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REGIONAL TRENDS IN DIAGENESIS AND RESERVOIR QUALITY OF JURASSIC COTTON VALLEY SANDSTONES, NORTHERN GULF OF MEXICO BASIN

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ABSTRACT

Jurassic Cotton Valley sandstones in East Texas, Louisiana, and Mississippi were deposited in shallow-marine and fluvial depositional environments in the northern Gulf of Mexico Basin. Reservoir quality of onshore Cotton Valley sandstones varies significantly across this area, increasing from west to east, despite greater eastern burial depths. Petrographic analysis was conducted to determine the influence of detrital composition, texture, and diagenesis on reservoir quality. The objective of this study was to determine the controls on reservoir quality in onshore Cotton Valley sandstones from East Texas to Mississippi.

Cotton Valley sandstones are mostly subarkoses and sublitharenites and have an average composition of 85.5% quartz, 8.5% feldspar, and 6.0% rock fragments ($Q_{85.5}F_{8.5}R_{6.0}$). Metamorphic rock fragments are the most common lithic grains. Sandstones in East Texas contain fewer rock fragments ($Q_{88.1}F_{9.9}R_{2.0}$) compared with Mississippi ($Q_{77.0}F_{10.5}R_{12.5}$). Cotton Valley average grain size increases from west to east.

Total volume of cements and replacement minerals ranges between 0 and 48.0% in the Cotton Valley sandstones analyzed. Chlorite and illite form partial to complete clay rims around some detrital grains in Cotton Valley sandstones. In shallow-marine sandstones from East Texas and Louisiana, clay rims are discontinuous and cover only a small percentage of the grains. Abundant quartz cement precipitated where clay-rim coverage was low. Some Cotton Valley sandstones from Mississippi contain continuous clay rims that inhibited later quartz cementation and preserved intergranular porosity in fluvial and shallow-marine sandstones. Average porosity is higher in Cotton Valley sandstones from Mississippi (15.7%) than it is in East Texas (5.7%) or Louisiana (4.4%). Geometric mean permeability is also higher in Cotton Valley sandstones from Mississippi (7.3 md) than it is in sandstones from East Texas (0.02 md) or Louisiana (0.06 md). Unconfined compressive strength (UCS) of Cotton Valley sandstones and mudstones was estimated using a rebound hammer. There is a statistically significant correlation between total volume of cement in Cotton Valley samples and UCS.

Vitrinite reflectance equivalent (R_{oe}), an estimate of thermal maturity, was calculated by burial-history modeling. R_{oe} is lowest for onshore Cotton Valley sandstones in Mississippi (1.05%) and increases westward to 1.2% in Louisiana and 1.4% in East Texas. Cotton Valley sandstones in Mississippi are buried to greater depths than those in Texas and Louisiana, but because the geothermal gradient is lower in Mississippi, thermal maturity is less than in Texas and Louisiana.

Reservoir quality of onshore Mississippi Cotton Valley sandstones is superior to that of Texas and Louisiana as a result of several factors: coarser grain size, more continuous clay rims on detrital grains, and lower geothermal gradient. This study of diagenesis of onshore Cotton Valley sandstones provides insight into reservoir quality of Cotton Valley sandstones in the northeastern Gulf of Mexico. Low porosity and high thermal maturity in offshore Cotton Valley sandstones in the northeastern Gulf of Mexico indicate that generally poor reservoir quality exists in this area.

INTRODUCTION

Sandstones of the Upper Jurassic Cotton Valley Group represent a major progradation of terrigenous clastics into the northern Gulf of Mexico Basin after the opening of the Gulf (Seni and Jackson, 1983). Cotton Valley sandstones in East Texas and northern Louisiana are shallow-marine facies deposited in a wave-dominated depositional setting, and Cotton Valley sandstones in Mississippi were deposited in the Ancestral Mississippi River fluvial-deltaic system (Ewing, 2001; Ambrose et al., 2017, this volume). Cotton Valley sandstones produce oil and gas in the study area and are potential exploration targets in the northeastern Gulf of Mexico.

Cotton Valley sandstones in Mississippi have significantly better reservoir quality (porosity and permeability) than Cotton

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Valley sandstones in East Texas and Louisiana, despite being buried to greater depths, as described in the 'Burial-History Modeling' section herein. The Cotton Valley was designated a tight gas formation in most of East Texas and Louisiana by the Federal Energy Regulatory Commission, having average in situ permeability throughout the pay section of 0.1 md or less (Dutton et al., 1993). In contrast, permeability in Cotton Valley oil and gas reservoirs in Mississippi ranges up to 500 md (Bebout et al., 1992).

In this study we characterize regional variation of detrital mineral composition, diagenesis, and reservoir quality of Cotton Valley sandstones from East Texas to Mississippi in order to identify the main controls on reservoir quality. Previous petrographic studies of the Cotton Valley sandstones have mainly investigated individual fields or specific areas (e.g., Wescott, 1983; Russell et al., 1984; Janks et al., 1985; Dutton et al., 1991). More recently, a regional analysis of diagenesis of Cotton Valley sandstones was conducted by Thomas et al. (2004, 2005). Our investigation builds on those previous studies. Petrographic and reservoir-quality data were collected from 12 wells in East Texas, Louisiana, and Mississippi (Fig. 1), from samples buried to depths of 8716 to 14,792 ft (2656 to 4508 m) and temperatures of 228 to 334°F (109 to 167°C). The goals of the project were to determine the controls on regional trends in diagenesis and reservoir quality in onshore Cotton Valley sandstones and to assess reservoir potential of Cotton Valley sandstones in the northeastern Gulf of Mexico.

GEOLOGIC SETTING

Cotton Valley cores from East Texas and northern Louisiana used in this study (Fig. 1) are located in the Terryville Bar and Poole Sand trends (Coleman and Coleman, 1981; Ewing, 2001; see Ambrose et al., 2017, this volume, their figure 1) and represent a suite of shallow-marine facies within a wave-dominated depositional setting. These shallow-marine facies include lower- and upper-shoreface, beach, tidal-inlet, washover-fan, and destructional-beach deposits associated with transgression and relative sea-level rise (Ambrose et al., 2017, this volume). Cotton Valley cores from Mississippi, which are located in an off-axis area of the ancestral Mississippi Delta, display a variety of fluvial channel-fill and muddy floodplain facies (Ambrose et al., 2017, this volume). Shallow-marine depositional systems are also represented. These shallow-marine deposits are composed almost entirely of aggradational, sandy upper-shoreface facies. The southeast-oriented trend of shallow-water Cotton Valley deposits in Mississippi is interpreted to extend into the northeastern Gulf of Mexico (Thomas et al., 2005), where they were cored in Viosca Knoll Block 251 (Fig. 1).

Most Cotton Valley sandstones in this study were deposited in early Cotton Valley (Tithonian) time. The Cotton Valley sandstones in East Texas were sourced from the Ouachita Mountains and Arbuckle Uplift to the northwest (Coleman, 1985; Wescott, 1983, 1985; Ewing, 2001; Elshayeb, 2004), whereas those in east-central Mississippi were derived from the Appalachian

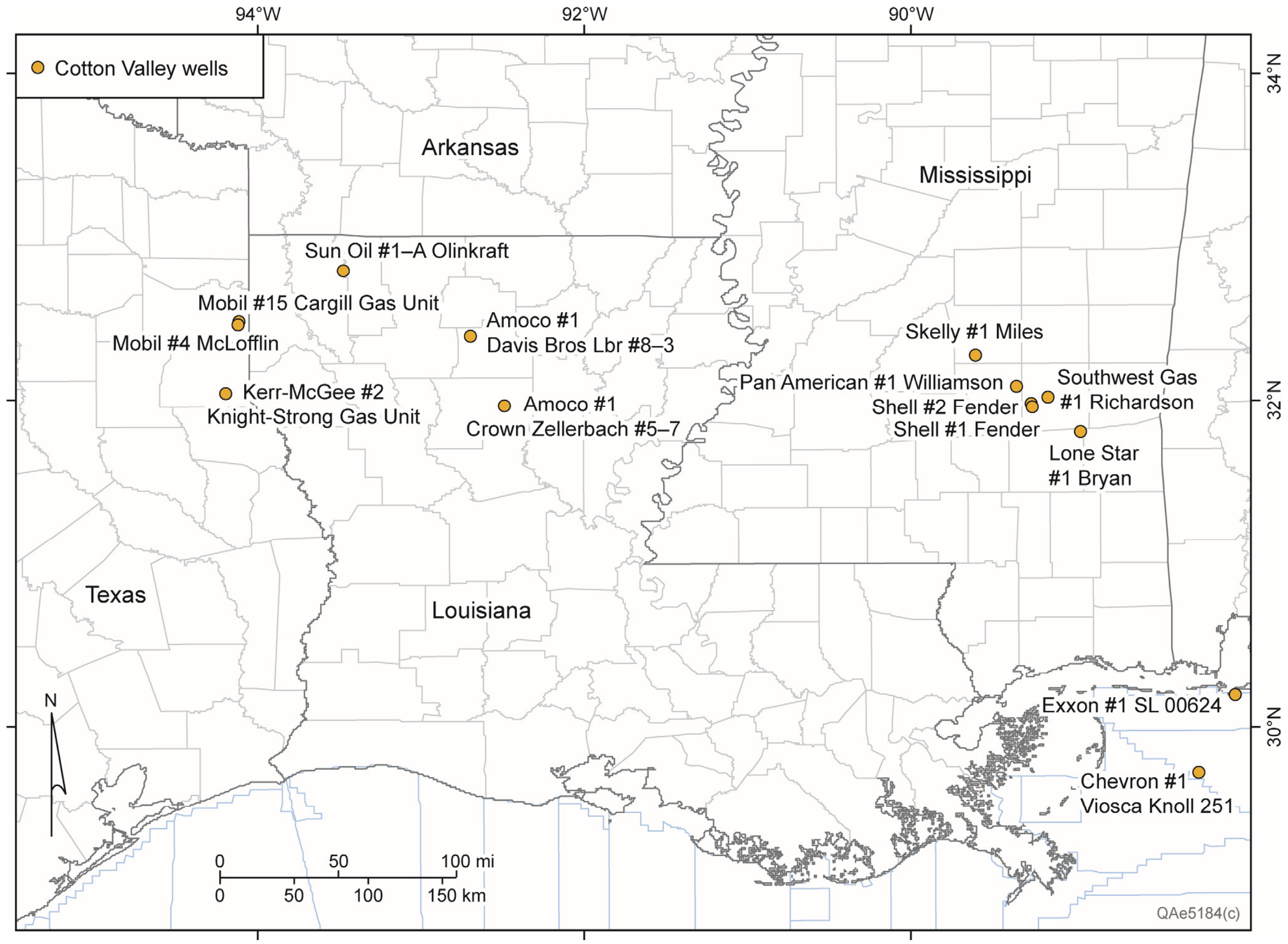


Figure 1. Location of wells used in study of Cotton Valley sandstones in East Texas, Louisiana, and Mississippi. Thin-section samples were available from all onshore wells except the Shell #2 Fender; only core-analysis data were available from that well. A burial-history model was made for the offshore Exxon #1 SL 00624 well, but no samples or core-analysis data were available. Cotton Valley sandstones cored in the Chevron #1 Viosca Knoll 251 well are discussed in Thomas et al. (2004, 2005).

drainage systems to the northeast and east (Moore, 1983; Ewing, 2001; Thomas et al., 2004). Cotton Valley sandstones in northern Louisiana are interpreted as being strike-fed from the west (Coleman and Coleman, 1981; Ewing, 2001). Two cores of upper Cotton Valley sandstones deposited during Tithonian-Berriasian time are included in this study. They are from the Shell #1 Fender and the Southwest Gas #1 Richardson wells in Mississippi (Fig. 1), and the source area for these Cotton Valley sandstones is interpreted as being the Appalachians as well (Moore, 1983; Ewing, 2001).

METHODS

Composition of Cotton Valley sandstones was determined by standard thin-section petrography. Point counts were completed on 103 thin sections of sandstones and mudstones from 11 wells (Fig. 1). Of those samples, 84 are sandstones that contain <10% detrital clay matrix, with the remainder being muddy sandstones (15) and sandy mudstones (4) (terminology of Folk [1974]). 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). Grain size and sorting were determined by measuring the long diameter of 100 competent grains (quartz and feldspar) per thin section. Rock strength (unconfined compressive strength, UCS) of Cotton Valley sandstones and mudstones was estimated from hardness data collected on cores using an Equotip^{TM} Micro-Rebound Hammer) (Proceq, 2017).

