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Reservoir Quality and Porosity-Permeability Trends in Onshore Wilcox Sandstones, Texas and Louisiana Gulf Coast: Application to Deep Wilcox Plays, Offshore Gulf of Mexico

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ABSTRACT

Evolution of porosity and permeability in Lower Tertiary Wilcox sandstones during burial diagenesis was evaluated using petrographic and petrophysical data from onshore sandstones of the Texas and Louisiana Gulf Coast. The results provide insight into reservoir quality of deeply buried Wilcox sandstones beneath the Gulf of Mexico shelf and in the deep Gulf. Wilcox sandstone samples used 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. Petrographic analysis of 534 Wilcox thin sections from 90 wells was combined with core-analysis data from >10,000 core samples from 189 wells to determine regional variation in pore-type evolution and porosity-permeability trends with increasing burial depth and temperature.

Petrographic data show that Wilcox sandstone pores change from a mix of primary and secondary pores and micropores at lower temperatures to predominantly secondary pores and micropores at temperatures >300°F (>150°C). Primary porosity, the most important control on permeability, decreases from an average of 40% at the time of deposition to 5–8% by 250°F (125°C) and 1–2% at temperatures >390°F (>200°C). Core-analysis data were used to calculate porosity-permeability transforms within different temperature intervals in each area. Because the sandstone pore types change with increasing temperature, porosity-permeability transforms also change; at higher temperatures, permeability is lower per porosity unit. A transform developed for low-temperature sandstones is not appropriate to use in higher-temperature sandstones. At temperatures >212°F (>100°C), Wilcox sandstones in the Houston Delta System have lower permeability for a given porosity than sandstones in the Holly Springs and Rosita delta systems. These data suggest that high-temperature Wilcox sandstones beneath the present shelf and in the deep Gulf that were sourced by the Holly Springs and Rosita deltas may have better reservoir quality than do sandstones derived from the Houston Delta.

INTRODUCTION

Lower Tertiary Wilcox Group sandstones deposited in lowstand systems tracts in deepwater depositional environments are deep (>15,000 ft [>4.5 km]) to ultradeep (>20,000 ft [>6 km]) exploration targets below the present-day shelf and deepwater of the Gulf of Mexico. Most target reservoirs occur at temperatures from 230°F (110°C) to >450°F (>230°C). At these depths and temperatures, the greatest unknown and most critical exploration risk factor is reservoir quality.

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Petrographic and petrophysical analysis of onshore Wilcox sandstones from the Texas and Louisiana Gulf Coast were conducted to document changes in reservoir quality during burial diagenesis. Previous studies interpreted the diagenetic history of Wilcox sandstones in south-central Texas (Loucks et al., 1984, 1986; Fisher and Land, 1986; Land and Fisher, 1987) and investigated pore-type distribution at depths ranging from 104 to 14,280 ft (32 to 4353 m) (Chuang and McBride, 1988). Diagenetic controls on pore types and porosity and permeability evolution with increasing temperature were documented in Wilcox sandstones from the upper Texas coast (Dutton and Loucks, 2010). Mechanical compaction and quartz cementation were the most important porosity-reducing diagenetic events.

In this study, Wilcox data from a larger area of the Gulf coast were examined for regional variations in pore-type evolution and porosity-permeability trends with increasing burial depth and temperature. Wilcox samples in this study come from on-

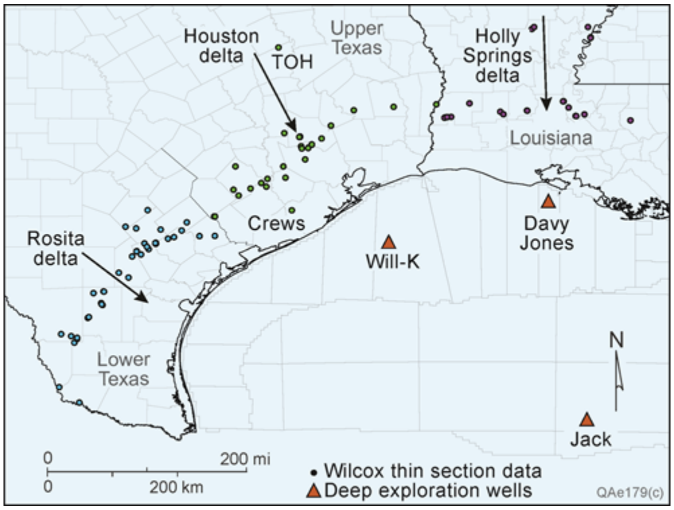

Figure 1. Distribution of wells with thin-section data from onshore Wilcox sandstones.

shore Texas and Louisiana (Fig. 1), at depths ranging from 560 to 21,953 ft (171 to 6691 m) and temperatures from 80 to 438°F (27 to 226°C). The sandstones 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) (Fig. 1). The data are from onshore Wilcox sandstones, but the results provide insight into 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 in Texas and Louisiana. Farther downdip, in the Gulf of Mexico, the Wilcox Group contains turbidite sandstones deposited on the slope and in large, sand-rich basin-floor fans (Meyer et al., 2007; Lewis et al., 2007).

