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Diagenetic Controls on Reservoir Quality in Deep Upper Wilcox Sandstones of the Rio Grande Delta System, South Texas

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ABSTRACT

Upper Wilcox sandstones in far South Texas were deposited in the Rio Grande Delta system. Petrographic analysis of these Eocene sandstones was conducted on reservoirs from Fandango Field in Zapata County, Texas, which produces gas from Wilcox sandstones at depths of 14,800 to 18,000 ft (4.5 to 5.6 km). The goal of the study was to determine the influence of detrital composition, texture, and diagenesis on reservoir quality. Study of reservoir quality in these sandstones is pertinent to predicting reservoir quality of upper Wilcox sandstones in the Perdido Fold Belt area in the deep Gulf of Mexico along the boundary between U.S. and Mexican waters.

Wilcox sandstones in Fandango Field are mostly sublitharenites, feldspathic litharenites, and litharenites, having an average composition of 71.9% quartz, 8.5% feldspar, and 19.6% rock fragments. Mean grain size ranges from lower to upper very fine sandstone. Quartz is the most abundant authigenic mineral (average whole-rock volume = 9.5%), followed by chlorite (4.5%) and carbonates (calcite, Fe–calcite, and ankerite = 3.0%). Some sandstone intervals in Fandango Field retain anomalously high porosity (≥20%) and permeability (≥10 md) at temperatures >400°F (>204°C) because extensive, continuous chlorite coats inhibited later quartz cementation. Other sandstones at the same depth and temperature are tightly cemented by quartz. Chlorite cement is more abundant in coarser grained sandstones, and there is a statistically significant correlation between chlorite-cement volume and permeability.

Wilcox sandstones in the Texas Gulf Coast show a clear trend of decreasing average and maximum permeability with increasing temperature. Upper Wilcox sandstones from Fandango Field, however, have permeability that is significantly higher than the regional trend as a result of the chlorite coats. Different provenance is interpreted as the reason for the formation of greater volumes of chlorite cement in Fandango Field than in other Wilcox sandstones. We interpret that the weathering of volcanic rock fragments and other iron-bearing minerals in the source area contributed iron to the Rio Grande fluvial system, which then transported the iron to the shallow-marine setting. Clay precursors formed where amorphous iron hydroxides carried in river water flocculated when mixed with seawater. Precursor clay flakes developed parallel to detrital grains by mechanical accretion as grains were rolled around by currents. The parallel-aligned clays provided a substrate for later precipitation of chlorite crystals oriented perpendicular to the grains. It is the presence of abundant, continuous chlorite coats that results in anomalously high porosity and permeability in some Fandango Field sandstones.

This study of detrital mineral composition and diagenesis of upper Wilcox sandstones in Fandango Field may provide insight into reservoir quality of Wilcox sandstones in the deepwater Gulf of Mexico. The Eocene Rio Grande system was a possible source of sand deposited in deepwater turbidites in the Perdido Fold Belt area. The iron-rich source area for the sediments might have led to development of chlorite coats in these deepwater sandstones and contributed to reservoir-quality preservation.

INTRODUCTION

Paleogene sandstones of the Wilcox Group are important exploration targets in the offshore Gulf of Mexico (Lewis et al., 2007), but reservoir quality and deliverability are critical risk factors in this play (Marchand et al., 2015). Petrographic study of the composition and diagenesis of onshore Wilcox sandstones provides insight into potential regional variations in reservoir quality in offshore Gulf of Mexico reservoirs.

Wilcox sandstones were sourced by continental-scale drainage systems that terminated in deltas in Texas and Louisiana (Galloway et al., 2000, 2011). Eocene upper Wilcox sandstones in far South Texas, which were deposited in the Rio Grande Delta system (Galloway et al., 2011), are the focus of this study.

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Previous petrographic studies of Wilcox sandstones in Texas have mainly investigated sandstones deposited farther north, in the Houston and Colorado delta systems (Loucks et al., 1984, 1986; Fisher and Land, 1986; Dutton and Loucks, 2010; Dutton et al., 2015b). Wilcox sandstones in the Rio Grande system, which were derived from different source areas and were deposited in a region with a higher geothermal gradient, have undergone a somewhat different diagenetic history. In particular, early development of chlorite coats was more extensive in Wilcox sandstones deposited in the Rio Grande Delta (this study) than in Wilcox deltas in other areas (Loucks et al., 1986; Dutton and Loucks, 2010; Dutton et al., 2015b), which resulted in preservation of better reservoir quality at high temperatures (>400°F [>204°C]).

Petrographic analysis of upper Wilcox sandstones in the Rio Grande Delta system was conducted using core samples from seven wells in Fandango Field, Zapata County, Texas (Fig. 1). The samples studied are from depths of 13,731 to 18,181 ft (4185 to 5541 m) and temperatures of 377 to 462°F (192 to 239°C). Fandango reservoirs are interpreted to have been deposited in shoreface/wave-dominated-delta environments (Ambrose et al., 2016, this volume). For comparison, petrographic analysis was conducted on samples of upper Wilcox sandstones deposited in the Colorado Delta system. These sandstones from Rosita Northwest Field in Duval County (Fig. 1) were also deposited in a shoreface/wave-dominated-delta environment.

The objective of this study is to determine the influence of detrital mineral composition, texture, and diagenesis on reservoir quality in these onshore Wilcox reservoirs. Study of reservoir quality in sandstones from the Rio Grande Delta system may be particularly applicable to predicting reservoir quality of upper Wilcox sandstones in the deepwater Perdido Fold Belt area along the boundary between U.S. and Mexican waters (Fig. 1).

GEOLOGIC SETTING

Wilcox sandstones, which were deposited during late Paleocene and early Eocene time, were the first major clastic influx into the Gulf of Mexico in the Cenozoic (Fisher and McGowen, 1967; Galloway et al., 2000, 2011). Extensive fluvial drainage networks carried sediment of varied composition from diverse source areas in central and western North America and delivered it to Wilcox deltas on the northwest margin of the Gulf. Farther downdip, the Wilcox Group contains gravity-flow sandstones deposited on the slope and in basin-floor fans in the deepwater Gulf of Mexico.

Upper Wilcox sandstones in Fandango Field, Zapata County, in far South Texas (Fig. 1) were deposited in the Rio Grande Delta system during the early Eocene (Levin, 1983; Galloway et al., 2011). The Rio Grande was one of three large fluvial systems that carried sediment to the Gulf of Mexico during the early

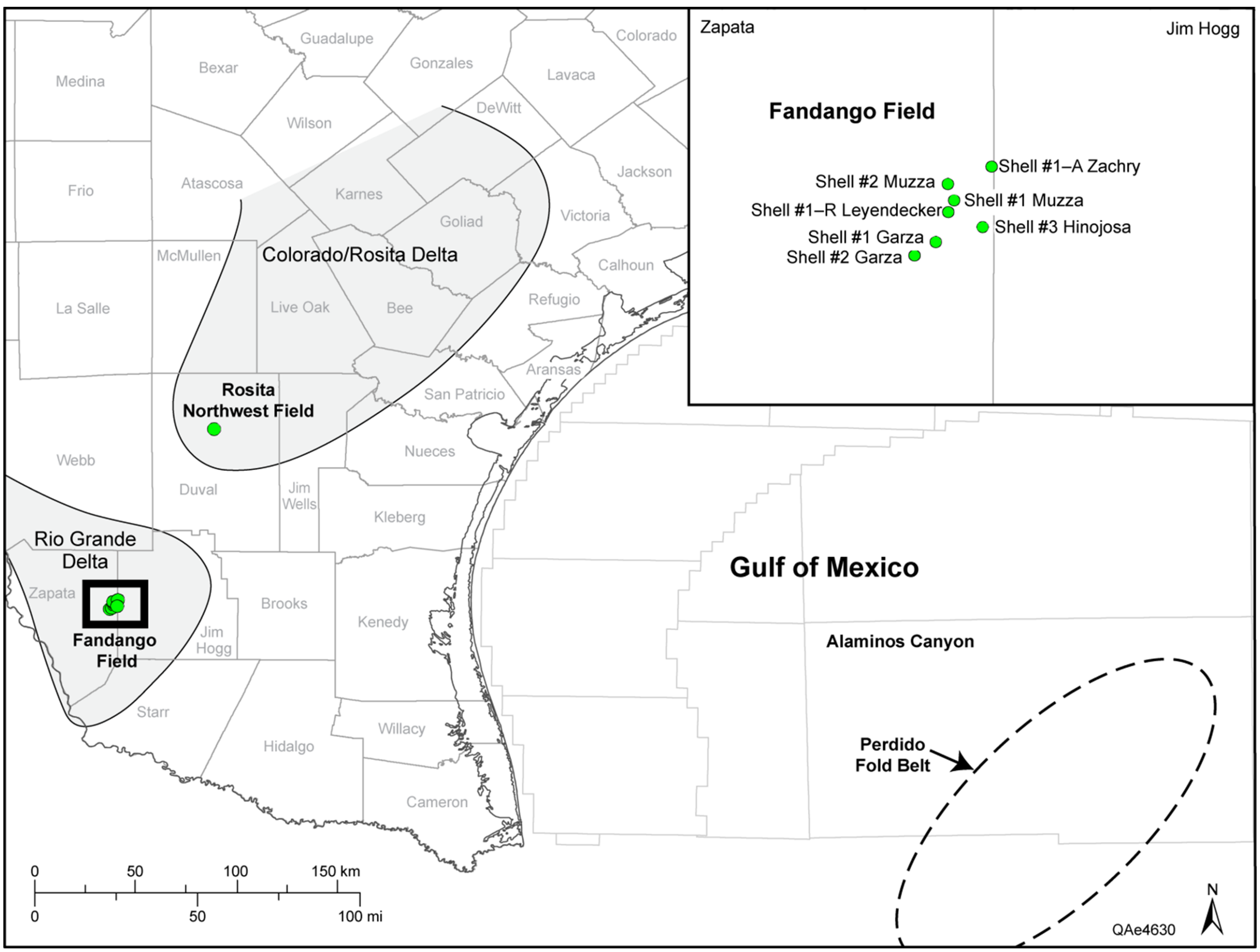


Figure 1. Location of wells with thin sections used in petrographic study of upper Wilcox sandstones, Fandango Field, Zapata County, Texas. Location of Shell #2 Weatherby well, Rosita Northwest Field, Duval County, Texas, is also shown. Outlines of the early Eocene Rio Grande and Colorado deltas are from Galloway et al. (2011).

