Research paper

Depositional settings and history of the Lower Miocene Fleming Group, Refugio County, Texas, as defined using seismic geomorphology

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ABSTRACT

A study of the Lower Miocene Fleming Group in Refugio County, Texas from 3-D seismic and wireline-log data documents continuous strandplain and associated lower-coastal-plain fluvial systems along a wave-dominated shoreline. This study delineates and characterizes, through the interpretation of seismic attributes and seismic geomorphology maps from 15 horizons, three principal styles of stratal patterns: (1) parallel and subparallel, strike-continuous sets of beach ridge and swale deposits within a strandplain system that prograded at least 12 km, (2) sinuous channel belts in a coeval mixed-load meanderbelt system, and (3) acoustically dim, nearly featureless seismic attribute patterns that record homogenous and topographically subdued, shallow-marine mudstones associated with transgressive marine deposits and flooding surfaces. Holocene depositional analogs for these Lower Miocene sandy strandplain deposits include the Nayarit coastline in Mexico, whereas the lower coastal plain between Galveston and Corpus Christi, Texas serves as an appropriate analog for mixed-load meanderbelt systems.

The Lower Miocene coastline in Refugio County consists of a regressive phase that was punctuated by two transgressive phases. These episodes of marine transgression correspond to the Anahuac Formation and the Marginulina A shale, respectively. Succeeding events record complex, amalgamated beach-ridge deposits and coeval fluvial-channel systems that exhibit patterns of channel migration, erosion, incision, and downdip fusion of channel belts.

This study concludes that potential reservoir geometries and architectures in the Lower Miocene succession are much more complex than previously inferred, the result of rapidly fluctuating and evolving strike-fed shoreline systems and contemporaneous fluvial dip-dispersal systems, some manifested by shore-parallel trends confined in swales. Improved reservoir-development strategies in this prolific hydrocarbon-bearing play should be guided by distribution of sandy depositional elements and the paleogeographic setting.

1. Introduction

Sedimentary deposits of the lower Miocene Fleming Group preserve a record of continental margin growth in south-central Texas. Previous regional studies of the Fleming Group were based on several thousand wireline logs, borehole cuttings, and whole cores (Galloway et al., 1982, 1986; Galloway, 1989a). Similar data sets continue to be used in large-scale paleoenvironmental analyses of central North America (Winker, 1982; Galloway et al., 2000, 2011). In contrast, analyses of limited outcrop exposures defined the sedimentology of a fluvial channel-fill deposits over local scales of only tens of meters (Galloway et al., 1982).

The objective of this study is a depositional analysis of lower Miocene strata at an intermediate scale between those associated with outcrop and regional studies. These scales range from hundreds to thousands of meters with a seismic volume covering 275 km² in Refugio County, south Texas (Fig. 1A). Observations and measurements assembled at this range of scales are critical to (1) reconstruct shoreline and fluvial systems and to (2) accurately quantify the stratigraphic elements composing potential reservoirs, baffles, and barriers.

While well-bore data serve as the framework defining the Miocene system of coastal Texas, their one-dimensional character limit defining the three-dimensional geometries of stratigraphic elements composing the stratal package. Using an industry-grade seismic volume tied to well control, we refine the local interpretation of depositional environments with a series of detailed seismic geomorphology maps. Using 15 mapped horizons between subsurface depths of 370 to 1430 m, we define the stratigraphic architecture for the lower Miocene depositional system with a level of detail that was previously unavailable.

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1.1. Depositional systems framework for Fleming Group strata

Sedimentary deposits of the Fleming Group comprise a succession of continental-margin strata that are bounded below and above by the deposits of two significant marine transgressions, the Chattian Anahuac Formation and the Burdigalian/Langhian Amphistegina B shale (Fig. 1B; Galloway et al., 1986; Galloway, 1989a).

