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Shelf and Lower-Shoreface Deposits in the Upper Midway Group and the Transition into Fluvial-Dominated Deltaic Deposits in the Hooper Formation (Lower Wilcox Group) in the Southeastern Texas Gulf Coast

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ABSTRACT

The Paleocene Upper Midway Group in the southeastern Texas Gulf Coast records a stratigraphic succession of shelf and lower-shoreface systems. Four (4) recognition criteria for these systems include (1) thin (<2 ft [<0.6 m]), erosion-based and lenticular, very fine-grained and fine-grained sandstone beds with swaley cross-stratification, (2) a diverse *Cruziana* trace-fossil assemblage consisting of *Teichichnus*, *Palaeophycus*, *Planolites*, and *Schaubcylindrichnus*, (3) net-sandstone trends consisting of strike-elongate ribbons and pods that merge updip (north and northwest) into broad, sheet-like patterns, and (4) an absence of northwestern and northern feeder systems inferred from net-sandstone maps.

Net-sandstone trends in Upper Midway shelf deposits in southeastern Texas are irregular and narrow, strike-elongate pods and ribbons ranging in thickness from 20 to 35 ft (6 to 11 m). They grade southward and southeastward into extensive, muddy areas with <10 ft (<3 m) of net sandstone. In contrast, lower-shoreface deposits at the top of the Upper Midway Group contain wide (>10 mi [>16 km]) strike-elongate belts of >40 ft (>12 m) of net sandstone. These belts extend northeastward >50 mi (>80 km) along depositional strike. Sandstone-body continuity, inferred from wireline-log cross-sections, differs greatly among these shelf and lower-shoreface deposits. Sandstone-body continuity in Upper Midway lower-shoreface deposits at 10 mi (16 km) well spacing is approximately 60%, whereas it is only 20% at the same well spacing in shelf deposits. At 20 mi (32 km) well spacing, lower-shoreface sandstone-body continuity is 37% but only 4% in shelf deposits.

Microscale heterogeneity in the Upper Midway Group is related to sedimentary structures and accessory features that disrupt vertical sandstone-bed continuity over scales of millimeters to centimeters. These include mudstone drapes, scour surfaces, shell debris, mudstone clasts, and trace fossils. Mesoscale heterogeneity, inferred from cores and wireline-log cross-sections, is defined by lateral sandstone-body pinchouts and vertical stacking patterns. In contrast, macroscale heterogeneities in the Upper Midway Group, inferred from net-sandstone maps, compose facies architecture at a regionally-mappable scale. They include paleogeographic elements such as shelf sand-shoal complexes, strike-fed shoreface systems, and abandoned-deltaic headlands. These paleogeographic elements extend for tens of miles or kilometers along depositional strike from southwest to northeast.

The transition in depositional systems in the Upper Midway Group to the Lower Wilcox Group is abrupt, recording a change from wave-dominated shelf and shoreface systems to fluvial-dominated deltaic depositional systems. Dip-elongate, fluvial-dominated deltaic deposits at the base of the Wilcox Group (Hooper 1 depositional unit) have depositional axes oriented orthogonally with respect to those in the underlying Midway Group. Hooper 1 depositional axes are narrow (commonly <4 mi [<6.4 km] across. They are erosionally-based, net upward-fining, and composed of fine- to medium-grained sandstone with abundant siltstone and mudstone rip-up clasts. Distributary-channel trends in the Hooper 1 depositional unit are connected southward and southwestward to downdip-bifurcating trends representing upward-coarsening sub-delta deposits that pinch out into interdistributary mudstones.

Microscale heterogeneity in fluvial-dominated deltaic deposits in the lower part of the Hooper Formation occurs at the scale of large (>2 in [>5.1 cm]) diameter siltstone and mudstone clasts in distributary-channel deposits. Mesoscale heterogeneity is controlled by lateral pinchouts of distribu-

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tary-channel sandstone bodies into floodplain and interdistributary mudstones. Macroscale heterogeneity is represented by numerous dip-elongate distributary-channel depositional axes that segment lower-coastal-plain systems into discrete sandy depocenters. Six Hooper 1 deltaic depocenters occur along a 60 mi (96 km) span along the Angelina-Caldwell Flexure. Sandstone-body continuity along depositional strike (southwest to northeast) in the Hooper 1 depositional unit is poor, being only approximately 25% at 10 mi (16 km) well spacing. These sandstone-body continuity values record the presence of multiple, locally occurring deltaic depocenters within a fluvial-dominated deltaic system, in contrast to the wave-dominated shelf and lower-shoreface deposits in the underlying Upper Midway Group.

INTRODUCTION AND OBJECTIVES

The Paleocene Upper Midway Group in southeastern Texas represents a transition from shelf to lower-shoreface systems. It is overlain by fluvial-dominated deltaic systems in the Hooper Formation, the basal stratigraphic unit in the Wilcox Group (Ambrose et al., 2020). This study defines and interprets facies and depositional systems in two depositional units in the upper part of the Midway Group along and updip of the Angelina-Caldwell Flexure (Figs. 1 and 2). These two depositional units, informally named Midway 1 and Midway 2, are each 120 to 300 ft (37 to 91 m) thick in the study area. The basal depositional unit in the Wilcox Group (Hooper 1) is commonly <50 ft (<15 m) thick where it is sandstone poor but is locally >100 ft (>30.5 m) thick (Fig. 2).

This study has seven (7) objectives. The first objective is to divide the upper part of the Midway Group into two high-frequency, regressive-transgressive episodes, informally named in this study as the Midway 1 and Midway 2 depositional units (Fig. 2). In addition, this study divides the Hooper Formation into four depositional units and focuses on the basal depositional unit (Hooper 1 [Fig. 2]). Other objectives are to (2) describe lithology and sedimentary features from slabbed core, (3) construct detailed net-sandstone maps of these depositional units to depict sandstone-body geometry, (4) integrate core data with net-sandstone maps to infer depositional systems and facies, reconstructing the paleogeography of the Upper Midway and basal Lower Wilcox groups, (5) provide a first-order analysis of sandstone-body continuity in these depositional units based on the ratio of continuous versus all sandstone bodies between wells interpreted on wireline-log cross-sections, (6) discuss three levels of heterogeneity (microscale, mesoscale, and macroscale) in depositional units inferred from core, wireline-log cross-sections, and net-sandstone maps, and (7) document changes in depositional style between the Hooper 1 depositional unit and the underlying Midway 2 depositional unit.

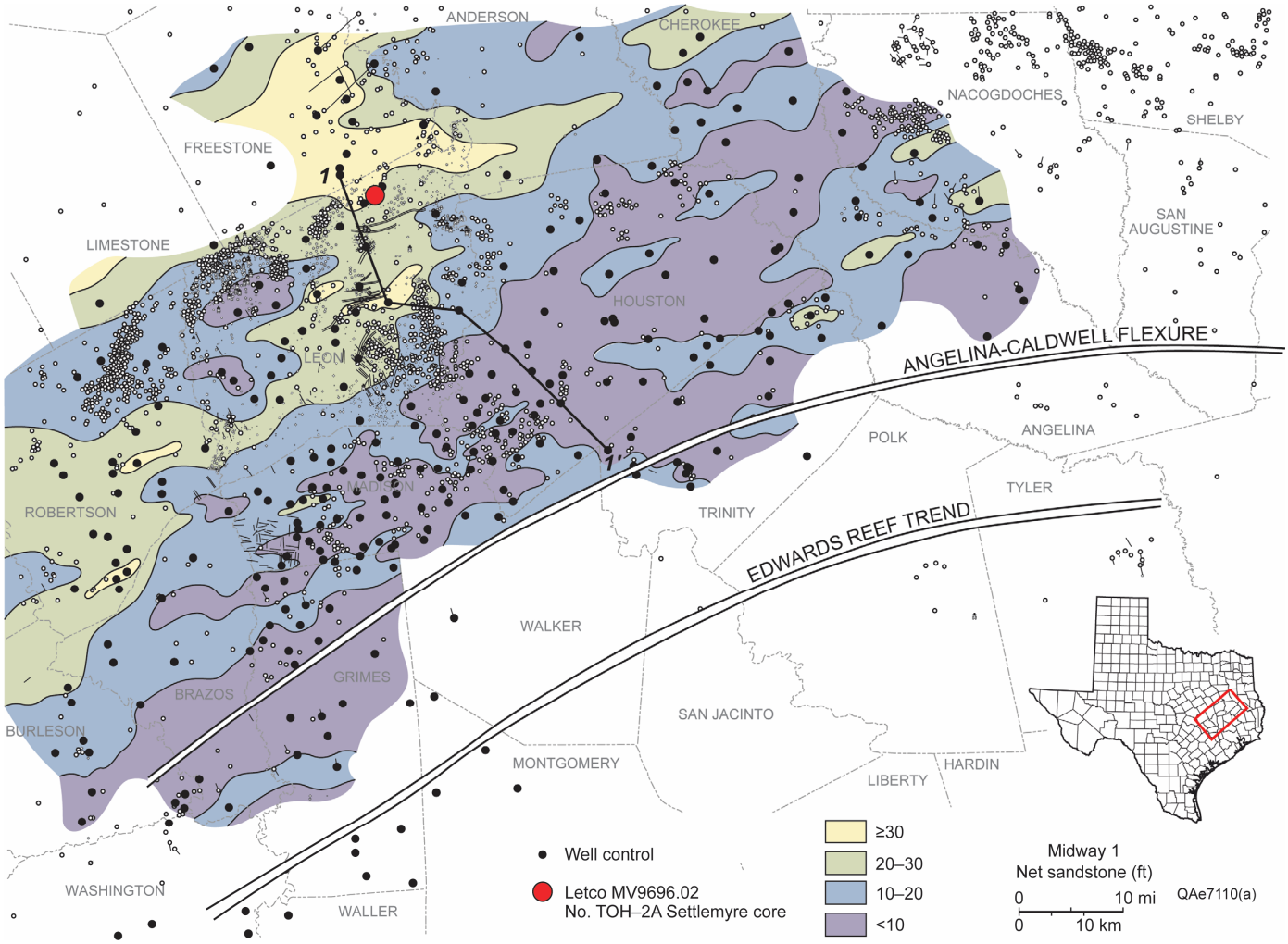

Figure 1. Net-sandstone map of the Midway 1 depositional unit in southeastern Texas. The type log (Letco MV 9696.02 No. TOH–2A Settlemyre in Leon County) is shown in Figure 2. Stratigraphic dip section 1–1' is shown in Figure 3. The core description and photographs of the Midway 1 depositional unit are shown in Figures 4 and 5.

