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Calibrated Seismic Stratigraphic Analysis of the Lavaca/Yoakum Canyon Complex, South Texas, U.S.A.

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ABSTRACT

The Lavaca/Yoakum Canyon Complex (LYCC) is comprised of two ancient submarine canyons located in Lavaca, Dewitt, and Gonzales counties of Texas. Previous studies have provided conflicting theories regarding the origin of such large erosional features within an overall progradational setting during deposition of the Wilcox Group. This study utilizes wireline log, sidewall core, biostratigraphic, and 2D seismic reflection datasets to provide insight into the processes responsible for the incision and fill of these canyons as well as generate a revised plan view morphology. The results show that the original morphologic maps of the Yoakum and Lavaca canyons which were interpreted as two separate canyons adjacent from one another is inaccurate. The relatively narrow Yoakum Canyon overlies the older, but broader Lavaca Canyon comprising a single canyon complex. We suggest that the older Lavaca Canyon was initiated during a phase of margin failure and slumping following shelf edge loading during Lower Wilcox deposition. Following this initial phase of incision, throughgoing upper slope turbidity currents contributed to further modification and retrogradational failure of the canyon. We suggest that the younger Yoakum Canyon was initially incised by high density turbidity currents and then subsequently filled uniformly by low density turbidites. The results from our observations on the LYCC evolution have important implications for the regional paleoclimatic conditions during the Paleocene-Eocene Thermal Maximum (PETM). Advocates for the Gulf of Mexico drawdown hypothesis suggest that during the <1 Myr duration of the PETM, the Gulf of Mexico experienced isolation and subsequent evaporative drawdown as the Cuban block docked against the Florida Straits. Development of the LYCC under subaerial conditions is thought to be linked to that basin scale drawdown of sea level. Our results show the development of the LYCC occurred entirely under subaqueous conditions indicating that at least this part of the drawdown hypothesis is an invalid model to explain the presence of the LYCC as well as other roughly coeval canyons along the Gulf Coast.

INTRODUCTION

Exploration History and the Discovery of the Lavaca/Yoakum Canyon Complex

The Lavaca/Yoakum Canyon Complex (LYCC) is comprised of two superimposed fossilized submarine canyons located in the subsurface of Lavaca, Dewitt, and Gonzales counties of Texas. Existence of the LYCC was first documented by Chuber (1979). Subsequent drilling of Wilcox deltaic reservoirs and the subjacent Edwards (Albian) reef outlined two large, erosional canyons incised into the progradational Lower Wilcox Delta System (Chuber and Begeman, 1982) (Fig. 1). Discovery of hydrocarbons in the canyon system's fill and flank in 1983 was followed by focused exploration efforts including acquisition of more extensive well and seismic data in the area. By 1989, 17 wells in 4 fields had produced about 900,000 barrels of oil and 10 billion cubic feet of gas (Galloway and McGilvery, 1995).

While the existence of the LYCC has previously been documented by well log correlations (Chuber and Begeman, 1982; Galloway and McGilvery, 1995), this study is the first to encompass recently reprocessed onshore 2D seismic data calibrated by modern gamma ray, spontaneous potential, and resistivity wireline logs and cores to analyze the internal stratigraphy and external morphology of the LYCC. Our results aim to improve age constraints on canyon development as well as to provide further insight into the processes controlling the canyon system's incision and fill by analyzing facies architecture at various scales with high-resolution data.

The Wilcox Depositional System

The subsurface Wilcox Group (Hargis, 1985) has been divided chronostratigraphically into three depositional episodes: Upper, Middle, and Lower Wilcox (Galloway, 2008) (Fig. 2). Biostratigraphic information that underlines this chronostrati-

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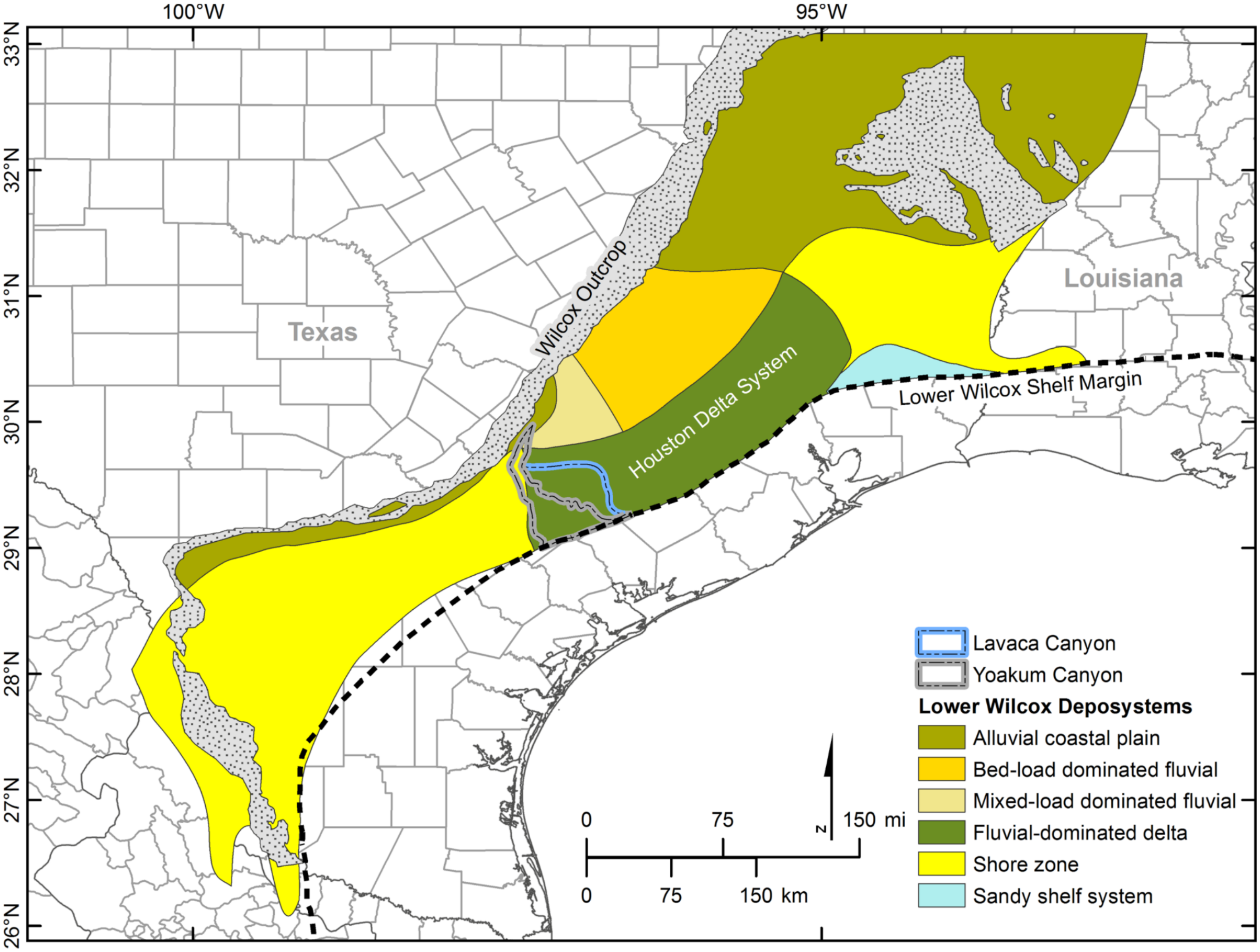

Figure 1. Regional index map showing the location of the Lavaca and Yoakum submarine canyons in relation to the Wilcox outcrop belt, Lower Wilcox shelf margin, and the coterminous fluvially dominated Houston Delta System. The Houston Delta System represents the first Cenozoic progradational siliciclastic wedge to build out into the Gulf of Mexico along the Texas and Louisiana coasts. Sediment supply was ample during Wilcox deposition due to a large pulse of sediment influx from the Laramide Orogeny and ongoing erosion of the Rocky Mountains.

graphic system is drawn from Bureau of Ocean Energy Management (BOEM) released offshore well reports and a set of onshore biostratigraphic reports donated to the University of Texas by Rashal Rosen. Regional onshore to offshore 2D seismic correlations further support these interpretations (Snedden et al., 2012; Fulthorpe et al., 2014).

The three chronostratigraphic units are locally associated with the Yoakum and Lavaca canyons (Galloway and McGilvery, 1995). The Lower Wilcox is a thick, sandstone, progradational sequence deposited during the late Paleocene. Our work and that of others (Galloway and McGilvery, 1995) suggests that the Lower Wilcox largely predates the Yoakum Canyon incision but is coincident with incision of the larger underlying Lavaca Canyon. The Middle Wilcox unit overlies Lower Wilcox progradational successions, and locally consists of a 3124 ft (952 m) thick, primarily aggradational shale sequence capped by the sandstone rich, aggradational Upper Wilcox. Following deposition of the Middle Wilcox, the Yoakum Canyon was incised and filled with the Yoakum Shale, a widespread, marine shale deposit (Ayers and Lewis, 1985; Hoyt, 1959). The base of the Upper Wilcox is defined as the contact with the Yoakum Shale (Fig. 2). The Upper Wilcox genetic sequence coarsens upward into a 1300 ft (396 m) thick, aggradational section of sandstone. The Wilcox Group is capped by the Reklaw Formation of the Clairborne Group, a marine shelf deposit. The Wilcox thus comprises the first major Cenozoic progradational siliciclastic wedge to build out into the Gulf of Mexico along the Texas and Louisiana coasts (Fisher and McGowan, 1969; Bebout et al., 1983). In several areas, Wilcox sediments prograded over the underlying Albian-age shelf margin and extended the shelf edge anywhere from 20–50 mi (32–80 km) basinward (Winker, 1982). This outbuilding was associated with a large pulse of sediment influx from the Laramide Orogeny (Winker, 1982; Ayers and Lewis, 1985; Galloway, 2008; Galloway et al., 2011; Snedden et al., 2018a). The continued erosion of the Rocky Mountains provided the large delta complexes along the ancestral Texas coast with ample sediment supply during the time of Wilcox deposition (Fig. 1).

Siliciclastics within the Lower Wilcox interval of the study area were dominantly transported through the Houston Delta System (Galloway, 2009) (Fig. 1). Sixteen individual delta lobes that made up the Houston Delta System comprise a large-scale paleo-delta comparable to the modern Mississippi Delta in size,