Temperature for each thin-section 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, ranges from 62 to 67.4°F (16.7 to 19.7° C) in the study area (U.S. Climate Data, 2016). Calculated geothermal gradients in wells used in this study range from 1.33 to 2.04°F/100 ft (24.2 to 37.2°C/km), and calculated subsurface temperatures of the samples range from 228 to 334°F (109 to 167°C). Cotton Valley sandstones in the study area are likely to be at or near their maximum burial depth and temperature now.

Core-analysis data were available from 214 samples of Cotton Valley sandstones from 10 of the wells (Fig. 1). Porosity and permeability were measured at unstressed conditions (800 psi [5.5 MPa]) by routine core analysis of plugs cut from conventional cores. Permeability was measured to air.

Burial-history models of 3 wells from the onshore Gulf of Mexico, in Texas (Mobil #15 Cargill), Louisiana (Amoco #1 Davis), and Mississippi (Shell #1 Fender) (Fig. 1), were created using the program Genesis 5.34 (ZetaWare, 2009) to characterize burial history of onshore Cotton Valley sandstones. A model was also generated to characterize the burial history of Cotton Valley sandstones on the Gulf of Mexico shelf in offshore Alabama (Exxon #1 SL 00624 well) (Fig. 1). Values of vitrinite reflectance equivalent (R_{oe}), an indicator of thermal maturity, were calculated in the burial-history models using the Lawrence Livermore National Laboratory (LLNL) vitrinite maturation model (Sweeney and Burnham, 1990). Comparing R_{oe} values of sandstones from these different areas provides an indication of relative thermal maturity of Cotton Valley sandstones in the northern Gulf of Mexico.

RESULTS

Petrographic properties of Cotton Valley sandstones, including grain size, detrital mineral composition, and diagenesis, vary across the study area. Reservoir quality also varies across the study area and generally increases from west to east.

Texture

Cotton Valley sandstones that contain <10% clay matrix have a wide range of mean grain sizes, from lower very fine- to lower medium-grained sandstone. Average grain size of competent grains increases from west to east. Mean grain size of Cotton Valley sandstones is 3.30 phi (0.102 mm) in East Texas, 2.76 phi (0.148 mm) in Louisiana, and 2.20 phi (0.218 mm) in Mississippi (Table 1). Most Cotton Valley sandstones are well sorted (0.35 to 0.5 phi standard deviation) to moderately well sorted (0.50 to 0.71 phi standard deviation), as defined by Folk (1974).

Framework Grain Composition

Cotton Valley sandstones are mostly subarkoses and sublitharenites (sandstone classification of Folk [1974]) (Fig. 2). Average composition is 85.5% quartz, 8.5% feldspar, and 6.0% rock fragments ($Q_{85.5}F_{8.5}R_{6.0}$). Detrital quartz is the most abundant mineral. Plagioclase is more abundant than potassium

Table 1. Comparison of Cotton Valley sandstones in East Texas, Louisiana, and Mississippi; values are averages for each area. Average depths of the petrographic samples from each of the three study areas are rounded to the nearest 100 ft (30.5 m). Well locations shown in Figure 1.

	East Texas	Louisiana	Mississippi
Grain size (mm)	0.102	0.148	0.218
Composition	$Q_{87.4}F_{10.3}R_{2.3}$	$Q_{87.5}F_{4.0}R_{8.5}$	$Q_{77.1}F_{10.3}R_{12.7}$
Quartz cement (%)	9.9	16.1	9.5
Authigenic carbonate (%)	12.4	9.5	5.1
Primary porosity (%)	0.8	1.6	7.7
Secondary porosity (%)	0.8	1.7	1.3
Microporosity (%)	4.4	1.7	4.6
Core-analysis porosity (%)	5.7	4.4	15.7
Geometric mean permeability (md)	0.02	0.06	7.3
Average depth (ft [m])	9200 [2804]	10,400 [3170]	14,300 [4359]
Number of samples	36	22	26

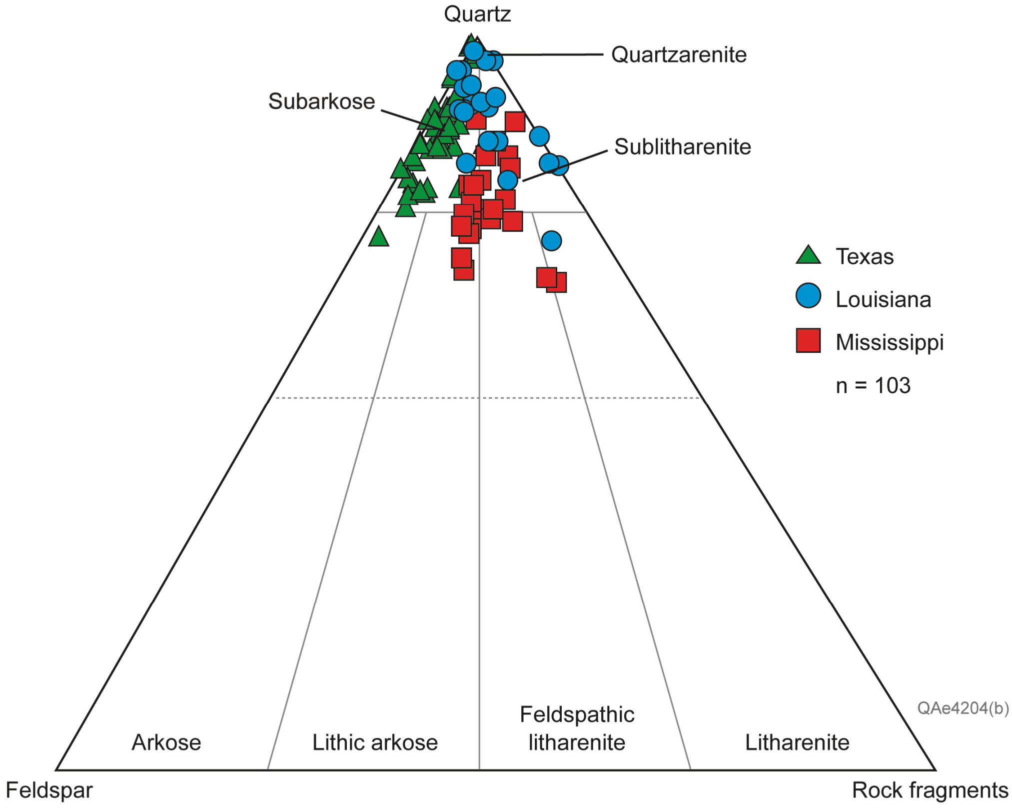


Figure 2. Compositional classification of Cotton Valley sandstones from East Texas, Louisiana, and Mississippi. Classification diagram from Folk (1974).

feldspar in the study area. Plagioclase composes an average of 3.4% of the whole-rock volume of Cotton Valley sandstones now, whereas orthoclase composes 2.3% and microcline, 0.1%.

Lithic grains in the Cotton Valley sandstones include metamorphic, sedimentary, and plutonic rock fragments. Metamorphic rock fragments (MRF) are the most common lithic grains in these Cotton Valley sandstones (Fig. 3), followed by sedimentary rock fragments (SRF), mainly chert. Cotton Valley sandstones in East Texas contain the fewest rock fragments ($Q_{88.1}F_{9.9}R_{2.0}$), whereas those in Mississippi contain the highest proportion ($Q_{77.0}F_{10.5}R_{12.5}$) (Table 1). The trend of decreasing quartz and increasing MRF content in Cotton Valley sandstones from East Texas to Mississippi was reported by Thomas et al. (2005). Biotite and muscovite grains are rare across the study area, each having an average volume of 0.04%. The only other detrital framework grains are heavy minerals, including zircon, tourmaline, and opaque grains that are probably magnetite and/or ilmenite. Average volume of heavy minerals is 0.3%.

Cotton Valley sandstones were cored in an offshore well in the northeastern Gulf of Mexico, in Viosca Knoll Block 251 (Fig. 1) at a depth of 20,500 ft (6250 m) (Thomas et al., 2005). These Cotton Valley sandstones are lithic arkoses that contain abundant MRFs, mainly schist fragments, as well as grains of biotite and muscovite (Thomas et al., 2004, 2005). The composition of Cotton Valley sandstones in Viosca Knoll is similar to that observed in east-central Mississippi, reflecting the Appalachian provenance for sandstones in both areas.

Matrix

Detrital clay matrix in Cotton Valley sandstones and mudstones sampled in this study constitutes between 0 and 81% of the whole-rock volume. X–ray diffraction analysis (XRD) of five burrowed tidal-channel sandstones from the Mobil #4 McLofflin well in Harrison County, Texas (Fig. 1) determined that clays constitute from 3 to 6% by weight of the bulk-rock composition. Within the <2 micron fraction, illite composes 57 to 81%, chlorite composes 7 to 29%, and illite-smectite (having 20% smectite layers) composes 1 to 23%. Petrographic analysis indicates that the clays in these samples are mostly detrital, not authigenic.

Cements/Diagenetic History

Cements and replacement minerals compose between 0 and 48.0% of the whole-rock volume of Cotton Valley sandstones that contain <10% clay matrix, with an average volume of 23.7%. Quartz is the most abundant authigenic mineral (average whole-rock volume = 11.7%), followed by carbonates (calcite, Fe–calcite, and ankerite; 9.6%). Other authigenic minerals, which are generally present in minor volumes, include illite, chlorite, kaolinite, pyrite, albite, siderite, and sphene.

On the basis of petrographic evidence, the relative order of occurrence of the major events in the diagenetic history of Cotton Valley sandstones is: (1) mechanical compaction by grain rearrangement and deformation of ductile grains, (2) formation of chlorite and illite rims, (3) precipitation of early calcite cement and grain replacement, (4) precipitation of quartz overgrowths, (5) precipitation of Fe–calcite cement and grain replacement, (6) dissolution of potassium feldspar and albitization of plagioclase, and (7) precipitation of ankerite cement and grain replacement. This sequence is similar to what has been interpreted in previous studies of Cotton Valley diagenesis (Wescott, 1983, 1985; Dutton et al., 1991, 1993; Elshayeb, 2004).

Compaction

Compaction caused significant porosity reduction in the majority of samples. Mechanical compaction took place both by rearrangement of mechanically stable grains, such as quartz and feldspar, and deformation of ductile grains, such as mud clasts,

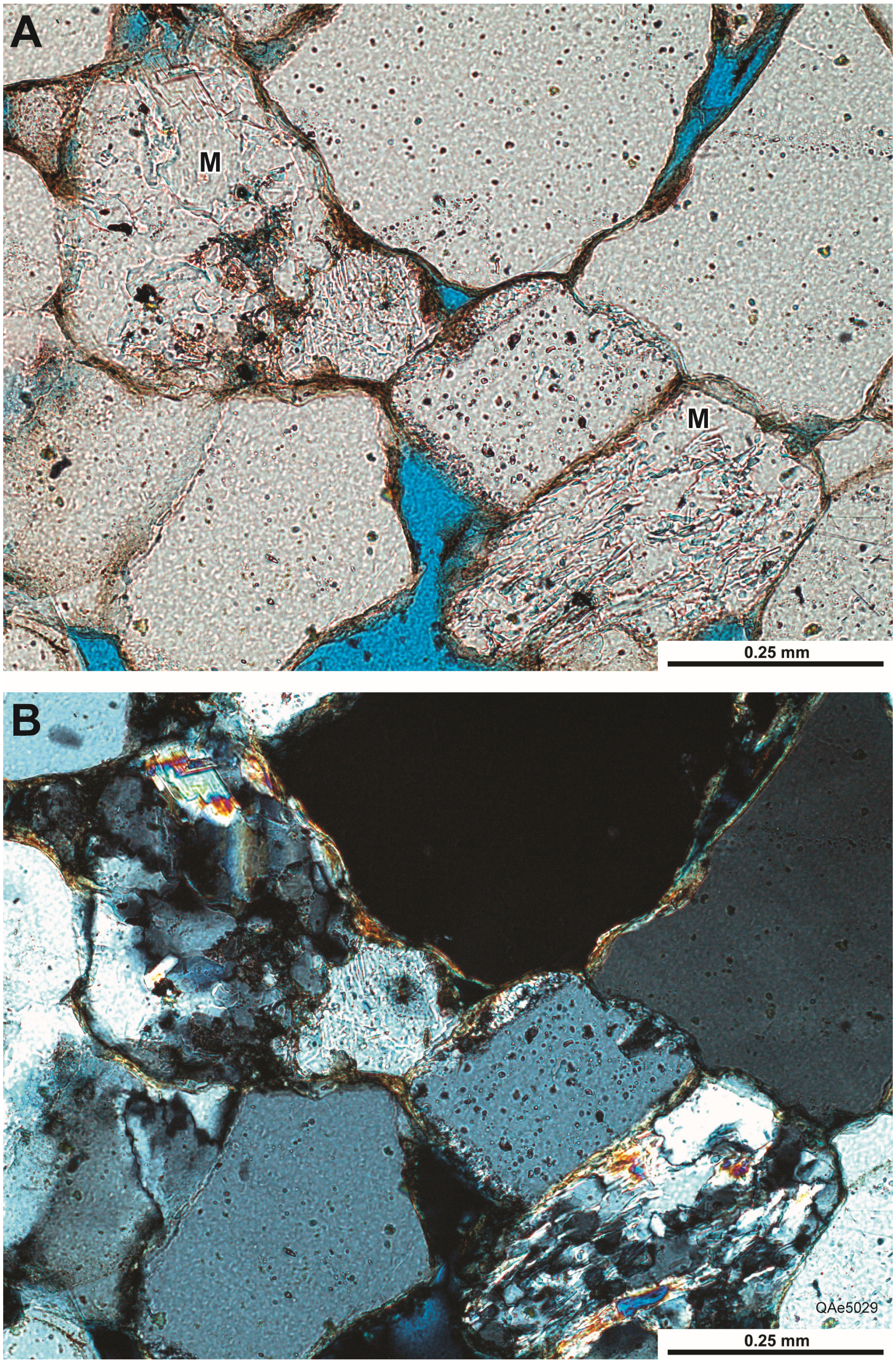


Figure 3. Metamorphic rock fragments (M) in Cotton Valley sandstone from the Shell #1 Fender well, Jasper County, Mississippi, at a depth of 14,520.5 ft (4425.8 m). (A) Plane-polarized light. (B) Crossed-polarized light.

