DEPARTMENT OF GEOSCIENCES

M.S. THESIS

TITLE: **Salt Reconstruction and Study of Depositional History, Upper Jurassic, East Texas Basin**

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RESEARCH COMMITTEE

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ABSTRACT:

In the East Texas Basin, the Middle Jurassic was marked by the opening of the Gulf of Mexico and the deposition of the Louann Salt. The Louann Salt was deposited in a restricted marine environment and reached thicknesses of approximately 5,000 feet, but over time, through dissolution and post-depositional halokinesis, the salt dissipated in many areas leaving a highly variable surface for future deposition (Maione, 2001). This surface controlled the distribution of overlying formations and changed through time with sediment loading and salt movement.

Since the initial discoveries in the 1930s, the Upper Jurassic rocks of the East Texas Basin and northern Louisiana have produced over 20 TCF of gas and 900 million barrels of oil (Ewing, 2001). While there are several published interpretations of the depositional environments of the formations of the East Texas Basin, there are varying ideas and conflicting models. The purpose of this study is to test these published interpretations by recreating the paleotopography and depositional setting of each formation to demonstrate the impact of salt movement and its affect on basin development at each depositional stage.

I will evaluate the interplay between salt movement and Upper Jurassic deposition in the East Texas Basin by reconstructing the base of salt on regional (2D) and local (3D) seismic data across Freestone, Leon, and Houston counties in Texas. The post-salt formations of interest, in depositional order, are the Cotton Valley Limestone, the Bossier, and the Cotton Valley sands. The main goal of this work is to better understand the basin history and influence of salt tectonics on deposition and hydrocarbon potential.

PROJECT: APPROVED AS PROPOSED APPROVED AS MODIFIED DISAPPROVED

INTRODUCTION

The East Texas Basin is a north-northeast-trending extensional salt basin with regional dips to the southeast. It covers a large part of eastern Texas, and is approximately 259 square kilometers, as seen in figure 1. According to Goldhammer and Johnson (2001), it is part of the eastern Gulf of Mexico tectono-stratigraphic province, meaning that during the Middle and Upper Jurassic, it was undergoing rifting due to the opening of the Gulf of Mexico. The tectonic evolution of this area significantly influenced its unique structures and affected sedimentary deposition throughout the region. The East Texas Basin is bounded to the east by the Sabine Uplift, while the Mexia-Talco Fault Zone forms the northern and western edges, and the Angeline Flexure defines the southern limit.

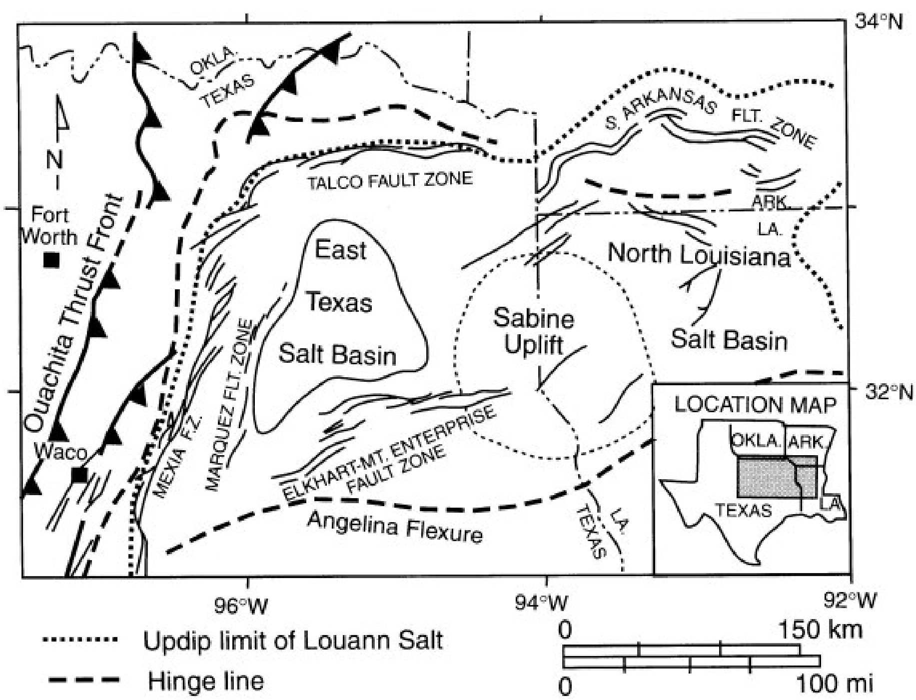

Figure 1: Regional and structural setting of the East Texas Basin (Montgomery et al., 1999).

In the East Texas Basin, the Middle Jurassic was marked by the opening of the Gulf of Mexico and the deposition of the Louann Salt. The Louann Salt was deposited in a restricted marine environment and reached thicknesses of approximately 1,524 m, but over time, through dissolution and post-depositional halokinesis, the salt dissipated in many areas leaving a highly variable surface for future deposition (Maione, 2001). This surface controlled the distribution of overlying formations and changed through time with sediment loading and salt movement.

Since the initial discoveries in the 1930s, the Upper Jurassic rocks of the East Texas Basin and northern Louisiana have proven to be major producers of hydrocarbons, producing over 20 TCF of gas and 900 million barrels of oil (Ewing, 2001). Today, researchers are looking to better understand the hydrocarbon potential by reassessing the salt tectonics, salt movement, and rifting in this area. There are several published interpretations of the depositional environments of the formations of the East Texas Basin, but there are varying ideas and conflicting models, such as whether or not the Bossier sandstones are shoreline sands or basin floor fans and where the shelf edge was during this time. New 3D seismic surveys and new well data in this area make it possible to study these formations closer and propose a model that provides a clearer understanding into the environments of deposition for each and the topography at the time of deposition (Fig. 2). The purpose of this study is to use these new data sets to re-evaluate the paleotopography and depositional setting of each formation to determine the impact of the underlying salt on sedimentation and its affect on subsequent basin development. This study focused on reconstructing the top of salt on a northwest to southeast oriented regional (2D) seismic line across Freestone, Leon, and Houston counties in Texas (Fig. 3). By examining the basin history and the influence of salt tectonics on deposition, this study evaluates what triggered salt movement, why the Cotton Valley Limestone is not laterally continuous, and clarifies the Bossier depositional environment (Fig. 4).

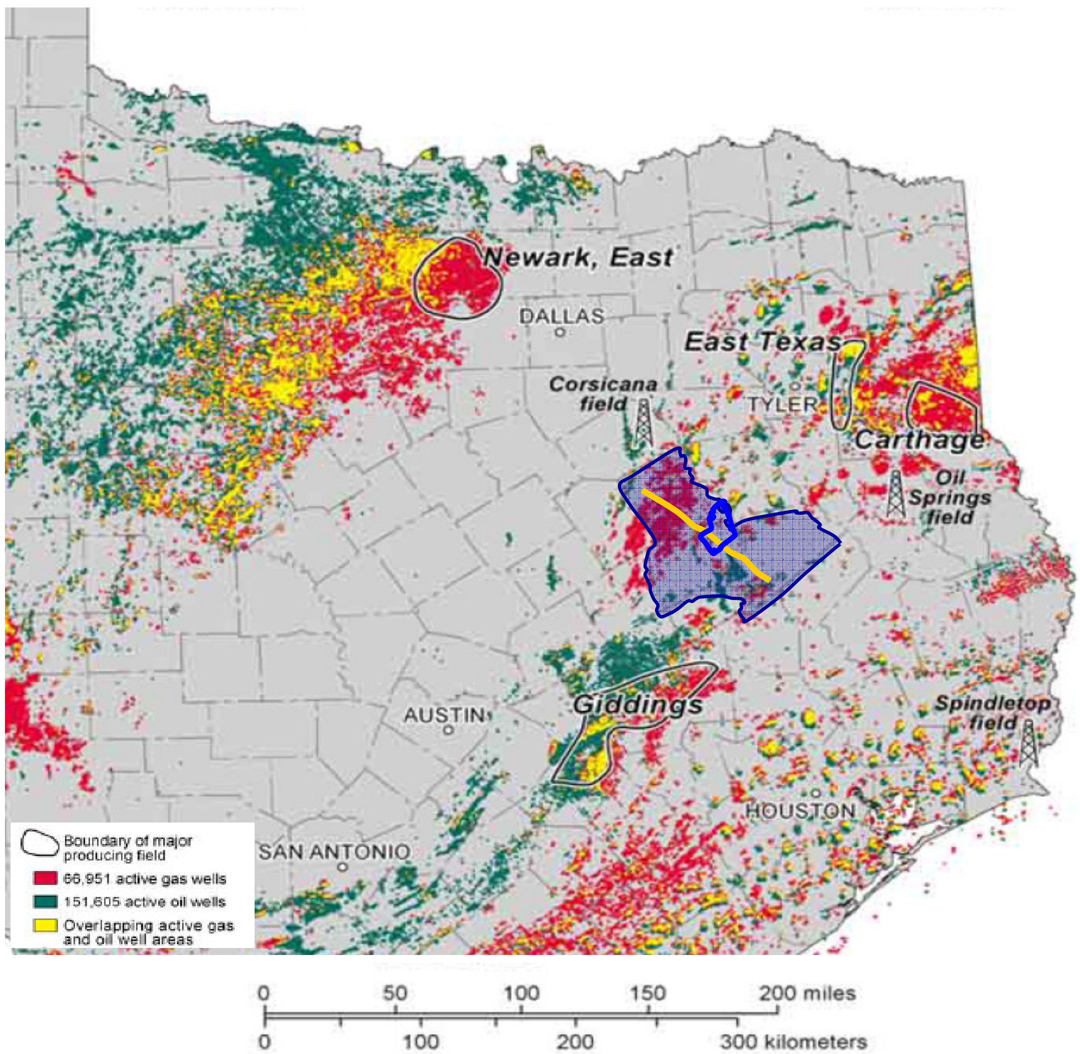

Figure 2: Oil and gas map of Texas showing oil wells in green and gas wells in red. The large blue polygon represents the study area, the yellow line is the seismic line that was restored, and the small bright blue polygon reflects 3D seismic data that was used alongside the 2D line. [Modified from Bureau of Economic Geology, The University of Texas at Austin, Oil and Gas Map 2005 lib.utexas.edu/geo/geologic_maps.html]

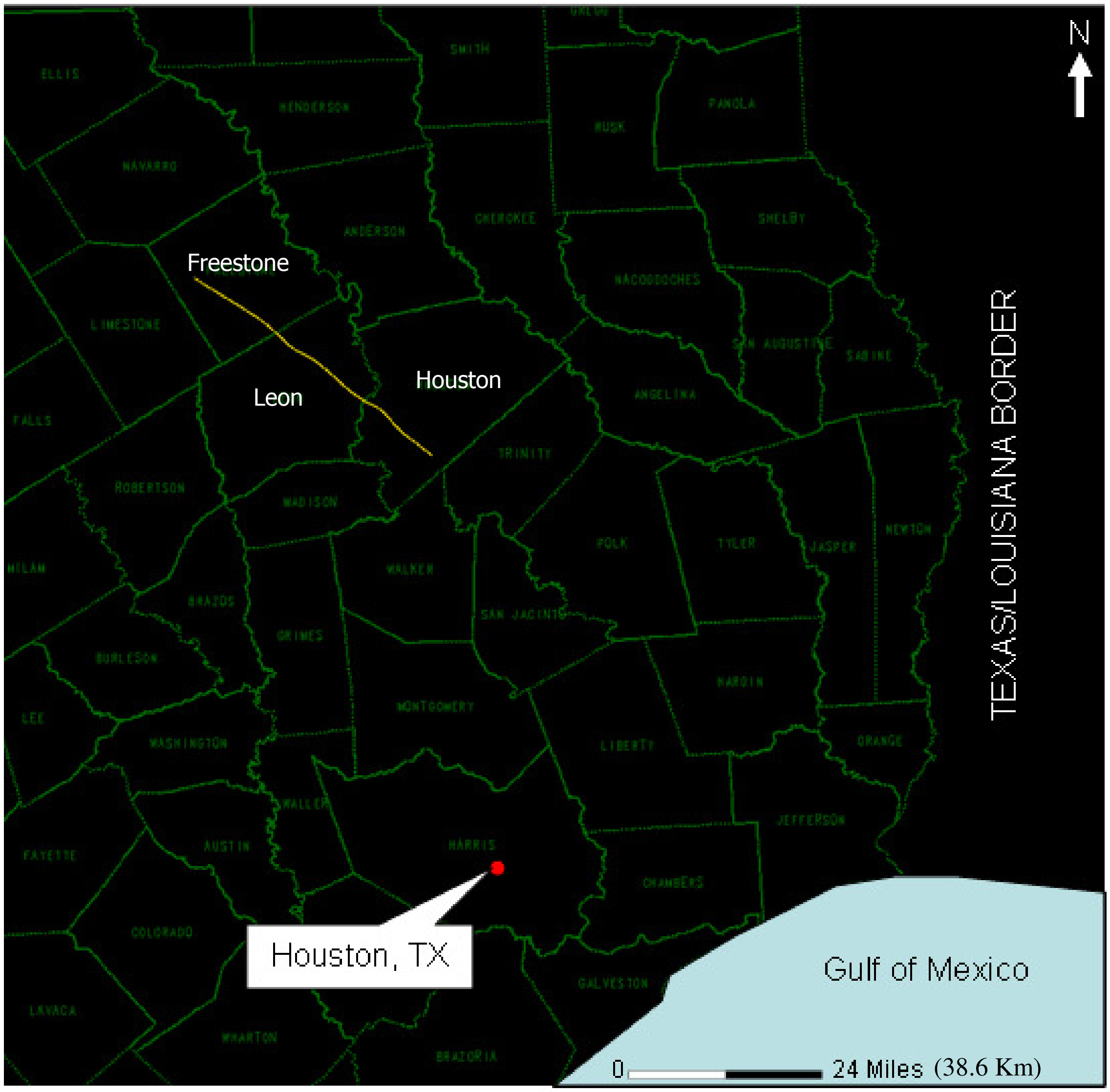

Figure 3: Approximate location of seismic line reconstruction.

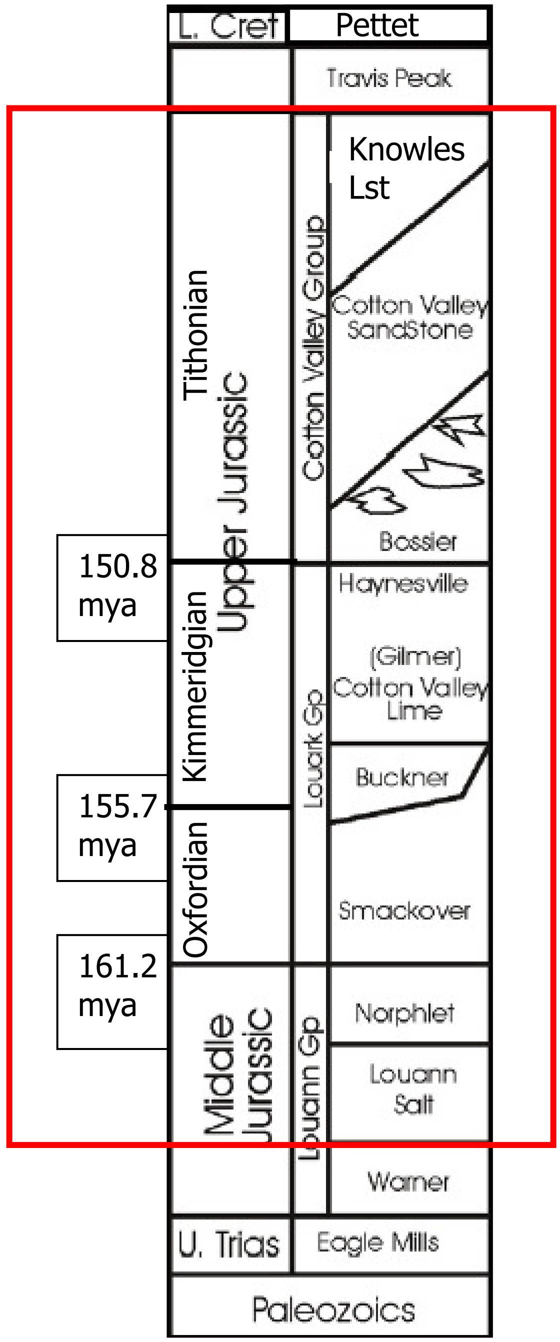

Figure 4: Stratigraphic column of the East Texas Basin. The red box denotes the main formations of interest. [Modified from Klein and Chaivre (2002)]

PURPOSE OF STUDY

The purpose of this study is to evaluate the interplay between salt movement and Upper Jurassic deposition in the East Texas Basin. By reconstructing the basin history, I examined the effects of varying rates of sedimentation for carbonates and clastics over a mobile substrate during Cotton Valley Limestone, Bossier, and Cotton Valley Sandstone time. Utilizing depositional models in the published literature as well as seismic and well data, a 103.8 km long regional 2D seismic line was interpreted and validated through restoration (Figs. 2 and 3). This northwest to southeast line was chosen because it is oriented perpendicular to the strike of faults, salt ridges, and basins, making it a good candidate for structural restoration. Based on this interpretation and its restoration, it is possible to estimate extension, compaction, sediment supply, and timing of subsequent depositional events. This study compared the final interpretation and restoration to the 3D seismic in the area as well as theories already published by Jackson and Seni (1983), Ewing (2001), Goldhammer and Johnson (2001), Williams *et al*. (2001), Klein and Chaivre (2002), and Adams (2009) in order to help explain the depositional history of the basin.

A key factor in the area is Upper Jurassic deposition and its relationship to the timing of salt movement and structural development. It is important to observe how each of these formations changed during the restoration in order to determine what triggered salt movement and if there was more than one period of salt mobilization. The post-salt formations of interest, in depositional order, are the Cotton Valley Limestone, the Bossier, and the Cotton Valley Sandstone. Figure 5 displays the 2D seismic line that was reconstructed with these formations of interest.

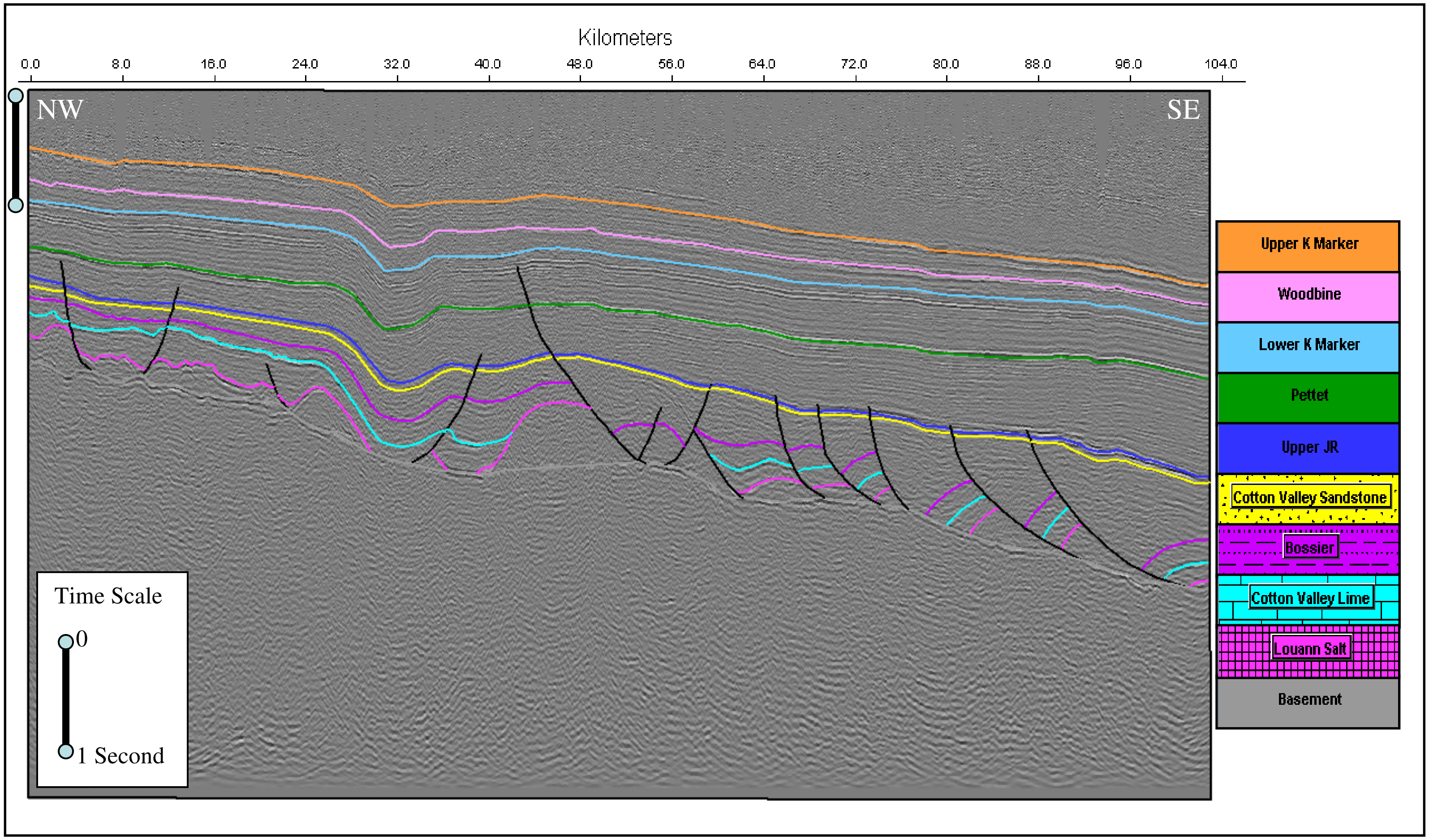

Figure 5: Time Interpretation supported by well data and 3D seismic in the area. Vertical exaggeration is 2:1. Courtesy of Seismic Exchange, Inc. and Marathon Oil Company.

Salt tectonics has had a huge impact on the basin history and was influenced by younger deposition and controlled the topography over which subsequent formations were distributed. The Louann Salt reached thicknesses of approximately 1,524 m; but over time, through dissolution and post-depositional halokinesis, the salt dissipated in many areas leaving a highly variable surface for future deposition (Maione, 2001). This surface controlled the distribution of the overlying formations and changed through time due to sediment loading and salt movement. Pillow structures, salt rollers, diapirs, and turtle structures are a few of the elements left behind that have influenced later deposition (Fig. 6). Through 2D restoration of this line, the salt features present were reconstructed at each depositional stage to better illustrate the timing and mechanisms of salt movement and their influence on the surrounding strata.

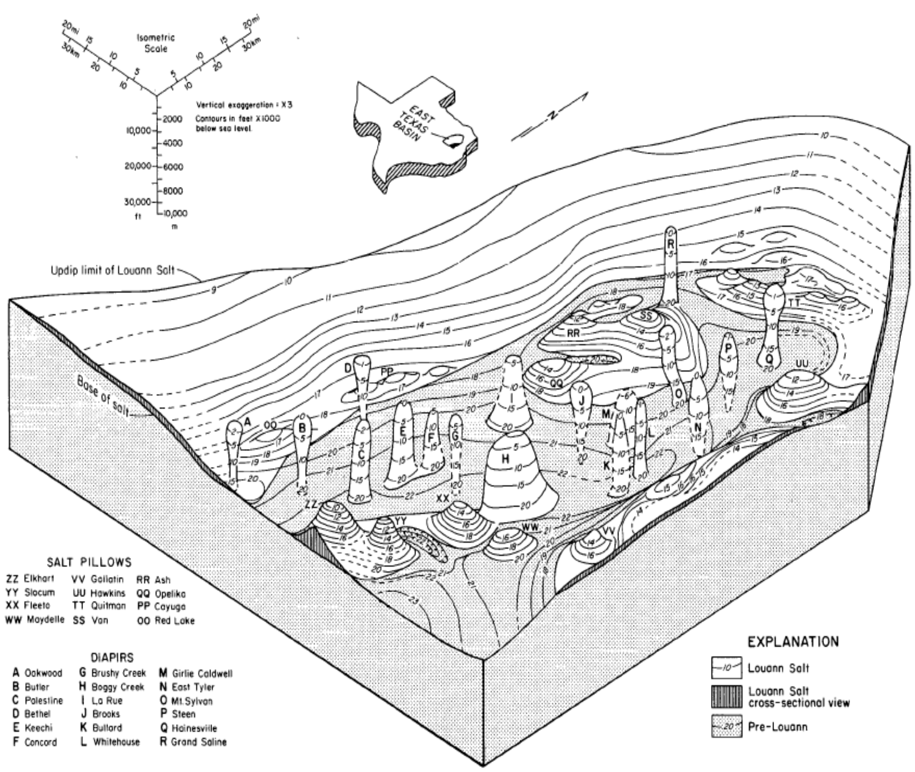

Figure 6: Salt structures present within the East Texas Basin (Jackson and Seni, 1983).

The Cotton Valley Limestone marks the top of the Louark Group, is synonymous with the Haynesville and Gilmer Formations, and is regionally underlain by the Buckner, Smackover, and Norphlet Formations respectively (for the purposes of this study these formations will all be considered part of the Cotton Valley Limestone) (Williams *et al*., 2001). One of the main objectives of this study was to better understand regional distribution of the Cotton Valley Limestone. Three theories were tested to explain the discontinuity of the limestone within the study area. They were rafting caused by salt movement, erosion, or the possibility of non-deposition.

The Bossier shales and sandstones overly the Cotton Valley Limestone, and represent the first deposits of the Cotton Valley Group. The Bossier Formation is poorly imaged in the 2D seismic; and thus, 3D seismic and well control was used to interpret this horizon and provide insight into its thickness and structure within the study area. The Bossier represents a major transgression at the end of Kimmeridgian time, which subsequently shifts to a lowstand prograding system, represented by sand-rich parasequences. These sandy units are deltaic according to well log data, but the question is how far out into the basin did these sands propagate or where they confined mainly to the shelf edge and slope? This question is highly debated and there are several contradicting published interpretations. For example, Williams et al. (2001) and Adams (2009) depict the sandstones as a distal equivalent to the Cotton Valley Sandstone, while Klein and Chaivre (2002) interpret the same line and suggest that the Bossier sandstones are possible basin floor fans, completely separate from the Cotton Valley Sandstone (Figs. 7 and 8). This discrepancy was a major focus in this study.