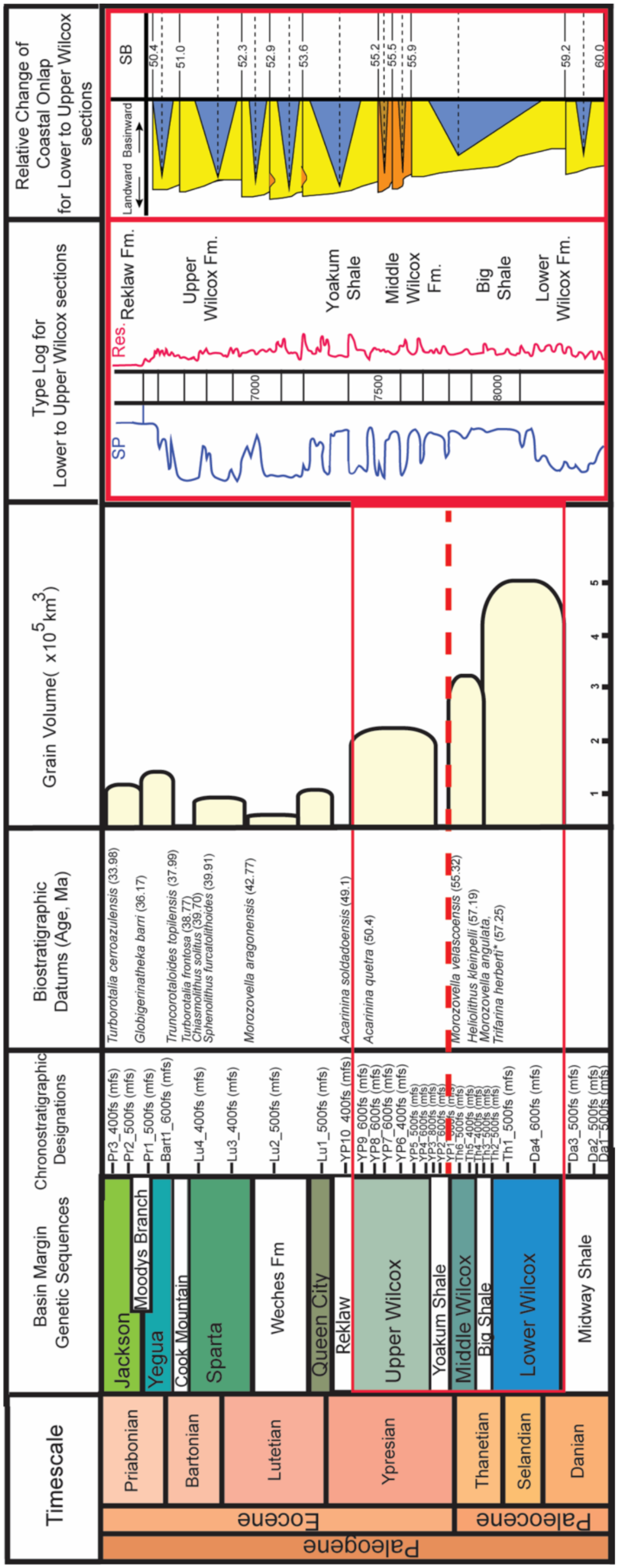

Figure 2. Gulf of Mexico regional stratigraphy with this study's interval of interest highlighted within the red box. The dashed red line shows the approximate location of the Paleocene/Eocene thermal maximum (PETM) at top of Middle Wilcox. Lower, Middle, and Upper Wilcox deposition are characterized by the time periods with the largest amounts of coarse-grained sediment delivery to the Gulf of Mexico Basin. Estimated volumes of transported grains are 120,000, 72,000, and 48,000 mi^3 (500,000, 300,000, and 200,000 km^3) for the Upper, Middle, and Lower Wilcox, respectively. A characteristic wireline motif is displayed for the Lower to Upper Wilcox transition from the A. Schumacher 1 well (ref. Figure 3 for location). Relative change of coastal onlap and identified sequence boundaries are also displayed for the Lower to Upper Wilcox sections (modified after Zarra, 2007; Galloway, 2008). 1000 ft = 304.8 m and 100,000 km^3 = 24,000 mi^3.

facies distribution, and shape (Fisher and McGowan, 1969; Galloway, 2009). During Middle Wilcox deposition, the Houston Delta was active, but local sediment influx was greatly reduced in the area of the LYCC (Ayers and Lewis, 1985). Consequently, progradation ceased and the shelf edge position remained stable until the local rejuvenation of sediment supply during Upper Wilcox deposition. As Upper Wilcox deposition began, progradation occurred with an overall shift in the site of the Texas Gulf Coast depocenter. Primary sediment deposition shifted then to the Rosita Delta located to the south within the Rio Grande Embayment.

Overview of Differing Canyon Formation Hypotheses

Previous work on the LYCC has provided somewhat conflicting theories about the origin of these erosional canyons found within an overall high-accommodation, progradational setting (Galloway, 2009). The LYCC is situated geographically and stratigraphically on the southwestern flanks of the Lower Wilcox Houston Delta System (Fisher and McGowen, 1969) (Fig. 1). The delta is hypothesized to have prograded rapidly across the Late Cretaceous carbonate platform, extending beyond the Cretaceous shelf edge (Dingus and Galloway, 1991). Large amounts of Lower Wilcox deltaic sediments are proposed to initiate failure of this Upper Cretaceous carbonate and coincide with the initial incision of the Lavaca Canyon. Following this initial failure, subsequent failures are interpreted to have propagated headwardly such that the Lavaca Canyon's terminal end progressively shifted up dip through time. After a short period of progradation, following waning sediment supply, the Houston Delta was terminated, and the depositional locus of the system shifted several hundred miles into South Texas (Ayers and Lewis, 1985; Dingus, 1987). The Yoakum Canyon's initial formation was originally suggested as a response to a sudden interruption of incoming sediment supply from the Houston Delta System that was followed by a period of rapid transgression (Dingus and Galloway, 1991). This rapid transgression is interpreted to be a result of widespread instability and slope failure caused by significant shelf-edge depositional loading of Lower Wilcox and Middle Wilcox deposits (Dingus and Galloway, 1991). Renewed progradation of the Upper Wilcox Rosita Delta System initiated a new episode of continental-margin outbuilding (Edwards, 1981).

Recent publications have proposed an alternative hypothesis relating initial incision of the LYCC as well as coeval canyons in eastern Mexico to two basin-wide sea-level falls during the Late Cretaceous and late Paleocene (Rosenfeld and Pindell, 2003; Cossey et al., 2016). This hypothesis suggests that following a basin wide drawdown event, fluvial systems feeding into the central Gulf of Mexico Basin further eroded the Lavaca and Yoakum canyons during subaerial exposure. One line of evidence is inferred from an outcrop near the village of Chicontepec in eastern Mexico, in proximity to an analogous canyon system (the Chicontepec Canyon of Cossey [2007]). A bitumen bed is observed at the Paleocene-Eocene boundary here is interpreted to be associated with a subaerial exposure surface but has yet to be illustrated in locations proximal to the LYCC (Cossey et al., 2016).

DATASET AND INTERPRETATION STRATEGY

The dataset utilized for this study consists of conventional industry multichannel 2D seismic reflection profiles, wireline logs, sidewall core, and a detailed biostratigraphic well report (Fig. 3). Available whole core data were also interpreted to provide ground truth in predicting depositional processes that sculpted and filled the LYCC. Core data were analyzed to identify changes in lithology as well as to describe sedimentary structures.

The processed 2D seismic data are part of the larger regional dataset, GulfSPAN Land, provided by ION Geophysical. This dataset was recently reprocessed in 2010 by ION utilizing over 11,450 wells to establish local velocity models for depth conversion (https://www.iongeo.com/wp-content/uploads/2019/03/DS_GEO_GulfSPAN.pdf). In addition to the depth converted seismic sections, 12 line-tie and 48 offset wells were selected to tie with the seismic for regional stratigraphic correlations. Seismic lines GSM3_11100, 11500, and 2400 were selected for seismic stratigraphic interpretation since they capture the entire canyon complex and allow for the identification of a number of key seismic surfaces marked H1–H5. Seismic reflection geometries and terminations were identified to aid in the interpretation of depositional sequences and depositional systems tracts. Bounding surfaces and sequences were correlated across seismic and wireline datasets to map their extent and geometry within the study area. Initial seismic interpretations began by identifying stratal terminations. Stratal terminations included angular unconformities and truncations as well as surfaces displaying reflection onlap and downlap (Snedden and Sarg, 2008). Surface associated with stratal onlap and angular unconformities were correlated as sequence boundaries. The base of the Yoakum and Lavaca canyons were identified as sequence boundaries with evidence of significant erosion, margin collapse and failure. Downlap surfac-

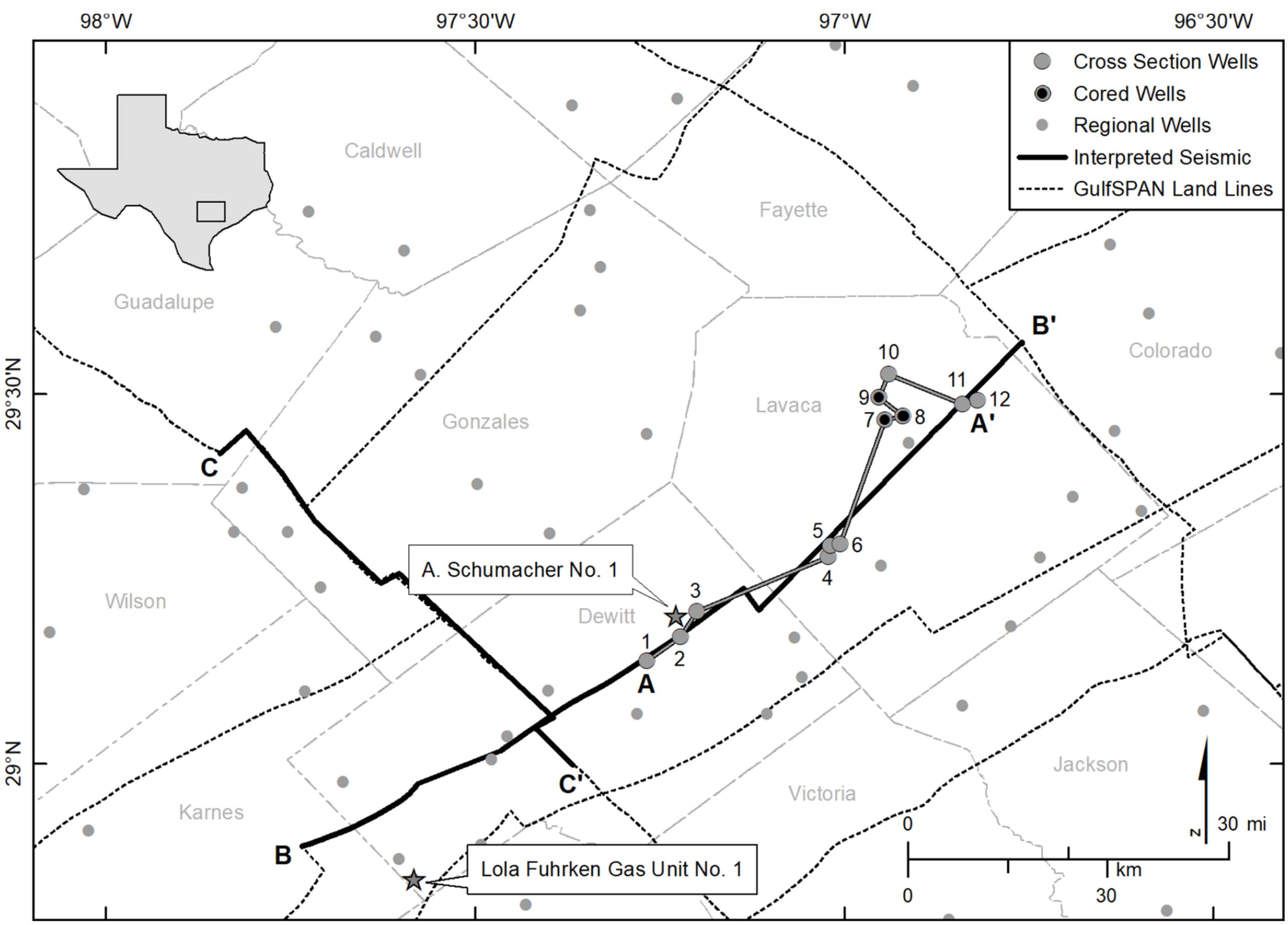

Figure 3. Basemap showing the locations of regional seismic and wireline data interpreted in this study. The locations for wells 1–12 utilized in Figure 4 are found between A and A'. The portion of the GulfSPAN land 11500 seismic line shown in Figure 7 is located between B and B'. The portion of the GulfSPAN land 2400 seismic line shown in Figure 8 is located between C and C'. The location of the A. Schumacher 1 well in Figure 2 and the Lola Fuhrken Gas Unit No. 1 well interpreted in Figure 9 are shown as stars with respective callout labels.

es were identified as maximum flooding surfaces and were observed to occasionally merge with sequence boundaries on canyon margins or in areas of reduced accommodation. Interpreted seismic sections were posted on a log cross section to integrate lithology and inferred stacking patterns observed on well logs. The seismic-consistent well log correlations also helped explain thicknesses and distributions of different seismic geometries, calibrated against well- and core-based lithology. Seismic sequence mapping facilitated paleoenvironmental interpretation in the inter-well space of the LYCC. Sequences were mapped based on regional changes in seismic facies, bounded by the surfaces described earlier. Seismic sequences illustrated the overall structure of the canyon system as well as provided insights into the distribution of different lithologies across the section.

Seismic facies analysis provides a framework for predicting rock types found within each seismic sequence. To characterize seismic facies, an amplitude and continuity-dependent scheme of Snedden and Sarg (2008) was utilized which included the following facies types (abbreviations in parenthesis): high amplitude continuous (HAC), low amplitude continuous (LAC), high amplitude semi-continuous (HASC), and low amplitude semi-continuous (LASC). This system has proven useful in a variety of tectonic and depositional settings (e.g., Snedden et al., 1996; 1997; Mansor et al., 1999; Snedden and Feldman, 2010; Snedden and Liu, 2011). Core interpretations were tied to seismic data to provide calibration of seismic facies analysis. Surface picks representing the cored interval were imported into DecisionSpace™ seismic interpretation software such that the cored interval, even at a seismic scale was easily recognizable. Once the interval of cored section was highlighted, core interpretations were tied to a specific seismic facies interval. This method allowed for more detailed and accurate interpretations regarding the depositional processes within specific interval and seismic facies.

