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Depositional Systems, Facies Variability, and their Relationship to Reservoir Quality in the Jurassic Cotton Valley Group, Texas, Louisiana, and Mississippi Onshore Gulf Coast

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ABSTRACT

Whole cores from four wells in the Jurassic Cotton Valley Group from northeastern Texas to southern Mississippi display a variety of facies and depositional systems that provide a context for understanding reservoir quality, defined in this study as porosity and permeability. Although some cores are from areas with established oil and gas production (Texas and Louisiana), others are in less-productive areas (southern Mississippi), where facies interpretations of these cores could be used as a guide for future exploration and development. Cores in northeastern Texas and northern Louisiana are located in the Terryville Bar Trend, which includes an extensive, east-west belt of tight-gas (low-permeability) sandstones. These cores display a suite of shallow-marine facies (lower- and upper-shoreface, beach, washover-fan, and tidal-channel) within a wave-dominated depositional setting. Sandstone beds in these cores have low permeability values, ranging from 0.001 to less than 1 millidarcys (md). Porosity values range from 2 to 12%. This study shows that little variation in permeability exists among shallow-marine facies in the Terryville Bar Trend, although muddy lower-shoreface and inner-shelf facies are less permeable by one to two orders of magnitude than sandy shoreface and tidal-channel facies.

Cotton Valley sandstones in southern Mississippi, located in an off-axis area of the ancestral Mississippi Delta, contain a variety of coarse-grained fluvial channel-fill and muddy floodplain facies. Channel-fill deposits in coarse-grained meanderbelt facies in this trend record multiple episodes of channel-fill with variable grain-size profiles. These sandy channel-fill deposits are contrasted with variably colored and mottled overbank/floodplain facies with insect burrows, root traces, and nodular textures that record pedogenesis.

Cotton Valley sandstone reservoirs of shallow-marine origin in the Bay Springs Field in southern Mississippi have greater reservoir quality than those of fluvial origin, with porosity values from 15 to 20% and permeability values ≥100 md. Vertical sandstone-bed continuity in upper-shoreface facies in the Bay Springs Field is great and comparable to that of thick (≥100 ft [≥30.5 m]), aggradational, upper-shoreface sandstones in the Pictured Cliffs Formation in the San Juan Basin in New Mexico and Colorado. This study shows that differences in the degree of facies complexity in Cotton Valley depositional trends should be considered in future reservoir development strategies, where facies complexity is great in the Texas-Louisiana Terryville Bar Trend and the Mississippi fluvial trend, but less in aggradational, upper-shoreface sandstone beds such as those in the Bay Springs Field.

INTRODUCTION AND OBJECTIVES

The Jurassic Cotton Valley Group has produced >180 MMbbl (million barrels) of oil and >10.5 Tcf (trillion cubic ft) of gas from Texas, Arkansas, Louisiana, and Mississippi. Most of this production is from deltaic sandstones in northeastern Texas and in the Terryville Bar Trend in Texas and Louisiana (Fig. 1) (Dyman and Condon, 1996; Ewing, 2001). Minor Cotton Valley oil production is from shallow-marine and fluvial reservoirs in Mississippi (Dyman and Condon, 1996). Although an extensive Cotton Valley fluviodeltaic depocenter occurs in northeastern Louisiana and southwestern Mississippi (Moore, 1983; Ewing, 2001), relatively little oil has been produced in this area. By presenting facies descriptions and interpretations from core, together with porosity and permeability data, this study provides a geological background for understanding facies controls on potential production in northeastern Louisiana and southwestern Mississippi, as well as in other areas in the Cotton Valley Group.

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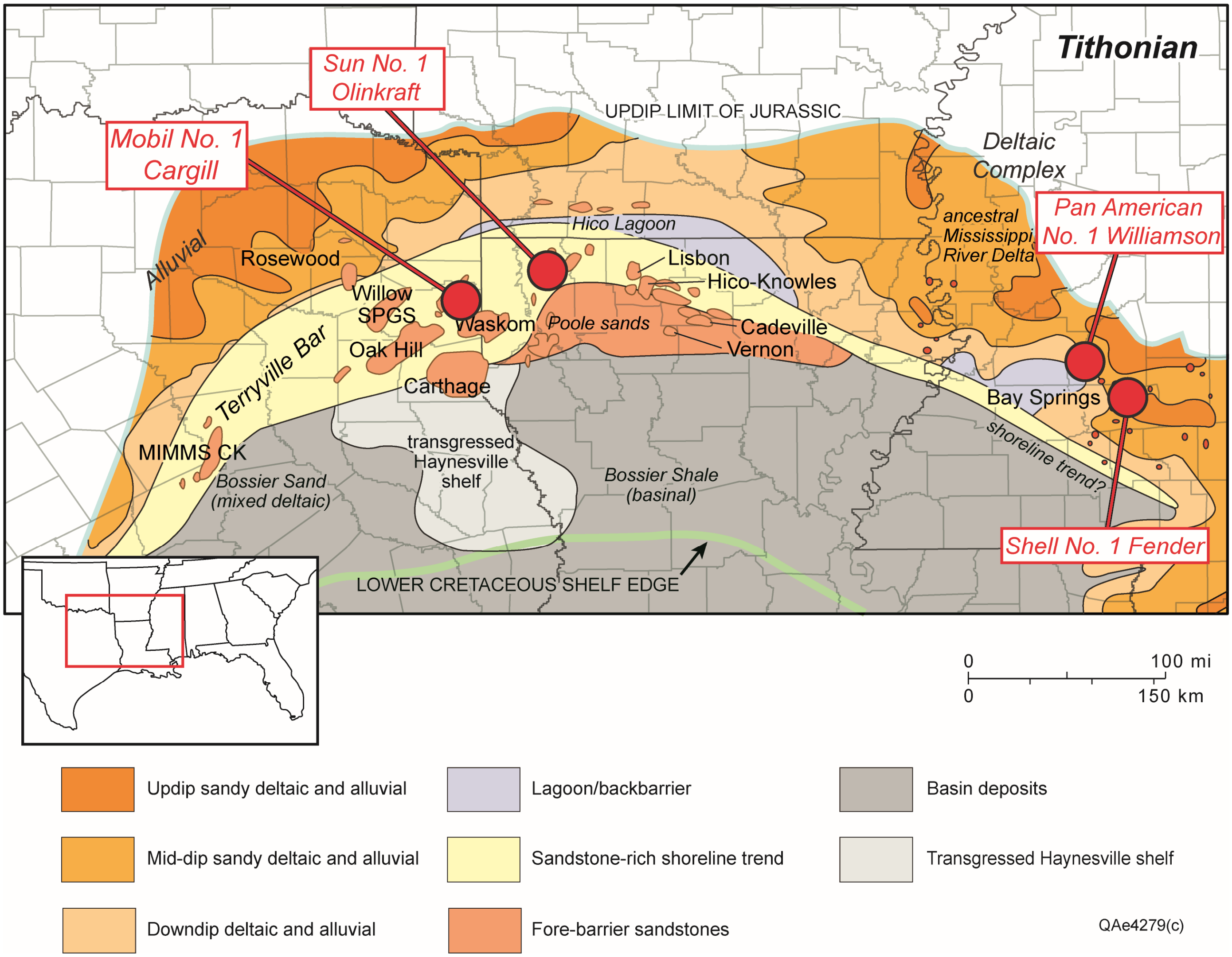

Figure 1. Regional summary of Lower Cotton Valley depositional systems from Texas to Mississippi (modified after Ewing, 2001). Distribution of cores presented in this study are also shown. Although the Shell No. 1 Fender core is within the upper part of the Cotton Valley Group, its paleogeographic setting is similar for both early and late Cotton Valley time.

Although facies variability, compaction, and variations in mineralogy are significant factors in controlling reservoir quality (Loucks et al., 1984, 1986; Dutton, 1987; Taylor et al., 2010), temperature, a function of heat flow, is also important for deeply buried strata (>8000 ft [>2440 m]) (Dutton and Loucks, 2010). Variations in reservoir quality in the Cotton Valley Group related to diagenesis are also important but are addressed in a companion paper (Dutton et al., 2017, this volume).

The four (4) objectives of this study are to: (1) provide a set of detailed descriptions of cores in the Jurassic Cotton Valley Group in Texas, Louisiana, and Mississippi, (2) interpret sedimentary processes and depositional facies in these cores, (3) provide facies analogs from modern shorelines and the rock record, and (4) relate porosity and permeability to facies.

Cores from the Cotton Valley Group, located in Figure 1, illustrate a variety of depositional systems, associated facies, and provide a context for reservoir-quality data. This study presents data from ~280 ft (~85 m) of slabbed whole cores, including porosity and permeability data from 51 core plugs. Although this study presents results from only four cores, they illustrate a variety of facies within wave-dominated shorezone systems in northeastern Texas and northern Louisiana, as well as within fluvial and coastal-barrier systems in southern Mississippi. Core-plug data in this study are presented alongside core descriptions for direct comparison with lithology and facies. Data recorded in the core descriptions and accompanying photographs include grain size, stratification, contacts, as well as accessory features such as soft-sediment deformation, burrows, clay clasts, root traces, and shell and organic fragments that are diagnostic of sedimentary processes and depositional environments.

GEOLOGIC FRAMEWORK

The Cotton Valley Group represents the first major phase of terrigenous clastic deposition in onshore areas in the Gulf of Mexico after late Triassic continental rifting (Salvador, 1987; Worrall and Snelson, 1989). The siliciclastic part of the Cotton Valley Group comprises an overall second-order, progradational highstand succession, the updip equivalent of the Bossier Shale (Goldhammer, 1999, 2002; Goldhammer and Johnson, 2001). During Tithonian time (142 to 150 Ma) (Palfy et al., 2000; Haq and Shutter, 2008) (Fig. 2), a regionally continuous, sandy coastal system composed of barrier-island and shoreface facies was deposited within multiple progradational-retrogradational episodes (Terryville Bar Trend [Dyman and Condon, 1996]) that extended along depositional strike from northeastern Texas to

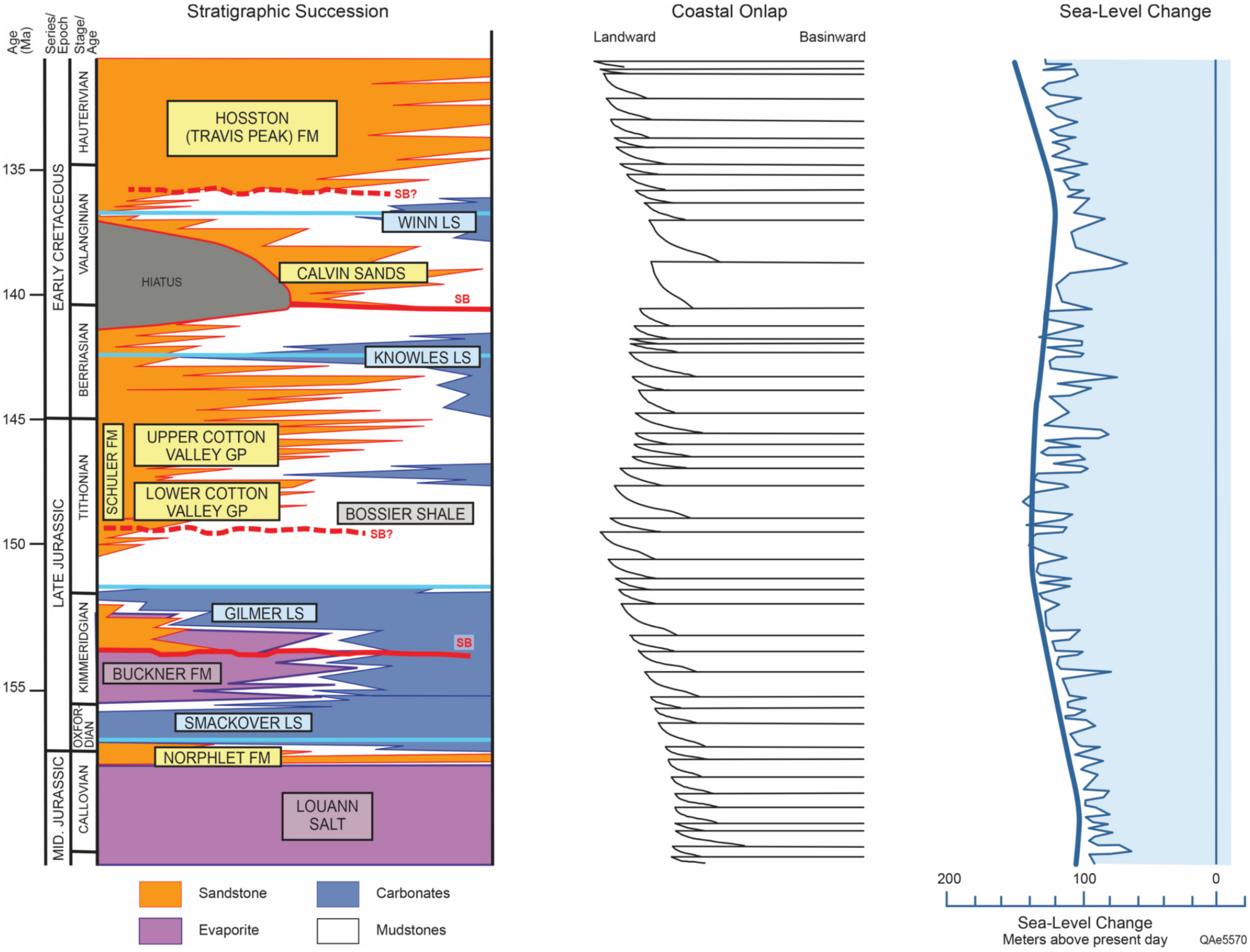

Figure 2. Middle Jurassic (Callovian) to Early Cretaceous (Hauterivian) chronostratigraphic chart, with major stratigraphic units in the Texas to Mississippi Gulf of Mexico. Stratigraphic succession modified after Ewing (2001). Modified timescale with unequal spacing between numbers representing that ages are based on coastal-onlap and sea-level change curves modified after Hardenbol et al. (1998), Haq and Al-Qahtani (2005), Haq and Shutter (2008), and Snedden and Liu (2010). Regional summary of Lower Cotton Valley depositional systems is shown in Figure 1.

southern Mississippi (Fig. 1). An alluvial system in northeastern Texas provided sandy sediments to the Terryville Bar Trend in East Texas, whereas a deltaic complex was associated with shoreline progradation in northeastern Louisiana and southern Mississippi (Ewing, 2001). Sediments in Cotton Valley fluviodeltaic systems were derived from Paleozoic and younger highlands to the north, northwest, and northeast (Kornfield, 1985). Shorezone sediments in the Terryville Bar Trend in northeastern Texas were fed from an alluvial system from the north and northwest (Ewing, 2001) (Fig. 1). The Terryville Bar Trend, which consists predominantly of quartzose sandstones (Dutton et al., 2017, this volume), was interpreted by Forgotson (1954), Sloane (1958), Mann and Thomas (1964), Thomas and Mann (1966), and Kornfield (1985) to have been deposited as a shoreface/barrier island system flanked northward by lagoonal facies. The Terryville Bar Trend in northeastern Texas contains a variety of facies types such as shoreface, barrier island, lagoon, tidal channel, washover-fan, marsh, and transgressive sand shoal (Dutton et al., 1991). A deltaic complex in Mississippi, present during early Cotton Valley time, persisted into late Cotton Valley time (Ewing, 2001). Minor fluviodeltaic systems in southern Mississippi also provided sediment to west-northwest-oriented shoreline trends in southern Mississippi. Differences in provenance for the Cotton Valley Group from Texas to Mississippi and their implications for reservoir properties are described in a companion paper by Dutton et al. (2017, this volume).