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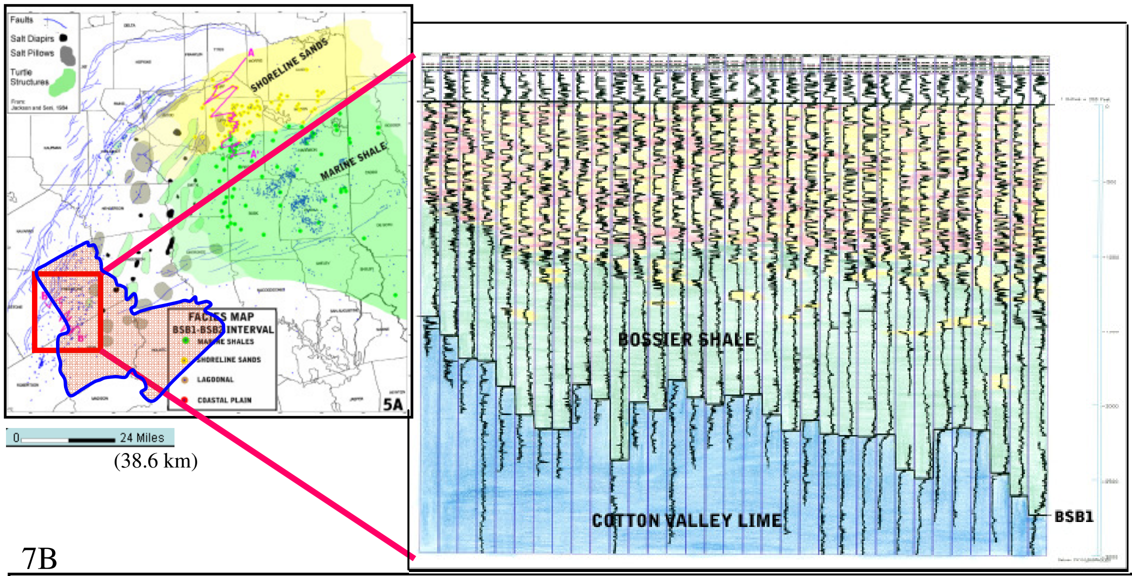

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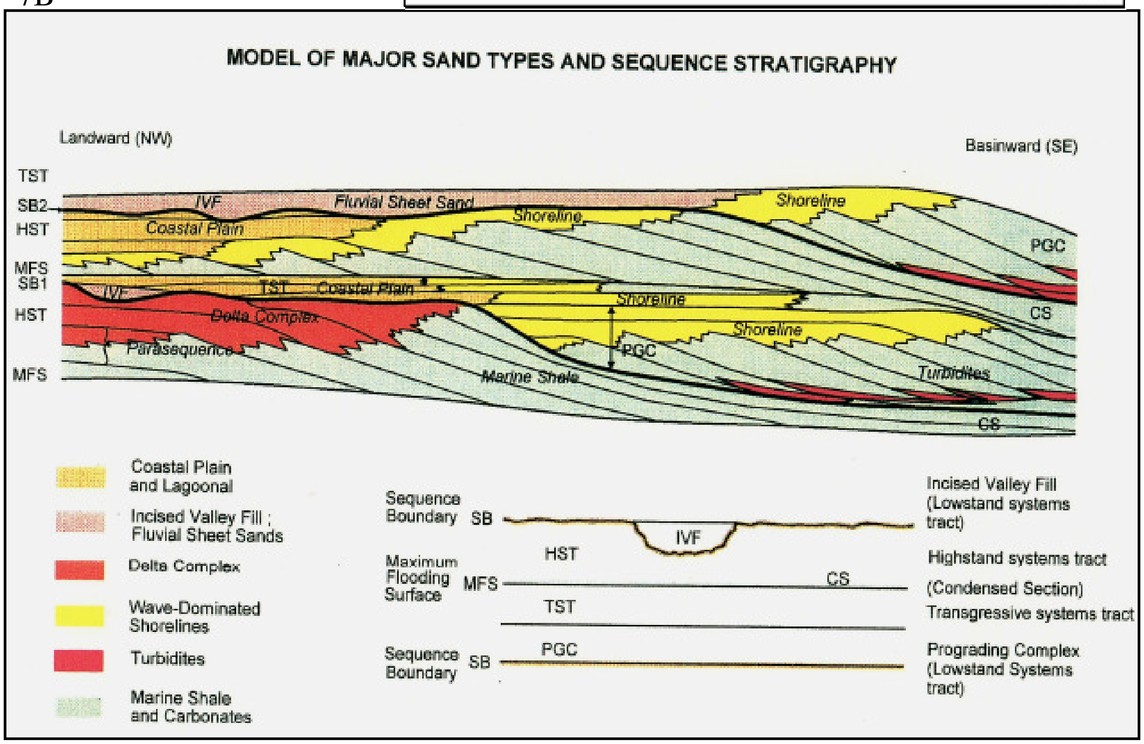

Figure 7: Williams' et al., (2001) interpretation of the Bossier sands as a distal equivalent of the Cotton Valley Sandstone. Figure 7A represents a cross-section roughly parallel to the 2D line in this study showing the sand-rich sequences within the Bossier as they appear to be similar to the Cotton Valley Sandstone. Figure 7B is a schematic of a typical slug model showing the shoreline sands that might represent the Cotton Valley deltaics and the Bossier slope turbidites (Williams et al., 2001).

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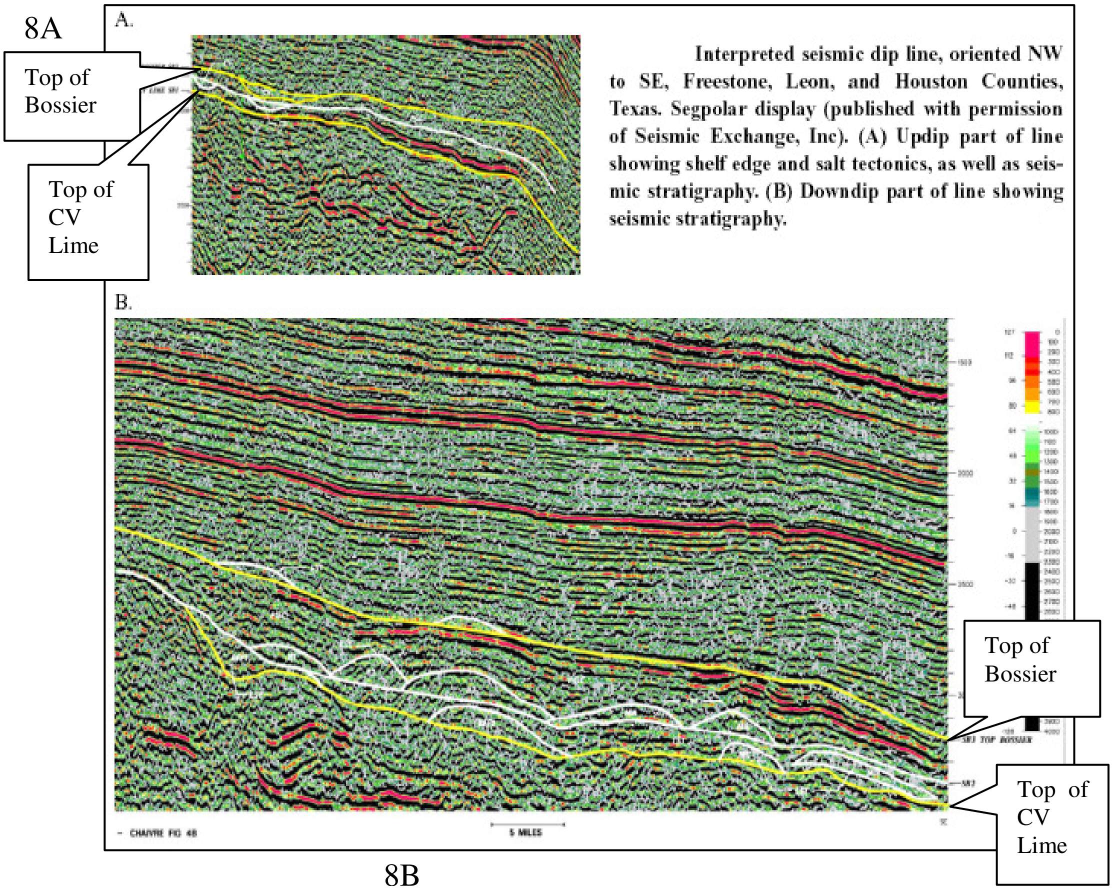

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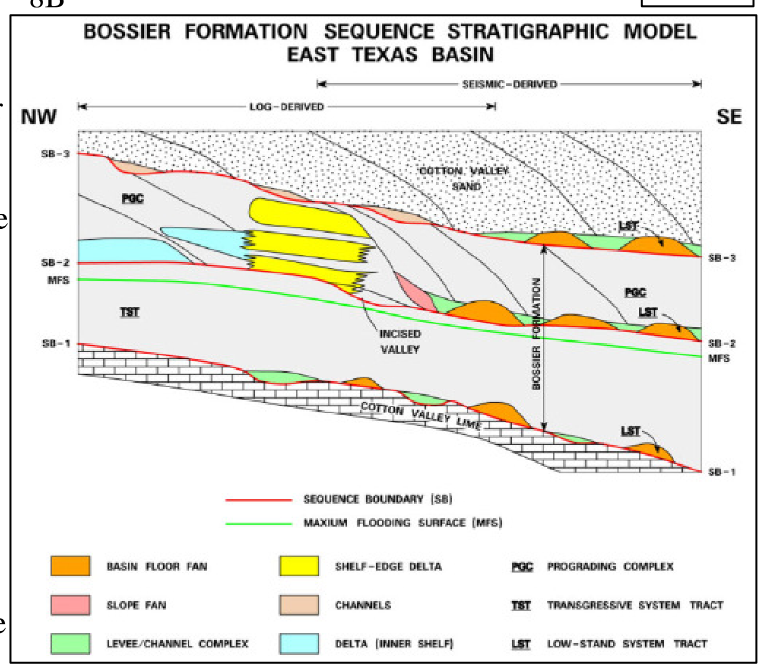


Figure 8: Klein and Chaivre's (2002) interpretation of the Bossier Formation. Figure 8A displays the seismic interpretation with the white line illustrating the stratigraphy within the Bossier. Figure 8B is an animation of the seismic interpretation showing that the mounded geometries represent basin floor fans. In this interpretation, the Cotton Valley Sandstone appears to have no gradational relation with the Bossier.

The Bossier is overlain by the Cotton Valley Sandstone, which comprises a thick wedge of terrigenous clastics that appears to be the loading trigger for salt movement over the southern portion of the regional 2D seismic line. Estimating the sedimentation rate and sediment supply during Cotton Valley Sandstone time indicates significant extension and salt movement during that time. Restoring the Cotton Valley will also help define the relationship between the Cotton Valley Sandstone and Bossier sandstone.

Relatively little is published about the depositional patterns and lateral continuity of the Cotton Valley Limestone and Bossier Formations. However, the influence of the large influx of Cotton Valley Sandstone on salt movement proved to be a key factor in piecing together the basin history.

REGIONAL SETTING AND TECTONICS

Geologic Setting

The East Texas Salt Basin formed along a divergent margin as a failed rift just north of the Gulf of Mexico rift zone as the Gulf of Mexico was opening during the Middle Jurassic (Jackson and Seni, 1983). However, the evolution of the East Texas Salt Basin began in the Triassic when the Gulf Coast was completely continental and the Pacific was the nearest ocean (Fig. 9). During this pre-rift time, there was expansion of the lithosphere and uplift, which caused the Paleozoic Ouachita fold belt to be eroded. As the lithosphere was uplifted and stretched, the zones of maximum uplift migrated away from the rift axes resulting in northwest-verging folds and thrusts (Jackson, 1982). In the late Triassic, the eroded basement was overlain by continental rift fill comprising the red beds of the Eagle Mills Formation. Erosion of the Triassic red beds and the Paleozoic basement formed an angular unconformity atop which the Louann Salt accumulated (Jackson and Seni, 1983).

By the Middle Jurassic, the East Texas Basin had subsided, possibly due to crustal cooling, and its margins became inundated by marine transgressions allowing the deposition of the Louann Salt (Jackson and Seni, 1983). During the Late Jurassic, as the continental shelf in the East Texas Basin continued to subside, shallow platform carbonates of the Smackover, Buckner, and Cotton Valley Limestone Formations were deposited. There was little terrigenous deposition during this time, possibly signifying that the rift margin was still highly elevated, thus diverting rivers around it. However, by the end of the Jurassic and the beginning of the Cretaceous, crustal cooling had allowed enough subsidence that substantial progradation of terrigenous clastics took place within the basin, depositing the Bossier and Cotton Valley Sandstone Formations. By this time the Gulf of Mexico had fully opened, and this rapid introduction of terrigenous sediments into the basin caused differential loading and triggered salt movement (Jackson and Seni, 1983). However, this would be the second trigger of salt movement as Jackson and Seni (1983) state that “[T]he earliest record of movement in the Louann Salt is in the overlying shallow-marine interval below the top of the Upper Oxfordian (Upper Jurassic) Gilmer Limestone”. This agrees with the hypothesis that during Smackover time there were small movements in salt, possibly slight shifts due to gravitational flow of salt, which is interpreted as the main influence on the deposition of Upper Jurassic sediments (Jackson and Seni, 1984).

The internal structure of the East Texas Basin is largely influenced by the salt, but the limits of the basin are controlled by tectonic elements. The up-dip limit of the

Louann salt strikes parallel to the Ouachita trend and is marked by the Mexia-Talco Fault zone, a graben-system that was active during the Jurassic through the Eocene (Jackson, 1982). The eastern margin of the basin is defined by the Sabine Uplift, which was a paleo-high during the Upper Jurassic, and the southern edge forms a low rim bounded by the Angelina Flexure, which is described as a hinge line with an anticlinal middle and monoclinal edges (Jackson, 1982).

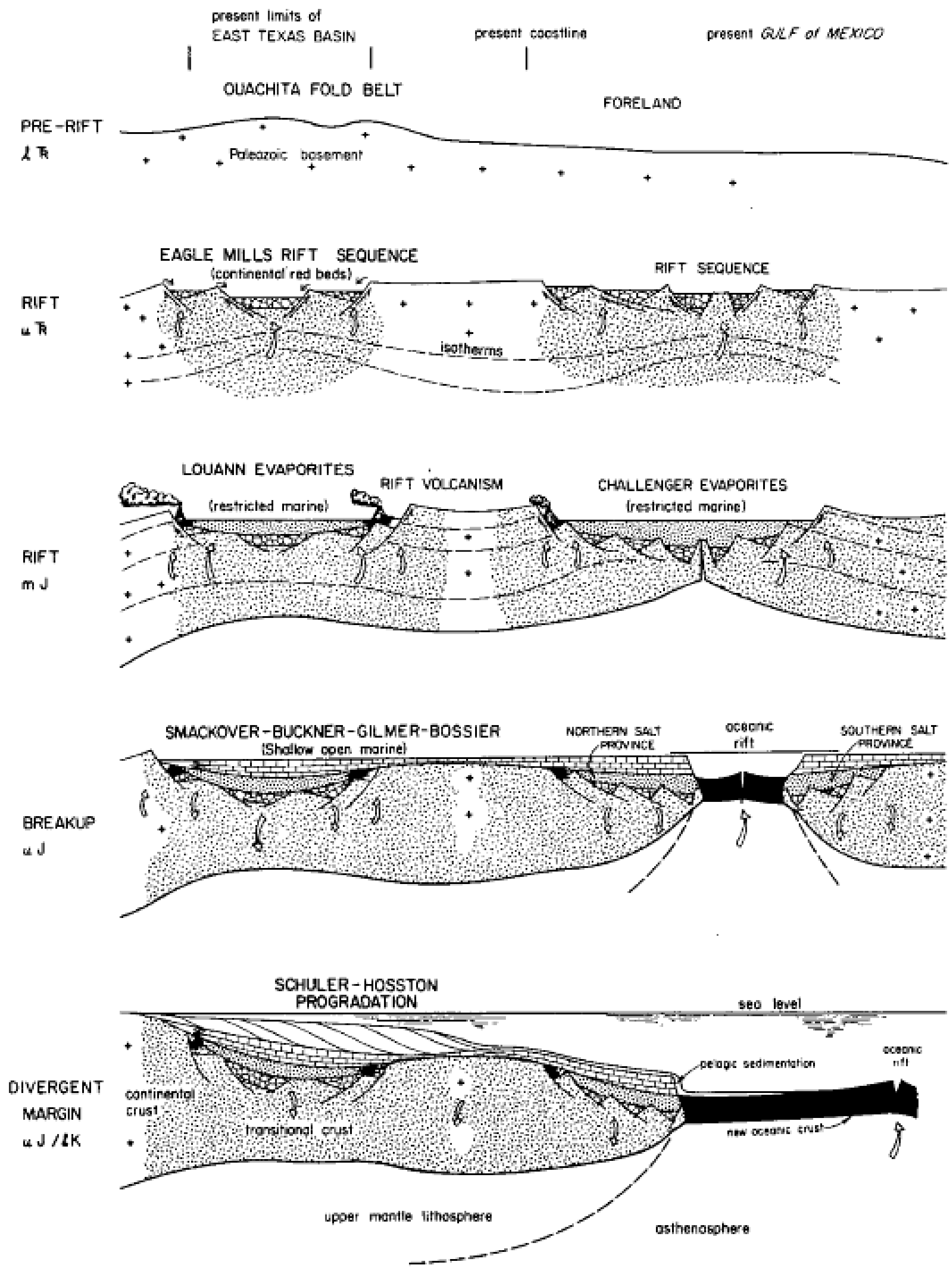


Figure 9: Schematic of the evolution of the East Texas Basin (Jackson and Seni, 1983).

Salt Tectonics

According to Jackson and Seni (1983), at least 1,500 m of Louann Salt was deposited in the north-northeast-trending East Texas Basin creating a stratigraphy that has been divided into four separate salt provinces. The provinces are focused around the central part of the basin which represents the oldest diapirs (Fig. 10). The first province follows the margins of the basin and consists of a practically undeformed salt wedge that ranges in thickness from 0 to 640m. The second province contains low-amplitude salt pillows flanked by salt synclines, while the third province comprises larger intermediate-amplitude salt pillows, which are separated by evacuation synclines. The original salt source layer was estimated to be 550 to >750m thick in the third province. The fourth province is in the center of the basin and contains the oldest diapirs, all of which have pierced their overburden and come within 23 meters of the present day surface (Jackson and Seni, 1983).

Studying these provinces and their structures, Jackson and Seni (1983) estimated that the Louann Salt was approximately 550-625 m thick prior to deformation. Based on this, they concluded that when salt thicknesses reached a threshold of approximately 600 meters, salt mobilization was possible due to “(1) loading beneath a carbonate wedge, (2) differential loading by prograding terrigenous clastics, and (3) basin-edge tilting and erosion” (Jackson and Seni, 1983).

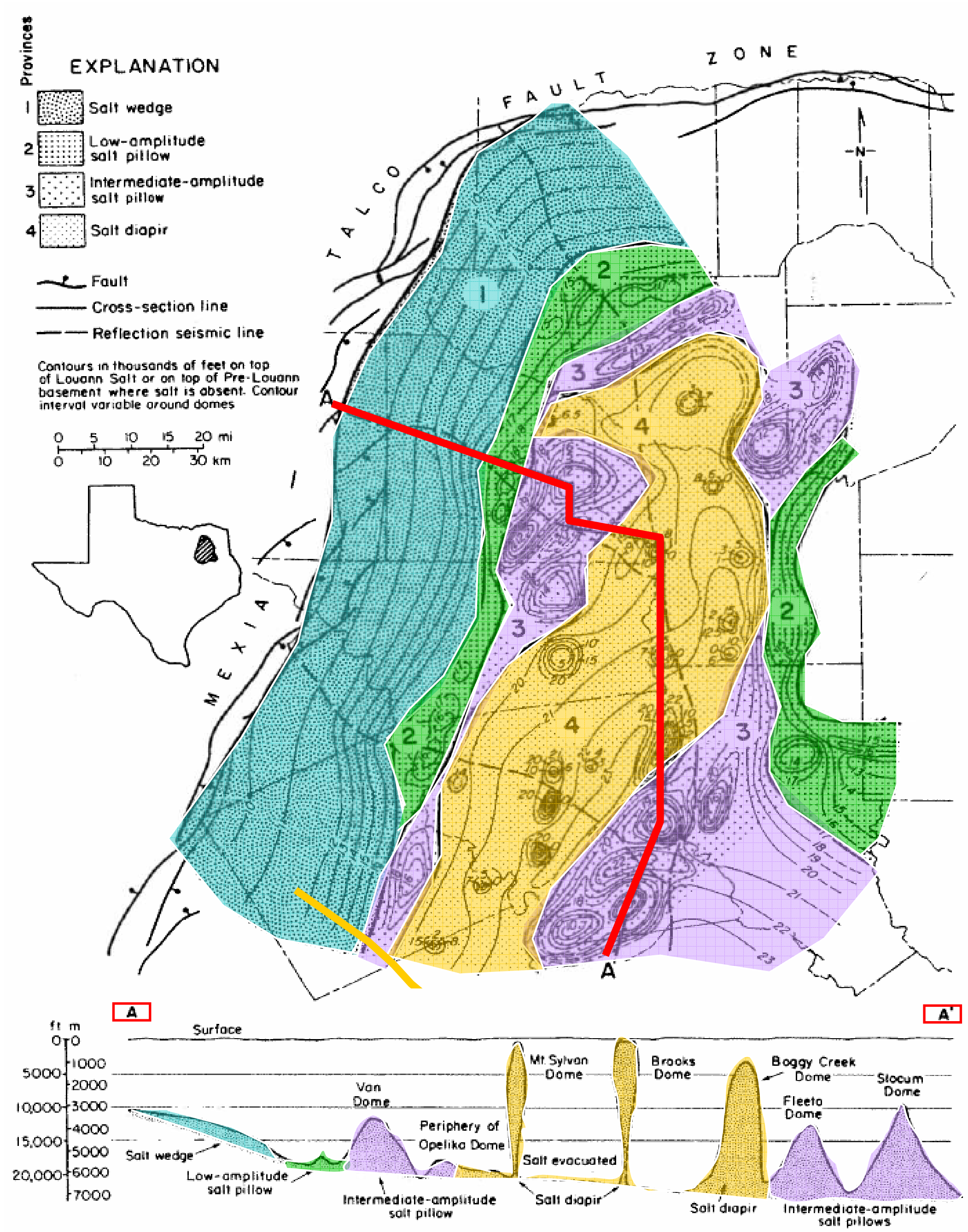


Figure 10: Structure map of the top of Louann Salt depicting the four salt provinces in the East Texas Basin. Red line represents the location of the cross-section. Yellow line is the approximate location of the northwestern portion of the 2D seismic line. [Modified from Jackson and Seni, (1983)]

My study dealt largely with salt structures and their evolution. As stated above, the East Texas Basin has four provinces, each characterized by a particular salt structure with the oldest and most evolved structures confined to the most central part of the basin (Fig. 11). There are several methods for salt evolution, but only those related to the East Texas Basin will be discussed. The progression of salt evolution in East Texas has been compared to that of the North German salt basin where there are three stages of salt growth (Seni and Jackson, 1983). This appears to also be the case in East Texas as the there are four provinces, the outermost containing the planar salt wedge, and the inner three comprising the three stages of growth, the salt pillow stage, diapir stage, and post-diapir stage (Turner, 1993).

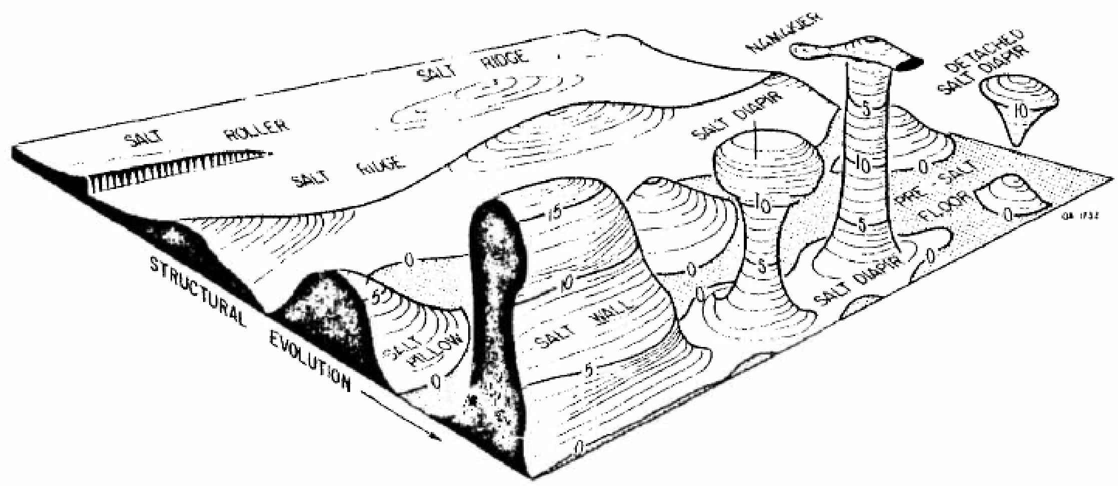


Figure 11: Evolution of salt features in the East Texas Basin. The oldest and most evolved structures are concentrated in the central most part of the basin (Jackson and Galloway, 1984).

While the there are three stages of evolution, this study focused only on those features contained in the seismic line, which is limited to the salt pillow stage of province three. Salt pillows evolve due to sediment loading on a body of salt. During this stage, sediments are draped over the salt body forming concordant anticlinal layers. Where sediment thins over the crest of the structure, growth of the salt pillow is considered to be syndepositional (Turner, 1993). The edges or flanks of the salt pillow serve as depositional sinks or minor thicks as a result of salt withdrawal toward the pillow (Fig. 12) (Turner, 1993). Salt pillow growth can be caused by differential sediment loading, gravity creep, subsalt discontinuities, as well as salt buoyancy and is influenced by the sedimentation and erosion rates of the overlying sediments (Seni and Jackson, 1983).

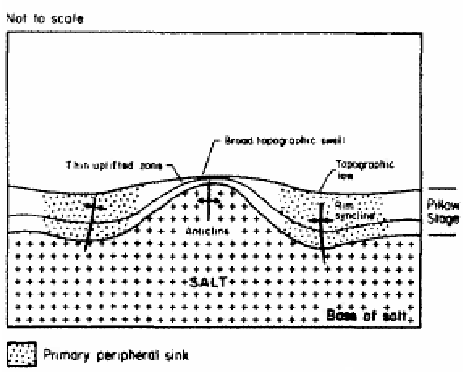
GROWTH STAGE	UPLIFTED AREA	WITHDRAWAL BASIN
PILLOW	Geometry Sediments above pillow are thin over broad, equidimensional to elongate area. Maximum thinning over crest. Area extends 100 to 400 km^2 (40 to 150 mi^2), depending on size of pillow. Percentage thinning, 10 to 100%.	Geometry Sediments are overthickened in broad to elongate primary peripheral sink, generally located on updip side of salt pillow. Axial trace of sink parallels axial trace of elongate uplift, generally separated by 10 to 20 km (6 to 12 mi). Sink attains 300 km^2 (120 mi^2) in extent, depending on size of pillow. Percentage thickening, 10 to 30%. Recognition of primary peripheral sink may be hindered by interference of nearby salt structures.
 	Facies Thin, sand-poor, fluvial-deltaic deposits over crest of pillow include interchannel and interdeltaic facies. Erosion common. Carbonate deposits on crest would include reef, reef-associated, and high-energy facies.	Facies Thick, sand-rich, fluvial-deltaic deposits in primary peripheral sink include channel axes and deltaic depocenters. Aggradation common in topographically low area of sink. Carbonate deposits in sink would include low-energy facies caused by increase in water depth.

Figure 12: Jackson and Seni's definition of a salt pillow and the geometries expected along the uplifted crest and the adjacent withdrawal basins (Jackson and Seni, 1983).

