



Depositional architecture of growth-fault related wave-dominated shelf edge deltas of the Oligocene Frio Formation in Corpus Christi Bay, Texas



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ABSTRACT

Growth faults within the Frio Formation define six subbasins on the South Texas shelf and add to the complexity of the sediment dispersal along the shelf margin. These growth faults influenced sediment pathways, controlled sediment partition and provided increased accommodation for deltaic depocenters. Rollover and thickening of sediments occur on the downthrown side of growth faults with offsets of at least 150 m and up to 750 m. Growth strata are indicated by intervals that thicken landward (by several tens of meters) from anticline crests. Individual 4th-order (100–500 ky) regressive cycles expand about five to seven times across growth faults; expansion ratios as great as 10 are observed. The shelf edge is associated with the largest displacement, expansion ratios and thickness of prograding deltaic sequences. Sedimentary structures and trace-fossil associations identified in cores from Nueces, Encinal and Red Fish Bay subbasins indicate deposition on a wave-dominated deltaic shoreline. The cores exhibit highly bioturbated muddy sandstones alternating with decimeter-thick clean sandstones with hummocky cross-stratification. Alternation of fair-weather wave deposits with sandy storm beds in two successive fault zones suggests that all subbasins developed under similar conditions during growth-fault development. High sediment supply conditions favored accumulation of thicker sediments on the downthrown sides of the faults. Wave dominance of deltas on the outer shelves in the growth compartments suggest that building of the upper slope rather lowers slope margin, and decreases the likelihood of the presence of sandy deep water fans.

Correlation of about 700 well logs integrated with seismic data provided the areal distribution and relative timing of sediment filling of the growth-faulted compartments to unravel the evolution of higher-order (fourth and fifth) sequences affected by these growth faults. Core data were used to recognize depositional environments, to calibrate lithology to well logs and to characterize seismic amplitude anomalies. Within this shoreface succession the clean sandy storm beds will make attractive hydrocarbon reservoirs especially on the crest of rollover anticlines in downthrown compartments. These sandstone bodies pinch out seaward into open marine shelf mudstones and are sealed by overlying shelf mudstones deposited during transgressive episodes.

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1. Introduction

Major deltas along the Gulf Coast delivered sediment to deep water during the Tertiary (Winker, 1982; Galloway, 1989). These deltas were associated with growth-fault systems that distorted the topset foreset geometry of the prograding shelf margin, hence making it difficult to recognize the paleo-shelf edge (Winker, 1982; Edwards, 1995). Changes in eustatic sea level, regional and local

subsidence rates and sediment supply affect the distribution of sediments and sedimentary facies. Changes in facies and depositional patterns reflect regional changes in shoreline position that is also influenced by accommodation created by local syndepositional fault movement. Processes of deposition control both time and type of growth fault (Winker and Edwards, 1983). Large shelf edge deltas (e.g., Niger, Nile, and Mahakam deltas) are affected by gravity driven deformation related to shale detachment and differential loading due to deltaic sedimentation (Sestini, 1989; McClay et al., 2000; Back et al., 2006; Magbagbeola and Willis, 2007). Extensional deformation usually remains localized below the delta front and the longer the progradation the greater the associated

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extension (Rouby et al., 2011). In the Frio section faulting is believed to be related to deeply-buried ridges of low-density and high-pressured shales (Bruce, 1972). Vicksburg and Frio sediments were deposited over an existing Jackson continental slope which is primarily composed of shale (Boyd and Dyer, 1964). The burden of these sediments caused the Frio–Vicksburg Flexure where large down-to-the-coast faults rapidly expand both the Frio and Vicksburg Formation (Fig. 1).

During the past three decades information has been acquired about growth faults in the Frio Formation, mostly in the form of seismic reflection profiles (e.g., Winker and Edwards, 1983; Zeng et al., 2007; Zeng and Loucks, 2007; Ambrose et al., 2010) and well-log correlations (Bebout et al., 1975; Galloway et al., 1982; Edwards, 1986, 1995; Brown et al., 2004; Hammes et al., 2007; Bonnaffé et al., 2008). Most of the high-resolution seismic data have sparse well and core control (Zeng and Loucks, 2007). As a

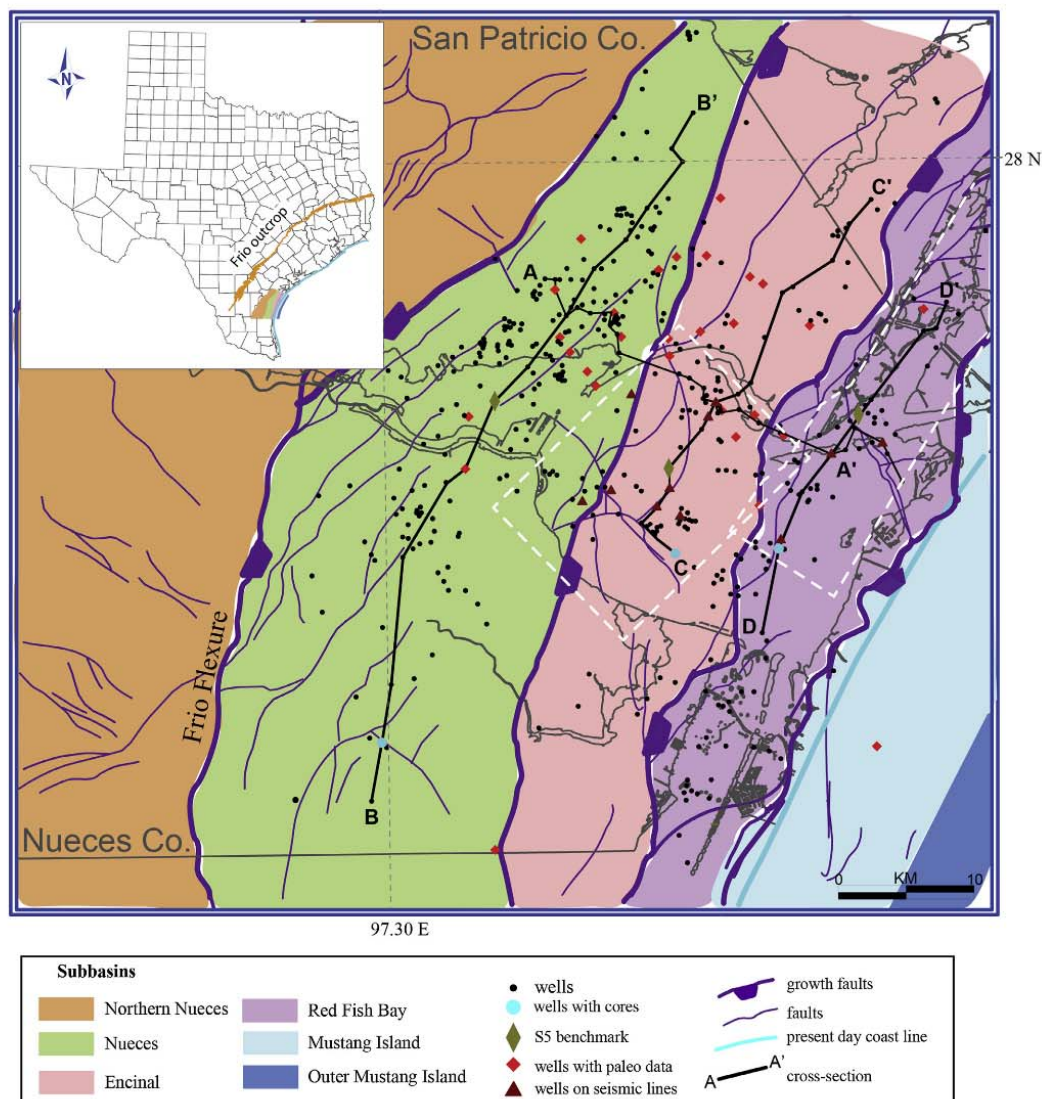


Figure 1. Location map of the Corpus Christi Bay showing the six growth-faulted Frio subbasins. More than 500 digital well logs have been used for subsurface correlation. Stratigraphic cross sections (black lines) and 3D seismic volumes (white dashed lines) are indicated.

result they are useful for predicting the fault geometry and structural history, but not the lithology or depositional environments (Winker and Edwards, 1983). For this reason there have been many publications with poor scientific method, e.g., making sequence stratigraphic conclusions directly from seismic or well data without arguing through a 'sedimentary process' step. Little work has been published on cores (Berg and Powell, 1976; Tyler and Han, 1982; Kerr and Jirik, 1990). In order to be able to identify the paleoshelf-edge, microfossils and sedimentary structures should be used (Winker, 1982). Gravity-dominated versus traction-dominated sedimentary structures indicate an important process threshold and therefore the position of the shelf break, whereas microfaunal assemblages reflect the paleo water depth.

This paper presents a study of detailed facies architecture reconstruction based on integration of cores with well logs supplemented by seismic data. The identified fourth-order sedimentary successions are interpreted to represent wave-dominated shorelines, in all likelihood wave-dominated deltas with along-strike shoreface reaches.

2. Geologic setting

The Frio Formation is a major clastic depositional unit in the Texas Gulf Coast underlain by the Lower Oligocene Vicksburg Formation and overlain by the transgressive Miocene Anahuac Shale (Galloway et al., 1982). The Frio sedimentary clastic wedge composed of interbedded sandstone and mudstone is up to 4.5 km thick and was deposited during late Oligocene over an interval of 10 million years. The average sedimentation rate was about 0.5 mm/year (Hardin and Hardin, 1961). The Frio sedimentary wedge thickens basinward from only 60 m near the outcrop to over 2745 m in the subsurface over a distance of more than 160 km (Bebout et al., 1975). The Norias delta system is the major depositional depocenter of the Frio Formation in south Texas within the Rio Grande Embayment and is separated from the northern Gulf Coast Tertiary depocenter by the San Marco Arch (Bruce, 1972). As the Norias delta prograded across the Frio shelf, sediment was supplied to the southeast (Duncan, 1983). Longshore currents transported sediment from the delta system to the adjacent Greta-Caracahua barrier/strandplain system to the east (Galloway and Morton, 1989). The extensive barrier-bar-system is analogous to modern Padre, Mustang and Matagorda Islands in the South Texas Gulf Coast (Boyd and Dyer, 1964; Wilkinson, 1975; Tyler and Ambrose, 1985; Galloway, 1986; Galloway and Cheng, 1985).

