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# The Midway to Carrizo Succession in the Southeastern Texas Gulf Coast: Evolution of a Tidally-influenced Coastline

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## ABSTRACT

**This study demonstrates that the Upper Midway to Carrizo stratigraphic succession in southeastern Texas contains a greater variability in depositional systems, facies, and reservoir sandstone-body geometry than previously documented. It also documents significant tidal processes on sedimentation in the Wilcox Group and Carrizo Formation.**

**The study integrates wireline-log, core, and outcrop data in a 13,770 mi$^2$ (~35,660 km$^2$) area updip of and along the Wilcox shelf margin in southeastern Texas. It resolves and delineates a variety of net-sandstone geometries in tidally-modified delta, wave-dominated shoreline, and inner-shelf systems. Analysis of 1730 ft (~530 m) of slabbed core in Leon County and strata in outcrops near Bastrop, Texas, provides evidence for tidal modification of sediments throughout much of the Wilcox to Carrizo stratigraphic succession. Sandy depositional axes in many Wilcox sequences are narrow (<3 mi [<4.8 km]) and exhibit complex, elongate and anastomosing geometries consistent with deposits of tidally-modified systems. Tidal deposits in the Wilcox Group and Carrizo Formation occur at a variety of scales—microscale, mesoscale, and macroscale. Microscale tidal signatures in Wilcox cores and outcrops include cyclic, double-mud-draped ripples, and flaser and lenticular bedding, as well as systematically upward-thinning and upward-thickening sets of mud-draped bedforms and laminae. These features are common in distributary-channel, crevasse-splay, marsh/swamp, interdistributary-bay, tidal-flat, tidal-inlet, and tidal-bar deposits in the Wilcox to Carrizo stratigraphic succession.**

**Mesoscale tidal features in the basal Carrizo Formation at Bastrop include >3 ft (>0.9 m) thick, trough crossbed sets in tidal-bar facies with common *Ophiomorpha* and *Teredolites*, similar in scale and morphology to those in tidal-delta and tidal-bar deposits in the Cretaceous Sego Formation in southeastern Utah. Other mesoscale tidal features in the Sabinetown Formation consist of tidal-creek facies. They occur as 3–10 ft (0.9–3 m) thick, upward-fining successions filled with mud-draped and contorted beds of fine-grained sandstone to siltstone or mudstone with dispersed mud rip-up clasts. These features constitute both vertical and lateral discontinuities over scales of 2–5 ft (0.3–1.5 m) vertically and 15–25 ft (4.5–7.6 m) laterally.**

**Macroscale tidal heterogeneities in the Wilcox to Carrizo succession comprise facies architecture and geometries at a regionally mappable scale. These include paleogeographic elements such as fluvial-tidal channel complexes and interdistributary-bay and marsh systems. Channel trends inferred from net-sandstone maps in many Wilcox sequences are sinuous and narrow (commonly ≤4 mi [≤6.4 km] across) with an overall anastomosing geometry typical of tidally-modified, lower-coastal-plain settings.**

**Because of pervasive tidal modification throughout the Wilcox to Carrizo stratigraphic succession, the vertical and lateral complexity of reservoir systems is greater than previously inferred, implying an increased potential for reservoir heterogeneity and compartmentalization. The value of this study for exploration for oil and gas in the Upper Midway to Carrizo stratigraphic succession is three-fold as it (1) better**

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**resolves the net-sandstone geometry and paleogeography of individual regressive-transgressive depositional episodes in a series of detailed lithology maps, enabling explorationists to specifically target sandstone-rich depositional axes, (2) provides evidence for pervasive and widespread tidally-modified facies, with implications for increased reservoir heterogeneity, both vertically and laterally, and (3) demonstrates a greater variability in depositional systems than previously documented, thereby drawing attention to the need for more-diverse exploration models that address differences in distribution of potential reservoir sandstone bodies. These include strike-elongate, wave-modified systems (Midway 2 and Simsboro 4 sequences), downdip-bifurcating, fluvial-dominated deltaic systems (Simsboro 2 sequence), tributary systems in fluvial-delta plain systems (Hooper 2 sequence), and dip-elongate, anastomosing systems in tidally-modified deltaic systems (Calvert Bluff 4 sequence).**

## INTRODUCTION

The Wilcox Group has a >80 yr history of oil and gas production in the Texas Gulf Coast (Fisher and McGowen, 1967; Edwards, 1981; Galloway et al., 1983, 2011). In southeastern Texas, the Wilcox Group has been previously interpreted to be a succession of fluvially-dominated, wave-modified deltas (Fisher and McGowen, 1967; Fisher et al., 1969; Edwards, 1981) (Fig. 1). A system of rivers defined by narrow (<4 mi [<6.4 km] sandy depositional axes delivered sediments to deltaic complexes (Kaiser, 1974, 1976; Kaiser et al., 1978), who mapped lignite of fluvial and upper-delta-plain origin within these net-sandstone trends. Facies interpretations in many previous studies were based on correlation of thick (200 to 400 ft [61.5 to 122 m]) sections that combined several fourth-order sequences, resulting in the mapping of composite depositional systems. Separating out individual sequences at a higher resolution results in a more accurate interpretation of depositional systems and their evolution, and helps to significantly improve reservoir models.

This study includes segments of the Colorado, Brazos, Trinity, Angelina, and Neches depocenters within the regionally extensive Lower Wilcox Rockdale Delta System (Fig. 1). During deposition of the Midway and Wilcox groups, sediments were transported mainly to Texas from the ancestral Rocky Mountains in Colorado and Wyoming. Other sediments were sourced from an integrated trunk-stream system in Nebraska, Kansas, and Oklahoma in the Mid-Continent (Galloway et al., 2011; Sharman et al., 2017) (Fig. 2).

This study divides the Upper Midway Group to Carrizo Formation into twenty (20) high-resolution, fourth-order regressive-transgressive sequences, documents depositional styles, and charts Upper Midway to Carrizo shoreline trajectories (Figs. 3 and 4).

## OBJECTIVES

This study has five objectives, to: (1) divide the stratigraphic succession from the Midway Group to the Carrizo Formation into numerous high-frequency, regressive-transgressive episodes (hereafter referred to as "sequences") (Figs. 3 and 4), (2) construct detailed net-sandstone maps of each sequence to accurately depict sandstone-body geometries, (3) integrate core data with net-sandstone maps to infer facies and depositional systems to reconstruct the Midway to Carrizo depositional systems and paleogeography, (4) delineate relative shoreline positions for each sequence from interpretations of facies and sandstone-body geometry, and (5) identify depositional controls on sandstone-body reservoir architecture and heterogeneity.

## DATABASE AND METHODS

### Wireline-Log and Core Data

This study used data from approximately 300 wells with wireline logs in the Midway and Wilcox groups in a 13,770 mi$^2$ (~35,660 km$^2$) area that includes 18 counties in onshore southeastern Texas (Fig. 1). Data from 1730 ft (~530 m) of slabbed core in the Letco MV 9696.02 No. TOH–2A Settlemyre well (hereafter referred to as "Letco" well) in Leon County (see location in Figure 1 and wireline log in Figure 3) were used to describe and interpret facies and to calibrate net-sandstone values from wireline logs. Data recorded in these cores included grain size, stratification, contacts, as well as accessory features such as burrows, clay clasts, shells, in-situ lignite seams, and rhizoliths diagnostic of sedimentary processes and facies.

The Letco core contains examples of inner-shelf to lower-shoreface parasequences in the upper Midway Group and deltaic parasequences in the Wilcox Group. These parasequences are defined by sandy intervals ranging from 10 to 30 ft (3 to 9 m) thick. They are bounded above and below by 10 to 40 ft (3.0 to 12.0 m]) sections of mudstone interbedded with thin (<3 ft [<0.9 m]) lignite seams. Parasequences in the Letco core represent individual episodes of regression. They are typically upward-shoaling and upward-coarsening, bounded at the top by flooding surfaces that record episodes of transgression and regionally extensive coastal inundation by marine waters (e.g., Vail et al. 1977; Van Wagoner, 1985; Van Wagoner et al., 1990).

### Outcrop Data

Outcrops in the Wilcox to Carrizo stratigraphic succession (Hooper, Calvert Bluff, Sabinetown, and Carrizo formations) near Bastrop, Texas (located in Figure 1) were described to document vertical and lateral lithologic and facies variability and to supplement core descriptions, wireline cross sections, and net-sandstone maps. Plant and coaly material as well as trace fossil type, diversity, and abundance were also examined in outcrops and core. These data were used to augment facies interpretations.

### Stratigraphic Units

The stratigraphic succession from the Upper Midway Group to the Carrizo Formation is divided into 20 high-frequency, fourth-order sequences (Fig. 4), making it possible to resolve the sandstone-body geometries at a finer scale and more accurately depict the facies architecture. These 20 sequences range individually in thickness from 100 to 250 ft (30 to 76 m). They are bounded by regionally continuous muddy sections representing flooding surfaces. In marginal-marine systems, thinner sequences of the type defined in this study commonly define reservoir units (Van Wagoner et al., 1990; Vakarelov and Ainsworth, 2013). Sequences defined in this study, based on ages spanning the late Midway to Carrizo succession (Galloway et al., 2011; Sharman et al., 2017), are interpreted to each span from 300,000 to 500,000 yr, consistent with or slightly exceeding the age duration of fourth-order sequences defined by Van Wagoner et al. (1990).

This study defines and interprets 2 stratigraphic intervals in the upper part of the Midway Group (Fig. 3). These 2 intervals, informally named the Midway 1 and Midway 2 sequences, are each 120 to 240 ft (37 to 74 m) thick. They have serrate and upward-coarsening/serrate wireline-log responses.

Four (4) sequences in the Hooper Formation, the basal stratigraphic unit in the Wilcox Group, are defined (Fig. 3). Ranging individually in thickness from 50 to 140 ft (15 to 43 m) in the north part of the study area, they are part of the initial Lower Wilcox deltaic and shoreface succession that overlies strike-fed, wave-dominated, inner-shelf deposits in the upper part of the Midway Group.

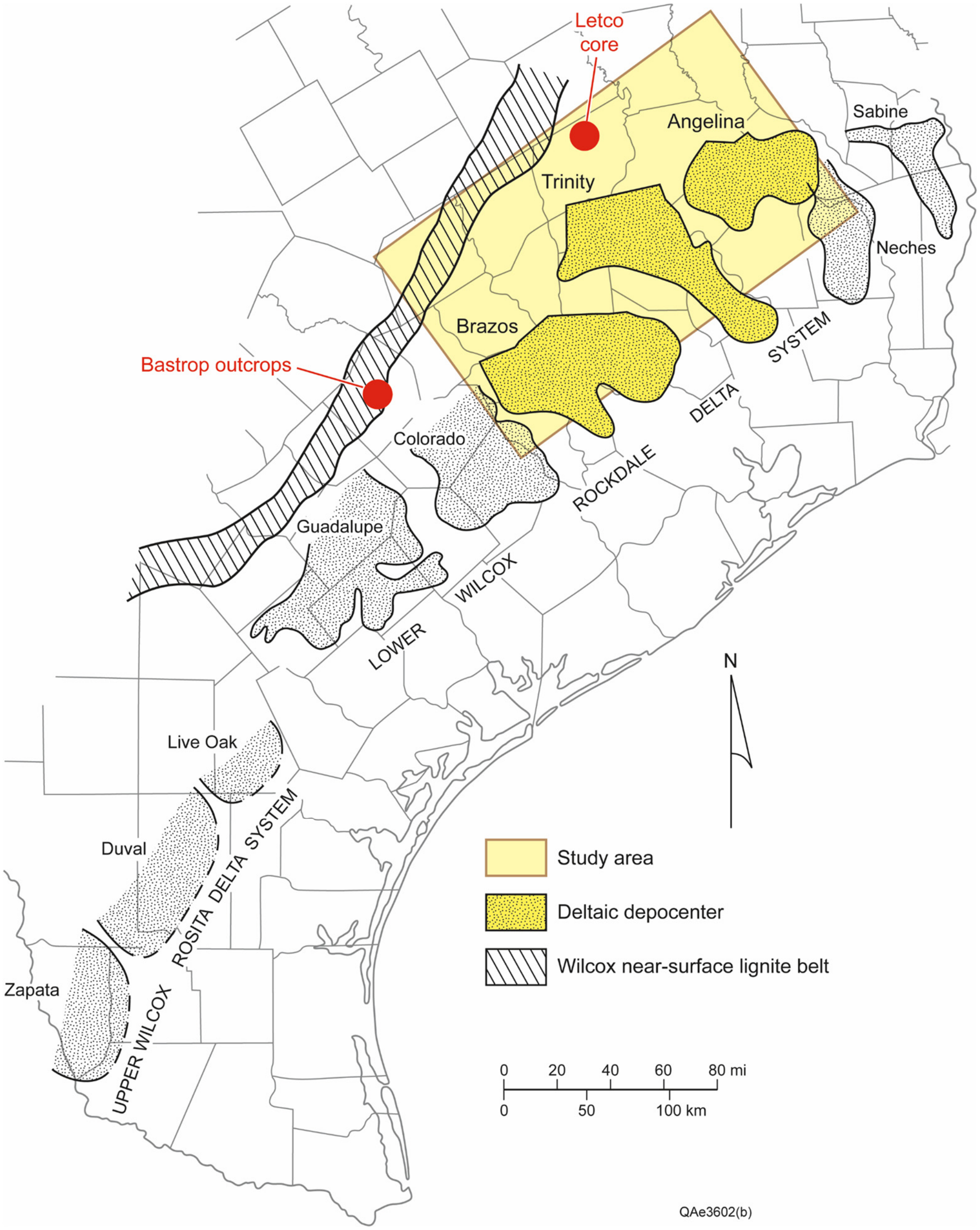

**Figure 1. Delta systems and deltaic depocenters in the Lower Wilcox Group in Texas, with outline of the study area. The study area includes parts of the Colorado, Brazos, Angelina, Trinity, and Neches depocenters. Location of the Letco MV 9696.02 No. TOH–2A Settlemyre core (referred to as the "Letco" core in successive figure captions) in Leon County is also shown. This core is located on the north margin of the Trinity depocenter in the Rockdale Delta System. Generalized location of Wilcox and Carrizo outcrops near Bastrop is also shown. Modified after Fisher and McGowen (1967) and Edwards (1981).**

The Simsboro Formation is divided into 6 sequences (Fig. 3). They collectively compose a 500 to 800 ft (152 to 244 m) succession in the upper half of the Lower Wilcox Group, consisting of a series of tidally-modified deltaic deposits, with minor occurrences of wave-modified shoreline deposits.

The Calvert Bluff Formation comprises the upper half of the Wilcox Group. It is divided into 6 sequences in this study (Fig. 3). The Calvert Bluff Formation is composed of sandy, tidally-modified deltaic deposits. As with the underlying Simsboro Formation, evidence for tidal modification of these deltaic deposits is observed in the Letco core, as well as in outcrops near Bastrop, Texas (located in Figure 3).

The Sabinetown Formation in the west-central part of the study area is a thin (40 to 50 ft [12 to 15 m]) section at the top of the Calvert Bluff Formation, where its upper surface is a high- gamma ray (GR), low-resistivity zone (Fig. 3). Representing a major transgressive section at the top of the Calvert Bluff Formation (Fisher and McGowen, 1967), the Sabinetown Formation is completely eroded by the Carrizo Formation in the northern part of the study area. The Carrizo Formation is sandstone-rich, with blocky and blocky-serrate wireline-log responses and exhibits abundant evidence of tidal processes in the Bastrop outcrops.

## Net-Sandstone Maps

Net sandstone from wireline logs was defined from a cutoff value of ~30% from a baseline of GR deflection to a consistent, leftward deflection that indicates minimum clay content. This value was determined by calibrating wireline-log response to values of net sandstone measured in core descriptions. For wells without the GR curve, the spontaneous potential (SP) curve was used to determine net-sandstone values with a cutoff value of 25%. The resistivity curve was also used in zones with poor GR and SP responses. These net-sandstone maps are isopach rather than isochore maps. Values of net sandstone were posted on maps and hand-contoured, with wireline-log responses used as a guide for contours.

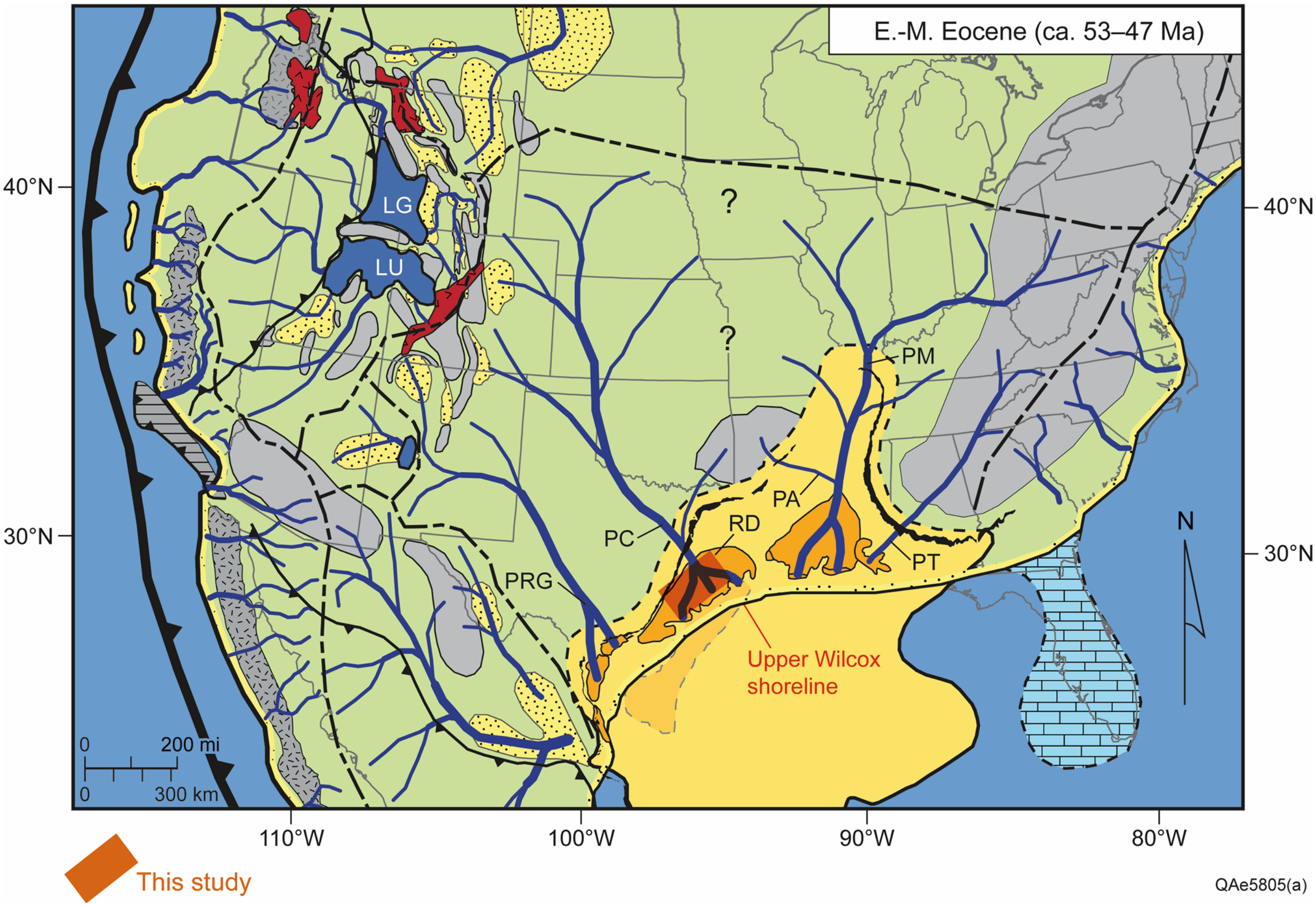

**Figure 2. Paleogeographic map of the early to middle Eocene (53 to 47 Ma) in the United States and parts of Mexico and Canada, showing source terranes, sediment-delivery systems, depositional settings, and location of study area. Southeastern Texas was located within the Rockdale (RD) depocenter that received sediments from the U.S. Mid-Continent and the central and northern ancestral Rocky Mountains. Modified after Sharman et al. (2017). Details of study area are shown in Figure 1.**

Use of wireline-log responses for facies types in Tertiary stratigraphic units in the Gulf Coast has been established by numerous authors, including the Wilcox Group (Fisher and McGowen, 1967; Edwards, 1981; Hamlin, 1983; Zhang et al., 2016), Frio Formation (Galloway and Cheng, 1985; Galloway, 1986; Tyler and Ambrose, 1986), and the Miocene succession (Doyle, 1979). Wireline-log responses for distributary-channel deposits were defined as blocky and upward-fining (upward-right deflections on GR and SP curves). Interchannel and floodplain facies were characterized by serrate and baseline wireline-log responses, respectively. Shoreface deposits were defined as having upward-coarsening (upward-left deflections) and upward-coarsening-to-blocky wireline-log responses. Shelf-bar facies in the Midway Group have predominantly upward-left, serrate and spiky deflections in GR and SP curves.

## Facies and Depositional Systems

Facies and depositional systems interpretations for each sequence were determined by integrating wireline-log character, net-sandstone maps, and core descriptions. Depositional systems were interpreted by analyzing spatial relationships between sandstone bodies in net-sandstone maps.

## Shelf Edges and Structural Controls on Deposition

The Angelina-Caldwell Flexure and Edwards Reef Trend were depicted on net-sandstone maps of all sequences in the Upper Midway to Carrizo stratigraphic succession in order to assess possible structural controls on sedimentation. Structural controls on deposition for each sequence defined and mapped were interpreted from increased net-thickness and net-sandstone values across faults. The Edwards Reef Trend and the Angelina-Caldwell Flexure were associated with the Upper Cretaceous shelf break (Siemers, 1978; Foss, 1979; Sohl et al., 1991; Bunge, 2007). These structural features also affected lower Tertiary accommodation and sedimentation patterns, documented in net-sandstone maps of Wilcox sequences.

