Understanding growth-faulted, intraslope subbasins by applying sequence-stratigraphic principles: Examples from the south Texas Oligocene Frio Formation

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ABSTRACT

A detailed analysis of Oligocene Frio Formation intraslope, growth-faulted subbasins in the Corpus Christi, Texas, area indicates that deposition during relative lowstands of sea level was the main initiator, or trigger, of growth faulting. Lowstand depocenters on the low-gradient, upper continental slope comprising basin-floor fan facies, slope-fan systems, and prograding lowstand delta systems exerted sufficient gravity stress to trigger major sections of outer shelf and upper slope strata to fail and move basinward. The faults sole out deep in the basin, and rotation of hanging-wall blocks mobilized deep-water muds and forced the mud basinward and upward to form mud (shale) ridges that constitute the basinward flank of intraslope subbasins overlying footwall fault blocks.

Sedimentation associated with third-order relative falls of sea level produced load stress that triggered a major regional syndepositional growth-fault system. Subbasins on the downthrown side of each arcuate fault segment that constitute a regional fault system are filled during the lowstands of sea level. Consequently, genetically similar but noncontemporaneous lowstand depositional systems filled each successive growth-faulted subbasin trend. The subbasin stratigraphy becomes younger basinward because the subbasin development and fill process extended the Frio shelf edge stepwise into the Oligocene Gulf of Mexico Basin, coinciding with relative third-order sea level cycles.

The subbasins have been prolific petroleum targets for decades and are now the focus of prospecting for deep gas. Lowstand sandstones are principal reservoirs, and synsedimentary tectonics produced...
ACKNOWLEDGEMENTS

The State of Texas Advanced Resource Recovery Program supported this research. Patricia Montoya and Randy Remington, geophysical associates at the Bureau of Economic Geology, contributed to the work on this project. Mike Pawelek of IBC Petroleum, Inc., Gary Biesiedecki and Gary Miller of SABCO Oil and Gas Corporation, and Matt Hammer of Royal Exploration Company, Inc., provided industrial support. We especially extend our gratitude to WesternGeco for use of seismic data. We thank David Jennette, Susann Doenges, and David Stephens, respectively, for critical reviews, technical editing, and graphics support during manuscript preparation.

Major credit for ideas expressed in this paper are due to Robert M. Mitchum Jr., John Sangree, and John C. Van Wagoner and their former Exxon associates, including Peter R. Vail and Henry W. Posamentier, for their original pioneering research in the field of siliciclastic sequence stratigraphy. These workers all contributed significantly not only to the entire field, but also to the valid, original static sequence model.

In addition, although conceptual differences exist between our sequence ideas and inferred processes proposed earlier by William E. Galloway and his associates and students, we are deeply indebted to them for providing a regional perspective of the character and distribution of Frio depositional systems. Our differing views are based on data and concepts unavailable to them and other prior workers who concentrated on the Tertiary systems of the Texas Gulf Coast Basin. To all of the numerous earlier contributors to this vital petroleum region, we extend our professional gratitude for their research efforts. For example, early work by both Merle C. Israelsky beginning in 1935 and S.W. Loman in 1949 contributed documentation of the cyclicity and deltaic facies characterizing the Tertiary rocks of the Gulf of Mexico Basin. These two geologists, among many others, such as pioneer micropaleontologists Helen Jean Plummer (Bureau of Economic Geology), Julia A. Gardner, Alva C. Ellisor, and Ester R. Applin (former University of Texas students of J.A. Udden, director, Bureau of Economic Geology, 1915–1932), who first established most benthic foraminiferal zones, are true giants in Gulf Coast Tertiary stratigraphy and micropaleontology and therefore deserve to be credited even long after their contributions. Likewise, William L. Fisher and J.H. McGowen contributed original concepts of siliciclastic depositional systems analysis applied to the Paleocene and Eocene Wilcox Group. We thank the Geology Foundation of the John A. and Katherine G. Jackson School of Geosciences at the University of Texas at Austin for funding the color figures and the partial page charges.

INTRODUCTION

Deltaic and other associated coastal reservoirs in the study area (Figure 1) exhibit closures provided by rollover anticlines and shale ridges inferred to have been activated by sediment discharge of river systems and consequent progradation of deltaic systems. Complex extensional fault systems associated with these anticlines also provide abundant fault-trap opportunities.

Sediment composing major global delta systems was supplied by the world’s principal rivers, which, during the Tertiary, discharged along thinned continental crustal margins (e.g., Niger, Amazon, and ancestral Mississippi). Tertiary reservoirs and synsedimentary structures are the principal hydrocarbon components in the Niger Delta and northern Gulf of Mexico Basin. Many smaller fluvial systems also entered the northwestern margin of the Gulf of Mexico Basin throughout the Tertiary. Most structures associated with these deltaic systems are syndepositional, but postdepositional reactivation of faults also produced traps for younger, onshelf, deltaic, and coastal facies. The term “onshelf” is used herein instead of simply “shelf” to avoid connoting sediment deposited under actual shelf environments (i.e., below maximum storm-wave base). Wire-line log and various vintages of two-dimensional (2-D) seismic data guided most of the early exploration directed toward identifying shallow-buried shelf structures.