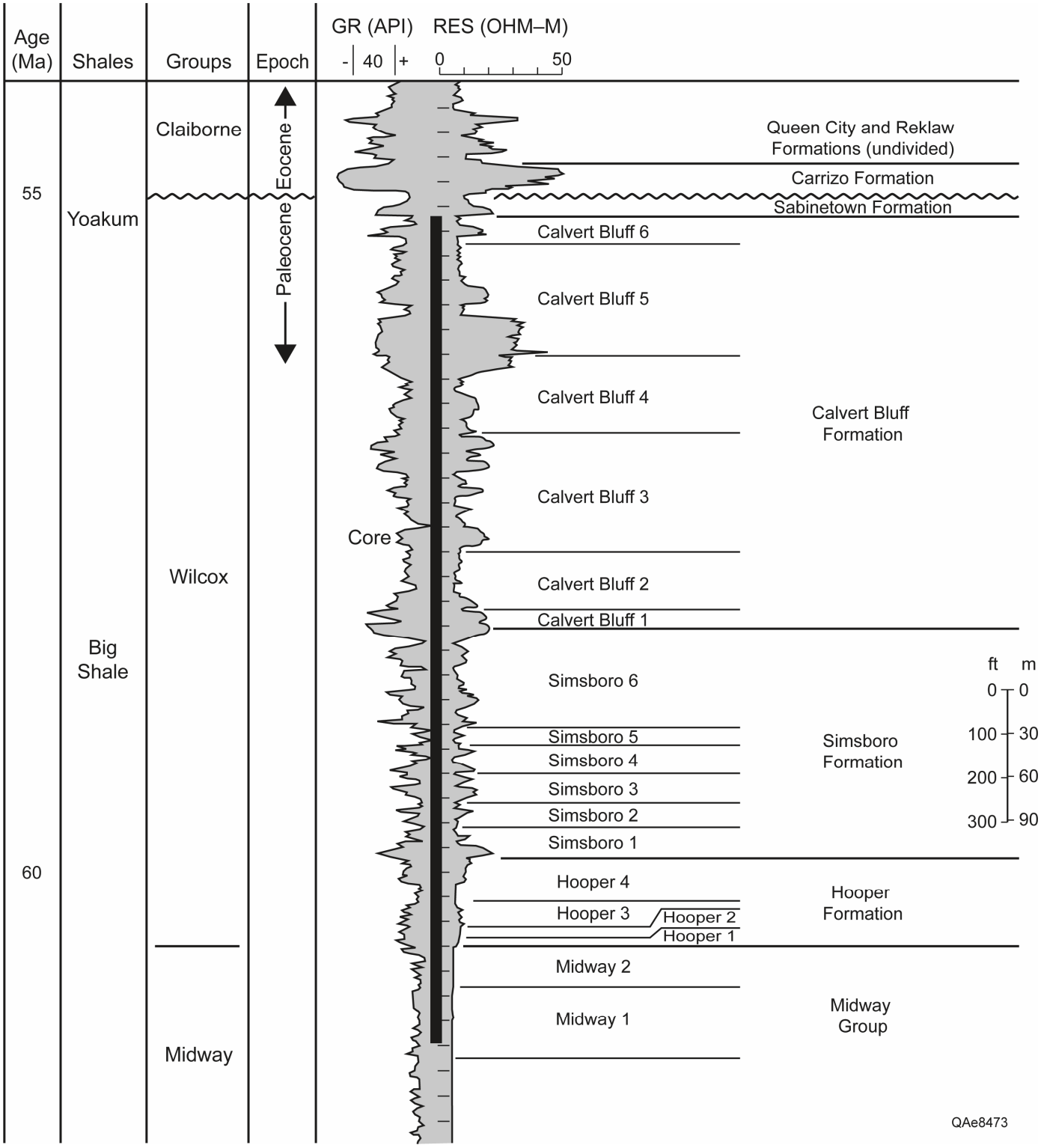

Figure 2. Wireline log of the Letco MV 9696.02 No. TOH–2A Settlemyre well in northeastern Leon County. The cored section and stratigraphic nomenclature of this study are also shown. The location of the cored well is shown in Figures 1 and 7 by Ambrose et al. (2020).

DATABASE AND METHODS

Wireline Logs and Core Data

This study uses wireline-log data from ~300 wells in a 13,770 mi^2 (~35,660 km^2) area that includes all or parts of 18 counties in southeastern Texas (Fig. 1). Data from the basal 240 ft (~73 m) of slabbed core in the Letco MV 9696.02 No. TOH–2A Settlemyre well in Leon County (Figs. 1 and 2) are used to describe and interpret facies and to calibrate net-sandstone values from wireline logs. These core data include lithology, vertical grain-size trends, stratification, contacts, and trace fossils diagnostic of shallow-marine depositional environments.

Net-Sandstone Maps

Net sandstone from wireline logs in this study is defined from a cutoff value of ~30% from the rightward baseline of gamma-ray (GR) deflection to a consistent, leftward deflection from which minimum clay content was inferred. This value is 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 is used to determine net-sandstone values with a cutoff value of 25% from the SP baseline to the static SP (SSP), defined as the consistent and maximum leftward deflection that indicates the theoretical maximum SP current that can be measured in a clean, non-shaly sandstone (Serra, 1984). The resistivity curve is also used in zones with poor GR and SP responses. Net-sandstone maps in this study are isopach rather than isochore maps. They are hand-contoured, with wireline-log responses used as a guide for contours. White areas in these net-sandstone maps indicate an absence of data rather than zero net-sandstone values.

Facies and Scales of Depositional Systems

Facies interpretations for each depositional unit in this study are based on integrating wireline-log responses, net-sandstone maps, and core data. Shelf-bar facies in the Upper Midway Group are interpreted from predominantly upward-left, serrate, and spiky deflections in GR and SP curves. In contrast, uppermost Midway shoreface facies have relatively-greater percent-sandstone values. They are interpreted from upward-coarsening (upward-left deflections) and upward-coarsening/blocky wireline-log responses. Distributary-channel facies in the Hooper 1 depositional unit (basal Wilcox Group) have upward-fining and blocky wireline-log responses. In contrast, channel-mouth-bar and delta-front facies have upward-coarsening and upward-coarsening/serrate wireline-log responses. Interdistributary facies are characterized by low net-sandstone content and baseline and serrate wireline-log responses. The use of wireline-log responses for facies interpretation in Tertiary stratigraphic units in the Gulf Coast Basin is established in numerous subsurface studies of the Texas Gulf Coast, including the Wilcox Group (Fisher and McGowen, 1967; Edwards, 1981; Hamlin, 1983; Zhang et al., 2016; Ambrose et al., 2018), Frio Formation (Galloway and Cheng, 1985; Galloway, 1986; Tyler and Ambrose, 1986), and the Miocene stratigraphic succession (Doyle, 1979).

Depositional systems in this study are interpreted by analyzing spatial relationships between sandstone bodies in net-sandstone maps. Scales of facies elements are considered in these depositional-systems interpretations. Dimensional data include sandstone bodies' width, length, and thickness in shallow-marine and lower-coastal-plain systems.

Sandstone-Body Continuity

Sandstone-body continuity in depositional units in this study is calculated from the number of continuous sandstone beds interpreted on cross-sections from wireline logs. Sandstone-body continuity in adjacent wells is defined as the ratio (or percentage) between continuous sandstone beds and all sandstone beds, expressed as a number between 0 and 1 (0 and 100%), with 0 (0%) indicating no continuous sandstone beds and 1 (100%) indicating continuity of all sandstone beds. For more greatly-spaced well pairs on wireline-log sections with intervening wells, sandstone-body continuity values are calculated by multiplying sandstone-body continuity values for each successive well pair between these greatly-spaced wells. Values of sandstone-body continuity are cross-plotted versus the distance between all possible well pairs from wireline-log cross-sections. Best-fit curves are applied to obtain sandstone-body continuity functions for each depositional unit in this study.

Levels of Reservoir Heterogeneity

Three levels of reservoir heterogeneity (microscale, mesoscale, and macroscale) are described and discussed for the Midway 1, Midway 2, and Hooper 1 depositional units. Microscale heterogeneity is evaluated from sedimentary features in cores. These include bed boundaries, lithologic contacts such as mudstone-draped ripples, vertical and lateral transitions in bedforms, and distribution of accessory features such as shell debris, mudstone clasts, and trace fossils. These features are inferred to disrupt the continuity of sandstone beds over scales of millimeters to centimeters. Mesoscale heterogeneity involves changes in the vertical succession rather than in individual beds or contacts between individual beds. Also inferred from wireline-log cross-sections, lateral sandstone-body pinchouts, and vertical stacking patterns define mesoscale heterogeneity in shelf sandstones. Macroscale heterogeneities in Midway 1 and Midway 2 shelf-sandstone systems compose facies architecture at a regionally-mappable scale. They include major paleogeographic elements such as deltaic headlands, strike-fed shoreface complexes, shelf sand-shoal complexes, and amalgamated storm sheets. These large-scale paleogeographic elements, portrayed in net-sandstone maps, extend for tens of miles or kilometers along depositional strike. Macroscale heterogeneity in the Hooper 1 depositional unit is defined by dip-elongate, sandstone-rich depocenters in net-sandstone maps. These depocenters pinch out laterally along depositional strike (southwest to northeast) over distances of <15 mi (<24 km).

MIDWAY 1

The Midway 1 depositional unit is 250 to 300 ft (76 to 91 m) thick in southeastern Texas (Figs. 2 and 3). It has baseline and muddy-serrate GR and SP responses, although some wells contain one or more upward-coarsening or upward-coarsening/serrate, sandy sections individually 40 to 60 ft (12 to 18 m) thick (Fig. 3). Percent-sandstone values in the Midway 1 depositional unit decrease from ~50% to 10% from northwest to southeast (Fig. 3). Individual sandstone bodies in the Midway 1 depositional unit are only 5 to 10 (1.5 to 3 m) thick, although they are as much as 40 ft (12 m) thick in the northwestern part of the study area. Many sandstone bodies are considered discontinuous, especially toward the southeast, where overall percent-sandstone values are <20% (Fig. 3).

Lithology

The Midway 1 depositional unit, cored in the Letco MV 9696.02 No. TOH–2A Settlemyre core, located in Figure 1, is composed of fine-grained, burrowed, silty mudstone beds sparsely interbedded with 6 in to 1 ft (0.15 to 0.3 m) beds of very fine- to fine-grained sandstones (Fig. 4). The top of the Midway 1 depositional unit is marked by an 8 ft (2.4 m), upward-coarsening section that grades upward from muddy siltstone to ripple-stratified, fine-grained sandstone. Many sandstone beds, individually ≤1 ft (≤0.3 m) thick, are scour-based. Trace fossils include *Planolites*, *Schaubcylindrichnus*, *Palaeophycus*, *Teichichnus*, and a rare *Rosellia* (Fig. 5A).

Net Sandstone

The Midway 1 depositional unit is composed of strike-elongate (northeast-trending) net-sandstone patterns (Fig. 1). The northwestern and northern part of the study area from Robertson to Anderson counties contains sandstone bodies with predominantly upward-coarsening wireline-log responses. They are collectively >30 ft (>9 m) thick, part of net-sandstone trends that extend along depositional strike >40 mi (>64 km). The northeast-trending belt of >30 ft (>9 m) of net sandstone in Freestone County is separated from the northeast-trending belt of

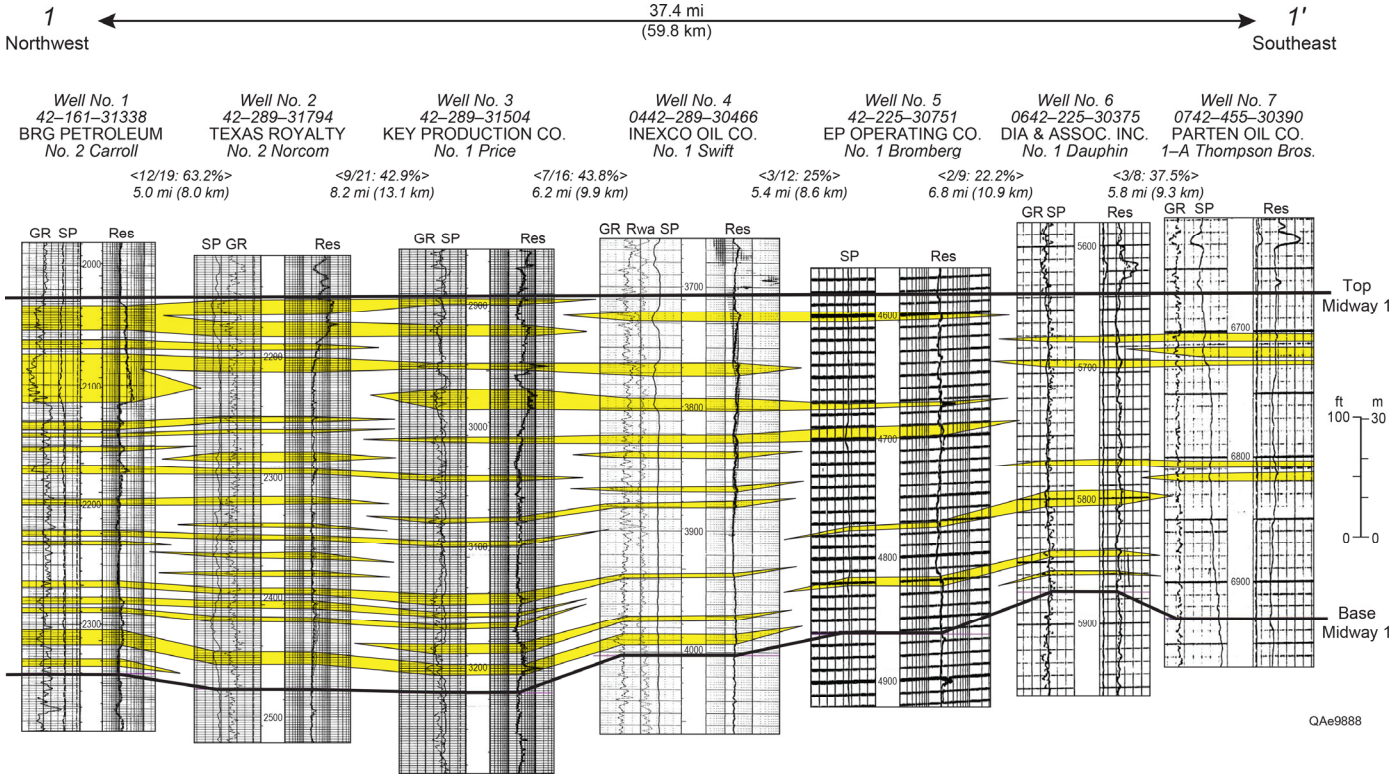

Figure 3. Stratigraphic dip section 1–1', portraying sandstone-body continuity in the Midway 1 depositional unit. Sandstone-body continuity between adjacent wells is indicated in angle brackets above wireline-log curves. The datum is the top of the Midway 1 depositional unit. Wireline-log curves: GR = gamma ray; SP = spontaneous potential, Res = resistivity, and Rwa = apparent resistivity of formation water. The location of the section is shown in Figure 1.

