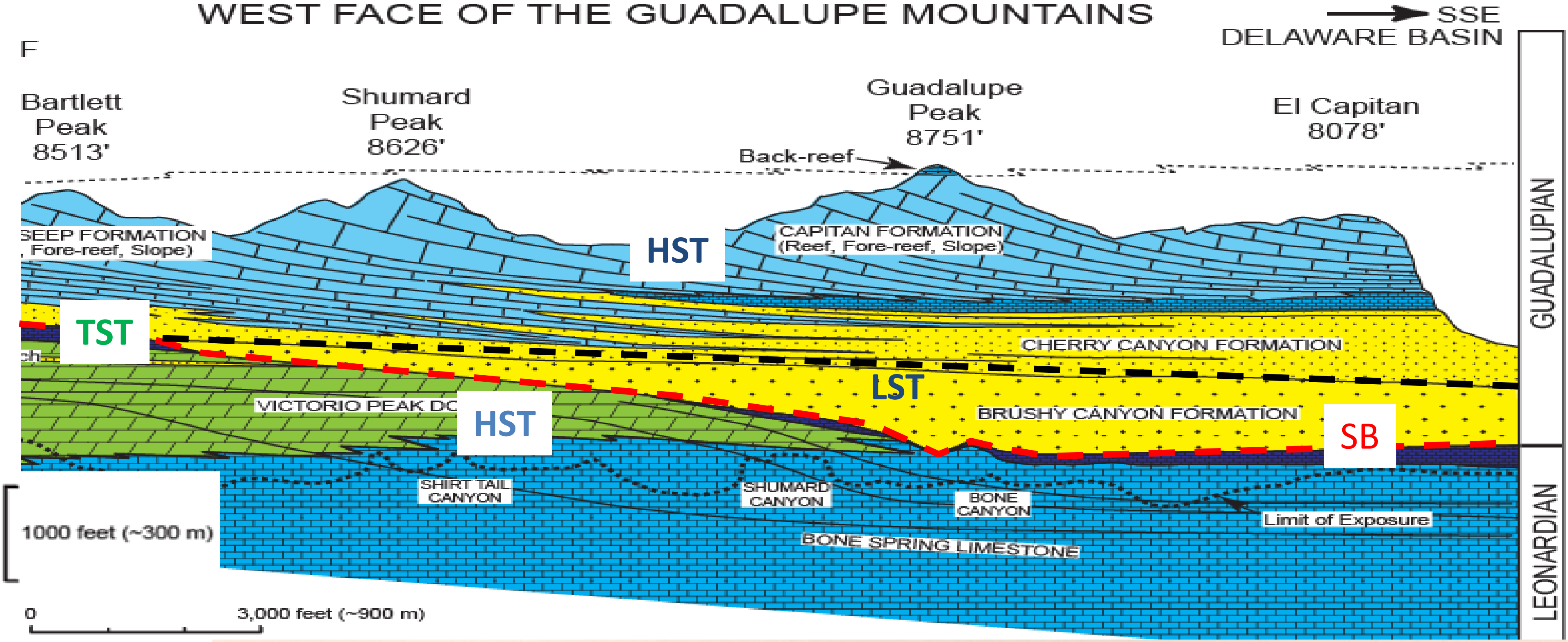
DELAWARE BASIN

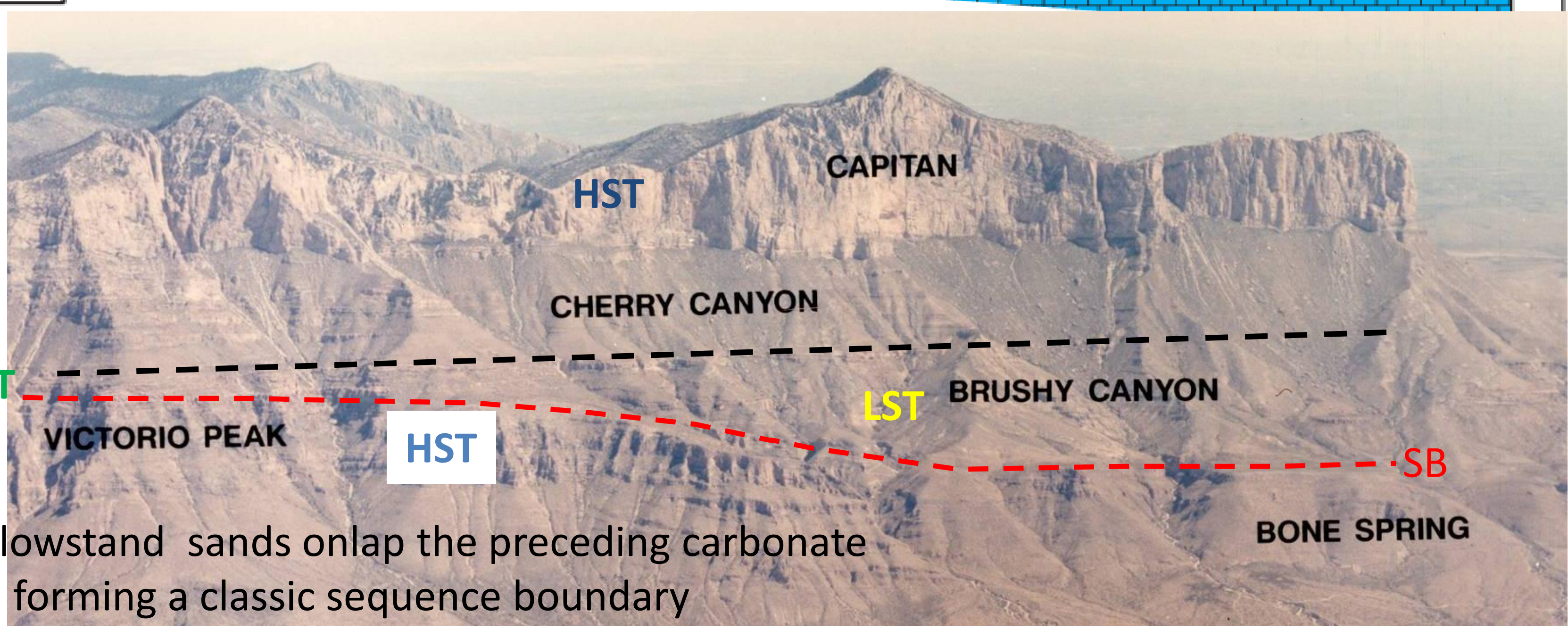


Middle Permian of the Guadalupe Mountains has sequences developed in an arid climate



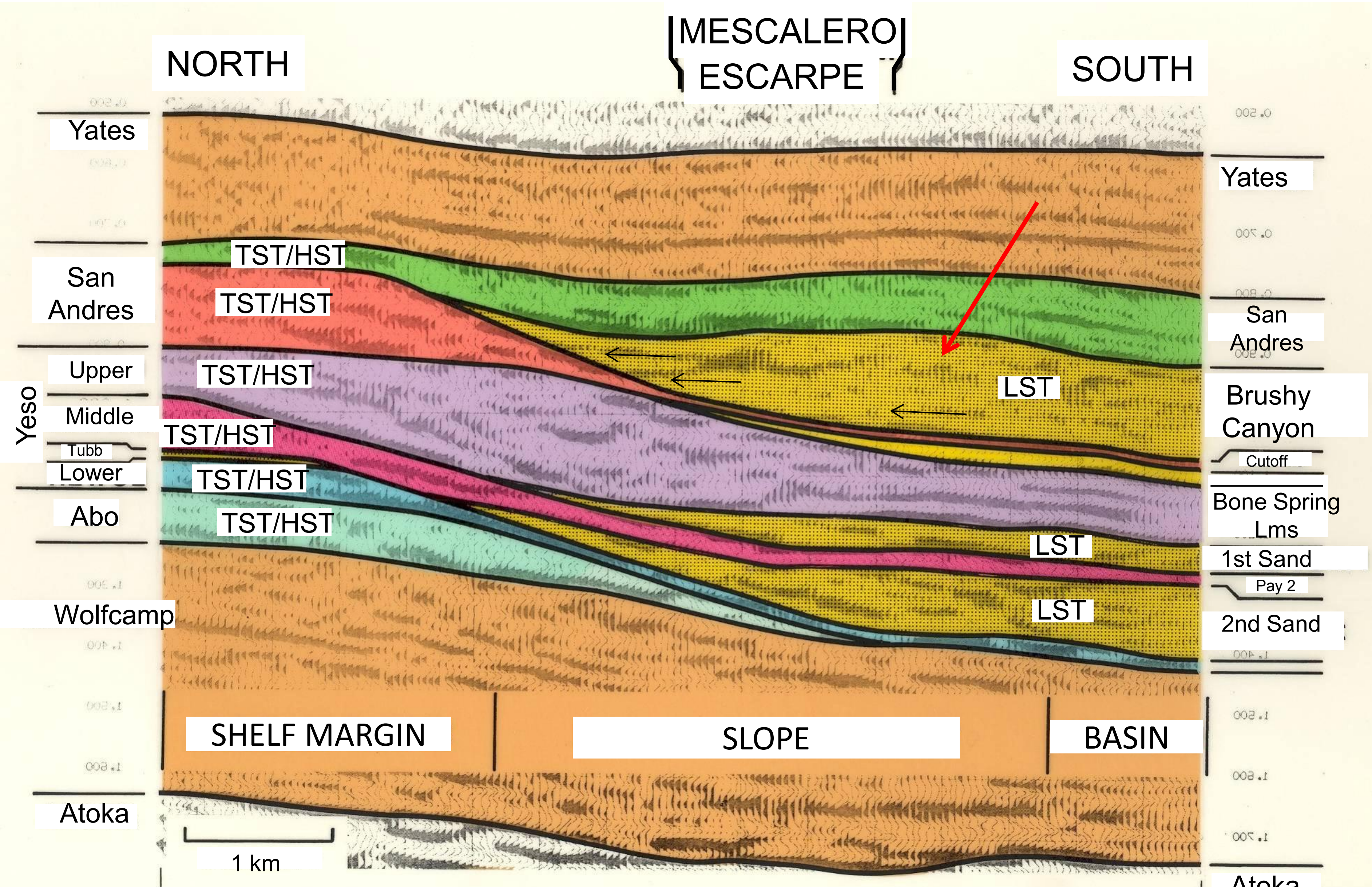
(from Tom Elliott, Unocal/Chevron)





Deepwater lowstand sands onlap the preceding carbonate shelf margin forming a classic sequence boundary

NORTH DELAWARE BASIN

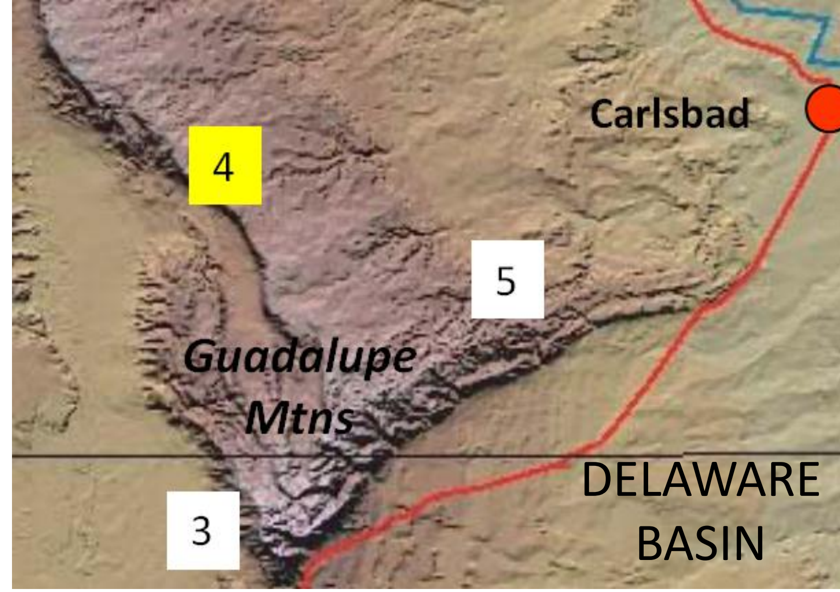


TST & HST = Deposited during high sea level

LST= Deposited during low sea level

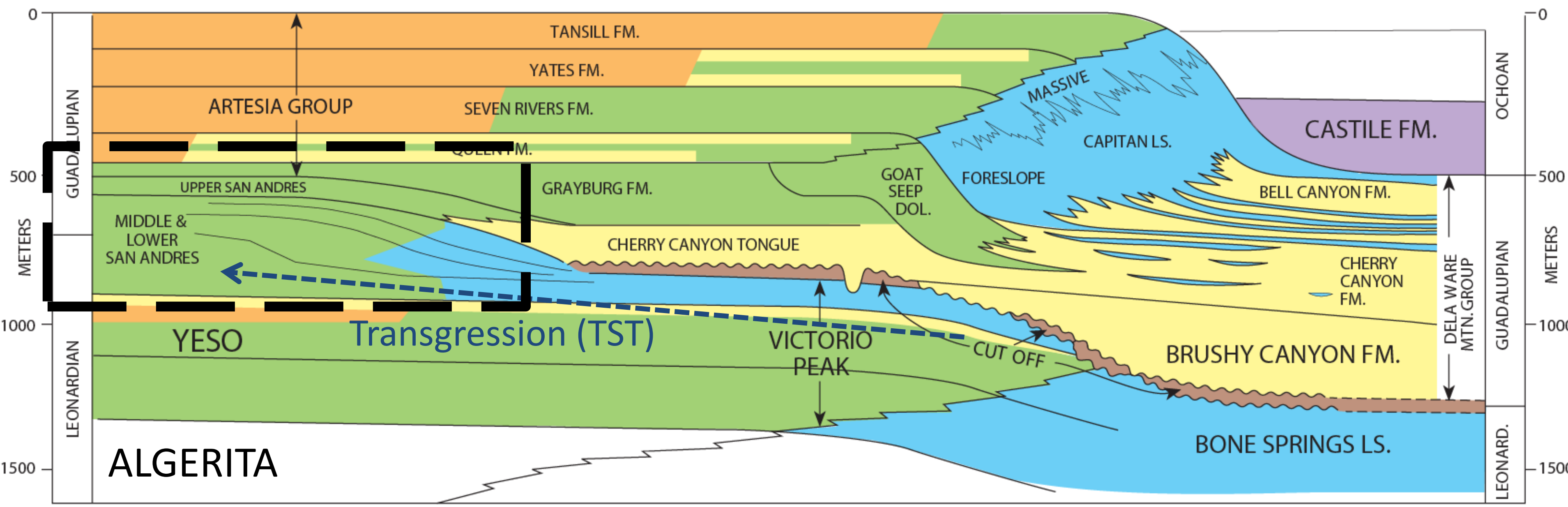
From Saller, Arthur H., Jane W. Barton, and Ricky E. Barton, 1989, Slope sedimentation associated with a vertically building shelf, Bone Spring Formation, Mescalero Escarpe Field, southeastern New Mexico, *in* Crevello and others, eds., *Controls on Carbonate Platform and Basin Development*: SEPM Special Publication No. 44, p. 275-288.