In the Corpus Christi Bay area six subbasins controlled by growth-faults developed during Oligocene (Brown et al., 2006; Brown et al., 2004; Hammes et al., 2007; Bonnaffé et al., 2008; Edwards, 2006). Structurally, the subbasins are located on the basinward downthrown hanging wall side of regional growth faults (Brown et al., 2004). Faults are concave in a basinward direction displaying a NE–SW trend (Fig. 1). Because growth faults are active during sedimentation, considerable thickening of the sedimentary units occurs on the downthrown side of the faults though the surface expression of this may have been barely noticeable. During the lower Frio deltas prograded over the pre-existing unstable shelf margin (Galloway et al., 1982) and built a thick sedimentary succession of deltaic and shoreface deposits. Wave processes reworked sediments into narrow, strike elongate barriers and strandplains. Vertically amalgamated, aggradational wave-dominated sandstone bodies formed the sedimentary succession of the lower Frio. The middle and upper Frio successions in the studied area consist of fluvial sediments in the form of channel fill, splay and flood-plain deposits (Galloway et al., 1982) also confirming the likely importance of delta supply to the lower Frio.

3. Methodology

Structural relationships in three Frio subbasins (Nueces, Encinal and Red Fish Bay) were characterized on well-log cross-sections (Fig. 2) and seismic profiles. The stratigraphic and sedimentological character of the Frio Formation was examined in detail in cores (106.5 m). Interpretation of about 700 correlated well logs (Spontaneous Potential and Resistivity) provided insights into the relative timing of the filling of the growth-faulted compartments. To correlate well-logs, the "site-specific sequence-stratigraphic section (S5) chart" approach developed by Brown et al. (2005) was used. Composite wire-line logs were built for each subbasin and captured the most complete succession within a robust biostratigraphic and sequence stratigraphic framework (Bonnaffé et al., 2008). Each S5 chart illustrates inferred depositional setting, ages, depositional sequences, and systems tracts. Wells that penetrated the entire Frio were selected except in the downdip areas, where most of the wells do not penetrate the entire Frio section. The top and base of the section were located with the aid of micropaleontology (benthic marker foraminifers) – *Heterostegina texana* and *Marginulina vaginata* are near the top of the Frio (used as a datum), and *Textularia warreni* is near the base (top of Vicksburg Formation). Biostratigraphic zones used in regional correlations indicate that the duration of individual sequences defined here is 0.5–1 m.y. (fourth order). Description of three slabbled cores was used to characterize facies and calibrate wire-line log curves (Fig. 2).

Estimating lithologies (sandstone and shale) requires log normalization and cutoff log values for each lithology. SP curves were normalized to make the maximum and minimum deflections equal in all wells by rescaling the curves. Normalization was done according to a type of SP curve (with –20 MV for sandstone–shale cutoff) and logs inspected to check that cutoff values adequately separate sandstone from shale in the log. Sandstone values between –90 and –20 MV were used to construct sandstone maps to delineate sandstone body geometry and to interpret depositional environments. In growth-faulted settings sandstone percentage maps are more meaningful to interpret depositional environments and to locate axes of sediment input as they remove the differential subsidence and emphasize depositional control on lithofacies distribution (Galloway et al., 1982; Winker and Edwards, 1983). The thickness calculation was performed with Petra™ software and involves the calculation of sandstone thickness between surfaces of interest, and the creation of a grid for the study area using the least squares method.

Serrated, blocky and bell-shaped (upward fining) log motifs are interpreted to represent heterolithic coastal plains and sandy fluvial channels. Funnel-shaped (upward coarsening) log motifs are interpreted as prograding delta-front deposits. Deltaic parasequences are separated by high frequency flooding surfaces marked by muddy sediments (right deflection on SP logs).

Correlation of about 700 well-logs was conducted using the genetic sequence approach of Galloway (1989) mainly because the shale-prone intervals formed during high-frequency basinward marine transgressions are easily identifiable on SP logs. Deltaic complexes (coarsening-upward units) are separated by thin fining-upward intervals of coastline transgression and high-frequency (fourth-order) flooding surfaces marked by muddy sediments (right deflection on SP logs) of local to subregional extent (Fig. 2). Mapping of the fourth-order cycles is accomplished through the identification of individual regressive deltaic complexes and thin transgressive units bounded by flooding surfaces within each well log. These flooding surfaces can be traced laterally to the surrounding wells and their correlation is done in 3-D.

Seismic and well-log data were combined within Landmark's Stratworks™ and Seisworks™ to map stratigraphic surfaces.

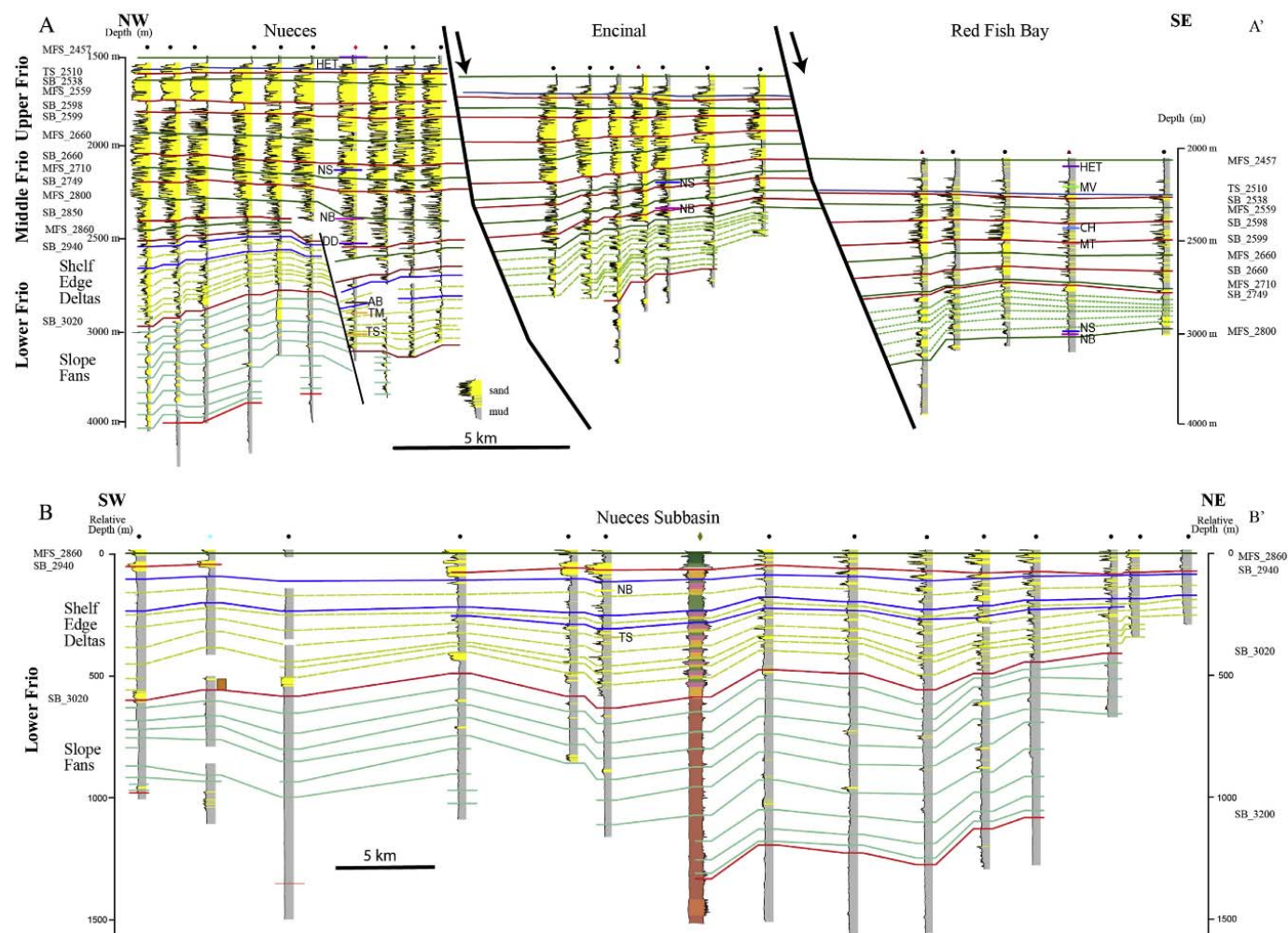


Figure 2. Stratigraphic cross-sections through Frio Formation. A. Stratigraphic dip section AA'. The stratigraphy of the Frio Formation is complicated by structural deformation associated with normal faulting. Stratigraphic strike sections in B. Nueces C. Encinal D. Red Fish Bay subbasins. All deltas are thicker in the west and become thinner towards east (examined cores are highlighted on the section; V.E. = 150). Lines of section are shown in Fig. 1.