Long-term oil and gas production in the Gulf of Mexico Basin has significantly depleted reserves in traditional onshore and offshore fields producing from shallow to medium depth ranges (i.e., 6000–12,000 ft [2000–4000 m]) associated with regional growth-fault systems (Figures 1–3). Nonetheless, deep gas reserves exist, and because of increased demand and improved gas economics, these deep gas reserves (i.e., >12,000 ft [>4000 m]) in lowstand sandstone reservoirs are currently being explored. However, finding deep reserves requires modification of earlier conventional interpretation techniques and concepts. Robust application of sequence-stratigraphic and depositional principles is the recommended method to search for deeper gas targets.

Conventional wisdom indicates that deeper gas in growth-faulted subbasins is restricted mostly to lowstand reservoirs in syndepositional structural and/or combination traps. During a relative lowstand of sea level, sediments were deposited basinward of existing highstand shelf edges (Figures 2, 3). Lowstand incised-valley systems transported sediment to shelf margins, where the entrenched rivers eroded notches (not to be confused with major submarine canyons) in the shelf edge. Small ephemeral deltas were developed...
at the mouths of entrenched valleys. The deltas, which are shallow-water depositional systems, were incapable of prograding into deep water on the continental slope of the Gulf of Mexico Basin. Oversteepened deltaic sediments repeatedly slumped from the distal delta front and flowed down the slope surface by gravity (turbidity and debris) flow. Density-flow sediments in basin-floor depressions or channels (Figure 3) accumulated wherever the gradient of the slope surface diminished and hydraulic jumps occurred. Therefore, reservoirs in lowstand systems tracts are fundamentally different from those in highstand and transgressive systems tracts.

Lowstand depositional systems also were subjected to contemporaneous structural activity that progressively modified the configuration of slope and basin floors. Growth-fault subsidence and uplift rates of displaced shale or salt ridges resulted in highly variable subbasin accommodation rates. These variations imposed characteristic parasequence stacking patterns and areal distribution on lowstand delta systems. Likewise, density-transported sediments were distributed to areas of maximum accommodation. Consequently, potentially deeply buried sandstone reservoir facies that were deposited basinward of shelf edges lack the continuity and predictability that characterized shallower reservoirs deposited on relatively stable shelves during highstands and transgressions. Lowstand sandstone reservoir discontinuity and pinch-out potential onto syndepositional structures (Figures 2, 3) require rethinking of exploration strategies from dominantly postdepositional domal and superimposed fault closures to combination trapping by updip and lateral reservoir pinch-outs related to syndepositional structural movement.

Models of growth-faulted lowstand depositional systems were proposed more than a decade ago by Vail (1987), Sangree et al. (1990), and Mitchum et al. (1994), among others, but our study expands their models to focus on depositional processes that occurred during relative lowstands of sea level, which played a major role in initiating growth faulting and filling of resulting intraslope subbasins (Figures 2, 3). A chronostratigraphic sequence framework permits precise correlation and prediction of timing and distribution of reservoir deposition and structural development. Understanding both of these factors complements the use of three-dimensional seismic data.

**CONVENTIONAL CONCEPTS APPLIED TO PAST EXPLORATION**

In growth-faulted areas, some stratigraphers constructed correlation frameworks based on marine-condensed sections or their contained maximum flooding surfaces while ignoring or denying relative changes in sea level that induced subaerial and submarine erosion and
type 1 unconformities (Edwards, 1980; Galloway et al., 1982; Galloway 1989a; Tyler and Ambrose, 1985, among many authors; see Galloway et al., 1982, and references therein). This framework led to the view that onshelf and basinal sandstone facies that were deposited between successive marine-condensed sections are time equivalent. Several workers incorrectly consider deep-water slope-fan facies to be time equivalent to shallow-marine, onshelf, wave-dominated, deltaic facies by extending their time lines coincident with maximum flooding surfaces through many successive intraslope subbasins, some of which had not yet been created (Edwards, 1984, among other publications). Marine-condensed facies containing maximum flooding surfaces were deposited from pelagic suspension and by in-situ seafloor deposition under biogenic and authigenic processes on shelves as well as in deep water. It is correct that marine-condensed sections are operational time lines, but that does not mean that all sandstone facies deposited between successive marine-condensed sections are time equivalent.

Onshelf current- and wave-dominated deposition in shallow-marine deltas and coastal strike systems occurred by totally different processes than those of slope fans and basin-floor fans. Furthermore, onshelf and offshelf depositional episodes are not only depositionally and environmentally different, but they were deposited during temporally discrete time intervals. To consider them time equivalent leads to serious miscorrelations.

