GCAGS JOURNAL
A Publication of the Gulf Coast Association of Geological Societies
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Depositional and Diagenetic Controls on Reservoir Quality in Deepwater Sandstones in the Lower Wilcox Group, Lavaca Canyon Complex in the Hallettsville Embayment, Southeastern Texas Gulf Coast

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ABSTRACT

The Lower Wilcox Group in the Lavaca Canyon Complex in the Hallettsville Embayment of southeastern Texas displays a variety of proximal-canyon-fill facies that includes channel-fill, levee, and heterogeneous debris-flow (debrite) and slump deposits. Reservoir quality in Lavaca Canyon sandstones is controlled by both depositional origin and diagenesis. Channel-fill sandstones are composed typically of aggradational successions of fine- to medium-grained, massively bedded sandstone with abundant mud rip-up clasts and organic fragments. Porosity values in these channel-fill sandstones range from 8 to 24% with an average of 18% and permeability values range from less than 0.1 to more than 100 millidarcys (md) with a geometric mean of 6.9 md. Levee facies consist of ripple-stratified beds of very fine- to fine-grained sandstone interbedded with sideritic mudstone and siltstone. In contrast to channel-fill facies, levee facies have lower porosity values that range from 1 to 19%, with an average porosity of 12%. Permeability values range from 0.002 to 47 md and geometric mean permeability in these levee deposits is 0.2 md. Debrite and associated slump facies are heterolithic sections of very fine- to upper fine-grained sandstones complexly interbedded with mudstone. Stratification is dominated by convolute bedding and subvertical to vertical beds that record mass transport and rotation of strata. Debrite facies have the lowest reservoir quality in the Lavaca Canyon Complex, with average porosity and geometric mean permeability values of 6.6% and 0.02 md, respectively.

Data from Wilcox sandstones in the Lavaca Canyon Complex, including 207 porosity and permeability analyses and point counts from 71 thin sections, were used to evaluate controls on reservoir quality. These sandstones occur at depths of 9681 to 10,086 ft (2950 to 3074 m) and temperatures of 250 to 266°F (121 to 130°C). They are composed mostly of feldspathic litharenites, lithic arkoses, and sublitharenites and have an average composition of 72% quartz, 13% feldspar, and 16% rock fragments. Ductile grains are abundant in these sandstones, averaging 14% of the whole-rock volume; they include metamorphic and volcanic rock fragments and contemporaneous mud rip-up clasts. Channel sandstones contain an average volume of 11.6% ductile grains, compared with 15.5% in debrite deposits and 18.7% in levee deposits.

The most important controls on reservoir quality in sandstones in the Lavaca Canyon Complex are related to depositional energy: detrital clay-matrix content, grain size, silt content, and ductile-grain content. Channel-fill sandstones have the best reservoir quality because they have the lowest volume of clay matrix, the coarsest average grain size, and the lowest average silt and ductile-grain content. Channel-fill sandstones contain an average of 0.6% clay matrix, whereas levee and debrite deposits contain significantly more (10.5% and 11.1%, respectively). Similarly, the percent of silt grains is lower in channel sandstones (4.2%) than in levee (33.9%) and debrite deposits (17.3%).

Burial history models indicate that thermal maturity in onshore Lavaca Canyon Wilcox sandstones is somewhat higher than offshore Wilcox sandstones in the Gulf of Mexico. Therefore, Lavaca Canyon should be a good analog for understanding depositional controls on reservoir quality in offshore Gulf of Mexico channel and levee sandstones, but diagenesis is probably a less important control in the offshore Gulf of Mexico than in Lavaca Canyon. Because of their lower thermal maturity, offshore Gulf of Mexico Wilcox sandstones are likely to have undergone less quartz cementation than Lavaca Canyon sandstones.

Manuscript received March 12, 2018; revised manuscript received May 11, 2018; manuscript accepted May 11, 2018.

GCAGS Journal, v. 7 (2018), p. 1–20.

INTRODUCTION AND GEOLOGIC FRAMEWORK

The Hallettsville Embayment is a wide (approximately 35 mi [56 km]), Paleocene reentrant that formed from collapse of

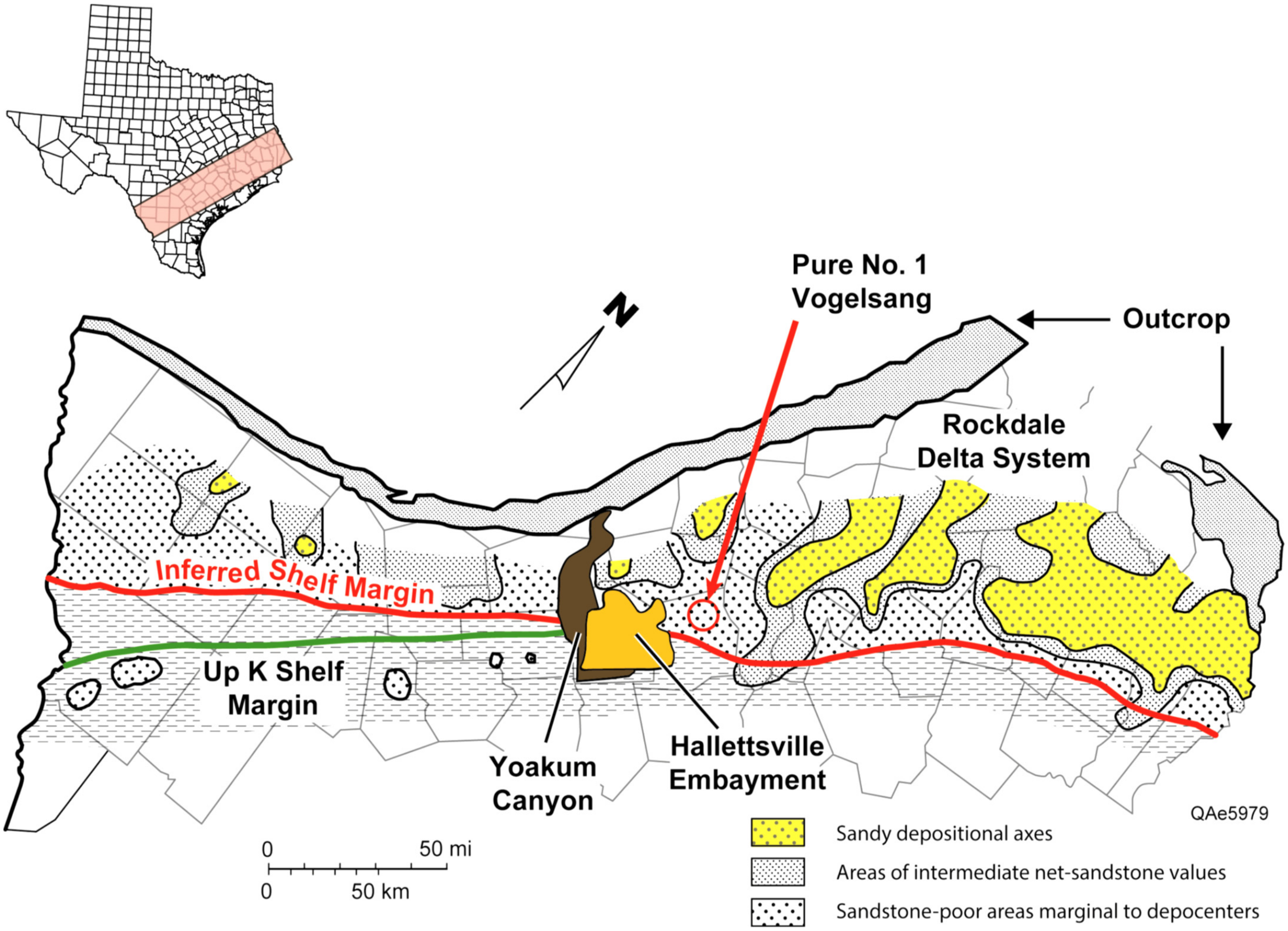


Figure 1. Regional geologic setting of the Lower Wilcox Group in southeastern Texas, showing the position of the Hallettsville Embayment, inferred Lower Wilcox shelf margin, Rockdale Delta System, and Upper Cretaceous shelf margin (modified after Chuber and Begeman [1982], Chuber and Howell [1986], Xue and Galloway [1993], and Galloway and McGilvery [1995]).

the Lower Wilcox shelf margin in southeastern Texas (Figs. 1 and 2) (Chuber and Howell, 1986; Chuber et al., 1989; Galloway and McGilvery, 1995; Galloway et al., 2011). The Lavaca Canyon Complex was first identified by Chuber (1979). It contains at least four submarine channel trends, the Renger, Hathaway, Golsch, and Orsak (Fig. 3). These canyons eroded shelf-margin and outer-shelf deposits associated with the Wilcox Rockdale Delta System (Fig. 1).

Sediment sources were primarily from the Colorado and New Mexico part of the ancestral Rocky Mountains, with other sediment sources from the mid-continent in central Oklahoma and the exposed remnants of the Ouachita system in southeastern Oklahoma and southwestern Arkansas (Galloway et al., 2011). Sharman et al. (2017), in a more recent study involving detrital zircon analysis, also documented a sediment source from Colorado and adjacent areas to the east and northeast.

Sediments in the Lavaca Canyon Complex consist mostly of confined slope-channel, levee, and debris-flow deposits in a proximal-canyon setting near the Lower Wilcox shelf edge. Other canyon-fill material is composed of displaced and rotated slide blocks associated with headward canyon erosion and large-scale mass-wasting events (Chuber and Begeman, 1982; Paige, 1988; Galloway et al., 1991; Galloway and McGilvery, 1995). In addition, deltas prograded to the canyon margin, directly providing gravity-fed turbidites on the upper slope (Galloway and McGilvery, 1995). These delta-fed deposits contain delta-front gravity flows and slumps with significant intraformational deformation and faulting. Debris and turbidity flows created density currents that developed channel/levee complexes downslope characterized by sandstone-rich channel-fills and less-sandy levee systems with a high degree of interbedded mudstone (Galloway and McGilvery, 1995).

Channel-fill systems constitute the main sandy framework facies. They are composed mostly of fine- to medium-grained sandstone with abundant mud rip-up clasts. The channel-fill facies record high-density turbidite deposits, modified by debris-flow and slump deposits (Paige, 1988; Galloway and McGilvery, 1995). These channel-fill systems are flanked by relatively fine-grained levee complexes representing decelerating-flow deposits recorded by sections of very fine- to fine-grained, predominantly rippled-stratified sandstone. A significant volume of canyon-fill deposits exhibits soft-sediment deformation, chaotic bedding, sediment mixing, and complex microfaults, consistent with deposition in mass-transport complexes that contain a variety of liquefied-flow, debris-flow, and slump deposits (Galloway and McGilvery, 1995). Reservoirs commonly occur in sinuous, shoestring- to pod-shaped sandstone bodies (Chuber et al., 1989).

OBJECTIVE, DATA, AND METHODS

The objective of this study was not to reinterpret depositional systems and facies in the Lavaca Canyon Complex, which are

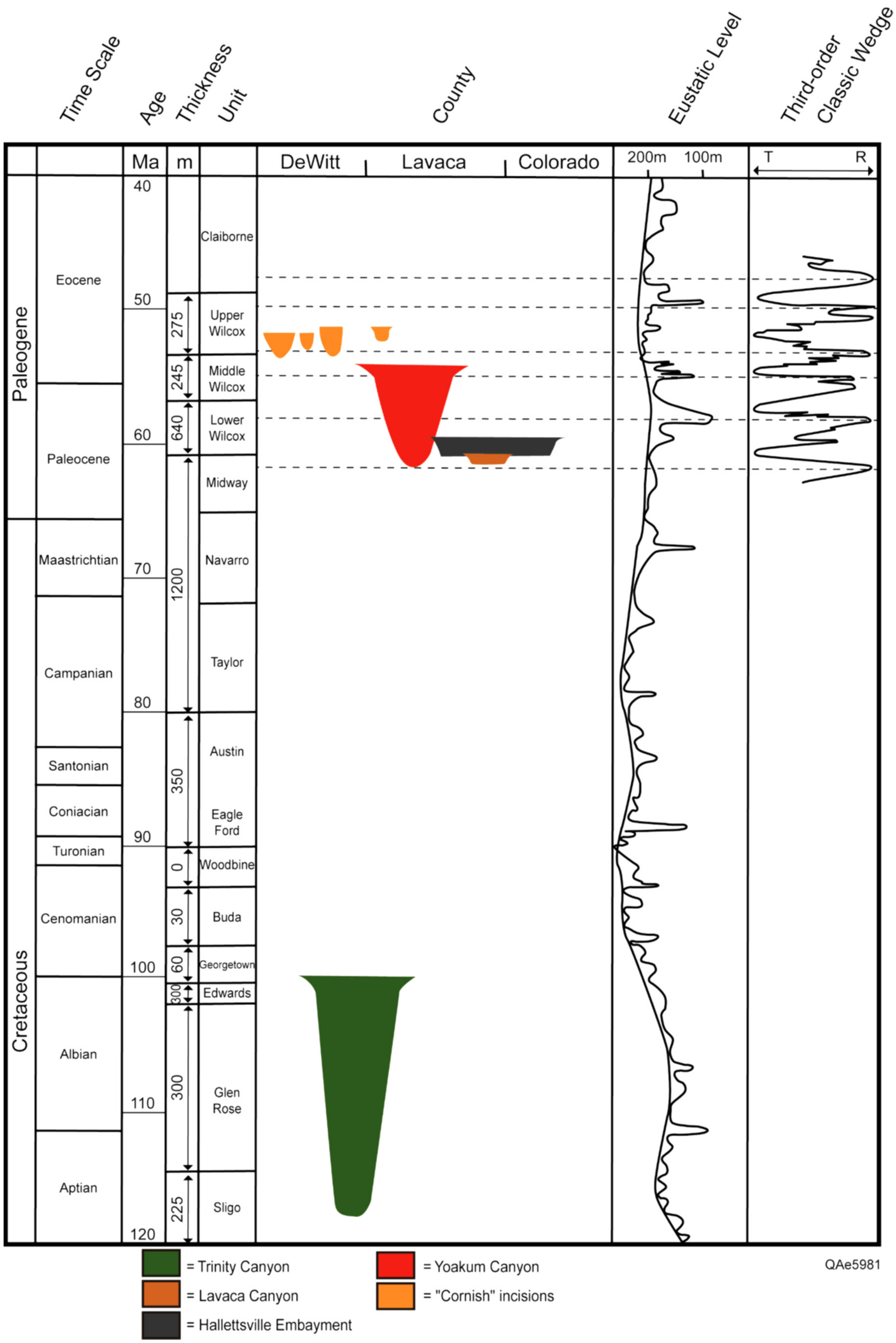


Figure 2. Cretaceous and Paleogene stratigraphic column in the area of Lavaca Canyon, with timing and position of canyon formation and eustatic sea-level curve (modified after Clayton [2017]). Third-order clastic wedges are also shown. T and R letters in right column refer to transgressive and regressive, respectively. Eustatic sea-level curve is from Haq et al. (1988) and third-order clastic wedges is from Crabaugh and Elsik (2000).

