GCAGS JOURNAL
A Publication of the
Gulf Coast Association of
Geological Societies
www.gcags.org

Factors Controlling Permeability Variation in Onshore, Deep Paleogene Wilcox Sandstones in the Northern Gulf of Mexico Basin: Targeting High-Quality Reservoirs

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ABSTRACT

Onshore Wilcox sandstones in the northern Gulf of Mexico Basin show a clear trend of decreasing average permeability with increasing temperature, but at any given temperature, permeability values commonly range over several orders of magnitude. Characteristics of Wilcox sandstones having permeability in the highest 10% of measured values within a given temperature interval were investigated to determine what parameters exert the greatest control on reservoir quality. The goal was to identify factors to consider in exploration for the best-quality reservoirs in Wilcox sandstones having the same provenance and burial/temperature history. The results provide insight into reservoir quality of deeply-buried Wilcox sandstones in the deepwater Gulf of Mexico.

Reservoir quality in Wilcox sandstones at temperatures ranging from 85–433°F (29–223°C) was investigated using core-analysis and thin-section data. Permeability data from samples located in Louisiana, the upper Texas coast, and the lower Texas coast were sorted by temperature and divided into 50°F (27.8°C) temperature intervals. The P10 value for each interval was calculated as the permeability value separating the highest 10% of the data from the lower 90%. Thin sections of samples having permeability values in the top 10% (P10 samples) were compared with lower-permeability samples from the same well and temperature interval.

Both depositional and diagenetic differences control permeability variation within a temperature interval. P10 sandstones have coarser grain size, better sorting, and lower volumes of detrital clay matrix, silt grains, and ductile grains, which are all parameters related to depositional processes of the sediments and hydraulic properties of the grains. Permeability is also a function of diagenetic differences in the volume of quartz, carbonate, illite, and chlorite cements. Depositional parameters can be addressed in an exploration strategy that focuses on sequence stratigraphic setting and depositional environment. Local variations in diagenesis are harder to predict; the presence of cements such as carbonate and chlorite must be assigned risk factors, because predicting their exact location and distribution is not currently possible.

INTRODUCTION

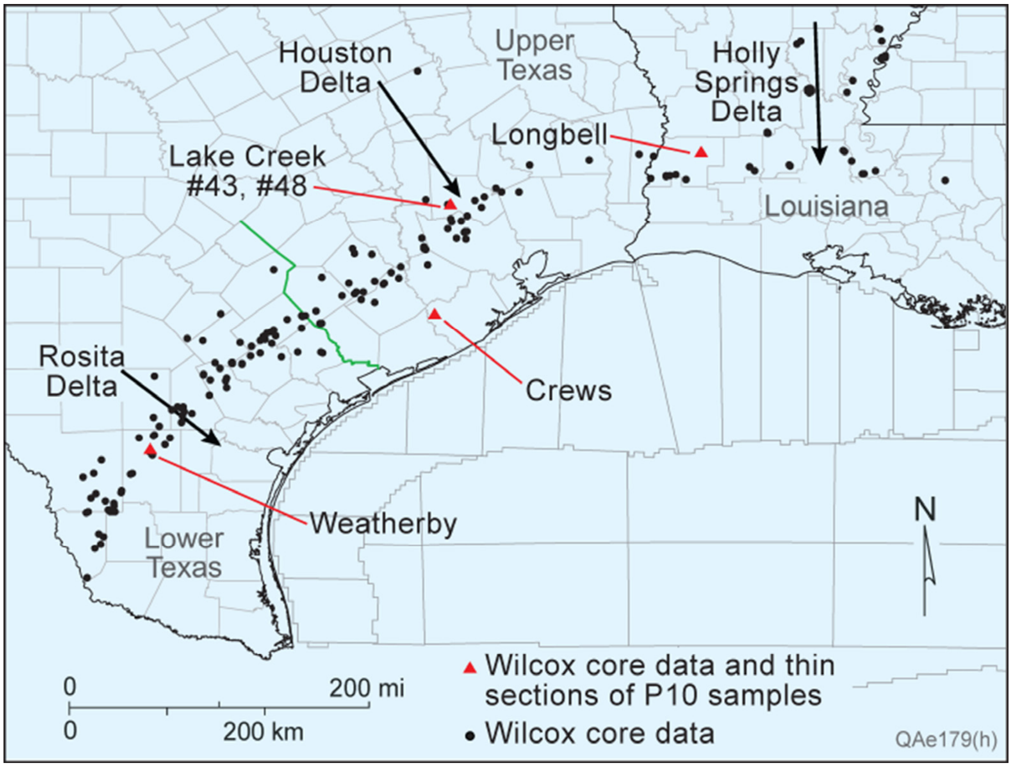
Wilcox Group sandstones in Texas and Louisiana along the northern Gulf of Mexico coast show a clear trend of decreasing average and maximum permeability with increasing temperature, but at any given temperature, permeability values commonly range over four or more orders of magnitude. A trend of decreasing permeability with increasing depth and temperature is generally observed in sandstones, and the diagenetic controls that cause loss of permeability with increasing temperature have been studied in many formations (e.g., Loucks et al., 1984, 1986; Paxton et al., 2002; Dutton and Loucks, 2010; Taylor et al., 2010). The objective of this study is to understand controls on large variations in permeability in Wilcox sandstones that are at the same temperature, have undergone the same burial history, and have the same provenance. The characteristics of Wilcox sandstones having permeabilities in the highest 10% of measured values within a given temperature interval were investigated to determine what parameters exert the greatest control on reservoir quality. The goal was to identify factors to consider in exploring for the best-quality reservoirs in Wilcox sandstones having the same provenance and burial/temperature history.

Wilcox sandstones investigated in this study were deposited in the Holly Springs Delta of Louisiana, the Houston Delta of the upper Texas coast, and the Rosita Delta of the lower Texas coast (Galloway et al., 2000, 2011; Dutton and Loucks, 2014) (Fig. 1). Samples are from onshore Texas and Louisiana (Fig. 1), at depths

Manuscript received March 18, 2015; revised manuscript received May 27, 2015; manuscript accepted May 28, 2015.

GCAGS Journal, v. 4 (2015), p. 1–14.

Figure 1. Distribution of wells with core-analysis data from onshore Wilcox sandstones. Wells with thin sections of P10 samples are labeled. Green line marks the boundary between the upper Texas and lower Texas study areas.



ranging from 560 to 21,953 ft (171 to 6691 m) and temperatures from 85–433°F (29–223°C). The data were divided into three study areas—Louisiana, upper Texas coast, and lower Texas coast (Fig. 1). The Wilcox sandstones in this investigation are from the onshore Gulf Coast, but the results can provide insight into controls on reservoir quality of deeply-buried Wilcox sandstones beneath the Gulf of Mexico shelf and in the deepwater Gulf.

GEOLOGIC SETTING

Wilcox sandstones were deposited during the Late Paleocene and Early Eocene, and they represent the first major Cenozoic clastic progradation into the Gulf of Mexico Basin (Fisher and McGowen, 1967; Galloway et al., 2000, 2011). Continental-scale fluvial drainage systems tapped diverse source areas in North America and delivered sediment of varying composition to Wilcox deltas that were deposited in what is now Texas and Louisiana. Farther downdip, the Wilcox Group contains gravity-flow sandstones deposited on the slope and in large, sand-rich, basin-floor fans in the Gulf of Mexico (Meyer et al., 2007; Lewis et al., 2007).

Lower and middle Wilcox sandstones were deposited during the Late Paleocene in two main fluvial-deltaic systems—the Houston Delta System along the upper Texas coast (Fisher and McGowen, 1967; Galloway et al., 2000) and the Holly Springs Delta System in Louisiana (Galloway, 1968; Galloway et al., 2000) (Fig. 1). The Houston and Holly Springs deltas were at their largest extent during the Late Paleocene, but they continued to supply sediment to upper Texas and Louisiana through Early Eocene time (Galloway et al., 2000). During the Early Eocene, upper Wilcox sediment was also deposited in the Rosita Delta System along the lower Texas coast (Edwards, 1981; Galloway et al., 2000, 2011). Most of the Wilcox samples used in this study were deposited in fluvial-deltaic depositional environments, but the farthest downdip samples, from the ARCO #1 Crews well in Brazoria County, Texas (Fig. 1), were deposited in a slope-fan complex (Dutton and Loucks, 2010; Ambrose et al., 2013).

The geothermal gradient increases southwestward along the Louisiana and Texas coast (DeFord et al., 1976; Blackwell and Richards, 2004). Because of this regional variation, parameters in the study were plotted against temperature and not depth. The geothermal gradient is higher onshore than offshore, so the temperature of onshore sandstones equals or exceeds that of offshore Wilcox reservoirs at similar depths.

