PS Depositional Controls and Sequence Stratigraphy of Lacustrine to Marine Transgressive Deposits in an Active Rift Basin, Lower Cretaceous Bluff Mesa, Indio Mountains, West Texas*

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Search and Discovery Article #10954 (2017)**
Posted June 19, 2017

*Adapted from poster presentation given at AAPG 2017 Annual Convention and Exhibition, Houston, Texas, United States, April 2-5, 2017

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Abstract

Successful hydrocarbon exploration in former rift basins of the South Atlantic pre-salt has generated interest in understanding depositional, diagenetic, and stratigraphic controls on pre-salt deposits. However, most studies to date have focused on attributes and controls on pre-salt lacustrine carbonate reservoir systems and little work has been done on the overlying marine sealing facies. Currently our standard sequence stratigraphic model of marine transgression of rift systems involves a single pulse of marine flooding over fluvially incised valleys resulting in backstepping of fluvial and estuarine siliciclastic facies within the erosionally confined zone of an incised valley. However, the pre-salt systems of the South Atlantic involve deep and broad alkaline lakes containing microbial carbonate facies that were deposited on rift structurally generated geomorphic surfaces. Using an outcrop analogue, this study aims to provide a depositional and stratigraphic model for marine transgression of lacustrine rift basin sediments that are similar in age, tectonic regime, and climatic setting to the pre-salt sealing facies of the South Atlantic.

The Lower Cretaceous Bluff Mesa Formation was deposited on the eastern margin of the Chihuahuan Trough failed rift and is exposed within multiple Laramide-age thrust panels in the Indio Mountains of West Texas. The mixed carbonate-siliciclastic system thins from 360m to 220m across the study area and contains six fourth-order sequences that record the transition from fluvio-lacustrine to shallow marine deposition. Sequences 1-2 are characterized by lacustrine siltstones or thin marine wackestones during highstands and fluvial-lacustrine sandstones during lowstands. Sequences 4-6 are composed of exclusively marine facies characterized by thick ooid grainstones and fossiliferous packstones deposited during highstands and shoreface to shelfal sandstones during lowstands. Sequence 3 records a significant rise in base level and the onset of marine deposition with lowstand fluvial sandstones overlain by thick marine carbonates during highstand. The presence of thin marine limestones in sequences 1and 3 suggest that periodic marine incursion occurred during highstands but the basin was still primarily an enclosed rift lake. This idea is supported by analysis of carbonate-associated sulfate from septarian nodules of lacustrine and marine origin. The observed succession of mixed terrestrial-marine sequences suggests transgression of rift basins involves multiple pulses.

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Abstract

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The Lower Cretaceous Bluff Mesa Formation was deposited on the eastern margin of the Chihuahuan Trough failed rift and is exposed within multiple Laramide-age thrust panels in the Indio Mountains of West Texas. The mixed carbonate-siliciclastic system thins from 360m to 220m across the study area and contains 6 fourth-order sequences that record the transition from fluvio-lacustrine to shallow marine deposition. Sequences 1-2 are characterized by lacustrine siltstones or thin marine wackestones during highstands and fluvial-lacustrine sandstones during lowstands. Sequences 4-6 are composed of exclusively marine facies characterized by thick ooid grainstones and fossiliferous packstones deposited during highstands and shoreface to shelfal sandstones during lowstands. Sequence 3 records a significant rise in base level and the onset of marine deposition with lowstand fluvial sandstones overlain by thick marine carbonates during highstand. The presence of thin marine limestones in sequences 1and 3 suggest that periodic marine incursion occurred during highstands but the basin was still primarily an enclosed rift lake. This idea is supported by analysis of carbonate associated sulfate from septarian nodules of lacustrine and marine origin. The observed succession of mixed terrestrial-marine sequences suggests transgression of rift basins involves multiple pulses.

Objectives

1. Document spatial and temporal trends in lithofacies distributions, geobody geometries and cyclicity in order to construct a sequence stratigraphic framework for the Bluff Mesa.

2. Compare the model with predictions made using the standard sequence stratigraphic model as well as the rift model proposed by Martins-Neto and Catuneanu (2010).

Methods

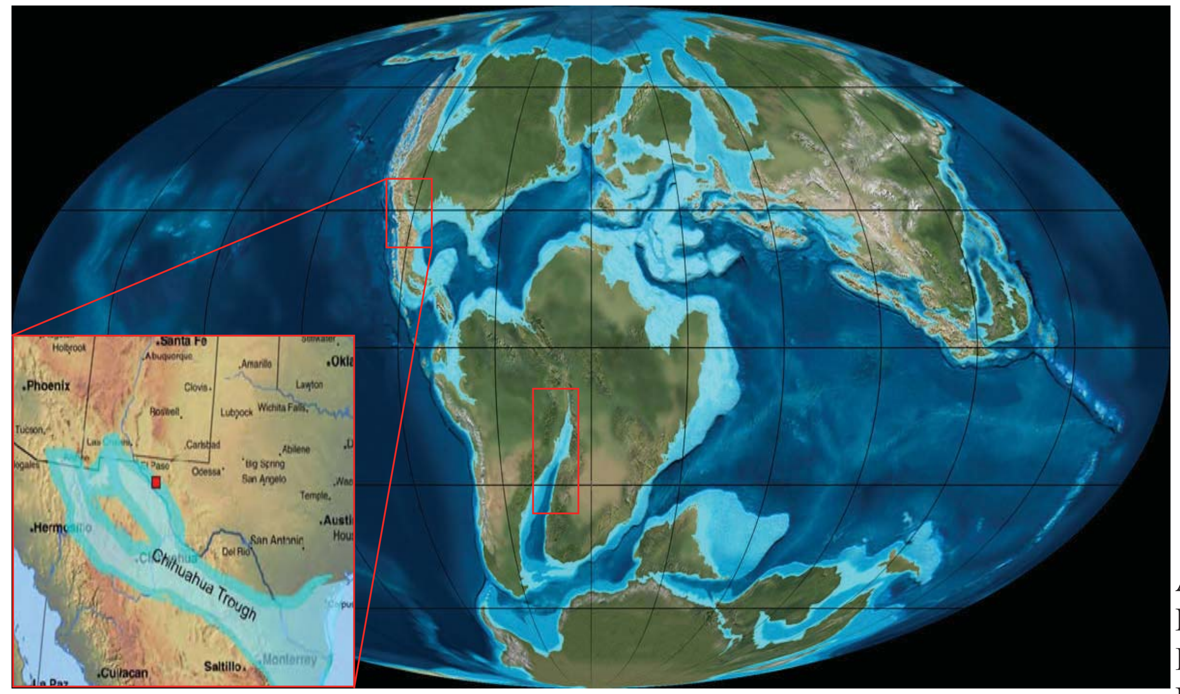
Outcrop Analysis 5 stratigraphic sections were measured documenting lithology, geobody geometries, sequence boundaries, and structural features.