In the East Texas Basin, there were at least two significant periods of salt movement. Uneven sediment loading and increased sedimentation rates appear to be the main factors affecting salt mobilization (Seni and Jackson, 1983). In a study of the "Influence of Differential Sediment Loading on Salt Tectonics in the East Texas Basin" by Harris and McGowen (1987), "seismic data suggest that salt movement was both pre-Gilmer and coeval with Cotton Valley-Hosston deposition". This implies that there was one period of salt mobilization during the Smackover time and another during Cotton Valley Sandstone time. According to Jackson et al. (1982), approximately 500 meters of salt would be required in the first province to initiate flow by loading; thus, the addition of the Smackover carbonate wedge, atop the tabular salt, resulted in the development of the salt pillows in the second province. This suggests that at this time, there was no salt flow in the center provinces, as only the second province was influenced. This lack of salt flow into the central part of the basin was possibly due to a thinner overburden in the area at Smackover time (Jackson et al., 1982).

Differential sediment loading is described as the main factor influencing salt flow, and thus, during Smackover time, movement would have been caused by the pressure of the overlying sediments on the salt body, which caused isostatic compensation as the lighter salt migrated or flowed to areas of lower overburden pressure (Hawkins and Jirik, 1965). This flow would represent a gravity-driven gliding event due to the basinward titling caused by increased subsidence during this time (Harris and McGowen, 1987). Gravity flow was easily possible during this time as it only requires a slight slope of greater than one degree and a low viscosity rock (Jackson and Galloway, 1984). While salt is similar to a Newtonian fluid, a shear-thinning fluid more closely resembles its flow characteristics, and thus, the velocity profile of a shear-thinning fluid can be used to describe salt flow. A stiff rock, such as carbonates or sandstone, over a soft rock, like salt, sets up the best case scenario for the most movement of a glide sheet (stiff rock) over a glide zone (salt) (Fig. 13) (Jackson and Galloway, 1984). With time, as salt movement evolves, the salt varies in thickness with the topography of the basement. As the stiff overburden is carried along the glide zone, it may be stretched over basement steps initiating extension through the development of growth faults that will later propagate upward through younger strata (Fig. 14) (Jackson and Galloway, 1984).

The East Texas Basin has undergone extension as a result of salt movement. According to Rowan et al., "[F]aults form in response to vertical movement (caused by downward salt withdrawal or upward diapirism) and to lateral translation above salt" (Rowan et al., 1999). In the study area, extensional faulting appears to be related to salt withdrawal and lateral translation above the salt. Fault-related salt withdrawal is evident in the northwestern portion of the line, while extensional faults resulting from lateral translation and salt withdrawal are present toward the southeastern portion of the line (Fig. 5). The listric fault system in the southeastern portion is comprised of roller faults, which are growth faults dipping basinward that sole out in salt or merge with salt at a cusp (Rowan et al., 1999). These faults young basinward and have a large impact on the overlying strata as they can accommodate gravity gliding and hold a large potential for significant amounts of extension. This fault system is representative of the dominant style of the growth faulting found in the northern Gulf of Mexico and had a large influence on the results found in this study (Rowan et al., 1999).

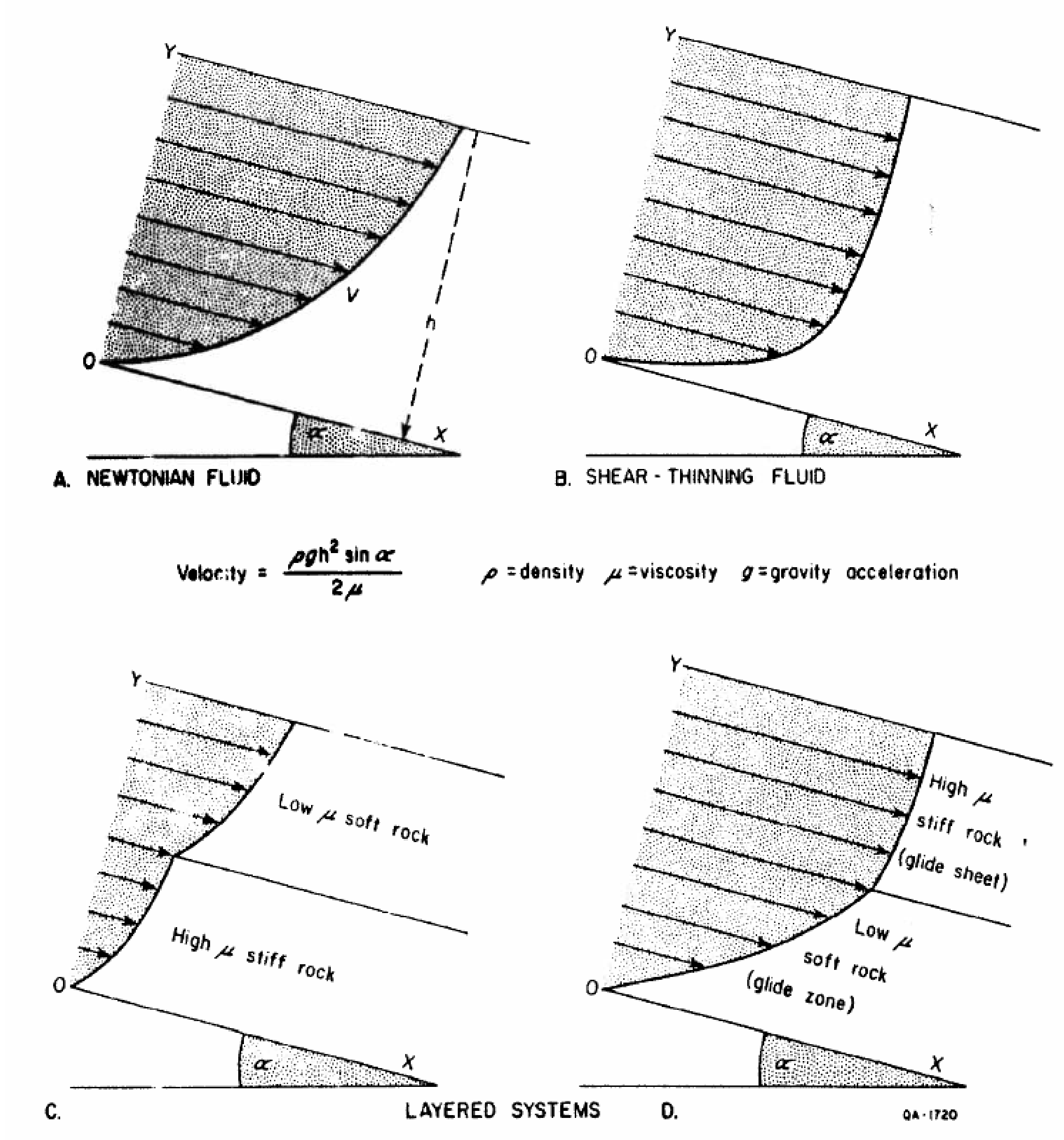


Figure 13: Velocity profiles for varying flow patterns. The dark line at the end of the arrows represents the velocity profile. Figure A shows the velocity profile in a true (Newtonian) fluid. Figure B is the velocity profile in a shear-thinning fluid, which more closely represents flowing rock salt. Figure C is a composite velocity profile in a soft layer overlying a stiff layer. Figure D is a composite velocity profile in a stiff layer overlying a soft layer. Velocities in Figure D are much greater than those in Figure C illustrating how stiff rock will flow faster over soft rock (Jackson and Galloway, 1984).

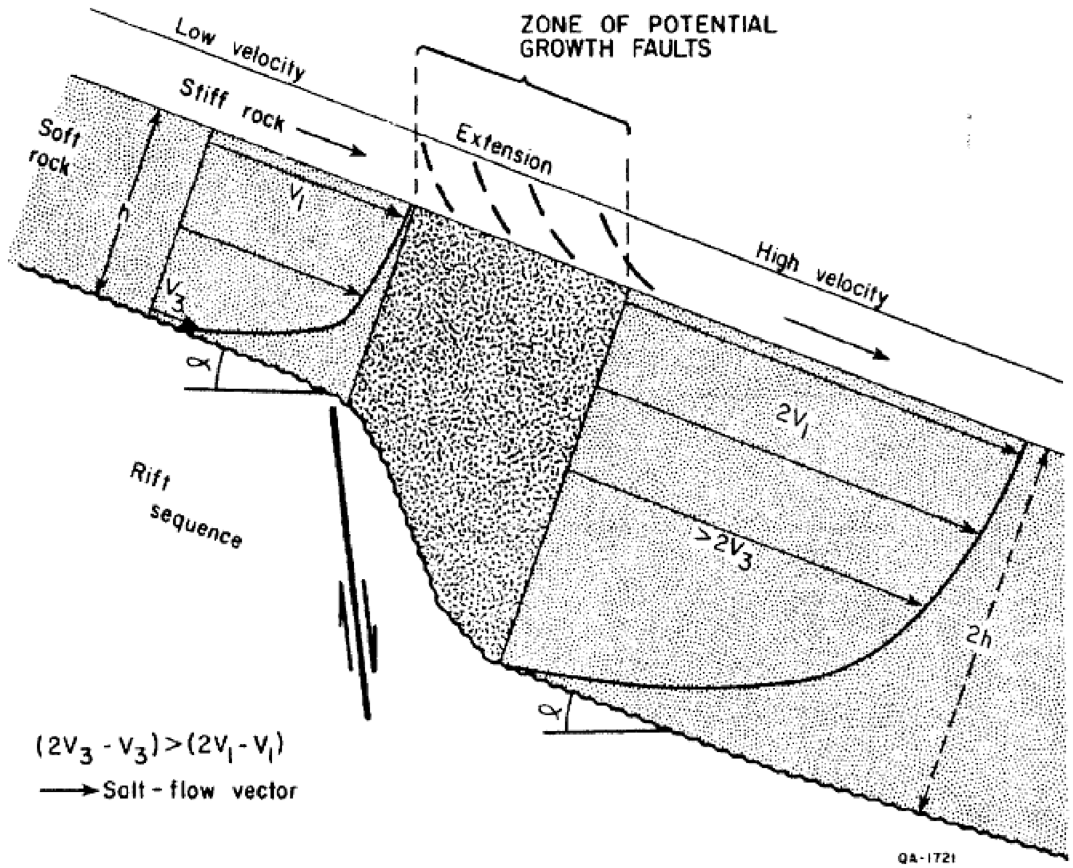


Figure 14: Illustration showing the development of a zone of extension due to a stiff glide sheet over an uneven thickness of a soft glide zone such as salt. As the soft glide zone flows faster the stiff overburden is strained and pulled apart resulting in normal faulting. This model could easily represent a salt body overlain by a carbonate system (Jackson and Galloway, 1984).

Stratigraphy and Depositional Environment

During the Upper Jurassic, four major river systems supplied sediment to the East Texas, North Louisiana, and Mississippi regions, which contain several salt filled post-rift basins. The ancestral Red River supplied sediments from the northwest, while the ancestral Ouachita River came in from the north, the ancestral Mississippi River from the northeast, and the ancestral Alabama River from the east (Ewing, 2001). The Norphlet Formation was deposited via these river systems during the Late Jurassic, as a thin siliciclastic fluvial and eolian formation over eastern Texas, northern Louisiana, Mississippi, and Alabama. Overlying the Norphlet is the Smackover Formation, which is Oxfordian in age and consists of limestones and a belt of oolite shoals deposited as part of a carbonate ramp system.

Above the Smackover, lies the Kimmeridgian aged Buckner evaporites. Due to a limited supply of terrigenous sediments from the north and northwest during Kimmeridgian time, the Buckner was deposited as part of a restricted carbonate platform-facies that allowed for development of evaporites behind carbonate belts (Ewing, 2001). A sequence boundary has been interpreted at the top of the Buckner to mark the transition into the Haynesville/Gilmer/Cotton Valley Limestone Formations.

The top of the Louark Group is defined by the Cotton Valley Limestone Formation, which sits atop the Buckner Formation and in this study. Similar to the Smackover Formation, the Cotton Valley Limestone consists of oolitic shoal complexes. However, they are found more seaward than the Smackover shoals; beyond them the Cotton Valley Limestone is present in the form of pinnacle reefs. The shoals reflect a pattern of deposition along the pre-Smackover structural highs, specifically Sabine and

Wiggins Islands, as well as older salt and basement highs (Fig. 15). The shoals and reefs of the Cotton Valley Limestone are structurally complex, as they were strongly impacted by salt movement (Ewing, 2001). Seismic reconstruction along this horizon helped to determine the overall influence of salt movement on the Cotton Valley Limestone as well as its effect on the deposition of overlying sediments.

The end of Kimmeridgian deposition is marked by a flooding surface representing a major transgression in which carbonate deposition ceased across the region (Goldhammer and Johnson, 2001). Above the Cotton Valley Limestone, the Bossier Formation marks the beginning of the Tithonian aged Cotton Valley Group, which includes the Bossier, Cotton Valley Sandstone, and Knowles (called Upper Jurassic in this study) Formations. At the beginning of Cotton Valley time, fine-grained marine shales of the Bossier Formation were deposited and drowned the Kimmeridgian carbonate system (Fig. 16) (Adams, 2009). Above these shales are several sand-rich parasequences that represent a lowstand progradation and comprise the Bossier sands (Williams *et al.*, 2001). Following the deposition of the Bossier, there is a transition from lowstand to highstand in which there is a shift from deposition of deep marine shaly units to more sand-rich shallow marine complexes. This corresponds to an increase in siliciclastics from the ancestral Red, Ouachita, and Mississippi Rivers, which created fluvial and progradational deltaic complexes known as the Cotton Valley Sandstones (Williams et al., 2001; Klein and Chaivre, 2002).

The youngest formation in the Cotton Valley Group, and the last of interest in this study, is the Knowles Limestone. It was deposited at the end of Tithonian time during a period of marine transgression, and it is interpreted to be a shelf-edge carbonate ramp that covers the southeastern portion of the East Texas Basin (Ewing, 2001).

These depositional models were incorporated into the seismic interpretation and served as a foundation upon which to reconstruct the basin history. These models were referred to at each stage of the reconstruction process in order to assess how well the restoration fit with the depositional models.

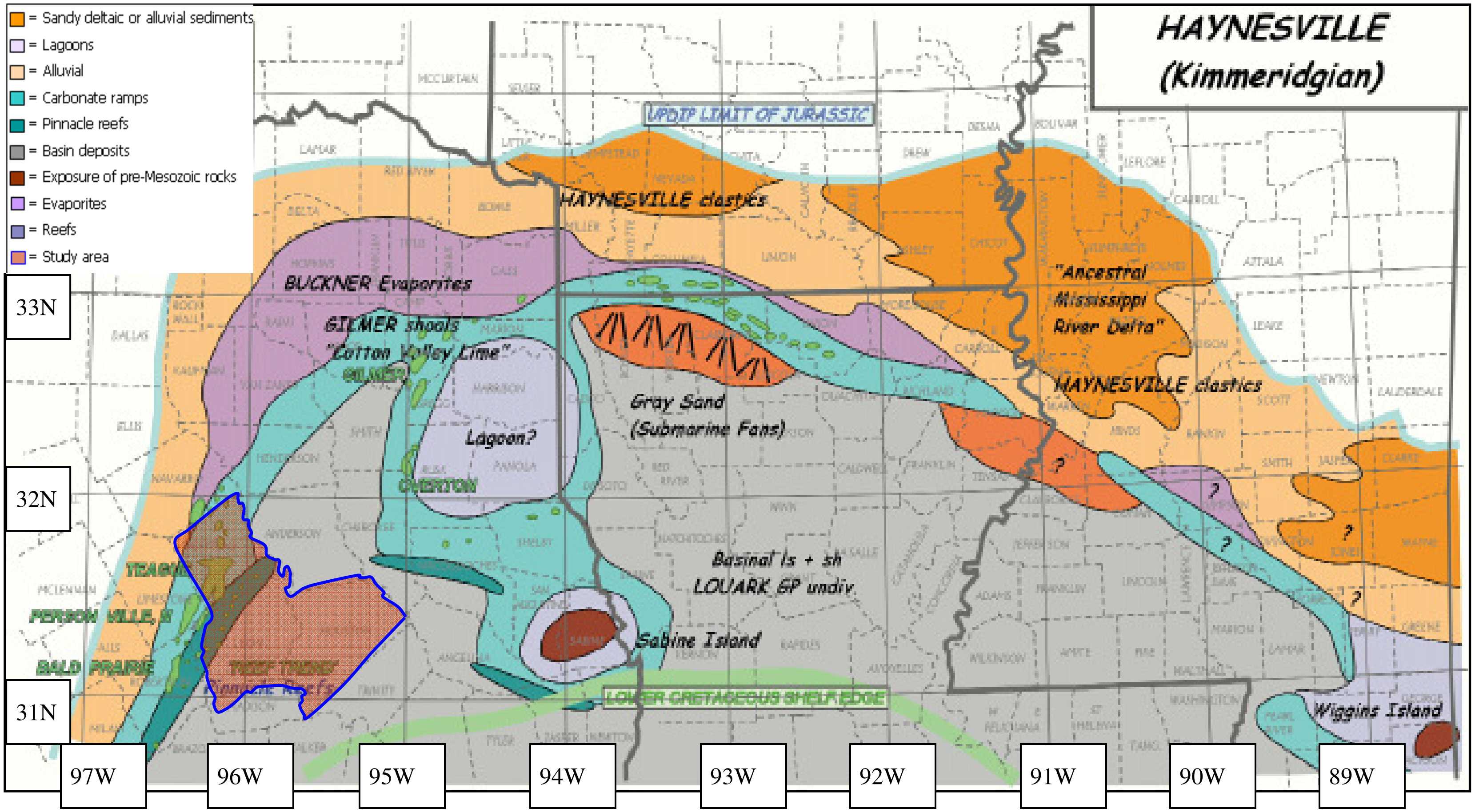


Figure 15: Map of the depositional environment during Cotton Valley Limestone deposition at the end of Kimmeridgian time. [Modified from Ewing (2001)]

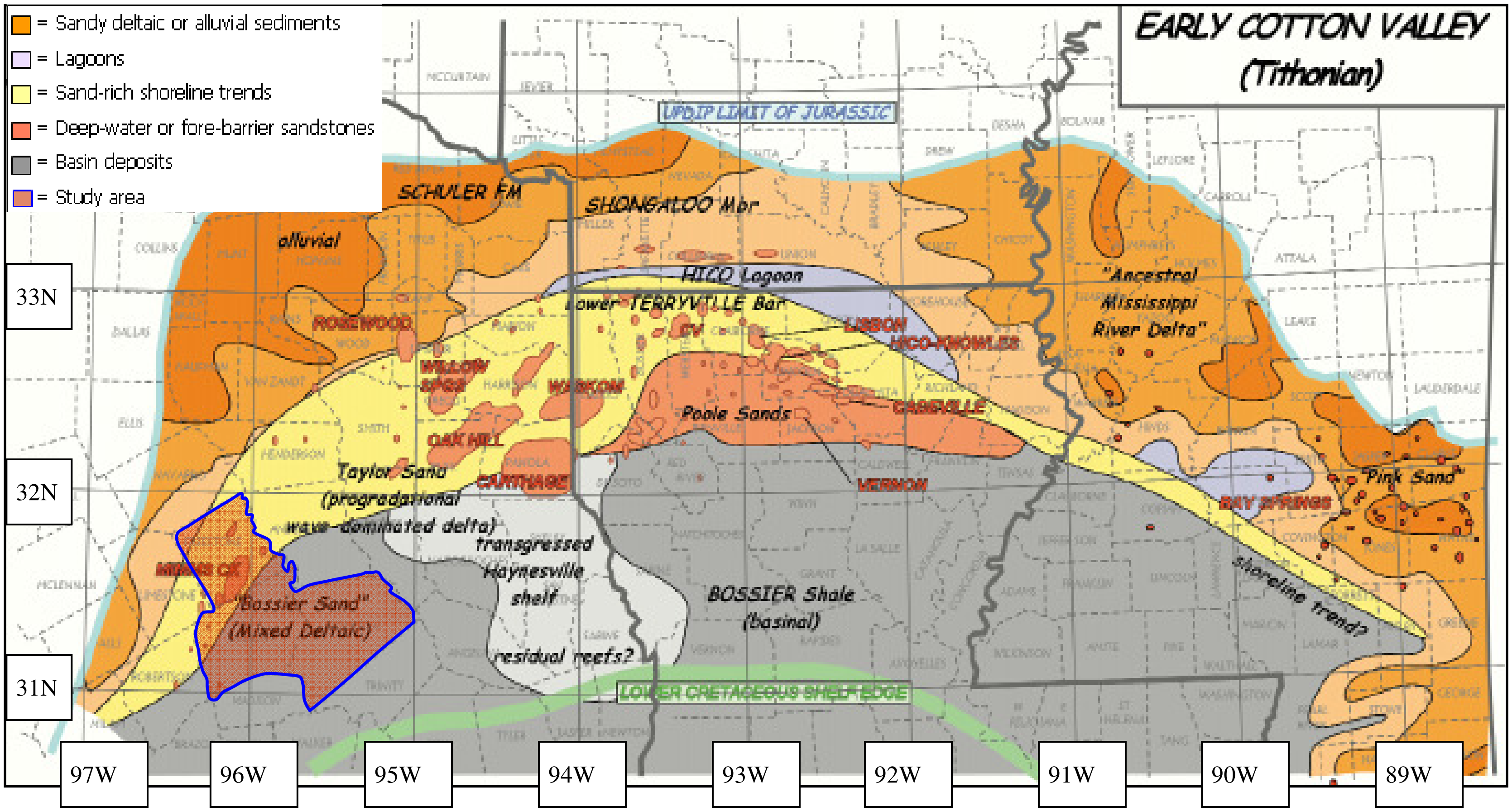


Figure 16: Map of the depositional environment during Bossier deposition at the beginning of Tithonian time. (Modified from Ewing, 2001)

METHODOLOGY

Reprocessing

Several interpretations have been published regarding the depositional history of the East Texas Basin. However, new 3D surveys have helped to enhance the seismic quality over the area and have contributed to new interpretations of the region. Before interpreting the 2D line, it was reprocessed in order to enhance the data quality in the areas where there was no 3D coverage. The southeastern portion of the line was the main focus, and in order to improve the data quality in this area, the reprocessing flow was tailored to fit this area and enhance the signal quality in that region of the line.

The first step was to correct the land geometry, as the field observations did not record the geometry accurately. The raw data were shot using dynamite and two recording trucks with 48 channels each. The geometry description had to be typed into the trace headers, and the bin widths were set to ½ the receiver interval. Datum statics were run using sea level as zero and a replacement velocity of 7,000 ft/s.

Next, refraction statics were run, but they did not improve the data so elevation statistics were processed to a final floating datum. Then, the data were clipped to 6 seconds and the trace edits and datum statics were applied. Velocity analysis resulted in a coarse grid of velocities or a raw stack that was picked every one hundred CDP gathers. The velocities were applied to the CDP gathers and surface consistent residual statics were run, which used eleven CDP gathers at twelve fold and created a trace model. The program took the first trace of the first gather and compared it to the model trace, found the best shift to make the real trace line up with the model, and continued this for each trace.

Spherical divergence was then applied to correct for energy attenuation and apply a surface amplitude correction to equalize anomalies. Then, deconvolution was used to increase resolution with depth, but spiking deconvolution resulted in over-whitening so short gap predictive deconvolution was used. Another round of residual statics was run and velocities were picked again to flatten the data, this time the CDP spacing was decreased to about one half of a mile. Trim statics were applied, resulting in a trace model that compared each live trace in each CDP with the model and only allowed for a shift of plus or minus 6ms for each trace. Once this was complete, the final stack was processed.

The final step in the reprocessing flow was pre-stack time migration. This was accomplished by taking the unstacked CDP gathers and binning them into six different offset groups. Each group was then migrated by combing the first traces from each group, which all had the same offset, and then the second traces all with the same offset, and so on until all six groups were migrated. Finally, another residual velocity analysis was applied, but velocities were picked every 25 CDP gathers and each trace in each CDP was corrected by a few milliseconds. Then, it was restacked to create a post-migration stack (Fig. 17).

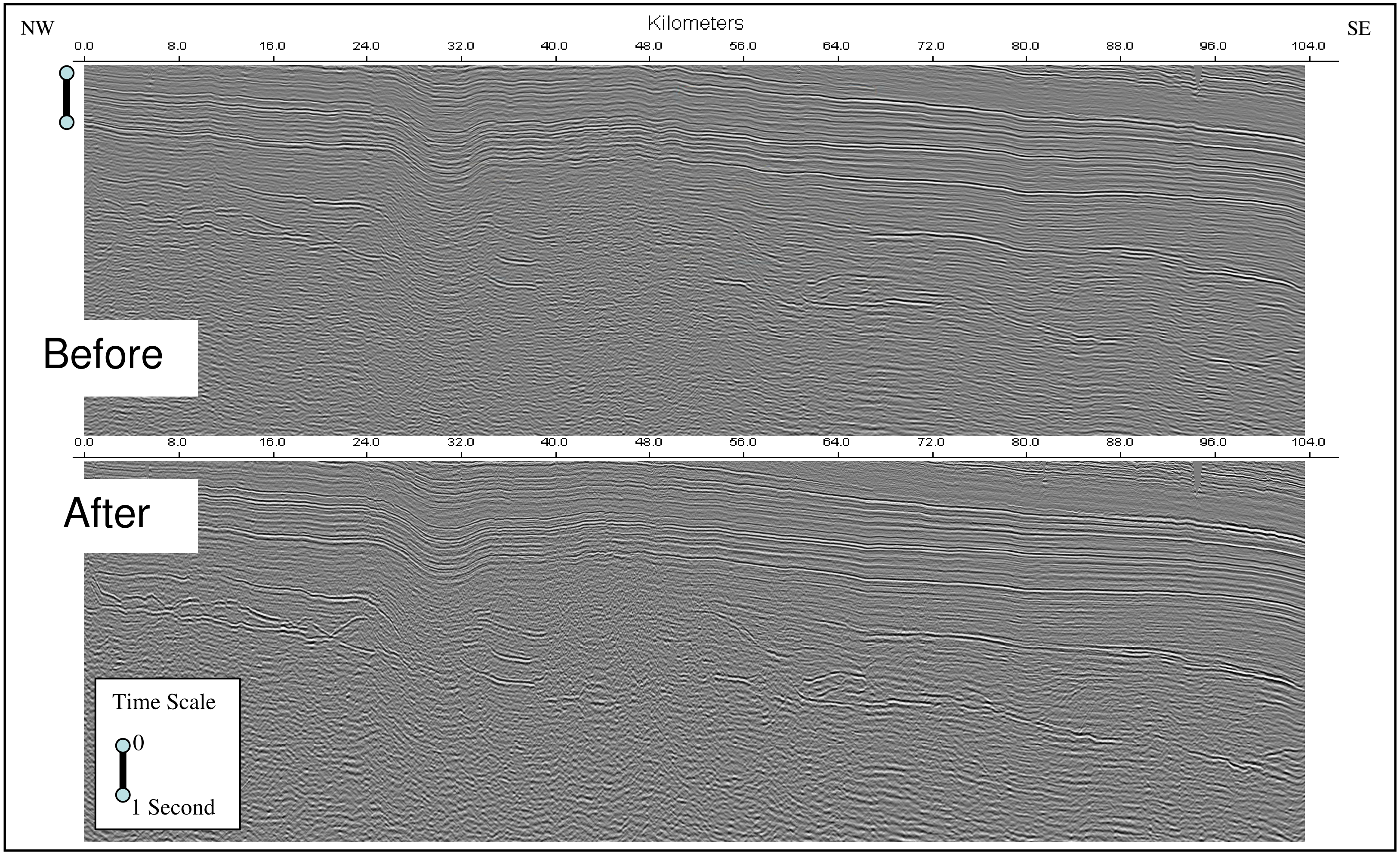


Figure 17: Before and after reprocessing. Courtesy of Seismic Exchange, Inc. and Marathon Oil Company.