DATA AND METHODS

Controls on permeability variation in Wilcox sandstones were investigated using core-analysis and thin-section data. Permeability data were available from 9871 Wilcox sandstone samples from 189 wells. Porosity and permeability were measured at unstressed conditions (800 psi) by routine core analysis of plugs cut from conventional cores. Permeability was measured to air; some of the data are Klinkenberg corrected.

Point counts were performed on a total of 534 Wilcox thin sections from 90 wells throughout the three study areas. Thin sections from Lake Creek Field in Montgomery County on the upper Texas coast (Fig. 1) were point counted by Jeffry Grigsby (Grigsby et al., 1992; Guevara and Grigsby, 1992). Samples with thin sections make up a small fraction of the total core-analysis samples because the majority of the core-analysis data come from wells for which we did not have access to cores. Wilcox sandstone composition was determined by standard thin-section petrography, and a total of 200 counts were made on each thin section. Counting error varies with the percentage of the constituent. A constituent that composes 50% of the sample has an error of ±3.6%, whereas a constituent that is 10% has an error of ±2.1% and one that is 2% of the sample has an error of ±0.9% (Folk, 1974). Point counts identified four major categories of rock volume: detrital framework grains, detrital clay matrix, authigenic minerals, and pores. Grain size and sorting were determined by point count measurements of the long axis of 100 quartz and feldspar (competent) grains per thin section.

Subsurface temperature of the Wilcox sandstone samples used in this study ranges from 85–438°F (29–226°C). Subsurface temperature was calculated for each thin-section and core-analysis sample by the following three-step procedure: (1) correct bottom-hole temperatures from geophysical logs from each well using the time-since-circulation correction (Waples et al., 2004; Corrigan, 2006), (2) calculate geothermal gradient for each well, and (3) use the geothermal gradient from the appropriate logging run to calculate temperature at the depth of each thin-section or core-analysis sample. Mean annual surface temperature, used to calculate temperature at depth, is 72°F (22.2°C) on the lower Texas coast, 68°F (20°C) on the upper Texas coast, and 67.4°F (19.7°C) on the Louisiana coast (Dutton and Loucks, 2014). In most of the study area, Wilcox sandstones are likely to be near their maximum burial depth and temperature now. The most updip samples in the upper Texas coast (Fig. 1) were buried about 1000 ft (300 m) deeper and reached temperatures approximately 22°F (12°C) higher than they are currently (Dutton and Loucks, 2010).

For each study area, the permeability data from that area were sorted by temperature and divided into temperature intervals of 50°F (27.8°C). The P10 value for each temperature interval was calculated as the permeability value separating the highest 10% of the data within that interval from the lower 90% of data. P50 and P90 permeability values were also calculated for each temperature interval within each study area. Within each temperature interval, core-analysis permeability values that were equal to or greater than the P10 value were identified. The list of these highest-10%-permeability values (the P10 samples) was then compared with the list of thin-section samples to identify thin sections from P10 sandstones. There are relatively few P10 samples with thin sections because: (1) only 10% of the core-analysis samples are in the highest permeability range, and (2) cores were not available from most of the wells having P10-permeability samples. Petrographic characteristics of the P10-permeability samples were then compared to lower-permeability samples from the same well and temperature interval. Most of the lower-permeability samples used for comparison have permeability between the P50 and P90 values. Thus, these samples are generally not the very lowest-permeability sandstones, but instead they represent the characteristics of sandstones having median permeability to about 1.3 standard deviations below the mean (Folk, 1974).

Petrographic characteristics having the largest difference between the P10 samples and the lower-permeability samples were interpreted to have the greatest effect on permeability. Because the sample sizes are small, t-tests were not done to test whether the differences are statistically significant. The comparison of high- and low-permeability samples was done using samples from the same well so that factors such as burial-history and provenance would be constant. This analysis provides useful insight into the controls on Wilcox reservoir quality, despite the limited number of P10 samples.

RESULTS

Wilcox sandstones in all three study areas show clear trends of decreasing average and maximum permeability with increasing temperature (Fig. 2). The calculated P10-, P50-, and P90-permeability values (Table 1) were plotted at the temperature midpoint of each interval (Fig. 2). In all three areas, P10-permeability values are >100 md in the temperature intervals through 200–250°F (93–121°C) (Table 1; Fig. 2D). At temperatures >350°F (>175°C), the P10-permeability values are <1 md (Fig. 2D). Loss of primary intergranular porosity—the main control on permeability—was mainly caused by mechanical compaction at temperatures <175°F (<80°C), whereas quartz cementation was the main cause of decreasing porosity and permeability at higher temperatures (Dutton and Loucks, 2010). At any given temperature, however, permeability values commonly range over four or more orders of magnitude (Fig. 2), although the range of values decreases at temperatures >350°F (>175°C). Identifying the characteristics of high-permeability sandstones within a temperature interval provides information that can be used to design an effective exploration strategy for finding sandstones with the best reservoir quality.

High-Permeability Wilcox Sandstones: Louisiana

P10-permeability samples with accompanying thin sections were available from Lower Wilcox sandstones in the Amoco #1 Longbell well, Beauregard Parish, Louisiana (Fig. 1). Wilcox sandstones in this area of western Louisiana were deposited on the outer fringe of the Holly Springs Delta (Galloway, 1968). Four thin-section samples from the #1 Longbell well have permeability in the top 10% of values; each of these samples has permeability >38 md at temperatures between 250–300°F (121–149° C) (Table 1A). These samples are at depths from 12,392–12,471 ft (3777–3801 m). The properties of these four P10 samples were compared with the two lowest permeability thin-section samples from this well (Fig. 2A). These two samples have permeability ≤0.81 md, which is in the lower 50% of permeability values in this temperature interval for Louisiana (Table 1A).

Differences in petrographic parameters between the four high and two low-permeability samples are summarized in Table 2. The parameters that show the greatest difference between high- and low-permeability samples and are interpreted as being the main controls on permeability in these sandstones are: (1) grain size, (2) sorting, (3) volume of silt-sized grains, (4) volume of ductile grains, and (5) volume of authigenic carbonate (defined as the total volume of carbonate cement and grain replacement). The high-permeability samples are coarser grained and better sorted, and they contain fewer silt grains and ductile grains (Fig. 3A). Average composition of the high-permeability samples is quartz = 78%, feldspar = 8%, and rock fragments = 15% ($Q_{78}F_8R_{15}$), whereas the low-permeability samples have an average composition of $Q_{67}F_9R_{24}$ (Table 2). Abundant ductile grains in the low-permeability samples include metamorphic rock fragments and ripped-up mud clasts (Fig. 3B). Grain size, sorting, and silt and ductile-grain content are related to depositional energy and hydraulic properties of the grains. Hydrodynamic fractionation of grains results from differences in grain size, density, and shape, causing detrital grains with different properties to be deposited preferentially in different energy settings (Stammer et al., 2012, 2014; Sullivan et al., 2014).

One of the two low-permeability samples contains abundant ankerite cement and grain replacement (11%), and permeability in this sample is controlled mainly by diagenesis. Permeability in the other low-permeability sample (Fig. 3B) is controlled by depositional properties. It is significantly finer grained (3.5ϕ versus an average of 2.0ϕ in the four P10 samples), more poorly sorted (0.47ϕ versus 0.32ϕ), and contains more abundant silt-sized grains (16% versus 0%) and ductile grains (19.5% versus 8.9%) than do the P10-permeability samples.

The P10 samples in the #1 Longbell well were deposited at or near the top of upward-coarsening intervals in both proximal-delta-front highstand deposits and transgressive deposits (Ambrose et al., 2013). The more quartz-rich composition (Table 2) may be a function of winnowing processes in high-energy, channel-mouth-bar and reworked delta-front settings. The sandstones deposited in these high-energy environments contain proportionately more quartz grains and larger-sized grains. The thickest continuous interval of P10 sandstones observed in this study is a 10-ft (3-m) thick section (determined from core-analysis data) that occurs at the top of the #1 Longbell highstand deposits. The two low-permeability samples were deposited in lower-energy depositional settings—near the base of a proximal delta-front, upward-coarsening sequence and the top of a fining-upward transgressive sequence (Ambrose et al., 2013). Metamorphic rock fragments are more abundant in these relatively low-energy settings, reflecting the hydrodynamic difference in grain density and grain shape between the rock fragments and quartz grains (Stammer et al., 2012).