Eocene and fed deltas along the Texas paleo-coastal plain (Galloway et al., 2011). From south to north, these were the Rio Grande Delta, the Colorado Delta (also called the Rosita Delta [Edwards, 1981]), and the Houston-Brazos Delta (Galloway et al., 2011). Fandango Field consists of a series of stacked upper Wilcox sandstones in a faulted rollover anticline that is associated with a major listric growth fault (Levin, 1983; Wilson et al., 1992). Upper Wilcox sandstones in Fandango Field were deposited in shoreface/wave-dominated delta environments (Ambrose et al., 2016, this volume).

The Eocene Rio Grande fluvial/deltaic system was a possible source of upper Wilcox sand deposited in deepwater in the Perdido Fold Belt area (Fig. 1) (Fulthorpe et al., 2014). Upper Wilcox deposits in the western Gulf of Mexico are interpreted to be basin-floor aprons that were derived from broad line sources and not from point-sourced submarine fans (Fulthorpe et al., 2014).

METHODS

Composition of the Fandango Field sandstones was determined by standard thin-section petrography. Matrix-poor (clean) sandstones were sampled preferentially because most conventional reservoirs are clean sandstones. Point counts were completed on 59 thin sections from seven wells (Fig. 1). 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). Two hundred counts per thin section were done because (1) more samples could be counted, and (2) counting error is improved only moderately with more counts. For example, if 400 counts are made, a constituent that composes 50% of the sample has an error of ±2.5%, whereas a constituent that is 10% has an error of ±1.5% and one that is 2% of the sample has an error of ±0.65% (Folk, 1974). For this reconnaissance study, point counting additional thin-section samples was more important than having greater precision from a smaller number of samples. Grain size and sorting were determined by measuring the long diameter of 100 competent grains (quartz and feldspar) per thin section.

Ambient, in-situ well temperature for each sample was calculated 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. Bottom-hole temperature corrections were done using the time-since-circulation correction found at the following website: http://zetaware.com/utilities/bht/timesince.html.

Mean annual surface temperature, which was used to calculate temperature at depth, is 73.6°F (23.1°C) in Zapata County (U.S. Climate Data, 2016). Calculated geothermal gradients in wells used in this study range from 2.13 to 2.21°F/100 ft (38.6 to 40.3°C/km), and calculated subsurface temperatures of the samples used in this study range from 377 to 462°F (192 to 239°C). Wilcox sandstones in Fandango Field are not at their maximum burial depth now. Strata were eroded from the updip part of the Texas coastal plain during the Oligocene and Miocene (Galloway et al., 1986), and maximum burial depth of Wilcox sandstones in Zapata County was an estimated 2500 ft (762 m) deeper than present depth (McBride et al., 1991). Maximum temperatures may have been approximately 54°F (30°C) higher than at present, assuming the present geothermal gradient.

Core-analysis porosity data were available from 703 samples of Wilcox sandstones from seven wells in Fandango Field, and 624 of these samples also have permeability analyses. Porosity and permeability analyses from 4701 samples were available from Wilcox sandstones in other areas of South Texas; most of these data are from upper Wilcox sandstones in the Colorado/Rosita Delta system (Dutton et al., 2015b). 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; most of the data are Klinkenberg corrected.

RESULTS

Texture

Upper Wilcox sandstones in Fandango Field have a narrow range of mean grain sizes, from lower to upper very fine grained sandstone. Average grain size of Wilcox sandstones in this study is 3.4 phi (0.098 mm) and the range is from 4.0 phi (0.063 mm) to 3.1 phi (0.116 mm). Most of the samples are well sorted (0.35 to 0.5 phi standard deviation, as defined by Folk [1974]). The coarsest sandstones in Fandango Field occur in transgressive deposits (average grain size = 3.25 phi [0.105 mm]) and upper-shoreface/proximal-delta-front deposits (average grain size = 3.32 phi [0.101 mm]). Finer-grained sandstones occur in lower-shoreface/distal-delta-front facies (average grain size = 3.56 phi [0.086 mm]) and in middle-shoreface facies (average grain size = 3.58 phi [0.085 mm]).

Framework Grain Composition

Upper Wilcox sandstones in Fandango Field are classified as sublitharenites, feldspathic litharenites, and litharenites (Folk, 1974) (Fig. 2). The average composition is 71.9% quartz, 8.5% feldspar, and 19.6% rock fragments ($Q_{71.9}F_{8.5}R_{19.6}$).

Plagioclase is the most abundant feldspar type observed, averaging 5.8% of the whole-rock volume. Some plagioclase grains are partly dissolved or replaced by calcite or ankerite. A significant volume of the originally deposited plagioclase has been removed by dissolution, generating secondary intragranular and moldic porosity. Estimated original composition of the upper Wilcox sandstones in Fandango Field was $Q_{66.4}F_{15.4}R_{18.2}$. Original composition was calculated by adding the volume of: (1) secondary pores within feldspars; (2) oversize pores whose origin is unknown; and (3) grain-replacing carbonate minerals to the total volume of existing feldspar and recalculating the ratio of quartz:feldspar:rock fragments. This method assumes that oversize pores of unknown origin are dissolved feldspars.

It is likely that potassium feldspar was also present, but it has been dissolved or replaced by authigenic carbonate during diagenesis. The only potassium feldspars observed were remnants of a few grains that were mostly replaced by calcite. No kaolinite was observed.

Lithic grains include volcanic (3% average whole-rock volume), metamorphic (9%), sedimentary (2%), and plutonic (0.2%) rock fragments. Most VRFs (volcanic rock fragments) are partly to completely dissolved, and some are silicified or replaced by authigenic chlorite. Both MRFs (metamorphic rock framents) and VRFs have undergone ductile-grain deformation. Chert is the most common SRF (sedimentary rock fragments; 1.5% average).

Wilcox sandstones in Fandango Field contain less total feldspar than sandstones in Rosita Northwest Field in Duval County to the north (Fig. 2), which is located in the Colorado/Rosita Delta system (Fig. 1). Current average composition of upper Wilcox sandstones in Rosita Northwest Field is $Q_{66.0}F_{19.9}R_{14.1}$, compared to $Q_{71.9}F_{8.5}R_{19.6}$ in Fandango Field (Fig. 2). The difference in feldspar content in the two fields is attributed to differences in provenance, with more feldspar being derived from the Rocky Mountains, the main source area for sediment in the Colorado/Rosita Delta system (Galloway et al., 2011). The Rio Grande system had a more diverse source area (Galloway et al., 2011;

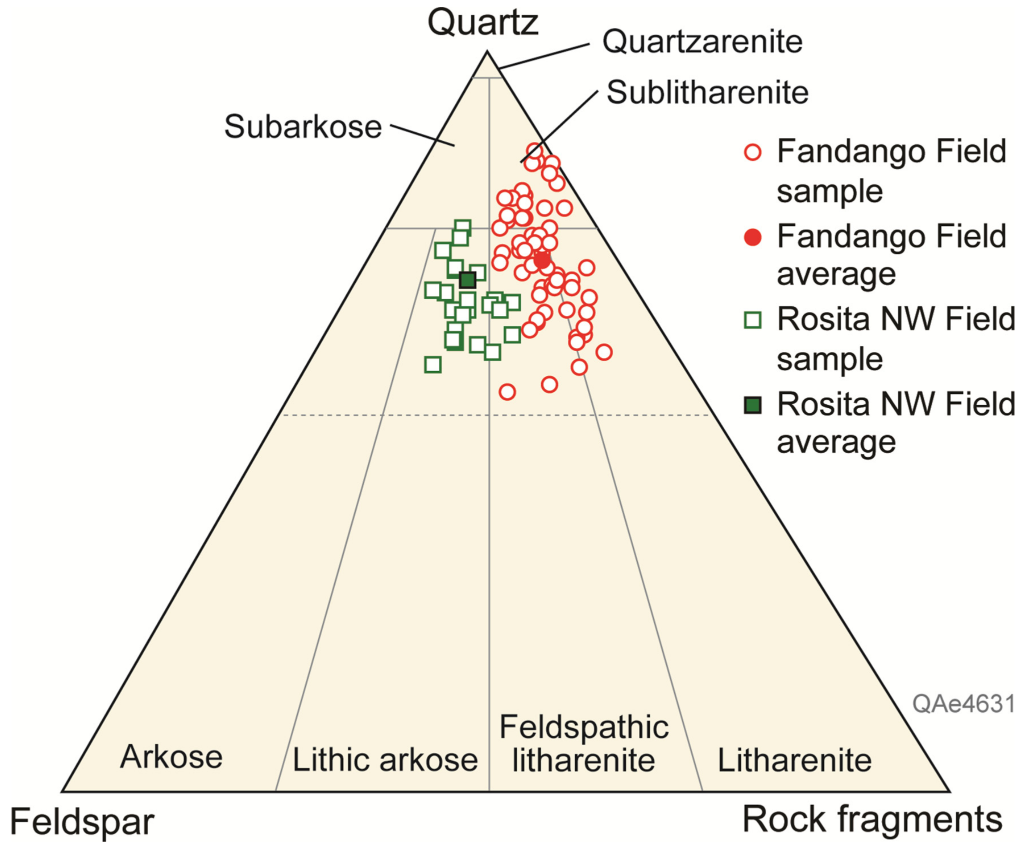


Figure 2. Compositional classification of upper Wilcox sandstones from Fandango Field, Zapata County, Texas. Classification of Folk (1974). Composition of upper Wilcox sandstones from the Shell #2 Weatherby well in Rosita Northwest Field, Duval County, Texas (Fig. 1) shown for comparison. Samples from Rosita Northwest Field are from depths of 14,822 to 15,049 ft (4517 to 4586 m).

Mackey et al., 2012), which resulted in a higher proportion of rock fragments in upper Wilcox sandstones in Fandango Field. Estimated original composition of upper Wilcox sandstones in Fandango Field averages $Q_{66.4}F_{15.4}R_{18.2}$, but estimated original composition of upper Wilcox sandstones in Rosita Northwest Field averages $Q_{58.3}F_{29.1}R_{12.6}$.

Matrix

Detrital clay matrix constitutes between 0 and 12% of the whole-rock volume in these samples. Many sandstones in Fandango Field are heavily burrowed and contain a higher volume of clay matrix (Ambrose et al., 2016, this volume), but matrix-poor (clean) sandstones were sampled preferentially for this study. Thin-section point counts of burrowed sandstones from the Shell #1 Muzza core (Fig. 1) at depths of 13,731 to 13,751 ft (4185 to 4191 m) identified 6–8% detrital clay matrix in middle- and upper-shoreface/wave-dominated-delta samples. X-ray analysis of samples from these depths determined that the clays are 48–58% illite-smectite (having 40–45% smectite layers), 24–31% chlorite, and 15–23% illite. The temperature of these #1 Muzza sandstone samples is 377°F (192°C).