micas, and MRFs (Fig. 3). Chemical compaction by quartz dissolution and grain interpenetration was less common but also reduced porosity in some samples by causing closer packing of framework grains (Bjørkum, 1996; Bloch et al., 2002). Intergranular volume (IGV) in Cotton Valley sandstones calculated by the method of Houseknecht (1987) (intergranular porosity + cement) averages 22.4%. Intergranular volume calculated by the method of Paxton et al. (2002), with matrix included (intergranular porosity + cement + depositional matrix), averages 23.8%.

Chlorite and Illite Rims

Chlorite and illite form partial to complete clay rims coating some detrital grains in Cotton Valley sandstones (Figs. 4 and 5). The clays that compose these rims are generally oriented parallel to the underlying detrital grains (Fig. 6). These clays may include inherited clay rims that were present on the grains when they were deposited (Wilson, 1992), infiltrated clays that formed after deposition (Bloch et al., 2002), and clay precursors such as berthierine or odinite (Worden and Morad, 2003) that formed

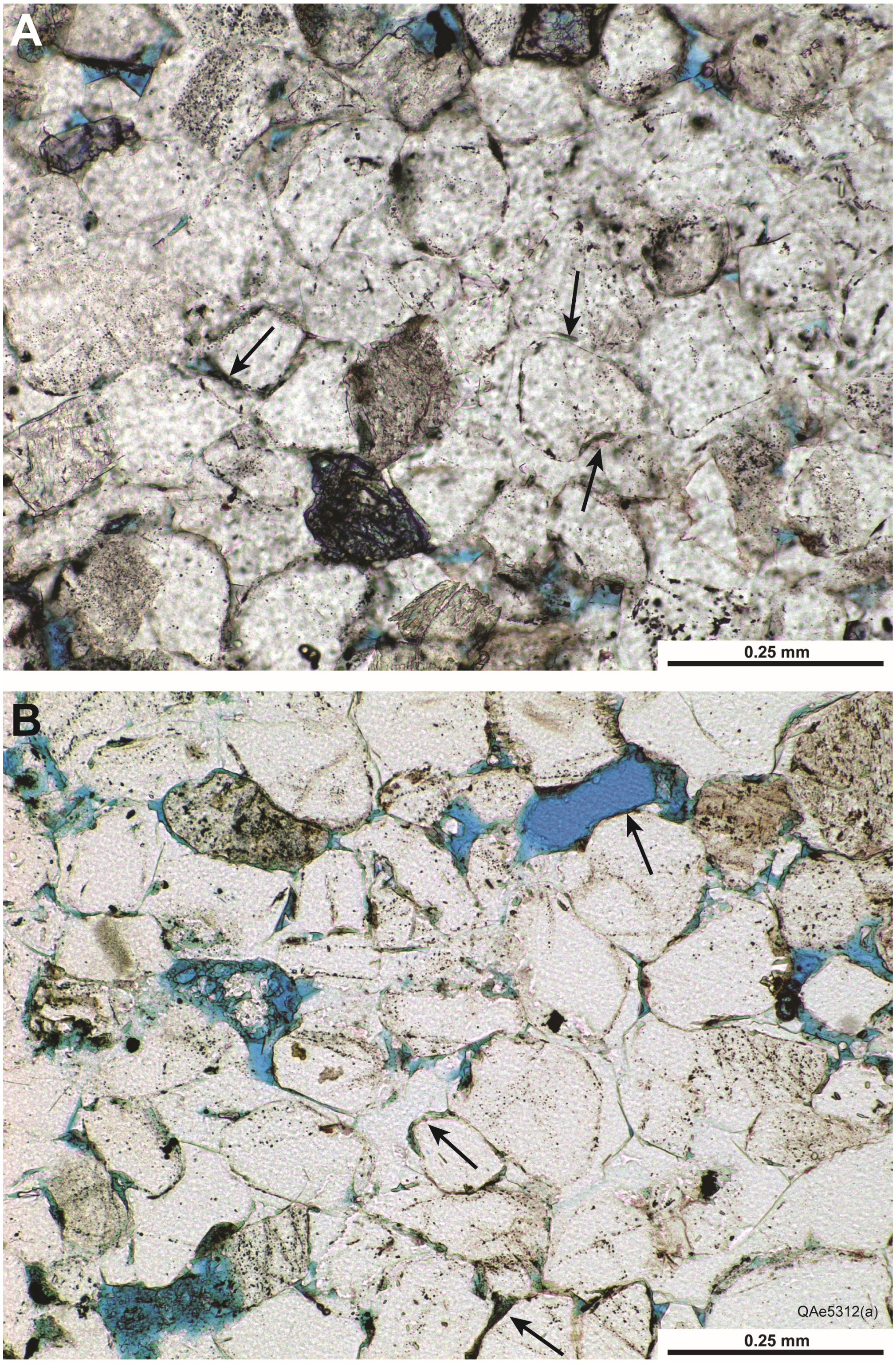


Figure 4. Short, discontinuous clay rims (see arrows) on some grains in Cotton Valley sandstone samples from East Texas and Louisiana. (A) Sample from the Mobil #15 Cargill well, Harrison County, Texas, at a depth of 9275.6 ft (2827.2 m). Core-analysis porosity of this sample is 3.2%, and permeability is 0.004 md. Plane-polarized light. (B) Sample from the Sun #1–A Olinkraft well, Bossier Parish, Louisiana, at a depth of 9221.1 ft (2810.6 m). Core-analysis porosity is 7.6%, and permeability is 0.166 md. Plane-polarized light.

where amorphous iron hydroxides carried in river water flocculated when mixed with seawater (Ehrenberg, 1993; Bloch et al., 2002). Precursor clay flakes may cover grains by mechanical accretion as the grains are rolled around by currents. Early, parallel-oriented clay crystals that formed as clay-mineral precursors were later altered to illite or chlorite during burial diagenesis, and additional illite and chlorite flakes precipitated during burial diagenesis (Fig. 6).

The percentage of clay coverage on detrital grains was not quantified, but in general clay rims in Cotton Valley sandstones in Texas and Louisiana are less extensive than those in Mississippi. Many grains in Cotton Valley sandstones in East Texas and Louisiana completely lack clay rims, and clay coverage is estimated as less than 30% on grains that do have partial rims (Fig. 4). Abundant quartz cement precipitated where clay rims were absent (Fig. 4). In contrast, more grains in Cotton Valley sandstones in Mississippi contain clay rims, and coverage on some grains is estimated as >70% (Fig. 5). These more continuous clay rims inhibited later quartz cementation and preserved intergranular porosity, although some quartz over-

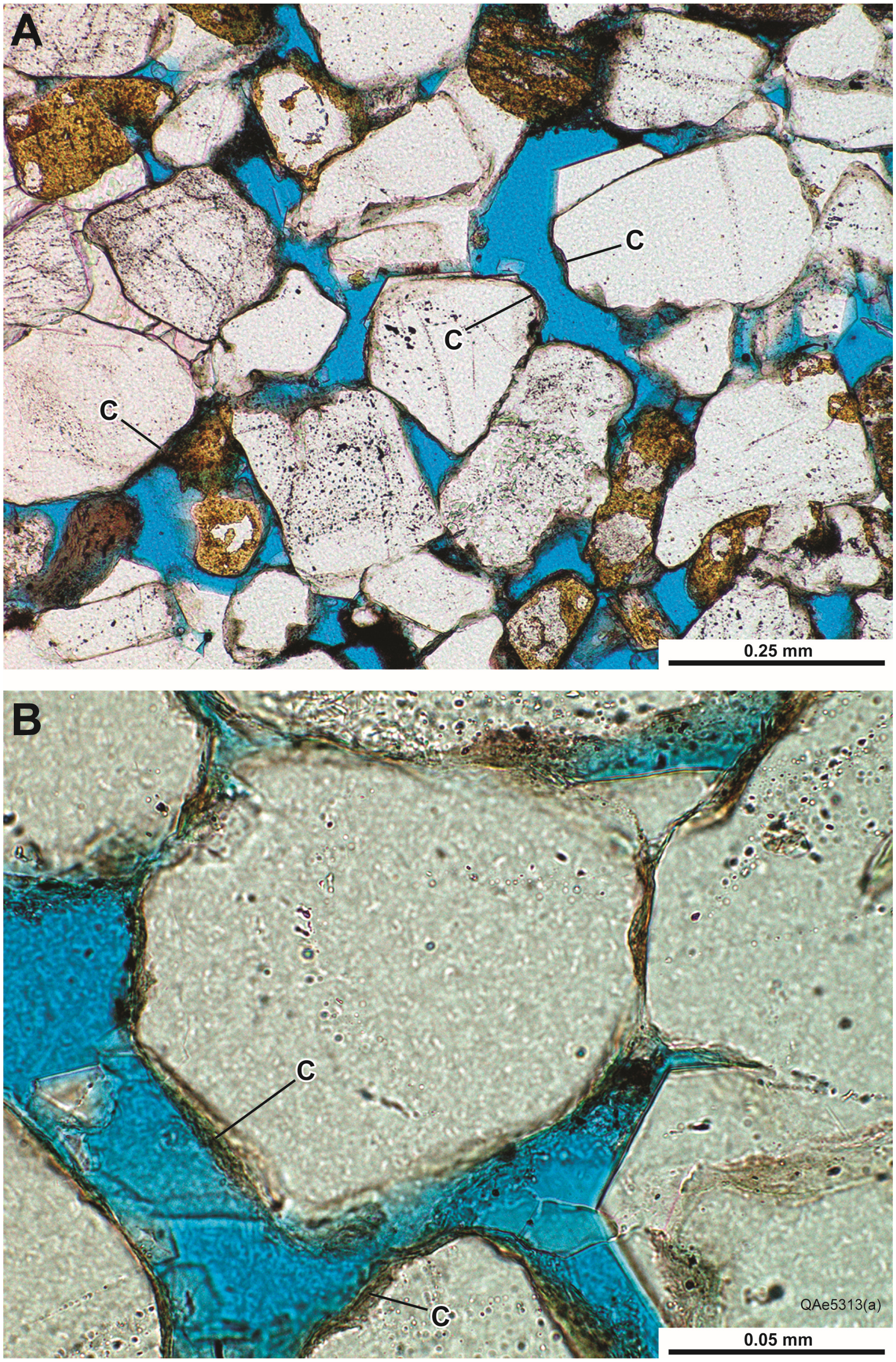


Figure 5. Continuous clay rims (C) on high permeability Cotton Valley sandstones from the Shell #1 Fender core, Jasper County, Mississippi. (A) Sample from a depth of 14,595.5 ft (4448.7 m). Core-analysis porosity is 19.6%, and permeability is 116 md. Plane-polarized light. (B) Sample from a depth of 14,557.5 ft (4437.1 m); too broken for porosity and permeability analysis. Plane-polarized light.

growths were able to nucleate at gaps in the clay rims (Fig. 5). Clay rims on Cotton Valley sandstones from Mississippi are composed mainly of chlorite flakes that are oriented parallel to the detrital grains, but there are illite fibers on the grains as well (Fig. 6).