## Shoreline Positions and Evolution of Depositional Systems

Shoreline positions were inferred from net-sandstone maps of each sequence in the Upper Midway to Carrizo stratigraphic succession. Relative shoreline positions for each sequence, shown in Figure 4, were interpreted from dominant facies and interpreted depositional environment along a strike-oriented (southwest-to-northeast) zone in the central part of the study area, approximately 10 mi (16 km) updip (northwest) of the

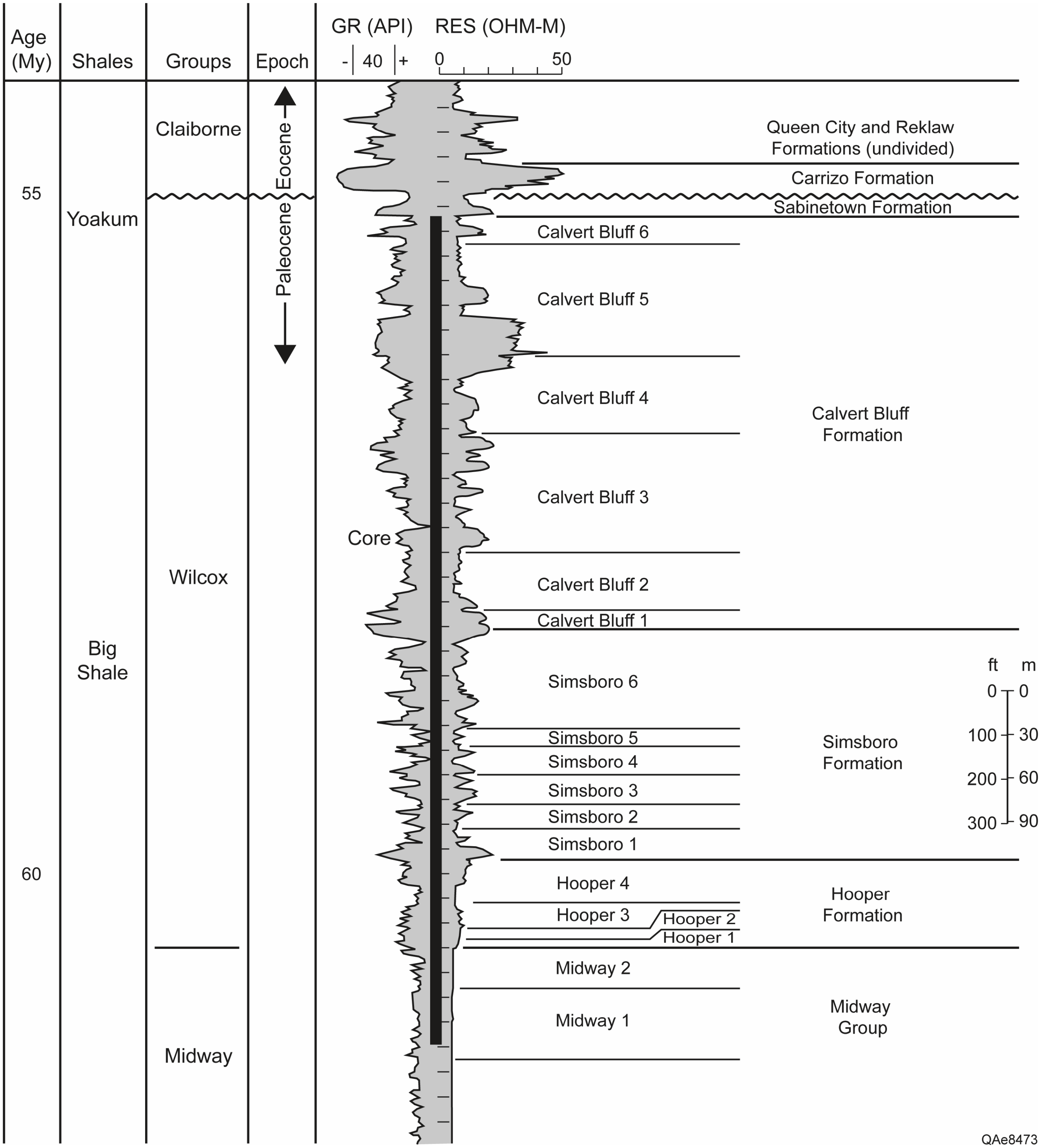

**Figure 3. Wireline log of the Letco well in northeast Leon County, including gamma ray (GR) and resistivity (Res) curves. Cored section and stratigraphic nomenclature used in this study are also shown. Location of cored well is shown in Figure 1. Modified after Sharman et al. (in press).**

Angelina-Caldwell Flexure. From distal to proximal, these are: (1) mid- to outer-shelf, (2) inner-shelf, (3) shoreface, (4) delta-front, (5) delta-plain, and (6) fluvial/delta plain.

For sequences composed of mid- to outer-shelf systems, average shoreline positions were interpreted to be updip (north and northwest) of the principal area of isolated and discontinuous, strike-elongate trends of net-sandstone bodies with <10 ft (<3 m) of net sandstone (Fig. 5A). Interpretation of inner-shelf systems was based on the occurrence of completely strike-elongate and relatively sandier systems with more laterally continuous trends compared to those of mid- to outer-shelf systems (Fig. 5B). Average shoreline positions within shoreface deposi-

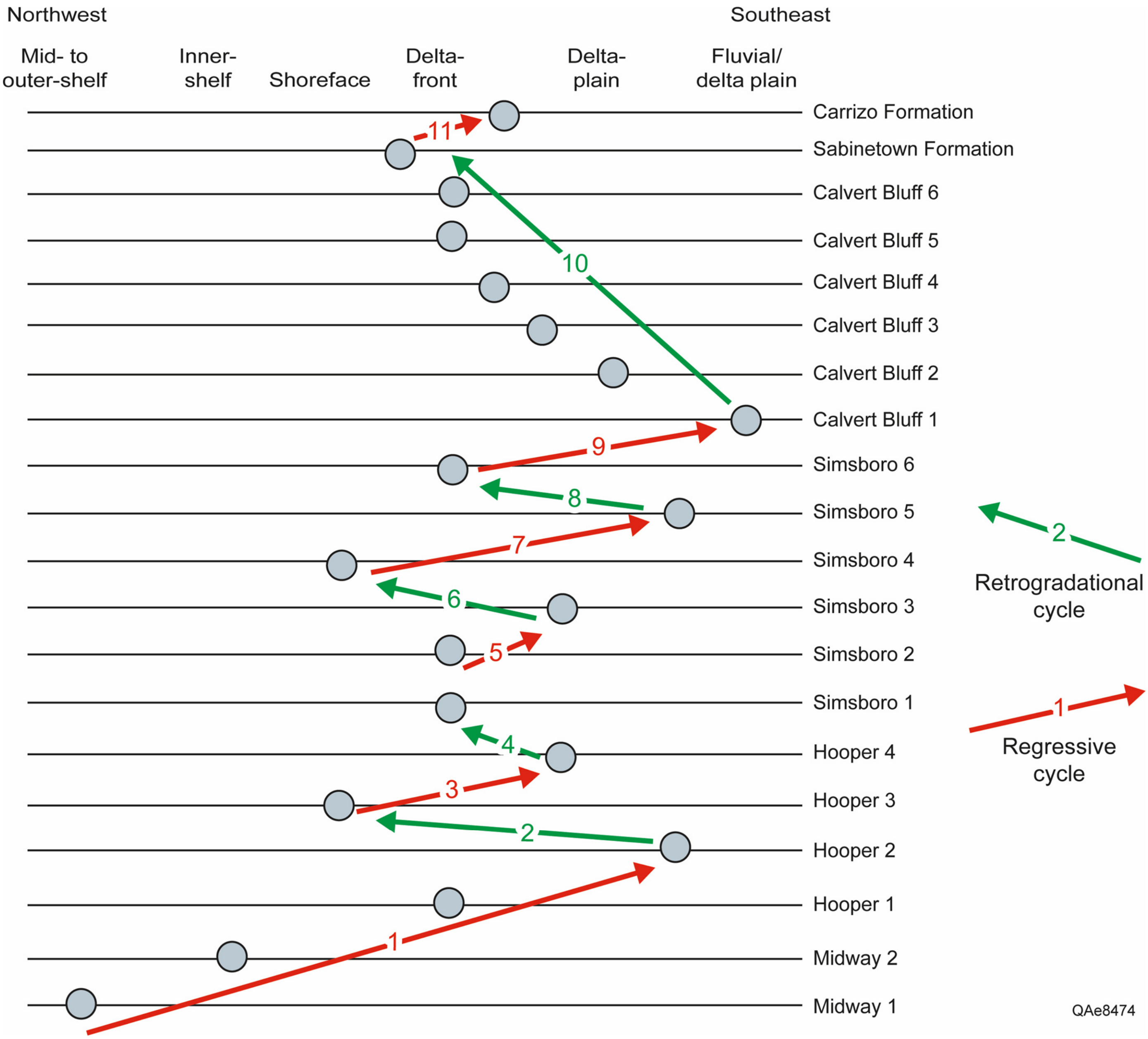

**Figure 4.** Shoreline-trajectory chart for twenty (20) Upper Midway to Carrizo fourth-order sequences in the study area. Interpretations of paleographic settings (mid- to outer-shelf, inner-shelf, shoreface, delta-front, delta-plain, and fluvial/delta plain) for each sequence are based on facies trends from core and net-sandstone patterns along the Angelina-Caldwell Flexure. Red arrows and associated circled red numbers indicate lower-frequency, regressive cycles, whereas green arrows and corresponding circled green numbers refer to retrogradational (transgressive) cycles. Explanation for interpretation of shoreline positions for each sequence is provided in "Database and Methods" section. Net-sandstone maps of representative sequences in the Upper Midway to Wilcox/Carrizo stratigraphic succession that illustrate these paleogeographic settings are shown in Figure 5.

tional systems were defined along the axis of regionally continuous, strike-elongate sandstone bodies where they merge with dip-elongate, south- and southeast-trending, narrow (commonly <2000 ft [<610 m]) sandstone bodies) (Fig. 5C). For delta-front settings, the average shoreline position was determined from the most downdip point of bifurcation of inferred distributary-channel elements, although points of downdip bifurcation of distributary-channel elements typically vary in downdip position within each sequence (Fig. 5D). Relative shoreline positions within delta-plain settings were determined in transitional areas between downdip-bifurcating, dip-elongate net-sandstone elements (interpreted as distributary channels) and similar net-sandstone elements exhibiting tributary patterns (Fig. 5E). Fluvial/delta plain interpretations were based on the identification of areas along and updip (north and northwest) of the point of tributary patterns within dip-elongate net-sandstone elements (Fig. 5F).

A shoreline-trajectory chart was constructed for these 20 sequences (Fig. 4). Because the paleoshoreline for many of these sequences was inferred to have been southward of the study area, this shoreline-trajectory chart only depicts relative paleographic positions. Lower-frequency depositional cycles are indicated by red and green arrows, from which major regressive and transgressive episodes are inferred, respectively. Examples of Midway

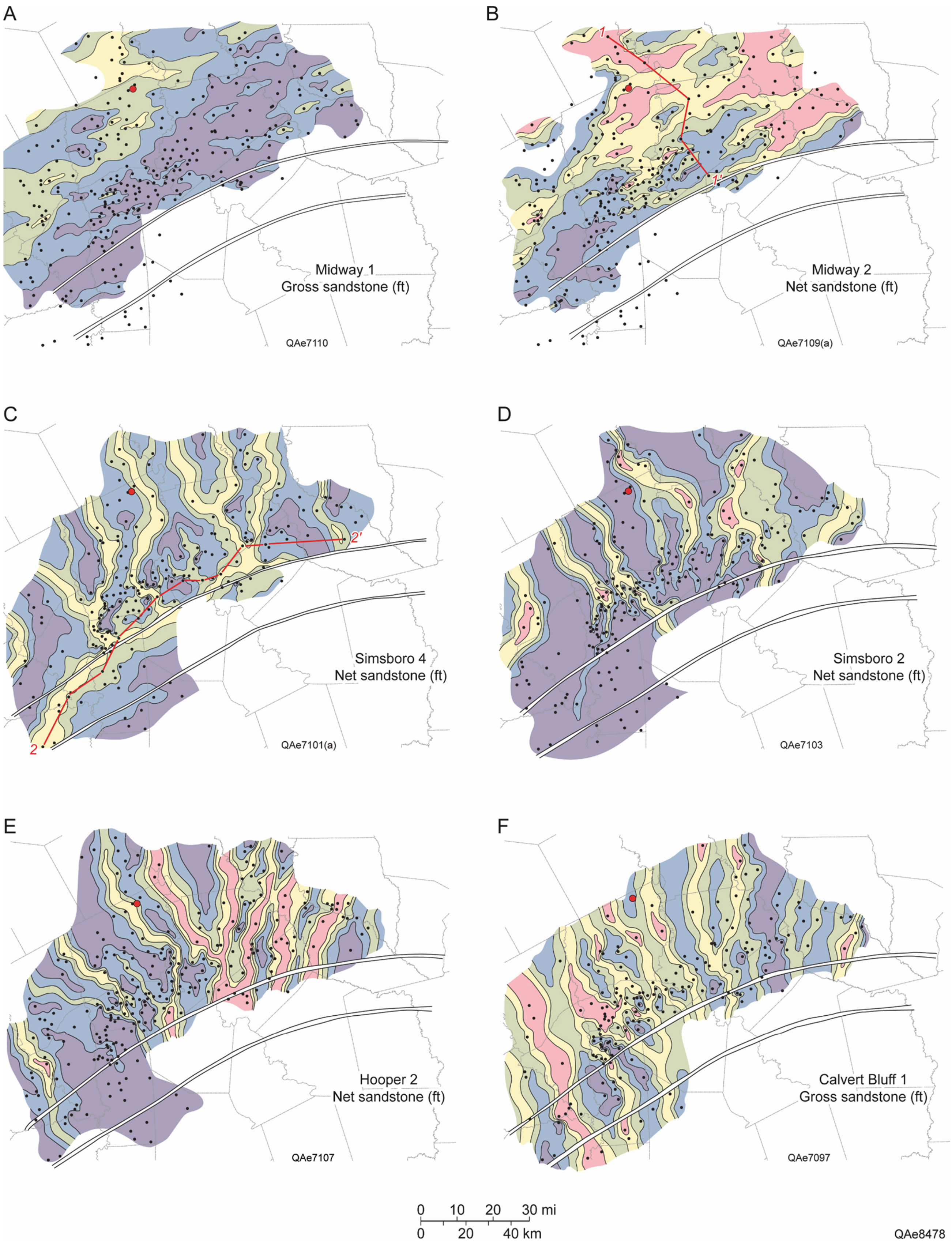

**Figure 5.** Net-sandstone maps that illustrate paleogeographic settings (mid- to outer-shelf, inner-shelf, shoreface, delta-front, delta-plain, and fluvial/delta plain) approximately 10 mi (16 km) updip of the Angelina-Caldwell Flexure from which relative shoreline positions are inferred in the Upper Midway to Wilcox/Carrizo stratigraphic succession. (A) Midway 1 sequence (mid- to outer-shelf). (B) Midway 2 sequence (inner-shelf). (C) Simsboro 4 sequence (shoreface). (D) Simsboro 2 sequence (delta-front). (E) Hooper 2 sequence (delta-plain). (F) Calvert Bluff 1 (fluvial/delta plain). These sequences are defined in the Letco type log in Figure 3. Shoreline-trajectory chart based on paleogeographic settings for each sequence is shown in Figure 4.

and Wilcox sequences that illustrate interpretations of different paleogeographic settings from net-sandstone maps are shown in Figure 5.

## SHELF SYSTEMS

## Midway 2

### Stratigraphic Occurrence

The Midway 2 sequence is the younger of 2 stratigraphic units in the Midway Group (Figs. 3 and 6). It ranges from 130 to ~200 ft (~40 to ~60 m) thick from northwest to southeast (Fig. 6). Wireline-log responses are upward-coarsening and muddy-serrate, with individual upward-coarsening sections ranging from 20 to 80 ft (6 to 24 m) thick (Fig. 6). Wireline-log responses in the updip (northwest) part of the Midway 2 sequence are dominantly upward-coarsening, whereas those downdip (southeast) are serrate, baseline, spiky, and muddy-serrate (Fig. 6).

### Lithology

The upper 37 ft (11.3 m) of the Midway 2 sequence is cored in the Letco well (Fig. 7). This interval consists of siltstone and mudstone beds and burrowed, fine-grained sandstone beds in 5 to 10 ft (1.5 to 3 m), upward-coarsening sections. These upward-coarsening sections range from silty, burrowed, very fine-grained sandstone with planar stratification at the base (Fig. 8A) to fine-grained sandstone with oversteepened stratification and soft-sediment deformation at the top (Fig. 8B). The tops of other upward-coarsening intervals contain cross-cutting and swaley cross stratification (Fig. 8C). The upper 15 ft (4.5 m) of the Midway 2 sequence is composed of very fine-grained sandstone and siltstone with abundant burrows (Fig. 8D). The top of the sequence occurs within a 4 ft (1.2 m) bed of silty mudstone at 2134 ft (650.6 m) (Fig. 7).

### Net-Sandstone Distribution

The Midway 2 sequence is dominated by northeast-trending sandstone bodies, with greatest values of net sandstone (>40 ft [>12 m]) in irregular patterns aligned along depositional strike (Fig. 9). There is no systematic decrease in net-sandstone values from northwest to southeast in the Midway 2 sequence, especially in the central and east parts of the study area, although an extensive, sandstone-poor area with <20 ft (<6 m) of net sandstone occurs in Grimes, Brazos, and Washington counties (Fig. 9).

### Facies Interpretation

The Midway 2 sequence represents a transition from inner-shelf to lower-shoreface deposits. This interpretation is based on (1) the dominant orientation of sandstone bodies along depositional strike (southwest to northeast), (2) an absence of updip feeder systems, (3) a *Cruziana*-dominated trace-fossil assemblage consisting mostly of *Schaubcylindrichnus*, *Planolites*, and *Teichichnus* (Figs. 7 and 8A), and (4) sedimentary structures that record open-marine, wave-dominated processes such as swaley bedding (Fig. 8C).

The upper part of the Campanian Lewis Shale and the overlying Lower Pictured Cliffs Sandstone in the San Juan Basin in Colorado and New Mexico are depositional analogs for the Midway 2 sequence. The Upper Lewis Shale consists of a silty mudstone grading upward into muddy siltstone interbedded with thin (<1 ft [<0.3 m]), very fine-grained, planar-stratified sandstones (Manfrino, 1984; Ayers et al., 1994). Individual sandstone beds in the Lower Pictured Cliffs Sandstone are sharp-based, with scoured bases. Stratification is dominated by low-angle and horizontal, planar stratification. Other stratification consists of concordant-to-wavy and swaley bedding overlain by ripples and plane beds that record storm and fair-weather processes, respectively, on a wave-dominated shelf.

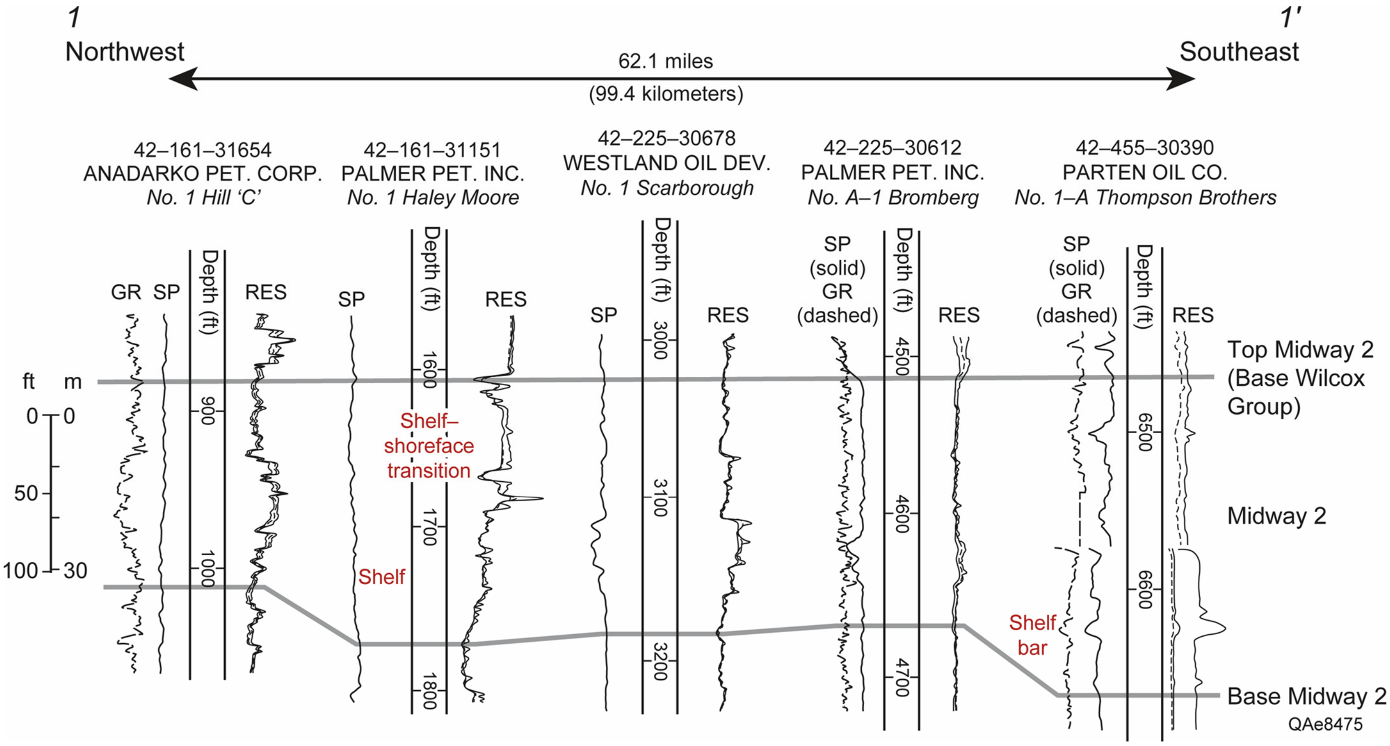

**Figure 6. Northwest-southeast stratigraphic dip section 1–1' in the Midway 2 sequence. Datum is the top of the Midway Group (top of the Midway 2 sequence). Line of section is shown in Figure 9.**