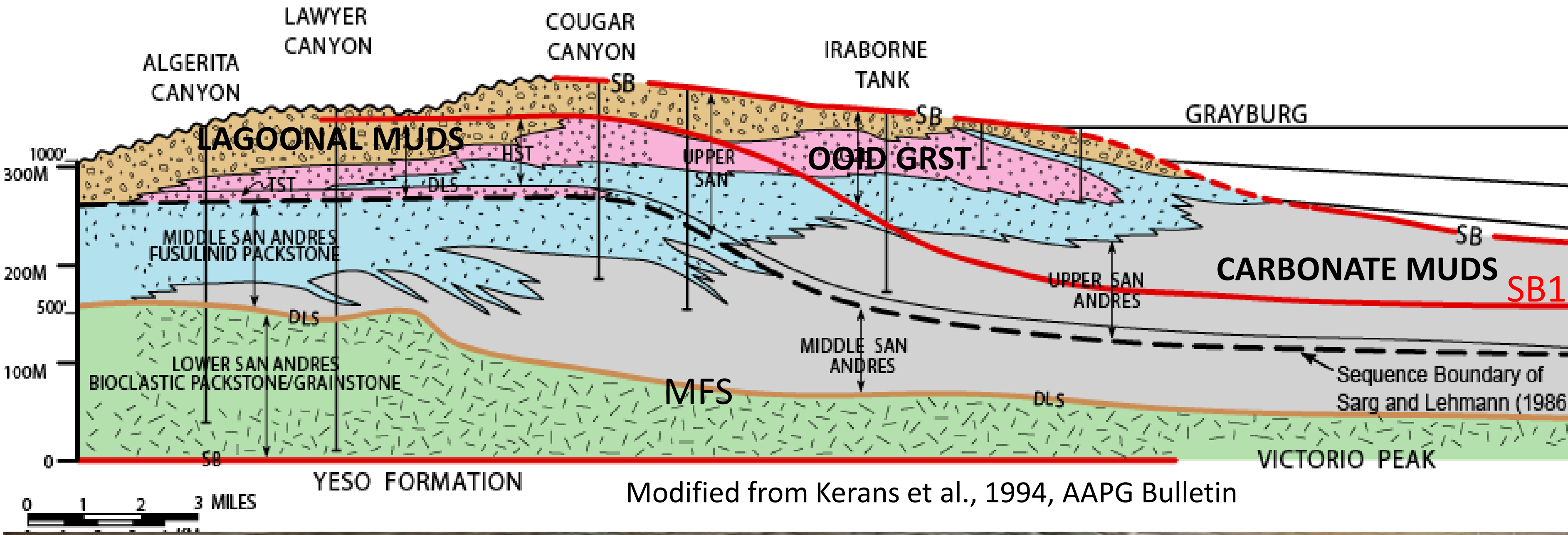
ALGERITA ESCARPMENT
GUADALUPE MOUNTAINS
San Andres Ramp System



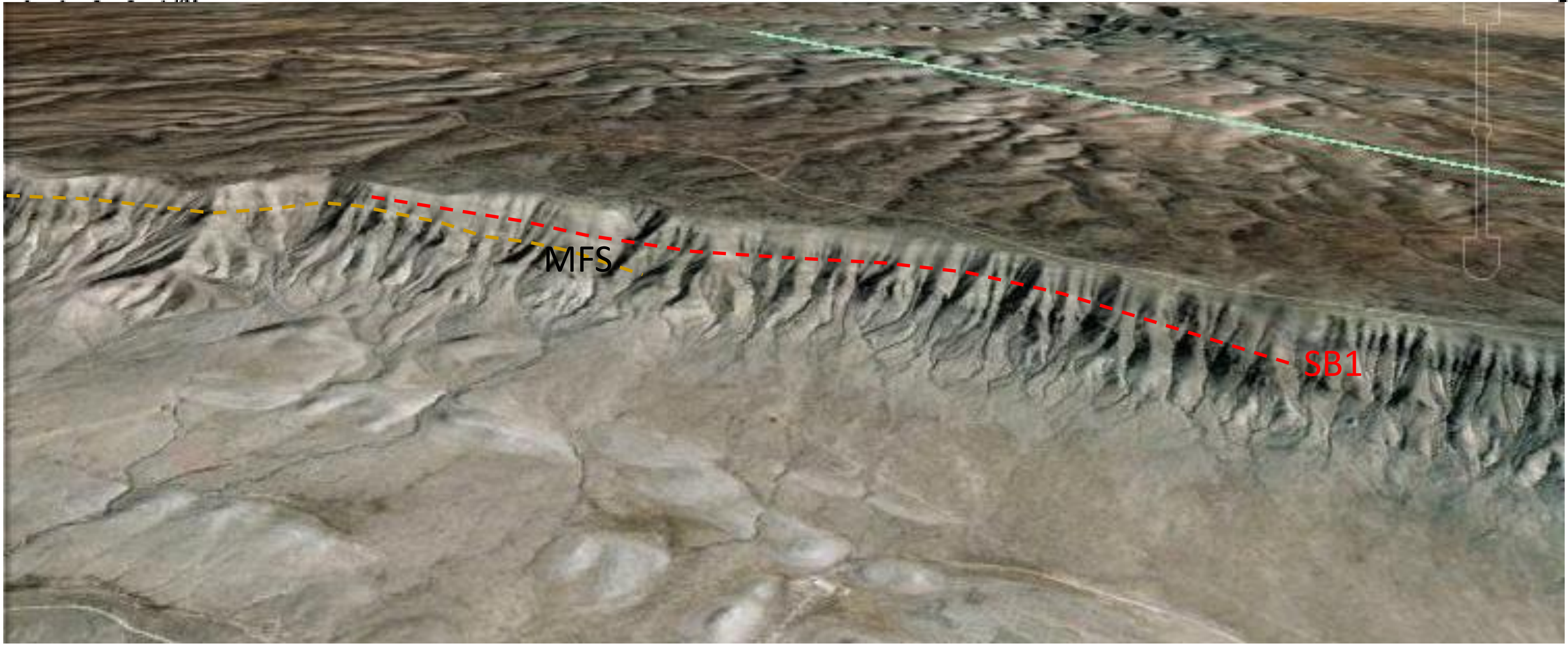
- Evaporite
- Dolomite
- Limestone
- Sandstone

DELAWARE
BASIN



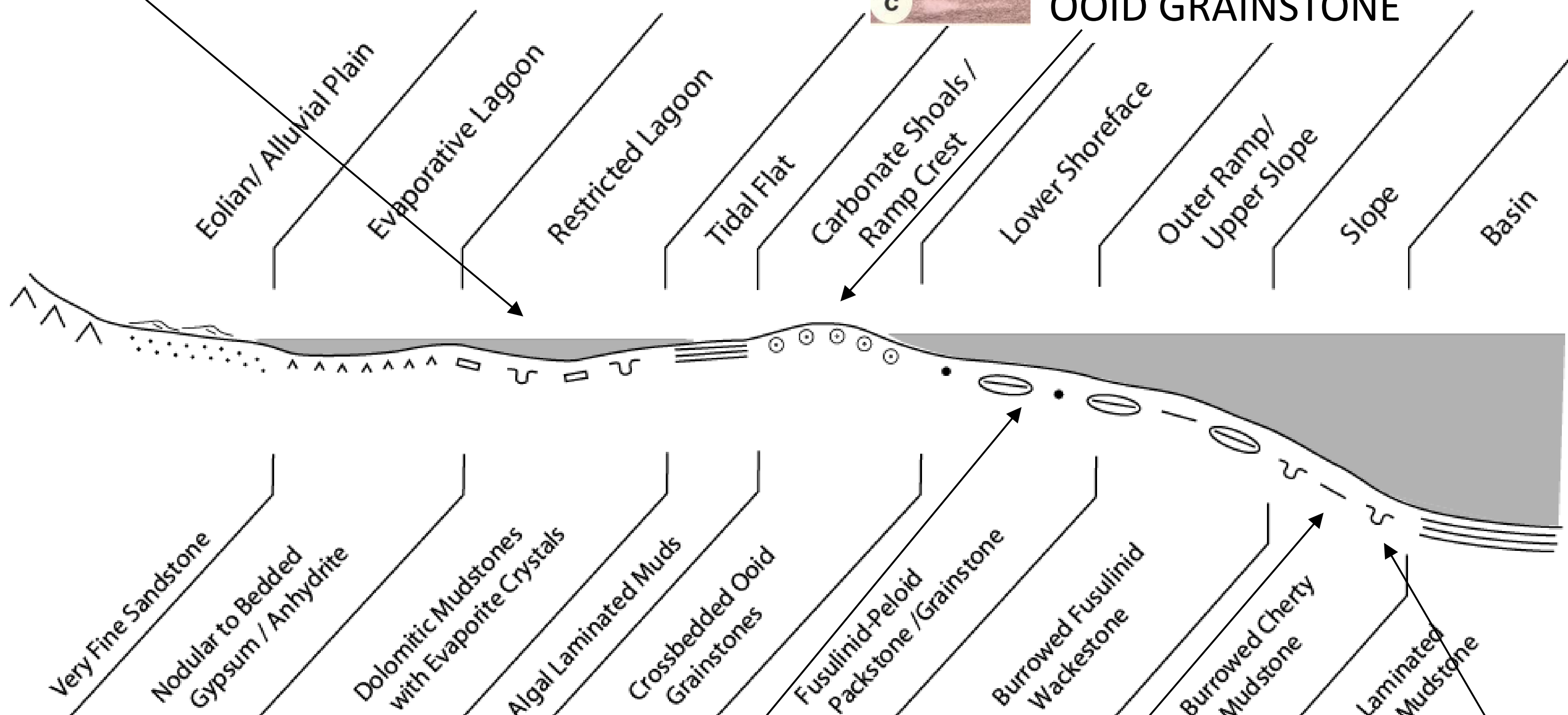


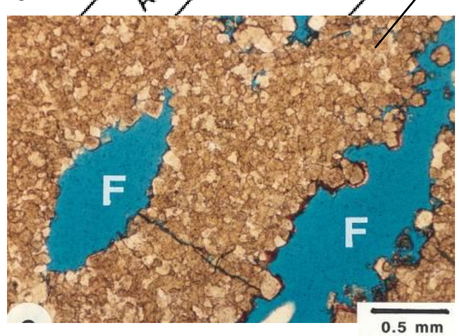
Modified from Kerans et al., 1994, AAPG Bulletin



