# Evaluating Source to Sink Controls on the Permian Record of Deep-Water Sedimentation in the Delaware Basin, West Texas, USA*

**Michael H. Gardner[1], James M. Borer[2], Jesse J. Melick[1], Erik R. Kling[3], Noelia Baptista[4], and Brian W. Romans[5]**

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*Adapted from 2008-2009 AAPG Distinguished Lecture.

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## Abstract

Linking basin-restricted subaqueous flows to external controls governing their initiation is difficult. Even though the influence of these controls (tectonics, eustasy, and climate) is best resolved in the basinal strata, internal controls (i.e., gradient, substrate mobility, topography and flow run-out length) can have a more profound effect on deep-water sedimentation style and resulting patterns. Source-to-sink correlations relating tectonic, eustatic and climatic forcing to deep-water facies, lithology, sedimentary bodies, and stratigraphic cycles were analyzed from 488 sedimentological profiles and detailed (20-m thick) mapping of continuous shelf-to-basin outcrops (255-km$^2$ area) correlated (355 well logs and 3300 km of 2D seismic) across the 33,500-km$^2$ Delaware Basin.

The record of external forcing, resolved in basinal strata, is obscure outside of the basin, and is only confidently isolated from internal controls through complete basin analysis. Tectonic movements controlled the staggered onset of deep-water clastic sedimentation from at least seven shelf feeders encircling the Delaware basin. Basin-restricted siltstone intervals correlated throughout the basin help define a threefold hierarchy of stratigraphic cycles within the Brushy Canyon lowstand systems tract (LST) of one 3rd-order composite sequence (1-2 my.). Although along-strike variations in sediment supply change the thickness, lithology and architecture of these basinal cycles, stratigraphic changes in multiple criteria permit regional correlation that reflects basin-scale sea-level change. Repetitive, multi-scale and organized clustering of varve-like laminations, present in carbonate, evaporite and clastic strata, reflect precipitation-modulated climate.

Stratigraphic changes in multiple criteria correlated throughout the basin suggest an evolution in sedimentation attributed to changes in relative sea level, which can be correlated across the Delaware basin. Younger carbonate MTDs of the Cherry Canyon Formation incise the Brushy Canyon LST top and resemble those at its base; both of which record mass failure during highstand outbuilding of carbonate ramps.

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Siltstone, resembling the basal drape, also is found at the LST top. Condensed sedimentation, recorded by the basal siltstone drape, most likely correlates to continual sea-level fall separating highstand and lowstand deposition, whereas the younger siltstone records the end of gradual sea-level rise and represents a downlap surface for the overlying Cherry Canyon LST. This is indicated by strata in the upper 100m of the Brushy Canyon LST showing an upward increase in shelf-derived carbonate allochems (>50%), a decrease in sand percent (<40%), and an increase in the thickness and organic richness of siltstones (>300%). This latter attribute suggests a decreased frequency of sandy subaqueous flow deposition. Furthermore, stratigraphically equivalent strata derived from the same shelf feeder system yet source-distant, show a doubling in silty sandstone and feldspar content that records hydraulic fractionation of grain size and mineralogy within these subaqueous flows. In this case, longitudinal fractionation was enhanced by more complete flow transformation enabled by transport along smoothed depositional profiles during late LST. Both slope expansion and back-stepping of aggradational upper-slope channels record decreased system efficiency, while more elongate basin-floor thicks in this upper part reflect the decreased sediment volume. These depositional patterns record a gradual sea-level rise and suggest that its onset commences within the LST. Organic-rich sand-poor basinal facies bracketing this LST could have been deposited during either sea level rise or fall because they simply record sediment starvation; this is only indirectly related to an extrinsic control.

As the ultimate sediment sink with a fragmented shelf record, these external controls are best resolved from the basinal record, but internal changes in gradient, substrate mobility, topography, and run-out length, have a greater impact on subaqueous flow behavior, which requires complete characterization of the basin to differentiate from external signatures.

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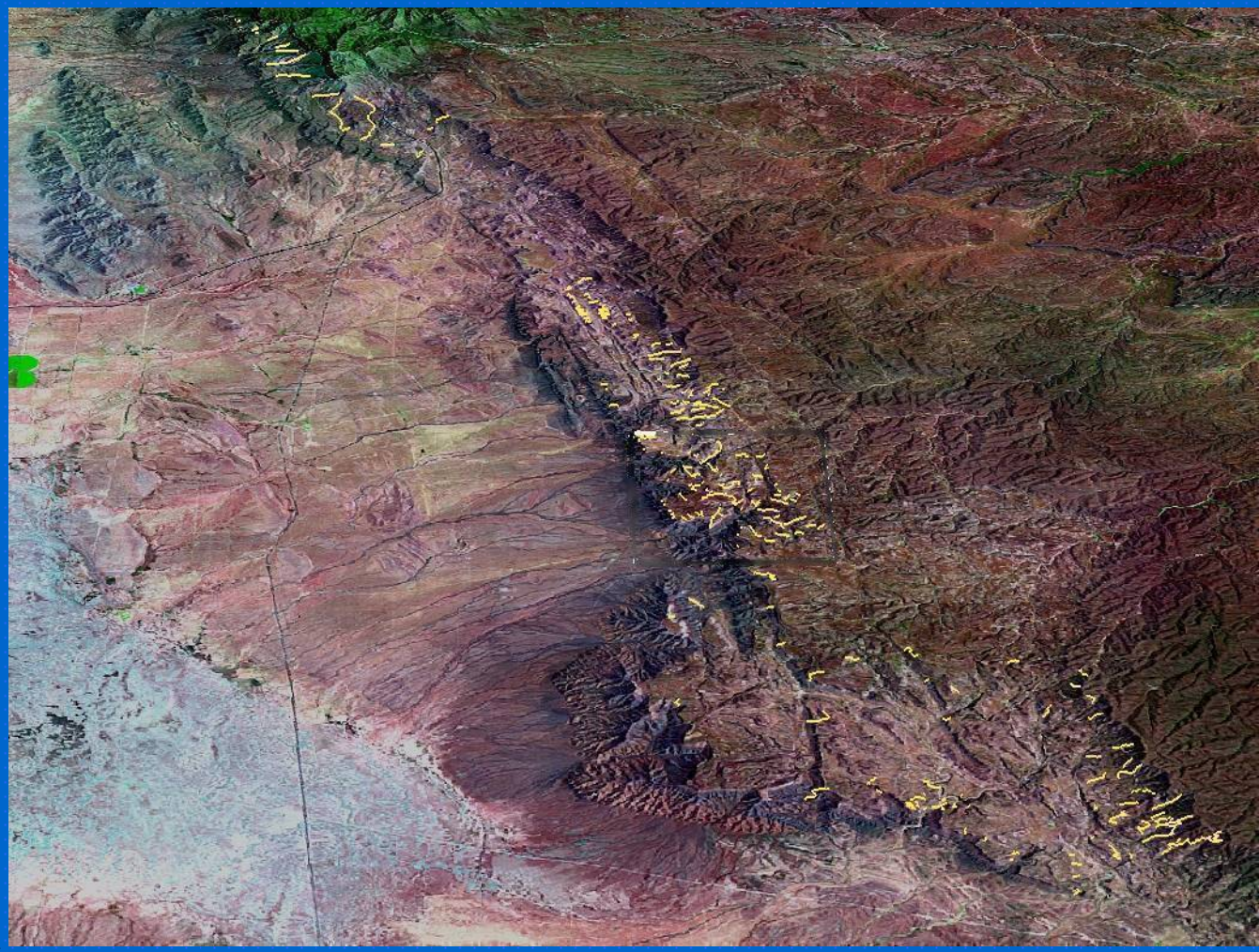
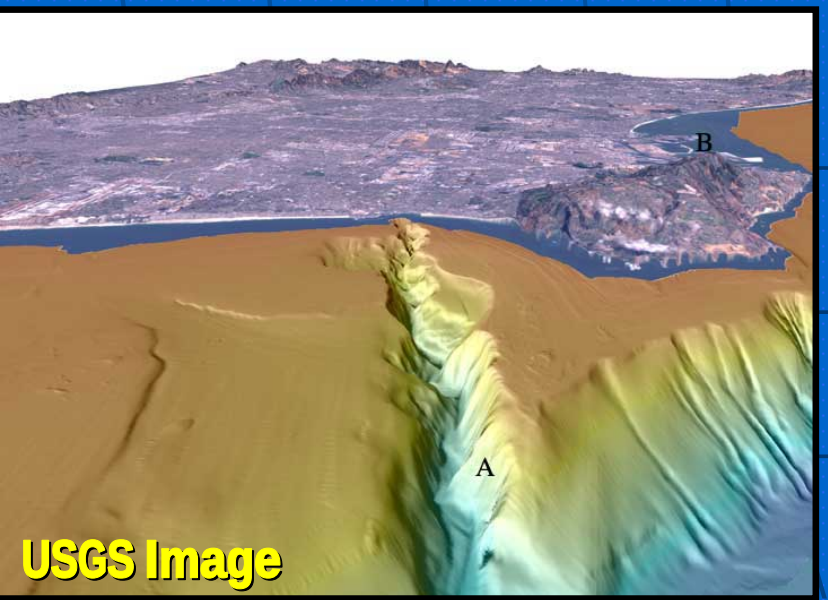


# The "Holy Grail" of Stratigraphy

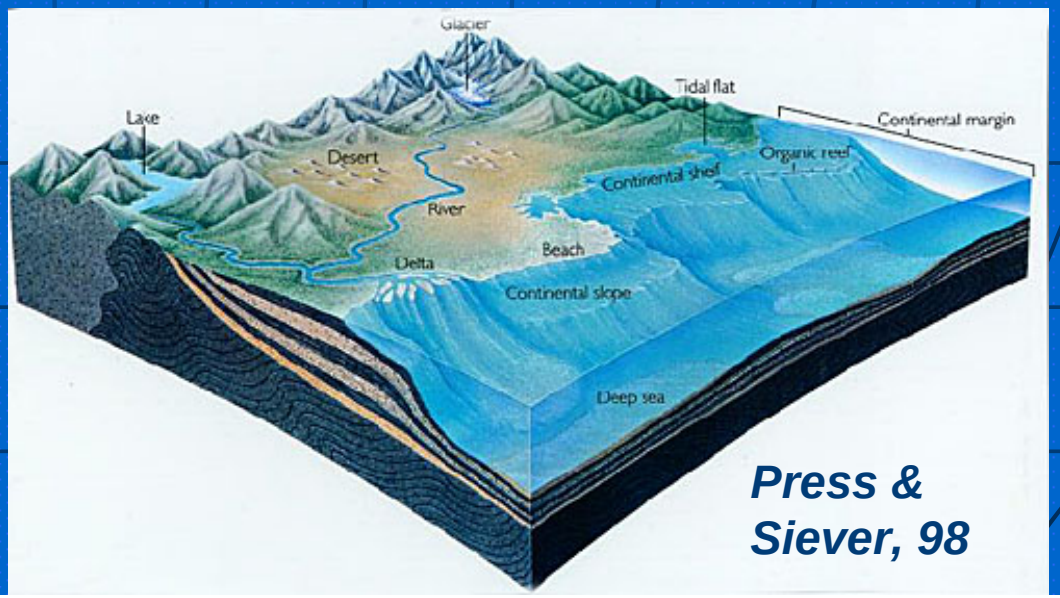
## Source

- Understanding the controls on patterns and trends in stratigraphy.
- The challenge is to link facies distributions, architectures and geometries to formative processes.
- This requires differentiating external from internal controls on stratigraphy.

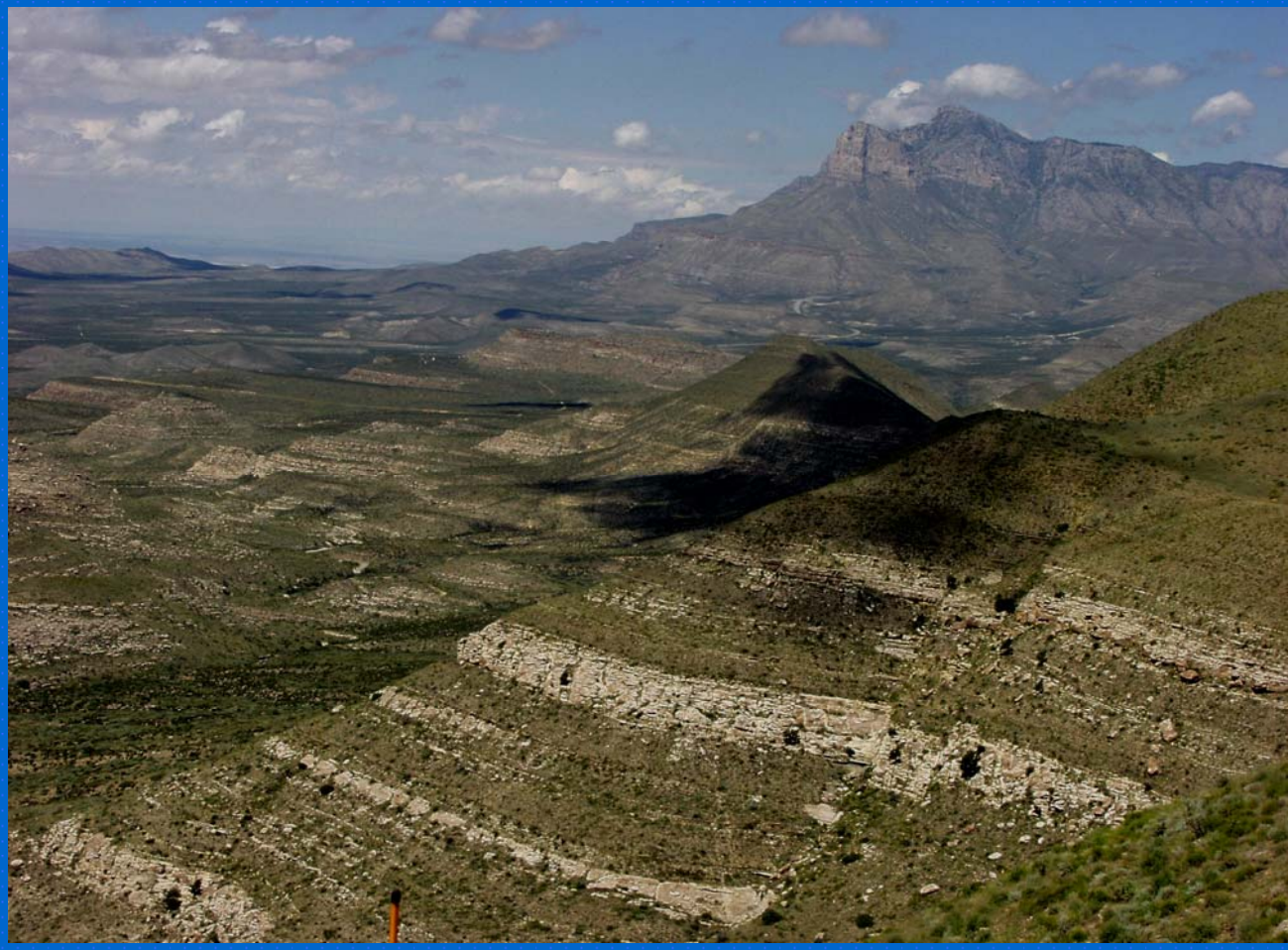
## Sink




## Result



# Themes



## External Controls

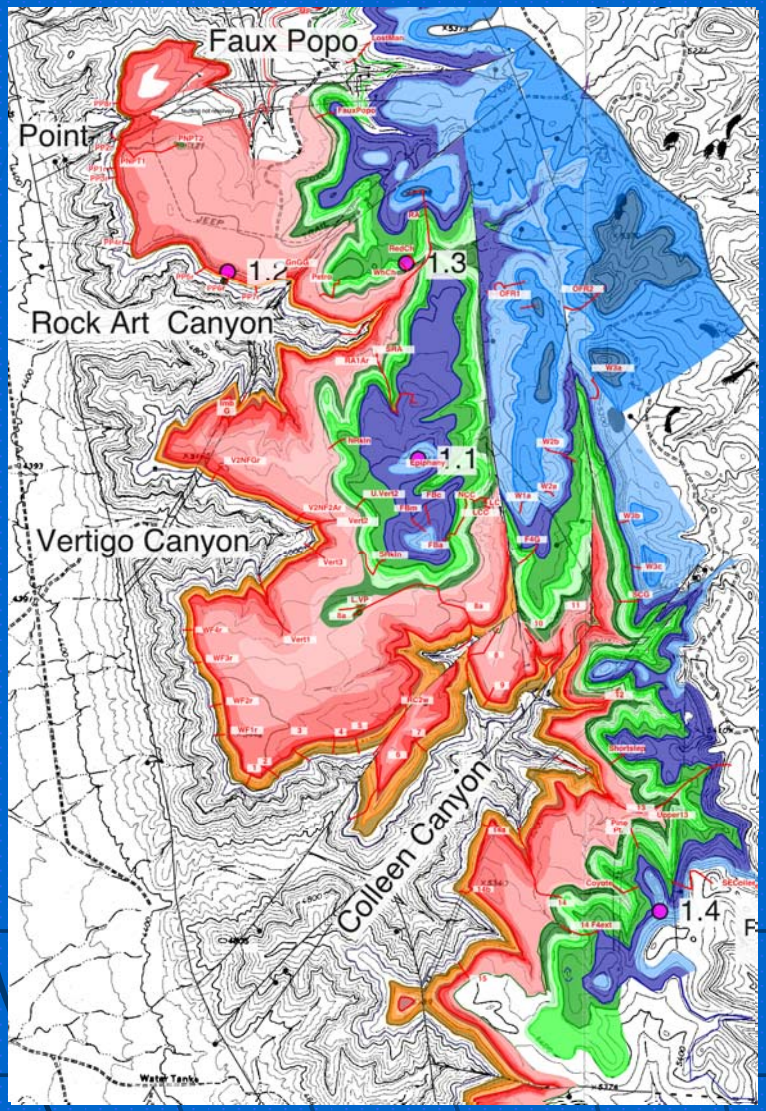
- Climate
- Tectonic
- Eustasy

## Internal Controls

- Topography
- Gradient
- Subaqueous Flow Evolution and Transformation

**Differentiating External From Internal Controls Requires Complete Basin Analysis**

# Complete Analysis of Deep-Marine System Required to Differentiate External from Internal Controls




- 9 MS and 4 PhD geological, petroleum engineering & geophysical studies
- 507 sedimentological logs most w/ scintellometer profiles tied to 300 photo-panels in 255 km² outcrop belt w/ GIS-based mapping of 33, 20-30 m intervals & 600 submarine channels.
- Stratigraphy & channel mapping across multiple fault blocks generated 3D models for 55% of outcrop.
- Outcrop to subsurface facies calibration by Johnson (1998) using 3D seismic & core from Cabin Lake Field in northern basin.
- Outcrop to subsurface cycle calibration by Romans (2003) used 65 wells nearby or within outcrop & 3 behind-outcrop cores to map 9 cycles.
- 301 wells w/ modern log suites tied to 1,675 km of 2D seismic by Baptista (2004) to map cycles in 33,500 km² basin.

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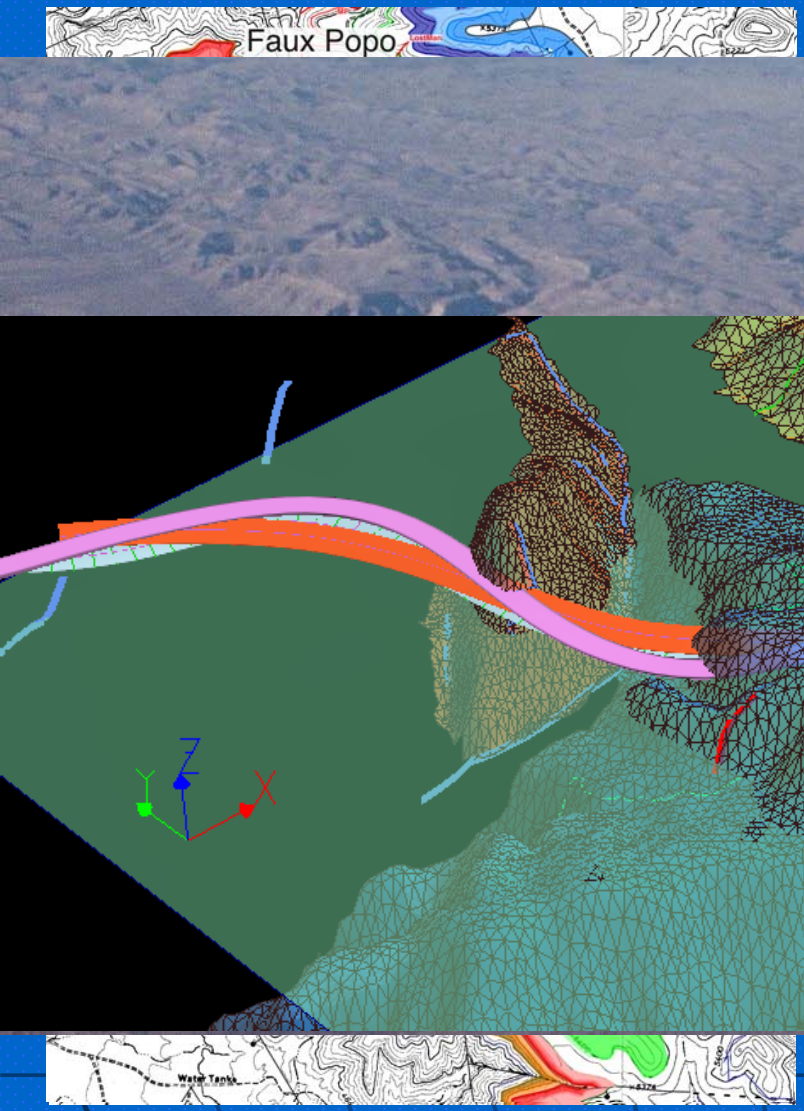


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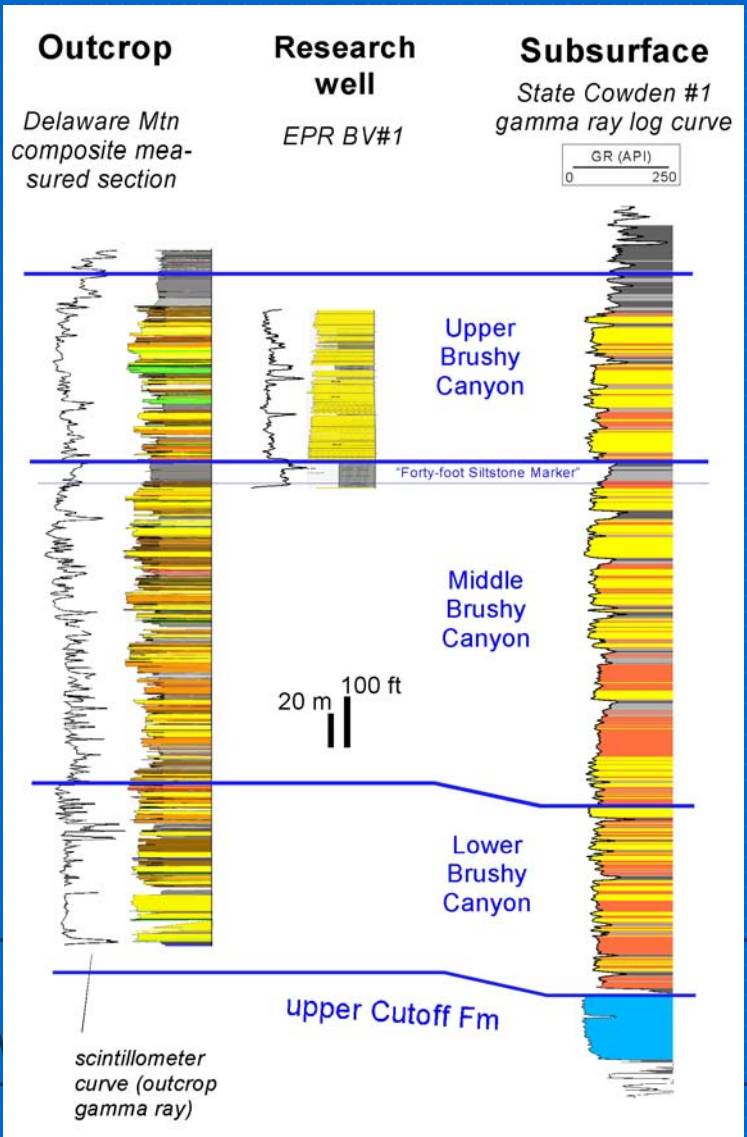