TERRYVILLE BAR SYSTEM, TEXAS AND LOUISIANA

Mobil No. 15 Cargill

The Mobil No. 15 Cargill well is located in the Terryville Bar Trend in northeastern Texas (Fig. 1). Lower Cotton Valley sandstones in this trend have low-permeability values (0.001 to 1 millidarcys [md]) and constitute tight-gas reservoirs (Dutton et al., 1991; Holditch, 2006).

Description

The cored section in the Mobil No. 15 Cargill well, spanning 9302.5 to 9366.5 ft (2836.1 to 2855.6 m) (Fig. 3), is from the lower one-third of an upward-coarsening section that extends from ~9200 to ~9370 ft (~2805 to ~2855 m), inferred from the gamma-ray (GR) curve (Fig. 3). The section ranges from silty

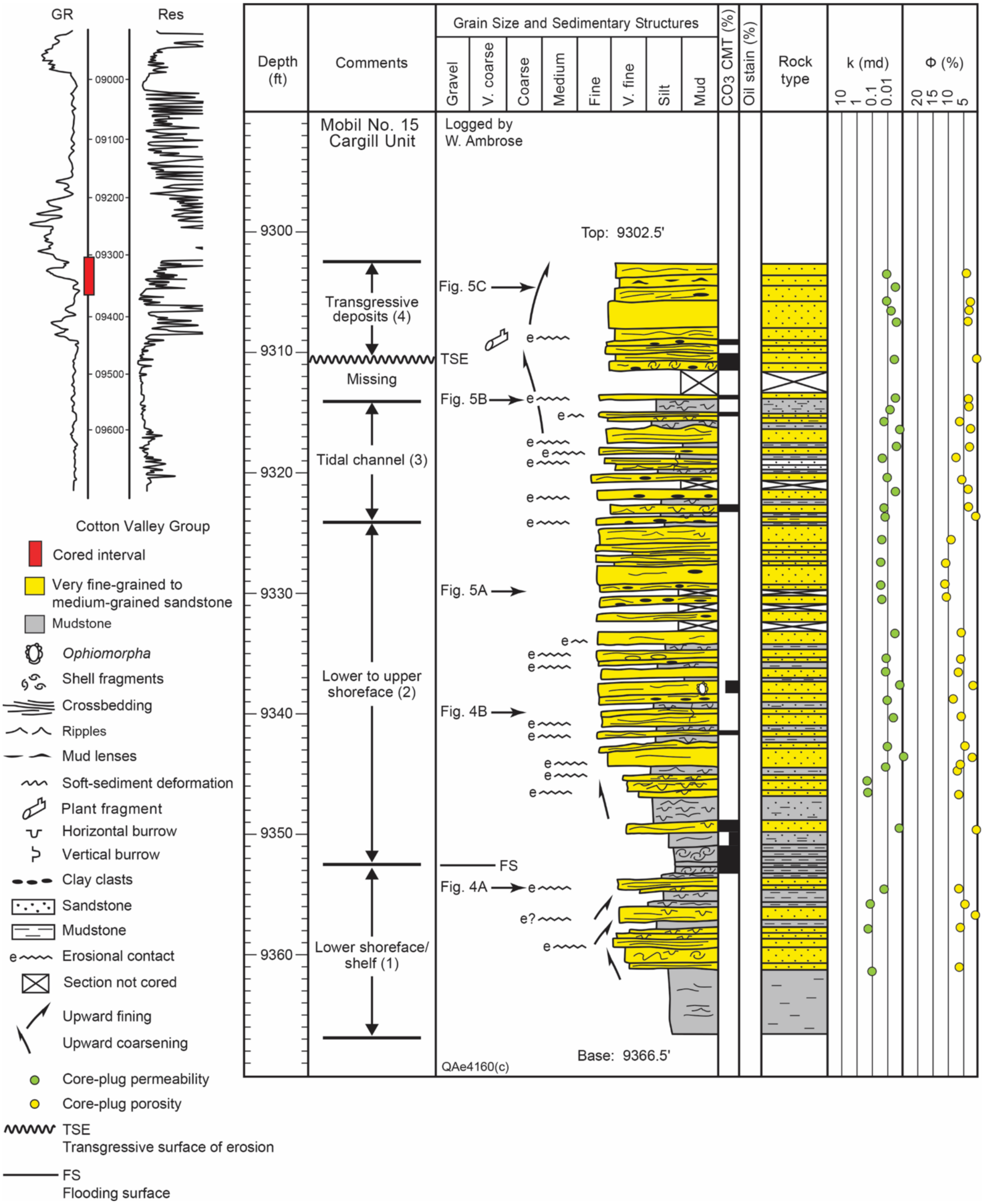

Figure 3. Core description and reservoir quality (core-plug permeability and core-plug porosity) data in the Mobil No. 15 Cargill well in Harrison County, Texas. Location of well is shown in Figure 1.

mudstone at the base to fine- to medium-grained sandstone at the top (Fig. 3). A shelly, silty mudstone bed at 9353 ft (2851.5 m) overlies a thin (8 ft [2.4 m]) section (1) of burrowed and planar-stratified, very fine- to fine-grained sandstone composed of a separate, slightly upward-coarsening section at the base of the cored interval (Fig. 3). Ichnofauna in this 8 ft (2.4 m) sandy interval are dominated by *Asterosoma* (Fig. 4A) with minor *Planolites*. The overlying cored section (2) contains an upward-coarsening section to 9324 ft (2842.7 m) composed of very fine-grained sandstone grading upward into fine-grained sandstone. Individual sandstone beds in this upward-coarsening section are erosion-based, planar-stratified, and contain thin (1 in [2.5 cm]) zones of clay clasts (Fig. 4B) and scour surfaces (Fig. 5A). Ichnofauna in this section contain *Ophiomorpha* (Fig. 5A), *Planolites*, and minor *Shaubcylindrichnus*. Section (3) from 9313.5 to 9324 ft (2839.5 to 2842.7 m) has no overall vertical grain-size trend and is composed of multiple, 1 to 2 ft (0.3 to 0.6 m) beds of mostly fine-grained sandstone with clay clasts and shell fragments, interbedded with burrowed, silty mudstone (Figs. 3 and 5B). The upper part of the section (4) from 9302.5 to 9311 ft (2836.1 to 2838.7 m) consists of an upward-fining interval that grades upward from fine- to very fine-grained sandstone. Shell fragments and clay clasts are common in the lower one-third of this upward-fining interval. Stratification in this upper cored section is dominated by low-angle plane beds with scour surfaces (Fig. 5C). Minor ripple stratification occurs near the top of the section at 9304 ft (2836.6 ft) (Fig. 3).

Interpretation

The cored section in the Mobil No. 15 Cargill well contains a lower, sandy interval from 9353 to 9361.5 ft (2851.5 m to 2854.1 m) of lower-shoreface to shelf deposits capped by a 4 ft (1.2 m) section of shelly, silty mudstone that contains a flooding surface (FS) at 9353 ft (2851.5 m), composed of dark-gray, featureless mudstone (Fig. 3). Other significant stratigraphic surfaces include a transgressive surface of erosion (TSE) at 9311 ft (2838.7 m) that caps an upward-coarsening section. This TSE is overlain by a 1 ft (0.3 m) zone of fine-grained sandstone with clay clasts and shell fragments. The section above the TSE is upward fining, grading upward from very fine- to fine-grained sandstone (Fig. 3).

The cored section in the Mobil No. 15 Cargill well represents four stratigraphic successions, with a lower section (1) of

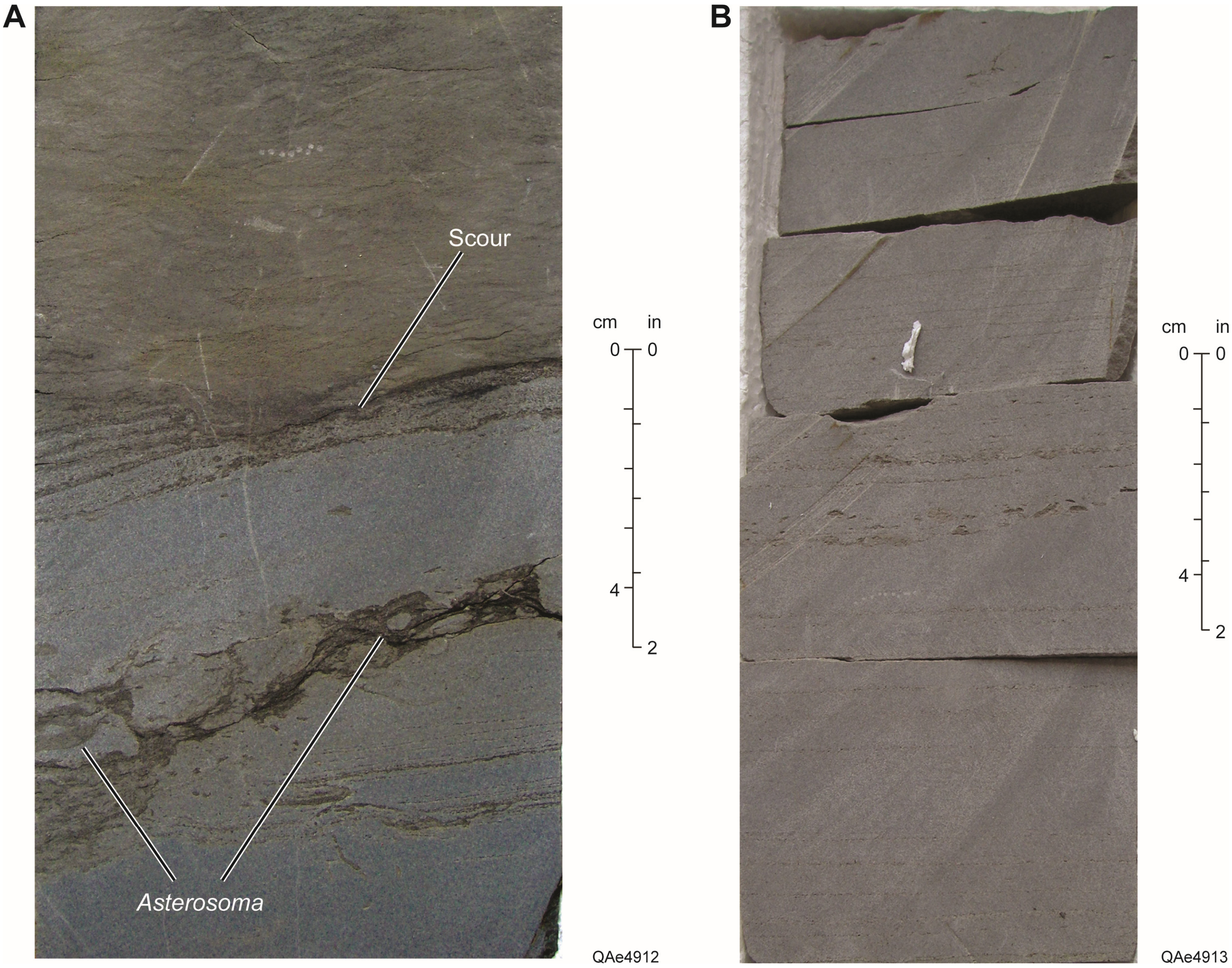

Figure 4. Photographs of the Mobil No. 15 Cargill core in Harrison County, Texas. (A) Fine-grained sandstone with inclined planar stratification and *Asterosoma* burrows at 9355.3 ft (2852.2 m) in lower-shoreface facies. Top of sandstone bed is scoured and overlain by burrowed silty mudstone bed. (B) Planar-stratified, upper-fine-grained sandstone with thin (1 in [2.5 cm]) zone of small, elongate clay clasts in upper-shoreface facies at 9339.0 ft (2847.3 m). Core description is shown in Figure 3.

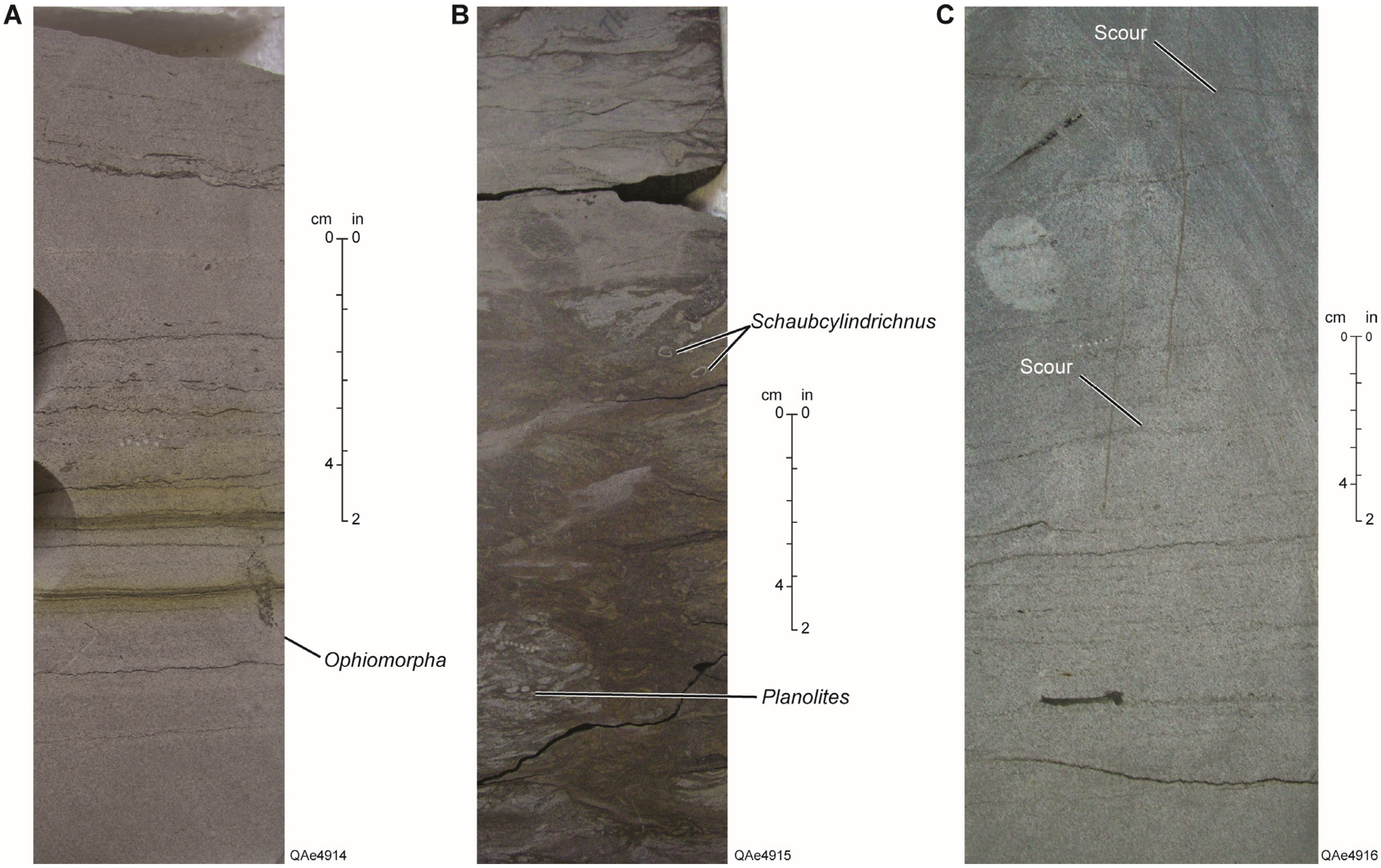

Figure 5. Photographs of the Mobil No. 15 Cargill core in Harrison County, Texas. (A) Planar-stratified, upper-fine-grained sandstone with internal scour surfaces and *Ophiomorpha* burrow in upper-shoreface facies at 9329.4 ft (2844.3 m). (B) Highly burrowed, very fine-grained sandstone overlying silty mudstone with *Schaubcylindrichnus* and *Planolites* burrows in backbarrier-lagoonal facies at 9313.5 ft (2839.5 m). (C) Fine-grained sandstone with low-angle planar stratification and numerous internal scour surfaces in washover-fan facies at 9304.1 ft (2836.6 m). Core description is shown in Figure 3.

shelf and lower-shoreface deposits from the base of the core to 9353 ft (2851.5 m). It is overlain by section (2) lower-shoreface deposits grading upward into upper-shoreface deposits to 9324 ft (2842.7 m), section (3) composed of tidal-channel deposits to 9313.5 ft (2839.5 m), and section (4), an upper, 8.5 ft (2.6 m) section of transgressive deposits (Fig. 3). Lower-shoreface facies in section (1) are composed of very fine- to fine-grained sandstone beds and extensively burrowed, silty mudstone beds (Figs. 3 and 4A). The ichnofaunal assemblage in in this section includes *Asterosoma*, *Schaubcylindrichnus*, *Chondrites*, and *Planolites*, common in muddy, lower-shoreface settings within the *Cruziana* ichnofacies (Seilacher, 1964; Frey et al., 1990; Bromley and Asgaard, 1991; Benton and Harper, 1997). Overlying upper-shoreface facies in section (2) consist of predominantly planar-stratified, fine-grained sandstone with minor, thin (<6 in [<15.2 cm]) beds of siltstone. Many sandstone beds in the upper-shoreface facies are erosionally based, with abundant *Ophiomorpha* burrows (Figs. 4B and 5A).