The fact that similar microfauna and microflora characterize marine-condensed sections, whether deposited in shallow or deep water, further encourages some workers to infer that all sediments between the same marine-condensed sections are time equivalent (Edwards, 1984). This idea pervaded stratigraphy for decades, when paleontologists inferred that thick coastal

Figure 2. Highly schematic block diagram illustrating depositional systems tracts operative during relative lowstands of sea level, middle and late Oligocene epoch. Distribution of fluvial systems and coastal systems are modified after Galloway et al. (1982) and Galloway (1986). Sketch infers paleogeography during the slope-fan deposition soon after activation of growth-fault movement. The shelf is subaerially exposed, and sediment is bypassing the shelf through incised river systems. See legend on Figure 3 for symbol definitions.
deltaic and fluvial systems existing stratigraphically between marine-condensed sections were deposited under similar neritic environments because their paleobathymetric maps used the abundant neritic fossils in deeper water bounding marine-condensed sections. Their maps were valid for water depths during maximum flooding but not for the intervening deltaic deposition.

More recently (Brown et al., 2003a), research has begun to address the repetitive and dynamic stratigraphic history of growth-faulted subbasins and their inferred stages of structural instability and depositional and erosional episodes. For decades, many published papers, principally about the Gulf of Mexico Basin, have described and offered interpretations and models addressing the geologic history of unstable continental margins that are characterized by syndepositional, down-to-the-coast normal faults (i.e., Galloway et al., 1982; Winker and Edwards, 1983; Galloway, 1989b; Ewing, 2002). None of the studies of growth-faulted continental margins include results based on a thorough test of the applicability of sequence-stratigraphic processes to provide a model that addresses all seismic and wire-line-log observations. Such a test is the principal goal of the research discussed herein.

NEW APPROACHES TO UNDERSTAND DEVELOPMENT OF GROWTH-FAULTED SUBBASINS

Sequence-Stratigraphic Methods

A valuable key stratigraphic approach or tool that evolved from our studies (Brown et al., 2003b) is a composite wire-line log that places the lithostratigraphy of a subbasin into a chronostratigraphic sequence framework. The tool, named a “site-specific sequence-stratigraphic section (S5) benchmark chart” (Figure 4), is a stratigraphic product for summarizing all available sedimentary-and time-related information into a single, integrated display. For example, systems tracts, stratigraphic surfaces, relative sea level cycles, petrophysics, and age data can be placed in chronostratigraphic context and correlated basinwide. S5 benchmark charts are based on composites of wire-line-log sections of several key wells spliced to avoid faulted-out sections and to display the most complete stratigraphic succession. Consequently, the S5 benchmark chart captures the record of maximum depositional history and cycles recorded in the subbasin strata. For example, sequence-bounding unconformities and parasequence maximum flooding surfaces of various frequencies are chronostratigraphic surfaces. Except for diachronous ravinement surfaces at the base of transgressive systems tracts, systems tracts are bounded by chronostratigraphic unconformities and maximum flooding surfaces. Internally, systems tracts comprise diachronous lithofacies successions. Furthermore, systems tracts link depositional processes and systems to relative changes of sea level.

A sequence model by Vail (1987) and Mitchum et al. (1994) clearly illustrates sequence-stratigraphic architecture of growth-faulted successions and the relationship to initiation and evolution of faulting. We fully agree with the static architectural model of Mitchum et al. (1994) but have added a dynamic scenario (Figures 3, 5) to it.

Application of Sequence Concepts and Ideas

Serving as examples, the Corpus Christi Bay and Red Fish Bay subbasins (Figure 1, subbasins 3A, 3B, and 4, respectively) in the greater Corpus Christi Bay area, Texas, are genetically similar to many growth-faulted subbasins that were filled during half a dozen second-order (∼10-m.y.) Tertiary cycles along the northwestern margin of the Gulf of Mexico Basin. We undertook detailed studies of the subbasins in Figure 1 to document their sequential (cyclic) erosional, depositional, and tectonic history to create a dynamic model that can be applied elsewhere in Tertiary strata of the Gulf of Mexico Basin and in other basins worldwide (Figures 3, 5). Our studies indicate that analyzed subbasins were filled during third-order lowstand depositional events of the Oligocene Frio Formation, a major, petroleum-producing lithostratigraphic unit along the Texas and Louisiana coasts. Each subbasin was the focus of lowstand deposition, serving as a depocenter during one third-order, sparsely fourth-order (Treviño et al., 2003), relative lowstand of sea level. Slope systems compose most of the sedimentary volume of each depocenter (Figures 6–9).

Structurally, the subbasins are located on the basinward, downthrown, hanging-wall side of regional growth-fault systems that, in plan view, comprise many typically connected and aligned, basinward-concave (arcuate) fault segments (Figures 1, 2), which are collectively called “flexures.” Evidence suggests that fault timing and approximate age of specific sedimentary fill are similar in the hanging-wall blocks of each regional fault system. Consequently, the factor(s) activating faults is (are) assumed to have existed simultaneously for tens of miles along the Oligocene shelf margin. Seismic
data (Figures 6, 10) document arcuate fault segments on the basinward flank of a shale ridge (salt ridges in other areas) mobilized during fault subsidence of an older, landward, growth-faulted intraslope subbasin.

**Chronostratigraphic Correlation**

Tracing seismic reflections, as proposed by Vail et al. (1977), best carries out chronostratigraphic correlation. Except for major erosional unconformities and secondary impedance boundaries (e.g., multiples, fluid interfaces, and diagenetic horizons), reflections represent impedance contrasts that mark the change above and below condensed shale drapes at tops of parasequences or parasequence sets. Generally, these widespread and thin shale beds parallel stratal surfaces and may persist laterally through facies changes.