Sandstones from the Amoco #1 Longbell well in Beauregard Parish differ from many of the other Louisiana Wilcox sandstones in that some grains contain clay rims in the form of chloritic ooids, which are made of concentric layers of chlorite oriented parallel to underlying quartz and other detrital grains (Fig. 3A). Chloritic ooids are interpreted to form where amorphous iron hydroxides carried by rivers flocculate when they mix with seawater; in high-energy environments, detrital grains roll over the flocculated clay and develop ooidal clay layers (Ehrenberg, 1993; Bloch et al., 2002). One of the four P10 samples contains a relatively high volume of chlorite rims (2.5%), which contributes to preservation of porosity and permeability by retarding quartz cementation (Fig. 3A). The chloritic ooids in the

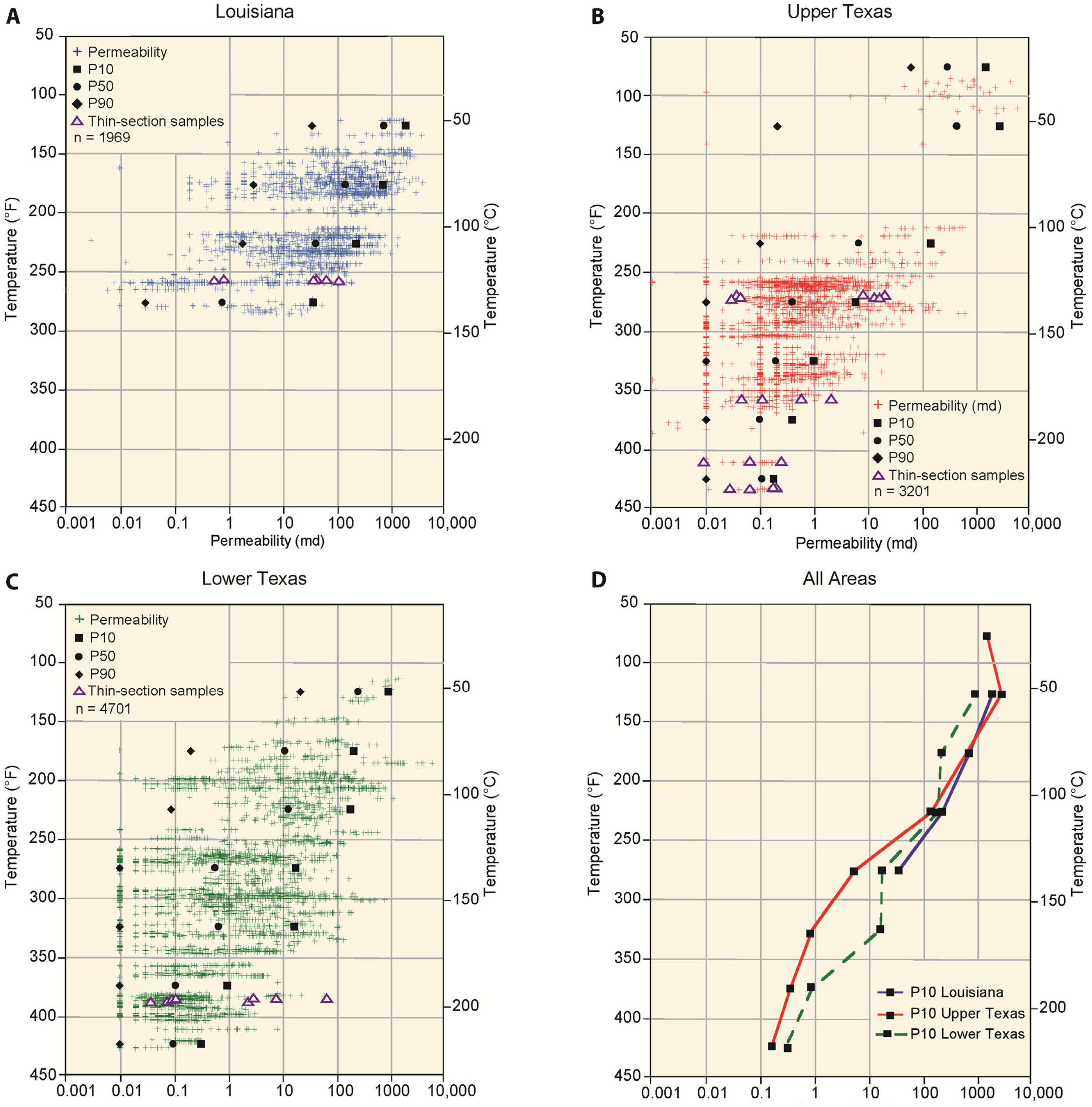


Figure 2. Plots of permeability versus temperature for Wilcox sandstones, showing the P10-, P50-, and P90-permeability values within each 50°F (27.8°C) temperature interval for (A) Louisiana, (B) upper Texas coast, and (C) lower Texas coast. The P10, P50, and P90 values were plotted at the temperature midpoint of each slice. Permeabilities of P10- and lower-permeability samples with thin sections are highlighted. (D) P10-permeability values calculated for each 50°F (27.8°C) temperature interval for Wilcox data from Louisiana, upper Texas coast, and lower Texas coast.

#1 Longbell well occur in high-energy, transgressive deposits capping wave-dominated delta deposits. Chlorite rims may occur preferentially in Wilcox sandstones in Beauregard Parish because this was a high-energy depositional setting in a wave-dominated area on the outer fringe of the Holly Springs Delta System (Ambrose et al., 2013).

High-Permeability Wilcox Sandstones: Upper Texas Coast

Thin sections of top-10%-permeability sandstone samples from the lower Wilcox were available from three wells along the upper Texas coast—Mobil Lake Creek #43 and #48, Montgom-

Table 1. P10, P50, and P90 permeability values calculated for Wilcox sandstones in each 50°F (27.8°C) temperature interval. Values are geometric-mean permeability. Intervals with no data are indicated by a dash.

(A) Louisiana study area.

Temperature interval midpoint (°F)	P90 permeability (md)	P50 permeability (md)	P10 permeability (md)
75	–	–	–
125	36	776	1971
175	3	150	740
225	2	43	240
275	0.03	0.8	38
325	–	–	–
375	–	–	–
425	–	–	–

(B) Upper Texas study area.

Temperature interval midpoint (°F)	P90 permeability (md)	P50 permeability (md)	P10 permeability (md)
75	64	311	1593
125	0.21	464	2898
175	–	–	–
225	0.1	7	152
275	0.01	0.4	6
325	0.01	0.2	1
375	0.01	0.1	0.4
425	0.01	0.11	0.2

(C) Lower Texas study area.

Temperature interval midpoint (°F)	P90 permeability (md)	P50 permeability (md)	P10 permeability (md)
75	–	–	–
125	23	275	1016
175	0.21	12	228
225	0.09	14	199
275	0.01	0.6	19
325	0.01	0.7	18
375	0.01	0.11	1
425	0.01	0.1	0.33

ery County (Grigsby et al., 1992; Guevara and Grigsby, 1992), and ARCO #1 Crews, Brazoria County (Dutton and Loucks, 2010) (Fig. 1; Table 3). In the Mobil #43 Lake Creek well, two P10 samples with permeabilities of 8.9 and 22 md, were available from the temperature interval from 250–300°F (121–149°C). These samples are at depths from 11,492–11,500 ft (3502–3505 m). They were compared with the two lowest-permeability samples with thin sections from this well (both 0.04 md) (Fig. 2B); these samples are in the lower 50% of permeability values in this temperature interval (Table 1B). The largest differences between high- and low-permeability samples in this well are in grain size and volumes of detrital clay matrix, illite cement, and authigenic carbonate (Table 3A). The two low-permeability samples are finer grained (an average of 4.1ϕ versus an average of 2.5ϕ in the P10 samples), and they contain more detrital clay matrix (3.3% versus 1.3%) (Table 3A). Total authigenic carbonate has an average volume of 4.8% in the low-permeability samples and 1.0% in the P10 samples. The low-permeability samples also contain an average of 3.8% illite cement, compared with 1.3% in the P10 samples (Table 3A). Fibrous illite cement is abundant in Wilcox sandstones in Lake Creek Field, and because it extends into pores and bridges across pore throats, it has a large impact on permeability (Grigsby et al., 1992).

In samples from the Mobil #48 Lake Creek well, grain size and volume of authigenic carbonate are the parameters having the greatest difference between the two P10 samples (14.4 and 17.8 md) and the two lowest-permeability samples (0.03 and 0.05 md) (Table 3B; Fig. 2B). The P10 samples, which are at depths of 11,515–11,528 ft (3509–3513 m), were deposited in a channel-mouth-bar environment (Guevara and Grigsby, 1992). One of the lower-permeability samples was also deposited in a channel-mouth bar, but that sandstone was burrowed and extensively cemented by calcite (22% calcite by volume). Permeability in this sample is controlled mainly by diagenesis. The other low-permeability sample was deposited in a fine-grained, interdistributary-bay environment (Guevara and Grigsby, 1992). This sample is significantly finer grained (3.3ϕ versus an average of 2.7ϕ) than the P10-permeability samples. Thus, in the two Lake Creek field wells, both depositional and diagenetic parameters control permeability.