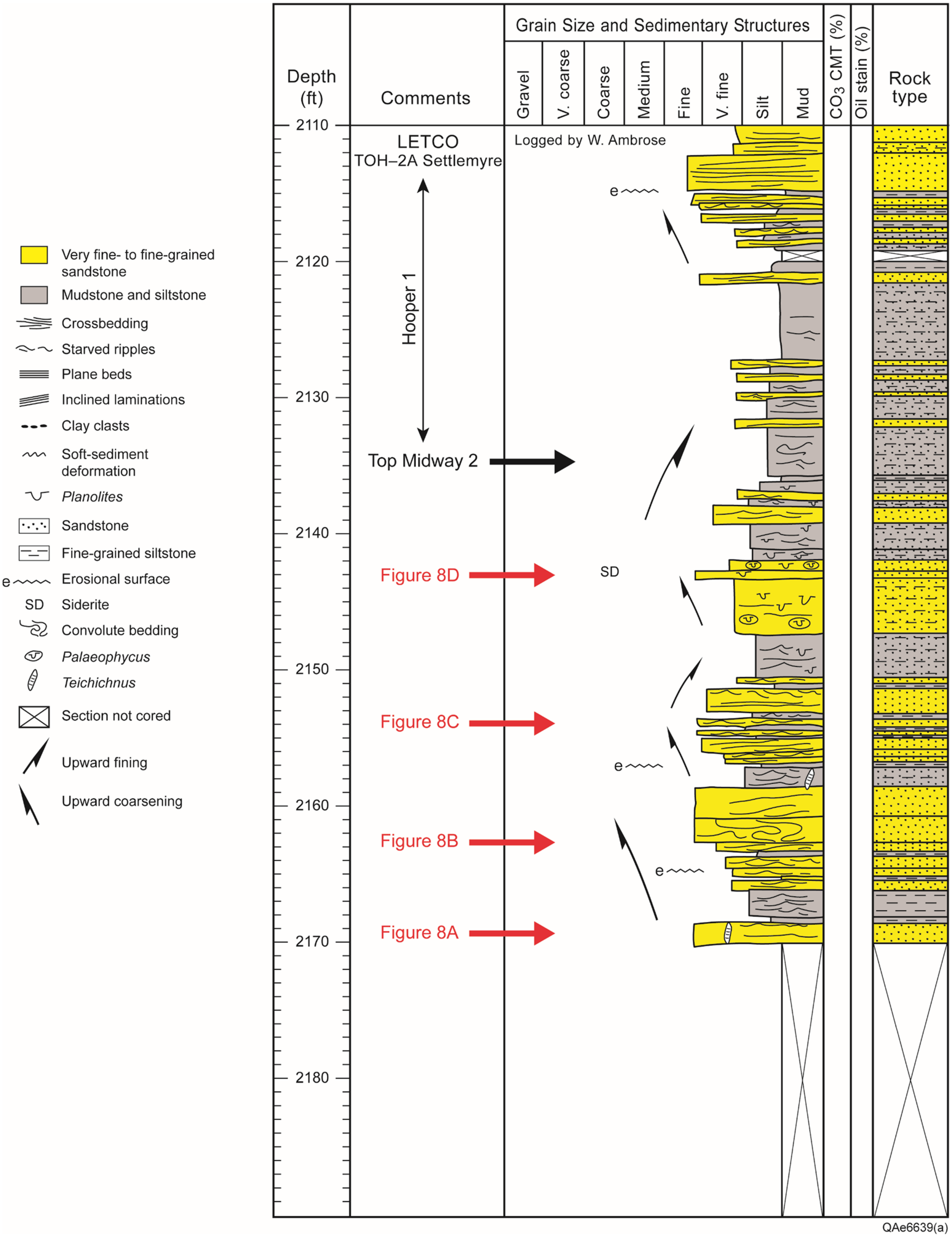

**Figure 7. Description of the Letco core from 2,110 to 2,170 ft (643.3 to 661.2 m), showing the upper 35 ft (10.7 m) of the Midway 2 sequence and the lower 25 ft (7.6 m) of the Hooper 1 sequence. Selected core photographs are shown in Figure 8. Location of cored well is shown in Figures 1 and 9.**

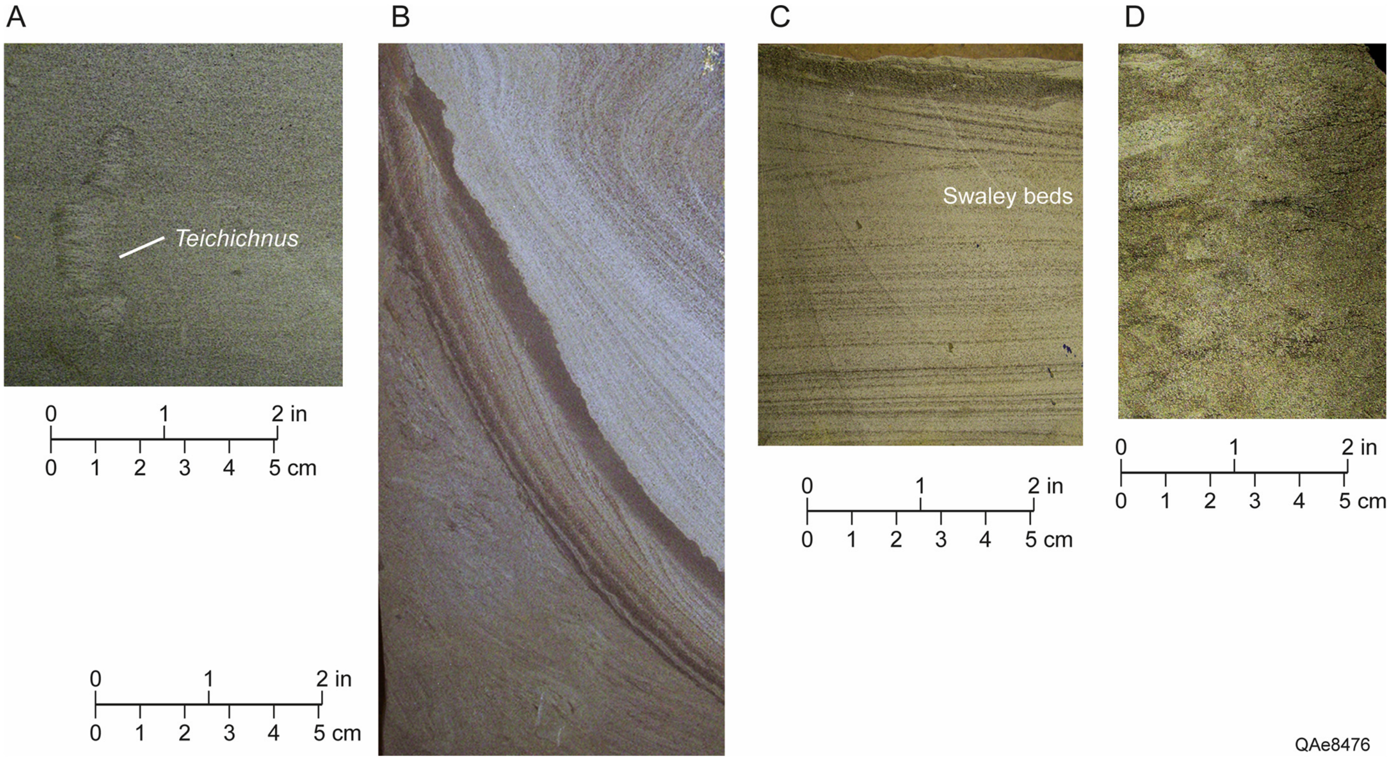

**Figure 8. Photographs of the Letco core in the Midway 2 sequence. (A) Silty, very fine-grained, laminated sandstone with *Teichichnus* at 2169.4.0 ft (661.4 m). (B) Fine-grained sandstone with folded and oversteepened stratification at 2162.0 ft (676.7 m). (C) Swaley cross stratification in fine-grained sandstone at 2154.0 ft (659.1 m). (D) Intensely-burrowed section of very fine- to fine-grained sandstone at 2142.4 ft (653.2 m). Dark material is composed of organic fragments. Core description is shown in Figure 7. Location of cored well is shown in Figures 1 and 9.**

# SHOREFACE SYSTEMS

## Simsboro 4

### Stratigraphic Occurrence

The Simsboro 4 sequence is in the middle part of the Simsboro Formation (Fig. 3). It is sandstone-rich and ranges in thickness from 80 to 150 ft (24 to ~45 m) in the central part of the study area (Fig. 10). Wireline-log responses include blocky, blocky-serrate, and upward-coarsening/blocky patterns (wells in the northeast part of cross section 2–2' in Fig. 10). The Simsboro 4 sequence truncates the Simsboro 3 sequence in the south part of Houston County (fourth well from the northeast end of cross section 2–2' in Figure 10).

### Lithology

The Simsboro 4 sequence in the Letco core contains 2 main sandy sections (Fig. 11). The lower sandy section extends from 1732 to 1752 ft (528.0 to 534.1 m). It consists of an upward-fining succession bounded above and below by lignite seams. The basal part of the section contains crossbedded and ripple-stratified, fine- to medium-grained sandstone (Figs. 12A and 12B). The middle part of the section is composed of ripple-stratified, very fine- to fine-grained sandstone with *Planolites* (Fig. 12C). The upper 10 ft (3 m) is composed of beds of very fine-grained sandstone and muddy siltstone rhizoliths (root traces) and organic fragments (Fig. 11).

The upper, sandy section in the Simsboro 4 sequence in the Letco core is upward-coarsening above a lignite seam at 1730 ft (527.4 m) (Fig. 11). A thin (<1 ft [<0.3 m]) lignite seam at 1720 ft (524.4 m) occurs above a siltstone bed and very fine-grained sandstone beds with rhizoliths. The section above this lignite seam is relatively coarser grained, with multiple beds of ripple-stratified, fine-grained sandstone (Fig. 12D). The top of the section contains 3 thin (individually <1 ft [<0.3 m]) lignite seams and carbonaceous shale beds above a rooted zone at 1716 ft (523.2 m) (Fig. 11).

### Net-Sandstone Distribution

The Simsboro 4 sequence displays 2 main net-sandstone trends (Fig. 13). Updip areas to the north and northwest contain south- and southeast-trending belts of ≥80 ft (≥24.4 m) of net-sandstone that merge into a narrow (up to 5 mi [8 km]) trend of ≥80 ft (≥24.4 m) of net-sandstone oriented southwest-to-northeast (Fig. 13). The south- and southeast-trending belts display downdip-tributary patterns, with merging sandstone bodies having >60 ft (>18 m) of net sandstone in southwest Madison, north Houston, and north Trinity counties. The southwest-northeast-trending belt of net sandstone is aligned along the Angelina-Caldwell Flexure throughout most of the study area, although it cuts across it to the southwest.

### Facies Interpretation

The Simsboro 4 sequence was deposited in a lower-coastal-plain setting along a wave-modified shoreline. This interpretation is based on continuous, southwest-northeast-trending sandstone bodies in the south part of the study area (Fig. 13). In contrast to the sandstone-body geometry of dip-feeder systems in many other Wilcox sequences that exhibit downdip-bifurcating patterns, the dip-feeder system in the Simsboro 4 sequence contains tributary patterns in the north part of the study area (Fig. 13).

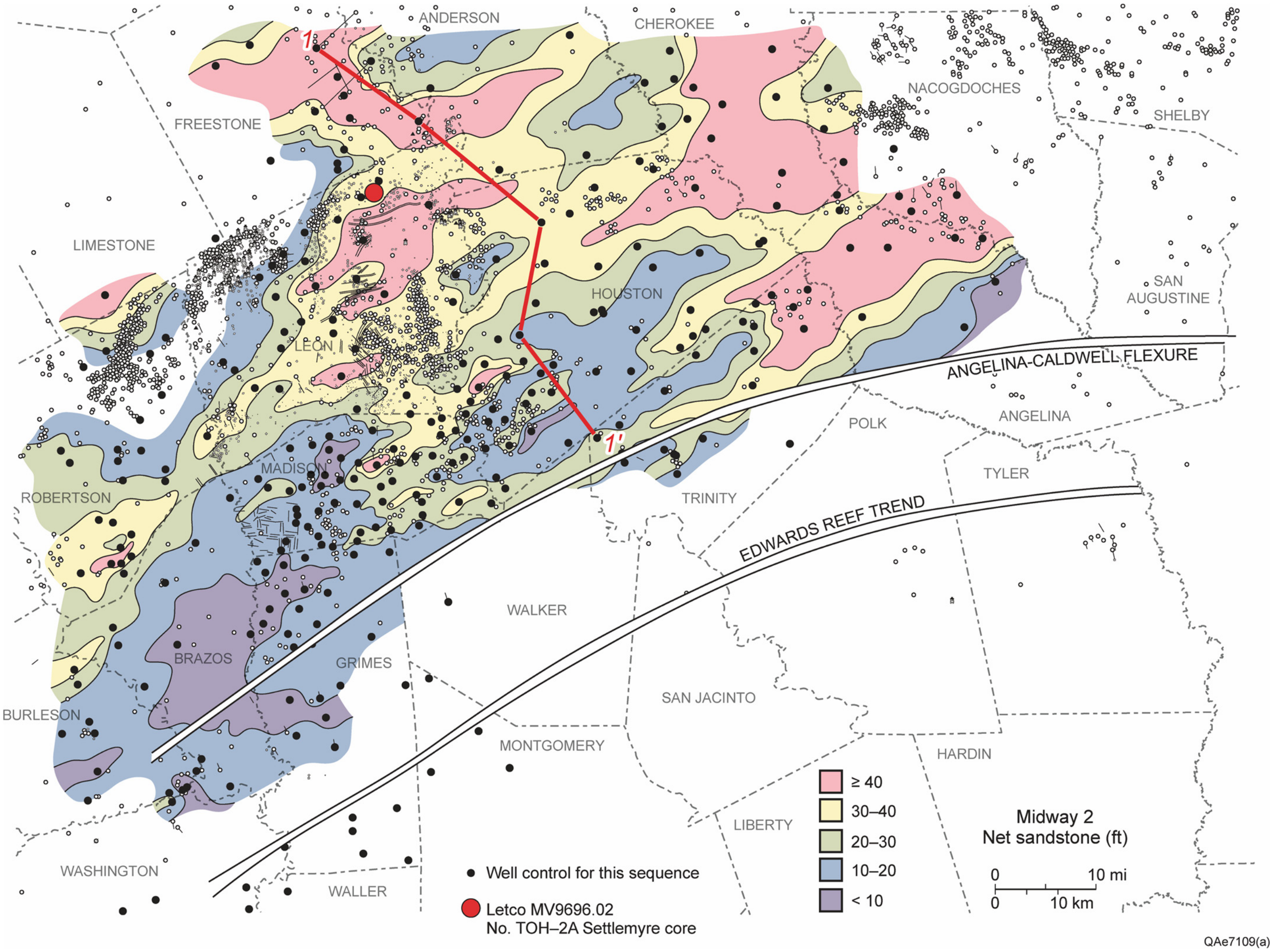

**Figure 9. Net sandstone, Midway 2 sequence. Northwest-southeast stratigraphic dip section 1–1' is shown in Figure 6. Core description is shown in Figure 7 and core photographs are shown in Figure 8.**

Facies in the Simsboro 4 sequence, interpreted in the Letco core, are distributary channel, crevasse splay, and swamp (Fig. 11). Crevasse-splay deposits are recorded by 10 ft (3 m), upward-coarsening sections of silty mudstone with abundant organic material, grading upward into fine-grained sandstone with rhizoliths (Fig. 11).

Distributary-channel facies in the Simsboro 4 sequence consist of 20 ft (6 m), upward-fining sections of crossbedded, medium-grained sandstone above an erosional base. The section grades upward into burrowed, very fine-grained sandstone and sandy siltstone with rhizoliths (Figs. 11, 12A, and 12B). The distributary-channel deposit in Figure 11 is in erosional contact with a lignite seam. This type of stratigraphic relationship of channel deposits directly overlying but not completely eroding lignite and coal seams is commonly observed in many outcrops and cores. Peat deposits are more resistant to erosion than less-cohesive sand partly because they have a durable, mat-like consistency and undergo compaction (Donaldson, 1979; van Asselen et al., 2009). This compaction inhibits vertical scouring and promotes lateral migration, creating laterally continuous sandbodies that overlie coals (Flaig et al., 2011). Examples of laterally continuous coal seams preserved directly below channel-fill sandstone bodies include extensive coal seams in the Fruitland Formation in the San Juan Basin (Roberts, 1989; Ambrose and Ayers, 1994), coal seams underriding channel-sandstone lenses in the Rock Springs Formation in the greater Green River Basin in Wyoming (Levey, 1985; Laubach et al., 1993; 2000), and laterally extensive sandbodies overlying coal and carbonaceous shale in lower-delta-plain deposits of the Prince Creek Formation in northern Alaska (Flaig et al., 2011).

The lower coastal plain between fluvial/distributary feeder systems is occupied by a system of small-scale creeks and streams in the Holocene Gulf Coast (Boyd and Dyer, 1964; Bernard et al., 1970), comparable to those of similar systems in the Simsboro 4 sequence. Net sand values in lower reaches of the Brazos River are 20 to 50 ft (6 to 15 m) (Bernard et al., 1970). In contrast, lower-coastal-plain, fluvial-distributary systems in the Simsboro 4 sequence contain >80 ft (>24 m) of net sandstone and are spaced at only 10 to 20 mi (16 to 32 km) intervals (Fig. 13), suggesting larger-scale and sandier rivers with greater sediment supply in the Simsboro 4 sequence relative to those in the Holocene Brazos streamplain.

## FLUVIAL-TIDAL SYSTEMS

### Calvert Bluff 2

#### Stratigraphic Occurrence

The Calvert Bluff 2 sequence is the second-oldest sequence in the Calvert Bluff Formation (Fig. 3). It is sandstone-rich,

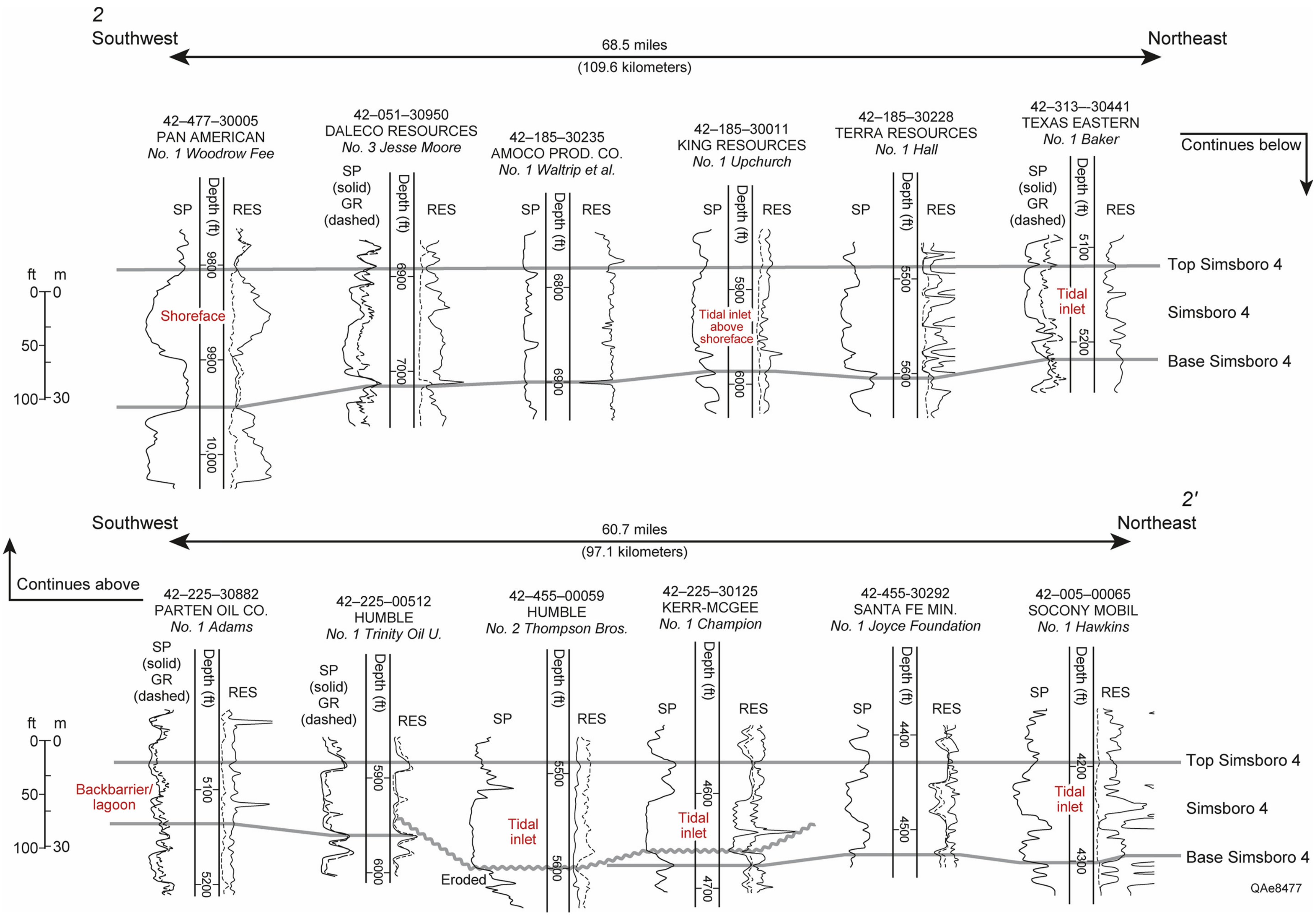

**Figure 10.** **Southwest-northeast stratigraphic strike section 2–2’ in the Simsboro 4 sequence. Datum is the top of the Simsboro 4 sequence. Line of section is shown in Figure 13.**