Cements and Diagenetic History

Cements and replacement minerals constitute between 9.5 and 35.5% of the sandstone volume in upper Wilcox thin-section samples from Fandango Field. Quartz cement is the most abundant authigenic mineral (average whole-rock volume = 9.5%), followed by chlorite (4.5%) and carbonates (calcite, Fe–calcite, and ankerite; 3.0%). Other authigenic minerals, present in minor volumes, include illite, pyrite, leucoxene, albite, siderite, and sphene.

On the basis of petrographic evidence, the relative order of occurrence of the major events in the diagenetic history of upper Wilcox sandstones from Fandango Field is: (1) mechanical compaction by grain rearrangement and deformation of ductile grains; (2) formation of chlorite coats; (3) precipitation of quartz overgrowths; (4) precipitation of calcite and Fe–calcite cement and grain replacement; (5) dissolution of potassium feldspar (K–spar) and albitization of plagioclase; and (6) 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).

Compaction

Mechanical compaction caused significant porosity reduction in Fandango Field sandstones. Compaction took place both by rearrangement of mechanically stable grains, such as quartz and feldspar, and deformation of ductile grains, such as mud clasts, micas, VRFs, and MRFs. Intergranular volume (IGV) in Wilcox sandstones in Fandango Field averages 20.4% (calculated by the method of Houseknecht, 1987). An inverse relationship exists between IGV and volume of rock fragments in Fandango Field because most lithic grains are ductile. Thus, mechanical compaction was most extensive in Wilcox sandstones containing abundant ductile grains.

Chemical compaction processes such as intergranular pressure solution reduce porosity by causing closer packing of framework grains. Intergranular pressure solution of quartz and other grains was observed, particularly along clay laminae, as well as dissolution along stylolites inclined at a high angle to bedding.

Compaction was the dominant porosity-reducing process in the upper Wilcox sandstones in Fandango Field. The average amount of porosity lost by compaction (COPL), calculated by the method of Ehrenberg (1989), is 23 porosity units out of the assumed initial 40 porosity units. After compaction, these sandstones would have about 22% bulk-rock-volume porosity (Ehrenberg, 1989). Final reservoir quality in most sandstones was determined by the extent to which the remaining primary pores and pore throats were occluded by cement during continued burial. Wilcox sandstones in Fandango Field lost an average of 11.9 porosity units by precipitation of cement in primary pores (CEPL).

Chlorite Cement

A key characteristic of some Wilcox sandstones in Fandango Field is the presence of thick, continuous chlorite coats on detrital grains (Fig. 3). These sandstones retain anomalously high porosity (≥20%) and permeability (≥10 md) at temperatures >400°F (>204°C) because the chlorite coats inhibited quartz cementation (Fig. 3A). Although most Fandango Field sandstones contain some chlorite cement, there is large variation in the volume of chlorite, ranging from 0 to 11.5% (average 4.5%). Chlorite cement has been observed in all facies but is most abundant in upper-shoreface/proximal-delta-front deposits (average volume = 4.8%) and in transgressive deposits (5.7%). In comparison, lower-shoreface/distal-delta-front and middle-shoreface deposits contain an average of 2.0 and 2.4% chlorite cement, respectively.

The percentage of detrital-grain coverage by chlorite was not quantified but was estimated in a few samples. Because almost all of the chlorite cement in the Fandango sandstones occurs as grain coats and not as pore-filling cement, volume of chlorite cement determined by point counts is an indicator of chlorite coverage. Samples that have a larger volume of chlorite cement will have more chlorite cement coating grains. This approach is supported by the observation that a statistically significant correlation between chlorite-cement volume and grain-coat coverage occurs in Cretaceous Tuscaloosa sandstones in central Louisiana (Dutton et al., 2015a). Tuscaloosa sandstones also contain thick, continuous chlorite coats that preserve porosity by inhibiting quartz cementation (Thomson, 1979; Smith, 1985; Pittman et al., 1992).

A Fandango sample containing 11.5% chlorite cement (Fig. 3A) is estimated to have 97% chlorite-coat coverage (R. Tobin, 2015, personal communication). This sample contains only 1% quartz cement. Many Wilcox sandstones in Fandango Field have only partial chlorite-coat coverage (Fig. 3B). Where detrital quartz grains are not completely covered by chlorite coats, quartz cement was able to precipitate and occlude much of the intergranular porosity. Even where clay rims are continuous on one grain, quartz cement commonly was able to nucleate on an adjacent grain and fill primary pores. The sandstone in Figure 3B, which contains a volume of 4.5% chlorite cement, is estimated as having 55% chlorite-coat coverage (R. Tobin, 2015, personal communication). Volume of quartz cement in this sample is 16.5%.

Many detrital grains in Fandango Field have two layers of chlorite (Fig. 4). The first layer consists of small chlorite crystals (≤1.5 µm long) forming rims (cutans) oriented parallel to the grains, overlain by larger chlorite crystals (5 µm) forming coats oriented perpendicular to the grains (Fig. 4). Energy-dispersive X-ray analysis (EDX) in a scanning electron microscope (SEM) indicates that both types of chlorite are iron-rich. Chlorite rims and coats can be clearly seen in sandstone samples prepared by argon-ion milling for viewing in SEM (Fig. 5). The argon-ion-milling technique produces a flat surface that is suitable for high-magnification imaging in SEM (Loucks et al., 2009). This process provides excellent resolution of grain/cement boundaries in sandstones (Dutton et al., 2016).

Authigenic Quartz

Quartz is the most abundant cement in Wilcox sandstones in Fandango Field, having an average volume of 9.5% in the thin-section samples and ranging from 1 to 21.5%. Clean sandstones with little clay matrix were sampled preferentially for this study, and these clean sandstones are likely to contain more quartz cement than do matrix-rich sandstones.

Wilcox sandstones in Fandango Field have a wide range of quartz-cement volume, from 0 to 21.5%. Most of the samples with low volumes of quartz cement contain continuous chlorite coats (Figs. 3A and 6), but others are tightly cemented by carbonate or contain abundant detrital clay matrix associated with burrows (Ambrose et al., 2016, this volume). Wilcox sandstones that contain a large volume of quartz cement (Fig. 3B) have incomplete chlorite coats that were not sufficiently thick and continuous to inhibit quartz cementation at temperatures >375°F (190°C) Chlorite coats inhibit quartz cementation by reducing the detrital-quartz surface area available for quartz-cement nuclea-

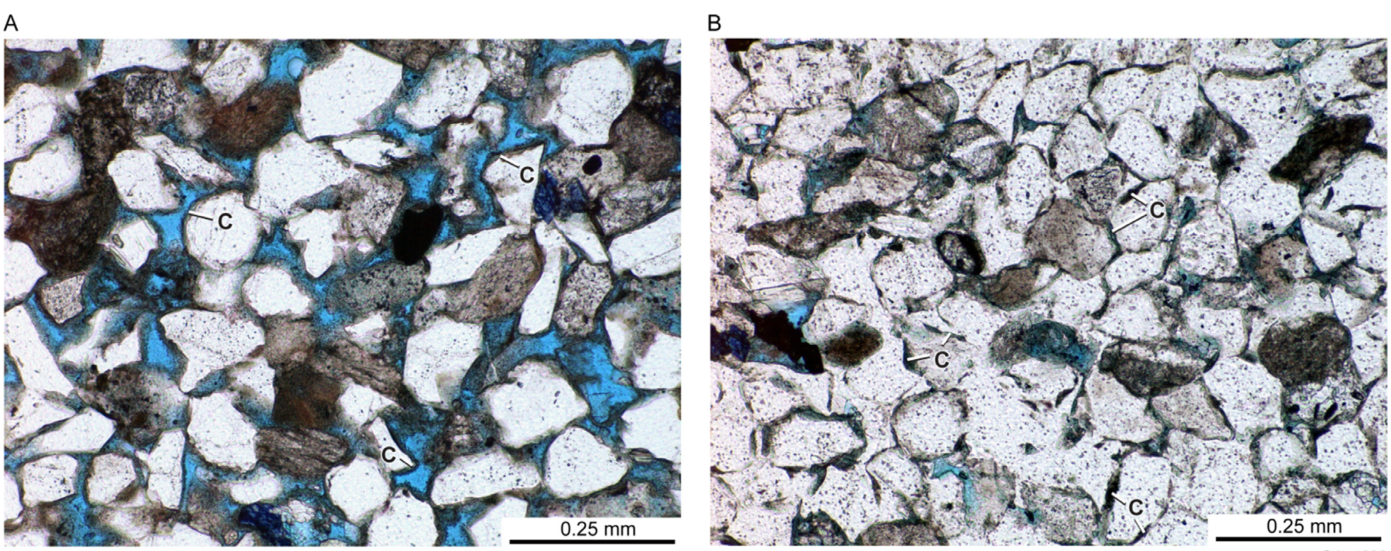
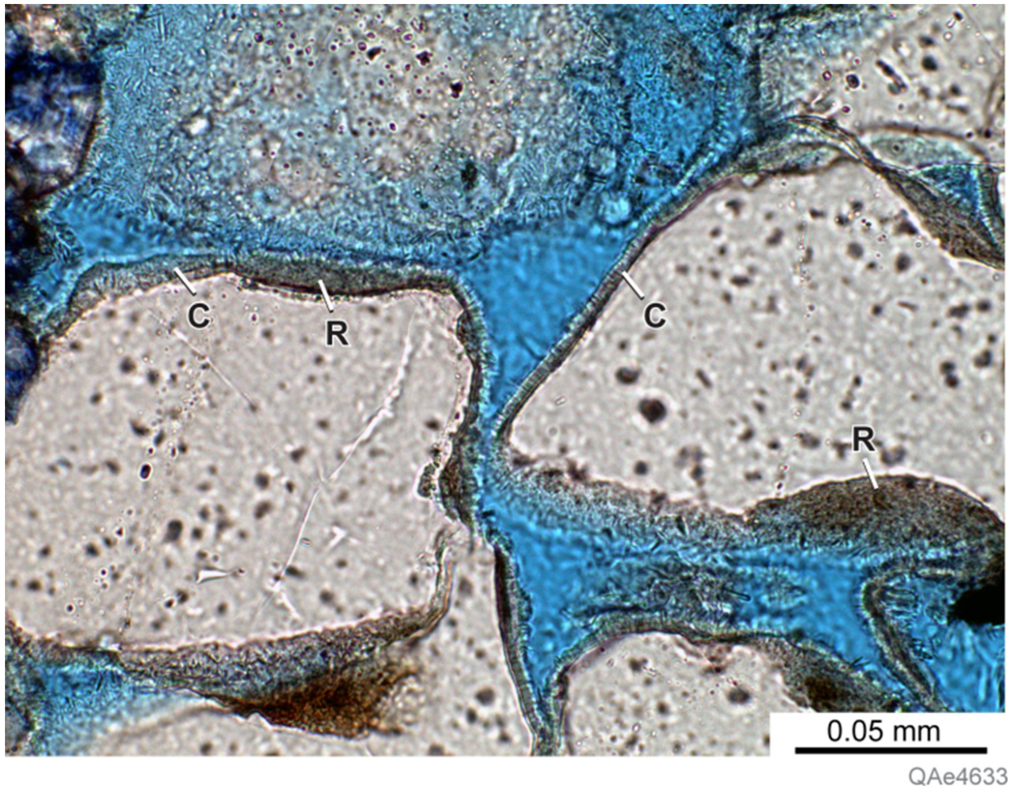