Tidal-channel facies in section (3) contain numerous erosionally based beds as well as shell fragments and clay clasts (Fig. 3). Diagnostic features for tidal-channel deposits include scour surfaces, clay rip-up clasts, and genetic association with wave-dominated shoreline facies. Modern examples of tidal-channel deposits include those on the South Carolina shoreline such as Price, Stono, and Edisto inlets (Imperato et al., 1988) (Fig. 7), and the main distributary channel in the Santee Delta in South Carolina, which because of transgression is a tidal inlet (Figs. 6 and 7) (Stephens et al., 1976; Hayes, 1979). The South Carolina shoreline in the area of the Santee Delta is tidally influenced, experiencing mesotidal conditions (diurnal tidal range between 6.6 to 19.7 ft [2 to 6 m]) (Davies, 1964). Other modern shorelines in North America such as those in the Gulf of Mexico have microtidal shorelines (diurnal range <6.6 ft [<2 m]) (Bernard et al., 1962; Davies, 1964). Given the limited core data in this study, the Terryville Bar Trend may represent either of these two types of tidal regimes. Additional study with detailed subsurface maps depicting the geometry and longshore extent of barrier/shoreface sandstone bodies, which have greatest continuity along strike in microtidal settings (Hayes, 1979), would be necessary to fully reconstruct the Cotton Valley paleotidal setting in the Terryville Bar Trend.

Although the overall Terryville Bar succession in northern Louisiana is composed of four, major, thick (500 ft [152 m]), offlapping clastic wedges, it contains numerous, high-frequency depositional cycles, each 50 to 100 ft (15 to 30 m) thick, that intertongue with backbarrier/lagoonal deposits in the Hico Shale (Dyman and Condon, 1996). These high-frequency depositional cycles are comparable in terms of net-sandstone content and facies to shoreline systems in South Carolina and Texas. For example, upper shoreface/beach facies in the Mobil No. 15 Cargill core are 20 ft (6 m) thick (9324 to 9344 ft [2842.7 to 2848.8 m]) (Fig. 3). Reservoir-quality sand in shoreface/beach deposits in South Carolina, defined in Hayes et al. (1984) as sands containing <15% mud, are 10 to 20 ft (3 to 6 m) thick, although some are as much as 29.5 ft (9 m) thick (Sexton and Hayes, 1996). Individual tidal-channel deposits in the Mobil No. 15 Cargill core, as well as those in the Sun No. 1 Olinkraft core (Fig. 8), range in thickness from 10 to 25 ft (3 to 7.6 m). In comparison, tidal-channel deposits near Kiawah Island in South Carolina (Fig. 7) are part of a succession that is 20 ft (6 m) thick.

Figure 6. (A) Photograph of the Santee River Delta along transgressive shoreline in South Carolina. Also depicted are washover-fan deposits and ebb-tidal delta complex. Photograph by William Ambrose, April 1985. (B) Satellite image of the Santee Delta. Location of Santee Delta and other physiographic features on the South Carolina shoreline is shown in Figure 7A. Satellite image is from Google, accessed at https://www.google.com/maps/@32.9296626,-79.303272,34785a,35y,36.14t/data=!3m1!1e3.

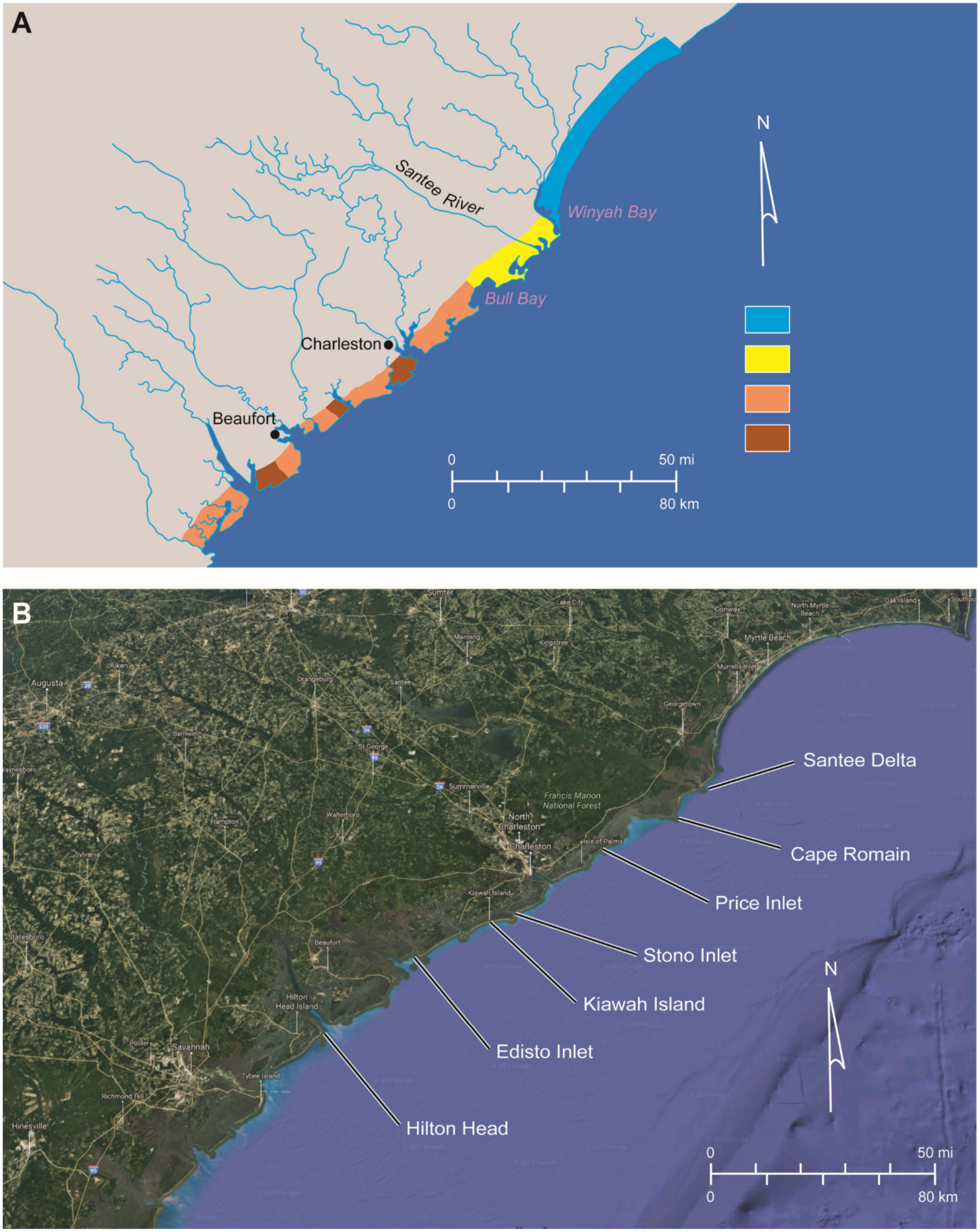

Figure 7. (A) Variations in coastal morphology along the South Carolina shoreline (modified after Hayes and Kana, 1976). (B) Satellite image, showing locations of Santee Delta, Cape Romain, Kiawah Island, Price Inlet, Stono Inlet, Edisto Inlet, and Hilton Head. Photograph of Santee Delta is shown in Figure 6. Photographs of oyster-shell berms and exhumed, muddy lower-coastal-plain deposits from Cape Romain are shown in Figures 9 and 10. Satellite image is from Google, accessed at https://www.google.com/maps/@30.9426598,-79.9189102,340763a,35y,29.17t/data=!3m1!1e3.

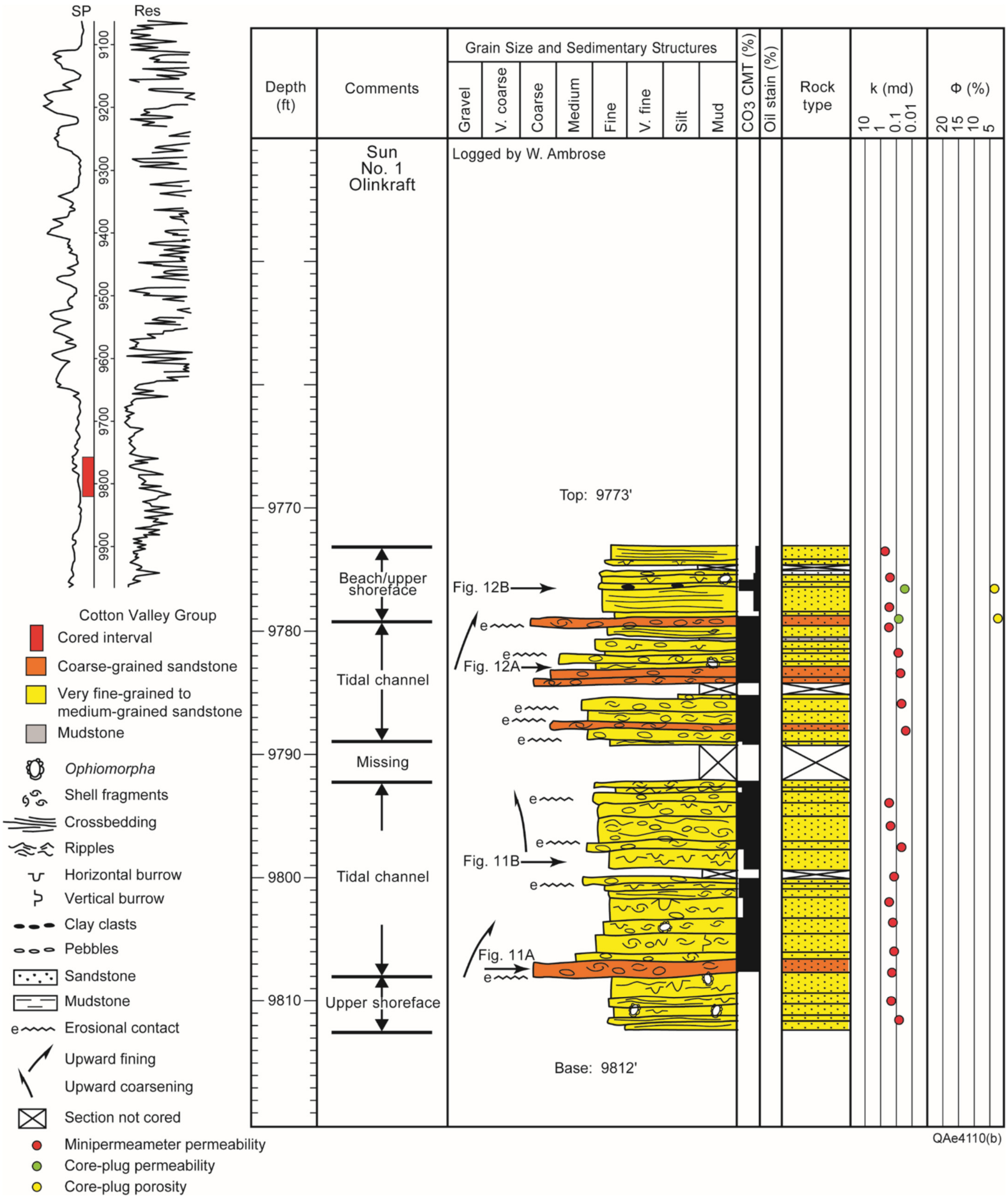

Figure 8. Core description and reservoir quality (core-plug permeability and porosity) data from the Sun No. 1 Olinkraft well in Bossier Parish, Louisiana. Location of well is shown in Figure 1.