Clay rims are abundant in Cotton Valley samples from the Southwest Gas #1 Richardson and the Shell #1 Fender wells in Mississippi (Fig. 1). However, Cotton Valley samples from the Pan American #3 Williamson well (Fig. 1) in Mississippi lack extensive clay rims and contain abundant quartz cement. These quartz-cemented sandstones in the #3 Williamson well are similar to Cotton Valley sandstones in East Texas and Louisiana.

Chlorite coats were observed on Cotton Valley sand grains in the Viosca Knoll Block 251 #1 well (Thomas et al., 2004, 2005). Chlorite-coat coverage in the Viosca Knoll sandstones averages 30% throughout the cored interval but ranges from 3% to 90% (Thomas et al., 2004). Thomas et al. (2005) interpreted the chlorite cement in Cotton Valley sandstones from the Viosca Knoll Block 251 #1 well as having formed by dissolution of detrital biotite derived from the Appalachian tectonic front. This

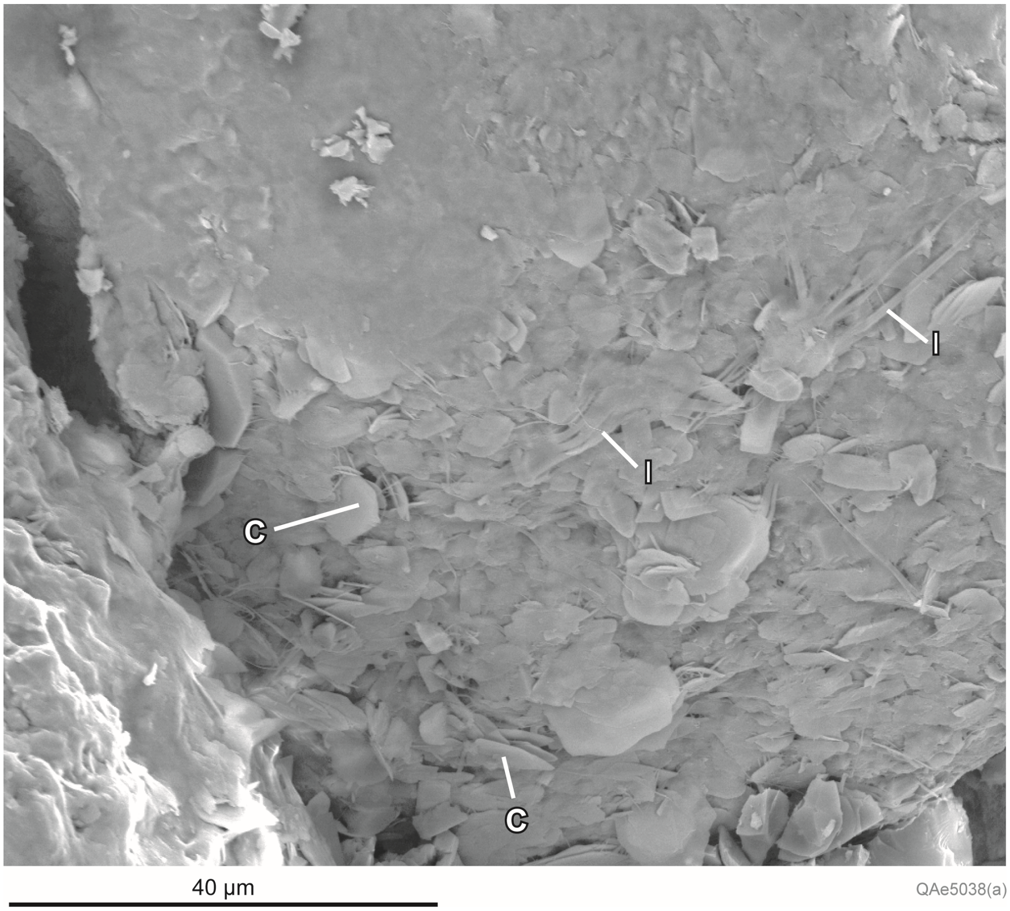


Figure 6. Mixed secondary and backscattered electron SEM (scanning electron microscope) image of chlorite (C) and illite (I) flakes oriented parallel to underlying detrital grain in Cotton Valley sandstone sample from the Shell #1 Fender well, Jasper County, Mississippi, at a depth of 14,557.5 ft (4437.1 m). The core sample was air dried, not critical-point dried or freeze dried, so fibrous illite may have originally extended into the pores but collapsed and matted against pore walls during air drying (Luffel et al., 1990). SEM image by Patrick Smith.

might not explain the origin of chlorite cement observed in Cotton Valley sandstones from onshore Mississippi, however. These onshore Mississippi sandstones were sourced by the ancestral Mississippi River (Ewing, 2001), but they do not contain a greater volume of detrital biotite (average = 0.04%) than Cotton Valley sandstones in either East Texas (0.06%) or Louisiana (0.04%).

Nevertheless, clay rims may be more abundant and continuous in Cotton Valley sandstones in Mississippi than in East Texas and Louisiana because of the difference in provenance, as suggested by Thomas et al. (2004). Weathering of iron-bearing metamorphic rock fragments and other iron-bearing minerals in the Appalachian Mountains may have contributed amorphous iron hydroxides to the Ancestral Mississippi fluvial system. The iron was carried by the river to the shallow-marine environment, where it could have formed clay precursors on sand grains (Land and Dutton, 1978; Ehrenberg, 1993; Grigsby, 2001; Bloch et al., 2002; Byrne et al., 2011). Continuous clay rims that occur in fluvial Cotton Valley sandstones in Mississippi may have formed by a similar process, or they may be a product of early mechanical infiltration (Moraes and De Ros, 1990).

Authigenic Quartz

Quartz is the most abundant cement in clean Cotton Valley sandstones, having an average volume of 11.7% and ranging in volume from 0 to 24%. The average volume of quartz cement is 9.9% in East Texas, 16.1% in Louisiana and 9.5% in Mississippi (Table 1). Cotton Valley sandstones have a wide range of quartz-cement volume, even in samples from the same well. Some of the samples with low volumes of quartz cement contain continuous clay rims (Fig. 6), whereas others are tightly cemented by early authigenic carbonate (Fig. 7) or contain abundant matrix and rock fragments.

Authigenic Carbonate

Calcite, Fe–calcite, and ankerite are the main authigenic carbonate minerals in Cotton Valley sandstones, although minor volumes of dolomite and siderite occur as well. Calcite and Fe–calcite occur in primary, intergranular pores (Fig. 7) and as grain replacements of unstable grains, mainly feldspars. Ankerite most commonly occurs as a grain-replacement mineral, particularly of feldspar, but some is also present in primary pores. The average total volume of carbonate cement and grain replacement in Cotton Valley sandstones is 9.6%, as determined by thin-section point counts. Of that, an average of 5.8% is primary pore-filling cement and 3.8% is grain replacement. Nearly 20% of the Cotton Valley sandstone samples contain significant volume (>25% whole-rock volume) of carbonate cement.

Authigenic carbonate in Cotton Valley sandstones is most abundant in East Texas (average volume 12.4%), with lower average volumes in Louisiana (9.5%) and Mississippi (5.1%) (Table 1). The volume of authigenic carbonate varies with depositional environment. Authigenic carbonate is most abundant in tidal-channel deposits (12.9%) and lower-shoreface deposits (average 10.6%). Authigenic carbonate is less common in fluvial-channel (9.2%), upper-shoreface (6.6%), and beach/upper-shoreface (3.4%) deposits.

Porosity

Total thin-section porosity (primary + secondary porosity) averages 4.0% and ranges from 0 to 21.5% in sandstones that contain <10% matrix. Average primary porosity is 2.8% and

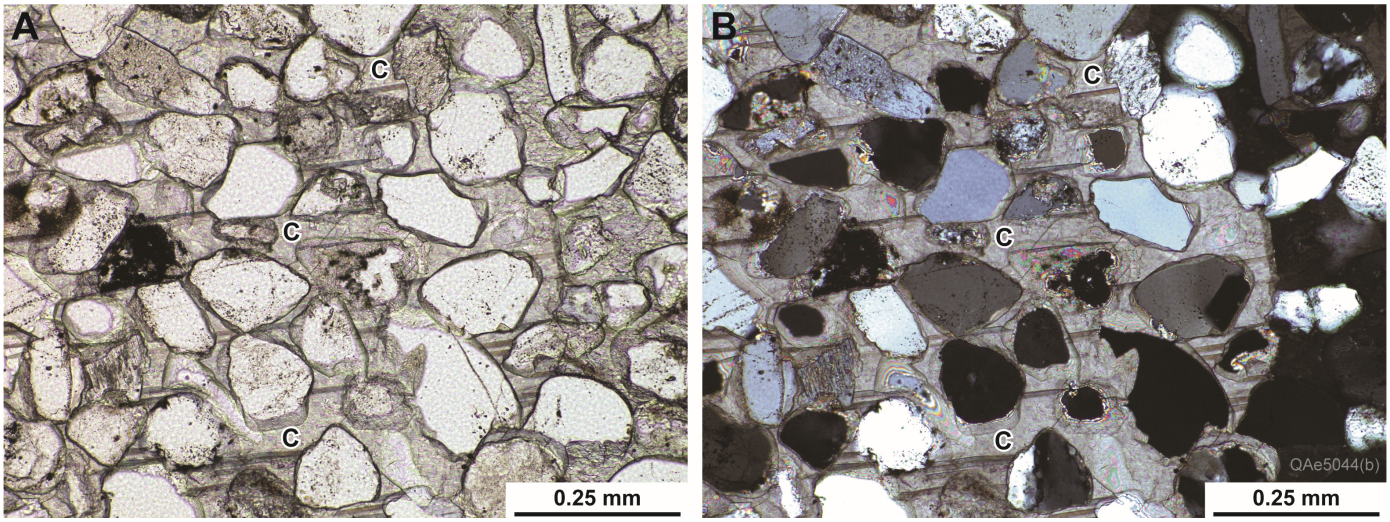


Figure 7. Abundant early calcite cement (C) in Cotton Valley sandstone from the Sun #1–A Olinkraft well, Bossier Parish, Louisiana, at a depth of 9201.5 ft (2804.6 m). Core-analysis porosity is 1.2%, and permeability is 0.013 md. Rare discontinuous chlorite rims are enclosed by the calcite. (A) Plane-polarized light. (B) Crossed-polarized light.

ranges from 0 to 20%. Average secondary porosity is 1.2% and ranges from 0 to 4%. Primary porosity is higher in Cotton Valley sandstones from Mississippi (average 7.7%) than it is in Cotton Valley sandstones from East Texas (0.8%) or Louisiana (1.6%) (Table 1). Abundant primary porosity (>10%) has been preserved in some Cotton Valley sandstones in Mississippi at temperatures as high as 266°F (130°C) and depths of 14,605 ft (4452 m) by the presence of continuous clay rims on detrital grains (Fig. 5) that inhibited quartz cementation.

Porosity measured by helium porosimeter represents total porosity, the sum of primary and secondary pores and micropores. Core-analysis porosity in Cotton Valley sandstones ranges from 0.6% to 23.8% and is higher in Cotton Valley sandstones from Mississippi (average = 15.7%) than in East Texas (5.7%) and Louisiana (4.4%) (Table 1). Porosimeter porosity plotted versus depth for the three study areas shows that porosity is higher in some of the more deeply buried Cotton Valley sandstones from Mississippi than it is in the shallower sandstones from Texas and Louisiana (Fig. 8). This unusual trend of higher porosity at greater depth occurs because continuous clay rims on detrital grains in some Cotton Valley sandstones in Mississippi preserved intergranular porosity by inhibiting quartz cementation. Cotton Valley sandstones in Texas and Louisiana lack continuous clay rims and have been extensively cemented by quartz.

Micropores, defined as pores having pore-aperture radii <0.5 µm (Pittman, 1979), cannot be accurately quantified by routine thin-section point counts but can be estimated as the difference between porosimeter porosity and thin-section porosity. Average microporosity in Cotton Valley sandstones having <10% clay matrix is 3.5%. Microporosity in Cotton Valley sandstones in Mississippi averages 4.6%, compared with 4.4% in East Texas and 1.7% in Louisiana (Table 1).

Permeability Trends

Geometric-mean permeability measured on Cotton Valley core-plug samples is 0.05 md and ranges from 0.001 to 356 md. Mean permeability is higher in Cotton Valley sandstones from Mississippi (7.3 md) than it is in sandstones from East Texas (0.02 md) or Louisiana (0.06 md) (Table 1). A plot of permeability versus temperature indicates that the hottest Cotton Valley samples (>330°F [>165°C]), which are from Louisiana, all have low permeability, but samples at temperatures from 230 to 280°F (110 to 138°C) have a wide range of permeabilities (Fig. 9).