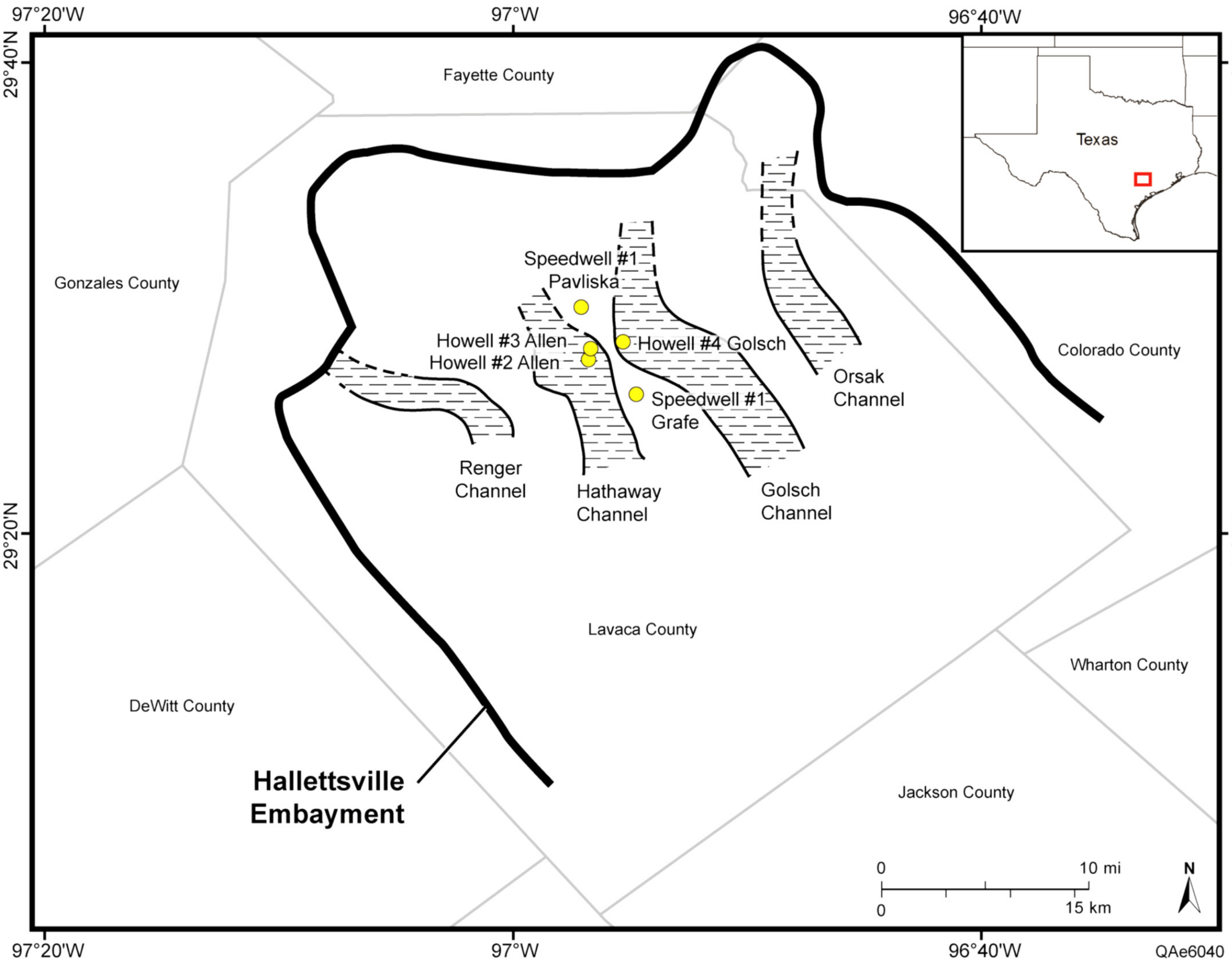


Figure 3. Distribution of five cored wells used in this study (modified after Chuber and Howell [1986], Paige [1988], and Xue and Galloway [1993]). Outline of Hallettsville Embayment and individual canyons, labeled Renger, Hathaway, Golsch, and Orsak channels, are also shown.

well documented with wireline-log cross sections, maps, and other core data by Chuber and Howell (1986), Paige (1988), and Galloway and McGilvery (1995). Instead, the objective was to describe and interpret depositional and diagenetic controls on reservoir quality, defined as porosity and permeability, in the principal facies (channel-fill, levee [channel-margin], and debris-flow [debrite]) in Lower Wilcox canyon-fill deposits in Lavaca County. Five whole cores in the Lower Wilcox Group in the Lavaca Canyon Complex (located in Fig. 3), composing approximately 760 ft (~232 m), were included in the study to provide a context for interpretations of facies, depositional systems, reservoir quality, and diagenesis. Selected intervals from cores in three of these wells (Howell No. 4 Golsch, Howell No. 3 Allen, and Speedwell No. 1 Pavliska) illustrated these features. Data recorded in core descriptions and accompanying photographs included grain size, stratification, contacts, as well as accessory features such as soft-sediment deformation, sediment mixing, microfaults, and mud rip-up clasts, diagnostic of sedimentary processes and depositional environments. Three main canyon-fill facies in the Lavaca Canyon Complex (channel-fill, levee [channel-margin], and debris-flow [debrite]) within unconfined mass-transport deposits were inferred from whole cores and wire-line-log responses. Galloway and McGilvery (1995) also recognized reworked levee deposits, possibly reworked by contour currents, and intact, delta-front slide blocks. However, this study is confined to channel-fill and debrite facies because contour-current deposits are minor features observed in cores in this study.

A total of 207 core plugs provided porosity and permeability data. These data were presented alongside core descriptions for direct comparison with lithology and facies. Composition of sandstones was determined by standard thin-section petrography. Point counts were completed on 71 thin sections of deep-water sandstones and mudstones from the five cored wells (Fig. 3). A total of 300 counts were made on each thin section. Grain size, sorting, and silt content were determined by measuring the long diameter of 100 quartz grains per thin section. Burial-history models were constructed using the program Genesis (ZetaWare, 2009) to compare thermal maturity of onshore Lower Wilcox sandstones near the Lavaca Canyon Complex (in the Pure No. 1 Vogelsang well, Colorado County) to Wilcox sandstones in the offshore Gulf of Mexico (in the BP Tiber well, Keathley Canyon Block 102, and the Shell No. 2 BAHA well, Alaminos Canyon Block 557).

FACIES

Channel-Fill

Description

Channel-fill facies in the Lavaca Canyon Complex occur in thick (commonly 50 to 100 ft [15.2 to 30.5 m]), sandy successions with blocky wireline-log responses (Fig. 4). These facies in the lower part of the Howell No. 4 Golsch core consist of amalgamated sections of fine- to medium-grained sandstone with abundant organic fragments (Fig. 4) and mud rip-up clasts (Figs. 5A, 5B, and 6B). These mud rip-up clasts range in size from mm-scale to as much as 2 in (5.1 cm) across (Fig. 6B). Individual sandstone beds range in thickness from 0.5 to 2 ft (0.15 to 0.6 m) and many are erosion-based (Fig. 4). The overall vertical grain-size profile is nearly uniform, although several 3 to 6 ft (0.9 to 1.8 m) thick, upward-fining zones are present. They are commonly lower medium grained at the base and fine grained at the top. Stratification in this succession is poorly developed, although 2 to 3 ft (0.6 to 0.9 m) thick sections with horizontal planar stratification occur locally (Fig. 6A), as well as thin (<1 ft [<0.3 m]) beds with ripples and convolute stratification.

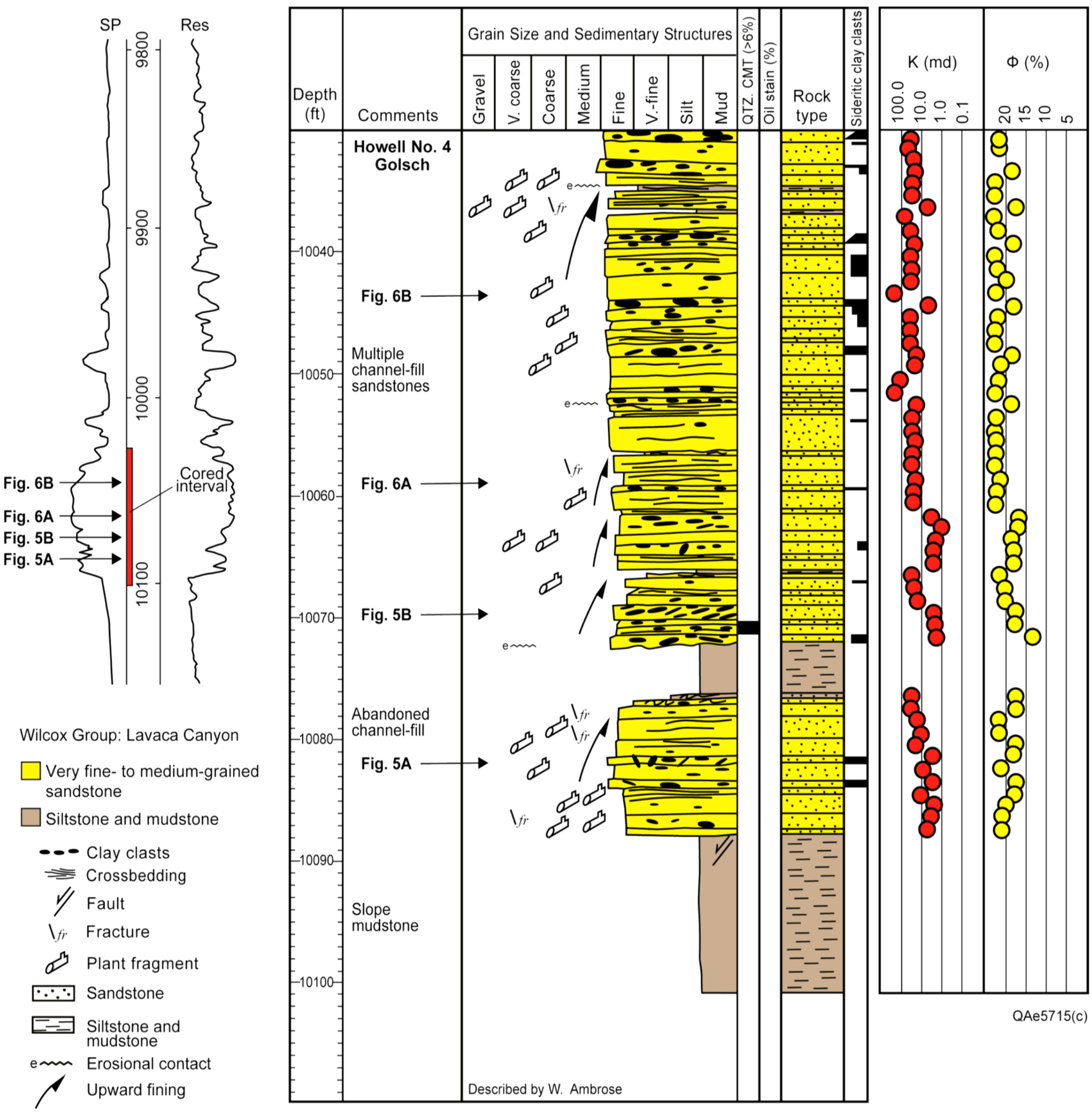


Figure 4. Core description of sandy Lower Wilcox channel-fill deposits in the Howell No. 4 Golsch well from 10,030 to 10,101 ft (3057.9 to 3079.6 m). Well location is shown in Figure 3. Core photographs are shown in Figures 5 and 6.