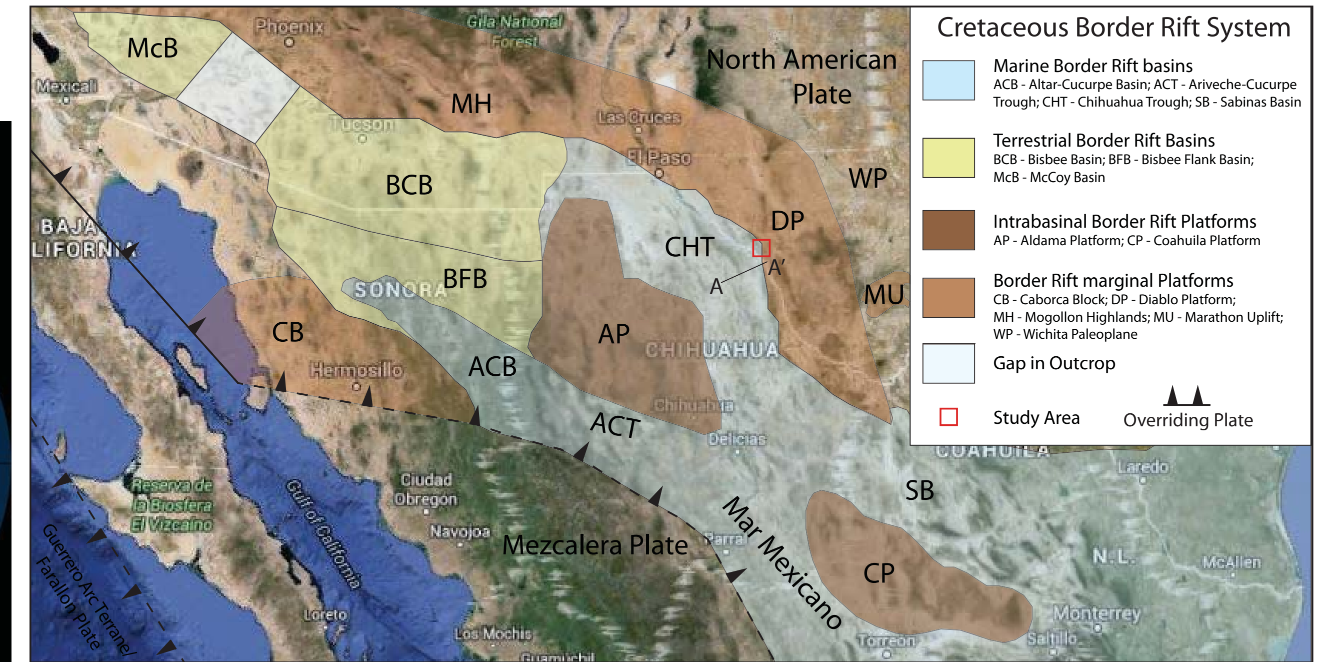
Aerial Photography Aerial photos were taken using a go pro camera attached to a 3DR Solo drone and were processed using Agisoft PhotoScan.

Petrographic Analysis Thin section analysis documented faunal assemblages, mineralogy, sedimentary structures, and diagenetic features.

Geochemical Analysis Isotopic sulfur compositions of septarian concretions were obtained by isolating carbonate associated sulfate