Reported ages for the top Anahuac Formation range from 24.4 Ma (Galloway et al., 2000) to 23.6 Ma (Loucks et al., 2011), whereas published ages for the first occurrence of Amphistegina B range from 18.22 Ma (Loucks et al., 2011), 16.6 Ma (Galloway et al., 1986), to 15.5 Ma (Galloway et al., 2000). The Fleming Group is further divided into lower and upper units that correspond to the Oakville Sandstone below and the Lagarto Formation, respectively (Fig. 1B; Galloway et al., 1982, 1986). These stratigraphic units have been more recently named the lower Miocene 1 deposode (LM1; Fig. 1B) and lower Miocene 2 deposode, respectively (LM2; Fig. 1B) by Galloway et al. (2011). The Marginulina A transgressive shale separates these deposodes. It represents a widespread stratigraphic marker and extends nearly as far updip as the Amphistegina B shale (Fig. 1B; Galloway et al., 1986; Galloway, 1989a, b). Reported ages for the first occurrence of Marginulina A range from 21.53 Ma (Loucks et al., 2011), 19.5 Ma (Galloway et al., 1986), to 18.2 Ma (Galloway et al., 2000).

Subsurface deposits of the basal Oakville Sandstone, or LM1 deposode host a thick, sandy barrier/strandplain system that extends across most of the Texas coast (Fig. 1A; Galloway et al., 1986). This complex of...
shoreline strata records extensive wave reworking and longshore transport and is called the Matagorda Barrier/Strandplain System by Galloway (1989a). In addition to barrier island and strandplain environments, onshore Oakville strata include deltaic, lagoonal, and fluviomarine deposits. These environments of deposition are documented in regional studies of the Lagarto Formation, or LM2 deposode (Galloway et al., 1986, 2000, 2011).

Lithic clasts of Cretaceous limestone and fossils are reported from outcrops of the Oakville Sandstone by Weeks (1945) and Galloway et al. (1982). These reworked materials are evidence for early Miocene uplift of the Edwards Plateau along the Balcones Fault Zone. The structural influence of the long-lived San Marcos Arch on stratigraphy was coming to an end at approximately the same time that deformation along the fault zone was reestablished (Halbouty, 1966; Culotta et al., 1992). This study also sought to infer Miocene activity on the San Marcos Arch from orientation of fluviomarine systems and stratal thickness trends. Tying the stratigraphy from Refugio County into the regional setting was facilitated by consultation with the Gulf Basin Depositional Synthesis Project (GBDSP) (2013) at the Institute for Geophysics, The University of Texas at Austin. With data provided by the GBDSP, we tied locations for Marginulina A and Amphistegina B into wireline-log seismic data (J.W. Snedden, pers. comm., 2015).

1.2. Identification of depositional elements using seismic volume

Our study applies principles of seismic geomorphology (Posamentier et al., 2008) using sets of planview images from the seismic volume. These data provide a degree of spatial resolution of Fleming depositional systems that cannot be obtained from wireline-log data. To reconstruct these depositional systems, we focused on three styles of stratal patterns: (1) channel belts that define the time-

Fig. 2. Data from the Holocene Mississippi River demonstrating the connection between channel-bend migration rate, channel-belt width, and distance from the Gulf of Mexico shoreline (from Fernandes et al., 2016). (A) Channel-belt width (gray dots) and average width calculated over 200 km moving window (black) plotted versus distance. (B) Channel-migration rate versus distance along channel belt axis from shoreline.

Fig. 3. Location map for the 17 wells used in this study. Thick black line defines the seismic volume border. Thin, black, arbitrary lines define seismic section A—A′ displayed in Fig. 4 and seismic section B—B displayed in Fig. 20.
integrated kinematic histories of migrating river channels, as well as the overall dimensions of genetically related channel-fill deposits (Wood, 2007; Armstrong et al., 2014; Blum et al., 2013; Fernandes et al., 2016). Other significant patterns (2) are associated with parallel and sub-parallel sets of beach ridge and swale topography that define progradational coastal strandplains (e.g., Jackson et al., 2010). Curvature and tapering of these sets is common proximal to sediment sources such as distributary channels (Gould and McFarlan, 1959). Other patterns (3) are coherent seismic reflections associated with thick, relatively homogenous and topographically subdued, shallow-marine mudstones. These coherent planview images are associated with transgressive marine deposits and overlying flooding surfaces.

The dimensions of channel belts, particularly their widths, have received a great deal of recent attention with the realization that rates of lateral migration for the channel bend of rivers vary in a predictable manner as a function of distance from the shoreline (Fig. 2; Hudson and Kesel, 2000; Nittouer et al., 2012). Blum et al. (2013) have documented correlations between channel-bend migration rate and the time-integrated width of the resulting channel belt, and Fernandes et al. (2016) have related the systematic upstream changes in both to the extent of the coastal backwater length, Lb (Fig. 2).