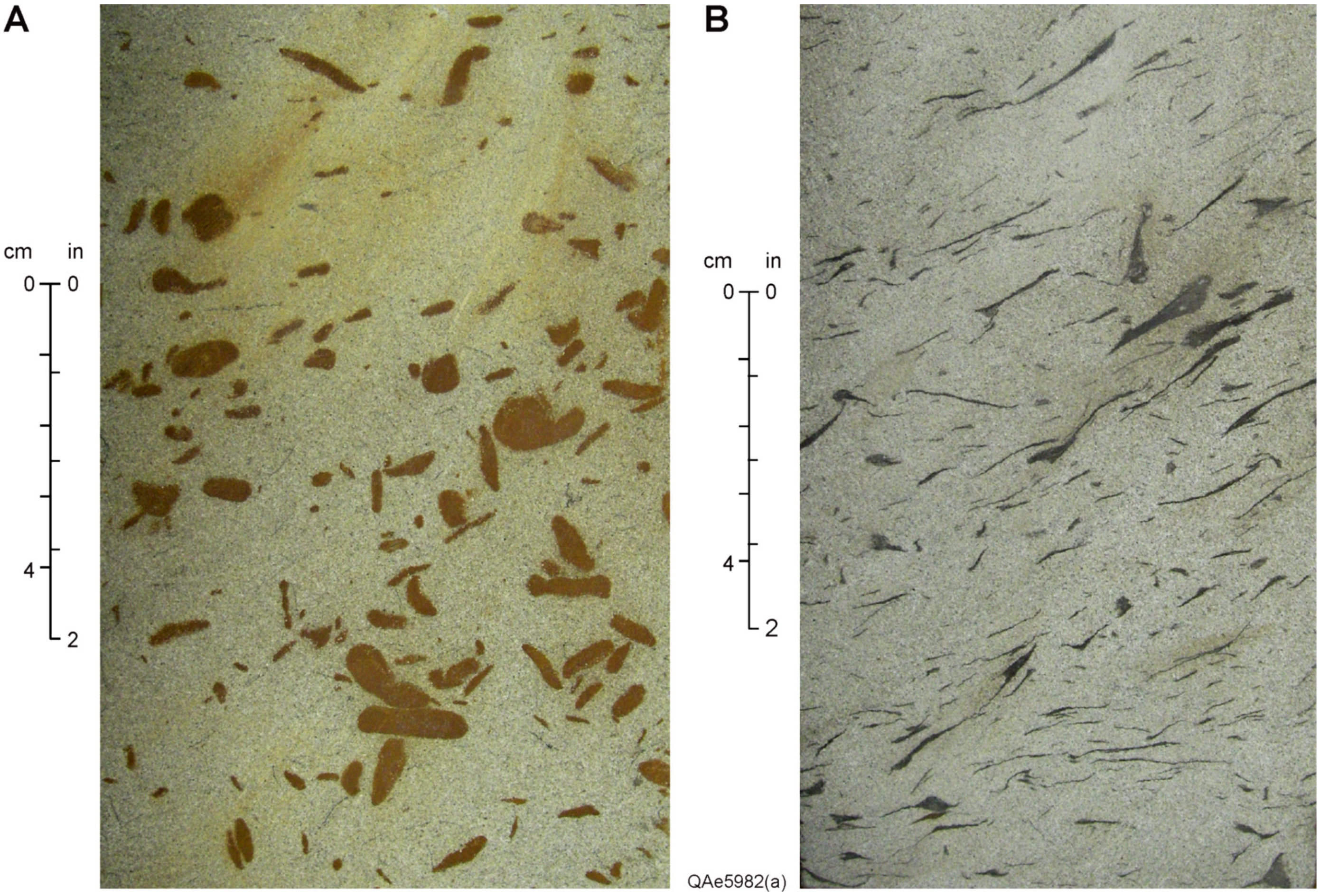


Figure 5. Photographs of channel-fill facies in the Howell No. 4 Golsch core. (A) Fine-grained sandstone with sideritic mud rip-up clasts with various orientations at 10,082.0 ft (3073.8 m). (B) Fine- to medium-grained sandstone with many aligned mud rip-up clasts at 10,069.3 ft (3069.9 m). Well location is shown in Figure 3. Core description is shown in Figure 4.

Interpretation

Massively stratified, fine- to medium-grained sandstone beds in the Howell No. 4 Golsch core represent high-density turbidity flows in a slope-channel setting. The aggregate succession in this core is composed of numerous, incomplete turbidity flows that collectively impart an overall blocky wireline-log response (Fig. 4). These turbidity flows were erosive and concentrated, based on their coarse-grained nature and the presence of numerous scour surfaces and zones with mud rip-up clasts (Figs. 4, 5, and 6B). Coarse-grained sandstones and conglomerates are common forms of basal lags in turbidite-channel systems (Mayall et al., 2006). Mud rip-up clasts are also common, which can form a permeability barrier or baffle at the base of the channel, if sufficiently thick or concentrated. The varying orientations of mud rip-up clasts in Figure 5A could also suggest re-sedimentation of channel-floor deposits by debris flows, features that are commonly observed in deepwater channel deposits (Clark and Pickering, 1996; Posamentier and Kolla, 2003; Kolla et al., 2001; Eschard et al., 2003).

Reservoir Quality

Reservoir quality (porosity and permeability), derived from the full data set of 71 samples from five cores in this study, is greatest in channel-fill facies (Fig. 7). Porosity ranges from approximately 8 to 24% and permeability from 0.03 to slightly over 100 md. Porosity values in the Howell No. 4 Golsch core range from 14.4 to 23.4%, with most values >20% (Fig. 4). Many porosity values in the lower part of the channel-fill succession (10,062.0 ft [3067.7 m] and below) are lower than those above (Fig. 4). This upward shift in porosity values coincides with a slight increase in overall grain size in sandstone beds to the top of the cored section (fine grained to fine to medium grained), although minor beds of very fine- to fine-grained sandstone occur in this upper section above 10,062.0 ft (3067.7 m).

Most values of permeability in the Howell No. 4 Golsch core are between 10 and 100 md (Fig. 4). Greatest values of permeability (~128 md) occur at two depths in the upper part of the core. As with values of porosity, a shift in increased values of permeability occurs at 10,062 ft (3067.7 m), where values of <10 md are overlain by values that are mostly >10 md, although permeability values >10 md also occur in the lower part of the core (Fig. 4).

Levee and Interchannel

Description

In contrast to channel-fill facies (Fig. 4), levee deposits in the Lavaca Canyon Complex are finer grained and relatively heterogeneous. They are composed commonly of heterolithic successions of very fine- to fine-grained sandstones, interbedded with siltstone and mudstone (Fig. 8). Individual sandstone beds in levee facies range in thickness from 0.5 to 2 ft (0.15 to 0.6 m). Stratification consists of thin (commonly ≤0.1 in [≤3 mm]) laminae of very fine-grained sandstone and mudstone (Fig. 9A) and

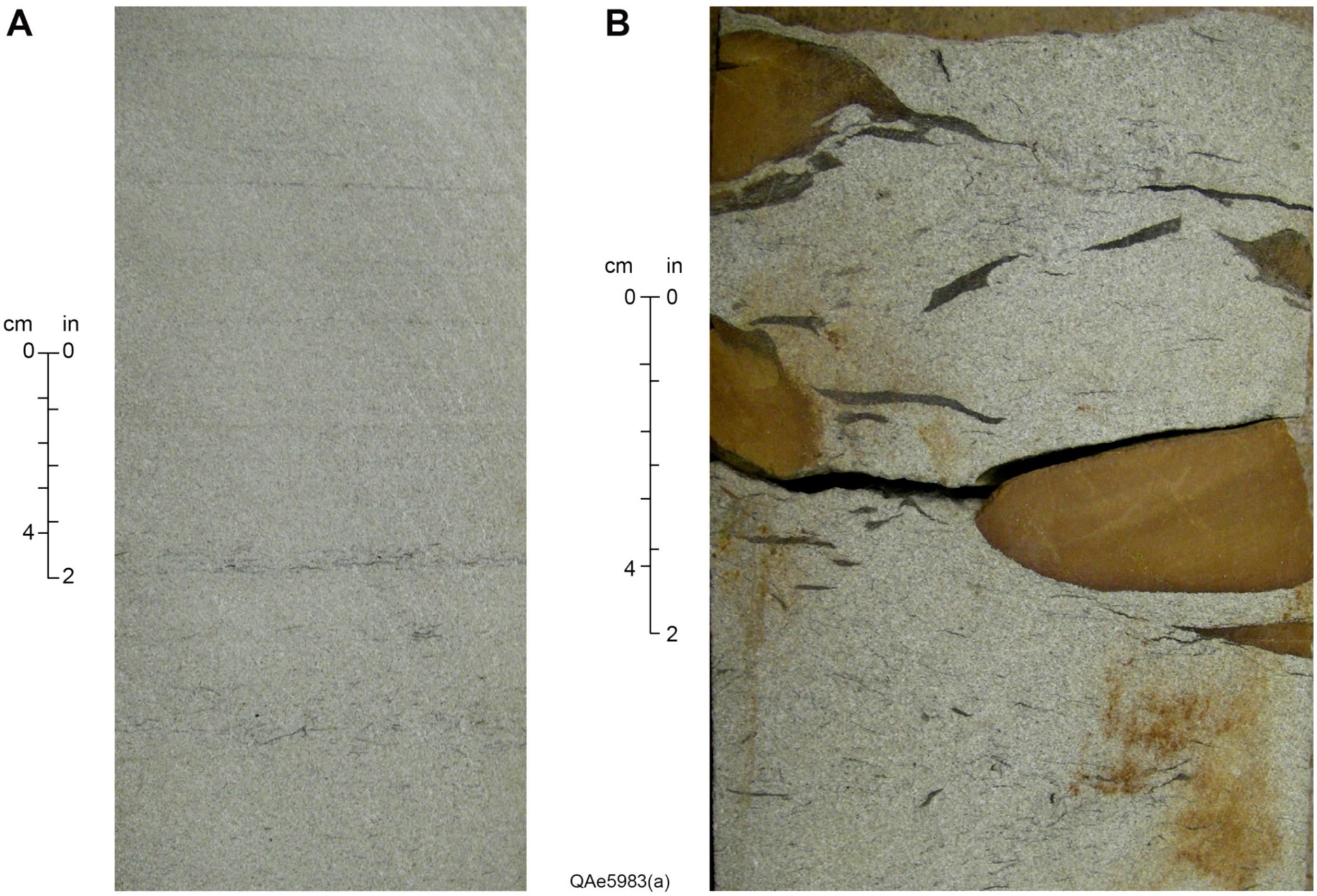


Figure 6. Photographs of channel-fill facies in the Howell No. 4 Golsch core. (A) Fine- to medium-grained, planar-stratified sandstone at 10,059.0 ft (3066.8 m). (B) Fine-to-medium-grained sandstone with large, sideritic mud rip-up clasts at 10,044.6 ft (3062.4 m). Well location is shown in Figure 3. Core description is shown in Figure 4.

ripples, both in the form of climbing ripples with prominent load structures (Fig. 9B) and isolated, mud-draped varieties (lower part of Figure 10A). Less-common sandstone beds are upper fine grained and underlain by scour surfaces, and contain mud rip-up clasts at the base (Fig. 10B). Stratification in these coarser-grained beds is massive to weakly planar-stratified, overlain by deformed ripples.

Soft-sediment deformation, convolute bedding, and microfaults are also well-developed in these levee facies. Some microfaults are complex, arranged in cross-cutting geometries and exhibiting both normal and reverse displacements at the same stratigraphic level (Fig. 9A). Other microfaults occur at low angles and are associated with folded and contorted beds (Fig. 10A).

Interpretation

Levee facies record fine-grained deposition of low-density turbidity flows associated with channel-overbank deposits. Sandy, low-density turbidity flows and traction currents, recorded by ripple stratification, are interbedded with relatively thin muddy interbeds that represent periods of suspension sedimentation. Sedimentary processes in these levee deposits are of the type that include continuous, traction currents involving a layer of turbulent flow above an active layer of traction, alternating with periods of fallout from suspension (Stow et al., 1996; Bouma, 2000). Abundant climbing-ripple stratification is the result of traction currents having carried high volumes of sediment. Microfaults, dipping beds, and convolute bedding record sediment failure, slumping, extension, and compressive loading on dipping, upper surfaces of lenticular levee complexes that taper away from the channel-fill axis.

Proximal-channel (channelized-levee) deposits in the Howell No. 3 Allen core from 9679 to 9682 ft (2950.9 to 2,951.8 m) (Fig. 8) are relatively coarser-grained and indicated by erosion-based, weakly planar-stratified beds of upper fine-grained sandstone with basal mud rip-up clasts. They typically have a low net-to-gross ratio and are commonly dominated by muddy fill above a sandy base (Mayall et al., 2006).

An alternative interpretation for levee facies in the Howell No. 3 Allen core, given the proximal position of this well (approximately 10 mi [~16 km]) from the northern margin of the Hallettsville Embayment, is a series of high-density turbidites directly supplied from a delta-front system that prograded southeastward to the canyon edge. For example, the stacking pattern of sandstone beds in the Howell No. 3 Allen core is atypical of levee/overbank systems that are commonly composed of a succession of multiple, individually upward-fining and mudstone-draped sandstone beds (Hansen et al. 2015, their figure 15D). In addition, several sandstone beds in the Howell No. 3 Allen core contain abundant and complex microfaults, convolute bedding (Fig. 10A), and slumps, suggesting high-energy sedimentation on a steep, proximal-canyon floor. However, many of these features are also commonly observed on the dipping surfaces of levee complexes adjacent to associated feeder channels. Moreover, the preponderance of climbing-ripple, cross-laminated sandstone beds in the Howell No. Allen core (Figs. 8 and 9B) and the domi-

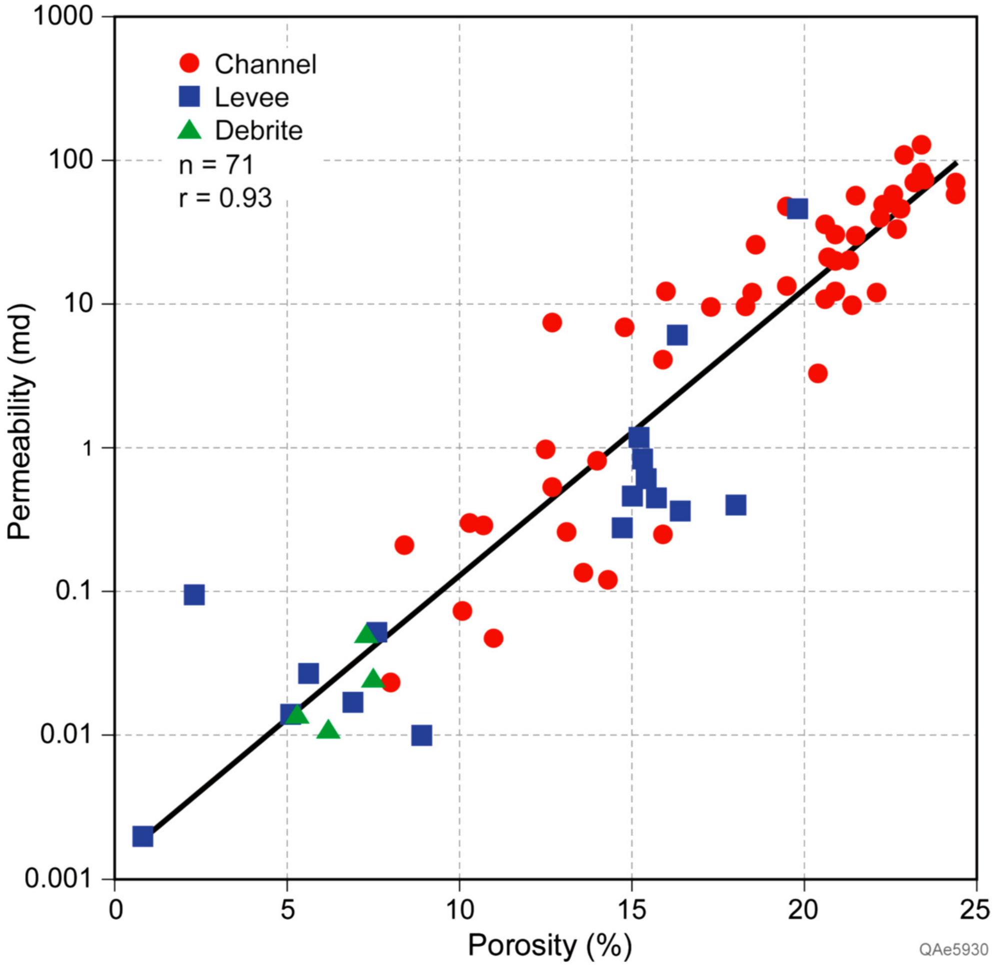


Figure 7. Reservoir quality (porosity and permeability) in channel, levee, and debrite facies in all five cores in this study. The equation relating porosity and permeability for Wilcox sandstones in Lavaca Canyon is as follows: log permeability = -2.88 + 0.20 x porosity, with an r value of 0.93. Locations of cored wells are shown in Figure 3.

nant grain size (fine grained) in these sandstones is also consistent with interchannel, overbank deposition in levee systems (Walker, 1985; Mutti and Normark, 1987).