Correlation of seismic reflections generally provides greater precision than correlation of microfossils. First or last occurrences of taxa marking the boundaries of a biozone are sparsely found at stratigraphic positions where the fossil-designated marker can be applied to a traceable log or seismic event, and suppression of biozone boundaries by high sedimentation rates locally introduces significant limitations in establishing valid chronostratigraphic faunal zone boundaries. When reflections are calibrated with conformable surfaces on wire-line logs, accurate tracing of the surfaces in a single sequence or systems tract using wire-line logs is another means of chronostratigraphic correlation.

Seismic reflections from onshelf strata are relatively parallel and continuous, reflecting the shallow-marine, laterally continuous coastal strata. The high-continuity seismic reflections and equivalent wire-line-log correlations exhibited by onshelf strata are commonly referred to as “railroad tracks.” The only major onshelf discontinuities are lowstand incised valleys that eroded into highstand systems during falling relative sea level and display orders-of-magnitude-deeper erosion than component distributary or other highstand-aggradational

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**Figure 3.** Diagrammatic dip cross section showing formation of successive growth-faulted subbasins. Note that each subbasin is filled with genetically similar but diachronous depositional systems. Note: this figure’s legend also applies to Figures 2, 4, 5, 7, 8, 12, and 14. Based on Vail (1987) and Mitchum et al. (1994). Note that 3 and 4 equal third- and fourth-order sequence events throughout this report.
fluvial-channel fills deposited during relative sea level rise (i.e., transgression or highstand) (Van Wagoner et al., 1990; personal observation, senior author).

In contrast, lowstand gravity-flow facies are highly discontinuous in a subbasin because they typically are transported into areas of irregular seafloor topography. Consequently, correlation of individual basin-floor fans or slope fans is highly challenging (Figures 7–9). Basin-floor fans may rest on the same unconformity and yet not represent contemporaneous deposition.

Sandstones in slope fans are the most discontinuous systems in a subbasin because of autocyclic shifting of depositional sites. Proximal parts of slope fans are typically thin but thicken toward the axes of basins, where the fans may undergo compaction and tend to amalgamate into very thick, highly contorted, sandstone bodies comprising the basinward parts of several high-frequency fan lobes. Continuity and, hence, approximate correlation of sandy facies in individual fans is poor, but general correlation of sand-rich facies bundles is fair in dip sections (Figures 6, 7). In strike profile (Figure 8), the fans exhibit lenticular geometry with abrupt facies terminations, making any correlation questionable. In dip sections, some workers incorrectly correlate proximal, updip-fan sandstones with deeper sandstone units by equating shallower sandstones with deeper ones simply in the order of downward well penetration or occurrence (Figure 9). This practice results in miscorrelations because a single, thick, deep, basinal, amalgamated sandstone package may be equivalent to several individual, thin, updip, fan sandstones (Figure 9). Sand-prone packages or zones may be delineated and correlated, but the individual sandstones in the packages display neither continuity nor time equivalence.

**Stages in Development of Growth-Faulted Subbasins**

Intraslope subbasin development history can be divided into several genetic stages (Figure 5). We infer that the stages were synchronized with relative cycles of sea level, during which depositional systems and systems tracts were deposited. Sequences are the products of the
Figure 4. S\textsuperscript{5} benchmark chart for Encinal Channel subbasin 3A, Corpus Christi Bay, Texas. Composite log exhibits color-coded sequence boundaries, flooding surfaces, and systems tracts, among other stratigraphic data. Type 1 unconformities and flooding surfaces constitute chronostratigraphic surfaces that may be used to construct a time-stratigraphic framework for the subbasin. The 27.49-Ma unconformity represents a major relative fall of sea level (Hackberry age of Curtis and Echols, 1985) accompanied by fluvial entrenchment and submarine canyon erosion. Compare with Figures 12 and 14.
Figure 5. Inferred stages in the tectonic and depositional history of Frio intraslope subbasins along the basinward side of a regional growth-fault system, middle and lower Texas Coast. Stages 1–7 are described in the text. Red arrows indicate change in relative sea level.
interplay of sediment supply, erosion, gravity tectonics, relative cycles of sea level, and changing accommodation rates. Process stages were repetitive, and we propose that they were driven principally by third-order (~1–2 m.y.) composite eustatic sea level cycles (Van Wagoner et al., 1990) that successively produced and filled resulting subbasins. However, as our studies in subbasins 4 and 5 (Figure 1) suggest, fourth-order sequences can also initiate these processes (Treviño et al., 2003; Hammes et al., in press).

Stage 1
During late relative sea level highstand, deltaic depositional systems prograded across the continental shelf to, or near, the shelf edge (Figure 5A). The low-gradient, highstand fluvial systems stored the sand-rich coarser fraction of their sediment load in channel fill and point bars. The relatively muddy sediment load of highstand deltaic depositional systems initially accumulated on the upper slope. Oversteepening of the muddy delta-front facies resulted in slumping of the upper slope and redeposition on the lower slope.