This point is approximately equal to the distance upstream where the bottom of a coastal river finally rises above mean sea level and is commonly approximated by Lb = H/SWS, where H is mean channel depth and SWS is the gradient of the water surface for the river closely upstream of the backwater zone (Paola and Mohrig, 1996). Fernandes et al. (2016) show that the ratio of channel-belt width to channel width can be used to accurately estimate whether a deposit occurs within the backwater zone, and is therefore positioned relatively close to the shoreline, versus being outside of the zone and occupying a relatively upstream location. The ratio of channel-belt width to channel depth at the backwater length is approximately 5:1 for Holocene channel belts of the Rhine River system, as well as the Mississippi River (Fig. 2) and is interpreted to be a defining geometric property of the stratigraphy of perennial coastal rivers (Fernandes et al., 2016).

2. Methods of investigation

The data set is a seismic volume encompassing 275 km² (106 mi²), with a bin spacing of 25 m × 25 m and a dominant frequency range of 30 Hz–45 Hz. Vertical resolution of lower Miocene strata in this 3-D seismic volume ranges from 16 m to 21 m. Landmark seismic interpretation software was used to map 15 horizons and to analyze structural and stratigraphic architecture. Wireline logs from 17 boreholes (Fig. 3) were integrated into the seismic study; 15 of them extend through the entire Miocene stratigraphic section. Gamma-ray, spontaneous-potential, resistivity, and sonic curves were particularly helpful for mapping many horizons, notably the base and top of the Anahuac Shale. Wireline-log responses from these curves were integrated with seismic-attribute maps to interpret facies and
depositional systems. Examples are shown in Figs. 4 and 5.

Several seismic attributes were tested to determine those that best define Fleming Group stratigraphy. These attributes included variance, semblance, root-mean-square amplitude (RMS), sweetness, and spectral decomposition. Variance was superior in delineating faults, edges of channel belts, and beach ridge and swale topography. It was therefore used as the primary attribute in our analyses of seismic geomorphology. RMS extraction was used to infer sandstone and shale lithology.

The spectral decomposition tool was used on both amplitude and variance attribute volumes at different frequency bands to enhance the resolution of both fine-scale and large structures (Subrahmanyam and Rao, 2008). The variance attribute volume was generated in Petrel and resolution of both amplitude re

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To image the thick sand body sitting on top of the Anahuac Shale, we employed both horizons 2 and 3—at horizon 2, the 16-ms-window was applied to image the sand body from below; whereas at horizon 3, 16-ms-window was applied in the opposite direction to image it from above. The results of these procedures are discussed below.

In addition to variance, the sweetness attribute was used to define stratigraphic geometries. It is calculated as the instantaneous amplitude envelope divided by the square root of the instantaneous frequency (Radovich and Oliveros, 1998). Whereas variance maps were used to detect edges of stratigraphic bodies, sweetness attribute maps were useful in differentiating sandstone-rich channel-belt deposits from mudstones (Hart, 2008; Ogiesoba et al., 2013; Armstrong et al., 2014; Sacrey and Roden, 2014; Ogiesoba, 2017). Both variance and sweetness attributes clearly defined channel-belt widths. Correlations between high values for the sweetness attribute and sandstone-rich Fleming Group deposits is shown in Fig. 5. Crossplots between Vclay and sweetness attribute were generated (Fig. 5A and B). The plot shows a strong, negative, linear relationship between the two parameters—sweetness increases as Vclay decreases, suggesting increasing sandstone content. The Vclay log was obtained by converting the gamma-ray log to the Vclay log to allow for better lithological interpretation.

3. Results

3.1. Mapped horizons and measured elements

The average subsurface depths associated with each one of the 15 mapped horizons are presented in Table 1. Geometric attributes from all 15 horizons were recorded and used to interpret depositional environments tied to seismically imaged deposits. Dominant stratigraphic elements in maps of these horizons are presented below. Our discussion of each is grouped by stratigraphic element. Based on this grouping, 10 out of the 15 horizon variant attribute maps are presented in this paper.

