Second-Order Accommodation Cycles and Points of Stratigraphic Turnaround:

Implications for High-Resolution Sequence Stratigraphy and Facies Architecture of the Haynesville and Cotton Valley Lime Pinnacle Reefs of the East Texas Salt Basin.

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Recent advances in high-resolution sequence stratigraphy of carbonate ramp systems have direct application to enhancing our understanding of Late Jurassic stratigraphy of the East Texas salt basin. Currently, the East Texas salt basin is enjoying a revival via the recent Cotton Valley lime pinnacle reef play. This play element complements the existing traditional Cotton Valley lime/Haynesville oolite shoal play type. Consideration of Gulf of Mexico regional Mesozoic sequence stratigraphy and paleogeography aids in linking the two plays together in an integrated chronostratigraphic framework, thus providing some predictive capability for reservoir distribution and quality.

Although the pinnacle play is currently perceived as a 3-D seismic play, regional sequence stratigraphic analysis assists greatly in locating favorable play trends and high-grading existing op-portunities. In this study, I present a high-resolution sequence stratigraphic analysis from the western shelf of the East Texas salt basin derived from the integration of 2-D and 3-D seismic, with well log and facies information obtained from cuttings.

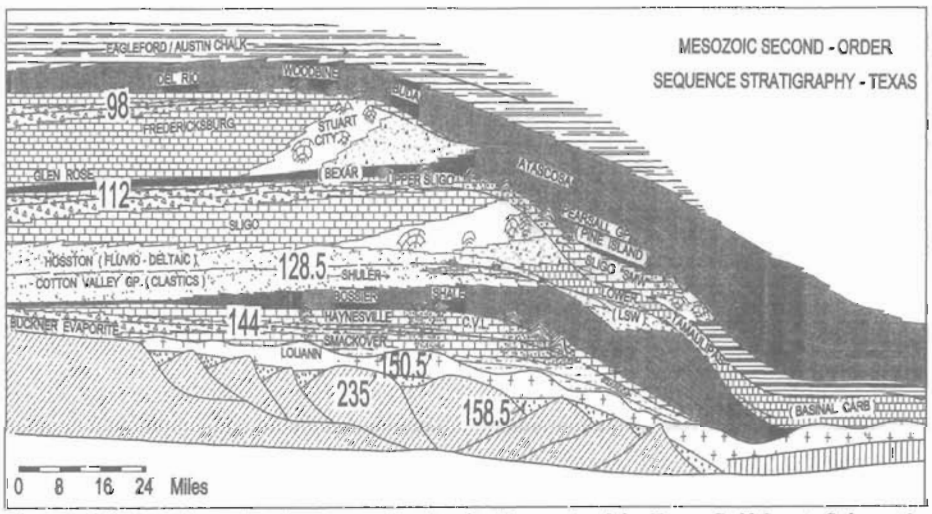

Figure 1 *Schematic regional cross-section for the Mesozoic of the Texas Gulf Coast. Schematic based on regional 2-D seismic, well log cross-sections, core/cuttings information from Texas subsurface and outcrop data from Northeast Mexico.*

The Middle Jurassic-Early Cretaceous stratigraphy in the East Texas salt basin consists of four major second-order supersequences of approximately 15 m.y. duration. These are defined as large, regionally correlative, retrogradational to aggradational/progradational accommodation packages. Each exhibits systematic vertical stacking patterns and associated lateral facies shifts within subordinate third-order sequences lasting between 1-3 m.y., with related facies and systems tracts. The four supersequences are: Supersequence 1(SS1)-Late Bathonian to Early Kimmeridgian (158.5-144 m.y.); SS2-Early Kimmeridgian to Berriasian (144-128.5 m.y.); SS3-Late Valanginian to Early Aptian (128.5-112 m.y.); SS4-Early Aptian to Late Albian (112-98 m.y.).

The Late Jurassic Smackover-Buckner-Cotton Valley lime-Haynesville-Bossier formational stratigraphy make up parts of two second-order supersequences, SS1 and SS2 (Figure 1). The Smackover represents the second-order, late transgressive systems tract (TST) and highstand systems tract (HST) of SS1; the Buckner evaporite/red bed facies depicts latest HST condition of SS1 and lowstand systems tract (LST) development of SS2. The Haynesville/Cotton Valley lime paired ramp-shoal carbonate and offshore detached pinnacle reef facies marks the second-order TST of SS2, and the overlying Bossier equates to the second-order interval of maximum flooding.