Section (4) consists of washover-fan and washover-channel facies composed of very fine- to fine-grained sandstone. They are characterized by parallel laminations, low-angle plane beds, abundant internal scour surfaces, and rip-up clasts (Fig. 5C). These features are commonly observed in destructional-beach deposits (Andrews, 1970; Schwartz, 1975, 1982; Leatherman et al., 1977; Pilkey and Davis, 1987), although washover-fan deposits are not limited to transgressive shorelines. Shell debris, mud clasts with a wide variety of shapes, as well as quartzite pebbles in the Mobil No. 15 Cargill core from 9302.5 to 9311.5 ft (2836.1 to 2838.9 m) (Fig. 3) indicate high-energy reworking of beach facies. Variability in the vertical profile and net thickness in transgressive deposits are dependent on the origin and lithology of the transgressed shoreline (spit, tidal channel, barrier core, etc.) and the degree and intensity of reworking by waves and storms. Transgressive-beach deposits in Cape Romain, South Carolina, a cuspate, retreating headland flanked southward by sandy spit deposits, range from meter-high oyster-shell berms (Fig. 9) to muddy blocks of eroded peat deposits (Fig. 10) (Ruby, 1981). The thickness of the preserved section of transgressive deposits at Cape Romain is predicted to be <3 ft (<0.9 m), based on similar profiles of transgressive deposits observed along the

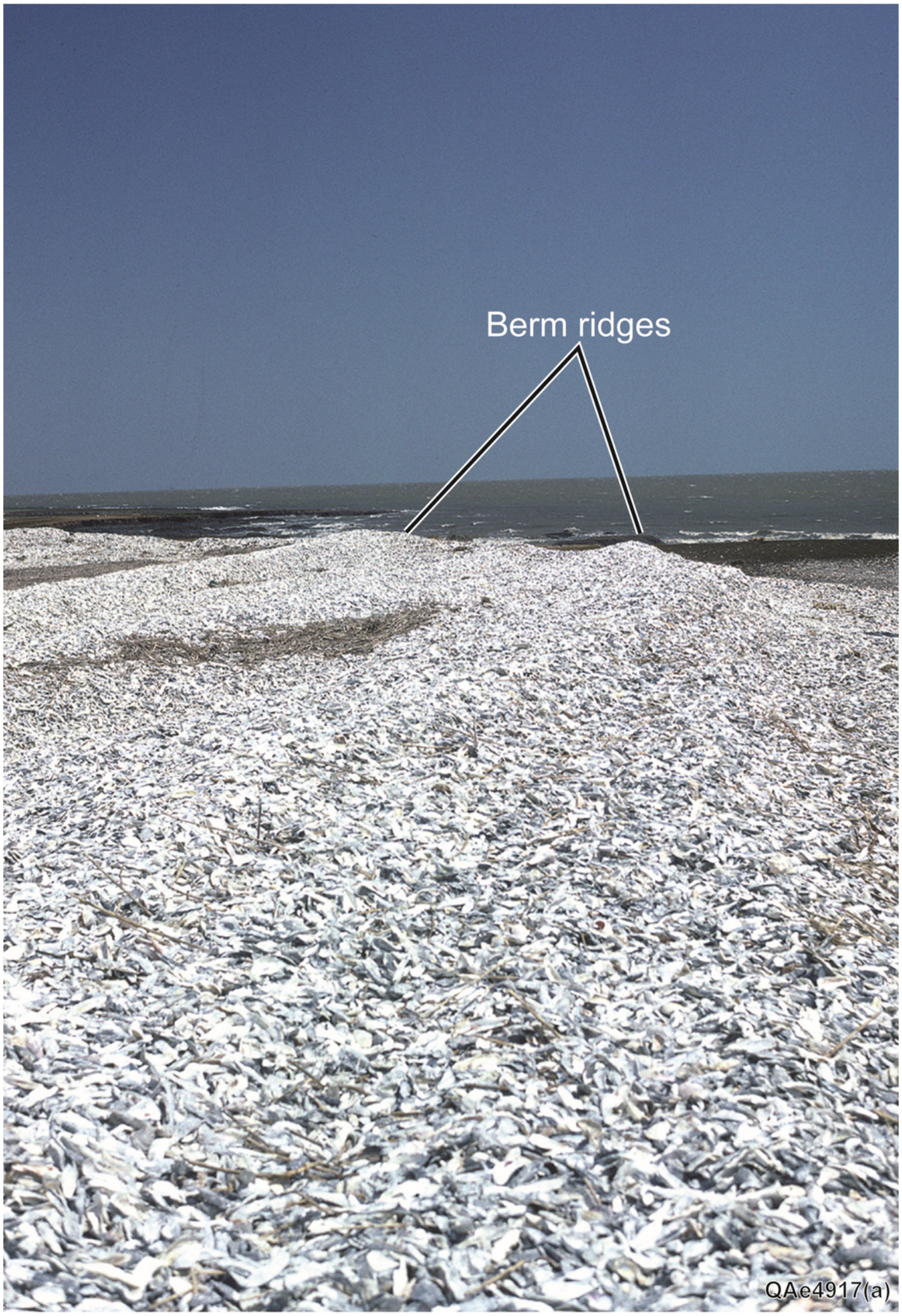

Figure 9. Photograph of oyster-shell berms along transgressive shoreline at Cape Romain, a cuspate, landward-retreating headland along the South Carolina shoreline. Photograph by William Ambrose, April 1985. Location of Cape Romain is shown in Figure 7.

South Carolina shoreline (Sexton and Hayes, 1996). The upward-fining section overlying these reworked shell and peat fragments, with continued water deepening and inundation of the shoreline, would consist of upward-fining foreshore and upper-shoreface deposits, similar to those interpreted in the upper 5 ft (1.5 m) of the Mobil No. 15 Cargill core (Fig. 3).

Subsurface depositional analogs for upper-shoreface and beach deposits for section (3) in the Mobil No. 15 Cargill well include the Upper Cretaceous (Campanian) Pictured Cliffs Sandstone in the northern part of the San Juan Basin in New Mexico and Colorado (Manfrino, 1984; Ambrose and Ayers, 2007). The Pictured Cliffs Sandstone consists of a series of offlapping, prograding clastic wedges composed of wave-dominated deltaic deposits flanked southeastward by strike-fed, shoreline sandstones (Ayers et al., 1994). The upper part of the Pictured Cliffs section is typically composed of upward-coarsening, upper-fine to lower-medium-grained sandstone with abundant horizontal and low-angle planar stratification with minor organic fragments and clay clasts (Ambrose and Ayers, 2007). Continuity of beach/upper-shoreface sandstone beds in the Pictured Cliffs Sandstone along depositional strike is great, extending for >20 mi (>32 km) in the northeastern part of the San Juan Basin (Ayers et al.,

Figure 10. Photograph of eroded mud deposits along transgressive shoreline at Cape Romain, a cuspate, landward-retreating headland along the South Carolina shoreline. Photograph by William Ambrose, April 1985. Location of Cape Romain is shown in Figure 7.

1994). Strike continuity of beach/upper-shoreface facies at the field scale can also be great. For example, Miocene beach/upper-shoreface facies in Northeast Hitchcock and Alta Loma fields in Galveston County, Texas, are continuous for >10 mi (>16 km) (Ambrose, 1990).

Reservoir Quality

Low permeability in Cotton Valley sandstones in northeastern Texas results from abundant quartz and calcite cement (Wescott, 1983; Dutton et al., 1991). Calcite cement in the Mobil No. 15 Cargill core is abundant (whole-rock volume of 10 to 29%) in thin-section samples from 9310.5 ft (2837.8 m), 9141.3 ft (2847.2 m), and 9158.5 ft (2852.5 m) (Dutton et al., 2017, this volume). These calcite-cemented intervals occur in or adjacent to mudstone and sandstone beds from tidal-channel and basal washover-fan facies that contain abundant shell debris, suggesting the possibility of early diagenesis from dissolution of shell fragments (Dutton et al., 2017, this volume).

Permeability and porosity in the Mobil No. 15 Cargill well are low. Permeability values range from <0.001 to 0.235 md (Dutton et al., 1991), whereas porosity values vary from 0.8 to 10.8% (Fig. 3). Greatest porosity values (>10%) are in upper-shoreface facies from 9325 to 9331 ft (2843.0 to 2844.8 m) (Fig. 3). Although individual sandstone beds in the washover-fan/backbarrier facies in the Mobil No. 15 Cargill core are up to 2 ft (0.6 m) thick and fine to medium grained, they are also planar laminated at a fine scale (0.2 to 0.4 in [0.5 to 1.0 cm]) and contain low permeability (<0.01 md) and porosity (<5%) values, suggesting that no relationships exist between sandstone bed thickness, grain size, and reservoir quality in this facies.

Sun No. 1 Olinkraft

Description

The Sun No. 1 Olinkraft well is in the Terryville Bar Trend in northwestern Louisiana (Ewing, 2001) (Fig. 1). The cored interval, which extends from 9773 to 9812 ft (2979.8 to 2991.5 m), is a sandy section composed of fine- to medium-grained, shelly and burrowed sandstone interbedded with multiple, 1 to 2 ft (0.3 to 0.6 m) beds of coarse-grained, shelly sandstone with mollusc fragments and abundant quartzite pebbles (Fig. 8). The basal 2 ft (0.6 m) is composed of planar-stratified, fine- to medium-grained sandstone (Fig. 8) overlain by burrowed, medium-grained sandstone, in turn truncated by a 2 ft (0.6 m) bed of coarse- to very coarse-grained sandstone with quartzite pebbles (Fig. 11A). The 8 ft (2.4 m) section above this coarse- to very coarse-grained, pebbly sandstone is upward fining, with burrowed beds of fine- to medium-grained sandstone (Fig. 11B). The remainder of the cored interval contains erosion-based zones of coarse-grained sandstone (Figs. 8 and Fig. 12A). The upper 6 ft (1.8 m) of section is composed of fine- to medium-grained sandstone with low-angle, inclined and horizontal planar stratification (Fig. 12B).

Interpretation

The cored interval in the Sun No. 1 Olinkraft well is composed of multiple tidal-channel deposits that truncate upper-shoreface and beach facies (Fig. 8). Individual tidal-channel deposits in the section are upward fining, consisting of medium- to coarse-grained, pebbly and shelly sandstone above an erosional base, grading upward into fine- to medium-grained, burrowed sandstone. Diagnostic features for tidal-channel deposits include an erosional base, multiple scour surfaces, clay rip-up clasts, shell debris, pebbles, and genetic association with wave-dominated shoreline facies. The mouth of the South Santee River in South Carolina (Stephens et al., 1976; Hayes, 1979; Hayes and Sexton, 1989) (Fig. 6A) on the U.S. Atlantic Coast and the Umpqua River in Oregon (Fig. 13), as well as Leadbetter Point at Willapa Bay, Washington, on the U.S. Pacific Coast (located in Fig. 13B), are examples of modern tidal-channel deposits analogous to those in the Sun No. 1 Olinkraft core. Other well-documented tidal channels on the South Carolina coastline include Price and Stono inlets (Barwis, 1978; Hayes and Sexton, 1989; Sexton and Hayes, 1996; Hayes and FitzGerald, 2013) (Fig. 7). Examples along the Texas Gulf Coast include inlets in Matagorda and Lavaca bays (Kraus and Militello, 1999; Maddox et al., 2008), Corpus Christi Bay (Smith, 1977; Simms et al., 2008), and the area of Galveston Bay (Israel et al., 1987; Bales and Holley, 1989; Siringan and Anderson, 1993; Anderson et al., 2008). Vertical profiles of tidal channels which erode into beach and upper-shoreface deposits commonly contain a basal shell lag. They have blocky and upward-fining grain-size profiles, although the upper tidal-channel fill can be modified by laterally accreting spit deposits migrating onto the tidal-channel margin. The sedimentary succession in these examples commonly includes gravel, pebble, or mud-clast lags above scour surfaces, shallow-marine ichnofauna, inclined and horizontal planar stratification, and variable grain size, with upward-fining being the most common grain-size trend (Shepard, 1960; Hoyt and Henry, 1967; Hayes, 1980; Israel et al., 1987; Bales and Holley, 1989; Kraus and Militello, 1999; Siringan and Anderson, 1993; Anderson et al., 2008, 2016).

A factor to consider in the preservation potential of barrier/shoreface systems in the Terryville Bar Trend is the relatively high proportion of preserved tidal-channel facies in the Sun No. 1 Olinkraft core (Fig. 8). Kumar and Sanders (1974), Hayes and Kana (1976), Sexton and Hayes (1996), and Simms et al. (2006) documented deep (>50 ft [>15 m]), laterally migrating tidal inlets that erode significant sections of the beach and upper shoreface, leaving behind an aggregate of tidal-inlet deposits that are collectively wider than individual tidal channels. Microtidal transgressive barriers in the Mississippi Delta area are also commonly reworked into a succession of tidal-channel deposits (Penland et al., 1988; Suter et al., 1988). Examples in the rock record include the Oligocene Frio Formation in West Ranch Field (Jackson County, Texas), where tidal-channel facies collectively extend >5000 ft (>1520 m) along depositional strike, greatly exceeding the width of individual tidal-channel deposits that are 1000 to 1500 ft (305 to 455 m) across (Galloway, 1986).

Significant variability in facies preservation can occur during transgression, depending on the shoreline gradient and whether transgressive deposits are developed above or below wave-ravinement surfaces (Cattaneo and Steel, 2002). These ravinement surfaces, caused by erosion from wave action, commonly separate basal marsh, lagoon, tidal-channel, and beach deposits from overlying marine sands (Swift, 1968). Sixsmith et al. (2008), in a study of the Cretaceous Hosta Sandstone in the San Juan Basin in New Mexico and Colorado, conclude that the distribution of transgressive deposits and bounding erosional surfaces is a function of relative sea level and sediment supply. Many individual tidal-ravinement surfaces in the Hosta Sandstone, defined as erosional surfaces produced by tidal currents, have a narrow (<1640 ft [<500 m]), channelized geometry dominated by tidal channels. The transgressive section in some parts of the Hosta Sandstone is commonly composed of multistoried tidal-channel-fill complexes, which reflects poor preservation of dune and beach deposits.

Nummedal and Swift (1987) concluded that ravinement surfaces in transgressive shoreline systems are diachronous surfaces associated with sediment transfer as well as erosion. They propose a variety of transgressive stratigraphic columns from Holocene examples, based on observations by Suter (1986), in which variability in the transgressive section is in part a function of original depositional setting. Sections of transgressive deposits in the Mobil No. 15 Cargill and Sun No. 1 Olinkraft cores (Figs. 3 and 8, respectively) are most consistent

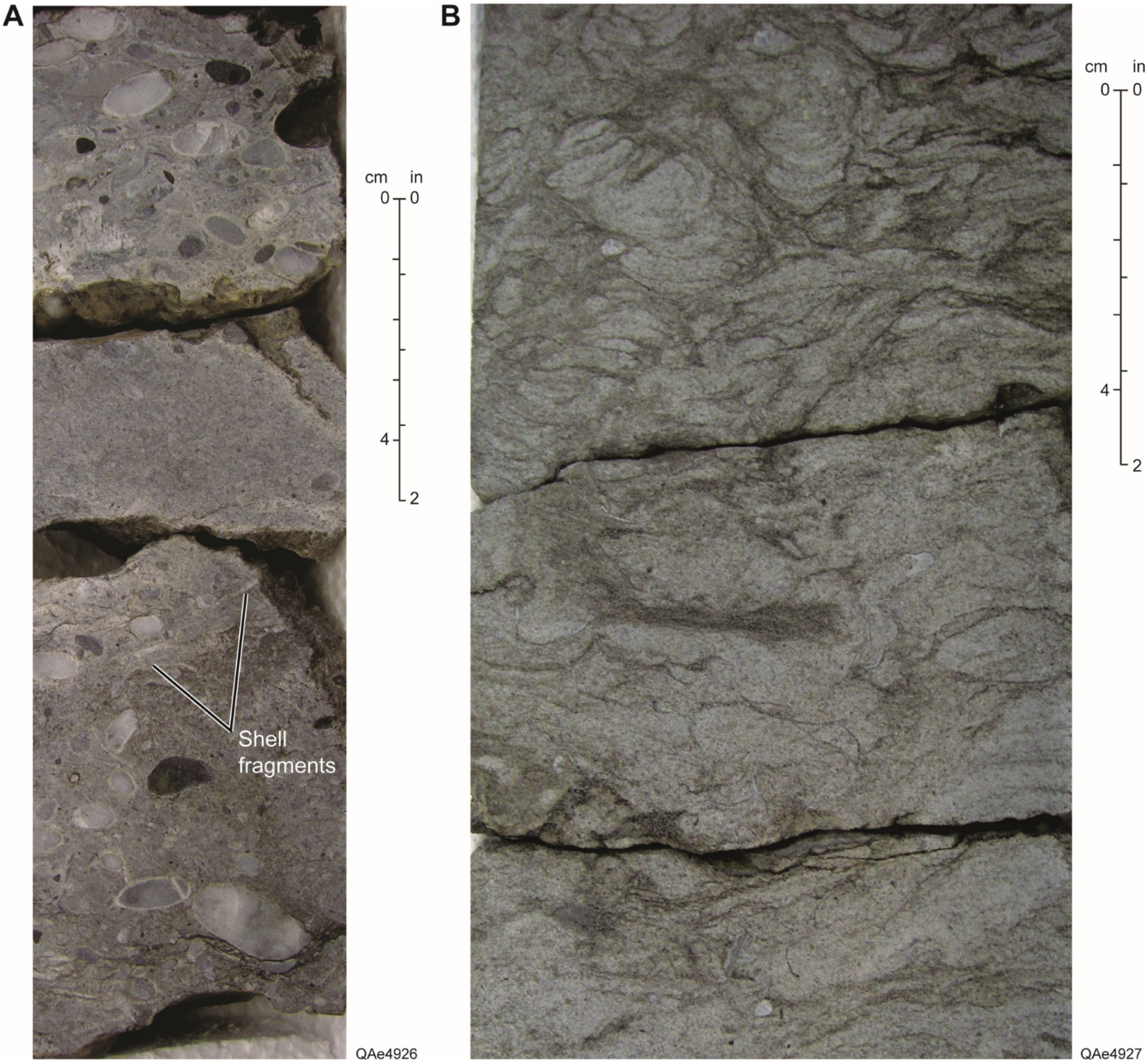

Figure 11. Photographs of the Sun No. 1 Olinkraft well in Bossier Parish, Louisiana. (A) Coarse- to very coarse-grained, pebbly sandstone with minor mollusc fragments in lower tidal-channel facies at 9807.6 ft (2990.1 m). (B) Intensely burrowed, fine- to medium-grained sandstone at 9799.2 ft (2987.6 m), of possible flood-tidal-delta origin interpreted to be eroded by overlying tidal-channel facies. Core description is shown in Figure 8.

with the model of Lavaca Bay, Texas, as well as the conceptual model of tidal channel and flood-tidal deltas (Nummedal and Swift, 1987, their figures 5C and 5E, respectively), because of the preponderance of preserved tidal-channel facies in these examples.