Figure 3. Chlorite coats occur on many detrital grains in upper Wilcox sandstones from Fandango Field, Zapata County, Texas. (A) Sandstone from the Shell #1 Garza well at a depth of 16,122 ft (4914.0 m) with continuous chlorite coats (labelled as C) that inhibited quartz cementation. Sample contains 11.5% chlorite cement, 1% quartz cement, and 9.5% primary porosity. Average grain size is 3.22 phi (0.107 mm). Plane-polarized light. (B) Sandstone from the Shell #1 Garza well at a depth of 16,138 ft (4918.9 m) with partial chlorite-coat coverage (labelled as C). Sample contains 4.5% chlorite cement, 16.5% quartz cement, and 2.0% primary porosity. Average grain size is 3.23 phi (0.106 mm). Plane-polarized light.

Figure 4. Two layers of chlorite occur on some detrital grains in upper Wilcox sandstones from Fandango Field, Zapata County, Texas. Sandstone from Shell #2 Muzza well at a depth of 15,182 ft (4627.5 m) with small chlorite crystals forming rims (R) oriented parallel to detrital grains and larger chlorite crystals forming coats (C) oriented perpendicular to the grains. Average grain size is 3.16 phi (0.112 mm). Plane-polarized light.



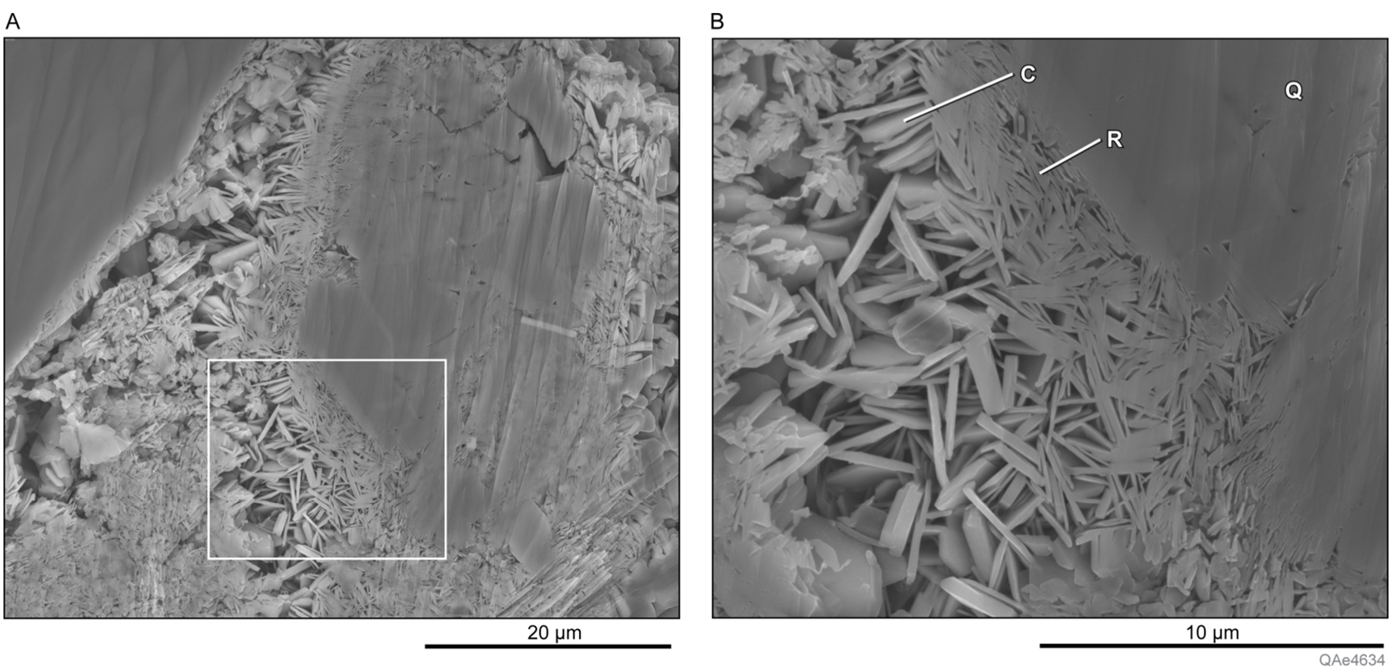


Figure 5. Chlorite rims and coats in upper Wilcox sandstones from Shell #2 Muzza well at a depth of 15,182 ft (4627.5 m), Fandango Field, Zapata County, Texas. Sample prepared by argon-ion-milling. (A) Detrital grains covered by chlorite crystals oriented parallel and perpendicular to grains. Box shows area of Figure 5B. (B) Chlorite crystals occur as rims (R) oriented parallel to detrital quartz grain (Q), overlain by larger chlorite crystals forming coats (C) oriented perpendicular to the grain. Photos by Patrick Smith.

tion. 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. Taylor et al. (2004) found that clay rims in the Norphlet sandstone needed to be 99% complete to retard quartz cement at temperatures of 392 to 430°F (200 to 220°C). Where Norphlet chlorite rims are only 92% complete, quartz cement fills the primary pores (Taylor et al., 2004).

The volumes of chlorite cement and quartz cement in Wilcox sandstones have a statistically significant inverse relationship at the 99% confidence level (Fig. 7), and thus the null hypothesis that the two variables are not correlated can be rejected. There is

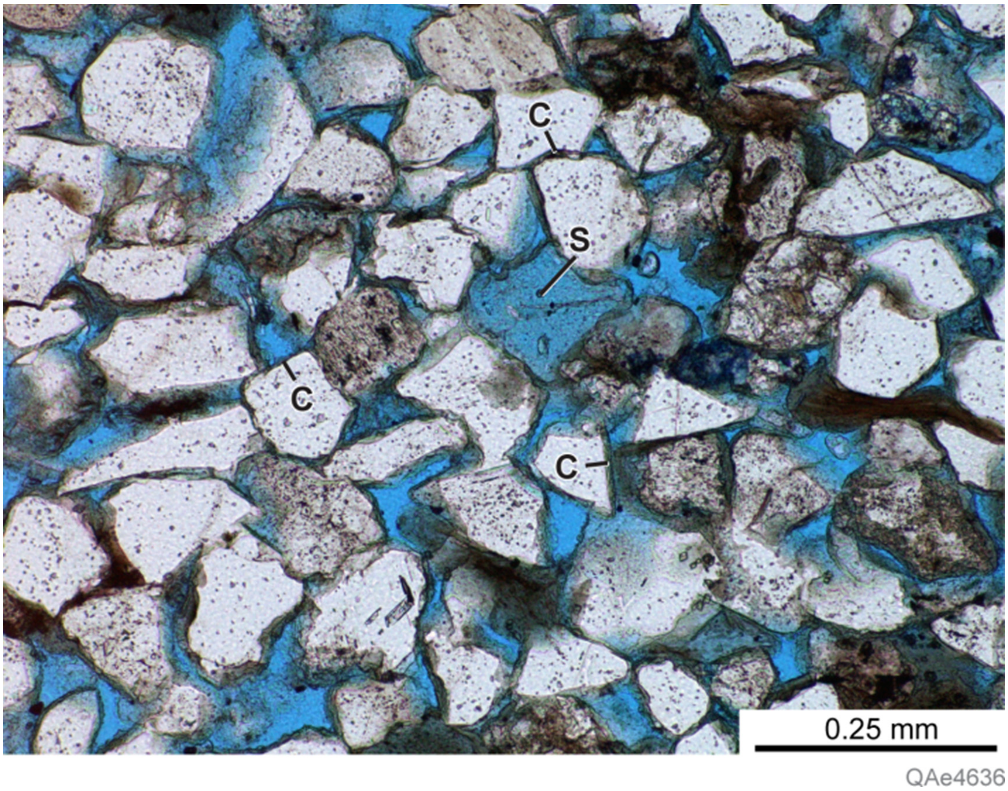


Figure 6. Continuous chlorite coats (C) inhibited quartz cementation in upper Wilcox sandstone from the Shell #2 Muzza well, Fandango Field, Zapata County, Texas, at a depth of 15,182 ft (4627.5 m). Sample contains only 1% quartz cement at a temperature of 397°F (203°C). Secondary pore (S) is outlined by chlorite cement. Porosity = 25.6% and permeability = 68 md. Average grain size is 3.16 phi (0.112 mm). Plane-polarized light.

considerable scatter in the data. A higher correlation coefficient might be observed between chlorite-coat coverage and volume of quartz cement (Taylor et al., 2004; Ajdukiewicz et al., 2010). Chlorite-cement volume ranges from 0 to 11.5%. We compared the quartz-cement content of sandstones that have higher volumes of chlorite cement (6.0 to 11.5%) with those that have lower volumes of chlorite cement (0 to 5.5%). Sandstones containing ≥6% chlorite cement have an average of 6.8% quartz cement, whereas sandstones that contain <6% chlorite cement have an average of 10.8% quartz cement (Table 1). It is hypothesized that where chlorite whole-rock volume is ≥6%, many of the chlorite coats are sufficiently continuous to inhibit quartz cementation at these temperatures.