A well-based paleobathymetric and sedimentation rate chart was constructed for the Lower Wilcox, Middle Wilcox, and Upper Wilcox. Conservative estimates of the rates of sedimentation were calculated for these units by dividing their total compacted thicknesses by depositional duration from microfaunal biohorizon age data (and ties to the geologic timescale of (Gradstein et al., 2012). Different points in the well were assigned paleoecological zonations (ecozones) based on the results of biostratigraphic analysis performed by Rashel Rosen (University of Texas data donation in 2015: ref. Table 1; APPENDIX). Ecozones were designated utilizing the Mineral Management Service (MMS) (now Bureau of Ocean Energy Management [BOEM]) classification scheme which provides a systematic way to make accurate paleoecologic interpretations based upon commonly observed planktonic and benthonic foraminifera across the Gulf of Mexico.

ANALYSIS OF WELL DATA

Core Lithofacies

Detailed analysis of the Mary B. Golsch No. 4, Howell Allen No. 3, and Pavliska No. 1 cored wells through the fill of the LYCC show that this Canyon Complex encompasses considerable variability in submarine depositional processes and associated lithofacies (Fig. 4; Wells 7,8, and 9 in Figs. 3 and 5). Understanding the diversity in lithofacies present across the LYCC provides necessary insight needed to determine the types of processes acting to incise, modify and fill this large fossilized canyon complex as well as constrain the paleobathymetric environment during the time of LYCC development. The results of this section also prove useful in addressing the fill of submarine canyons as potential reservoir targets.

The Mary B. Golsch core is comprised of sandy lithologies that grade up from primarily massive sands into sands containing sparse planar parallel laminations. The Howell Allen No. 3 core is comprised of a dominantly clay matrix interbedded with thin sandstone beds displaying micro faults, climbing ripples, and flat laminations. The Speedwell Pavliska No. 1 well consists of roughly 16 ft (4.9 m) scale, fine-grained sandstone beds displaying convolute laminations, microfaulting, and water escape structures with intervening mudstone sections also marked by convolute laminations, microfaulting, and water escape features throughout.

Lithofacies Interpretations

Within the Mary B. Golsch No. 4 core the progression of structures within a sandy lithology is characteristic of Ta and Tb subdivisions, respectively of the basal Bouma sequence (Bouma, 1962). This core is illustrative of an ideal reservoir element, primarily consisting of thick-bedded sandstone turbidites likely deposited in the thalweg or axis of a large-scale channel complex. Thick-bedded sandstones (Bouma Ta) are primarily massive, however, flat to inclined laminations (Bouma Tb), microfaulting, and mud clasts are also observed throughout these beds. Lithology and associated sedimentary structures are consistent with submarine intra-channel depositional environments (McHargue et al., 2011) (Fig. 4). The Howell Allen No. 3 core is comprised of sandstone beds ranging from sub-foot to foot scale in thickness that are marked by ripple cross laminations (Bouma Tc), microfaulting, and convolute laminations (Morris and Nor-

Table 1. Depth intervals of varying chronostratigraphic units, biostratigraphic datums, and associated paleoecology for the Lola Fuhrken well based on the results of analysis performed by Rashel Rosen (University of Texas data donation; ref. APPENDIX). Depth averages for these intervals were plotted as respective MMS (now BOEM) ecozones in Figure 8 (ref. Figure 9 for ecozone designation).

Depth (ft)	Age	Formation	Datum	Paleoecology
7200	Eocene	Upper Wilcox	*Marcinulina brantlyi*	Upper Slope
7200–8760	Eocene	Upper Wilcox	*Globorotalia quetra*	Outer Shelf
8760–9030	Eocene	Upper Wilcox	*Gyroidina* aff. *lassis*	Deep Outer Shelf
9030–9390	Paleocene	Lower Wilcox	*Marginulina Tuberculata Globorotalia angulata*	Upper Slope
9390–9450	Paleocene	Lower Wilcox	*Globorotalia pseudo-menardii*	Deep Outer Shelf
9450–10,710	Paleocene	Lower Wilcox	*Gyroidina medialis*	Upper Slope

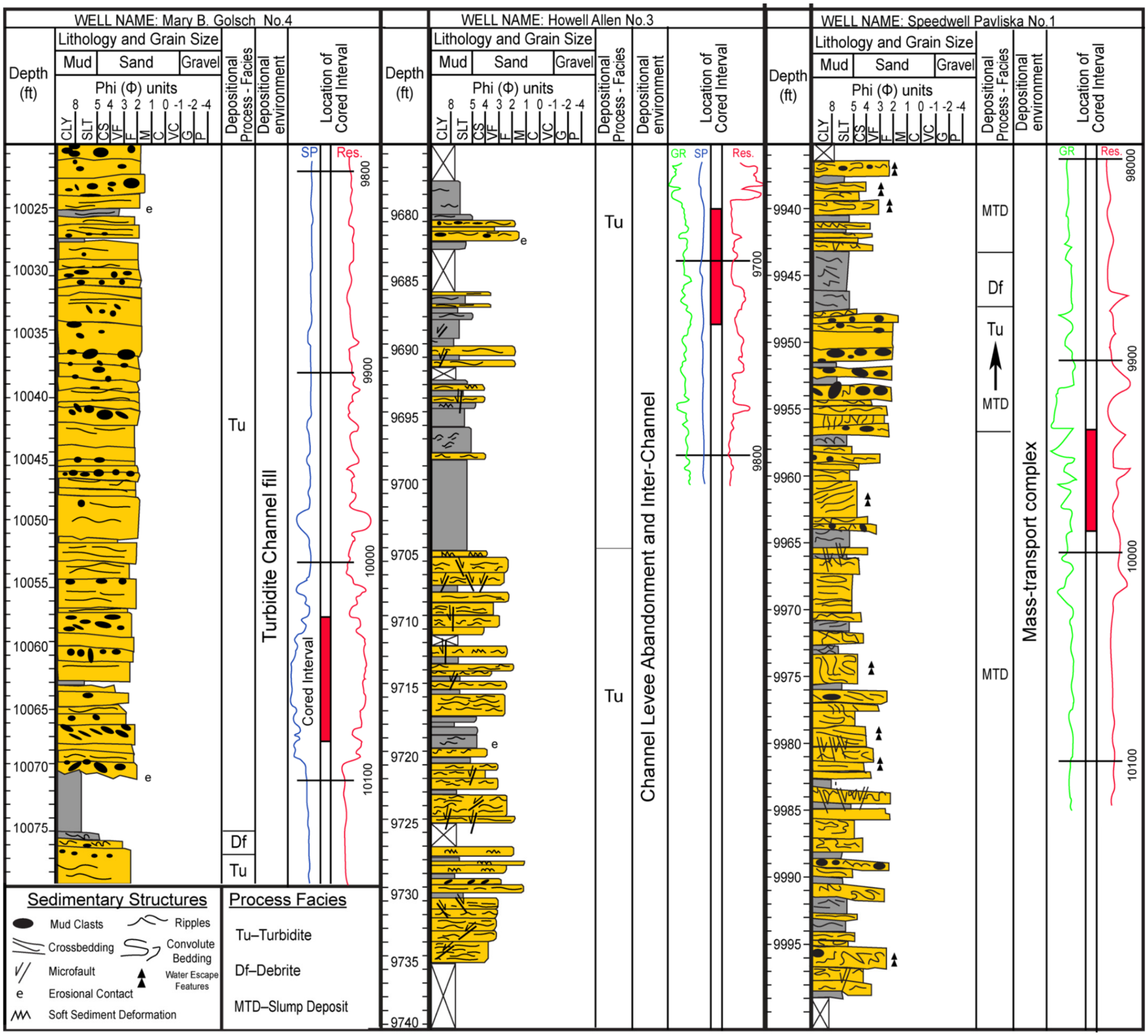

Figure 4. Core facies present in the Mary B. Golsch No. 4, Howell Allen No. 3, and Speedwell Pavliska No. 1 cores with respective locations of cored intervals at log scale. The presence of interpreted sedimentary structures consistent with turbidites and debris flows throughout these cores suggests that deposition was marked by a range of subaqueous sediment gravity flows. Lack of observable paleosols or root structures through these cores further suggests that at no point during deposition of this interval did the preserved fill of the Yoakum/Lavaca Canyon Complex undergo subaerial exposure. Channel fill facies observed in the Mary B. Golsch core is illustrative of an ideal reservoir element while facies of the proximally located Speedwell Pavliska No. 1 core are representative of non-reservoir mass transport deposits. Core descriptions from Ambrose and Dutton, (2018). 10 ft = 3.05 m.

mark, 2000) (Fig. 4). Ripple cross laminations are indicative of rapid deposition in a high energy environment of deposition suggestive of submarine channel overbank, while microfaulting and convolute laminations may be indicative of post-depositional deformation potentially associated with local periods of intra-canyon slumping, or mass failure. The presence of interbedding at sub-meter and meter scale in addition to the presence of ripple cross laminations within sandstone beds of the Howell Allen No. 3 core suggests that this interval is representative of channel levee and/or inter-channel depositional environment. Due to the pervasive nature of deformation and water escape structures across all the beds in the Pavliska No. 1 core we interpret this cored well to be solely representative of a mass-transport complex indicative of through-going shear and deformation during deposition of sandstone and mudstone intervals (Tripsanas et al., 2008; Piper et al., 1999) (Fig. 4). Sandy and muddy debrite deposits are likely associated with a single or multiple phases of mass wasting and/or slumping due to sediment loading or local fault movement along the confines of the LYCC.

The presence of observable turbidites and debris flows throughout these cores suggests that deposition was marked by a range of subaqueous sediment gravity flows. Lack of observable paleosols or root structures through these cores further suggests that at no point during the deposition of this interval did the Can-

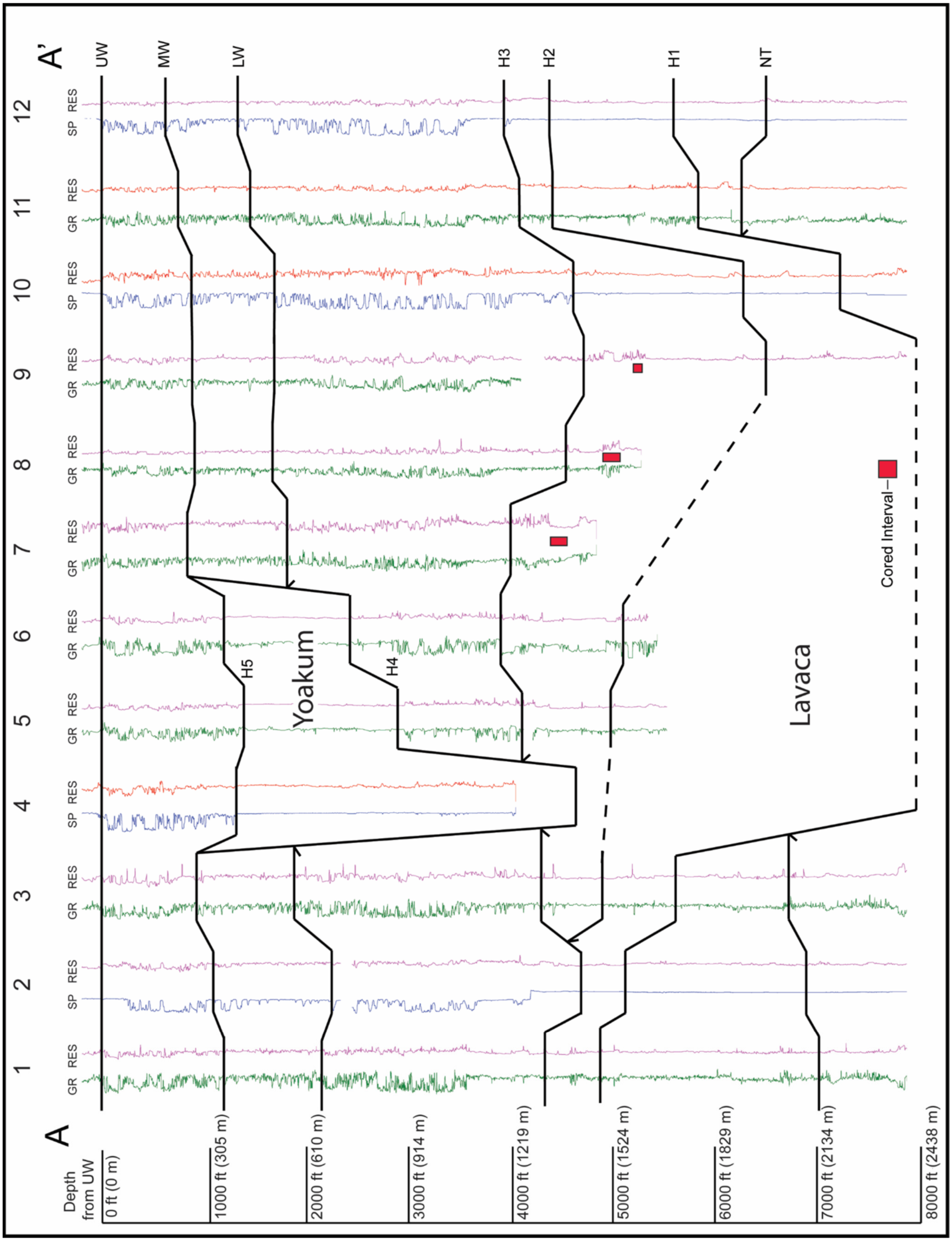

Figure 5. Stratigraphic cross section from A–A' comprised of 12 industry wells located proximally to GulfSPAN Land 11500 (ref. Figure 3 for location). Gamma ray (GR), spontaneous potential (SP), and resistivity (RES) logs were correlated to regional well and seismic control to define Navarro-Taylor (NT) and Wilcox unit tops (Lower, Middle, and Upper Wilcox [LW, MW, and UW, respectively]) as well as local canyon erosional horizons H1–H5. Cored intervals illustrated in Figure 4 illustrated by the red boxes are shown to reside between the H2 and H3 surfaces. Information for wells marked 1–12 is provided in Table 2.