Two temperature slices in the ARCO #1 Crews well, Brazoria County (Fig. 1), contain thin sections of P10 lower Wilcox sandstones (Table 3). Wilcox sandstones in the ARCO #1 Crews well were deposited in a lowstand, outer-slope to inner-basin-floor setting (Dutton and Loucks, 2010; Ambrose et al., 2013). These lowstand slope sandstones contain more ductile grains,

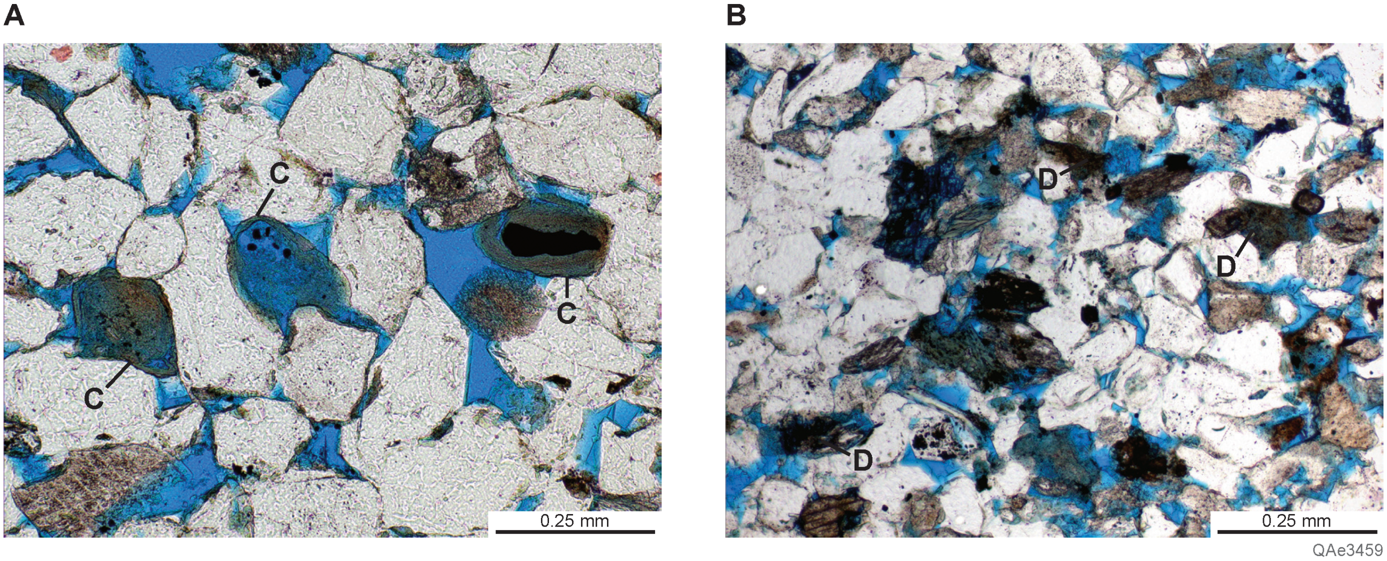


Figure 3. Photomicrographs of a P10-permeability Wilcox sandstone sample and a lower-permeability sample from the Amoco #1 Longbell well, Beauregard Parish, Louisiana, in the 250–300°F (121–149°C) temperature interval. Differences in properties between the four P10 samples and four lower-permeability samples from this well are summarized in Table 2. (A) Photomicrograph of P10-permeability sample from a depth of 12,392 ft (3777.1 m); permeability is 43 md and porosity is 15.0%. Some grains are coated by chlorite rims (C); these rims are concentrically-banded, ooidal grain coatings in which the clay is oriented parallel to the detrital grains. (B) Photomicrograph of a lower-permeability sample from 12,383 ft (3774.3 m); permeability is 0.8 md and porosity is 12.1%. Sample contains abundant ductile grains (D).

Table 2. Characteristics of high-permeability (P10) versus low-permeability Wilcox samples from the Amoco #1 Longbell well, Beauregard Parish, Louisiana. Parameters in bold are interpreted as having the greatest impact on permeability in these samples. All samples are at temperatures between 250–300°F (121–149°C).

Parameter	**High permeability (n = 4)**	**Low permeability (n = 2)**
Geometric mean permeability (md)	59.8	0.66
Core-analysis porosity (%)	15.8	10.4
Grain size (phi)	2.0 (0.25 mm)	2.8 (0.16 mm)
Sorting (phi standard deviation)	0.32	0.41
Detrital clay matrix (%)	0	0
Detrital silt grains (%)	0	8
Composition QFR	$Q_{78}F_8R_{15}$	$Q_{67}F_9R_{24}$
Ductile grains (%)	8.9	15.5
Chlorite cement (%)	1.5	1.3
Quartz cement (%)	8.0	10.5
Authigenic carbonate* (%)	2.5	6.5
Primary porosity (%)	10.0	6.8
Secondary porosity (%)	6.0	5.0

*Both cement and grain replacement

particularly metamorphic rock fragments and mudstone clasts, than do the highstand, on-shelf deposits (Table 3). We interpret this compositional difference as reflecting the depositional setting and not a difference in provenance. Highstand sandstones were probably subjected to more reworking and winnowing, which reduced the volume of rock fragments. Lowstand deposits on the slope probably were deposited rapidly and not reworked in a high-energy environment, preserving more of the lithic grains. Mudstone clasts in the slope deposits have a local origin from erosion and redeposition of clasts of older, fine-grained slope deposits (Dutton and Loucks, 2010).

Among samples from 350–400°F (177–204°C), the two P10-permeability samples (0.6 and 2.3 md) have better sorting and lower volumes of quartz, illite, chlorite, and carbonate cements than do the two low-permeability samples (0.05 and 0.12 md) (Table 3C; Fig. 2B). These parameters are related to both depositional energy and diagenesis. The two P10-permeability samples are from lowstand debrite and levee sandstones at a depth of 19,001–19,008 ft (5791–5793 m), in a transitional environment from outer slope to basin floor (Ambrose et al., 2013). The lower-permeability samples were deposited in an underlying channel-fill turbidite. Poor reservoir quality in the low-permeability samples is caused in part by poor sorting (Table 3C) resulting from the large quantity of fine-grained material scoured from an underlying muddy interchannel slope deposit (Ambrose et al., 2013). The main controls on reservoir quality appear to be diagenetic; quartz cement occludes more of the primary porosity in the lower-permeability samples, and ankerite fills both primary and secondary pores (Fig. 4). Illite and chlorite cements are also more abundant in the low-permeability samples. The P10 samples contain an average of 2% less quartz cement (7.8% versus 9.8%), 1.5% less authigenic carbonate (5.8% versus 7.3%), and 2.2% less authigenic clays (0.8% versus 3.0%) (Table 3C).

In the highest-temperature interval, from 400–450°F (204–232°C), three P10-permeability samples in the ARCO #1 Crews well have permeabilities ≥ 0.2 md (0.2, 0.22, and 0.27 md) (Fig. 2B). Four lower-permeability samples have permeabilities of 0.01 to 0.07 md, which are less than the P50 value of 0.11 md (Table 1B). In these very deep (20,907–21,685 ft [6372–6610 m]), hot sandstones, the total range of permeabilities is only about 1.5 orders of magnitude (Fig. 2B). One of the P10 samples was deposited in a debrite sandstone and the other two were deposited in amalgamated Bouma A units within channel-fill turbidites (Ambrose et al., 2013). The lower-permeability samples were deposited at the base of a debrite sandstone, in a channel-fill turbidite, and in levee sandstones (Ambrose et al., 2013).

The P10 samples contain lower volumes of detrital clay matrix (0.2% versus 2.8%), fewer silt grains (2.7% versus 5.0%) and ductile grains (18% versus 24.3%), and less authigenic carbonate (6.3% versus 7.6%) than the low-permeability samples (Table 3D). The first three parameters are controlled by depositional energy and hydraulic properties of the grains. Thus, even in sandstones that have undergone extensive diagenesis at high temperatures, local variation in permeability is still controlled by original depositional conditions as well as by diagenesis.

Secondary pores are considerably more abundant in the P10 samples (average 6.0%) than in the lower-permeability ones (average 0.1%) (Table 3D), and primary pores are rare in both the high- and low-permeability samples (0.8% versus 0%, respectively). This suggests that in these high-temperature sandstones, which have undergone extensive diagenetic alteration and the loss of most of the primary pores, permeability is related to secondary porosity (Dutton and Loucks, 2010, 2014). In the lowest-permeability samples, much of the secondary porosity has been occluded by ankerite (Fig. 5).