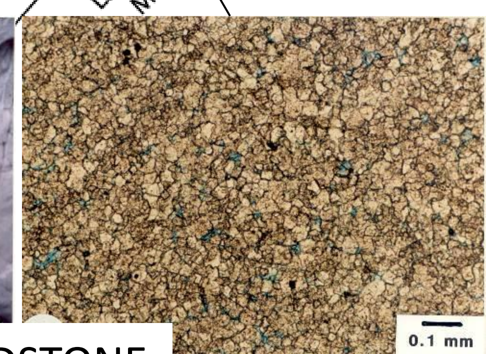
SAN ANDRES DEPOSITIONAL MODEL

OOID GRAINSTONE

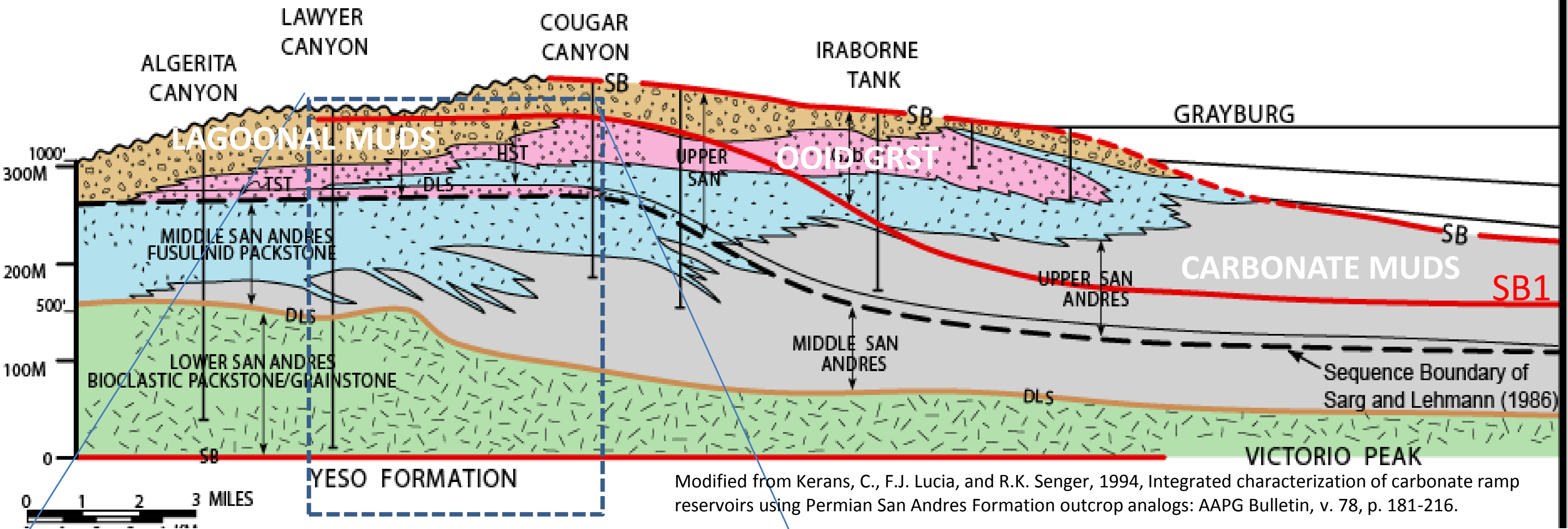




BURROWED FUSULINID PACKSTONE

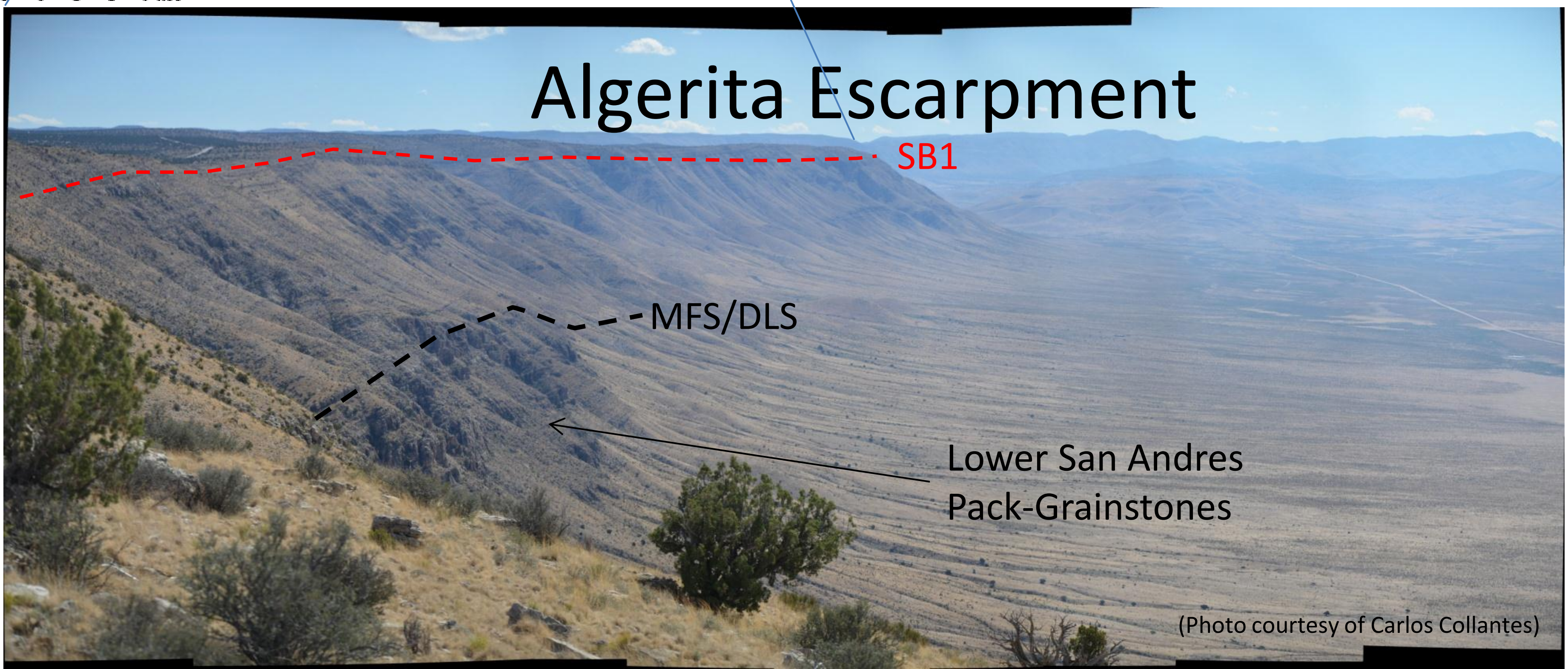


BURROWED MUDSTONE



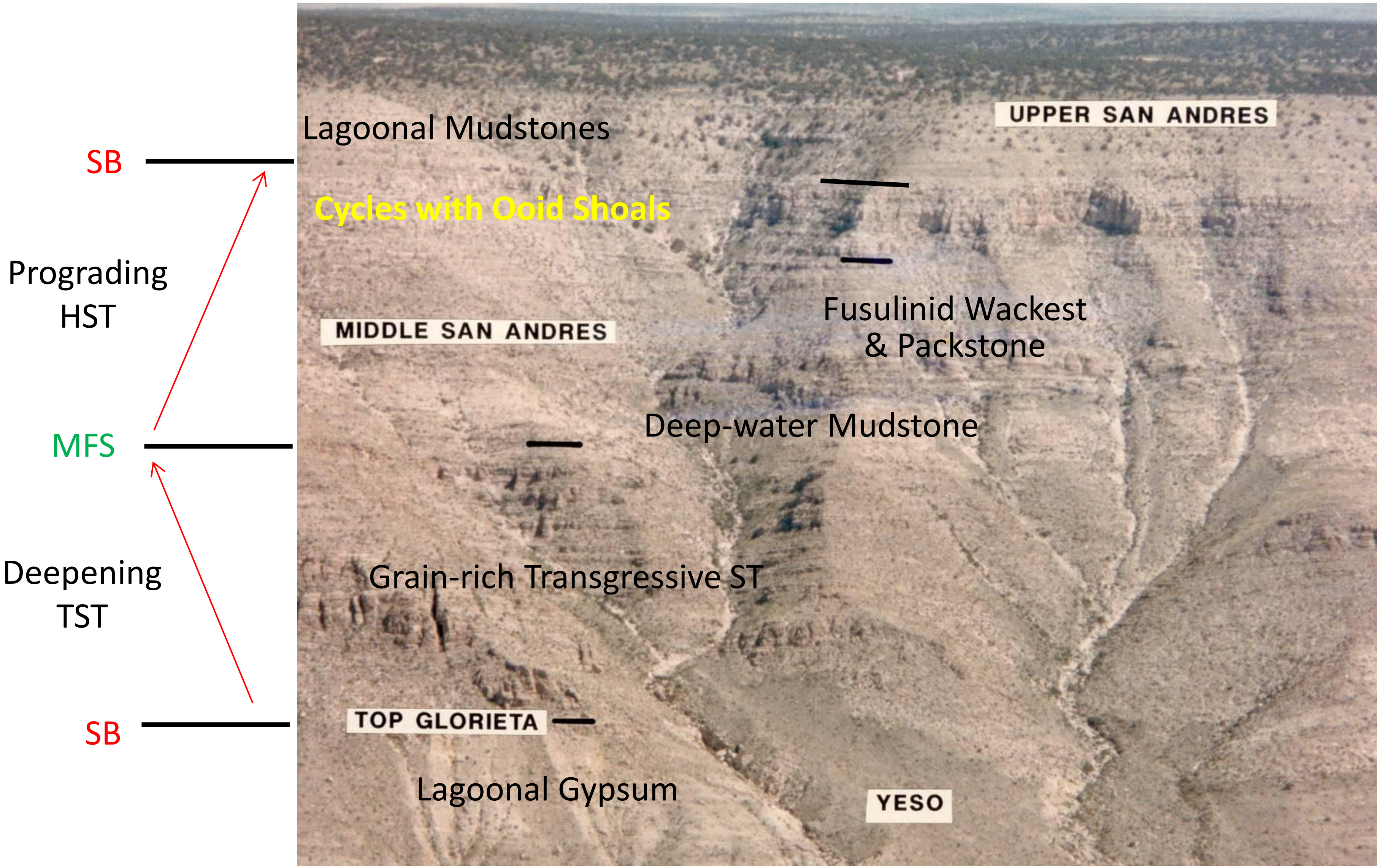
Modified from Kerans, C., F.J. Lucia, and R.K. Senger, 1994, Integrated characterization of carbonate ramp reservoirs using Permian San Andres Formation outcrop analogs: AAPG Bulletin, v. 78, p. 181-216.

Algerita Escarpment

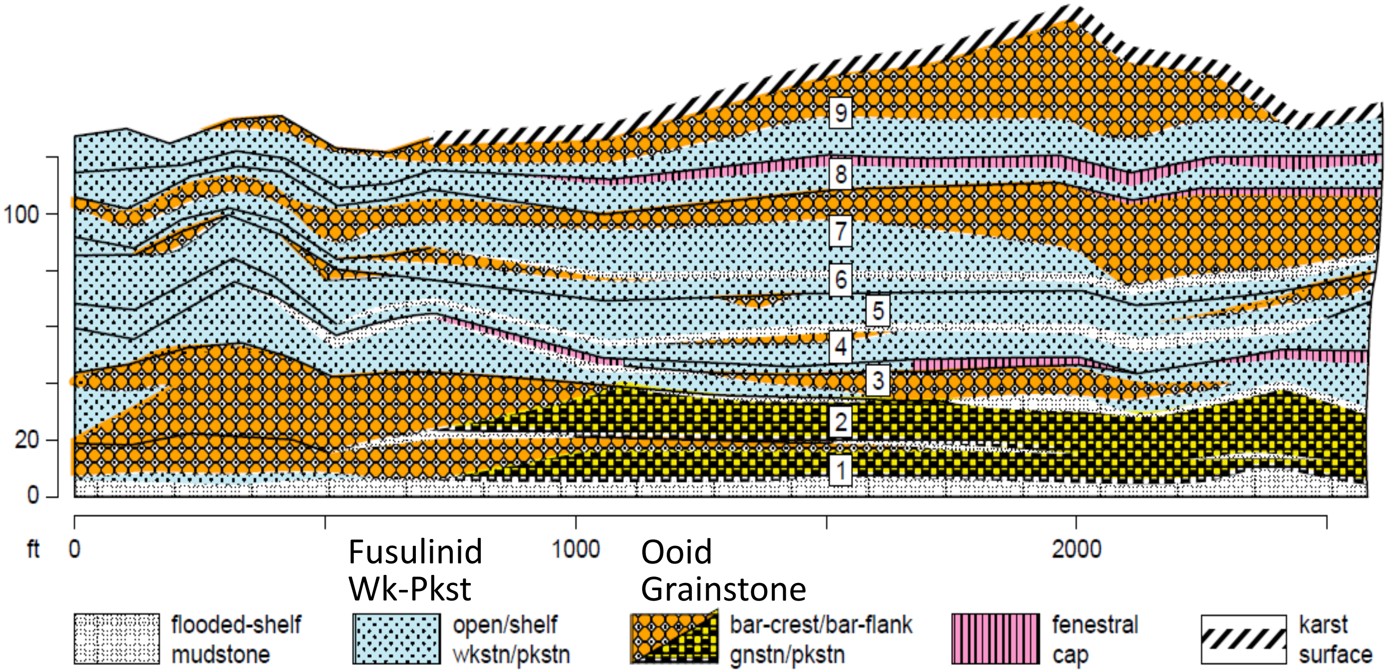


(Photo courtesy of Carlos Collantes)

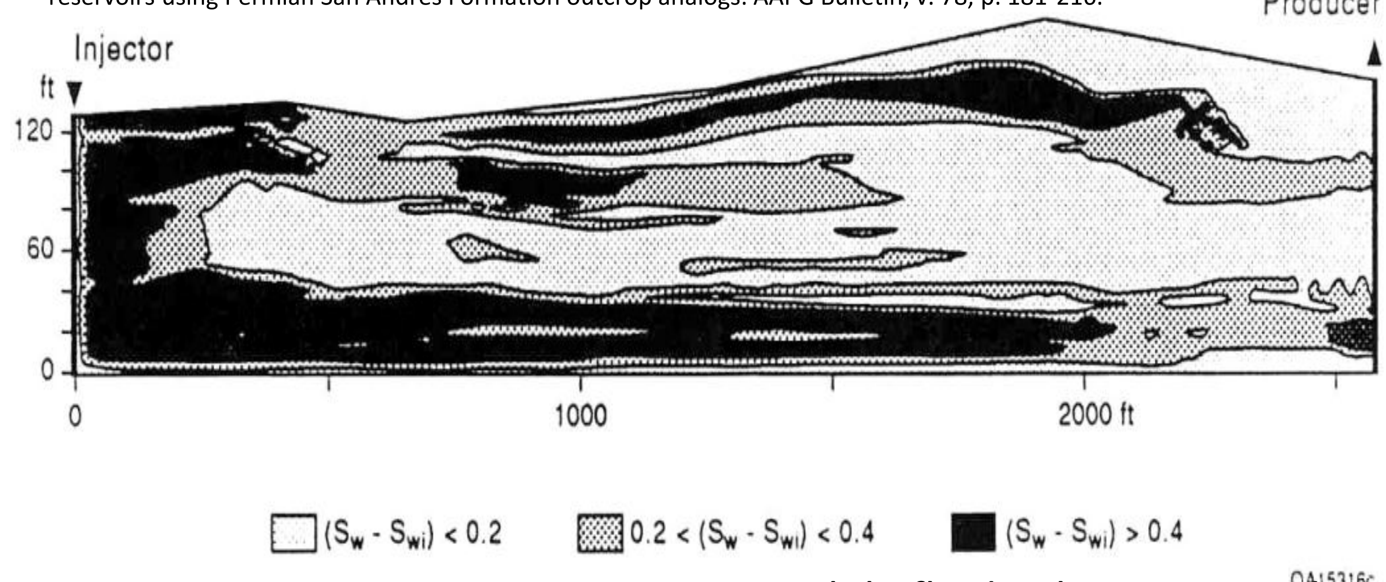
LAWYER CANYON



RESERVOIR SIMULATION OF LAWYER CANYON OUTCROP

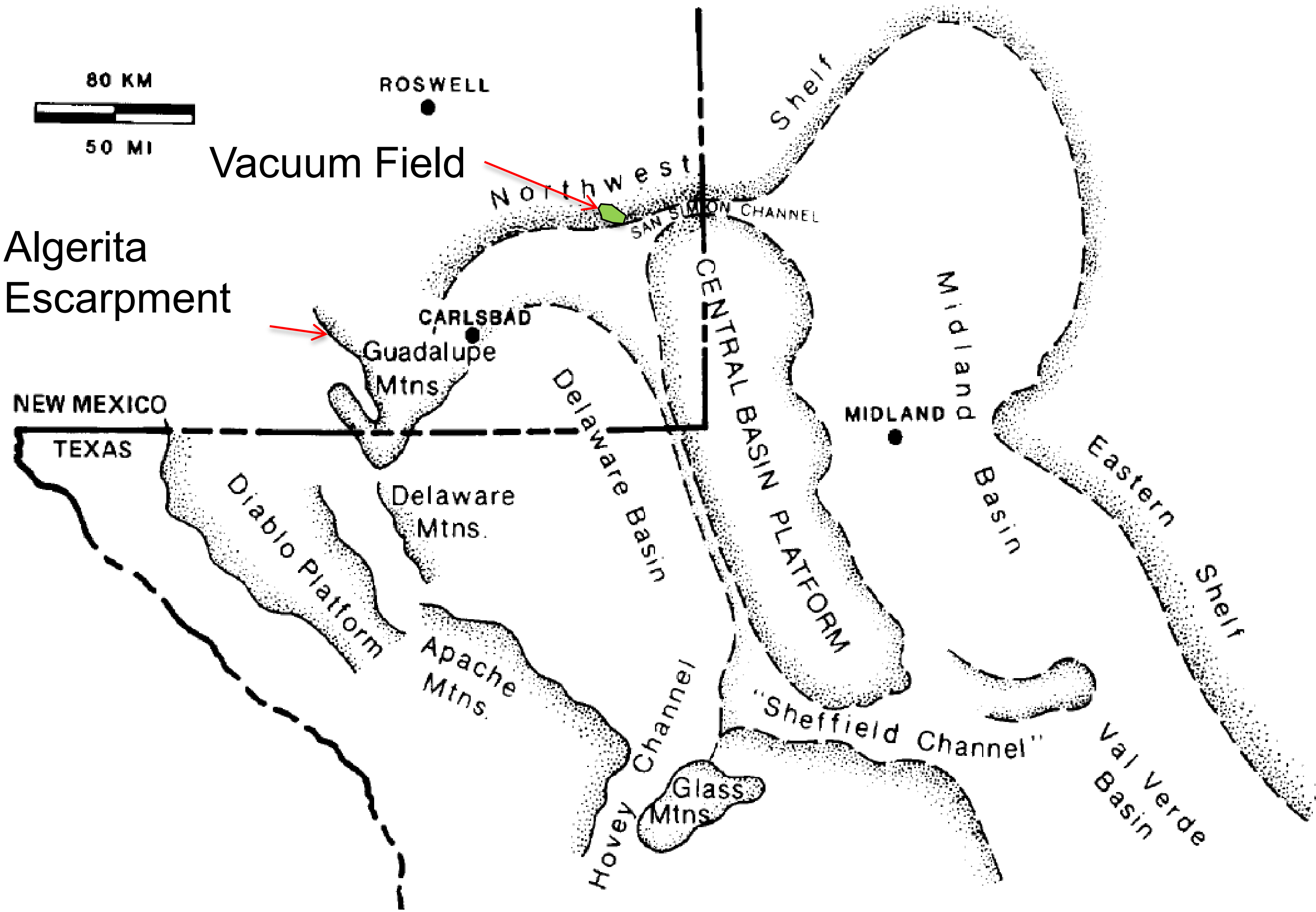


Modified from Kerans, C., F.J. Lucia, and R.K. Senger, 1994, Integrated characterization of carbonate ramp reservoirs using Permian San Andres Formation outcrop analogs: AAPG Bulletin, v. 78, p. 181-216.



Increase in water saturation at 1.0 mobile fluid volume injected.