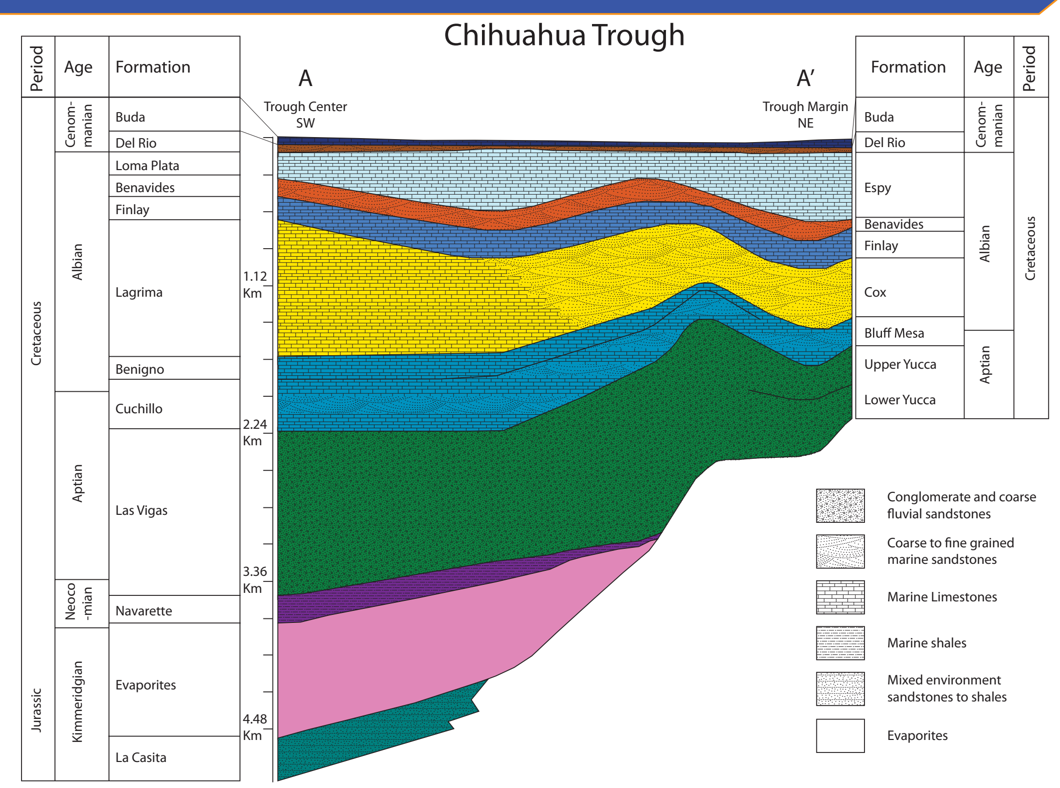
Chihuahua Trough

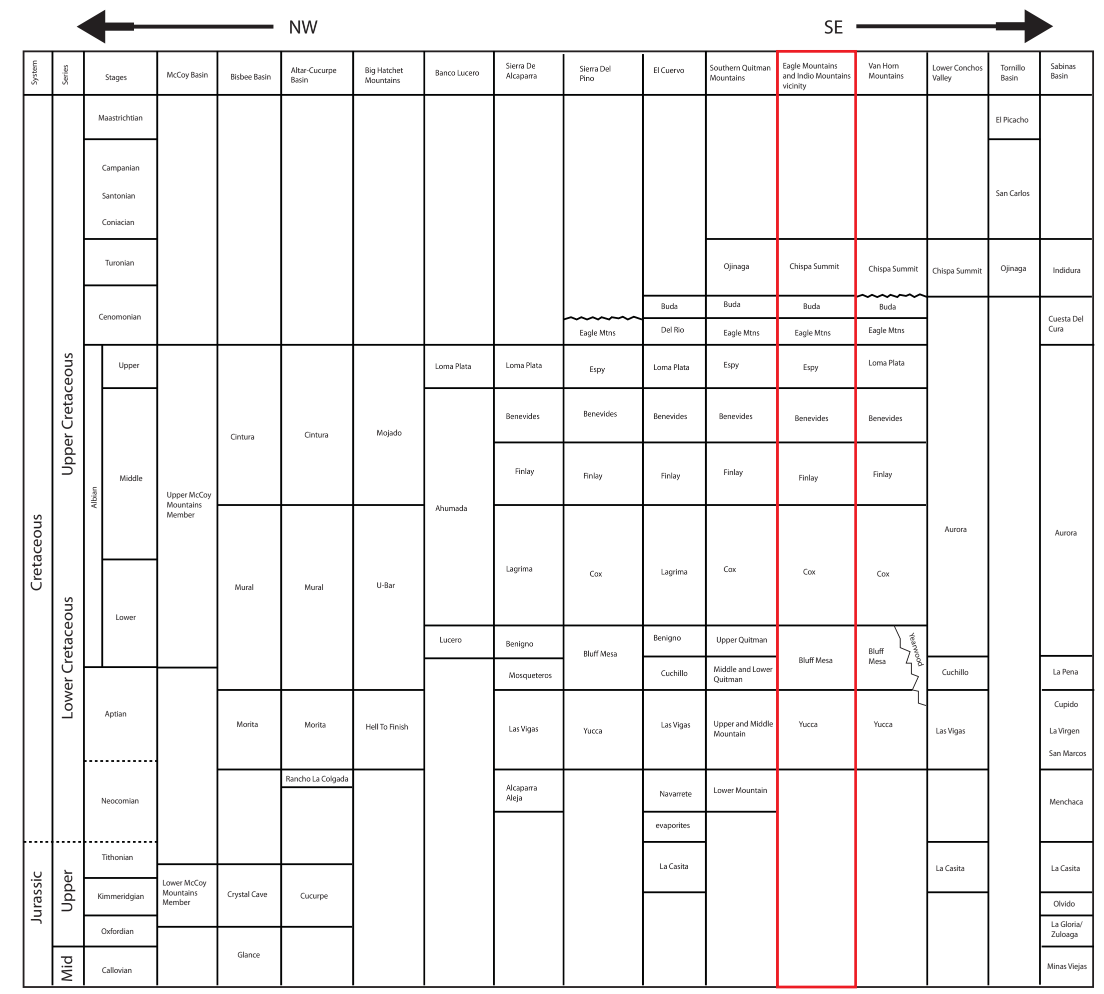


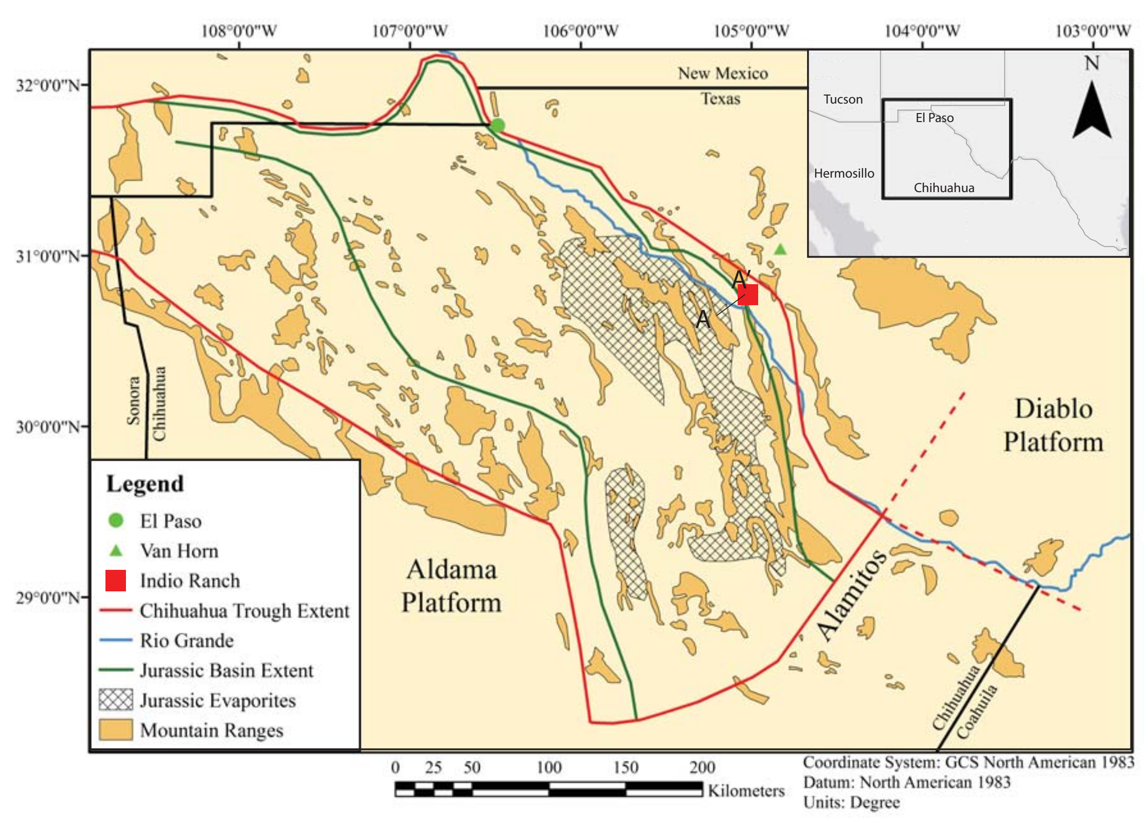


Above: Basins and platforms of the Cretaceous Border Rift System during the Jurassic. Modified from Dickinson and Lawton (2001), Stern and Dickinson (2010), and Mauel et al. (2011).
Left: The Chihuahua Trough and the South Atlantic Rift during the Cretaceous (120 MA). Modified from Blakey (2003) and Budhathoki et al. (2010).

Stratigraphy and Evaporite Distribution



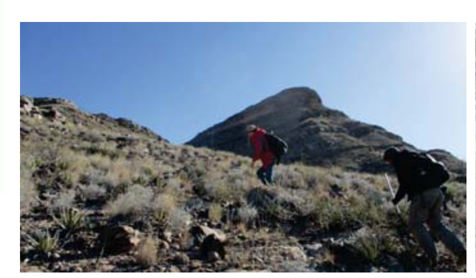


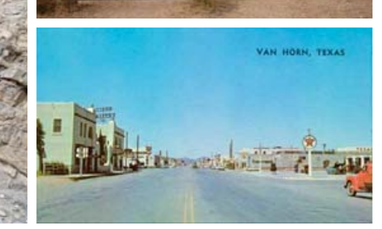


Above: Regional stratigraphy of the Chihuahua Trough from southwest (trough center) to northwest (trough margin).