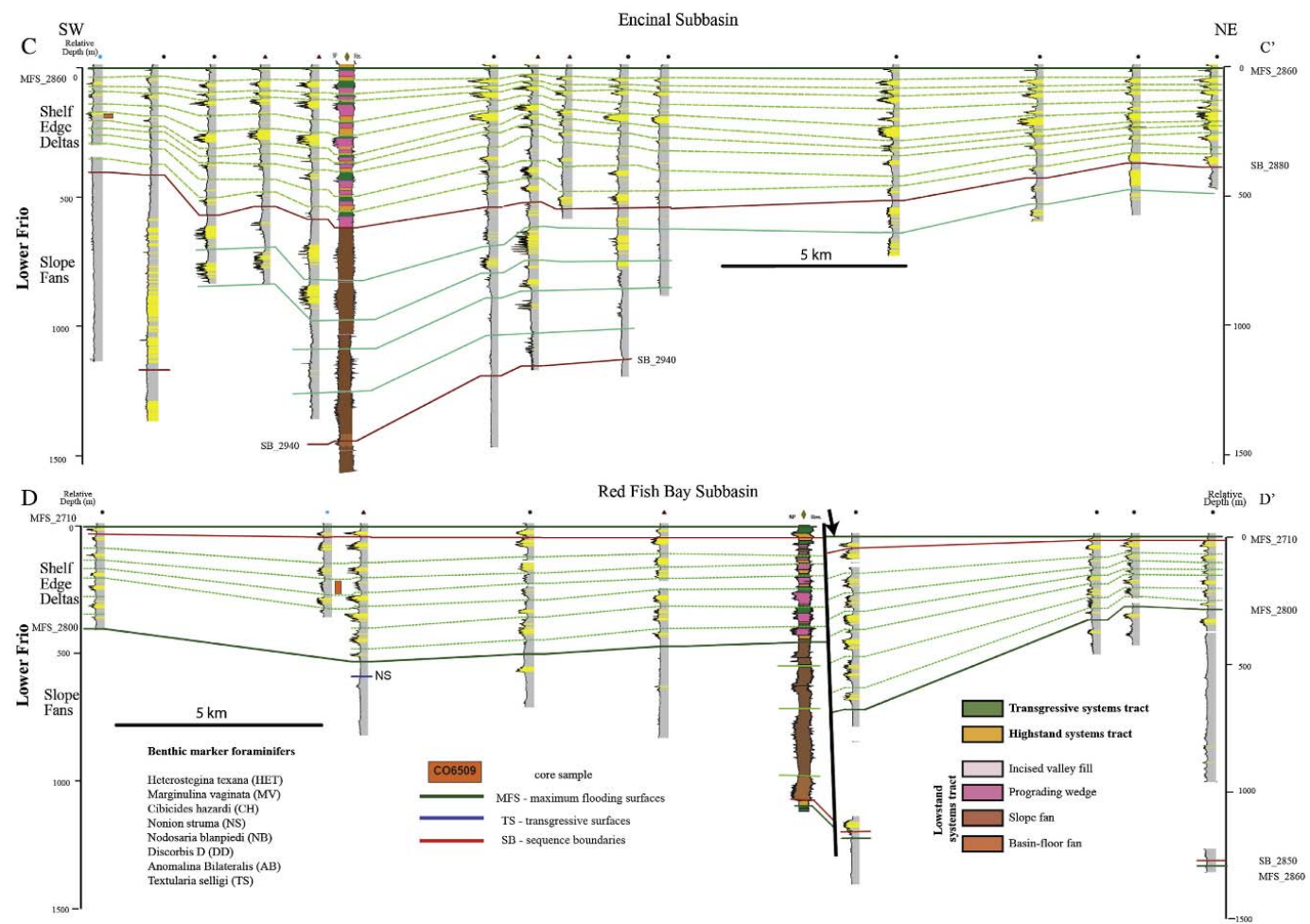


Figure 2. (continued).

Mapped stratigraphic surfaces and faults were converted to depth using Landmark's TDQ.

4. Results

4.1. Structural deformation

The stratigraphy of the Frio Formation is complicated by structural deformation associated with normal faulting (Treviño and Vendeville, 2008). Fault displacement is accommodated by movement of underlying mobile prodelta muds (shale diapirs) (Fig. 3). During shoreline regression growth faults are developed primarily by differential compaction with some associated gravity adjustments (McClay et al., 2000). Differential loading by deltaic sedimentation caused fault movement and deposition of thicker sediments in the downthrown compartments (Brown et al., 2004).

The examined seismic volume spans the distal part of Nueces, Encinal and Red Fish Bay subbasins and is characterized by continuous, subparallel reflections in the upper part (upper and middle Frio) which become inclined and increasingly offset by faults in the lower part (lower Frio). Two major faults and associated rollover anticlines on the downthrown side are the dominant structures with several antithetic and synthetic faults (Fig. 3A). All faults in the study area exhibit syndimentary growth, thickened or additional sedimentary units on their downthrown sides. Major faults have broadly basinward-concave, northeast-southwest strike trends and basinward dips toward the southeast. These faults decrease in dip with depth from nearly vertical to less than 30°. Offsets become progressively less up-section, suggesting that rates of fault movement decreased over time. Upper horizons show displacements of about 200 m, whereas lower ones can be displaced with more than 700 m (Fig. 3B). Smaller synthetic and antithetic faults that cut the rollover anticline crests have throws of less than 100 m and rarely exceed few kilometers in length. Thickness changes between seismic reflectors are influenced by structural deformation with stratal thickening on downthrown sides adjacent to faults and thinning over anticlinal crests. Growth strata are indicated by intervals that thicken landward (by several tens of meters) from anticline crests. Individual 4th-order (100–500 ky) regressive cycles expand about five to seven times across growth faults. Expansion ratios (downthrown thickness divided by upthrown thickness) as great as 10 are observed (Fig. 3B). Structure on top of the Frio Formation shows only weak reversal of dip toward the fault zone, but thickening of the Frio section on the downthrown side produced increasing northwest dip on deeper horizons.

4.2. Sandstone maps

Subsurface maps of forth-order cycles bounded by flooding surfaces illustrate several deltaic complexes in each of the three subbasins. Sandstone and sandstone-percent maps have been built to depict the depositional environments. Overall the sandstone and sandstone-percent maps display a strike elongate geometry (NNE–SSW; Figs. 4, 5 and 6). Sandstone thickness increases towards the fault with thinning laterally toward the east and seaward. Progressive basinward shift of depositional environments are thought to be best illustrated on sandstone-percent maps since they best reflect primary facies and reservoir trends particularly where abrupt thickness change results from syn-depositional structural movement. However, since both types of maps have a similar appearance the strike-oriented nature of the sandstone body is interpreted to form as a response to the process regime of the delta rather than as a

response to the geometry of the growth-fault structure which defined the depocenter. Therefore sandstone maps were considered for a better representation of the real thickness of the deposits.

Seven deltaic complexes about 100 m thick each (53 m–162 m) have been identified in the Nueces subbasin (Fig. 4). The whole deltaic wedge of the 3rd-order sequence thins away from the fault from about 580 m to 490 m in the west and from 295 m to 260 m in the east. The sandstones within each delta are about 3–4 km wide, 25–35 km long and reach a maximum thickness of about 60 m. The sandstone body geometry is complicated by the presence of a series of closely spaced (fault spacing ranges between 2 km and up to 3 km) normal (crestral) faults. The faults dip in a basinward (southeastern) direction (Fig. 4). Increased sandstone deposition occurs also on the downthrown side of the normal fault orthogonal (trends NW–SE) to the main growth fault.

The 3rd-order succession in Encinal subbasin comprises eight deltaic complexes about 80 m each (60 m–105 m) (Fig. 5). The whole deltaic wedge thins away from the fault from about 650 m to 500 m in the west and from 500 m to 400 m in the east over a distance of 3 km. The sandstone bodies are continuous along strike and are about 2–3 km wide, 20–30 km long and reach a thickness of about 40–50 m.

Seven deltaic complexes about 100 m each (90 m–136 m) have been identified in the Red Fish Bay subbasin (Fig. 6). They become increasingly sandier with time. The sandstone in the oldest delta reaches a thickness of only 30 m, whereas the youngest has 75 m of sandstone. The whole 3rd-order deltaic wedge thins away from the fault from about 645 m to 380 m in the west and from 305 m to 280 m in the east. Increased sandstone deposition occurs also on the downthrown side of the normal fault orthogonal (trends NW–SE) to the main growth fault.

4.3. Shoreline migration

Strong sediment transport parallel to the coastline by long-shore currents reduces shore normal delta progradation rate and concentrates sandstone in elongate belts along the shelf margin. There is slight evidence of landward or seaward migration of the shoreline, rather deltas steeply aggraded during regression (Fig. 7). Strong aggradation stacking is due to a combination of high subsidence rates and high sediment supply enhanced by extensive growth faulting. This implies that accommodation is continually generated and filled and the maximum regressive point of the shoreline remains roughly in the same position. Shoreline advance and retreat of successive sequences occurs across small distances of some 2–4 km (Fig. 7). There is a slightly variable shoreline behavior for individual shoreline excursions, but when combined it results in an overall steeply stacked shoreline pattern.

4.4. Facies description and interpretation

Delta deposits were examined in three cores located in Nueces, Encinal and Red Fish Bay subbasins (Figs. 8, 9 and 10) covering a total of 106.5 m. The sampled cores are located within the prograding wedges described by Brown et al. (2004). Sedimentary sections record physical and biologic sedimentary structures. The degree of bioturbation is described by the bioturbation index (BI) of Taylor and Goldring (1993); BI ranges from 0 (no bioturbation) to 6 (bioturbation has blurred primary structures). The sedimentary succession in the three cores consists of upward-coarsening parasequences that are each several meters thick and composed of associations of the following facies.