Data Interpretation

Once the 2D line had been reprocessed, it was then possible to begin making interpretations. However, the process of data interpretation was iterative as changes and adjustments were constantly being made due to inconsistencies in the interpretation once restoration was attempted. The initial interpretation was created using only the 2D line and picking significant horizons. The base of salt, top of salt, top of the Cotton Valley Limestone, top of the Knowles Limestone, and top of the Pettet Formation were the main horizons (Fig. 5).

Using Landmark's Seisworks software, the 2D line was merged with 3D data that overlapped. From this, it was possible to more accurately interpret the 2D line by comparing areas of uncertainty with the 3D data and well data. From the 3D data and well control, the Bossier and Cotton Valley Sandstone horizons were picked, as well as shallower marker horizons. The northern and southeastern portions of the line, however, do not have 3D coverage; thus, the interpretation was based solely on well data and comparison to similar regions.

In order to support the interpretation of the down-dip portion of the line, eight wells were chosen along that portion of the 2D line and a cross-section was created using the gamma ray, sonic, resistivity, neutron porosity, and density logs from each well (Fig. 18). Based on this cross-section, it was possible to interpret how the regions reacted with regards to thickening and thinning in the down-dip direction. This aided in supporting the interpretation of the Cotton Valley Sandstone and Bossier in this section where the seismic data quality suffered.

Once the interpretation of the 2D line was completed, it was then compared to the well data and 3D data to confirm the validity of the interpretation, and the 2D line and the wells were imported into Geologic Systems' LithoTect software. Using LithoTect's forward modeling tool, fault geometries were tested to see how they would restore and thicknesses were compared to well data, and based on this, the time interpretation was tweaked before running the depth conversion (Fig. 19).

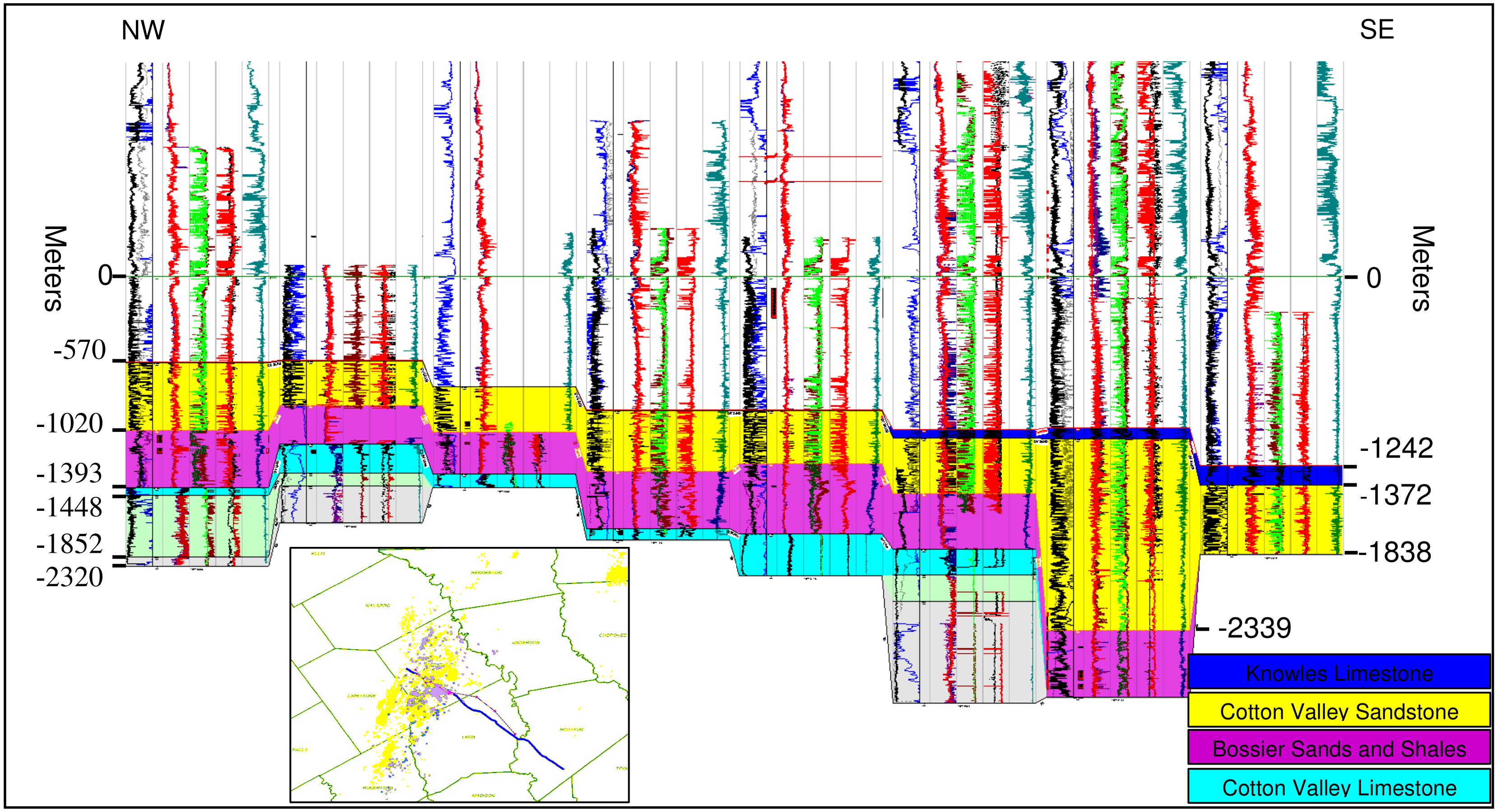


Figure 18: Cross-section through 8 wells running roughly parallel to the 2D line in the study. The cross-section shows a noticeable thickening in the Knowles and Cotton Valley Sands to the southeast, which is consistent with the seismic interpretation. The small map in the left corner displays the location of the cross-section in pink relative to the 2D line in blue.

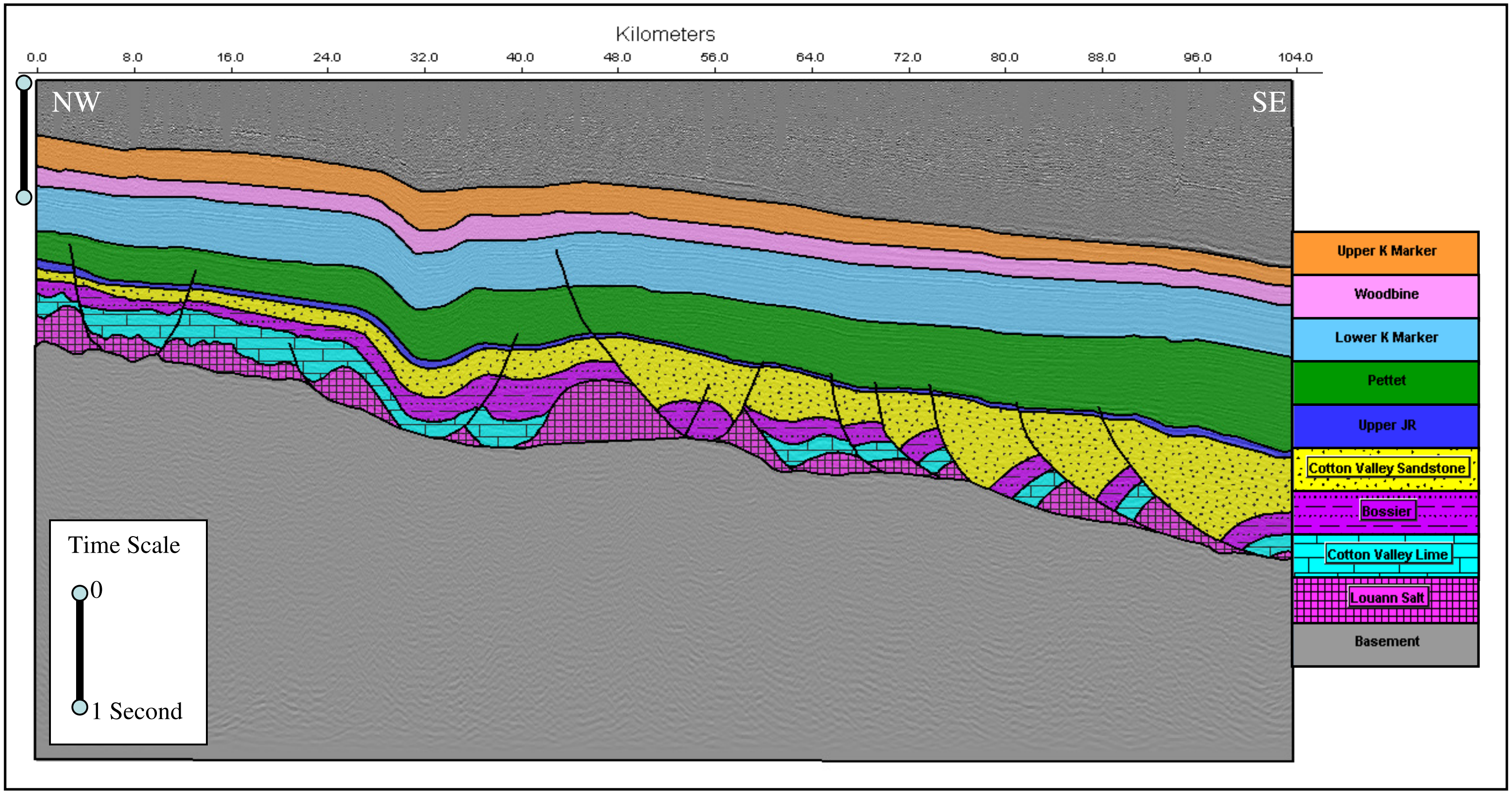


Figure 19: Time Interpretation supported by well data and 3D seismic in the area. Vertical exaggeration is 2:1. Courtesy of Seismic Exchange, Inc. and Marathon Oil Company.

Depth Conversion

In order to convert the time interpretation to depth, the background velocities were determined as well as the velocities of all the formations in the interpretation. First, the background velocities were calculated from the paper 2D line by averaging the RMS interval velocities across the line and inputting them into software called CurveExpert. CurveExpert plotted the background velocities and produced an equation for the best fit line along the values (Fig. 20). The MMF model was chosen as the equation that described the line with the best fit to the data points. This equation would later be needed in the depth conversion process.

Next, the sonic log values from the cross-section were used to determine the velocities for each formation in the interpretation. The top and base picks for each formation in all eight wells were utilized, and the velocities were averaged between the top and base picks for each formation. Then, that data was averaged from each well to come up with an average velocity for each formation. These values were compared with a Marathon Oil Company internal velocity study that had already been done in the same area to make sure the values were consistent (Fig. 21).

These velocities were input into LithoTect's stratigraphic column. Next, the depth conversion module was used to input the MMF model and each formation velocity to create a velocity model (Fig. 22). Then, the depth conversion was run using the velocity model. When the interpretation was converted from time to depth, many of the lines became jagged so each line in the interpretation had to be smoothed before the restoration process could begin (Fig. 23).

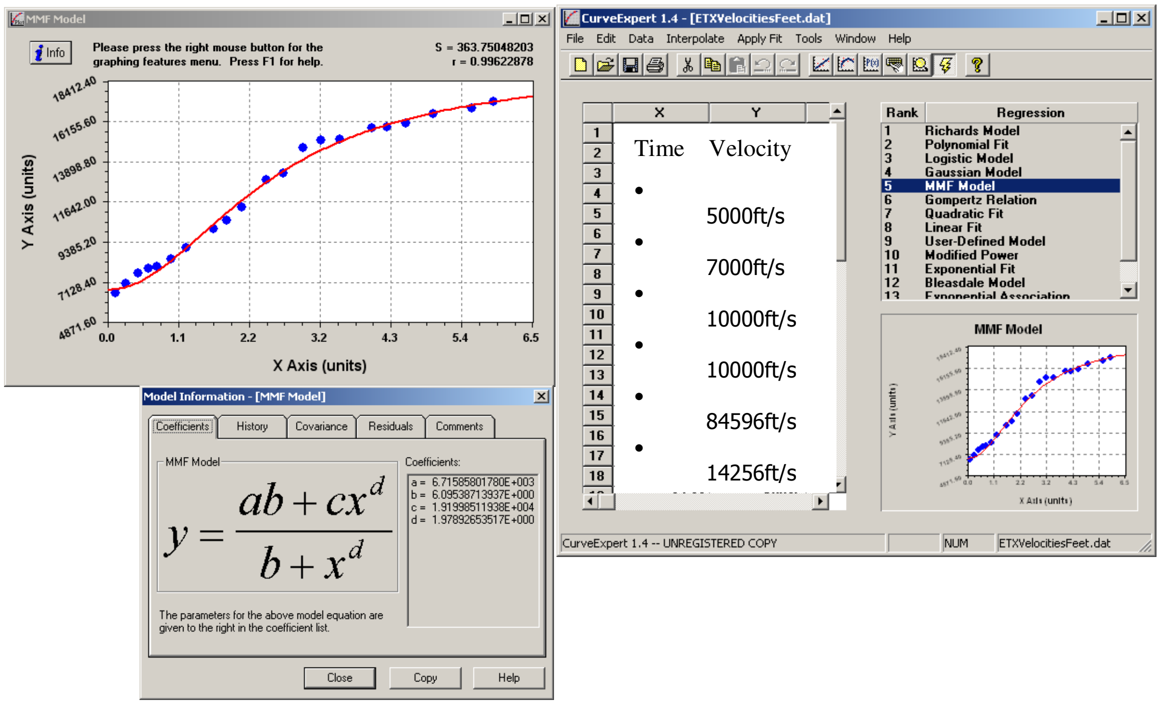


Figure 20: CurveExpert software that was used to do the velocity analysis and produce an equation for the best fit line along the values. The MMF model was the fifth closest fit, but was the only one that would work with the LithoTect software.

Region	Average Velocities (m/s)		Calculated Velocities (m/s)
Datum	3,174		3,183
Buda			4,575
Pettet	5,188	<-- A little too fast but ok	4,989
Knowles Limestone	4,760	<-- Looks pretty good	5097
Cotton Valley Sandstone			4,851
Bossier	4403	<-- Might be a little too fast in Deep Bossier	3950
Cotton Valley Limestone	6098		4976
Salt	~4573		4573

Figure 21: Comparison of velocity analysis with regional velocity study. Velocities calculated in this study are in yellow. Blue represents the average velocities and comments on those velocities that were determined in a regional velocity study. (Marathon Internal Velocity Analysis)

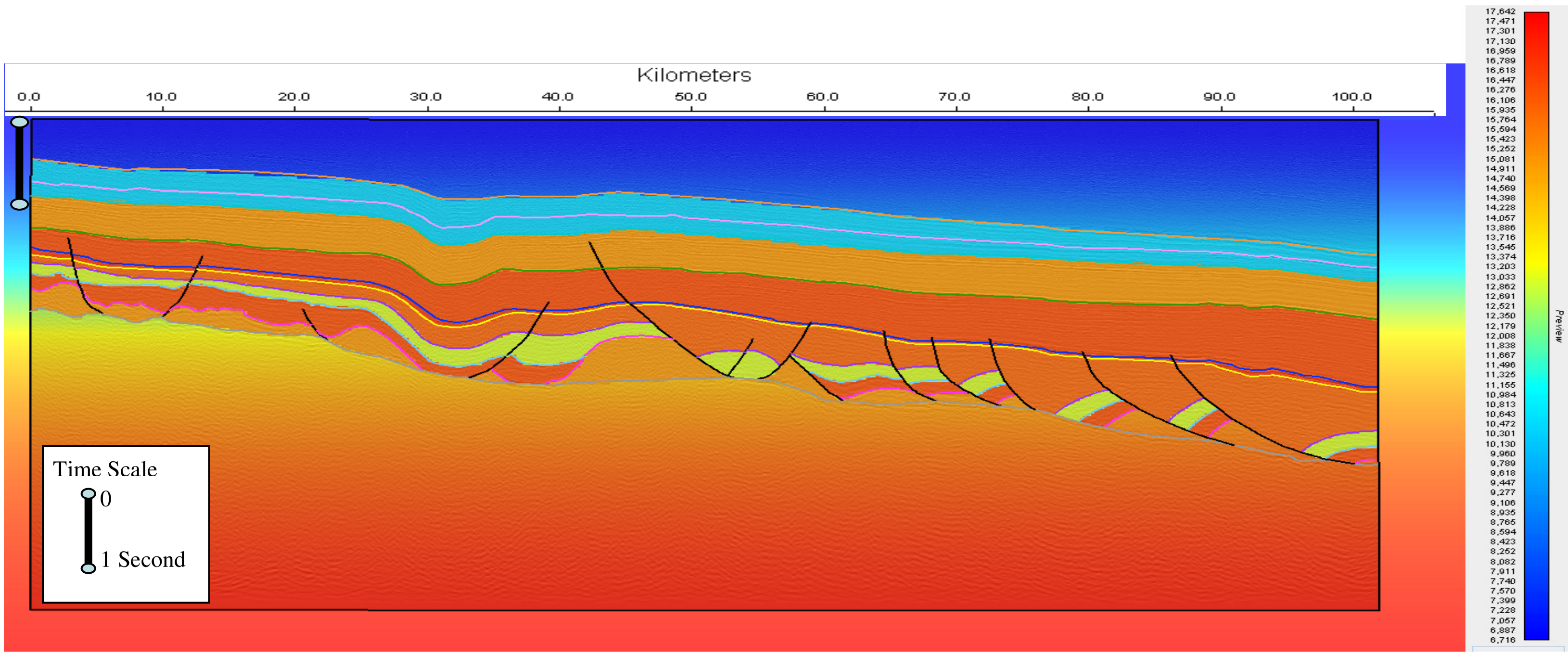


Figure 22: Velocity preview prior to depth conversion. Vertical exaggeration is 2:1. Courtesy of Seismic Exchange, Inc. and Marathon Oil Company.

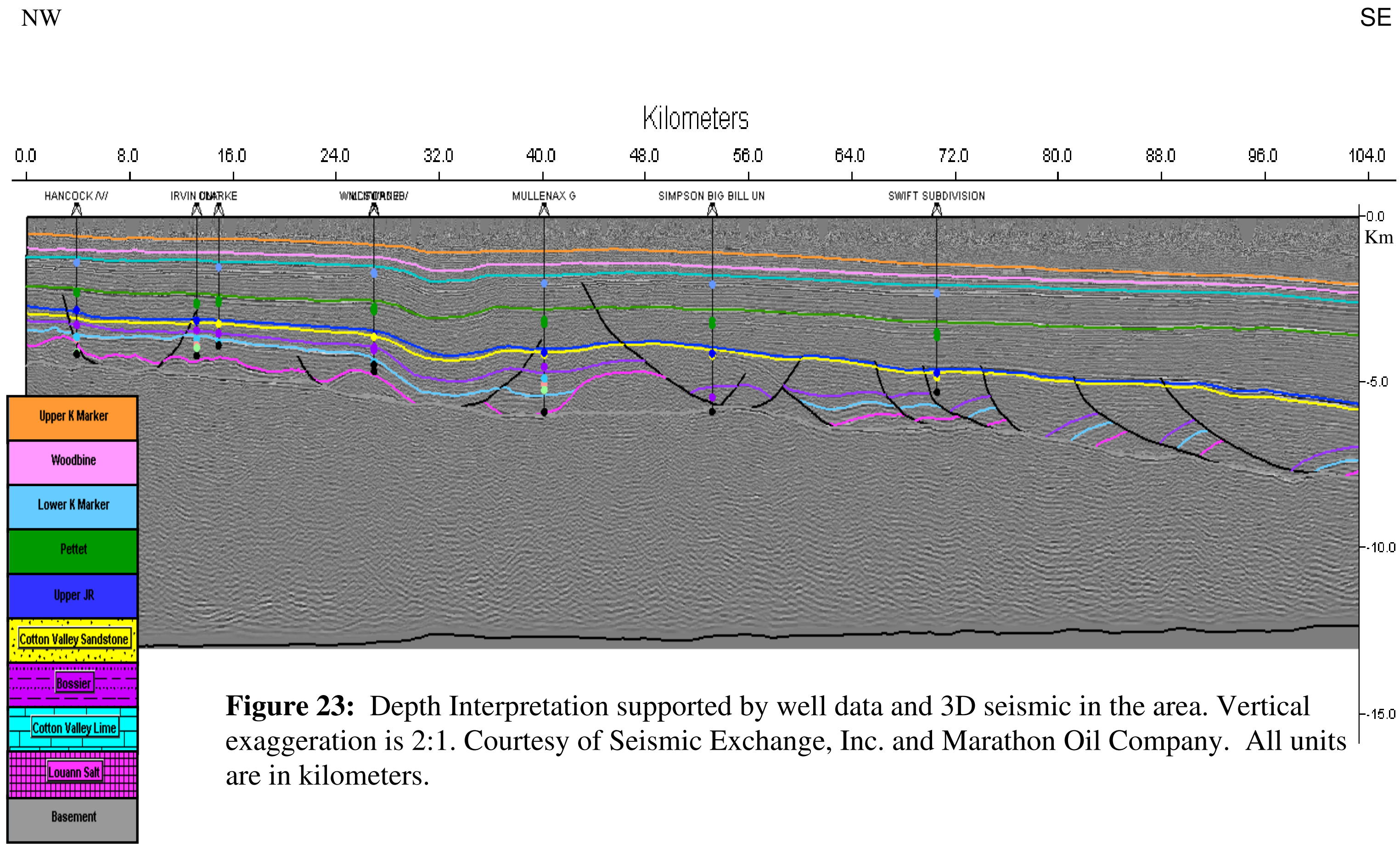


Figure 23: Depth Interpretation supported by well data and 3D seismic in the area. Vertical exaggeration is 2:1. Courtesy of Seismic Exchange, Inc. and Marathon Oil Company. All units are in kilometers.

Restoration and Decompaction

To begin restoring the interpretation, a regional elevation had to be taken into account for each formation as this would serve as the restoration surface. The regional elevation for each formation was chosen to allow for maximum salt thickness. While this elevation could be adjusted and the restoration redone, it would only change the final model by reducing the salt thickness and thus, the values that were chosen depict a maximum salt thickness. The regional salt elevation was used to determine whether there was an excess of salt due to basin uplift, basement shortening, or salt flow from out of the plane, or if there was a deficiency due to dissolution (Hudec and Jackson, 2004). During the restoration process, a spreadsheet was used to record the perimeter, area, line length, and thickness of each stratigraphic unit within fault-bounded blocks in the cross-section. This spreadsheet was updated during each stage and the changes recorded and used to calculate the rates of sedimentation, horizontal, northwest to southeast extension and compaction over the basin, as well as the isostatic subsidence and the ratio of salt to Cotton Valley Limestone.

Restoration began with the keystone fault block on the northern end of the line. Working across the line, it soon became clear that the 2D seismic line was too large and there was too much faulting to be able to reconstruct the whole line at once. After attempting to restore several different areas of the line, it was determined that it would be more effective to break the line into four regions based mainly on timing of fault movement and style of deformation (Fig. 24).

The regions are numbered one through four starting at the northern end of the line and working down-dip as that appeared to follow the chronologic order of deformation.

Each region was restored using vertical oblique slip, which is the kinematic model commonly associated with extensional restorations. Then horizon thicknesses and bed geometries that did not restore to the regional elevation without overlap were adjusted in the time domain and the depth conversion re-run to try to restore them again and see if the restoration was better. This was the main technique for interpretation validation, and it helped to shed light on the timing of events and to start to piece together the influence of salt movement on these formations. After restoring each region, they had to be re-connected at each stage of reconstruction to make sure they fit with each other. This caused another round of adjustments, but assembling the entire restored line helped to confirm the model on which the interpretation was based.

Once the interpretation was adjusted such that it finally fit when restored, decompaction was performed. Figure 25 describes the solidity functions used for each formation during decompaction. Starting with the original section, one formation at a time was backstripped and then decompacted. Once this process reached the deformed layers (i.e. Upper Jr and older), the top deformed formation was restored to a regional elevation and then backstripped and decompacted. This method was used from the Upper Jurassic down to the top of salt. A record of each region's perimeter, area, line length, and thickness was kept to record changes in each region at each stage. Any changes or modifications in bed shape or thickness that were necessary to balance the reconstruction were made so that no region had an area change greater than 0.0929 square meters (one square foot).

Once the restoration was complete for all stages, the results in the spreadsheet were combined to form a series of graphs illustrating the results of compaction, extension, sedimentation rate, and the ratio of salt to limestone. The results from manually measuring the extension at each stage were compared to the values given from LithoTect's bedlength balancing tool. The bedlength balancing tool shows the same amount of extension, but also illustrates the amount of new salt added at each stage (Fig. 26).

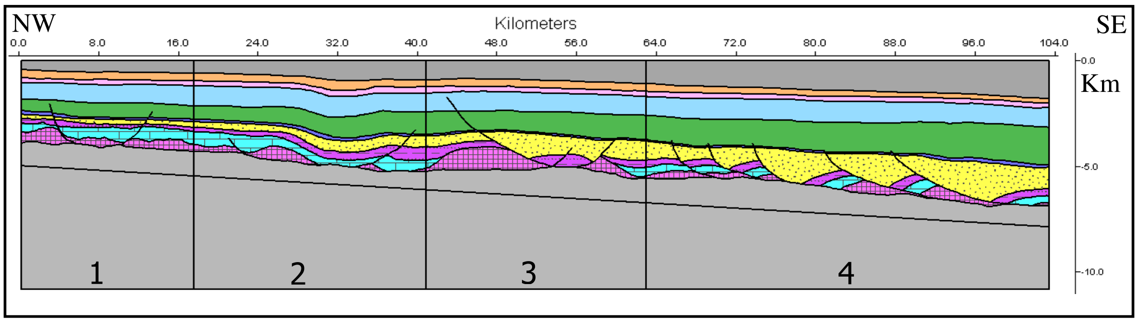
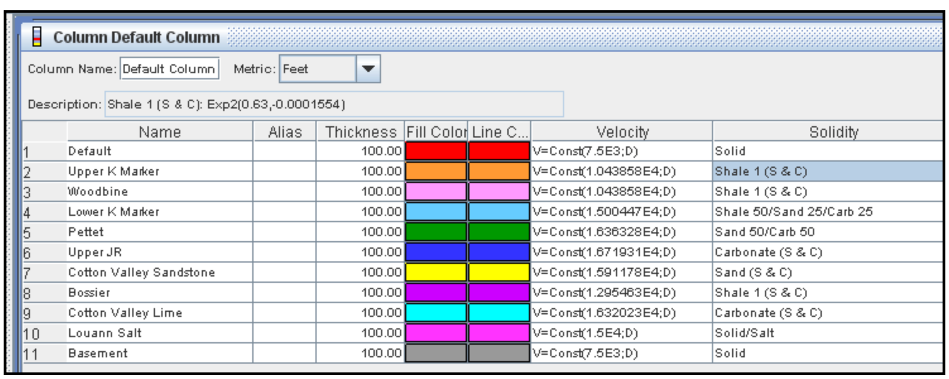


Figure 24: In order to restore the whole line, it was necessary to divide the line into four regions and restore each region separately, and then, put the regions together and confirm they could be reconstructed as a whole. Vertical exaggeration is 2:1. All units are in kilometers. Refer to Figure 23 for stratigraphic column.