Within the above framework, the second-order HST of SS1 (Smackover-Buckner carbonate-evaporite facies) consist of four to five regionally correlative third-order sequences, 250-350 ft thick and 1 m.y. duration, which systematically stack in a progradational fashion such that successive ramp margins are progressively offset downdip. In detail, each successive sequence is thinner than the underlying one and each is progressively enriched in blocky highstand carbonates and proximal evaporite-red bed facies. A typical sequence contains an updip anhydrite facies and a ramp margin, high-energy grainstone belt composed of a series of higher-frequency, offlapping, clinoforming shoal packages beneath each third-order sequence boundary. There is little, if any, pinnacle reef development linked to these sequences.

The 144 m.y. supersequence boundary marks a zone of minimum second-order accommodation (a point of stratigraphic turnaround) and serves as a regional stratigraphic datum useful for hanging well log cross-sections. This surface is recognized in well logs by analyzing the vertical stacking patterns of third-order sequences, as recorded by overall thickness trends, and the ratio of blocky highstand carbonates (low gamma ray response) to spikey, transgressive carbonates (high gamma ray response). By tieing the wells to the 3-D seismic with velocity surveys, the true geometry of the 144 m.y. terminal progradational ramp sequence is defined. Downdip from the terminal ramp margin of the underlying second-order HST, 2-3 basinally restricted reef cycles are recognized within older, larger downdip pinnacle reefs which were in a mid-slope position. These basinally restricted reef cycles record the initial floodback following the 144 m.y. relative sea-level drop and they have no equivalent ramp carbonate on the shelf, which may have been subaerially exposed.