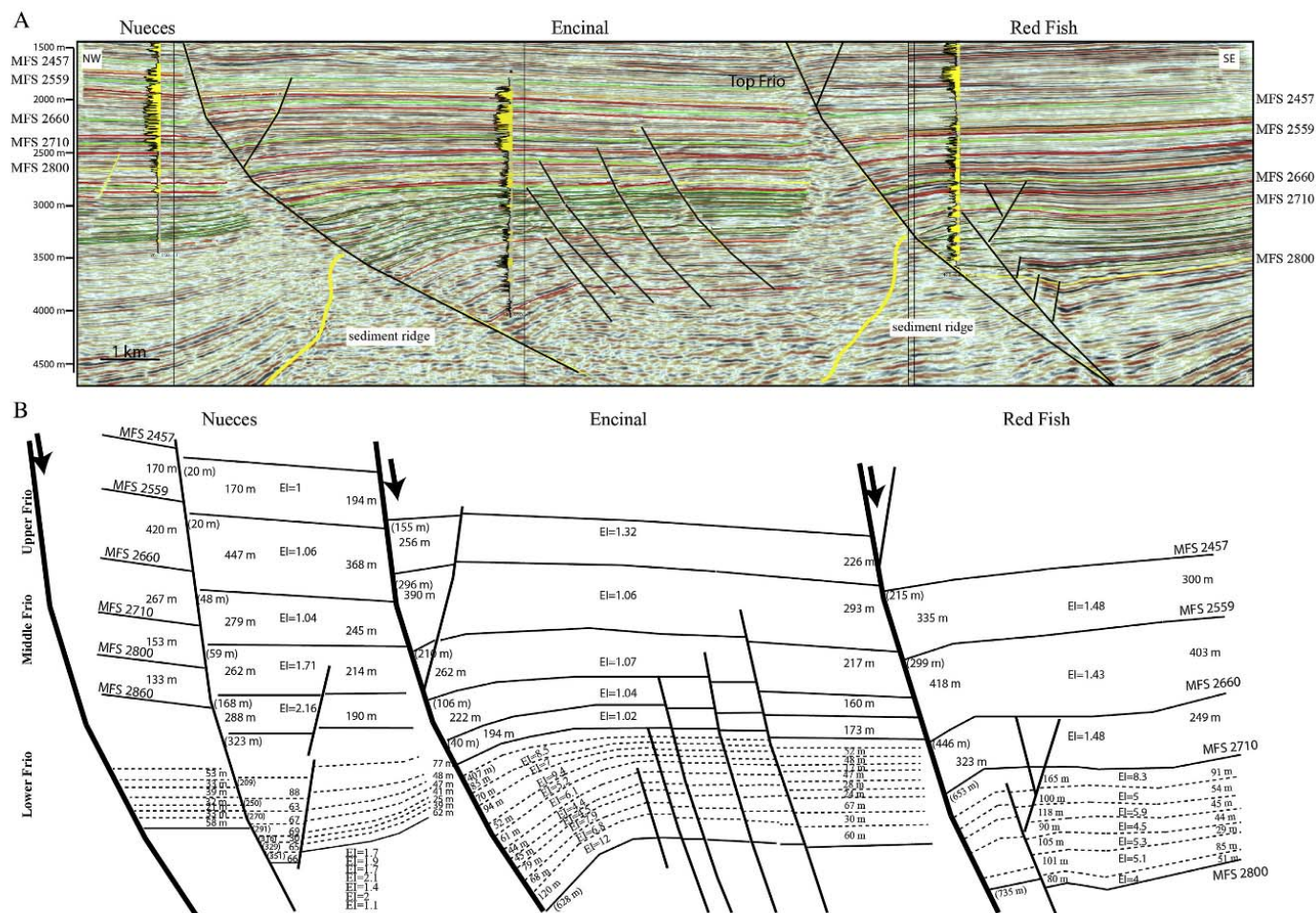


Figure 3. Seismic profile through Frio Formation in the Corpus Christi Bay. A. Interpreted oblique-dip depth-converted seismic section through Nueces, Encinal and Red Fish Bay subbasins. Two major growth faults and associated rollover anticlines on the downthrown side are the dominant structures with several antithetic and synthetic faults. Major faults have broadly basinward-concave northeast-southwest strike trends and basinward dips towards southeast. Continuous, nearly parallel reflections occur in the upper part of the seismic section. Reflectors become inclined and increasingly offset by faults in the lower part. B. Sketch diagram showing offsets and expansion indexes for individual fourth-order cycles (V.E. = 200). The 3D seismic survey does not include the synthetic fault in Nueces subbasin. Seismic data courtesy of Western Geco.

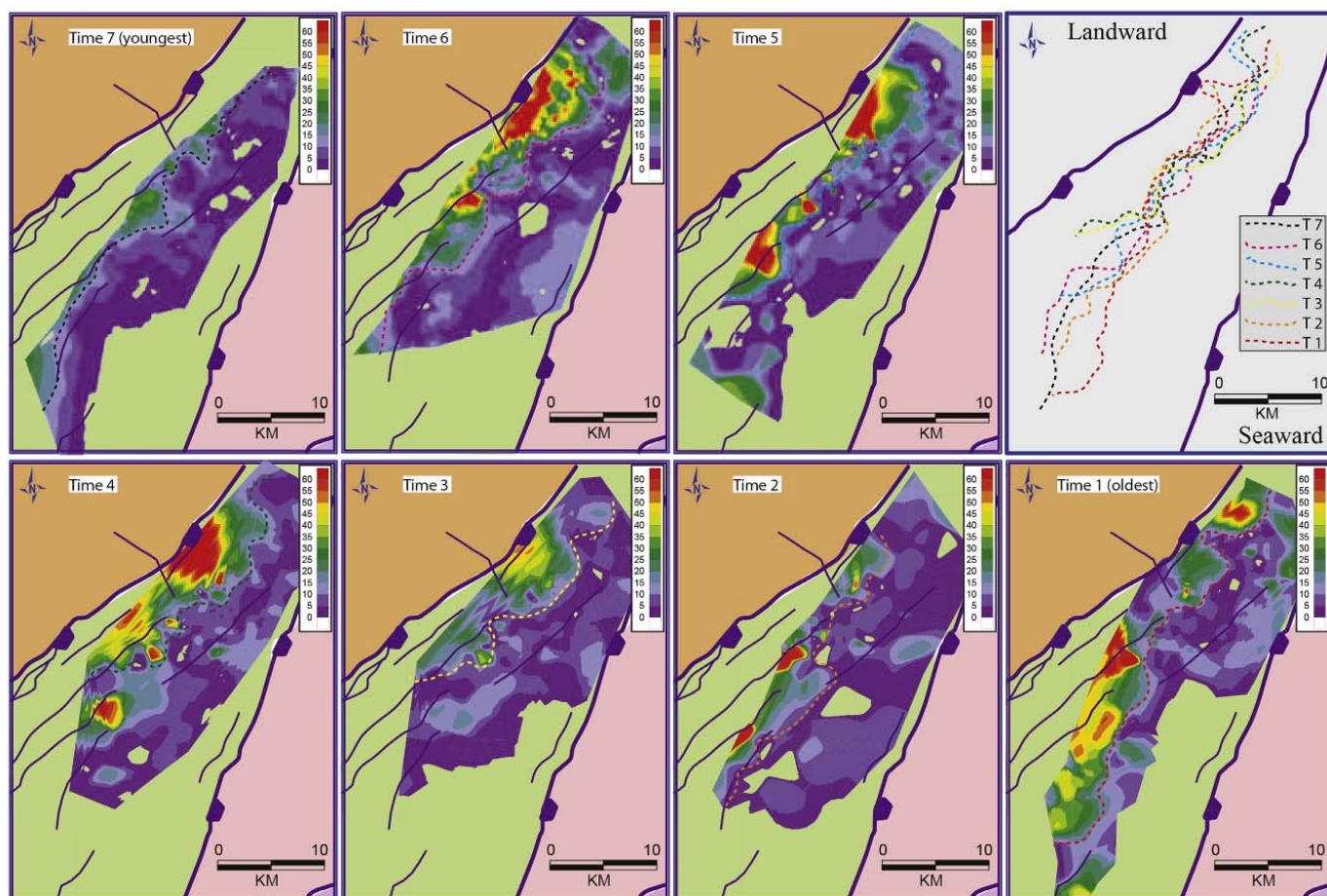


Figure 4. Sandstone maps for shelf edge deltas in Nueces subbasin. Narrow elongate sand belts are developed along the depositional strike which suggests wave dominance. The sandstone is thicker towards the fault and thins laterally toward east and seaward. The sandstone bodies are about 3–4 km wide, 25–35 km long and reach a thickness of about 50–60 m. Notice the presence of closely spaced normal faults (trend NE–SW) and a normal fault orthogonal to the main growth fault (trends NW–SE). There is slight evidence of landward or seaward migration of the shoreline; the shoreline remains roughly in the same position.