Reservoir Quality

Overall reservoir quality in levee facies is intermediate, exceeding reservoir quality in debrite facies, but less than that for channel-fill facies (Fig. 7). Porosity values in levee facies in the Howell No. 3 Allen core range from 7.5 to 20%, with many values between 15 and 16%, particularly in the lower part of the Howell No. 3 Allen core. Permeabilities range from less than 0.1 to approximately 0.5 md, although two values in the core are greater than 10 md. They occur in fine- to medium-grained sandstone beds, the coarsest-grained sandstone beds (Fig. 8). The upper sandstone bed at 9681 ft (2951.5 m) has a permeability value >10 md also features the greatest porosity value of 20% in the cored section. Other than these two most-permeable sandstone beds, no apparent relationship exists between reservoir quality and grain size in this cored section.

Debrites and Slump Deposits

Description

The Speedwell No. 1 Pavliska core consists mostly of very fine to upper fine-grained sandstone beds interbedded with siltstone and mudstone (Fig. 11). Most of these sandstone beds range in thickness from 0.5 to 2 ft (0.15 to 0.6 m). An exception is a 10 ft (3 m) section of fine- to medium-grained sandstone beds with abundant mud rip-up clasts in the upper part of the cored section. Stratification in the thinner sandstone beds is extremely poorly developed, with abundant sediment mixing (swirled, shattered, and diffused bedding), folded beds, abrupt contacts between beds, and detached sediment layers (Fig. 12). Lithoclasts, the result of sediment mixing, are commonly irregular and subangular in shape (Fig. 12A). Other features include titled beds at various angles, ranging from moderately tilted (>30°) to nearly vertical (Figs. 13A and 13B, respectively). Microfaults, broken beds, and kinked beds are also common (Fig. 13B).

Interpretation

With the exception of the 10 ft (3 m) section of fine- to medium-grained sandstone beds with mud rip-up clasts from 9947.5 to 9957.5 ft (3032.8 to 3035.8 m) that may be part of a minor channel-fill succession, the Speedwell No. 1 Pavliska core is composed of debrite (debris-flow) deposits (Fig. 11). Extreme convolute bedding, sediment mixing, and greatly tilted beds in the Speedwell No. 1 Pavliska core record debris flows within mass-transport units. These debris flows range in character from liquid (Fig. 12) to semi-coherent to coherent, where original bedding is well preserved within steeply tilted blocks (Fig. 13). There is no overall, systematic vertical trend in grain size, nor overall stacking pattern of sandstone and mudstone beds in debrite facies in the Speedwell No. 1 Pavliska core. This is reflected in the serrate wireline-log response (Fig. 11).

Reservoir Quality

The few data points for debrite facies in the Speedwell No. 1 Pavliska core indicate poor reservoir quality relative to other

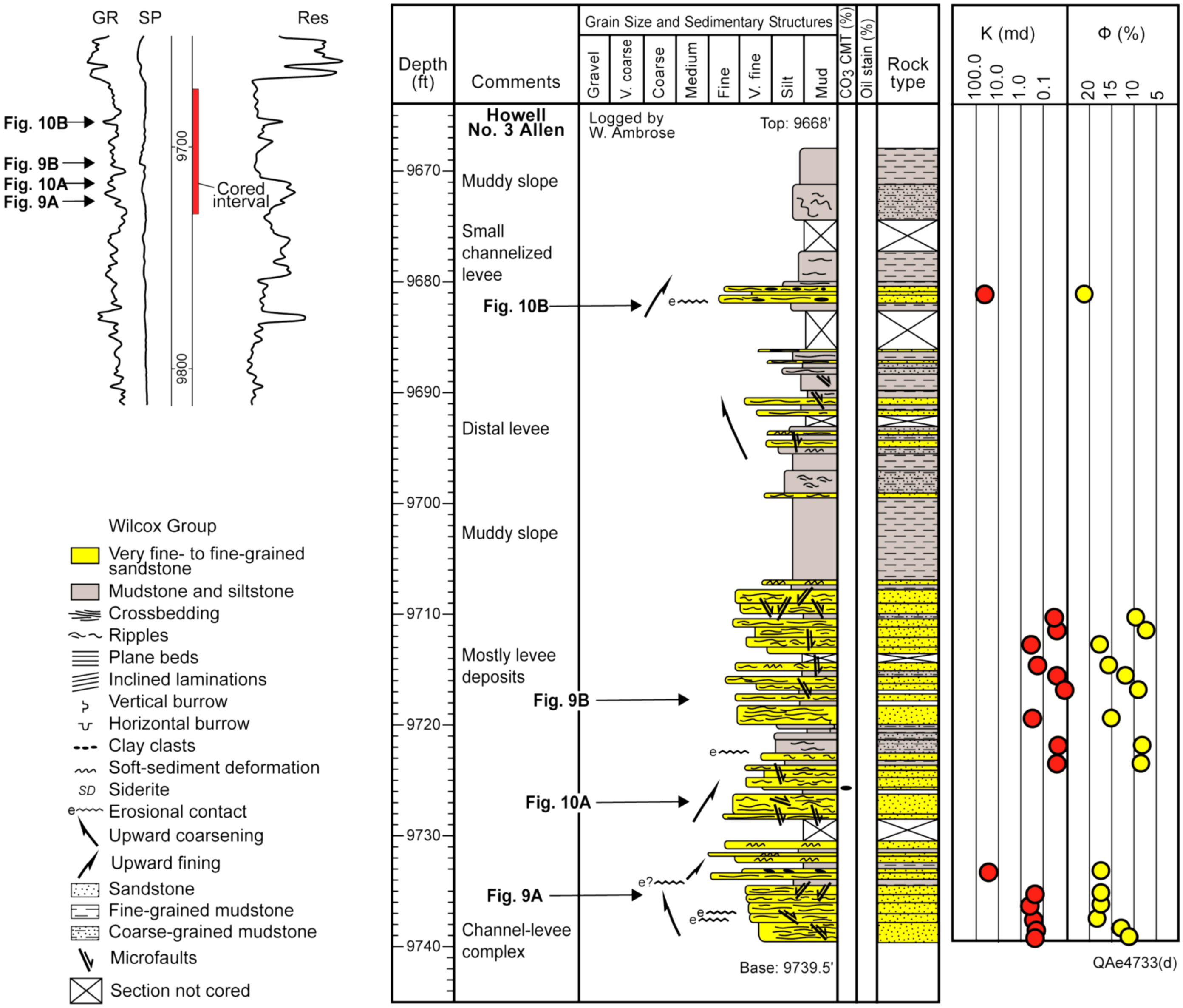


Figure 8. Core description of heterogeneous Lower Wilcox levee and muddy slope deposits in the Howell No. 3 Allen well from 9668 to 9739.5 ft (2947.6 to 2969.4 m). Well location is shown in Figure 3. Core photographs are shown in Figures 9 and 10.

canyon-fill facies, with porosity values ranging from 5.3 to 7.5% (Figs. 7 and 11). All permeability values are less than 0.1 md. This is contrasted against the 10 ft (3 m) section of channel-fill facies in the Speedwell No. 1 Pavliska core that contain more than 10% porosity and more than 0.1 md values (Fig. 11).

SANDSTONE COMPOSITION AND DIAGENESIS

Previous petrographic studies of Wilcox sandstones in onshore Texas have mainly investigated sandstones that were deposited in delta systems (Loucks et al., 1984, 1986; Fisher and Land, 1986; Dutton and Loucks, 2010). Wilcox sandstones in the Lavaca Canyon Complex have undergone a very different depositional history, having been deposited by turbidity currents and debris flows in channel and levee environments. Differences in depositional processes can have important impacts on many of the parameters that control sandstone reservoir quality, including detrital-mineral composition, grain size, sorting, and clay-matrix-, silt-, and ductile-grain content. Study of reservoir quality in these Lavaca Canyon sandstones is applicable to predicting reservoir-quality variation in turbidite and debrite Wilcox sandstones in the western Gulf of Mexico.

The objective of the petrographic study was to determine the influence of detrital mineral composition, texture, and diagenesis on reservoir quality in Lower Wilcox reservoirs in the Lavaca Canyon Complex. The three main deepwater facies—channel, levee, and mass-transport debris-flow deposits—were sampled, but sandstones from channel deposits were sampled preferentially because they have the best reservoir quality.

Texture

Lavaca Canyon samples studied in thin section have a wide range of mean grain sizes, from coarse silt to lower medium-grained sandstone; average grain size measured in thin section is lower fine-grained sandstone (2.85 phi [0.138 mm]). The coarsest sandstones of slope origin occur in channel deposits (average grain size = 2.58 phi [0.167 mm]) (Table 1, Fig. 14). Finer-grained sandstones occur in the levee facies (average grain size = 3.58 phi [0.090 mm]) and in the debrite deposits (average grain

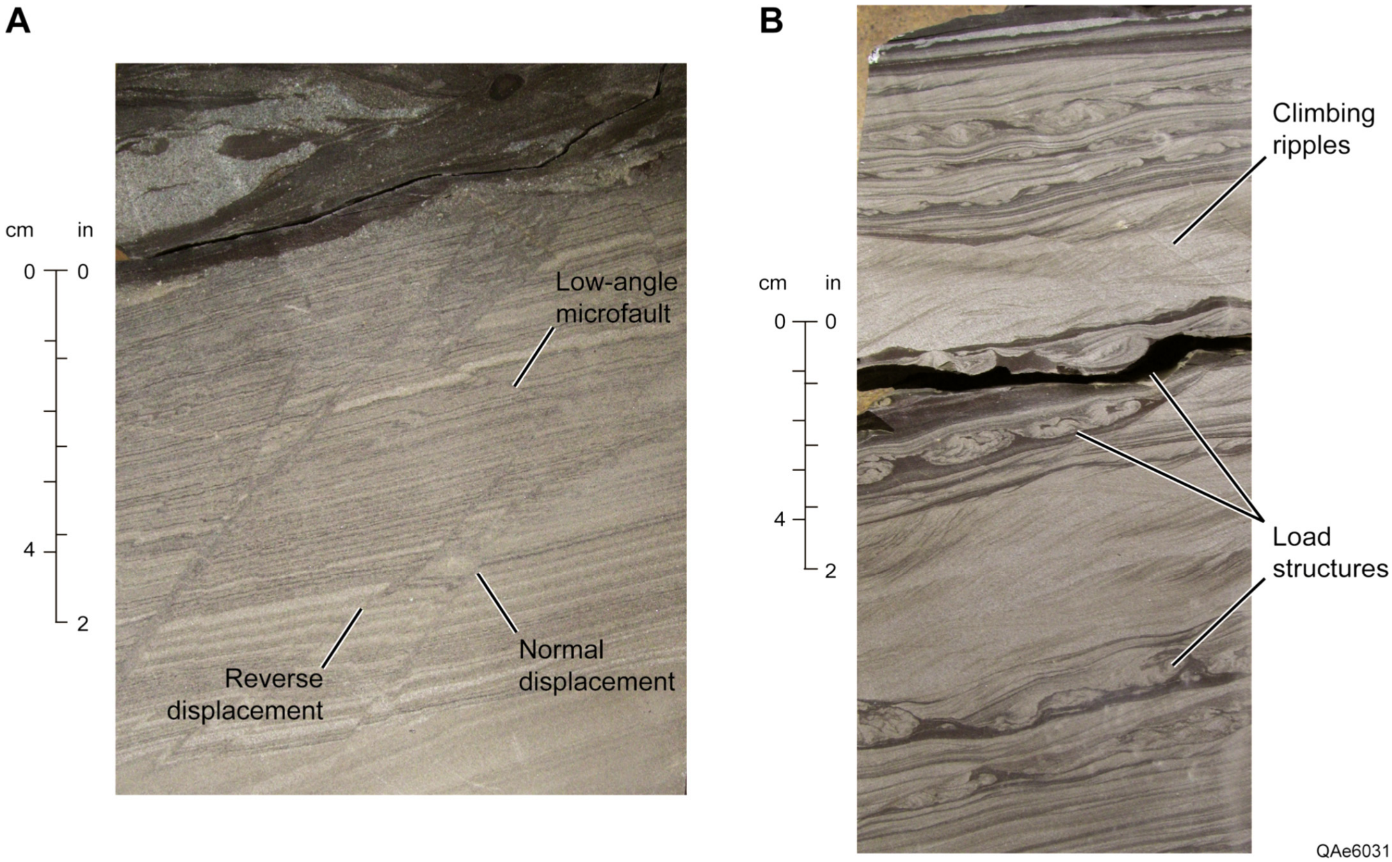


Figure 9. Photographs of levee facies in the Howell No. 3 Allen core. (A) Very fine-grained sandstone with microfaulted, mm-scale laminae at 9735.0 ft (2968.0 m). (B) Very fine- to fine-grained sandstone with climbing ripples and abundant load structures in levee facies at 9718.0 ft (2962.8 m). Well location is shown in Figure 3. Core description is shown in Figure 8.

size = 3.11 phi [0.116 mm]) (Fig. 14). The thin-section samples are well sorted to moderately well sorted, as defined by Folk [1974]), having an average sorting of 0.58 phi standard deviation. Channel and levee deposits have better sorting (average = 0.57 phi) than the debrite deposits (0.72 phi) (Table 1).