Table 2. Well information for Figure 5. 1000 ft = 304.8 m.

Well Number	API	Operator Name	Well Name	Latitude (degrees)	Longitude (degrees)	Total Depth (ft)
1	421233223400	Pioneer	Myra Sue Kelley Gas Unit No 3–4	29.13914	-97.26745	15,386
2	421233143500	Arco	Covey Morrow #1	29.17164	-97.22149	15,920
3	421233212800	Pioneer	Myra Kelley 1	29.20607	-97.20019	15,130
4	422850035800	Chavanne	Carter #1	29.27949	-97.02210	10,252
5	422853357400	Lighthouse	Pritchard #1	29.29507	-97.01917	12,014
6	422853358600	Strand	Clark Creek #1	29.29620	-97.00585	11,552
7	422853184900	Howell	Allen Oil Unit #3	29.46463	-96.94498	10,205
8	422853175600	Howell	Mary B Golsch #4	29.46935	-96.92091	10,410
9	422853200900	Speedwell Oil and Gas Co.	Pavliska #1	29.49501	-96.95324	10,218
10	NA	Sohio & Skelly	Paul Stock #1	29.52647	-96.94026	14,037
11	422853244500	Chevron & Coby	Coby #1	29.48575	-96.83935	15,964
12	422853160600	Exxon	Joe Zaruba #1	29.49073	-96.81975	14,979

yon Complex undergo subaerial exposure, as confirmed by faunal content indicative of paleo-slope to outer shelf water depths (see below).

Interpretation and Correlation of Wireline Log Motifs

A depositional strike stratigraphic cross section A–A' was generated across the LYCC utilizing wireline data from twelve industry wells lying close to seismic section 11500 (Fig. 5). The datum is the Upper Wilcox unit top. Unit tops are abbreviated for the Upper, Middle, and Lower Wilcox (UW, MW, and LW, respectively) and the underlying Late Cretaceous age Navarro-Taylor (NT) supersequence (Olson et al., 2015) which is dominated by deep marine carbonates. Key canyon horizons (sequence boundaries), marked as H1–H5, are identified by seismic stratal terminations as well as changes in regional lithology. Truncation of the Middle Wilcox and Lower Wilcox units are associated with incision of the Yoakum Canyon that is filled largely with the Yoakum Shale, as evidenced by the large intervals of characteristically shale-dominate spontaneous potential and gamma ray responses between the H4 and H5 horizons. The Yoakum Canyon is defined by the basal incision of the canyon marked as horizon H4. Underlying the Yoakum Canyon, the Lavaca Canyon's basal incision surface, H1, erodes into the Navarro-Taylor (Cretaceous) unit. Horizons H2 and H3 were correlated using resistivity peaks that are interpreted as condensed sections (maximum flooding surfaces). Depths for these surfaces in wells were confirmed by importing them as surface picks into seismic interpretation software. Horizon H5 is interpreted to mark the boundary between the Yoakum Shale and the Upper Wilcox. The Yoakum shale experienced differential compaction as the overlying sandstone-rich upper Wilcox thickens by 365 ft (111 m) above this unit. The Yoakum Canyon incises into the middle Wilcox prior to Upper Wilcox deposition and fill. The Lavaca Canyon incises into the Navarro-Taylor unit, indicating that it is younger than the Cretaceous. The interpreted width of the Yoakum Canyon is much smaller than that of the Lavaca Canyon although overall depths of incision appear to be relatively similar.

SEISMIC STRATIGRAPHIC INTERPRETATION

Core-Seismic Calibration

Cored intervals were tied to 2D seismic reflections based on matching depth intervals with changes in lithology coinciding with seismic reflection boundaries due to changes in acoustic impedance (Fig. 6). The cored intervals of the Allen Oil Unit #3 and Golsch #4 wells occur between the H3 and H2 surfaces that mark the boundaries of the laterally continuous HASC seismic facies interval (Figs. 5 and 6). Calibrating sedimentary structure interpretations within this seismic interval suggests deposits represent a mix of high- and low-density turbidity current, debris flow, and mass transport deposits (Fig. 4). The core-seismic correlation suggests that the laterally continuous interval between the H2 and H3 horizons within the Lavaca Canyon fill represents varying deepwater deposits from intra and inter-channel slope depositional environments based upon observed sedimentary structures (Figs. 4 and 6). Given associated uncertainties with core-seismic ties, we find cored intervals would still fall within the same HASC seismic facies interval given that this interval encompasses over 2000 ft (609 m) of stratigraphy where core-seismic ties were made (Figs. 6 and 7). Similar sets of sedimentary structures and lithofacies have been recognized in slope channel-fills in West Africa (Mayall and Stewart, 2000) and Wilcox channel-fills in the deepwater Gulf of Mexico (Power et al., 2013)

Seismic Sequence and Facies Mapping

Five seismic sequence boundaries (labeled as H1–H5) were mapped along the 2D strike seismic lines GSM3_11000, 11500, and GSM3_2400 dip line (Figs. 3, 7, and 8). Consistent with wireline interpretations, the H1 surface is interpreted to mark the basal incision of the Lavaca Canyon while the H4 horizon is interpreted to mark the basal incision of the Middle Wilcox age Yoakum Canyon. The H1 horizon is observed to truncate the Cretaceous age Navarro-Taylor seismic surface while the H4 horizon truncates the Middle Wilcox and Lower Wilcox seismic surface as correlated from both seismic and wireline data (Figs. 5 and 7). The Upper Wilcox, which overlies the Yoakum Canyon,

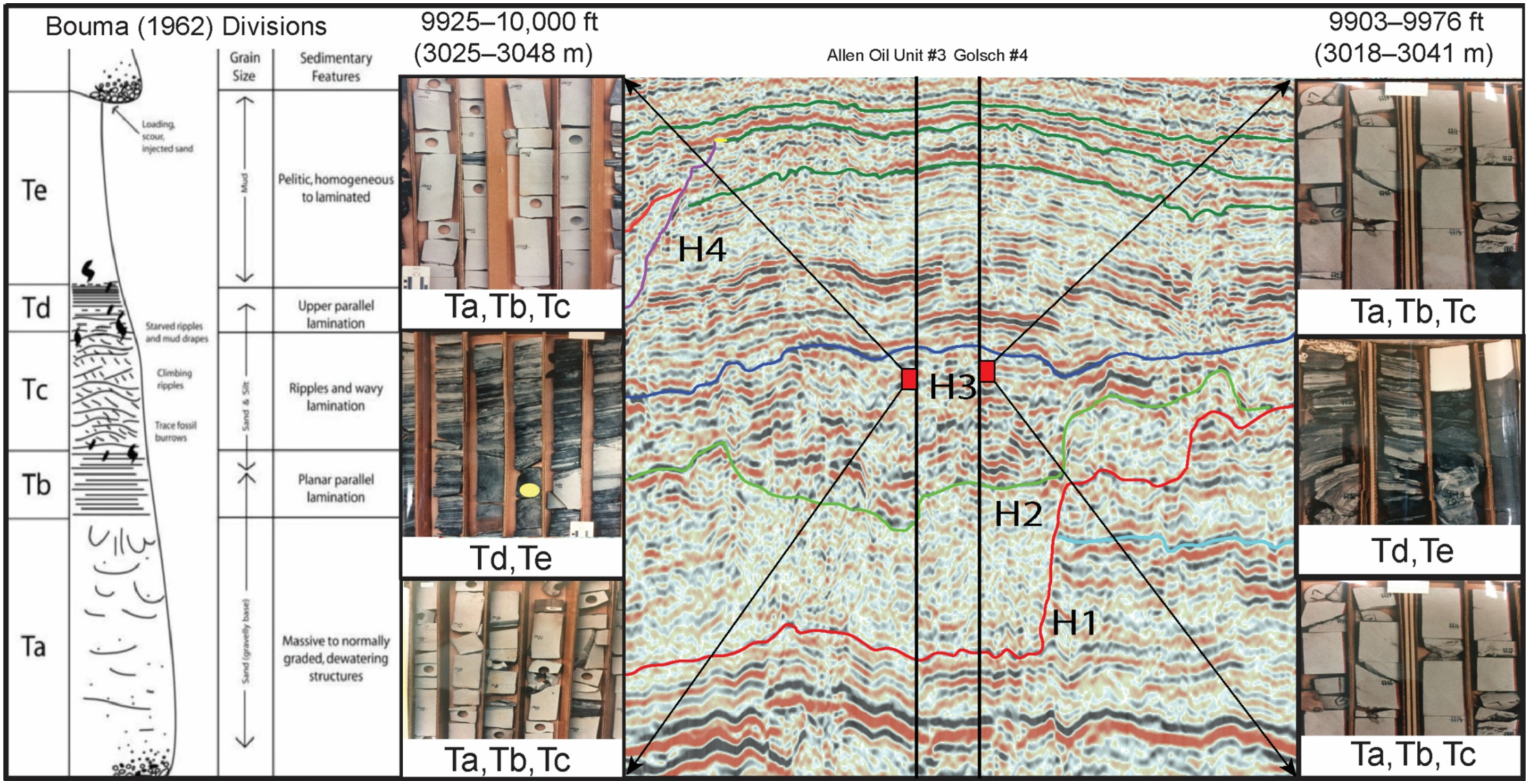

Figure 6. Cored intervals calibrated to seismic data between erosional surfaces H2 and H3 within the HASC seismic facies. Analysis of core data suggests that high seismic impedance contrasts are caused by a transition from primarily sandy to muddy turbidite deposits. Sandy turbidites show massive fine-grained high net to gross sandstone fining upwards and containing parallel laminations as well as current ripples characteristic of Ta, Tb, and Tc sections of the classic Bouma sequence. Moving upsection, the sandy turbidites fine into muddy turbidites displaying alternating mud and silt beds that grade upwards into a massive mudstone. These muddy turbidites are interpreted to be channel margin to overbank deposits and are representative of Td and Te sections of the classic Bouma sequence. Inset chart illustrates divisions of the Bouma sequence (modified after Bouma, 1962).