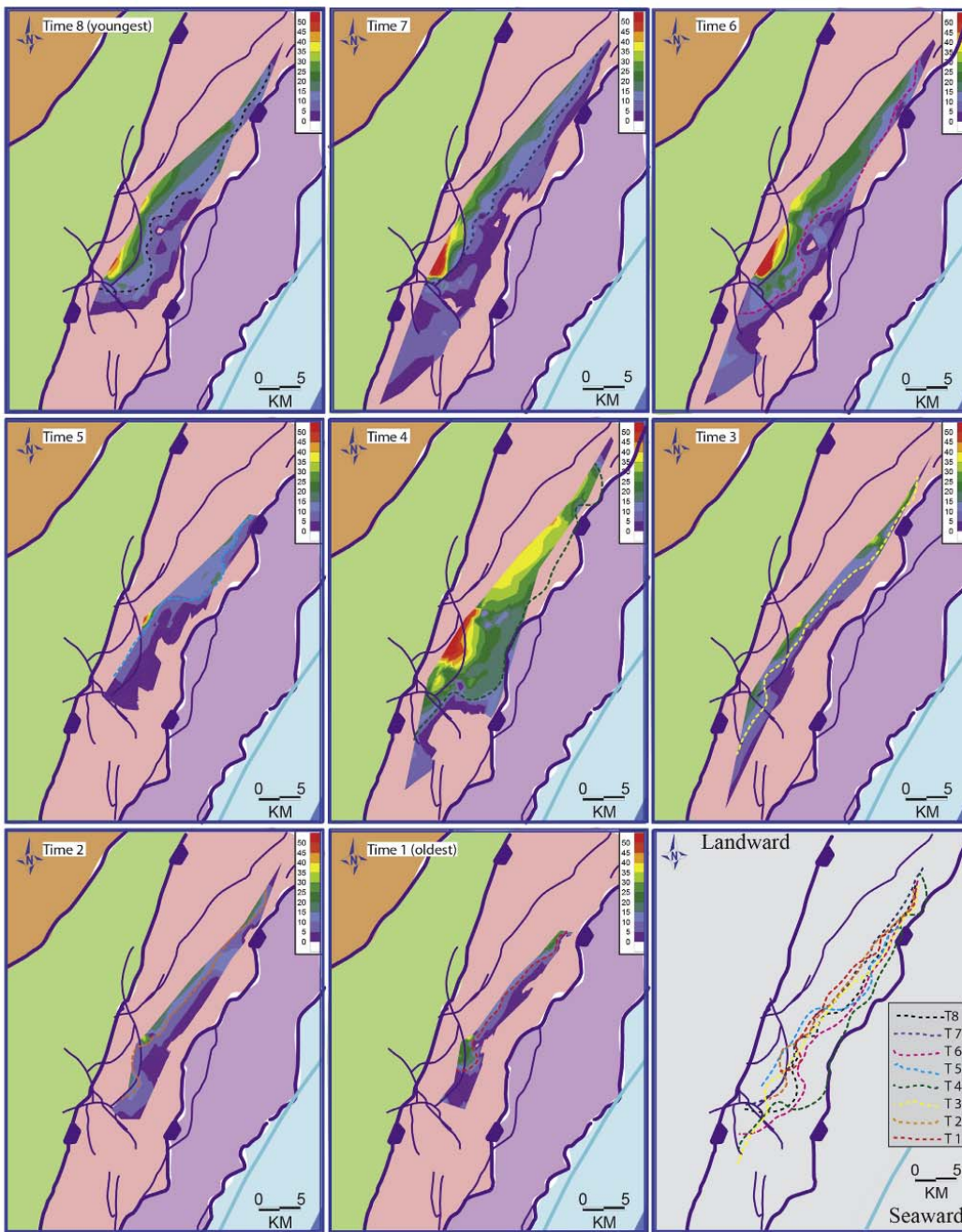


Figure 5. Sandstone maps for shelf edge deltas in Encinal subbasin. Narrow elongate sandstone belts are developed along the depositional strike which suggests wave dominance. The sandstone is thicker towards the fault and thins laterally toward east and seaward. The sandstone bodies are about 2–3 km wide, 20–30 km long and reach a thickness of about 40–50 m. There is slight evidence of landward or seaward migration of the shoreline; the shoreline remains roughly in the same position.

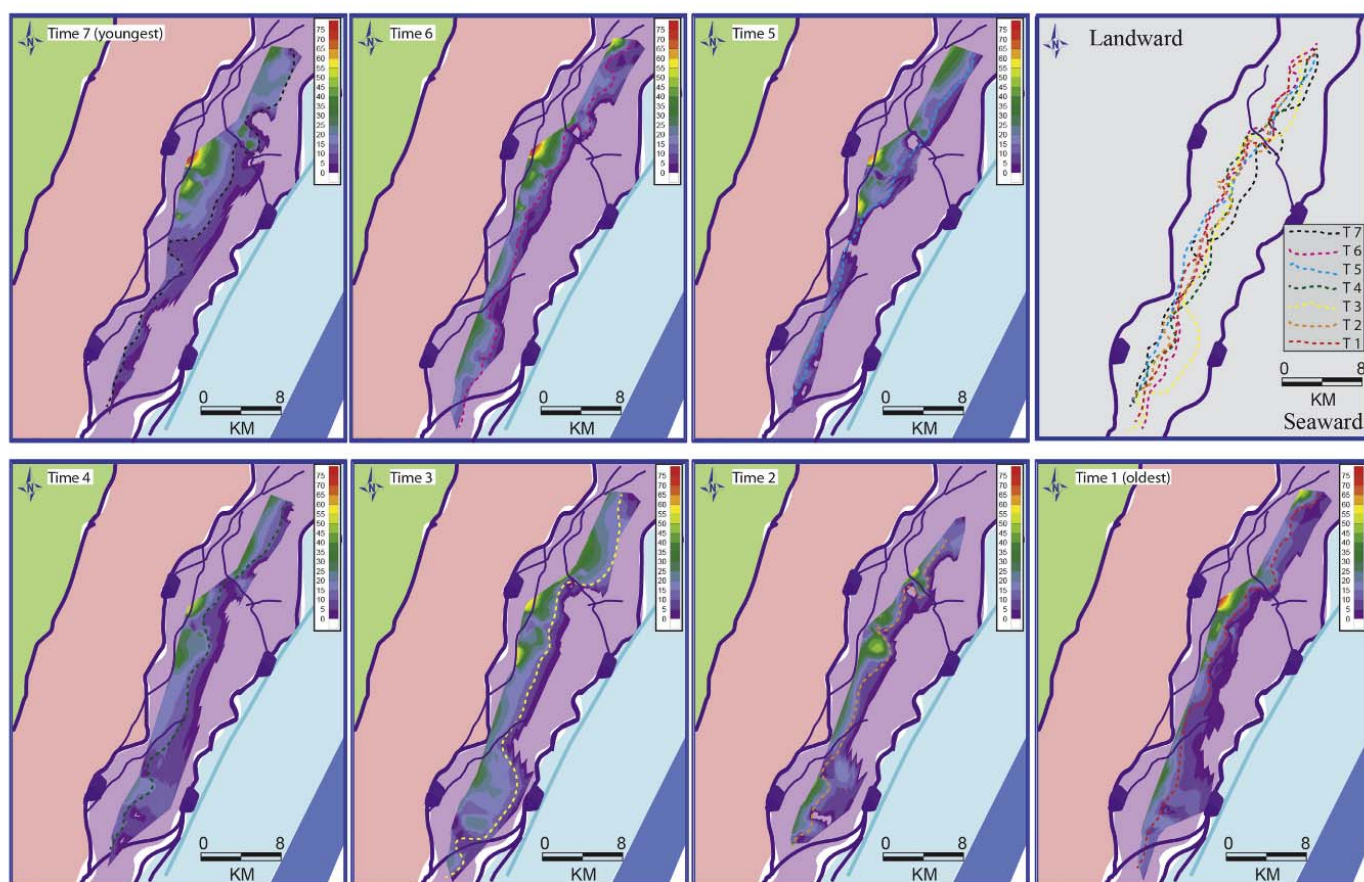


Figure 6. Sandstone maps for shelf edge deltas in Red Fish Bay subbasin. Narrow elongate sandstone belts are developed along the depositional strike suggesting wave dominance. The sandstone is thicker towards the fault and thins seaward. Sandstone bodies are about 2–3 km wide, 20–30 km long and reach a thickness of about 60–70 m. Notice the presence of a normal fault orthogonal to the main growth fault (trends NW–SE). There is slight evidence of landward or seaward migration of the shoreline; the shoreline remains roughly in the same position.

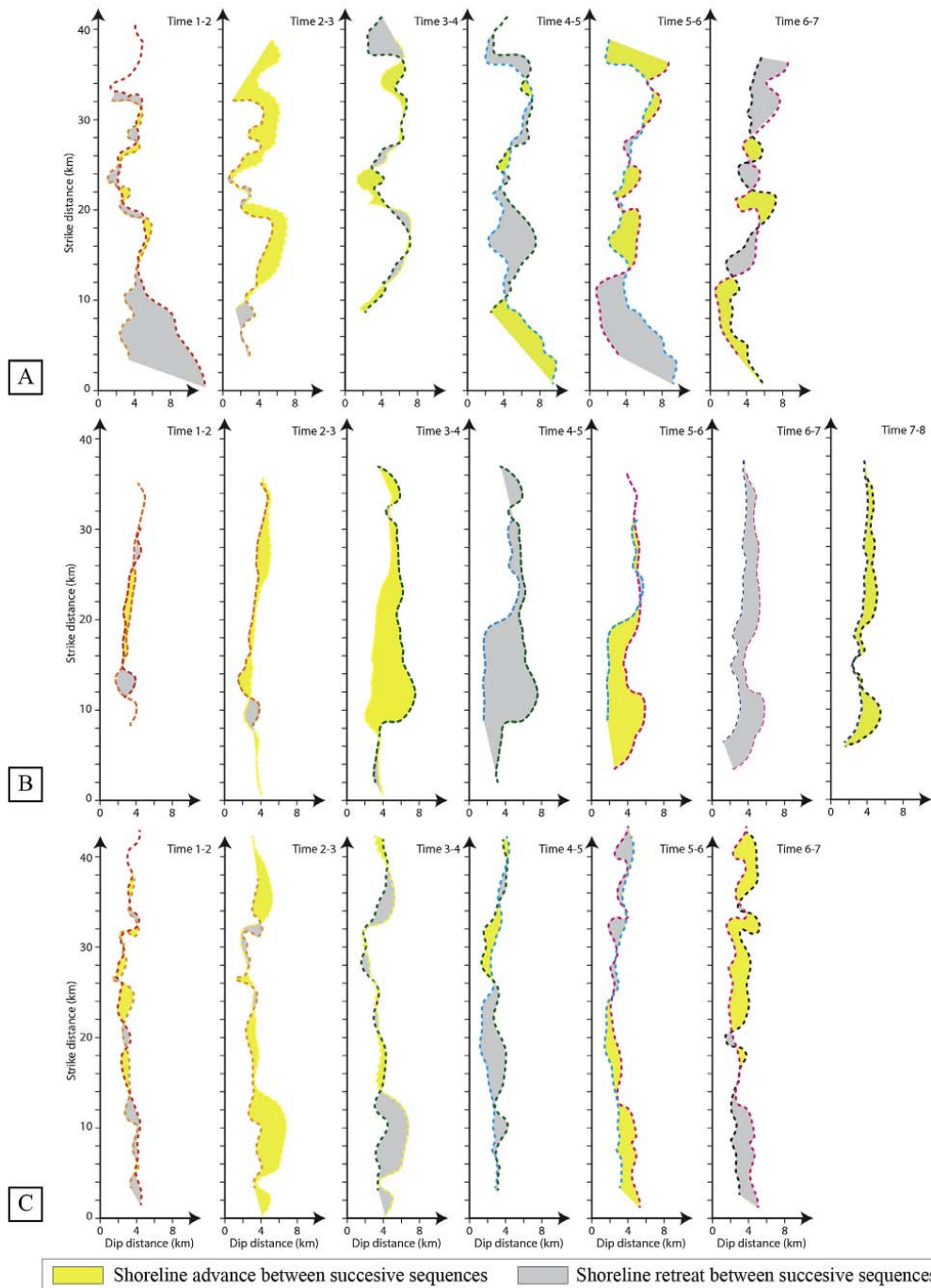


Figure 7. Shoreline position in A. Nueces B. Encinal and C. Red Fish Bay subbasins. There is slight evidence of shoreline advance or retreat; rather deltas vertically aggraded maintaining the shoreline roughly in the same position with the overall result of a "steady" shoreline and vertical stacking of successive shoreface sequences.