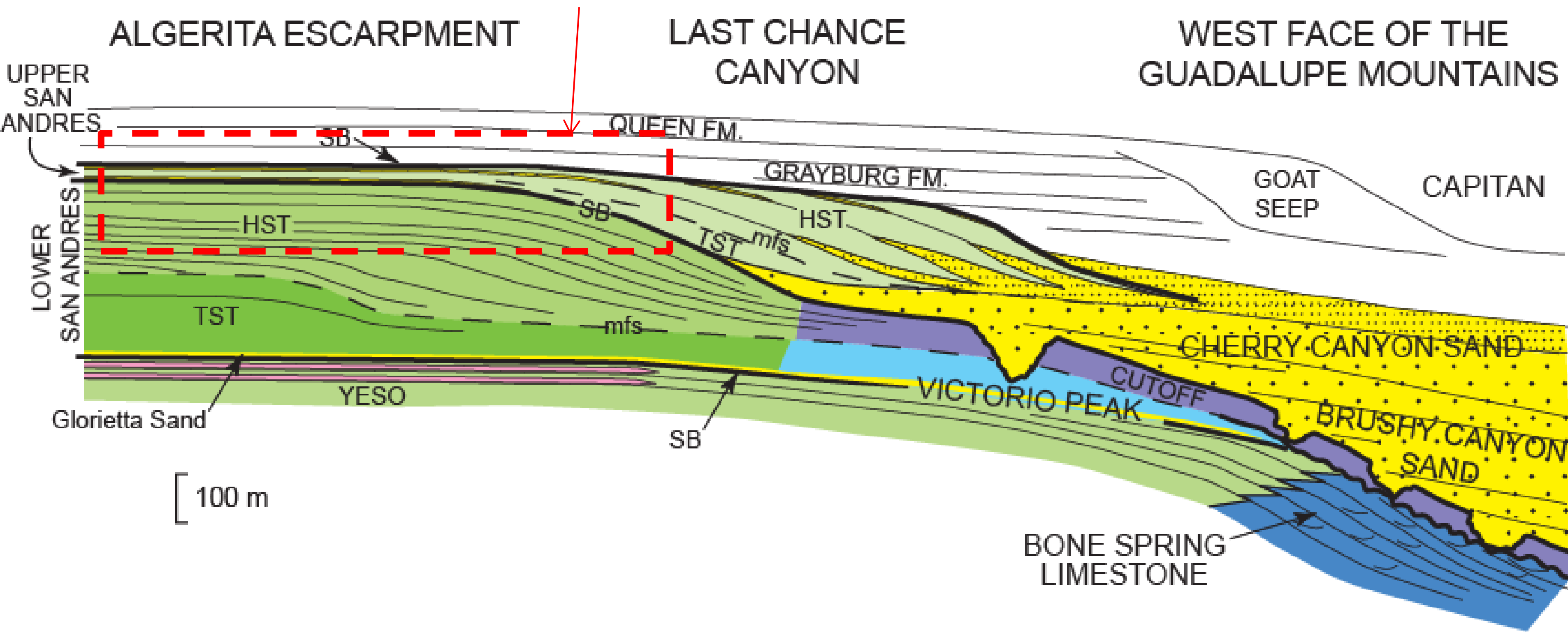
MIDDLE PERMIAN PALEOGEOGRAPHY



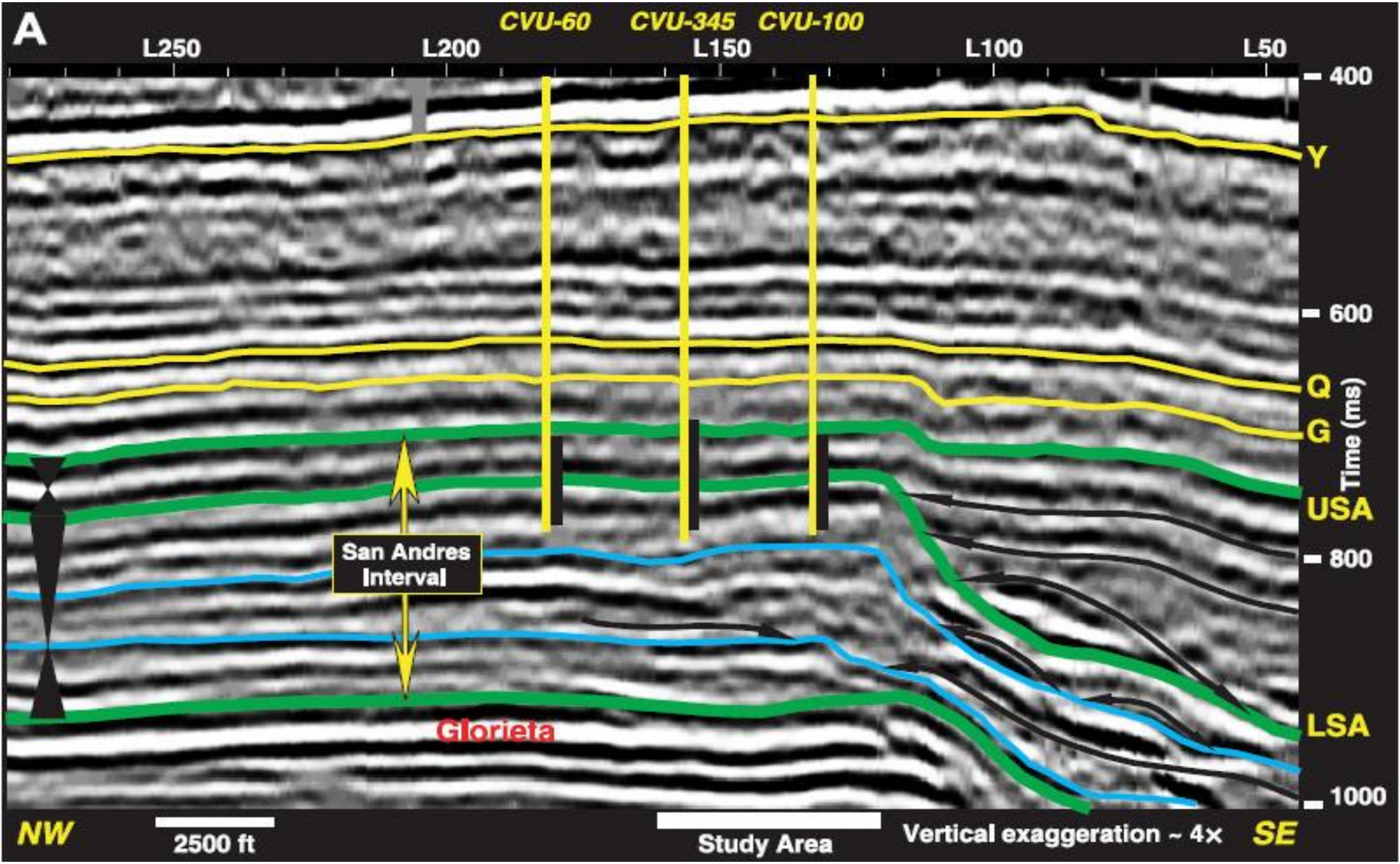
Modified from Ward, R.F., C.G. St. C. Kendall, Paul M. Harris, 1986, Upper Permian (Guadalupian) Facies and Their Association with Hydrocarbons--Permian Basin, West Texas and New Mexico: AAPG Bulletin, v. 70, p. 239-262.

SCHEMATIC STRATIGRAPHY OF THE SAN ANDRES SYSTEM

Vacuum producing zone

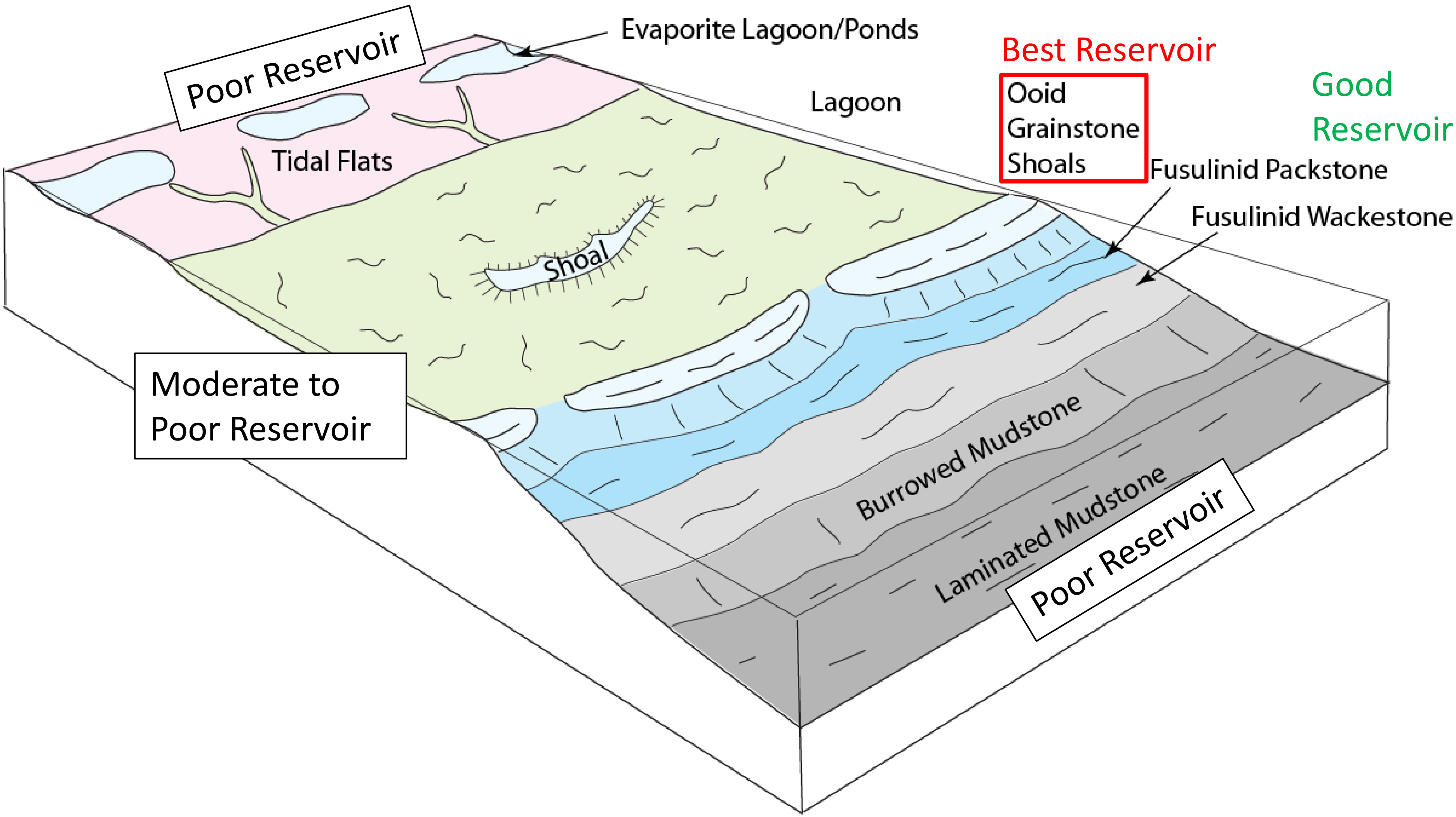


N (Landward) Vacuum Field S (Delaware Basin)



From: Pranter, M. J., N. F. Hurley, and T. L. Davis, 2004, Sequence-stratigraphic, petrophysical, and multicomponent seismic analysis of a shelf-margin reservoir: San Andres Formation (Permian), Vacuum field, New Mexico, United States, in Seismic imaging of carbonate reservoirs and systems: AAPG Memoir 81, p. 59– 89.

SAN ANDRES DEPOSITIONAL MODEL



Depositional facies and textures occur in predictable patterns

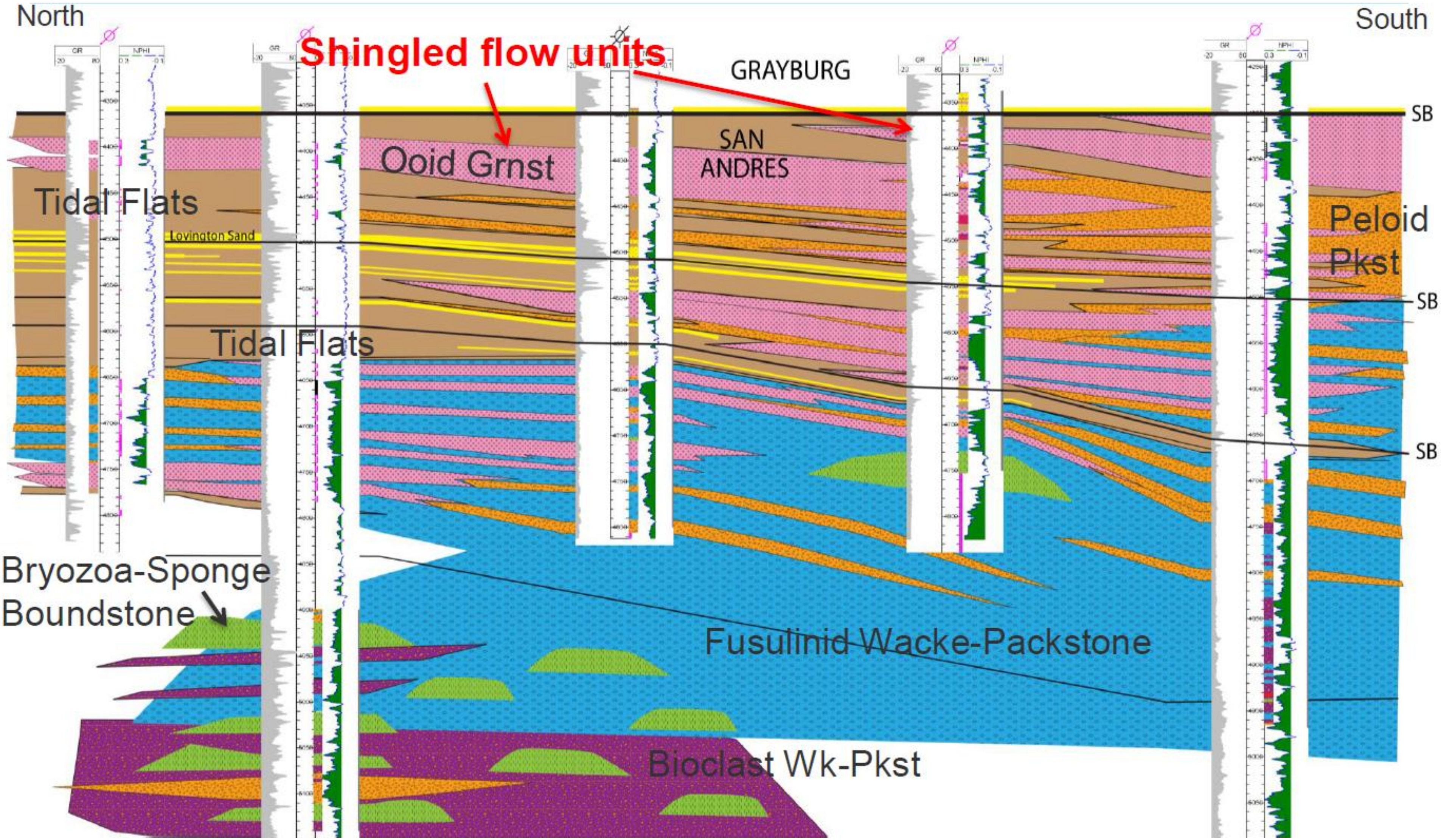
Landward

Vacuum Field

Basinward

Less Porous Shelf Interior

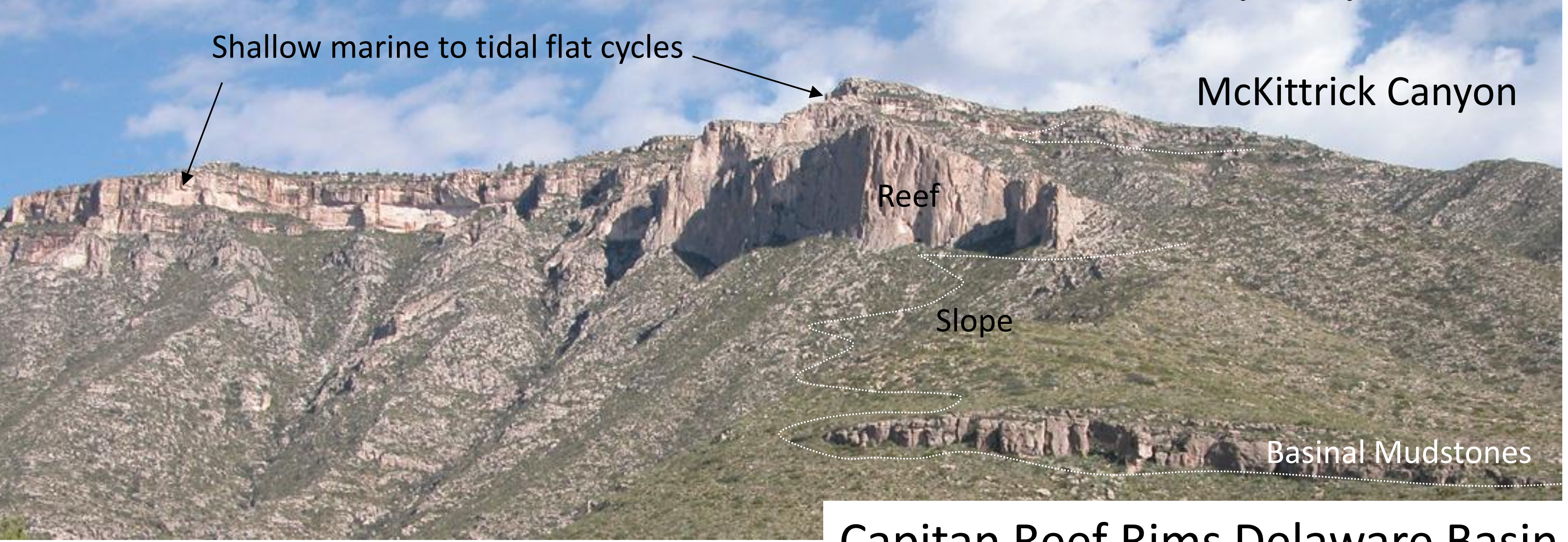
Porous Shelf Margin Ooid Grainstones, Fusulinid Packstones

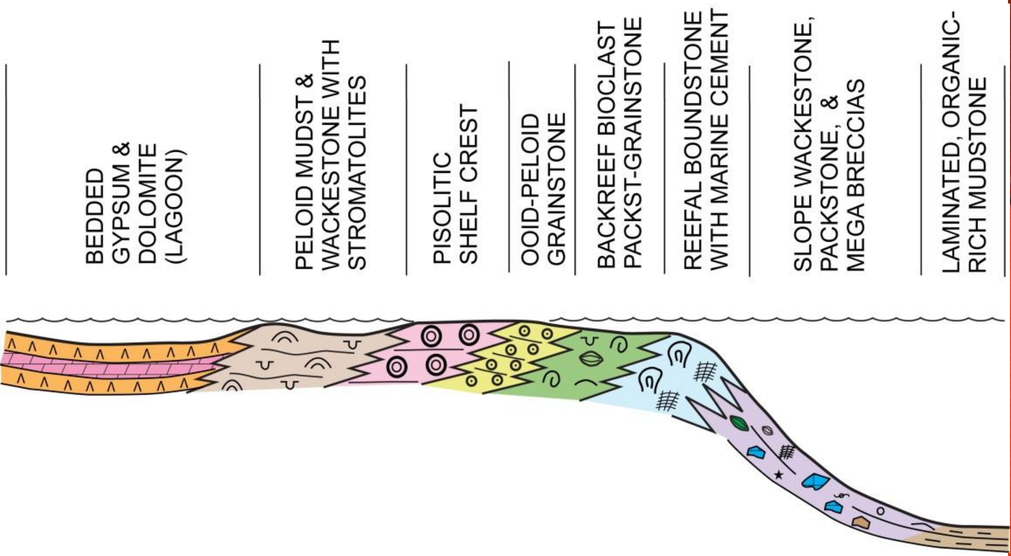


Average porosity= 7.4%; Average Permeability = 15.7 mD

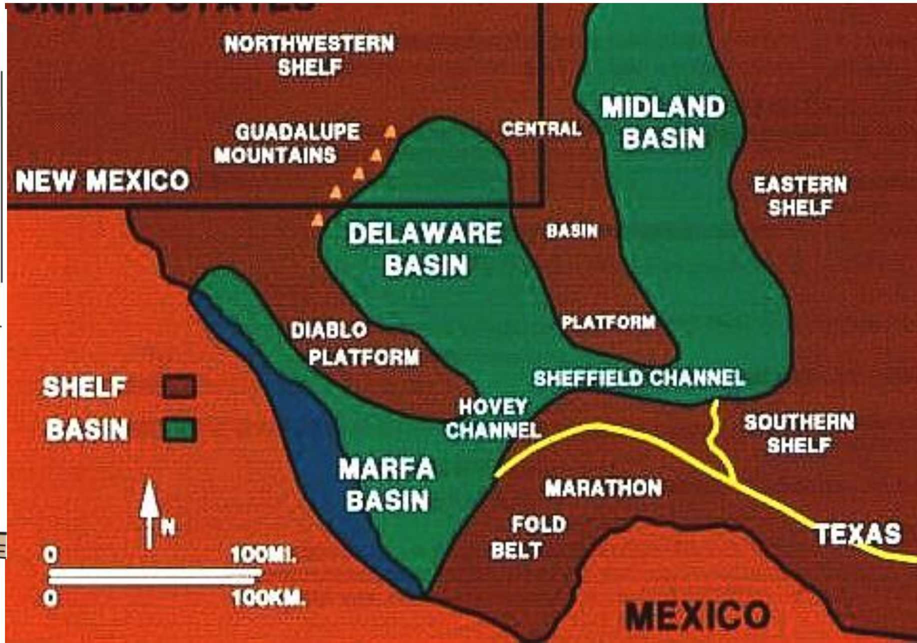
From Saller, Arthur, Lauren Bierly, David Shafer, and Leigh Owens, 2012, Contrasting Styles of San Andres Reservoirs: Vacuum Versus Slaughter Fields, Middle Permian, West Texas and Southeast New Mexico: AAPG Search and Discovery Article #20168