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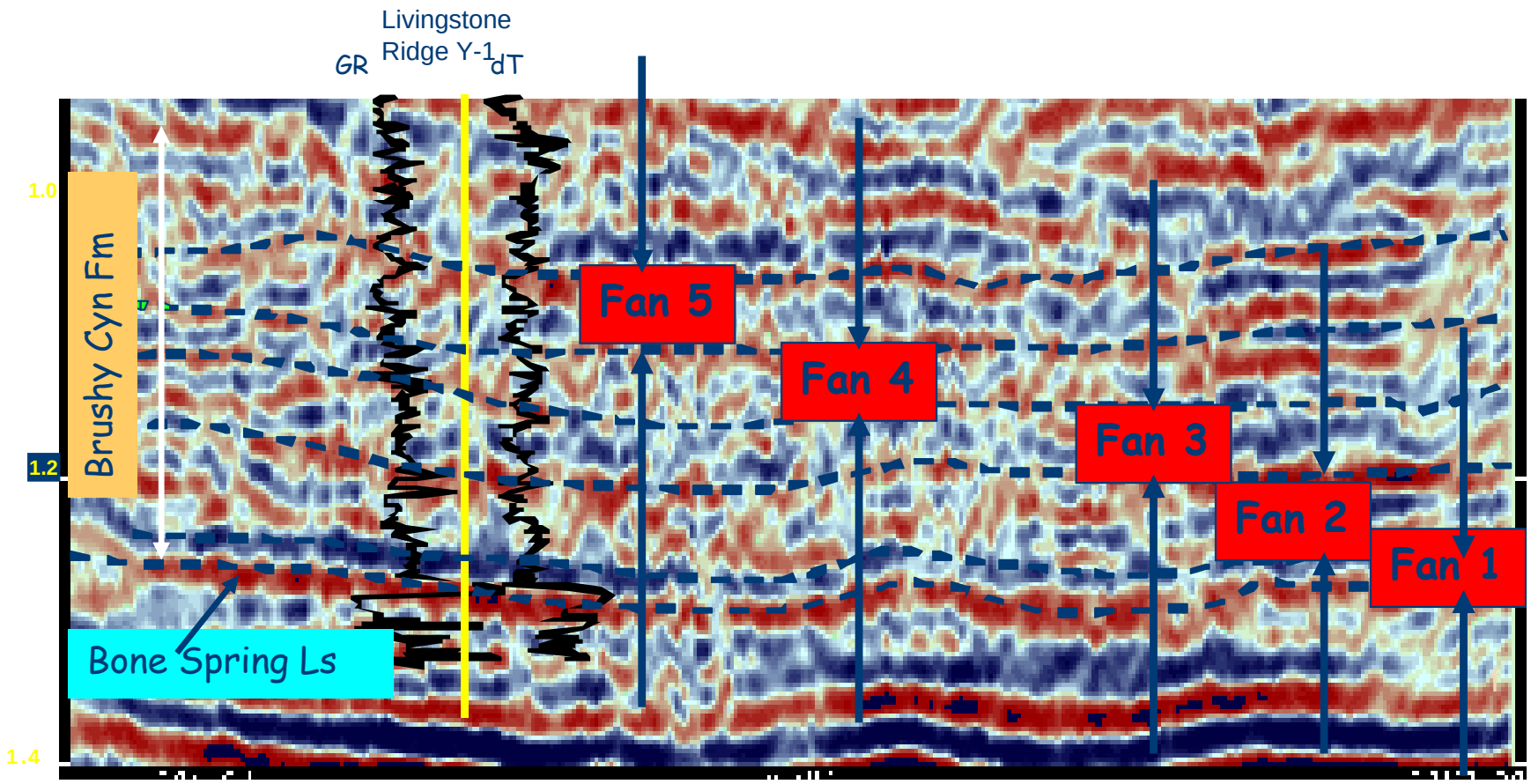
View Note for Slide 8 (Page 10)

# Complete Analysis of Deep-Marine System Required to Differentiate External from Internal Controls

## Dip-View RMS Amplitude Display of Brushy Canyon Fm at Cabin Lake Field, 50 miles east of outcrop



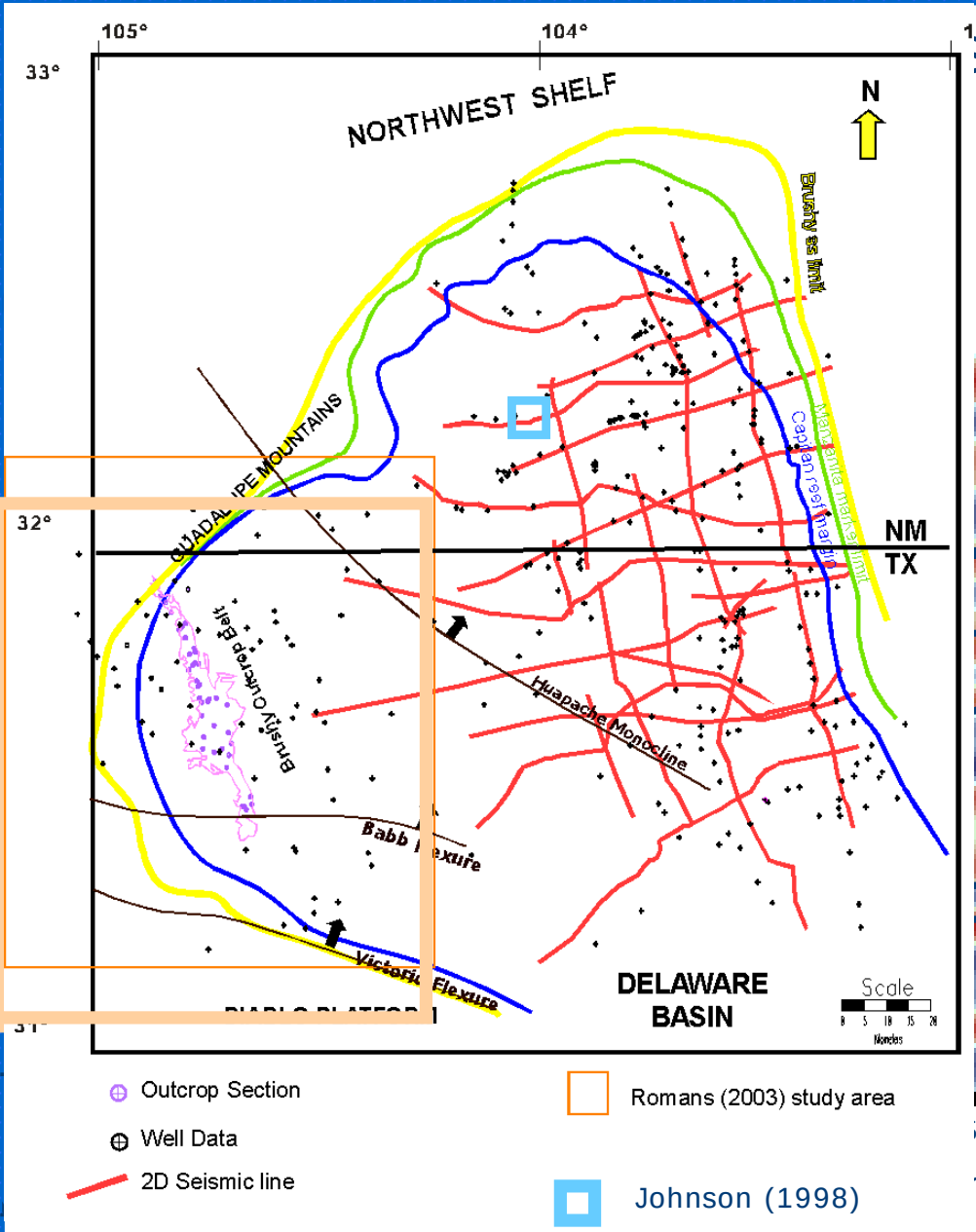

From Kyle Johnson, 1998 (MS Thesis, CSM, SBC)

3-D survey acquired by Phillips Petroleum

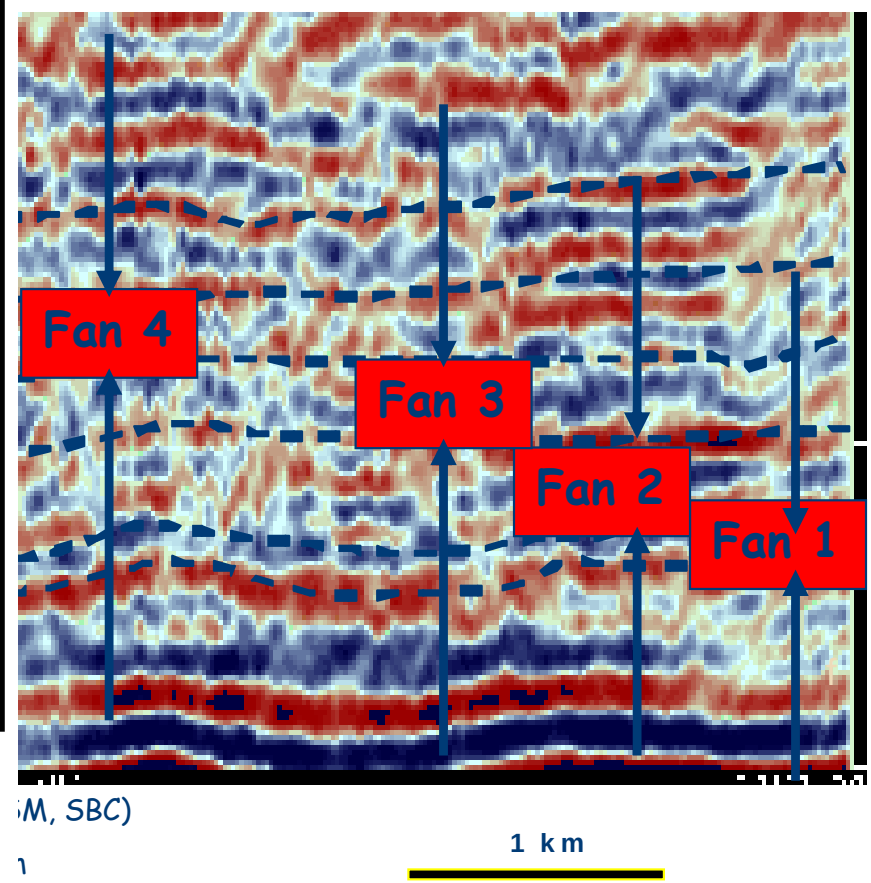
1 km

basin.

# Complete Analysis of Deep-Marine System Required to Differentiate External from Internal Controls




splay of Brushy Canyon Fm at
miles east of outcrop

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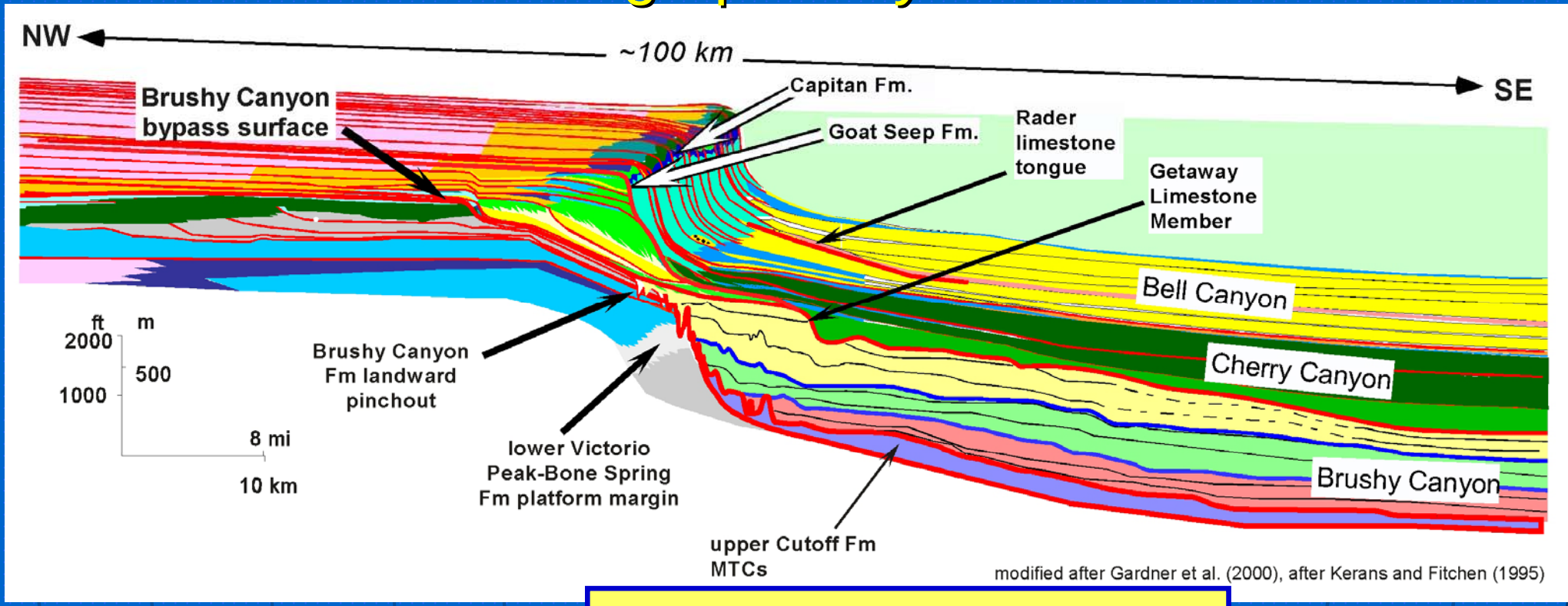
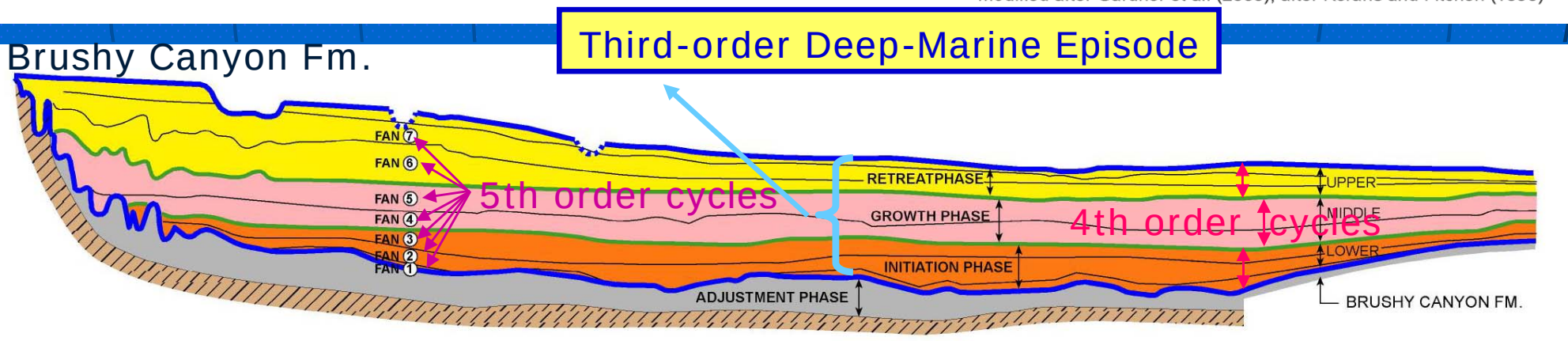
# Stratigraphic Framework: Second- and Third-Order Stratigraphic Cycles



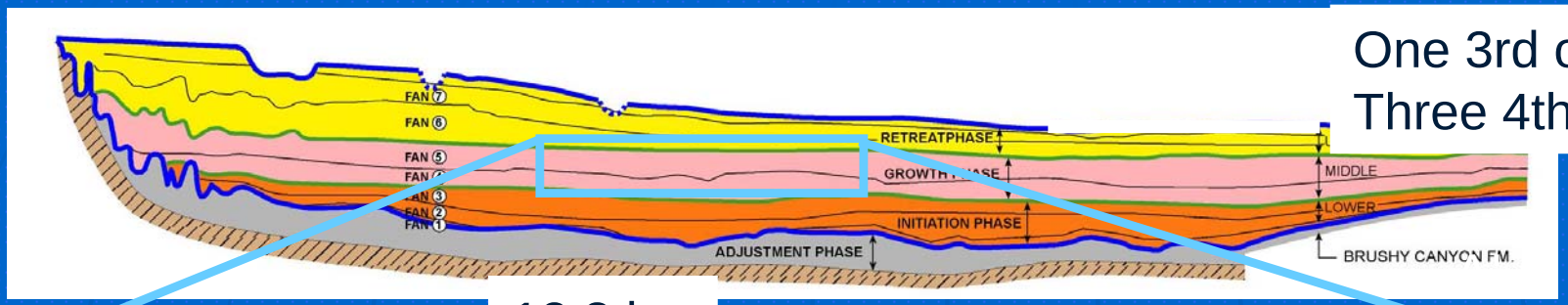




100m

10km

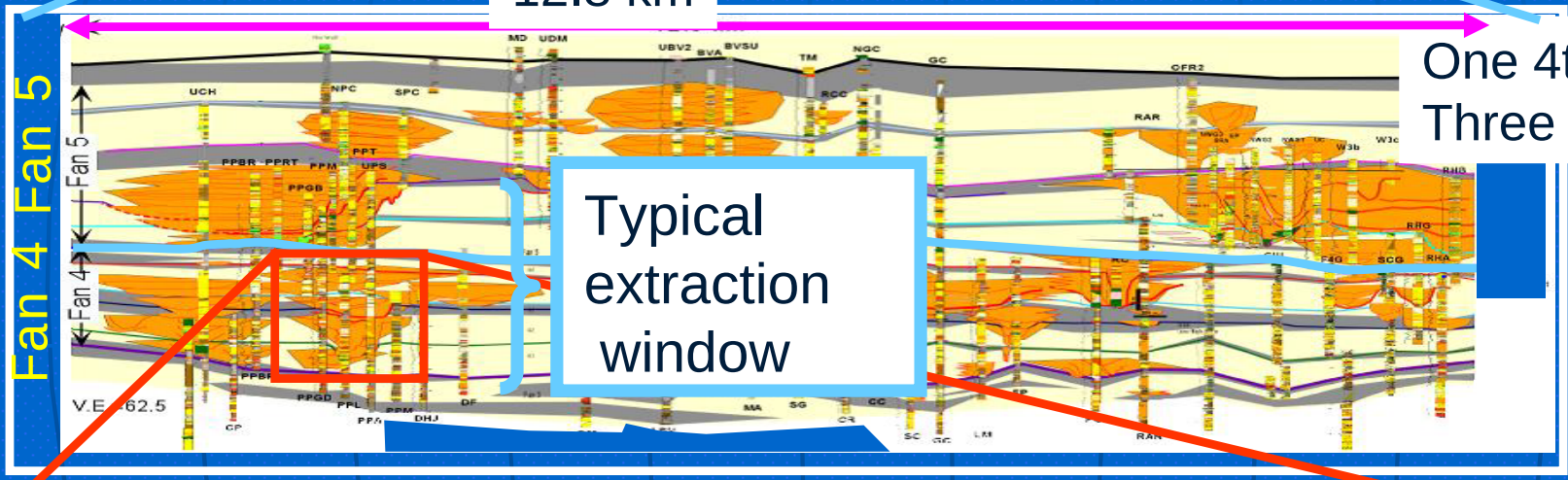
Left half portion: Oblique Dip Section
Right half portion: Oblique Strike Section

# Stratigraphic Framework: Hierarchy of Stratigraphic Cycles




One 3rd order cycle
Three 4th order cycles

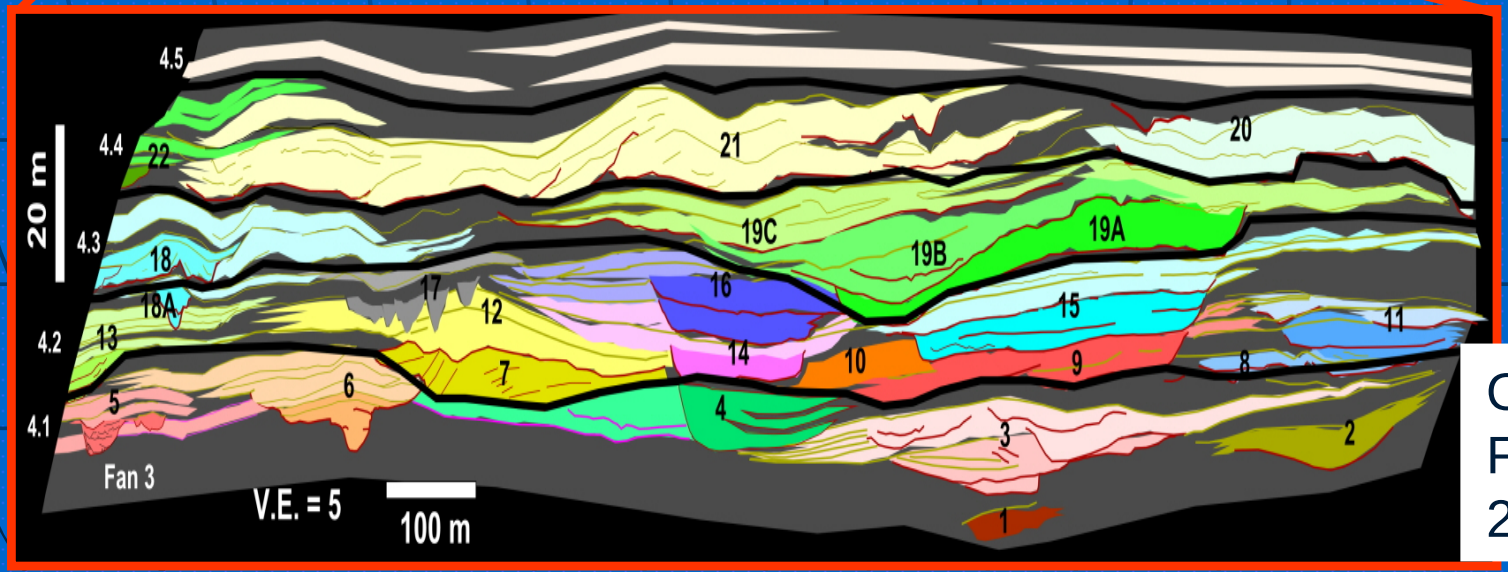
12.8 km




One 4th order cycle
Three 5th order cycles

Typical extraction window

Middle Brushy Canyon, fourth-order cycle shown




One 5th order cycle
Four 6th order cyles
22 channel bodies

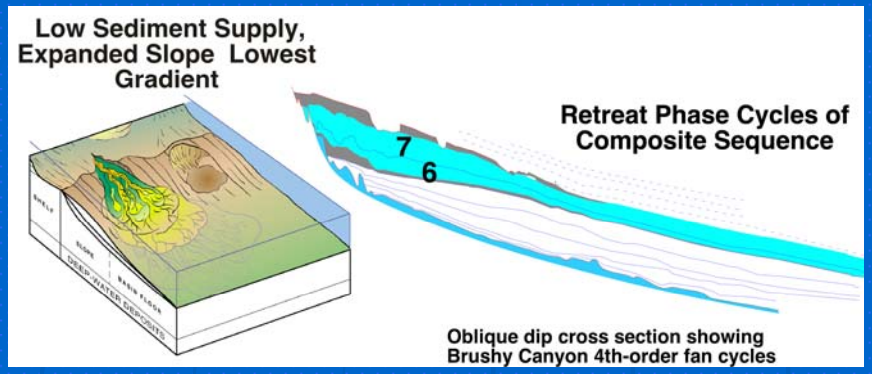
# Phases of Submarine Fan Evolution

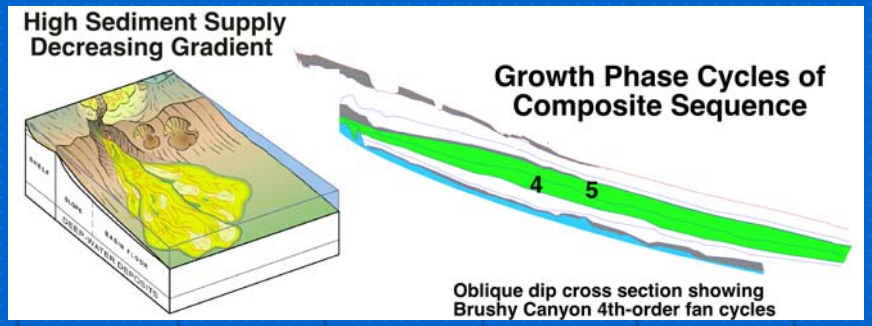
Retreat Phase (R)

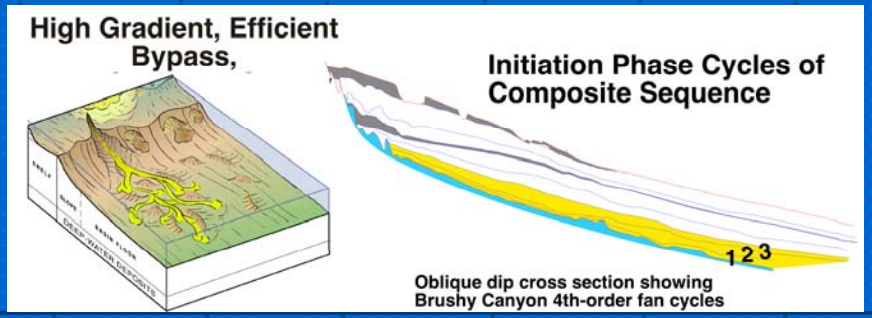
Growth Phase (G)

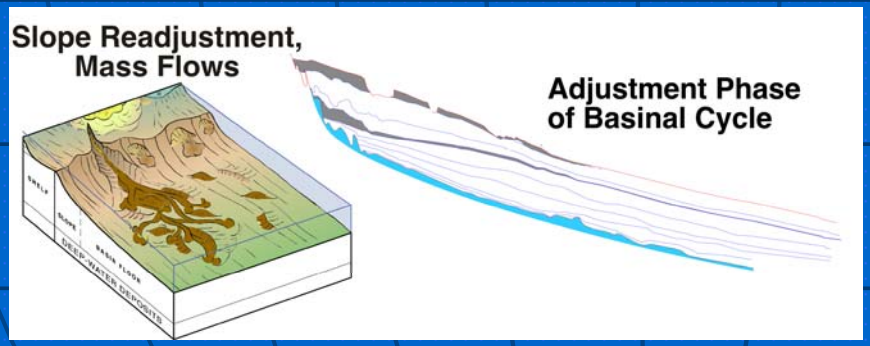
Initiation Phase (I)

Adjustment Phase (A)

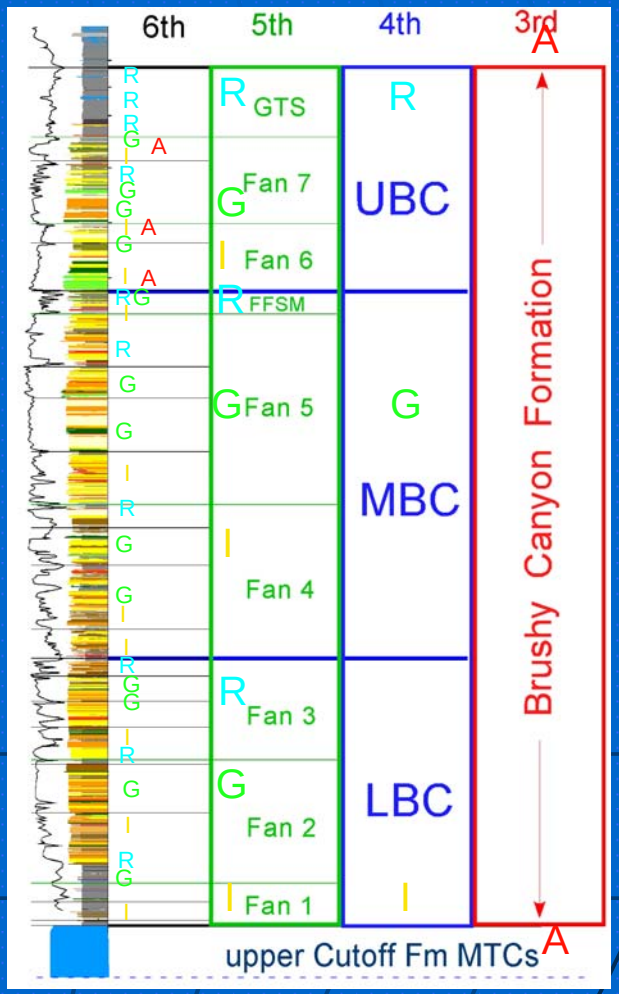



## Deep-water Depocenters & Channel Types Define IGR Phases of Submarine Fan Sedimentation




Fourfold Hierarchy of Stratigraphic Cycles for Brushy Canyon Third-Order Depositional Episode