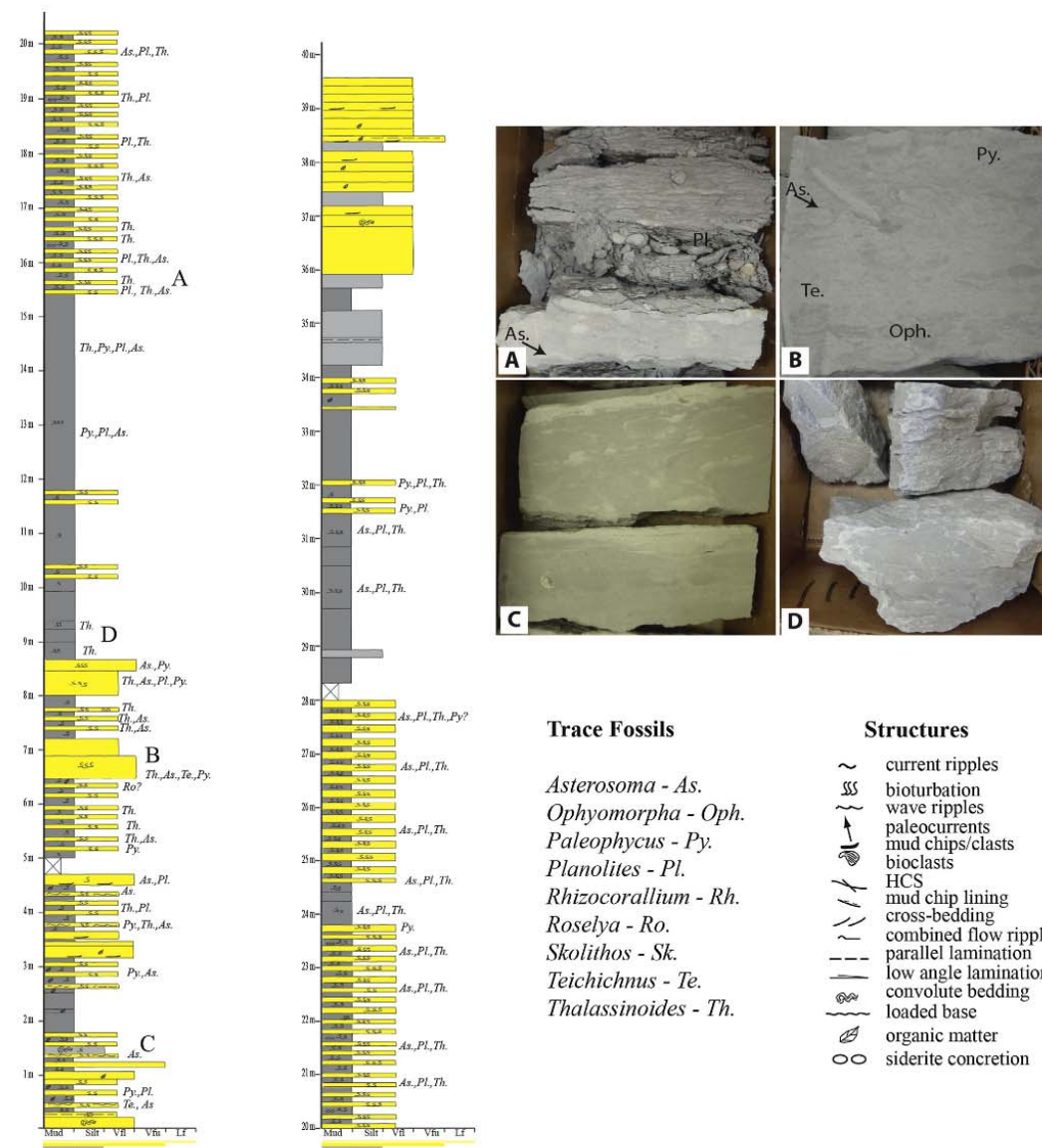


Figure 8. Lithologic column (3362 m – 3408 m) and representative core samples of lithofacies for shoreface successions in Nueces subbasin (each core sample is 7.6 cm wide). A. Facies 1 – Highly bioturbated very fine-grained muddy sandstone. The trace fossil assemblage is represented by *Thalassinoides* (Th.), *Paleophycus* (Py.), *Asterosoma* (As.), and *Planolites* (Pl.). B. Facies 2 – Highly bioturbated fine-grained sandstone with *Ophiomorpha* (Oph.), *Teichichnus* (Te.), *Paleophycus* (Py.) and *Asterosoma* (As.). C. Facies 5 – Slightly bioturbated very fine-grained sandstone with soft sediment deformations. D. Facies 7 – gray structureless mudstone.

4.4.1. Facies 1 – highly bioturbated, very fine-grained muddy sandstone

The sandstone is lower very fine to upper very fine grained, decimeter thick, moderately sorted and displays wavy parallel lamination (Figs. 8A and 9A). The trace fossil diversity is high with

assemblages reflecting *Cruziana* ichnofacies represented by *Thalassinoides*, *Asterosoma*, *Teichichnus*, *Paleophycus*, and *Planolites*. The dominant ichnogenera reflect deposit feeding or grazing trophic strategies. The intensity of bioturbation is high (BI 4). Organisms colonize the sandy substrate, but are not capable to homogenize

the sand and therefore the physical sedimentary structures are only partially preserved.

The predominance of deposit feeding and grazing behaviors, the high diversity of trace fossils and the burrowing intensity indicate that these sediments are fair-weather deposits. The presence of oscillation ripples is interpreted to represent wave reworking in an open marine upper offshore to distal lower shoreface environment.

4.4.2. Facies 2 – highly bioturbated very fine-grained sandstone

The sandstone is upper very fine grained, decimeter thick, and slightly cleaner compared to the sandstone of facies 1. The trace fossil diversity is high with assemblages reflecting *Cruziana* ichnofacies represented by *Thalassinoides*, *Asterosoma*, *Teichichnus*, *Ophiomorpha*, *Paleophycus*, and *Planolites* (Figs. 8B and 10A). The intense biogenic reworking (BI 5) commonly obscures physical sedimentary structures (bedding) although some remnant wavy parallel laminations are preserved.

The high diversity of trace fossils and the burrowing intensity is interpreted to represent deposition under fair-weather conditions. The occasional presence of oscillation ripples suggest wave reworking in open marine distal lower shoreface.

4.4.3. Facies 3 – thoroughly bioturbated very fine-grained sandstone

The sandstone is very fine-grained, centimeter-to-decimeter thick, thoroughly burrowed (BI 6) with no discernible sedimentary structures (Fig. 9C). The trace fossil diversity is low with the most common trace fossil being *Paleophycus*. Pervasive bioturbation obscures any trace of remnant physical sedimentary structure making this facies to have an overall churned fabric.

Intense bioturbation, low trace fossil diversity and position of these sandstones above sandstones of facies 2 suggest deposition in a proximal lower shoreface to distal middle shoreface environment. The thoroughly burrowed sediments imply deposition under fair weather conditions between storm events when the substrate was colonized by organisms.

4.4.4. Facies 4 – weakly bioturbated fine-grained sandstone

The sandstones have sharp bases which are overlain by a basal lag consisting of rip-up clasts and shell debris. Sandstone beds are amalgamated (decimeter thick) and appear to be massive (Figs. 9B and 10B), but sometimes low-angle parallel to sub-parallel laminations are visible. The trace fossil diversity is low with the dominant trace fossil being *Ophiomorpha*. The intensity of bioturbation is low (BI 1–2).

The presence of *Ophiomorpha* mostly towards the top of the beds represents recolonization of the substrate after storms. Amalgamated beds of parallel and low-angle cross-stratification are interpreted as hummocky cross stratification that suggests deposition in a storm-dominated distal to proximal middle shoreface where sustained wave erosion prevented mud deposition.

4.4.5. Facies 5 – deformed very fine-grained sandstone

The sandstone is very fine-grained, centimeter-to-decimeter thick, slightly bioturbated (BI 0–1) and displays soft sediment deformation such as convolute bedding (Figs. 8C and 10C). The contorted sand is intercalated with a muddy siltstone which implies sedimentary loading caused by the deposition of sand over muddy layers. Reduced burrowing intensity and the presence of small-scale soft sediment deformation suggests rapid deposition of sand during storm events along a wave-dominated delta front.

4.4.6. Facies 6 – gray calcareous highly bioturbated siltstone

The highly bioturbated (BI 5–6) siltstone is decimeter thick (20–50 cm) and cemented with calcite (Fig. 9D). The trace fossil

diversity is low with assemblages dominated by *Planolites* and *Palaephycus* (*Cruziana* ichnofacies).

The burrowing intensity indicates that these sediments are fair-weather deposits. Remnant low-angle and wavy parallel lamination suggests wave reworking in a low-energy, offshore environment. The siltstone in the distal basins has more carbonate cement may be due to the greater burial depth (approximate 3200 m) (Loucks et al., 1977).