Column Default Column

Column Name: Default Column Metric: Feet

Description: Shale 1 (S & C): Exp2(0.63,-0.0001554)

	Name	Alias	Thickness	Fill Color	Line C...	Velocity	Solidity
1	Default		100.00			V=Const(7.5E3;D)	Solid
2	Upper K Marker		100.00			V=Const(1.043858E4;D)	Shale 1 (S & C)
3	Woodbine		100.00			V=Const(1.043858E4;D)	Shale 1 (S & C)
4	Lower K Marker		100.00			V=Const(1.500447E4;D)	Shale 50/Sand 25/Carb 25
5	Pettet		100.00			V=Const(1.636328E4;D)	Sand 50/Carb 50
6	Upper JR		100.00			V=Const(1.671931E4;D)	Carbonate (S & C)
7	Cotton Valley Sandstone		100.00			V=Const(1.591178E4;D)	Sand (S & C)
8	Bossier		100.00			V=Const(1.295463E4;D)	Shale 1 (S & C)
9	Cotton Valley Lime		100.00			V=Const(1.632023E4;D)	Carbonate (S & C)
10	Louann Salt		100.00			V=Const(1.5E4;D)	Solid/Salt
11	Basement		100.00			V=Const(7.5E3;D)	Solid

Figure 25: Table listing the solidity functions used for each formation in the decompaction process. Shaly units were described as Shale 1, units that were a mix of interbedded shales and sandstones were described according to approximate percentages of shale and sandstone comprised in the unit, and carbonate and sandstone units were named accordingly.

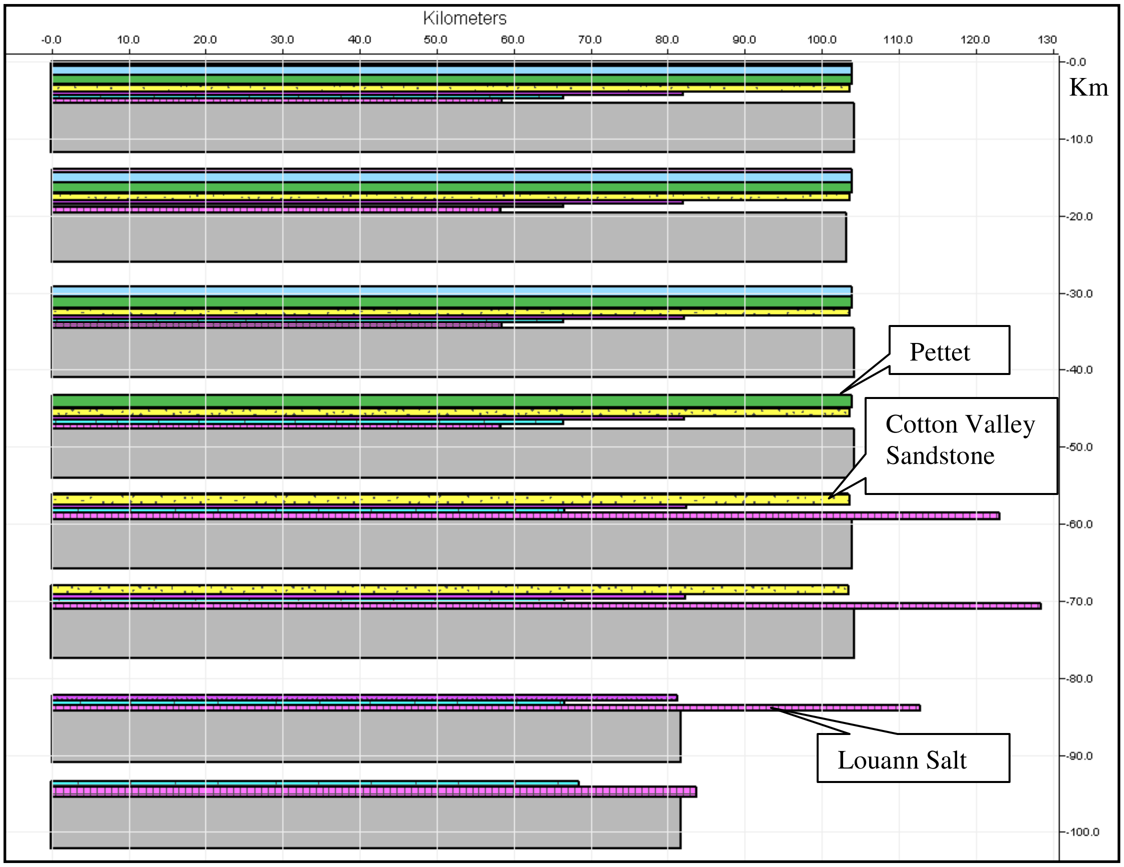


Figure 26: Results of bed-length balancing at each stage in the restoration. The variation in the salt bed-length represents salt movement at each stage. It appears that the length of the salt is consistent until the Pettet is removed, which suggests that due to the large overburden pressure there was salt withdrawal from Cotton Valley Sandstone time up until Pettet. There appears to be a loss of salt when the Cotton Valley Sandstone is removed. This can be explained by extension that was triggered by the loading of the Cotton Valley Sandstone so that at Bossier time there was less salt because the section was shorter and there was less deformation. Finally, at the end of Cotton Valley Limestone deposition, there appears to be even less salt. This is probably due to less deformation within the salt so the bedlength was shorter at this time. Refer to Figure 23 for stratigraphic column. All units are in kilometers.

RESULTS

The results of the 2D restoration helped confirm the interpretation and supported the models upon which the interpretation was based by creating a picture of the basin at each stage of deposition. This was accomplished by calculating rates of extension, compaction, sedimentation, and subsidence, as well as the ratio of salt to limestone.

The process of restoring the line began by backstripping the upper layers until the deformed layers were reached. The Upper Jurassic was the first deformed horizon and it measured an average of 115 meters thick on the present day seismic line ranging from 82 to 162 meters thick. After the overburden had been stripped away and the Upper Jurassic had been decompacted and restored, it measured approximately 188 meters thick. Thus, it underwent roughly 65 meters of compaction (Fig. 27). From the end of Upper Jurassic to Pettet time, it appears that there was approximately 0.4 kilometers of extension possibly due to salt withdrawal and reactivation along listric faults (Fig. 28).

Next, was the Cotton Valley Sandstone, which ranged from 211 to 1500 meters thick and had an average thickness of about 850 meters before decompaction or restoration. Once it had been decompacted and reconstructed, the Cotton Valley Sandstone, which consists of mostly deltaic sands, had an average thickness of 1240 meters signifying almost 390 meters of compaction on average, but in some areas over 1000 meters of compaction was calculated. It does not appear that any extension took place from the end of Cotton Valley Sandstone deposition to the top of the Upper Jurassic (Fig. 29). This could possibly be due to the marine transgression at the end of Cotton Valley time and the rapid decrease in sedimentation rate from the 19.2 cm/1000 yr during Cotton Valley deposition to that of the Upper Jurassic at about 7.3 cm/1000 yr (Fig. 30).

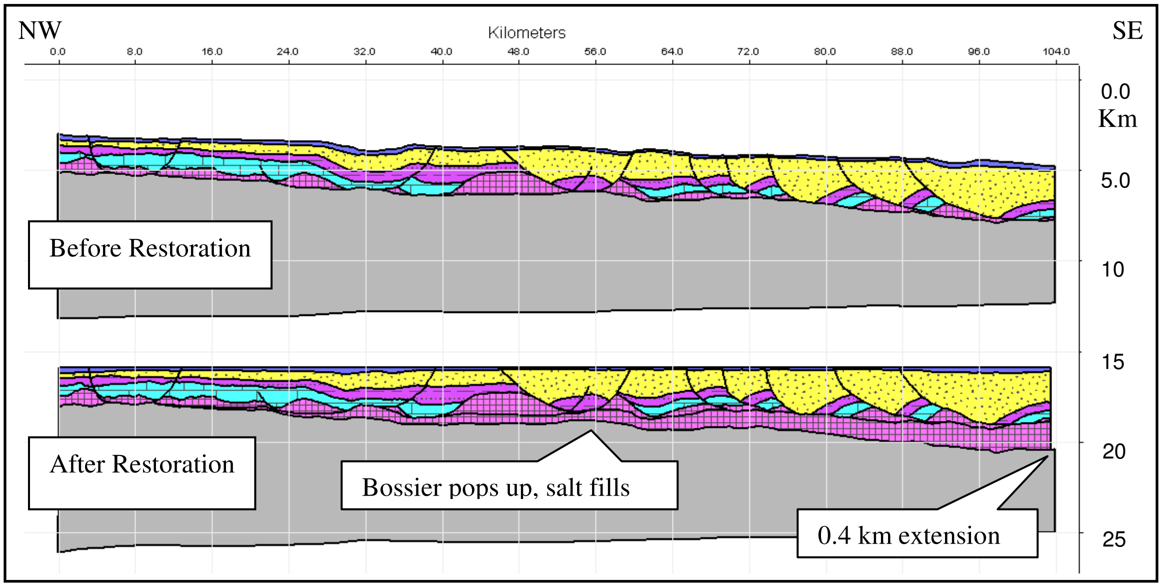


Figure 27: Before and after reconstruction of the Upper Jurassic unit. When the Upper Jurassic is returned to regional, there is a significant amount of salt added to the system as the small Bossier deposition between the salt blocks is popped up and salt fills in between the basement and the Bossier. There also appears to be some extension that took place as the restored section is shorter than the original. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column. All units are in kilometers.

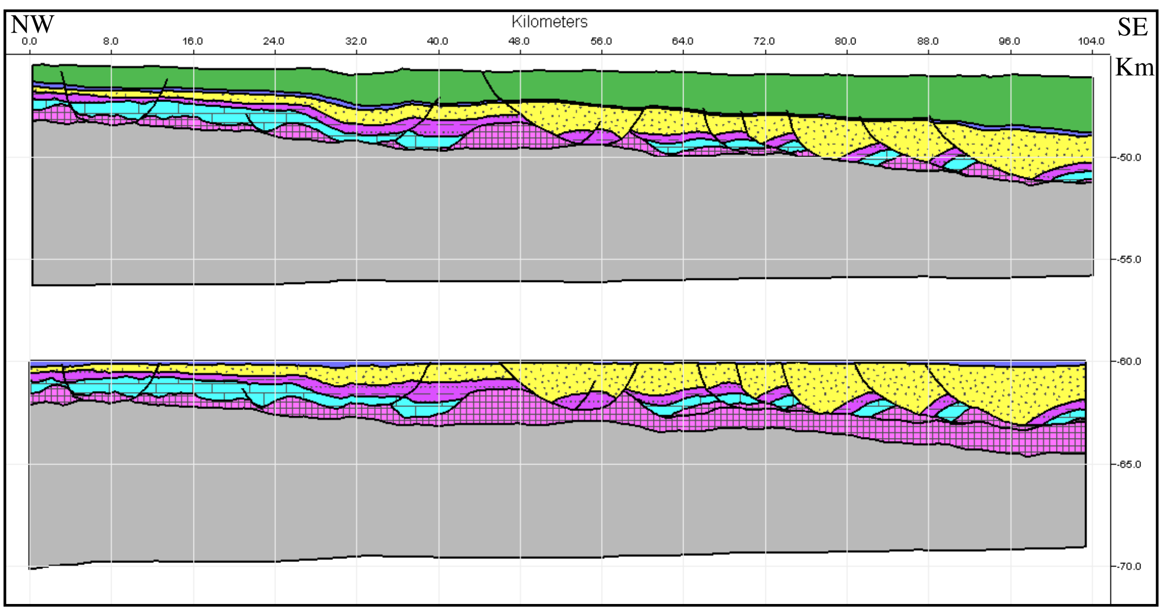


Figure 28: After reconstructing the Upper Jurassic, it appears that there was about a 0.4 kilometers of extension between the Upper Jurassic and Pettet. This could be due to salt withdrawal and reactivation along the listric faults to the southeast. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column. All units are in kilometers.

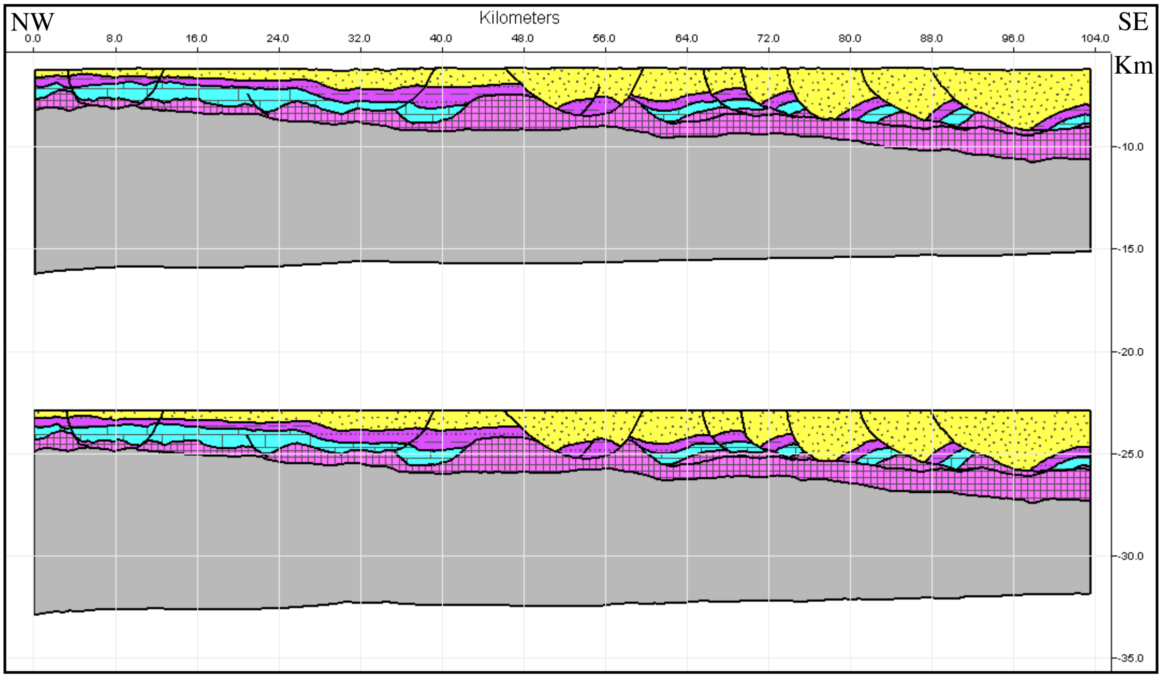


Figure 29: Before and after reconstruction of the Cotton Valley Sandstone. When the Cotton Valley Sandstone are returned to regional, there is slightly more salt added to the system, but there is no evidence of extension at this stage. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column. All units are in kilometers.

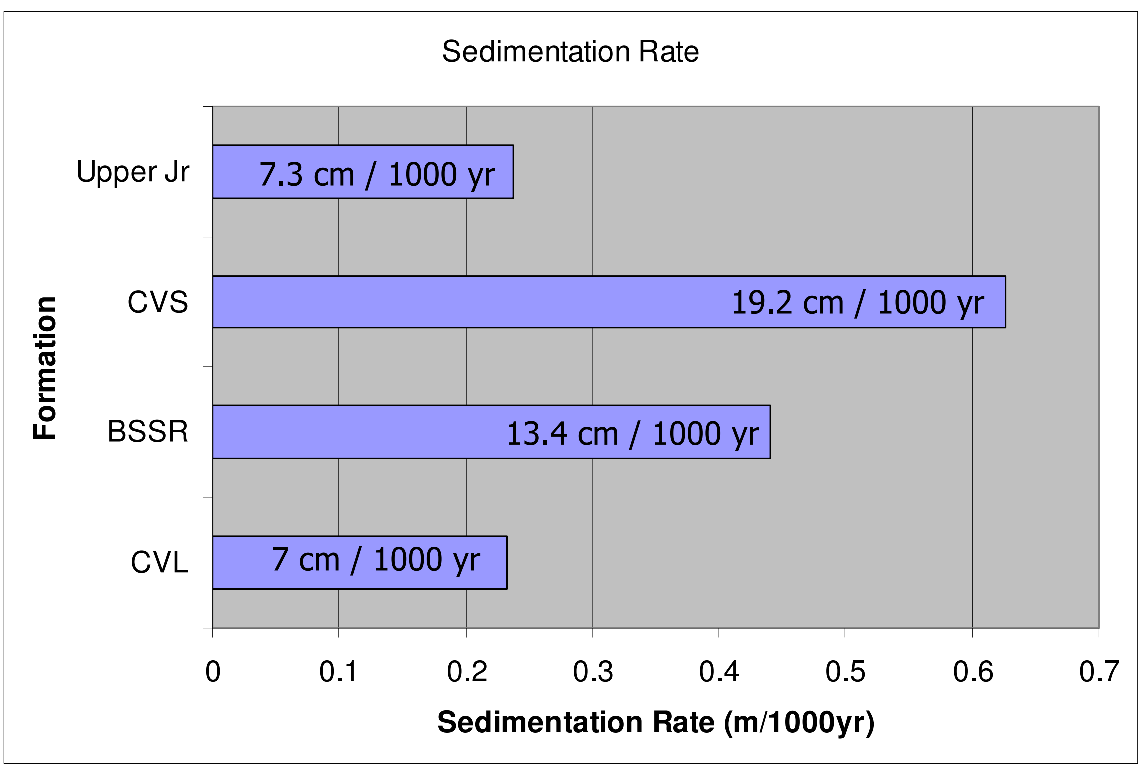


Figure 30: Graph illustrating the sedimentation rates for each formation.

Once the Cotton Valley Sandstone was backstripped, the Bossier was decompacted and restored. The Bossier Formation has a present day average thickness of approximately 370 meters thick, ranging from 222 meters to 682 meters thick. After decompaction and restoration, it has an average thickness of ~700 meters (Fig. 31). This corresponds to about 333 meters of compaction, which when compared to its average thickness of ~370 meters before backstripping the Cotton Valley Sandstone, implies that the Cotton Valley Sandstone had a large impact on the Bossier and must have been part of a large increase in sediment supply and sedimentation rate. This corresponds to the increase in sedimentation rates from Bossier time at 13.4 cm/1000 yr to 19.2 cm/1000 yr during Cotton Valley Sandstone deposition. This large increase in sedimentation from the end of Bossier to the top of Cotton Valley Sandstone time also had a significant impact on extension, as there was approximately 22 kilometers of extension during this time (Fig. 32). This averages out to approximately 3.41 mm/yr and can most likely be attributed to the large influx of sediments into the starved basin. The pressure of this large overburden contributed to gravity-driven sliding over the Louann Salt resulting in large listric growth faults, 5 to 13 kilometers in length with small, about 0.02 kilometers in the Upper Jurassic, to large amounts, almost 8 kilometers in the Bossier, of displacement that accommodated the extension.

Backstripping the Bossier exposed the Cotton Valley Limestone, which has a present day average thickness of about 500 meters on the 2D line with values ranging from 320 meters to 600 meters. After decompaction and restoration, the average thickness approximately 740 meters (Fig. 33). That equates to almost 238 meters of compaction. There was little to no extension during this time, although it appears that there was salt growth taking place syndepositionally as the limestone thins over the northernmost salt body when reconstructed.

By reconstructing the Upper Jurassic strata at each depositional stage, new values of salt volume were introduced into the system, which agreed with the interpretation and depositional model. For example, in the northern portion of the line in region three, when the Upper Jurassic layer is restored, there is a pop up and separation between the basement and Cotton Valley Limestone where salt was once present (Fig. 27). As the restoration continues, more salt is added into the system at each stage. The thickness of salt was compared to Cotton Valley Limestone because it is present throughout each restoration step and is not lost down-dip off the line when the Bossier and its extension is restored (Fig. 34). As previously mentioned, regional elevation was used to compare the area of salt to the surrounding sediments because typically salt will only be displaced upward if the surrounding sediments sink below the regional salt elevation (Hudec and Jackson, 2004). This suggests that the amount of salt above regional elevation should be equal to the amount of sediments below regional elevation (Fig. 35). This is not the case in this study, there is more salt above regional elevation than there is Cotton Valley Limestone below, 18.7 km^2 of salt versus 8.9 km^2 of Cotton Valley Limestone. According to Hudec and Jackson (2004), this is possible due to either basin uplift relative to the flanks of the basin, basement shortening, or salt flow from out of plane. In this case, it appears to be caused by salt flow from out of the plane, which can be correlated with surrounding areas of salt lows seen on an isochron map of the area (Fig. 36). Bedlength balancing also provided a good indication of the amount of salt added to the system.

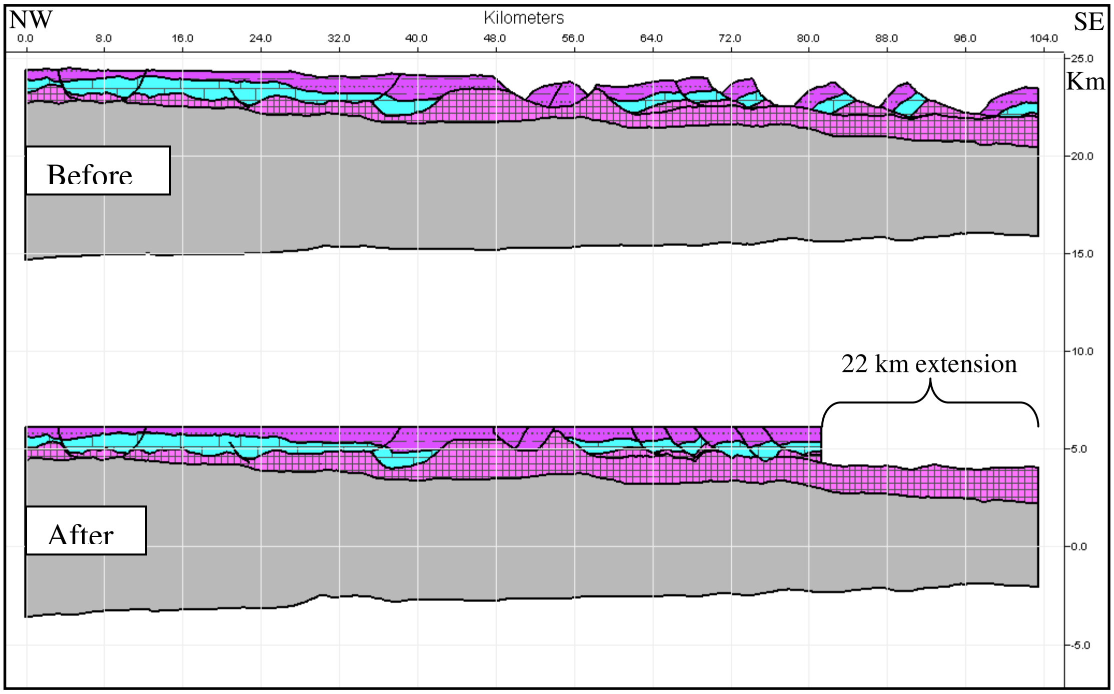


Figure 31: Before and after reconstruction of the Bossier Formation. Upon returning the Bossier to regional, it is obvious that the salt is thicker, and there was a significant amount of extension during Cotton Valley Sandstone deposition. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column.

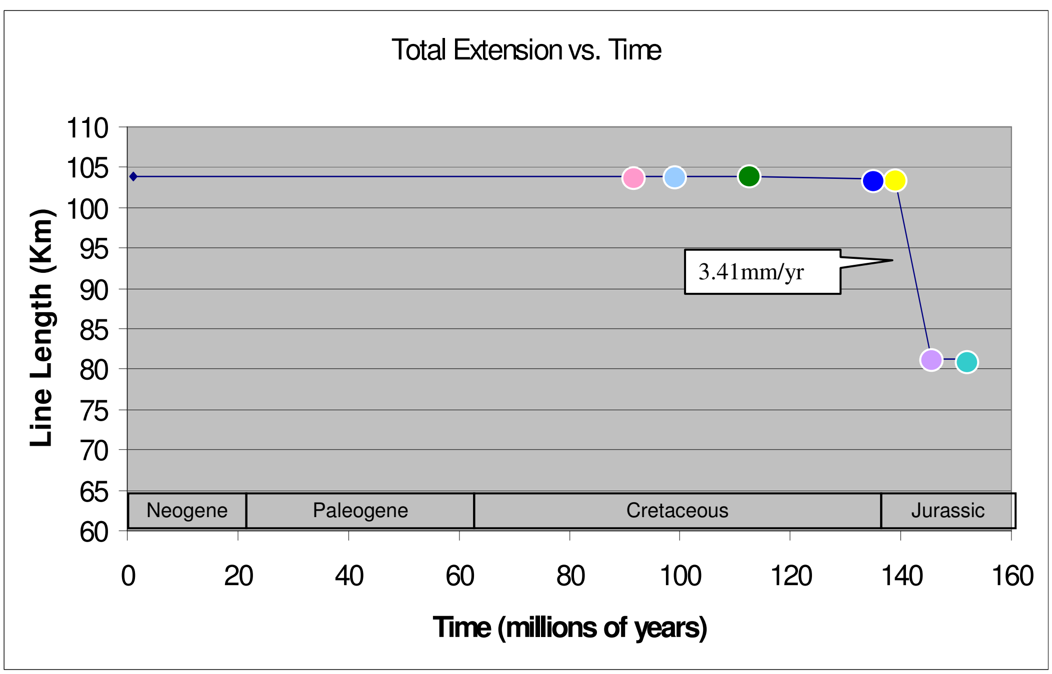


Figure 32: There was approximately 22 km of extension during Cotton Valley Sandstone time, which equates to approximately 3.41mm/year. Colors correspond to formations. Refer to Figure 23 for stratigraphic column.