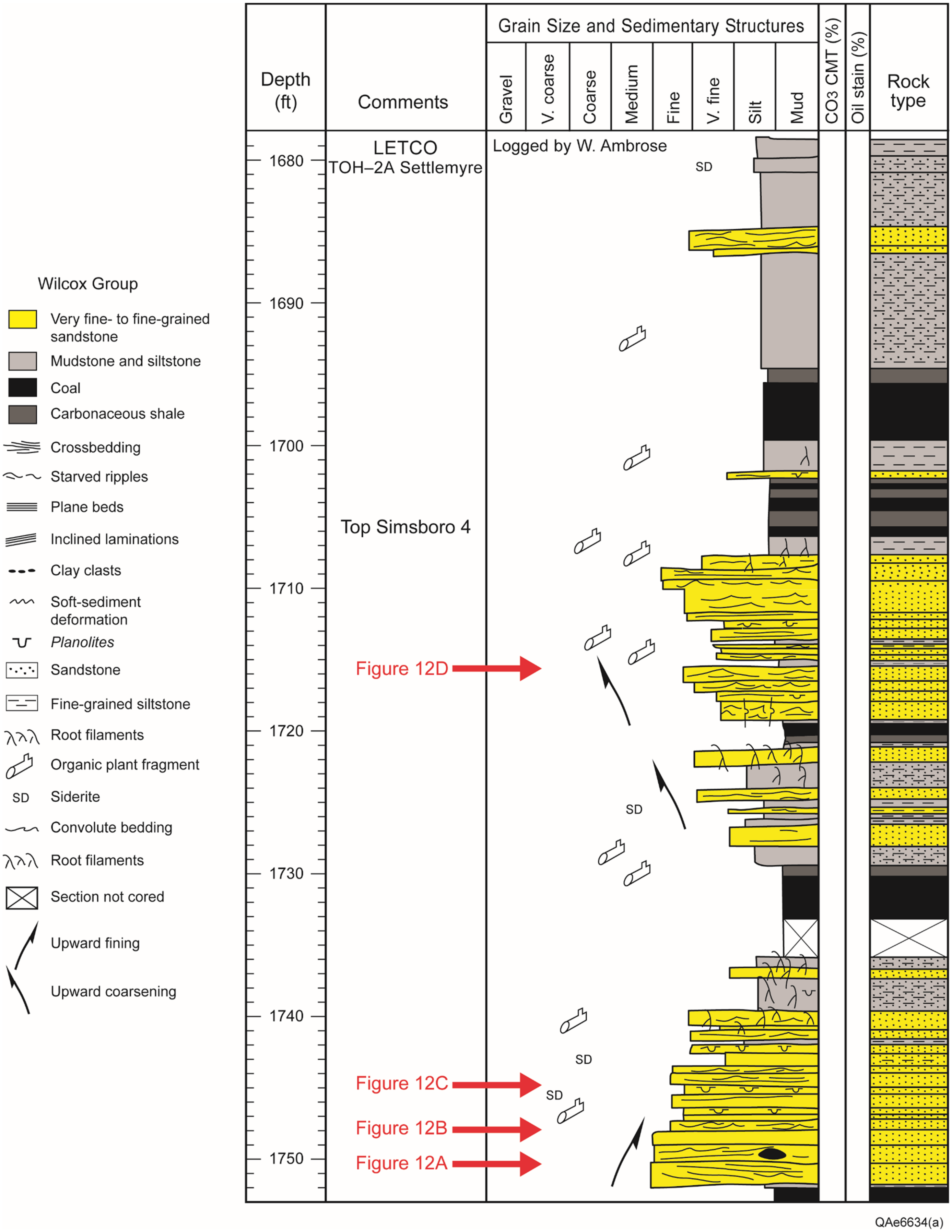

**Figure 11. Description of the Letco core from 1678 to 1753 ft (511.6 to 534.5 m), showing most of the Simsboro 4 sequence. Location of cored well is shown in Figures 1 and 13. Selected core photographs are shown in Figure 12.**

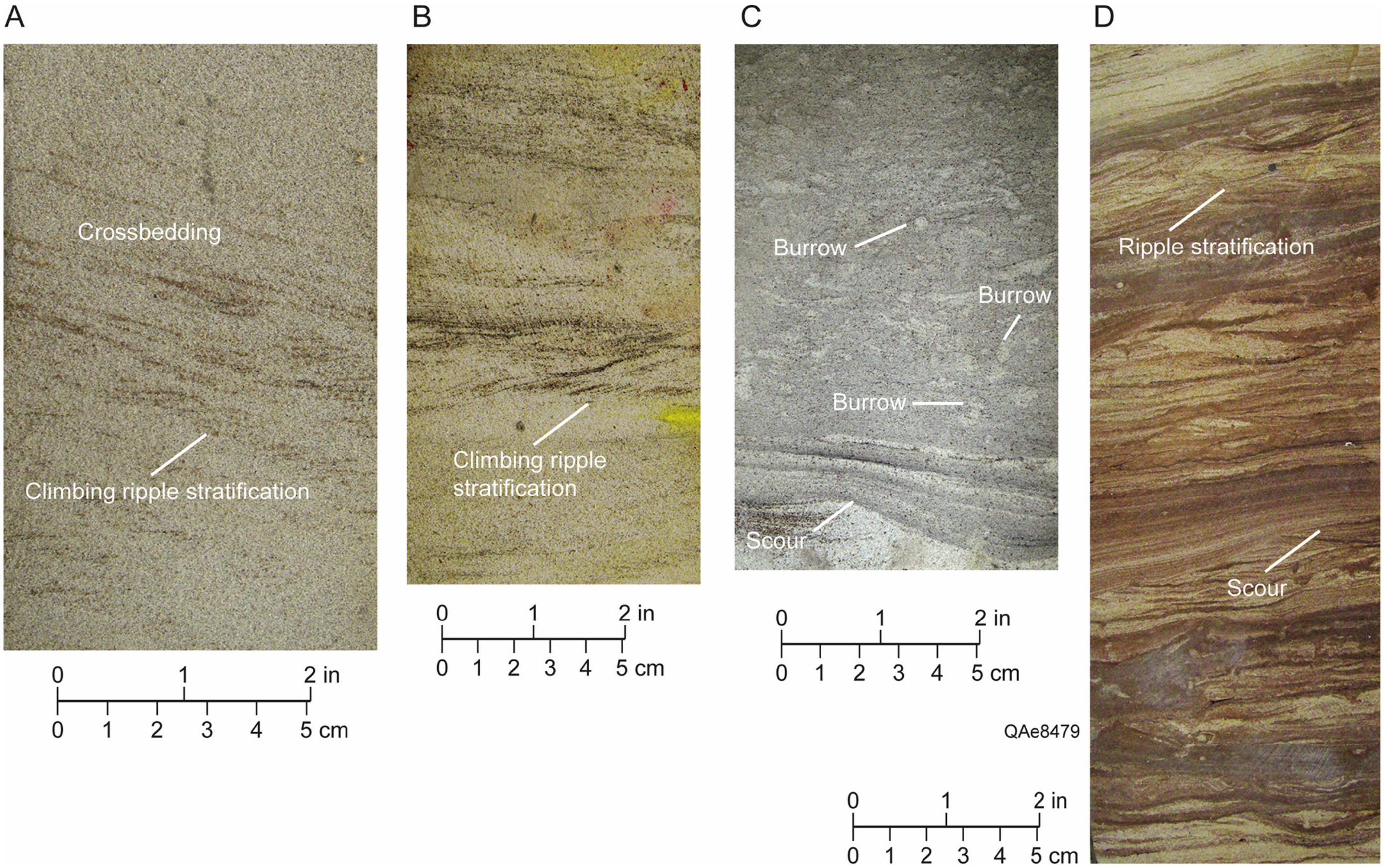

**Figure 12. Photographs of the Letco core in the Simsboro 4 sequence. (A) Medium-grained, crossbedded sandstone with minor ripple stratification at 1750.6 ft (535.4 m). (B) Upper fine-grained sandstone with climbing ripples and inclined planar stratification at 1748.0 ft (532.9 m). (C) Very fine-grained sandstone at 1745.0 ft (532.0 m). Burrows are primarily *Planolites* with minor *Teichichnus*. (D) Fine-grained, ripple-stratified and arcuate-to-planar-stratified sandstone with scour surfaces and iron-oxide staining at 1715.6 ft (523.0 m). Core description is shown in Figure 11. Location of cored well is shown in Figures 1 and 13.**

commonly displaying blocky and blocky-serrate wireline-log responses (Fig. 14). The Calvert Bluff 2 sequence increases in thickness downdip (northwest to southeast) from 230 ft (70 m) to >400 ft (>122 m) where it truncates the Calvert Bluff 1 sequence (see Galjour Exploration Company No. 1 Cole: third well from southeast end of cross section 3–3' in Figure 14). Wireline-log responses in the Calvert Bluff 2 sequence have a greater upward-coarsening component from northwest to southeast (see the HNG Fossil Fuels No. 1 Central Cole & Coke and Phillips Petroleum Company No. 1 Coke A wells on the southeast end of cross section 3–3' in Figure 14).

## Lithology

The Calvert Bluff 2 sequence in the Letco core is from 1298 to 1413 ft (395.7 to 430.8 m) (Figs. 15 and 16). It is composed of 2 upward-coarsening sections, with a lower section from 1363 to 1413 ft (425.6 to 430.8 m) (Fig. 15) and an upper section from 1298 to 1350 ft (411.6 m) (Figs. 15 and 16). The lower, upward-coarsening section grades upward from mudstone with discontinuous lenses of very fine-grained sandstone with starved current ripples (Fig. 17A) to very fine- to fine-grained, burrowed sandstone with millimeter-scale mud drapes (Fig. 17B). In contrast, the upper section is thicker and coarser grained. The lower part of this section consists of millimeter- to centimeter-scale beds of very fine-grained sandstone with coaly laminae (Fig. 17C). The thickness of individual sandstone beds between coaly laminae systematically decreases upward in some intervals in this section (lower part of Fig. 17C). The section is composed of beds of very fine- to fine-grained sandstone with stratification dominated by mud-draped current ripples above organic-rich beds of very fine-grained sandstone with coaly laminae (Fig. 18). As with sandstone beds in the lower part of Figure 17C, individual sandstone beds in Figure 18C are upward-thinning, associated with correspondingly thicker mud drapes. Other stratification in the section occurs as truncated, high-angle planar beds (Fig. 18B).

## Net-Sandstone Distribution

The Calvert Bluff 2 sequence is sandy, with depositional axes composed of dip-elongate and sinuous belts of >200 ft (>61 m) of net sandstone (Fig. 19). These belts have both tributary and anastomosing patterns, with an anastomosing geometry in Houston, Trinity, Madison, and Grimes counties. Minor tributary patterns occur in north Washington and northeast Houston counties.

## Facies Interpretation

Although the net-sandstone geometry of the Calvert Bluff 2 sequence appears to be fluvial because it contains tributary patterns (Fig. 19), the section in the Letco core suggests a tidally-influenced, lower-delta-plain setting, with muddy, burrowed siltstones and very fine-grained sandstone beds with *Planolites*

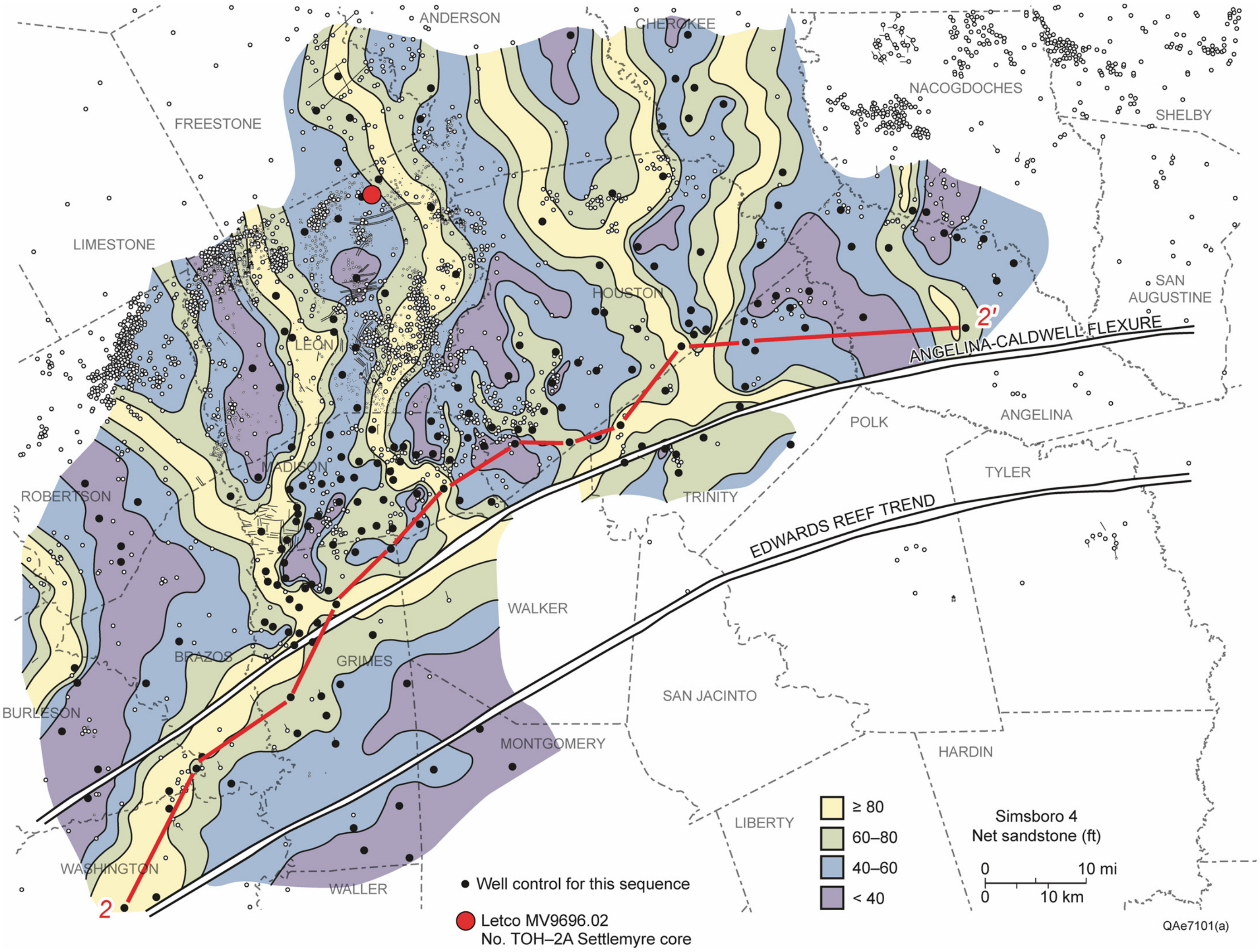

**Figure 13. Net sandstone, Simsboro 4 sequence. Southwest-northeast stratigraphic strike section 2–2' is shown in Figure 10. Core description is shown in Figure 11.**

and *Schaubcylindrichnus*, overlain by upward-coarsening sections with *Skolithos* (Figs. 15 and 16). Stratification in the Calvert Bluff 2 sequence is dominated by lenticular beds of very fine-grained sandstone and repetitive mud-draped current ripples, features consistent with tidal processes with fluctuating depositional energy (Figs. 17A, 18A, 18C, and 18D). Moreover, many sandstone beds in zones composed of these mud-draped ripples and muddy laminae exhibit systematic changes in bed thickness upward, consistent with cyclicity and sequentially changing amplitude in strength of tidal currents (Kvale et al., 1989; Kvale and Archer, 1990; Kvale et al., 1999; Ambrose et al., 2015). Anastomosing and sinuous distributary-channel patterns such as those in the net-sandstone map of the Calvert Bluff 2 sequence, particularly in Houston and Trinity counties (Fig. 19), are common in tidally-influenced, distal distributive settings. Vigorous flood-tidal currents in these systems choke distributaries with sediment, which meander and merge to maintain channels of constant depth (Wright et al., 1973; Oomkens, 1974; Dalrymple, 1992). In contrast to abandoned distributaries in fluvial-dominated deltas, those in tide-dominated deltas are commonly kept open by repetitive tidal action, resulting in heterogeneous abandoned-distributary channel fills and dip elongate architectural elements.

# SABINETOWN FORMATION

## Stratigraphic Occurrence

The Sabinetown Formation in south Madison County is a 40 to 50 ft (12 to 15 m) section at the top of the Calvert Bluff Formation, where its upper surface is a high-GR, low-resistivity zone (see Brewster Bartle No. 1 M.D. Neville well on the northwestern end of cross section 4–4' in Figure 20). The Sabinetown Formation thickens to approximately 120 ft (36.6 m) to the southeast in Grimes County (see Phillips Petroleum Company No. 1 Coke A well on southeast end of cross cross section 4–4' in Figure 20). It is completely eroded by the Carrizo Formation along a line extending from northeast Brazos to northwest Angelina County (Fig. 21), where net-sandstone patterns in the Carrizo Formation are dominated by dip-elongate, south-trending elements (Fig. 22).

## Lithology and Paleontology

The Sabinetown stratigraphic succession at Copperas Creek southeast of Bastrop, Texas, consists of an upward-coarsening section of sparsely- to moderately-burrowed, silty mudstone with thin sand lenses that grades upward into moderately-burrowed,

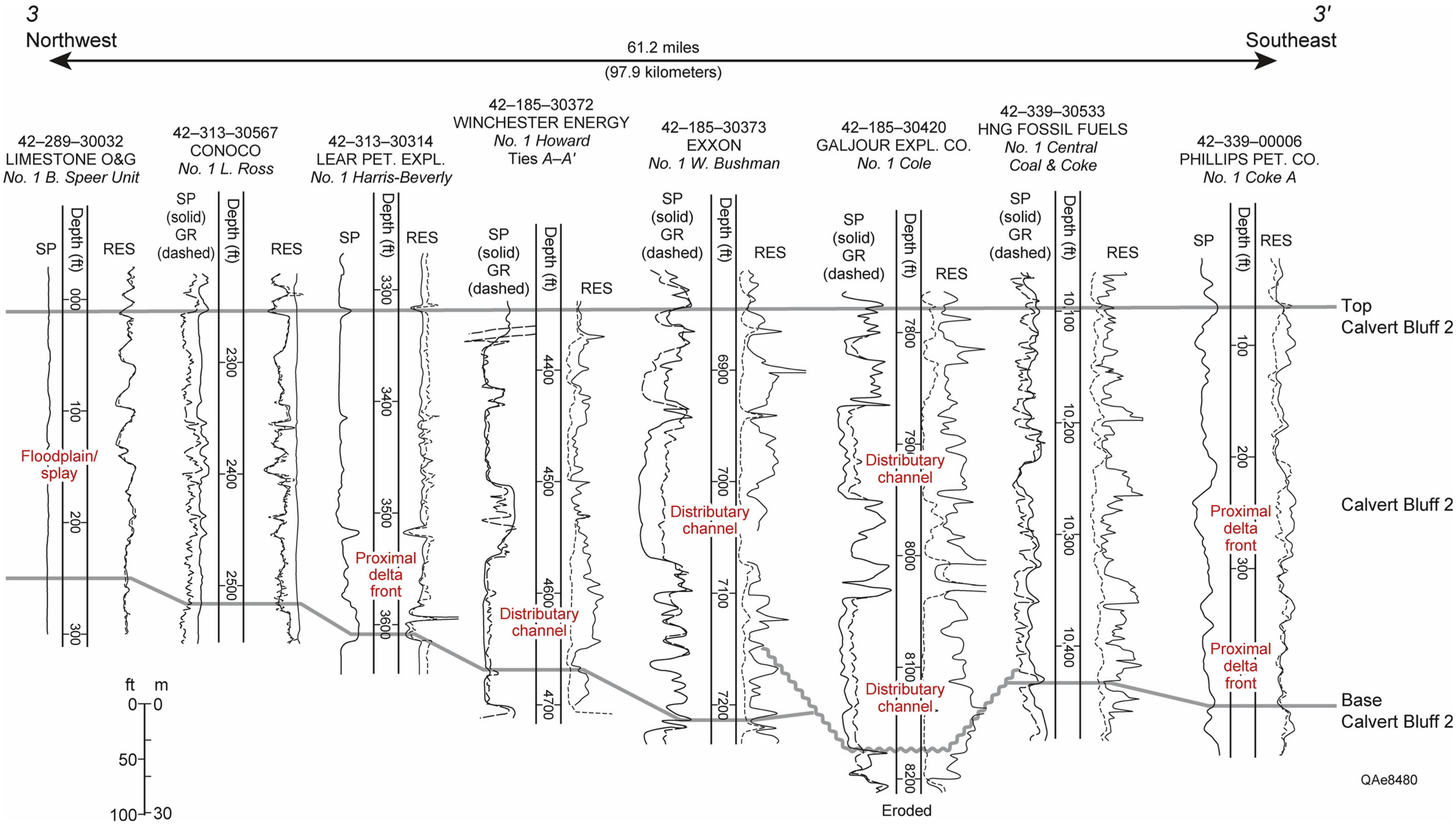

**Figure 14.** Northwest-southeast stratigraphic dip section 3–3’ in the Calvert Bluff 2 sequence. Datum is the top of the Calvert Bluff 2 sequence. Line of section is shown in Figure 19.