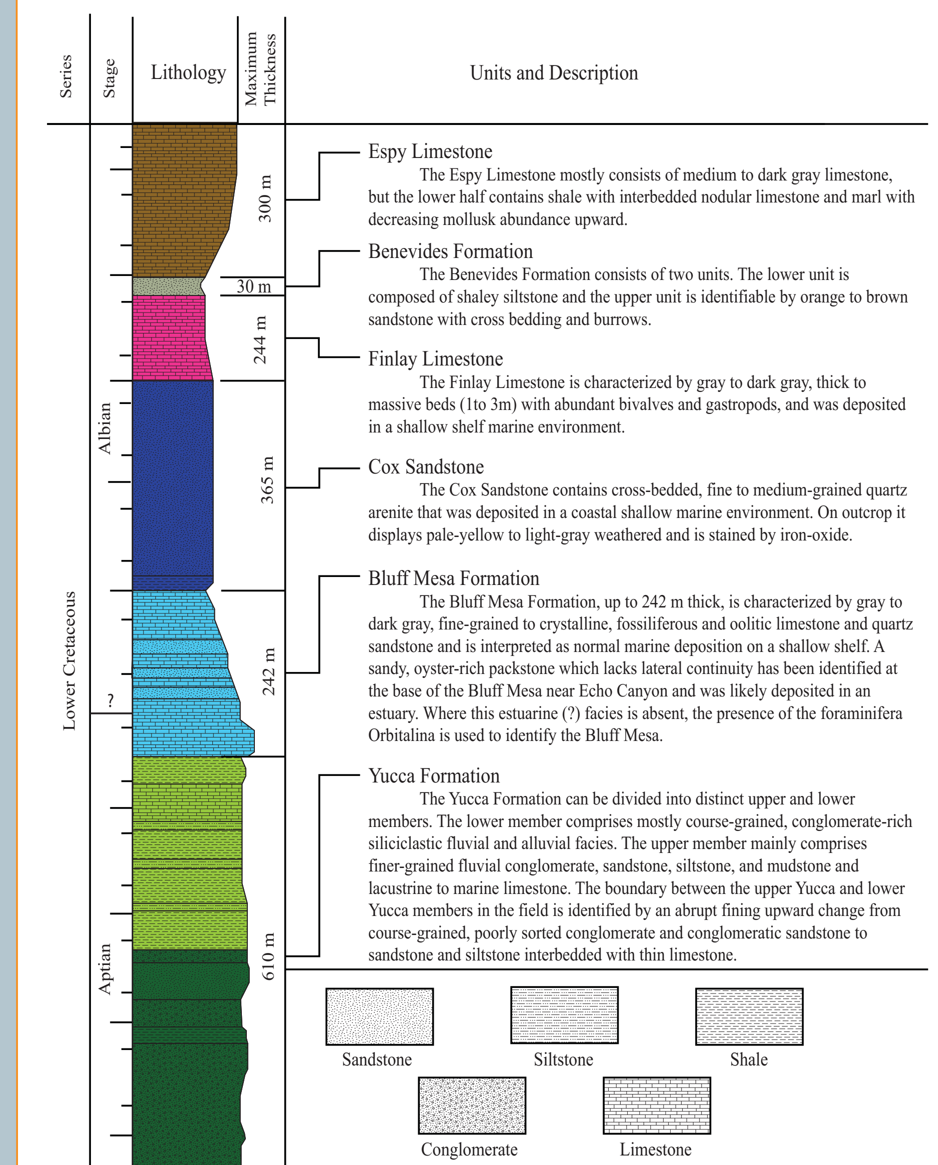
Top Left: Cross-section showing typical Cretaceous syn-rift sediment distributions from the trough center to the northeast margin. Location of cross-section in figure to the left. Modified from Underwood (1962), Haenggi (2002), and Budhathoki (2013).

Left: Distribution of Jurassic evaporites within the Chihuahua Trough. Modified from Haenggi (2002).

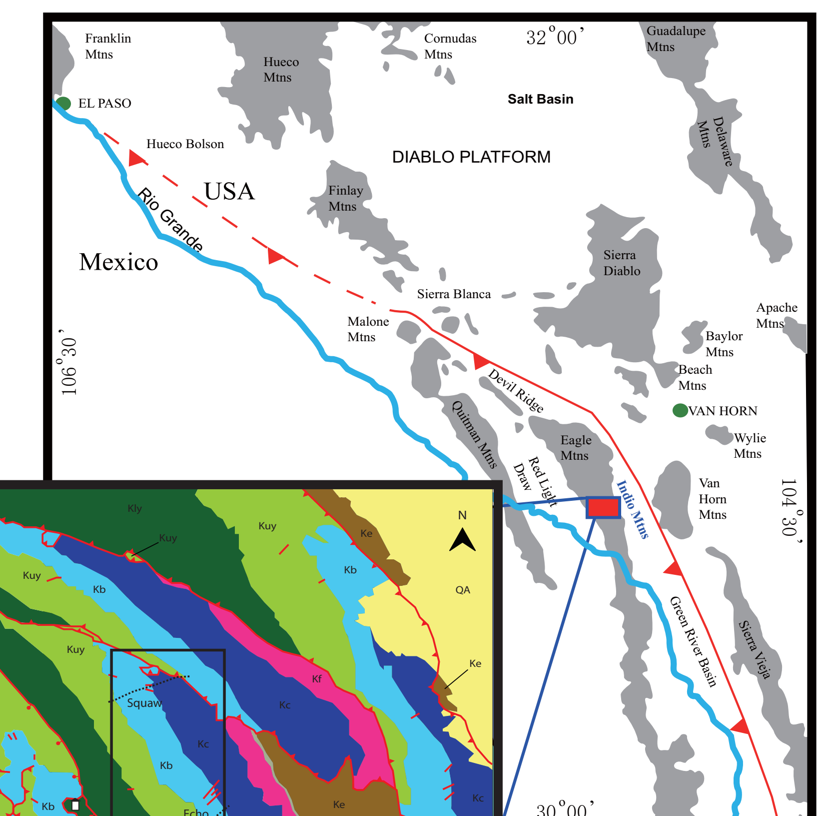


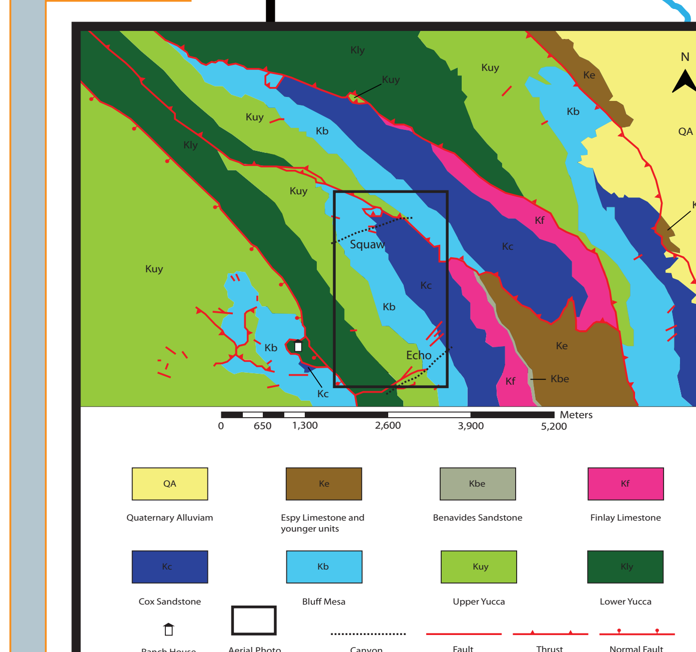


Study Area



Above: Cretaceous syn-rift stratigraphy of the Indio Mountains. Modified from Li (2014).





Regional mountain belts and detailed Indio Mountains geologic map (inset). Aerial photo is located on panel #3. Modified from Page (2011) and Li (2014).