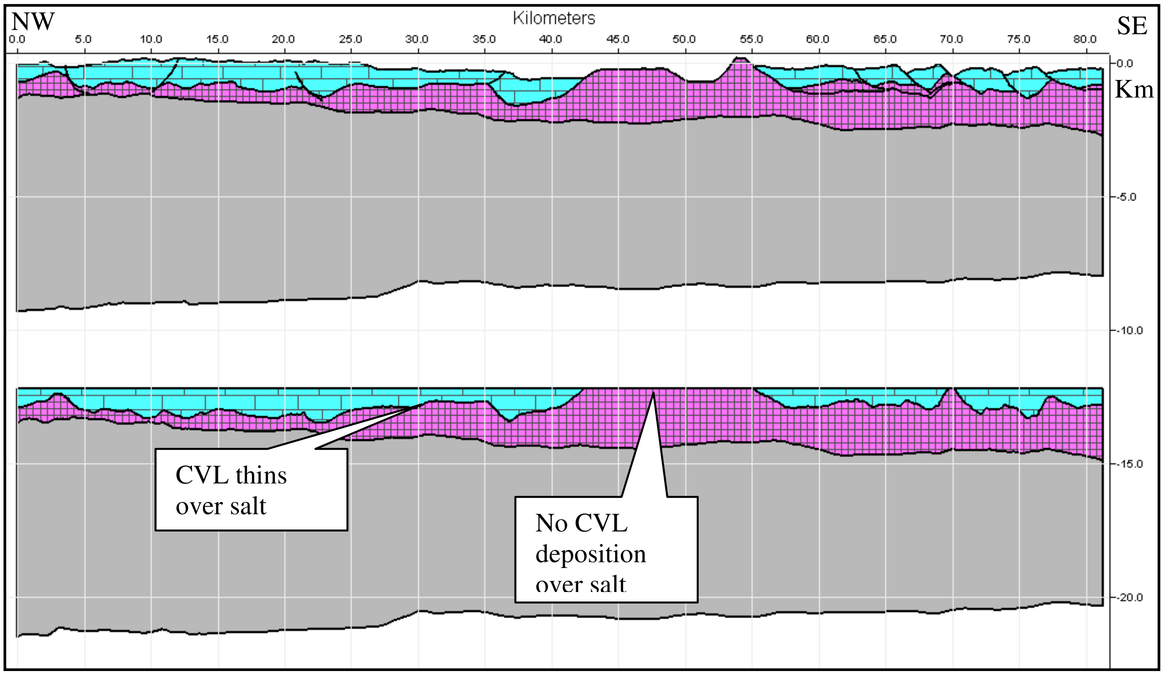


Figure 33: Before and after reconstruction of the Cotton Valley Limestone (CVL). Once the Cotton Valley Limestone is returned to regional, it is apparent that the limestone thins over first large salt body, implying that it was a paleo-high at the time of deposition. From this restoration, it is obvious that the large salt body was higher than the regional elevation of the limestone, and therefore, there was no Louark Group deposition over that body. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column.

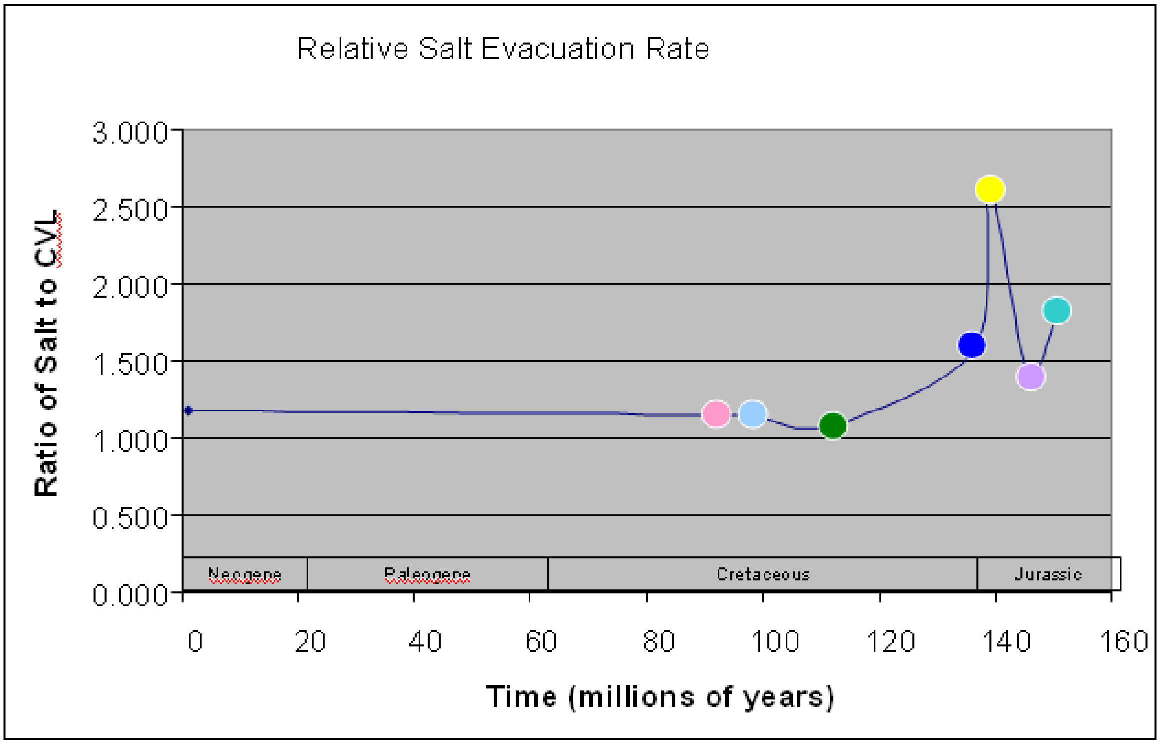


Figure 34: Ratio of Louann Salt to Cotton Valley Limestone. The Cotton Valley Limestone was used to compare to the thickness of salt because it is present in the same length as the salt, it is not lost down-dip off the line when the Bossier extension is restored.

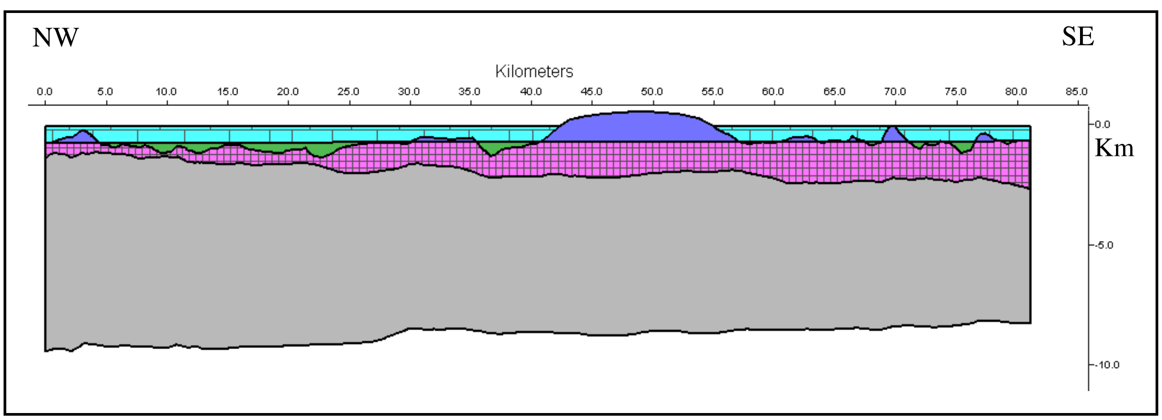


Figure 35: The areas of salt (dark blue) above the regional salt elevation should be equal to the Cotton Valley Limestone (green) below regional elevation. The dark blue salt has an area of 18.7 km^2 versus 8.9 km^2 of green Cotton Valley Limestone. Since the areas are not equal, this suggests that there was salt flow from out of plane. Vertical exaggeration is 2:1. All units are in kilometers.

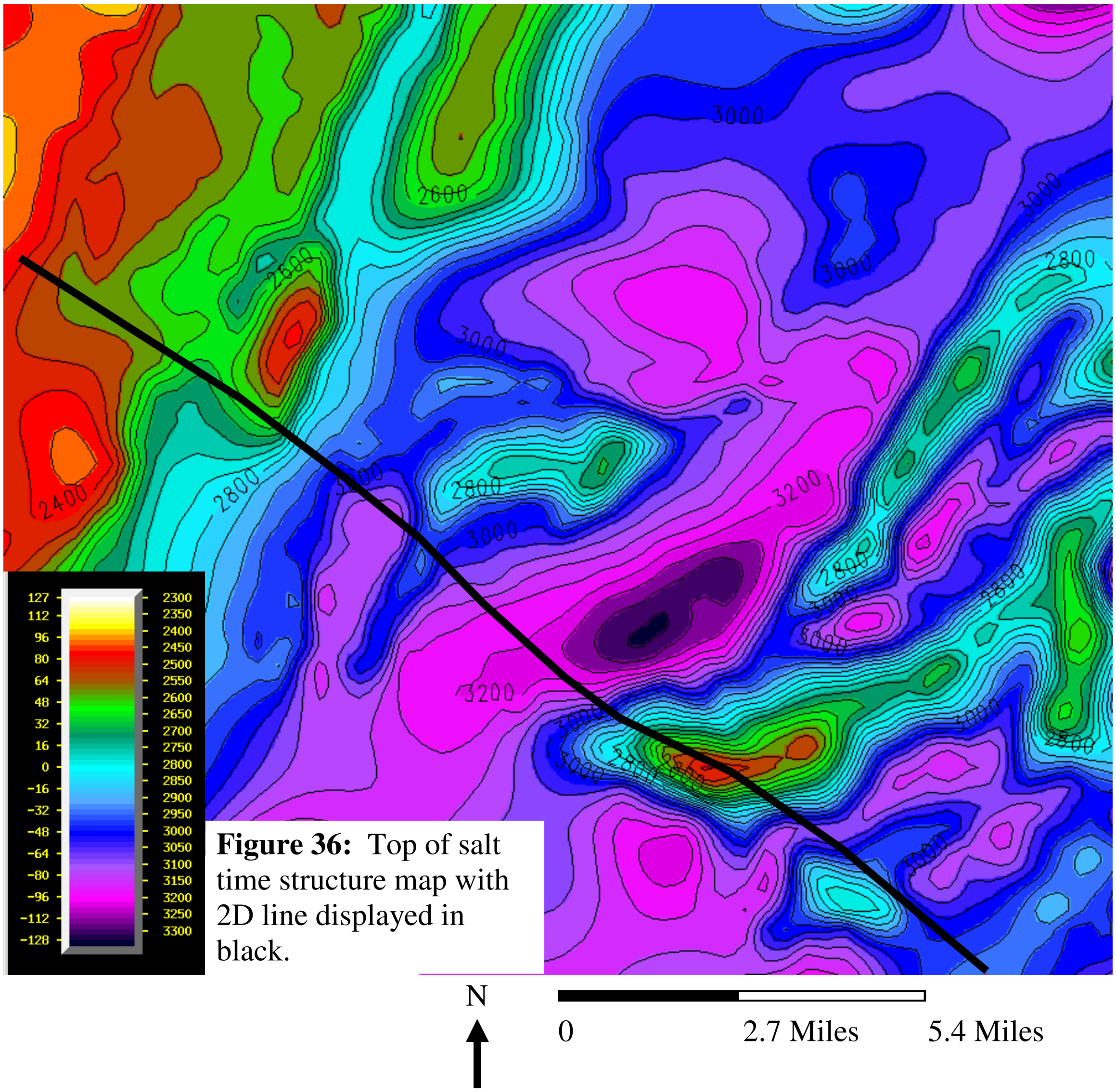


Figure 36: Top of salt time structure map with 2D line displayed in black.

Once the results were compiled, the rates of extension, compaction, sedimentation, and subsidence were calculated. Figure 32 shows the rate of extension at each stage in time. Overall, there was approximately 21% extension across the whole line, and figure 37 shows roughly 48 kilometers of the 2D seismic line across the southern end of the basin. In comparison with the whole basin, 21% might be low but is probably a fairly close estimate since the line almost covers the average width of the basin. The rate of extension varied at each depositional stage, but was highest during Cotton Valley Sandstone time when the basin underwent approximately 22 kilometers of extension. In order for there to have been this much extension there must be a linked contractional region down-dip where the extension was taken up. While this area is not visible on the 2D line or the 3D data in the area, it must be present at a much greater depth basinward. The extension estimate provided here suggests the down-dip contractional region accommodates approximately 22 kilometers of northwest to southeast shortening.

Figure 38 shows the rate of compaction for each formation. From the graph, it is evident that the Pettet was the thickest formation and during Pettet time, approximately 112 million years ago, there is a large increase in the compaction rate. There is another large increase shown during Cotton Valley Sandstone time. These formations appear to have had the greatest impact on compaction in the basin.

Sedimentation rates were calculated by taking the average thickness of the formations and dividing that by elapsed time. The rates of sedimentation for the Bossier and Cotton Valley Sandstone are shown in figure 30. The Cotton Valley Sandstone posts a much higher sedimentation rate than the surrounding formations suggesting that during this time there must have been an increase in sediment supply.

The final calculations noted were the rates of subsidence over the 2D line (Fig. 39). A horizontal line was placed along the base of the original section and as each layer was backstripped and decompacted, the distance between the horizontal and the reconstructed base was measured. This value was then plotted against the time in millions of years, and the slope of that line is the rate of subsidence at that time. Based on the measurements taken in this study, it is evident that after the deposition of the Cotton Valley Sandstone, the subsidence rate increases from 0.024 mm/yr to 0.083mm/yr. According to Harris and McGowen (1987), the rate of subsidence that took place contemporaneously with sedimentation is largely controlled by the thickness of the Louann Salt. This is evident in figures 34 and 39 where the large increase in the ratio of Louann Salt to Cotton Valley Limestone corresponds to the highest subsidence rate. It also appears that the rate of subsidence begins to level off during the mid to late Cretaceous. This observation is consistent with theories published by Jackson and Seni (1983).

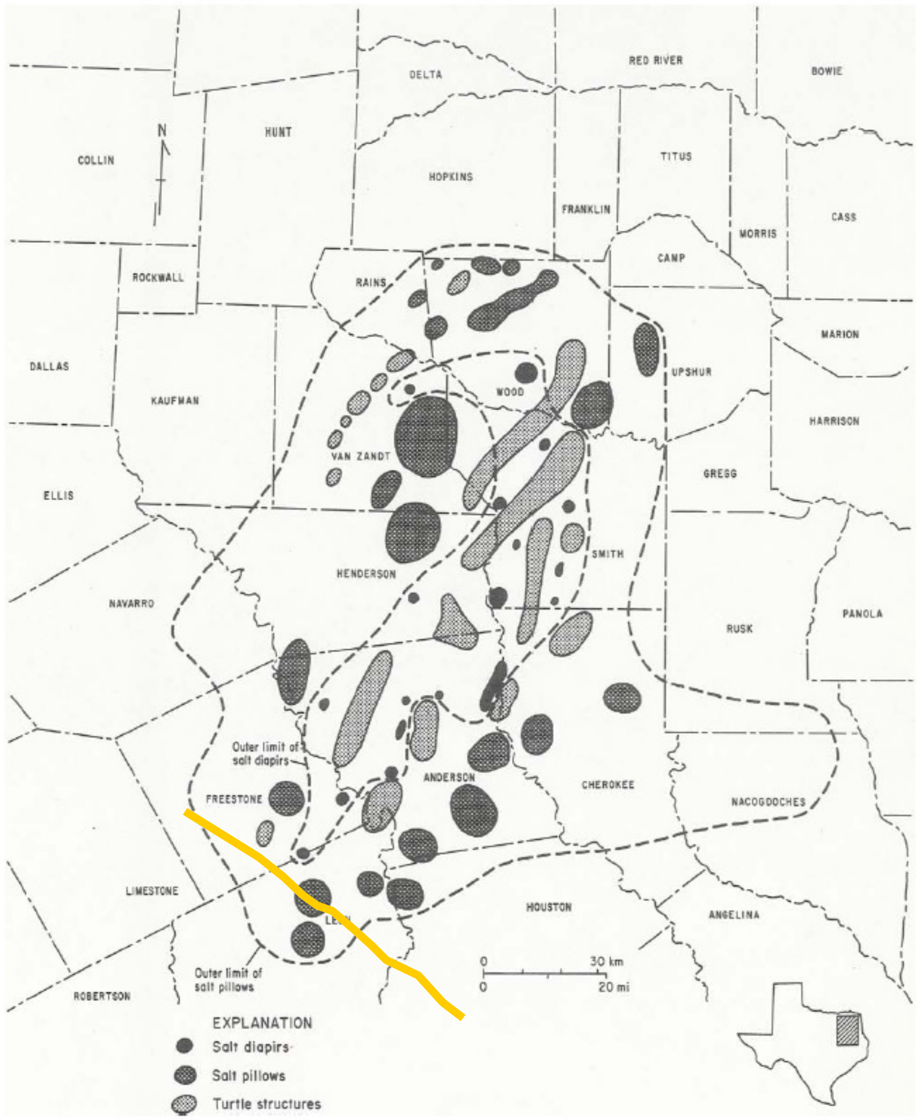


Figure 37: Map of the salt provinces of the East Texas Basin with the 2D line superimposed to show its size in relation to the basin. The line covers approximately 30 miles across the southern end of the basin. [Modified from Jackson (1982)]

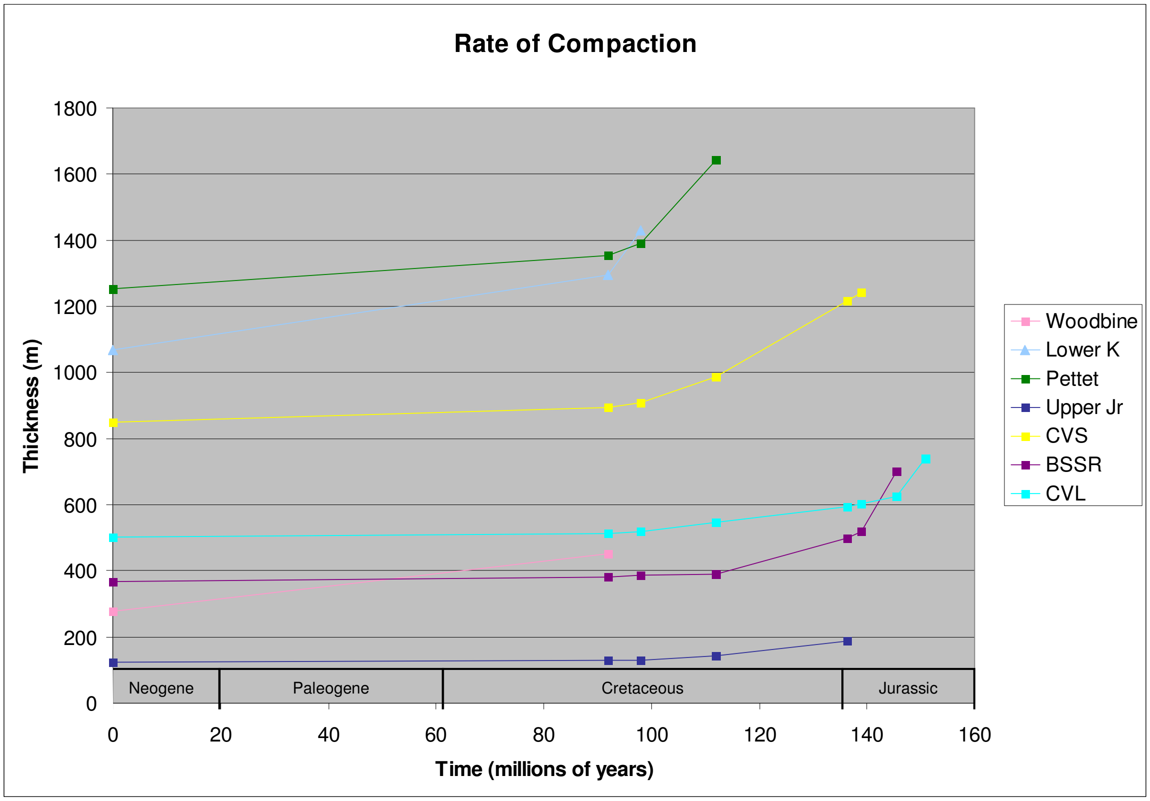


Figure 38: The rate of compaction over time for each formation.

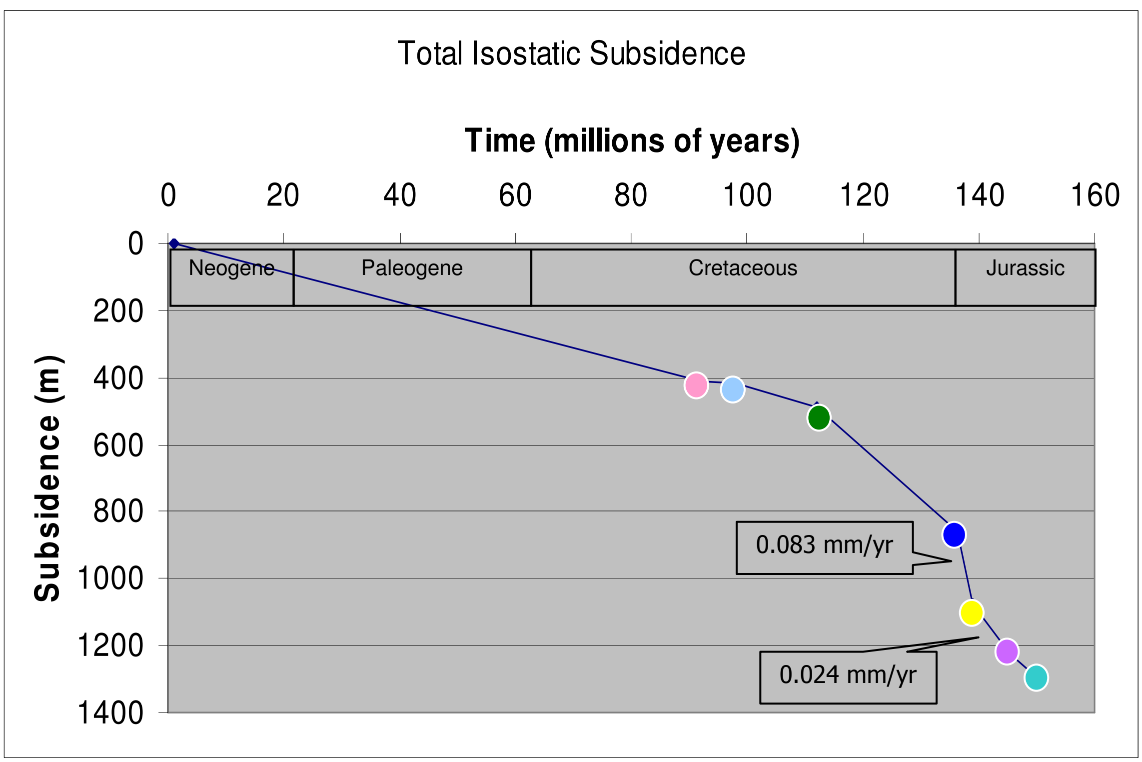


Figure 39: The rate of isostatic subsidence over time. Colors correspond to formations.

DISCUSSION

Based on the results of this study, there are several key conclusions that can be made, which helped in reconstructing the basin history. First, the restoration shows that there were two significant periods of salt movement, one during Smackover time and another during Cotton Valley Sandstone time. Secondly, it also suggests that there was no deposition of the Louark Group where salt was significantly above regional elevation. Thirdly, it helped to better define the depositional environment of the Bossier sands by giving a better estimate of the location of the shelf edge. These results are consistent with isochron and gravity maps in the area showing how salt may have moved.

As mentioned previously, there were at least two significant periods of salt movement, one during Smackover time due to the loading of the Norphlet and Smackover Formations, and another due to the large influx of deltaic sediments during the deposition of the Cotton Valley Sandstone as it migrated out into the starved basin. Upon restoring the Cotton Valley Limestone, it is evident that the limestone thinned over the ancient low-amplitude salt pillow in the northern portion of the 2D line signifying its presence prior to the limestone deposition and suggesting salt movement likely to have occurred during Smackover time.

The oolitic shoals of the Smackover were deposited in shallow marine conditions of approximately 10-15m water depth (Fig. 40). It reached thicknesses of 229 meters to 252 meters over salt thicknesses of approximately 762 meters in the northern part of the line (Fig. 41) (Chisholm, 1968). This agrees with Jackson and Seni's numbers for a salt threshold of 500 meters in the first province, and thus, it likely triggered a gravity flow of salt basinward. This would be responsible for the low to intermediate amplitude salt pillows within the basin. In this line, it appears that a basement high in the middle of the line may have stopped the salt from sliding further down dip and allowed salt to build up behind it, creating a salt high or ridge over which the Cotton Valley Limestone was not deposited. The reconstruction illustrates this, as the salt appears to be higher than the regional elevation of the limestone at the end of deposition (Fig. 33). Biofacies analysis done by Spaw et al. (2000) reveals that the water depths during Cotton Valley Limestone deposition were fairly shallow, less than 20 meters, and there were very shallow periods where there is evidence of subaerial exposure of the reefs. These findings support the reconstructed model that suggests a lagoonal setting with shallow water depths where either salt was exposed or too shallow for Cotton Valley Limestone deposition.

During Bossier time, there was a brief marine transgression depositing the Bossier shales, but then shortly after, sea level began to fall and along with continual thermal relaxation and subsidence, the first terrigenous sediments began to make their way out over the older carbonates (Fig. 42). At this time the sedimentation rate was greater than the rate of subsidence, therefore allowing the Bossier to overrun the salt ridge that had served as a structural high during Cotton Valley Limestone deposition. Progradation slowed at the break in the carbonate platform, which served as the shelf edge at the time and Bossier deposition thickened as it was deposited down the slope in localized depositional centers due to salt withdrawal of the low-amplitude salt pillows (Fig. 43). This salt withdrawal most likely occurred on the continental slope so the farthest reaching sand of the Bossier Formation may be equivalent to slope fans, but not likely basin floor fans as predicted by Klein and Chaivre (2002) since the Bossier is restored almost 22 km updip.