High-Permeability Wilcox Sandstones: Lower Texas Coast

The only P10 samples of upper Wilcox sandstones from the lower Texas coast for which thin sections are available are from the Shell #2 Weatherby well, Duval County (Fig. 1). Four thin-section samples from the #2 Weatherby well have permeabilities in the top 10%; each of these samples has permeability >1 md (2.2 to 63 md) at temperatures between 350–400°F (177–204°C) (Table 1C). The P10 samples are at depths of 14,857–15,007 ft (4528–4574 m). These samples were compared to the four lowest-permeability samples in the #2 Weatherby well, which all have permeabilities <0.1 md (0.035 to 0.097 md) and are in the lower 50% of permeability samples (Fig. 2C). All of the high-permeability samples were deposited in highstand, upper-shoreface/wave-dominated-delta environments. Two of the lower-permeability samples are from middle-shoreface/wave-dominated-delta environments and two are from upper-shoreface/wave-dominated-delta environments.

Differences in petrographic parameters between the high- and low-permeability samples are summarized in Table 4. The parameters that are the main controls on permeability in these sandstones are: (1) volume of quartz cement and (2) volume of chlorite coats. The high-permeability samples contain more continuous chlorite coats around detrital grains; these chlorite coats partly inhibited quartz cementation and preserved more primary porosity in the P10 sandstones (Fig. 6). The P10 sandstones contain an average of 9.0% quartz cement, compared with 17.6% in the low-permeability samples. The low-permeability samples are better sorted and contain fewer silt grains and ductile grains than do the high-permeability samples. Nevertheless, these parameters do not have as much impact on permeability as the presence of chlorite coats that reduced quartz-cement volume and preserved primary pores (Fig. 6). In this well, diagenetic differences, not differences in depositional energy, clearly have the most control on permeability.

DISCUSSION

Investigation of the properties of Wilcox sandstones that have permeability in the top 10% of samples within a given temperature interval reveals that both depositional and diagenetic properties are important controls on permeability at temperatures from 250–400°F (177–204°C). Depositional properties that control permeability in these Wilcox sandstones include grain size, sorting, and the volume of ductile grains, silt grains, and detrital clay matrix; diagenetic properties include the volume of carbonate, illite, chlorite, and quartz cements (Tables 2–4). Comparison of the P10 samples to lower-permeability samples from the same well allows us to quantify the amount of difference that is observed in each of these different depositional and diagenetic properties.

Most of the P10 sandstones occur in thin zones scattered within the cores. In the wells we studied, the thickest zone composed entirely of P10 sandstones was 10-ft (3-m) thick; it was located at the top of the upward-coarsening highstand deposits in the #1 Longbell well (Fig. 1). In this 10-ft (3-m) thick section, all of the core analyses had values ≥38 md (Table 1A). Core-analysis permeability measurements were available from a total of 57 ft (17.4 m) of the #1 Longbell core; 33% of the values are ≥P10 and 65% are between P50 and P90. In the other wells with thin sections of P10 samples (Fig. 1), core-analysis data indicate that the thickness of P10-sandstone intervals ranged from 1–4 ft (0.3–1.2 m) thick and averaged 1.9 ft (0.6 m) thick. Thus, even in favorable depositional settings such as proximal delta-front deposits, many of the Wilcox permeability values are in the P50 to P10 interval. Reservoirs do not produce solely from sandstones having >P10-permeability values.

Controls on Wilcox Permeability: Depositional Properties

Grain size and sorting are important controls on permeability that are related to the energy of the depositional environment (Beard and Weyl, 1973). In samples from the #1 Longbell well in Louisiana and the #43 and #48 Lake Creek wells on the upper Texas coast (Fig. 1), grain size is a major control on permeability. The difference in grain size between P10- and lower-permeability samples in these wells ranges from 0.6ϕ to 1.6ϕ, and the average difference is 1.0ϕ. A difference of 1.0ϕ is the order of magnitude difference in grain size that is observed in Wilcox sandstones between the base and top of a proximal-delta-front upward-coarsening sequence or a turbidite channel-fill deposit (Ambrose et al., 2013). Wilcox samples in this permeability study are all well sorted (0.35–0.50ϕ) or moderately well sorted (0.50–0.71ϕ), using the definitions of Folk (1974). The difference in average sorting values between the P10- and lower-permeability samples is 0.08ϕ in both the deltaic deposits of the #1 Longbell well and in the turbidite and debrite deposits of the #1 Crews well. Sorting was recognized as an important control on permeability in deepwater Wilcox deposits in the Gulf of Mexico, where most sandstones are poorly to moderately sorted (Lewis et al., 2007).

The other depositional properties that affect Wilcox permeability are the volume of ductile grains, silt grains, and detrital clay matrix. The difference in average volume of ductile grains between P10- and lower-permeability sandstones is 6% in both the #1 Longbell well (8.9% versus 15.5%) (Table 2) and the hotter interval in the #1 Crews well (18% versus 24.3%) (Table 3D). The difference in the percentage of silt grains between the P10 samples and one of the lower-permeability samples in the #1 Longbell well is 16% (0% versus 16%) (Fig. 3). Difference in silt content is recognized as an important control on reservoir quality in Wilcox deepwater turbidite deposits, with silt content being greater in lobe-margin and fringe deposits (47%) than in channelized lobes (32%) and trunk distributary channels (<24%) (Marchand et al., 2014, in press; Sullivan et al., 2014). The difference in volume of detrital clay matrix between P10- and

Table 3. Characteristics of high-permeability (P10) versus low-permeability Wilcox samples from the upper Texas coast, from wells Mobil #43 Lake Creek and Mobil #48 Lake Creek, Montgomery County, and ARCO #1 Crews, Brazoria County, Texas. Parameters in bold are interpreted as having the greatest impact on permeability in these samples.

(A) Mobil #43 Lake Creek, Montgomery County, Texas, samples between 250–300°F (121–149°C).

Parameter	High permeability (n = 2)	Low permeability (n = 2)
Geometric mean permeability (md)	13.8	0.04
Core-analysis porosity (%)	14.6	8.4
Grain size (phi)	2.5 (0.18 mm)	4.1 (0.06 mm)
Sorting (phi standard deviation)	0.57	0.45
Detrital clay matrix (%)	1.3	3.3
Composition QFR	$Q_{65}F_{23}R_{12}$	$Q_{66}F_{21}R_{13}$
Ductile grains (%)	8.0	8.0
Illite cement (%)	1.3	3.8
Quartz cement (%)	15.3	12.5
Authigenic carbonate* (%)	1.0	4.8
Primary porosity (%)	6.0	5.0
Secondary porosity (%)	5.0	2.3

*Both cement and grain replacement

(B) Mobil #48 Lake Creek, Montgomery County, Texas, samples between 250–300°F (121–149°C).

Parameter	High permeability (n = 2)	Low permeability (n = 2)
Geometric mean permeability (md)	15.8	0.04
Core-analysis porosity (%)	15.1	7.0
Grain size (phi)	2.7 (0.15 mm)	3.1 (0.12 mm)
Sorting (phi standard deviation)	0.58	0.66
Detrital clay matrix (%)	1.0	0.5
Composition QFR	$Q_{64}F_{27}R_{9}$	$Q_{56}F_{32}R_{12}$
Ductile grains (%)	5.3	7.8
Illite cement (%)	3.0	1.0
Quartz cement (%)	13.3	9.8
Authigenic carbonate* (%)	1.3	11.8
Primary porosity (%)	8.0	0.8
Secondary porosity (%)	4.8	1.3

*Both cement and grain replacement

(C) ARCO #1 Crews, Brazoria County, Texas, samples between 350–400°F (177–204°C).

Parameter	High permeability (n = 2)	Low permeability (n = 2)
Geometric mean permeability (md)	1.2	0.08
Core-analysis porosity (%)	19.4	12.7
Grain size (phi)	2.6 (0.17 mm)	2.7 (0.16 mm)
Sorting (phi standard deviation)	0.51	0.57
Detrital clay matrix (%)	0	0
Detrital silt grains (%)	0	1.5
Composition QFR	$Q_{45}F_{27}R_{28}$	$Q_{48}F_{26}R_{25}$
Ductile grains (%)	23.8	20.8
Chlorite + illite cement (%)	0.8	3.0
Quartz cement (%)	7.8	9.8
Authigenic carbonate* (%)	5.8	7.3
Primary porosity (%)	3.8	1.3
Secondary porosity (%)	8.0	5.3

*Both cement and grain replacement

Table 3 (continued). (D) ARCO #1 Crews, Brazoria County, Texas, samples between 400–450°F (204–232°C).