Upper Paleocene lower and middle Wilcox sandstones were deposited 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). 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). Early Eocene upper Wilcox sediment in the lower Texas coast was deposited in the Rosita Delta System (Edwards, 1981; Galloway et al., 2000). Most of the Wilcox petrographic 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 (Ambrose et al., 2013).

Geothermal gradient increases westward along the Louisiana and Texas coast (DeFord et al., 1976). 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 temperature of onshore sandstones equals or exceeds that of offshore Wilcox targets at similar depths.

METHODS

The data used in this study include petrographic analyses from 534 Wilcox thin sections and core analyses from >10,000 core samples from Texas and Louisiana. Wilcox sandstone composition was determined by standard thin-section petrography, and a total of 200 counts were made on each thin section. Point counts identified four major categories of rock volume: detrital framework grains, matrix, authigenic minerals, and pores. Pores in Wilcox sandstones were interpreted as either (1) primary, intergranular pores, (2) secondary pores that formed by partial or complete dissolution of framework grains, or (3) micropores (Fig. 2). The volumes of primary and secondary pores were quantified by thin-section point counts and reported as percent of whole-rock volume. 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 total porosity measured by porosimeter and thin-section porosity. Micropores typically occur in matrix, authigenic clays, and altered grains (Fig. 2c) (Dutton and Loucks, 2010). Microporosity was estimated only for samples in which the thin section was made from either an end trim of a core-analysis plug or a sample taken immediately adjacent to the plug. 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; not all the data are Klinkenberg corrected.

Burial temperature was calculated for each thin-section and core-analysis sample by the following three-step procedure: (1) correcting bottom-hole temperatures from geophysical logs from each well using the time-since-circulation correction (Waples et al., 2004; Corrigan, 2006), (2) calculating geothermal gradient for each well, and (3) using 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. These temperatures were calculated by averaging the mean annual surface temperature for each county or parish in the three study areas (Fig. 1).

The onshore Wilcox sandstone samples used in this study range in temperature from 80–438°F (27–226°C). Across most of the study area, subsidence continued during the Tertiary, and Wilcox sandstones are likely to be near their maximum burial depth and temperature now (Fisher and Land, 1986; Galloway et al., 1986; McBride et al., 1991; Dutton and Loucks, 2010). Only the most updip samples in the upper Texas coast (from the Law Engineering #2A TOH well, Leon County) were probably buried at greater depths and reached temperatures higher than they are currently (Dutton and Loucks, 2010).

EVOLUTION OF PORE TYPES

Pore-type evolution in Wilcox sandstones with increasing temperature was calculated using the approach developed in Dutton and Loucks (2010). Wilcox petrographic data from each study area were divided into 50°F (27.8°C) temperature intervals, and average values of primary and secondary pores and micropores (Fig. 2) were plotted by temperature interval (Fig. 3). Porosity values are plotted at the average temperature of all the samples in the area from that 50°F (27.8°C) interval. In each plot, average primary porosity in Wilcox sandstones was assumed to be 40% shortly after deposition (Houseknecht, 1987) at a temperature of 77°F (25°C). Secondary porosity was assumed to be 0%, although some grains may have contained small intragranular pores at deposition (Dutton and Loucks, 2010). Studies of Wilcox sandstones in outcrop indicated that micropores are present in weathered framework grains (Chuang and McBride, 1988; Loucks and Dutton, 2007), so we assigned a value of 4% microporosity to the Wilcox sandstones at the time of deposition (Dutton and Loucks, 2010). Total porosity was assumed to be 44% at deposition in each area (Fig. 3).