The percentage of silt grains in offshore Wilcox sandstones in the Gulf of Mexico is an important control on reservoir quality (Marchand et al., 2015). The percent of silt grains in Lavaca Canyon sandstones reported in Table 1 is the percentage of silt-sized quartz grains that were measured in the grain-size point counts. Channel sandstones have low silt content (average = 4%), whereas the levee and debrite deposits contain an average of 34% and 17% silt-size grains, respectively (Table 1). The percentage of silt grains in channel sandstones (4%) is considerably lower than it is in channel sandstones in the offshore Gulf of Mexico described by Marchand et al. (2015), where the average silt content is 24%.

Framework Grain Composition

Wilcox sandstones in the Lavaca Canyon Complex are mainly feldspathic litharenites, lithic arkoses, and sublitharenites (sandstone classification of Folk [1974]). Average composition is 71.5% quartz, 12.6% feldspar, and 15.8% rock fragments ($Q_{71.5}F_{12.6}R_{15.8}$). Plagioclase is the most abundant feldspar; very little orthoclase was observed. Some plagioclase grains are completely or partly dissolved or replaced by calcite or ankerite cement. A significant volume of the originally deposited plagioclase has been lost by dissolution, generating secondary porosity. It is likely that potassium feldspar was also deposited in the canyon system, but it has been almost entirely dissolved or replaced by carbonate cement during diagenesis. Lithic grains include volcanic, metamorphic, sedimentary, and plutonic rock fragments. Volcanic rock fragments (VRF) are the most common lithic grains, followed by sedimentary rock fragments (SRF), mainly chert, and metamorphic rock fragments (MRF). Mudstone rock fragments occur in most samples, and they are interpreted as being contemporaneous mud rip-up clasts.

Clay Matrix

Detrital clay matrix constitutes between 0 and 30% of the whole-rock volume in the sandstones sampled in this study. Clay matrix is most abundant in levee and debrite samples. The levee samples contain an average of 10.5% clay matrix, and the debrite samples, 11.1%; in contrast, the channel samples contain an average of only 0.6% clay matrix (Table 1).

Cements and Diagenetic History

Cements and replacement minerals constitute an average of 12.0% of the sandstone volume in Lavaca Canyon thin-section samples. The volume ranges from 1.3% to 24.3%. Carbonates are the most abundant authigenic minerals (average whole-rock volume of calcite, Fe–calcite, ankerite, and siderite = 5.1%), followed by quartz (4.5%), chlorite (2.1%), and kaolinite (0.9%). On the basis of petrographic evidence, the relative order of occurrence of the major events in the diagenetic history was found to be: (1) precipitation of siderite, mainly within detrital clay matrix and mud rip-up clasts (Figs. 5A and 6B), (2) mechanical compaction by grain rearrangement and deformation of ductile grains, (3) precipitation of chlorite cement, (4) precipitation of

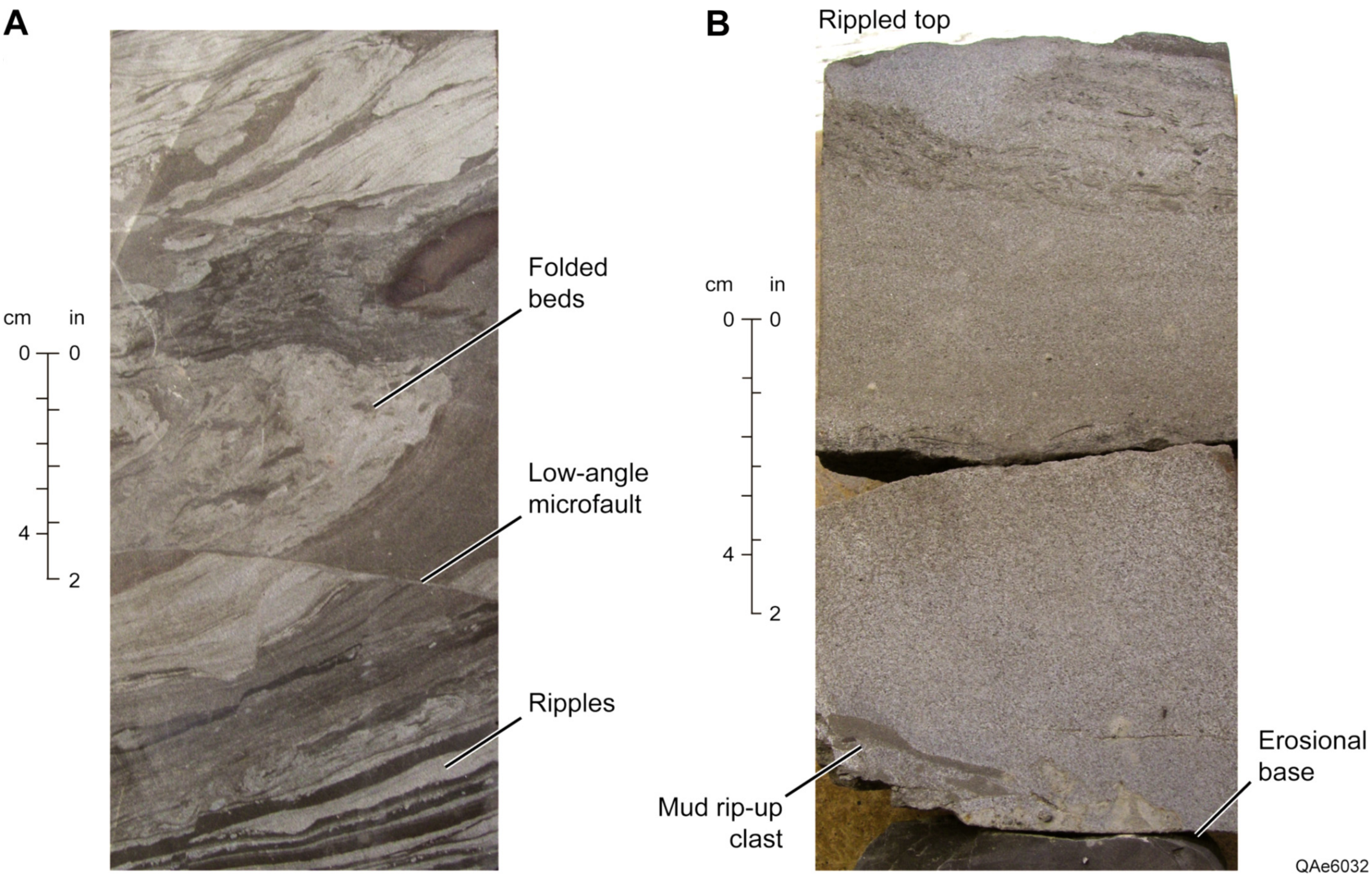


Figure 10. Photographs of levee and channelized-levee facies in the Howell No. 3 Allen core. (A) Faulted and folded beds of very fine- and fine-grained sandstone interbedded with silty mudstone at 9726.0 ft (2965.2 m). (B) Upper-fine-grained sandstone with erosional base and ripple-stratified upper surface in channelized-levee facies at 9682.0 ft (2951.8 m). Well location is shown in Figure 3. Core description is shown in Figure 8.

quartz overgrowths, (5) precipitation of calcite and Fe–calcite cement and grain replacement, (6) dissolution of potassium feldspar (K–spar) and albitization of plagioclase, and (7) precipitation of ankerite cement and grain replacement. This sequence is similar to what has been interpreted in previous studies of Wilcox diagenesis (for example, Loucks et al., 1981, 1984, 1986; Fisher and Land, 1986; Land and Fisher, 1987; Dutton and Loucks, 2010).

Porosity

Total thin-section porosity (primary + secondary porosity) quantified by point counts averages 11.1% and ranges from 0 to 23.7%. Average primary porosity is 5.9% and ranges from 0 to 15%. Average secondary porosity is 5.2% and ranges from 0 to 10.3%.

Porosity measured by porosimeter represents total porosity, the sum of primary and secondary pores and micropores. Average core-analysis porosity in samples with accompanying thin sections is 16.1% and ranges from 0.8% to 24.4%. Micropores, defined as pores having pore-aperture radii <0.5 µm (Pittman, 1979), cannot be accurately quantified by routine thin-section point counts but can be estimated as the difference between porosimeter porosity and thin-section porosity. Average microporosity in these samples is 5.1%. Most micropores occur within detrital clay matrix, altered detrital grains such as feldspars and VRFs, and in areas containing chlorite cement. Abundant chlorite in primary and secondary pores in some channel sandstones increases the volume of microporosity and decreases permeability (Fig. 15). Some sand grains have continuous chlorite coats on detrital grains that inhibited the precipitation of quartz cement. However, much of the chlorite cement occurs in small, isolated clumps that are not continuous around detrital grains (Fig. 15A) and thus do not prevent quartz cementation. Some primary and secondary pores in sandstones are largely filled by authigenic chlorite (Fig. 15B).

Porosity varies with depositional environment in the Lavaca Canyon Complex as a result of both original depositional environment and diagenesis. Average total (core-analysis) porosity is highest in channel sandstones (18.4%) and lower in levee (11.7%) and debrite sandstones (6.6%) (Table 2).

Estimates of porosity loss by compaction and cementation indicate that these sandstones lost an average of 27.8 porosity units by compaction (COPL) and 5.3 porosity units by cementation (CEPL) (calculated using method of Ehrenberg [1989]). Loss of porosity by compaction is similar in the channel, levee, and debrite facies (Table 2). Channel sandstones have lost more porosity by cementation than either levee or debrite sandstones (Table 2) because these high-energy sandstones retained more intergranular porosity where cement could precipitate.

Permeability

Geometric mean permeability of all Lavaca Canyon sandstones is 2.3 md and permeability ranges from 0.001 to 129 md. Permeability varies with depositional environment. In sandstone samples with both core-analysis and thin-section data, geometric mean permeability is highest in channel deposits (6.9 md)

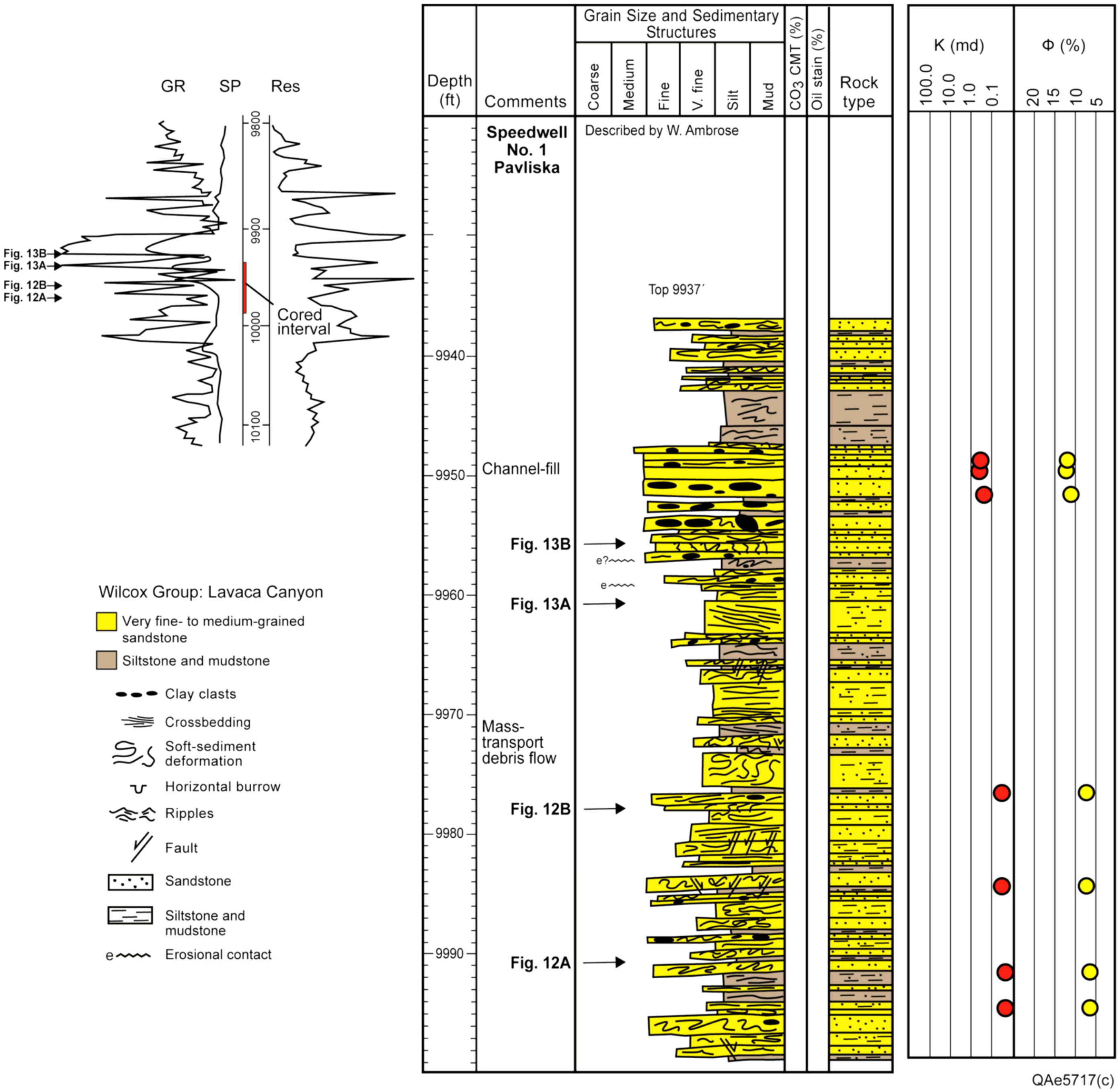


Figure 11. Core description of Lower Wilcox debris-flow (debrite) and minor channel-fill deposits in the Speedwell No. 1 Pavliska well from 9937 to 9999 ft (3029.6 to 3048.5 m). Well location is shown in Figure 3. Core photographs are shown in Figures 12 and 13.

and lowest in levee (0.2 md) and debrite (0.02 md) sandstones (Table 2).