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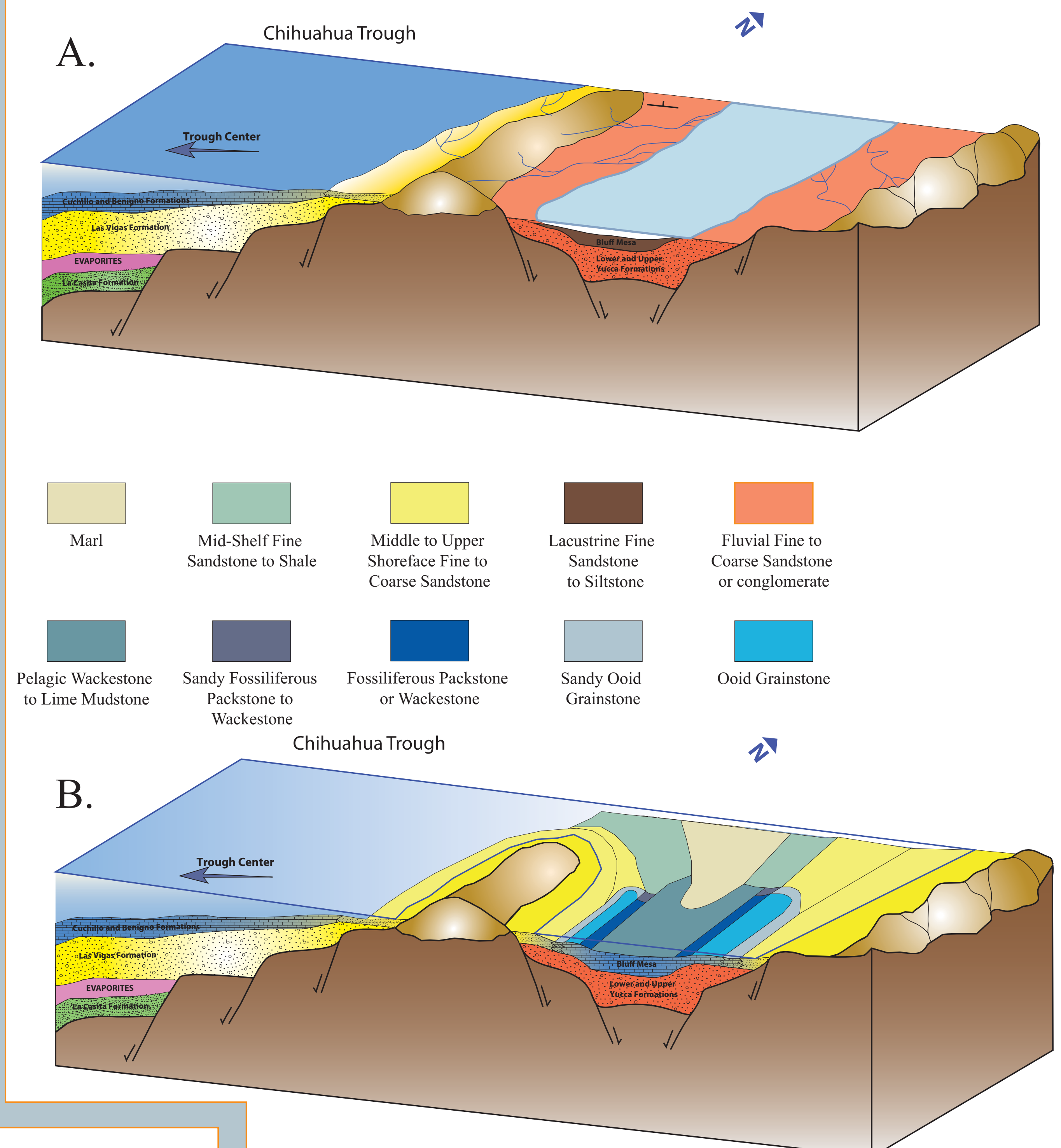
Facies Table

Lithology	Code	Color and Weathering Profile	Clast/Grain Type	Bedding	Sedimentary Structures	Depositional Interpretation
Conglomerate	Fc	Light to dark tan, gray, maroon	Medium – coarse detrital quartz matrix, chert pebbles, chalcedony, and limestone clasts	Medium – massive lenticular	Trough cross bedded, inclined cross strata	Fluvial Channel
Fine – Coarse Quartz Arenite	Fs	Light tan, light beige, light gray, pinkish; well exposed/ledge former	Fine – coarse detrital quartz, rare chert pebbles, mudstone clasts and limestone clasts	Thin – thick lenticular	Channelized, trough crossbedding, horizontal laminae, inclined laminae, soft sediment deformation, burrows, ripple cross laminae, overturned troughs	Fluvial channel and point bar
Silt – fine grained quartz arenite	Ls	Sandstone: medium to dark brown; siltstone: tan to dark green, dark brown, poorly exposed	Silt – fine detrital quartz, chert, rare limestone clasts	Thin – thick tabular or lenticular	Burrowed/mottled, horizontal laminae, ripple cross laminae, and rare lenses of limestone pebbles	Lacustrine littoral
Fine grained quartz arenite	Ln	Light red to maroon, very poorly exposed	Fine detrital quartz and micritic septarian nodules	Thick – massive tabular	Structureless	Lacustrine littoral
Ooid grainstone	Cg	Dark gray, rusty orange striping, grayish green; well exposed/ledge former, blocky weathering pattern	Ooids, peloids, echinoids, crinoids, brachiopods, bivalves, gastropods, forams, micrite rip up clasts; 5-10% detrital quartz by volume	Medium – massive lenticular	Trough cross stratified, chickenwire fabrics, burrows, barforms can have erosive bases	Shallow open marine
Fossiliferous wackestone - packstone	Cf	Blue, dark blue, gray; well exposed/ledge former, nodular weathering pattern	Larger intact fossils than Cg, peloids, echinoids, crinoids, brachiopods, bivalves, gastropods, forams, and ostracods in a micritic matrix; 5-10% detrital quartz by volume	Thin – massive lenticular, can be wavy	Chickenwire fabrics and shell-rich bands	Shallow open marine; basinward from Cg
Sandy limestones	Cs	Light to dark gray, dark tan; moderate weathering and exposures	Ooids, peloids, echinoids, crinoids, brachiopods, bivalves, gastropods, forams, micrite rip up clasts; 20-60% detrital quartz by volume	Medium – thick, lenticular	Burrows, chickenwire fabrics, shell-rich bands ripple cross laminae, possible ray feeding trace	Shallow open marine; landward from Cg
Marl	Cm	Gray, tan with black splotches; poorly exposed	Very fine detrital quartz and lime mud, rare micritic limestone nodules or clasts	Thin - massive	Structureless	Normal marine mid-shelf basinward from Cg, Cf, and Cs
Fine – coarse quartz arenite	Ss	Sandstones: light gray, off-white, black and white speckles, can be tan to orange in thin bedded exposures; moderately weathered; Siltstones: Tan, khaki, olive green, dark green approaching black, dark brown, reddish brown; generally friable and poorly exposed	Fine – coarse detrital quartz; phosphate, rare brachiopod and gastropod fragments	Thin – massive lenticular or tabular	Trough cross stratified, inclined laminae, planar laminae, ripple laminae, overturned troughs, channelized, hummocks and swales, burrows	Middle shoreface, upper shoreface, and foreshore
Shell-rich Conglomerate	Sc	Light to dark brown, dark gray	Limestone pebbles and rip up clasts, chert pebbles, bivalve and brachiopod fragments in a coarse detrital quartz matrix	Thick – massive lenticular	Channel scours, inclined laminae	Shallow marine channel
Shale – fine grained sandstone	Ps	Tan or khaki with green undertones, faded olive green, dark olive green; poorly exposed	Fine detrital quartz, rare gastropods, chert, and shale clasts	Thin – medium lenticular or tabular	Horizontal laminae, inclined laminae, symmetrical ripples, mud drapes, can be burrowed/mottled	Normal marine mid-shelf
Pelagic Wackestone	Pf	Dark olive green with orange tints, blue-green; moderately exposed, nodular weathering pattern	Bivalves, brachiopods, ostracods, echinoids, forams, gastropods, and rare detrital quartz in a micrite matrix	Thin to massive lenticular, can be wavy	Wavy laminae, possible ripple laminae	Normal marine mid-shelf
Lime mudstone	Pm	Dark gray, dark green; poorly exposed	Rare detrital quartz, forams, and bivalves in a micrite matrix	Medium	Structureless	Normal marine mid-shelf

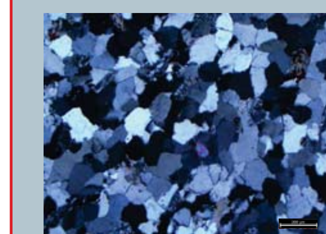
Facies Associations

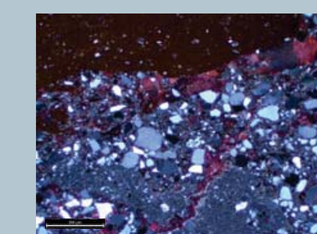


General depositional environments during fluvio-lacustrine deposition (A) and post-transgression marine deposition (B).