4.4.7. Facies 7 – gray structureless mudstone

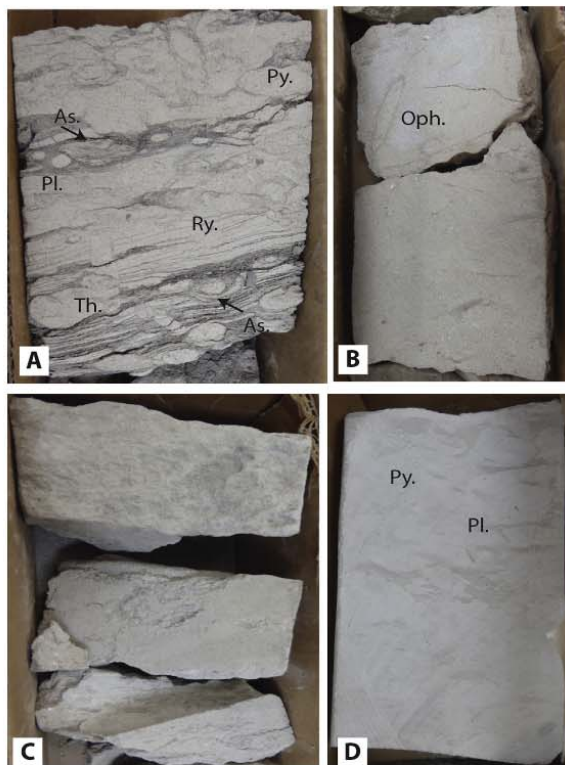
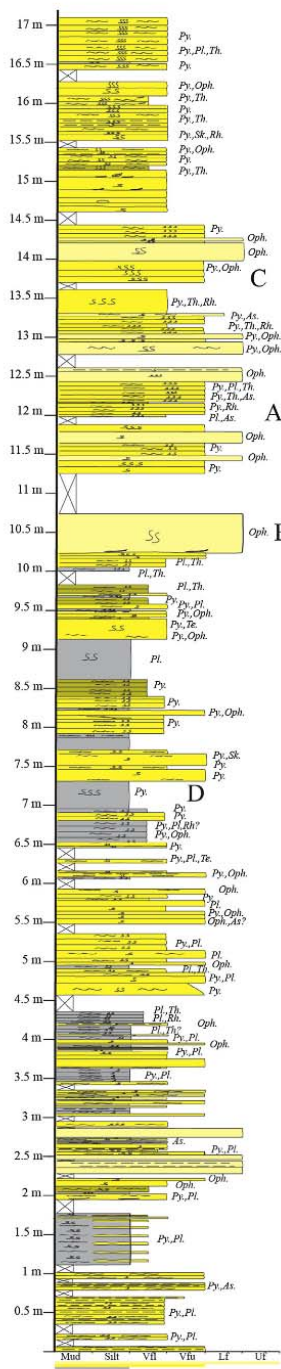
The mudstone is light gray, weakly bioturbated (BI 0–1) and structureless. The trace fossil assemblage is represented by grazing and feeding traces (*Planolites*) of the *Cruziana* ichnofacies.

Sedimentary structures are not common due to the depth which is generally below storm wave base. Sediments are interpreted to be deposited from suspension in an offshore setting (Figs. 8D and 10D).

Overall sedimentary structures and trace fossil associations indicate a transition of depositional environments from open marine upper offshore (mostly mudstone and siltstone with rare thin, intensely bioturbated sandstone) to lower shoreface (alternation of fair-weather suites with storm beds) to middle shoreface (clean amalgamated sandy storm beds) (Fig. 11). The typical vertical facies succession (Fig. 11) consists of mudstone and siltstone at the base followed by highly bioturbated very fine-grained muddy sandstone with *Cruziana* ichnofacies (fair-weather conditions) and topped by weakly bioturbated fine-grained sandstone with *Ophiomorpha* (storm-dominated conditions). These upward-coarsening successions are capped by offshore mudstone. Shoreface deposits are recognized in the subsurface by an upward-coarsening wire-line log motif (Fig. 2).

5. Discussion

Growth-faulted shelf edge deltas are difficult to recognize in the subsurface due to the distorted nature of the topset–foreset geometry of the prograding shelf margin (Winker, 1982; Edwards, 1995). However, criteria have been developed to help with the interpretation of the paleo-shelf edge (Winker, 1982; Cummings and Arnott, 2005). Regional growth faults develop on the seaward side of major depocenters during shoreline regression and are characterized by stratal thickening on the basinward (down-thrown) side where rollover (reverse drag) is exhibited (Winker and Edwards, 1983). Depositional architecture on both sides of the fault is influenced by eustatic sea-level change, regional subsidence, local subsidence caused by growth fault and rate of sediment supply (Van Heijst et al., 2002). Hanging-wall and footwall successions may be very different in thickness and may exhibit a different development of system tracts (Van Heijst et al., 2002). When a rate of sediment supply comparable with rate of subsidence is maintained through time, sediments tend to accumulate vertically or aggrade rather than prograde (Winker and Edwards, 1983). As a result the period of maximum growth corresponds to time of deposition of thick deltaic/shelf successions on the down-thrown side of the faults. The stratigraphical successions of shelf edge deltas are thick and localized within major growth fault structures and are characterized by short progradation distances (Elliott, 1989). The maximum regression point of the shelf edge Mahakam delta remained in the same geographic position during the Pliocene and Pleistocene (McClay et al., 2000). Significant aggradation was also noticed in Niger Delta (Jermannaud et al., 2010; Rouby et al., 2011). Increased subsidence along growth faults in the Champion delta, on the Brunei shelf slowed basinward progradation of the delta complex (Saller and Blake, 2012).



Thick, upward-coarsening successions (>100 m), association with large-scale growth faults, short progradation distances, abrupt facies change across the fault, evidence of storm-wave deposition (wave-ripple lamination and hummocky cross-stratification) and occurrence of soft-sediment deformation structures (convolute lamination) support the idea that the deltas described in this study are in the proximity or at the shelf-edge. These criteria have proven useful in identifying shelf margin trends in other passive margin basins (e.g., Winker and Edwards, 1983; Suter and Berryhill, 1985; Porębski and Steel, 2003; Carvajal and Steel, 2009; Dixon et al., 2012).

In the Frio subbasins growth faulting is the mechanism for providing space to thicken the section downdip (Ewing, 1986; Brown et al., 2004; Hammes et al., 2007; Bonnaffé et al., 2008; Brown et al., 2006; Edwards, 2006). The structural and depositional systems migrated with the southeast progradation of the delta as sedimentation rates kept pace with fault displacement rates. The sedimentary succession in the downthrown basin is characterized by repeated vertical stacking of shoreface sequences and pronounced increase in sediment thickness close to the fault. Most preserved deltaic strata display an aggradational architecture (Figs. 4, 5, and 6). This architecture is interpreted to result from high subsidence rates and high sediment supply combined with extensive growth faulting responsible of producing cumulatively greater accommodation through time. As a result the Lower Frio regional growth faults are inferred to have been developed in an outer shelf to upper slope setting where the sedimentary load was higher. The shelf edge is associated with the largest displacements (400 m–700 m), expansion ratios (4–12) and thicknesses of prograding deltaic sequences (Fig. 3). High subsidence rates consistent with the structural instability of the shelf edge made the earliest deltas in each subbasin thicker. As the regression proceeded subsidence rates decreased as progradation advanced up the very slightly tilted slopes. The shelf edge deltas of the younger sequences are thinner. A likely decrease of the subsidence rate through time is also reflected in the shoreline position of the earliest deltas which are slightly progradational, whereas the later deltas are slightly retrogradational (Fig. 7). Individual 4th-order (100–500 ky) cycles expand about five to seven times across growth faults. The stratigraphic succession just above the shelf edge deltas in each of the three subbasins experiences less expansion (EI = 1.3–1.5). Similar aggrading trends for the deltaic system have been observed in Niger delta (Rouby et al., 2011). The highest displacement rates as calculated in the Red Fish Bay subbasin (0.21 mm/yr – 735 m in 3.5 m.y.) are equivalent to moderate displacement rates (0.004–1 mm/yr) for normal faults in similar tectonic settings (Nicol et al., 1997, 2005), and to present-day normal faults in the Mississippi river delta (i.e., 0.1–1 mm/yr; Gagliano et al., 2003).

The development of continuous strike-oriented sandstone belts suggests a wave-dominated environment. As the shoreline advanced during deltaic progradation more sediment was deposited on the downthrown side of the fault and reworked along shore by wave processes. Shoreline sands were deposited by longshore currents coming from the southwest. A greater thickness of sandstone in the west is caused by proximity to the deltas of the ancestral Rio Grande River. Longshore sediment drift transported

sand eastward from these deltas and deposited it in elongated ridges along strike.

By examining three cores in adjacent subbasins it has been noticed that sediments deposited in two successive fault zones exhibit lithologic and faunal similarities. All three cores display shoreface deposits in upward coarsening parasequences (Figs. 8, 9 and 10). The sediments have been interpreted as wave-dominated deltaic shorelines. The studied core interval in the Red Fish Bay subbasin is part of a longer core that cuts through several wave-dominated deltas (for a detailed description of facies see Zhang, 2013). The presence of similar facies suggests that all subbasins developed under similar conditions during successive growth-fault development. Although the facies is similar, correlation across growth faults is not possible because of the progressively younger development of these subbasins (Hammes et al., 2004; Brown et al., 2004; Hammes et al., 2007). The core in the most proximal basin displays coarsening-upward packages with abundant wave structures and at the same time subtle evidence of rapid sedimentation and fresh-water input such as mudstone rip-up clasts, massive bedding and soft sediment deformation which suggest mixed river and wave influence. The presence of soft sediment deformation structures (convolute lamination) indicates abrupt deposition of sandstone or oversteepening of a wave-dominated delta front in vicinity of the shelf edge. Shelf edge deltas tend to be more wave-dominated perhaps because wave energy is high when shorelines are at the shelf margin due to unrestricted fetch and water depth (Porębski and Steel, 2003). Wave-dominated shelf edge deltas are common and long lived features on shelves in growth-faulted, extensional basins. The character of the depositional environments (wave-dominated deltas) of the Niger Delta has persisted since the Miocene (Doust and Omatsola, 1989). Growth-faulted basins trapped large amounts of sand and shale in wave-dominated deltaic systems in Baram and Champion deltas on the Brunei shelf (Saller and Blake, 2012).