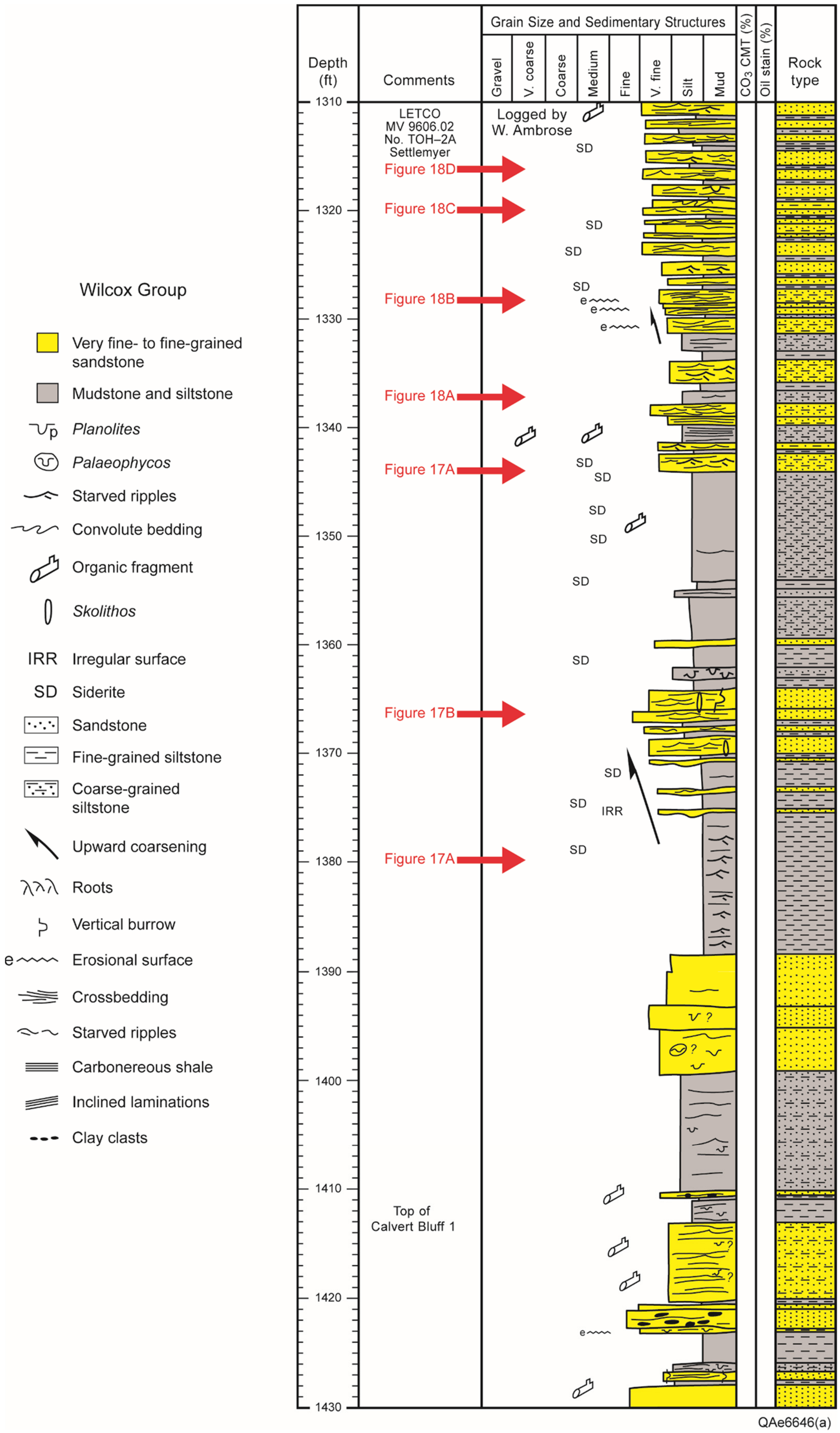

**Figure 15. Description of the Letco core from 1310 to 1430 ft (399.4 to 436.0 m), showing most of the Calvert Bluff 2 sequence. Location of cored well is shown in Figures 1 and 19.**

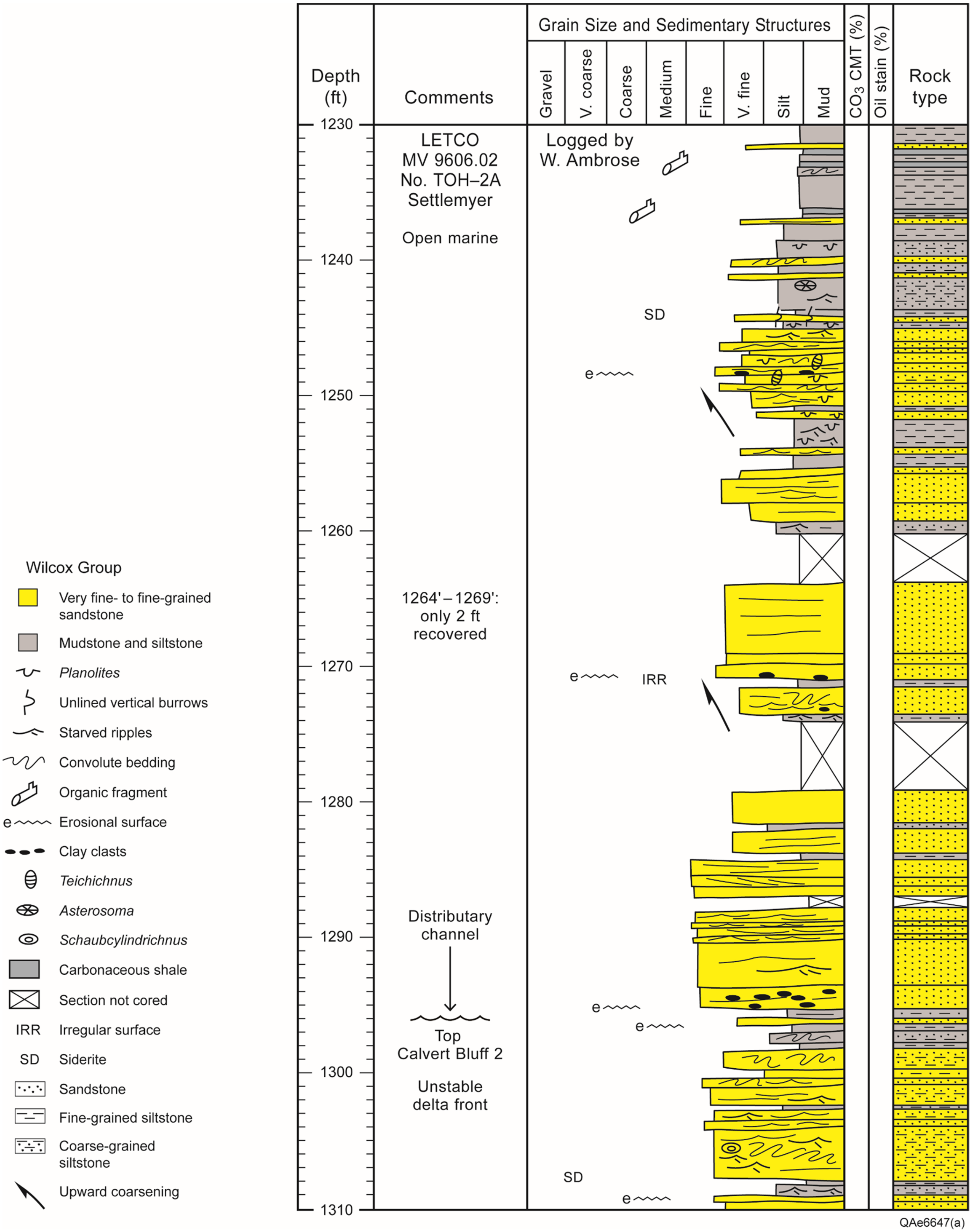

**Figure 16.** Description of the Letco core from 1230 to 1310 ft (375.0 to 399.4 m), showing the upper 12 ft (3.7 m) of the Calvert Bluff 2 sequence and the lower 68 ft (20.7 m) of the Calvert Bluff 3 sequence. Location of cored well is shown in Figures 1 and 19.

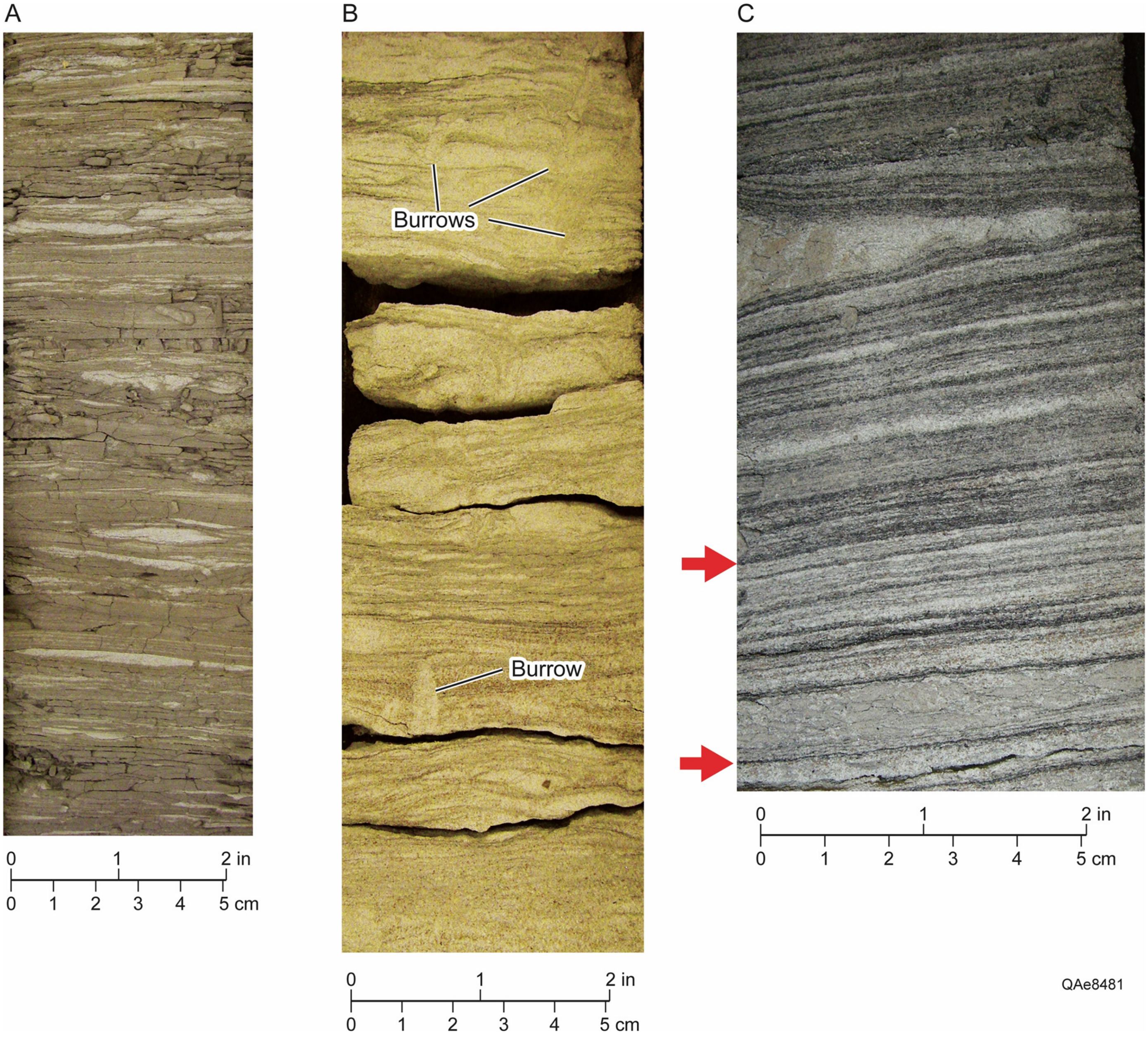

**Figure 17. Photographs of the Letco core in the Calvert Bluff 2 sequence. (A) Silty mudstone with discontinuous lenses of very fine-grained sandstone at 1379.3 ft (420.5 m). (B) Very fine- to fine-grained sandstone with dominantly vertical burrows at 1366.0 ft (416.5 m). (C) Thin (millimeter to sub-centimeter) beds of very fine sandstone interbedded with organic laminae at 1344.0 ft (409.8 m). Thickness of individual sandstone beds decreases upward within 1.6 in (4.1 cm) interval between arrows, suggesting this interval may be part of a tidal cycle recording upward-diminishing tidal energy. Core description is shown in Figure 15. Location of cored well is shown in Figures 1 and 19.**

fine-grained and ripple-stratified sandstone (Figs. 23–25). This upward-coarsening section is capped by a 2 ft (0.6 m), burrowed zone of carbonaceous mudstone and lignitic mudstone, in turn overlain by extensively-burrowed, very fine-grained sandstone (Fig. 23). This muddy and lignitic zone, informally termed the “dark band” is truncated by the overlying Carrizo Formation. The dark band contains woody detritus, pollen, resins, spores, and disseminated charcoal, indicating that these were peats that formed from emergent vegetation in a ponded-water setting.

The Sabinetown outcrop near the golf course at Riverside Drive southeast of Bastrop is complex. It has several erosion surfaces, truncations, and vertical and lateral facies changes. The basal section, exposed only in the southernmost part of the outcrop belt, is at least 5 ft (1.5 m) thick and is composed of sparsely- to moderately-bioturbated, laminated heterolithic mudstone, siltstone and interbedded planar-stratified to modified current ripple cross-laminated fine-grained sandstone with *Teichichnus*, *Planolites*, and *Skolithos*. These heterolithic strata are cut by an erosional surface with several feet (>1 m) of relief that dips into the subsurface (Fig. 26). This erosion surface may represent a surface of sediment bypass because it is draped by a bioturbated siltstone to silty, very fine-grained sandstone. This is in turn erosionally truncated by a 1–3 ft (0.3–1.0 m) thick bed of fine-grained sandstone with an arcuate shape. This arcuate sand body is overlain by a 6 in to 2 ft ( 25 cm to 0.6 m) thick lignite seam with in-place logs and overlying carbonaceous mudstone that thicken to the north. This carbonaceous mudstone and lignite seam are both truncated by the Carrizo Formation. The Sabi-

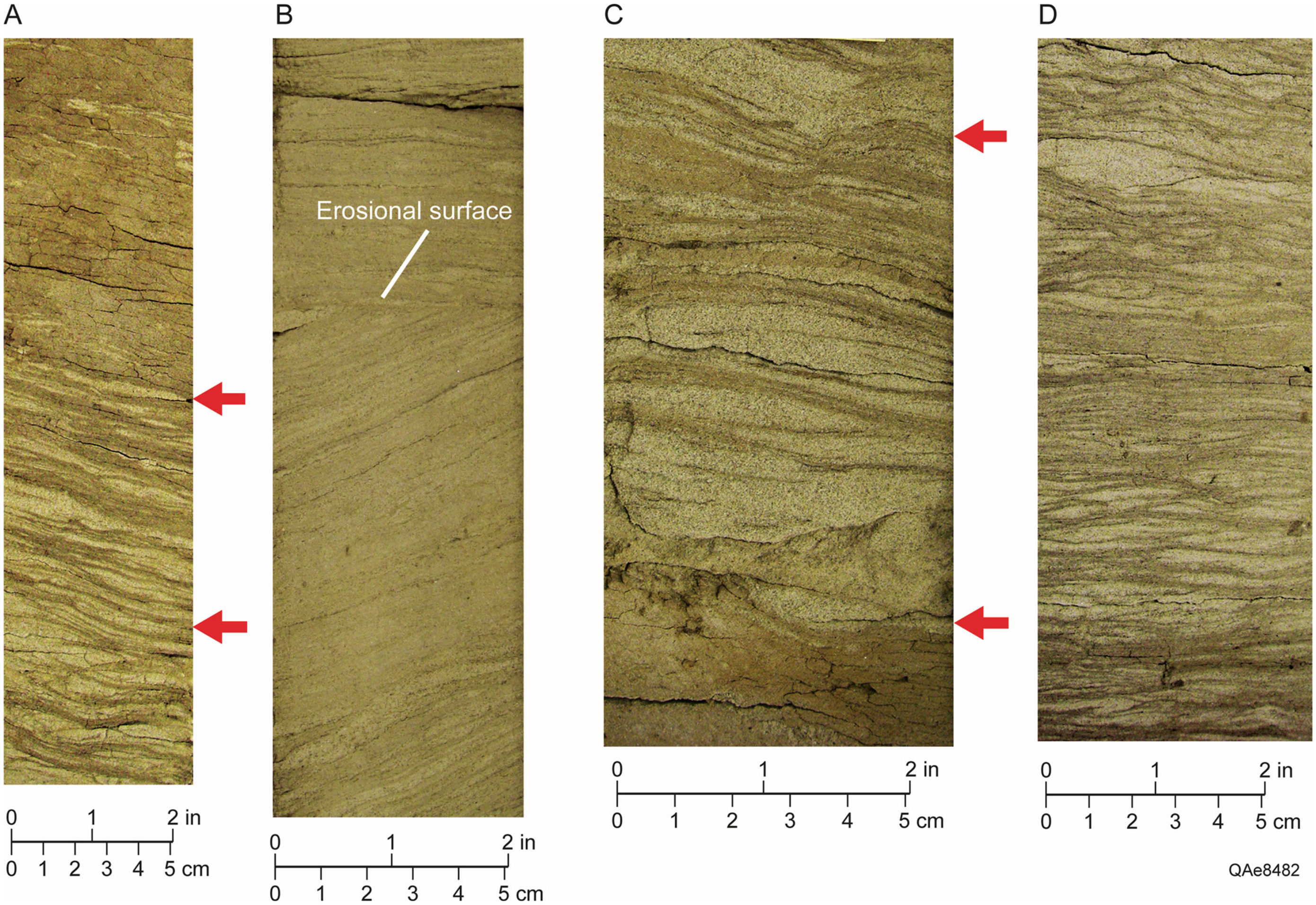

**Figure 18. Photographs of the Letco core in the Calvert Bluff 2 sequence with evidence of tidal sedimentation. (A) Lenticular, mud-draped beds of very fine-grained sandstone at 1337.4 ft (407.7 m). Thickness of individual sandstone beds decreases upward, coupled with upward-thickening mud drapes within a 5 in (12.7 cm) interval between arrows, suggesting this interval may be part of a tidal cycle recording upward-diminishing tidal energy. (B) Very fine-grained sandstone with erosional surface above steeply dipping beds at 1329.0 ft (405.2 m). (C) Mud-draped ripples composed of very fine-grained sandstone at 1320.0 ft (402.4 m). Many ripples are double-mud-draped. Scale of bedforms systematically decreases upward between arrows. Vertical features on left side of photograph are the result of core damage. (D) Lenticular, mud-draped beds of very fine-grained sandstone at 1316.1 ft (401.3 m). Core description is shown in Figure 15. Location of cored well is shown in Figures 1 and 19.**

netown section, 1 to 2 ft (0.3 to 0.6 m) below the Carrizo Formation, approximately 30 ft (9 m) away from the section in Figure 26, consists of centimeter-scale beds of very fine- to fine-grained, ripple-stratified sandstone interbedded with silty mudstone (Fig. 27A) and organic-rich, muddy siltstone with abundant, large Teredolites at the Sabinetown-Carrizo contact (Fig. 27B).

Other sandstone bodies in outcrops of the Sabinetown Formation near Bastrop consist of erosionally based, lenticular features as much as 4 ft (1.2 m) thick and 10 to 20 ft (3 to 6 m) across encased in organic-rich mudstone (Fig. 28). These lenticular sandstone bodies contain abundant soft-sediment deformation, with folded and discontinuous beds.

## Net-Sandstone Distribution

Net-sandstone distribution in the Sabinetown Formation is dip-elongate, with south-trending patterns (Fig. 21). Depositional axes, updip of the Angelina-Caldwell Flexure, contain >30 ft (>9 m) of net-sandstone, whereas those southward have as much as 57 ft (17.4) of net sandstone. The Sabinetown Formation is eroded by the Carrizo Formation along a northeast-trending line that extends from northern Brazos to Angelina counties (Fig. 21).

## Facies Interpretation

The Sabinetown Formation was deposited in a tidally-modified, lower-coastal-plain to shallow marine setting. Outcrops of the Sabinetown Formation in the area of Bastrop, Texas, are composed of tidal-flat, swamp/marsh, and tidal-channel facies (Figs. 23–28). Tidal-flat facies in the Sabinetown Formation at Copperas Creek consist of an upward-coarsening succession of burrowed mudstone and siltstone with interbedded thin (<1 in [2.5 cm) sandstone lenses grading upward into 1–2 in (2.5–5.1 cm) beds of current to modified current ripple-stratified, very fine-grained sandstone (Figs. 23, 24, and 25A), in turn overlain by thicker (1 ft [0.3 m]) beds of very fine- to fine-grained, modified current ripple-stratified sandstone with discontinuous mud drapes (Fig. 25B). Flaser-ripple stratification is common throughout the section. These beds are crosscut by *Ophiomorpha* (Fig. 25B), with other ichnofauna represented by sparse *Skolithos*, *Planolites*, and *Teichichnus*.

Swamp deposits in the Sabinetown Formation overlie tidal-flat and tidal-creek deposits (Figs. 23 and 26). They are recorded as thin (<2 ft [<0.6 m]), carbonaceous mudstones and lignite seams that overlie silty mudstones with rhizoliths (Fig. 23). Swamp deposits at Copperas Creek are composed of a burrowed,

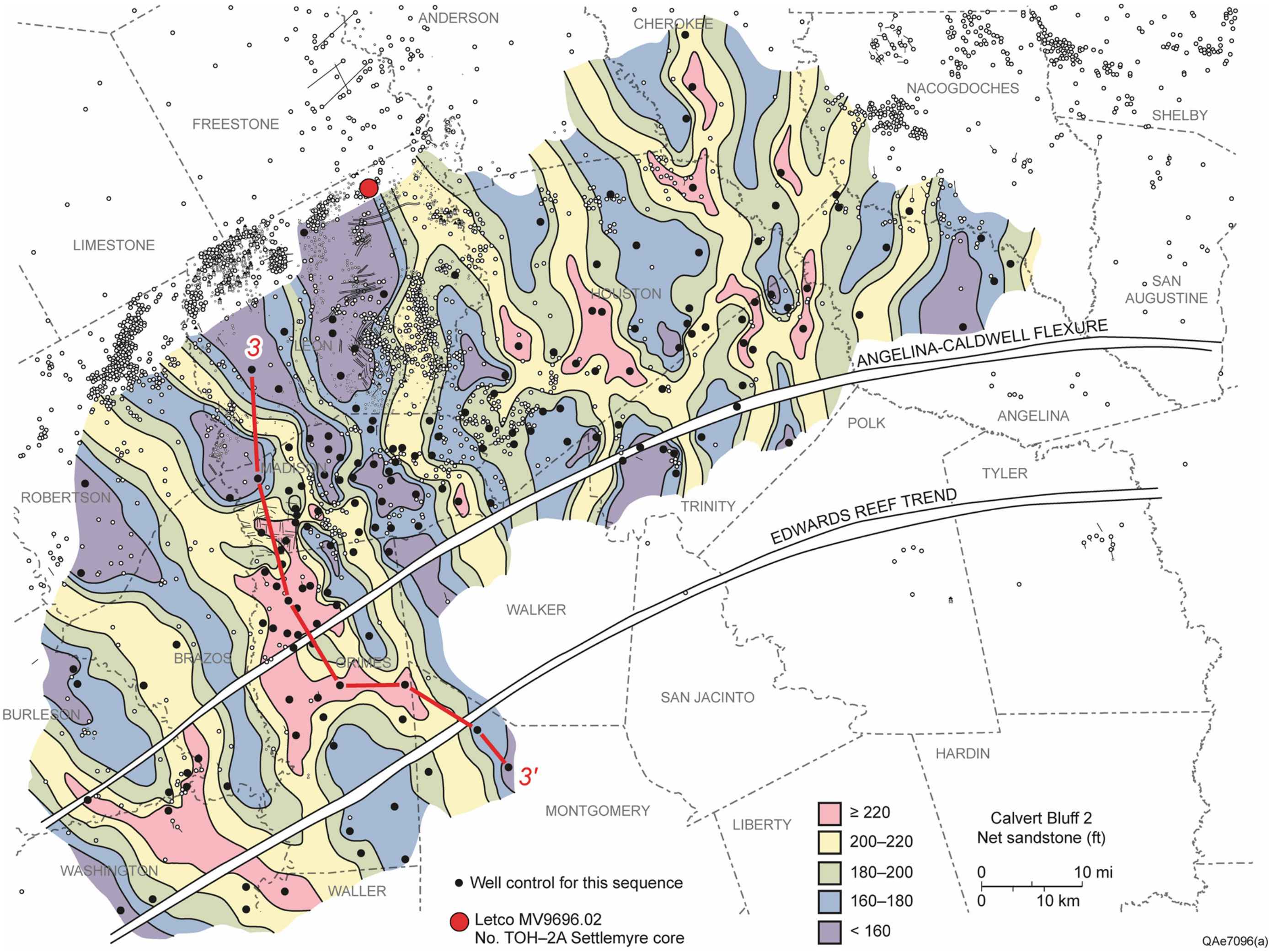

**Figure 19. Net sandstone, Calvert Bluff 2 sequence. Southwest-northeast stratigraphic dip section 3–3' is shown in Figure 14. Core descriptions are shown in Figures 16 and 17.**

carbonaceous mudstone that grades upward into a lignitic mudstone, in turn truncated by an extensively-burrowed *Glossifungites* surface (Denison et al., 2017). Sabinetown swamp facies near the golf course southeast of Bastrop are composed of a 6 in (25 cm) lignite seam above a 1 ft (0.3 m), erosionally-based sandstone bed interpreted to be a minor tidal-channel deposit (Fig. 26). The large erosion surface exposed at the golf course may represent the edge of a valley or relatively deep tidal-channel incision that was subsequently infilled with heterolithic facies during a transgressive rising-stage.