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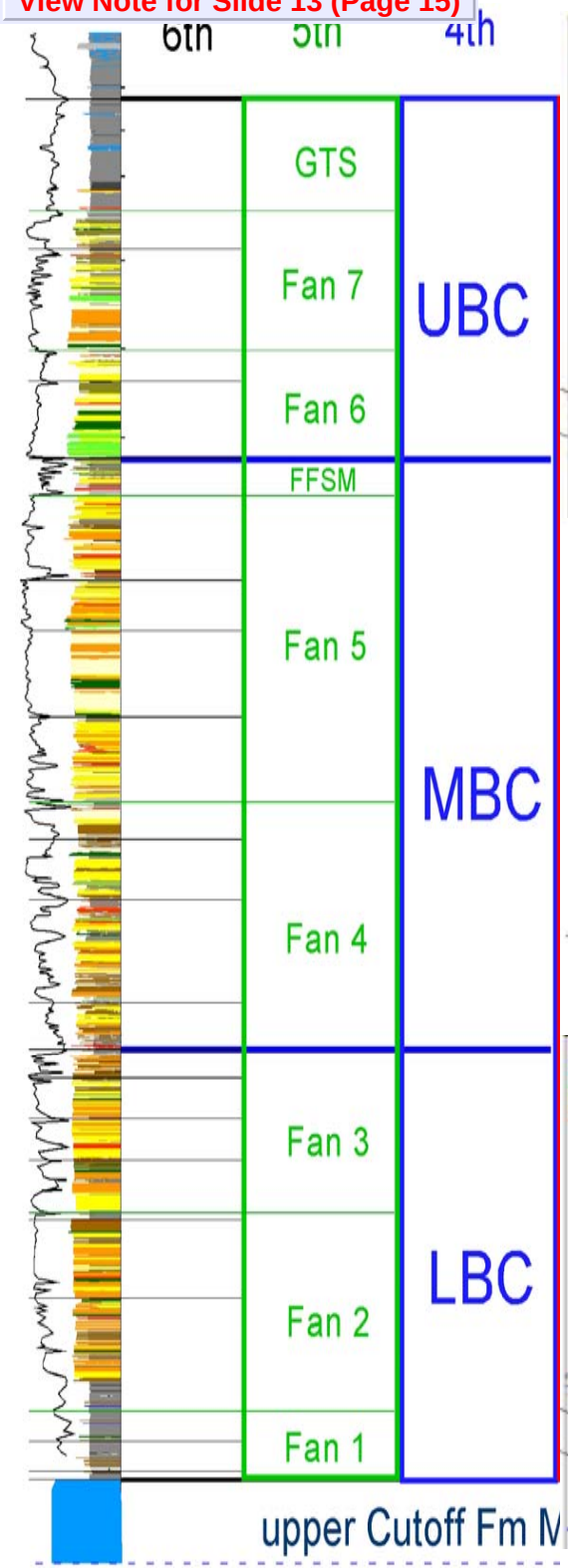
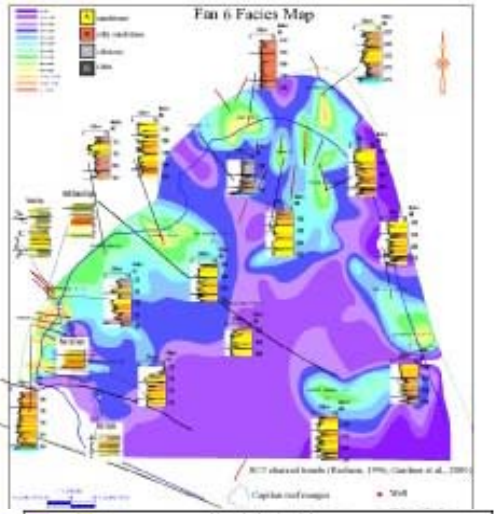
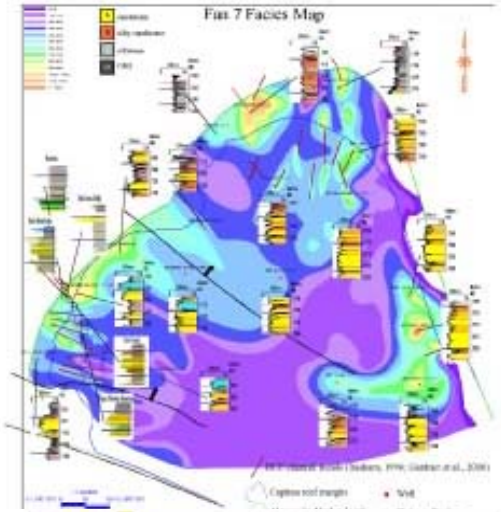
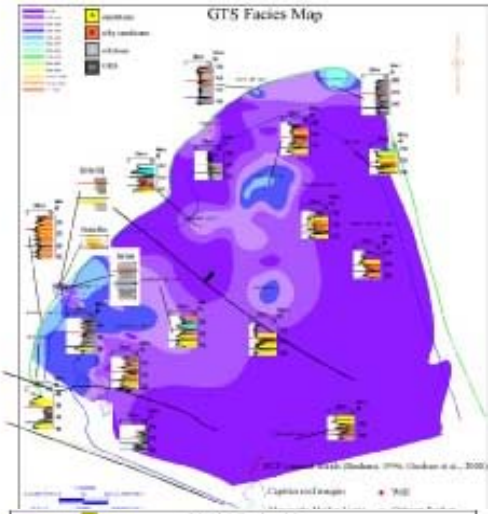
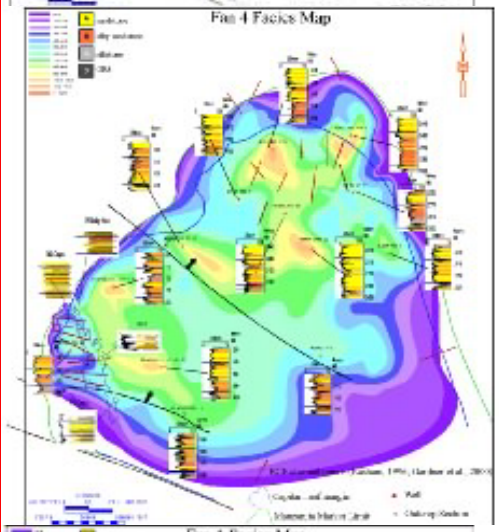
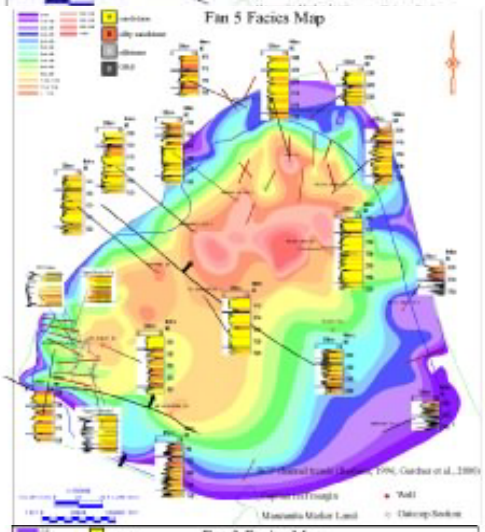


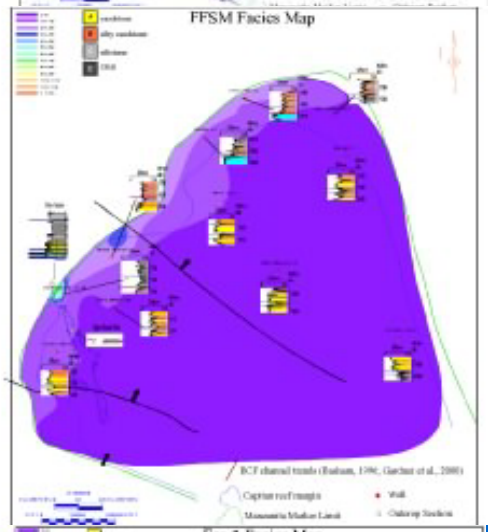



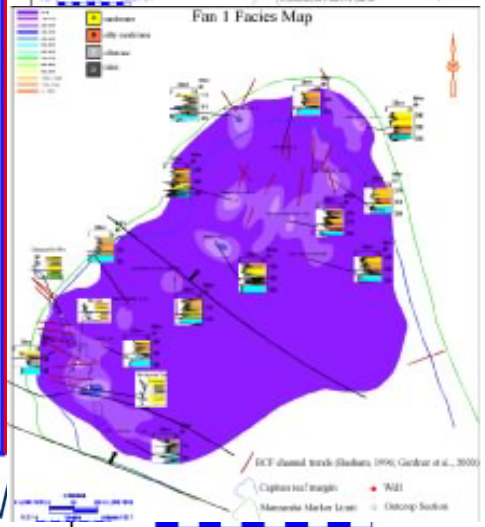



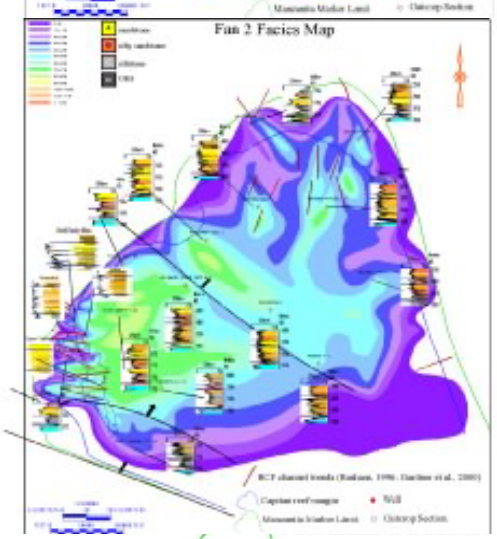



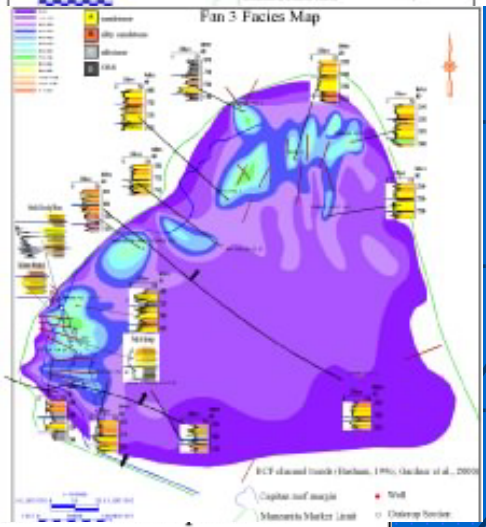



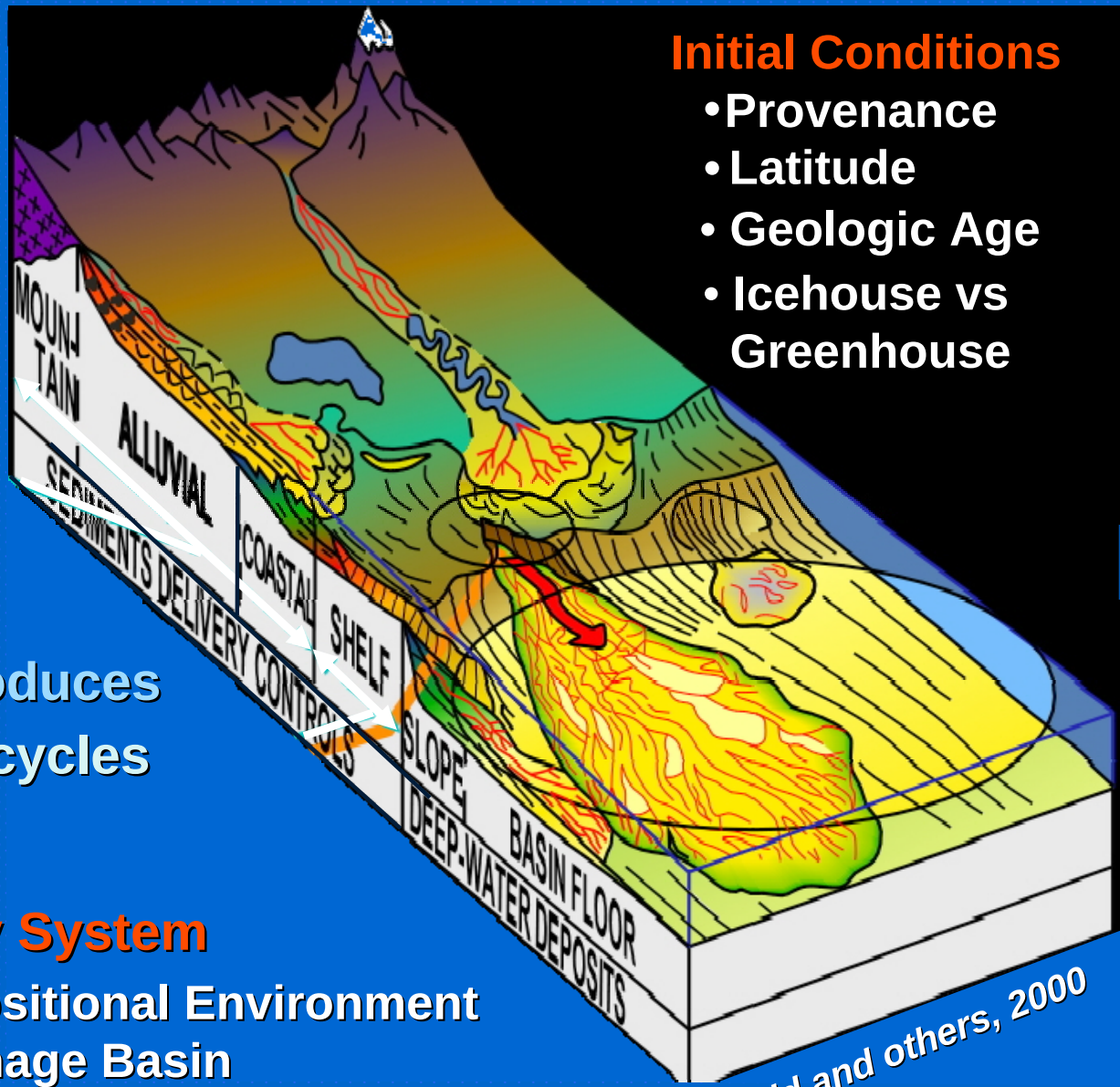



# External Controls

- **CLIMATE** modulates
  - •fine sediment fraction
  - •organic matter
- **TECTONICS** determine
  - •coarse sediment fraction
  - •aspect ratio of basin fill
- **SEA LEVEL CHANGE** produces
  - •hierarchy of stratigraphic cycles




**Initial Conditions**

- •Provenance
- • Latitude
- • Geologic Age
- • Icehouse vs Greenhouse

**Delivery System**

- • Depositional Environment
- • Drainage Basin
- • Accommodation
- • Hypsometry (Area-Elevation)
- • Continental Assemblage

*Garfield and others, 2000*

MONTANA STATE UNIVERSITY
Mountains & Minds

AAPG FOUNDATION

SBC Slope & Basin Consortium

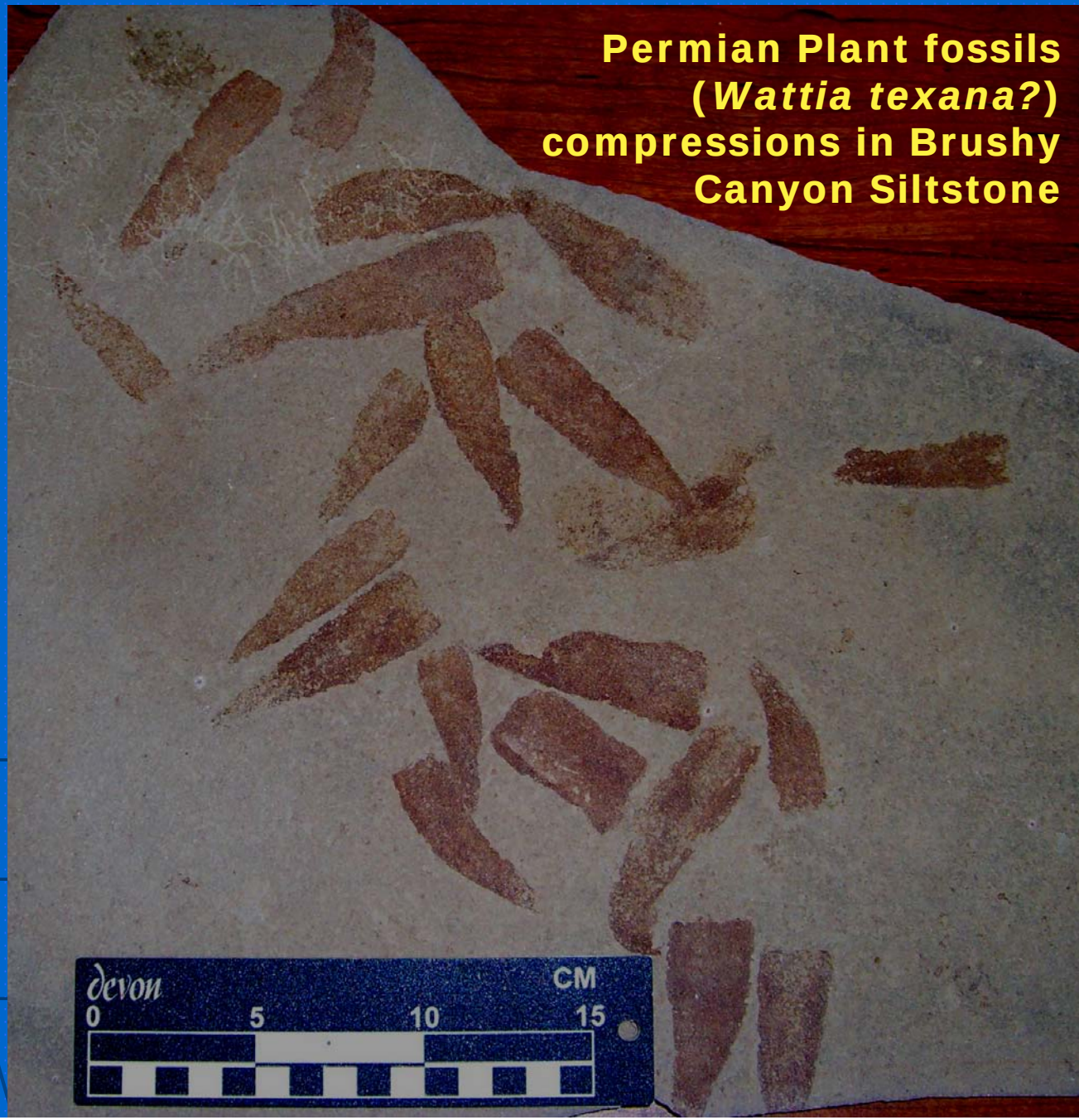
# Fine-grained Facies & Lithology Record Climatic Modulation of Carbon and Hydrologic Cycles

**Organic Matter in Basin:**

- amorphous marine and biogenic silica
- minor terrestrial plants

**Eolian dust and surface water production generates siltstone source rocks that reflect extreme condensation**

**Elevated organic matter along the basin margins reflects sand bypass across high-gradient slope**




**Permian Plant fossils (*Wattia texana?*) compressions in Brushy Canyon Siltstone**

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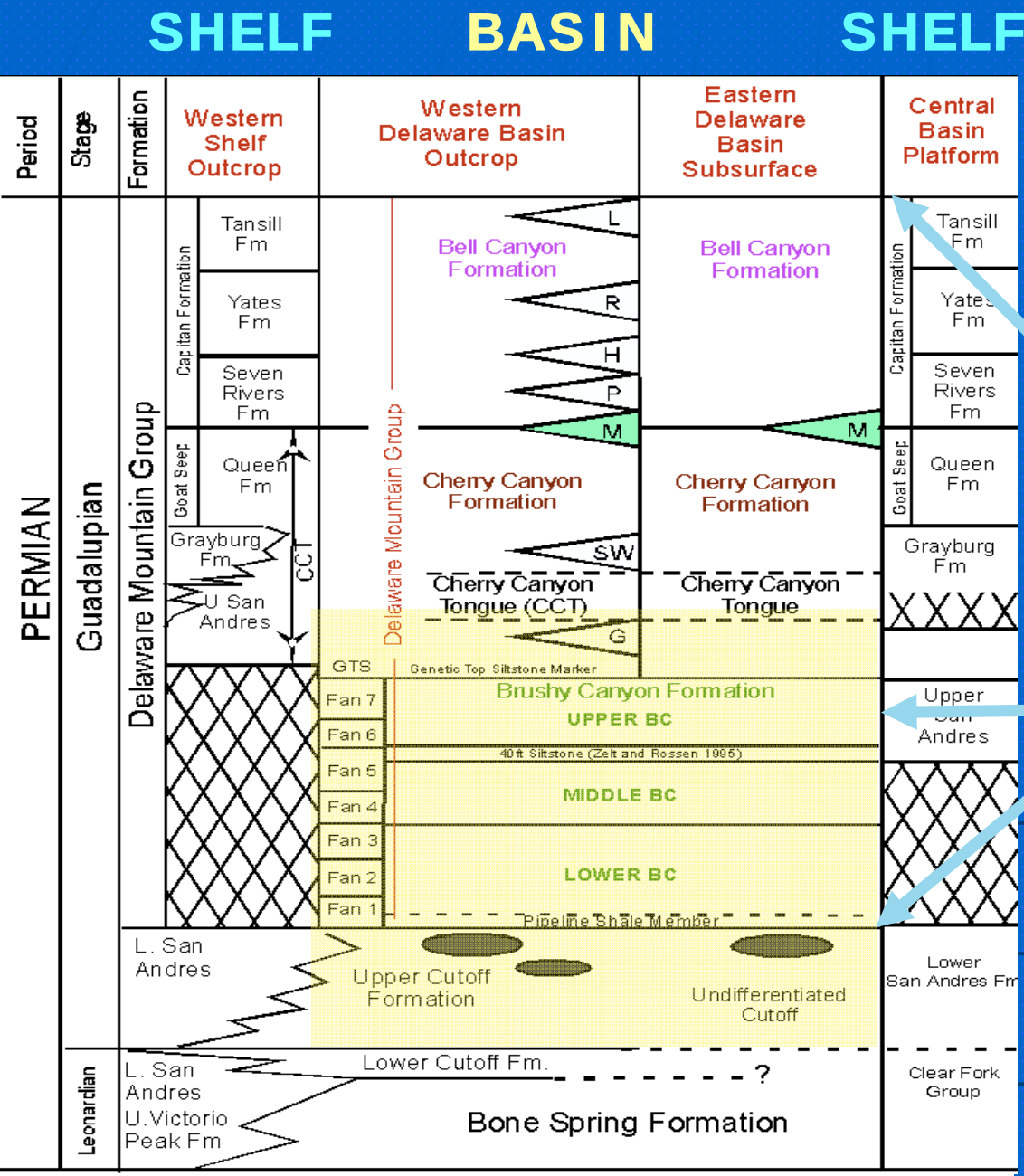
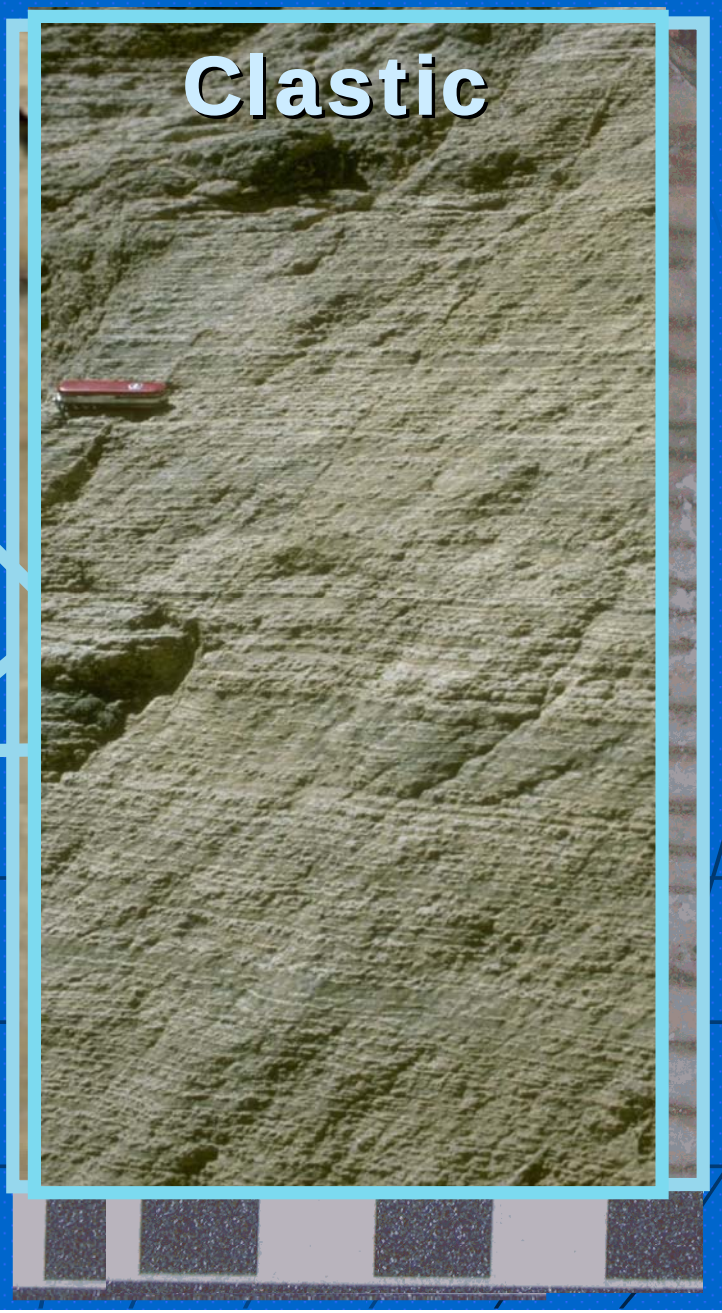
# Deep-marine Laminites record 15 m.y. of Monsoonal Climate Change