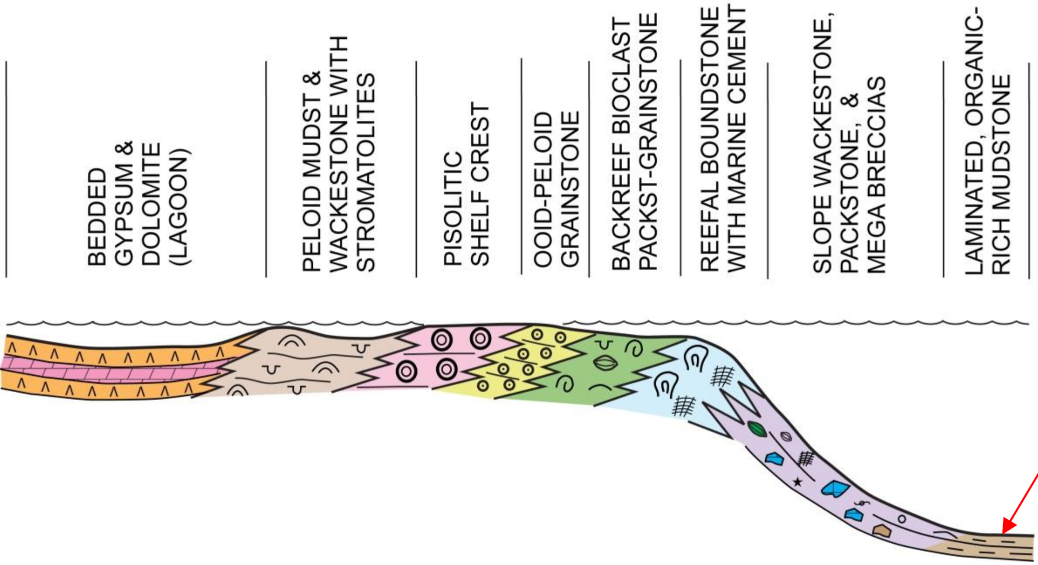
CAPITAN: PROGRADING SHELF MARGIN SYSTEM (HST)



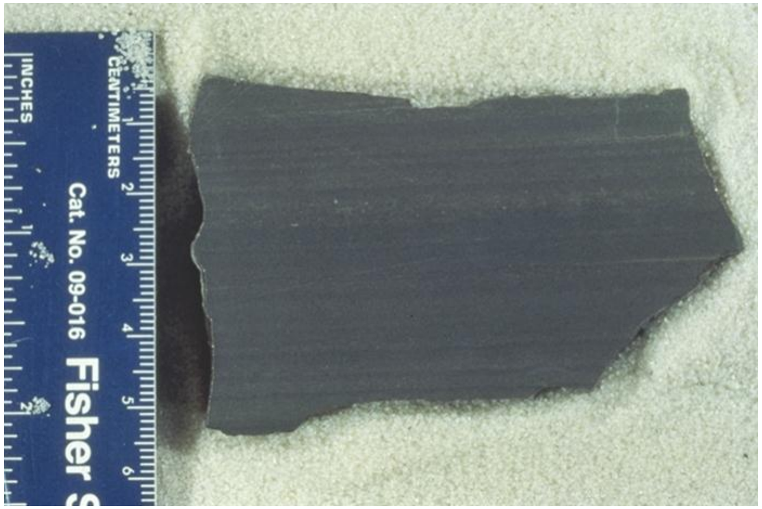


Capitan Reef Rims Delaware Basin





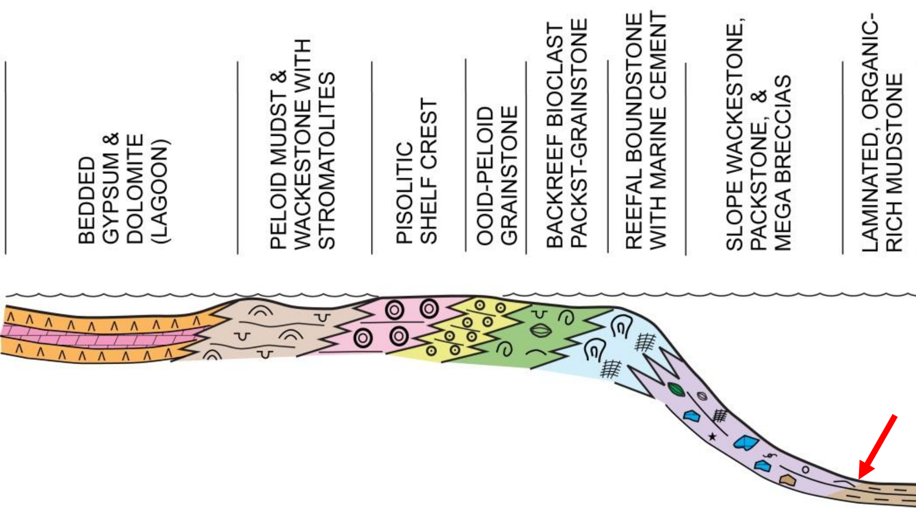
LAMINATED BASINAL CARBONATE MUDS

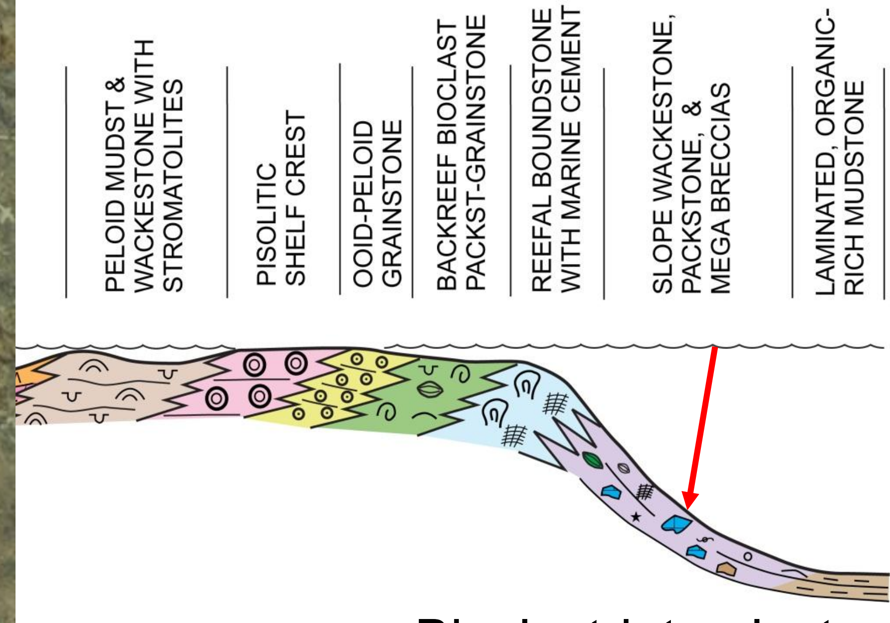


Lamar member of Bell Canyon Fm (Permian Capitan system);
Potential source rock

Gravity flows in basinal mudstones

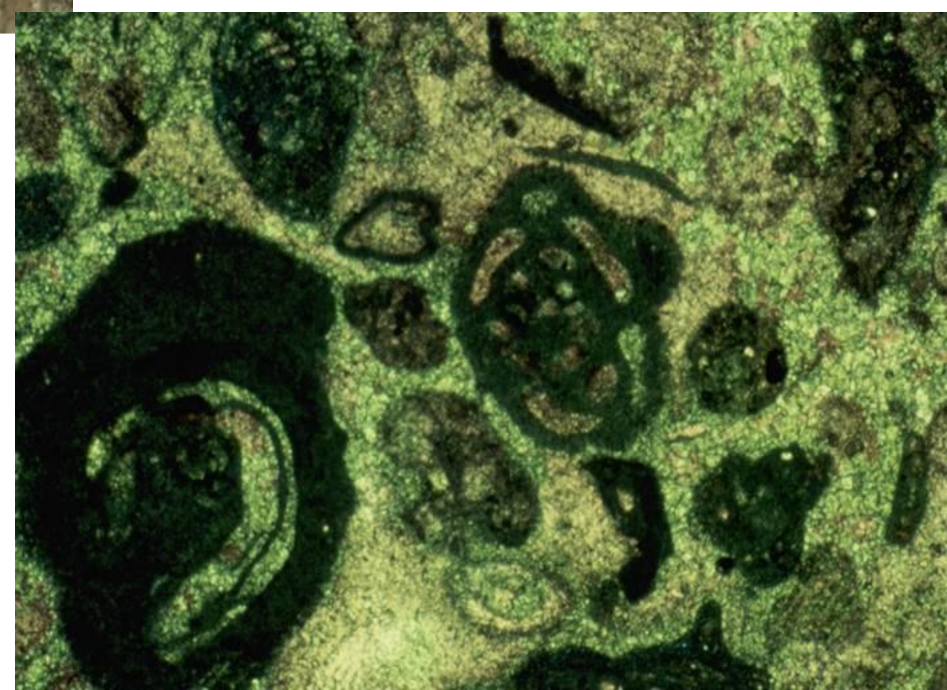
Basinal, near toe-of-slope



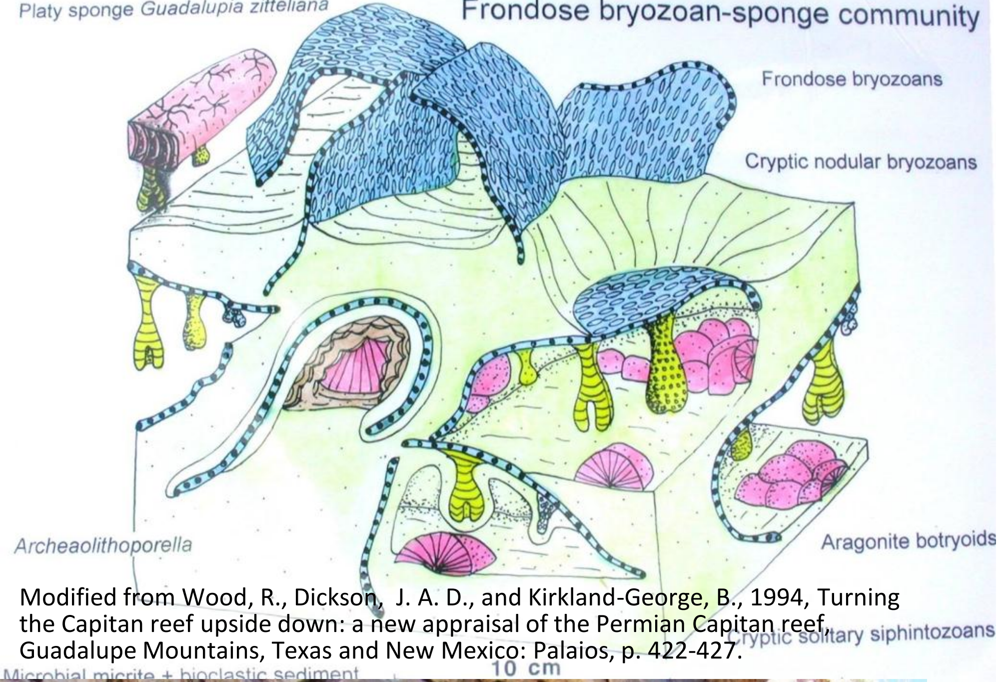


Bioclast-intraclast Packstone-Grainstone

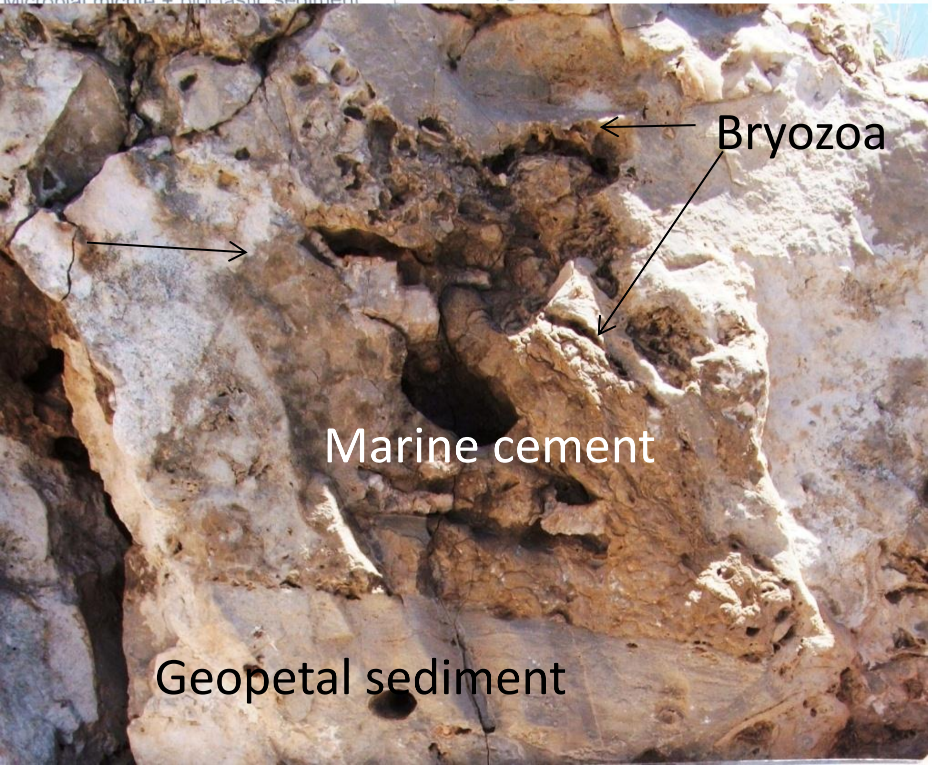
Capitan slope. Conglomerates of reef and slope debris.



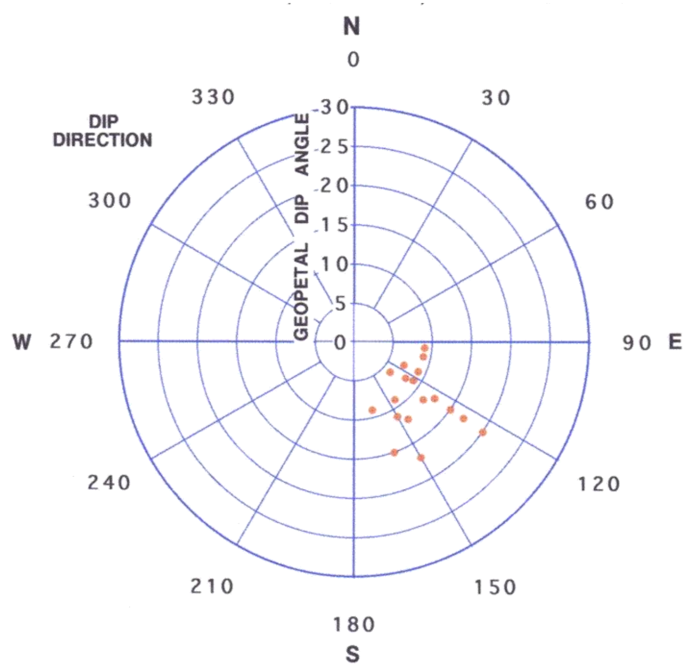
Capitan Reef, McKittrick Trail



Modified from Wood, R., Dickson, J. A. D., and Kirkland-George, B., 1994, Turning the Capitan reef upside down: a new appraisal of the Permian Capitan reef, Guadalupe Mountains, Texas and New Mexico: Palaios, p. 422-427.