Crossbedded fluvial conglomerate


Stacked fluvial channels with erosive concave-up bases


Typical fluvial sandstone composed of highly compacted detrital quartz and rare chert and zircons

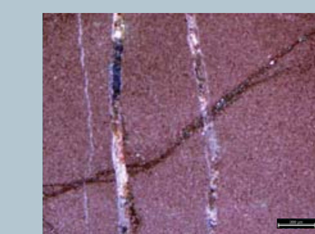

Angular limestone and shale rip-up clasts in a fluvial conglomerate

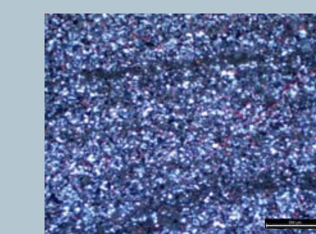

Trace fossils and burrows in a lacustrine siltstone (plan view)


Lacustrine nodule-bearing fine grained sandstone overlain by a competent tabular bed


Ripple laminated fine-grained sandstone with mottled tops

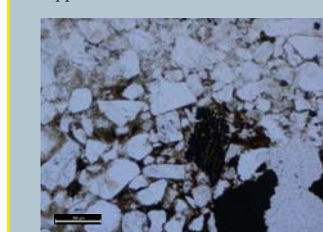

Septarian concretions weathering out of a fine-grained lacustrine sandstone

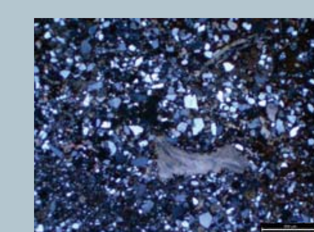

Vein-filling calcite cross-cutting micrite matrix and an immature septarian crack in a lacustrine septarian concretion


Fine ripple laminae typical of lacustrine facies in the study area


Laminated foreshore sandstone overlying a trough crossbedded upper shoreface sandstone

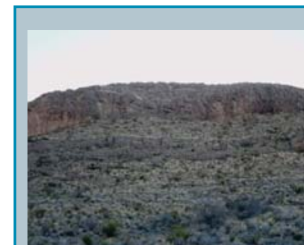

Hummocks and swales typical of the middle shoreface environment


Plant material in a medium grained sandstone indicating proximity to the shoreline

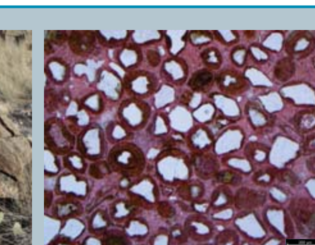

Pelecypod shell fragment in a fine to medium-grained shoreface sandstone

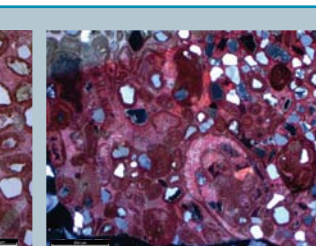

Heavily burrowed shoreface sandstone


Slightly asymmetric channel fill with a basal lag

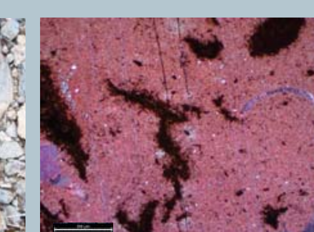

Prograding barforms of fossiliferous packstone (lower outcrop) and massive ooid grainstone

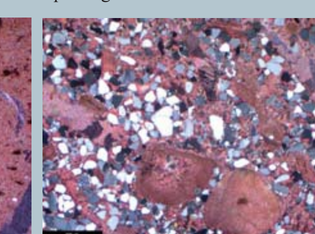

Crossbedded ooid grainstone with chickenwire fabric


Ooids in different stages of formation nucleating primarily on sub-angular quartz grains


heavily micritized grains and ooids

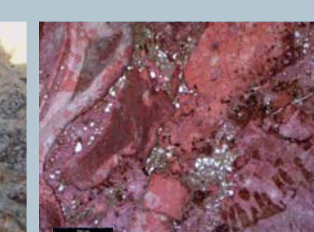

Diverse intact faunal assemblage including pelecypods, gastropods, and benthic foraminifera in a micrite matrix


Fabric-selective organic staining in a wackestone


Echinoid and pelecypod fossil grains within a quartz-rich matrix


Sandy ooid grainstone overlying medium-grained sandstone

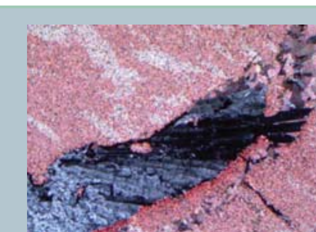

Intensely bored pelecypods in close proximity to intact shells

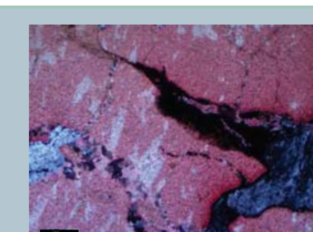

Extensive borings on pelecypod fossils associated with a transgressive lag deposit


Alternating layers of replacive calcite associated with a poorly preserved sponge


Irregular labyrinthine pore structure of an unidentified sponge (*Corynella Mexicana*?)

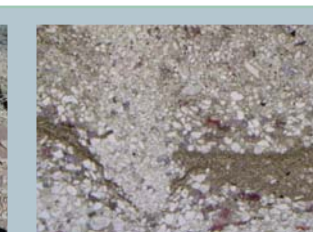

Symmetric wave ripples in a fine-grained sandstone


Bladed silica cement that has replaced gypsum in a septarian concretion

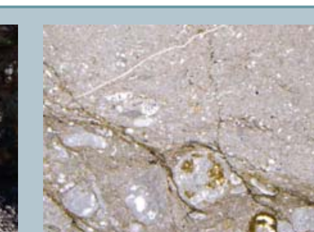

Silica cement nucleating in the center of a well developed septarian crack and forcing organic matter into veins


Septarian concretions weathering out of a fine-grained marine sandstone with long axis perpendicular to bedding


Coarsening-upward parasequences composed of shale grading into well cemented siltstone


Soft sediment deformation of laminae separating deposits of different grain size

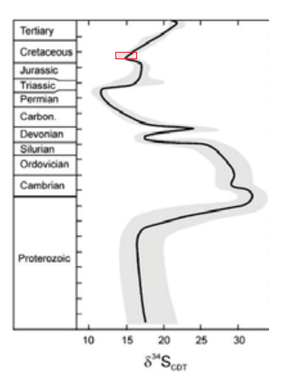

Marl-wackestone parasequence overlying marine shale


Mid-shelf wackestone containing planktonic foraminifera


Parasequences composed of marl coarsening-up into wackestone

Geochemistry

Sample	ppm	δ34S	Observations	Interpretation
BM-4	172	13.6	green in hand sample, found in fine grained marine sandstone	δ34S is similar to expected values for early Albian seas
BM-0	241	18.7	red to tan but can have green tints in basinward samples, found in fine lacustrine sand above initial marine transgression	significantly higher sulfur content than other lacustrine samples and color change in basinward samples suggests minor marine influence on lacustrine deposition
L-2	11	17.1	red to tan, found in fine lacustrine sand in the Upper Yucca	extremely low sulfur content suggests a lack of marine influence on lacustrine deposition