20 to 30 ft (6 to 9 m) of net sandstone in Robertson and Leon counties by a muddy area with 4 to 20 ft (1.2 to 6 m) of net sandstone. Most of the southwestern and south-central parts of the study area (Washington to Trinity counties) contain <10 ft (<3 m) of net sandstone (Fig. 1). The muddy, downdip area of <10 ft (<3 m) net sandstone contains discontinuous pods of 10 to 20 ft (3 to 6 m) of net sandstone in Houston and Trinity counties, as well as other pods of 20 to 30 ft (6 to 9 m) of net sandstone in northern Angelina and southwestern Nacogdoches counties.

Facies Interpretation

The Midway 1 depositional unit is composed of shelf deposits. This interpretation is based on four (4) criteria. These include (1) *Planolites*, *Palaeophycus*, *Rosellia*, and *Schaubcylindrichnus*, common in *Cruziana* trace-fossil assemblages (Seilacher, 1964; Pemberton et al., 1992). Two other criteria are (2) thin (<1 ft [<0.3 m]), ripple-stratified and swaley sandstone beds in mudstone-dominated sections (Figs. 4 and 5A) and (3) strike-parallel and elongate sandstone bodies with upward-coarsening and serrate wireline-log responses that pinch out into extensive areas of mudstone with baseline and muddy-serrate wireline-log responses. A fourth (4) criterion is the absence of dip-elongate (south- and southeast-trending) sandstone bodies representing fluvial or deltaic feeder systems to the north and northwest (Fig. 1).

Depositional Analogs

Sandstone bodies in the Midway 1 depositional unit are comparable to those on modern shelves where wave and storm processes have reworked relict sand from older coastal or deltaic systems into lenticular, coast-parallel bars (Swift and Field, 1981; Snedden and Dalrymple, 1999). Modern shelf-sand ridges are elon-gate bodies with lengths on the order of 6 mi (10 km) (Swift, 1985; Dalrymple and Hoogendoorn, 1997; Snedden and Dalrymple, 1999). However, shelf-sand ridges offshore of Galveston Bay in the Gulf of Mexico are irregular and larger, being almost 24 mi (38 km) long and as much as 4.8 mi (7.7 km) wide (Thomas and Anderson, 1994), comparable in scale with those in the Midway 1 depositional unit.

MIDWAY 2

The Midway 2 depositional unit is the youngest stratigraphic unit in the Midway Group (Fig. 2). It ranges in thickness from 130 to ~200 ft (~40 to 61 m) from northwest to southeast (Fig. 6). The Midway 2 depositional unit is composed commonly of >50% sandstone, in contrast to the underlying, muddier Midway 1 depositional unit. Sandstone bodies in the Midway 2 depositional unit are more laterally continuous than those in the Midway 1 depositional unit (Figs. 6 and 3, respectively). Wireline-log responses in the Midway 2 depositional unit are mainly upward-coarsening and muddy-serrate, with individual sandy sections ranging in thickness from 20 to 80 ft (6 to 24 m). Wireline-log responses in the updip (northwestern) part of the Midway 2 depositional unit (Fig. 6 and 7) are upward coarsening, whereas those in downdip areas to the southeast are serrate, baseline, spiky, and muddy-serrate.

Lithology

The lower ~30 ft (~9 m) of the Midway 2 depositional unit is present in the Letco MV 9696.02 No. TOH–2A Settlemyre core (Fig. 4). It consists of a muddy section with thin (<1 ft [<0.3 m]) beds of very fine-grained and fine-grained sandstone (Fig. 4). Many sandstone beds are <1 cm thick and are disrupted from post-depositional compaction (Fig. 5B). Trace fossils include

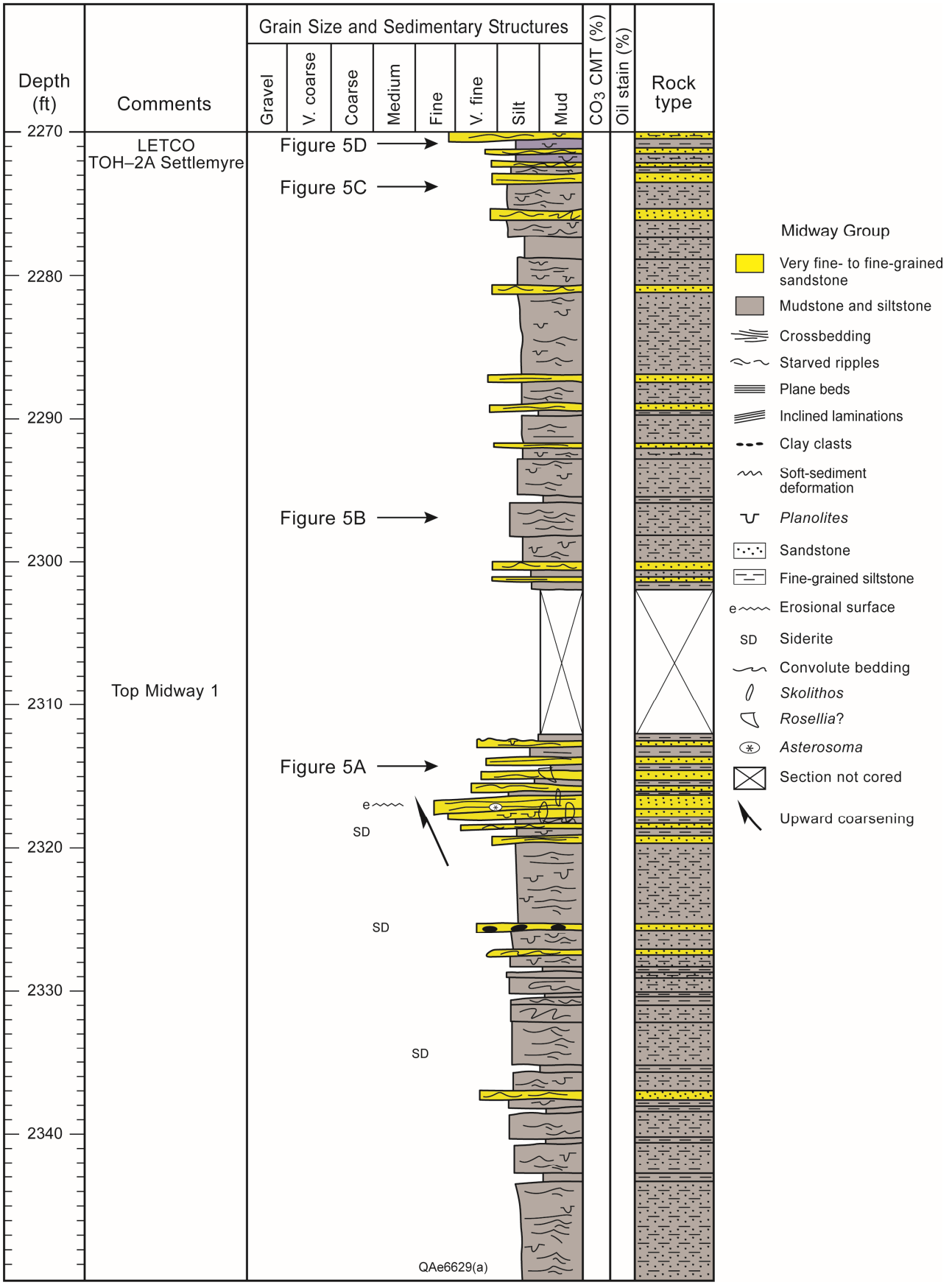

Figure 4. Description of the Letco MV 9696.02 No. TOH–2A Settlemyre core from 2270 to 2350 ft (691.9 to 716.3 m), showing the upper 40 ft (12 m) of the Midway 1 depositional unit and the lower 30 ft (9 m) of the Midway 2 depositional unit (modified after Ambrose et al. [2020]). The wireline log is shown in Figure 2. Core photographs are shown in Figure 5. The location of the cored well is shown in Figures 1 and 7.

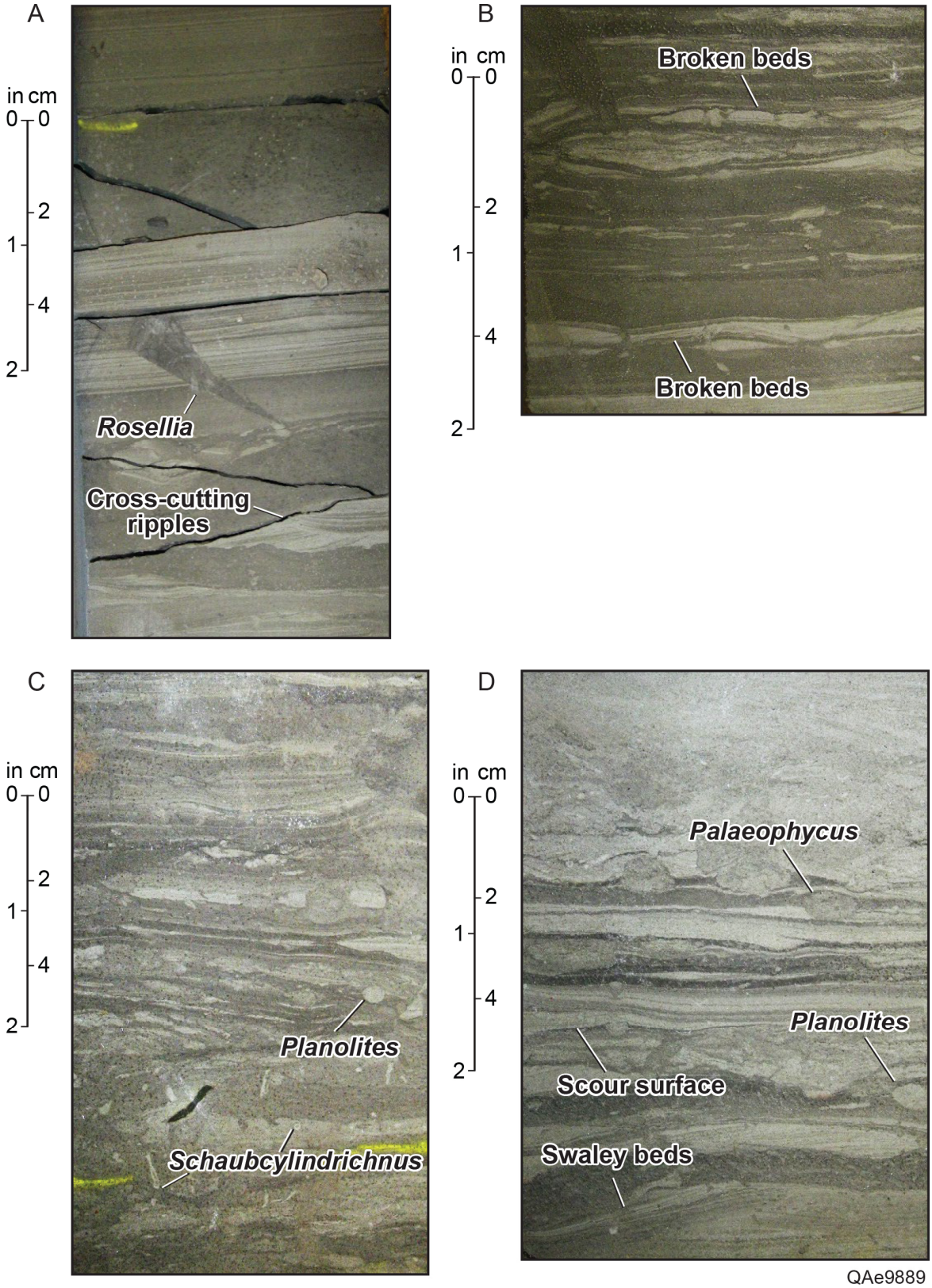

Figure 5. Photographs of the Letco MV 9696.02 No. TOH–2A Settlemyre core in the Midway 1 and 2 depositional units (modified after Ambrose et al. [2020]). (A) Very fine-grained, laminated sandstone above cross-cutting ripples interbedded with muddy siltstone below the top of the Midway 1 depositional unit at 2314.0 ft (705.3 m). Sandstone beds are crosscut by *Rosellia*. (B) Broken and lenticular beds of rippled-stratified, very fine-grained sandstone and silty mudstone in the lower part of the Midway 2 depositional unit at 2297.5 ft (700.3 m). (C) Very fine-grained sandstone and siltstone with *Planolites* and *Schaubcylindrichnus* in the lower part of the Midway 1 depositional unit at 2273.6 ft (693.0 m). (D) Fine-grained, shelly sandstone with thin interbeds of siltstone in the lower part of the Midway 2 depositional unit at 2270.0 ft (691.9 m). Swaley beds are shown at the base of the photograph. Trace fossils are *Palaeophycus* and *Planolites*. The wireline log is shown in Figure 2. The core description is shown in Figure 4. Location of cored well is shown in Figures 1 and 7.