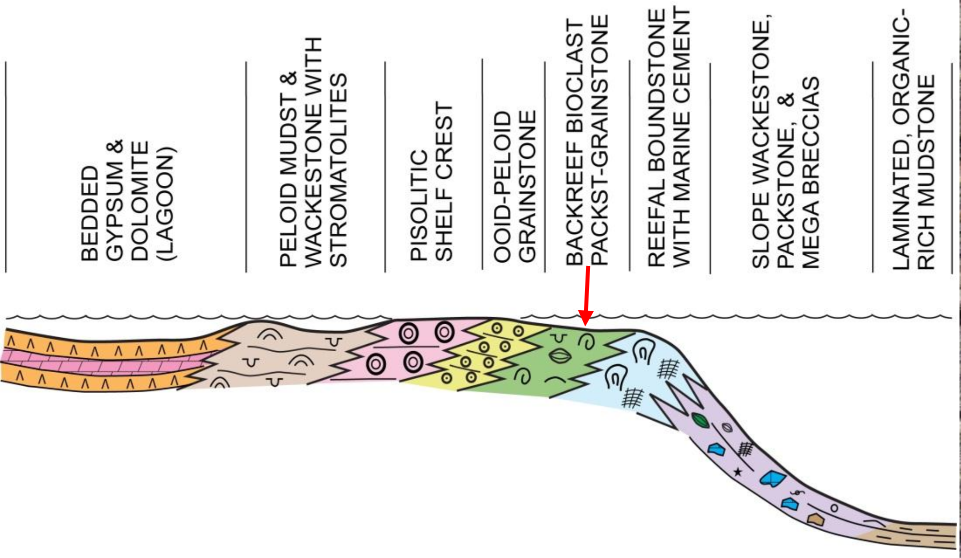


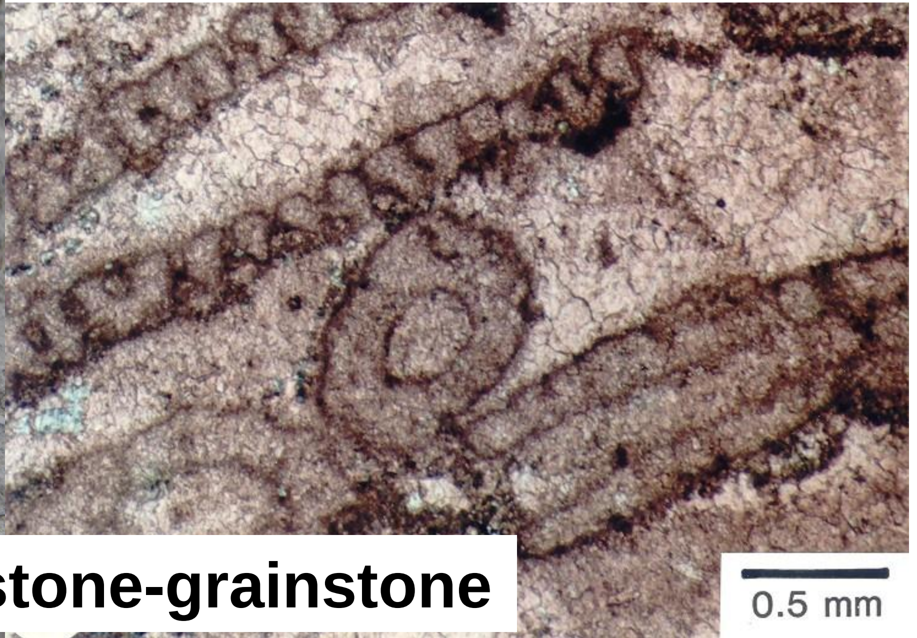
Average Geopetal Dip 10° @ 124° to the SE (basinward); n = 28



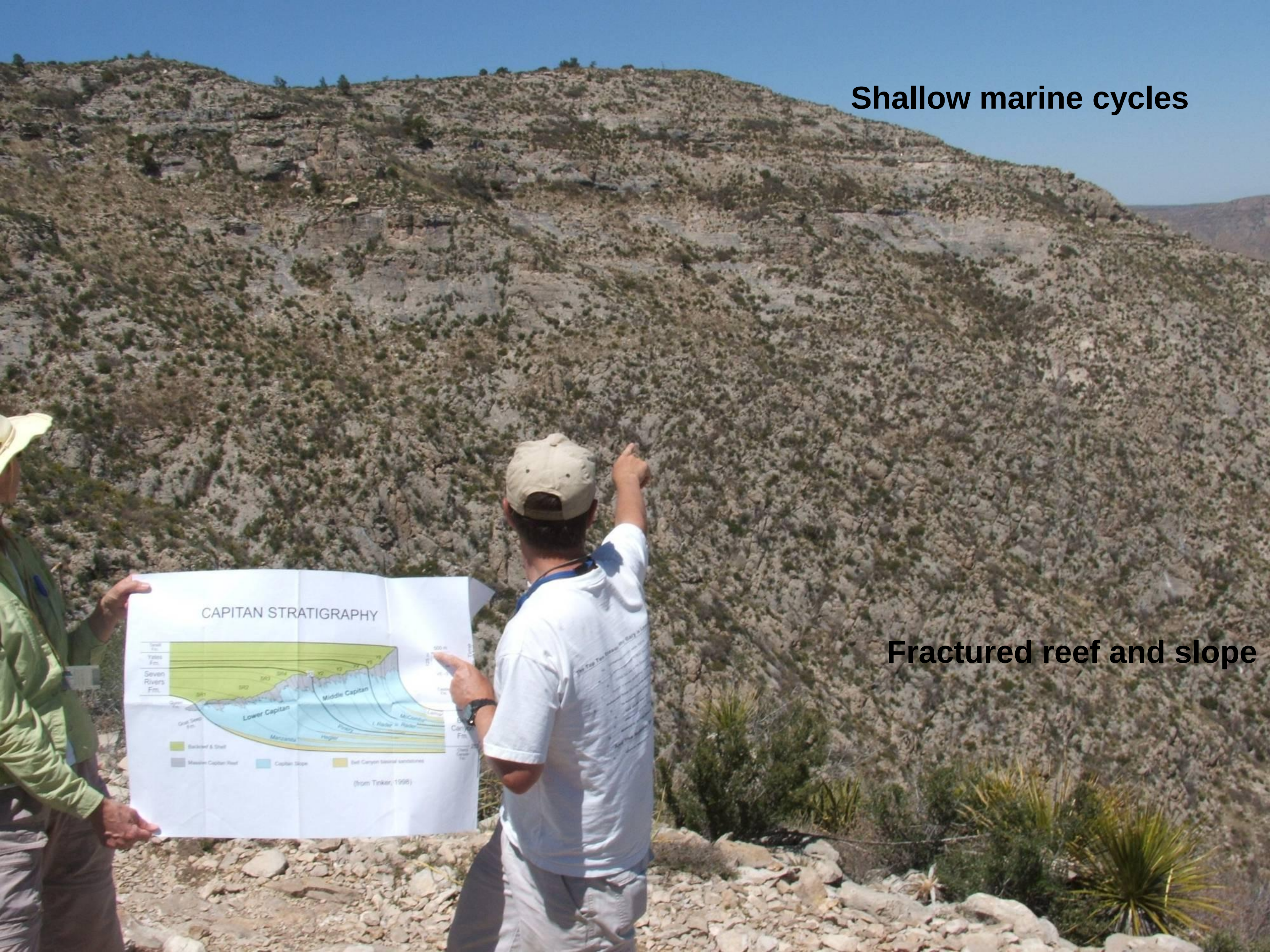
Overlying fall-in beds have a similar dip and orientation

From Saller, A.H., 1996, Differential compaction and basinward tilting of the prograding Capitan reef complex, Permian, west Texas and southeast New Mexico, USA: *Sedimentary Geology*, v. 101, p. 21-30.





Dasyclad packstone-grainstone

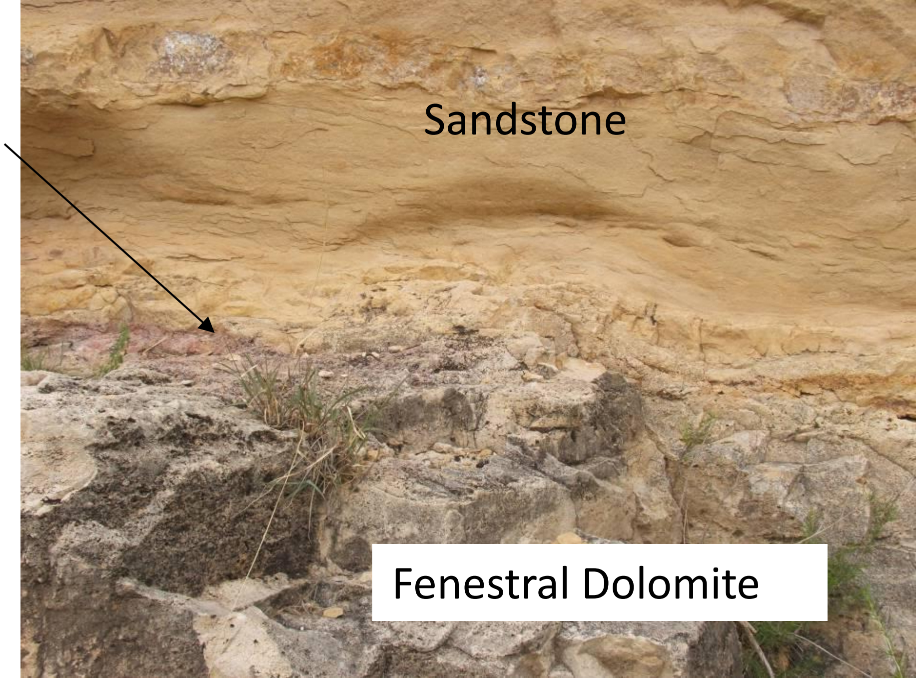

Shallow marine cycles
Fractured reef and slope
CAPITAN STRATIGRAPHY
Yates Fm.
Seven Rivers Fm.
Lower Capitan
Middle Capitan
(from Tinker, 1998)