Tidal-creek deposits in the Sabinetown Formation are composed of fine-grained, erosion-based, lenticular sandstone beds (Figs. 26 and 28). They range in thickness from 1 to almost 4 ft (0.3 to 1.2 m) and width from 10 to 20 ft (3 to 6 m). They are in erosional contact with organic-rich mudstone and siltstone beds. Soft-sediment deformation is common (Fig. 28), attributed to channel-bank collapse and sediment loading. These features are observed commonly in tidal-creek deposits associated with tidal flats (Reineck and Singh, 1973). Lateral deposition in tidal creeks is rapid as a result of episodic flood- and ebb-tidal currents. Fault planes develop commonly as a result of exposure during low tides, resulting in sediment collapse of water-rich material.

# CARRIZO FORMATION

## Stratigraphic Occurrence

The Carrizo Formation erodes the Sabinetown Formation in the study area (Fig. 20). It varies in thickness from 200 to 400 ft (61 to 122 m) along depositional dip (Fig. 20). Wireline-log responses are blocky to upward-fining in the northwest part of the study area, but are mixed toward the southeast, although blocky and upward-fining wireline-responses occur at the top of the section throughout the study area (Fig. 20).

The Carrizo Formation truncates the Sabinetown Formation within a northeast-southwest-trending, 10 to 15 mi (16 to 24 km) zone that extends from Brazos to Trinity County (Fig. 21). The Sabinetown Formation is completely eroded north and northwest of a line from northeast Brazos to northwest Angelina County (Fig. 21). The unconformity at the base of the Carrizo Formation is interpreted by Harris (1962) to be the result of early Eocene uplift and subsequent regression, resulting in a significant readjustment in drainage patterns in a non-marine, fluvial setting. However, this study and another by Denison et al. (2017), documents pervasive marine trace fossils in the Carrizo Formation, including *Teredolites*, *Thalassinoides*, *Planolites*, and *Ophiomorpha* (Figs. 23, 26, 27, and 29).

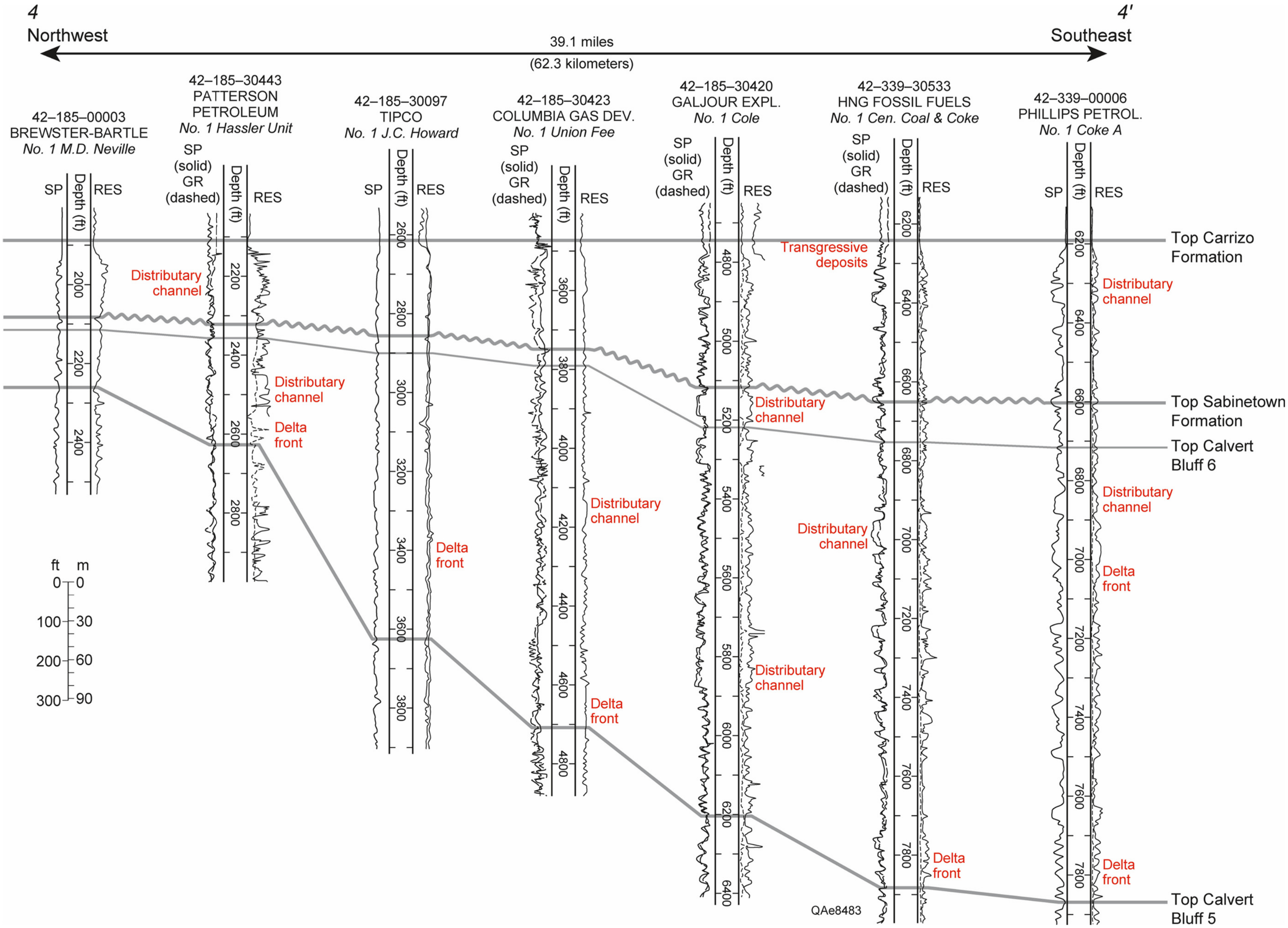

Figure 20. Northwest-southeast stratigraphic dip section 4–4' in the Calvert Bluff 6 sequence, the Sabinetown Formation, and the Carrizo Formation. Datum is the top of the Carrizo Formation. Line of section is shown in Figures 21 and 22.

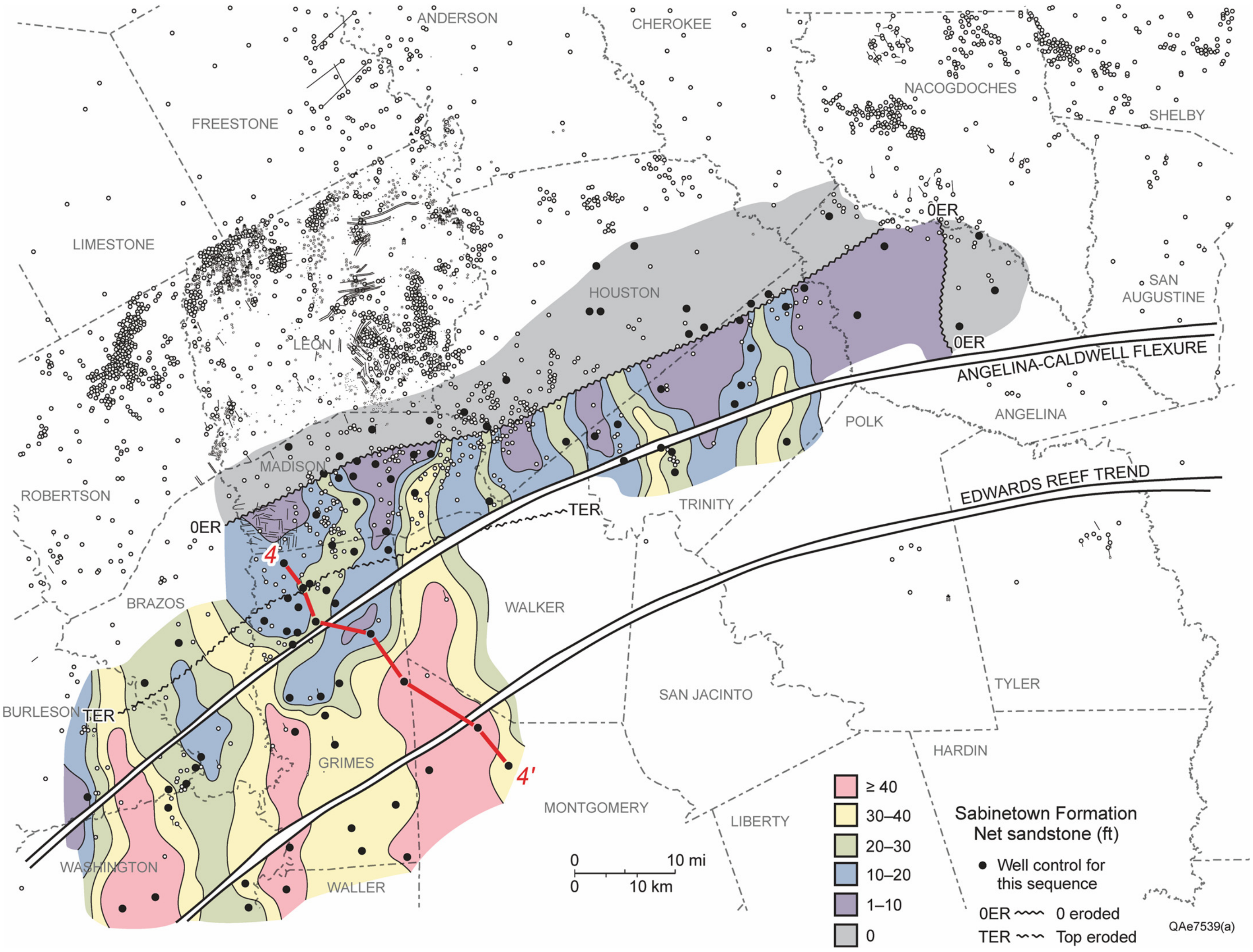

Figure 21. Net sandstone, Sabinetown Formation. Northwest-southeast stratigraphic dip section 4–4' is shown in Figure 20.

## Lithology

The Carrizo Formation near Bastrop Texas consists of a 20 to 35 ft (6 to 10.7 m) section of erosionally-based, fine- to medium-grained, crossbedded sandstone with marine burrows dominated by *Ophiomorpha* (Figs. 23, 26, and 29). The base of the Carrizo Formation features a well-developed and continuous Glossifungites hardground surface (Fig. 23) (Denison et al., 2017). At some localities it also contains abundant Teredolites that extend downward into organic-rich mudstone, siltstone, and coal in the underlying Sabinetown Formation (Fig. 27B). Some *Ophiomorpha* in the Carrizo Formation attain lengths of as much as 2 ft (0.6 m) (Fig. 29). Large-scale trough crossbed sets are prominent, with some bedsets up to 3 ft (0.9 m) thick (Fig. 29B).

## Net-Sandstone Distribution

The Carrizo Formation is composed of dip-elongate (south- and southeast-trending) sandstone bodies, with the main depositional axes containing >160 ft (>48.8 m) of net sandstone (Fig. 22). These dip-elongate sandstone bodies merge updip (northward) into a broad, sheetlike configuration in Madison and Houston counties.

## Facies Interpretation

The Carrizo Formation in the vicinity of Bastrop was deposited in a shallow-marine setting. Evidence is from pervasive marine ichnofauna that include large *Teredolites* and *Ophiomorpha* (Figs. 27B and 29, respectively). *Teredolites* extending downward from the Carrizo Formation into the Sabinetown succession indicate that marine salinities dominated at the base of the Carrizo, allowing for extensive burrowing by marine clams associated with this type of trace fossil (Bromley et al., 1984; Gingras et al., 2004). Deeply-penetrating *Ophiomorpha* are also highly indicative of marine salinities and well-oxygenated bottom water conditions and sediment pore spaces, likely enhanced by tidal currents and tidal oscillations (Flaig et al., 2019).

A basal erosional surface, crossbeds, and silty rip-up drapes on toes of sigmoidal beds, coupled with shallow-marine ichnofauna, suggests a tidally-influenced, shallow-marine depositional setting for the Carrizo Sandstone at outcrops near Bastrop. Steep and thick (2 to 3 ft [0.6 to 0.9 m]) crossbed sets with *Ophiomorpha* (Fig. 29) record dune migration within tidal channels. The heavily-burrowed, upper Carrizo section represents an open-marine depositional setting above the tidal-channel facies, likely tidal bars or delta mouth bars along a delta front.

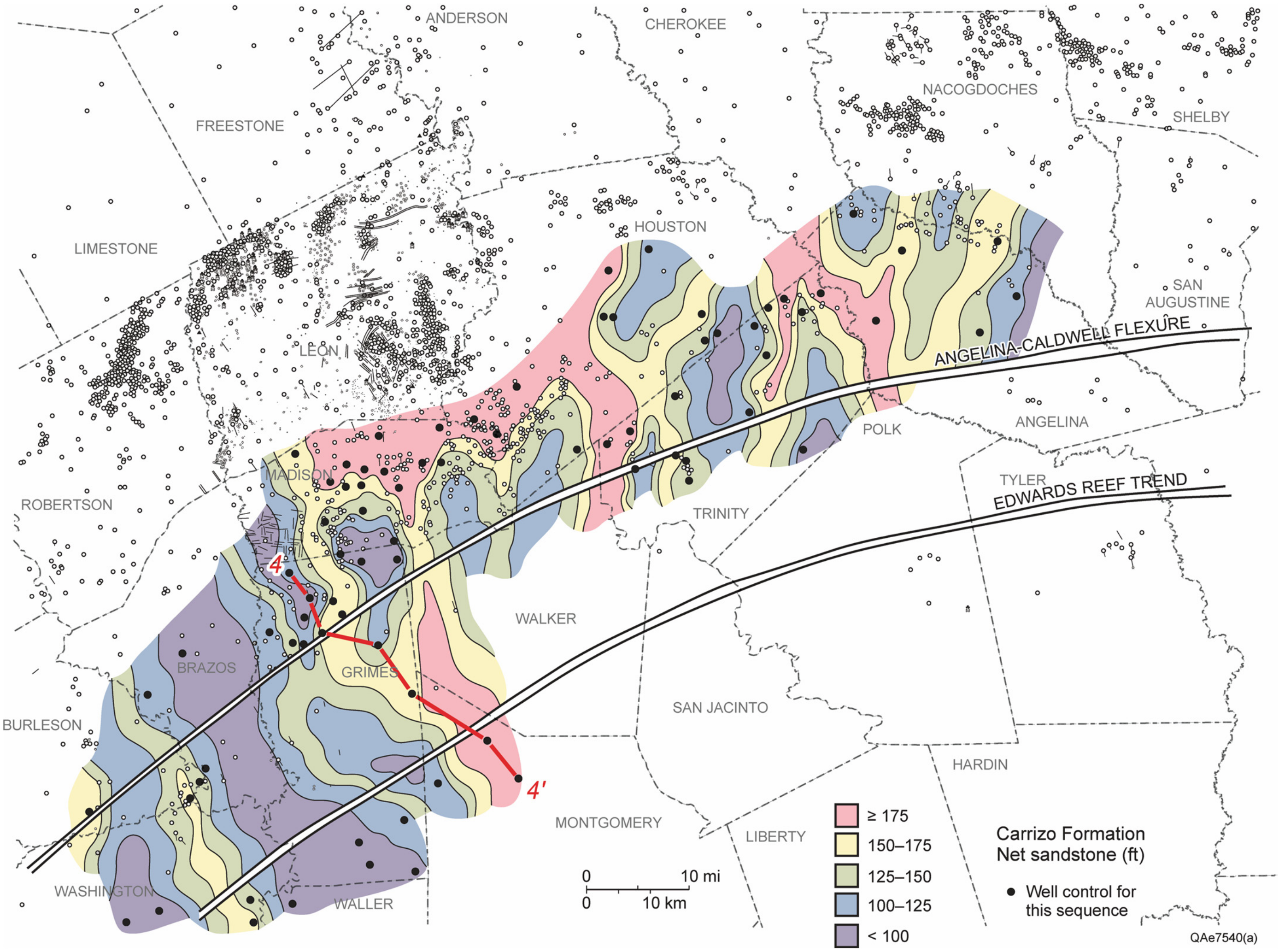

**Figure 22. Net sandstone, Carrizo Formation. Northwest-southeast stratigraphic dip section 4–4' is shown in Figure 20.**

Previous interpretations of the channelized cut-and-fill Carrizo section are downcutting fluvial sands (Harris, 1962; Dickey and Yancey, 2010; Yancey et al., 2013). However, the continuous *Glossifungites* surface at the base of the Carrizo section (Denison et al., 2017), in conjunction with common *Teredolites*, *Thalassinoides*, and *Ophiomorpha*, suggest that these are marine deposits associated with marine erosion processes, consistent with scours at the base of a tidal deltaic complex. A facies analog for the base of the Carrizo Formation at Bastrop is the Sego Sandstone Member of the Mancos Shale in east-central Utah, described by Willis and Gabel (2001) and Willis (2005). Tidal sandstones in the Sego Sandstone have abrupt, erosional bases that formed as falling relative sea-level resulted in tidal currents scouring underlying strata. This indicates that tidal processes can be well-developed and preserved in regressive phases of deposition as well as in subsequent transgressive phases dominated by estuarine, tide-dominated fills.

## SHORELINE POSITIONS AND EVOLUTION OF DEPOSITIONAL SYSTEMS

Relative shoreline positions for each sequence in the Upper Midway to Carrizo stratigraphic succession are displayed in Figure 4. They illustrate a net-progradational system along the north margin of the Angelina-Caldwell Flexure from the Midway Group to the base of the Calvert Bluff Formation. Construction of delta-platform to delta/fluvial floodplain systems in the Midway-to-Carrizo stratigraphic succession occurred in several stages, with 11 major episodes of regression and transgression (Fig. 4).

A major regressive cycle occurs from the Upper Midway Group (Midway 1 and Midway 2 sequences) to the Hooper 2 sequence. This major regressive cycle commenced with shelf deposits in the Midway 1 sequence and culminated in delta-plain systems along the north margin of the Angelina-Caldwell Flexure (Fig. 4). The Lower Wilcox paleoshoreline was developed approximately 30 mi (48 km) basinward during this major regressive cycle, based on facies interpretations from net-sandstone maps of the Midway 1 and Hooper 2 sequences, respectively.

The Hooper 2 to Hooper 3 succession records a minor transgressive cycle (cycle number 2) and development of a strike-fed, wave-dominated coastline along the north margin of the Angelina-Caldwell Flexure (Fig. 4). The Lower Wilcox paleoshoreline advanced basinward in cycle number 3, with distributary-channel systems in the Hooper 4 sequence superimposed over shorezone deposits of the Hooper 3 sequence (Fig. 4). Facies from the Simsboro 1 to Simsboro 3 sequences, inferred from the Letco core and net-sandstone maps are those of delta-plain, interdistributary-bay, and swamp, within a tidally-influenced, fluvially dominated deltaic system.

The Simsboro 3 to Simsboro 4 succession (cycle number 6) represents a transgressive cycle similar to that of cycle number 2,

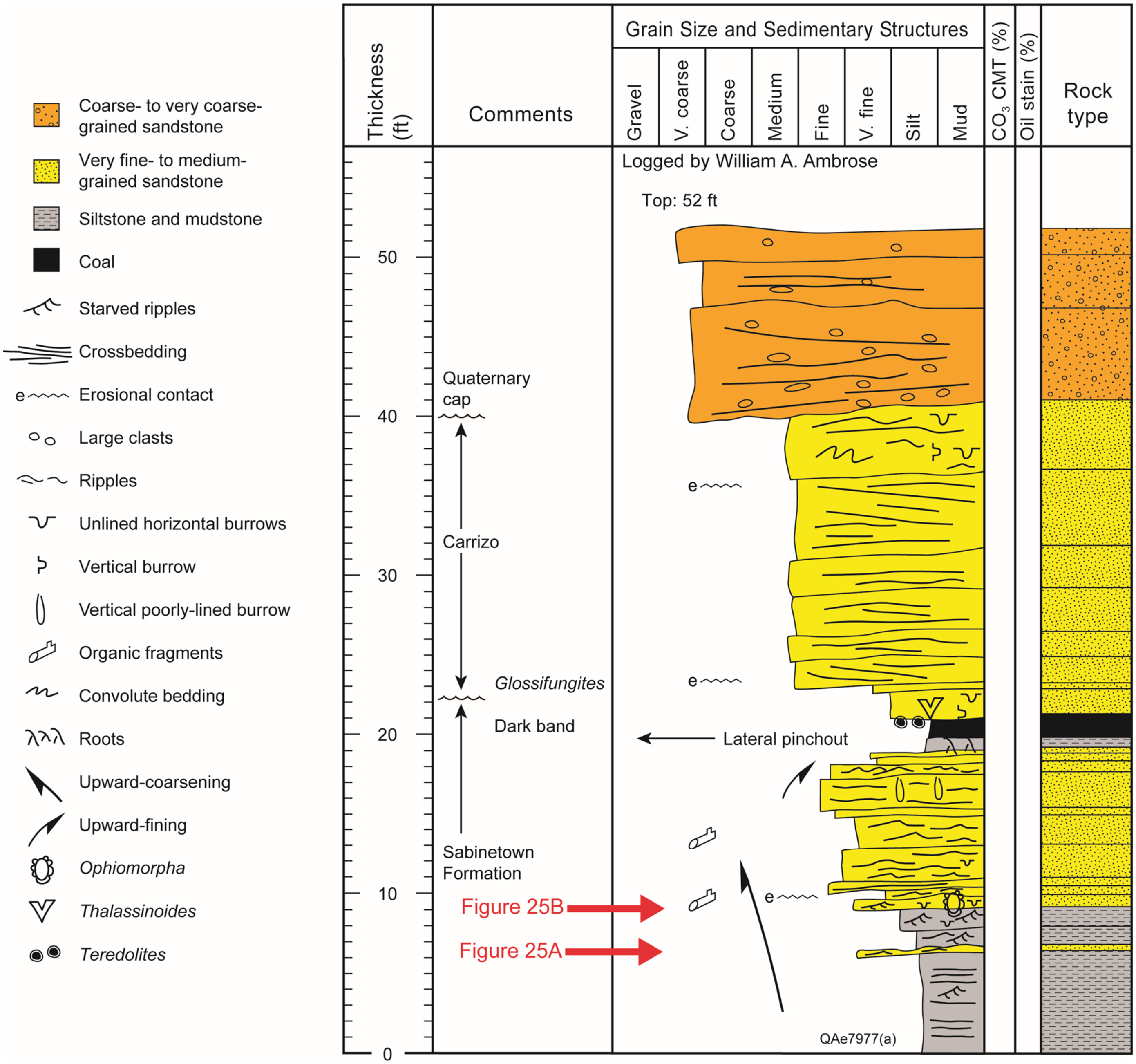

**Figure 23. Outcrop description of the Sabinetown and Carrizo formations at Copperas Creek, southeast of Bastrop, Texas. Photographs of this stratigraphic section are shown in Figures 24 and 25. Regional location of outcrop is shown in Figure 1.**

culminating with transgressive-shoreline deposits in the Simsboro 4 sequence having strike-elongate net-sandstone trends along the Angeline-Caldwell Flexure (Fig. 4).