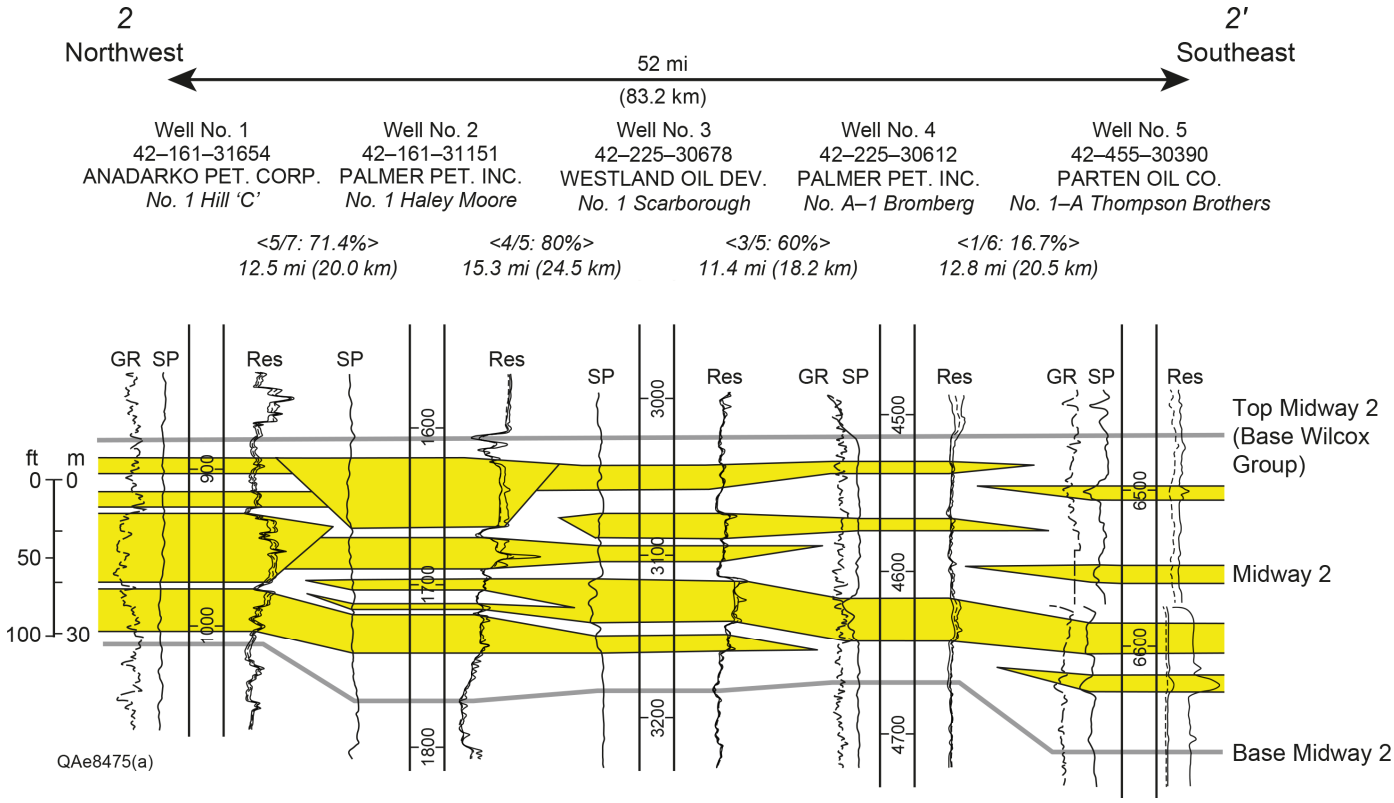

Figure 6. Stratigraphic dip section 2–2', portraying sandstone-body continuity between wells in the Midway 2 depositional unit. Sandstone-body continuity between adjacent wells is indicated in angle brackets above wireline-log curves. Datum is the top of the Midway 2 depositional unit (base of Wilcox Group). Wireline-log curves: GR = gamma ray; SP = spontaneous potential, and Res = resistivity. The location of the section is shown in Figure 7.

Planolites, *Schaubcylindrichnus*, and *Palaeophycus* (Figs. 5C and 5D). Stratification consists of thin (millimeter-scale) laminae and faint, swaley bedding. Some sandstone beds are scour-based (Fig. 5D).

The upper 37 ft (11.3 m) of the Midway 2 depositional unit in the Letco MV 9696.02 No. TOH–2A Settlemyre core consists of siltstone and mudstone beds and burrowed, fine-grained sandstone beds within 5 to 10 ft (1.5 to 3 m), upward-coarsening intervals (Fig. 8). The top of Midway 2 depositional unit is within a 4 ft (1.2 m) bed of sparsely-burrowed, silty mudstone at 2134 ft (650.4 m). Sandstone beds in the Midway 2 depositional unit range from silty, burrowed, very fine-grained sandstone (Fig. 9A) to fine-grained sandstone with oversteepened stratification and soft-sediment deformation at the tops of beds (Fig. 9B). The tops of other upward-coarsening sandstone beds contain cross-cutting, swaley stratification and onlapping laminae (Fig. 9C). The upper 15 ft (4.5 m) of the Midway 2 depositional unit consists of very fine-grained sandstone and siltstone with abundant trace fossils (Fig. 9D).

Net Sandstone

The Midway 2 depositional unit has a net-sandstone geometry similar to the underlying Midway 1 depositional unit (Figs. 7 and 1, respectively). It is composed of strike-elongate (northeast-trending) net-sandstone patterns, with greatest values of net sandstone (>40 ft [>12 m]) in discontinuous and irregular pods (Fig. 7). There is no systematic decrease in net-sandstone values from northwest to southeast in the Midway 2 depositional unit, although an extensive, muddy area having <20 ft (<6 m) of net sandstone occurs in downdip (southwestern) areas in Grimes, Brazos, and Washington counties (Fig. 7).

Facies Interpretation

The Midway 2 depositional unit represents a transition from inner-shelf to lower-shoreface deposits, in turn, overlain by fluvial-dominated deltaic deposits in the Hooper Formation (Fig. 2). This interpretation is based on (1) the dominant orientation of strike-parallel sandstone bodies (Fig. 7), (2) an absence of dip-elongate, fluvial or deltaic feeder systems from the north and northwest, (3) relatively-greater net-sandstone content with respect to the underlying Midway 1 depositional unit, interpreted to be mid- to outer-shelf in origin (Fig. 1), (4) a *Cruziana* trace-fossil assemblage that includes *Schaubcylindrichnus*, *Planolites*, and *Teichichnus*, and (5) sedimentary structures such as swaley bedding that record open-marine, wave-dominated processes (Fig. 9C). The presence of numerous, sub-millimeter-scale mud drapes in these swaley beds may indicate tidal influence, although double-mud drapes and bidirectional bedding are absent. Statistical analysis of thickness trends of individual, mud-draped sandstone beds and silty laminae (see Kvale et al. [1989] and Ambrose et al. [2015]) would be necessary to document rhythmic bedding consistent with tidal processes.

Depositional Analogs

The upper part of the Campanian (Upper Cretaceous) Lewis Shale and the overlying lower Pictured Cliffs Sandstone in the San Juan Basin in southwestern Colorado and northwestern New Mexico are depositional analogs for the Midway 2 depositional unit. The upper Lewis Shale is a silty mudstone grading upward into thin (<1 ft [<0.3 m]), very fine-grained, laminated sandstones interbedded with muddy siltstone (Manfrino, 1984; Ayers et al., 1994). Many sandstone beds in the lower Pictured Cliffs Sandstone are scoured and sharp-based. Stratification is dominat-

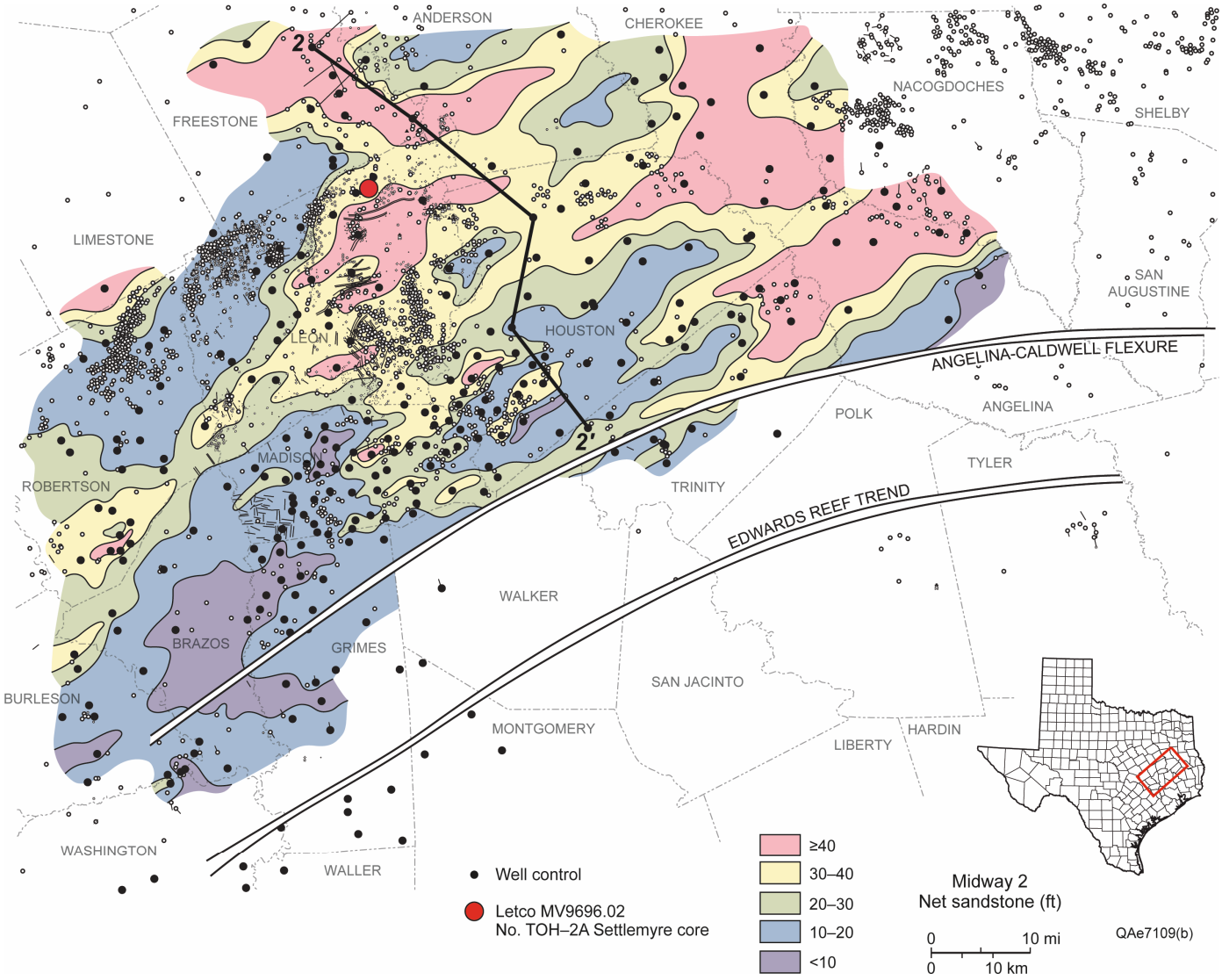

Figure 7. Net-sandstone map of the Midway 2 depositional unit in southeastern Texas. The type log (Letco MV 9696.02 No. TOH–2A Settlemyre in Leon County) is shown in Figure 2. Stratigraphic dip section 2–2' is shown in Figure 6. The core description is shown in Figures 4 and 8. Core photographs are shown in Figures 5 and 9.

ed by low-angle and horizontal laminations, swaley stratification, and wavy bedding overlain by ripples and plane beds that record storm and fair-weather processes on a wave-dominated shelf. The Pictured Cliffs Sandstone, together with the underlying Lewis Shale and the overlying, coal-bearing Fruitland Formation (analogous to coal-bearing strata in the Wilcox Group in southeast Texas), compose a stratigraphic succession recording an evolution of shelf to wave-dominated shoreface/lower-coastal-plain depositional systems in the San Juan Basin, with northeastward progradation on a weakly subsiding platform (Flores and Erpenbeck, 1971; Cumella, 1983; Ayers et al., 1994; Ambrose and Ayers, 2007). Progradation of the Pictured Cliffs shoreline onto a wave-dominated shelf, dependent on complex interactions of sediment supply, basin subsidence, and eustasy, was intermittent, and was punctuated by shoreline stillstands (Kauffman, 1977; Weimer, 1986).