Authigenic Carbonate

Calcite, Fe–calcite, and ankerite are the main authigenic carbonate minerals in the Wilcox sandstones in Fandango Field, although minor volumes of dolomite and siderite occur as well. Calcite and Fe–calcite occur in primary, intergranular pores and as grain replacements of unstable grains, mainly feldspars. Ankerite most commonly occurs as a grain-replacement mineral, particularly replacing feldspar and chert, but some is also present in primary pores. The average total volume of carbonate cement and grain-replacement minerals in Fandango Field sandstones is 3.0%, as determined by thin-section point counts. Of that, an average of 1.0% is primary-pore-filling cement and 2.0% is grain replacement.

The volume of authigenic carbonate varies with depositional environment. Authigenic calcite and Fe–calcite are most abundant in middle-shoreface and transgressive deposits, whereas ankerite is most abundant in lower-shoreface/distal-delta-front and upper-shoreface/proximal-delta-front deposits. Most calcite and Fe–calcite precipitated after quartz cement; it is common to see quartz overgrowths under pore-filling calcite. However, it appears that at least some of the calcite concretions formed early, before quartz cementation.

Carbonate cement is not a major control on reservoir quality in Fandango Field sandstones. Most samples contain <2% carbonate cement, and only 4 samples contain >7% primary-pore-filling carbonate cement.

Porosity

Total thin-section macroporosity (primary + secondary porosity) quantified by point counts of Wilcox sandstone samples from Fandango Field averages 8.6% and ranges from 0 to 23.0%. Average primary porosity is 4.9% and ranges from 0 to 12% (Fig. 8). Average secondary porosity is 3.7% and ranges from 0 to 13%. High values of primary porosity (5 to 12%) have been preserved in some samples at temperatures as high as 421°F (216°C) (Fig. 8) by the presence of continuous chlorite coats on detrital grains. As shown in Figure 8, Fandango sandstones at temperatures >378°F (>200°C) have retained higher average primary porosity (4.7%) than Wilcox sandstones at equivalent temperatures from the rest of the South Texas coast (2.3%) (Dutton and Loucks, 2014).

Core-analysis porosity measured by porosimeter represents total porosity, the sum of primary and secondary pores as well as micropores (Pittman, 1979). Average total porosity in the 703 Fandango sandstones having porosimeter data is 13.4% and ranges from 4.5 to 26.3%. 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 is 7.6% in the 57 samples with thin sections and core-analysis porosity data. Most micropores in Fandango Field occur within chlorite coats, detrital clay matrix, and altered detrital grains such as feldspars and VRFs.

Porosity varies with depositional environment in Fandango Field as a result of both original depositional environment (Ambrose et al., 2016, this volume) and diagenesis. Average total porosity in the petrographic data set is highest in transgressive (16.5%) and upper-shoreface/proximal-delta-front (17.9%)

Figure 7. Chlorite and quartz cement have an inverse relationship in all upper Wilcox sandstone samples from Fandango Field, Zapata County, Texas.

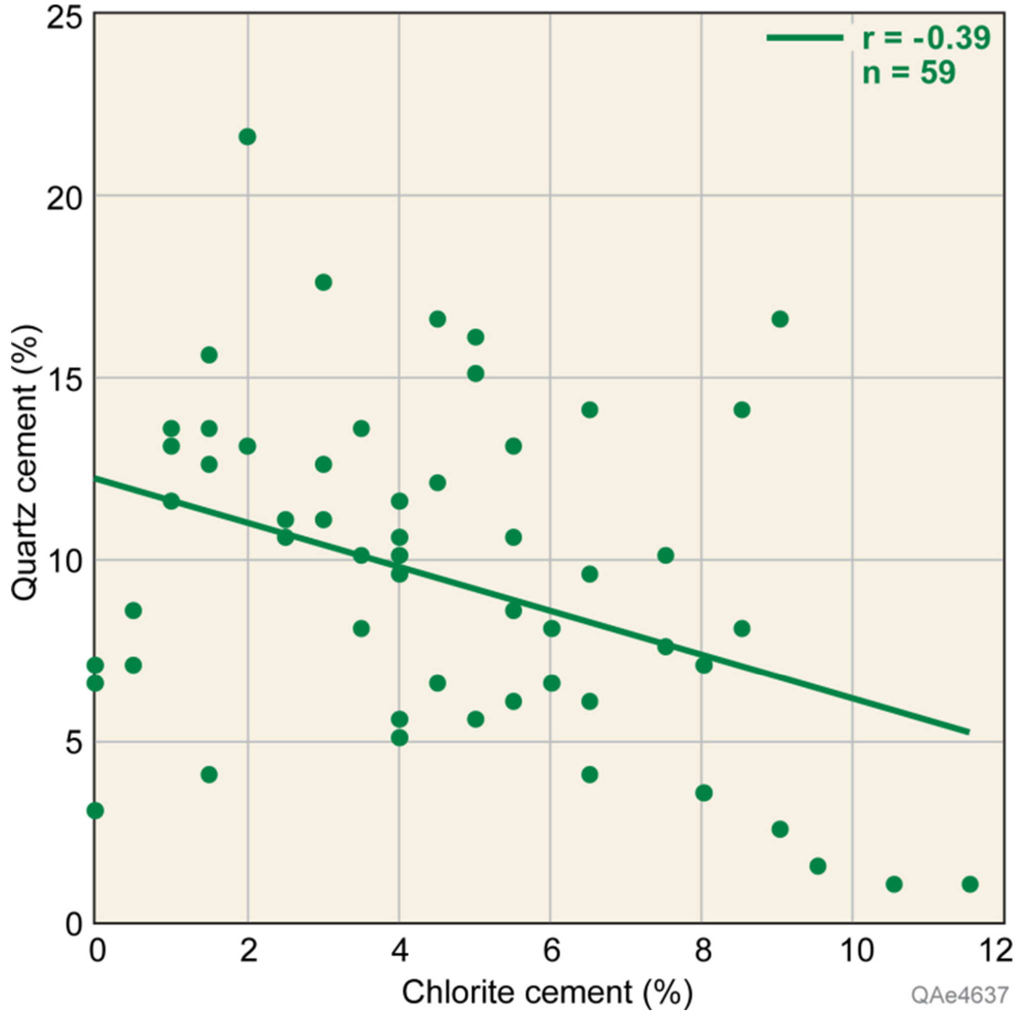


Table 1. Comparison of reservoir quality in sandstones having lower versus higher volumes of chlorite cement in upper Wilcox sandstones, Fandango Field, Zapata County, Texas. Values shown are arithmetic averages except for permeability, which are geometric means.

	<6% Chlorite Cement	≥6% Chlorite Cement
Chlorite cement (%)	2.9	7.9
Quartz cement (%)	10.8	6.8
Grain size (phi)	3.4	3.2
Primary porosity (%)	4.1	6.7
Core-analysis porosity (%)	14.5	19.2
Permeability (md)	0.3	3
Number of samples with point-count	40	19
Number of samples with permeability	34	19

deposits and lowest in lower-shoreface/distal-delta-front (6.4%) and middle-shoreface (10.5%) sandstones.

Permeability

Geometric-mean permeability of the 624 Fandango Field sandstones with measured permeability data is 0.33 md, and permeability ranges from 0.01 to 155 md. Permeability in Wilcox sandstones in Fandango Field has a wide range of values at all depths and temperatures. Relatively high permeability (≥10 md) has been preserved in some Fandango Field sandstones at temperatures as high as 421°F (216°C) (Fig. 9) by the presence of continuous chlorite coats on detrital grains. The hottest sandstones in Fandango Field, at temperatures >457°F (>236°C), lack continuous chlorite-coat coverage, and these sandstones have permeability values <0.2 md (Fig. 9). Geometric-mean permeability varies with depositional environment. In Fandango sandstones with petrographic data, geometric-mean permeability is highest in transgressive (2.0 md) and upper-shoreface/proximal-delta-front (0.8 md) deposits and lowest in lower-shoreface/distal-delta-front (0.01 md) and middle-shoreface (0.07 md) sandstones.

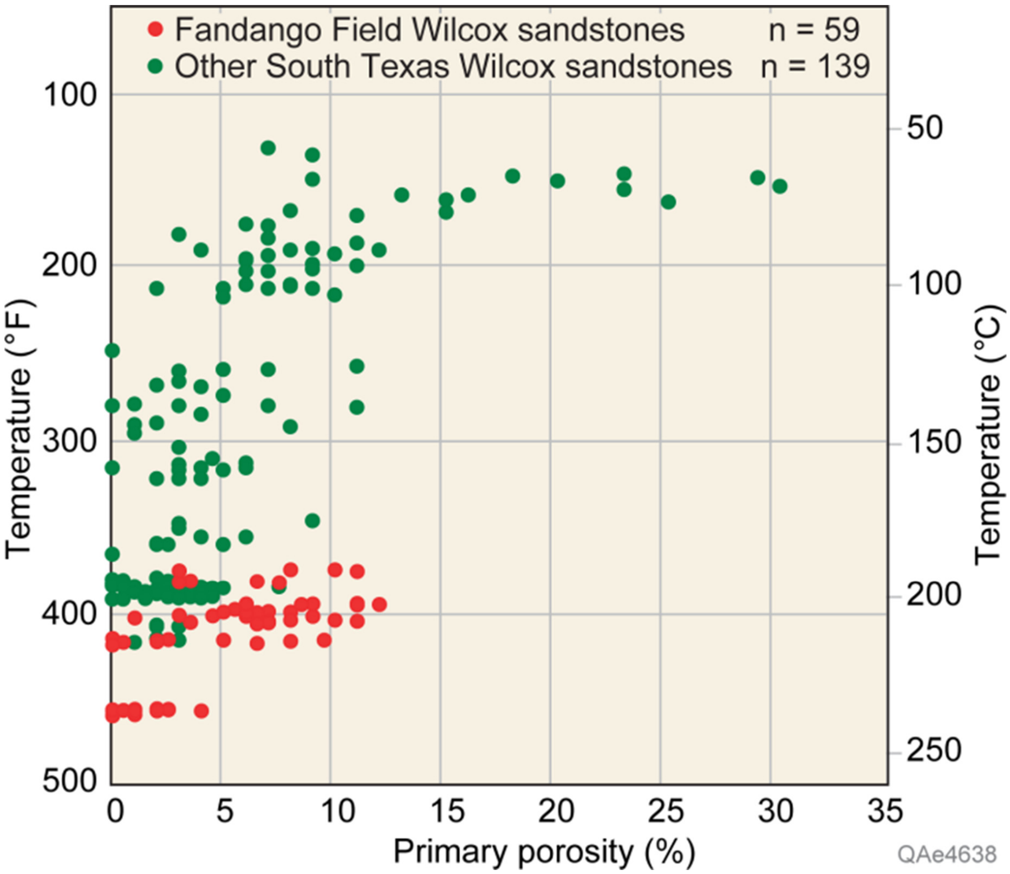


Figure 8. Primary porosity determined by thin-section point counts versus temperature in Wilcox sandstones from South Texas (well locations shown in Dutton and Loucks, 2014). Fandango Field data, shown in red, have higher primary porosity than other Wilcox sandstones from South Texas, probably because of the presence of continuous chlorite coats on some sandstones.