Maximum offlap and regression is inferred at the Calvert Bluff 1 stratigraphic level, where delta-plain systems are inferred to have existed as far south as the Edwards Reef Trend (Fig. 4). Net-transgressive systems are recorded for the remainder of the Wilcox succession to the base of the Carrizo Formation (Fig. 4). Tidal deposits, shallow-marine infauna, and marine trace fossils are observed in core within the Calvert Bluff 1 to Calvert Bluff 6 stratigraphic succession (e.g., Figs. 17 and 18).

The Carrizo Formation represents a downcutting, regressive episode, truncating the Sabinetown Formation (Figs. 21 and 23). The marine-dominated section above the unconformity at the base of the Carrizo Formation (Figs. 23 and 27) records tidally-influenced, transgressive rising-stage infill of scours above the basal regressive surface, with large-scale tidal sand bars and tidal channels dominating (Fig. 29).

## IMPLICATIONS FOR RESERVOIR HETEROGENEITY

### Scales of Heterogeneity

Deposits of tidal origin are significant because tidally-modified sedimentary structures, facies trends, and stratal architectures-geometries impart a significant degree of heterogeneity to sedimentary successions. The scale of heterogeneity in tidal systems ranges from the microscale, where double-draped ripples and laminae reflect diurnal tidal cycles (Reineck and Singh,

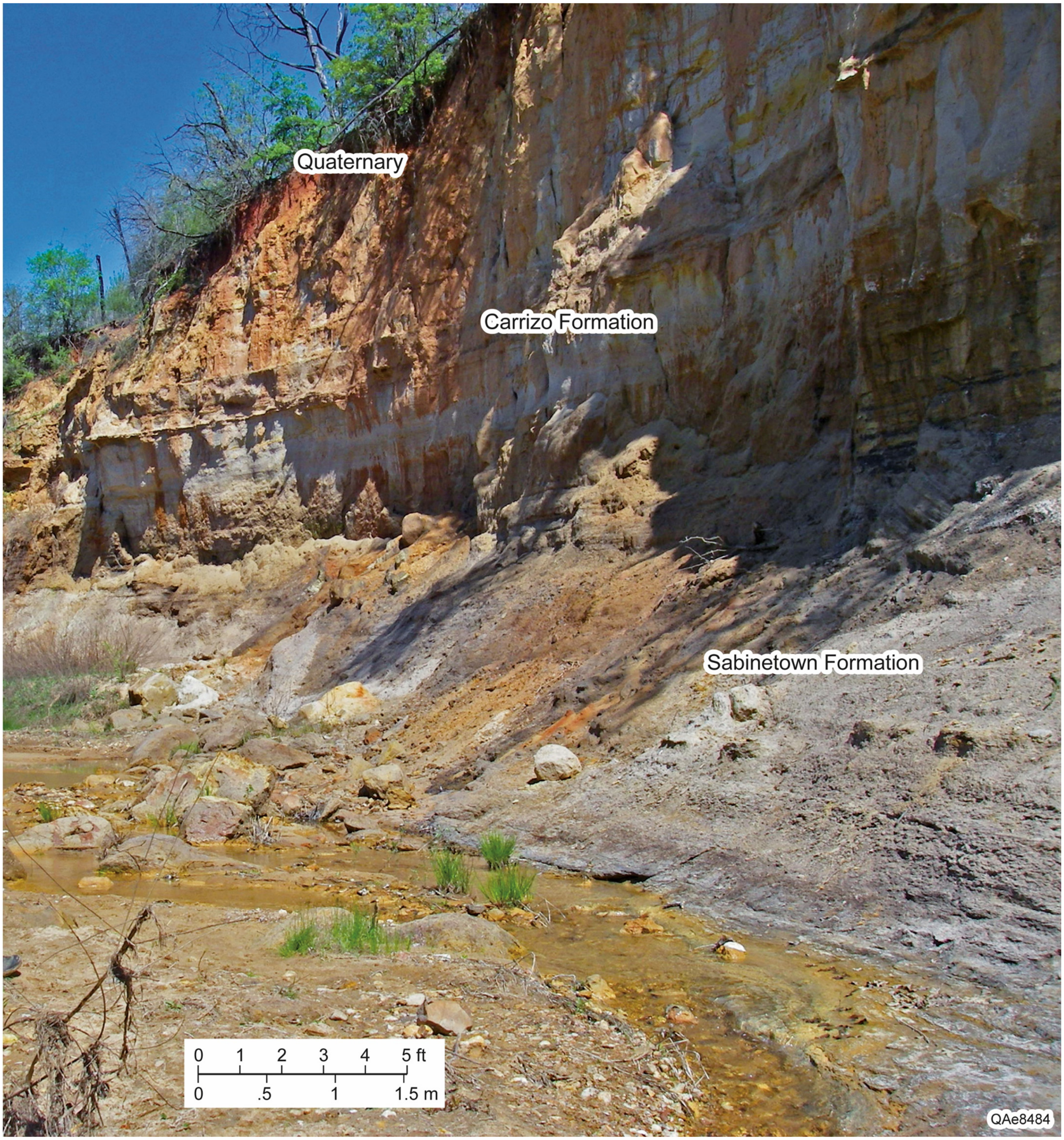

**Figure 24. Photograph of outcrop of the Sabinetown and Carrizo formations at Copperas Creek, southeast of Bastrop, Texas. Graphic description of this outcrop is shown in Figure 23. Regional location of outcrop is shown in Figure 1.**

1973) to the mesoscale including tidal-creek, tidal-inlet, tidal-flat, and tidal-bar facies (Visser, 1980; Kvale et al., 1989; Dalrymple, 1992; Tape et al., 2003). Macroscale heterogeneities in tidal systems comprise regionally mappable facies trends. They record long-term evolution of estuarine-fill and deltaic progradational cycles and development of tidally-modified shoreline systems (Anthony and Orford, 2002).

### Microscale

Microscale heterogeneities in tidal systems are introduced at the small scale (commonly 1 to 3 in [2.5 to 7.6 cm]) of cyclic, mud-draped ripples (including double-draped ripples), flaser-wavy-lenticular bedding, and rhythmic and repetitive upward-thinning and upward-thickening sets of mud-draped bedforms

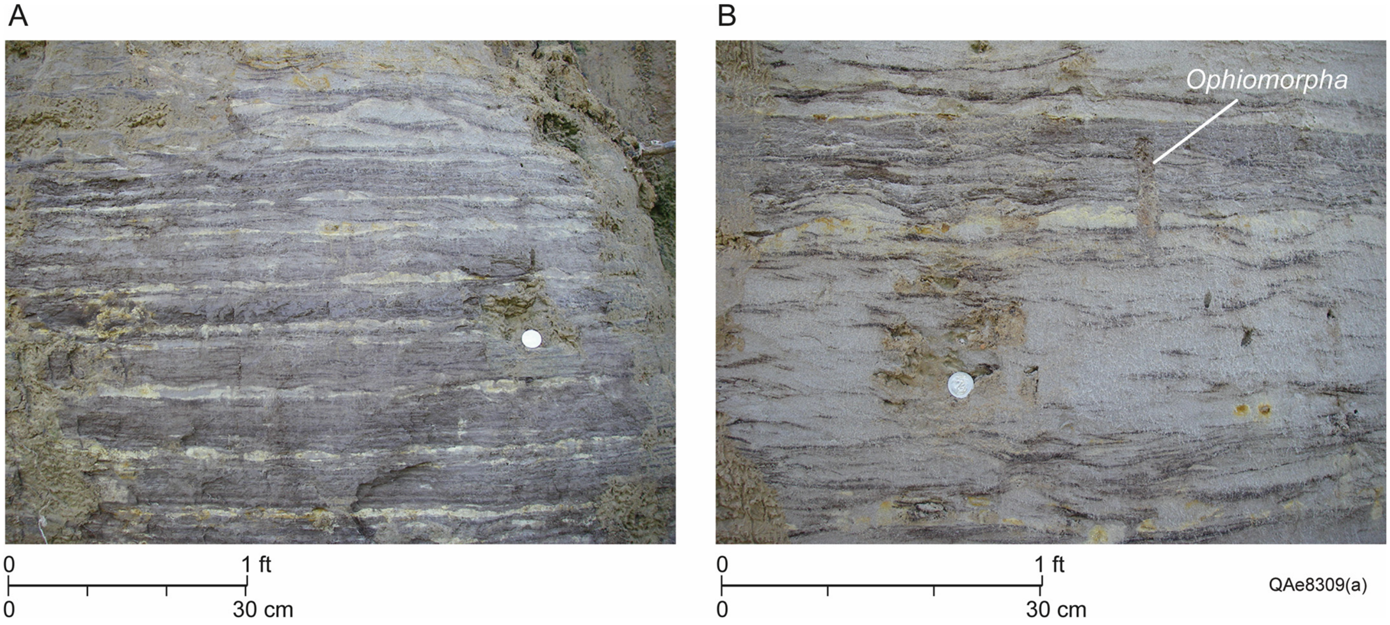

**Figure 25. (A) Photograph of tidal-flat deposits, consisting of lenticular, ripple-stratified beds of very fine-grained sandstone interbedded with silty mudstone in the upper part of the Sabinetown Formation. (B) Closer view, with lenticular beds of very fine-grained sandstone crosscut by *Ophiomorpha*. Stratigraphic positions of these photographs are shown in the outcrop description in Figure 23. Regional location of outcrop is shown in Figure 1.**

and laminae. Holocene examples of these types of stratification include tidal-flat deposits along the southwest coast of the Netherlands (Reineck and Singh, 1973; Weimer et al., 1982) and the South Carolina–Georgia Atlantic Coast (Hayes and Sexton, 1989).

Examples of microscale tidal features in the subsurface are documented in tide-dominated-delta, tidal-inlet, and tidal-flat deposits in the lower and middle Eocene Misoa Formation in the Maracaibo Basin, Venezuela (Ambrose et al., 1995 and Maguregui and Tyler, 1991, respectively). Other examples occur in tidal-bar, tidal-channel, and tidal-flat facies in Pennsylvanian strata (Marmaton Group, Cleveland Formation, and Douglas Group) in the northwest Anadarko Basin, U.S.A. (Ambrose et al., 2015).

Cyclic, mud-draped current ripples (including double-draped ripples), flaser bedding, upward-thinning and upward-thickening sets of mud-draped bedforms and laminae greatly impact vertical permeability (Dalrymple, 1992). These features are abundant in Wilcox sequences as seen in the Letco core. Double-draped ripples are shown in Figure 30. Cyclic mud drapes are illustrated in Figure 30E. Flaser bedding is pervasive throughout the Wilcox succession. Prominent examples are in Figures 18A, 18B, and 25. Upward-thinning sets of intensely draped bedforms and laminae are shown in Figures 18A, 18C, and 18D.

### Mesoscale

Mesoscale heterogeneities in tidal systems occur at the scale of 1 to 4 ft (0.3 to 1.2 m) and are commonly represented by crossbed sets composed of mud-draped bedforms. These crossbed sets compose tidal bundles that record lunar cycles, comparable to those documented in the Cretaceous Sego Sandstone in southeast Utah (Willis and Gabel, 2001). Examples in outcrops in Texas include festoon crossbeds in the Upper Calvert Bluff Formation at Pancake Rock (Fig. 31) and large, trough crossbeds in the Carrizo Formation also near Bastrop, Texas (Fig. 29).

Other mesoscale heterogeneities in tidal systems occur at the scale of small tidal creeks and channels, recorded as 3 to 10 ft, upward-fining sections with abundant mud rip-up clasts. Examples in the Wilcox to Carrizo succession in outcrop include lenticular tidal-creek deposits in the Sabinetown Formation composed of mud-draped and contorted beds of fine-grained sandstone with dispersed mud rip-up clasts (Fig. 28). These features constitute both vertical and lateral discontinuities in the facies framework over scales of 2 to 5 ft (0.3 to 1.5 m) vertically and 15 to 25 ft (4.5 to 7.6 m) laterally. Examples in core include a 12 ft (3.7 m), upward-fining section between 2 thin coal seams in the Simsboro 4 sequence (Fig. 11). This tidal-creek deposit contains crossbeds, climbing ripples, and has rhizoliths toward the top.

### Macroscale

Macroscale heterogeneities in tidally-modified systems compose facies architecture at a regionally mappable scale. They include major paleogeographic elements such as interdistributary-bay and marsh, tidal-distributary channel complexes, and fluvial-tidal networks. Channel trends inferred from net-sandstone maps in many Wilcox sequences are narrow (commonly ≤4 m [≤6.4 km] across), moderately sinuous, and have an anastomosing geometry.

Channels in the Hooper 3 sequence transported sediments to a wave-influenced shoreline along the updip (northwestern) margin of the Angeline-Caldwell Flexure, where these channel trends are interpreted to be tidal-inlet deposits (Fig. 32A). Channel systems in the Simsboro 6 sequence exhibit mainly downdip-bifurcating trends, consistent with distributaries and channel-mouth-bar facies (Fig. 32B). Deltaic depocenters in the Simsboro 6 sequence are narrow (<10 m [<16 km]) across. Spacing between these deltaic depocenters ranges from 15 to 25 mi (24 to 40 km), indicating that these delta systems were minor in scale.

Prominent examples of anastomosing geometry of channel systems include the Calvert Bluff 1 and Calvert Bluff 2 sequences (Figs. 5F and 19, respectively). Individual channel trends in these sequences are narrow (commonly <5 m [<8 km]) across. In areas of dense well control (Madison County), these channel trends are resolved into highly sinuous patterns where many are <2 mi (<3.2 km) across.

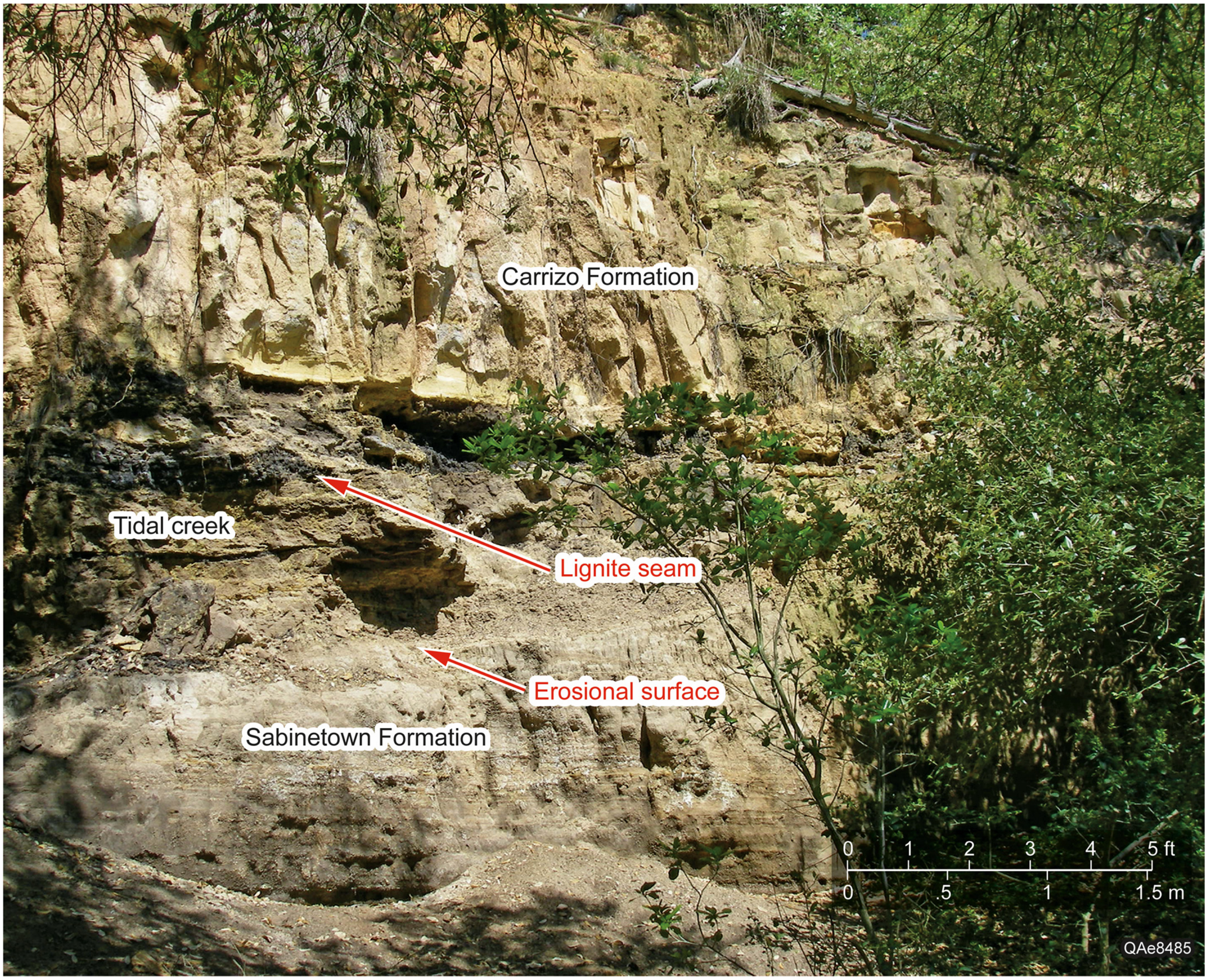

**Figure 26. Photograph of complex stratigraphic relations between the Sabinetown and Carrizo formations near the golf course along Riverside Drive, southeast of Bastrop, Texas. Regional location of outcrop is shown in Figure 1.**

Interchannel areas in Wilcox sequences include muddy interdistributary-bay, swamp, tidal-flat, and lower-delta-plain facies. These areas are extensive, occurring between narrow and widely spaced sandier depositional axes. Examples include those within the Simsboro 2 and Simsboro 6 sequences (Figs. 5D and 32B, respectively). In contrast, muddy interchannel facies are limited in other Wilcox sequences where the net-sandstone geometry is anastomosing with closely spaced channel axes (for example, the Calvert Bluff 2 sequence [Fig. 19]).

Anastomosing distributary-channel patterns commonly occur in lower-delta-plain settings of tidally-influenced deltas. Flood-tidal currents in these systems provide distributaries with sediment from offshore, forcing them to meander and form complex, sinuous patterns to maintain channels of constant depth (Wright et al., 1973; Oomkens, 1974; Dalrymple, 1992). In contrast to abandoned distributaries in fluvial-dominated deltas, those in tide-dominated deltas are commonly kept open by continuous tidal action, resulting in heterogeneous abandoned-distributary channel fills. Examples include the Georgia Bight (St. Helena Sound) on the U.S. Atlantic coastline (Hayes, 1976; Hayes and Sexton, 1989), and the estuarine system of the Ganges-Brahmaputra Delta (Barua et al., 1994; Allison et al., 2003; Kuehl et al., 2005).

## CONTROLS ON TIDALLY-MODIFIED SYSTEMS IN THE WILCOX TO CARRIZO SUCCESSION

Tidal stratification occurs throughout much of the Wilcox to Carrizo succession, both in cores and in outcrops in the study area. Moreover, similar evidence of tidal modification of sediments in this stratigraphic succession has been observed both in other areas in the Texas Gulf Coast and in southeastern Texas (Breyer and McCabe, 1986; Denison et al., 2017).