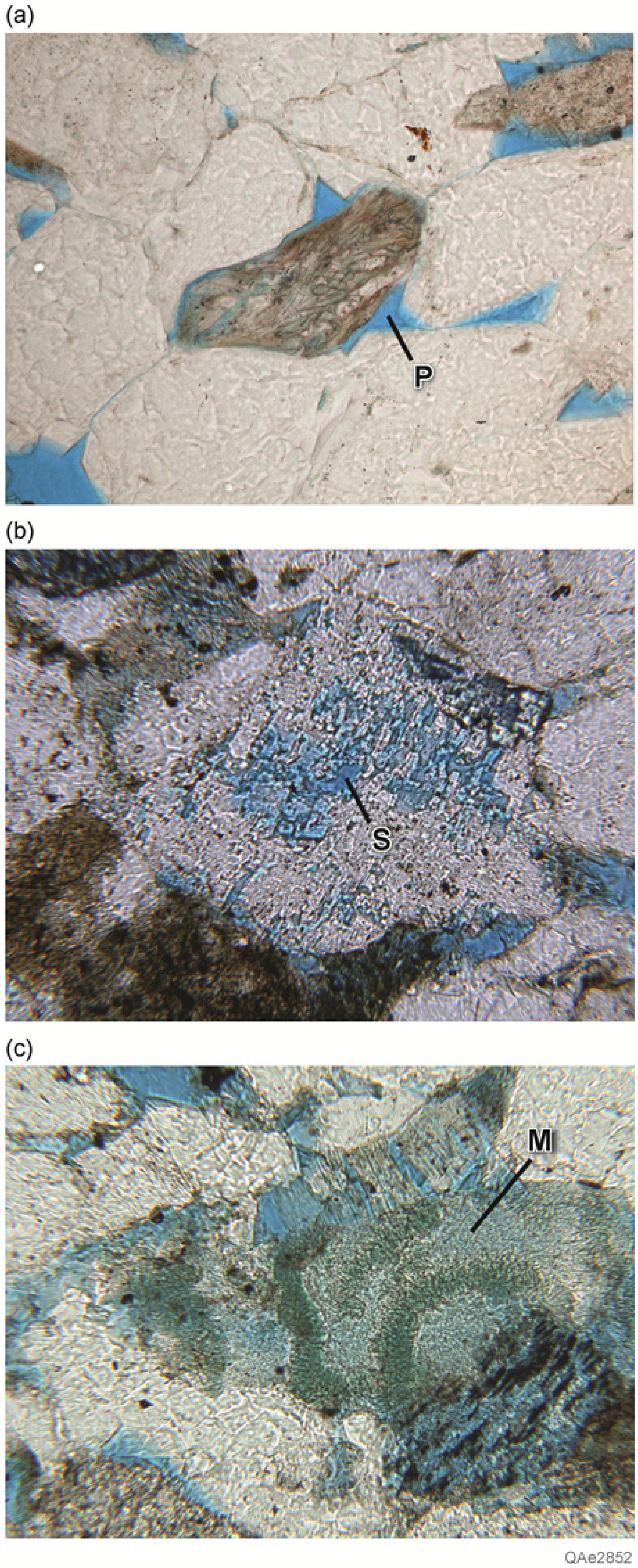

Figure 2. Examples of pore types in Wilcox sandstones: (a) primary, intergranular pores (P) in sample from 11,131 ft (3393 m), Louisiana; (b) secondary pores (S) formed by partial dissolution of plagioclase grain in sample from 20,898 ft (6370 m), upper Texas coast; and (c) micropores (M) in altered volcanic rock fragment from 19,008 ft (5794 m), upper Texas coast.

Petrographic analysis shows that primary pores are the dominant pore type in Wilcox sandstones at low temperatures, but at higher temperatures the pores are a mixture of primary and secondary pores and micropores (Dutton and Loucks, 2010) (Fig. 3). The change in proportion of pore types with increasing temperature is the result of (1) decreasing volume of primary pores due to compaction and cementation, combined with (2) nearly constant volume of secondary pores and micropores (Fig. 3). The average volume of secondary porosity shows little change with increasing temperature and varies from 1 to 9% (Fig. 3). Taylor et al. (2010) also reported no discernable trend in secondary-porosity volume with depth in Wilcox sandstones in Texas.

We have not observed a correlation between overpressure and porosity preservation in Wilcox sandstones, possibly because overpressure developed after much of the mechanical compaction had taken place (Bloch et al., 2002). Harrison and Summa (1991) suggested that Tertiary formations in the Gulf of Mexico, including the Wilcox, were at near-normal pressures for most of their burial history and became strongly overpressured only in the last 2–3 million years.

The deepest, hottest (>390°F [>200°C]) Wilcox sandstones from the upper Texas coast, which were deposited in a lowstand slope setting downdip of the Houston Delta System, contain an average of 0.6% primary pores, 4.2% secondary pores, and 4.8% micropores (Fig. 3a). Average total porosity measured by porosimeter is 9.6%. The hottest Wilcox sandstones (>390°F [>200°C]) from the lower Texas coast, which were deposited in the Rosita Delta System, contain an average of 2% primary pores, 5% secondary pores, and 2% micropores (Fig. 3b). Average total porosity measured by porosimeter is 9%. No Wilcox sandstones from the Holly Springs Delta System in onshore Louisiana were available from temperatures >285°F (>140°C) (Fig. 3c).

Primary pores are the most important controls on permeability (Pittman, 1979). Primary pores are connected by larger pore throats than are secondary pores or micropores (McCreesh et al., 1991), and pore-throat size controls permeability (Pittman, 1992). Primary porosity determined by thin-section point counts decreases by mechanical compaction (grain rearrangement and ductile-grain deformation) and quartz cementation (Dutton and Loucks, 2010) at similar rates in all three Wilcox study areas (Fig. 4). Average primary porosity decreases from an estimated 40% at the time of deposition to 5–8% by 250°F (125°C) and 1–2% at temperatures >390°F (>200°C) (Fig. 5).