CONTROLS ON RESERVOIR QUALITY IN LAVACA CANYON SANDSTONES

Depositional Controls on Reservoir Quality

Textural parameters related to the energy of the depositional environment exert the most important controls on reservoir quality in sandstones in the Lavaca Canyon Complex. Statistically significant correlations exist between permeability and the following depositional parameters: clay-matrix content ($r = -0.59$), grain size ($r = 0.55$), percent silt grains ($r = -0.46$), and volume of ductile grains ($r = -0.44$), where r is the correlation coefficient. The high-energy channel deposits have coarser grain size and lower volumes of clay matrix, silt grains, and ductile grains than do the lower-energy levee and debrite deposits (Table 1).

These observations are consistent with the work of Marchand et al. (2015), who have shown that reservoir quality is controlled mostly by grain size, silt content, and ductile-grain content in a case study of Wilcox reservoirs in the offshore Gulf of Mexico. Similarly, a study of Wilcox sandstones in the Walker Ridge area (Lewis et al., 2007) also concluded that textural properties are first-order depositional controls on reservoir

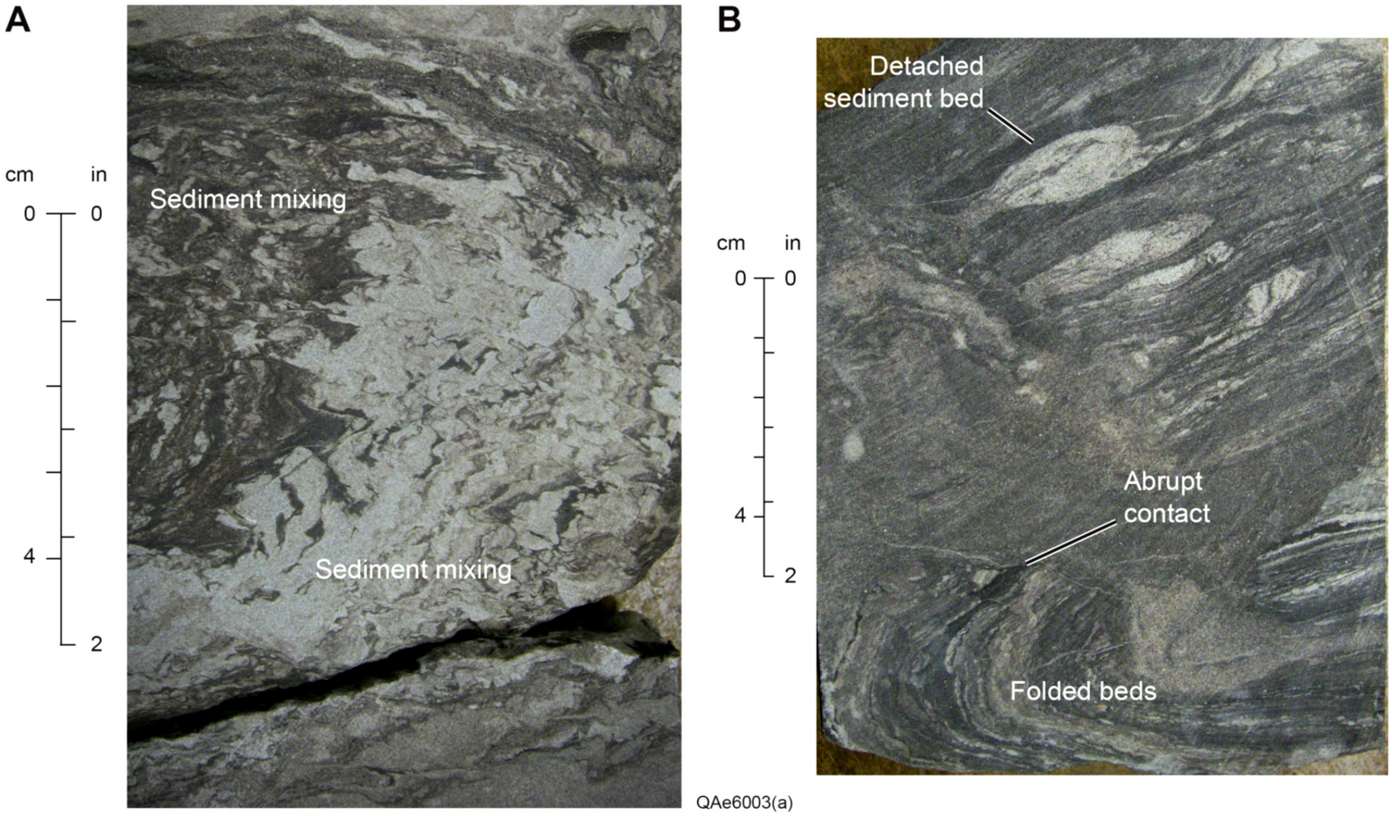


Figure 12. Photographs of debris-flow deposits (debrites) in the Speedwell No. 1 Pavliska core. (A) Sediment mixing with very fine- to fine-grained sandstone intricately interbedded and folded with silty mudstone at 9990.6 ft (3045.9 m). (B) Silty, very fine-grained sandstone and muddy siltstone beds with abrupt contacts, folded beds, and detached sediment beds at 9977.9 ft (3042.0 m). Well location is shown in Figure 3. Core description is shown in Figure 11.

quality. In Wilcox sandstones in both the Lavaca Canyon Complex and the offshore Gulf of Mexico (Marchand et al., 2015), the volume of ductile grains has a significant correlation with the percent of silt grains. The percentage of silt grains was determined in our study by measuring only quartz grains, so the ductile grains themselves are not silt size. Ductile grains are more abundant in samples with higher percentages of silt grains because of the shape and density of the ductile grains, not because of their size. The platy shape of ductile grains such as micas, mud rip-up clasts, VRFs, and MRFs caused them to be deposited with finer-grained quartz and feldspar grains in lower-energy depositional environments (Marchand et al., 2015). Lavaca Canyon sandstones that contain abundant ductile grains lost significant porosity by compaction (Fig. 16).

There is not a significant correlation between sorting and permeability in these samples, perhaps because only four of the samples selected for petrographic analysis have moderate sorting (phi standard deviation between 0.71 and 1.0 phi). These four samples all have permeability less than 0.1 md. The rest of the samples in the thin-section sample set are all well sorted (0.35 to 0.5 phi) or moderately well sorted (0.5 to 0.71 phi) but have a wide range of permeability values.

Depositional Facies with the Best Reservoir Quality

On average, reservoir quality in Lavaca Canyon sandstones is best in the channel-sandstone facies (Table 2), but there is a broad range of porosity and permeability values within the channel sandstones (Fig. 7). The channel facies with the best average reservoir quality are channel-fill sandstones with low-angle planar stratification (average porosity = 20.3% and geometric mean permeability = 21 md) and poorly stratified channel-fill sandstones (average porosity = 19.9% and geometric mean permeability = 17 md). Channel fill sandstones with clay clasts and rippled channel-fill sandstones have poorer average reservoir quality. Therefore, exploration for channel sandstones with the best reservoir quality should focus on channel deposits with low-angle planar stratification and poorly stratified channel sandstones.

Reservoir quality also varies widely in levee sandstones (Fig. 7). The best reservoir quality occurs in a levee sandstone with massive bedding (porosity = 19.8% and permeability = 47 md) and in laminated levee sandstones (average porosity = 16.4% and geometric mean permeability = 1.5 md). The levee sandstone with massive bedding is a small channelized levee in the Howell No. 3 Allen well (Fig. 8), at a depth of 9681 ft (2951 m).

Diagenetic Controls on Reservoir Quality

Authigenic cements and grain replacements occur in most of the Lavaca Canyon sandstones, but their effect on reservoir quality varies. Siderite is most abundant in levee and debrite sandstones, where it precipitated mainly within detrital clay matrix and mud rip-up clasts. Debrite sandstones and most levee deposits have poor reservoir quality mainly because of the depositional characteristics (Table 1), but siderite contributes to the low permeability.

The other cements in Lavaca Canyon sandstones—chlorite (Fig. 15), quartz (Fig. 17), calcite, and ankerite—are most abundant in channel sandstones, but nevertheless the channel sandstones retain the best reservoir quality (Table 2). Cements are abundant in the channel sandstones because they had the most intergranular pore space where cement could precipitate. Be-

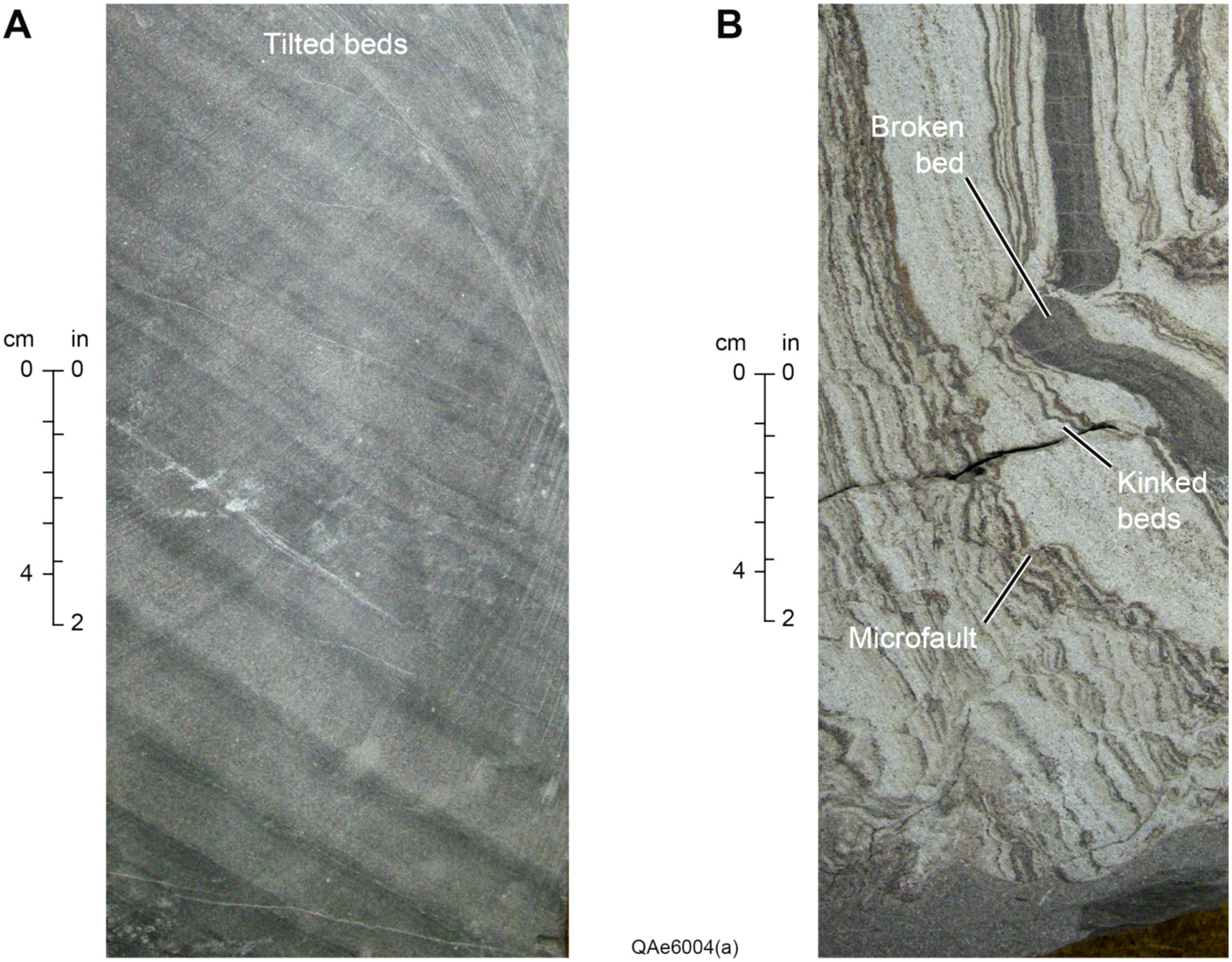


Figure 13. Photographs of rotated beds within debris-flow deposits (debrites) in the Speedwell No. 1 Pavliska core. Steeply dipping, graded beds of very fine-grained sandstone and muddy siltstone at 9961.0 ft (3036.9 m). (B) Subvertical beds of fine-grained sandstone and silty mudstone at 9955.7 ft (3035.3 m). Well location is shown in Figure 3. Core description is shown in Figure 11.