Wave-dominated deltas at the shelf edge are inefficient suppliers of sediment to adjacent deep water regions, because of longshore drift of the sediment (Carvajal and Steel, 2009; Dixon et al., 2012). Wave dominance of deltas on the outer shelves in the growth compartments suggest that building of the upper slope rather lowers slope margin, and decreases the likelihood of the presence of deep water fans. None of the six Frio sub-basins developed deeper water than neritic shelf depths implying aggradation of successive deltaic shorelines rather than significant progressive progradation that would have caused the shoreline deposits of the higher levels to overlie deep water deposits of older levels.

Within a shoreface succession the clean sandy storm beds will make attractive hydrocarbon reservoirs especially on the crest of rollover anticlines in downthrown compartments. These sandstone bodies pinch out seaward into open marine shelf mudstones and are sealed by overlying shelf mudstones deposited during transgressive episodes. The vertical permeability would be good within the stacked sandstone beds (Galloway, 1986). The mud within the lower shoreface interval might buffer vertical flow in places. However, the overall lateral continuity of the clean sandstone beds will make wave-dominated deltas prolific reservoirs.

Figure 9. Lithologic column (3185.6 m – 3203.4 m) and representative core samples of lithofacies for shoreface successions in Encinal subbasin (each core sample is 7.6 cm wide). A. Facies 1 – Highly bioturbated very fine-grained muddy sandstone. The trace fossil diversity is high with assemblages reflecting Cruziana ichnofacies represented by *Thalassinoides* (Th.), *Asterosoma* (As.), *Rhizocorallium* (Ry.), *Paleophycus* (Py.), and *Planolites* (Pl.). B. Facies 4 – moderately bioturbated fine-grained sandstone with *Ophiomorpha* (Oph.). C. Facies 3 – Thoroughly bioturbated very fine-grained sandstone with no discernible sedimentary structures. D. Facies 6 – gray calcareous highly bioturbated siltstone with *Planolites* and *Paleophycus*.

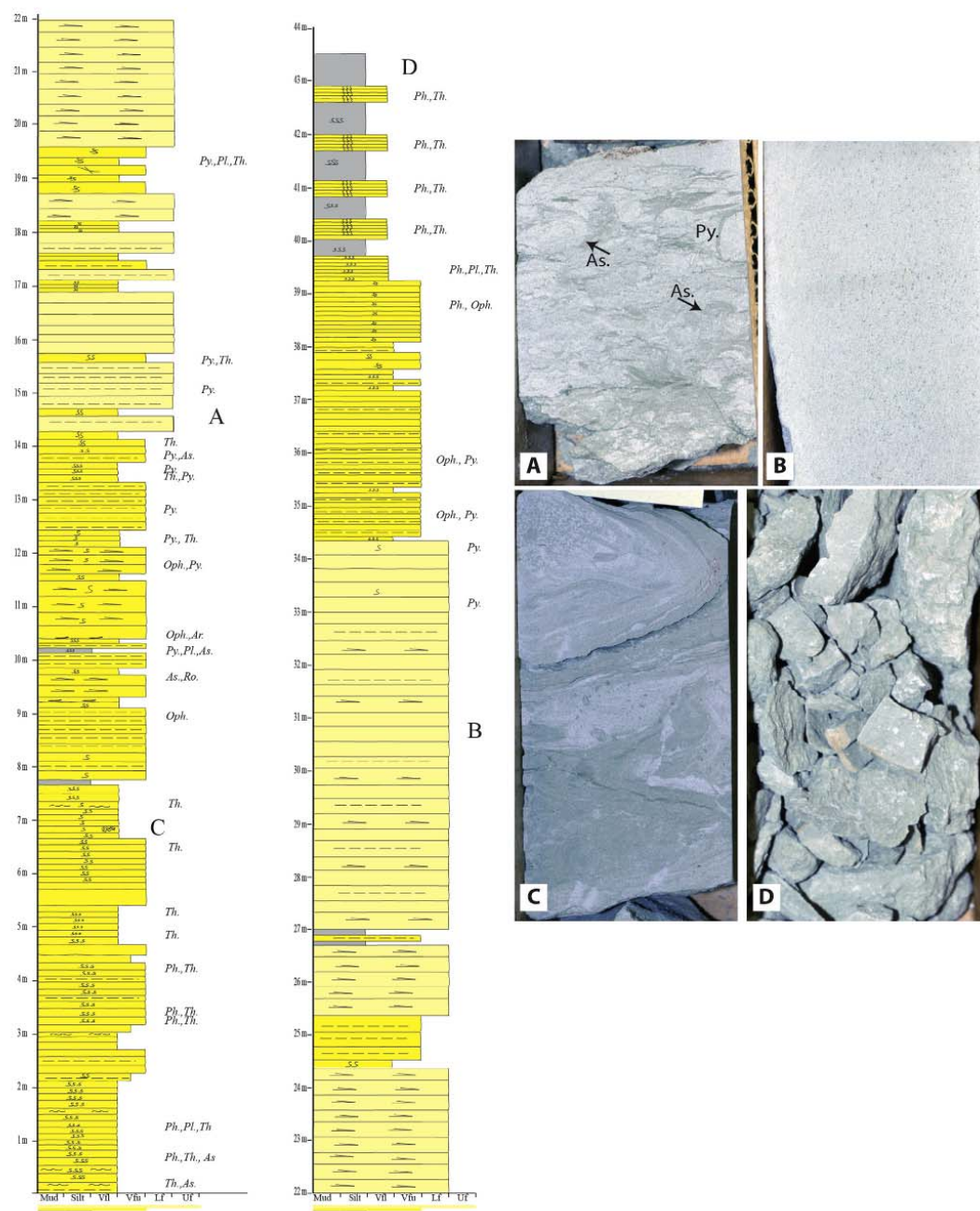


Figure 10. Lithologic column (3410.7 m – 3453.4 m) and representative core samples of lithofacies for shoreface succession in Red Fish Bay subbasin (each core sample is 7.6 cm wide). A. Facies 1 – Highly bioturbated very fine-grained muddy sandstone. The trace fossil diversity is high with assemblages reflecting Cruziana ichnofacies represented by *Thalassinoides*, *Paleophycus*, *Asterosoma* and *Planolites*. B. Facies 4 – Unbioturbated massive fine-grained sandstone. C. Facies 5 – Slightly bioturbated very fine-grained sandstone with soft sediment deformations. D. Facies 7 – gray structureless mudstone.

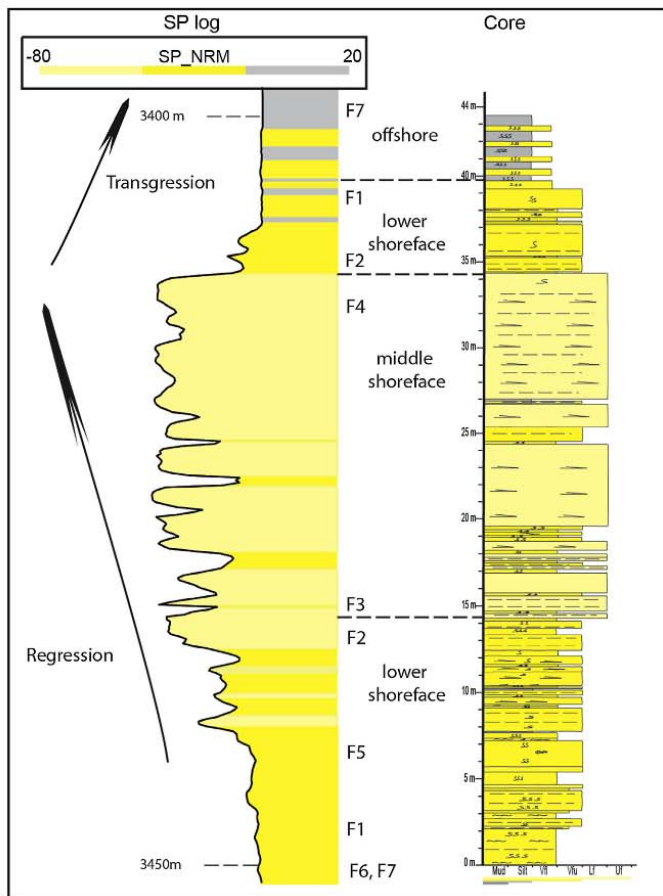


Figure 11. Core-to-log calibration Description of the core in Red Fish Bay subbasin is shown against the SP log (normalized) to illustrate typical shoreface facies succession (for details of the lithologic column see Fig. 10). The sequence begins with offshore or lower shoreface deposits (alternation of fair-weather suites with storm beds) and passes upward into middle shoreface deposits (clean amalgamated sandy storm beds). Progressive deepening of the shoreface during transgression favors accumulation of lower shoreface and offshore sediments at the top of the sequence.

6. Conclusions

The stratigraphic and sedimentological character of the Frio Formation was examined in detail in cores and interpreted from well-logs and seismic data. Multiple, vertically stacked upward-coarsening parasequences separated by thin fining-upward intervals of coastline transgression and high-frequency (fourth-order) flooding surfaces indicate a transition of depositional environments from offshore to lower and middle shoreface. The sediments were interpreted to have been deposited on a wave-dominated deltaic shoreline in the vicinity of the shelf edge. Changes in facies and depositional patterns reflected regional changes in shoreline position that can be also influenced by accommodation created by local syndepositional fault movement. Faults were accompanied by development of rollover anticlines and accumulation of growth strata on downthrown sides. Subsidence along growth faults slowed basinward progradation of the delta complexes. A balance between the rate of creation of

accommodation and rate of sediment supply generated thick, aggradational deltaic succession. There is slight evidence (small distances of some 2–4 km) of landward or seaward migration of the shoreline. The shelf edge is associated with maximum displacement, maximum expansion ratios and maximum thickness of prograding deltaic sequences. Despite the fact that cores were located in different subbasins separated by growth-faults they display lithologic and faunal similarities suggesting that all subbasins developed under similar conditions during growth-fault development. The dominance of wave processes on the outer shelves in growth-faulted depocenters suggest that building of the upper slope rather lowers slope margin, and decreases the likelihood of the presence of deep water fans.

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