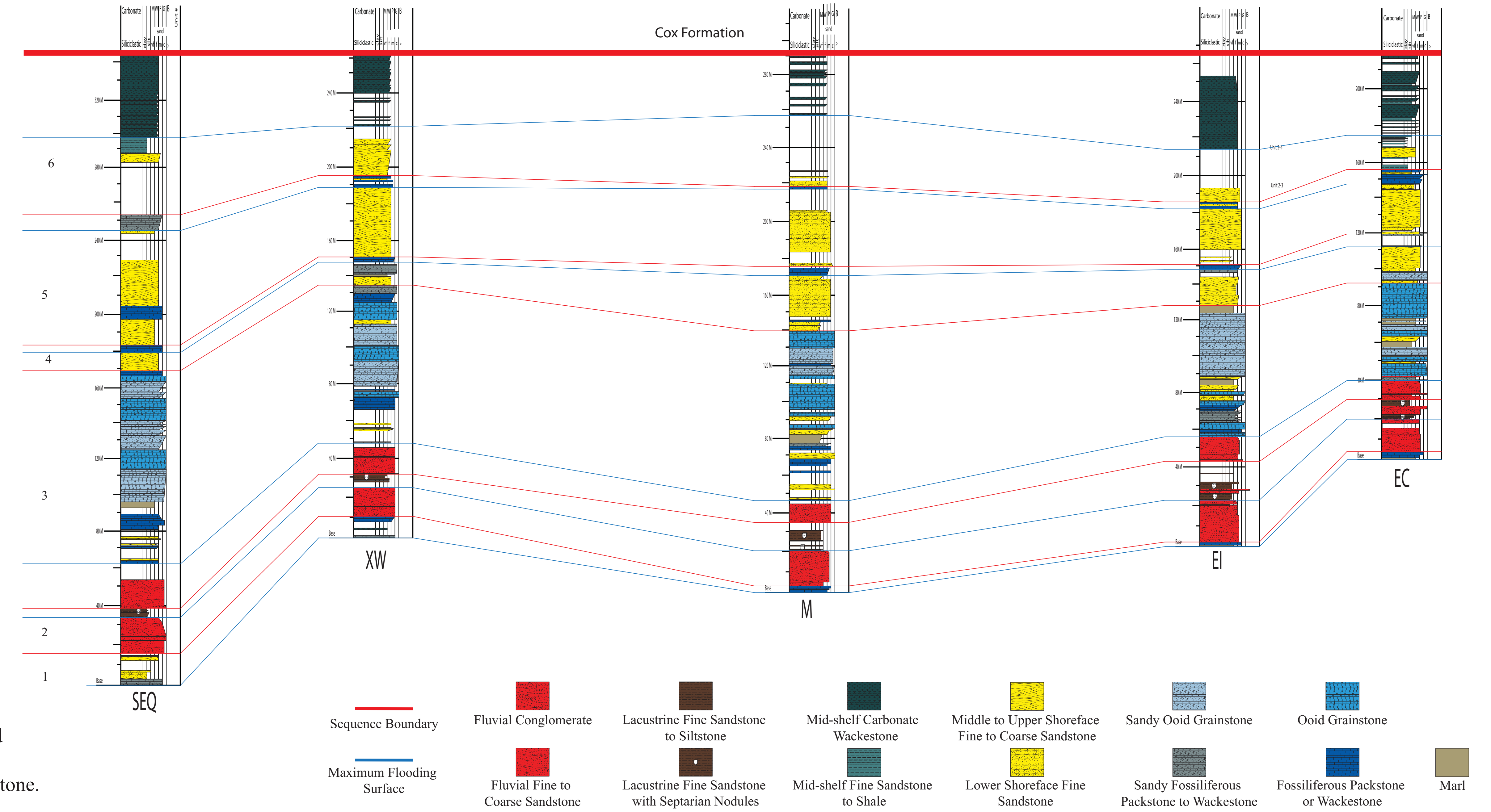


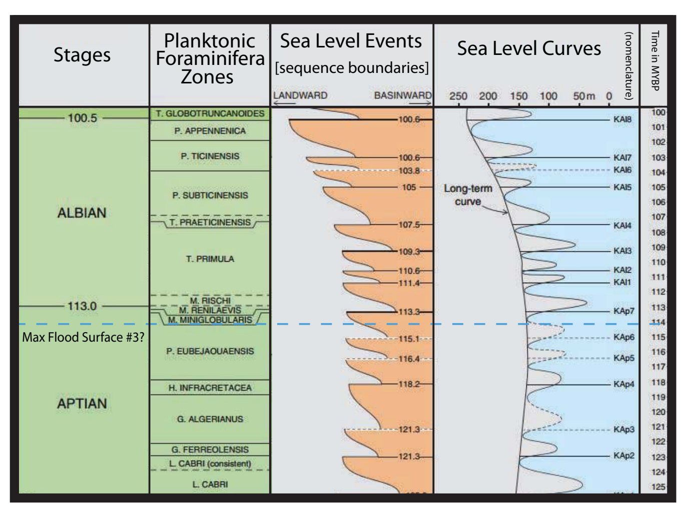
Summary of sulfur content in septarian nodules. 3 additional samples from the Upper Yucca were tested but sulfur content was too low for isotopic analysis. Global sulfur curve modified from Claypool et al. (1980).

Stratigraphy

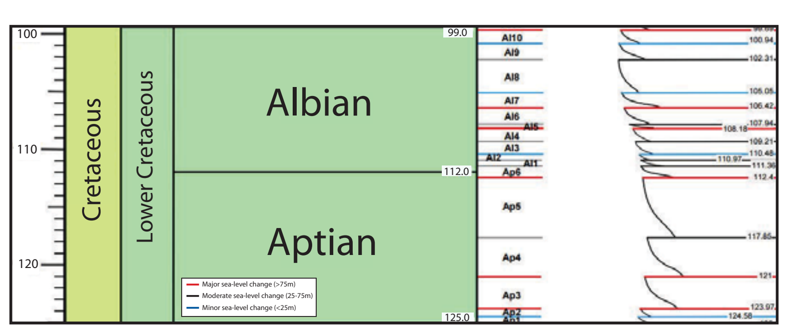
1. The Bluff Mesa thickens basinward from 220 meters in Echo Canyon to 360 meters in Squaw Canyon.
   - Transect is oblique to paleoshoreline.

2. Six 4th order transgressive/regressive cycles are recorded in the Bluff Mesa Formation across the southern thrust panel.
   - 1 - Represents the initial marine transgression into the basin over lacustrine sands of the Upper Yucca Formation.
     - Thickens to the north as the basal limestone is overlain by a wedge of discontinuous marine sands.
   - 2 - Represents base-level fall and a return to fluvio-lacustrine deposition.
     - Lacustrine conditions returned during highstand, although geochemical analysis suggests that the lake was marine influenced.
     - Fluvial channels are scattered throughout the lacustrine interval and increase in prevalence marginward to the south.
   - 3 - Represents a major transgression which drowned the basin.
     - Max flood surface #3 represents the onset of marine conditions following fluvial deposition during lowstand.
     - A clear margin to basin transect is established as the sequence thickens to the north and ooid grainstone bars prograde northwards over packstones and wackestones.
   - 4 - Represents base level fall and an abrupt influx of marine sand.
     - Differs from lower marine sand intervals in that it cuts channels into the highstand grainstones of sequence #3 and is laterally continuous across the transect.
   - 5 - Represents a fall in base level similar to sequence #4.
     - Contains similar channelized features at the base but differs from sequence #4 in that it is significantly thicker in basinward sections.
   - 6 - Represents a general basinward facies shift as both lowstand siliciclastics and highstand carbonates are finer and contain more pelagic faunal assemblages.
     - Overlying sequence boundary is marked by fluvial deposits of the Cox Sandstone.