Parameter	High permeability (n = 3)	Low permeability (n = 4)
Geometric mean permeability (md)	0.23	0.04
Core-analysis porosity (%)	13.8	5.4
Grain size (phi)	2.8 (0.15 mm)	2.9 (0.14 mm)
Sorting (phi standard deviation)	0.65	0.63
Detrital clay matrix (%)	0.2	2.8
Detrital silt grains (%)	2.7	5.0
Composition QFR	$Q_{59}F_{22}R_{19}$	$Q_{58}F_{20}R_{23}$
Ductile grains (%)	18.0	24.3
Chlorite + illite cement (%)	1.2	1.5
Quartz cement (%)	7.2	7.6
Authigenic carbonate* (%)	6.3	7.6
Primary porosity (%)	0.8	0
Secondary porosity (%)	6.0	0.1

*Both cement and grain replacement

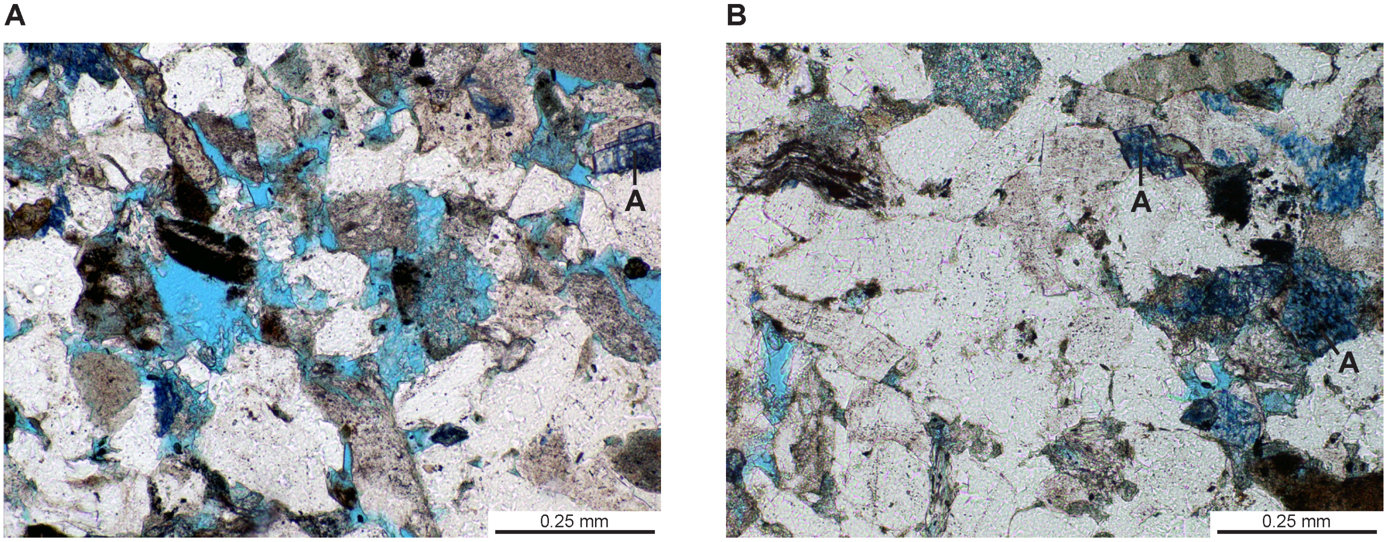


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Figure 4. Photomicrographs of a P10-permeability Wilcox sandstone sample and a lower-permeability sample from the ARCO #1 Crews well, Brazoria County, Texas, in the 350–400°F (177–204°C) temperature interval. Differences in properties between the two P10 samples and two lower-permeability samples from this well are summarized in Table 3C. (A) Photomicrograph of P10-permeability sample from a depth of 19,001 ft (5791.5 m); permeability is 2.3 md and porosity is 19.6%. (B) Photomicrograph of a lower-permeability sample from 19,021 ft (5797.6 m); permeability is 0.05 md and porosity is 12.7%. Dark blue areas in both pictures are ankerite cement and grain replacement (A).

lower-permeability samples is 2% in the #43 Lake Creek well (1.3% versus 3.3%) and 2.6% in the #1 Crews well from 400–450°F (204–232°C) (0.2% versus 2.8%). These differences are not large, but they are apparently enough to affect permeability, particularly when multiple factors are involved. Detrital clay content also influences reservoir quality of deepwater Wilcox sandstones (Pontén et al., 2014; Power et al., 2014). Argillaceous sandstones are most common in deepwater sediments deposited during conditions of decreasing flow velocity, when more silt and clay grains come out of suspension (Power et al., 2014). These poorly-sorted, transitional-flow deposits have lower reservoir quality than turbidite deposits (Pontén et al., 2014).

Controls on Wilcox Permeability: Diagenetic Properties

Diagenetic differences also control permeability in Wilcox sandstones. In five of the six cases in this study, permeability is influenced by the volume of authigenic carbonate (Tables 2–4). One low-permeability sample from the #1 Longbell well contains 11% authigenic carbonate and one from the Lake Creek #48 well contains 21.5%. In these sandstones, extensive carbonate cement and grain replacement explain the low permeabilities. In other wells, the difference in carbonate content between P10- and

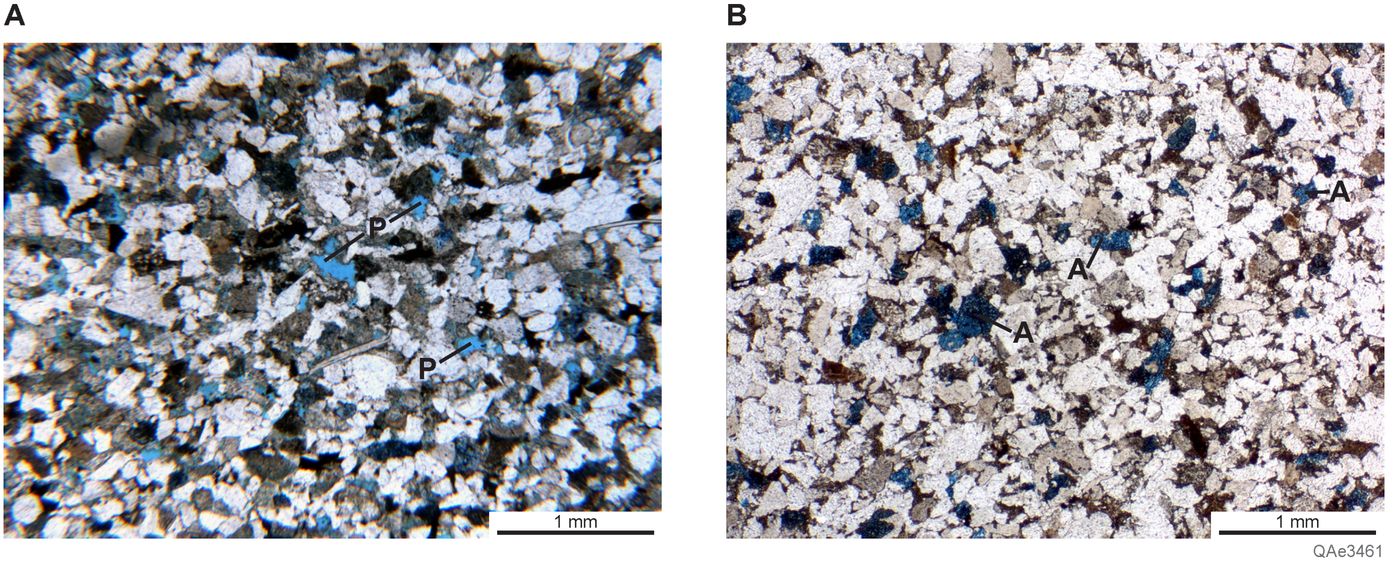

Figure 5. Photomicrographs of a P10-permeability Wilcox sandstone sample and a lower-permeability sample from the ARCO #1 Crews well, Brazoria County, Texas, in the 400–450°F (204–232°C) temperature interval. Differences in properties between the three P10 samples and four lower-permeability samples from this well are summarized in Table 3D. (A) Photomicrograph of P10-permeability sample from a depth of 20,907 ft (6372.5 m); permeability is 2.3 md and porosity is 19.6%. Most of the macropores in this sample are secondary pores (P). (B) Photomicrograph of a lower-permeability sample from 20,911 ft (6373.7 m); permeability is 0.05 md and porosity is 12.7%. Dark blue areas are ankerite cement and grain replacement (A).

Table 4. Characteristics of high-permeability (P10) versus low-permeability Wilcox samples, Shell #2 Weatherby Gas Unit, Duval County, Texas. Parameters in bold are interpreted as having the greatest impact on permeability in these samples. Samples between 350–400°F (177–204°C).