Sandstone-Body Continuity

Sandstone-body continuity in the Upper Midway Group, portrayed in wireline-log sections 1–1' and 2–2' (Figs. 3 and 6, respectively), differs greatly among the Midway 1 and Midway 2 depositional units. Sandstone-body continuity in the Midway 2 depositional unit at 10 mi (16 km) well spacing in the study area is approximately 60%, whereas it is only 20% at the same well spacing in the Midway 1 depositional unit. At 20 mi (32 km) well spacing, sandstone-body continuity is 37% in the Midway 2 depositional unit but only 4% in the Midway 1 depositional unit (Figs. 10B and 10A, respectively). These differences in sandstone-body continuity record laterally extensive, lower-shoreface facies in the Midway 2 depositional unit contrasted with lenticular, shelf-bar deposits in the Midway 1 depositional unit.

HOOPER 1 (BASE OF WILCOX GROUP)

The Hooper 1 depositional unit is the basal stratigraphic unit in the Wilcox Group (Fig. 2). It is commonly <50 ft (<15 m) thick where it is sandstone poor but is locally >100 ft (>30.5 m) thick where net-sandstone content exceeds 50 ft (>15 m) (Fig. 11), where it is composed of multiple, lenticular sandstone bodies, with individual sandstone beds are as much as 40 ft (12 m) thick (Fig. 12).

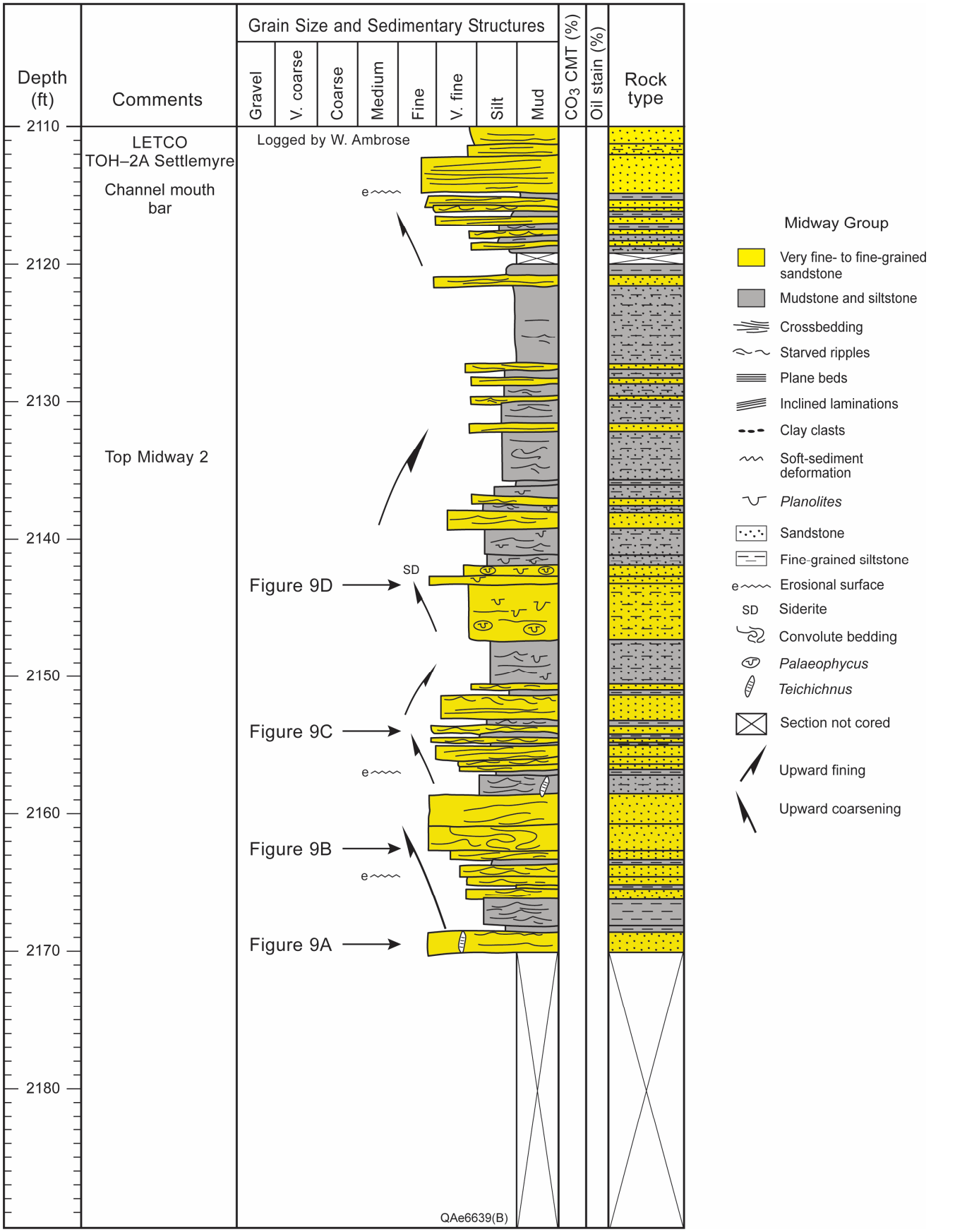

Figure 8. Description of the Letco MV 9696.02 No. TOH–2A Settlemyre core from 2110 to 2170 ft (643.1 to 661.4 m), showing the upper 35 ft (11 m) of the Midway 2 depositional unit and the lower 25 ft (7.6 m) of the Hooper Formation (modified after Ambrose et al. [2020]). The wireline log is shown in Figure 2. Core photographs are shown in Figure 9. Location of cored well is shown in Figures 1 and 7.

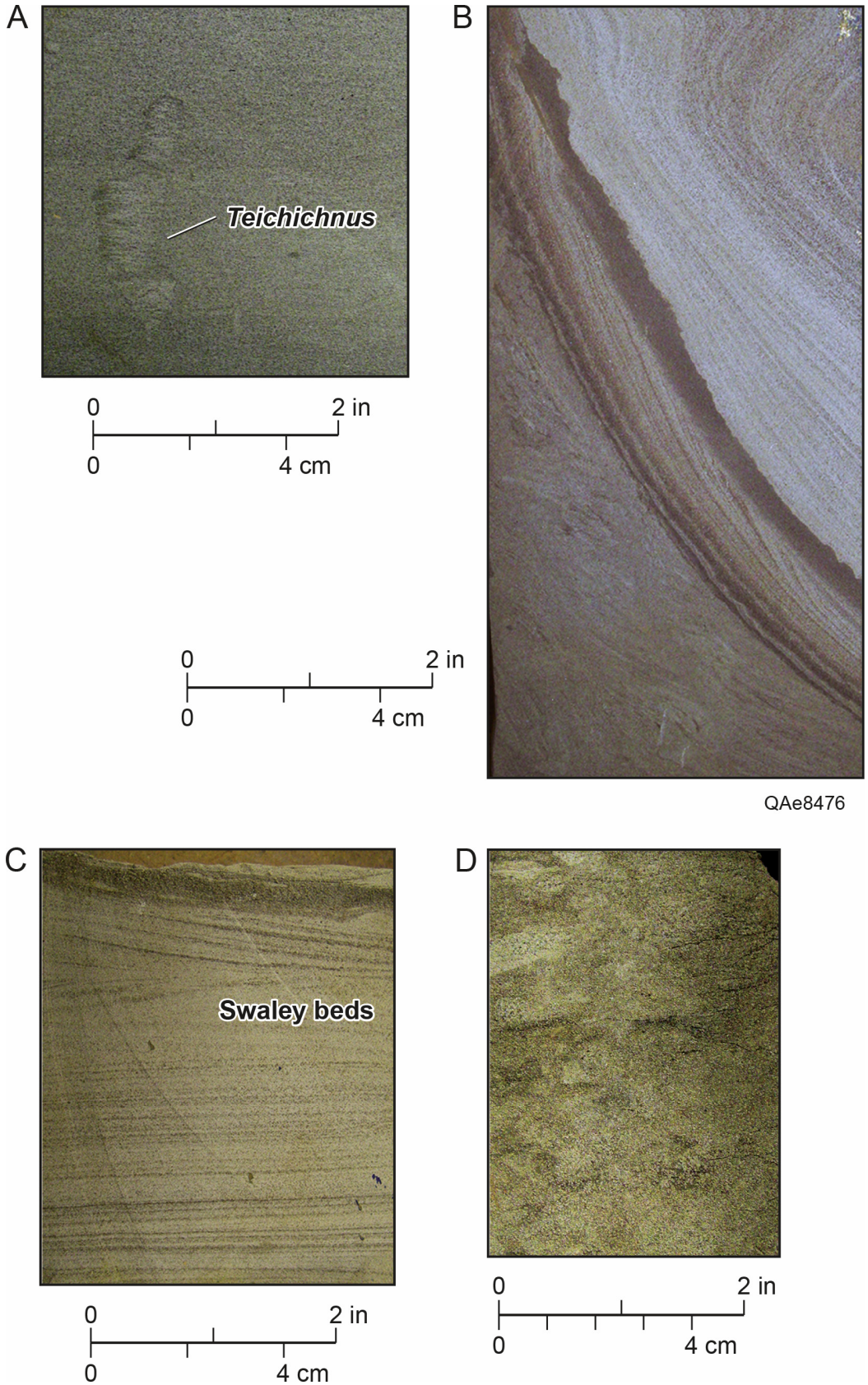

Figure 9. Photographs of the Letco MV 9696.02 No. TOH–2A Settlemyre core in the Midway 2 depositional unit (modified after Ambrose et al. [2020]). (A) Silty, very fine-grained, laminated sandstone with *Teichichnus* at 2169.4 ft (661.2 m). (B) Fine-grained sandstone with folded and oversteepened stratification at 2162.0 ft (658.9 m). (C) Swaley cross-stratification in fine-grained sandstone at 2154.0 ft (656.5 m). (D) Intensely-burrowed section of very fine- to fine-grained sandstone at 2142.4 ft (653.0 m). Dark material is composed of organic fragments. The wireline log is shown in Figure 2. The core description is shown in Figure 8. The location of the cored well is shown in Figures 1 and 7.