Horizons 1 and 2 were mapped at the base and top of the Anahuac Formation (Figs. 1B and 4). Horizon 2 is characterized by facies variation—changing from sandstone into shale basinward. For example, in Wells 4 and 7, the sandstone body that sits on the top of the Anahuac
Shale is composed of two sandstone units—a thick and a thin sandstone units with the thin one sitting directly on the Anahuac Shale. This thin sandstone unit shaled out southward in Wells 10, 8, and 2. This shaling out effect makes tracking of this horizon difficult. Thus to avoid cutting across events, we mapped the base of the thicker sand body that is more consistent as the top of the Anahuac Shale (Fig. 4). The variance attribute map for each of these horizons is notable for its homogeneity and lack of detectable stratigraphic edges. For example, the map of Horizon 2 is presented as Fig. 6. Besides Horizons 1 and 2, other interpreted surfaces that possess a similar lack of organized pattern are Horizons 6 and 15 (Figs. 7 and 8). Baseline to serrate wireline-log responses for Horizons 1 and 2 (Fig. 4) indicate a high mudstone content, consistent with a muddy-shelf depositional setting.

Horizon 6 (Fig. 7) display a homogeneity in map pattern consistent with a marine flooding interval. In addition, this horizon correlates with the Marginulina A shale (J.W. Snedden, pers. comm., 2015) that separates the LM1 and LM2 depositions of Galloway et al. (2011). Although there appears to be some sinuous pattern in the southwest (Fig. 8), Horizon 15 also displays an overall homogeneity in map pattern for the variance attribute. However, because of its relatively shallow depth (Fig. 4, Table 1), it is difficult to determine if the absence of detectable organized pattern is the product of poor illumination of the subsurface strata tied to the spacing of receivers during seismic acquisition.

Horizons 1, 2, and 6 (Figs. 4, 6 and 7) document laterally continuous, shallow-marine mudstones. Horizon 15 (Fig. 8) is less certain, but based on regional correlations provided by the Gulf Basin Depositional Synthesis Project, its position is correlated approximately with the Amphistegina B shale (J.W. Snedden, pers. comm., 2015) that defines the top of the Fleming succession (Fig. 1B).

Variance maps for Horizons 3 (Fig. 9) and 7 (Fig. 10) both display straight, linear stratigraphic elements. These lineations are subparallel on Horizon 3 and cover the entire map (Fig. 9). The representative strike for these subparallel lineations is N33° E. This direction is not consistent with inline and cross-line orientations for the seismic volume, so the possibility of this fabric being a seismic artifact is small. The isochron map displays lineations between Horizons 2 and 3 (Fig. 11). Comparison of this isochron map to the variance map (Fig. 9) reveals that the trend in deposit thickness and the lineations defined by the variance attribute are nearly identical. Lineations observed on Horizon 7 differ from those on Horizon 3 in two important ways. First, lineations on Horizon 7 are restricted to the southeastern corner of the seismic volume (red arrows, Fig. 10 inset). Second, the lineations on Horizon 7 are flared rather than subparallel. The strike directions for these lineations range from N38° E, an orientation that is approximately similar to that observed on Horizon 3, to N50° E. This range in strike direction produces a wedge-shaped package in linear elements oriented southwestward (Fig. 10). These seismically imaged linear features are interpreted as the product of beach ridge and swale topography (e.g., Jackson et al., 2010). Horizons 1, 2, and 6 are interpreted as strata of prograding strandplains.

Variance maps for Horizons 4, 5 (Fig. 12), 8 (Fig. 13), 9 (Fig. 14), 10, 11 (Fig. 15), 12, 13 (Fig. 16), 14, and part of 7 (Fig. 10) are dominated by sinuous, channel-like forms. We focused on collecting multiple width measurements from the more complete channel-like forms—from elements exceeding 3 km in length. The widest element observed on a map was always selected for measurement. Width values were also collected from additional elements if a single map displayed elements with a range of sizes.

All of the measurements from a single element are used to calculate its mean value and standard deviation; these data are presented in Fig. 17. Almost every channel-like feature defined by the variance attribute map shows a homogeneity in map pattern consistent with a marine flooding interval.
Fig. 7. Horizon 6 (Fig. 4) imaged using 16-ms-window size for the variance attribute. Notice the sheet-like homogeneous feature with lack of any significant sinuosity. The mapped horizon defines the top marine flooding surface. Note: Faults A—D are discussed in Section 4.