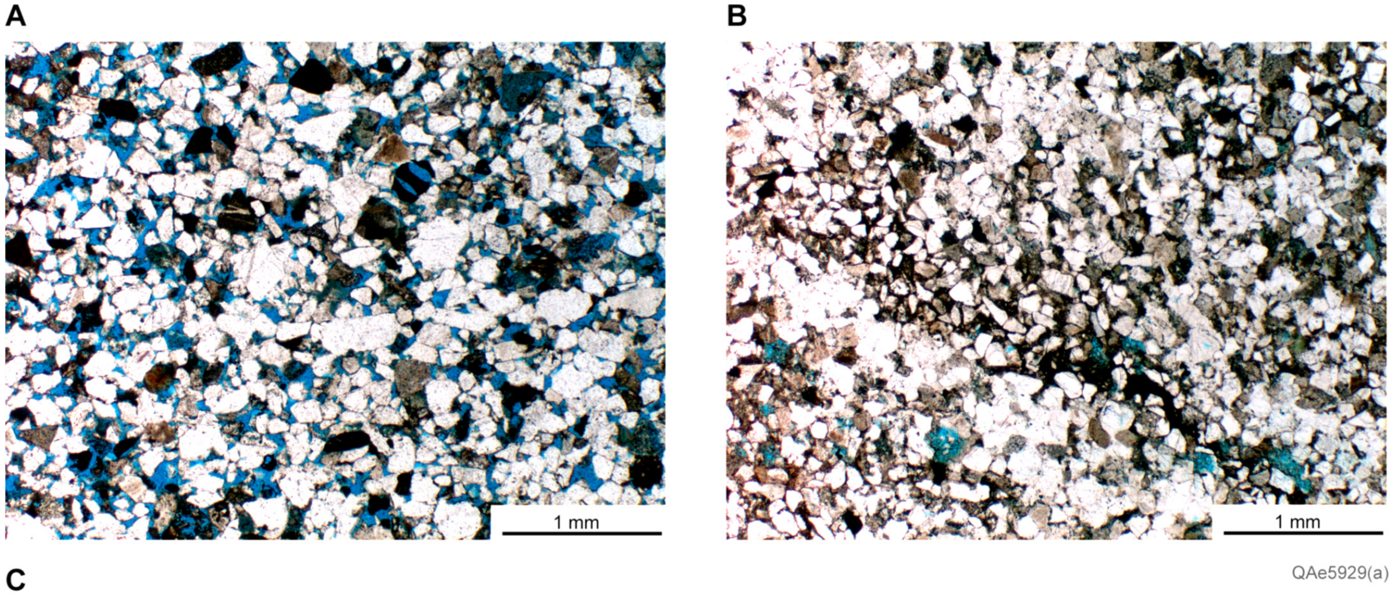
Table 1. Average textural properties of facies in Wilcox sandstones, Lavaca Canyon Complex, and number of samples.

Property	Channel (50)	Levee (17)	Debrite (4)
Grain size (phi)	2.58	3.58	3.11
Grain size (mm)	0.167	0.090	0.116
Sorting (phi)	0.57	0.57	0.72
Silt grains (%)	4	34	17
Clay Matrix (%)	0.6	10.5	11.1
Ductile grains (%)	11.6	18.7	15.5

cause the volume of authigenic cement is limited, most channel sandstones retain good reservoir quality.

The influence of diagenesis on reservoir quality is greatest in channel-fill sandstones. Channel sandstones have the best reservoir quality in Lavaca Canyon sandstones (Fig. 7), and both depositional and diagenetic parameters influence their permeability. Statistically significant correlations occur between permeability in channel sandstones and the following parameters: quartz-cement volume (r = -0.57) (Fig. 17), percent silt grains (r = -0.49), grain size (r = 0.39), and volume of authigenic carbonate (siderite, calcite, and ankerite) (r = -0.37).

The most important diagenetic control on permeability in channel sandstones is the volume of quartz cement (Fig. 18). Channel-fill sandstones that contain ≤6% quartz cement have an average porosity of 20.2% and geometric mean permeability of 16 md, whereas those with >6% quartz cement have an average



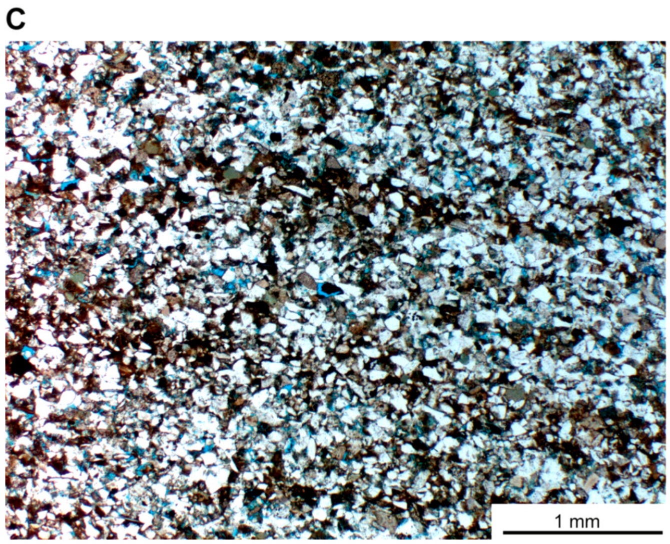


Figure 14. Wilcox sandstones in the Lavaca Canyon Complex were deposited in three main facies: channel, levee, and debrite. (A) Channel sandstone from the Howell No. 2 Allen well, Hallettsville Field, Lavaca County, Texas. Sample is from sandy channel-fill with clay clasts at a depth of 9736.5 ft (2967.7 m). Porosity = 23.5% and permeability = 74 md. (B) Levee sandstone from the Howell No. 3 Allen, Hallettsville Field, Lavaca County, Texas. Sample is from a rippled levee deposit at a depth of 9715.1 ft (2961.2 m). Porosity = 15.4% and permeability = 0.6 md. (C) Debrite sandstone from the Speedwell No. 1 Pavliska well, Campbell Creek Field, Lavaca County, Texas. Sample is from a depth of 9977.1 ft (3041.0 m). Porosity = 7.3% and permeability = 0.05 md.

porosity of 13.6% and geometric mean permeability of 0.8 md. It is difficult to predict where the most abundant quartz cement occurs in Lavaca Canyon channel sandstones. There is no significant relationship in channel sandstones from the Howell No. 4 Golsch well (Fig. 4) between the volume of quartz cement and the volume of clay matrix, ductile grains, detrital quartz grains, grain size, or sorting. However, abundant quartz cement (>6%) is observed to occur mainly in thinner sandstone beds and near the top or base of thicker sandstones adjacent to shale intervals.

DISCUSSION

Wilcox sandstones from the Lavaca Canyon Complex provide critical information about composition and diagenesis of Wilcox reservoirs in the western Gulf of Mexico and controls on reservoir quality in deepwater sandstones, but there are differences between these onshore Wilcox sandstones and those in the offshore Gulf of Mexico. Wilcox sandstones in both the Lavaca Canyon Complex and the offshore Gulf of Mexico were deposited by submarine gravity flows, but sandstones in the Lavaca Canyon Complex were deposited in a slope setting, whereas Wilcox sandstones in the offshore Gulf of Mexico were deposited on the basin floor. Lavaca Canyon sandstones were deposited in channel, levee, and debris-flow environments, but offshore Gulf of Mexico Wilcox sandstones were deposited in channel-fill, lobe, and lobe-margin environments (Marchand et al., 2015). Sandstone textural properties related to the energy of the depositional environment—particularly clay-matrix content, grain size, abundance of silt-sized particles, and volume of ductile grains—are the most important controls on reservoir quality in both settings. Average grain size in the Lavaca Canyon sandstones is lower fine-grained sandstone (2.85 phi [0.138 mm]), which is the same average grain size as the lower reservoir interval studied by Marchand et al. (2015). Lavaca Canyon sandstones are more quartz rich than are the offshore sandstones discussed in the Marchand et al. (2015) study. Quartz-cement volume is a significant control on permeability in Lavaca Canyon channel sandstones but not in the offshore Gulf of Mexico Wilcox sandstones (Marchand et al., 2015).

In Lavaca Canyon channel sandstones, two diagenetic parameters—the volume of quartz cement and the volume of total authigenic carbonate—have a statistically significant correlation with permeability. These sandstones contain an average of 7.0% cement, and quartz cement is volumetrically most abundant (average = 4.5%). Marchand et al. (2015) did not mention if diagenetic cements are significant controls on permeability in any of the offshore Gulf of Mexico facies in their study. These offshore Gulf of Mexico Wilcox sandstones contain an average of 5% whole-rock volume of authigenic cements, including quartz, clay minerals, and carbonates, but the volumes of each cement

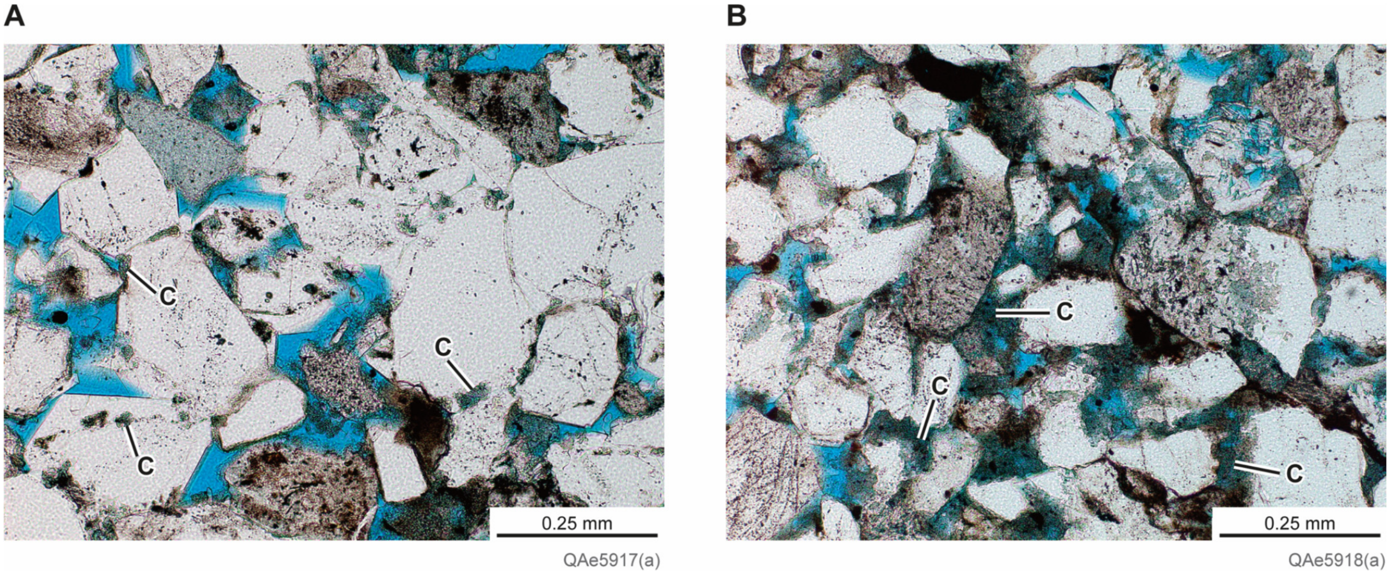


Figure 15. Chlorite cement in Wilcox channel sandstones from the Howell No. 4 Golsch well, East Hallettsville Field, Lavaca County, Texas. (A) Discontinuous clumps of chlorite cement (C) on quartz grains in a channel-fill sandstone with low-angle planar stratification from 10,020.9 ft (3054.4 m). Porosity = 16.0% and permeability = 12 md. Volume of chlorite = 6.7% and microporosity = 6.0%. Plane-polarized light. (B) Chlorite cement (C) fills intergranular and secondary pores in a poorly stratified channel sandstone from 10,063.4 ft (3067.3 m). Porosity = 20.4% and permeability = 3.3 md. Volume of chlorite = 3.7% and microporosity = 10.7%. Plane-polarized light.

Table 2. Average reservoir-quality properties of facies in Wilcox sandstones, Lavaca Canyon Complex, and number of samples.

Property	Channel (50)	Levee (17)	Debrite (4)
Core-analysis porosity (%)	18.4	11.7	6.6
Permeability (geometric mean) (md)	6.9	0.2	0.02
Primary porosity (%)	7.6	2.2	0.3
Secondary porosity (%)	6.3	2.8	1.4
Microporosity (%)	4.6	6.7	4.8
COPL[1]	27.9	27.5	28.5
CEPL[2]	6.2	3.1	3.0

[1]Compactional porosity loss (Ehrenberg, 1989)
[2]Cementational porosity loss (Ehrenberg, 1989)

are not differentiated (Marchand et al., 2015). Wilcox sandstones in the Walker Ridge area also contain minor to moderate amounts of quartz cement, as well as chlorite and carbonate minerals (Lewis et al., 2007).

Wilcox sandstones in the offshore Gulf of Mexico have experienced different burial and thermal histories than have onshore Lavaca Canyon Wilcox sandstones, which may explain their different levels of diagenetic alteration. Geothermal gradient is lower in the offshore Gulf of Mexico than it is onshore (Blackwell and Richards, 2004). In the offshore Gulf of Mexico Tiber well (BP No. 1 OCS–G–25782, Keathley Canyon Block 102), the top of the Wilcox Group is at a depth of about 28,050 ft (8550 m) below the sediment-water interface, with an additional 4200 ft (1280 m) of water above. The sediment above the Wilcox interval in the Tiber well includes about 16,500 ft (5030 m) of salt. Salt transmits heat very effectively and significantly reduces the temperature in subsalt plays (Mello et al., 1995). If the salt is thick enough and stays in place for long enough, the thermal maturity of the underlying reservoir target is less than it would be otherwise (Mello et al., 1995; Taylor et al., 2010). Burial-history models done for this study indicate that the calculated vitrinite reflectance equivalent (R_{oe}) in the lower part of the Wilcox interval in the Tiber well at 30,643 ft (9340 m) is about 0.69%. Wilcox sandstone in the offshore Gulf of Mexico Shell No. 2 BAHA well (OCS–G–08272) in Alaminos Canyon Block 557 has even lower thermal maturity than in the Tiber well. Lower Wilcox sandstone at a depth of 14,541 ft (4432 m) in the No. 2 BAHA well has a calculated R_{oe} of 0.48%, and the Boomer Sand at 15,168 ft (4623 m) has a calculated R_{oe} of 0.52%. For comparison, the R_{oe} in the lower part of the Wilcox interval in the onshore Pure No. 1 Vogelsang well in Colorado County, Texas, at a burial depth of 9900 ft (3018 m) is higher, about 0.85%.