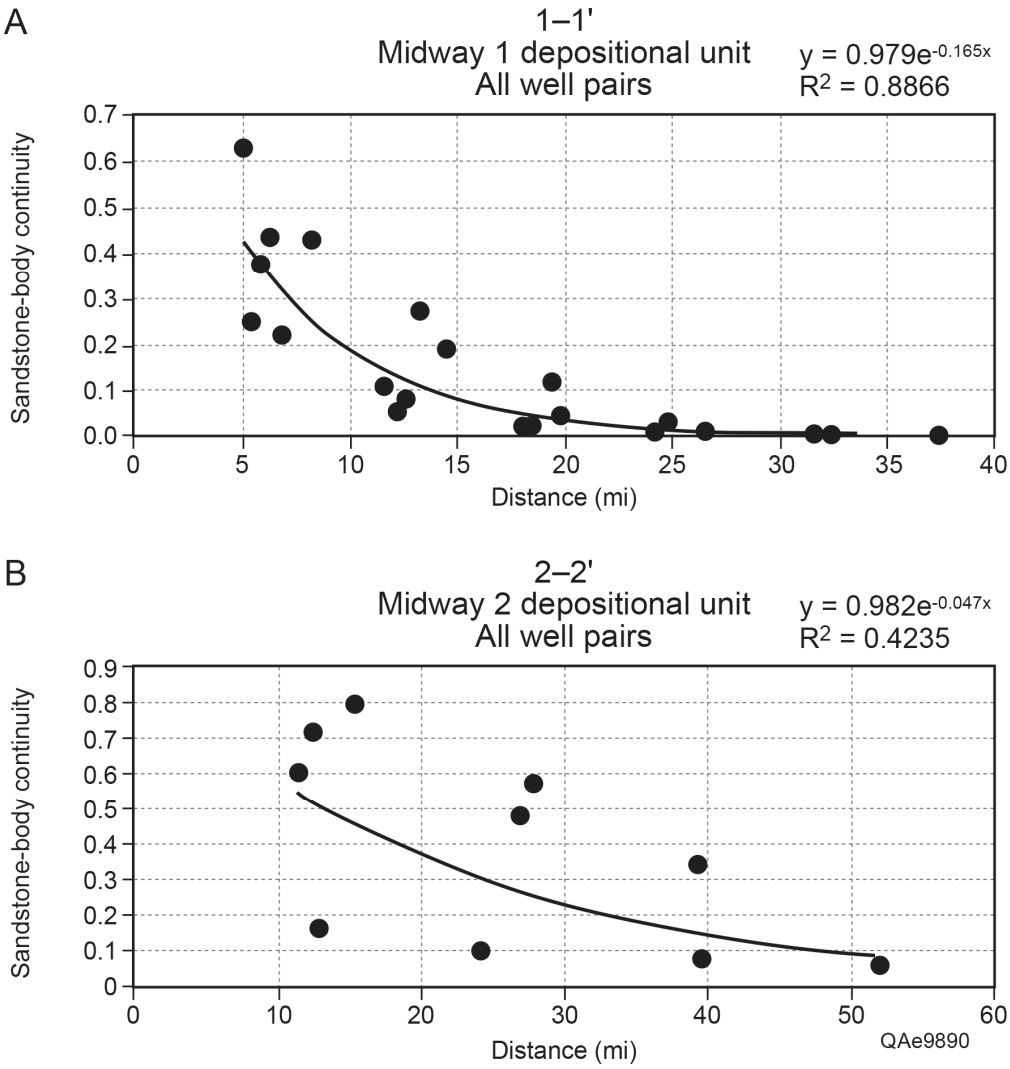

Figure 10. (A) Sandstone-body continuity cross plot and best-fit exponential curve for the Midway 1 depositional unit along wireline-log cross-section 1–1' oriented parallel to depositional dip (northwest to southeast). (B) Sandstone-body continuity cross plot and best-fit exponential curve for the Midway 2 depositional unit along wireline-log cross-section 2–2', which is also oriented parallel to depositional dip (northwest to southeast). Cross-sections 1–1' and 2–2' are shown in Figures 3 and 6, respectively. Locations of cross-sections 1–1' and 2–2' are shown in Figures 1 and 7, respectively.

Lithology

The Hooper 1 depositional unit in the Letco MV 9696.02 No. TOH–2A Settlemyre core extends from approximately 2060 to 2134 ft (627.9 to 650.4 m) (Figs. 8 and 13). The basal 27 ft (8.2 m) is a net upward-coarsening section, grading upward from muddy siltstone to fine-grained sandstone with inclined-planar stratification (Fig. 8). It is overlain abruptly at 2106 ft (641.9 m) by a ~40 ft (~12 m) section of an erosionally-based and upward-fining section of fine- to medium-grained sandstone with elongate mudstone and siltstone rip-up clasts (Figs. 13 and 14). Average size of these mudstone and siltstone rip-up clasts decreases upward from ~2 in (~5.1 cm) to <1 in (<2.5 cm) (Figs. 14A and 14B, respectively). Stratification in the section is poorly developed, consisting mostly of contorted bedding at 2081 to 2086 ft (634.3 to 635.8 m) and 2094 to 2097 ft (638.3 to 639.2 m) (Fig. 13). Bedding at the top of the section is better developed, where it is composed of centimeter-scale, inclined laminae highlighted with organic material (Fig. 14C).

Net Sandstone

In contrast to strike-oriented (southwest-to-northeast) net-sandstone trends in the underlying Midway 2 depositional unit (Fig. 7), those in the Hooper 1 depositional unit are dip elongate, oriented northwest to southeast (Fig.11). Depositional axes in the Hooper 1 depositional unit are narrow, commonly <4 mi (<6.4 km) across and contain locally >50 ft (>15 m) of net sandstone (Fig. 11). The depositional axis with the Letco MV 9696.02 No. TOH–2A Settlemyre core exhibits tributary net-sandstone patterns in the northern part of the study area, but also has southward-bifurcating trends to the south near the Angelina-Caldwell Flexure, where a lobate net-sandstone trend pinches our into a muddy area with <30 ft (<9 m) of net sandstone.

Stratigraphic architecture in the Hooper 1 depositional unit along depositional strike (southwest to northeast) is dominated by lenticular sandstone bodies (Fig. 12). Sandstone bodies in the lower half of the Hooper 1 depositional unit range in thickness from 5 to 20 ft (1.5 to 6 m) are extend laterally for as much as 20 mi (32 km). An example is the sandstone body in the middle part of the Hooper 1 depositional unit in wells 2, 3, and 4 (upper half of Figure 12). In contrast, thicker sandstone bodies in the upper half of the Hooper 1 depositional unit are less laterally continuous, typically extending into only adjacent wells in cross-section 3–3'–3" (Fig. 12). These thicker sandstone bodies in the upper half of the Hooper 1 depositional unit have blocky and upward-fining wireline-log responses, whereas the thinner sandstone bodies in the middle and lower parts of the Hooper 1 depositional unit have spiky and upward-coarsening wireline-log responses.

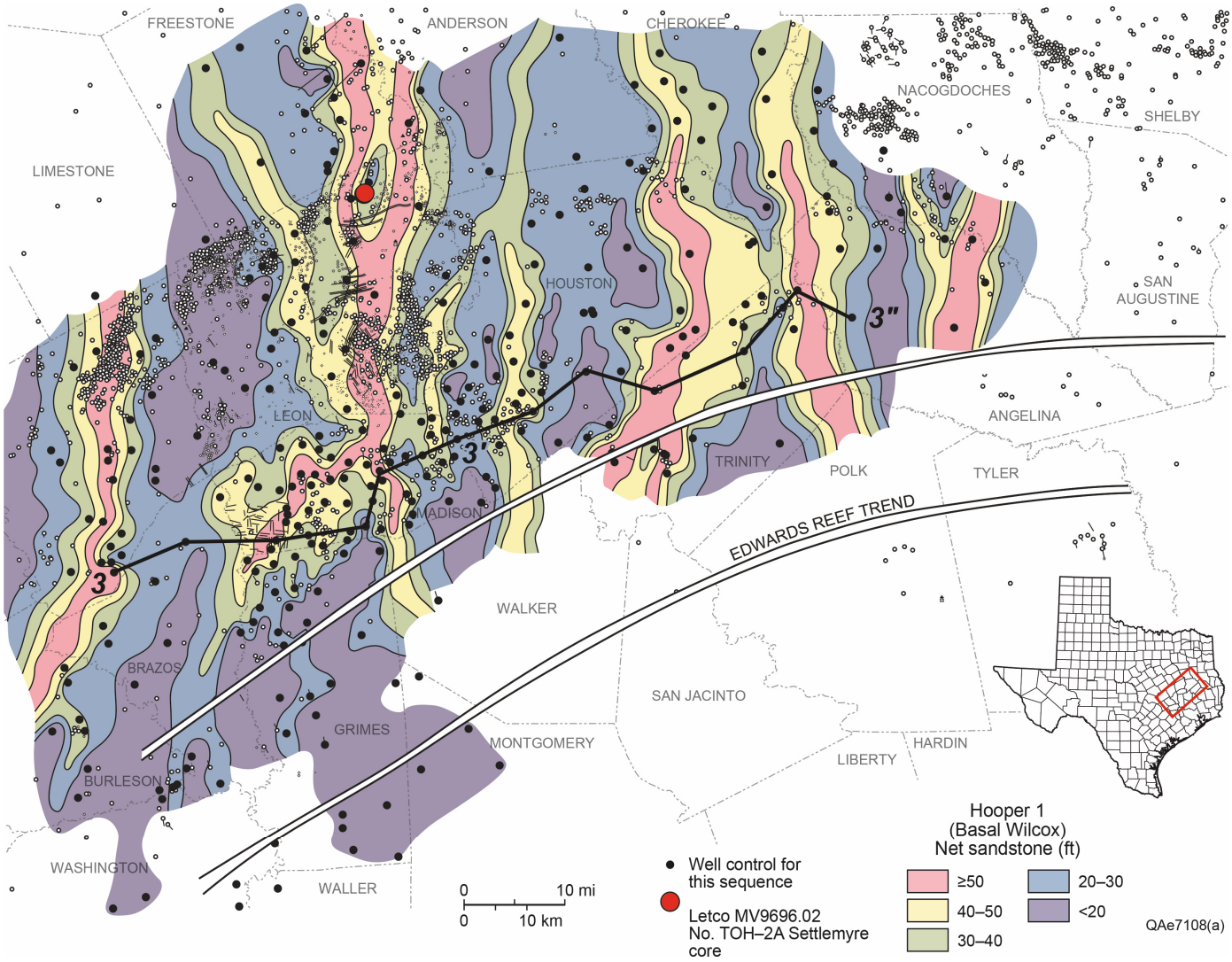

Figure 11. Net-sandstone map of the Hooper 1 (Basal Wilcox) depositional unit in southeastern Texas. The type log (Letco MV 9696.02 No. TOH–2A Settlemyre in Leon County) is shown in Figure 2. The stratigraphic dip section 3–3'–3" is shown in Figure 12. The core description is shown in Figure 13. Core photographs are shown in Figures 14 and 15.

Facies Interpretation

The Hooper 1 depositional unit represents the initial pulse of significant deltaic sedimentation and progradation above the Midway Group in the Texas Gulf Coast during the late Paleocene. Depositional axes, defined by distributary-channel deposits, are narrow (commonly <4 mi [<6.4 km] across, and dip elongate, oriented mainly north to south in the study area (Fig. 11). They are erosionally based, net upward fining, and composed of fine- to medium-grained sandstone with abundant siltstone and mudstone rip-up clasts (Figs. 13, 14A, and 14B). Some distributary channel trends in the Hooper 1 depositional unit are connected southward and southwestward to downdip-bifurcating trends. Examples include a downdip-bifurcating trend associated with a lobate depocenter in Brazos and Grimes counties, as well as a downdip-bifurcating trend along the Angelina-Caldwell Flexure in southwestern Trinity County (Fig. 11). The lobate feature in Brazos and Grimes counties contains channel-mouth-bar and delta-front deposits (Fig. 11 and well number 3 in Figure 12). The three lower sandstone beds in well number 3 in Figure 12 represent an upward progression from delta-front to channel-mouth-bar deposits in a net-upward-coarsening section, whereas the upper sandstone bed represents distributary-channel deposits locally incised into the delta front.

Depositional Analogs

The sandstone-body geometry in the Hooper 1 depositional unit is consistent with a fluvially-dominated deltaic system (Fisher et al., 1969; Galloway and Hobday, 1996). The scale of individual deltaic depocenters in Hooper 1 depositional unit are consistent with that of the Holocene Wax Lake Delta in Louisiana (Neill and Allison, 2005; Shaw et al., 2013) and fluvially-dominated deltaic sandstone bodies in the lower Woodbine Group in East Texas Field (Ambrose and Hentz, 2010). Both of these examples feature small-scale deltaic depositional elements where the width of individual deltaic lobes is <15 mi (<24 km).