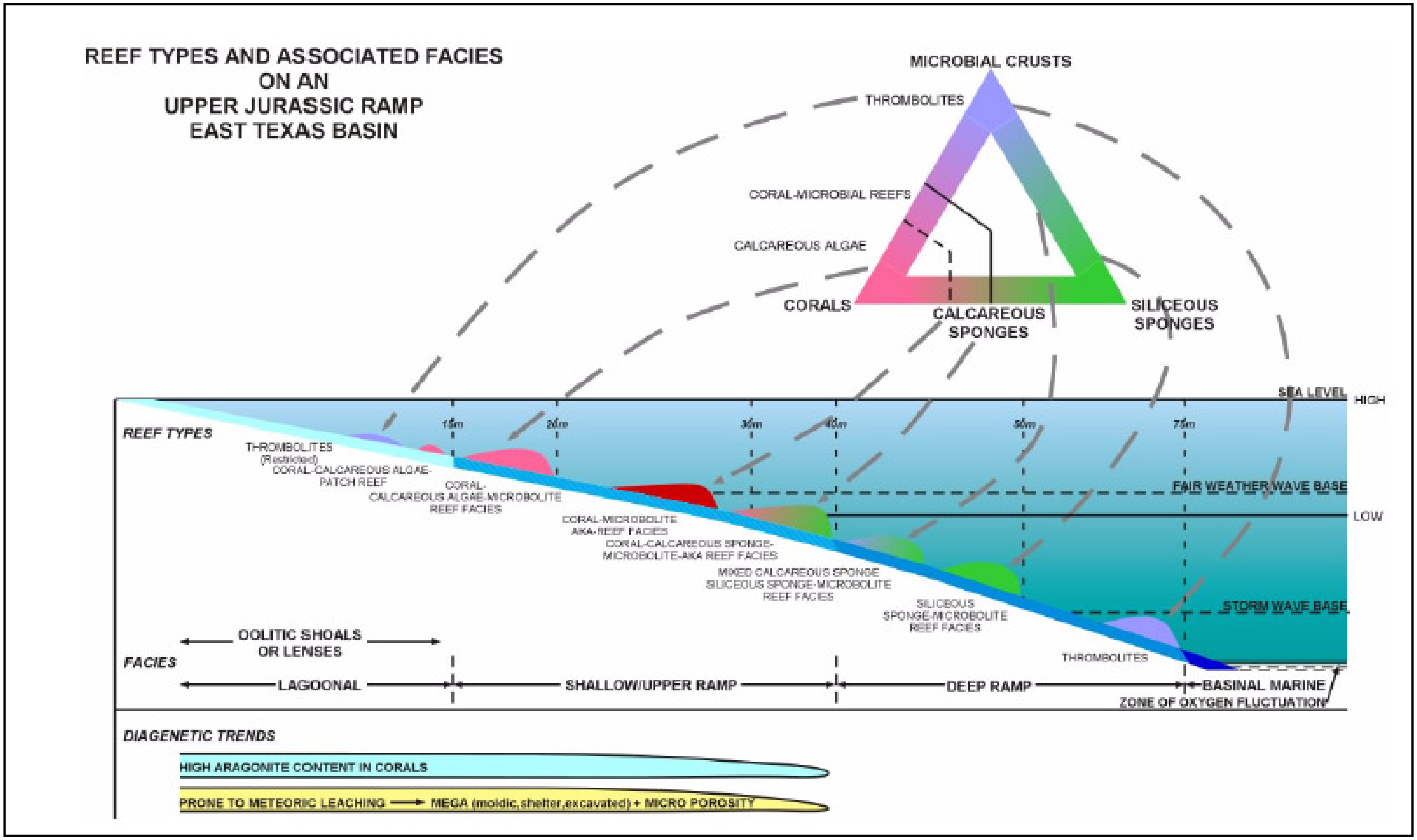


Figure 40: Upper Jurassic Reef Types of the East Texas Basin (Spaw et al., 2000).

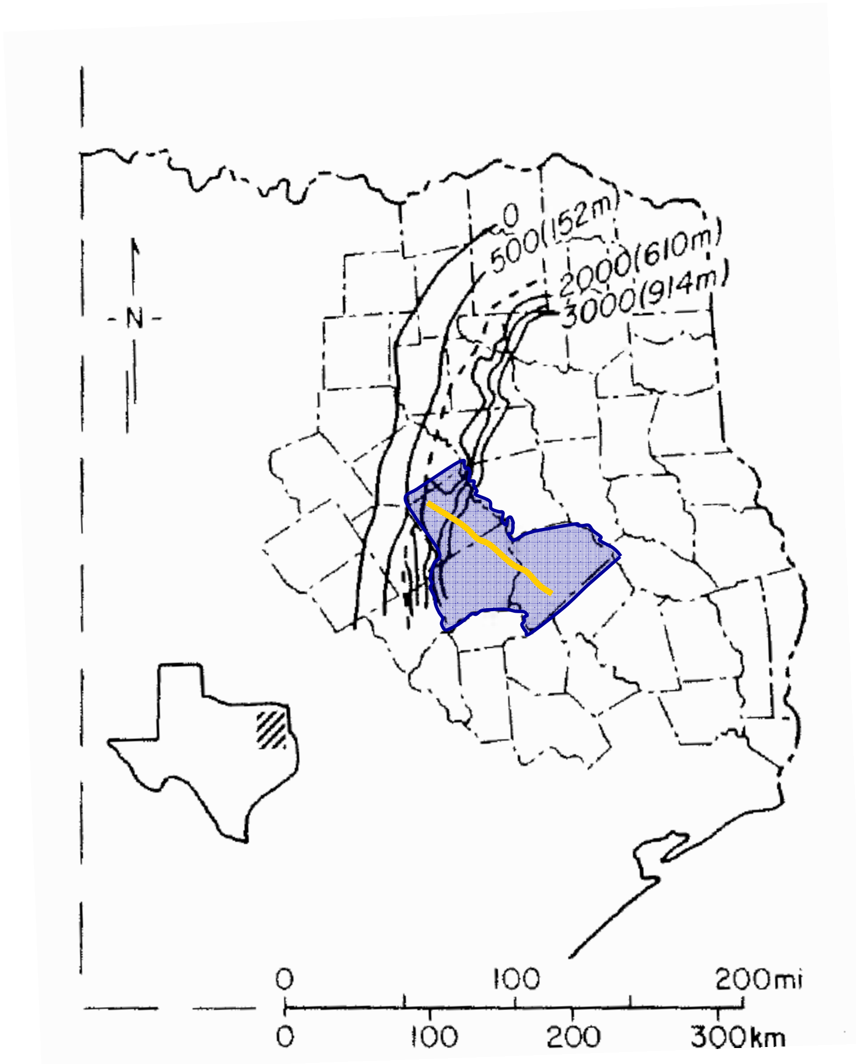


Figure 41: Isopach map of Smackover-Cotton Valley Limestone carbonate facies. Northwest of dashed line is an isopach of Smackover alone. Southeast of dashed line is a combined Smackover-Cotton Valley Limestone isopach. Study area in blue and 2D line in yellow. [Modified from Harris and McGowen (1987)]

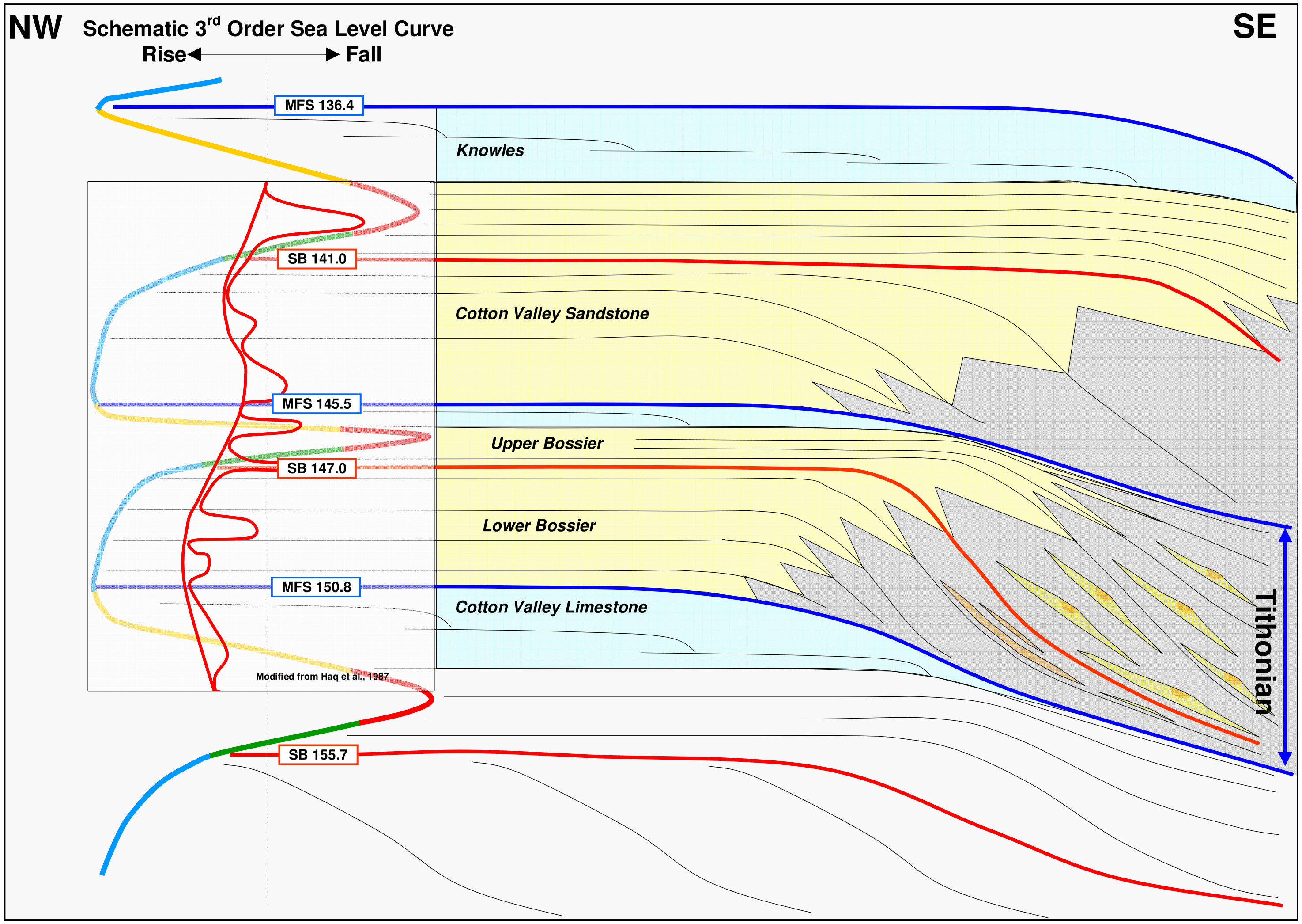


Figure 42: Schematic sea level curve for the East Texas Basin. [Modified from Butler (2009)]

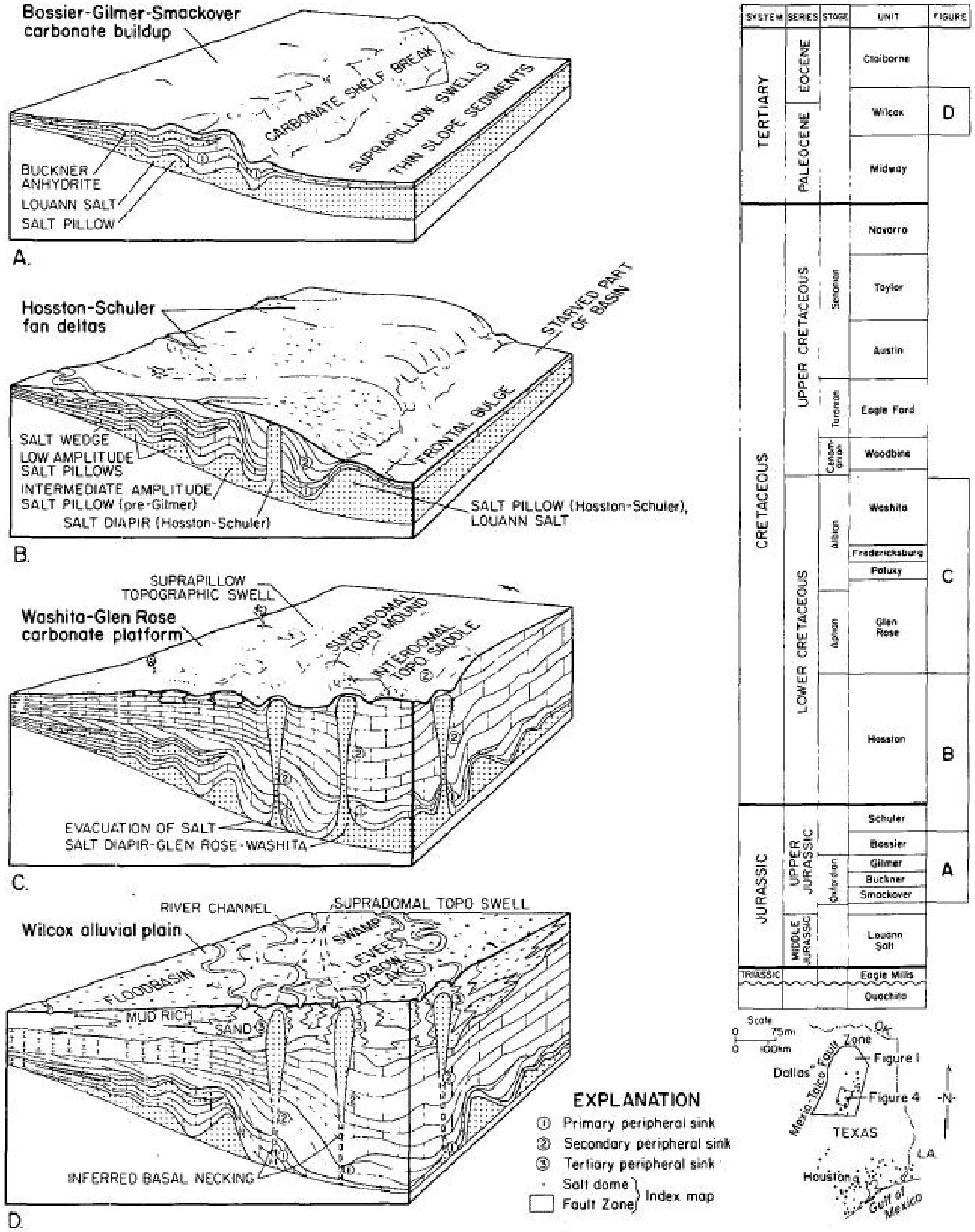


Figure 43: Schematic of salt evolution in the East Texas Basin. Figure A illustrates the initiation of salt flow developing salt pillows during the Late Jurassic. Figure B shows the evolution from low-amplitude salt pillows to intermediate pillows and the first generation of diapirism in the Late Jurassic to Early Cretaceous. Figure C describes the second generation of diapirism in the Early Cretaceous, and Figure D represents the waning of diapirism in the Early Tertiary (Jackson and Seni, 1983).

The Cotton Valley Sandstone then prograded over the Bossier and was deposited farther down the slope and into the starved basin. The previous thickening of Bossier sediments on the continental slope contributed to reduced accommodation along the shelf break and slope during Cotton Valley Sandstone time so that the deltaic sands prograded further out into the starved basin where there was greater accommodation space to handle the large sediment influx. The large increase in sedimentation triggered the second period of salt movement as the loading caused an increase in overburden pressure resulting in salt withdrawal from the area. This influenced the gravitational flow of the salt and resulted in basinward lateral translation of the sediments along a system of listric growth faults that extended the basin almost twenty-two kilometers to the southeast (Fig. 29).

The extension seen during Cotton Valley Sandstone time demonstrates that these deposits were the cause of the second significant salt movement. However, at the end of Cotton Valley Sandstone time, there appears to still be a significant amount of salt on the southeast end of the line, and from examining the overlying horizons, it appears that the salt continues to withdraw up until the end of Pettet time. This is evident from the slight synform structure seen at the top of the Pettet where the horizon begins to recover and move back toward regional elevation (Fig. 44).

In Klein and Chaivre's (2002) interpretation of the 2D line, they denoted the shelf edge as the loss of the seismic reflectors (Fig. 8). After restoring the line, it becomes evident that area is simply a result of salt withdrawal (Fig. 45). The shelf edge during Bossier time would have been close to this area and could possibly be defined by the thickening Bossier depositional center, which shows the contrast from a planar deposition to an increase in accommodation. This increase allowed for a noticeable thickening in Bossier sedimentation as the prograding sediments crossed the shelf break. The Bossier shelf edge was likely very nearby as the Bossier depositional center is in close proximity to this salt withdrawal. However, it appears that as the Bossier prograded out, and then the Cotton Valley Sandstone prograded over it, the shelf edge migrated basinward so that by Cotton Valley Sandstone time, the shelf edge was possibly near the southern edge of the large salt body shown on the 2D line. This agrees with Adams' (2009) theory that the Bossier-Cotton Valley deltaic system caused the migration of the shoreline seaward across the East Texas Basin.

According to Ge and Jackson (1998), salt dissolution features are most commonly found in areas where the salt was still tabular before deformation of the overburden and had not formed structures such as pillows or diapirs. This agrees with previous statements that the presence of salt withdrawal within this study is most likely due to gravity flow of the salt rather than dissolution. Salt withdrawal in the upper section of the line resulted in a syncline, which formed a salt weld. An isochron map of the top of salt in this area shows a salt high just north of this area suggesting that this salt possibly flowed north to produce what is known today as the Oakwood Dome in East Texas (Fig. 36). Studies of the Oakwood dome state that the caprock on the dome formed around Early Cretaceous time (Kreitler and Dutton, 1983). This would support salt movement from the south prior to Cretaceous time. Based on previous evidence showing that there is a thickening of Bossier sediments in this area, this implies that salt withdrawal began at this stage and that the top of the Cotton Valley Sandstone can be restored to regional, suggesting that salt withdrawal was complete by the end of its deposition. This agrees with the timeline that salt was moving into the area of the Oakwood dome from late Jurassic through early Cretaceous.

From the results of this study, it was possible to illustrate the stages of basin history by sketching a cross-section along the same 2D line at each depositional stage (Fig. 46). These sketches show how the topography changed through time with respect to salt movement and deposition. The first sketch depicts the end of mother salt deposition where the Louann Salt was still tabular.

The second sketch implies that sediment loading during the deposition of the Norphlet and Smackover triggered the initial stage of salt movement. This first salt movement represents the beginning of the salt pillow stage, which would later contribute to the progression of salt features toward the center of the basin. This sketch shows the topography during the deposition of the Cotton Valley Limestone. During this time, salt movement had developed two large bodies of salt, the largest of which appears to sit atop a basement high and that may explain why there is so much salt in this location as the basement high acted as a dam to prevent further gravity flow of the salt down-dip. This is the highest salt body in the line at this time and may have caused the smaller pillow behind it to form as it caused a domino effect back up-dip containing any salt from flowing further down-dip. As the Cotton Valley Limestone was deposited, it thins over the first salt body confirming that there was growth of a salt structure during this time. However, further down-dip, the Cotton Valley Limestone is absent from the top of the larger salt body and appears to onlap it on both sides. This suggests that during this time, the elevation of the top of this salt body was too high for Cotton Valley Limestone deposition. This would require that either this salt body was extruded subaerially or more likely it was in water depths too shallow for Cotton Valley deposition, such as a lagoonal setting. Also depicted in this sketch is the fact that in order for the smaller salt pillow to have been present during this time, one would expect a normal fault facing down-dip with a thickening section of the Cotton Valley Limestone in the hanging wall. This contradicts the present seismic interpretation where there is a normal fault facing up-dip. The third and fourth sketches illustrate how this is possible due to salt withdrawal causing the collapse of the overlying sediments.

The third sketch illustrates deposition during Bossier time. As salt from the northwestern body begins to withdraw, the beds form a syncline in the area of salt withdrawal. During this time, the beds begin to over steepen setting up the development of a fault on the southeastern edge of the syncline. Stage three also displays the thinning of the Bossier over the second salt body, and the second sketch in this phase depicts the beginning of the graben as the overburden pressure from the Bossier causes salt withdrawal.

Stage four marks the beginning of Cotton Valley Sandstone deposition. It demonstrates the large sediment accumulation as the deltaics prograded across the shelf, and it shows over steepening in the salt withdrawal syncline where the previous southeast dipping fault has almost been completely overprinted. There is further salt withdrawal from the large body as there is a thickening of Cotton Valley Sandstone in the graben, and the large sediment load causes salt to begin to withdraw from the southeastern portion of the line developing large listric faults. Further deposition of the Cotton Valley Sandstone, would trigger movement along these faults and transport Salt, Cotton Valley Limestone and Bossier 22 kilometers basinward.

The last sketch in the series represents the topography at the end of the Upper Jurassic, as the Knowles Limestone was deposited. The Upper Jurassic is deposited along the topography that was filled in by the Cotton Valley Sandstone and the faults from Cotton Valley Sandstone time propagate upward through the section.

The complete restoration appears to be a balanced interpretation of the seismic line across Freestone, Leon, and Houston counties. It gives compelling results as to the timing of salt movement, the amount of extension, the rates of compaction, subsidence, and sedimentation across the southern portion of the basin (Fig. 47).

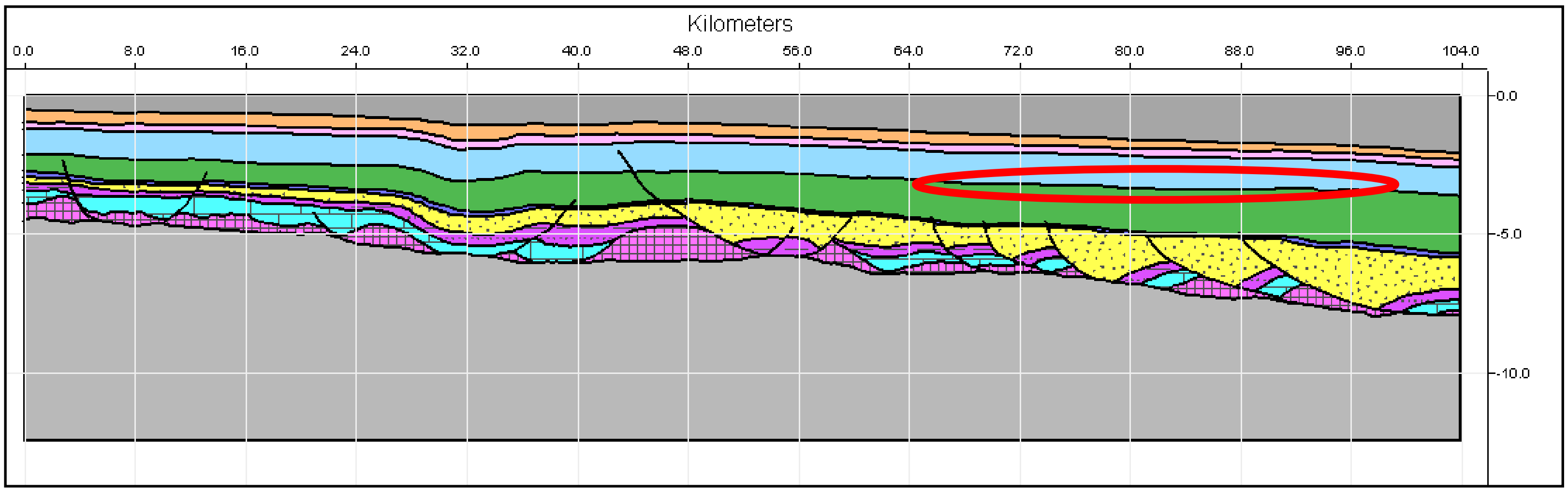
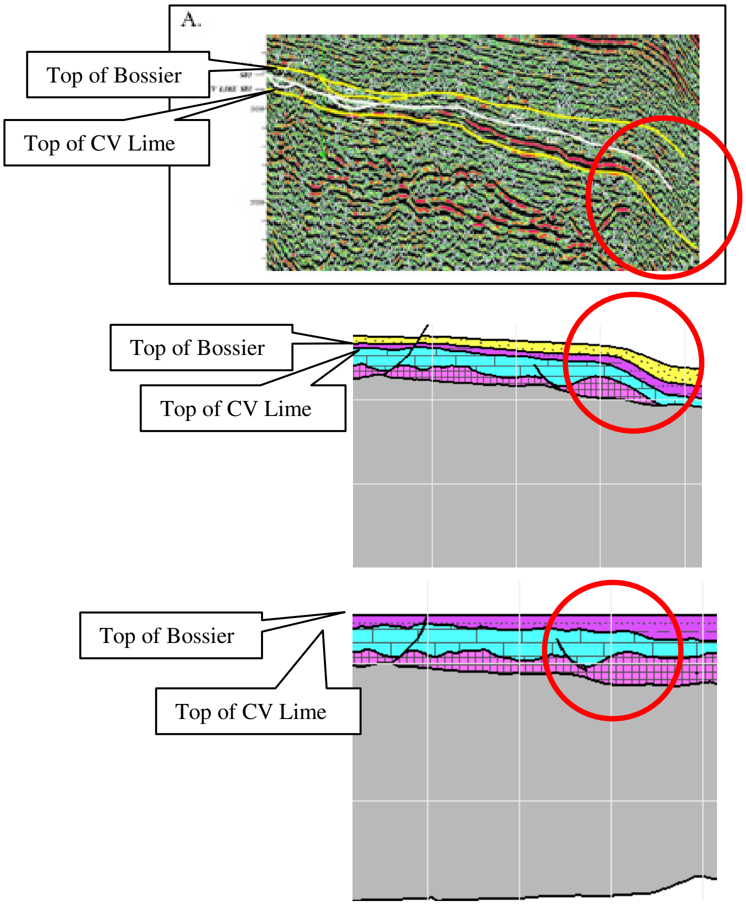


Figure 44: Small synform suggesting that salt withdrawal had taken place, but there is recovery and it almost reaches the regional elevation to suggest that salt withdrawal was complete by the end of Pettet time. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column.



Klein and Chaivre (2002) Interpretation of the shelf edge.

Prior to restoration, depth interpretation of the same area as above.

After reconstruction, it appears that dip in reflectors was due to beds forming a syncline in response to salt withdrawal in the area and does not represent the shelf edge.

Figure 45: Comparison of Klein and Chaivre (2002) interpretation with before and after images of the reconstruction to conclude that the dipping reflectors were due to salt withdrawal rather than the drop off of the shelf edge (Klein and Chaivre, 2002).

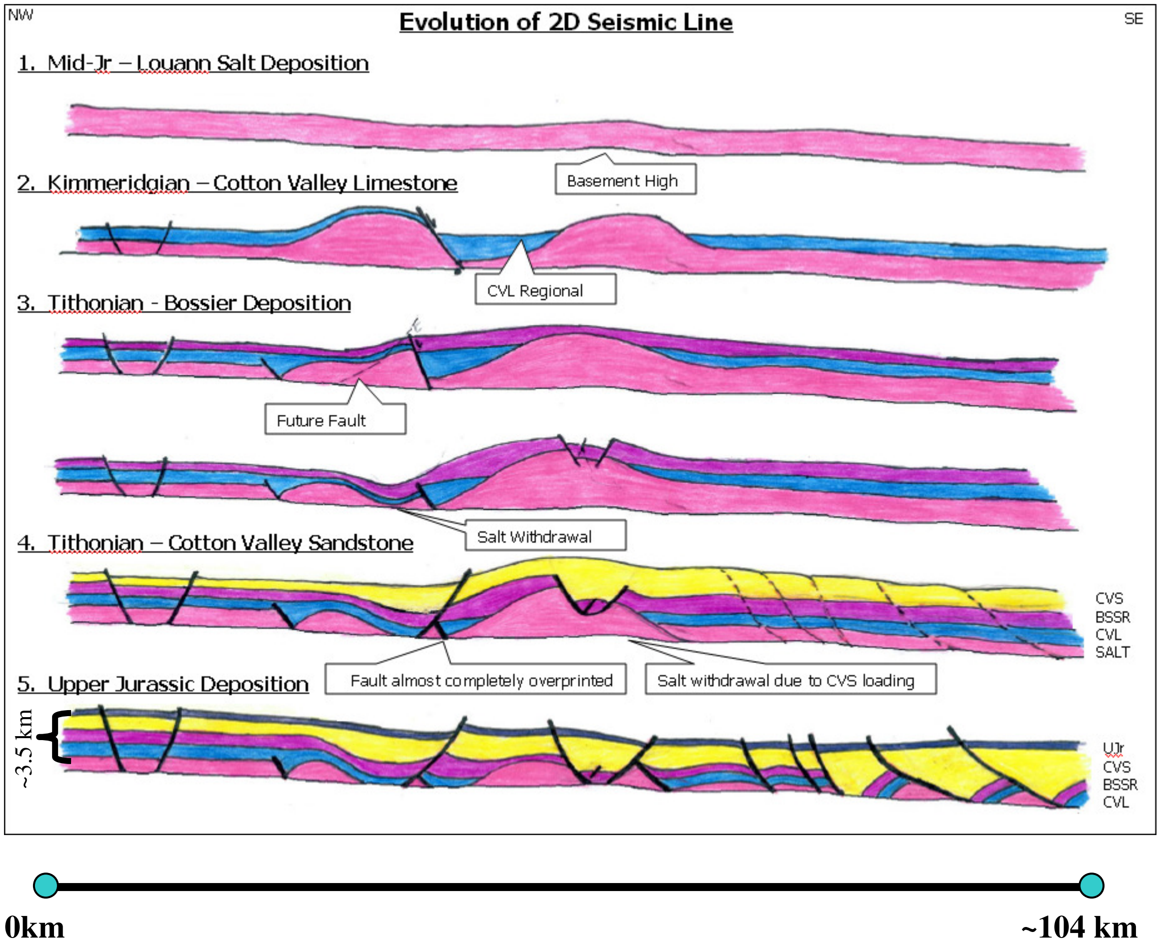


Figure 46: Sketches of the evolution of the 2d line at each major depositional stage based on results from the restoration. Stage 1 represents the deposition of the Louann Salt. Stage 2 marks the deposition of the Cotton Valley Limestone suggesting that the initial salt movement has already occurred creating two salt paleo-highs. The first is small enough for the limestone to be thinly deposited on top, while the second is larger and the limestone is not deposited across it. Stage 3 illustrates Bossier deposition showing steeping of the fault on the southeast side of the first salt body and thinning of the Bossier atop the second until the salt starts to withdraw due to the overburden pressure and the graben begins to form. Stage 4 depicts the deposition of the Cotton Valley Sandstone. The fault that was originally part of the first salt body begins to be overprinted by the large sediment accumulation of the sands in the accommodation space created by the salt withdrawal. As the Cotton Valley Sandstone was deposited, they triggered faulting in the southeastern portion of the line represented by the red dotted lines. Further deposition, caused an increase in overburden pressure which triggered the second salt movement, and resulted in large listric faults that transported the Bossier, Cotton Valley Limestone and Salt down-dip approximately 22 kilometers as can be seen in Stage 5. Sketches are not drawn to scale.