Fig. 8. Horizon 15 (Fig. 4) imaged using 16-ms-window size for the variance attribute. Notice the sheet-like homogeneous feature with minor sinuosity southwest. The mapped horizon defines the top of marine flooding surface. Note: Faults A—D are discussed in Section 4.
Fig. 9. Horizon 3 (Fig. 4) imaged using a 16-ms-window size for the variance attribute. This window extends from Horizon 3–16 ms below and defines the top of the thick basal sandstone of the Oakville Sandstone (LM1 of Galloway et al., 2011). Fabric is defined by subparallel lineations, with majority of wireline logs having an upward-coarsening response. Note: Faults A—D are discussed in Section 4.

Fig. 10. Horizon 7 (Fig. 4) imaged using the variance attribute. The two arrows seen in the inset point to linear features similar to those seen on Horizon 3 (Fig. 9). Majority of wireline-log responses are serrate to upward-fining/serrate, indicating a high degree of interbedded sandstone and mudstone.
Fig. 11. Isochron map for the sand-rich deposit between Horizon 2 and Horizon 3 (Fig. 4). Warm colors are associated with a thinner deposit, while cooler colors are associated with greater thicknesses. Notice that the trend in deposit thickness has the same orientation as the fabric defined by the variance attribute in Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. Horizon 5 (Fig. 4) imaged by the variance attribute. Wireline-log responses range from muddy-serrate to sandy-serrate, indicating high degree of interbedded sandstone and mudstone.
3.2. Interpreted depositional history for the Fleming Group in Refugio County

The basal stratigraphic unit in the Fleming Group is a 150 m-thick (Fig. 11), sandstone-rich strandplain deposit that comprises the basal Oakville Sandstone (Fig. 4). Horizon 3 records 12 km of shoreline progradation characterized by continuous, northeast-oriented parallel beach ridge and swale topography (Fig. 9). This topography and shoreline form is consistent with depositional environments interpreted from wireline-log analysis by Galloway et al. (1986). Wireline-log responses for these parallel seismic patterns are predominantly upward-coarsening to blocky/upward-coarsening (see Fig. 4), consistent with progradation. Additional detail in the facies geometry is provided by a variance attribute map of Horizon 3 that resolves at least one sinuous channel trend confined to a beach swale between Wells 7 and 11 (Fig. 9). The straight ridge and swale topography requires both wave and longshore transport for shoreline construction, as well as a nearby deltaic source (Tyler and Ambrose, 1985). Individual beach ridges or beach-ridge complexes are continuous for a least 23 km in the shoreline direction. A minimum of 12 km of strandplain progradation is evidence for a significant influx of sand to the coastline at the beginning of the Miocene (Galloway, 1989a, b).

A comparable modern strandplain system is the Costa de Nayarit, Mexico. It consists of beach ridges having prograded up to 15 km offshore. It extends alongshore up to 200 km (Curray et al., 1969). The Nayarit strandplain system occurs between two wave-dominated deltaic headlands approximately 120 km apart (Fig. 18A). Small-scale rivers and creeks, some shore-parallel, are distributed between these deltaic headlands (Fig. 18B). Beach-ridge complexes in the Nayarit system are composed primarily of sand and shelly sand that are collectively 5–10 m thick and as much as 20 km across (Fig. 18A), although individual sets (defined by associations of parallel ridges in plan view) are commonly no more than 5 km across (Fig. 18B). They overlie mud, shelly sand and silt and are flanked landward by a complex of irregular lakes having a patchy distribution (Curray et al., 1969).

Strandplain systems flanking the Holocene Sabine River delta along the Texas-Louisiana border are composed of a regionally continuous assemblage of subparallel beach ridges that taper and diverge toward a wave-dominated deltaic depocenter, producing a flaring morphology (Gould and McFarlan, 1959) (Fig. 19A and B). In contrast to the Costa de Nayarit, beach ridges flanking the Sabine River Delta have poorly developed to absent bays and lagoons. These beach ridges are also associated with an overall muddy coastal system (Fig. 19A) on a passive basin margin, in contrast to a collisional margin on the western Mexico coastline.