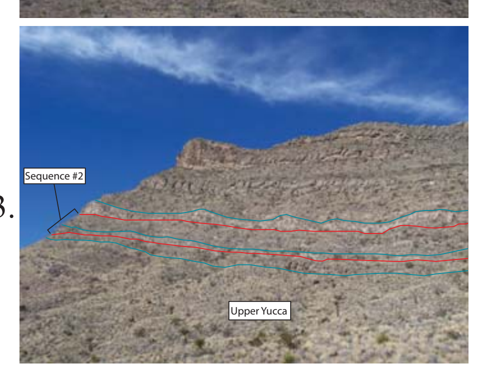
3. Max flood surface #3 represents a significant increase in base level
   - Tectonism which permanently reconfigured the basin?
   - Higher order eustasy? May represent transgression preceding the KAp7 sequence boundary (Haq, 2014).



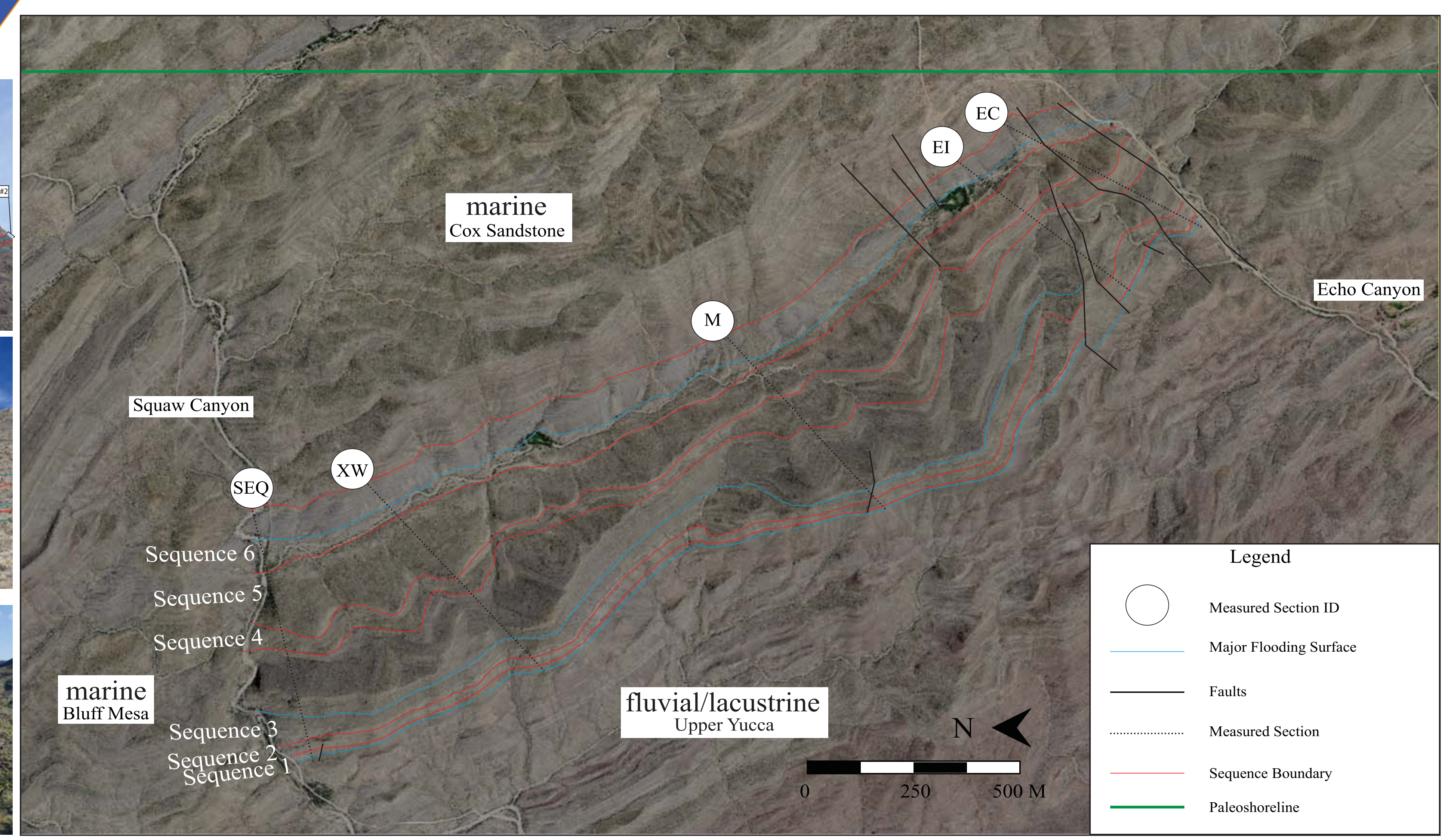
4. Sequence #6 likely coincides with global sequence Al3 or Al4 with Cox Sandstone deposition having initiated by Al5. Modified from Snedden and Liu (2010).

Nature of Contacts

Base of the Bluff Mesa Formation overlies fluvio-lacustrine deposits of the Upper Yucca Formation. Note the scattered fluvial channels within the lacustrine interval between max flood surface #2 and the base of sequence #3.



Medium-grained sandstone base of sequence #4 cutting into marl of sequence #3.



Conclusions and Future Work

1. Detailed mapping has shown that multiple transgressions occurred before the basin was finally drowned. Geochemical and thin section analysis show that the basin returned to a lacustrine environment following initial marine transgression. These results suggest that pre-salt carbonate lacustrine reservoirs may be separated from overlying evaporite seal facies by several pulses of marine/non-marine transgressive/regressive cycles and therefore marine carbonate facies may represent a significant component of the upper pre-salt reservoir. This is contrary to the current model which places lacustrine carbonate facies directly below the evaporite sealing facies.

2. Syn-depositional faulting was a minor depositional control on the observed scale. Changes in bed thickness across faults are generally minor and facies changes are rare (for example, presence of a sandy limestone below max flood surface #3 on the downthrown section (EC) but not on the horst (EI)).

3. Evaporite deposition would have occured during sequence #2 had conditions been ideal. The lack of evaporites in the Indio Mountains is likely a function of basin geometry influenced by the location near the trough margin. Future studies would benefit from the inclusion of outcrops located closer to the center of the Chihuahua Trough where conditions were ideal.

4. It is unclear whether the transgression recorded by the max flooding surface of sequence #3 was related to a local tectonic event or global eustasy. Future work will focus on identifying planktonic foraminifera that may act as an age constraint and tie transgression to the global sea level curve.

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Acknowledgements

Funding: The Institute of Tectonics Studies, ConocoPhillips, and The West Texas Geological Society
Advisors: Dr. Kate Giles and Dr. Rip Langford
Logistics and Coordination: Nila Matsler
Field Assistants: Matthew Fox, Andre Llanos, Alan Venneman, and Ryan Jimenez
Drone Data: Myra Guerrero and Guillermo Vargas