Parameter	High permeability (n = 4)	Low permeability (n = 4)
Geometric mean permeability (md)	7.3	0.07
Core-analysis porosity (%)	16.7	10.4
Grain size (phi)	2.9 (0.13 mm)	2.8 (0.15 mm)
Sorting (phi standard deviation)	0.50	0.39
Detrital clay matrix (%)	0	0
Detrital silt grains (%)	3.8	0.3
Composition QFR	$Q_{63}F_{22}R_{15}$	$Q_{72}F_{19}R_{9}$
Ductile grains (%)	10.3	6.9
Chlorite cement (%)	4.4	2.5
Quartz cement (%)	9.0	17.6
Authigenic carbonate (%)^2	3.9	0.9
Primary porosity (%)	4.9	2.8
Secondary porosity (%)	7.1	6.3

*Both cement and grain replacement

lower-permeability samples is smaller (1–4%), and permeability is influenced by other factors as well.

Calcite and ankerite are the main authigenic carbonate minerals in Wilcox sandstones (Loucks et al., 1984, 1986; Fisher and Land, 1986; Dutton and Loucks, 2010). Most Wilcox sandstones contain <10% authigenic carbonate (Fig. 7), but a few sandstones contain very abundant carbonate, as much as 52%. In each study area, sandstone samples containing ≥10% authigenic carbonate have about an order of magnitude lower permeability than samples containing <10% authigenic carbonate. In Louisiana, samples containing <10% authigenic carbonate have a geometric-mean permeability of 2.7 md, whereas in samples containing ≥10% authigenic carbonate the geometric-mean permeability is 0.27 md. Authigenic carbonate is slightly more abundant in the Louisiana study area, where 17% of the thin-section samples contain ≥10% authigenic carbonate (Fig. 7). In the upper Texas study area, 15% of the sandstone samples contain ≥10% authigenic carbonate, compared with 11% in the lower Texas study area. On average, 15% of all Wilcox thin-section samples in this study contain ≥10% authigenic carbonate.

It is not currently possible to predict the location of extensively carbonate-cemented zones within a sandstone interval, although recent work has made progress in linking carbonate cementation to sequence stratigraphy and depositional facies (e.g., Taylor et al., 2000; Dutton, 2008; Morad et al., 2010). Most calcite-cemented zones in Wilcox sandstones are <0.5 ft (0.15 m) thick, and they are not interpreted to be laterally extensive. Therefore, it would be difficult to devise an exploration strategy to avoid carbonate-cemented zones, but instead a risk estimate can be assigned to the probability of encountering poor

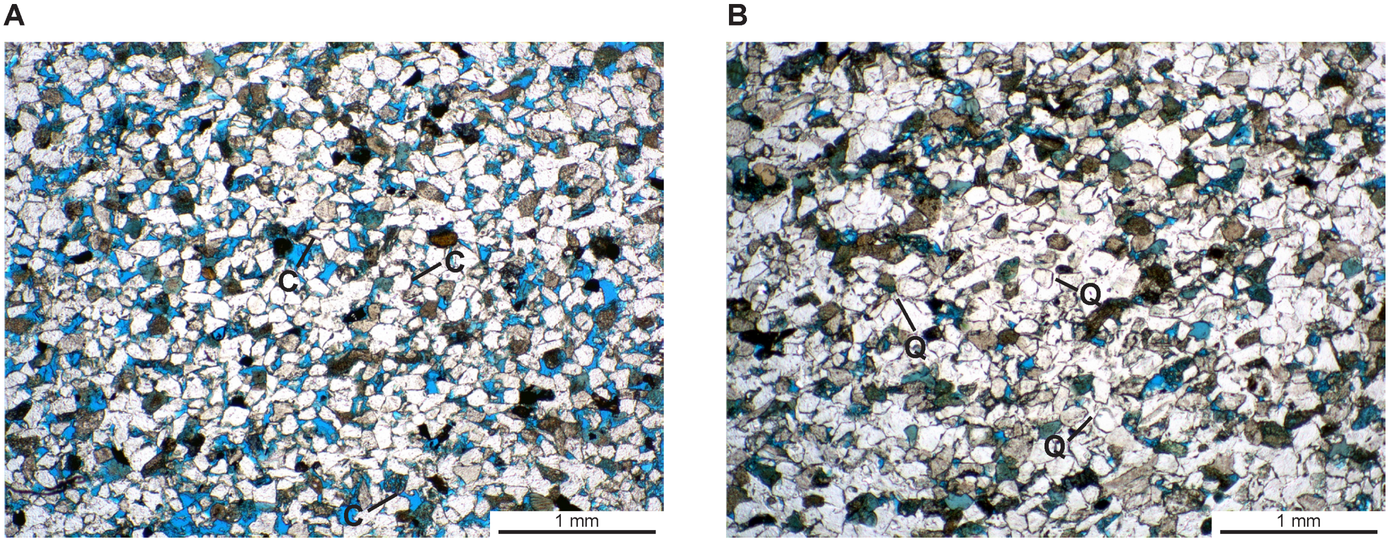

Figure 6. Photomicrographs of a P10-permeability Wilcox sandstone sample and a lower-permeability sample from the Shell #2 Weatherby well, Duval County, Texas, in the 350–400°F (177–204°C) temperature interval. Differences in properties between the four P10 samples and four lower-permeability samples from this well are summarized in Table 4. (A) Photomicrograph of P10-permeability sample from a depth of 14,858 ft (4,528.7 m); permeability is 63 md and porosity is 21.2%. Chlorite coats (C) inhibited quartz cement. (B) Photomicrograph of a lower-permeability sample from 15,038 ft (4,583.6 m); permeability is 0.07 md and porosity is 10.7%. Sample contains fewer chlorite coats and more abundant quartz cement (Q).

reservoir quality caused by abundant authigenic carbonate in about 15% of Wilcox sandstones.

Fibrous illite, which extends into and across pore throats, has an important influence on permeability in Wilcox sandstones in Lake Creek Field (Grigsby et al., 1992; Guevara and Grigsby, 1992). Low-permeability samples in the #43 Lake Creek well contain an average of 2.5% more illite than do the high-permeability samples (1.3% versus 3.8%) (Table 3A). Illite cement is not abundant in most Wilcox sandstones in this study. The average volume of illite cement is 0.2% in Louisiana, 1.1% in the upper Texas coast, and 0.5% in the lower Texas coast. Illite is particularly abundant in Lake Creek Field, where the volume ranges from 0 to 7% and averages 2.9%.

Increasing volume of quartz cement is the major cause of decreasing permeability in Wilcox sandstones with increasing temperature (Loucks et al., 1984, 1986; Fisher and Land, 1986; Dutton and Loucks, 2010). The average volume of quartz cement is 4.5% in Wilcox thin-section samples from Louisiana, 8.3% in the upper Texas coast, and 8.5% in the lower Texas coast. The reason for the lower average volume of quartz cement in Wilcox sandstones from Louisiana is because these sandstones have not been buried as deeply or reached as high temperatures as the Wilcox samples from Texas (Fig. 2). Wilcox sandstones in Texas and Louisiana have similar proportions of detrital quartz grains, therefore the difference in quartz cement volume is not attributed to differences in availability of quartz nucleation surfaces. Lower Wilcox sandstones from the upper Texas coast, which were deposited in the Houston Delta system, have a current average composition of $Q_{61}F_{25}R_{14}$ (Dutton et al., 2011). Prior to diagenetic modification, mainly by dissolution and alteration of feldspars, original detrital composition was estimated as $Q_{55}F_{32}R_{13}$. Lower Wilcox sandstones from the Holly Springs Delta system in Louisiana have an average composition of $Q_{62}F_{15}R_{24}$ now, and $Q_{55}F_{24}R_{21}$ originally.

Local variations in the volume of quartz cement can also cause permeability differences in sandstones with the same burial and temperature histories. The best example of the influence of local variation in quartz-cement volume on permeability comes from the #2 Weatherby well (Fig. 1) in the lower Texas coast. P10-permeability sandstones contain an average of 1.9% more chlorite cement than the lower-permeability samples (Table 4). This additional volume of chlorite apparently resulted in more complete chlorite-coat coverage on detrital quartz grains and subsequent reduction of quartz cementation in these samples (Fig. 6). The P10 sandstones with abundant chlorite coats have an average of 8.6% less quartz cement than do the lower-permeability sandstones (Table 4).

Chlorite cement is most abundant in Wilcox sandstones in the lower Texas study area, where the average volume is 2.2%, compared with an average of 0.2% in upper Texas coast and 0.3% in Louisiana. Even in lower Texas, however, preservation of porosity and permeability in Wilcox sandstones by complete chlorite-coat coverage on detrital quartz grains and subsequent inhibition of quartz cementation is not common. Only 9% of Wilcox sandstone samples at temperatures >350°F (>177°C) in south Texas have permeability >1 md (Fig. 2C). Even if the (relatively) high permeability in all of these samples is related to the presence of chlorite coats, more than 90% of Wilcox sandstones apparently do not contain sufficiently continuous chlorite coverage to inhibit quartz cementation. Using reservoir-quality modeling software, Tobin (2007) determined that at high temperatures (>392°F [>200°C]), grain coats must be nearly complete to significantly retard the rate of quartz cement growth. Thus, there is a high risk of poor reservoir quality due to quartz cementation in Wilcox sandstones at temperatures >350°F (>177°C) because continuous chlorite coats are uncommon.