Subsurface examples of strandplain deposits in Texas include the Frio Formation in North Markham—North Bay City field in Matagorda County, Texas (Tyler and Ambrose, 1985). Many reservoirs there are of shallow-marine origin and are composed of both sand-rich, beach-ridge-plain and muddy chenier-plain deposits. Sand-rich, beach-ridge-plain deposits in North Markham—North Bay City field contain parallel to subparallel, strike-elongate sandstone bodies associated updip (northwestward) with fluvial-deltaic feeder systems having muddy crevasse-splay, swamp, and floodplain facies.

In the Lower Miocene succession in our study area, an attribute occurs as a high-amplitude corridor using the sweetness attribute. These elements are enriched in sand relative to surrounding strata, and we interpret them as fluvial channel belts in a coastal-plain setting.
Fig. 14. Horizon 9 (Fig. 4) imaged using the variance attribute featuring large incisional channels to the northeast. Wireline responses in northeastern part of study area are predominantly sandy-serrate to spiky, whereas those to the southwest are baseline and muddy-serrate. Note: Faults A—D discussed in Section 4.

Fig. 15. Horizon 11 (Fig. 4) imaged using the variance attribute. Wireline-log response in areas of bright amplitudes are sandy-serrate to upward-fining, whereas other areas are predominantly spiky and muddy-serrate.
approximately 100 m-thick, coastal-plain succession (Table 1), dominated by fluvial channel belts, overlies strandplain deposits associated with Horizon 3 (e.g., Fig. 5). Local widths for these belts range between 150 m and 660 m, with an average width between 300 m and 400 m (Fig. 17). Net-sandstone trends of these feeder systems are sinuous (see imaged examples in Fig. 10), consistent with morphology of rivers in the lower coastal plain along the modern Texas Gulf Coast between Corpus Christi and Galveston (McGowen and Garner, 1970; Bernard et al., 1970; McGowen et al., 1976). In contrast with the Holocene Texas coastline southwest of Galveston, shorezone sediments in the Miocene section in Refugio County are interpreted to have been attached to the shoreline, with bay and lagoonal environments having been poorly developed.

Rivers along the Texas coastline deliver sediments to a microtidal coastline with a diurnal tidal range less than 6.6 ft (≤ 2 m) (Davies, 1964). They occur within moderately sinuous and weakly anastomosing belts of main feeder systems and associated tributaries that together define alluvial plains that range in width from 3 to 15 km (Bernard et al., 1970). Individual meanderbelts in these fluvial systems are sinuous and are flanked by mud-filled, abandoned channels, small-scale and arcuate oxbow lakes, and well-developed levees.

The coastal-plain succession is overlain by a transgressive section defined by Horizon 6 (Figs. 4 and 7). This transgressive section is within the Marginulina A shale (Fig. 1B) that separates the underlying Oakville Sandstone from the overlying Lagarto Formation.

Horizon 7 (Fig. 10) is the base of the Lagarto Formation and records a second strandplain succession. This complex of beach ridges and swales is different from the basal Oakville strandplain (Fig. 9). The shallower strandplain is interpreted as basal Lagarto Formation, or LM2 deposode (Horizon 7, Fig. 12).
tapering patterns (Fig. 10) suggest that a deltaic point source was proximal to the northeast.

The Lagarto strandplain is overlain by an approximately 400 m-thick section that in map view is dominated by fluvial channel-belt strata (Figs. 12, 13 and 15). We interpret these deposits as an amalgamated coastal-plain succession. Measurements of channel-belt width from this section are summarized in Fig. 17. The belts of the Lagarto Formation display an overall increase in width through time.

4. Discussion

Our map-based analysis of the depositional environments that comprise the Fleming Group strata in Refugio County, South Texas, reveals a system composed of wave-dominated coastline and fluvial coastal-plain deposits. The strandplains preserved as the basal components of both the Oakville Sandstone and Lagarto Formation are attached to a nonmarine system rather than separated from the mainland by lagoons or bays. We find no seismic evidence for lagoonal facies representing a dominant depositional setting for Refugio County (Fig. 1A) as proposed from wireline-log analysis by Galloway et al. (1986) and Galloway (1989a). However, because of the small size of the study area, it is possible that lagoonal facies may occur in other areas beyond Refugio County.