Reservoir Quality

Insufficient permeability and porosity data exist for the Sun No. 1 Olinkraft core to infer relationships between facies and reservoir quality. Core-analysis permeability values in two samples from the cored interval in the Sun No. 1 Olinkraft well are 0.03 and 0.08 md, and porosity values are 2.3 and 3.8%, respectively (Fig. 8). Calcite cement is abundant (16.5%) in an upper tidal-channel deposit of very coarse-grained sandstone from 9779.3 ft (2980.7 m). In contrast, a beach/upper shoreface sandstone from 9776.2 ft (2979.8 m) contains only 3.5% calcite cement but 17% quartz cement (Dutton et al., 2017, this volume).

LOWER COASTAL PLAIN SYSTEMS, MISSISSIPPI

Pan American No. 1 Williamson

The Pan American No. 1 Williamson well, cored in the middle to upper Cotton Valley Group, is located in Smith County, Mississippi in a lower-coastal-plain setting, southeast of a deltaic complex (Ewing, 2001) (Fig. 1). This deltaic complex is termed the “Ancestral Mississippi Delta” by Moore (1983). Alluvial and coastal-plain systems in the Cotton Valley Group, characterized by coarse-grained and mixed-load fluvial deposits, supplied sediments to lagoons and bays on the northern margin of this shore-

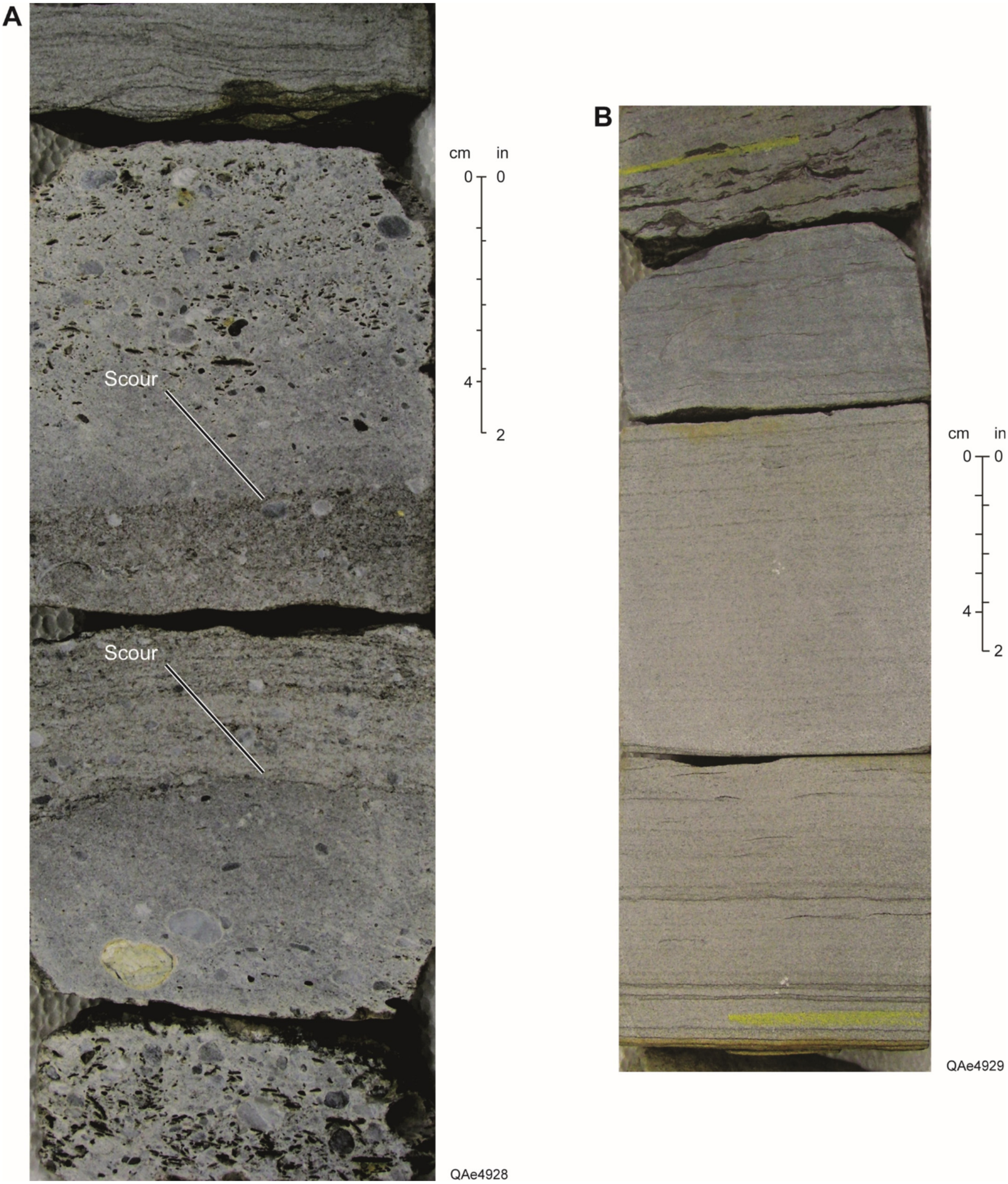

Figure 12. (A) Photographs of the Sun No. 1 Olinkraft well in Bossier Parish, Louisiana. Medium- to coarse-grained, pebbly sandstone with scour surfaces in tidal-channel facies at 9782.6 ft (2982.5 m). (B) Fine-grained sandstone with low-angle and planar beds at 9777.0 ft (2980.8 m) in beach/upper-shoreface facies. Core description is shown in Figure 8.

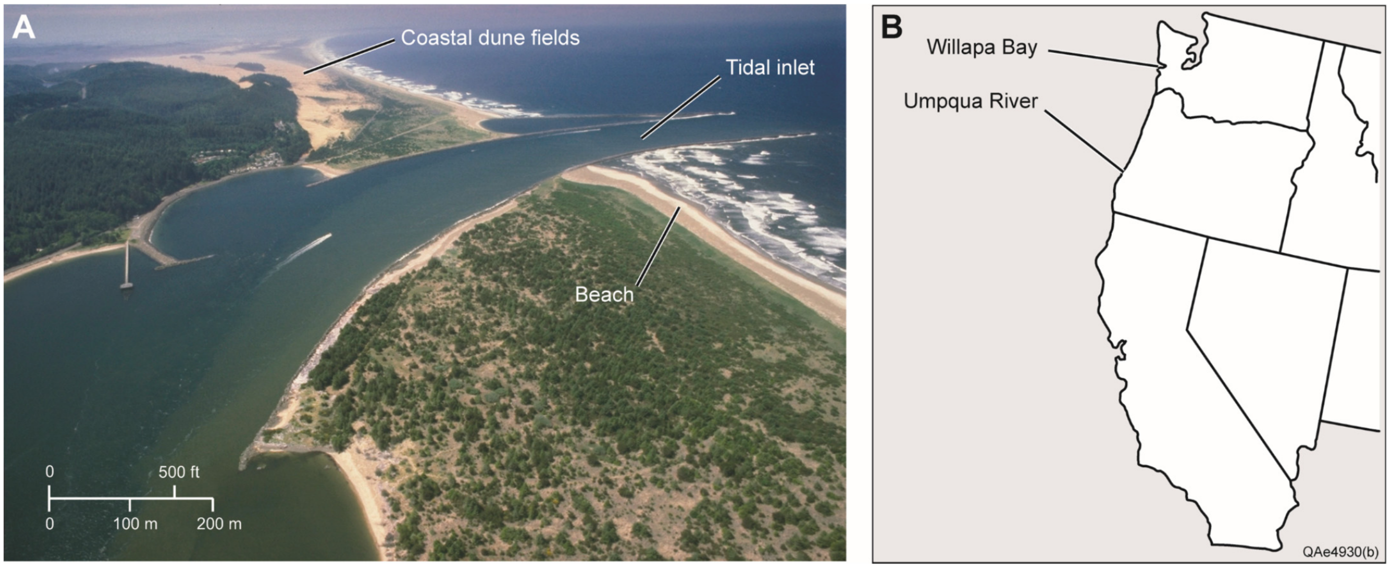

Figure 13. (A) Mouth of the Umpqua River on the Pacific coastline at Winchester Bay, Oregon (modified after public domain photo courtesy of B. Heims, U.S. Army Corps of Engineers, available at https://en.wikipedia.org/wiki/File:USACE_Winchester_Bay,_Umpqua_River_mouth.jpg). (B) Location of the Umpqua River mouth, Oregon, and Willapa Bay, Washington.

line trend (Swain, 1944; Bartberger et al., 2002). Cotton Valley alluvial deposits in southern Mississippi and southwestern Alabama formed in environments alternating between emergent oxidizing and submerged reducing environments as illustrated by variegated (red, orange-red, reddish-brown, and green) mudstones with abundant mottled textures (Tolson et al., 1983; Mink et al., 1989).

Description: Lower Cored Interval

The Pan American No. 1 Williamson well features two cored intervals (Figs. 14 and 15). The lower cored interval in Pan American No. 1 Williamson well, which extends from 14,079 to 14,131 ft (4292.4 to 4308.2 m), is composed of multiple, mostly erosion-based, very fine- to lower-medium-grained sandstone beds, interbedded with mudstone beds with variegated colors ranging from purple-brown to gray-green (Fig. 14). Erosion-based sandstone beds are fine to medium grained and contain abundant clay clasts and organic fragments (Fig. 16A). Stratification consists commonly of low- to medium-angle crossbeds (Figs. 16B and 16C). Mudstone beds in the lower cored interval are dominantly purple, purple-brown, and brown with minor occurrences of gray-green colors. They are mottled by burrows and contain irregular, oval gray-green patches (Fig. 17A). The cored section contains abundant insect burrows that include beetle and insect-larvae burrows (Figs. 17B and 17C). Trace fossils from soil-dwelling arthropods are common in continental deposits (Genise et al., 2004; Buatois and Mangano, 2004; O'Geen and Busacca, 2001; Hasiotis, 2004). Beetle larvae in the Pan American No. 1 Williamson core, form backfilled, meniscate burrows that are distinct from backfilled burrows constructed by marine organisms (Hasiotis and Bourke, 2006; Smith and Hasiotis, 2008; Counts and Hasiotis, 2009; Hasiotis and Platt, 2012).

Description: Upper Cored Interval

The upper cored interval in Pan American No. 1 Williamson well, which extends from 13,696 to 13,751 ft (4175.6 to 4192.4 m), contains a section below 13,715 ft (4181.4 m) composed of thin (0.5 to 3 ft [0.15 to 0.9 m]) beds of very fine- to very coarse-grained sandstone interbedded within purple and gray-green mudstone beds. Burrows and contorted bedding are common in the section (Fig. 15). The upper 18 ft (5.5 m) of core is dominated by a 13 ft (4.0 m) interval of upward-coarsening, fine- to medium-grained sandstone capped by a 5 ft (1.5 m) siltstone bed with nodules and deformed bedding. Significant features in the upper cored interval include insect larvae and *Naktodemasis* beetle burrows (Figs. 18A and 18B), thin (<2 in [<5.1 cm]) beds of conglomeratic sandstone with clay clasts (Fig. 18C), crossbedded, fine- to medium-grained sandstone (Figs. 19A and 19B), and mottled, silty mudstone with nodules and vertical filaments (Fig. 19C).

Interpretation: Lower and Upper Cored Intervals

Both the lower and upper cored intervals in Pan American No. 1 Williamson well contain fluvial facies in a coarse-grained meanderbelt system (Figs. 14 and 15). Coarse-grained meanderbelt systems are mixed-load, sandy fluvial systems that tend to straighten their own courses with chute channels during flood stage. The Holocene Colorado River in southeastern Texas is an example of a coarse-grained meanderbelt system with well-developed, cross-stratified chute channels and chute bars (McGowen and Garner, 1970).

Channel-fill deposits in the Pan American No. 1 Williamson core are composed of multiple, amalgamated beds of planar- and cross-stratified sandstone that commonly occur in 10 to 15 ft (3 to 4.5 m) sections. Many individual sandstone beds in these sections are <2 ft (<0.6 m) thick and erosionally based, with abundant clay rip-up clasts (Figs. 16A and 16B). Because individual sandstone beds in these channel-fill deposits in the Pan American No. 1 Williamson core are <2 ft (<0.6 m) thick, they were deposited in smaller-scale rivers than the Colorado River, where chute- and point-bar complexes are as much as 20 to 25 ft (6 to 7.6 m) thick (McGowen and Garner, 1970).