Depositional Setting and Detrital Mineral Composition

Most of the Wilcox samples in this study were deposited in highstand and transgressive systems tracts in an on-shelf depositional setting, but turbidite and debris-flow deposits from a lowstand slope- to basin-floor setting were sampled in the downdip ARCO #1 Crews well from the upper Texas coast (Fig. 1). These lowstand deposits contain more metamorphic rock fragments than do on-shelf highstand and transgressive deposits from the upper Texas coast. Average composition of lowstand sandstones from the ARCO #1 Crews well is Q58F21R21 (Quartz %, Feldspar %, and Rock Fragment %), compared with an average composition of Q61R25R15 for on-shelf highstand and transgressive deposits from upper Texas coast. We interpret this difference as reflecting the depositional setting and not as a difference in provenance (Dutton and Loucks, 2010). Highstand and transgressive sandstones were probably subjected to more reworking and winnowing, which reduced the volume of rock fragments. Lowstand sandstones were deposited rapidly by turbidity currents and debris flows, preserving more of the lithic grains. Lowstand deposits also contain more contemporaneous ripped-up mud clasts compared with the highstand and transgressive deposits (9% versus 4%, respectively).

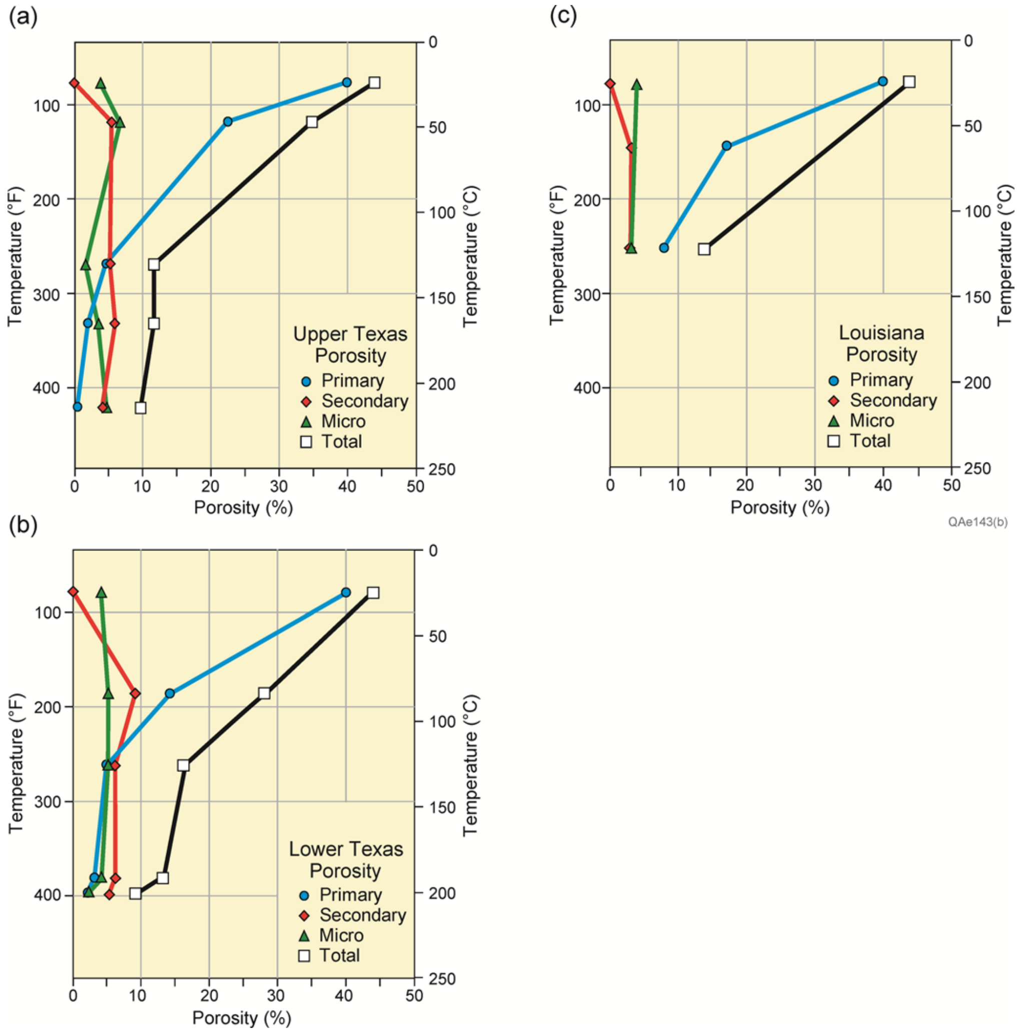

Figure 3. Summary plots of evolution of average total porosity and pore types with increasing temperature in Wilcox sandstones from the (a) upper Texas coast, (b) lower Texas coast, and (c) Louisiana.

Ductile-grain content (detrital rock fragments + micas + contemporaneous ripped-up mud clasts) and microporosity volume have a statistically significant positive correlation in upper Texas Wilcox sandstones. The greater abundance of ductile grains in lowstand slope- to basin-floor sandstones suggests that lowstand Wilcox deposits in the Gulf of Mexico may contain a higher proportion of microporosity than do most onshore Wilcox sandstones, which are mainly on-shelf highstand and transgressive deposits.