Possible controls on tidally-modified systems in the Wilcox Group and Carrizo Formation may have been the result of either (1) locally complex paleogeography that included embayments where the tidal range was amplified locally (Davies, 1964; Hayes, 1976; Hayes and Sexton, 1989), or (2) regional paleogeography, where the large-scale configuration of the Gulf of Mexico in the Paleocene and Eocene may have controlled an areally extensive tidal regime through an open connection with the Atlantic Ocean and Caribbean Sea. Another possible control of an

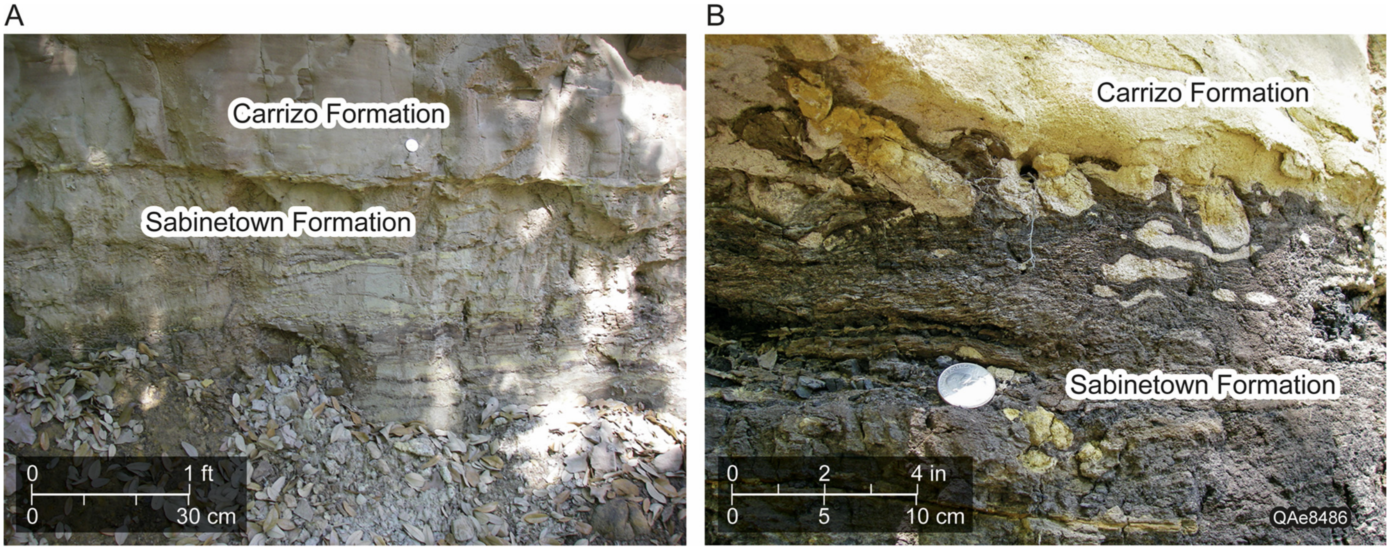

**Figure 27.** **Photographs of the Sabinetown and Carrizo formations near the golf course along Riverside Drive, southeast of Bastrop, Texas. (A) Medium-grained sandstone beds of the Carrizo Formation in erosional contact with Sabinetown Formation, composed of mudstones, siltstones, and lenticular beds of very fine-grained sandstone. (B) Base of the Carrizo Formation, featuring *Teredolites* penetrating into underlying silty mudstones in the Sabinetown Formation. Position of outcrop is 30 ft (9 m) lateral (westward) of outcrop in Figure 26. Regional location of outcrop is shown in Figure 1.**

**Figure 28.** **Soft-sediment deformation within lenticular tidal-channel deposit in the Sabinetown Formation, approximately 6 ft (1.8 m) below the base of the Carrizo Formation. Regional location of outcrop is shown in Figure 1.**

enhanced tidal regime could be the result of a shallow dipping shelf with a small degree of slope, as inferred on the shelf updip (northwest) of the Angelina-Caldwell Flexure during deposition of the Wilcox Group (Fisher and McGowen, 1967).

Muddy embayments in interdeltaic areas are inferred from net-sandstone maps in many Wilcox sequences in the study area, including sandstone-poor areas in the Simsboro 2 sequence (Fig. 5D), the west part of the study area in the Hooper 2 Sequence (Fig. 5E), and the southwest part of the study area in the Carrizo Formation (Fig. 22). However, tidal stratification in core is not limited to these areas, but is also observed in other facies, including channel-fill, channel-margin, and delta-front deposits.

A fluvial or fluvial-dominated deltaic setting has been commonly invoked for the Wilcox Group in the southeastern Texas Gulf Coast (Fisher and McGowen, 1967; Fisher et al., 1969; Kaiser, 1976; Kaiser et al., 1978; Edwards, 1981). However, tidal sedimentary structures are pervasive in cores and in outcrops, even in updip (northwest and north) areas in north Leon and Bastrop counties and as far northeast as Freestone County (O'Keefe et al., 2005). Such pervasive evidence of tidal stratifi-

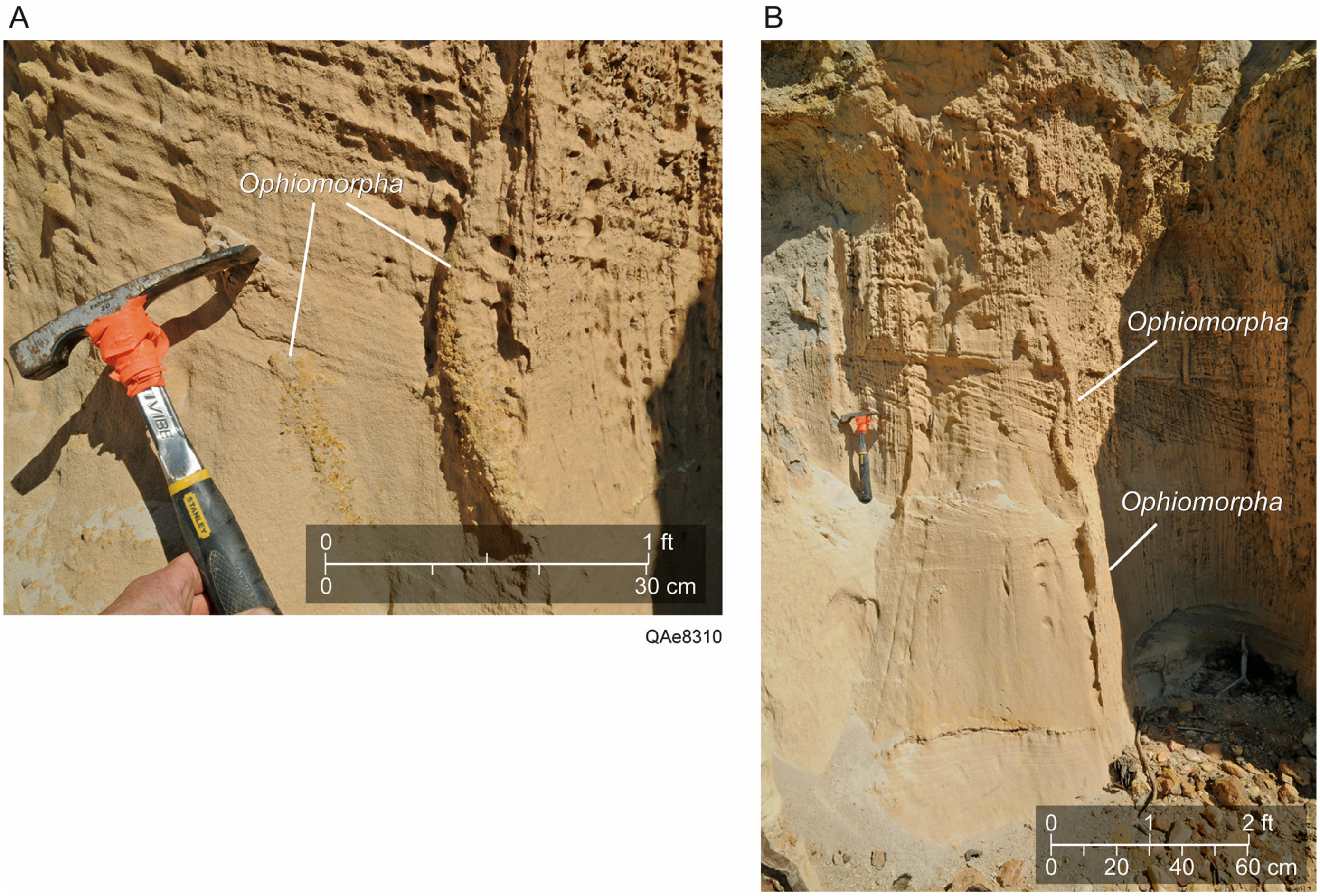

**Figure 29. Long (>1 ft [>0.3 m]) deeply-penetrating *Ophiomorpha* in crossbedded, fine- to medium-grained sandstone in the Carrizo Formation. (A) Two *Ophiomorpha* with one nearly completely exhumed in three dimensions. (B) Wide view of the same outcrop, with upper *Ophiomorpha* corresponding to rightward example in photograph (A). Regional location of outcrop is shown in Figure 1.**

cation suggests at least a mesotidal setting (diurnal tidal range from 6.6 to 13.2 ft [2 to 4 m]; Davies, 1964). In microtidal settings (diurnal tidal range less than 6.6 ft ([<2 m]), fluvial and wave processes are commonly dominant, preserving evidence of fluvial processes and wave reworking of most tidal stratification that otherwise would be preserved under a higher tidal regime (Hayes, 1976; Denison et al., 2017).

The Gulf of Mexico may have been periodically open during the late Eocene. This is suggested by evidence of strata of open-marine origin found in Panama (Montes et al., 2012). The Tertiary history of the Panamanian isthmus is complex, recording intermittent periods of emergence and submergence (Coates and Obando, 1996; Uhen et al., 2010; Cadena et al., 2012; Bacon et al., 2013). An open Gulf of Mexico with a connection between the Atlantic and Pacific oceans would have resulted in an unimpeded tidal bulge across the Gulf of Mexico. This could have served to amplify tides on the wide, shallow shelf in southeastern Texas and northward into the Mississippi Embayment. Additional studies would help establish a solid link between the regional paleogeography and the prevailing tidal regime.

## CONCLUSIONS

The Upper Midway, Wilcox, Sabinetown, and Carrizo stratigraphic succession in southeastern Texas contains a greater variability in depositional systems, facies, and reservoir sandstone-body geometry than previously documented. Previous studies interpreted fluvial-dominated, wave-modified deltaic systems from thick (>600 ft [>183 m]), undivided intervals that encompass multiple depositional episodes. In contrast, this study, which integrates wireline-log, core, and outcrop data in a 13,770-mi$^2$ (~35,660 km$^2$) area updip and along the Wilcox shelf margin in southeastern Texas, resolves and delineates a variety of net-sandstone geometries in tidally-modified distributary systems and associated deltas, wave-dominated shoreline, and inner-shelf systems.

Tidally-modified deltaic systems are common in many Wilcox sequences, as well as in the overlying Carrizo Formation. Depositional axes in these sequences are narrow (<3 mi [<4.8 km]) and exhibit complex, anastomosing geometries consistent with tidally-modified systems. Microscale tidal signatures in the Wilcox to Carrizo succession include rhythmically bedded, double-mud-draped ripples as well as flaser and lenticular bedding, and systematically upward-thinning and upward-thickening sets of mud-draped bedforms and laminae. Mesoscale tidal features include >3 ft (>0.9 m) tabular crossbed sets with *Ophiomorpha* and *Teredolites* in tidal-bar facies as well as tidal-creek facies in 3 to 10 ft (0.9 to 3 m) thick, upward-fining sections filled with mud-draped and contorted beds of fine-grained sandstone with dispersed mud rip-up clasts. Macroscale tidal heterogeneities the Wilcox to Carrizo succession define major paleogeographic elements such as interdistributary-bay and marsh, tidal-distributary channel complexes, and fluvial-tidal networks.

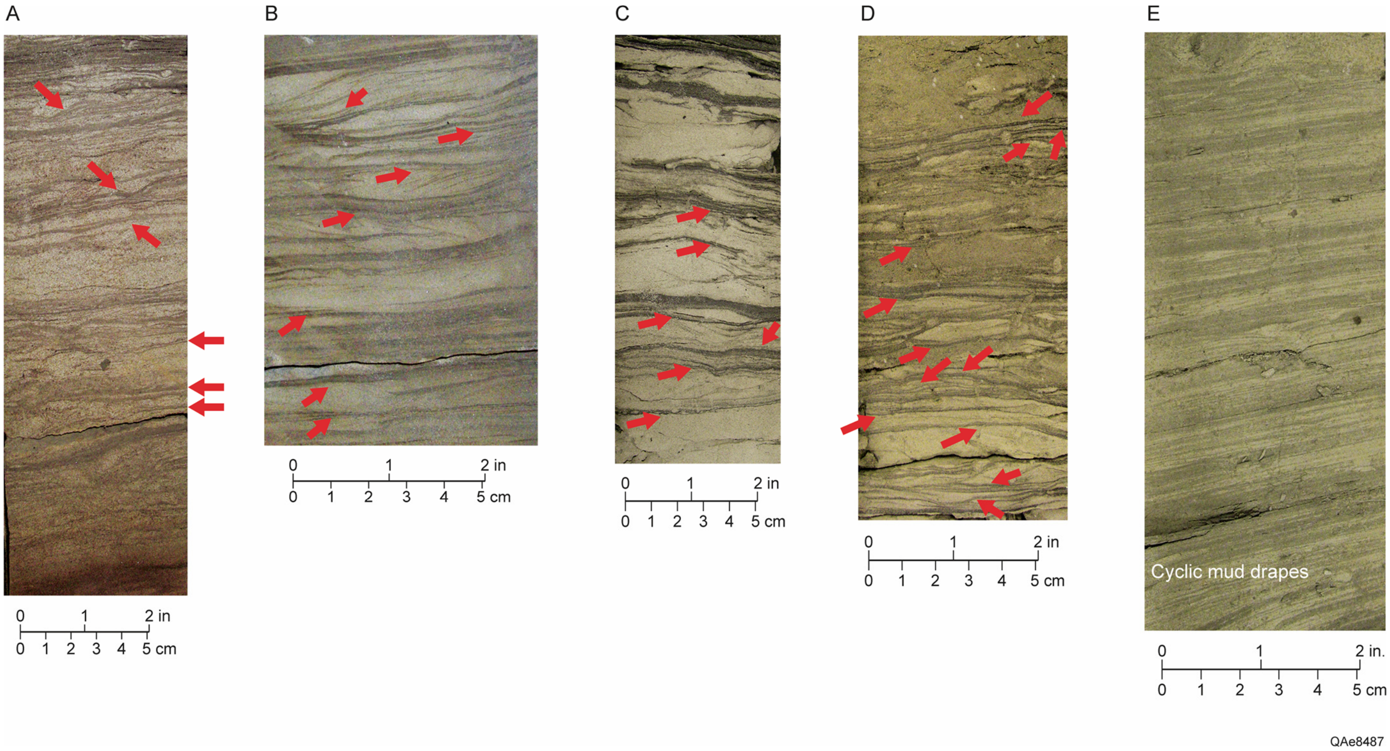

**Figure 30.** **Examples of double-draped ripples and cyclic strata in the Wilcox Group in the Letco core, illustrating microscale heterogeneity in tidally-modified systems. (A) Very fine- to fine-grained sandstone with millimeter-scale mudstone drapes at 2032.2 ft (619.6 m) in the Hooper 3 sequence. (B) Double-draped ripples composed of very fine-grained sandstone at 1169.0 ft (356.4 m) in the Calvert Bluff 3 sequence. (C) Mud-draped ripples, many double-draped at 1079.0 ft (329.0 m) in the Calvert Bluff 3 sequence. (D) Mud-draped ripples overlain by sparsely-burrowed, sandy siltstone at 1074.0 ft (327.4 m) in the Calvert Bluff 3 sequence. (E) cyclic mud drapes and thin beds of very fine-grained sandstone in the Calvert Bluff 6 sequence at 655.0 ft (199.7 m). Arrows indicate double-draped ripples. Location of cored well is shown in Figure 1.**

Because of pervasive tidal signatures throughout the Wilcox to Carrizo stratigraphic succession, both the vertical and lateral complexity of reservoir systems is significantly greater than previously inferred, implying an increased potential for reservoir heterogeneity and compartmentalization. This complexity should be considered in future reservoir development strategies in the Wilcox to Carrizo stratigraphic succession. The value of this study for exploration for oil and gas in the Upper Midway to Carrizo stratigraphic succession is three-fold as it (1) better resolves the net-sandstone geometry and paleogeography of individual regressive-transgressive depositional episodes in a series of detailed lithology maps, enabling explorationists to specifically target sandstone-rich depositional axes, (2) provides evidence for pervasive and widespread tidally-modified facies, with implications for increased reservoir heterogeneity, both vertically and laterally, and (3) demonstrates a greater variability in depositional systems than previously documented, thereby drawing attention to the need for more-diverse exploration models that address differences in distribution of potential reservoir sandstone bodies. Examples include strike-elongate, wave-modified systems (Midway 2 and Simsboro 4 sequences), downdip-bifurcating, fluvial-dominated deltaic systems (Simsboro 2 sequence), tributary systems in fluvial-delta plain systems (Hooper 2 sequence), and dip-elongate, anastomosing systems in tidally-modified deltaic systems (Calvert Bluff 4 sequence).

## ACKNOWLEDGMENTS

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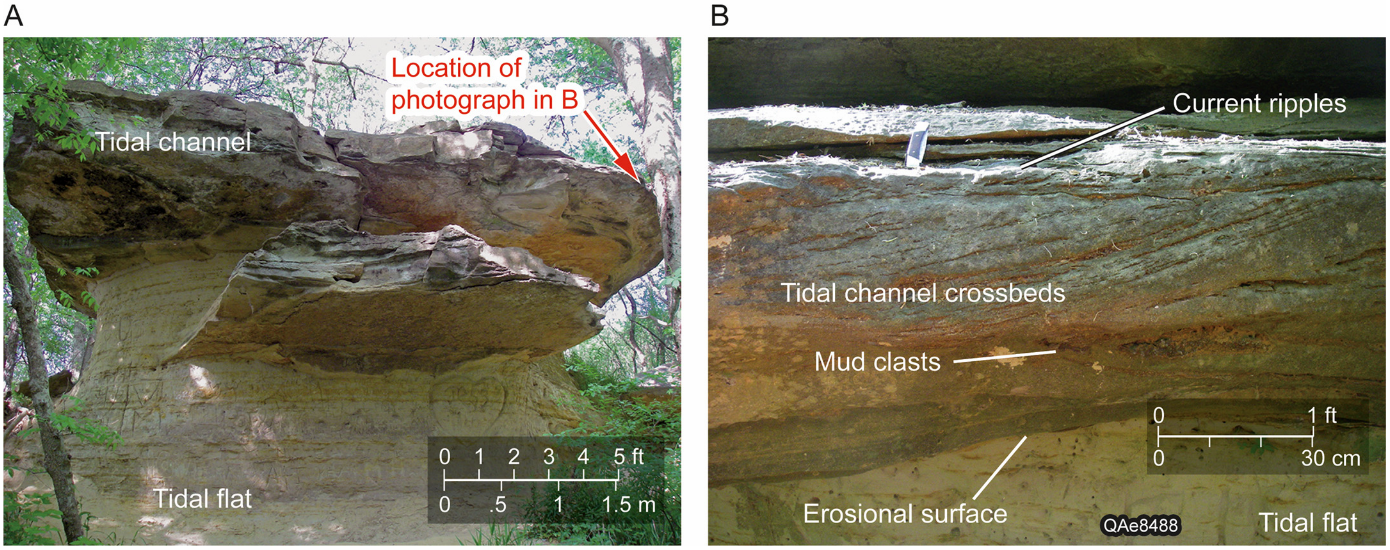

**Figure 31. Upper Calvert Bluff Formation at Pancake Rocks along the Colorado River, southeast of Bastrop, Texas. (A) Tidal flat and tidal channel deposits. (B) Cross-bedded tidal-channel facies, with location of photograph indicated in (A). Regional location of outcrop is shown in Figure 1.**

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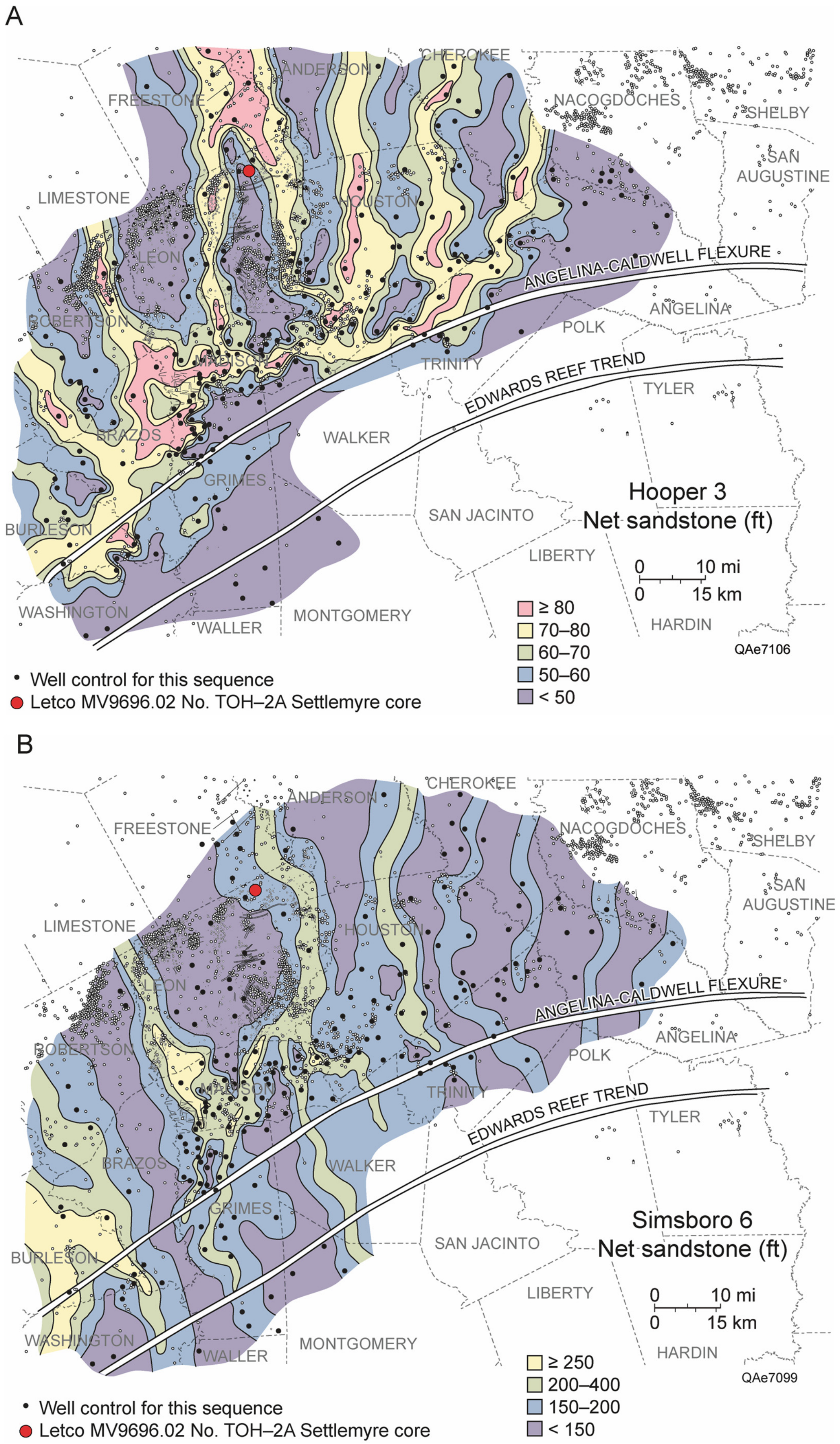

**Figure 32. (A) Net sandstone, Hooper 3 sequence. (B) Net sandstone, Simsboro 6 sequence. These stratigraphic units are defined in Figure 1.**

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