The grain-size profile of these channel-fill successions varies because of complex superposition of individual sandstone beds. Several of these successions are upward fining (for example, the section from 14,118 to 14,127 ft [4304.3 to 4307.0 m]) (Fig. 14). However, examples of net upward-coarsening profiles also occur, such as the section from 13,702 to 13,715 ft (4177.4 to 4181.4 m), which records the superposition of relatively coarser-grained channel-fill bodies onto finer-grained channel-fill bodies (Fig. 15). Variability in the classic upward-fining grain-size profile in fluvial channel-fill sandstone bodies (Jackson, 1975; Galloway, 1977; Schumm, 1981) can be introduced by point-bar

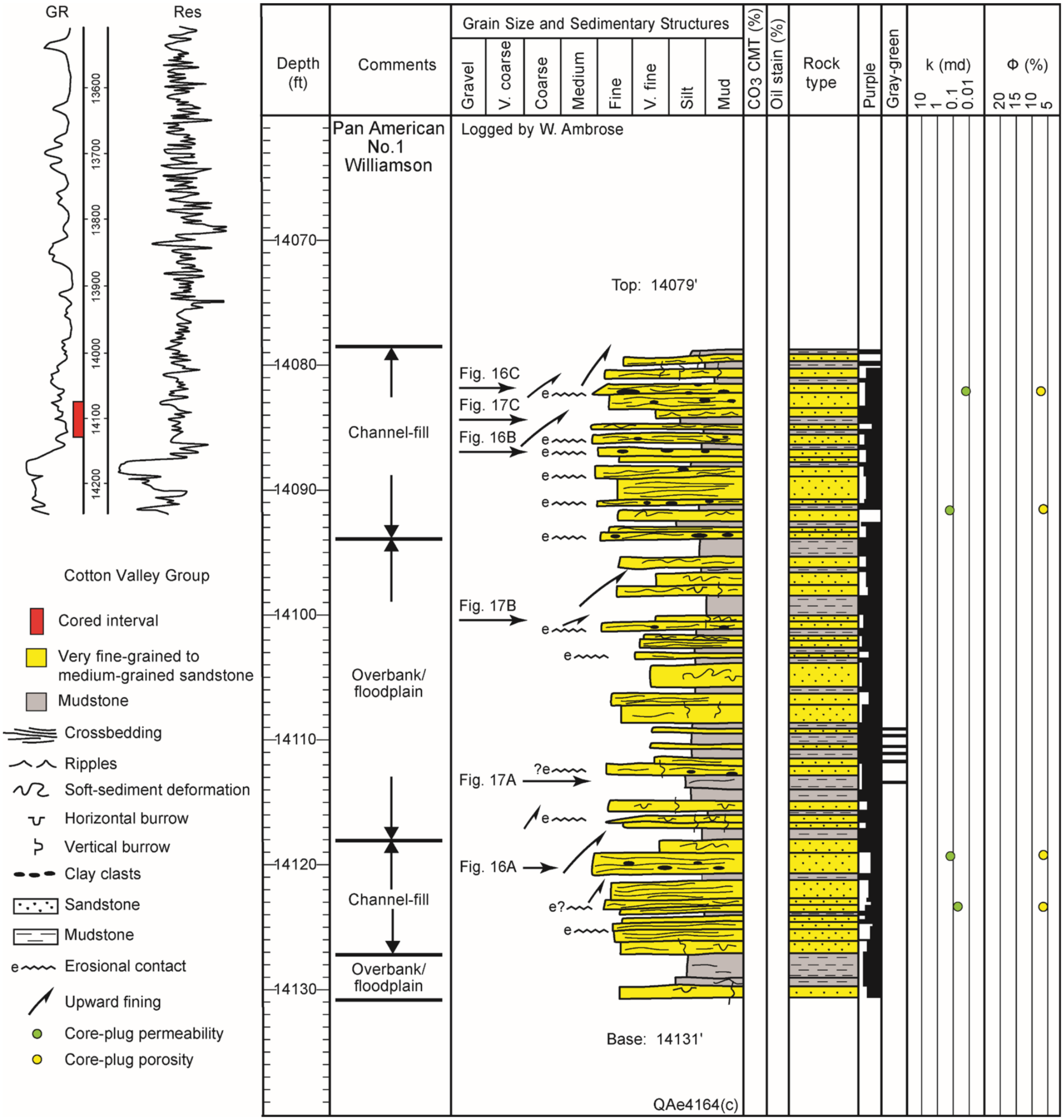

Figure 14. Core description and reservoir quality (core-plug permeability porosity) data from the Pan American No. 1 Williamson well in Smith County, Mississippi. Location of well is shown in Figure 1.

modification by high-energy barforms deposited during flood-stage conditions (McGowen and Garner, 1970). Alternatively, net upward-coarsening vertical grain-size profiles in fluvial channel-fill sandstone deposits may record an evolution in the fluvial system where successive channel-fill sandstone bodies record a gradual progression to relatively sandier channel systems. An example is the Oligocene Frio Formation in South Texas (Ambrose et al., 1988; Ambrose and Jackson, 1989; Jackson and Ambrose, 1989). Knox and McRae (1995) documented changing fluvial style in the upper-delta plain during depositional cycles in the Frio Formation that could result in a pattern of upward-increasing net-sandstone percentage with an overall upward-coarsening vertical grain-size profile. They hypothesized that during the early period of relative sea-level rise, fluvial gradients had not fully equilibrated with the rapidly rising base level, and initial backstepping of the delta had favored sand deposition and preservation in the lower-delta plain. During the later rising phase, deposition and preservation then shifted to the upper-delta plain, resulting in an upward increase in net-sandstone percentage.

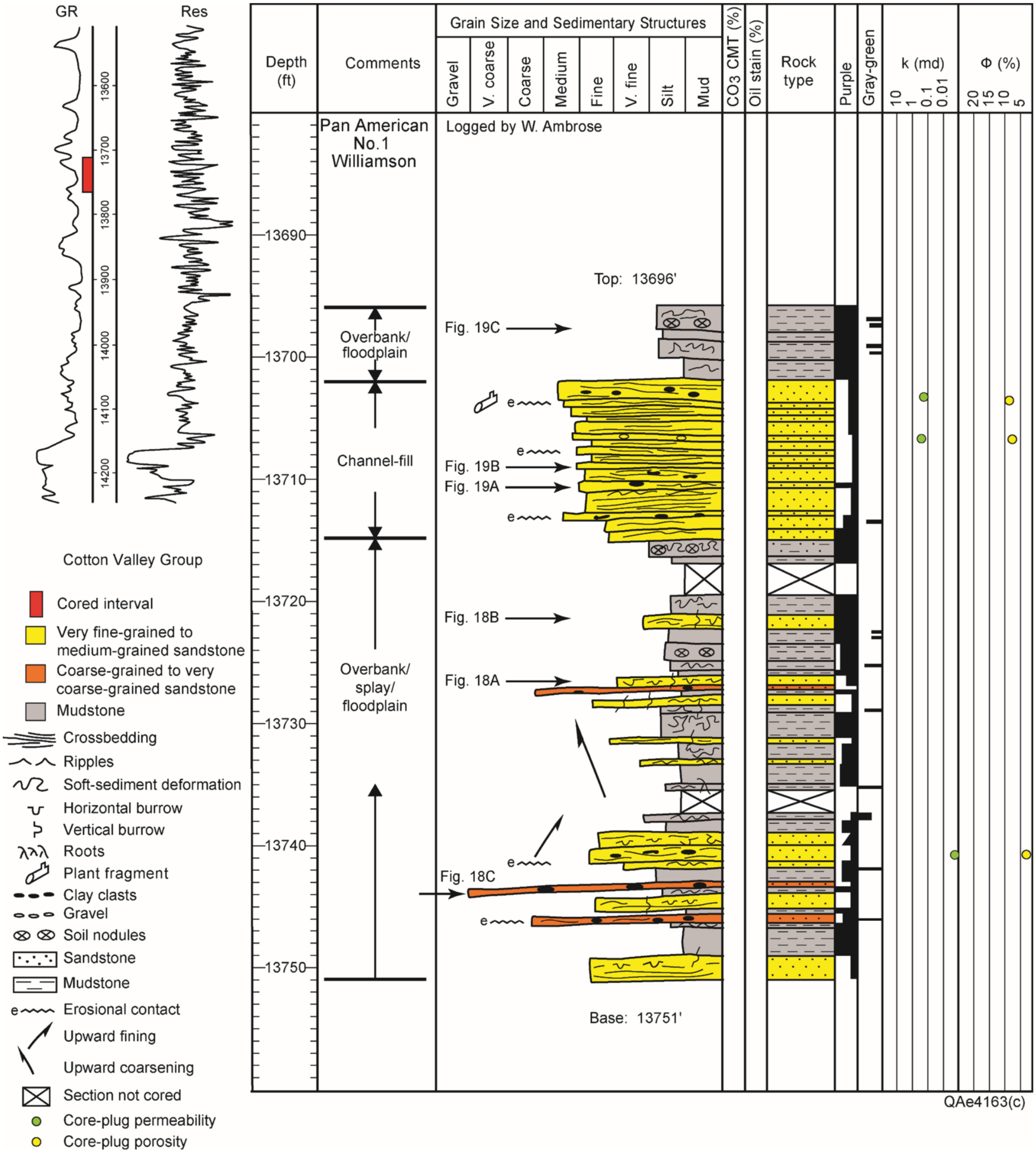

Figure 15. Core description and reservoir quality (core-plug permeability and porosity) data from the Pan American No. 1 Williamson well in Smith County, Mississippi. Location of well is shown in Figure 1.

Overbank facies in the Pan American No. 1 Williamson well are composed of 5 to 10 ft (1.5 to 3 m) sections of predominantly very fine- to fine-grained, thin (≤1 ft [≤0.3 m]) sandstone beds interbedded with mottled, silty mudstone (14,095 to 14,106 ft [4297.3 to 4300.7 m] in Figure 14). Other sections of overbank deposits contain coarse-grained sandstone beds, although the dominant lithology is silty mudstone (13,727 to 13,733 ft [4185.1 to 4186.9 m] in Figure 15). Stratification in these sandstone beds is planar laminations and asymmetric current ripples.

Floodplain deposits in in the Pan American No. 1 Williamson well, which include paleosols, are represented by variably thick sections of variegated mudstone with abundant insect burrows, root structures, and soil nodules (Figs. 17A, 18B, and 19C). Paleosols are indicators of geomorphic stability and record sus-

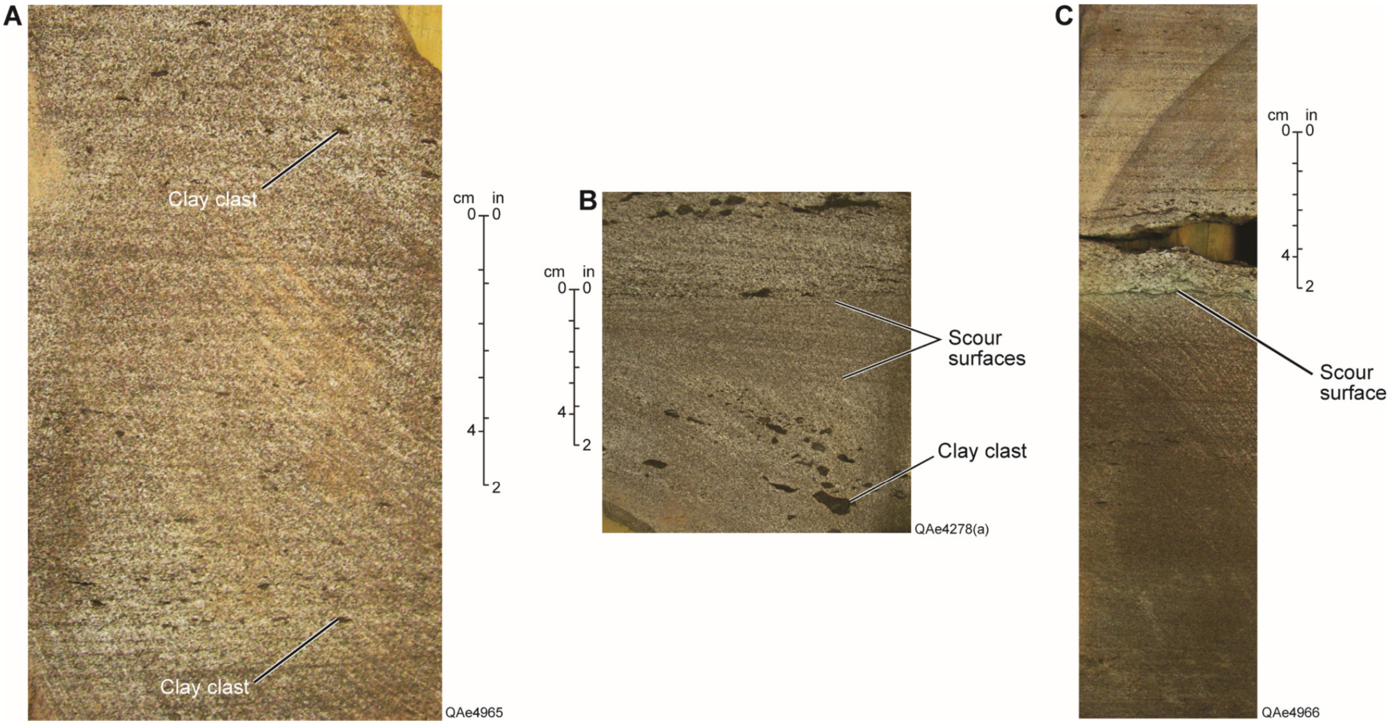

Figure 16. Photographs of the Pan American No. 1 Williamson well in Smith County, Mississippi. (A) Medium-grained sandstone with low-angle cross stratification in fluvial channel-fill facies at 14,120.5 ft (4305.0 m). (B) Medium-grained sandstone with crossbeds, scour surfaces, and clay clasts in fluvial channel-fill facies at 14,086.6 ft (4294.7 m). (C) Fine-grained sandstone with scour surfaces and small clay clasts in fluvial channel-fill facies at 14,082.3 ft (4293.4 m). Core description is shown in Figure 14.

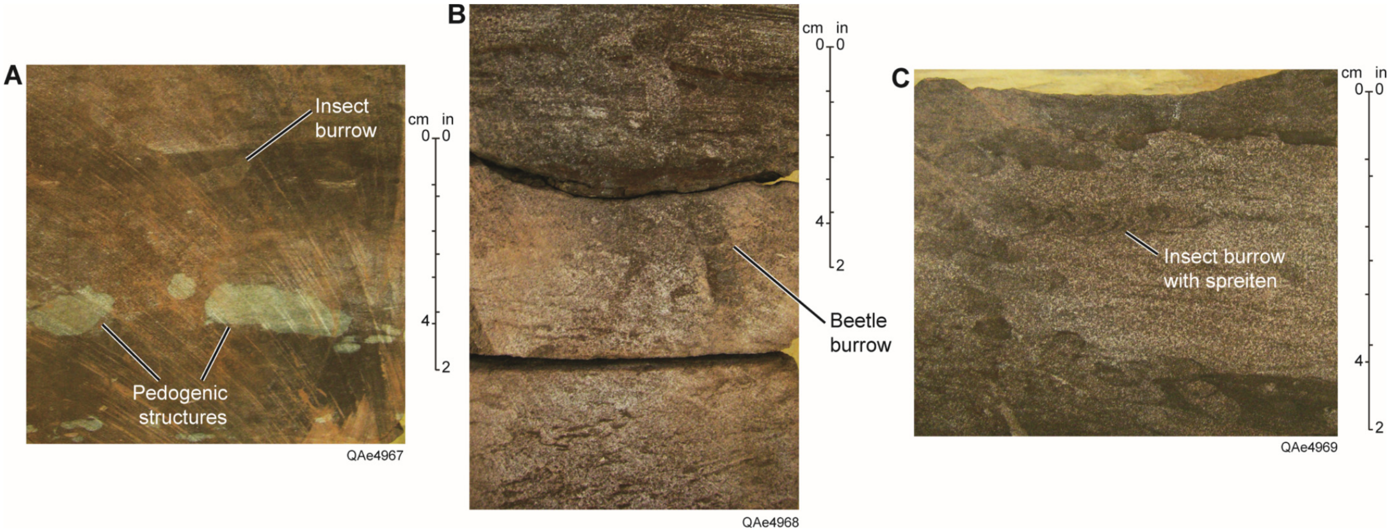

Figure 17. Photographs of the Pan American No. 1 Williamson well in Smith County, Mississippi. (A) Mottled, muddy siltstone with light-green pedogenic structures at in floodplain facies at 14,113.7 ft (4303.0 m). (B) Fine- to medium-grained sandstone with beetle burrows at the top of small-scale, splay-channel facies at 14,100.7 ft (4299.0 m). (C) Mottled, very fine- to fine-grained sandstone with horizontal insect burrows with spreiten at in channel-fill facies at 14,083.9 ft (4293.9 m). Core description is shown in Figure 14.

tained periods of subaerial exposure in fluvial systems (Behrensmeyer and Tauxe, 1982; Marriott and Wright, 1993). Recognition criteria for paleosols, summarized in Tabor and Miles (2015), include (1) mottled texture as a result of predominantly insect burrows, (2) red, reddish-brown, purple, and reddish-purple colors, indicating subaerial exposure and oxidation of mudstone, and (3) nodular texture with vertical, downward-bifurcating filaments, interpreted to be root traces (Fig. 19C).