Gulf of Mexico Sandstones

Wilcox reservoirs in wells in the deepwater Gulf of Mexico, such as the Chevron #1 Jack well in Walker Ridge Block 759 (#1 OCS–G–17016) (Fig. 1), occur at temperatures of approximately 265°F (130°C). Using the onshore Wilcox sandstones as analogs, primary porosity in these deepwater Wilcox sandstones might range from 0–15% (Fig. 4), with an average value of 5–8% (Fig. 5). Secondary porosity plus microporosity in these lowstand sandstones is estimated to average 6–11% (fig. 3) or more, because of abundant microporosity in rock fragments and mud clasts.

Wilcox sandstones that are ultradeep exploration targets below the continental shelf, in wells such as the BP Will-K well in High Island Block A119 (#1 OCS–G–26519) and the McMoRan Davy Jones well in South Marsh Island Block 230 (#1 OCS–

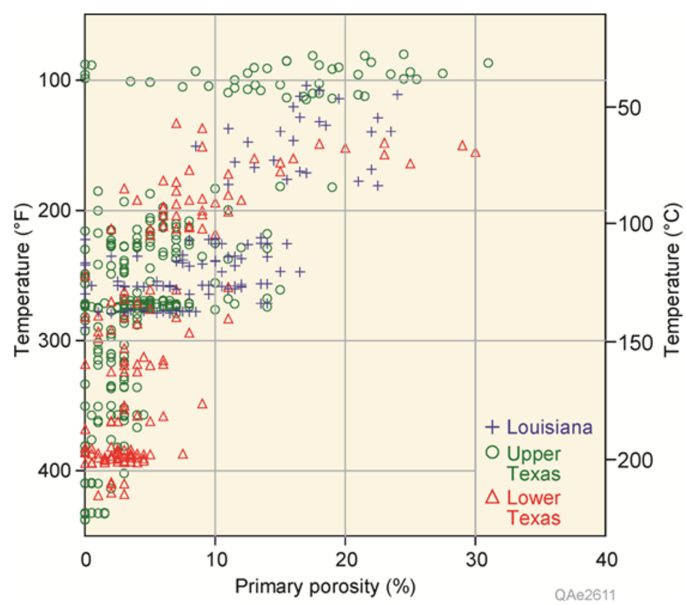

Figure 4. Primary-pore volume decreases with increasing temperature in Wilcox sandstones from the lower Texas coast, upper Texas coast, and Louisiana. Primary-pore volume was determined by thin-section point counts.

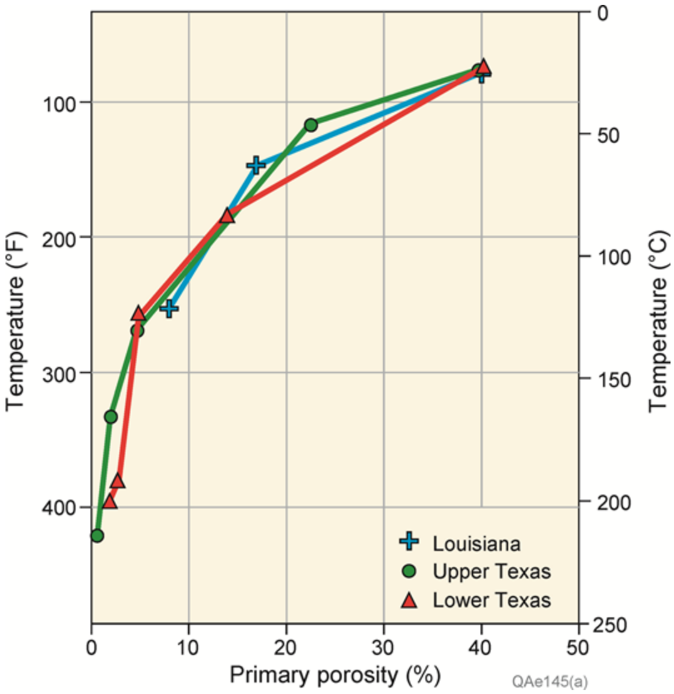

Figure 5. Evolution of average primary-pore volume with temperature in Wilcox sandstones from the lower Texas coast, upper Texas coast (modified after Dutton and Loucks, 2010), and Louisiana.

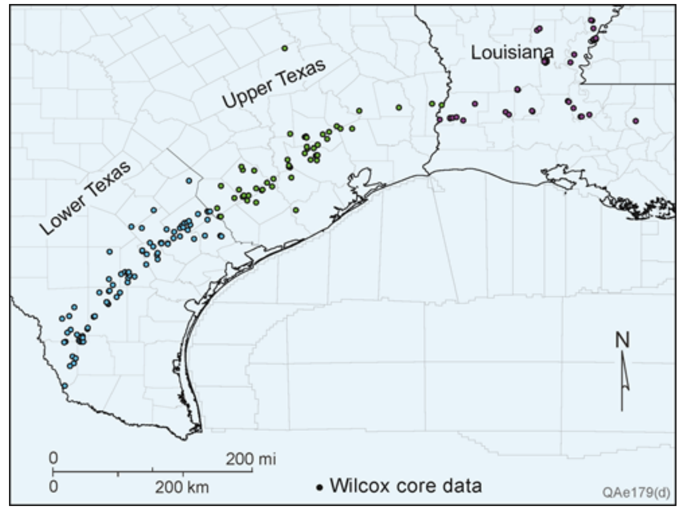

Figure 6. Distribution of wells with core-analysis data from onshore Wilcox sandstones.