Sandstone-Body Continuity

Sandstone-body continuity in the Hooper 1 depositional unit along depositional strike (southwest to northeast), portrayed in wireline-log 3–3'–3" (Fig. 12), is a function of two types of del-

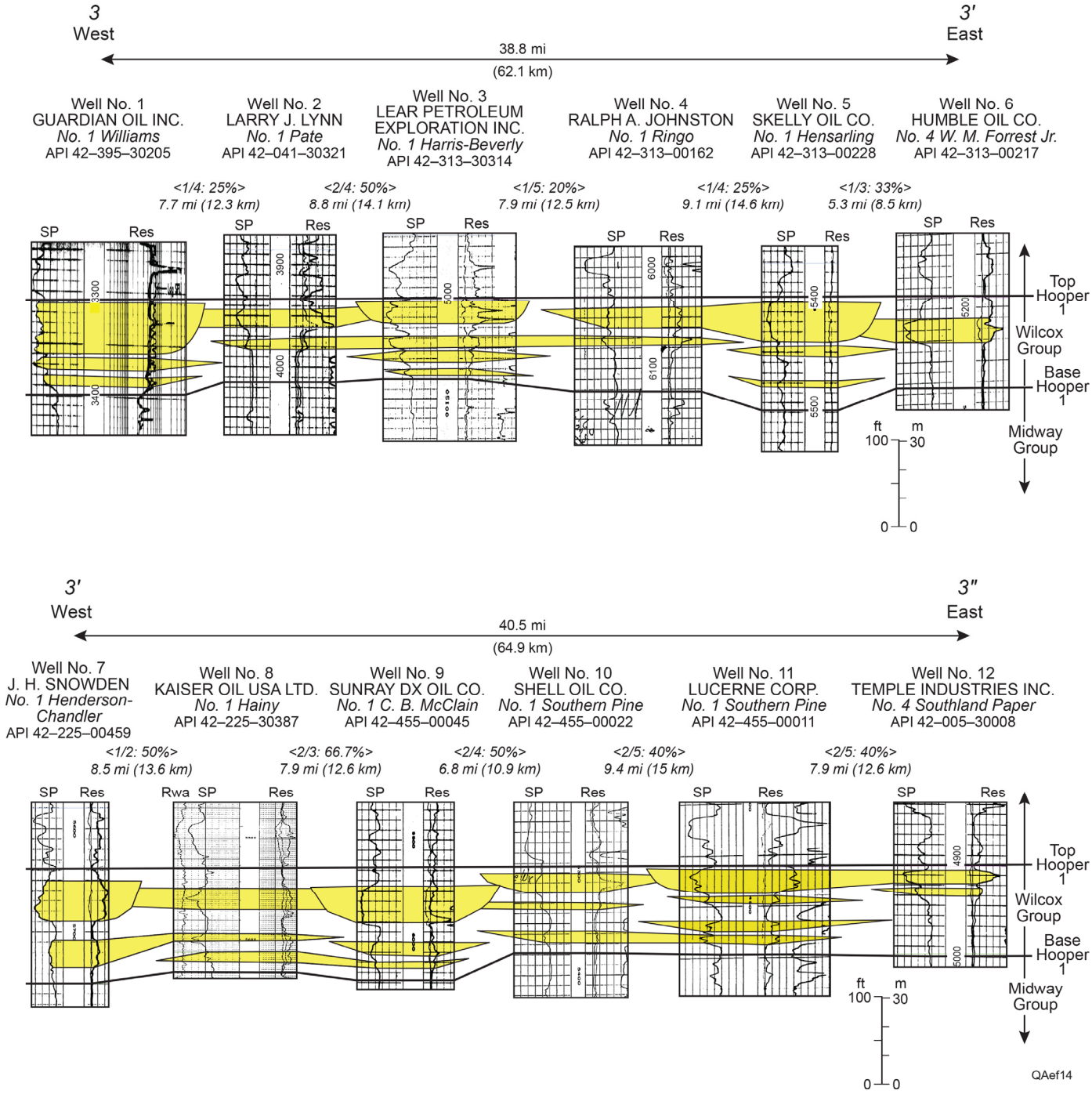

Figure 12. Stratigraphic strike section 3–3′–3″ in the Hooper 1 (basal Wilcox) depositional unit. Sandstone-body continuity between adjacent wells is indicated in angle brackets above wireline-log curves. Datum is the top of the Hooper 1 depositional unit (base of Wilcox Group). Wireline-log curves: SP = spontaneous potential, Rwa = apparent water saturation, and Res = resistivity. The location of the section is shown in Figure 11.

taic deposits, namely delta-front facies in the lower half of the section and distributary-channel facies in the upper half. These sandstone bodies represent complexes of multiple sandstone beds rather than individual sandstone beds that are resolvable only in cores. Sandstone-body continuity values in the Hooper 1 depositional unit represent sandstone-body complexes within deltaic depocenters that consist of distributary-channel sandstones, channel-mouth-bar, and delta-front sandstones that have been locally reworked along depositional strike by marine processes.

Delta-front sandstone bodies in Figure 12 range in thickness from 5 to 15 ft (1.5 to 4.5 m), whereas distributary-channel sandstone-body complexes are as much as 50 ft (15 m) thick where they locally are incised into delta-front sandstone bodies (wells 1 and 9, for example, in Figure 12). Collectively, Hooper 1 sandstone bodies along depositional strike are approximately 32% continuous at 5 mi (9 km) well spacing and only about 12% continuous at 20 mi (32 km) well spacing (Fig. 15).

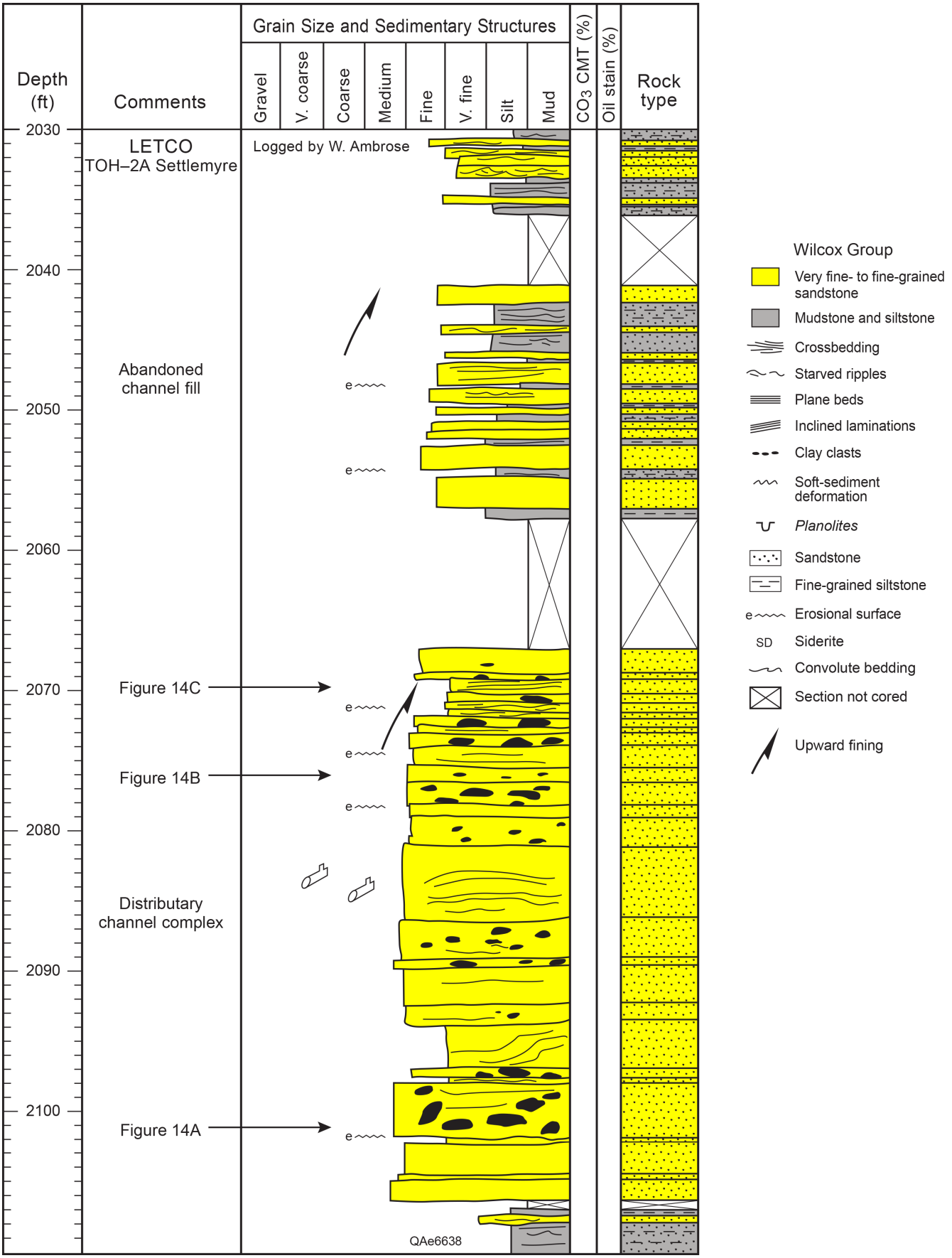

Figure 13. Description of the Letco MV 9696.02 No. TOH–2A Settlemyre core from 2030 to 2110 ft (618.7 to 643.1 m), showing distributary-channel deposits in the Hooper 1 (basal Wilcox) depositional unit. The wireline log is shown in Figure 2. Core photographs are shown in Figures 14 and 15. The location of the cored well is shown in Figure 11.

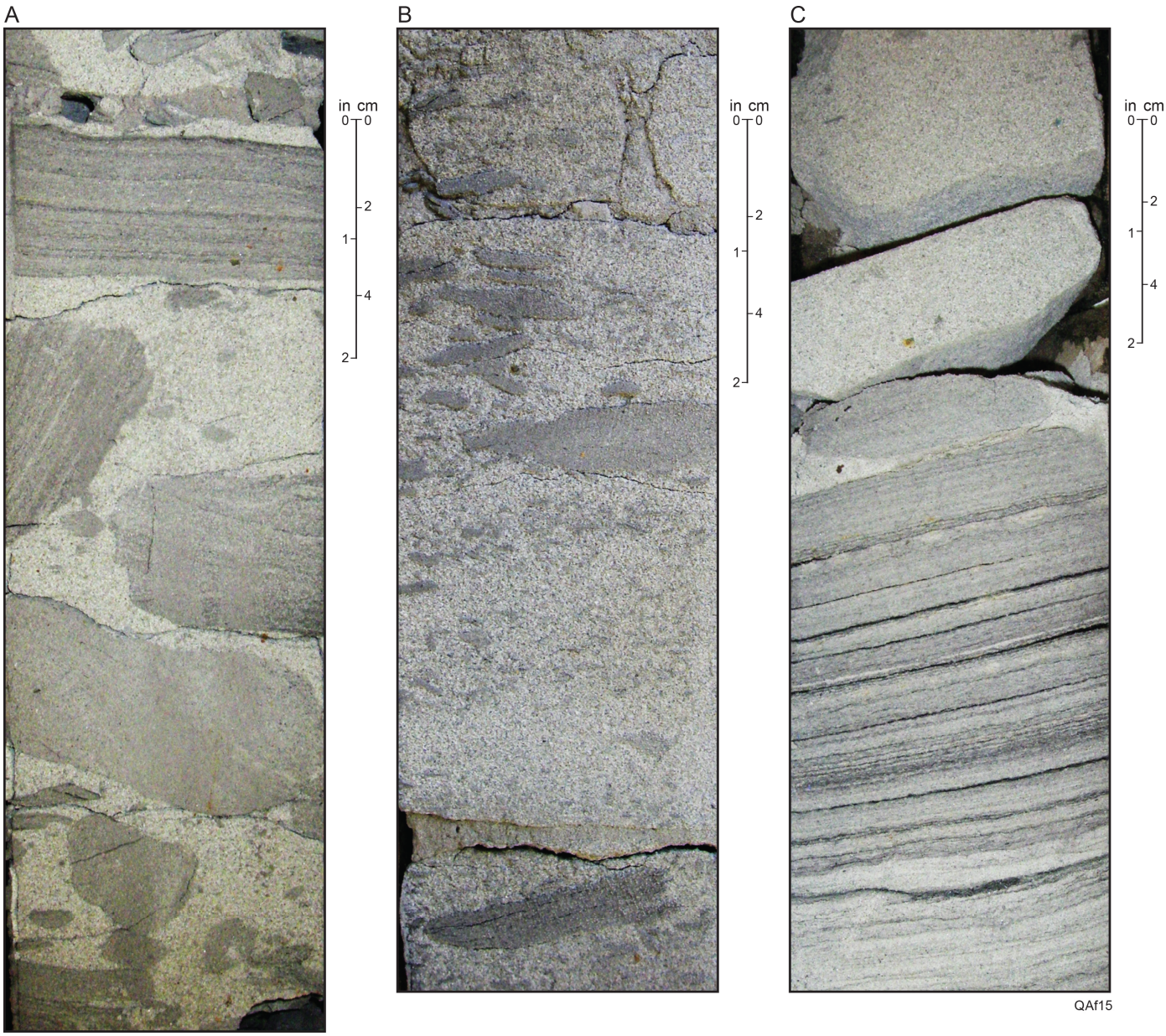

Figure 14. Photographs of the Letco MV 9696.02 No. TOH–2A Settlemyre core in the Hooper 1 depositional unit. (A) Medium-grained sandstone with large mudstone and siltstone rip-up clasts in basal distributary-channel deposits at 2101.0 ft (640.4 m). (B) Fine- to medium-grained sandstone with elongate mudstone and siltstone rip-up clasts in medial distributary-channel deposits at 2076.2 ft (632.8 m). (C) Laminated siltstone beds are overlain by structureless, fine-grained sandstone in upper distributary-channel deposits at 2069.6 ft (630.8 m). The wireline log is shown in Figure 2. The core description is shown in Figure 12. The location of the cored well is shown in Figure 11.