Reservoir Quality: Lower and Upper Cored Intervals

Reservoir quality in the lower cored interval in the Pan American No. 1 Williamson well is poor, with permeability values ranging from 0.01 to 0.1 md (Figs. 14 and 15). Core-plug porosity values in this interval are low, ranging from 6.4 to 7.5% (Fig. 14). As in the lower cored section, the upper cored section in the Pan American No. 1 Williamson well also features low permeability values (Fig. 15). Permeability in one sample from a

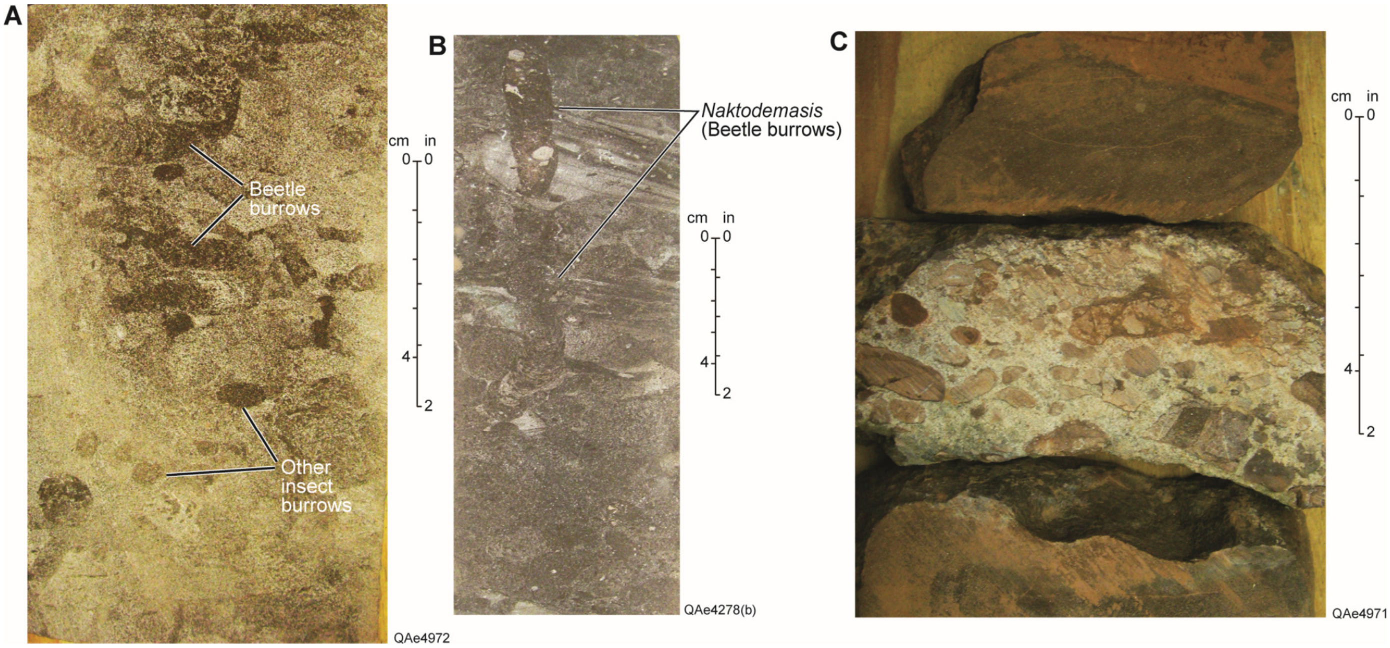

Figure 18. Photographs of the Pan American No. 1 Williamson well in Smith County, Mississippi. (A) Extensively burrowed, upper-fine-grained sandstone in overbank/floodplain facies at 13,726.5 ft (4,184.9 m). (B) Thin (1 in [2.5 cm]) beds of laminated, very fine-grained sandstone disrupted by *Naktodemasis* burrows in silty and muddy levee-overbank facies at 13,721.0 ft (4183.2 m). (C) Conglomerate composed of angular and sub-angular, brown mud clasts in matrix of medium- to coarse-grained sandstone in splay-channel facies at 13,743.3 ft (4190.0 m). Core description is shown in Figure 15.

small-scale channel-fill sandstone bed at 13,741 ft (4189.3 m) is 0.004 md. Permeability values in two samples in the thick (13 ft [4.0 m]) succession of fluvial channel-fill sandstones near the top of the cored are 0.4 and 0.1 md (Fig. 15). Limited core-plug porosity data indicate that this fluvial channel-fill succession has values <10%. Abundant quartz cement (12 to 21%) and lesser volumes of calcite cement (2 to 5.5%) fill much of the intergranular pore space in these sandstones (Dutton et al., 2017, this volume).

SHORELINE SYSTEMS, MISSISSIPPI

Shell No. 1 Fender

A narrow (<20 mi [<32 km]), southeast-northwest-oriented trend of shoreline deposits is inferred in southern Mississippi (Ewing, 2001) (Fig. 1). The Shell No. 1 Fender well is located north of this shoreline trend in the Bay Springs Field, which produces oil and gas from marginal-marine and shallow-marine shoreface deposits (Aultman, 1975; Champlin, 2010).

Description

The cored interval in the Shell No. 1 Fender well, which extends from to 14,540 to 14,612 ft (4432.9 to 4454.9 m), consists of a sandy section of fine- and medium-grained sandstone (Fig. 20) with rare, interbedded zones of very fine-grained, mottled sandstone (Fig. 21A). Textures range from inclined planar stratification in lower-medium-grained sandstone (Fig. 21B) to mottled, fine- to medium-grained sandstone (Fig. 21C). Contacts between sandstone beds in the Shell No. 1 Fender core are obscure, although some scour surfaces are inferred (Fig. 20).

Interpretation

The cored interval in the Shell No. 1 Fender well is composed of amalgamated upper-shoreface deposits. Recognition criteria include: (1) a sandstone-dominated succession, (2) low-angle planar stratification, and (3) zones of extensive burrow mottling (*Planolites* and *Palaeophycus* [Fig. 21A]), although biogenic structures from plants and insects can be encountered in other settings such as eolian interdune areas (Kocurek, 1981; Brookfield, 1992). The Upper Cretaceous Pictured Cliffs Sandstone in the San Juan Basin, New Mexico and Colorado, is a depositional analog for the Cotton Valley Group in the Shell No. 1 Fender core (Erpenbeck, 1979; Cumella, 1981; Manfrino, 1984; Ambrose and Ayers, 2007) (Fig. 22). The Upper Pictured Cliffs Sandstone records high-frequency, Late Cretaceous transgressive-regressive episodes composed of amalgamated barrier-strandplain sandstone bodies in individual successions up to 100 ft (30 m) thick. The Pictured Cliffs Sandstone typically has a blocky to upward-coarsening wireline-log response and is composed of amalgamated sandstone bodies having a composite thickness of 40 to 120 ft (12 to 36 m) (Ayers et al., 1994).

Other depositional analogs for the Shell No. 1 Fender core from the rock record include amalgamated, sandy upper-shoreface successions in upper Miocene strata in the southern part of the Macuspana Basin in Mexico (Ambrose et al., 2004) and sandy and homogeneous barrier/shoreface deposits in the Frio Formation in West Ranch Field in Jackson County, Texas (Galloway and Cheng, 1985; Galloway, 1986). Examples from modern depositional settings include progradational barrier/shoreface deposits in Galveston Island, Texas (Bernard et al., 1962) and Kiawah Island, South Carolina (located in Figure 7B) (Barwis, 1976; Hayes and Kana, 1976). They are located along wave-dominated, microtidal and mesotidal coastlines, respectively.

An alternate facies model for the core in the Shell No. 1 Fender well calls for eolian, coastal dune fields such as the Alexandria Coastal Dunefield near the wave-dominated Sundays River Delta in South Africa (Fig. 23) (CERM, 2016) or coastal dune fields near the Umpqua River Delta in Oregon (Fig. 13A). However, this study favors an upper-shoreface interpretation because: (1) inclined planar stratification in the Shell No. 1 Fender core is commonly <15º, inconsistent with high-angle (>30º) slipfaces commonly encountered in eolian dune deposits (McKee, 1957; Reineck and Singh, 1973), particularly in the Coconino Sand-

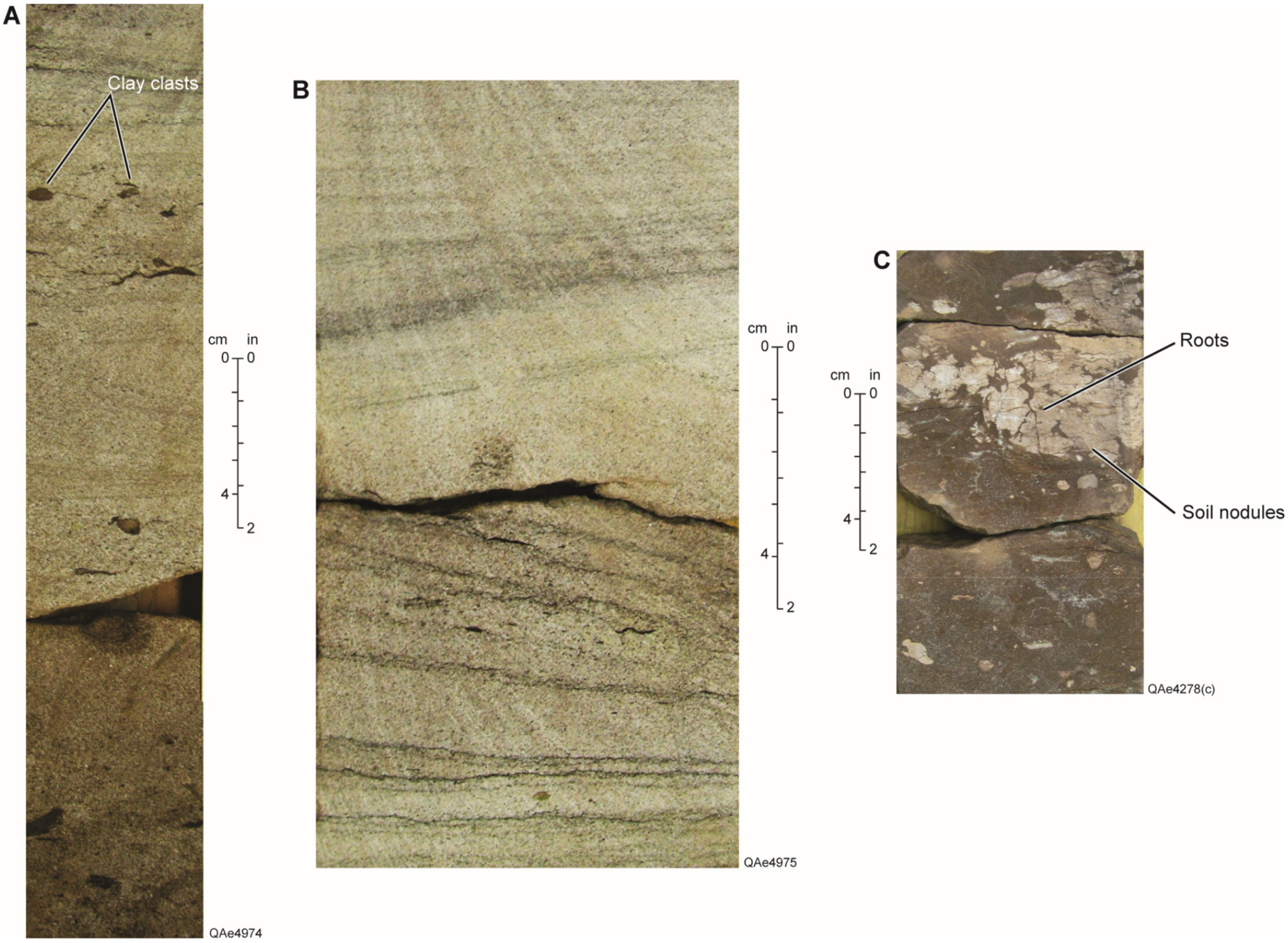

Figure 19. Photographs of the Pan American No. 1 Williamson well in Smith County, Mississippi. (A) Crossbedded, lower-medium-grained sandstone with clay clasts at 13,710.5 ft (4180.0 m) in fluvial channel-fill facies. (B) Lower-medium-grained sandstone with crossbedding in fluvial channel-fill facies at 13,709.0 ft (4179.6 m). (C) Brown, silty mudstone with soil nodules and root traces in floodplain facies at 13,698.0 ft (4176.2 m). Core description is shown in Figure 15.

stone in Arizona (Reiche, 1938; McKee, 1940), (2) pervasive burrow mottling occurs in several zones, commonly observed in shallow-marine environments, and (3) inverse grading, the result of shear-sorting processes in eolian systems, is absent (Salles et al., 2011). Other features observed in eolian strata that are absent in the Shell No. 1 Fender core include: (1) tabular-planar and wedge-planar types of large-scale cross stratification (Hunter, 1977), (2) slump marks indicating dry-sand avalanches, (3) climbing-ripple marks on surfaces of high-angle crossbeds, (4) pinstripe laminations, and (5) grain-fall and grain-flow deposits (McKee, 1979).

Reservoir Quality

Reservoir quality in the Shell No. 1 Fender core is high compared to that of fluvial deposits in the Pan American No. 1 Williamson core, with permeability values ranging from 0.4 to 116 md (Fig. 20). Core-plug porosity values are also higher, varying from 16.8 to 19.6% (Fig. 20), with one lesser value of 12.3% at 14,530 ft (4429.9 m). Core-analysis permeability measured in the adjacent Shell No. 2 Fender well ranges from 180 to 350 md, and porosity ranges from 18.3 to 23.8% (Dutton et al., 2017, this volume). The relatively high porosity and permeability in these sandstones is attributed to the presence of continuous chlorite clay rims on detrital grains that inhibited later quartz cementation (Dutton et al., 2017, this volume).

CONCLUSIONS

Cores in the Cotton Valley Group in the Terryville Bar Trend in northeastern Texas and northern Louisiana display a variety of shallow-marine facies within a wave-dominated depositional setting. These shallow-marine facies include lower- and upper-shoreface, beach, tidal-channel, washover-fan, and transgressive deposits. All facies in the Terryville Bar Trend in this study exhibit low-permeability values that range from 0.001 to 0.5 md. Because of extensive cementation in these sandstones, little variation in permeability exists between shallow-marine facies. Depositional origin cannot be used as a guide to predict reservoir quality in the Cotton Valley Group in the Terryville Bar Trend. However, muddy lower-shoreface and inner-shelf facies have lower permeability values than those in sandy shoreface and tidal-channel facies.