G–26013) (Fig. 1) occur at temperatures of ~450°F (~230°C) (Johnston et al., 2010). On the basis of observations from the onshore Wilcox samples, average primary porosity in Wilcox sandstones at these high temperatures is likely to range from 0–4%, with an average of 1–2% of the whole-rock volume (Figs. 4 and 5). Secondary pores and micropores, which contribute less to permeability, are likely to compose 7–9% of the whole-rock volume (Fig. 3) or more, because of abundant microporosity in lithic grains. However, average primary porosity decreases at a somewhat slower rate in Louisiana Wilcox sandstones than in Texas Wilcox sandstones at temperatures <302°F (<150°C) (Figs. 3 and 5), therefore Wilcox sandstones below the deep Louisiana shelf at 450°F (230°C) might be predicted to contain more primary pores than Wilcox sandstones below the deep Texas shelf at the same temperature.

EVOLUTION OF POROSITY-PERMEABILITY TRANSFORMS

Core-analysis data from onshore Wilcox wells (Fig. 6) were used to calculate porosity-permeability transforms within different temperature intervals in each study area. These transforms are modeled as power-law relationships (following the methods of Bryant et al., 1993), which give realistic permeability estimates at low porosities (Jennings and Lucia, 2003). Porosity-permeability transforms were calculated for temperature intervals of <212°F (<100°C), 212–302°F (100–150°C), and >302°F (>150°C) (Fig. 7) (Dutton and Loucks, 2012). Because the total pore volume and the pore types present in the sandstones change with increasing temperature (Fig. 3) and burial diagenesis, one would expect that the porosity-permeability transforms also change with increasing temperature. A transform developed for low-temperature sandstones will not be appropriate to use in higher-temperature sandstones.

The porosity-permeability transforms for Wilcox sandstones from the upper Texas coast show the largest change with increasing temperature (Dutton and Loucks, 2010) (Fig. 7a). Most shallow Wilcox sandstones at temperatures <212°F (<100°C) have high porosity and permeability because abundant primary pores are present (Fig. 4). Intermediate temperature sandstones (212–302°F [100–150°C]) have lower permeability per porosity unit because many primary pores have been closed by mechanical compaction or occluded by quartz cement (Figs. 3a and 4). The wide range in abundance of primary and secondary pores results in a permeability range that spans several orders of magnitude (Fig. 7a). In the hottest sandstones (>302°F [>150°C]), permeability is mostly <1 md (Fig. 7a). Total porosity remains about the same as in sandstones at intermediate temperatures because microporosity increases as primary porosity decreases (Fig. 3a). Permeability is lower, however, because almost all the pores are secondary pores and micropores (Fig. 3a) that contribute little to permeability. The influence of grain size and sorting on the porosity-permeability transforms could not be evaluated because textural data were not available for most of the samples in the core-analysis database.

Similar trends with temperature are observed in the porosity-permeability transforms for Wilcox sandstones from the Rosita Delta System in the lower Texas coast (Fig. 7b). However, in the Rosita Delta sandstones, there are some high-permeability sandstones (100–1000 md) even in the highest temperature interval. Chlorite coats inhibit quartz cement in some lower Texas coast Wilcox sandstones, preserving more primary porosity (Fig. 4) and resulting in higher permeability than was observed in the sandstones from the upper Texas coast (Fig. 7a).

Porosity-permeability transforms for Louisiana Wilcox sandstones show little difference in the two temperature intervals (Fig. 7c). At temperatures between 212–302°F (100–150°C), primary pores compose a higher proportion of the total porosity in Louisiana Wilcox sandstones than in Wilcox sandstones from either the upper or lower Texas coast (Fig. 3). The slower loss of primary pores results in porosity-permeability transforms that do not change much over this temperature range.

Porosity-permeability transforms for Wilcox sandstones from the three different areas were also compared for each temperature interval (Fig. 8). At temperatures <212°F (<100°C), the transforms for all three areas are similar (Fig. 8a). At 212–302°F (100–150°C), Louisiana Wilcox sandstones have higher permeability per porosity unit those in the upper and lower Texas coast (Fig. 8b). At temperatures >302°F (>150°C), sandstones from the lower Texas coast have higher permeability per porosity unit than those from the upper Texas coast (Fig. 8c). No Louisi-