The high permeability sandstones in Mississippi are from the Shell #1 Fender (Ambrose et al., 2017, this volume), the Shell #2 Fender, and the Southwest Gas #1Richardson wells (Fig. 1). Sandstones from these cores are interpreted as having been deposited in both fluvial-channel and shoreface depositional environments. These sandstones have chlorite and illite clay rims that preserved intergranular porosity by inhibiting quartz cementation. Volume of quartz cement in these cores ranges from 0 to 11.5%. In contrast, sandstones from the Pan American #1 Williamson well in Mississippi (Fig. 1) have generally small, discontinuous clay rims, more abundant quartz cement (12 to 21%), and lower permeability. These sandstones were deposited in fluvial-channel environments (Ambrose et al., 2017, this volume).

Cotton Valley sandstones from East Texas, Louisiana, and Mississippi each have different porosity-permeability relationships (Fig. 10). The sandstones from East Texas and Louisiana have uniformly low porosity and permeability, whereas those from Mississippi show a wide range of porosity and permeability (Fig. 10). The reason for the two different permeability populations in Cotton Valley sandstones in Mississippi is not clear. Continuous clay rims that inhibited quartz cementation occur in both fluvial and shoreface sandstones, so the difference does not appear to be related to depositional environment. However, the low-permeability sandstones in the #1 Williamson core are interpreted as being Tithonian in age (early Cotton Valley), whereas the higher permeability sandstones in the #1 and #2 Fender and #1 Southwest Gas cores are interpreted as being Tithonian to Berriasian in age (late Cotton Valley). Differences in provenance between early and late Cotton Valley sandstones in Mississippi may account for the difference in abundance of clay rims. The age of the Cotton Valley sandstones studied by Thomas et al. (2004) in Mississippi was not stated, but they attributed the abundance of clay rims in Mississippi to a different provenance than the Cotton Valley sandstones in East Texas and Louisiana.

Rock Strength

Data on unconfined compressive strength (UCS), Poisson's Ratio, and Young's Modulus of reservoir sandstones and overlying and underlying mudstone layers can be used to help predict vertical hydraulic fracture growth in low-permeability gas reservoirs (CER Corporation and S. A. Holditch & Associates, 1991). UCS of Cotton Valley sandstones and mudstones was estimated in this study using a rebound hammer, which measures

Figure 8. Core-analysis porosity versus depth in Cotton Valley sandstones in East Texas, Louisiana, and Mississippi. Some deep sandstones in Mississippi have high porosity because continuous clay rims on detrital grains preserved intergranular porosity by inhibiting quartz cementation.

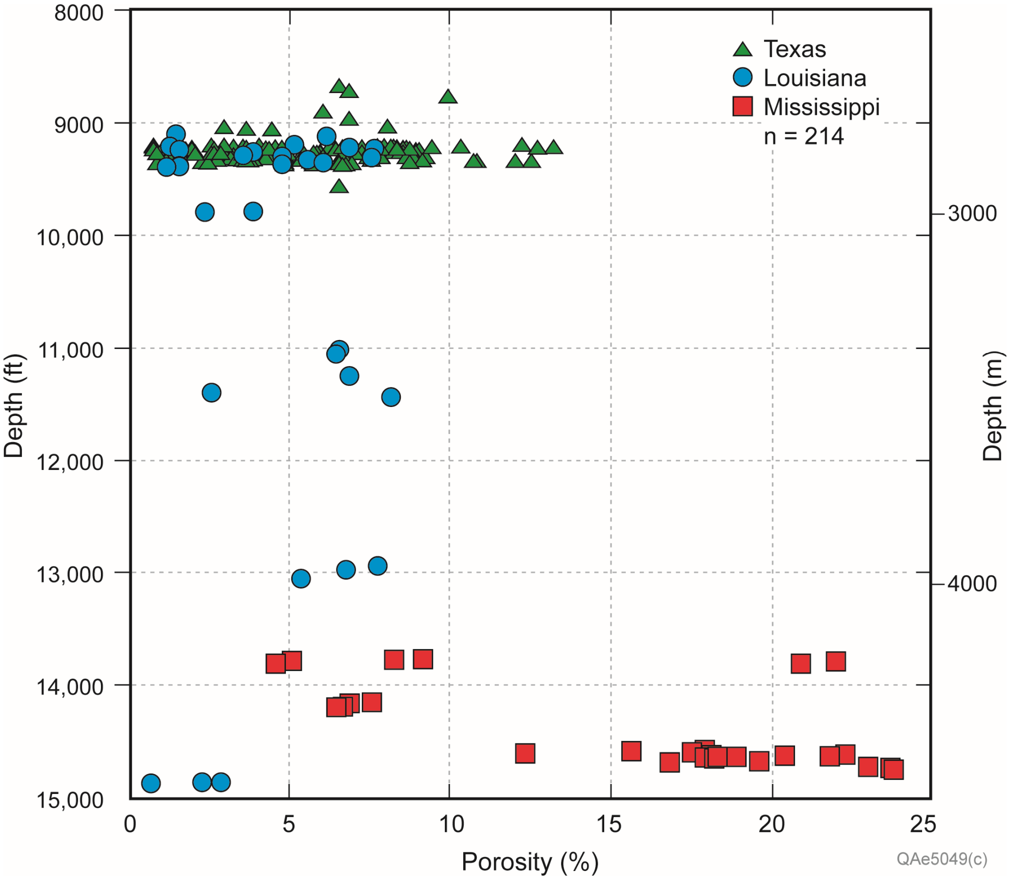
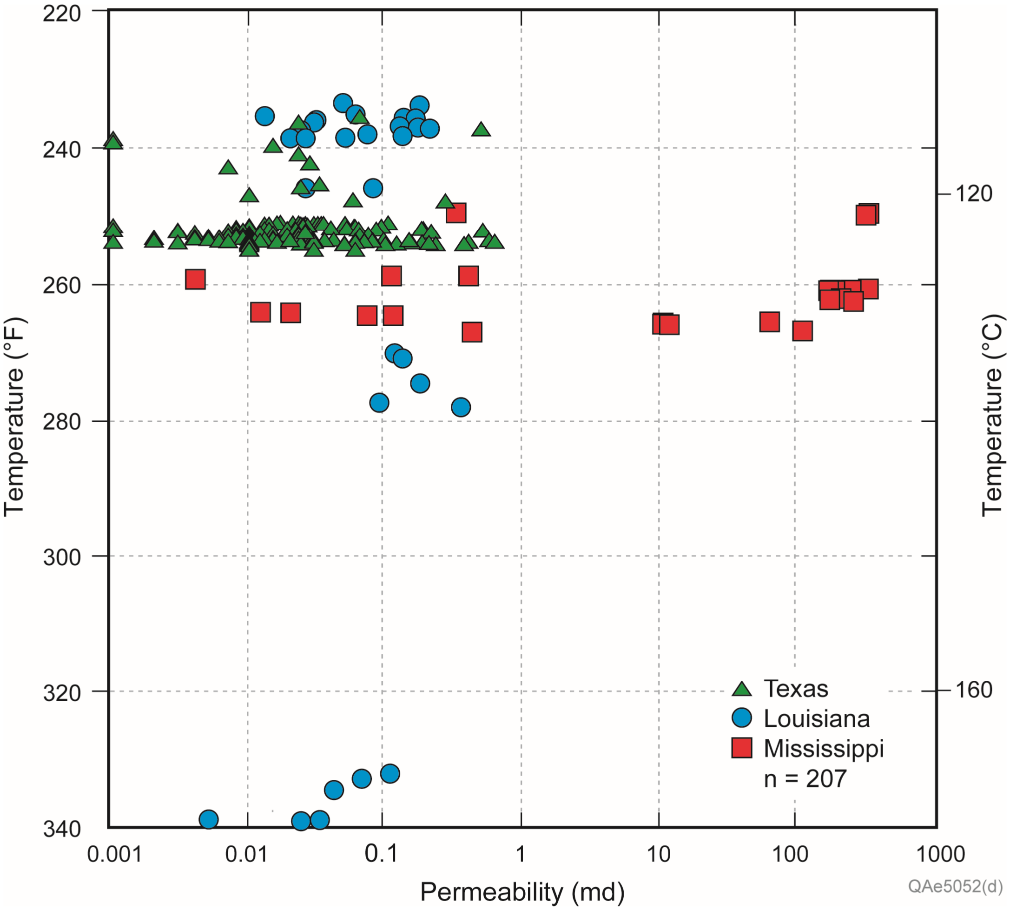


Figure 9. Core-analysis permeability versus temperature in Cotton Valley sandstones in East Texas, Louisiana, and Mississippi.



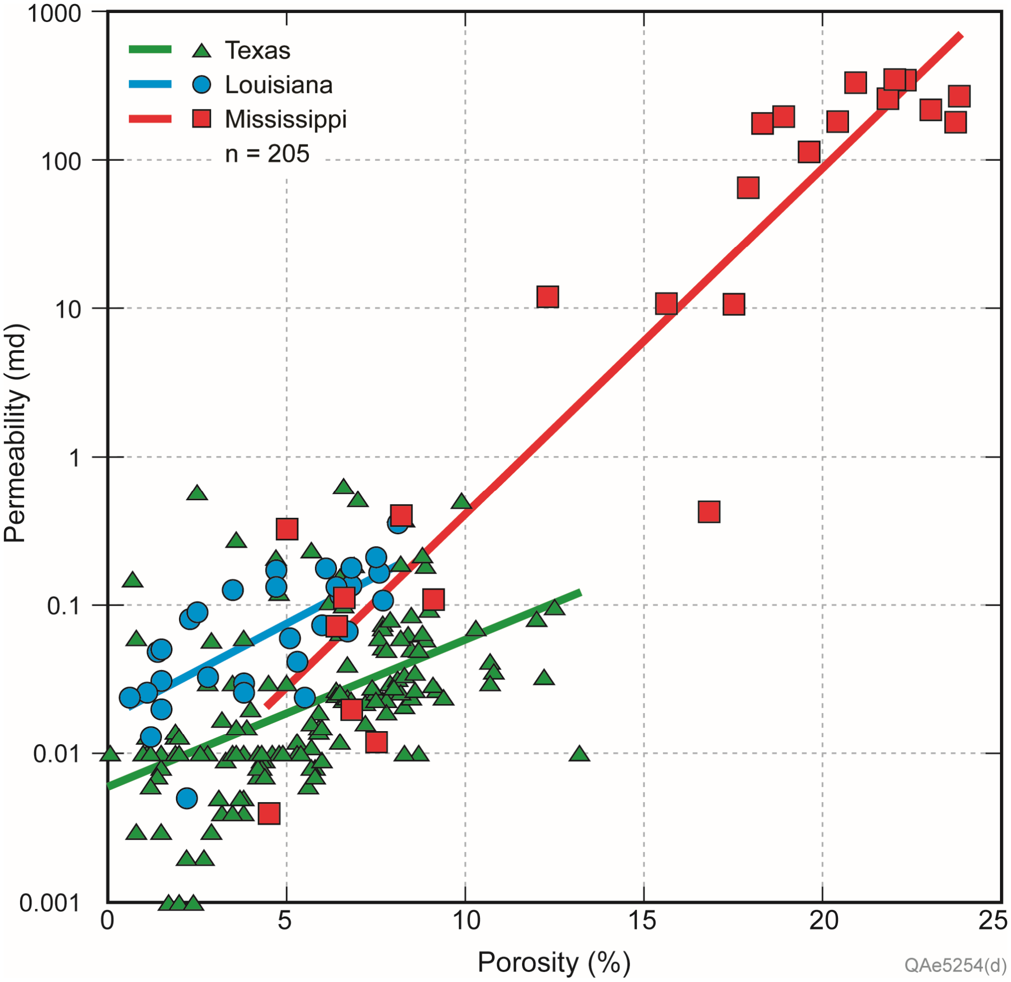


Figure 10. Porosity versus permeability relationships for Cotton Valley sandstones in East Texas (n = 151, r = 0.15), Louisiana (n = 30, r = 0.75), and Mississippi (n = 24, r = 0.67).

the rebound of a metallic anvil after it strikes a flat core surface (Kompatscher, 2004). Electronic sensors measure the velocity of the anvil as it travels toward and away from the surface of the sample. The rebound hammer records a value of hardness for the material struck known as Leeb Hardness (HLD), which is the ratio of the rebound velocity (v_r) to the impact velocity (v_i), multiplied by 100 (Kompatscher, 2004). Leeb Hardness measurements acquired by the rebound hammer have been correlated with unconfined compressive strength (UCS) (Zahm and Enderlin, 2010). Leeb Hardness is converted to UCS by the following equation: UCS (in megapascals [MPa]) = 0.000000683 * HLD^2.9 (Zahm and Enderlin, 2010).