Fluvial depositional systems in southern Mississippi contain examples of sandy channel-fill deposits in coarse-grained meanderbelt facies, whereas floodplain and overbank facies display a well-developed suite of insect burrows and variety of pedogenic structures associated with reduced permeability values that record a fine-grained, muddy matrix. Amalgamated, sandy upper-shoreface deposits downdip (southeast) of these fluvial systems in the Bay Springs Field are composed almost entirely of fine- and medium-grained sandstone with core-plug porosity values ranging from 16 to 20%.

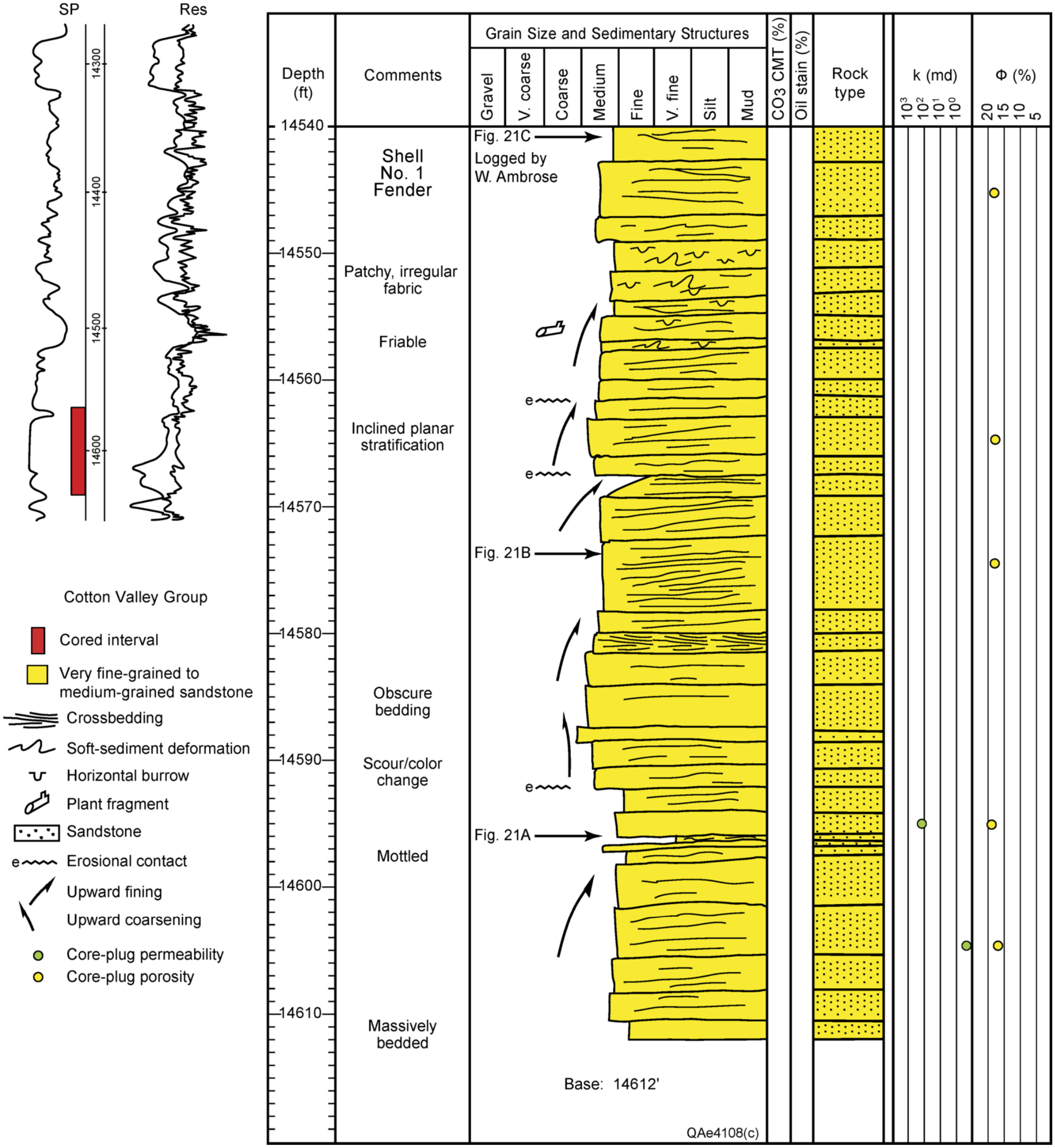

Figure 20. Core description and reservoir quality (core-plug permeability and porosity) data in the Shell No. 1 Fender well in Jasper County, Mississippi. Location of well is shown in Figure 1.

Although the Cotton Valley Group displays significant variability in depositional systems and facies types from Texas to Mississippi, grain-size and facies variability are poor indicators and predictors of reservoir quality, particularly in the East Texas Basin and in the Terryville Bar Trend in northern Louisiana. Although greater variation in range and average values of permeability and porosity exists between fluvial channel-fill and floodplain facies in Mississippi, diagenesis may be concluded to be the main control on reservoir quality in the Cotton Valley Trend.

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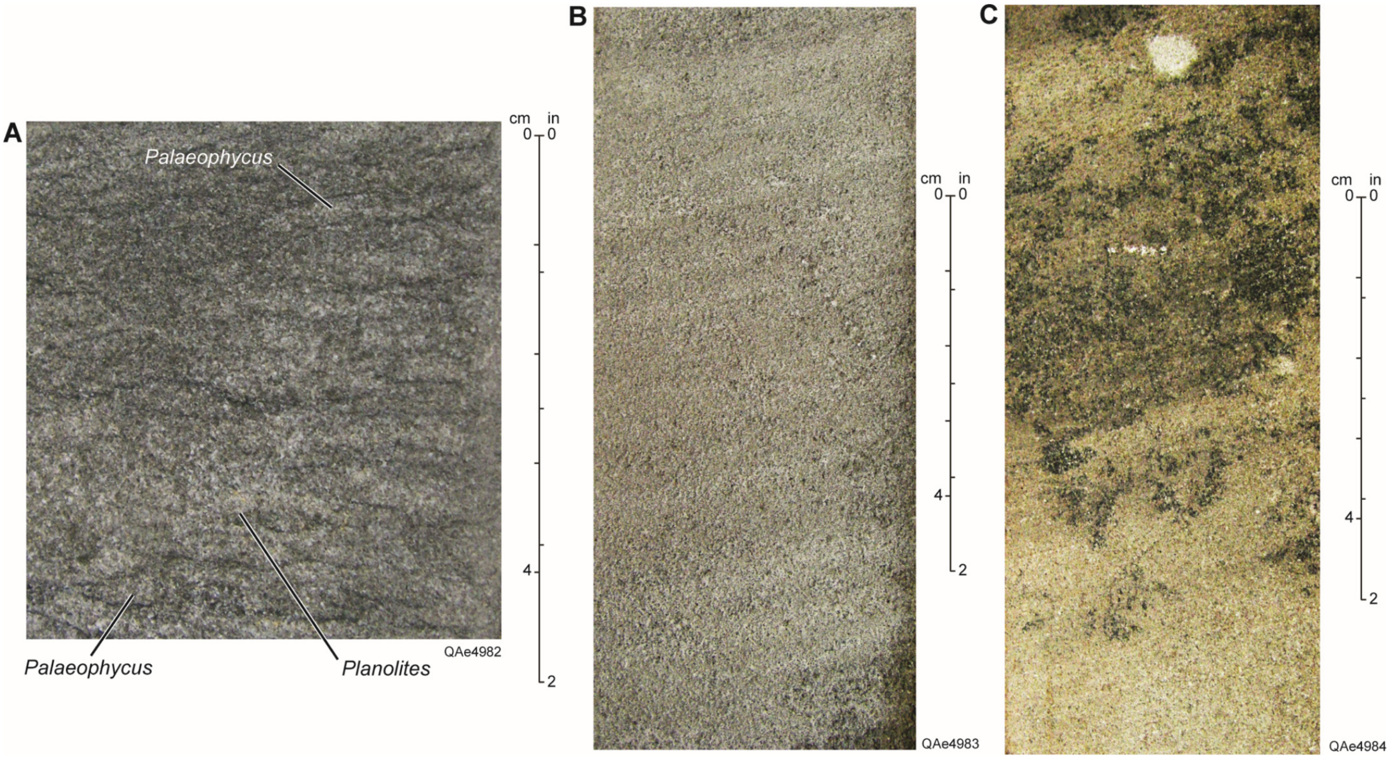

Figure 21. Photographs of the Shell No. 1 Fender well in Jasper County, Mississippi. (A) Mottled, very fine-grained sandstone in lower-shoreface facies at 14,596.0 ft (4450.0 m). (B) Medium-grained sandstone with inclined planar stratification in upper-shoreface facies at 14,573.0 ft (4443.0 m). (C) Lower-medium-grained sandstone with faint inclined planar stratification and dark mottling in upper-shoreface facies at 14,540.2 ft (4433.0 m). Core description is shown in Figure 20.

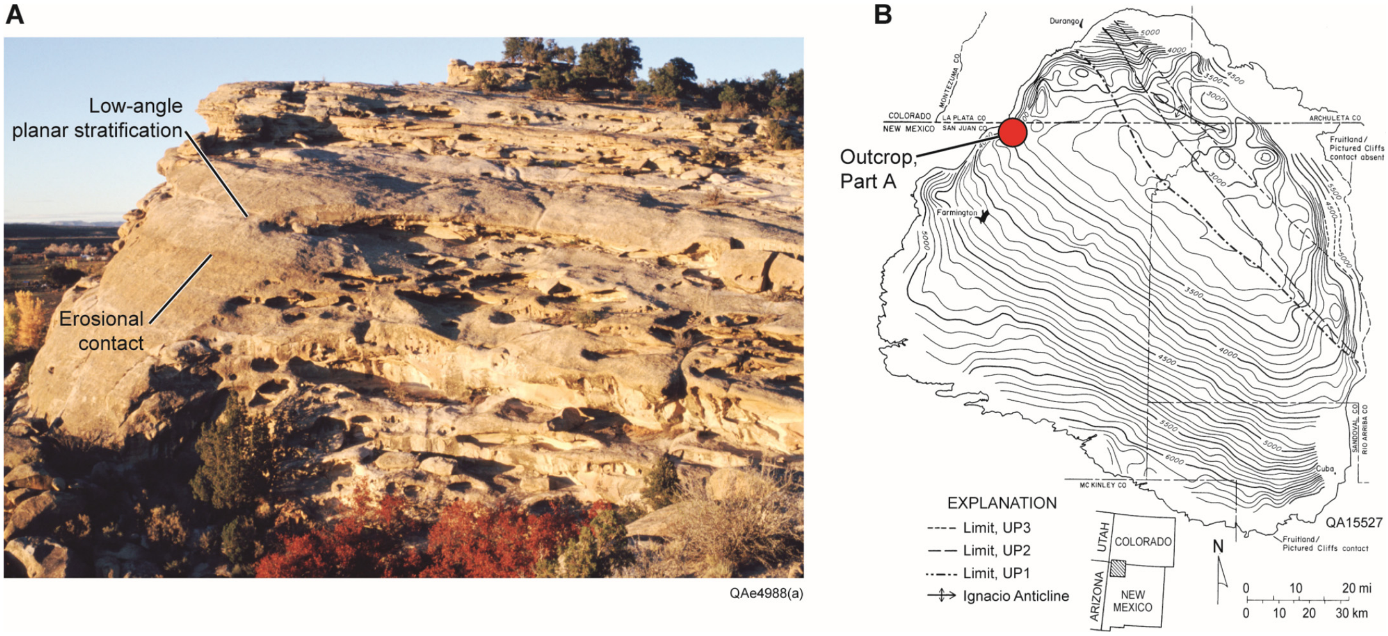

Figure 22. (A) Aggradational upper-shoreface deposits in the Pictured Cliffs Sandstone along New Mexico State Highway 170, 2 mi (3.2 km) west of La Plata Mine in the San Juan Basin in northwestern New Mexico. This succession of upper-shoreface deposits is a depositional analog for the Cotton Valley Group in the Shell No. 1 Fender core, described in Figure 20. Photograph by William Ambrose, October 1989. (B) Structural elevation map on top of the Pictured Cliffs Sandstone in the San Juan Basin, with location of outcrop in photograph in part A (modified after Ayers at al., 1994).

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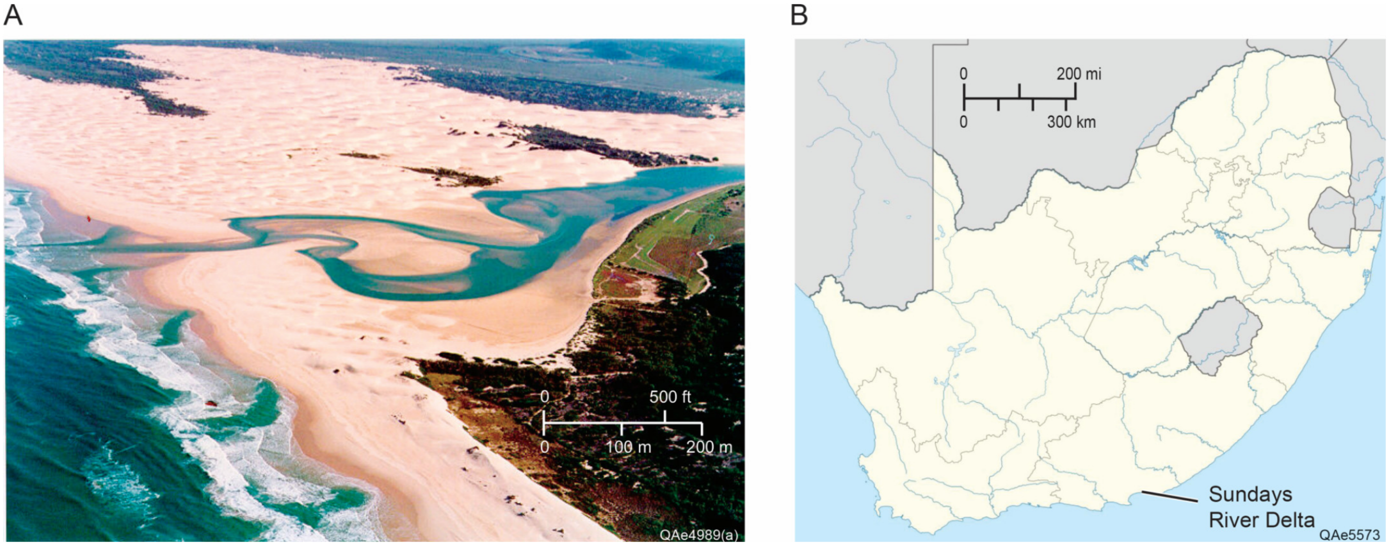

Figure 23. (A) Photograph of the Sundays River Delta on the wave-dominated coast of South Africa. Extensive coastal dune fields are located in background. Photograph modified after CERM (2016). (B) Location of the Sundays River Delta. Location map modified after Wikipedia, accessed at https://en.wikipedia.org/wiki/Sundays_River#/media/File:South_Africa_location_map.svg.

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