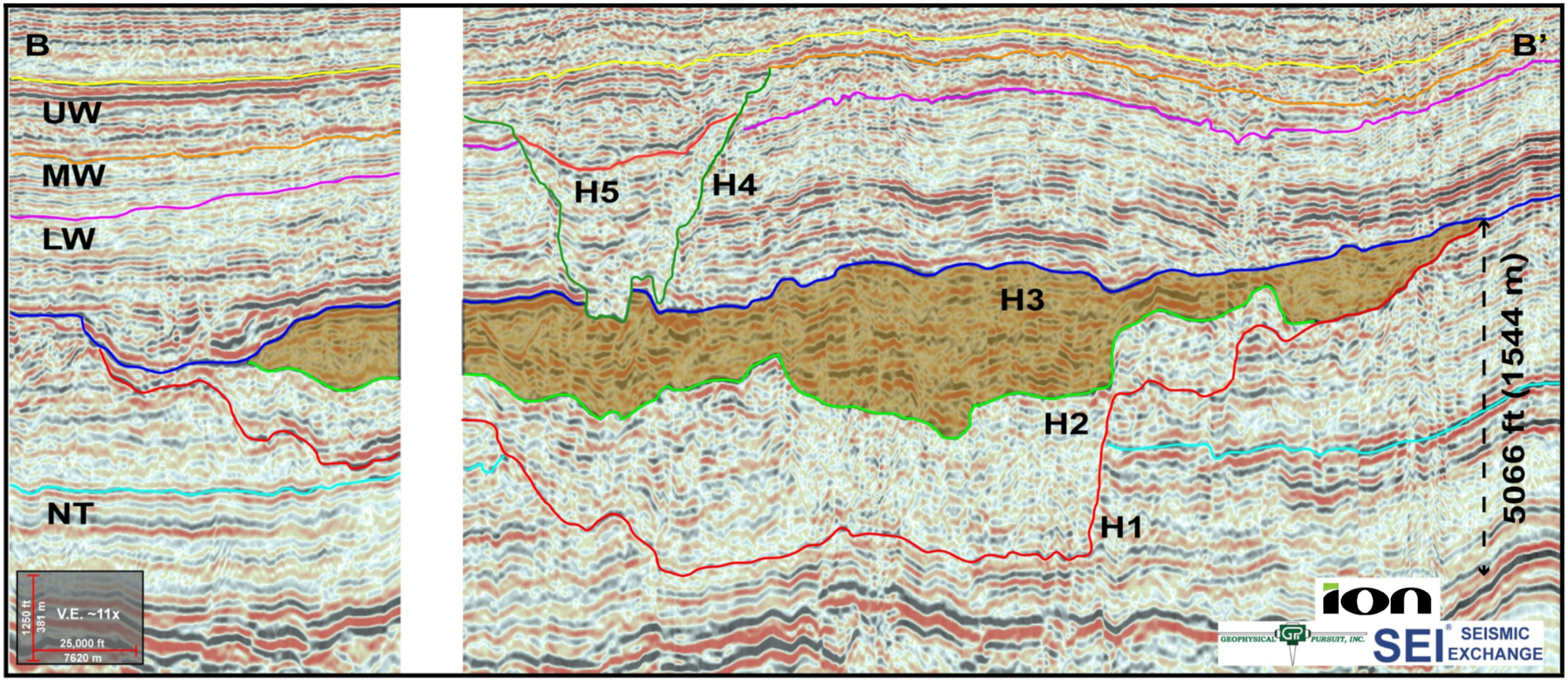

Figure 7. Interpretation of GulfSPAN Land 11500 strike line from B–B' illustrating erosional surfaces H1–H5 bounding different seismic sequences of the Lavaca/Yoakum Canyon Complex. Unit tops for the Upper, Middle, and Lower Wilcox (UW, MW, and LW, respectively) and Navarro-Taylor (NT) are labeled. H1 is interpreted as the basal surface of the Lavaca Canyon while H4 is interpreted as the basal surface of the overlying Yoakum Canyon. Core-seismic calibration confirms that the HASC seismic facies is dominated by upper slope turbidity channel fills as shown by the brown highlighted interval. The measured width of the Lavaca/Yoakum Canyon Complex is 261,227 ft (79, 662 m) while the measured maximum depth of incision is 5066 ft (1544 m). The magnitude of these resulting dimensions combined with the associated core fill interpretations, are conclusive to submarine processes, not exclusive periods of eustatic drawdown and subaerial exposure controlling the formation of this canyon complex.

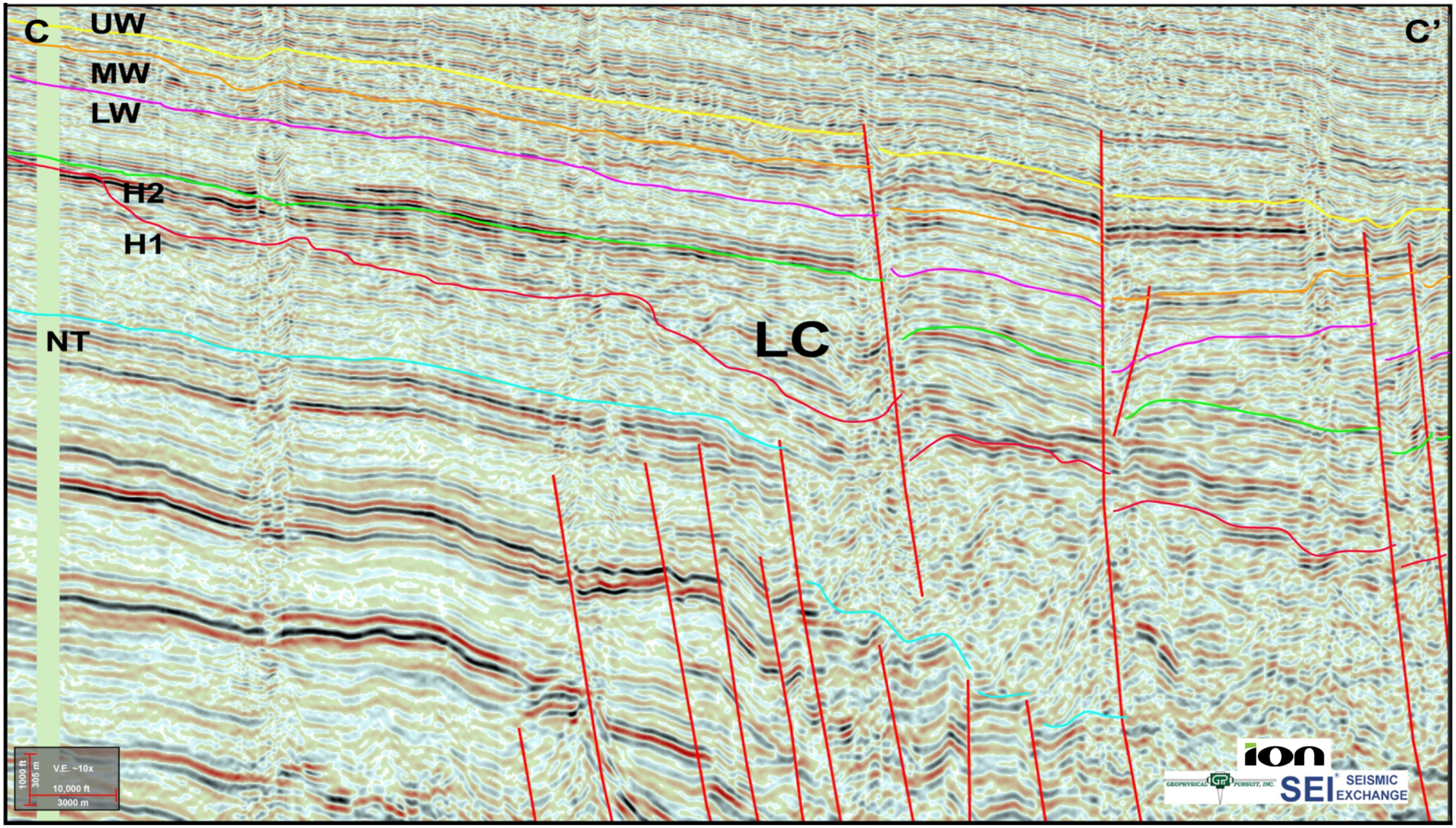

Figure 8. Interpretation of GulfSPAN Land 2400 dip line from C–C' illustrating the faulted erosional H1 surface that marks the basal incision of the Lavaca Canyon (marked LC). Erosional surface H2 marks the transition into the HASC seismic facies within the Lavaca Canyon (ref. Figure 5). This dip line falls outside of the confines of the Yoakum Canyon, therefore erosional surfaces H4 and H5 are absent (ref. Figure 3). The Lavaca Canyon is bordered by large listric growth faults (shown in red) that are localized to the coeval shelf margin. Syn-sedimentary faulting and the subsequent development of slump blocks are probably the result of undercutting by erosive turbidity currents which caused the walls of Lavaca Canyon to reach a state of severe instability. Unit tops for the Upper, Middle, and Lower Wilcox (UW, MW, and LW, respectively) and Navarro-Taylor (NT) are labeled.

thickens above the canyon likely because of differential compaction of the underlying shale sequence.

Seismic facies analysis resulted in the recognition of a set of distinct laterally extensive facies that change above and below seismic sequence boundaries. Seismic facies vary within differing portions of the LYCC reflecting a high variability in lithologies and stratigraphic architecture within the complex fill of this series of canyons. Despite wireline logs suggesting a shale prone Yoakum Canyon, this canyon's fill does incorporate some medium amplitude, discontinuous horizons, likely evident of thin deepwater sandstone beds not penetrated by wells (Fig. 7). Within the underlying larger, Lavaca Canyon we observe three different seismic facies. The upper portion of the canyon-fill bounded by sequence boundaries H2 and H3, shows an interval comprised of HASC seismic facies. The lower portion of fill found below the H2 horizon shows a decrease in amplitudes, defined as MASC as well as LAC seismic facies. We interpret this lower section of Lavaca Canyon fill to be primarily mud-dominated compared to the overlying more sand-prone higher amplitude and discontinuous seismic facies. Shallow wireline log penetrations support this interpretation (Fig. 7).

Possible Structural Influence on Canyon Formation

The Lavaca Canyon is bordered by a number of listric growth faults that here, as elsewhere, are common downdip of the coeval Wilcox and older shelf margins. These growth faults tend to localize sedimentary accommodation and section expansion (Fig. 8). These syn-sedimentary faults are associated with extensively rotated bedding generated by slumping. Syn-sedimentary faulting and the subsequent development of slump blocks are probably the result of sediment loading by turbidity currents which caused the walls of Lavaca Canyon to reach a state of severe instability. Fault activity was terminated shortly after deposition of the Upper Wilcox, though later reactivation appears to be the case on some of the Wilcox faults. Depositional fill between surfaces H1 and H2 likely aided the initiation of sliding by providing significant sediment loading. The resulting uneven topography following periods of sliding and slumping likely influenced the pathways of subsequent sediment gravity flows down the canyon (Armitage et al., 2009). The presence of these faults suggests that submarine mass wasting likely contributed to development of the Lavaca Canyon (Galloway and McGilvery, 1995).

PALEOBATHYMETRIC INTERPRETATIONS

The Lola Fuhrken well contains paleobathymetric data from identified microfaunal assemblages. As it lies outside the interpreted extent of the LYCC, it serves as a conservative estimate of paleowater depth (Fig. 3). More importantly, however, the deposits in this well are in-situ paleobathymetric indicators, unaffected by the incision, transport and fill processes within the LYCC. This in turn, provides a more accurate regional paleodepth during the time of incision and fill of the nearby LYCC. Ecozones were plotted, illustrating the changes in interpreted paleo-bathymetric environments for Wilcox Group deposition. A table of the biostratigraphic results from the analysis for this well contained in the APPENDIX is shown in Table 1 illustrating changes in paleoecology at differing depths, primarily based on the abundance and species diversity distributions of planktonic, benthic calcareous, and arenaceous foraminifera.

The Wilcox in the well is characterized by low gamma ray and spontaneous potential responses and moderate-to-high resistivity values. As seen on the lithology track (from cuttings), the Wilcox Group is dominantly represented by sandstone interbedded with thinner shale beds (Fig. 8), Sediment influx is high throughout Wilcox Group deposition ranging from a conservative rate of 450 ft/Myr (137 m/Myr) in the Lower Wilcox to 280 ft/Myr (85 m/Myr) in the Upper Wilcox. Sedimentation rates decrease upward, mirroring the basin-wide retrogradation of the Wilcox with changes in Laramide drainage (Galloway, 2008; Snedden et al., 2018a).