Stage 2
During a later relative lowstand of sea level, lowstand incised-valley systems transported their entire sediment loads (including coarser stored component) to shelf margins, where these entrenched rivers eroded notches in their respective shelf edges (Figure 5B). Small ephemeral deltas developed at the mouths of entrenched valleys. Shelf-edge deltas were shallow-water lowstand depositional systems that were incapable of prograding into deeper water on the continental slope. Oversteepened deltaic sediments slumped from the distal delta front and flowed down the slope surface by gravity flow. Density-flow sediments stacked in depocenters to form basin-floor fans (Figure 5B).

Stage 3
Lowstand deposition continued on the continental slope while the rate of relative fall of sea level decreased (Figure 5D, E). This deposition continued until leveed slope channels constructed aggradational slope fans that onlapped the upper slope and downlapped the type 1 surface or any basin-floor fan. Continued deposition
Figure 7. Dip-aligned wire-line-log sequence-stratigraphic cross section AA’, Red Fish Bay subbasin. Individual high-frequency deltaic systems (composite sequences of Mitchum et al., 1994), compose this third-order Frio deltaic system (sequence 4 of Figure 1). Sandstone content in one of the high-frequency deltaic systems is displayed in Figure 11. Faults are based on 3-D seismic and well-log analyses. See Figure 3 for legend.
Figure 8. Strike-aligned wire-line-log sequence stratigraphic cross section BB', Red Fish Bay subbasin, exhibits lateral relationships among lowstand leveed slope fans, and deltaic systems (sequence 4, Figure 1) were deposited by autocyclically shifting slope channels. See Figure 3 for legend.
of thick slope fans created substantial depocenters (Figures 2, 5E) basinward of entrenched river mouths. Several fourth- and fifth-order fans typically composed a third-order slope fan (Figures 7, 8).

In dip profile, slope fans are typically lenticular to wedge shaped, but strike sections exhibit mounded seismic geometry. The geologic record shows that major blocks of outer shelf and upper slope have failed and shifted basinward, producing a major evacuation embayment in the shelf margin. An example is the Hackberry embayment of southeastern Texas and southwestern Louisiana (Halbouty and Barber, 1961; Ewing and Reed, 1984). The slump-generated embayment occurred during a relative fall in sea level at about 27.49 Ma (Figure 4). Rapid subaerial exposure of about 600 ft (200 m) of outer shelf and upper slope eliminated submerged buoyancy support (per Archimedes’ principle). We agree with Winker and Edwards (1983) that de-watering of coastal aquifers along the failure zone perhaps lubricated the rupture zone, exacerbating the basinward slide of the large block. We do not, however, invoke this process of slumping to explain most lowstand systems tracts.

Figure 9. Schematic dip representation of amalgamation of high-frequency, autocyclic slope fans (subbasin 2, Figure 1) along the axis of upper Nueces Bay faulted intraslope subbasin. Incorrect correlations of sands are illustrated in red. Correct correlation of sandstones deposited during higher order cycles is illustrated in green (abandonment surfaces), which meld into several fourth-order slope fans. Attempts to correlate each proximal slope-fan sandstone unit with a single amalgamated axial basinal slope fan (e.g., SS1 proximal to SS1 axial) lead to major miscorrelations. Slope fans in strike section (see Figure 8) are discontinuous and make correlation highly questionable.

Stage 4
The occurrence of major lowstand depocenters basinward of arcuate growth-fault segments indicates that stress created by the intraslope depocenters overloaded the previously deposited unstable, mud-rich slopes. Eventually, the loading stress produced failure of large sections of the outer shelf and upper slope that slowly slipped downward along curved (fault) failure surfaces (Figure 5D). Dip of fault surfaces eventually flattened downward to produce rotational movement of the hanging-wall block (Figure 3). Slope-fan deposition continued to displace and mobilize the underlying, high, pore-pressured muds, thus rotating the more cohesive hanging-wall block. Resulting greater accommodation rates (Figure 5D) near the growth fault accommodated deposition of thicker proximal facies. Eventually, subsidence-generated accommodation rates diminished, and fans thinned basinward onto uplifted shale ridges, producing a landward dip of slope-fan sandstone bodies. Mobilized older mud-rich units near the base of the hanging-wall block were slowly pushed basinward and upward into a ridge (Figures 2, 3, 5D) that eventually became the basinward margin of the growth-faulted
graben. With downslope uplift, the faulted hanging-wall block attained complete closure of the intraslope subbasin (Figures 3, 5, 6).

Stage 5
Shale-ridge growth and fault-surface friction decreased the rate of hanging-wall subsidence, permitting slope-fan deposition to elevate the floor of the subbasin (by continued deposition) until water depth was sufficiently shallow to permit the small, entrenched, river-mouth delta system to prograde over the slope deposits (Figure 5E). These deltas extended the shelf edge basinward. Because subsidence (accommodation) rates are initially high at the onset of lowstand delta progradation, deltaic facies also thicken (expand) toward the fault (Figures 3, 10). High-frequency sequences, if deposited, are typically components of third-order lowstand-prograding systems (Van Wagoner et al., 1990; Brink et al., 1993; Brown et al., 1995).