Application to Deep Shelf and Deepwater Gulf of Mexico Wilcox Reservoirs

This study focused on onshore Wilcox sandstones, but the results can be applied to understanding potential controls on local variation in reservoir quality of Wilcox sandstones beneath the Gulf of Mexico shelf and adjacent deepwater. Loss of permeability with increasing temperature, which is observed in all three onshore study areas (Fig. 2), is expected to occur in offshore Wilcox reservoirs as well. Loss of primary porosity in onshore sandstones at temperatures < ~175°F (< ~80°C) and depths < ~ 6600 ft (< ~2 km) was due mainly to mechanical compaction (Dutton and Loucks, 2010). Quartz cementation was the main cause of primary-porosity loss at temperatures >175°F (>80°C), and the average volume of quartz cement increases with increasing temperature (Dutton and Loucks, 2010). P10-permeability values in onshore Wilcox reservoirs at temperatures of 400°F (200°C) are significantly lower than in reservoirs at 265°F (130°C) (Fig. 2), and we expect that the same trend occurs

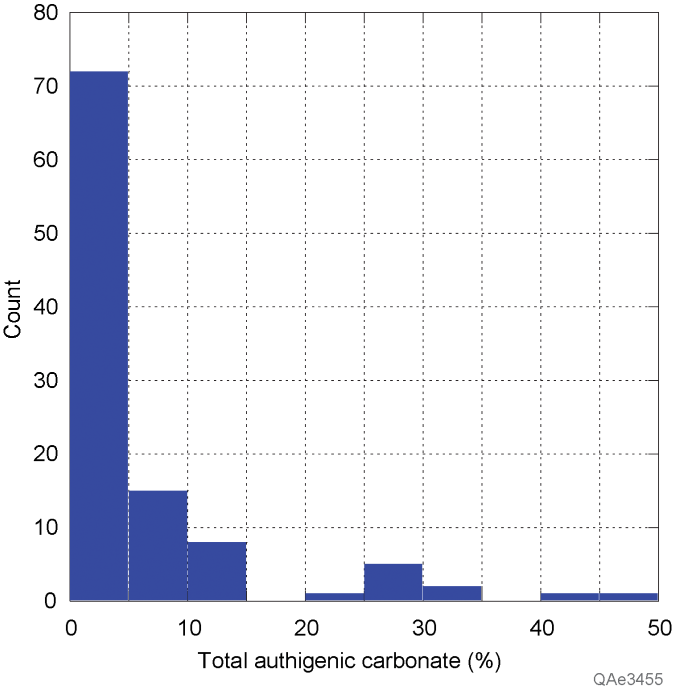

Figure 7. Histogram of percent authigenic carbonate (cement + grain replacement) in Wilcox sandstones from Louisiana study area.

in offshore Wilcox reservoirs. Reservoir quality in Wilcox sandstones at a temperature of approximately 265°F (130°C) in the deepwater Jack–1 (Walker Ridge 759 #1) well (Lewis et al., 2007) is better than in Wilcox sandstones below the shelf at approximately 450°F (230°C) in the Will K well (High Island A119 #1) (Johnston et al., 2010). However, temperature is a regional control on reservoir quality that varies with heat flow and geothermal gradient, and thus it does not explain local permeability variation in sandstones that have the same burial and temperature history.

The depositional parameters of grain size, sorting, and volume of detrital clay matrix, silt grains, and ductile grains, which influence reservoir quality in onshore Wilcox sandstones, have also been identified as important controls on local permeability variation in deepwater Wilcox sandstones (Lewis et al., 2007; Winker, 2011; Marchand et al., 2014, in press; Pontén et al., 2014; Power et al., 2014; Sullivan et al., 2014). Study of onshore Wilcox sandstones indicates that ductile rock fragments are more abundant in lowstand slope deposits than in highstand and transgressive deposits (Dutton and Loucks, 2010). Winker et al. (2011) showed that deepwater Wilcox sandstones contain a higher proportion of rock fragments than do onshore sandstones, and they concluded that the difference is mainly the result of transport processes and not a difference in provenance. Because of the greater proportion of ductile rock fragments in Wilcox sandstones deposited in deepwater depositional environments, the influence of depositional parameters on reservoir quality in deepwater reservoirs is likely to be even more important than it is for onshore highstand and transgressive deposits.

It is uncertain how much local permeability variation in deepwater Wilcox sandstones might be caused by other diagenetic parameters, specifically chlorite and carbonate-cement distribution. Nearly-complete grain coatings of chlorite inhibited quartz cementation in some deepwater Wilcox sandstones in the Jack–1 (Walker Ridge 759 #1) well (Lewis et al., 2007), and chlorite rims have been reported as occurring in deepwater Wilcox sandstone in the eastern part of the play (J. B. Wagner, 2009, personal communication). Chlorite rims and coats have been observed in deepwater turbidite sandstones in other parts of the world (e.g., Houseknecht and Ross, 1992; Sullivan et al., 1999; Bloch et al., 2002; Anjos et al., 2003), so the presence of chlorite in some deepwater Wilcox sandstones would not be unusual. Although there have been only a few reports of chlorite coats in deepwater Wilcox sandstones in the Gulf of Mexico, chlorite cement apparently is present in some samples and may be locally important in preserving reservoir quality.

Carbonate cement is present in the deepwater (Walker Ridge 759 #1) well (Lewis et al., 2007), although no volume information is provided. Ankerite cement and grain replacement are abundant in some intervals of the ARCO #1 Crews sandstones (Dutton and Loucks, 2010), which were deposited in a lowstand, outer-slope to inner-basin-floor setting (Ambrose et al., 2013). The Crews sandstones are at temperatures of 357–438°F (180–225°C). It is possible that local zones of deepwater Wilcox sandstones in the Gulf of Mexico have poor reservoir quality because of carbonate cement, particularly in the hottest sandstones located in the deep shelf play. On average, 15% of onshore Wilcox sandstone samples in this study contain $\geq$10% authigenic carbonate. Until additional data are available, this value may provide an estimate of the possible risk of local zones of poor reservoir quality caused by authigenic carbonate.

CONCLUSIONS

This study of the highest-permeability sandstones (top 10%) within temperature intervals allows us to distinguish the parameters that have the largest impact on permeability among sandstones that share the same burial and thermal histories. In many cases, the parameters with the greatest local impact on permeability are differences in grain size, sorting, detrital silt grains, clay matrix, and ductile grains. These parameters, which are all related to depositional energy and process, can be addressed in an exploration strategy that focuses on sequence-stratigraphic setting and depositional environment. Sandstones deposited in high-energy settings, such as channel-mouth-bar, proximal-delta-front, or submarine-fan-channel environments, will generally have higher permeability than deposits from lower-energy environments, such as distal-delta-front, interdistributary-bay, or outer-submarine-fan-lobe environments (Galloway and Hobday, 1983). Depositional parameters remain important controls on local variation in permeability in Wilcox sandstones even after extensive burial diagenesis at high temperatures.

In fewer of the cases we studied, local diagenetic differences were the main controls on permeability variation within a given temperature interval. The main local diagenetic controls were variations in carbonate, illite, chlorite, and quartz cement volume. It is not currently possible to predict the occurrence of carbonate-cemented beds within a sandstone interval. An understanding of the controls on local variation of continuous chlorite coats that inhibit quartz cementation also remains elusive. Therefore, local variations in diagenesis remain hard to predict and must be assigned risk factors, because predicting their exact location is not currently possible.

ACKNOWLEDGMENTS

This research was funded by member companies of the Deep Shelf Gas consortium at the Bureau of Economic Geology, University of Texas. Dr. Douglas Carlson, Louisiana Geological Survey, provided much of the core-analysis data for Wilcox sandstones in Louisiana. Student research assistant Nur Liyana Rafiuddin analyzed data to identify the P10 sandstones and summarize their properties, and Sumiyyah Ahmed, Younis Altobi, Julie Helfrich, Trevor Hutton, Nur Liyana Rafiuddin, and Jessica Schilling performed grain-size point counts of Wilcox sandstones. Caroline Breton designed and maintains the Deep Shelf Gas GIS project. We thank Jeffrey D. Grigsby for allowing us to use his point-count data of Wilcox sandstones from Lake Creek field, Montgomery County. Figures were drafted by the media department staff of the Bureau of Economic Geology under the direction of Cathy Brown, media department manager. Ann Marchand, Jane Stammer, and Associate Editor Thomas Dunn provided thorough and constructive reviews that improved this article. Publication authorized by the Director, Bureau of Economic Geology.

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