Strandplain deposits define a shoreline oriented north-northeast to south-southwest, and channel-belt deposits define rivers that traversed the coastal plain at an angle orthogonal to the paleocoastline direction. Other orientations for fluvial-channel belts (Fig. 9) suggest sediment-delivery pathways being confined by swales, observed also in the Holocene Nayarit coastal plain (Figs. 18 and 19). The orientations and distributions for both the strandplain deposits and the channel belts yield no stratigraphic evidence for deformation of the paleosurface by the long-lived San Marcos Arch (Halbouty, 1966; Culotta et al., 1992), which is located roughly 40 km northeast of the seismic volume studied. Apart from four minor faults (Faults A, B, C, and D) that cut the formation in the south (Fig. 20), there no other visible faults in the area. Of these four faults, Fault A is the biggest and has a maximum down-to-northeast throw of ∼25 ms (∼100–200 ft; ∼30–60 m). It persists almost to the surface cutting Horizon 15 but died out within the Frio Formation just below the Anahuac Shale (Fig. 20).

The other three faults are barely visible with minor displacements, and do not extend to Horizon 15. In general, these faults are essentially coast-perpendicular and are confined to the Miocene. As can be seen in Fig. 21, the structure is faulted at the crest by the down-to-the-northeast Fault A. It is asymmetric anticline with the longer limb to the south-west. In this direction, the dip is steeper than it is in the northeast.

According to Ogiesoba and Hernandez (2015), major structural deformation (coast-orthogonal diapiric shale and faults) prevalent during the Eocene, died out in the early Oligocene within the Vicksburg and lower Frio Formations in Refugio County. In fact, there is little evidence for significant structural deformation of Fleming Group strata in the seismic volume studied. This observation suggests that by the earliest Miocene, the province of extensional deformation and faulting had shifted seaward to the southeast of present-day Refugio County.

Our interpreted subsurface depths for the positions of the top...
Anahuac Formation, the *Marginulina* A shale, and the *Amphistegina* B shale (Table 1, Fig. 1B), combined with the age control (Galloway et al., 1986, 2000; Loucks et al., 2011), allow an estimation of Fleming sediment accumulation rates. This rate is independently estimated for both the Oakville Sandstone and the Lagarto Formation at 0.2 mm/yr (2 × 10² m/Ma). This rate is similar to that from seismic geomorphological studies of middle to upper Miocene strata by Wood (2007) and upper Miocene strata by Armstrong et al. (2014). Sediment accumulation rates for these coastal Gulf of Mexico systems are 0.2 mm/yr (Hentz and Zeng, 2003) and 0.3 mm/yr (Straub et al., 2009), respectively. Both Wood (2007) and Armstrong et al. (2014) focus on providing the best possible resolution of channel-belt stratigraphy and the channel forms producing them using industry-grade seismic volumes similar to those studied here. Of particular importance to our study are the empirical relationships developed by Armstrong et al. (2014; see their Fig. 11) that relate channel-belt width to channel-belt thickness. Their data, taken from 43 channel belts mapped for at least 10 km in the downstream direction, define power-law scaling relationships for the upper and lower limits on fluvial channel-belt geometry. We use these relationships here to estimate the range of thickness associated with our range for average belt width summarized in Fig. 17. These estimated thicknesses range from 16 m to 44 m.

Meandering channels are commonly characterized by point bars and lateral accretion of sediments. These processes result in mixed facies deposition of sediments as observed within the upper sections of the Oakville Sandstone and most of the Lagarto Formation. The Upper Biloxi Sandstone and Prairie Formation within the Belle Fontaine Point in Jackson County, Mississippi, preserve similar mixed-load facies (Otvos, 2001). Lateral migration and avulsion of a river channel is connected with incision and local removal of strata at least one channel depth thick. Substituting channel-belt thickness for bankfill river depth, we estimate local erosion tied to river-channel movement to range between 16 m and 44 m. No attempt to correct for compaction of the channel-belts is made here because porosity estimates at these burial depths yield a range of values overlapping those measured in modern environments (e.g., Armstrong et al., 2014). Given the relatively slow rates of sediment aggradation in the coastal system—0.2 mm/yr—these eroded thicknesses translate into stratigraphic time gaps of 8.1 × 10⁴ to 2.2 × 10⁵ years. These durations are long compared to the mobility of individual channels (Jerolmack and Mohrig, 2007). As a result, we should expect much channel movement over the time required to deposit strata greater than one channel belt in thickness, producing a discontinuous time-stratigraphic record dominated by amalgamated channel belts. Evidence for this belt amalgamation, preserved as discontinuous erosional remnants of channel-fill deposits, is clearly seen in the map-view plots of the variance attribute in Figs. 12, 13, 15 and 16.