There is a significant correlation between volume of primary pores and permeability in Wilcox sandstones in Fandango Field (Fig. 10), but not between secondary pores and permeability. Pore-throat size controls permeability (Pittman, 1992), and in general primary pores are connected by larger pore throats than are secondary pores (McCreesh et al., 1991). Permeability in Fandango Field is higher in coarser grained sandstones because pore-throat radii are larger.

The plot of permeability versus temperature (Fig. 9) shows the trend of decreasing average and maximum permeability in Wilcox sandstones from wells in South Texas, including Fandango Field. Some Wilcox sandstones in Fandango Field retain significantly higher permeability compared with Wilcox sandstones in other areas of South Texas (Fig. 9). A total of 53 of the 624 Fandango samples with permeability data also have petrographic data. On the basis of petrographic analysis of those samples (Table 1), it is inferred that most or all of the high-permeability samples in Fandango Field contain high volumes of chlorite cement.

Wilcox sandstone samples from Fandango Field have a statistically significant correlation between porosity and permeability (Fig. 11). The equation relating core-analysis porosity and permeability for the Wilcox sandstone in Fandango Field is as follows: log permeability = -2.98 + (0.17 × porosity).

DISCUSSION

Origin of Chlorite Cement

Wilcox sandstones from Fandango Field, in the Rio Grande Delta system, have a higher average volume of chlorite cement (4.5%) than Wilcox sandstones deposited in the Holly Springs Delta system in Louisiana (0.3%), the Houston Delta system in the upper Texas coast (0.2%), or the Colorado/Rosita Delta system (2.2%) (Dutton and Loucks, 2010; Dutton et al., 2015b). The abundance of chlorite cement in Fandango Field is interpreted to be a result of the provenance of the Rio Grande Delta system. Mackey et al. (2012) used detrital zircon U–Pb geochronological analysis to interpret the early Eocene paleodrainage areas for Wilcox sandstones in South Texas, including in the Rio Grande system. They concluded that the sediment source areas included: (1) basement uplifts in the southern Rockies and northern Mexico; (2) the Cordilleran magmatic arc; and (3) inland magmatic centers of northern Mexico. However, Wilcox sandstones in cores from South Texas are more quartz-rich than would be expected for sediment derived from these source areas (Mackey et al., 2012). They hypothesized that preferential loss of VRFs in these sediments resulted from a humid climate that enhanced weathering and loss of VRFs during transport on a low-relief coastal plain.

Weathering of VRFs during transport would have contributed more iron to the Rio Grande system than to the Colorado/Rosita system during the early Eocene. The Rio Grande system derived sediment mainly from the Cordilleran arc and northern Mexico, whereas the Colorado/Rosita system was derived mainly from the Rocky Mountains (Galloway et al., 2011). The more diverse source area for the Rio Grande system most likely included a higher proportion of VRFs and other iron-bearing minerals. Iron derived from weathering of those minerals was then carried by the Rio Grande into a shallow-marine setting at the Rio Grande Delta. Clay precursors such as berthierine or odinite (Worden and Morad, 2003) could have formed where amorphous iron hydroxides carried in the river water flocculated when mixed with seawater (Ehrenberg, 1993; Grigsby, 2001; Bloch et al., 2002; Byrne et al., 2011). These precursor clay flakes developed parallel to detrital grains by mechanical accretion, as grains were rolled around by currents. The parallel-aligned clays provided a substrate for later precipitation of chlorite crystals oriented perpendicular to the grains.

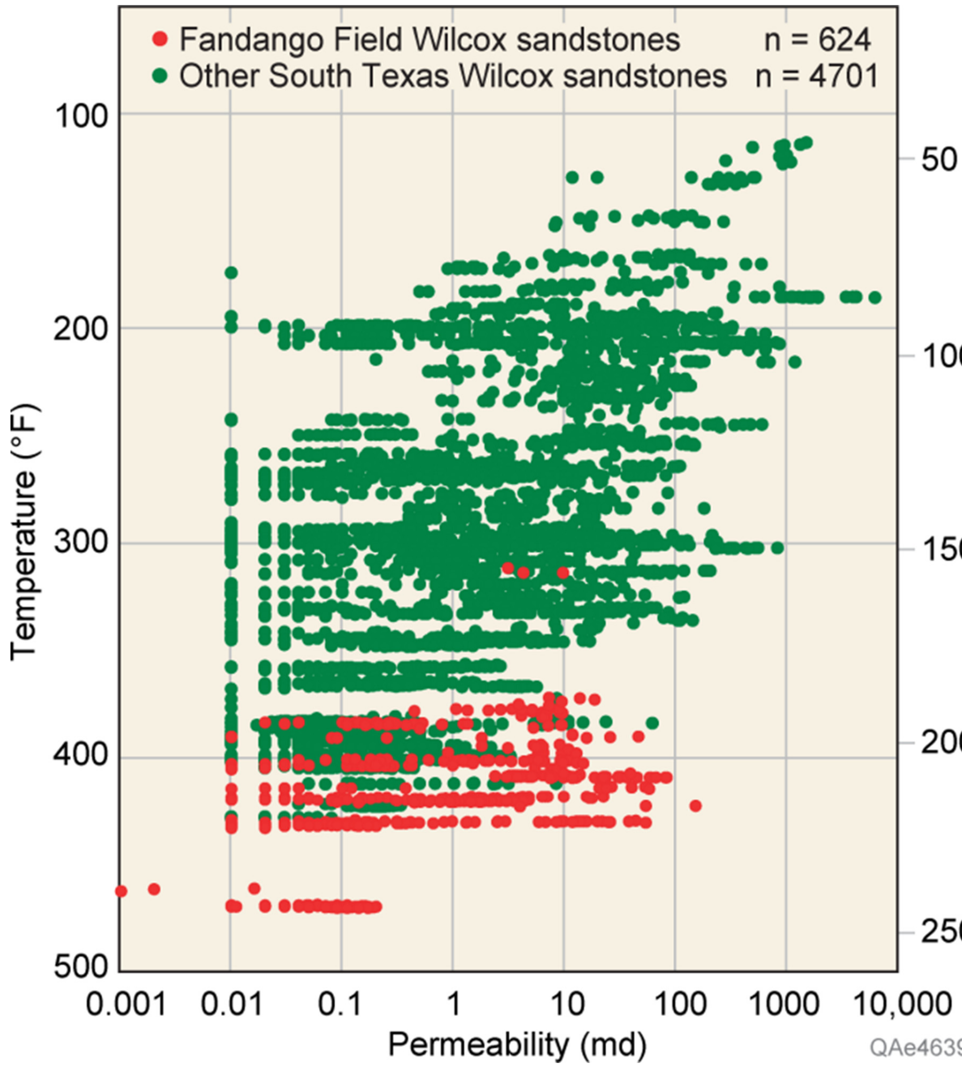


Figure 9. Permeability versus temperature in Wilcox sandstones from South Texas (well locations shown in Dutton and Loucks, 2014). Fandango Field data, shown in red, have higher permeability than other Wilcox sandstones from South Texas, probably because of the presence of continuous chlorite coats on some sandstones.

Early clay rims are also known to form where worms ingest sediment containing ferro-magnesian minerals and produce clay minerals coating detrital grains (Worden and Morad, 2003; Needham et al., 2006). This is not interpreted to be the source of chlorite rims in Fandango Field because few ferro-magnesian minerals survived to be deposited in these sandstones. Most of the VRFs were lost by weathering in the source area and not deposited in the delta/shoreface system. Furthermore, the greatest volume of chlorite cement in Fandango Field occurs in unburrowed, planar-stratified sandstones deposited in high-energy environments.

Controls on Chlorite Distribution in Fandango Field

Volume of chlorite cement (total of both parallel chlorite rims and perpendicular chlorite coats) is a good predictor of permeability in upper Wilcox sandstones in Fandango Field (Fig. 12). Sandstones that contain abundant chlorite retain anomalously high porosity (≥20%) and permeability (≥10 md) even at temperatures >400°F (>200°C), whereas Wilcox sandstones at the same depth and temperature that lack chlorite cement are tightly cemented by quartz. Fandango Field sandstones that contain ≥6% chlorite cement have an order of magnitude higher geometric-mean permeability than do sandstones with <6% chlorite cement (3.0 md versus 0.3 md, respectively), as well as higher average porosity (19.2% versus 14.5%) (Table 1). The better reservoir quality is a result of lower average quartz-cement volume. Samples that contain <6% chlorite cement have an average volume of 10.8% quartz cement, whereas samples that contain ≥6% chlorite cement have an average volume of 6.8% quartz cement (Table 1). Some of the difference in permeability between the two groups may also be related to the difference in grain size (Beard and Weyl, 1973). Samples that contain <6% chlorite cement have an average grain size of 3.42 phi (0.093 mm), whereas samples that contain ≥6% chlorite cement have an average grain size of 3.21 phi (0.108 mm) (Table 1).

Variations in the distribution of chlorite cement and reservoir quality were examined to try to determine why some sandstones developed robust chlorite coats and retained good porosity and permeability, but others did not. Chlorite cement has been observed in all facies, but it is most abundant in upper-shoreface/proximal-delta-front deposits (average volume = 4.8%) and in transgressive deposits (5.7%). Consistent with the observation that chlorite cement is most abundant in sandstones deposited in high-energy environments, there is a statistically significant correlation (r = 0.58) between grain size and chlorite-cement volume (Fig. 13).