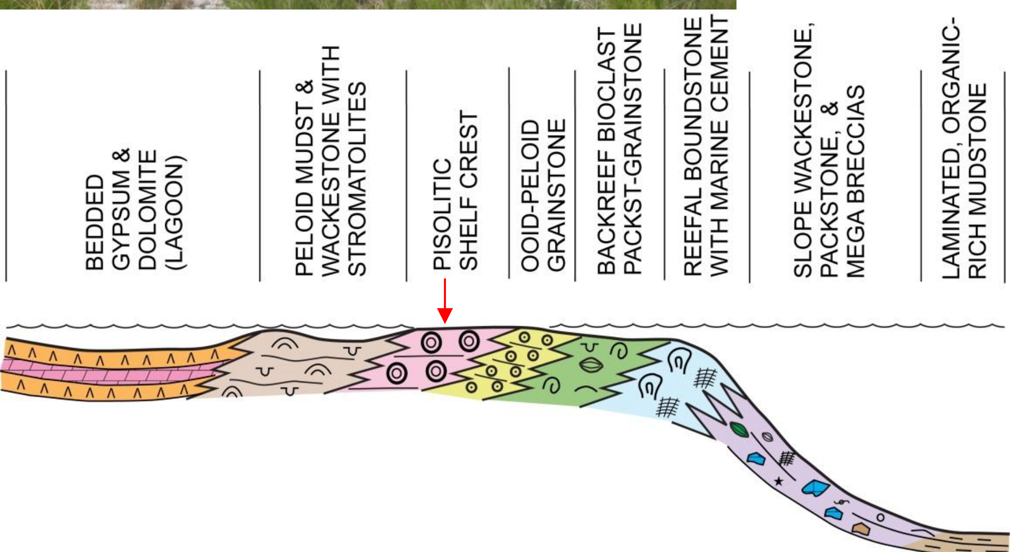
Sequence Boundary

Fenestral Dolomite

Sandstone

Fenestral Dolomite

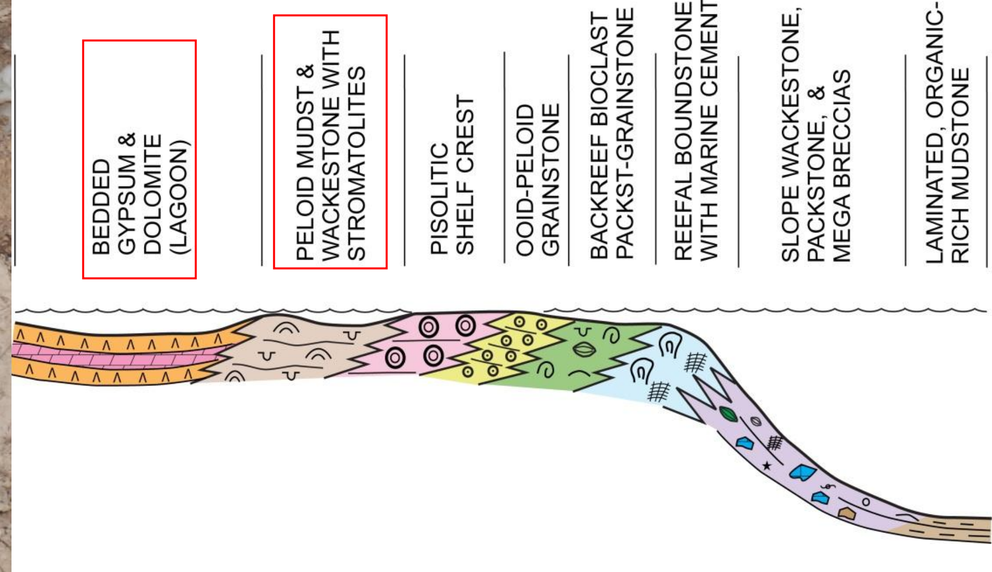


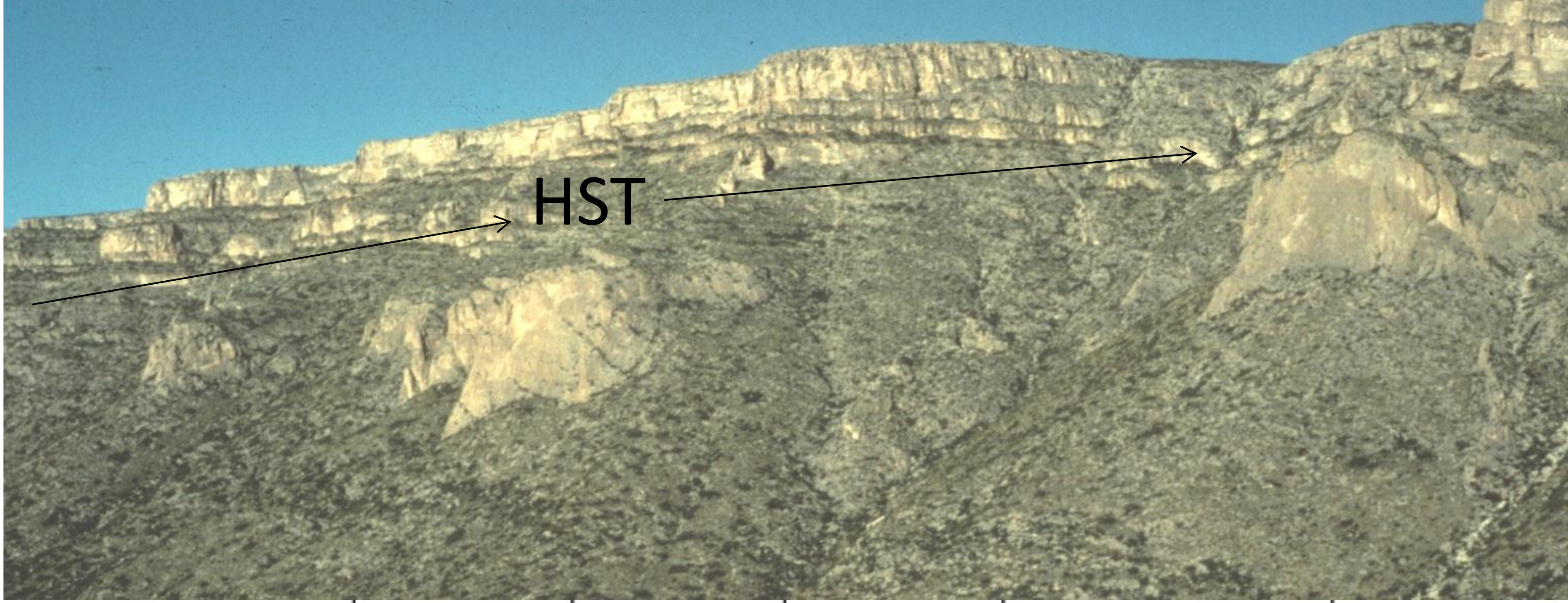


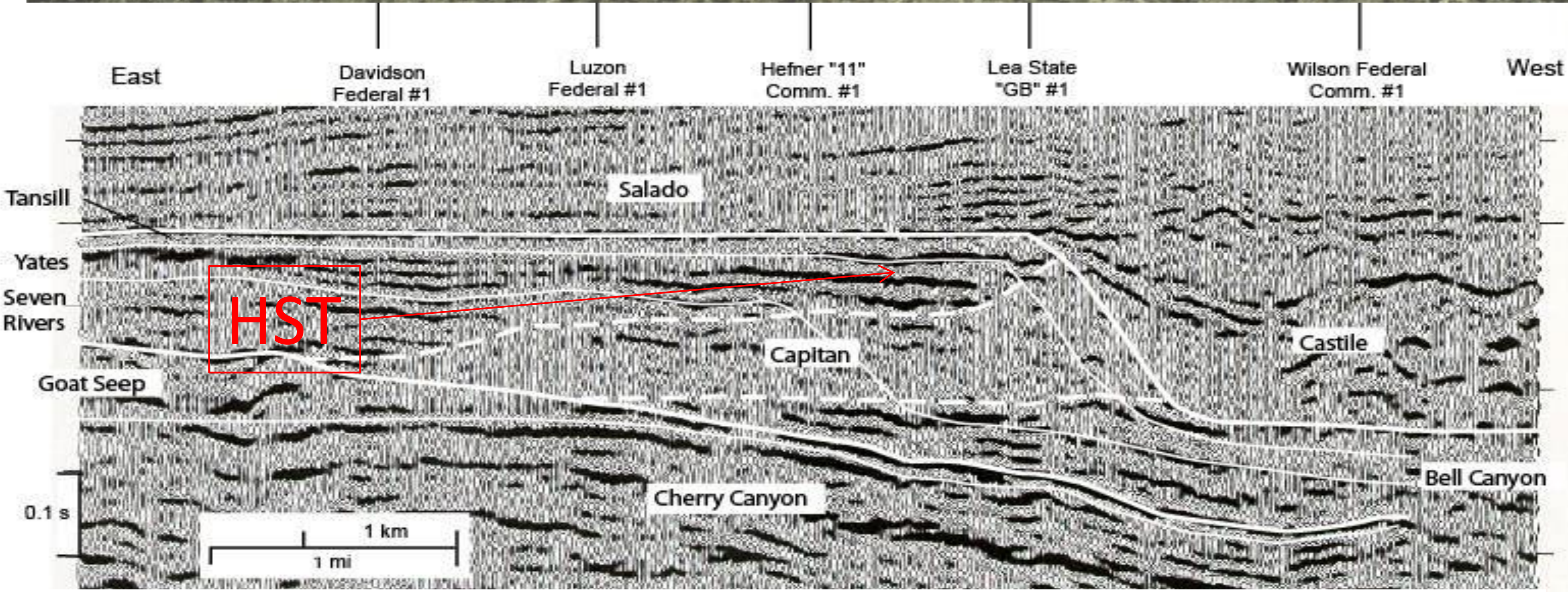
Restricted Lagoonal Dolomite

Dolomite Mudstone with evaporite molds

Domal stromatolites

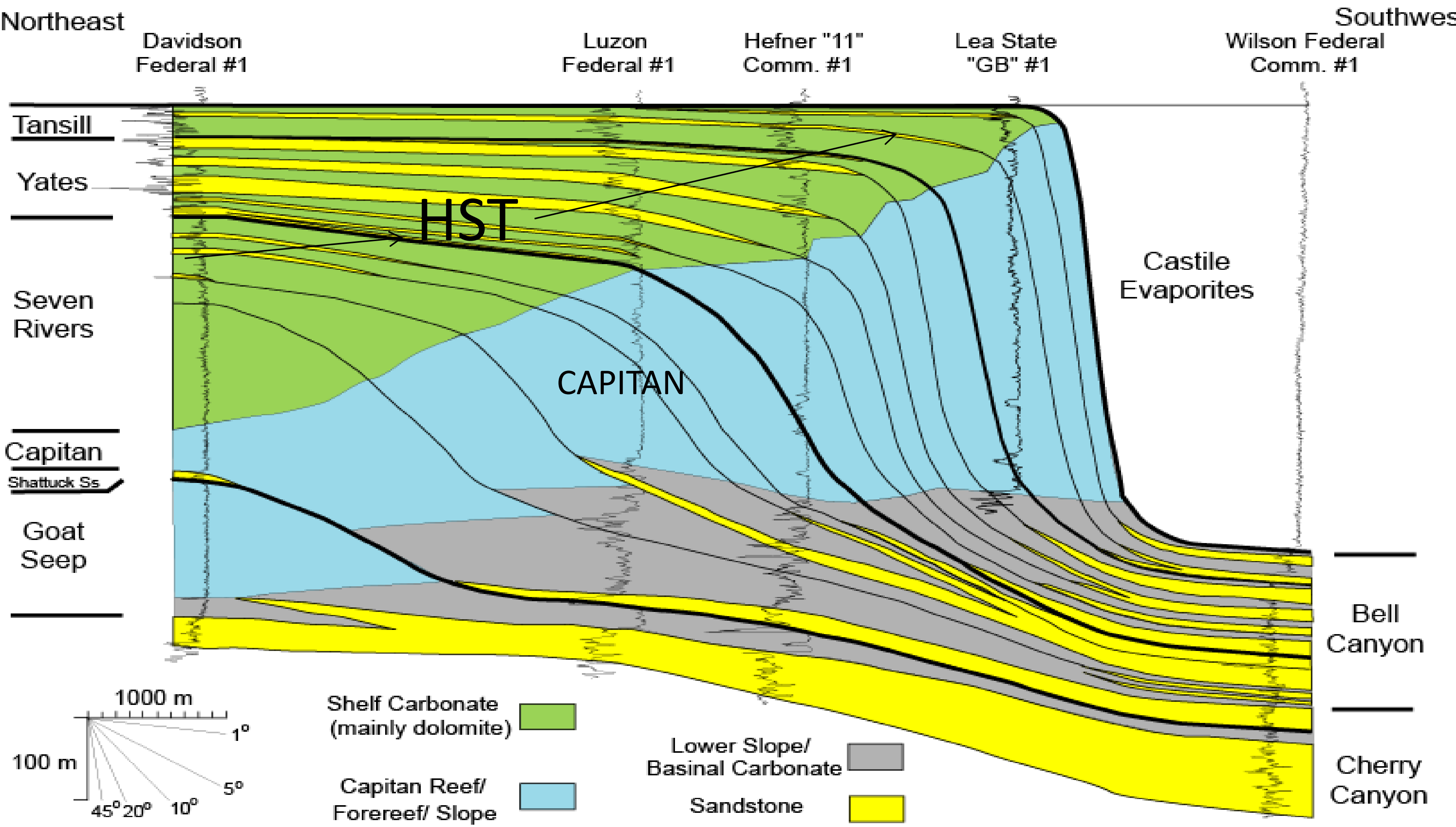






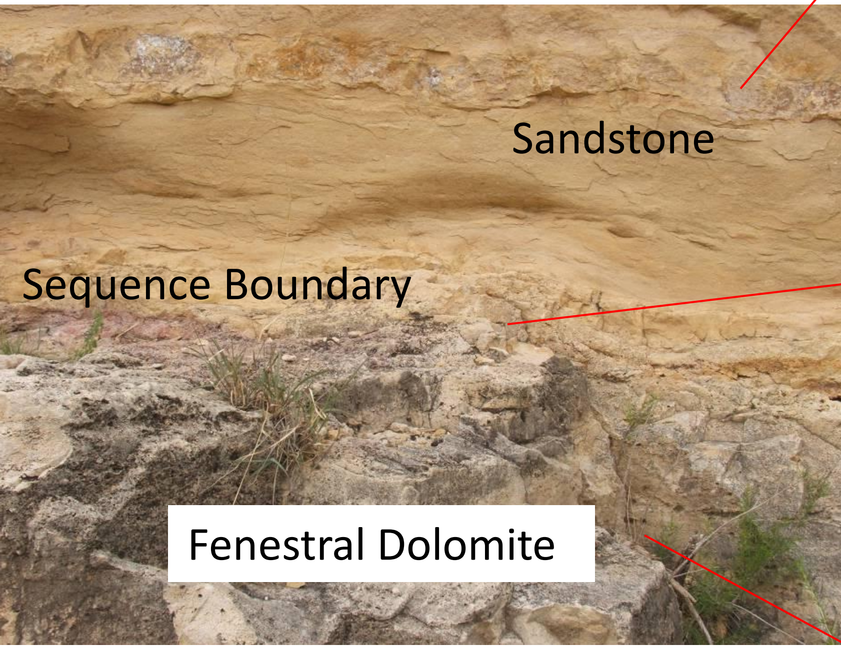
From Harris, P.M., and A.H. Saller, 1999, Subsurface expression of the Capitan depositional system and implications for hydrocarbon reservoirs, northeastern Delaware basin, *in* A.H. Saller, P.M. Harris, B. Kirkland, and S. Mazzullo, eds., *Geologic Framework of the Capitan Reef:* SEPM (Society for Sedimentary Geology) Special Publication No. 65, p. 37-49.

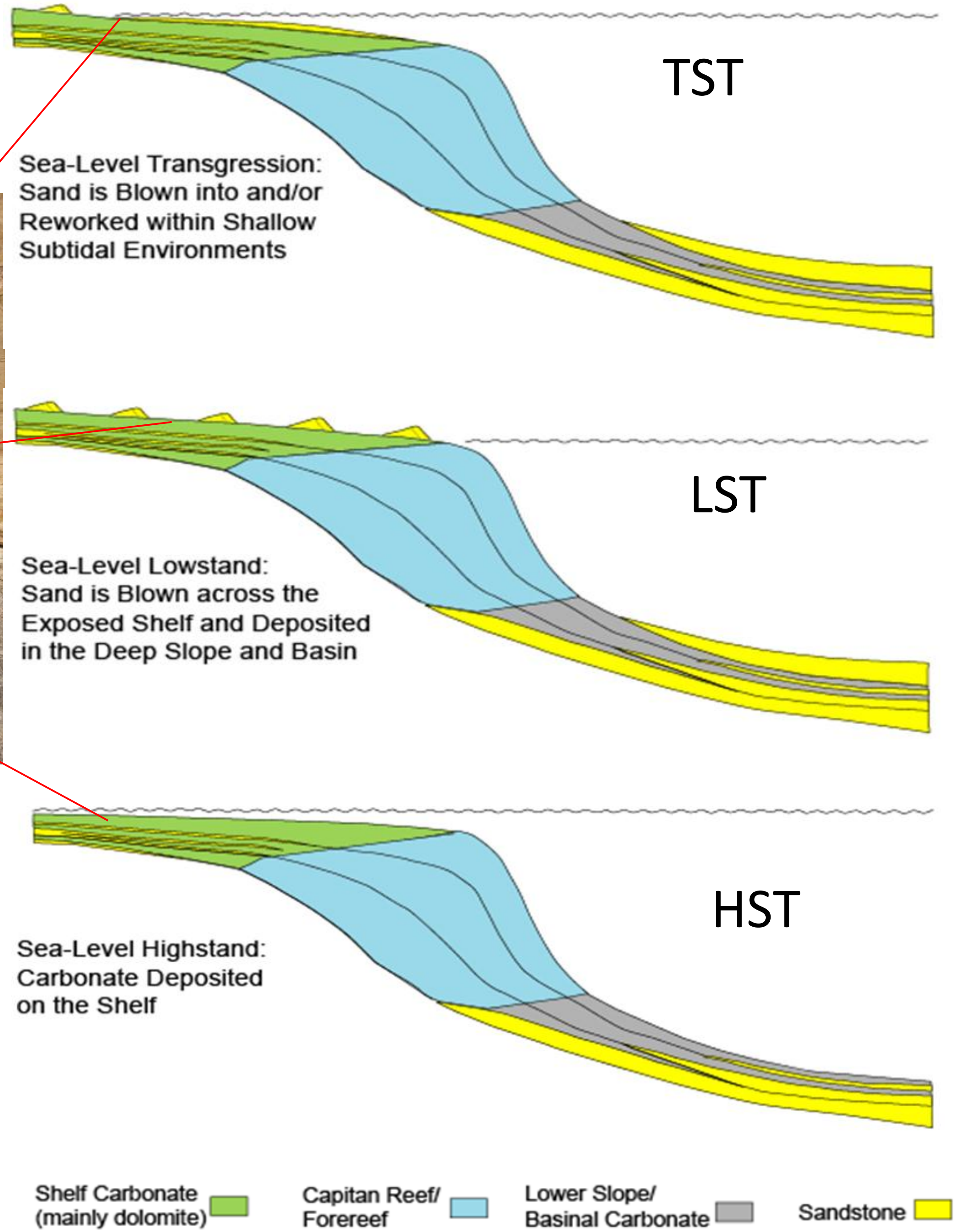
Well Log Cross Section NE Delaware Basin



From Harris, P.M., and A.H. Saller, 1999, Subsurface expression of the Capitan depositional system and implications for hydrocarbon reservoirs, northeastern Delaware basin, *in* A.H. Saller, P.M. Harris, B. Kirkland, and S. Mazzullo, eds., *Geologic Framework of the Capitan Reef:* SEPM (Society for Sedimentary Geology) Special Publication No. 65, p. 37-49.