The high-frequency deltaic systems are highstand tracts of fourth- or fifth-order lowstand-prograding systems (Van Wagoner et al., 1990). Therefore, high-frequency type 1 unconformities may erode the component highstand tracts, and high-frequency basement fans are then deposited basinward at the toe of the deltaic slope (Figure 3). The high-frequency fans are components of the third-order lowstand-prograding wedges and have been called “shingled toe-of-slope” fans (Vail, 1987, p. 10). Some workers consider these shingled fans to represent random slumping from shelf-edge deltas (Galloway, 1986, p. 10), but they always rest on fourth- or fifth-order type 1 surfaces (observation of senior author). The higher frequency deltas typically thin onto the sea bottom, which is being progressively uplifted over salt or, in the case of the current study area, shale ridges.

Because of higher subsidence rates next to growth faults and uplift of the seafloor basinward of the fault (Figures 2, 6), the lowstand slope fan and deltaic systems dip and expand in thickness toward the principal growth fault and thin onto a domal structural configuration commonly called a “rollover anticline” (Figures 3, 5, 10, 11). These structures are primary petroleum traps in growth-faulted subbasins. Sand-rich, deltaic, lowstand-prograding wedges are reservoirs on rollover anticlines (Figure 6). The distal parts of some lowstand depositional systems were deposited basinward of shale or salt ridges (Figure 3); hence, these distal segments

Figure 10. Isopach map of Frio (sub-basin 4, Figure 1), third-order lowstand deltaic wedge (pw) deposited in Red Fish Bay subbasin. Cool colors indicate thicker values. Greatest thickness = 2640 ft (804 m). Map illustrates thickening (expansion) toward growth faults, documenting fault movement during deposition of the delta systems. Expansion is best exhibited in dip-aligned sections, such as Figure 7. Arrows indicate approximate location of sediment input via incised valleys. The center of the map is at lat. 27.86°N, long. 97.11°W. Faults are based on 3-D seismic and well-log analyses.
of the systems tracts display only regional depositional thickness variations and were not expanded across contemporaneous faults (Figure 3).

**Stage 6**
Note that until this point in time, the only deposition on the previous highstand delta plain (Figure 5A, E) occurred in the incised valley(s), whereas interfluves were subaerially exposed. When the relative sea level began to rise at a rate greater than sediment was supplied to the lowstand deltas, retrogradation of shorelines marked the onset of regional transgression or retrogradation. The delta plain of the third-order lowstand delta system was flooded and became a shallow submerged ramp or shelf between the shale ridge and the growth fault (Figure 5F). The shale ridge served as a buttress that defined the location of a new shelf edge. Lowstand deltas onlapped and downlapped uplifted shale-ridge structures (Figures 5F, 6).

Following active deposition, marine-condensed environments expanded out of isolated parts of the basin and contemporaneously blanketed both shelf and deep basin. However, as stages 1–5 illustrate (Figure 5A–E), facies deposited between successive maximum floods are not necessarily time equivalent, and correlation using this concept may introduce chronostratigraphic errors.

**Stage 7**
During the latter part of the third-order relative cycle of sea level, highstand delta systems prograded across the submerged ramp to the new shelf-edge location (Figure 5G), and during a subsequent relative fall of sea level, the highstand river again became entrenched, and its sediments initiated another lowstand depocenter that eventually resulted in another growth-faulted subbasin (Figures 2, 3). Other previous highstand rivers along the coast similarly became entrenched, and collectively, the faulted depocenters defined another regional flexure or growth-fault system with subbasin hanging-wall blocks buried by younger lowstand sediments (Figure 2).

**Control on the Location of Incised-Valley-Fill Systems**
The areal intersection of growth faults (Figure 2) may have produced minor strike-slip accommodation faults normal to the average regional trend of the faults because rates of movement along normal faults were not necessarily the same in adjacent fault segments. After maximum flooding, onshelf rivers avulsed from previous fluvial axes, which exhibited paleotopographic relief caused by differential sand and mud compaction. The positive paleotopographic axes deflected river flow laterally during the next cycle. When the next highstand rivers incised because of falling relative sea level, their entrenched mouths notched the shelf edge at positions lateral to the previous point sources. Entrenched rivers commonly followed paths that crossed previous growth faults at fractured and faulted intersections of two adjacent arcuate fault segments (Figure 2).
Sequence Perspective

Understanding the tectonic and depositional factors generating intraslope subbasins improves understanding of reservoir architecture and trapping potential in their hydrocarbon systems (Figures 12, 13). Predicting reservoir discontinuity and lateral facies changes in the lowstand systems tracts depends on the understanding of the interplay of depositional processes and syndepositional tectonics (Figures 12–14) that are temporally related to relative changes in sea level (i.e., sequence stratigraphy). Routine geologic tasks in production...