Some of the most abundant chlorite cement and the best reservoir quality in the cored intervals occur in sandstones in the Shell #1 Garza well (Fig. 1) at depths of 16,120 to 16,152 ft (4913 to 4923 m) and in the Shell #2 Muzza well (Fig. 1) at depths of 15,170 to 15,182 ft (4623 to 4627 m). These chlorite-cemented samples from the #1 Garza and #2 Muzza cores both come from the same sandstone interval, called the T–6 Upper

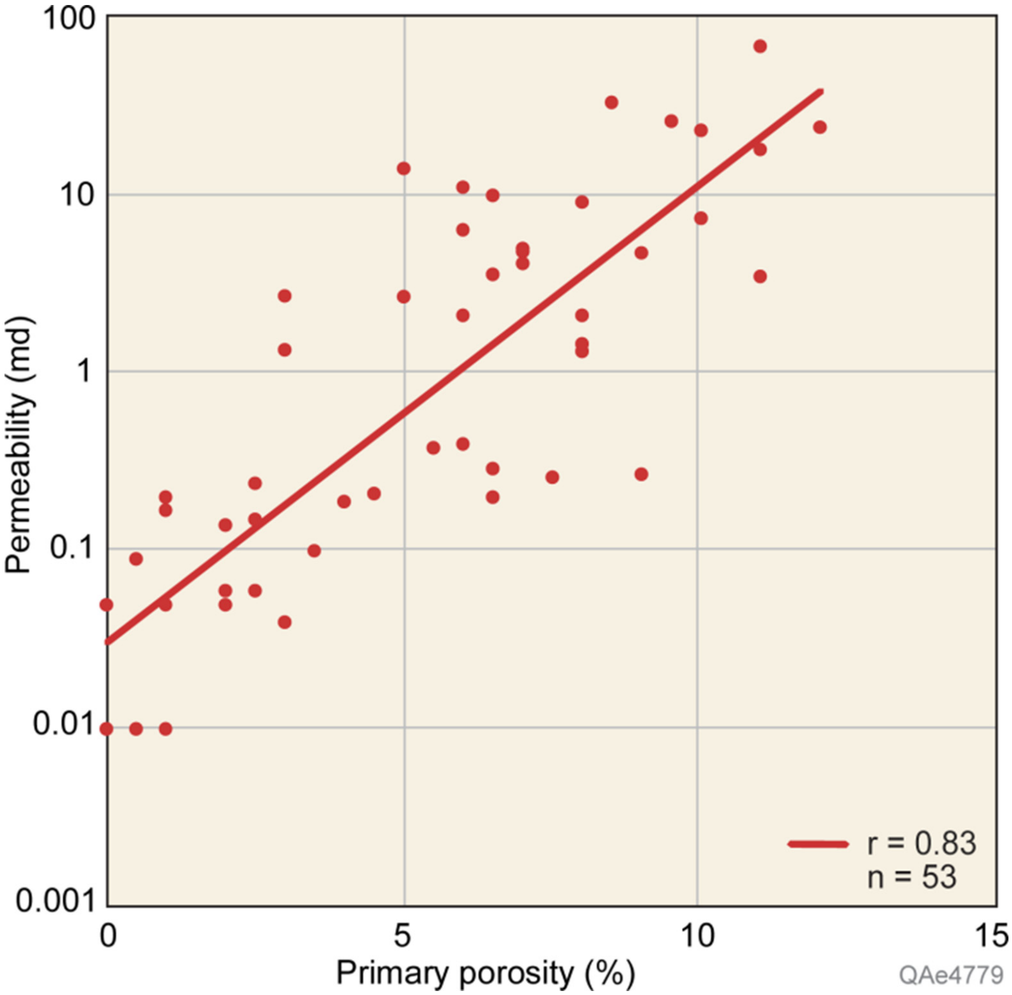


Figure 10. Primary porosity has a statistically significant correlation with permeability in upper Wilcox sandstone samples from Fandango Field, Zapata County, Texas. Primary porosity was determined by thin-section point counts.

(M. Collins, 2014, personal communication). The presence of abundant chlorite in this sandstone might indicate that the T–6 Upper sandstone was deposited during a period of high river discharge, when unusually large amounts of particulate iron were carried by the ancestral Rio Grande and deposited in the delta system. Alternatively, the T–6 Upper sandstone may have been deposited during a time of increased volcanism or when the climate resulted in greater weathering. A deeper interval in the #2 Muzza well (15,590 to 15,621 ft [4751 to 4761]) with abundant chlorite cement occurs in the T–6 Lower sandstone (M. Collins, 2014, personal communication), which may also have been deposited during a time of particularly high river discharge.

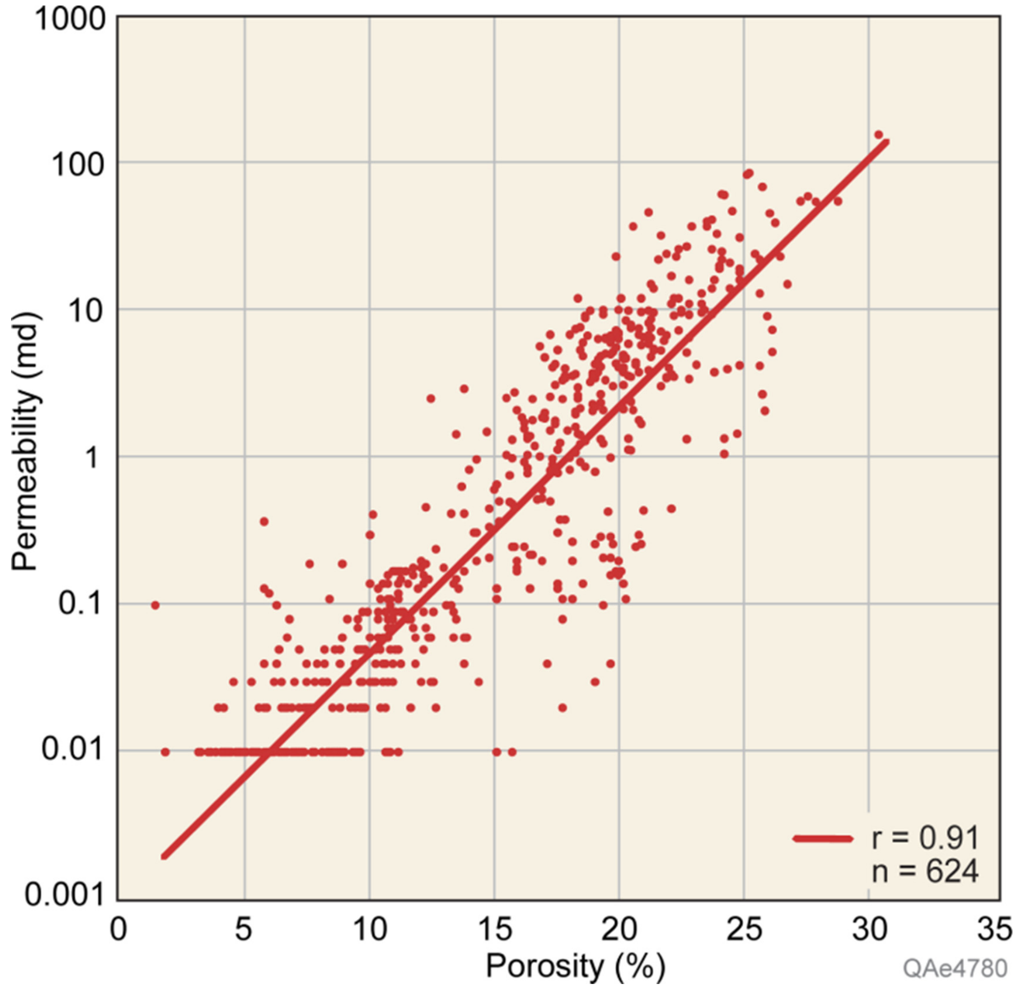
Implications for Deepwater Gulf of Mexico Wilcox Sandstones

Chlorite cement is abundant in shallow-marine deposits in Fandango Field, but it is unclear whether upper Wilcox sandstones deposited in the deepwater Gulf of Mexico might also contain chlorite coats. Sandstones compose 50 to 150 ft (15 to 45 m) of the 100 to 200 ft (30 to 60 m) upper Wilcox interval in the Perdido Fold Belt area (Fig. 1), and the Eocene Rio Grande fluvial/deltaic axis was a possible source of sand deposited in deepwater turbidites in this area (Fulthorpe et al., 2014). Sand grains derived from the Rio Grande system might have developed parallel chlorite rims in shallow-water environments before being carried down the slope and deposited in deepwater by turbidity currents. The dominant grain-support mechanism in turbidity currents is by turbulent support, not grain-to-grain support (Mulder and Alexander, 2001), so sands carried into the deepwater by turbidity flows may not have experienced grain-to-grain collisions, therefore avoiding abrasion of early chlorite rims. If chlorite rims did develop on grains in shallow water and were then transported intact into deep water, they might later have been overlain by more complete chlorite coats that precipitated during burial diagenesis. The source of iron could include the smectite-to-illite transformation and dissolution of remaining VRFs. Thus, the iron-rich source area for sediments in the Rio Grande system might have led to the development of chlorite coats in deepwater sandstones in the Perdido Fold Belt and other areas in the western Gulf of Mexico, contributing to reservoir-quality preservation.

The areal extent of upper Wilcox sandstones derived from the Rio Grande Delta system is interpreted as being confined to the western Gulf of Mexico, in both U.S. and Mexican waters offshore South Texas and northern Mexico (Fulthorpe et al., 2014). Upper Wilcox deposits in the western Gulf of Mexico are interpreted to be basin-floor aprons derived from broad line sources and not from point-sourced submarine fans (Fulthorpe et al., 2014). Sediments in basin-floor aprons did not extend as far into the basin as those in submarine fans, and upper Wilcox sandstones derived from the Rio Grande system probably were not deposited much farther east than the Perdido Fold Belt in the Alaminos Canyon area (Fulthorpe et al., 2014) (Fig. 1).

Onshore Wilcox sandstones deposited in the Rio Grande Delta system contain more chlorite cement than Wilcox sandstones in the Colorado, Houston, and Holly Springs delta systems, so deepwater sandstones derived from the Rio Grande Del-

Figure 11. Core-analysis porosity versus permeability in upper Wilcox sandstone samples from Fandango Field, Zapata County, Texas.



ta might be more likely to contain chlorite cement. However, there have been reports of chlorite coats in deepwater Wilcox sandstones in other areas of the Gulf of Mexico, where sediment was derived from the Houston and Holly Springs delta systems. In these areas, chlorite cement is present in some sandstones and may be locally important in preserving reservoir quality. Nearly complete grain coatings of chlorite inhibited quartz cementation in some deepwater Wilcox sandstones in the Jack–1 well (Walker Ridge 759 #1) (Lewis et al., 2007), and chlorite rims have been reported as occurring in deepwater Wilcox sandstone in the eastern part of the Lower Tertiary play (J. B. Wagner, 2009, personal communication). Chlorite rims and coats have been observed in deepwater turbidite sandstones in other parts of the world (for example, Houseknecht and Ross, 1992; Sullivan et al., 1999; Bloch et al., 2002; Anjos et al., 2003), so the presence of chlorite cement in some deepwater Wilcox sandstones would not be unusual and should be considered when risking reservoir quality.