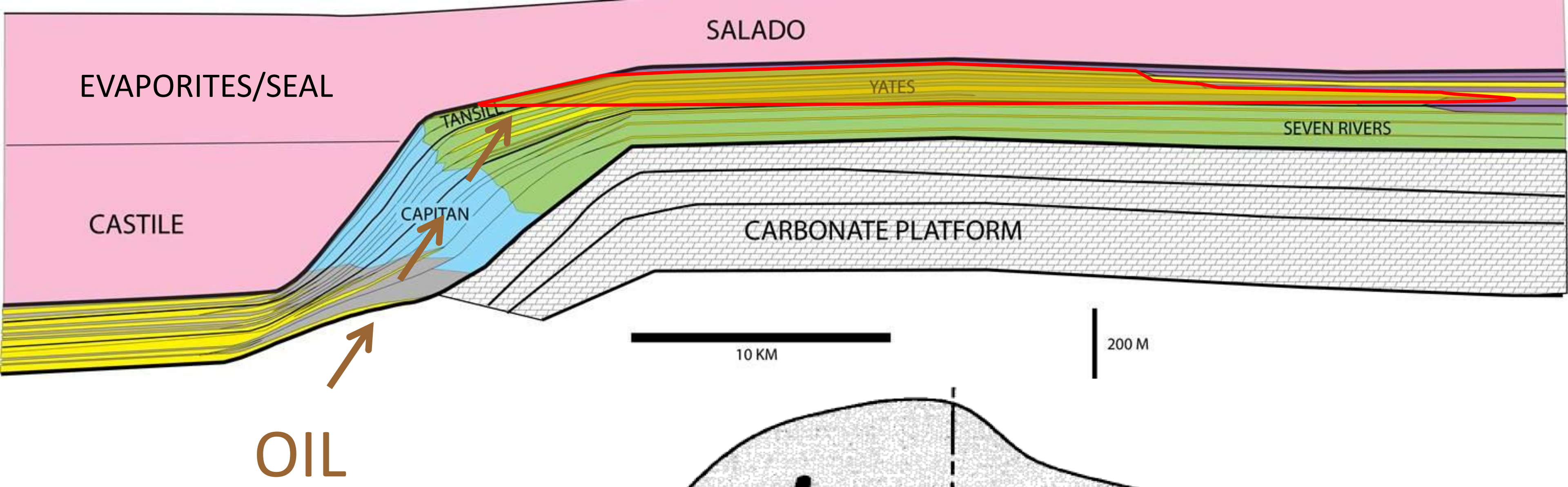
High Frequency Sequences



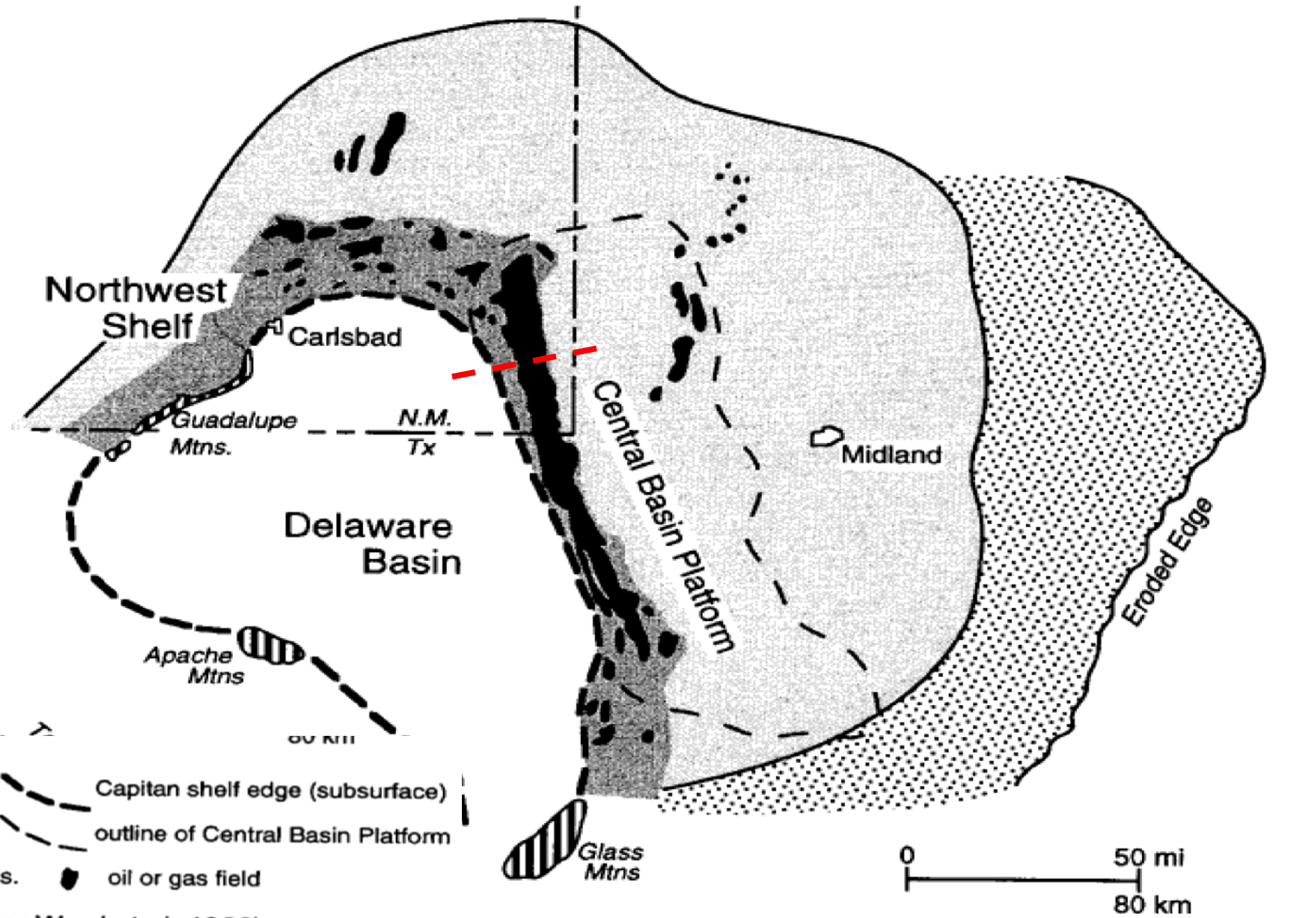


DEPOSITIONAL/SEQUENCE STRATIGRAPHIC MODEL FOR THE CAPITAN SYSTEM

From Harris, P.M., and A.H. Saller, 1999, Subsurface expression of the Capitan depositional system and implications for hydrocarbon reservoirs, northeastern Delaware basin, *in* A.H. Saller, P.M. Harris, B. Kirkland, and S. Mazzullo, eds., *Geologic Framework of the Capitan Reef:* SEPM (Society for Sedimentary Geology) Special Publication No. 65, p. 37-49.



Capitan age reservoirs are in backreef carbonates & sandstones. Although permeable, the Capitan is generally wet (an aquifer)

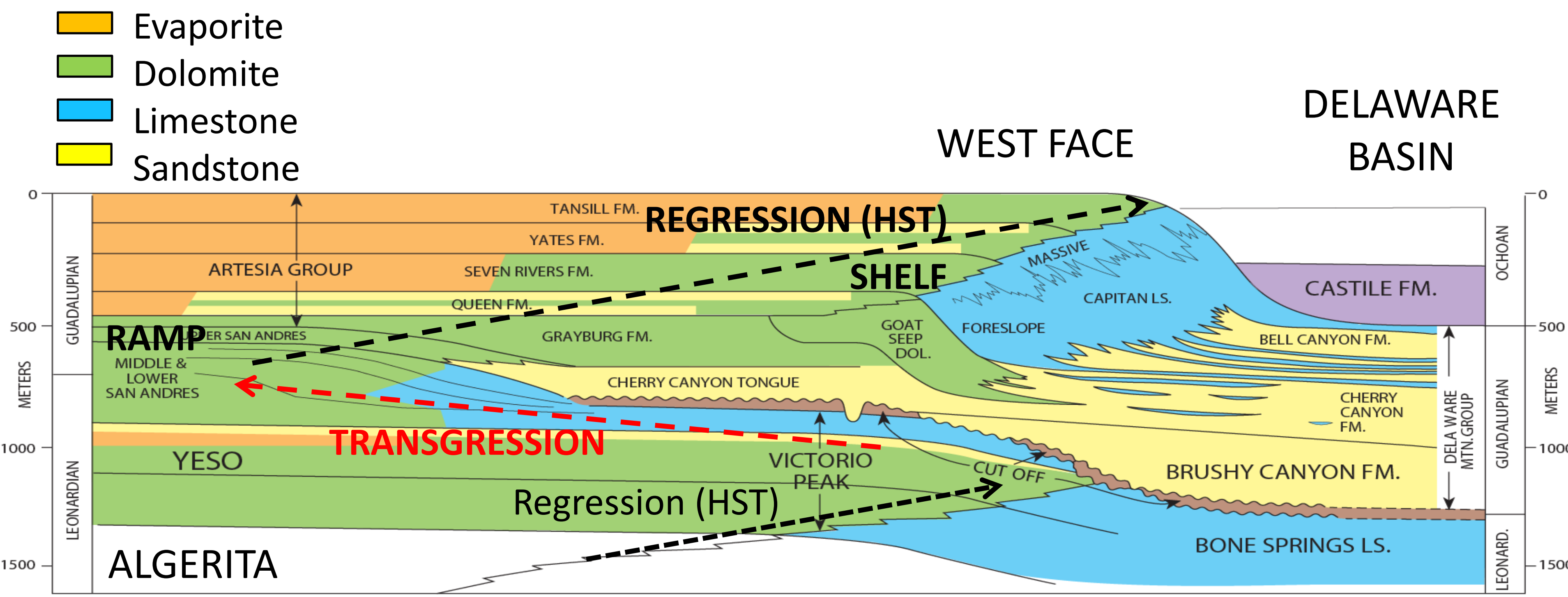


(after Ward et al. 1986)

GUADALUPE MOUNTAINS

Ramps & shelf systems

- Layered &/or prograding
- Commonly stratified
- Predictable lateral distribution of facies
- Differential compaction causes basinward dip
- Evaporitic lagoonal and sabkha facies may cause updip seals & stratigraphic traps



GUADALUPE MOUNTAINS

- Ramps & shelf systems
- Layered &/or prograding
- Commonly stratified
- Predictable lateral distribution of facies
- Differential compaction causes basinward dip
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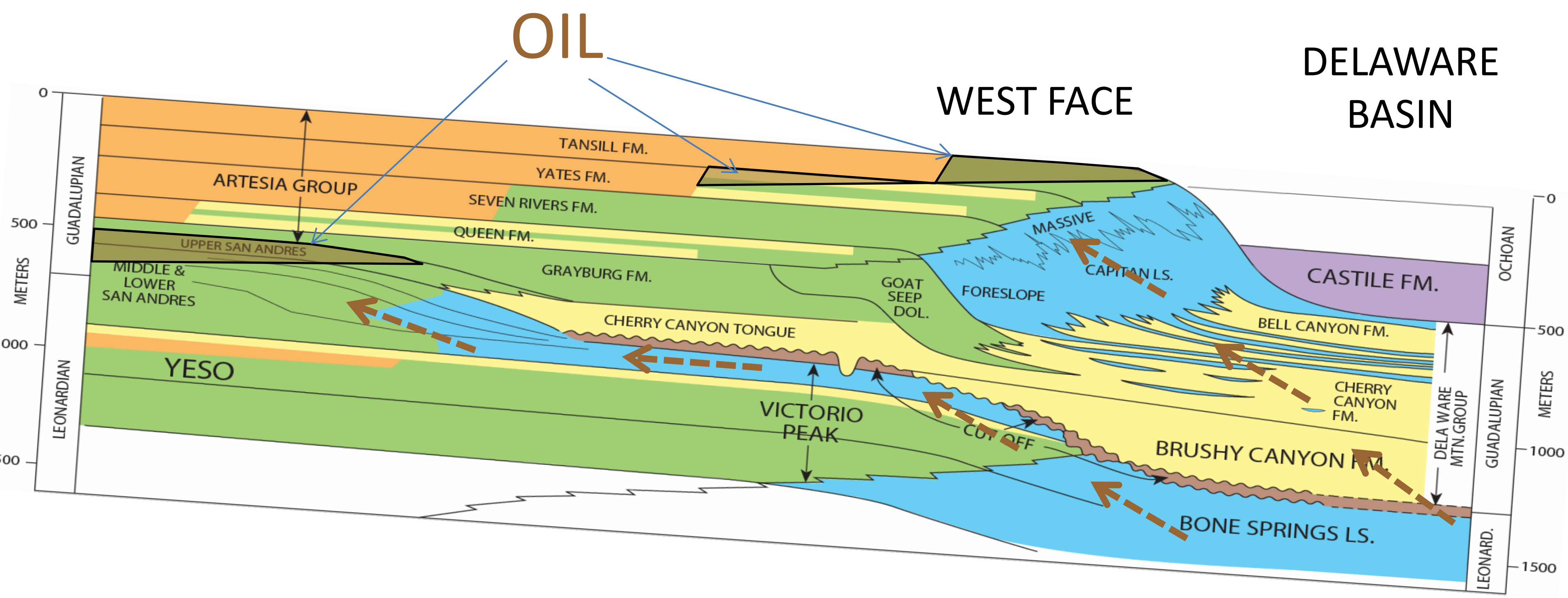
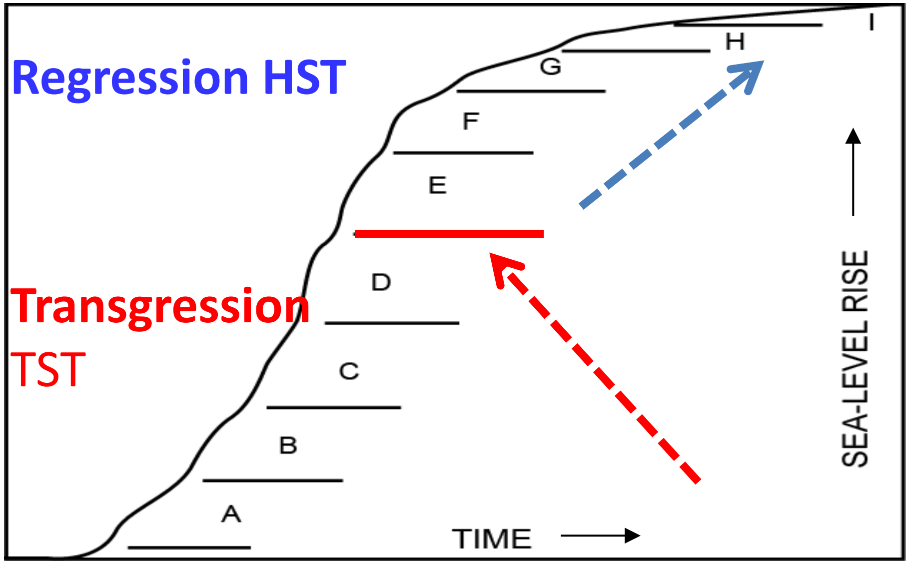
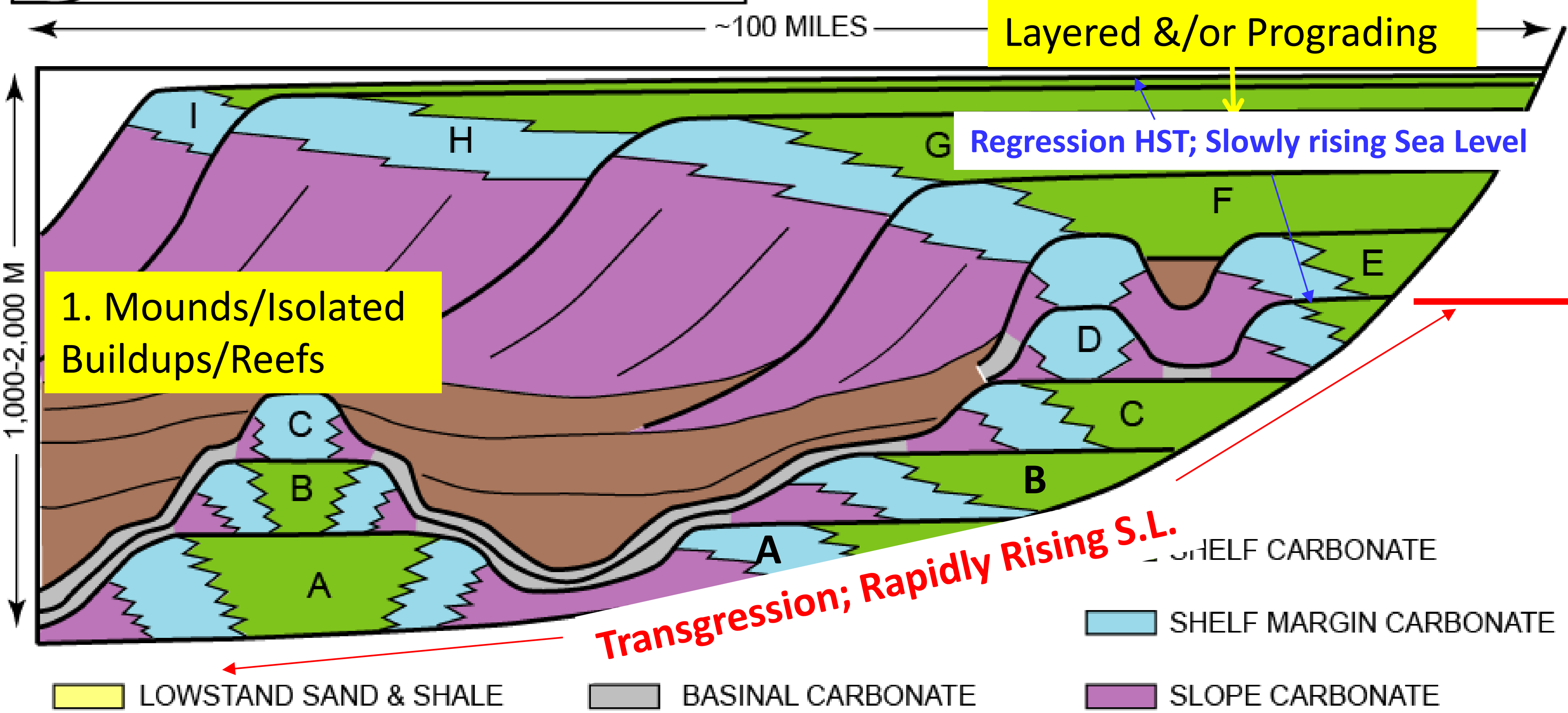


CARBONATE SEQUENCE STRATIGRAPHIC MODEL

(from Greenlee & Lehmann, 1993)





Thanks to

- AAPG, AAPG Foundation, Shell, Cobalt International Energy
- Many wonderful people with whom I have been in the SE New Mexico & W Texas mountains, especially
  - Tom Elliott, Lynn Soreghan, Tony Dickson, Rachel Wood, Ted Playton, Rich Armin, Al Crawford, George Moore

(Photo courtesy of Carlos Collantes)