IMPLICATIONS FOR RESERVOIR HETEROGENEITY

Microscale

Microscale heterogeneity in shelf and lower-shoreface sandstones in the Midway 1 and Midway 2 depositional units, as observed in cores, is related to bed boundaries, lithologic contacts such as mudstone-draped ripples, vertical and lateral transitions in bedforms, and accessory features such as shell debris, mudstone clasts, and trace fossils. These features are inferred to disrupt continuity of relatively-permeable sandstone beds over scales of millimeters to centimeters.

Examples in the Upper Midway Group are thin (1 in [2.5 cm]) beds of very fine- to fine-grained sandstone bounded above and below by silty mudstone (Fig. 5A), disrupted and discontinuous beds (Fig. 5B), burial compaction and burrows (Fig. 5C), as well as mudstone drapes and burrows (Fig. 5D). The transition from shelf to lower-shoreface deposits in the Midway Group (Midway 1 to Midway 2 depositional units, respectively) involves fewer muddy interbeds. Here, microscale heterogeneity is also related to slumps and convolute bedding (Fig. 9B), cross-cutting bands of very fine- to fine-grained sandstone with zones of swaley stratification (Fig. 9C), and intensely burrowed sections where stratification is absent or poorly preserved (Fig. 9D).

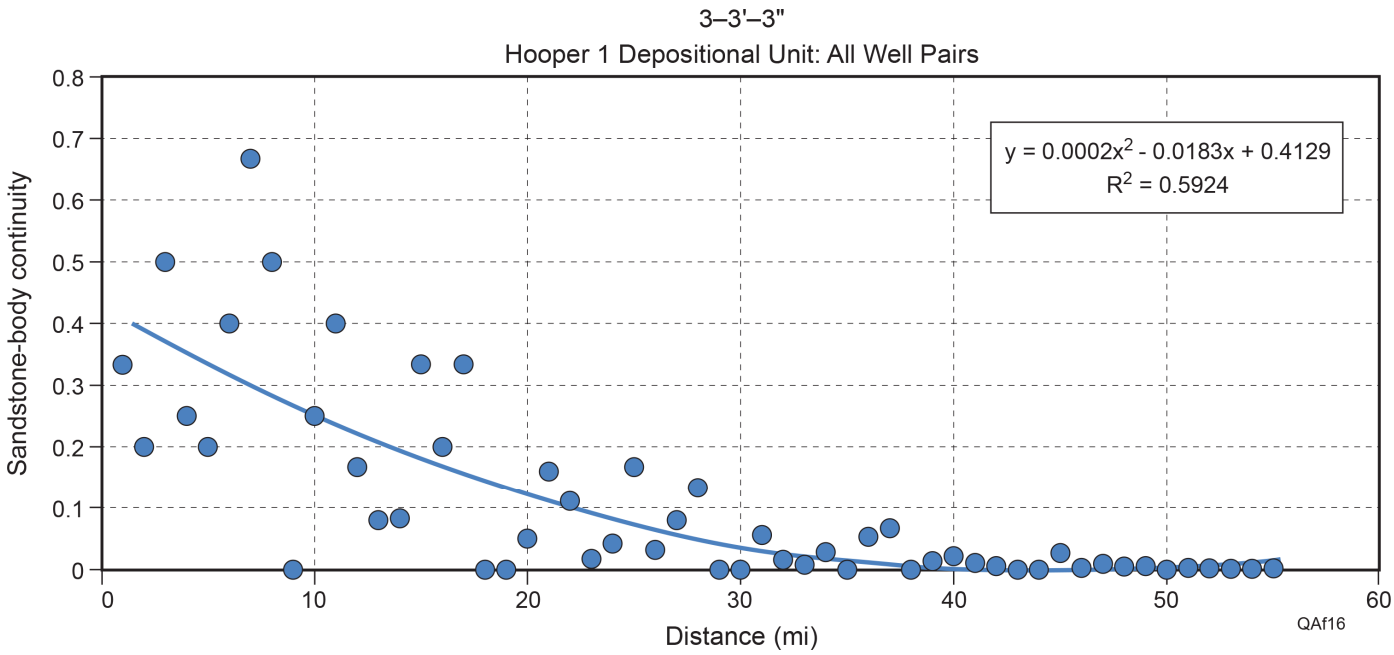

Figure 15. Sandstone-body continuity cross plot and best-fit logarithmic curve for the Hooper 1 depositional unit along wireline-log cross-section 3–3'–3" oriented parallel to depositional dip (northwest to southeast). Cross-section 3–3'–3" is displayed in Figure 12, with location shown in Figure 11.

Microscale heterogeneity in distributary-channel deposits in the Hooper 1 depositional unit is related to large, ~2 in (~5.1 cm) mudstone and siltstone rip-up clasts, some of which are in contact and extend across the core face (Figs. 13 and 14A). Vertical heterogeneity in these distributary-channel deposits is also a function of upward-fining grain size, where the sandy, lower channel section is capped by multiple siltstone laminae in abandoned-channel facies (Fig. 14C).

Mesoscale

Vertical mesoscale heterogeneity involves changes in stacking patterns between beds rather than in individual beds or contacts between individual beds. Lateral mesoscale heterogeneity is defined by sandstone-body pinchouts over scales of hundreds to thousands of feet or meters.

Mesoscale heterogeneity inferred from wireline-log cross-sections in the Midway Group is great for shelf deposits in the Midway 1 depositional unit but less for the transition from inner-shelf to lower-shoreface deposits in the Midway 2 depositional unit (Figs. 3 and 6, respectively). The Midway 1 depositional unit contains numerous sandstone beds in poor mutual contact in distal areas in the southeastern half of depositional dip section 1–1' [Fig. 3]). In contrast, sandstone beds are relatively thicker and better connected toward the north and northwest (northwestern two wells [wells 1 and 2] in Figure 3).

Mesoscale heterogeneity in the Hooper 1 depositional unit is portrayed in wireline-log cross-section 3–3'–3" (Fig. 12). Sandstone bodies in the lower part of the Hooper 1 depositional unit, composed of delta-front deposits are thinner than overlying distributary-channel sandstone bodies. Both types of these sandstone bodies are lenticular, although delta-front sandstones in the middle part of the Hooper 1 depositional unit in wells 2 to 4 are the most continuous in the section.

Macroscale

Macroscale heterogeneities in shelf sandstones in the Upper Midway Group compose a facies architecture at a regionally-mappable scale. They include major paleogeographic elements such as strike-fed, shelf sand-shoal complexes, amalgamated sand sheets, and wave-reworked deltaic headlands. Macroscale heterogeneity in the Midway Group is related to the distribution of strike-oriented, shelf, and lower-shoreface sandy complexes (Figs. 1 and 7, respectively). In the distal facies tract in the Midway 1 depositional unit, sandstone bodies are limited to small, elongate pods that pinch out into extensive, muddy areas with <10 ft (<3 m) of net sandstone (Fig. 1). In contrast, the updip part of the Midway 1 facies tract contains regionally-continuous, shoreline-parallel belts of >20 ft (>6 m) of net sandstone composed of amalgamated shelf-bar complexes. The overlying Midway 2 depositional unit represents proximal wave-dominated facies that include lower-shoreface sandstones. It is more homogenous than the Midway 1 depositional unit, although several areas exist in the net-sandstone map of the Midway 2 depositional unit where sandstone complexes are bounded by muddy areas. Examples include muddy areas in Brazos and Madison counties, where lower-shoreface sandstones pinch out into inner-shelf mudstones (Fig. 7).

Macroscale heterogeneity in the Hooper 1 depositional unit, best portrayed in the regional net-sandstone map in Figure 11, is dominated by the dip-elongate sandstone-body geometry represented by distributary-channel trends. The net-sandstone map shows that the average spacing of sandy deltaic depocenters along depositional strike (southwest to northeast) is approximately 15 mi (24 km), although some depocenters are only 8 mi (13 km) apart, whereas others are separated by as much as 20 mi (32 km). The absence of strike-oriented sandstone bodies in the downdip (southern) part of the map area is consistent with a fluvial-dominated deltaic system, in which thick (>50 ft [>15 m]) distributary-channel and channel-mouth-bar sandstone bodies pinch out into muddy, interdistributary-bay mudstones over distances of less than 4 mi (<6.4 km).

CONCLUSIONS

The Upper Midway Group along and updip of the Angelina-Caldwell Flexure in southeastern Texas records a stratigraphic

succession from shelf to lower-shoreface systems. Four (4) main recognition criteria for shelf and lower-shoreface systems include:

(1) Thin (<2 ft [<0.6 m]), erosion-based sandstone beds with swaley cross-stratification;
(2) Centimeter-scale, lenticular beds of very fine- to fine-grained sandstone;
(3) A diverse *Cruziana* trace-fossil assemblage, with *Teichichnus*, *Palaeophycus*, *Planolites*, *Schaubcylindrichnus*, and rare *Rosellia*; and
(4) Net-sandstone distribution composed of strike-elongate ribbons and pods that merge locally into broad, sheet-like patterns without updip feeder systems.

Upper Midway shelf deposits in the Midway 1 depositional unit have net-sandstone trends that are irregular and narrow, strike-elongate pods, and ribbons 20 to 35 ft (6 to 11 m) thick. They grade downdip (southward and southeastward) into extensive, muddy trends with <10 ft (<3 m) of net sandstone. In contrast, lower-shoreface deposits in the Midway 2 depositional unit at the top of the Upper Midway Group have primarily upward-coarsening wireline-log responses. They contain extensive and wide (>10 mi [>16 km]) strike-elongate belts of >40 ft (>12 m) of net sandstone that extend northeastward for >50 mi (>80 km) along depositional strike.

Sandstone-body continuity in the Upper Midway Group, analyzed from wireline-log cross-sections, differs greatly between shelf (Midway 1 depositional unit) and lower-shoreface systems (Upper Midway 2 depositional unit). Sandstone-body continuity in lower-shoreface systems at 10 mi (16 km) well spacing in the study area is approximately 60%, whereas it is only 20% at the same well spacing in shelf systems. At 20 mi (32 km) well spacing, sandstone-body continuity is 37% in these lower-shoreface systems but only 4% in shelf systems.

The transition in depositional systems from the Midway to Wilcox Group records a change from wave-dominated to fluvial-dominated depositional systems during a period of major sediment influx and coastal offlap. Three (3) main recognition criteria for fluvial-dominated deltaic systems in the Hooper 1 depositional unit (basal Wilcox Group) include:

(1) Narrow (<4 mi [<6.4 km]), dip-elongate depositional axes trending northwest to southeast, in contrast, to strike-elongate pods and sheetlike sandstone bodies in the underlying Upper Midway Group;
(2) Depositional axes composed of erosionally-based, upward-fining, fine- to medium-grained sandstone with abundant siltstone and mudstone rip-up clasts, grading upward into ripple-stratified and laminated siltstone and mudstone; and
(3) Downdip-bifurcating depositional axes that pinch out into extensive, sandstone-poor areas.

Sandstone-body continuity in the Hooper 1 depositional unit along depositional strike is poor, being approximately 32% at 5 mi (9 km) well spacing and only about 12% at 20 mi (32 km) well spacing. These sandstone-body continuity values record the presence of multiple, locally occurring deltaic depocenters within a fluvial-dominated deltaic system, in contrast to the wave-dominated shelf and lower-shoreface deposits in the underlying Upper Midway Group.

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