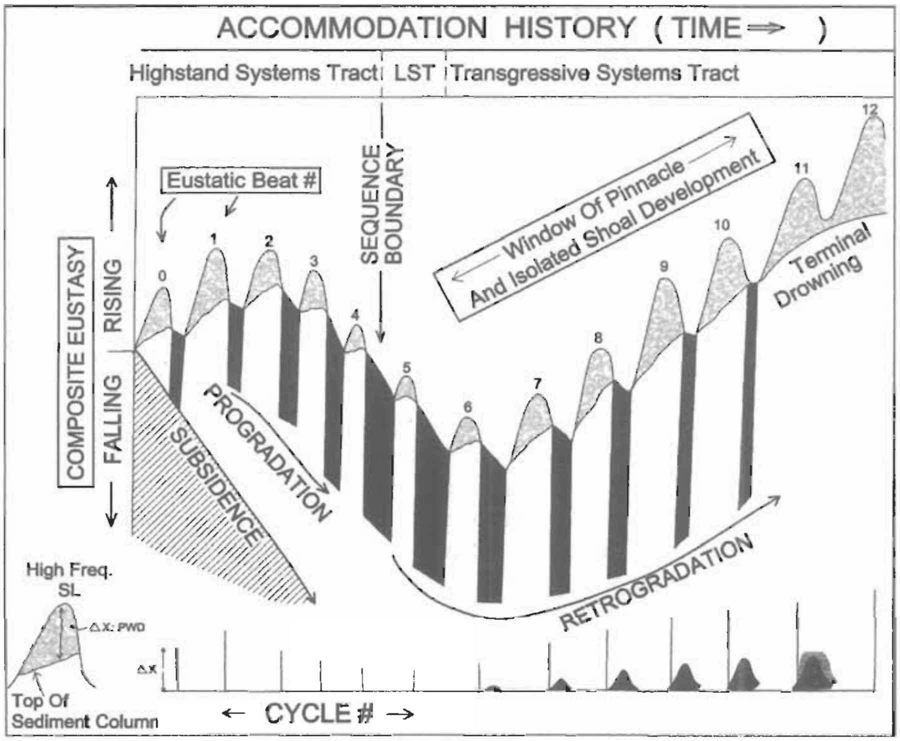

Figure 2: *Composite accommodation model proposed for Lou-Ark stratigraphy.*

Updip from the terminal ramp margin, above the 144 m.y. horizon, the second-order TST of SS2 (Haynesville/Cotton Valley lime carbonate shoal-pinnacle reef facies) consists of 4-5 regionally correlative third-order ramp sequences and 4-5 pinnacle reef cycles, each 50-150 ft thick, lasting 1 m.y. Pinnacle reef cycles are detached in plan view from the ramp cycles, yet linked in accommodation space and time. Ramp sequences systematically stack in a retrogradational or aggradational fashion, whereas individual pinnacle reefs progressively decrease in diameter as they aggraded vertically. Each ramp sequence consisted of an updip, proximal evaporite-red bed facies, a ramp-margin oolite shoal belt (traditional Haynesville reservoirs), and an outer ramp slope composed of muddy, argillaceous carbonate. During the second-order regional transgression (TST of SS2) older pinnacle reefs, over 1300 ft thick, grew in progressively deeper water and were eventually stranded downdip, passing updip to younger pinnacles, typically less than 300-500 ft thick, which grew in successively more landward positions. Younger pinnacles are missing the earlier reef cycles, are not as tall, and are enriched in shallower-water facies as compared to their older, downdip counterparts.

Through high-resolution correlation of ramp sequences with reef cycles, guided by integrated seismic and well log control, updip oolite shoal regional porosity can be correlated directly with time-equivalent pinnacle reef reservoirs, casting light on porosity distribution as well as mechanisms for porosity development within the East Texas salt basin. The top of the Cotton Valley lime/Haynesville carbonate is a diachronous surface characterized by appreciable depositional topography, onlapped by the Bossier shale along a well-documented submarine condensed section. Little evidence exists for a relative sea-level drop at this surface.

A high-resolution sequence stratigraphic model which summarizes the Smackover-Buckner-Cotton Valley Lime/Haynesville (Lou-Ark) stratigraphy is presented in Figures 1 and 2. Figure 2 depicts the accommodation history over the temporal interval of concern. In this model, composite accommodation changes are produced by superimposing high-frequency 4th-3rd-order relative sea-level changes and lower frequency 2nd-order relative sea-level changes on background, regional tectonic, subsidence. The horizontal axis (Figure 2) represents time moving forward from left to right. The vertical axis depicts changes in sea level. The timing of second-order systems tracts are shown at the top of the diagram. Each high-frequency eustatic cycle (eustatic beat) is numbered from 0 to 12. As each beat floods the ramp top, sedimentation takes place (light gray stipple beneath the high-frequency sea-level curve in Figure 2; "PWD" refers to paleowater depth and delta X shows changes in PWD). During high-frequency submergence, the top of the sediment surface climbs from lower left to upper right in the diagram. When high-frequency sea level falls beneath the ramp top (times depicted by darker vertical shading), marine sedimentation ceases.

Due to the effects of composite eustasy, the proportion of marine submergence and concomitant sedimentation to exposure and non-deposition per high-frequency beat varies systematically as the beats migrate through the lower-frequency 2nd-order eustatic cycles. These systematic and sequential changes in accommodation space during eustatic beats result in a predictable stacking architecture of high-frequency stratigraphic cycles. Eustatic beats 0-4 are within the 2nd-order highstand systems tract, and each eustatic beat is capable of generating one stratigraphic cycle.

During the 2nd-order HST, accommodation is progressively declining and submergence-prone eustatic beats pass into exposure-prone eustatic beats. Thus, ramp cycles 1-4 thin upward and prograde laterally into the basin. Each ramp cycle has an updip evaporite facies (Buckner), a mid-ramp quiet-water facies, a ramp crest grainstone ooliticfacies and a ramp slope facies. Small patches of biohermal or reefal facies are depicted by dark grey shading and these biohermal entities are located at the seaward margin of the ramp crest or slightly down the ramp slope. Biohermal masses within cycles 1-3 are spatially restricted and inhibited from becoming pinnacle buildups due to two factors: (1) the declining accommodation within 2nd-order HST, each biohermal entity is smothered in carbonate sand from above as the next cycle progrades out and over the bioherm; (2) related to the same accommodation problem, "nasty" bank water of elevated salinities from the Buckner facies washes seaward over the bioherms adversely affecting their growth.