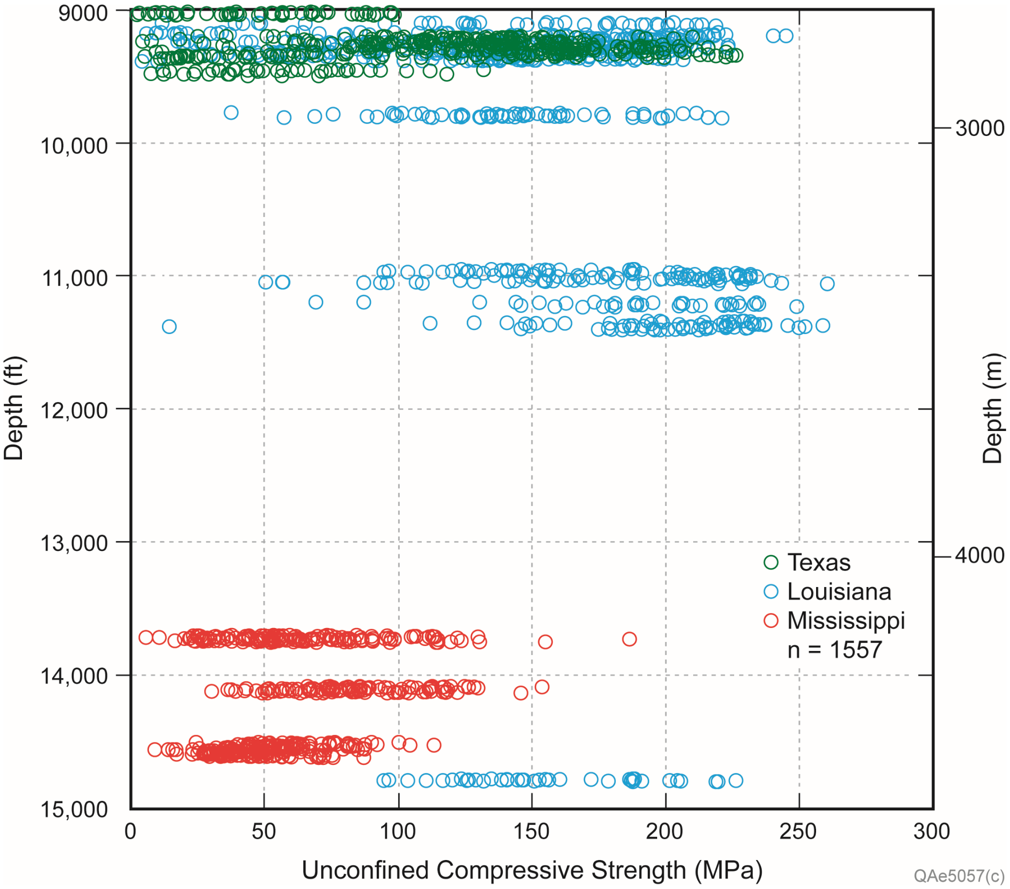
UCS is the uniaxial strength of a rock sample when pressed in a single direction from an applied force. The conventional method of measuring UCS is by the unconfined compression test (UCT). UCTs are conducted by placing core samples between two plates, one stationary and another that is lowered with a measured force. Core samples are compressed until the sample's strength is overcome (the sample is unable to rebound elastically), and the core breaks (Nazir et al., 2013). The advantages of using the rebound hammer to estimate rock strength instead of the unconfined compression test are (1) it is non-destructive, (2) it is inexpensive, and (3) samples can be collected at high resolution, on a scale of centimeters (Zahm and Enderlin, 2010). The drawback is that UCS is not measured directly but is estimated by a correlation between UCS and Leebs Hardness. Measurement of Leebs Hardness by rebound hammer is sensitive to sample volume (Verwall and Mulder, 1993; Brooks et al., 2016). In small core samples having volumes less than 12 in^3 (197 cm^3), UCS estimated from Leebs Hardness values is lower than values of USC measured by the unconfined compression test (Brooks et al., 2016).

UCS was measured every 0.5 ft (0.15 m) on Cotton Valley cores from Texas (Mobil #15 Cargill well), Louisiana (Sun #1–A Olinkraft, Amoco #1 Davis, and Amoco #1 Crown Zellerbach wells), and Mississippi (Shell #1 Fender, Pan American #1 Williamson, and Southwest Gas #1 Richardson wells) (Fig. 1). The objective of this investigation was to test if rebound hammer data can be correlated to variations in rock composition determined by thin-section point counts.

UCS values measured on Cotton Valley cores range from <1450 to >36,200 psi (<10 to >250 MPa) (Fig. 11). For samples with accompanying thin-section point count data, UCS in Cotton Valley mudstones ranges from (2750 to 14,200 psi [19 to 98 MPa]). Muddy sandstones with abundant clay matrix (>20% whole-rock volume) have UCS values of 5080 to 19,900 psi (35 to 137 MPa). UCS values in tightly cemented Cotton Valley sandstones in Texas and Louisiana are higher, ranging from 11,900 to 34,400 psi (82 to 237 MPa). UCS in low-permeability Cotton Valley sandstones from the Pan American #1 Richardson well in Smith County, Mississippi, ranges from 3340 to 22,300 psi (23 to 154 MPa), whereas UCS in the higher permeability sandstones from the Shell #1 Fender and the Southwest Gas #1 Richardson wells in Jasper County, Mississippi, ranges from 3920 to 13,100 psi (27 to 90 MPa).

There is a statistically significant correlation between total volume of cement in Cotton Valley samples and UCS (Fig. 12). Samples with low volumes of authigenic cement—either shales or porous sandstones—have low values of UCS. When struck by the rebound hammer, these 'soft' lithologies have slow

Figure 11. Unconfined compressive strength (UCS) versus depth in Cotton Valley sandstones in East Texas, Louisiana, and Mississippi. UCS was estimated from Leeb Hardness values measured on flat core surfaces by a rebound hammer (Kompatscher, 2004). 1 MPa = 145 psi.



rebound velocities and low calculated values of Leeb Hardness and UCS. Cotton Valley sandstones that are tightly cemented have a higher rebound velocity and high calculated values of Leeb Hardness and UCS. Positive correlation between cement volume and UCS was previously documented in sandstones of the Upper Cretaceous Woodbine Group in East Texas (Horodecky, 2015).

Cotton Valley sandstones that are tightly cemented by quartz have higher values of UCS than sandstones tightly cemented by carbonates (calcite and ankerite). Cotton Valley sandstones that contain ≥10% quartz cement (average = 15.3%) have average UCS of 22,300 psi (154 MPa), and sandstones that contain ≥20% quartz cement (average = 21.9%) have average UCS of 26,100 psi (180 MPa). In contrast, Cotton Valley sandstones with ≥10% carbonate cement (average = 20.0%) have average UCS of 18,900 psi (130 MPa), and sandstones with ≥20% carbonate cement (average = 25.0%) have average UCS of 21,300 psi (147 MPa). The higher UCS in quartz-cemented sandstones might be explained by a stronger bond between detrital quartz grains and quartz overgrowths than between detrital quartz grains and carbonate cement.

Burial-History Modeling

Burial-history models were prepared for representative wells in onshore East Texas, Louisiana, and Mississippi (Fig. 13) using a 1D thermal model. The models for the Mobil #15 Cargill well in East Texas and the Amoco #1 Davis well in Louisiana were calibrated with measured vitrinite reflectance values (R_o) (Dutton, 1987; Rushing et al., 2004; Goddard et al., 2008), but no measured R_o values were available for the Shell #1 Fender well in Mississippi (Fig. 1). The models calculated values of vitrinite reflectance equivalent (R_{oe}) of Cotton Valley sandstones from time-temperature history using the Lawrence Livermore National Laboratory (LLNL) model (Sweeney and Burnham, 1990) (Table 2). R_{oe} values in Table 2 are reported for an intermediate depth within the cored interval of each modeled well.

R_{oe} values in onshore Cotton Valley sandstones decrease from west to east, even though burial depth increases (Table 2). Cotton Valley sandstones at 9280 ft (2828 m) in the Mobil #15 Cargill well in East Texas have a calculated R_{oe} of 1.4%, and those in the Amoco #1 Davis well in Louisiana at a depth of 11,410 ft (3477 m) have a calculated R_{oe} of 1.2% (Table 2). In contrast, Cotton Valley sandstones at 14,590 ft (4447 m) in the Shell #1 Fender well in Mississippi have calculated R_{oe} of 1.05%. The reason for the lower thermal maturity of Cotton Valley sandstones in Mississippi than in East Texas and Louisiana is because the geothermal gradient increases from 1.4°F/100 ft (26°C/km) in Mississippi to 1.9°F/100 ft (35°C/km) in Louisiana and 2.0°F/100 ft (36°C/km) in East Texas (Table 2). Geothermal gradient generally increases from east to west along the northern Gulf of Mexico Coast and from offshore to onshore (DeFord et al., 1976; Blackwell and Richards, 2004; Nagihara and Jones, 2005; Forrest et al., 2005). The differences in burial- and thermal-history explain in part the greater volumes of quartz cement that precipitated in Cotton Valley sandstones in East Texas and Louisiana than in Mississippi. Because of the variation in geothermal gradient across the study area, it is more appropriate to plot parameters in the study against temperature and not depth.

A burial-history model was also prepared for Cotton Valley sandstones in the Exxon #1 SL 00624 well in offshore Baldwin County, Alabama (Fig. 1), to compare R_{oe} in onshore and offshore Cotton Valley sandstones. The model was calibrated with measured R_o data published by Rice et al. (1997). Cotton Valley sandstones in this well on the northeastern Gulf of Mexico shelf are buried to depths of 16,300 to 18,900 ft (4968 to 5760 m). The R_{oe} values of 1.45 to 1.9% are significantly higher than those of onshore Cotton Valley sandstones in Mississippi.

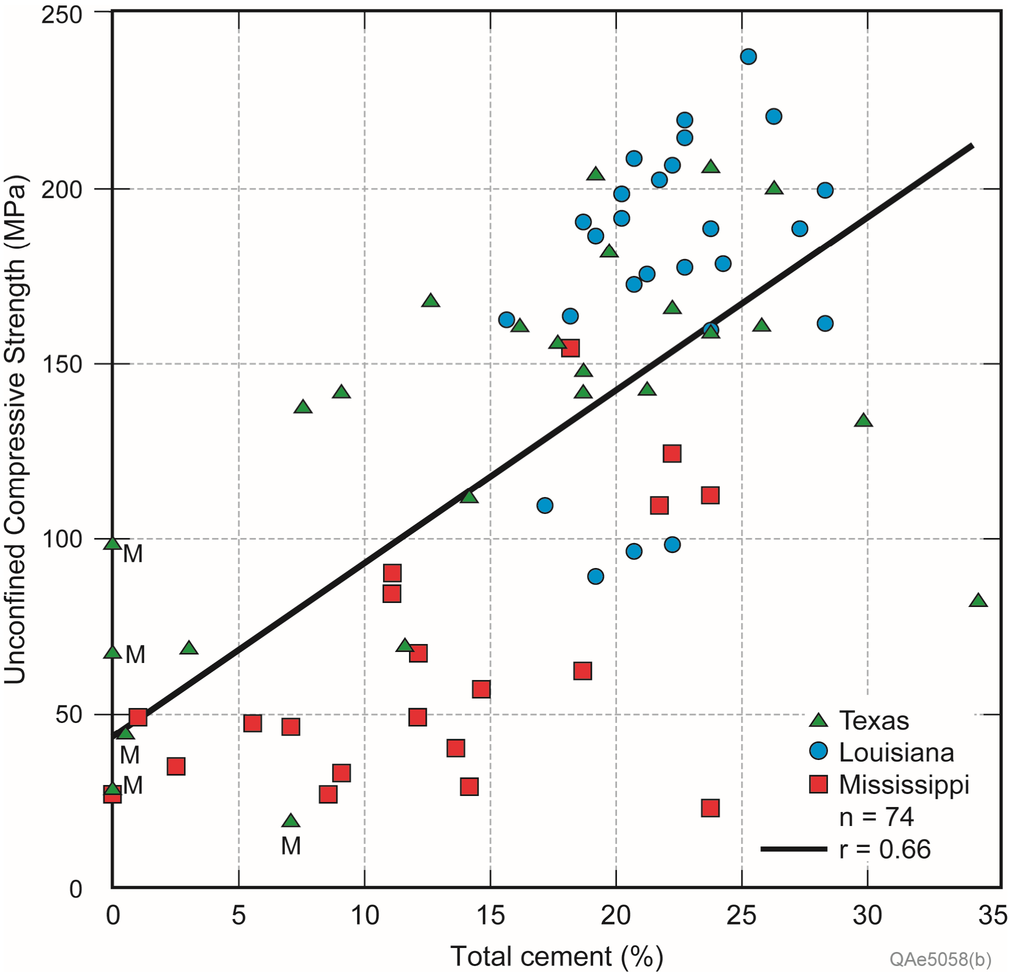


Figure 12. Total cement volume in Cotton Valley samples in East Texas, Louisiana, and Mississippi versus unconfined compressive strength (UCS) estimated from Leeb Hardness values measured by a rebound hammer. Samples labelled M are mudstones, and the rest of the samples are sandstones. 1 MPa = 145 psi.