Figure 12. Chronostratigraphic diagram (Wheeler, 1958) of Frio depositional sequences 2–6 and their relationship to geologic age, microfossil biozones, and other time-related factors. Note that benthic zone ages (Berggren et al., 1985) have been converted to new ages (Berggren et al., 1995) using a timescale program (GEOMAR, 2002) located at http://www.odsn.de/odsn/services/conv_ts/conv_ts.html on the basis of more recent unstable isotope and oxygen stable isotope ratios (Abreu and Haddad, 1998), and that ages of T, unconformities have been adjusted from Haq et al. (1987) to those of Hardenbol et al. (1998). Marine condensed sections (i.e., maximum flooding surfaces) have been readjusted from Haq et al. (1987) to Wornardt et al. (2001). See Hardenbol et al. (1998) for further credits and information. Polarity chronozones from Cande and Kent (1992, 1995).

SIGNIFICANCE IN PETROLEUM EXPLORATION

Sequence Perspective

Understanding the tectonic and depositional factors generating intraslope subbasins improves understanding of reservoir architecture and trapping potential in their hydrocarbon systems (Figures 12, 13). Predicting reservoir discontinuity and lateral facies changes in the lowstand systems tracts depends on the understanding of the interplay of depositional processes and syndepositional tectonics (Figures 12–14) that are temporally related to relative changes in sea level (i.e., sequence stratigraphy). Routine geologic tasks in production...
operations, such as reservoir correlations and accurate structural mapping, benefit from using a reliable sequence-stratigraphic framework (Figures 4, 12) that provides chronostratigraphic map envelopes and seismic reflections that are generated by essentially chronostratigraphic impedance boundaries.

Commonly, lithofacies inferred to be correlative are incorrectly correlated by assuming that genetically similar wire-line-log facies patterns were deposited contemporaneously. Placing the stratigraphy and structure of a field into a sequence-stratigraphic context precludes miscorrelation of reservoirs and incorrect structural assumptions based on traditional log-facies correlations (Figure 12). Log-facies maps are useful only if facies are time equivalent, not simply because they look alike. Similarly, detailed structural contour maps of a diachronous stratigraphic surface introduce false assumptions into information required for production and field-development decisions. Correlating field production and engineering information in a sequence framework is the only method to ensure large-scale comparisons of similar temporal events or age-equivalent data needed to record, compare, and interpret significance of field data.
Growth-Faulted, Intraslope Subbasin Analysis by Applying Sequence-Stratigraphic Principles

(A) Rate of eustatic change of sea level (second derivative)

(B) Subbasin 2, Subbasin 3

(C) Anomalous accommodation rate caused by growth faulting

(D) Regional subsidence

(E) Water depth at site of maximum depositional rates

(F) Systems tracts

(G) Rise of relative sea level

(H) Relative change of sea level in intraslope subbasin

Subsidence
\[ \pm \text{eustasy} = \text{net relative rise} \]

Rate of relative change of sea level and accommodation space [Eustasy ± subsidence] (Second derivative)
Petroleum Geology

Intraslope subbasins contain traps, reservoirs, and seals that are typical of river-dominated deltaic systems. Intraslope subbasins (Figures 1, 3, 14), however, are bounded by major fault systems that are migration pathways linking reservoirs and source beds comprising deep-marine mudstones from within the overpressured parent basin. Magara in Galloway et al. (1982, p. 24) discussed the elements of the Frio hydrocarbon system, including source beds, maturity, expulsion, and migration information. Deeply buried, hot, overpressured strata trapped below the shelf by regional second-order transgressive surfaces and marine-condensed facies provide a regional seal (Figures 4, 6, 14). Petroleum-bearing fluids move from a deep geopressed environment upward to permeable fault gouge (fault rock) along fault planes until the fluids reach potential sandstone reservoirs. This is the only mechanism for hydrocarbons to reach onshore reservoirs above the regional seal. Consequently, most hydrocarbons are trapped in lowstand reservoirs below the regional seal.

Trapping in prograding-wedge deltaic sandstones occurred on hanging-wall rollover anticlinal or crestal fault closures or by updip pinch-out of reservoir facies against sealed growth faults in the footwall block (Figures 3, 14). Deltaic sandstones are base sealed by mud-rich prodelta and top sealed by delta-plain facies. The potential for updip pinch-out of sandstone facies adds excellent combination structural-stratigraphic trapping potential. These elements make this petroleum system one of the best encountered in siliciclastic provinces.

Basin-floor fans that are typically blocky and massive provide the maximum potential for stratigraphic trapping because most of them pinch out in all directions and are overlain and underlain by basal shale facies (Figures 5B, 12, 14). Fans may be both sealed and sourced by adjacent deep-basin condensed sections. Third-order fans rest on surfaces that are concordant basin equivalents of sequence-bounding unconformities (Figures 12, 14). Early lowstand and density flows that occurred before shale-ridge uplift provided a basinward barrier, permitting bypass of the local hanging wall and deposition much farther into the basin. In contrast, although shingled fans at the toes of high-frequency lowstand deltaic systems (Figures 12, 14) remained in the hanging-wall subbasin, they exhibit poor updip seals because of feeder channels.