The 2nd-order HST passes into the 2nd-order LST between eustatic beats 4 and 5 where the rate of 2nd-order fall is at a maximum (the inflection point on the 2nd-order eustatic curve). This point marks the 2nd-order super-sequence boundary and equates hypothetically to the 144 m.y. supersequence boundary in the Lou-Ark framework presented previously. In this position of stratigraphic reversal, the system turns around from progradation related to progressive accommodation loss, to retrogradation caused by progressive accommodation gain.

From here on, each high-frequency beat becomes progressively submergence prone and the ramp cycles display a retrogradational stacking architecture with increasing topographic relief as they march updip. Pinnacle buildup development is now promoted as problems (1) and (2) outlined previously are alleviated. For example, between ramp cycles 4 and 5, biohermal growth which initiated during cycle 4 can continue because the ramp crest of cycle 5 (or rollover point) is now located slightly updip, or landward, of the ramp crest of cycle 4. Because of this relationship, it is hypothesized that the biohermal contribution from cycle 5 will stack vertically on the ready-made foundation of the healthy bioherm from cycle 4.

The 2nd-order TST occurs between eustatic beats 6-12 as the rate of 2nd-order fall declines, and passes through its trough and back into a 2nd-order rise. The composite eustatic effect each of high-frequency beat becomes progressively submergence- prone and overall accommodation increases, promoting pinnacle development. In detail, above cycle 5, each reef cycle is broken into its high-frequency transgressive and regressive phases. The net result is that each pinnacle buildup is cyclic with contributions from 2 to 4 eustatic beats. The furthest downdip pinnacle reef consists of contributions from cycle 4 through the transgressive part of cycle 7. By contrast, the most updip pinnacle only contains contributions from cycle 8 and the transgressive phase of cycle 9. The most downdip pinnacles are therefore the oldest and were drowned during the overall regional 2nd-order transgression prior to the inception of the most updip pinnacle. A lack of appreciation of the true chronostratigraphic and dynamic relations summarized here has lead to the misperception by some workers that the downdip pinnacles are deep water and the updip pinnacles shallow water. With respect to internal facies composition and petrophysical parameters, each pinnacle is vertically heterogeneous.

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Inspection of thin sections from cuttings and rotary sidewall cores, coupled with core descriptions from various operators, indicates that the transgressive phase of each pinnacle reef consists of slightly argillaceous lime wackestones (increased gamma ray count) composed of thrombolitic facies or microbiolite facies marked by an abundance of algal binding and clotting. These facies, with associated delicate deeper-water skeletal allochems, suggest moderate water depths related to high-frequency rise in sea level. The maximum flooding surface of each reef cycle is approximated by the highest gamma ray count. The regressive cap or highstand systems tract of the reef cycles is composed of in situ, apparently low-energy Late Jurassic reef-builders, such as sponges and delicate corals. The caps to some of the reef cycles consist of high-energy grainstones with oncolites and abraded, well-washed, skeletal-peloidal sand, indicative of shoaling to very shallow water depths. On well logs, the gamma ray within the highstand portion of a reef cycle cleans upward, becoming blocky to remarkably flat. A lack of core data has hampered a complete understanding of facies and diagenesis.

Carbonate systems in similar accommodation settings, such as the younger Sligo formation in south Texas, provide stratigraphic analogues useful for driving well log correlations and seismic interpretation. Analogous buildup or pinnacle reef facies typically occur linked to the terminal phase of carbonate deposition near the top of regiona, second-order TST's beneath deep marine shales (second-order MFS) which serve as source and seal facies. Pinnacle geometries are promoted by increasing accommodation within an overall retrogradational stacking of carbonate facies belts. Differential compaction of shaly, onlapping facies around pre-existing rigid carbonate buildups enhances their seismic recognition. Hydrocarbon-producing examples include the Devonian of Canada, the Miocene of Southeast Asia, the Mississippian Lodgepole of the Williston basin, and the Upper Pennsylvanian Horseshoe Atoll of the Midland basin, among others. Integration of key principles from the Late Jurassic of the East Texas salt basin with these and other examples should fuel the search for other, as yet, unrecognized carbonate buildups and pinnacle reefs within similar accommodation windows in other areas.

References

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