DISCUSSION

Predicting the Presence of Clay Rims

Cotton Valley sandstones provide another example in which early clay rims on detrital grains preserve reservoir quality in sandstones. Previous petrographic studies of Cotton Valley sandstones reported the presence of chlorite rims on detrital grains in southern Mississippi (Janks et al., 1985) and offshore Viosca Knoll block 251 (Thomas et al., 2004, 2005). This study of Cotton Valley sandstones from central Mississippi also identified samples with abundant, continuous chlorite and illite grain rims that preserved good intergranular porosity by inhibiting quartz cementation. In contrast, Cotton Valley sandstones from East Texas and Louisiana contain fewer, and more discontinuous, clay rims and have poor reservoir quality.

It would be difficult to predict in advance of any petrographic work that Cotton Valley sandstones from Mississippi developed clay rims that were sufficiently abundant and continuous to preserve reservoir quality, whereas those in East Texas and Louisiana did not. The provenance of Cotton Valley sandstones in Mississippi does not contain ultrabasic volcanic rocks, which was the source of the abundant chlorite cement in Cretaceous Tuscaloosa sandstones in Louisiana (Thomson, 1979). However, Cotton Valley sandstones in Mississippi were derived from the Appalachian Mountains (Moore, 1983; Ewing, 2001; Thomas et al., 2004), a different source area than that of Cotton Valley sandstones in East Texas and Louisiana, which were derived from the Ouachita Mountains and Arbuckle Uplift (Coleman, 1985; Wescott, 1983, 1985; Ewing, 2001; Elshayeb, 2004). Metamorphic rock fragments are more abundant in Cotton Valley sandstones in Mississippi than those in East Texas and Louisiana. We agree with the conclusion of Thomas et al. (2004, 2005), that the difference in source areas for Cotton Valley sandstones deposited in the eastern versus western parts of the study area apparently resulted in differences in clay-rim coverage. The development of continuous clay rims in sandstone formations cannot yet be confidently predicted prior to petrographic analysis. However, because differences in provenance can lead to differences in clay-rim formation and reservoir quality, it is important to be alert to that possibility when reservoir-quality studies are initiated and to integrate reservoir-quality and basin-analysis studies.

Cotton Valley Sandstones, Northeastern Gulf of Mexico

Cotton Valley sandstones deposited in shallow-marine environments are exploration targets in the northeast Gulf of Mexico, offshore from Mississippi, Alabama, and Florida (Thomas et al., 2005; Petty, 2008). There is currently no production from these offshore Cotton Valley sandstones, although there have been gas shows in Cotton Valley clastics and carbonates in the Mississippi Sound, Mobile, Viosca Knoll, and Main Pass areas (Petty, 2008). Cotton Valley sandstones have not been detected in the northwestern Gulf of Mexico, offshore from Texas and Louisiana; in that area, the Tithonian interval consists of fine-grained, basinal deposits of the Bossier Formation (Salvador, 1991).

Cotton Valley sandstones cored in the Viosca Knoll 251 #1 well at a depth of 20,500 ft (6248 m) were deposited in a shoreface environment (Thomas et al., 2004). Measured core-analysis porosity in this well is 1.0 to 6.7%; porosity derived from log analysis ranges from 1 to 14% (Thomas et al., 2004). This porosity is significantly lower than Cotton Valley sandstones from onshore Mississippi, which ranges from 4.5 to

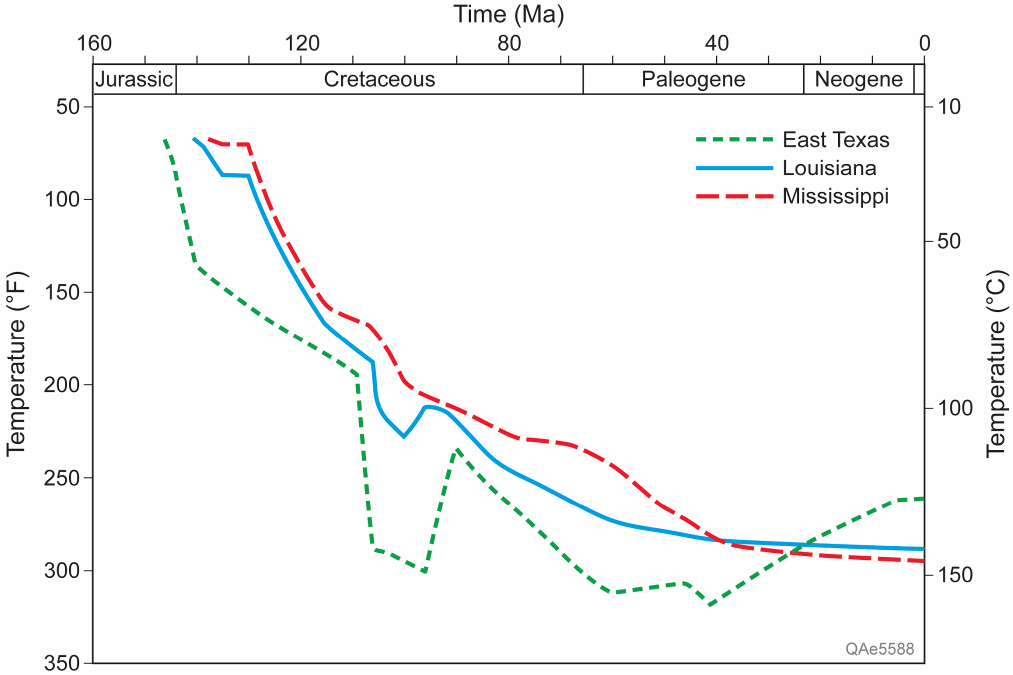


Figure 13. Burial-history curves showing temperature through time for Cotton Valley sandstones within the cored-interval depths of the Mobil #15 Cargill well in East Texas, the Amoco #1 Davis well in Louisiana, and the Shell #1 Fender well in Mississippi (Table 2). Well locations shown in Figure 1.

Table 2. Thermal maturity (vitrinite reflectance equivalent [R_{oe}]) of Cotton Valley sandstones was calculated in representative wells from East Texas, Louisiana, and Mississippi. R_{oe} was calculated for an intermediate depth within the cored interval of each well.

	East Texas	Louisiana	Mississippi
	(Mobil #15 Cargill)	(Amoco #1 Davis)	(Shell #1 Fender)
Present geothermal gradient (°F/100 ft [°C/km])	2.0 [36]	1.9 [35]	1.4 [26]
Intermediate cored-interval depth (ft [m])	9280 [2829]	11,410 [3478]	14,590 [4447]
R_{oe} (%) at cored-interval depth	1.4	1.2	1.05

23.8%. Chlorite cement is present in the Viosca Knoll sandstones, which were derived from the Appalachian Mountains, but chlorite-coat coverage averages only 30% (Thomas et al., 2004). Reservoir-quality modeling of the Viosca Knoll 251 #1 Cotton Valley sandstones indicates that intervals with only moderate chlorite-coat coverage will have low porosity because of extensive quartz cementation at these depths and temperatures (Thomas et al., 2004). However, modeling indicates that if grain-coating chlorite were extensive, reservoir quality could be preserved (Thomas et al., 2004). Thermal maturity was not calculated for this well, but because of the greater burial depth it is likely higher than that of Cotton Valley sandstones in the Exxon #1 SL 00624 well, where R_{oe} is 1.9% at a depth of 18,900 ft (5760 m). Thus, despite the presence of some chlorite coats, low porosity values and high thermal maturity suggest that reservoir quality is generally poor in offshore Cotton Valley sandstones.

CONCLUSIONS

Reservoir quality in onshore Cotton Valley sandstones varies significantly across the northern Gulf of Mexico Basin, increasing from East Texas to Mississippi. Core-analysis porosity in Cotton Valley sandstones from Mississippi averages 15.7%, compared with 5.7% in East Texas and 4.4% in Louisiana. Geometric mean permeability is 7.3 md in Cotton Valley sandstones from Mississippi, but only 0.02 md in East Texas and 0.06 md in Louisiana.

The increase in porosity and permeability from west to east resulted from a combination of factors: (1) coarser grain size, (2) more continuous clay rims on detrital grains, and (3) lower geothermal gradient. Mean grain size of Cotton Valley sandstones is 3.51 phi (0.088 mm) in East Texas, 2.76 phi (0.148 mm) in Louisiana, and 2.22 phi (0.214 mm) in Mississippi. Most grains in Cotton Valley sandstones in East Texas and Louisiana lack clay rims, and clay coverage is estimated as less than 30% on grains that do have partial rims. Abundant quartz cement precipitated where clay-rim coverage was low. In contrast, more grains in Cotton Valley sandstones in Mississippi contain clay rims, and coverage on some grains is estimated as >70%. The clay rims inhibited later quartz cementation and preserved intergranular porosity. UCS of Cotton Valley sandstones is highest in tightly quartz-cemented samples from East Texas and Louisiana.

Cotton Valley reservoir sandstones at 9280 ft (2828 m) in East Texas have R_{oe} of 1.4%, and those in Louisiana at a depth of 11,410 ft (3477 m) have R_{oe} of 1.2%. In contrast, Cotton Valley sandstones at 14,590 ft (4447 m) in Mississippi have R_{oe} of 1.05%. The reason for the lower thermal maturity of Cotton Valley sandstones in Mississippi than in East Texas and Louisiana is because the geothermal gradient increases from 1.4°F/100 ft in Mississippi to 1.9°F/100 ft in Louisiana and 2.0°F/100 in East Texas. Low porosity and high thermal maturity in offshore Cotton Valley sandstones in the northeastern Gulf of Mexico indicate that generally poor reservoir quality exists in this area.

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REFERENCES CITED

Ambrose, W. A., S. P. Dutton, and R. G. Loucks, 2017, Depositional systems, facies variability, and their relationship to reservoir quality in the Jurassic Cotton Valley Group, Texas, Louisiana, and Mississippi Gulf Coast: Gulf Coast Association of Geological Societies Journal, v. 6, p. 21–46, <http://www.gcags.org/Journal/2017.GCAGS.Journal/2017.GCAGS.Journal.v6.02.p21-46.Ambrose.et.al.pdf> Last accessed September 16, 2017.

Bebout, D. G., W. A. White, C. M. Garrett, Jr., and T. F. Hentz, eds., 1992, Atlas of major central and eastern Gulf Coast gas reservoirs: Texas Bureau of Economic Geology, Austin, 88 p., 4 pl.

Bjorkum, P. A., 1996, How important is pressure solution in causing dissolution of quartz in sandstones?: Journal of Sedimentary Research, v. 66, p. 147–154, doi:10.1306/d42682de-2b26-11d7-8648000102c1865d.

Blackwell, D. D., and M. C. Richards, 2004, Geothermal map of North America: American Association of Petroleum Geologists, Tulsa, Oklahoma, scale 1:6,500,000.

Bloch, S., R. H. Lander, and L. Bonnell, 2002, Anomalously high porosity and permeability in deeply buried sandstone reservoirs: origin and predictability: American Association of Petroleum Geologists Bulletin, v. 86, p. 301–328, doi:10.1306/61eedabc-173e-11d7-8645000102c1865d.

Brooks, D., X. Janson, and C. Zahm, 2016, The effect of sample volume on micro-rebound hammer UCS measurements in Gulf Coast Cretaceous carbonate cores: Gulf Coast Association of Geological Societies Journal, v. 5, p. 189–202, <http://www.gcags.org/Journal/2016.GCAGS.Journal/2016.GCAGS.Journal.v5. 11.p189-202.Brooks.et.al.pdf> Last accessed September 10, 2017.

Byrne, G. M., R. H. Worden, D. M. Hodgson, D. A. Polya, and P. R. Luthgoe, 2011, Understanding the fate of iron in a modern temperate estuary: Leirárvogur, Iceland: Applied Geochemistry, v. 26, p. S16–S19, doi:10.1016/j.apgeochem.2011.03.018.