Beginning at a depth of 12,150 ft (3703 m) true vertical depth (TVD), the deepest interpreted section of Lower Wilcox where paleoecology is available (Fig. 9) is assigned to ecozone 4, representing the upper slope (MMS [now BOEM] classification; see Figure 10). Moving up borehole, paleobathymetry varies from ecozone 3.5 (deep outer shelf) in the Middle Wilcox deposits at 9300 ft (2834 m) TVD, transition back to the upper slope (ecozone 4). The overlying Cenozoic deposits at 8580 ft TVD fall within the bathymetrically shallower, deep outer shelf ecozone. A continued fall in relative sea level shows the overlying deposits at 7935 ft (2418 m) TVD to be deposited within the outer shelf environment. After a presumable transgression, younger deposits of the Upper Wilcox at 7395 ft (2418 m) TVD are in ecozone four representing a transition back to the upper slope paleo-water depths.

Throughout Wilcox Group deposition in this well, the shallowest ecozone observed is outer shelf (water depths of 330–660 ft [100–200 m]) while the deepest is upper slope, 660–1640 ft (200–500 m) paleowater depth (Fig. 9). These data from a well outside of the LYCC strongly suggests that, during Wilcox Group deposition, the LYCC was formed completely under subaqueous conditions and at no point experienced subaerial exposure. It is not logical to expect fluvial incision of the LYCC during Wilcox drawdown when wells outside the canyon complex are under at least 330 ft (100 m) of marine water. This conclusion of a fully marine Gulf of Mexico during the Paleogene is further supported by regional to basin-scale data on the Wilcox in the northern Gulf of Mexico which shows mainly slope to basinal planktonic microfauna (Zarra, 2007). Further, Umbarger and Snedden (2016) interpreted slope-depth (330 ft+ [100 m+]) or deeper paleoenvironments at the entrance to the Suwannee Strait, a direct connection to the Atlantic Ocean, for the entire Paleogene.

RECONSTRUCTED GEOMORPHOLOGY

Seismic Geomorphology

Submarine canyons incise at significantly deeper depths than that of fluvial systems whose maximum scour depths range from 65 ft (20 m) to 230 ft (70 m) (Talling, 1998). The range of incision for submarine canyons is from 518 ft (158 m) to a maximum of 21,463 ft (6542 m) (Harris and Whiteway, 2011). We estimate maximum depth of incision for the Yoakum Canyon at 3662 ft (1116 m) while the Lavaca Canyon is cut to 5066 ft (1544 m) (Fig. 7). The relief of these surfaces is not representative of the bathymetric relief associated with one stage of incision, but rather a series of cut and fill episodes arising from periodic turbidity currents moving through the canyon. Physical stratigraphic models suggest preserved stratigraphic relief, observed in the seismic data, is often subject to dynamic reshaping during subsequent phases of erosion and deposition through time (Strong and Paola, 2008). Despite the expected discrepancies between preserved stratigraphic relief and bathymetric (instantaneous) geometries of canyons, the magnitude of the mapped geomorphic dimensions of these canyons, combined with the associated core fill interpretations, imply that submarine processes, not sea-level drawdown and subaerial exposure, controlled formation of the LYCC.

Additionally, it is well documented that submarine canyons undergo retrogradational failure and terminate landward during subsequent transgressions (Pratson and Coakley, 1996). This process is in sharp contrast to fluvial incised valleys, which pro-

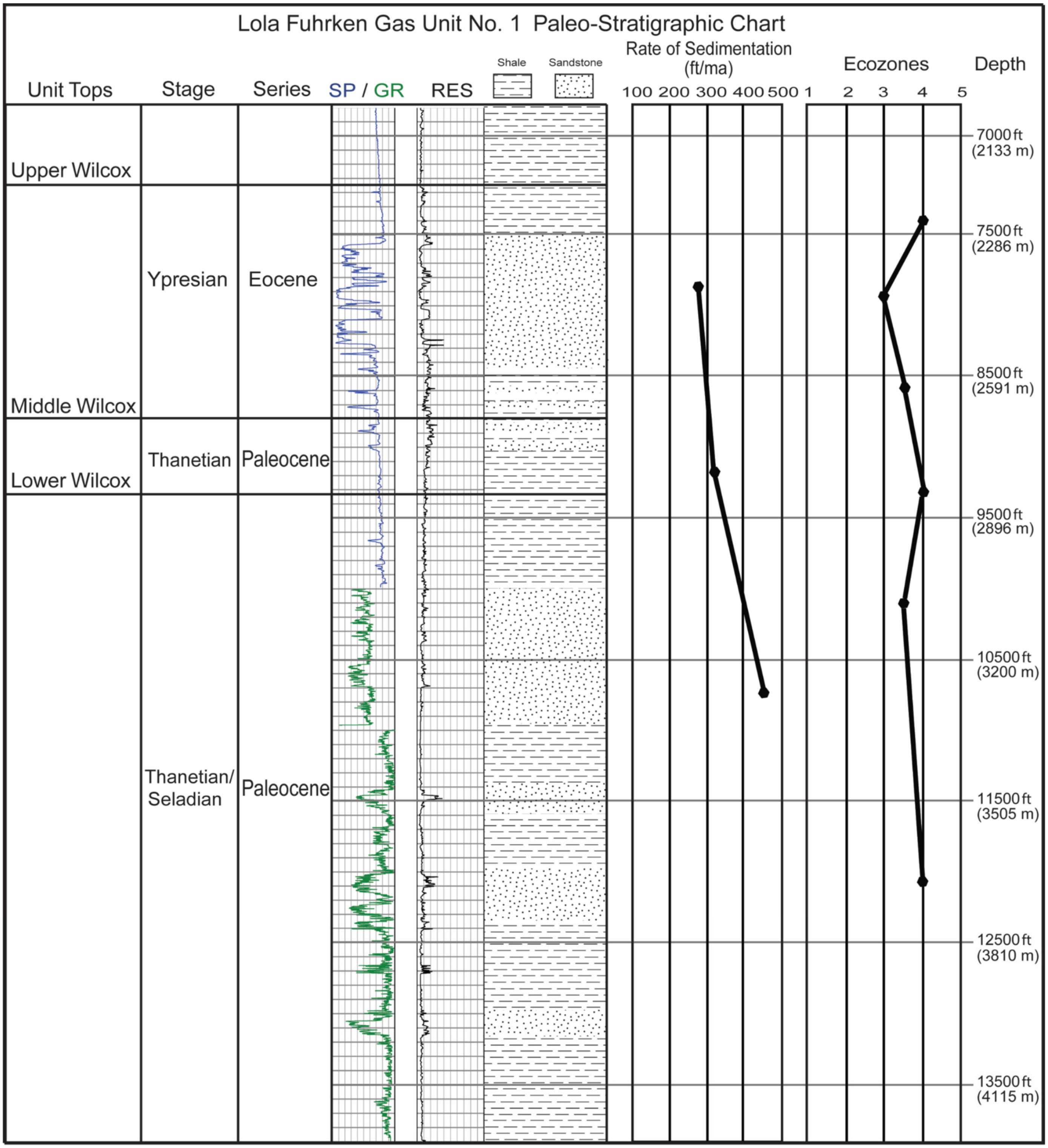

Figure 9. Stratigraphic subdivisions, paleoecology, and sedimentations rates for the Lola Fuhrken well. Rates of sedimentation are observed to near or over 300 ft/Myr (91 m/Myr) throughout Wilcox Group deposition. Paleo-bathymetric ecozones were defined for different intervals by the presence of specific microfaunal taxa in the core of the well utilizing the MMS (now BOEM) marine environment classification (ref. Figure 10; Table 2). Throughout Wilcox Group deposition, we find that this well was between the outer shelf and upper slope (330–1640 ft [100–500 m]) paleowater depths. These data support the hypothesis that the LYCC developed entirely under subaqueous conditions.

gressively shallow towards the highstand shoreline or lowstand shelf edge, depending on relative sea-level position (Sweet and Blum, 2016). Following the extensive mapping of unit tops and bounding surfaces across all wells and seismic data in the study area, a map of the interpreted geometry of the LYCC was generated (Fig. 10). Both canyons map dip trends suggestive of headward failure and landward termination. Despite both canyons intersecting nearby fluvial channels, these canyons were formed

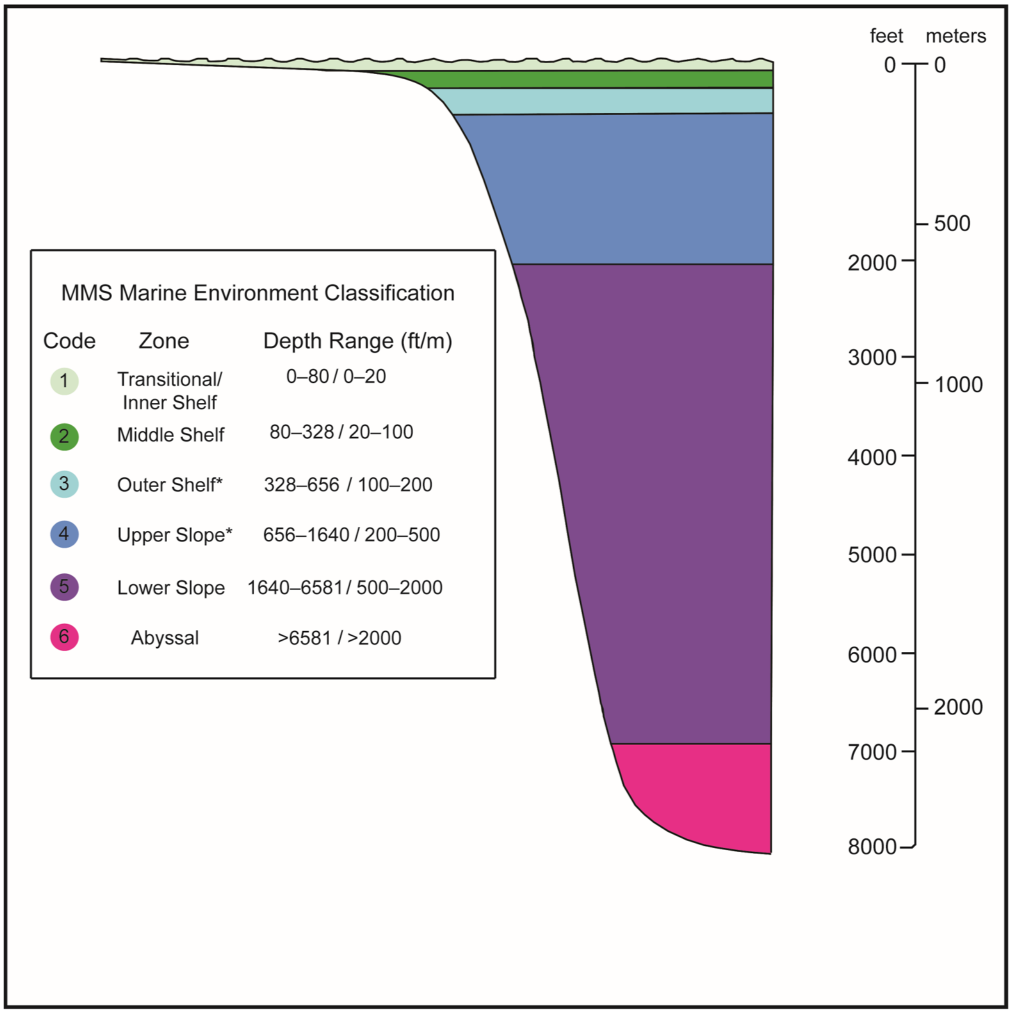

Figure 10. MMS (now BOEM) marine environment classification scheme illustrating different paleobathymetric ecozones and their respective depth ranges (modified after Tipsword et al., 1966).

by fundamentally different processes under submarine conditions.

Previous attempts at morphological characterization of the LYCC have been primarily based on limited resolution, older vintage 2D seismic lines and wireline logs (Dingus and Galloway, 1991). Our revised morphology provides a more accurate plan view map of this fossilized canyon complex by incorporating new digital well logs and higher resolution seismic data. The results show that the original morphologic maps of the Yoakum and Lavaca canyons which were interpreted as two separate canyons adjacent from one another is inaccurate. The relatively narrow Yoakum Canyon is in fact, overlies the older but broader Lavaca Canyon comprising a set of canyons. This revised morphology suggests a long-lived, stable fluvial drainage network linked to these canyons, episodically providing sandstone and mudstone during phases of high discharge or locally lower sea-level states.