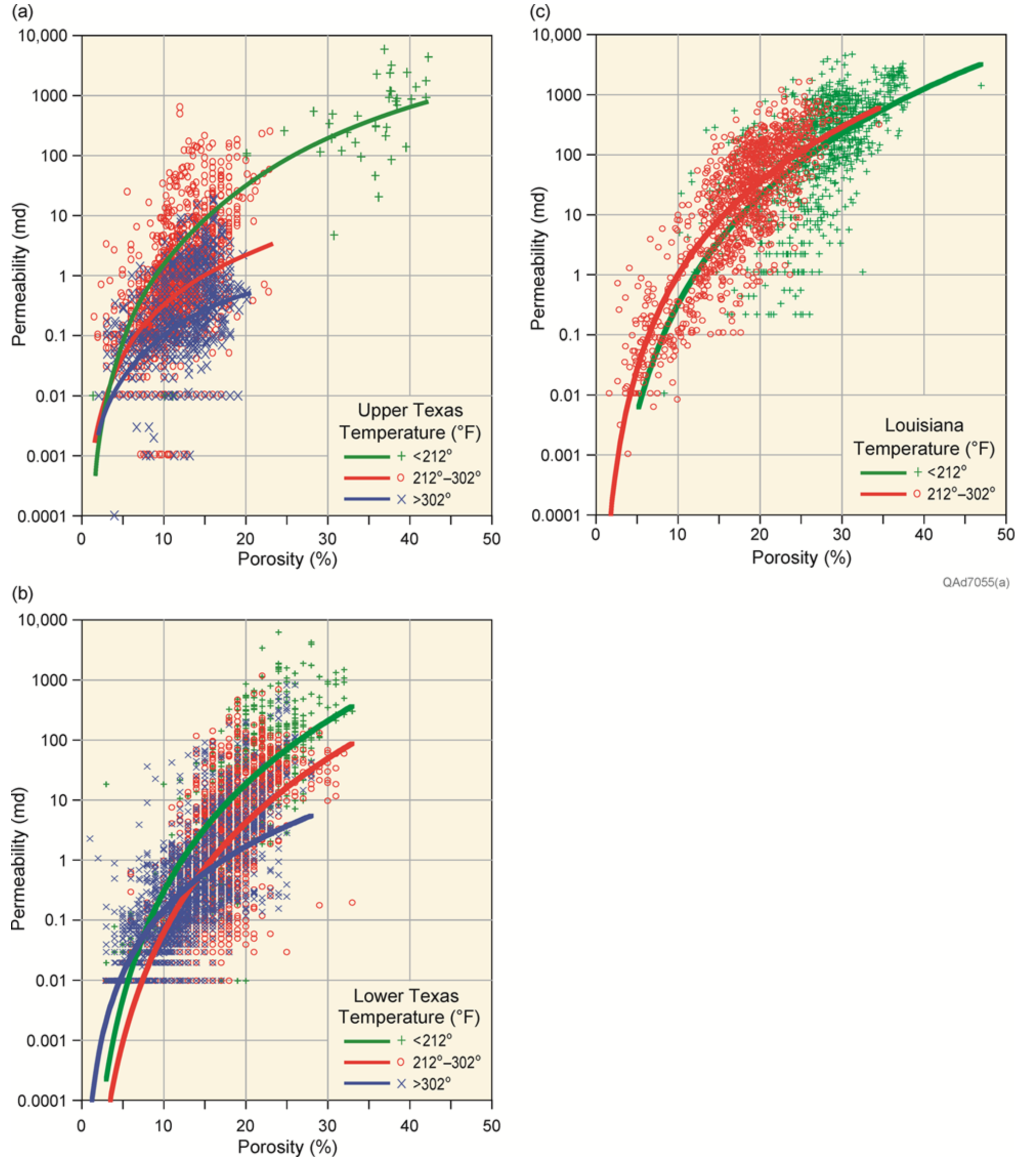

Figure 7. Porosity versus permeability plots for Wilcox sandstones in three temperature intervals [<212°F (<100°C), 212–302°F (100–150°C), and >302°F (>150°C)], showing power-law curve for each interval. In hotter sandstones, permeability is lower per porosity unit because most pores are secondary or micropores that contribute little to permeability. (a) upper Texas coast (modified after Dutton and Loucks, 2010), (b) lower Texas coast, and (c) Louisiana.

ana Wilcox samples were available from this temperature interval.

CONCLUSIONS

Petrographic and petrophysical data from onshore Wilcox sandstones in Texas and Louisiana were used to evaluate the evolution of porosity and permeability during burial diagenesis at temperatures ranging from 80–438°F (27–226°C). Primary pores are the most abundant pore type in most Wilcox sandstones at temperatures <212°F (<100°C), but at higher temperatures the total pore volume is a mixture of primary and secondary pores and micropores. At temperatures >390°F (>200°C), primary porosity composes only 1–2% of the whole-rock volume as determined from thin-section point counts. Secondary pores and micropores constitute 7–9% of the whole-rock volume at temperatures >390°F (>200°C).

Primary pores are the most important controls on permeability. Because the volume and proportion of pore types in Wilcox sandstones change with increasing temperature, porosity-permeability transforms for each area also change with temperature. At higher temperatures, permeability is lower per porosity unit because a smaller proportion of the total pores are primary pores. A transform developed for low-temperature sandstones will not be appropriate to use in higher-temperature sandstones. This is important to understand when attempting to calculate permeability from wireline-log data at different depths.