CER Corporation and S. A. Holditch & Associates, eds., 1991, Staged field experiment no. 3: Application of advanced technologies in tight-gas sandstones—Travis Peak and Cotton Valley formations, Waskom Field, Harrison County, Texas: Gas Research Institute Report GRI–91/0048, Chicago, Illinois, 253 p.

Coleman, J. L., Jr., and C. J. Coleman, 1981, Stratigraphic, sedimentologic, and diagenetic framework for the Jurassic Cotton Valley Terryville massive sandstone complex, northern Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 71–79, doi:10.1306/a1adda26-0dfe-11d7-8641000102c1865d.

Coleman, J. L., Jr., 1985, Diagenesis of Cotton Valley sandstone (Upper Jurassic), East Texas: Implications for tight gas formation pay recognition: Discussion: American Association of Petroleum Geologists Bulletin, v. 69, p. 813–815, doi:10.1306/ad46281c-16f7-11d7-8645000102c1865d.

Corrigan, J., 2006, Correcting bottom hole temperature data, <http://www.zetaware.com/utilities/bht/default.html> Accessed January 4, 2017.

DeFord, R. K., R. O. Kehle, and E. T. Connolly, 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists, Tulsa, Oklahoma, and U.S. Geological Survey, Reston, Virginia, scale 1:5,000,000.

Dutton, S. P., 1987, Diagenesis and burial history of the Lower Cretaceous Travis Peak Formation, East Texas: Texas Bureau of Economic Geology Report of Investigations 164, Austin, 58 p.

Dutton, S. P., S. E. Laubach, R. S. Tye, K. L. Herrington, and T. N. Diggs, 1991, Geological analysis of the Travis Peak Formation and Cotton Valley Sandstone, *in* CER Corporation and S. A. Holditch & Associates, eds., Staged field experiment no. 3: Application of advanced technologies in tight gas sandstones—Travis Peak and Cotton Valley formations, Waskom Field, Harrison County, Texas: Gas Research Institute Report GRI–91/0048, Chicago, Illinois, p. 27–66.

Dutton, S. P., S. J. Clift, D. S. Hamilton, H. S. Hamlin, T. F. Hentz, W. E. Howard, M. S. Akhter, and S. E. Laubach, 1993, Major low-permeability-sandstone gas reservoirs in the continental United States: Texas Bureau of Economic Geology Report of Investigations 211, Austin, 221 p.

Ehrenberg, S. N., 1993, Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: Examples from the Norwegian continental shelf: American Association of Petroleum Geologists Bulletin, v. 77, p. 1260–1286, doi:10.1306/bdff8e5c-1718-11d7-8645000102c1865d.

Elshayeb, T. A. S., 2004, Integrated sequence stratigraphy, depositional environments, diagenesis, and reservoir characterization of the Cotton Valley sandstones (Jurassic), East Texas Basin, USA: Ph.D. Dissertation, University of Texas at Austin, 361 p.

Ewing, T. E., 2001, Review of Late Jurassic depositional systems and potential hydrocarbon plays, northern Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions, v. 51, p. 85–96, doi:10.1306/2dc40cde-0e47-11d7-8643000102c1865d.

Folk, R. L, 1974, Petrology of sedimentary rocks: Hemphill, Austin, Texas, 182 p.

Forrest, J., E. Marcucci, and P. Scott, 2005, Geothermal gradients and subsurface temperatures in the northern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 55, p. 233–248.

Goddard, D. A., E. A. Mancini, M. Horn, and S. C. Talukdar, 2008, Hydrocarbon generating potential: Jurassic Cotton Valley–Bossier Group, North Louisiana Salt Basin: Gulf Coast Association of Geological Societies Transactions, v. 58, p. 305–325.

Grigsby, J. D., 2001, Origin and growth mechanism of authigenic chlorite in sandstones of the Lower Vicksburg Formation, South Texas: Journal of Sedimentary Research, v. 71, p. 27–36, doi:10.1306/060100710027.

Horodecky, B. B., 2015, Mechanical stratigraphy and reservoir quality in sandstones of the Upper Cretaceous Woodbine Group, East Texas Field: B.S. Thesis, University of Texas at Austin, 36 p.

Houseknecht, D. W., 1987, Assessing the relative importance of compactional processes and cementation to the reduction of porosity in sandstones: American Association of Petroleum Geologists Bulletin, v. 71, p. 633–642, doi:10.1306/948872f3-1704-11d7-8645000102c1865d.

Janks, J. S., T. Sanness, and B. A. Rasmussen, 1985, Diagenesis of the Cotton Valley sandstones, Catahoula Creek Field, southern Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 35, p. 415–423, doi:10.1306/a1addb6d-0dfe-11d7-8641000102c1865d.

Kompatscher, M., 2004, Equotip-rebound hardness testing after D. Leeb: Proceedings of the Conference of Hardness Measurements Theory and Application in Laboratories and Industries, November 11–12, 2004, Washington, D.C., 7 p.

Land, L. S., and S. P. Dutton, 1978, Cementation of a Pennsylvanian deltaic sandstone: Isotopic data: Journal of Sedimentary Petrology, v. 48, p. 1167–1176, doi:10.1306/212f761c-2b24-11d7-8648000102c1865d.

Luffel, D. L., K. L. Herrington, and J. D. Walls, 1990, Effect of extraction and drying on flow, capillary, and electrical properties of Travis Peak cores containing fibrous illite: Society of Petroleum Engineers Paper SPE–20725–PA, Richardson, Texas, 7 p., doi:10.2118/20725-PA.

Moraes, M. A. S., and L. F. De Ros, 1990, Infiltrated clays in fluvial Jurassic sandstones of Recôncavo Basin, northeastern Brazil: Journal of Sedimentary Petrology, v. 60, p. 809–819, doi:10.1306/212f928c-2b24-11d7-8648000102c1865d.

Moore, T., 1983, Cotton Valley depositional systems of Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 163–167, doi:10.1306/a1addacd-0dfe-11d7-8641000102c1865d.

Nagihara, S., and K. O. Jones, 2005, Geothermal heat flow in the northeast margin of the Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 89, p. 821–831, doi:10.1306/01170504057.

Nazir, R., E. Momeni, D. J. Araghani, and M. F. M. Amin, 2013, Correlation between unconfined compressive strength and indirect tensile strength of limestone rock samples: Electronic Journal of Geotechnical Engineering, v. 18, p. 1737–1746, <http://www.ejge.com/2013/Ppr2013.168clr.pdf> Last accessed September 16, 2017.

Paxton, S. T., J. O. Szabo, J. M. Ajdukiewicz, and R. E. Klimentidis, 2002, Construction of an intergranular volume compaction curve for evaluating and predicting compaction and porosity loss in rigid-grain sandstone reservoirs: American Association of Petroleum Geologists Bulletin, v. 86, p. 2047–2067, doi:10.1306/61eeddfa-173e-11d7-8645000102c1865d.

Petty, A. J., 2008, Stratigraphy and petroleum exploration history of the Cotton Valley Group (Lower Cretaceous to Upper Jurassic) and Haynesville Group (Upper Jurassic), offshore northeastern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 58, p.713–728.

Pittman, E. D., 1979, Porosity, diagenesis, and productive capability of sandstone reservoirs, *in* P. A. Scholle and P. R. Schluger, eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication 26, Tulsa, Oklahoma, p. 159–173, doi:10.2110/pec.79.26.0159.

Proceq, 2017, <http://www.proceq.com> Accessed March 1, 2017.

Rice, D. D., C. J. Schenk, J. W. Schmoker, J. E. Fox, J. L. Clayton, T. S. Dyman, D. K. Higley, C. W. Keighin, B. E. Law, and R. M. Pollastro, 1997, Deep natural gas resources in the eastern Gulf of Mexico: U.S. Geological Survey Bulletin 2146–N, 229 p., <https://pubs.usgs.gov/bul/b2146/N.pdf> Last accessed July 3, 2017.

Rushing, J. A., A. Chaouche, and K. E. Newsham, 2004, A mass balance approach for assessing basin-centred gas prospects: integrating reservoir engineering, geochemistry and petrophysics, *in* J. M. Cubitt, W. A. England, and S. Larter, eds., Understanding petroleum reservoirs: Towards an integrated reservoir engineering and geochemical approach: Geological Society of London Special Publications 237, U.K., p. 373–390, doi:10.1144/gsl.sp.2004.237.01.19.

Russell, B. J., Jr., A. A. Sartin, and E. B. Ledger, 1984, Depositional and diagenetic history of the Bodcaw sand, Cotton Valley Group (Upper Jurassic), Longwood Field, Caddo Parish, Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 34, p. 217–228, doi:10.1306/a1addb0e-0dfe-11d7-8641000102c1865d.

Salvador, A., 1991, Triassic-Jurassic, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico Basin: Geological Society of America, Boulder, Colorado, p. 131–180, doi:10.1130/DNAG-GNA-J.131.

Seni, S. J., and M. P. A. Jackson, 1983, Evolution of salt structures, East Texas Diapir Province, part 1: Sedimentary record of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, p. 1219–1244, doi:10.1306/03b5b731-16d1-11d7-8645000102c1865d.

Sweeney, J. J., and A. K. Burnham, 1990, Evaluation of a simple model of vitrinite reflectance based on chemical kinetics: American Association of Petroleum Geologists Bulletin, v. 74, p. 1559–1570, doi:10.1306/0c9b251f-1710-11d7-8645000102c1865d.

Thomas, A., D. Balcer, T. Himes, L. M. Bonnell, J. Jones, and L. O'Mahoney, 2004, Deep Cotton Valley Formation diagenesis and reservoir quality, Viosca Knoll area, offshore Gulf of Mexico: American Association of Petroleum Geologists Search and Discovery Article 90029, Tulsa, Oklahoma, 2 p., <http://www.searchanddiscovery.com/documents/abstracts/hedberg2004austin/short/thomas.htm> Last accessed July 3, 2017.

Thomas, A., D. Balcer, T. Himes, L. M. Bonnell, and J. Jones, 2005, Jurassic Cotton Valley Formation reservoir quality, eastern offshore Gulf of Mexico; life below 20,000 feet: American Association of Petroleum Geologists Search and Discovery Article 90039, Tulsa, Oklahoma, 1 p. <http://www.searchanddiscovery.com/abstracts/html/2005/annual/abstracts/thomas03.htm> Last accessed July 3, 2017.

Thomson, A., 1979, Preservation of porosity in the deep Woodbine/Tuscaloosa trend, Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 29, p. 396–403.

U.S. Climate Data, 2016, <http://www.usclimatedata.com/climate/zapata/texas/united-states/ustx1499m> Last accessed January 4, 2017.

Verwall, W., and A. Mulder, 1993, Estimating rock strength with the Equotip hardness tester: International Journal of Rock Mechanics, Mining Science and Geomechanics Abstracts, v. 30, p. 659–662.

Waples, D. W., J. Pacheco, and A. Vera, 2004, A method for correcting log-derived temperatures in deep wells, calibrated in the Gulf of Mexico: Petroleum Geoscience, v. 10, p. 239–245, doi:10.1144/1354-079302-542.

Wescott, W. A., 1983, Diagenesis of Cotton Valley Sandstone (Upper Jurassic), East Texas: Implications for tight gas formation pay recognition: American Association of Petroleum Geologists Bulletin, v. 67, p. 1002–1013, doi:10.1306/03b5b6e6-16d1-11d7-8645000102c1865d.

Wescott, W. A., 1985, Diagenesis of Cotton Valley Sandstone (Upper Jurassic), East Texas: Implications for tight gas formation pay recognition: Reply: American Association of Petroleum Geologists Bulletin, v. 69, p. 816–818, doi:10.1306/ad462821-16f7-11d7-8645000102c1865d.

Wilson, M. D., 1992, Inherited grain-rimming clays in sandstones from eolian and shelf environments: Their origin and control on reservoir properties, *in* D. W. Houseknecht and E. D. Pittman, eds., Origin, diagenesis, and petrophysics of clay minerals in sandstones: Society of Economic Paleontologists and Mineralogists Special Publication 47, Tulsa, Oklahoma, p. 209–225, doi:10.2110/pec.92.47.0209.

Worden, R. H., and S. Morad, 2003, Clay minerals in sandstones: controls on formation, distribution, and evolution: International Association of Sedimentologists Special Publication 34, Gent, Belgium, p. 3–41, doi:10.1002/9781444304336.ch1.

Zahm, C. K., and M. Enderlin, 2010, Characterization of rock strength in Cretaceous strata along the Stuart City Trend, Texas: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 693–702.

ZetaWare, 2009, <http://www.zetaware.com> Accessed January 4, 2017.