On the basis of calculated thermal maturity (R_{oe}) values, we conclude that offshore Wilcox reservoirs in the offshore Gulf of Mexico are likely to have undergone less quartz cementation than have Wilcox sandstones in the Lavaca Canyon Complex. We have observed that at the relatively moderate temperatures and thermal maturity values of Lavaca Canyon Wilcox sandstones, reservoir quality is controlled more by original depositional processes than by diagenesis. Therefore, in the offshore areas of the Gulf of Mexico such as Alaminos Canyon and Keathley Canyon,

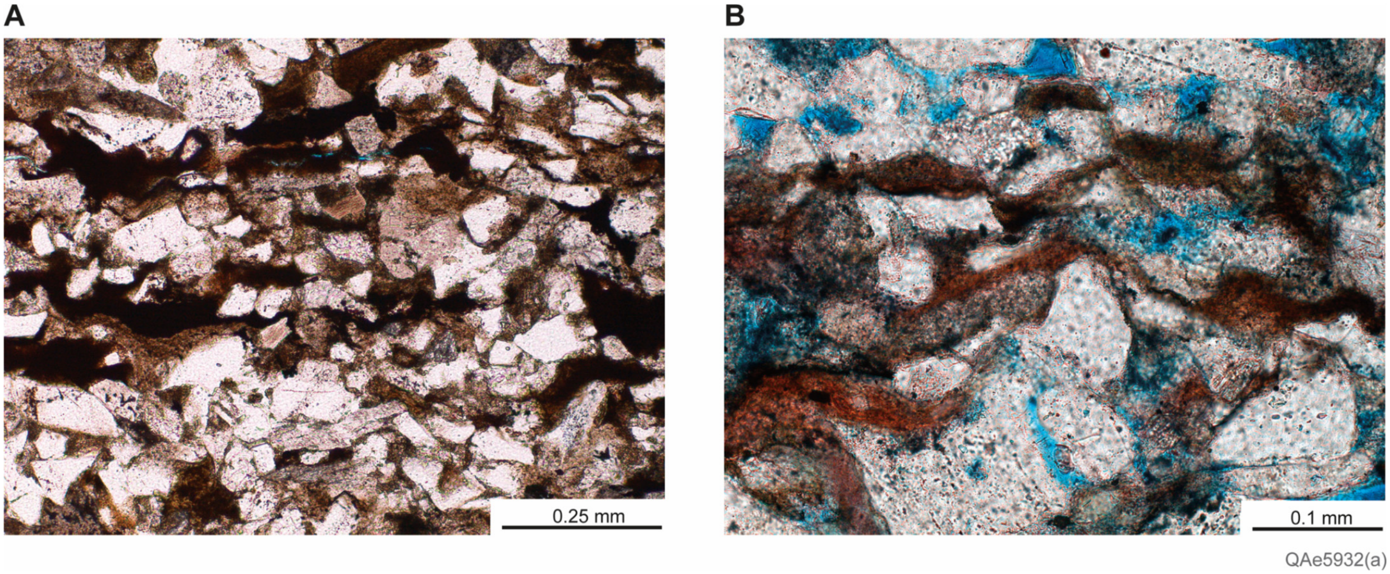


Figure 16. Ductile-grain compaction contributes to porosity loss in Lavaca Canyon sandstones from all facies. (A) Levee sandstone with convolute bedding from the Speedwell No. 1 Pavliska well, Campbell Creek Field, Lavaca County, Texas. Sample is from a depth of 9535.5 ft (2906.4 m). Porosity = 0.8% and permeability = 0.002 md. (B) Channel sandstone with planar stratification from the Howell No. 4 Golsch well, East Hallettsville Field, Lavaca County, Texas. Sample is from a depth of 10,061.5 ft (3066.7 m). Porosity = 14.8% and permeability = 6.9 md.

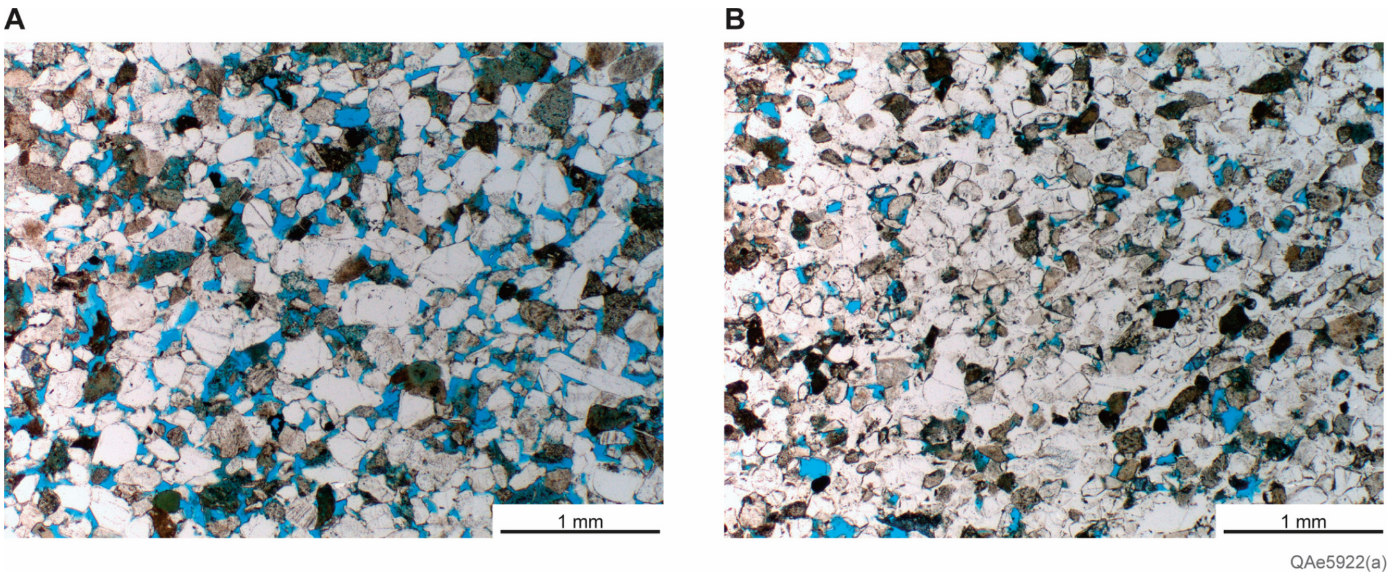


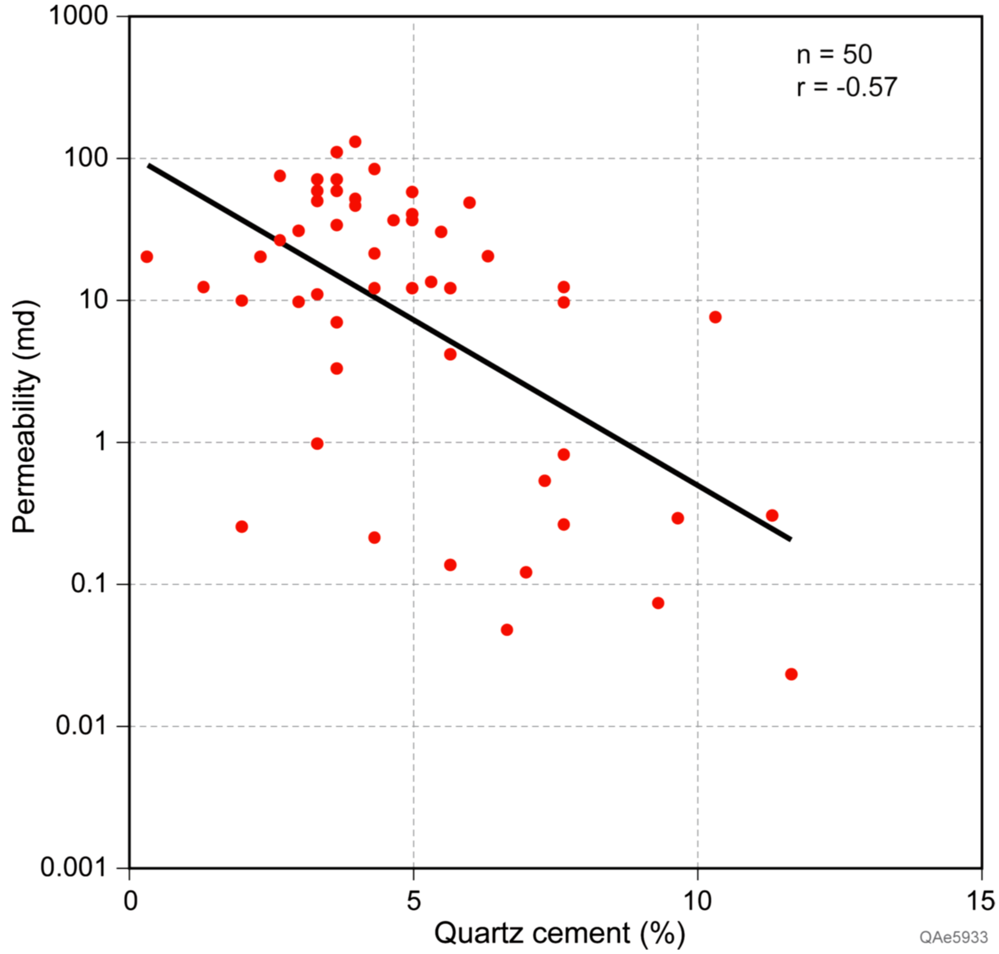
Figure 17. Quartz cement in Wilcox channel sandstones from the Howell No. 4 Golsch well, East Hallettsville Field, Lavaca County, Texas. (A) Poorly stratified sandstone from 10,043.5 ft (3061.3 m) with 3.7% quartz cement, 22.9% porosity, and 110 md permeability. (B) Channel sandstone with clay clasts from 9977.9 ft (3041.3 m) with 11.9% quartz cement, 8.0% porosity, and 0.023 md permeability.

where our burial-history modeling indicates that the thermal maturity of the Wilcox sandstones is even lower, we would expect that depositional processes are the dominant controls on reservoir quality. This is the same conclusion reached by Marchand et al. (2015) in their study of controls on reservoir quality in offshore Wilcox sandstones. Exploration along the axis of Wilcox fairways, focusing on facies having relatively coarser-grained, better sorted sandstone, with little detrital clay, silt, or detrital mud rip-up clasts, is the optimal strategy in targeting the best reservoir quality.

CONCLUSIONS

Study of Wilcox cores from the Lavaca Canyon Complex provides information about depositional and diagenetic controls on reservoir quality in Wilcox sandstones deposited in deepwater depositional environments. Cores available from five wells in the Lavaca Canyon Complex display a variety of deepwater facies, including turbidite-channel fill, levee/overbank, and debris-flow deposits. Our investigation of Wilcox sandstones in the Lavaca Canyon Complex provides insights into the relationship

Figure 18. Volume of quartz cement measured by thin-section point counts versus permeability in channel sandstones in the Lavaca Canyon Complex.



of composition, texture, and diagenesis to reservoir quality and is applicable to predicting reservoir quality in Wilcox sandstones in the onshore western Gulf of Mexico.

The most important controls on reservoir quality in Lavaca Canyon sandstones are factors related to depositional energy: detrital clay-matrix content, grain size, silt content, and ductile-grain content. Channel-fill sandstones have the best reservoir quality because they have the lowest volume of clay matrix, the coarsest average grain size, and the lowest average silt and ductile-grain content. Channel-fill sandstones contain an average of 0.6% clay matrix, whereas levee and debrite deposits contain significantly more (10.5% and 11.1%, respectively). Similarly, the percent of silt grains is lower in channel sandstones (4.2%) than in levee (33.9%) and debrite deposits (17.3%). Average grain size in channel samples is 2.58 phi (0.167 mm), compared with 3.58 phi (0.090 mm) in the levee samples and 3.11 phi (0.116 mm) in debrite samples.

The influence of diagenesis on reservoir quality is greatest in the channel sandstones in the Lavaca Canyon Complex. Permeability decreases with increasing volumes of quartz cement and total authigenic carbonate (siderite, calcite, and ankerite). Channel-fill sandstones with ≤6% quartz cement have an average porosity of 20.2% and geometric mean permeability of 16 md, whereas those with >6% quartz cement have an average porosity of 13.6% and geometric mean permeability of 0.8 md. It is difficult to predict where the most abundant quartz cement occurs, but quartz-cemented zones are observed mainly in thinner sandstone beds and near the top or base of thicker sandstones adjacent to shale intervals.

Burial history models indicate that thermal maturity in the onshore Lavaca Canyon Wilcox sandstones is somewhat higher than offshore Wilcox sandstones in the Gulf of Mexico. Therefore, although Lavaca Canyon should be a good analog for understanding depositional controls on reservoir quality in deep-water Gulf of Mexico channel and levee sandstones, diagenesis is probably a less important control in the Gulf of Mexico than in Lavaca Canyon.

ACKNOWLEDGMENTS

This research was funded by member companies of the Deep Reservoir Quality consortium at the Bureau of Economic Geology, University of Texas at Austin: Anadarko Petroleum Corporation, ExxonMobil Exploration Company, Hess Corporation, and Total E&P USA. We thank Stewart Chuber, Harvey Howell, and Pioneer Natural Resources for providing us thin sections, porosity and permeability analyses, and other data from Lavaca Canyon cores. Bill Galloway, who has done extensive work on the Lavaca Canyon Complex along with his students, provided very helpful insight and discussion about Lavaca Canyon sandstones. Ruarri Day-Stirrat generated the burial-history model for the Pure No. 1 Vogelsang well. The manuscript benefitted from the reviews of Stewart Chuber and Brad Prather. Francine Mastrangelo prepared the illustrations under the direction of Cathy Brown, Manager, Media Information Technology. Publication authorized by the Director, Bureau of Economic Geology.

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