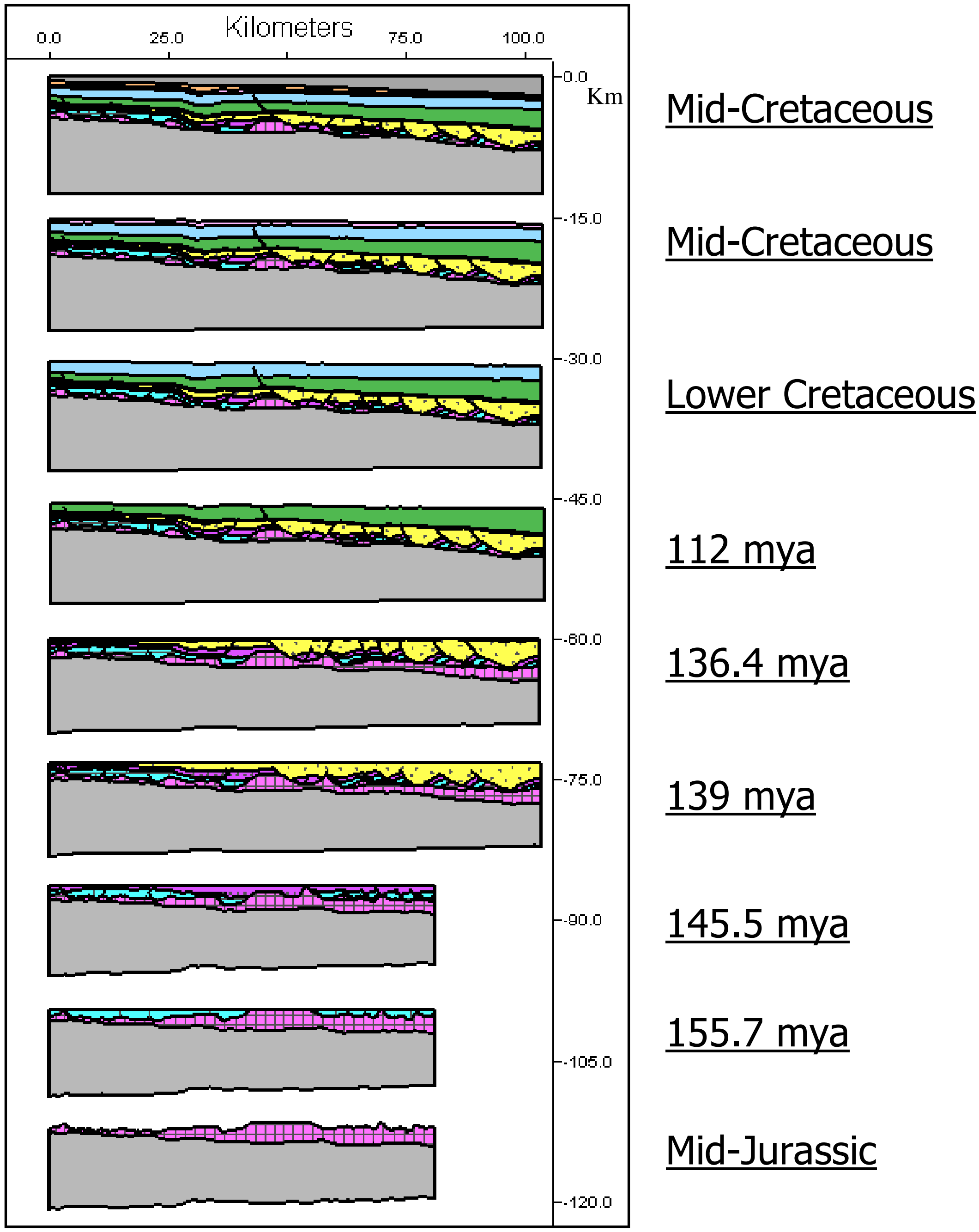


Figure 47: Complete LithoTect restoration of depth-converted 2D line through Freestone, Leon, and Houston counties in the East Texas Basin. Vertical exaggeration is 2:1. Refer to Figure 23 for stratigraphic column. Time in millions of years ago (mya).

ANALOGS

Kwanza Basin, Angola

In order to support the interpretation and the large amount of extension interpreted in the East Texas Basin, comparison with other passive margin basins, such as the Kwanza Basin proves to be useful. The Kwanza Basin is off the western coast of Africa, which is part of the Aptian salt basin that extends northward toward Gabon. The Kwanza Basin is divided into the onshore Inner Kwanza Basin and the offshore Outer Kwanza Basin. The outer basin more closely resembles the East Texas Basin, as it is characterized as a passive margin with salt movement due to gravity-sliding resulting in approximately 12 miles of up-dip extension and corresponding down-dip compression (Jackson and Hudec, 2009).

Both the Kwanza and East Texas are rift basins that were filled with rift sediments prior to salt deposition, and then dominated by marine deposition until the initial salt deformation (Liro and Coen, 1995). They both suggest that salt mobilization was not confined to one period, but was a result of multiple stages. While in the East Texas Basin mobilization appears to be first, a result of basin edge tilting due to thermal relaxation and then, reactivation due to a large increase in sediment influx causing extension and basinward translation. The Kwanza Basin suggests three periods of salt deformation (Hudec and Martin, 2004). The first, like that in East Texas, is thought to be due to thermal subsidence and basin tilting, but the second and third stages are attributed to periods of uplift that triggered basinward translation (Hudec and Martin, 2004).

The Kwanza Basin is also similar to East Texas in that both have an observable change and progression in salt features across the basin. In both cases, these features can be divided into distinct provinces that mature basinward (Hudec and Martin, 2004). The starved Kwanza Basin shows a progression from an undeformed wedge to an area of salt pillows and turtle structures that progress to a raft domain and then to a diapir province (Fig. 48). The Outer Kwanza Basin comprises the raft domain and all provinces basinward. This is comparable to the southeastern edge of the 2D line in this study where the listric growth faults accommodate the rafted sediments. The outer basin shows a correlative relationship to the East Texas Basin as the Aptian salt serves as the detachment surface much like the Louann Salt along which there are periods of thin-skinned gravity driven translation of post-salt sediments along an analogous extensional system (Fig. 49).

Overall, these basins are very similar as they both represent multiple stages of salt deformation caused by gravity-driven translation resulting in mild deformation landward and more complex salt structures toward the center of the basin (Liro and Coen, 1995). They both also have significant extensional regions, which must contribute to an equal amount of shortening farther out in the basin. Comparison of the salt features within these basins gives insight into the characteristics of salt flow and the tectonic regimes associated with salt deformation.

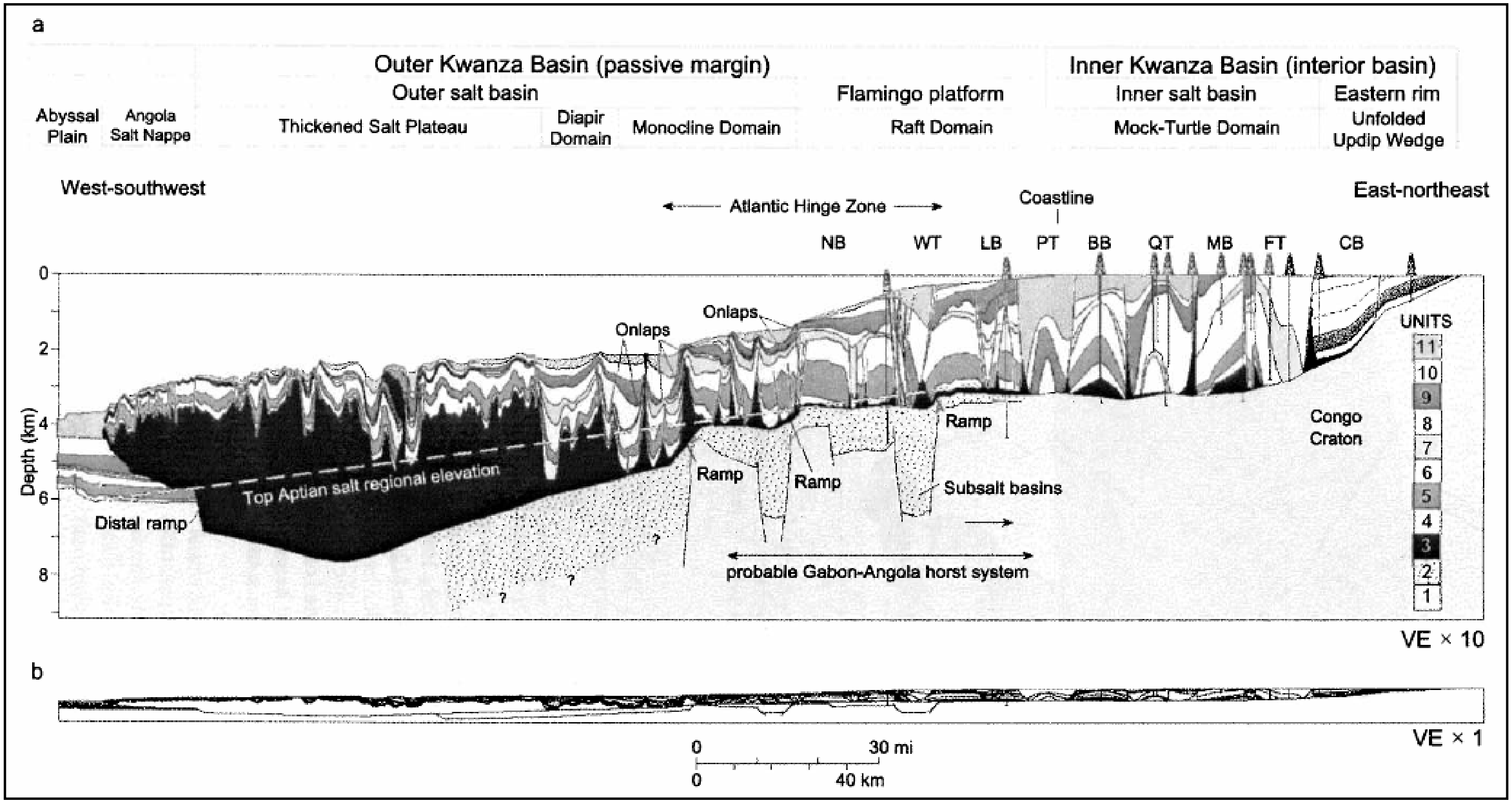
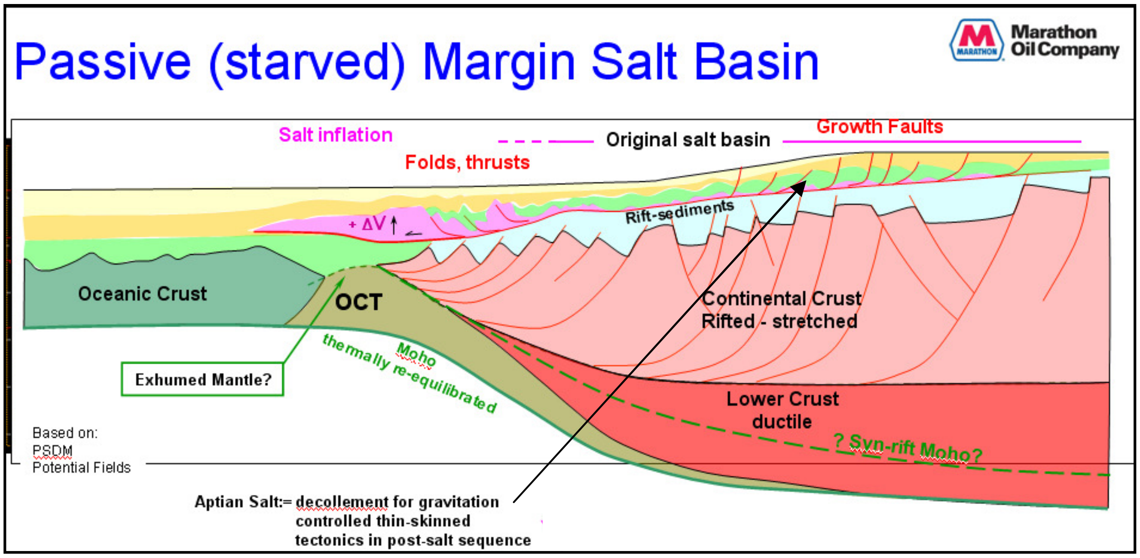


Figure 48: Regional cross-section of the Kwanza Basin vertically exaggerated. It shows the progression from an undeformed wedge in the east to salt pillows, turtle structures, raft features, and diapirs down-dip. This type of evolution of salt features is similar to that seen in the East Texas Basin (Hudec and Martin, 2004).

A



B

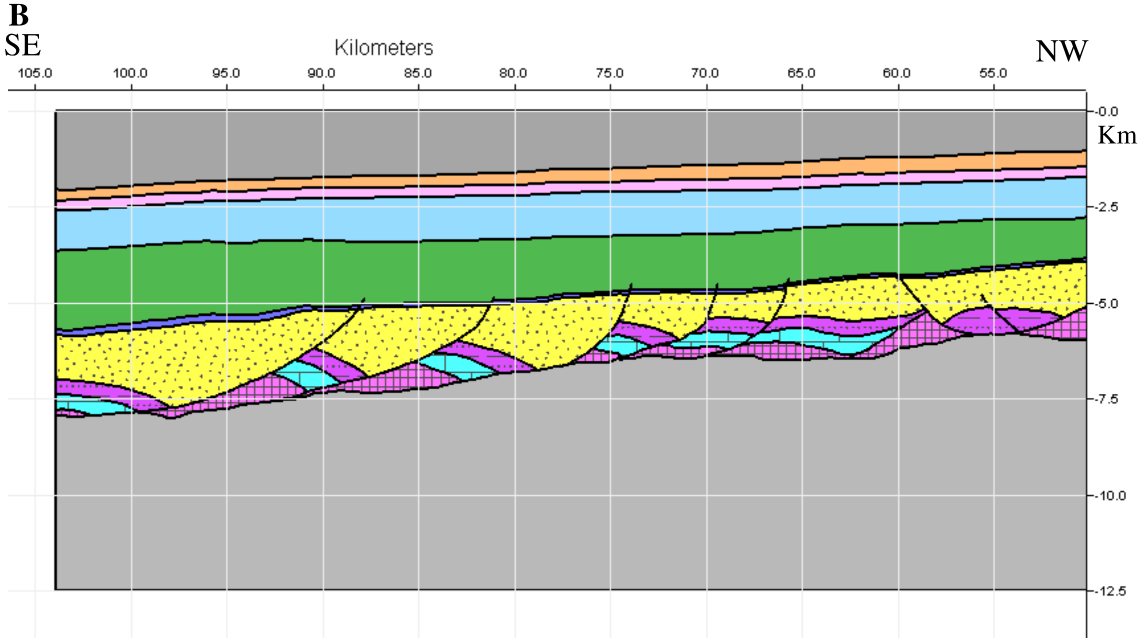


Figure 49: Figure A shows the interpretation for the Outer Kwanza Basin. The Aptian Salt serves as a detachment surface for extensional listric faults much like the Louann Salt does in the East Texas Basin in Figure B (Lebit and Jensen, 2009).

Gulf of Suez, Red Sea, and the Persian Gulf

The southern Gulf of Suez in the Red Sea represents another area with salt features that can be compared to those of the East Texas Basin. In this area, the basin is characterized by an increase in structural maturity from the east and west toward the basin center, much like the East Texas Basin, and has a similar evolution of salt tectonics (Heaton et al., 1995).

Following rifting, the confined basin was filled with salt and was then overlain by a carbonate system, which in accordance with a period of thermal relaxation, caused the basin to tilt seaward and the eastern edge of the basin underwent extension as listric growth faults detached in the main salt layer and gravity carried them basinward (Heaton et al., 1995) (Fig. 50). In southern part of the Gulf of Suez, near Yemen, water depths range from 15 to 100 meters, and there are many islands and shoals on the shelf that appear to be caused by rising salt features (Heaton et al., 1995). These shallow salt structures developed shoals rimmed by carbonate reefs, but exposed on top much like the large salt body in this study, where the Cotton Valley Limestone was not deposited atop the salt possibly due to shallow water conditions. While the Gulf of Suez may not be a direct analogy for the East Texas Basin, it holds evidence of similar features found in East Texas and provides insight into how these features might be interpreted.

Like the Gulf of Suez, the Persian Gulf can be compared to the East Texas Basin. It is almost a modern day equivalent of the East Texas Basin during the Mesozoic (Seni and Jackson, 1983). In the Persian Gulf, there are shallow salt domes or mounds that rise from the ocean floor, while more mature diapirs pierce the surface exposing salt as islands. The Yas and Jebel Dhana salt domes are two such islands that are surrounded by a fringe of coral reefs and flanked by muds and carbonate sands that fill in the rim syncline feature surrounding the domes (Fig. 51) (Seni and Jackson, 1983). These two domes represent an example of the type of depositional setting that might have occurred during the non-deposition of the Cotton Valley Limestone over the large salt dome. The ancient dome appears to be similar to these in that it is fringed by carbonate facies and has depositional centers on both flanks, where Bossier shales and sands were deposited.

The Kwanza Basin, Gulf of Suez, and Persian Gulf are only a few examples of similar rift basins. While the inner dynamics of the basins may vary, the overall evolution of salt tectonics from the rifting stages through to diapirism appears to be very similar. The Gulf of Suez and Kwanza basins are characterized by a structural maturity that progresses basinward, as well as by significant extension along the landward flank of the basin. They also have a similar stratigraphic style, as they all illustrate a salt layer overlain by a carbonate system, which initiated the first periods of salt mobilization due to thermal subsidence and gravity flow. Based on the comparisons with these basins, there is evidence to support the interpretations of the East Texas Basin in this study and suggests that further studies might find more correlations between these basins.

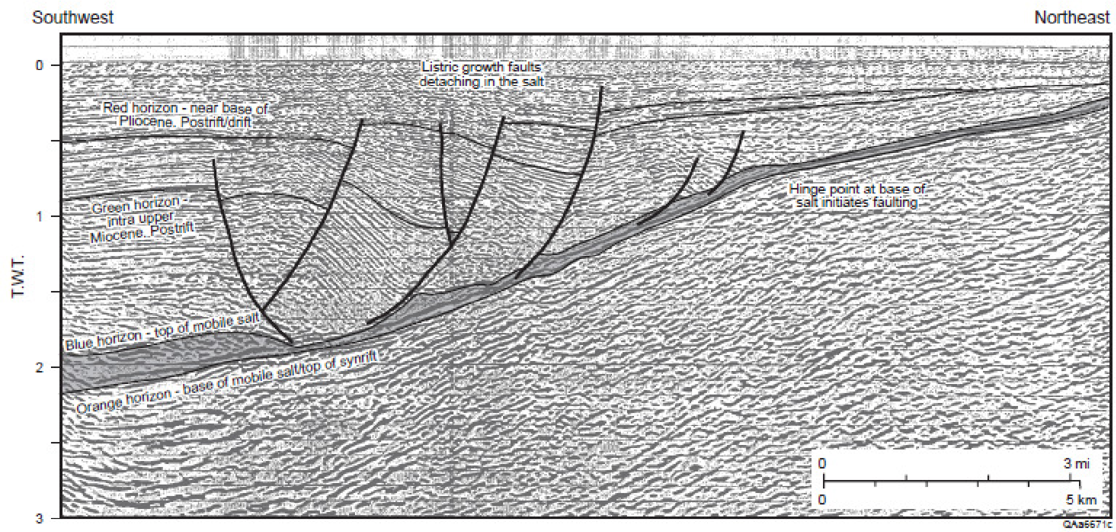


Figure 50: Listric growth faults in the Yemeni Red Sea detaching in salt and sliding basinward causing extension and rollover of the beds into the fault block, much like the listric faults in this study. [Modified from Heaton et al. (1995)]

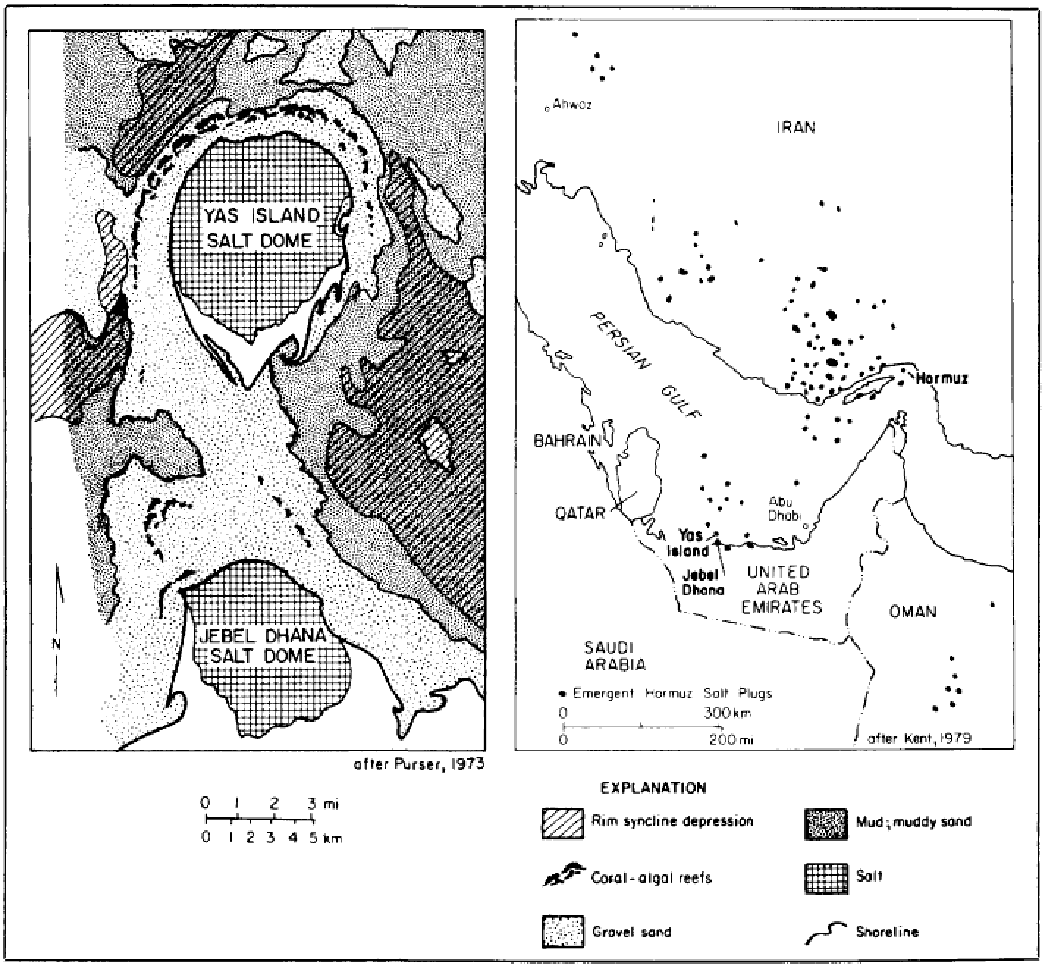


Figure 51: The Yas and Jebel Dhana salt domes in the Persian Gulf. Both are exposed at the surface and surrounded by a fringe of coral reefs with carbonate sands on their flanks forming a rim syncline (Seni and Jackson, 1983).

CONCLUSION

Based on the results of this study, salt movement was initiated during Smackover time due to differential loading of carbonates atop the Louann Salt. By Cotton Valley Limestone time, salt pillows had developed and created a depositional surface of topographic highs and lows. The Cotton Valley Limestone was deposited in a shallow marine environment, forming rims along the salt highs and leaving areas of non-deposition over the highest salt bodies.

The sand-rich parasequences of the Bossier Formation represent a distal equivalent of the Cotton Valley Sandstone. During Bossier deposition, the sedimentation rate was greater than the rate of subsidence allowing the Bossier to overrun the salt ridge that had served as a structural high during Cotton Valley Limestone deposition. Progradation slowed at the break in the carbonate platform, which served as the shelf edge at the time, and Bossier deposition thickened, as it was deposited down the slope in localized depositional centers due to salt withdrawal of the low-amplitude salt pillows (Fig. 43). This salt withdrawal most likely occurred on the continental slope so the farthest reaching sands of the Bossier Formation may be equivalent to slope fans.

As sea level continued to fall and the basin subsided, the deltaic sands of the Cotton Valley Sandstone Formation prograded across the shelf introducing a large influx of sediments into the relatively starved basin. This large increase in sediment triggered another period of salt movement and resulted in approximately 22 kilometers of extension across the basin as the Bossier Formation was carried down the continental slope along large listric faults.

Overall, restoring this 2D line led to new insights about the basin history and confirmed many previous theories concerning salt movement and deposition in the East Texas Basin. Most importantly this study supports the theory that there were two significant periods of salt movement, one during Smackover time and another during Cotton Valley Sandstone time. Secondly, it indicates that there was no deposition of the Louark Group in areas where the salt was significantly higher than the regional elevation; and thirdly, it clarifies the depositional environment of the Bossier sands by estimating of the location of the shelf edge.

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