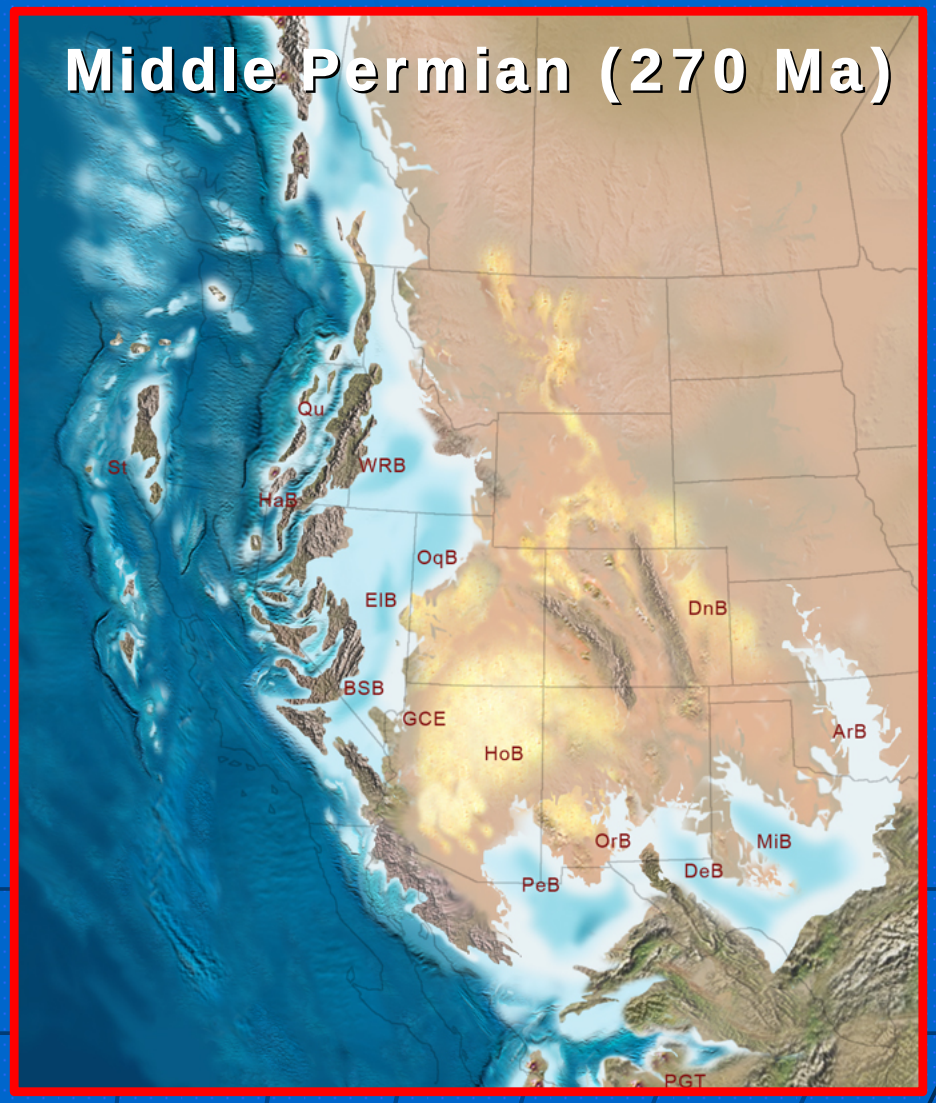
View Note for Slide 17 (Page 19)

# Plate Collision (Marathon Orogeny) and Subduction Combine to Segment the Permian Basin into Foreland Sub-Basins

- Tectonic Controls:

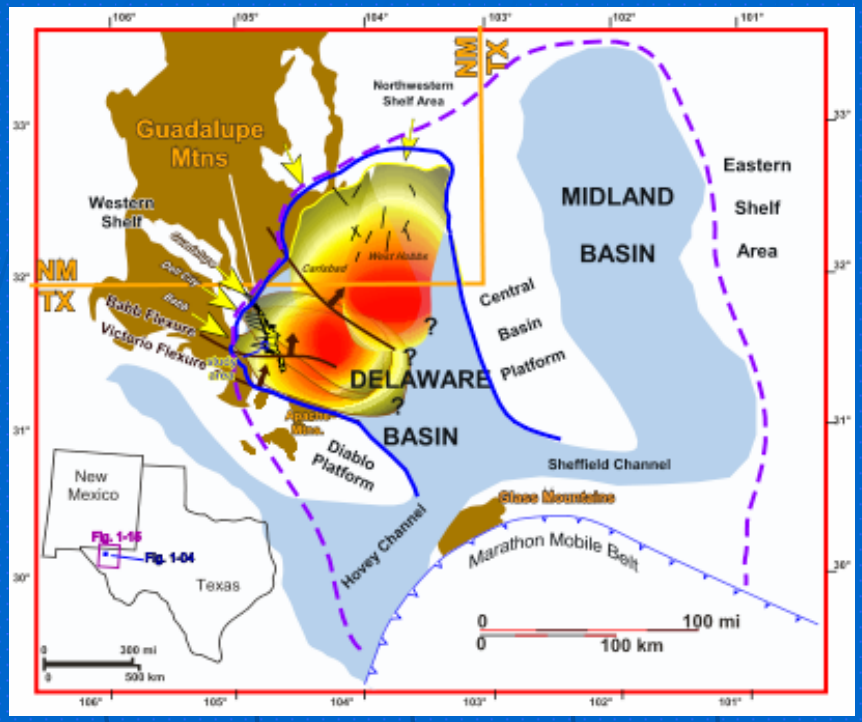
- Flat slab subduction generated epeirogenic uplift in source terrain, regional unconformity and distributed uplifts

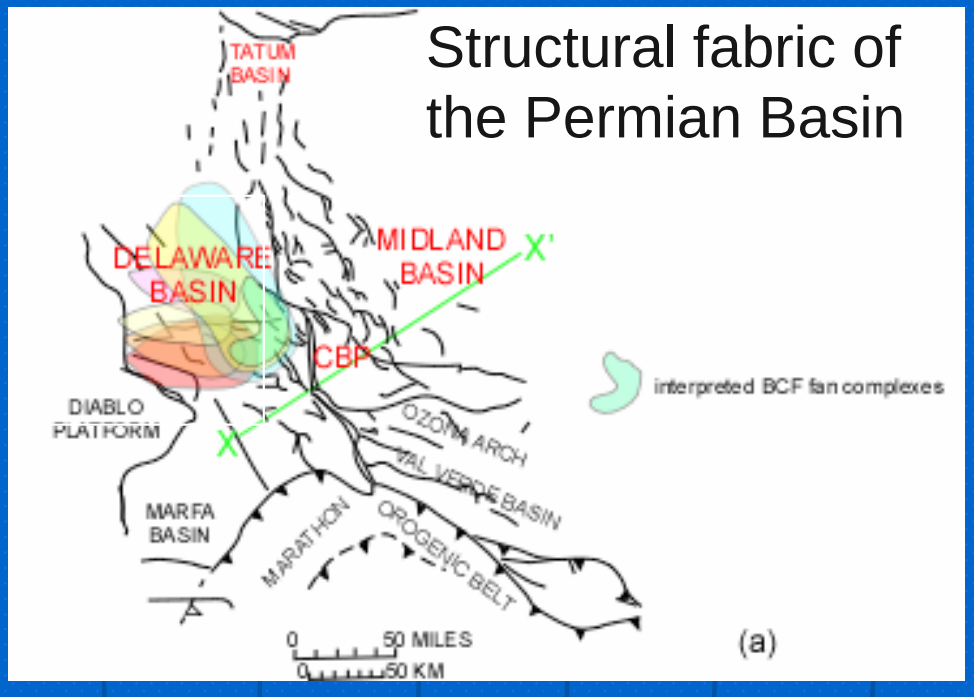
- Marathon foredeep provided opening to ocean and sink for sediment derived from the orogenic belt




Ronald Blakey, Northern Arizona University website
http://jan.ucc.nau.edu

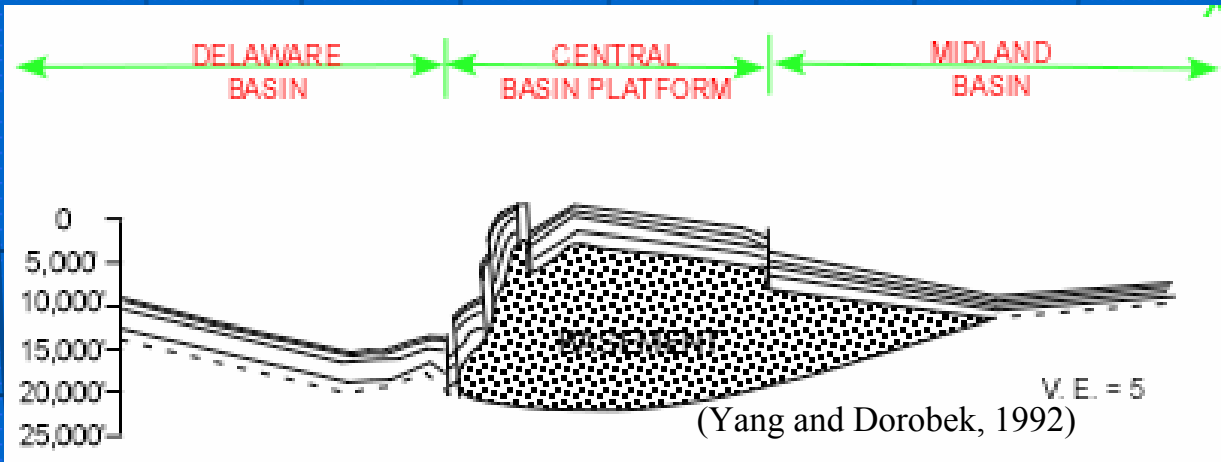
# Generalized Tectonic Map and Structural Cross Section across Delaware and Midland Basins




**Differential subsidence in foreland sub-basins determined:**

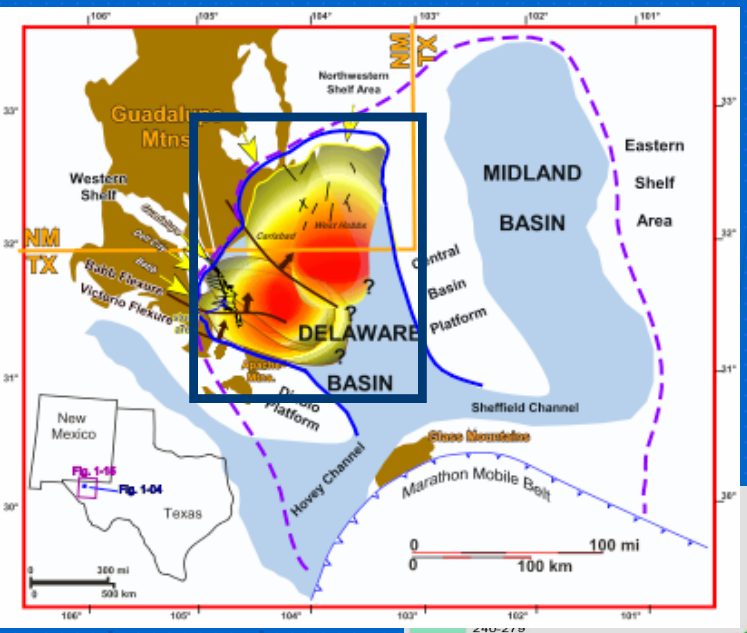
- **basin depocenters**
- **delivery of coarse sediment fraction**

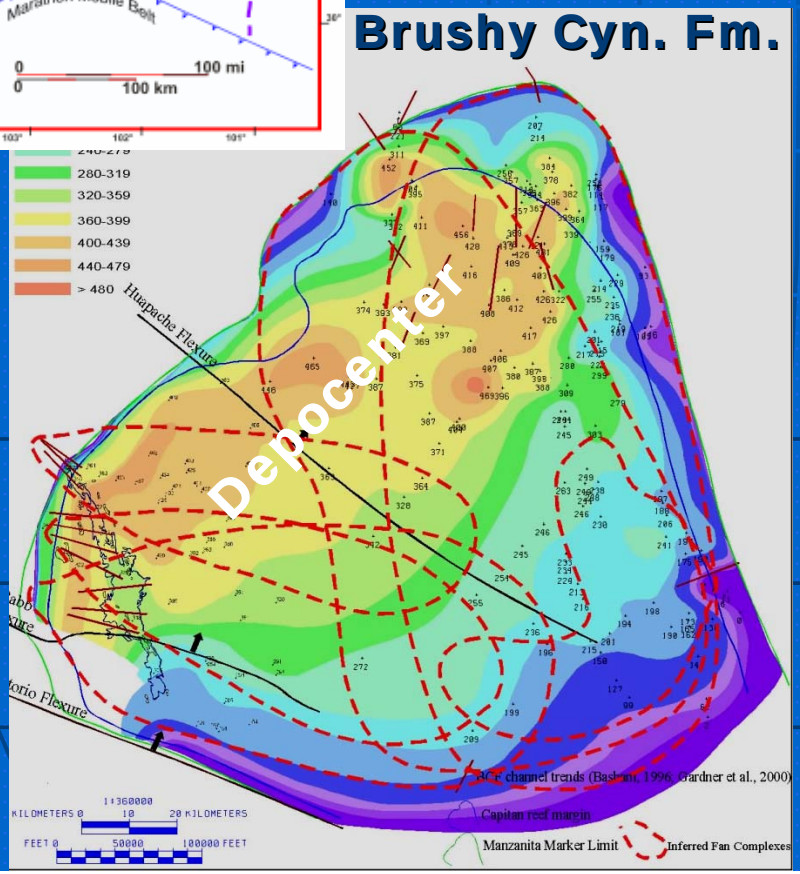


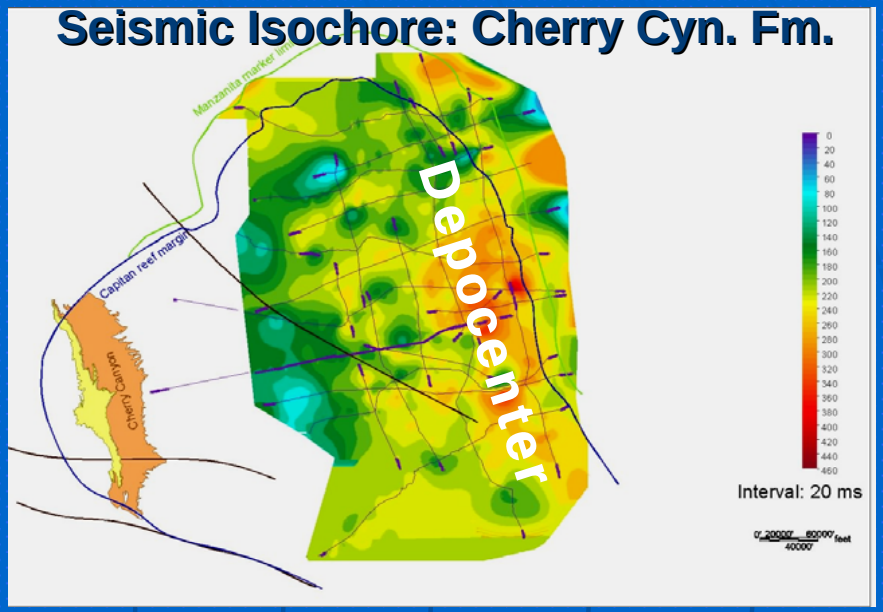

(Yang and Dorobek, 1992)

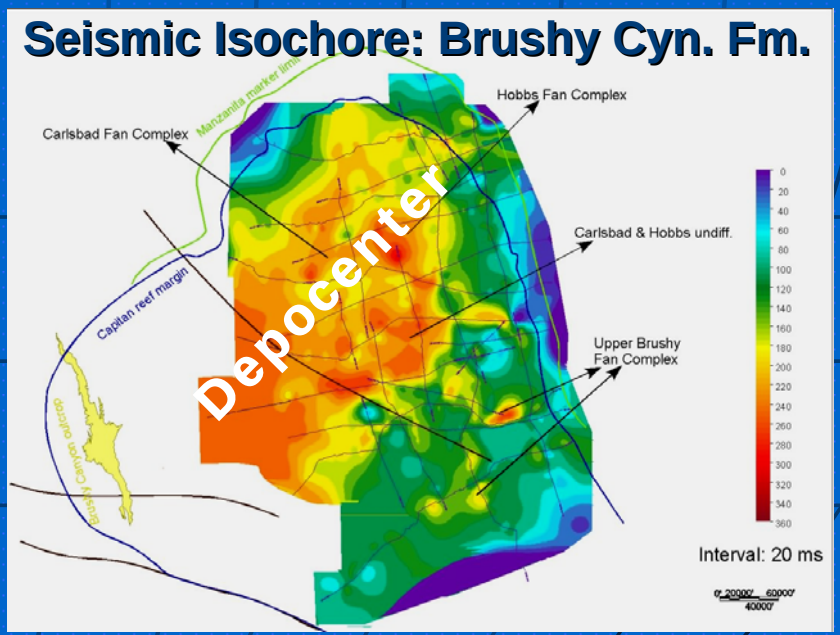
**Timing of deposition from seven different shelf sediment sources**

# Deep-Marine Depocenters Shift Due to Decreased Subsidence from Delaware to Midland Basins



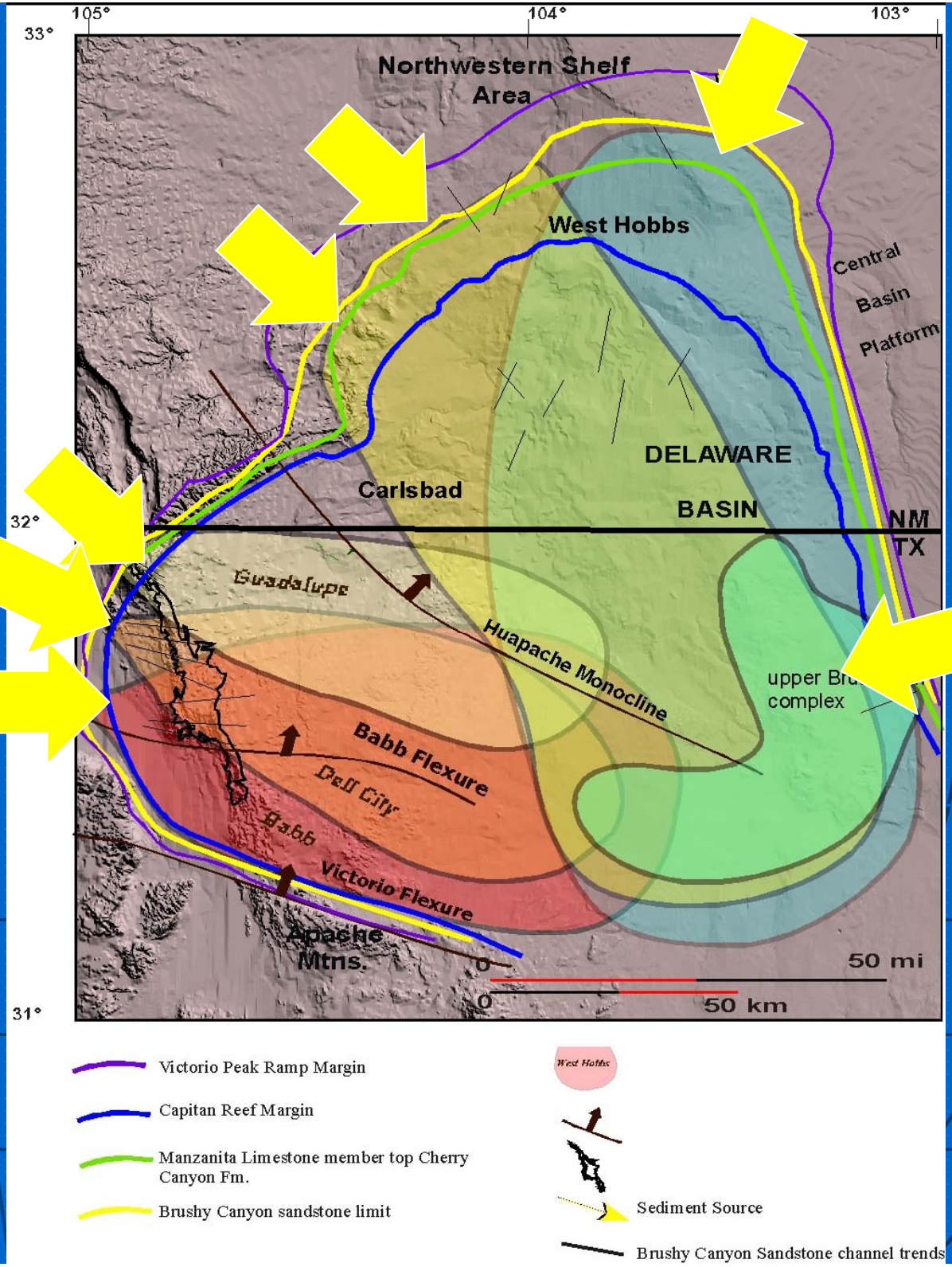



View Note for Slide 20 (Page 22)

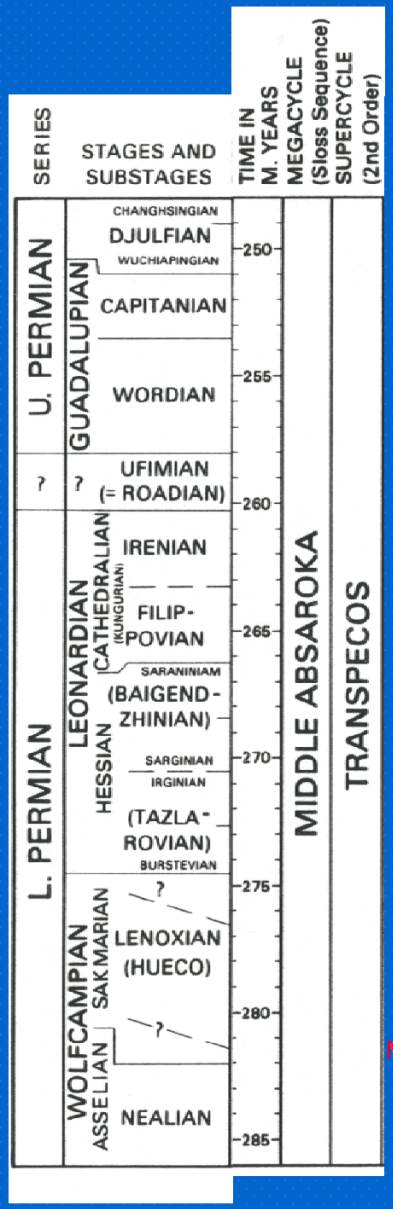
# Clockwise Shift in Deep-Marine Depocenters in Delaware Basin

- 250 km long and 180 km wide area encompassing approximately 33,500 km$^2$
- Colored lines outline multiple carbonate platform margins with the youngest Capitan Reef Complex forming a narrow belt that extends for 600 to 700 km around the basin
- Tectonically driven changes in the onset of deep-marine sedimentation in basin related to eastward diminution of subsidence linked to flat-slab subduction.