DISCUSSION

Evolution of the Lavaca/Yoakum Canyon Complex

The Yoakum and Lavaca canyons are part of an ancient submarine canyon complex that likely developed by processes similar to that documented in modern day submarine canyons (e.g., Zaire-Congo Canyon). Initiation of these submarine canyons was the probable byproduct of shelf-margin failure and the generation of submarine mass movement, periodically followed by turbidity-current flows issuing from linked river systems. Observations from modern submarine canyons suggests that submarine canyons on passive margins are generally the result of shelf edge instabilities occurring under subaqueous conditions (Babonneau et al., 2002), not strictly major eustatic drawdowns as suggested earlier from sequence stratigraphic models (e.g., Vail et al., 1977; Posamentier and Vail, 1988).

Following sediment loading from the prograding southern margin of the Houston Delta System, the underlying relict Albian shelf edge reached a state of instability (Galloway and McGilvery, 1995). The Lavaca Canyon incision is interpreted to have been initiated by large scale margin failure and headward erosion of the underlying shelf. Margins of the Lavaca Canyon show preserved slump scars on the H1 horizon that are identified by a characteristic stair-stepping, sub-vertical, margin truncation pattern (Fig. 7). We suggest that following an initial phase of failure and slumping initiated by underlying fault movement (Figs. 7 and 8), a period of episodic sediment-gravity-flow deposition occurred. This interpretation is supported by the change into the HASC seismic facies bounded by horizons H2 and H3 in the upper section of the canyon fill. Core-seismic calibration has demonstrated that this interval of Lavaca Canyon fill is dominated by upper slope turbidity flow deposits. Based on this analysis, the stratigraphically preserved basal surface of the Lavaca Canyon (H1) is likely a composite surface that encompasses two failure/cut and fill episodes within the Lavaca Canyon. Following canyon fill, we postulate that a final terminal phase of proximal deltaic sedimentation came close to but did not reach the Lavaca Canyon. This transition is observable in subsurface data by the change into the HAC seismic facies of the Lower Wilcox formation as well as in wireline log data by the transition into dominantly sand-prone lithologies above the H3 horizon. These are probably representative of proximal delta-mouth generated turbidity flows (e.g., Carvajal and Steel, 2006). Further incision and fill of the Lavaca Canyon occurred during the deposition of the Lower Wilcox in the late Paleocene.

After deposition of the Middle Wilcox unit, a regional transgression submerged the shelf and reduced incoming sediment supply, coincident with the PETM (Winker, 1982; Galloway, 2009). As the slope began to retrograde, central portions of the under-filled canyon Lavaca Canyon may have guided low-density turbidity flows toward basinal areas. Continued erosion by these low-density submarine gravity flows may have promoted further headward erosion and formed the narrow, but high relief Yoakum Canyon. Based on log data, the fill of the Yoakum Canyon is uniformly mudstone-rich dominated by high gamma ray and spontaneous potential responses, as well as low resistivity readings indicating a lack of hydrocarbon-bearing sandstone. The absence of significant sandstone packages in the fill of the canyon as well as preserved slump scars on the near vertical margins of the canyon (Fig. 8) leads one to believe that bypassing of the Yoakum Canyon occurred in Upper Wilcox time, linked to small fans observed in the present-day shelf (McDonnell et al., 2008). Similar to the H1 surface, the basal surface of the Yoakum Canyon (H4) is likely representative of multiple cut and fill episodes which dynamically reshaped the preserved geomorphology of the canyon through differing stages of erosion and deposition through time, as observed in experimental models (e.g., Strong and Paola, 2008).

The Yoakum Canyon is overlain by Upper Wilcox sediments. It was later abandoned during a regional transgression in the early to mid-Eocene (Galloway, 2009). This regional transgression may have reduced sediment input into the Gulf of Mexico and is coincident with the formation of the Gosiute and Uinta lakes in the Rocky Mountains as well as internal drainage in the sediment source area of the Houston fluvial-deltaic system (Dickinson, 1988; Smith et al., 2014; Sharman et al., 2016). Reduction of sediment influx into the Gulf of Mexico during the middle Eocene has also been postulated to have been caused by a decline in Laramide tectonism (Dickinson, 1988).

IMPLICATIONS

Gulf of Mexico Paleoclimate and the Gulf of Mexico Drawdown Hypothesis

Observations made in this study strongly contradict the view that Yoakum and Lavaca canyons were products of basin isolation and major sea-level drawdown event as some have suggested (Rosenfeld and Pindell, 2003; Cossey et al., 2016). Implications for the regional Gulf of Mexico paleoclimate reconstructions, based on these results, suggest that during the Paleocene-Eocene Thermal Maximum (PETM), the Gulf of Mexico Basin did not experience isolation from the world's oceans and subsequent Mediterranean Messinian-like evaporative drawdown (Hsü et al., 1978; Ryan, 2009). Nor did this event likely generate a sea -level fall up to 5905 ft (1800 m), the estimated relief of the LYCC.

In the Gulf of Mexico drawdown model, development of the areally large and thick Wilcox basin-floor fans is explained by means of bringing the fluvial-deltaic feeder system immediately adjacent to locations of basin-floor deposition (Rosenfeld and Pindall, 2003). This model proposes that the Yoakum and Lavaca canyons are the products of substantial reductions in Gulf of Mexico interior sea level following isolation of the Gulf of Mexico through the docking of Cuba against the Florida Straits. Rosenfeld and Pindall (2003) argue that canyon incisions of this scale are only seen on the shelf margins of basins that underwent desiccation such as during the Mediterranean Messinian crisis (e.g., Ryan, 2009). Results from deepwater drilling of the Wilcox play were also cited to infer that the drawdown of the Gulf of Mexico was on the order of 5900 ft (1800 m) necessary to explain the occurrence of the abnormally thick sandstone-rich Wilcox fan deposits located more than 250 mi (400 km) from the delta source (Berman and Rosenfeld, 2007).

Sømme et al. (2009) compiled global data to document that submarine canyons are a common feature of many continental margins and that they occur updip of many large submarine fans. The Quaternary Zaire Canyon has relief up to 4300 ft (1300 m) and extends over 80 mi (130 km) across the continental shelf to the base of slope (Babonneau et al., 2002). The large subaqueous canyon is not attributed to desiccation of the Atlantic, but rather an active long-lived connection between the Congo river and the canyon head. Furthermore, modern slope canyons with widths greater than 6 mi (10 km) and depths of 2000–3300 ft (600–1000 m) or more are commonly observed (Sømme et al., 2009). The scale of shelfal incision of the Yoakum and Lavaca canyons is therefore not unique when compared to modern day submarine canyons. The Wilcox submarine fan systems, mapped from numerous deepwater wells, are linked directly with long rivers and large catchments that extend over 620 mi (1000 km) to headwaters in the northern Rockies (Galloway et al., 2011; Snedden et al., 2018a). It is unnecessary to evoke such catastrophic drawdown mechanism for the long-run out Wilcox fans when long (and thus large discharge) rivers are available to deliver sediment to the deepwater basin.

Lack of Eustatic Control on Sediment Routing within the Wilcox Depositional System

Paleodrainage reconstructions for the Gulf of Mexico during the early Paleocene to mid-Eocene suggests that the LYCC was one of the primary conduits by which Wilcox sediment was transported from the paleo-Colorado-Brazos system to laterally extensive basin floor fans (Galloway et al., 2011). These fans were first recognized in the deepwater Gulf of Mexico in 2001 and are located ~250 mi (~400 km) basinward from coeval onshore deltaic strata (Zarra, 2007). Wilcox deepwater fans are renowned hydrocarbon reservoirs with thicknesses commonly over reaching over 3300 ft (1000 m) with ratios of sand to shale ranging from 40–70% (Blum et al., 2017).

While sequence stratigraphy has traditionally focused primarily on the depositional sink, the recent approach of source-to-sink (S2S) is fundamental in understanding how sediment is transported and stored throughout segments of sediment-dispersal systems. Recent work has established various linkages between these different segments through analysis of empirical source-to-sink scaling relationships (Sømme et al., 2009). A strong relationship between river length and submarine fan runout length for Cenozoic depositional systems in the Gulf of Mexico implies that when large submarine fans exist, the larger catchment area exerts a greater influence on the scale of the submarine fan than the local deltaic sediment storage (Snedden et al., 2018a). Our results support that the additional notion that there is an apparent lack of empirical scaling relationships between the size of submarine canyons and the associated basin floor fans to which they fed (Normark and Carlson, 2003). The existence or lack thereof empirical scaling relationships in S2S analysis has important implications for models of sediment routing within a depositional system.

Workers have traditionally thought of eustasy as the primary control on sediment flux to basin floor fans such that a relative sea-level fall produces incision, and an upstream-propagating wave of sediment rejuvenation (e.g., Vail et al., 1977; Posamentier and Vail, 1988). These newly produced sediments entirely bypass the coastal plain and shelf to provide a substantial volume of sediment for systems tracts basinward (Blum and Tornquist,

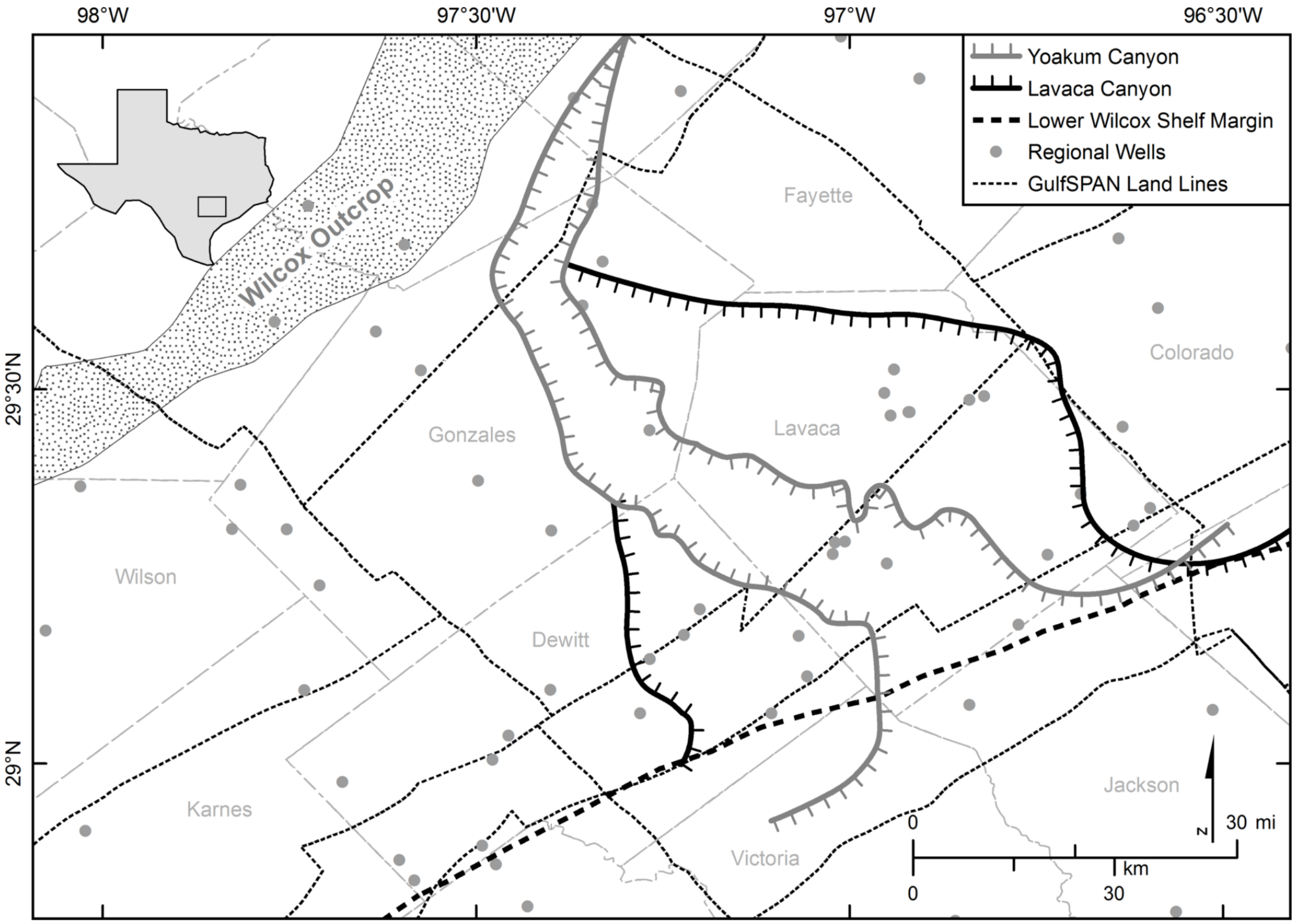

Figure 11. Interpreted geometry of the Lavaca/Yoakum Canyon Complex based on subsurface interpretation of all regional seismic and well data shown (ref. Figure 3). The proximity of the head of the Lavaca/Yoakum Canyon Complex to fluvial outcrops of the Wilcox strongly suggests that a fluvial to submarine canyon connection was maintained between the paleo-Colorado and Brazos rivers and the Lavaca and Yoakum canyons during the time of Wilcox deposition. Both the Lavaca and Yoakum canyons show dip trends suggestive of headward failure and landward termination, more characteristic of submarine canyon formation than subaerial valley incision. The Yoakum Canyon is shown to be superimposed on the underlying Lavaca Canyon, with both canyons comprising the singular, Lavaca/Yoakum Canyon Complex.