Channel-belt dimensions have been recently shown to serve as useful parameters for estimating relative distance from the shoreline (Fig. 2; Blum et al., 2013; Fernandes et al., 2016). This proxy for shoreline proximity has been developed using data from modern rivers,
Fig. 20. Seismic transect B—B’ showing Faults A through D identified within the Miocene.

Fig. 21. Structure time map at Horizon 7 showing main deformational features (Faults A through D) identified in study area. Notice the asymmetric nature of the structure.
where spatial change can be directly measured. We have applied this newly developed tool to the interpretation of a thick stratigraphic section by substituting measurements collected through time from many rivers for horizontally distributed measurements from a single river. We justify swapping time for space because all of our data are collected from within a single environmental system represented by Fleming Group strata. Assuming that this substitution is valid, the following vertical patterns are expected for changes in shoreline position. For positions located within the backwater zone (Fernandes et al., 2016), shoreline progradation should be associated with a relative increase in channel-belt width. Shoreline retrogradation would show the inverse trend, with channel belts narrowing upward. Constancy in shoreline position would be recorded by aggradation with no systematic change in channel-belt width. This lack of a vertical trend is suggested by our measurements from belts of the Oakville Sandstone (Fig. 17), while channel belts from the Lagarto Formation display a widening-upward trend consistent with shoreline progradation. Because of these measured trends, we interpret the upper Oakville Sandstone of Refugio County as relatively aggradational coastal-plain deposit and the upper Lagarto Formation as a relatively progradational coastal-plain deposit. This relatively local interpretation is opposite of the preferred regional interpretations for both units originally proposed by Galloway et al. (1986).

5. Conclusions

This analysis of the paleogeographic evolution of the Lower Miocene Fleming Group in Refugio County, Texas documents two primary depositional systems—(1) shore-parallel beach-ridges within a continuous strandplain system and (2) dip-elongate fluvial systems composed of sinuous, mixed-load meanderbelts. These two systems together are associated with at least 12 km of shoreline progradation. A predominantly regressive phase was punctuated by two transgressive, retrogradational phases within the Anahua Formation and the Marginulina A shale, respectively. An overlying progradational succession records the formation of a thick and laterally extensive complex of amalgamated beach-ridge deposits and complex coeval fluvial-channel systems.

Strandplain systems in preserved as the basal components of both the Oakville Sandstone and Lagarto Formation in Refugio County are attached to a nonmarine system rather than separated from the mainland by lagoons or bays. We find no seismic evidence for lagoon facies representing a dominant depositional setting for Refugio County as proposed from well-log analysis by Galloway et al. (1986) and Galloway (1989a).

Lower Miocene depositional trends were controlled by sea-level changes and variations in sediment-dispersal as a result of avulsion. Long-lived strandplain systems record longshore-current transport processes coupled with limited sediment supply from poorly developed lower-coastal-plain fluvial systems. In contrast, strandplain systems in the basal Lagarto Formation were overrun by integrated fluvial systems that record complex depositional patterns of channel migration, erosion, and incision. Thick channel-belt systems were associated with efficient downstream channel movement and extensive fusion of channel belts.

This study concludes that potential reservoir geometries and architectures in the Lower Miocene stratigraphic succession on the central Texas Gulf Coast are much more complex than previously inferred, the result of rapidly fluctuating and evolving strike-fied shoreline systems and contemporaneous fluvial dip-dispersal systems. Three-dimensional seismic attribute maps show that thickness and areal extent of Lower Miocene reservoir systems are more variable than previously interpreted, as well as being dominantly shoreline-attached. Detailed knowledge of the lower Miocene paleogeography and dimensions of inferred sandstone bodies from this study can be a guide in improved reservoir-development strategies in this important hydrocarbon-bearing stratigraphic succession.

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