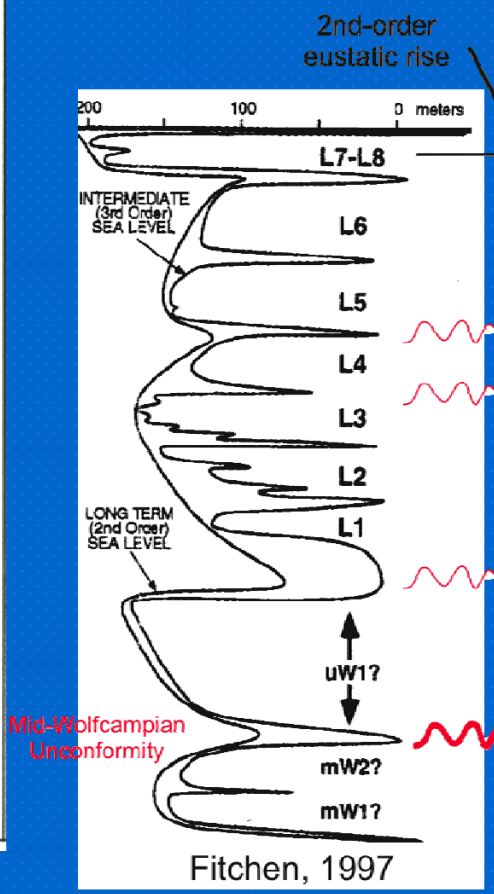


View Note for Slide 21 (Page 23)

# Permian Eustasy

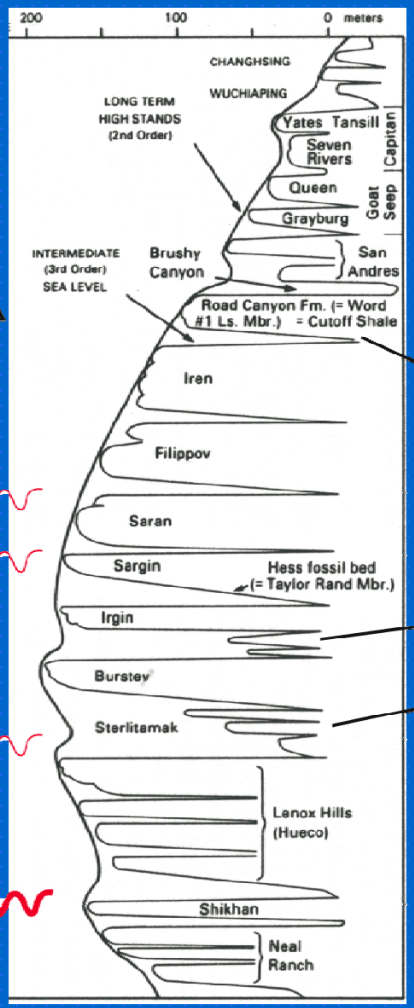



## Eustasy Curve derived from Sierra Diablo Platform (showing Pre-Brushy changes)



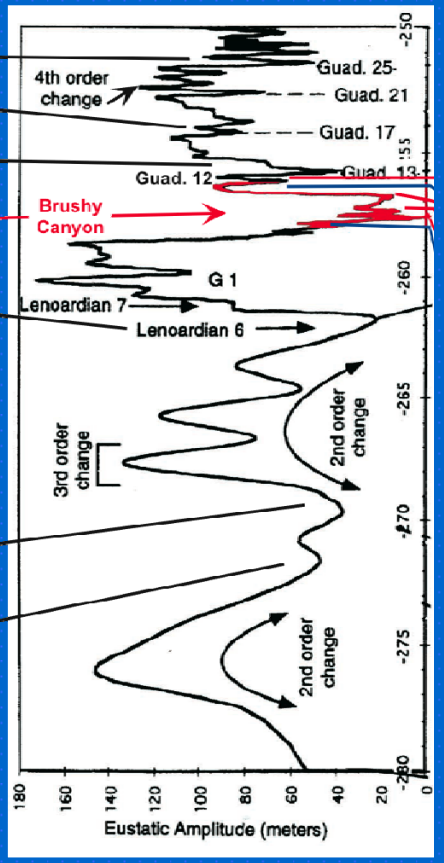

Fitchen, 1997

## Eustasy Curve derived from Russian Platform and Ural Mountains




Ross and Ross, 1987

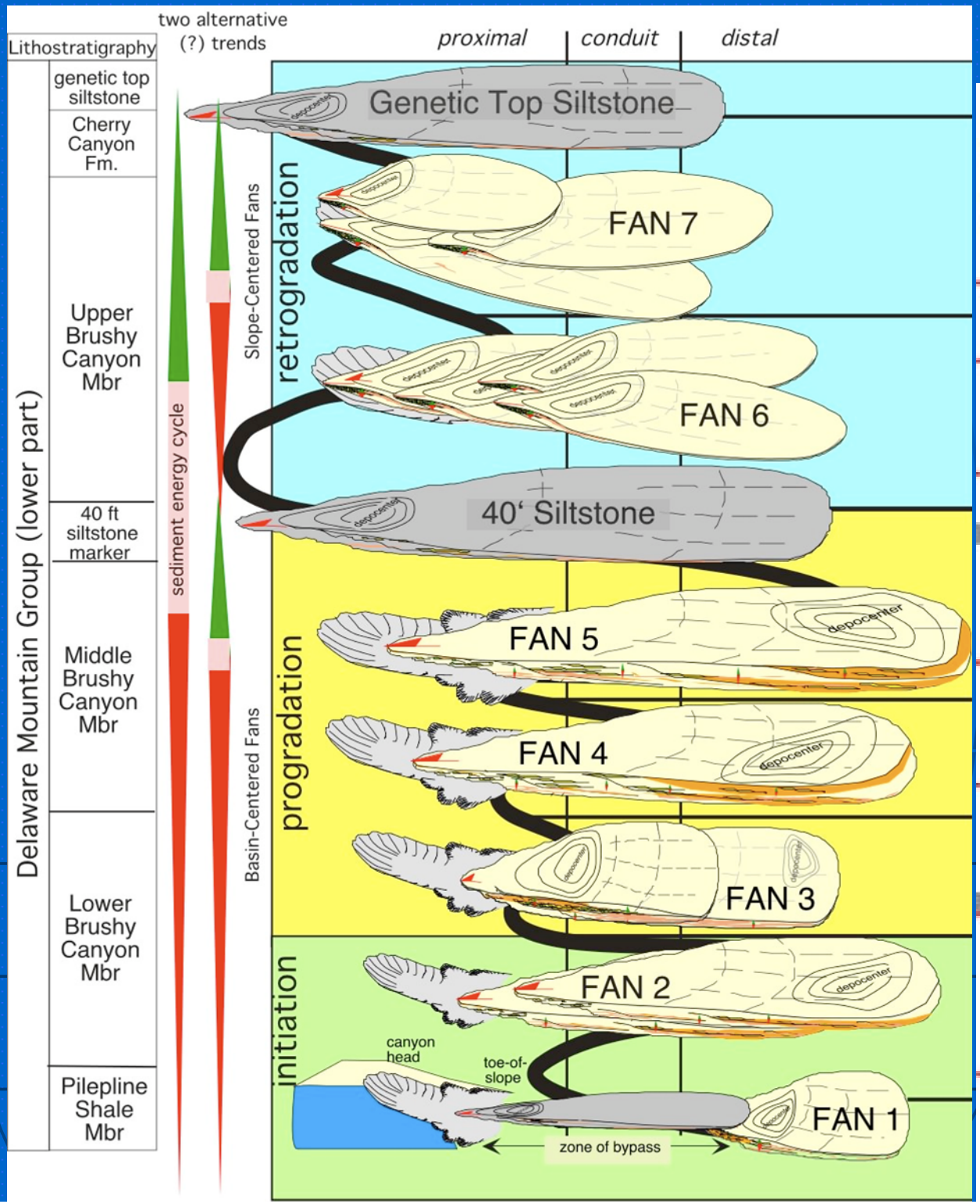
## Calculated Permian Eustatic SL Curve derived from Delaware Basin



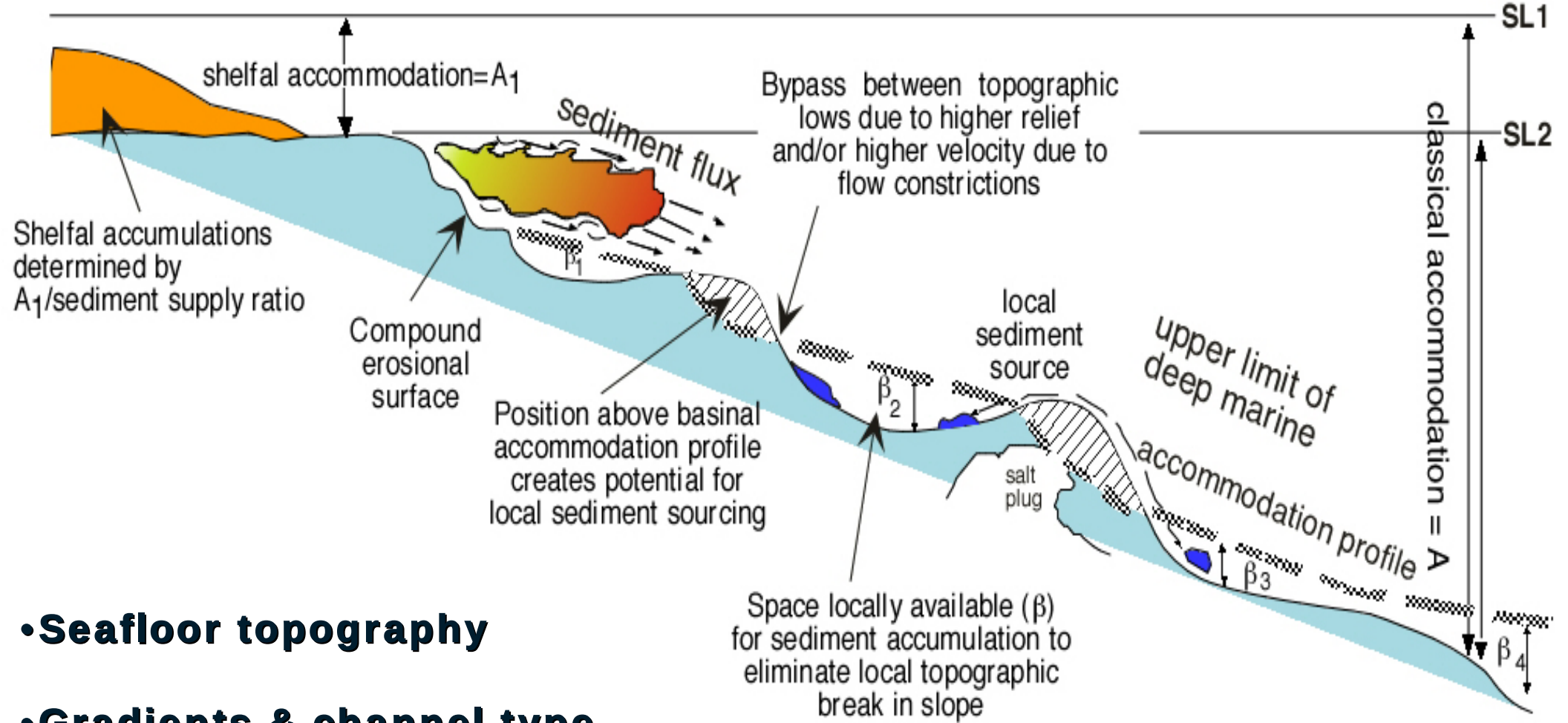

From Ye and Kerans, 1996

View Note for Slide 22 (Page 24)

# Correlation of Permian Sea Level Change to Sediment Starvation in Deep-Marine Basin

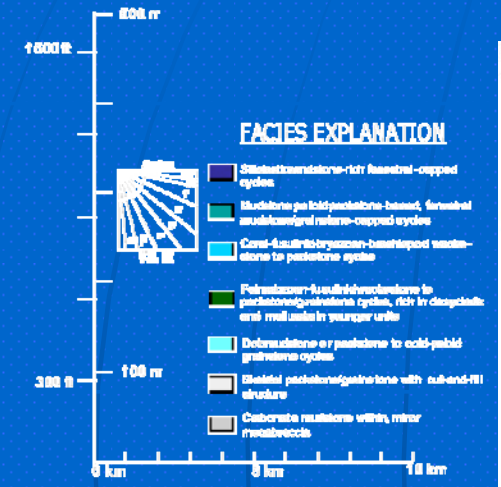


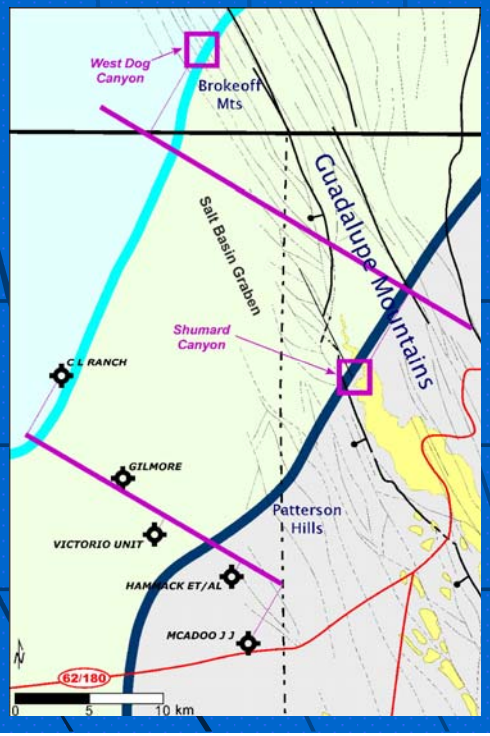
# Internal Controls

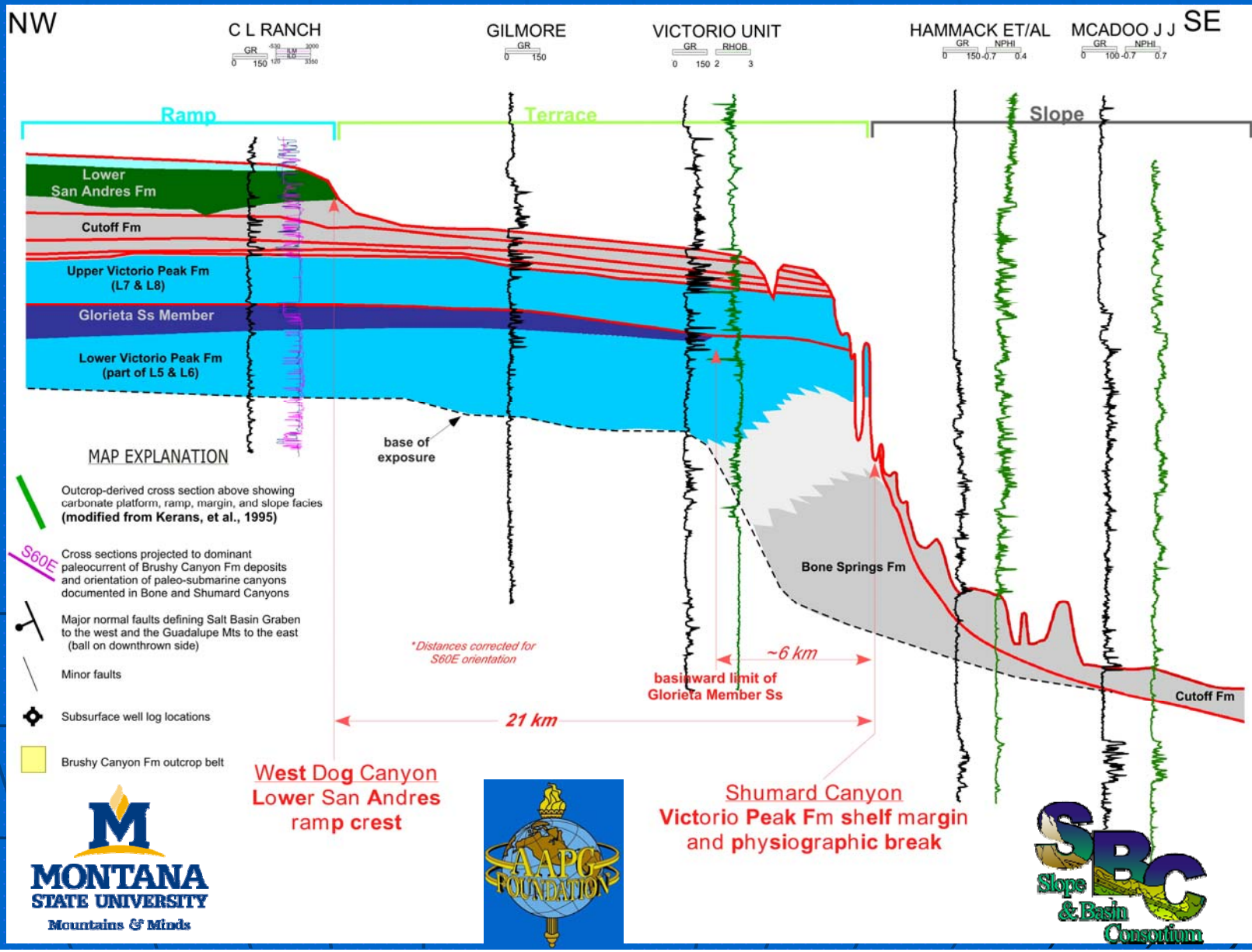



- **Seafloor topography**
- **Gradients & channel type**
- **Subaqueous flow evolution & run-out length**

# Setting the Stage: Carbonate Platforms Rimming Delaware Basin Affect Sea-Floor Topography

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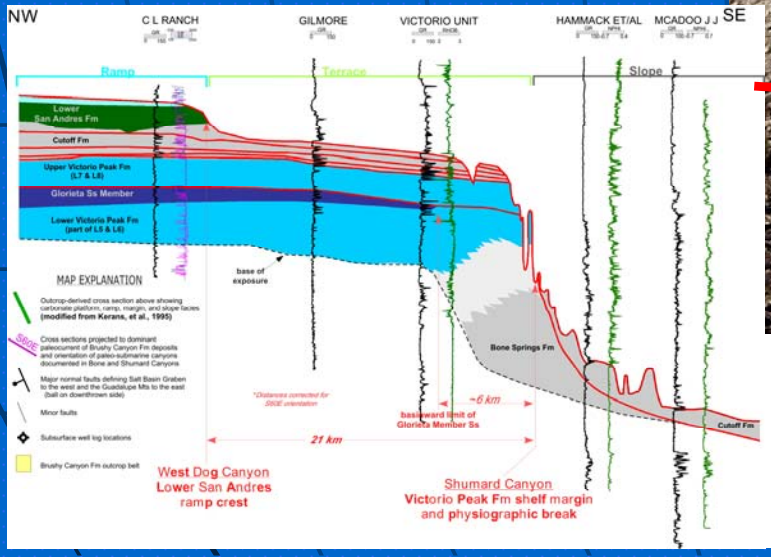
SBC Slope & Basin Consortium

# Contractional Deformation in Carbonate Mass Transport Deposits of the Upper Cutoff Fm.

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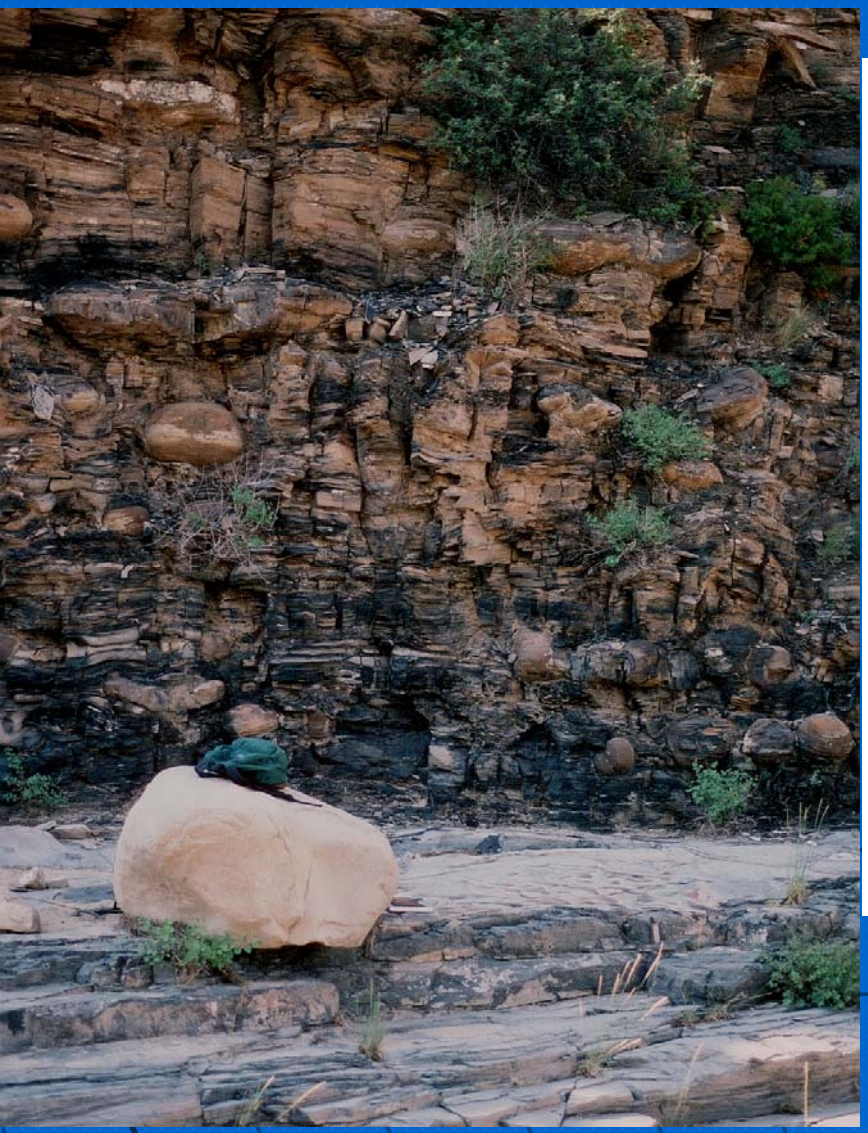
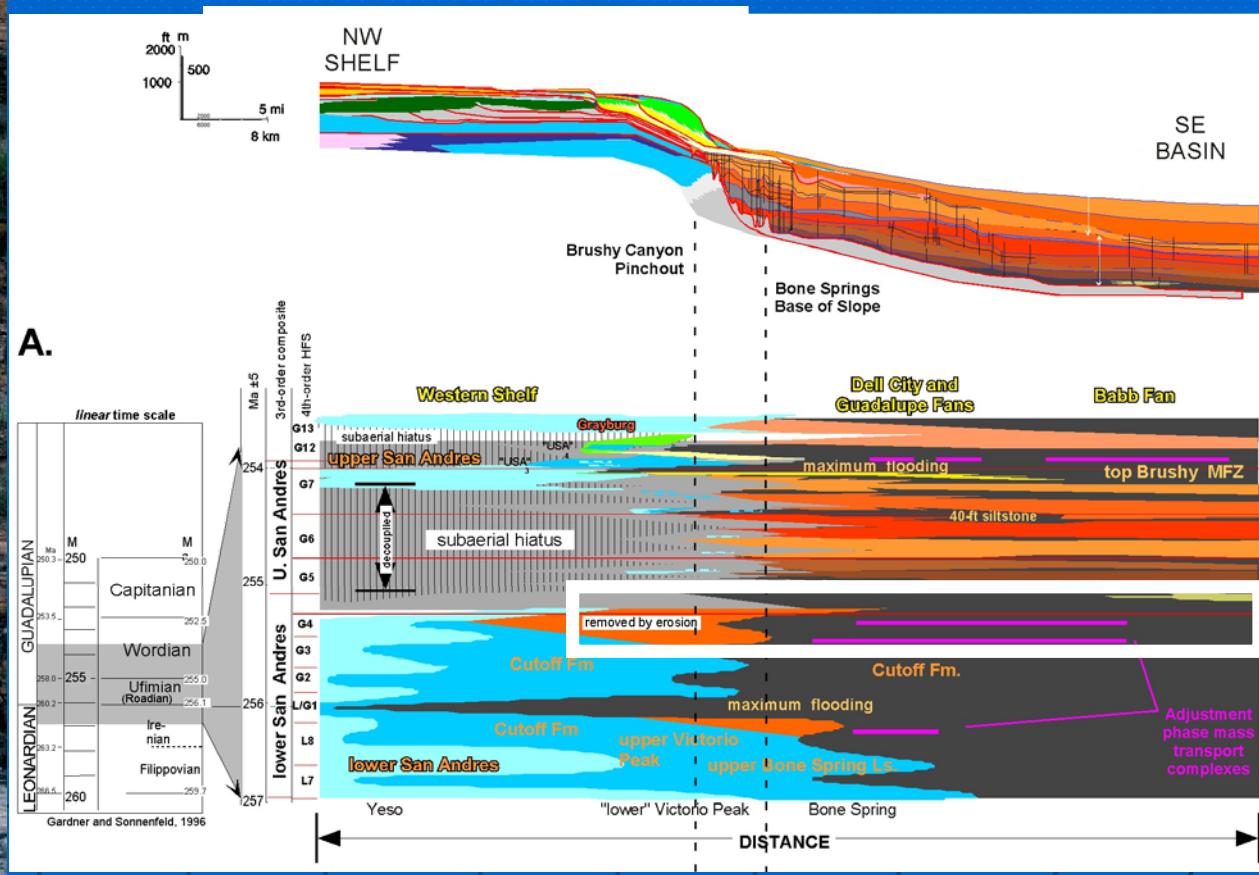
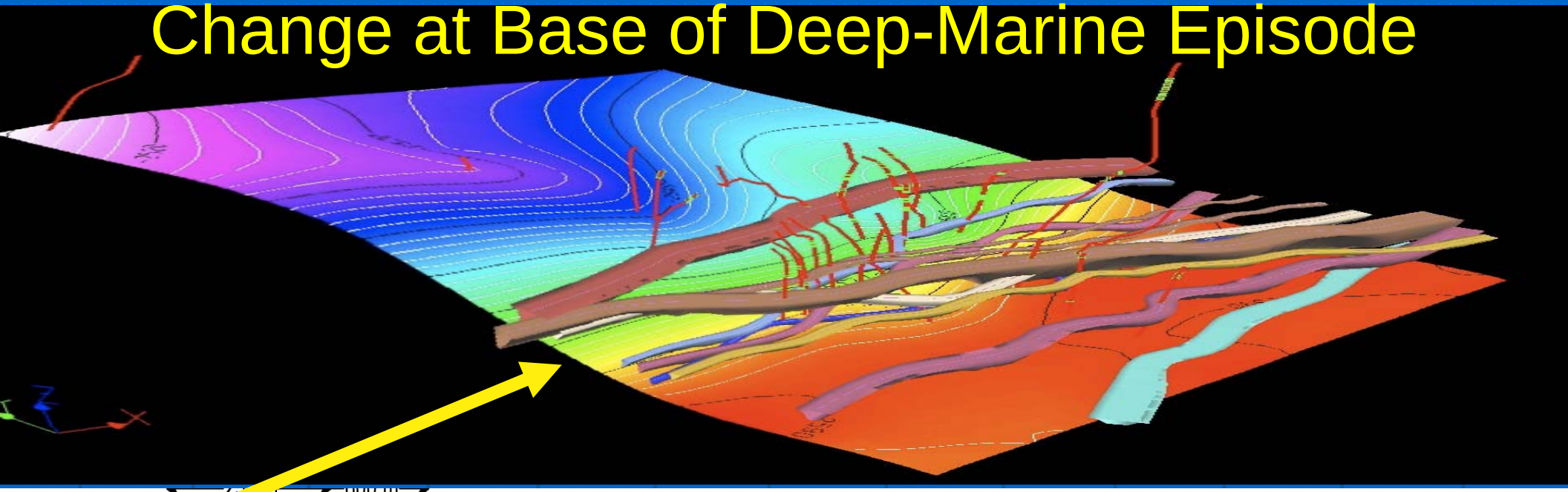
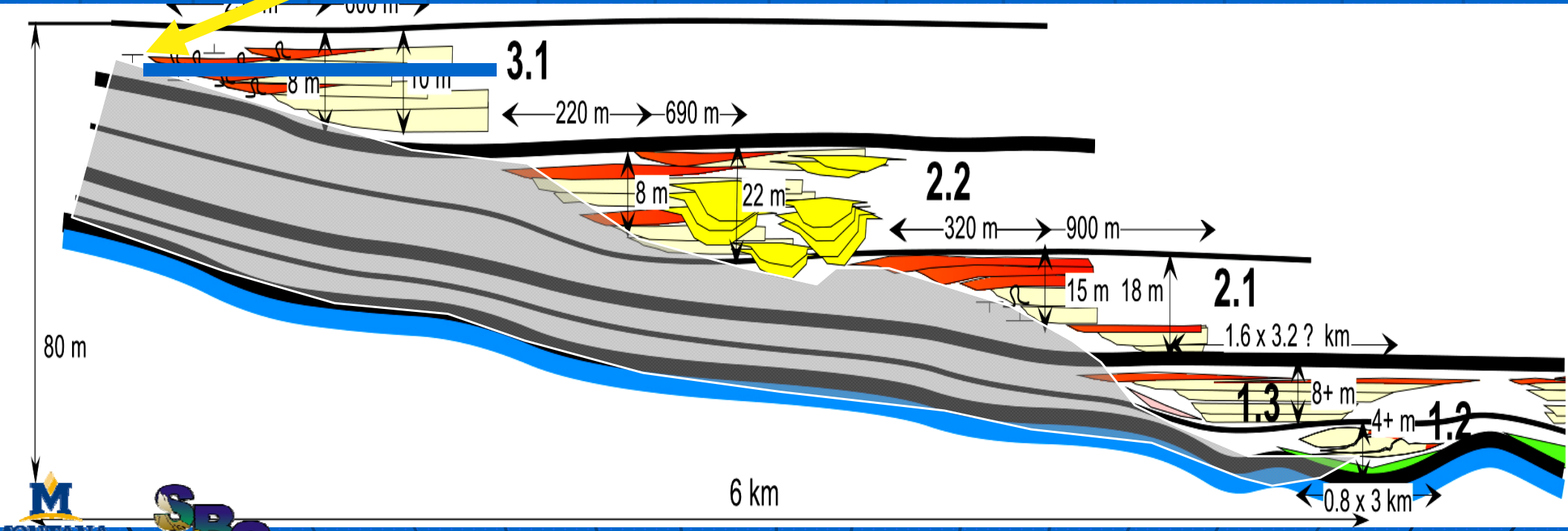
# Organic-Rich Siltstone Drapes Carbonate Mass Transport Deposits and Forms Most Diachronous Surface Within Deep-Marine Succession