CONCLUSIONS

Wilcox sandstones in Fandango Field, Zapata County, Texas, provide information about mineral composition and reservoir quality of sandstones deposited in the Eocene Rio Grande Delta system in far South Texas, which is particularly applicable to understanding upper Wilcox sandstones in the Perdido Fold Belt area along the boundary between U.S. and Mexican waters. Wilcox sandstones in Fandango Field are mostly sublitharenites, litharenites, and feldspathic litharenites, with average composition of $Q_{71.9}F_{8.5}R_{19.6}$. Estimated original composition of the Upper Wilcox sandstones in Fandango Field was $Q_{66.4}F_{15.4}R_{18.2}$.

Compaction was the dominant porosity-reducing process in the upper Wilcox sandstones in Fandango Field. The amount of porosity lost by compaction (COPL) is 23 porosity units out of the assumed initial 40 porosity units. Cements and replacement minerals constitute between 9.5 and 35.5% of the sandstone volume. Quartz is the most abundant authigenic mineral (average whole-rock volume = 9.5%), followed by chlorite (4.5%) and carbonates (calcite, Fe–calcite, and ankerite) (3.0%). Wilcox sandstones in Fandango Field lost an average of 11.9 porosity units by precipitation of cement in primary pores (CEPL).

Average core-analysis porosity in Fandango Field sandstones is 13.4%, and geometric-mean permeability is 0.33 md. Some Wilcox sandstones in Fandango Field retain anomalously good reservoir quality (porosity ≥20% and permeability ≥10 md) at temperatures >400°F (>200°C) because extensive, continuous chlorite coats inhibited later quartz cementation by reducing the detrital quartz surface area available for quartz-cement nucleation. Chlorite cement is present in all facies, but it is most abundant in relatively coarser-grained upper-shoreface/wave-dominated-delta deposits (average volume = 4.6%) and in transgressive deposits (5.6%). Where chlorite coats are rare or discontinuous, quartz cement has filled most intergranular pores.

Many detrital grains in Fandango Field have two layers of chlorite cement. The first layer consists of small chlorite crystals (≤1.5 µm long) oriented parallel to the grains (chlorite rims), overlain by larger chlorite crystals (5 µm) oriented perpendicular to the grains (chlorite coats). The early, parallel-oriented clay crystals are interpreted to have formed as Fe–rich clay-mineral precursors that later altered to chlorite during burial diagenesis.

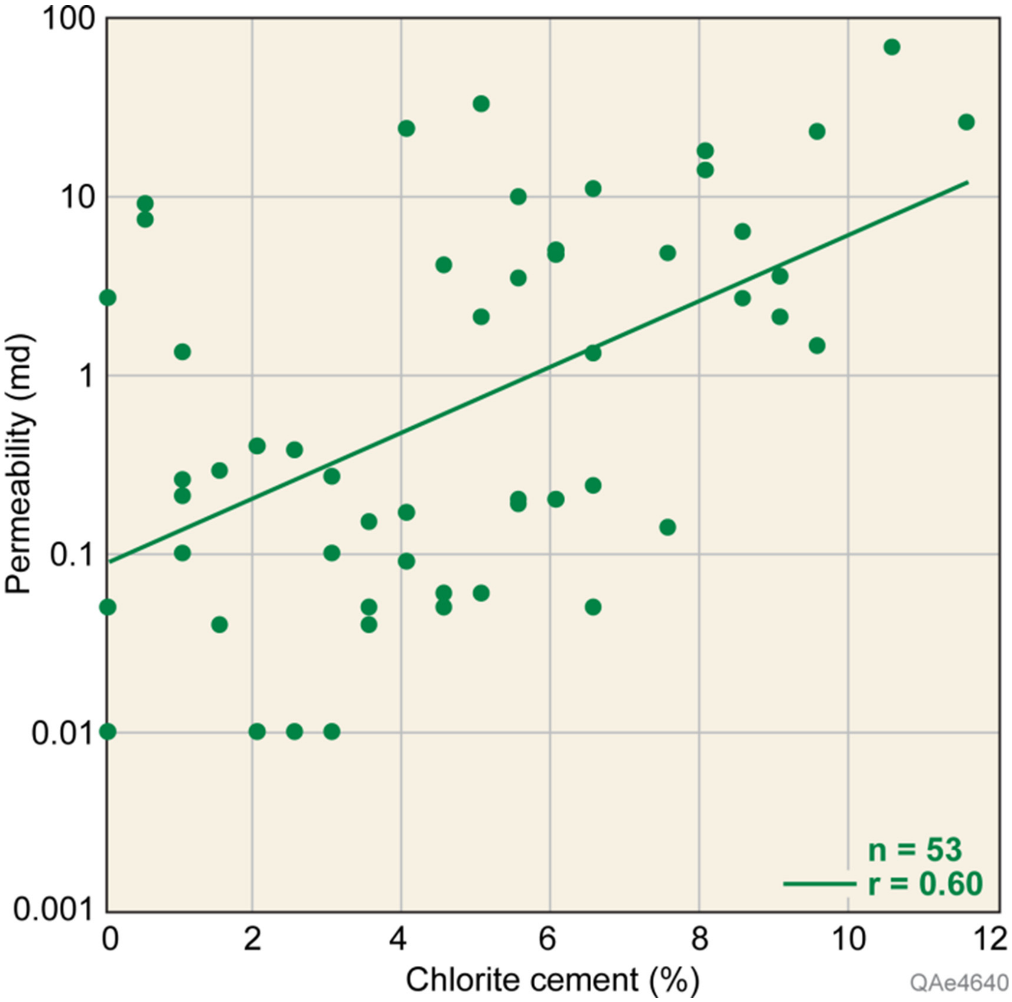


Figure 12. Volume of chlorite cement (total of both parallel chlorite rims and perpendicular chlorite coats) versus permeability in upper Wilcox sandstones, Fandango Field, Zapata County, Texas.

Clay precursors formed when amorphous iron hydroxides carried in river water flocculated when mixed with seawater. Precursor clay flakes developed parallel to detrital grains by mechanical accretion as grains were transported by currents. The parallel-aligned clays provided a substrate for later precipitation of chlorite crystals oriented perpendicular to the grains.

Wilcox sandstones from the Rio Grande Delta system contain more chlorite cement than Wilcox sandstones from the Houston Delta system or the Colorado/Rosita Delta system because of provenance differences. The Cordilleran magmatic arc and inland magmatic centers of northern Mexico in the Rio Grande source area contained abundant VRFs, and these regions likely contributed more sediment to South Texas than to areas of Wilcox deposition farther north. Weathering of the magmatic rocks contributed iron to the Rio Grande fluvial system, which then carried the iron into the shallow-marine environment.

Chlorite cement is abundant in shallow-marine deposits in Fandango Field, but it is unclear whether upper Wilcox sandstones deposited in the deepwater Gulf of Mexico might also contain chlorite coats. Sand grains derived from the Rio Grande system may have developed chlorite rims in shallow-water environments before being carried down the slope and deposited in deeper water. If chlorite rims did develop on grains in shallow water and were then transported intact into deep water, subsequent chlorite coats could have precipitated during burial diagenesis. Thus, the iron-rich source area for the sediments in the Rio Grande fluvial/deltaic system might have led to the development of chlorite coats in deepwater sandstones in the western Gulf of Mexico and contributed to reservoir-quality preservation.

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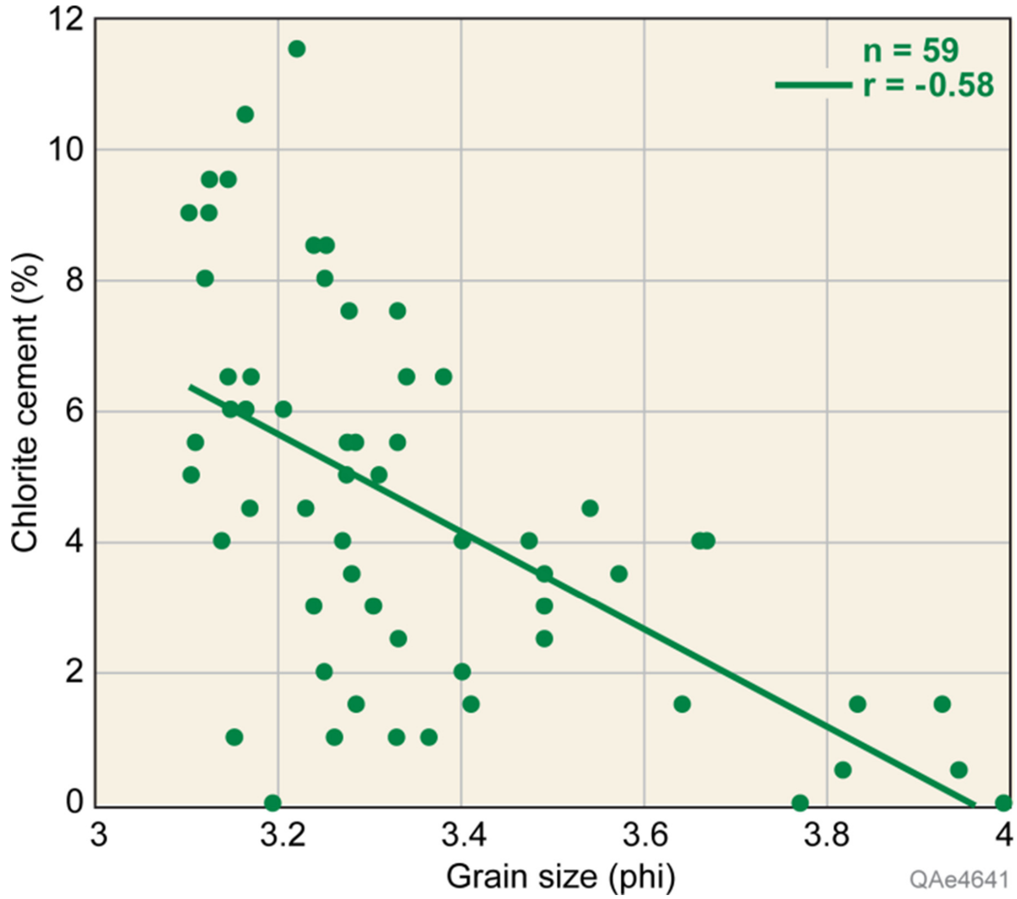
Figure 13. Volume of chlorite cement (total of both parallel chlorite rims and perpendicular chlorite coats) versus grain size in upper Wilcox sandstones, Fandango Field, Zapata County, Texas.



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