2000). This model implies the bigger the eustatic drawdown, the more transportable sediment available for deposition basinward.

However, recent studies have shown that the excavation of incised valleys provide a sediment volume that is only 5 to 10% of the normal flux through the system (e.g., Burgess and Hovius, 1998; Blum and Törnqvist, 2000; Blum et al., 2013). Likewise, submarine canyon excavation does not contribute significant quantities of sediment that lead to the growth of basin floor fans. This was also demonstrated for the Tuscaloosa submarine fan (Snedden et al., 2016). The growth of deepwater submarine fans is thus a product of sediment influx from hinterland source terrains that are conveyed through fluvial systems and subsequent submarine canyons. The recently introduced "conveyor belt model" (Blum and Törnqvist, 2000) allows for sediment to be continuously delivered to the basin margin from large inland drainages regardless of sea-level fluctuations. Therefore, it is not surprising that the large drainage catchments associated with the Wilcox Group, constructed laterally extensive, coarse-grained submarine fans even during times of relative sea-level highstands.

Consistent with the conveyor belt model (Blum and Törnqvist, 2000), our results suggest that in this case there is in fact, limited eustatic influence on the ability of sediment to be transferred from terrestrial sources through submarine canyons to deep basin sinks. Recent publications have proposed that the main control is rather the distance between the terminal head of the submarine canyon and the shoreline during deposition. Furthermore, the width of this zone may be directly related to the caliber of sediment transported through submarine canyons to deepwater depositional sinks (Babonneau et al., 2002; Sweet and Blum, 2016).

The importance of this proposed control to our study is the proximity of the terminal head of the LYCC to Wilcox outcrops (Figs. 1 and 11). Outcrops of the Wilcox Group are known to be primarily comprised of both fluvial and nearshore sandstones representative of the axial river systems of the Houston delta in the updip region of the LYCC. The proximity of the head of the LYCC to these fluvial outcrops strongly suggests that a fluvial to submarine canyon connection was maintained between the paleo-Colorado and Brazos rivers and the LYCC during the time of Wilcox deposition.

It is well documented that the early Wilcox deposition occurred in a climatic greenhouse phase with high global sea levels (Miller et al, 2003). Furthermore, climate and oceanographic reconstructions suggests that an absolute minima in global ice volumes existed during this time period (Sweet and Blum, 2016). This probably inhibited high frequency, large magnitude, Milankovitch-scale glacio-eustatic fluctuations during Wilcox deposition. The lack of high frequency sea-level fluctuations, combined with high sediment fluxes of the large rivers, would suggest that the terminal end of fluvial drainages of the Wilcox (i.e. river mouths) remained in proximity at either the shelf margin or canyon head for extended periods of time, regularly delivering sediment to the LYCC submarine canyon slope channels and eventually to the basin floor. This connection allowed for regular, long-lived Wilcox sediment delivery to the basinal depositional sink.

Reservoir Potential in and adjacent to Submarine Canyons

Submarine canyons are important conduits for funneling sediment from continents to oceans, however, they are commonly zones of sediment bypass with their preserved fills not entirely representative of the final volume of sedimentary deposits basinward (Sweet and Blum, 2016). While many explorationists have traditionally thought of submarine canyons as being high risk and heterogenous targets for development, channel-fills contained within submarine canyons and traps set up along the margins of mud-filled canyons do constitute significant petroleum prospects.

As shown in the Mary B. Golsch No. 4 well (Fig. 4), stacked successions of higher net to gross, high-density turbidites channel fills are important architectural elements of submarine canyon fills. For example, in California alone, much of the four billion barrels of oil sequestered in the Miocene Stevens sandstone of the San Joaquin is contained within sand-rich, coarse-grained, high-density turbidites that have filled small channels within the larger container of the canyon (Webb, 1981). While intra-channel reservoir facies are present within the fill of the LYCC, observed large variations in lithofacies across relatively small distances within this system provides evidence for submarine canyons traditionally representing high risk conventional exploration targets, especially in scenarios of sparse well control and conventional seismic data (Figs. 4 and 5). However, if seismic data resolution is high enough such that individual channels are identified within the larger canyon, it may be possible that these higher order channels within the overall LYCC fill constitute viable reservoir targets.

Additionally, the stratigraphic trapping of Wilcox sandstones outside of the canyon against the margin of the younger shale-filled Yoakum Canyon have traditionally proved to be excellent hydrocarbon reservoirs comprising the Hallettsville, Good Hope, and Campbell Creek gas fields in Yoakum County, Texas (Galloway and McGilvery, 1995) and Benbow Field in Lavaca County (Johnson, 1988). This is important where structural closures are rare or absent.

Finally, the presence of the LYCC canyons within the Wilcox section of onshore Texas should have been an early sign that large submarine fan reservoirs existed downdip (Fig. 12). The Wilcox deepwater fan play was not recognized until drilling of the BAHA II well was completed in 2001 (Zarra, 2007), over 20 yr after the first publications on the Yoakum Canyon (Chuber, 1979). Large-scale canyons in proximity to Wilcox fluvial systems and large catchments draining the Laramide tectonic source terrane represents the quintessential source to sink transport system.

CONCLUSIONS

The LYCC is comprised of two ancient submarine canyons located onshore in Lavaca, Dewitt, and Gonzales counties of Texas. Integration of wireline log and seismic stratigraphic interpretations confirm the stratigraphically younger, Yoakum Canyon, is nested within, and truncates the older Lavaca Canyon, comprising a complex canyon system. Basal surfaces of the canyons, as well as laterally extensive changes in seismic facies of the canyon system are indicative of multiple stages of incision, failure and fill. Hence, we conclude this canyon system is a composite canyon system, formed by at least five separate retrogradational failure events (horizons H1–H5) of varying sizes, which separate channelized deposits of mixed sediment gravity flow depositional processes. Therefore, it is unnecessary to call upon a single, extreme event such as basin isolation and sea-level drawdown event during the PETM to generate such a stratigraphically complex canyon system or the basin floor fans that link to these canyons.

Integration of core, log, and microfaunal paleobathymetric data into the seismic stratigraphic analysis of the LYCC shows that the complex incision and fill within these canyons during Wilcox deposition must have been entirely subaqueous, dominated by sediment gravity flows. The succession of observed deep-water sedimentary structures from cored wells that tie to the HASC seismic facies interval of the Lavaca Canyon fill are consistent with models of turbidity current deposition in channel-fills and levees. Cores of the Lavaca Canyon also lack apparent paleosols or evaporites that are more commonly observed in the rock record during times of desiccation such as during the Miocene Messinian crisis in the Mediterranean Sea (Ryan, 2009). Furthermore, analysis of biostratigraphic and paleoecologic data reported for the Lola Fuhrken well, proximally located to the canyon system, suggest that throughout Wilcox Group deposition, the Lavaca and Yoakum canyons were submerged under at least 330 ft (100 m) water depth.

Results from the integration of seismic, log, and core data over the LYCC support the interpretation of a submerged shelf edge during Wilcox deposition, a period defined by only limited eustatic fluctuations and high global sea levels. Future work on roughly time equivalent canyon systems such as Chicotepec and Bejuco canyons, located along the paleo-shelf margin of the southern Gulf of Mexico, would be useful to determine if a similar set of processes formed and shaped these canyons, which new work suggests have routed sediment to submarine fans east of the Tampico-Misantla structural high (Snedden et al., 2018b). True scientific evaluation of the Paleogene Gulf of Mexico drawdown model (Rosenfeld et al., 2003; Cossey et al., 2016) requires a more rigorous testing of the evidence offered to support this hypothesis. Finally, insights from modern canyons, in parallel with our observations from this ancient canyon complex, strongly support our refined alternative model for the LYCC.

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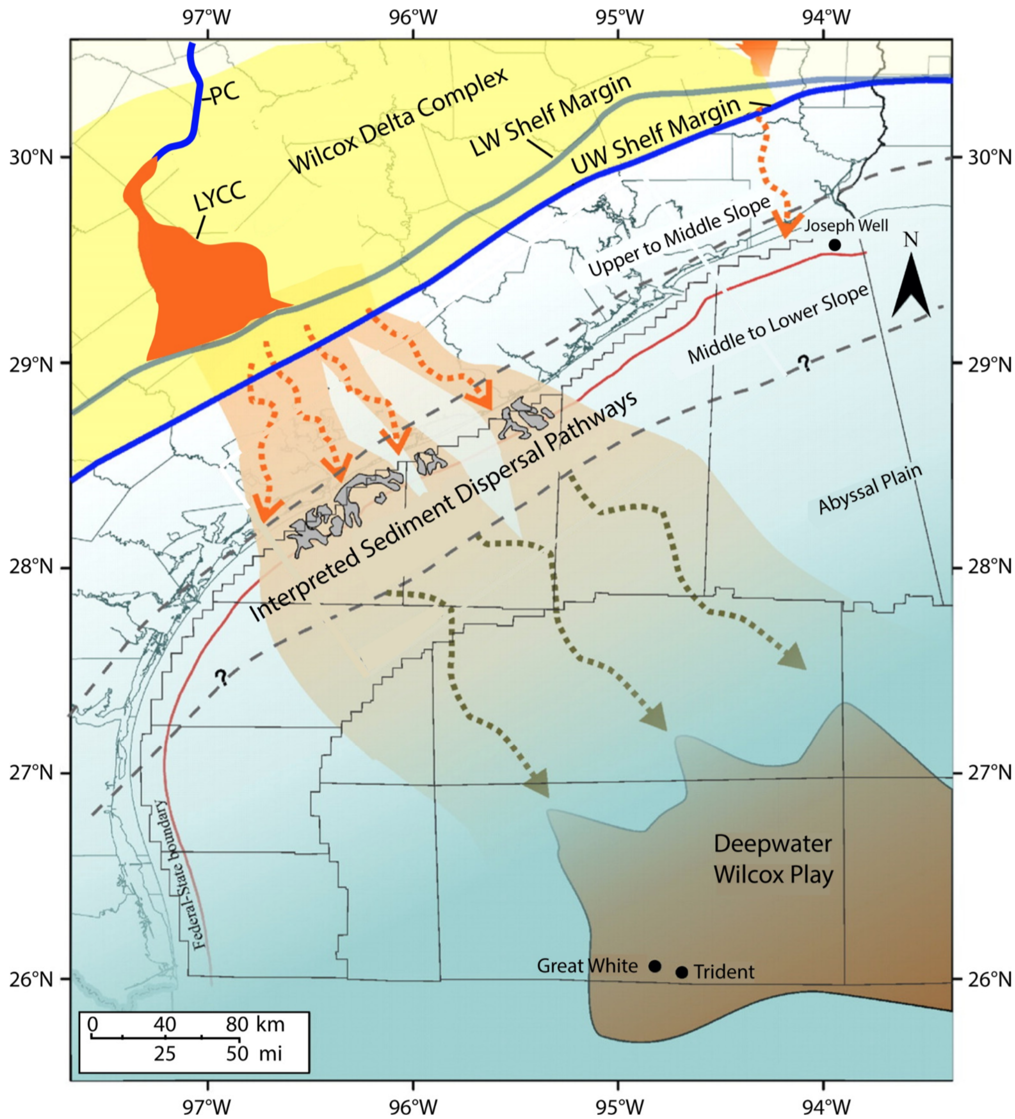

Figure 12. Interpreted source-to-sink sediment dispersal pathways linking the location of the paleo-Colorado river (PC), the Lavaca/Yoakum Canyon Complex (LYCC), and the downdip basin floor fans comprising the deepwater Wilcox play (modified after McDonnell et al., 2008). Key discovery wells are delineated.

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APPENDIX

Figure A–1. Biostratigraphic log of the Lola Fuhrken Gas Unit No. 1 in Dewitt County, Texas.