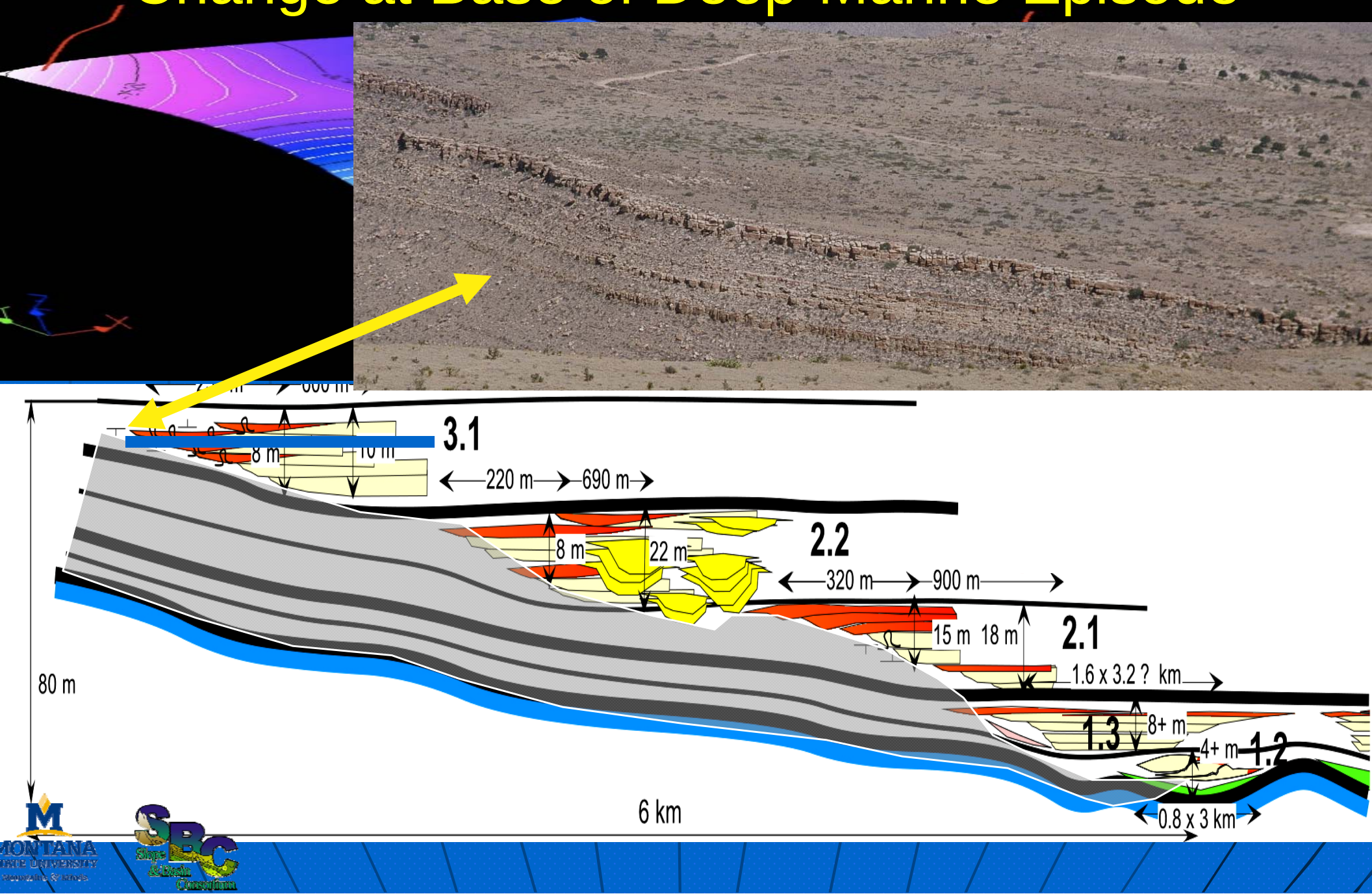


# Progressive Sandstone Pinch-outs & Facies Change at Base of Deep-Marine Episode

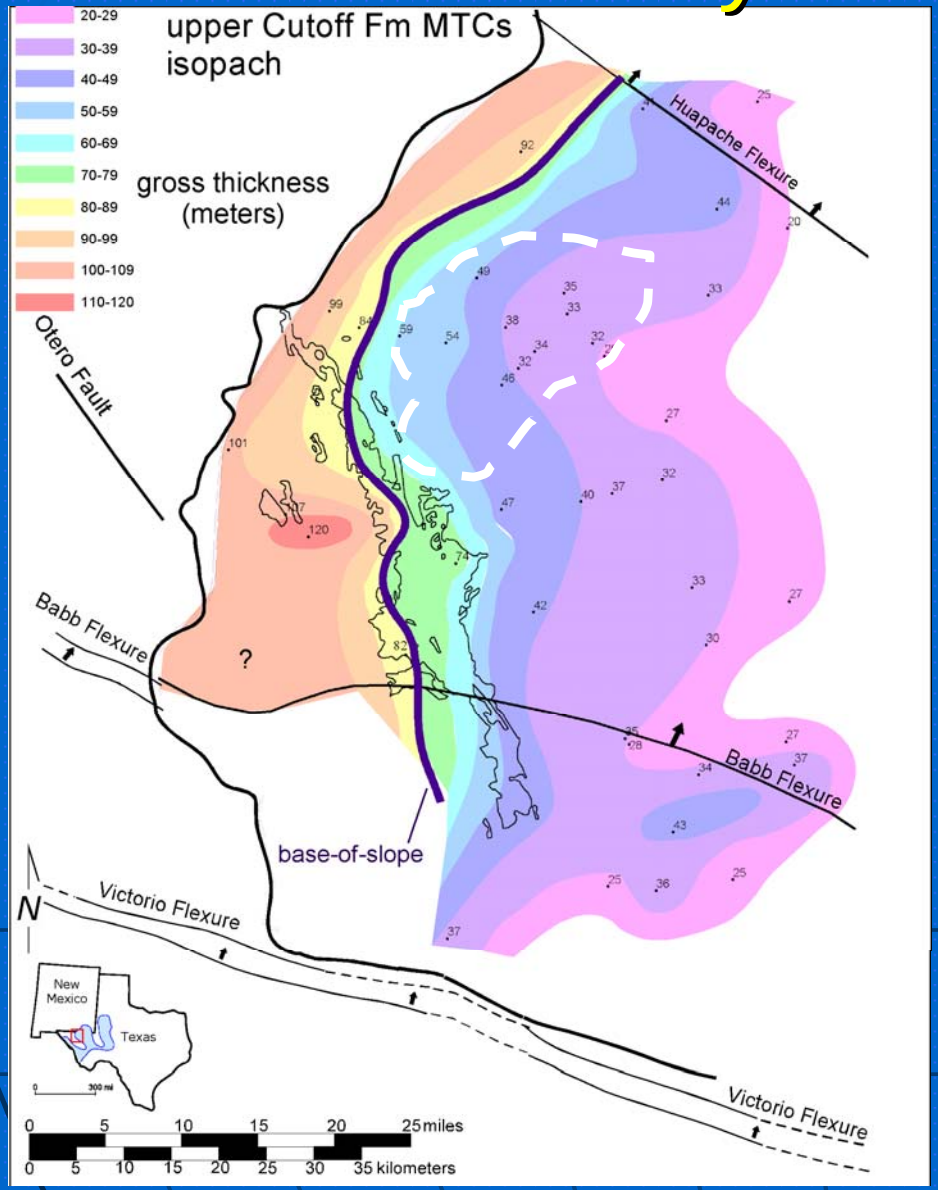


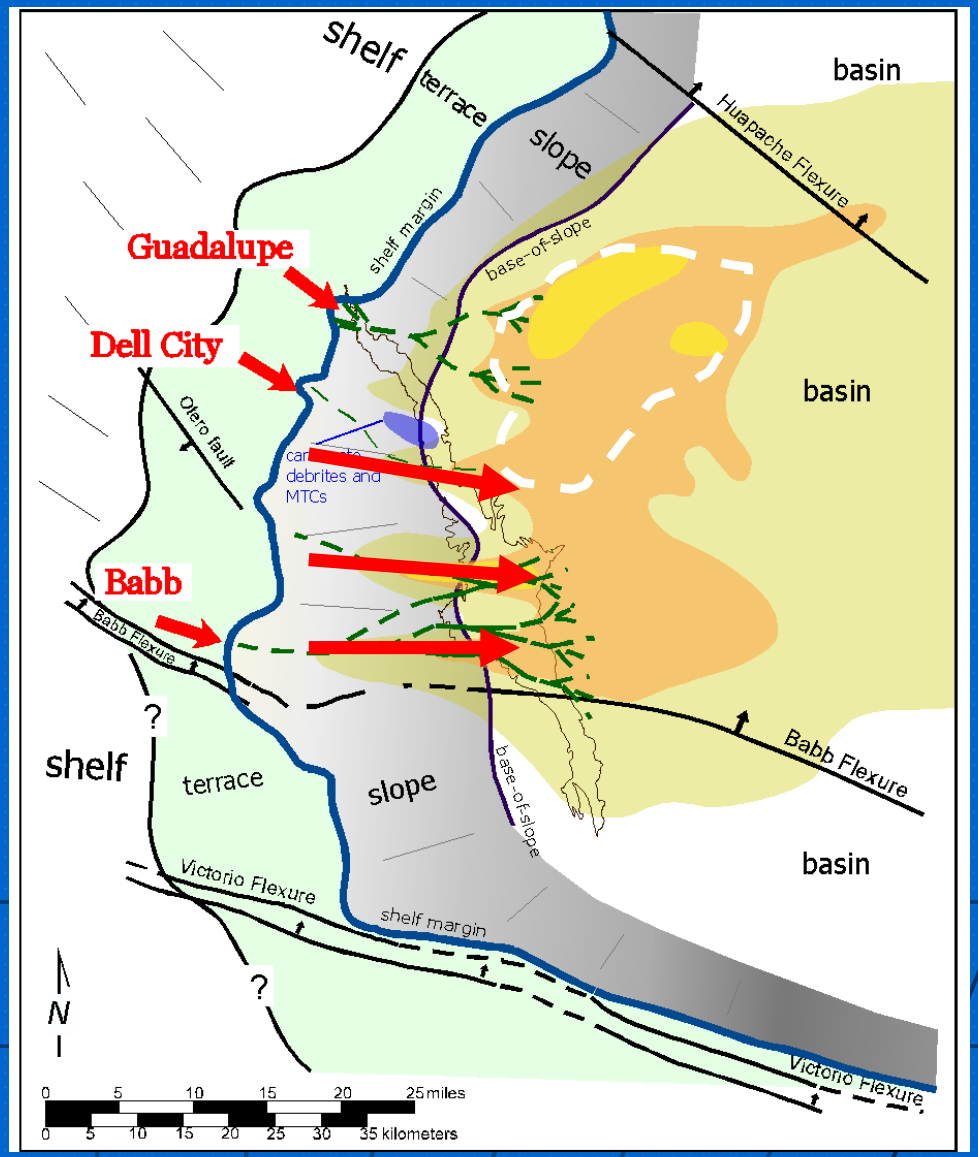


# Progressive Sandstone Pinch-outs & Facies Change at Base of Deep-Marine Episode



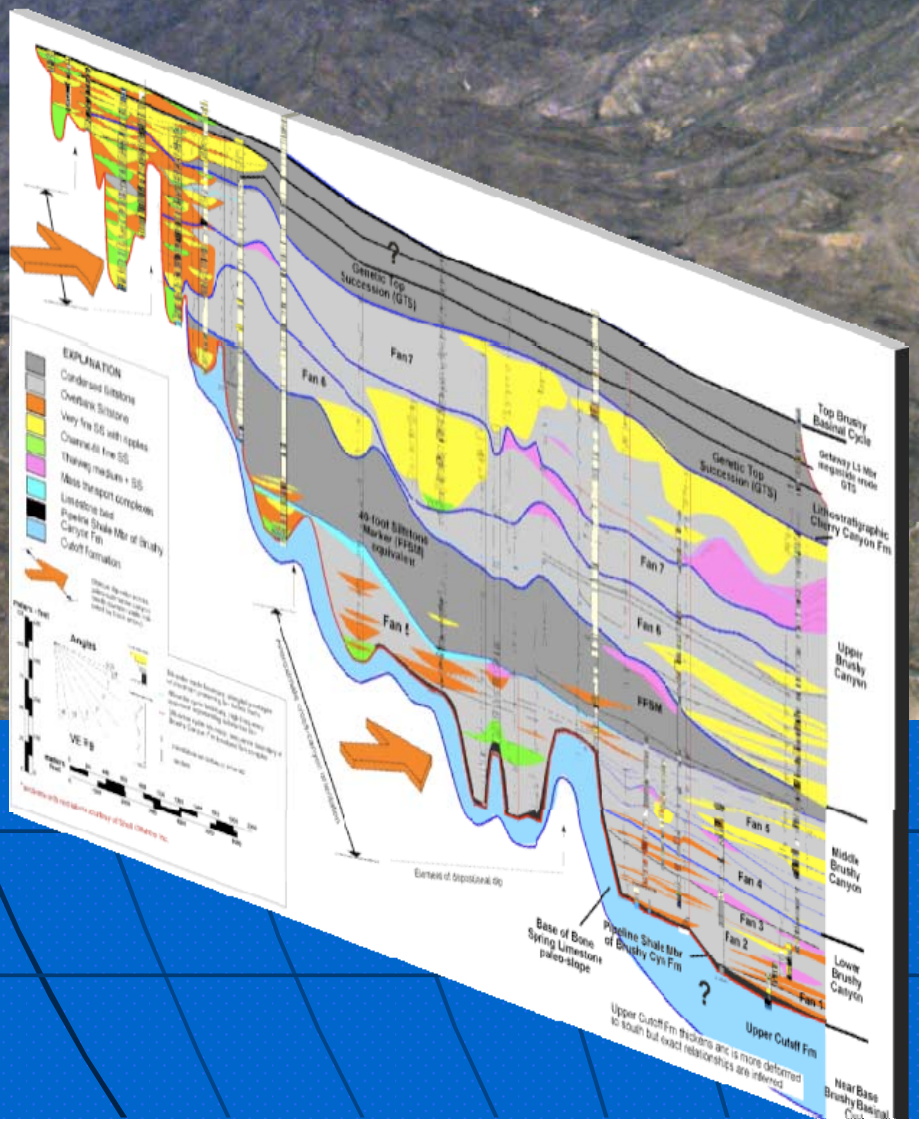
# Deep-Marine Sands In-fill Seafloor Topography Generated by Mass Transport Events




Romans, 2003

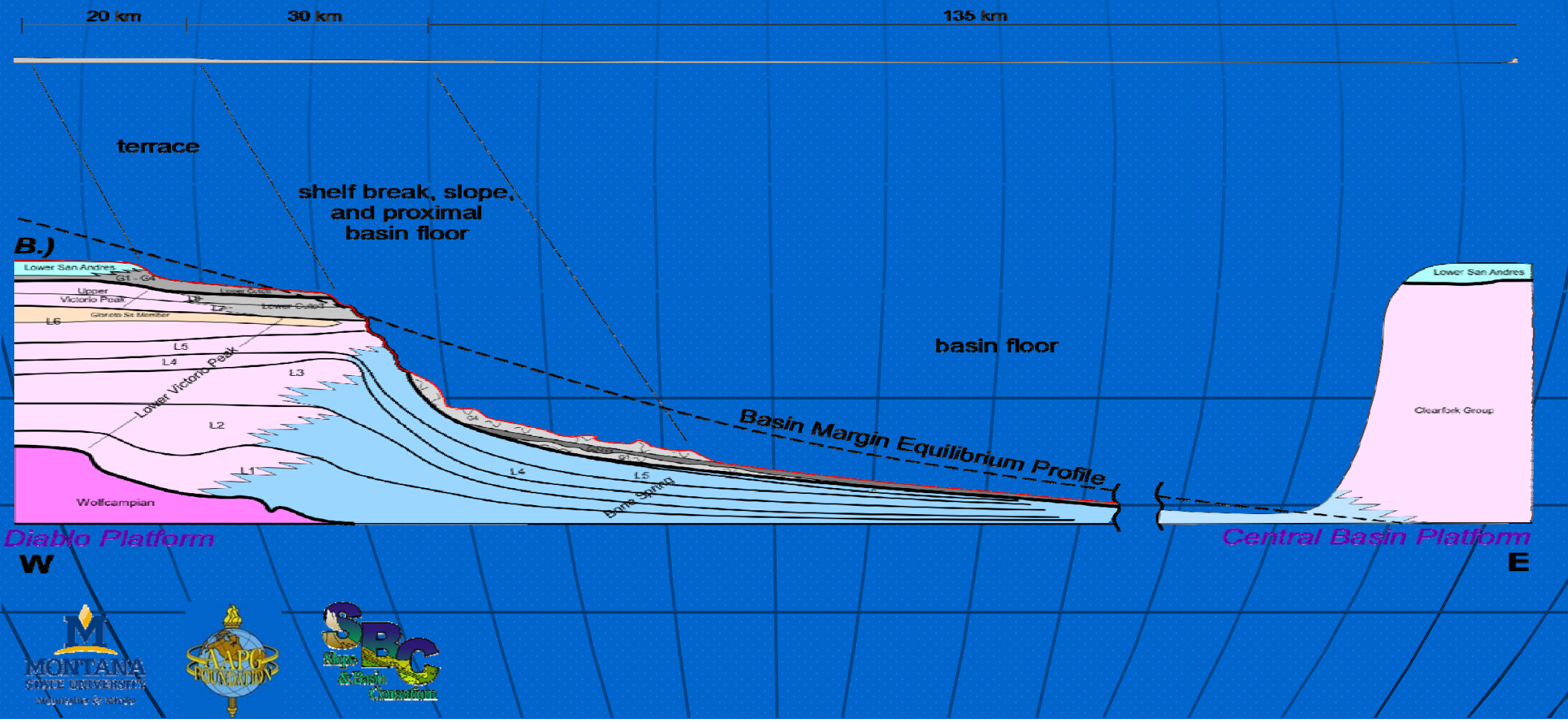
# Low Gradient Basin Floor Near Basin Margin




Sediment bypass across inherited carbonate slope in lower and middle Brushy Cyn replaced by sedimentation and expansion of constructional slope in upper Brushy Cyn depocenter

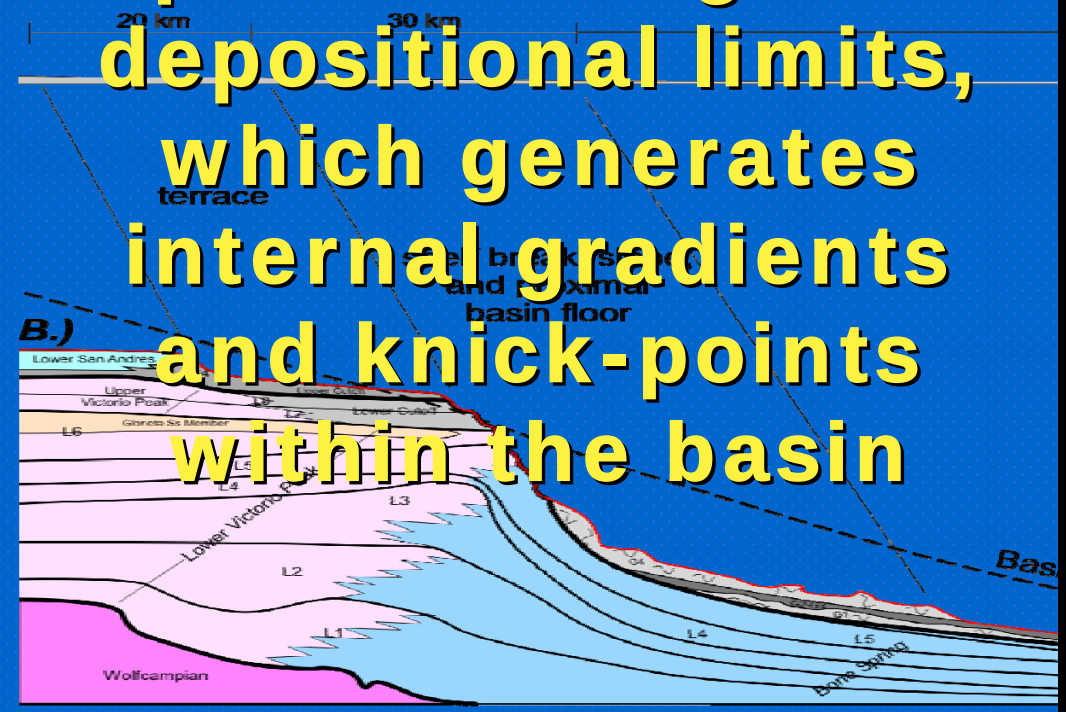
# Equilibrium Profile for Submarine Fan Sedimentation in Basin

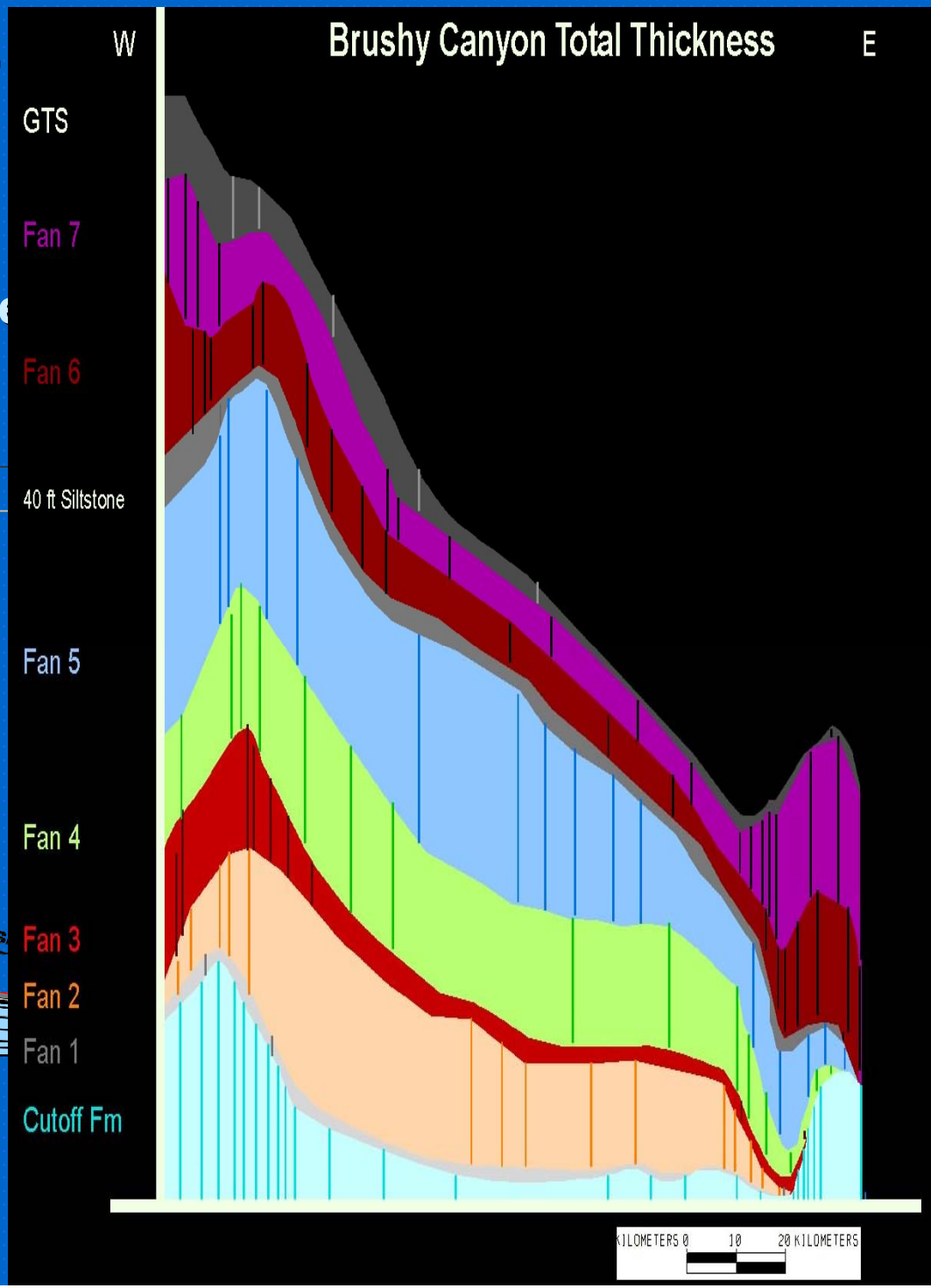
## Brushy Canyon Equilibrium Profile Across 185 Km Delaware Basin