Slope fans are composed dominantly of shale and siltstone. Potential reservoir facies are thin, blocky, channel-fill, and digitate levee-splay facies. Slope-fan facies are highly discontinuous and limited in volume, lacking lateral continuity. Levee facies are characteristically tight because of high silt and mud content. Slope-fan channels exhibit limited updip trapping and seal, because they are conduits for fluids to exit into incised-valley fill (Figure 3). Hanging-wall block rollover closures and extensional (crestal) faults are the only viable traps. In this area, exploration for slope channel-fill facies with adequate trapping requires random drilling that might intersect a structurally trapped channel.

SUMMARY AND CONCLUSIONS

Our depositional model of progressively younger lowstand depositional systems in successively younger and basinward-stepping subbasins (Figures 12, 14) provides a mechanism to explain (1) growth-fault genesis, (2) occurrence of lowstand systems in subbasins, and (3) diachroneity of successive subbasin strata that exhibit similar facies and lithostratigraphy (Figures 3, 12, 14). These observations are consistent with the idea that lowstand depocenters exerted load stress on upper slope sediments, triggering growth-fault movement that was coincident with late Oligocene third-order relative lowstands. These data-based observations support the inferences discussed below.

Figure 13. Eustatic sea level, subsidence, and relative sea level and accommodation rates (A–C: x meters per x time per interval) and actual estimated changes (D–H: x meters) in evolution of growth-faulted hypothetical subbasins 1 and 2. Note that red vertical dashed lines connect all sketches at equivalent times. (A) Eustatic sea level change rates. (B) Anomalous growth-fault subsidence rates superimposed on regional subsidence curve. (C) Relative sea level change (eustatic change − subsidence rate = relative sea level rate). Note that the anomalous subsidence rate in the subbasin produces an anomalous positive accommodation rate, but that subsidence negates some of the eustatic fall. (D) Anomalous growth-fault subsidence is in x meters superimposed on regional subsidence curve. Note initial growth of shale ridges. (E) Absolute sea level at times of maximum depositional rates. (F) Eustatic (absolute) sea level changes in x meters. Note the relationship of the eustatic curve with depositional systems tracts. Relative (actual) change in sea level is in x meters (accommodation envelope) outside of growth-faulted subbasin. (H) Relative (actual) change in sea level in x meters (accommodation envelope) in growth-faulted subbasins. Note the anomalous added lowstand of relative sea level in x meters in subbasins. Based on Posamentier and Vail (1988). No value for x is intended.
Figure 14. Simplified chronostratigraphic diagram (subbasins in Figure 1) of Oligocene Frio Formation (32 Ma–25.38 Ma) in Corpus Christi area, Texas. This display exhibits shelf, slope, and basinal depositional systems tracts and their geologic time relationships in each sequence that comprises the Frio lithostratigraphic unit. Chart documents approximate age and basinward shift of subbasins 1–6 during Frio deposition and implies temporal independence of lowstand depositional systems among the subbasins. Average duration of third-order Frio sequences is about 1.4 m.y.
Activation of each fault system correlates temporally with a third-order fall of relative sea level (Figures 3, 12, 14), terminating highstand progradation. Because of falling relative sea level, subsequent highstand rivers were entrenched and shifted basinward to shelf edges. The avulsing rivers typically relocated from previous highstand river axes and occupied a negative paleotopographic pathway, where two arcuate growth-fault system segments intersected (Figure 2).

Although marine-condensed sections (containing a maximum flooding surface) and unique concentrated fossil taxa may correlate from shelf to intraslope subbasins, sandstone facies deposited on shelves and in intraslope subbasins between successive flooding events are not necessarily contemporaneous and should not be correlated (Figure 12). Onshelf highstand and transgressive deposition was temporally distinct from offshore lowstand slope-fan, basin-floor fan, and prograding-wedge deltaic deposition (Figures 12, 14).

Shelves were subaerially exposed during lowstands. Simply because condensed sections comprise the same microfossils throughout the basin does not imply that all intermediate facies are time equivalent. In fact, the zone fossils also accumulated basinward in areas where future subbasin subsidence and lowstand sedimentation had not yet occurred. Successive condensed sections obviously do not necessarily enclose equivalent sandstone facies.

Entrenched river mouths that eroded shelf-edge notches served as point sources that focused the total lowstand fluvial-sediment load onto specific localized sites on the upper slope and consequently produced depocenters that can be interpreted to have exerted sufficient load stress to trigger slumping and normal faulting that created intraslope subbasins. This trigger may also have released stored stress related to regional basin subsidence and tectonics. Conclusions indicate that relative sea level and sedimentary processes may generate and combine with tectonic subsidence (Figures 5, 13) and compactional stress to generate important structural events (Figure 6).

Sequence-stratigraphic analysis is an appropriate method for identifying subtle variations exhibited in a stratigraphic succession (Figure 8). Application of sequence stratigraphy provides the potential for chronostratigraphic correlation within and among growth-faulted subbasins, thus improving prediction of stratigraphic and areal distribution of deeply buried lowstand reservoirs; providing a guide to potential combination traps; opening a window on exploration for deep, unexpanded subfault reservoirs and traps; placing the subbasin into a petroleum system framework; and focusing on improper correlation of genetically similar wireline-log patterns of temporally lithostratigraphic units.

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