This study of pore types in onshore Wilcox sandstones provides insight into reservoir quality of deeply buried Wilcox sandstones beneath the present day shelf and in the deepwater Gulf of Mexico. Wilcox reservoirs in the deepwater Gulf of Mexico, which are at temperatures of ~265°F (~130°C), are likely to retain 5–8% average primary porosity. Wilcox sandstones below the Gulf of Mexico shelf are at temperatures >450°F (>230°C) and are likely to contain only 1–2% primary porosity, with the remainder of the total porosity composed of secondary pores and micropores. At temperatures >212°F (>100°C), onshore Wilcox sandstones from the Houston Delta System of the upper Texas coast have lower permeability for a given porosity than do Wilcox sandstones from either the Holly Spring Delta System in Louisiana or the Rosita Delta System in the lower Texas coast. These data suggest that high-temperature Wilcox sandstones beneath the present shelf and in the deep Gulf that were sourced by the Holly Springs and Rosita deltas may have better reservoir quality than do sandstones derived from the Houston Delta.

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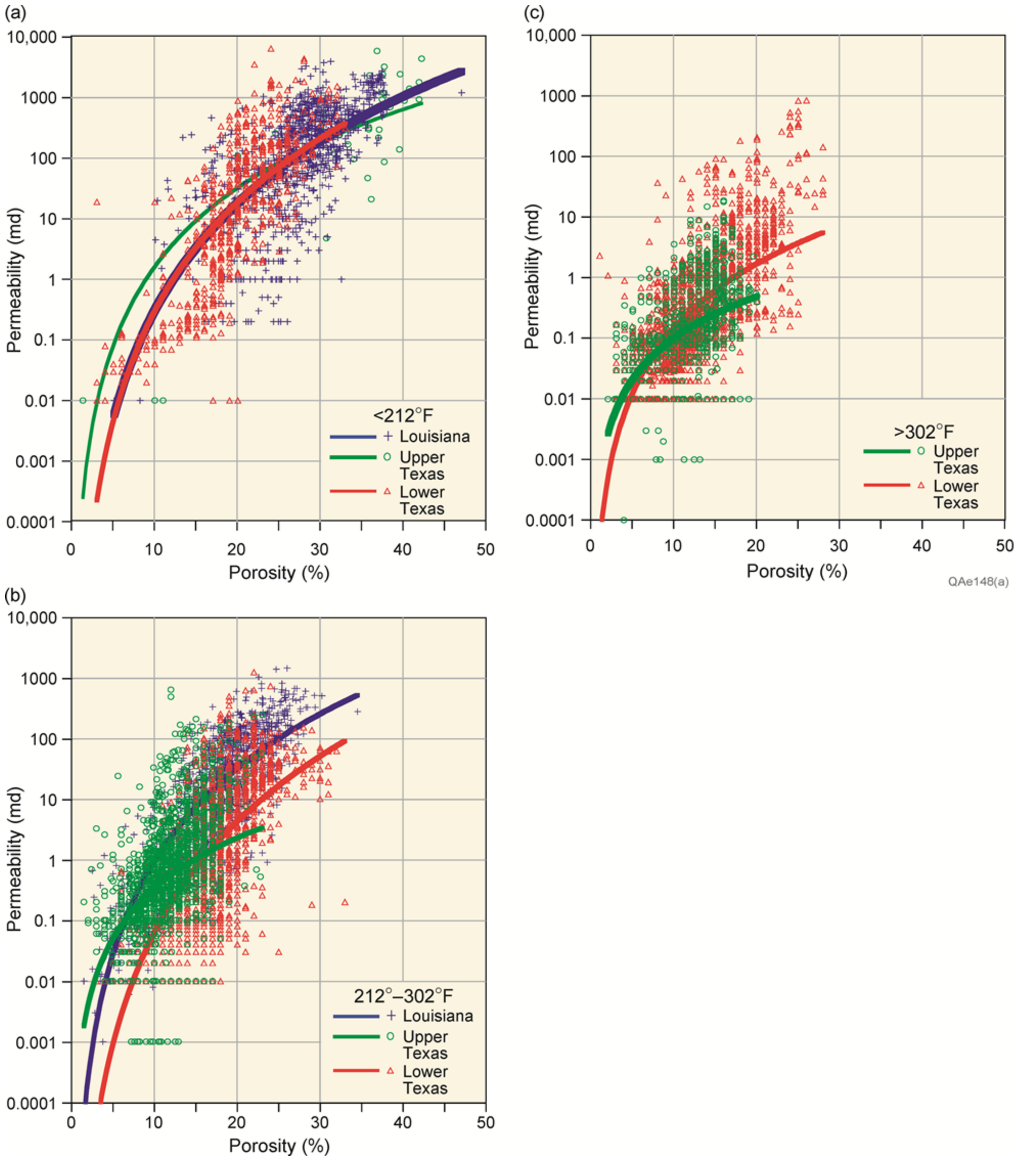

Figure 8. Porosity versus permeability power-law curves for Wilcox sandstones in specific temperature slices from three different areas. (a) sandstones at temperatures <212°F (<100°C), b) sandstones at temperatures from 212–302°F (100–150°C), and, (c) temperatures >302°F (>150°C).

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