# Equilibrium Profile for Submarine Fan Sedimentat

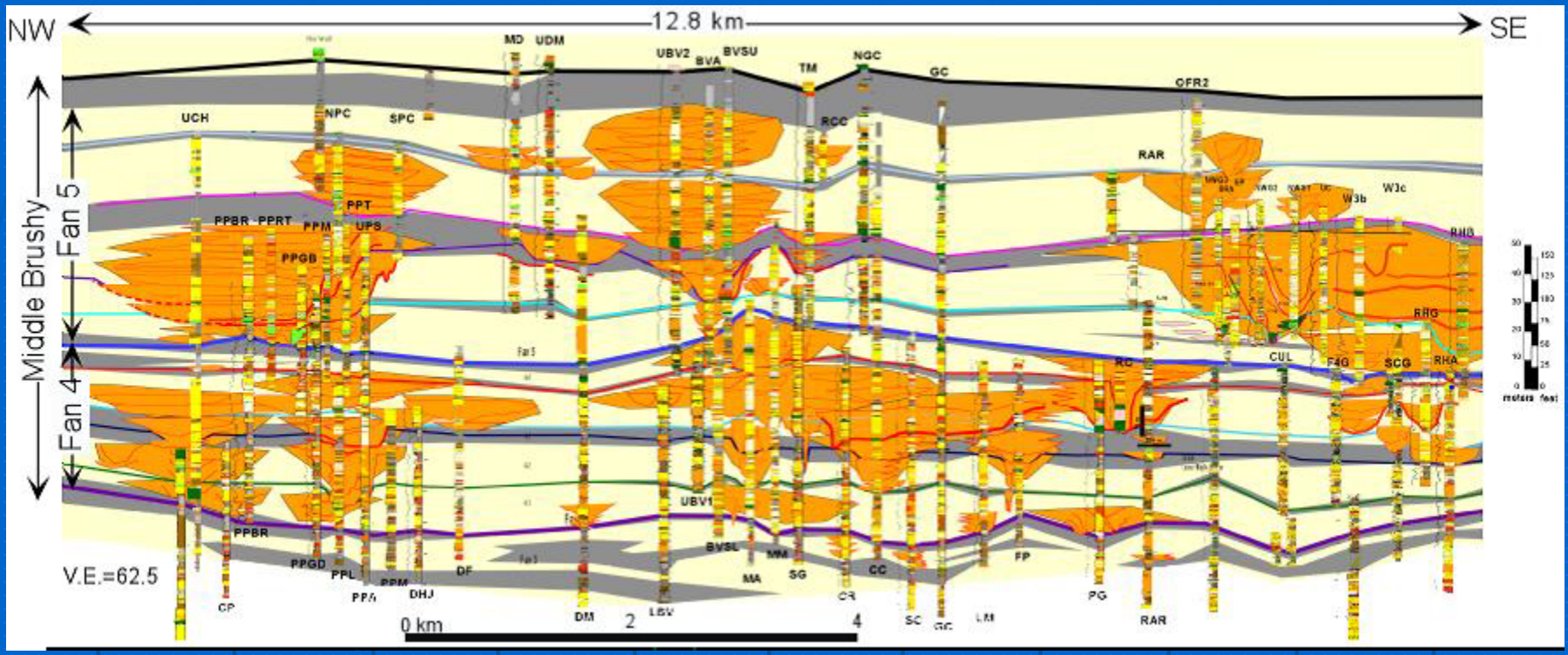
**Cumulative thickness plot showing fan depositional limits, which generates internal gradients and knick-points within the basin**



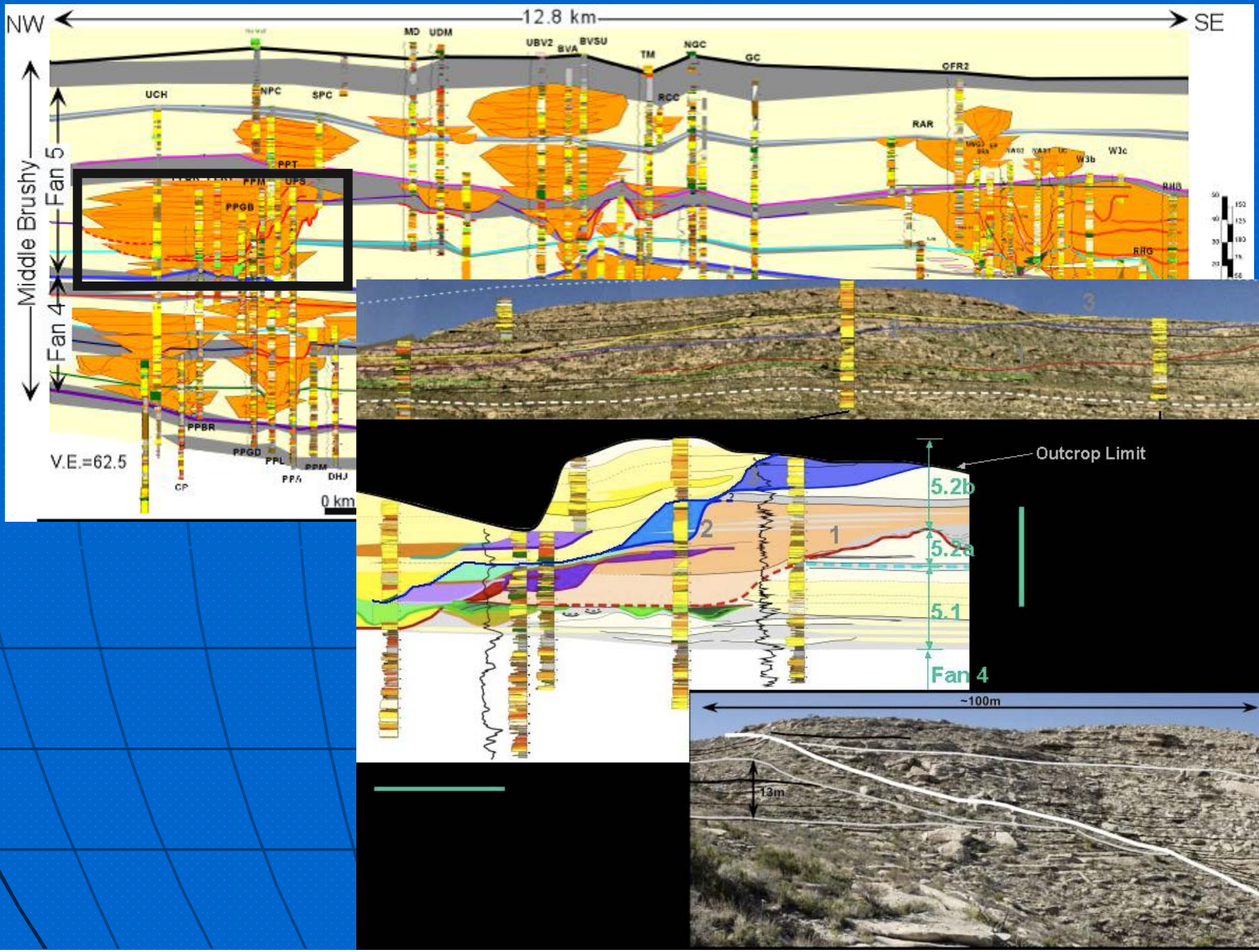



View Note for Slide 33 (Page 35)

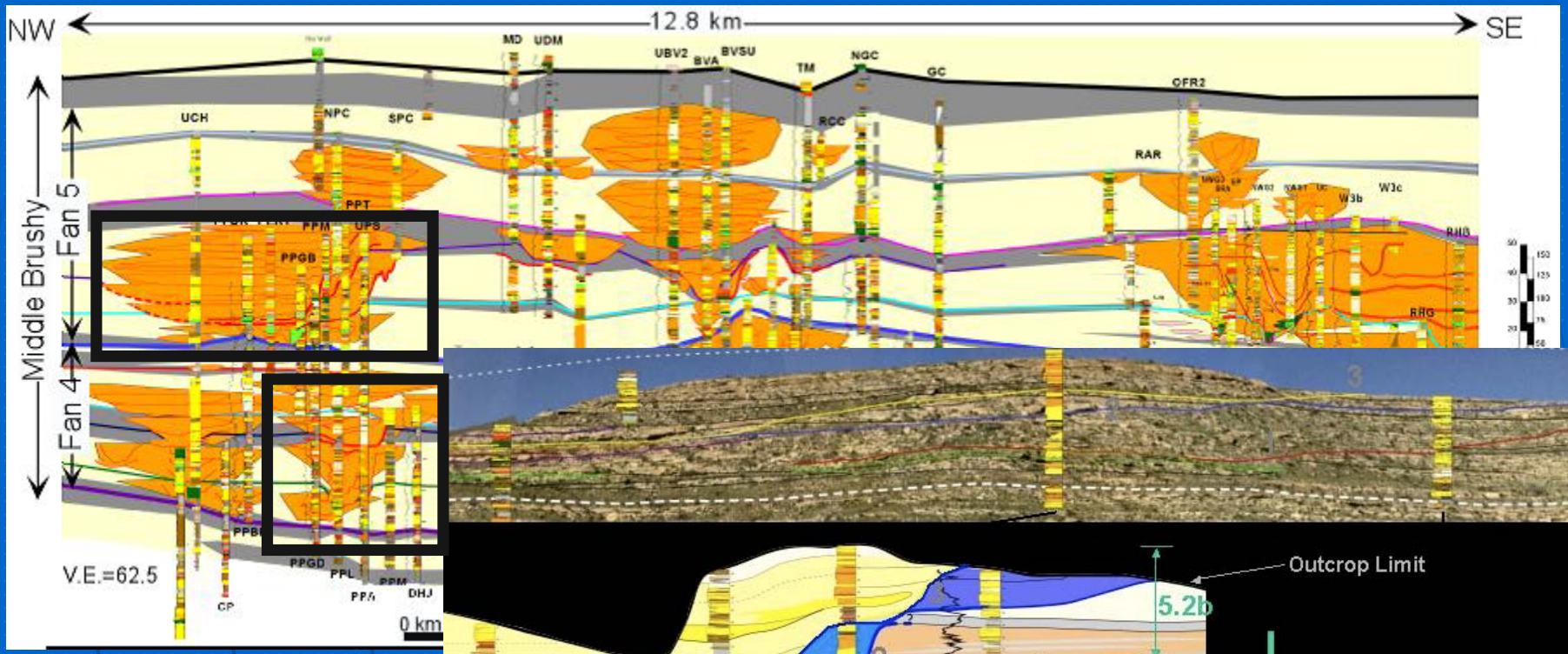
# Changes in Submarine Channel Architecture Related to Internal Changes in Local Basin-Floor Gradient

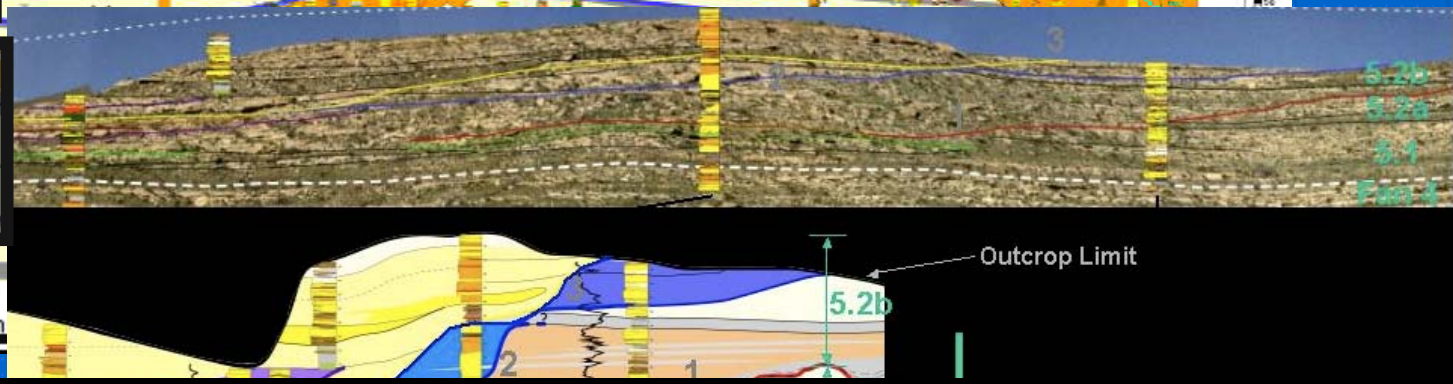


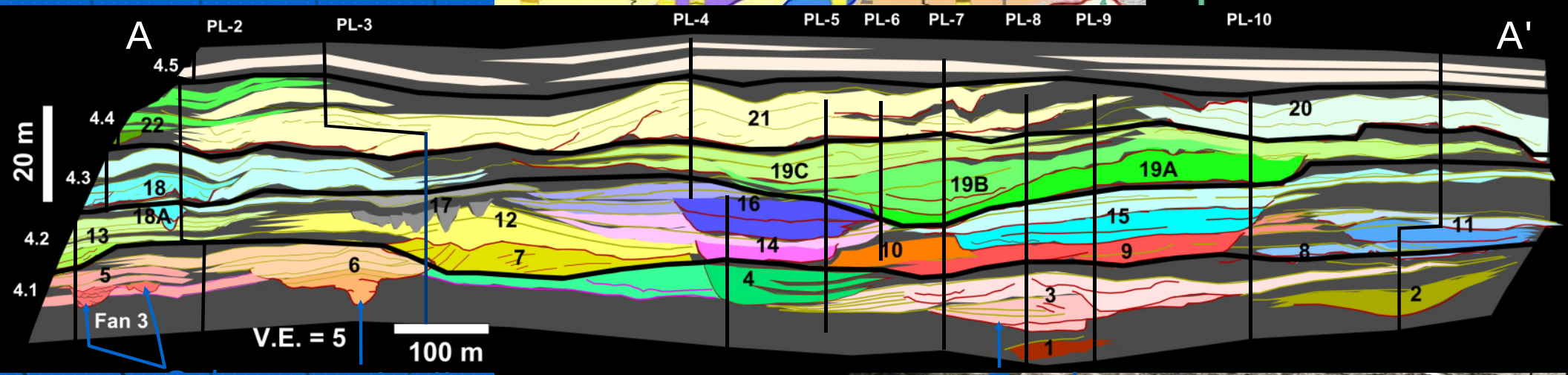
# Changes in Submarine Channel Architecture Related to Internal Changes in Local Basin-Floor Gradient



# Changes in Submarine Channel Architecture Related to Internal Changes in Local Basin-Floor Gradient



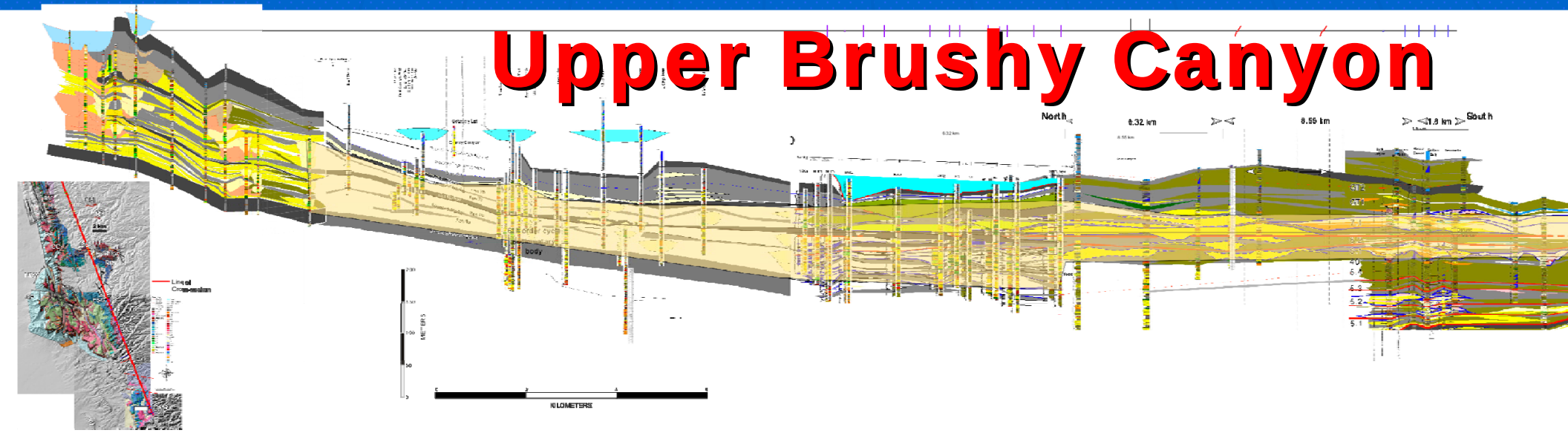



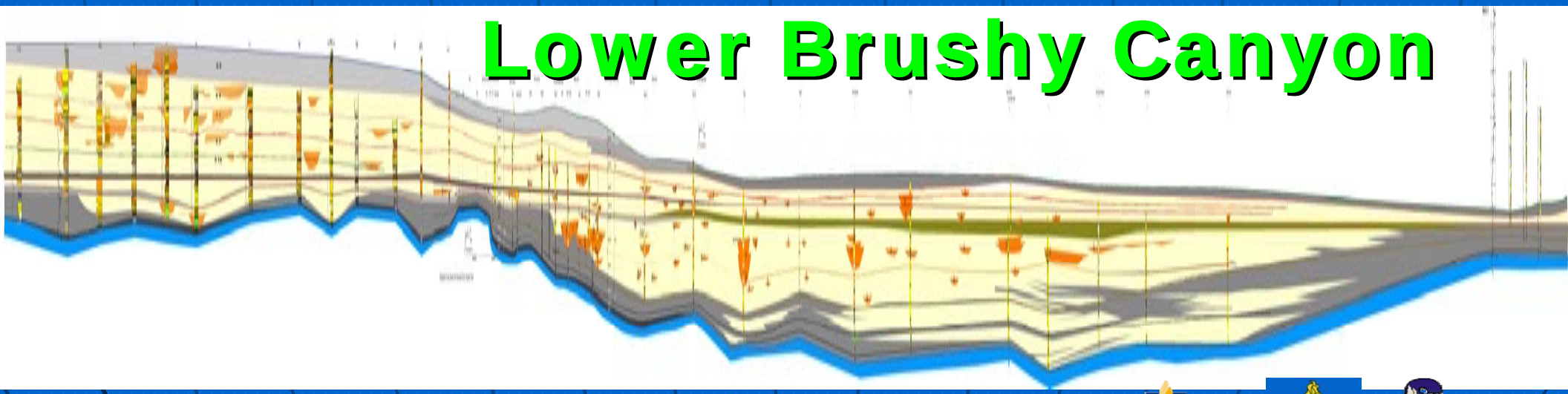



# Depositional Gradient Changes and Knick-point Migration

Click on black rectangle to view movie.

# Rough and Smooth Longitudinal Profiles of Lower and Upper Brushy Canyon Fm.

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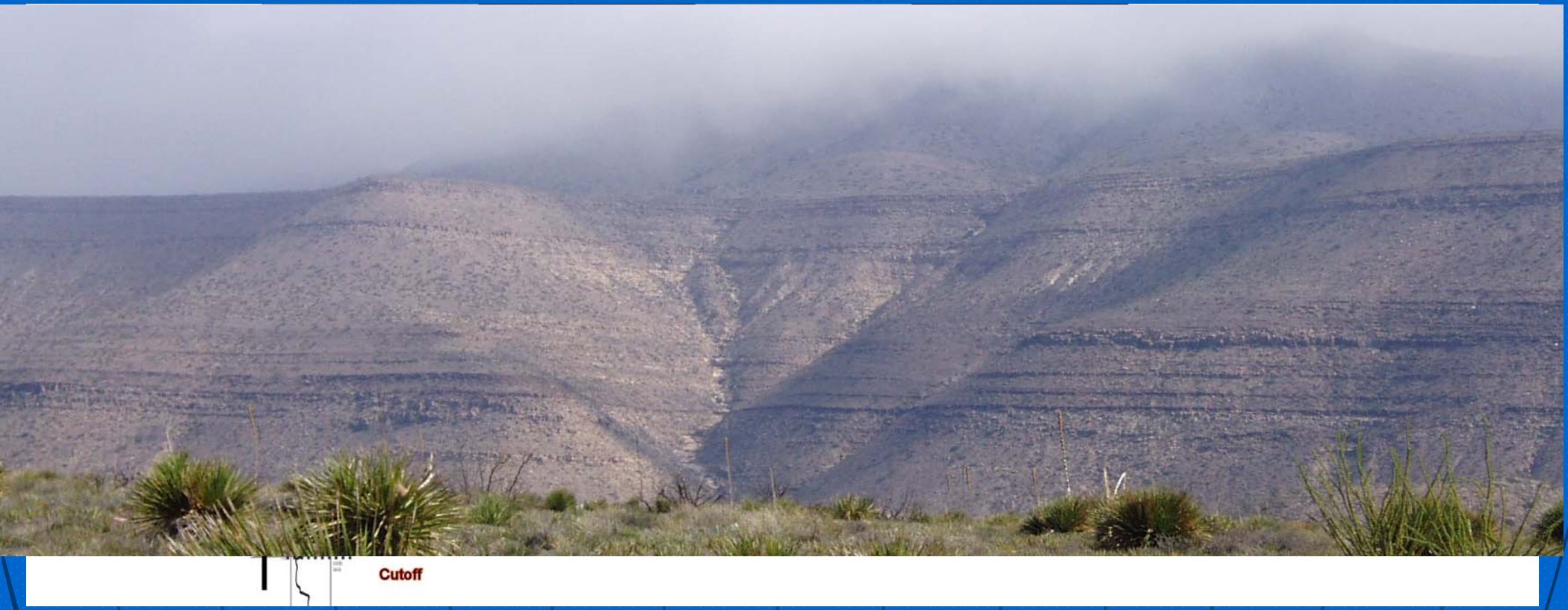
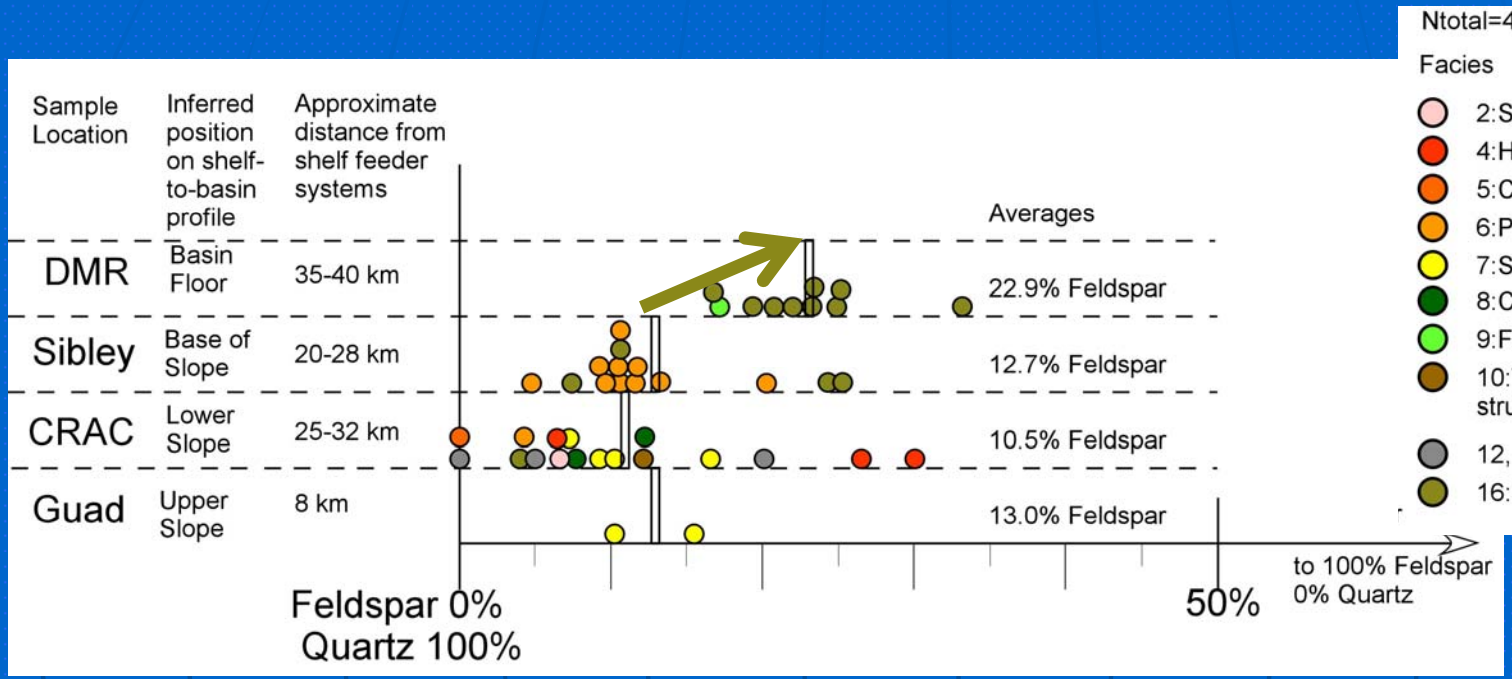
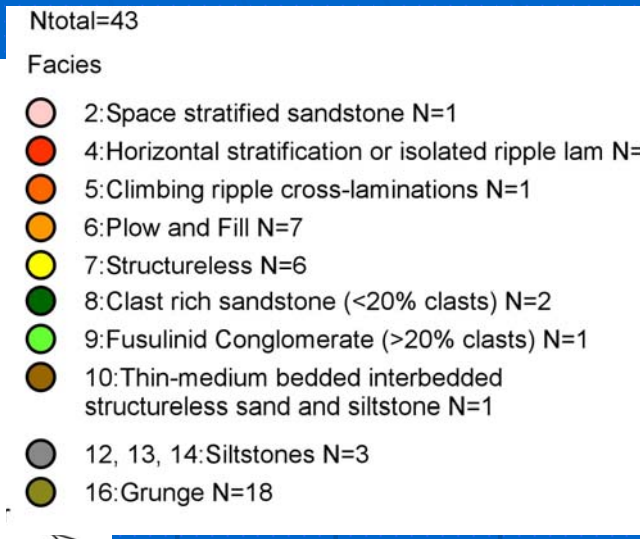
# Conspicuous increase in silty sandstone (olive green) in Upper Brushy Canyon distributary channels and lobes forming sandstone sheets

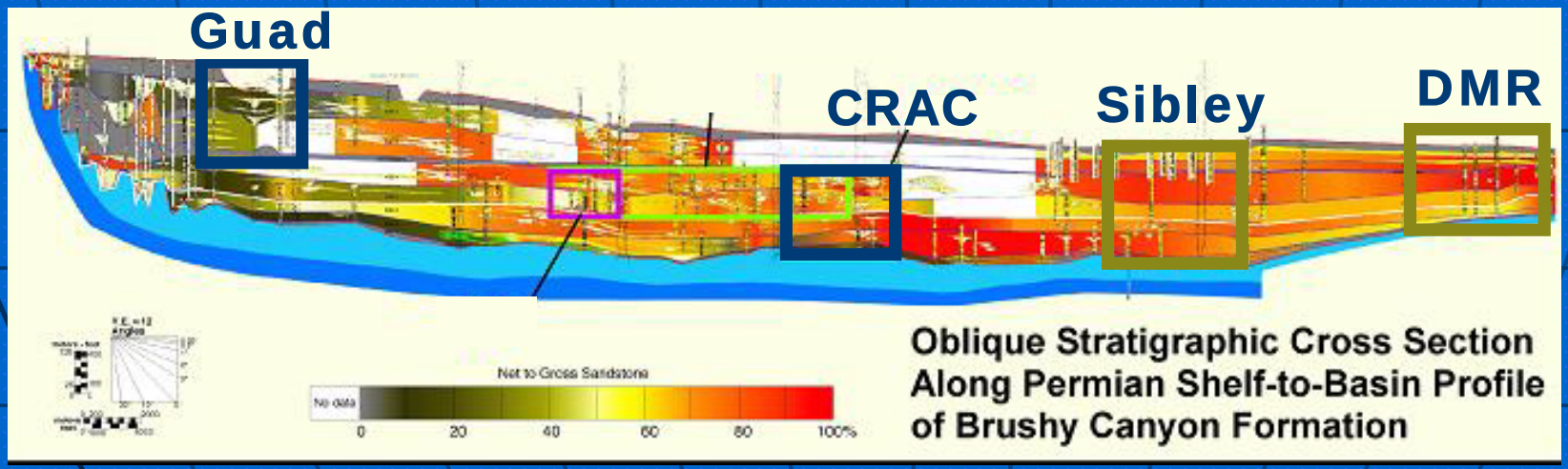



- LBC sand-silt partitioning reflects competence controlled deposition from subaqueous flows heavily influenced by inherited local topography
- UBC sand-silt mixing reflects capacity controlled deposition from more fully evolved subaqueous flows recording longer run-out lengths across smoother profile.

# Increased Feldspar, Silt Fraction, Carbonate mud, and Organic Matter Related to Hydraulic Fractionation and Longitudinal Flow Transformation

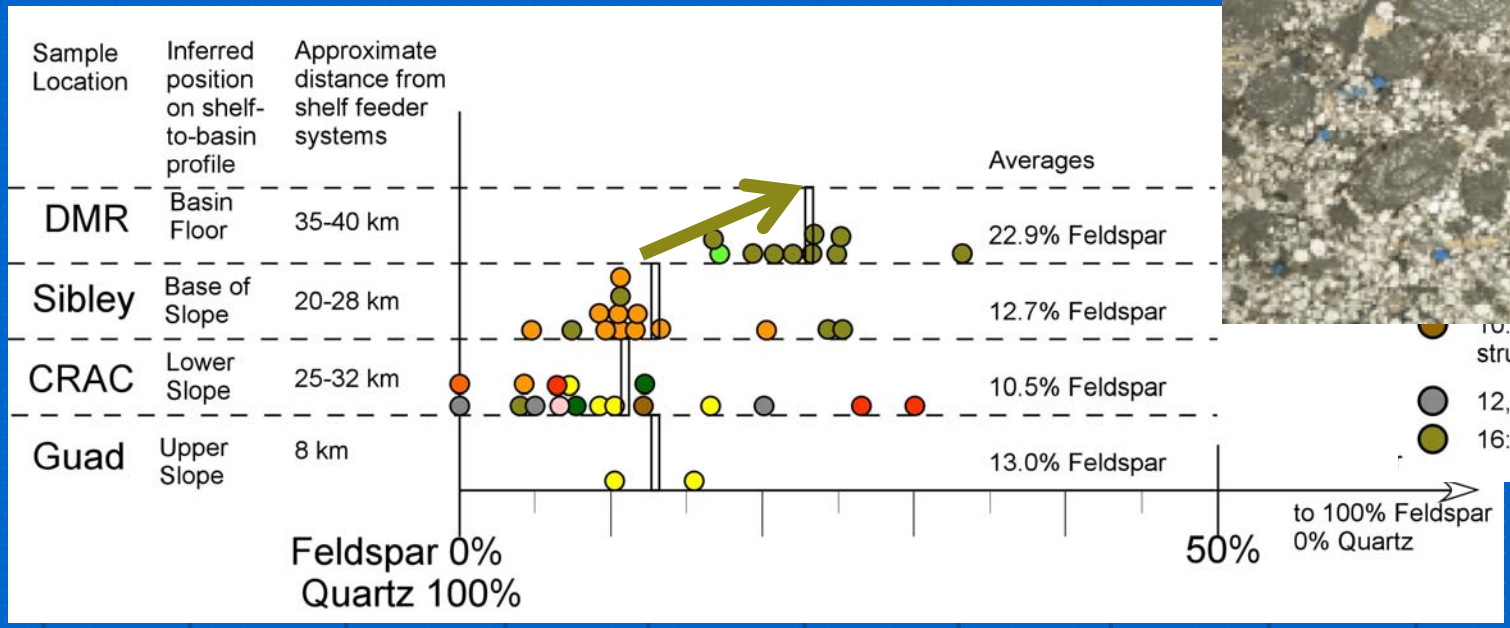


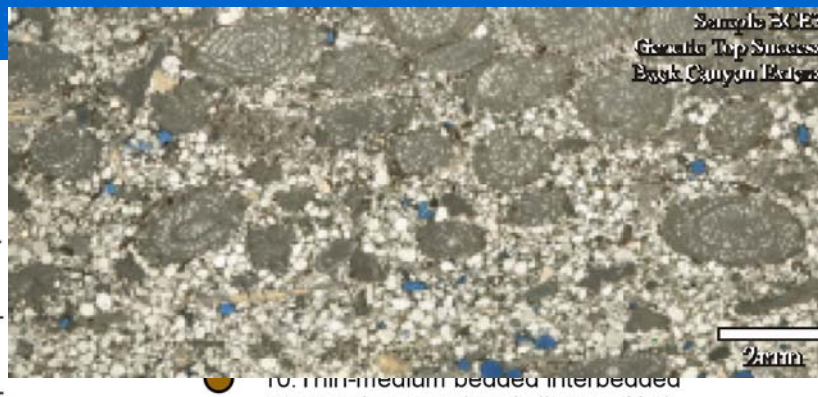




Oblique Stratigraphic Cross Section Along Permian Shelf-to-Basin Profile of Brushy Canyon Formation

# Increased Feldspar, Silt Fraction, Carbonate mud, and Organic Matter Related to Hydraulic Fractionation and Longitudinal Flow Transformation

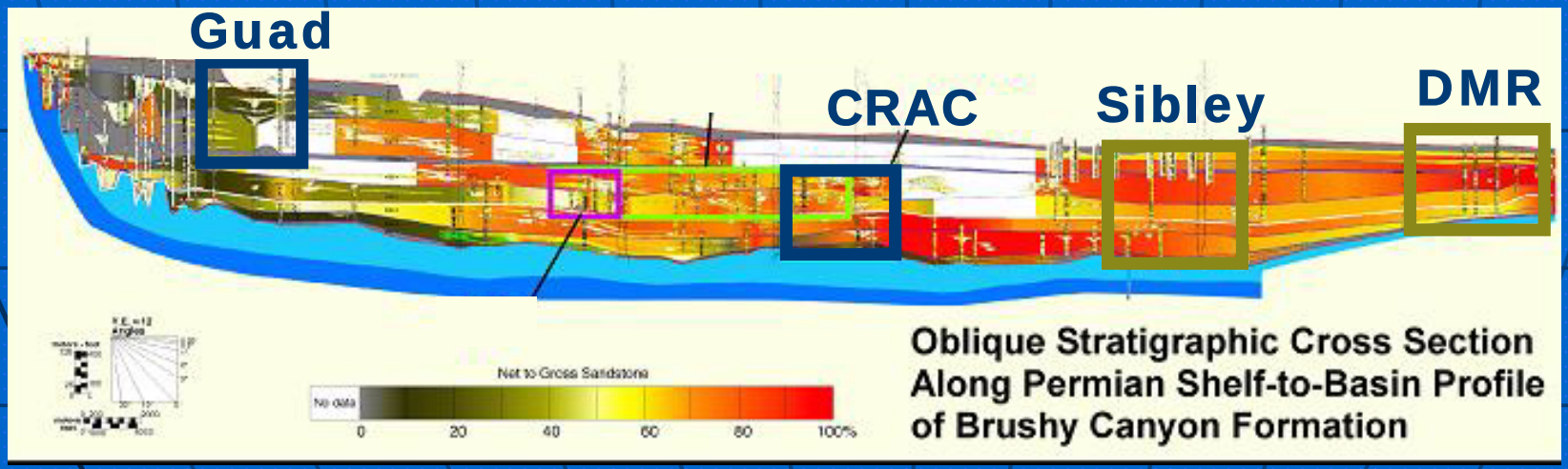


structureless sand and siltstone N=1

12, 13, 14:Siltstones N=3

16:Grunge N=18




Oblique Stratigraphic Cross Section Along Permian Shelf-to-Basin Profile of Brushy Canyon Formation

# Conclusions

- Climate control on fine sediment fraction, organic matter and laminites
- Tectonic control on timing of deposition of coarse sediment fraction and aspect ratio of basin fill
- Eustatic control related to Gondwanan deglaciation w/basin-wide sea-level change reflected in correlation of threefold stratigraphic hierarchy across seven shelf sediment sources

# Conclusions

Climate, Tectonic and Eustatic signatures best resolved from the deep-marine record, require complete basin analysis of high density data

Depositional limit of fan and lobe sedimentation produces internal changes in gradient and knick-point migration affecting submarine fan architecture

Changes in longitudinal profile affect flow behavior and basin sedimentation

Internal controls increase the uncertainty in the interpretation of external controls

# Slope and Basin Consortium Projects

## Phase IV Brushy Project (2002-2005)

Amerada Hess Corporation
BHP-Billiton
ChevronTexaco
ConocoPhillips
ExxonMobil
Kerr-McGee Corporation
Marathon Oil Company
PetroBras
Statoil
Total
Unocal Corporation

## SCReeM Project (2000-2003)

bp
BHP-Billiton
ConocoPhillips
Kerr McGee Corporation
Statoil
Unocal

## Prairie Canyon Project (2001-2004)

Amerada Hess Corporation
ChevronTexaco
ConocoPhillips
Del Rio Resources
Devon Energy
EOG Resources
Nexen
Samson Resources

## Software Contributors

ESRI
eCognition
Landmark (RC2)
Petra
Schlumberger (Petrel)
Roxar
Research Systems Inc. (ENVI)
Earth DecisionSciences GOCAD

# Slope and Basin Graduate Students

Kyle Johnson, 1998
Roger Wagerle, 2001
Jesse Melick, 2002
Syafiul Uman, 2002
Brian Romans, 2003
Noelia Baptista, 2004
Astuti Purawati, 2004
Jim Borer, 2005
Brad Sinex, 2006
Erik Kling, 2006
Safian Atan, 2006
Diah Hanggoro, 2007
Rob Amerman, 2008

Kim Stevens, 2004
Nick Delebo, 2005
Nikhom Chaiwongsaen, 2007

**Slide 8 of 49 (Page 10 of 52)**
This represents the integrated outcrop and subsurface database used for analysis of external and internal controls.
To evaluate these changes requires a robust stratigraphic framework, as illustrated by the seismic line from the Cabin Lake 3D dataset and introduced in the subsequent slides.
Return to Slide 8 (Page 10)

**Slide 13 of 49 (Page 15 of 52)**
We will view these maps in a different context when we examine the role of depositional topography on patterns of sedimentation
This is the framework upon which we will analyze the aforementioned external and internal controls on sedimentation.
Of note is the lack of overlap between values from Brushy Canyon Formation samples and values reported from both Permian *Tasmanites* green algae and Quaternary low-latitude, arid, coastal-upwelling zones.
The absence of overlap between δ13Corg values of the Brushy Canyon Formation and Quaternary values from coastal upwelling zones of low-latitude, arid settings (the Delaware Basin is also interpreted as arid, low-latitude) suggests that the Delaware Basin was not an area of active upwelling in Brushy Canyon time.
The ORS intervals are interpreted to reflect deposition of marine organic matter associated with modest rates of surface water production and eolian derived silt.
Bottom and pore water chemistry was likely dysoxic, and degradation of organic matter at the seafloor and in the sediment reduced the amount of carbon supplied to the seafloor. Not all the organic material was respired; the siltstones have an average TOC of about 1.5%. This enrichment is interpreted to reflect extreme condensation, in comparison to typical black shale facies, with respect to siliciclastic and carbonate fractions.
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Siliciclastic delivery to the Delaware Basin is characterized by two modes: (1) episodic sand delivery by sediment gravity flow and (2) settling of eolian derived silt (Fischer and Sarnthein, 1988).
Light-grey layers are dominantly gypsum; dark laminae are calcite and admixed organic matter.
Doug Kirkland, UT Dallas: “During the season of high relative humidity, more marine groundwater entered the lake through the permeable reef barrier than exited as reflux and, secondarily, as evaporation. Consequently, the lake level rose by up to several meters to sea level. The ‘refreshening’ decreased salinity and replenished dissolved CO2 – the critical nutrient limiting growth of indigenous phytoplankton. Algae proliferated, pH increased and CaCO3 precipitated. It mixed with organic matter to form a thin, dark lamina.
“The couplets are inferred to have been deposited within 1 year time based on:
(1) similarity to lacustrine varves, marine varves and tree rings;
(2) cyclicity,
(3) regularity and lateral persistence,

(4) carbon and oxygen isotopic profiles;
(5) thickness matches reasonable annual rates of evaporite deposition.

“Any hypothesis calling for a period less than or more than 1 year would be exceedingly difficult to support.

“The different varve types recur with a period of 1800–3000 years reflecting climatic changes on a millennial time scale. Millennial cycles have a period of 1800–3000 years, based on varve counts, and a typical thickness of about 4 m.

“During the season of low relative humidity, tens of cubic kilometers of water evaporated from and, secondarily, leaked out through the surrounding reef.

“Directions of prevailing northwest monsoonal winds during the Castile dry winter season and the Castile humid summer winds to the southeast.”

Magaritz et al. (1983) report δ13Corg results in the range of –28.4 to –29.1 per mil from the Bell Canyon Formation. They interpret these results to reflect ‘normal’ conditions of the oceanic-carbon cycle.

Positive shifts in both the δ13Corg and δ13Corg upsection are, therein, interpreted to reflect increased deposition of isotopically light organic matter in the Delaware Basin and, perhaps, globally.

The positive relation of isotopically light marine OC and elevated atmospheric pCO2, as hypothesized by Dean et al. (1986), does not appear to apply to marine OC of the Permian, a period of pCO2 partial pressures near modern levels (Berner and Kothavala, 2001).

Monsoon systems accompanied the formation of supercontinents such as Pangaea, with their extreme continental climates. Summer monsoons are directed onshore and produce copious amounts of rain for generation of sediment gravity flows. Winter monsoons are directed offshore and cause drought and deposition of eolian silt and increased surface water productivity.

Increased sea surface temperature increases monsoon intensity.

Times of high dust influx and reduced soil development coincided with strengthened winter monsoon conditions, which are inferred from variations in loess grain size.

Times of decreased dust accumulation and strong pedogenesis, marked by high values of magnetic susceptibility, represent times of strengthened summer monsoon conditions.

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Though the structural fabric inherited from the failed aulacogen might explain basement uplifts oriented perpendicular to the northward-directed deformation front, when combined with: eastward decreasing subsidence, regional uplift.

Basement cored uplifts in the western interior of North America points to the western and not southern plate boundary as the causal mechanism.

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Despite the tectonic control on the timing of sediment delivery to the basin, the hierarchy of stratigraphic cycles outlined in the previous slides can be correlated across the seven shelf sediment sources which point to a record of relative sea level change that can be correlated across the basin.

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Good correlation across continents for the pre-Brushy carbonates,
Record of Brushy Canyon sea level change not recorded in the shelf record.
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The positive relationship between OC enrichment and higher Ti/SI ratios, especially in the distal settings and sea level rise at third, fourth, and fifth order cycle boundaries. However, the correlation of sea level and TOC is not as strong at the scale of 5th-order cycles, as it is in the 3rd- and 4th-order cycles.
Causal relationship between sea level rise.
Shift in depocenters to slope during the retreat phase.
Sediment-starvation related to the absence of sediment-gravity-flow deposits.
Ti/Si ratio is a proxy for siliciclastic flux in traction-suspension regimes, where higher values have been interpreted to reflect greater flux of detritus.
Yet, there is no consistent relationship between TOC and any of the siliciclastic proxies on an all-encompassing sample basis.
One might expect some relationship given interpretations of siliciclastic sedimentation rate as a primary factor leading to organic enrichment (fast- Bohacs et al., 2005; slow – this study).
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Slope channel architecture documented from middle Brushy Canyon outcrops in the central Delaware Mountains and captured in the RAP outcrop reservoir model. The multilateral and multistory architecture at the Popo Fault Blocks is shown here and in subsequent displays. The Fan 5 multistory channel complex at Colleen Canyon is considered representative of the channelized sheet architecture.
The timing and style of channel deposition in major versus minor sandstone fairways are controlled, to a large-extent, by fairway-scale compensation, related to 5th-order IGR patterns. In general, major fairways, dominated by confined channel complexes, are the primary site for deposition and build substantial topography during the growth phase. During the retreat phase, flows are preferentially focused into the lower, minor fairway areas, where deposition is dominated by weakly confined, depositional channels.
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## References


Baptista, N., 2004, Deep-water depositional patterns and sequence stratigraphic framework of the Permian Brushy Canyon Formation across the Delaware Basin, West Texas and Southeastern New Mexico, USA [Unpublished Master's Thesis]: Colorado School of Mines, 181 p.

Berner, R. A., and Kothavala, Z., 2001, GEOCARB III: A Revised Model of Atmospheric CO2 over Phanerozoic Time: American Journal of Science, v. 308, p. 182–204

Blakely, Ronald, 2005, Paleogeography and geologic evolution of Ancestral Rocky Mountains (Images from poster session at GSA Annual Meeting, Salt Lake City, October, 2005), http://jan.ucc.nau.edu; http://jan.ucc.nau.edu/~rcb7/garm278.jpg.

Bohacs, K.M., G.J. Grabowski, Jr., A.R. Carroll, et al., 2005, Production, destruction, and dilution; the many paths to source-rock development *in* N.B. Harris, ed., The deposition of organic-carbon-rich sediments; models, mechanisms, and consequences: Special Publication Society for Sedimentary Geology, v. 82, p. 61-101.

Dean, W.E., MA. Arthur, and G.E. Claypool, 1986, Depletion of 13C in Cretaceous marine organic matter: source, diagenesis, or environmental signal?: Marine Geology, v. 70, p. 119-157.

Fitchen, W.M., 1997, Carbonate sequence stratigraphy and its application to hydrocarbon exploration and reservoir development, *in* Palaz, I., and Marfurt, K.J., eds., Carbonate Seismology, Society of Exploration Geophyscists, Geophysical Development Series, no. 6, p. 121–178.

Fischer, A.G. and M. Sarnthein, 1988, Airborne silts and dune-derived sands in the Permian of the Delaware Basin: Journal of Sedimentary Petrology, v. 58, p. 637-643.

Garfield, T. R., R.T. Beaubouef, D.C. Jennette, D.C. Mohrig, and A.R. Sprague, 2000, New insight into the three-dimensional architecture of deep-water facies: The product of a multidisciplinary approach, *in* C. Appi, R.S. F. d'Avila and A. R. Viana, eds., Deep-Water Sedimentation: Challenges for the Next Millennium: 31st International Geological Congress Workshop Proceedings, Addendum p. 1-9.

Garfield, T.R., R.T. Beaubouef, and D.K. Sickafoose, 2000, High-resolution Sequence Stratigraphy: A tool for improved reservoir delineation in passive margin settings — Examples from the divergent margin of the South Atlantic Salt Basin: 31st International Geological Congress, Abstracts volume - CD.

Gibbs M.T., P.M. Rees, J.E. Kutzbach, A.M. Ziegler, P.J. Behling, and D.B. Rowley, 2002, Simulations of Permian climate and comparisons with climate-sensitive sediments: Journal of Geology, v. 110, p. 33–55.

Hays, P.D., and T.T. Tieh, 1992, Organic geochemistry and diagenesis of the Delaware Mountain Group west Texas and southeast New Mexico, *in* D.W. Cromwell, M.T. Moussa, and L.J. Mazzullo, eds., Transactions Southwest Section American Association of Petroleum Geologists, 1992 convention: Southwest Section American Association of Petroleum Geologists, publication SWS 92-90, pp. 155-175.

Hays, P.D., S.D. Walling, and T.T. Tieh, 1996, Organic and authigenic mineral geochemistry of the Permian Delaware Mountain Group, west Texas: Implications for chemical evolution of pore fluids, *in* Crossey, L.J., Loucks, R., and Totten, M.W., eds., Siliciclastic Diagenesis and Fluid Flow: Concepts and Applications: Tulsa, OK, SEPM Special Publication No. 55, p. 163-186.

Johnson, Kyle R., 1998, Outcrop and reservoir characterization of the Brushy Canyon Formation : Guadalupe Mountains National Park, West Texas, and Cabin Lake Field, Eddy county, New Mexico: Colorado School of Mines M.S. Thesis, 256 p.

Kerans, C., and W.M. Fitchen, 1995, Sequence hierarchy and facies architecture of a carbonate-ramp system: San Andres Formation of Algerita Escarpment and Western Guadalupe Mountains, West Texas and New Mexico, Report of Investigations No. 235, Bureau of Economic Geology, 86 p.

Kerans, C., W.M. Fitchen, M.H. Gardner, M.D. Sonnenfeld, S.W. Tinker, and B.R. Wardlaw, 1992, Styles of sequence development within uppermost Leonardian through Guadalupian strata of the Guadalupe Mountains, Texas and New Mexico, *in* D.H. Murk and B.C. Curran, , eds., Permian Basin Exploration and Production Strategies—Applications of Sequence Stratigraphic and Reservoir Characterization Concepts, West Texas Geological Society, Symposium, Publication 92-91, 117 p.

Magaritz, M., R.Y. Anderson, W.T. Holser, E.S. Saltzman, and J.H. Garber, 1983, Isotope shifts in the Late Permian of the Delaware Basin, Texas, precisely timed by varved sediments: Earth and Planetary Science Letters, v. 66, p. 111-124.

Meissner, F.F., 1972, Cyclical sedimentation in Middle Permian strata of the Permian basin, *in* Elam, J.G., and Chuber, S., eds., Cyclic sedimentation in the Permian basin (2nd edition): West Texas Geological Society Publication 72-60, p. 203–232.

Paola, Chris, 2010, Braided stream sediment flume experiment: http://www.encyclopedia.com/video/WDXs2LEe0Gk-braided-stream-sediment-flume-experiment.aspx (assessed February 8, 2010)

Parrish, J.T. and F. Peterson, 1988, Wind directions predicted from global circulation models and wind directions determined from aeolian sandstones of the western United States:. Sedimentary Geology, v. 56, p. 261–282.

Peterson, F., 1988, Pennsylvanian to Jurassic aeolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207–260.

Press, F., and Siever, R., 1998, Earth (4th ed.): New York: Freeman Press.

Rees, P.M., M.T. Gibbs, A.M. Ziegler, J.E. Kutzbach, and P.J. Behling, 1999, Permian climates: Evaluating model predictions using global paleobotanical data: Geology, v. 27, p. 891-894.

Romans, B., 2003, Sedimentation patterns of a Permian basinal cycle, Upper Cutoff, Brushy Canyon, and lower Cherry Canyon formations, western Delaware Basin, west Texas and southeastern New Mexico [Unpublished Master's Thesis]: Colorado School of Mines, 175 p.

Ross, C.A., and J.R.P. Ross, 1985, Late Paleozoic depositional sequences are synchronous and worldwide: Geology, v. 13, p. 194–197.

Ross, C.A., and J.R.P. Ross, 1987, Late Paleozoic sea levels and depositional sequences, *in* Ross, C.A., and Haman, D., eds., Timing and Depositional History of Eustatic Sequences: Constraints on Seismic Stratigraphy: Cushman Foundation for Foraminiferal Research, Special Publication 24, p. 137–149.

Yang, K.M., and S.L. Dorobek, 1992, Mechanisms for Late Paleozoic synorogenic subsidence of the Midland and Delaware basins, Permian Basin, Texas and New Mexico, *in* Mruk, D.H., and Curran, B.C., eds., Permian Basin Exploration and Production Strategies: Applications of Sequence Stratigraphic and Reservoir Characterization Concepts: West Texas Geological Society, Publication 91, p. 45–60.

Yang, K.M., and S.L. Dorobek, 1995, The Permian Basin of West Texas and New Mexico: Flexural modeling and evidence for lithospheric heterogeneity across the Marathon Foreland, *in* Dorobek, S., and Ross, J., eds., Stratigraphic Evolution of Foreland Basins, SEPM, Special Publication 52, p. 37–53.

Ye, Qiucheng, and Charles Kerans, 1996, Reconstructing Permian eustacy from 2-D backstripping and its use in forward models, *in* DeMis, W. D., and Cole, A. G., eds., The Brushy Canyon play in outcrop and subsurface: concepts and examples: guidebook: Permian Basin Section, SEPM, Publication 96-38, p. 69–74.