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Preservation of Reservoir Quality by Chlorite Coats in Deep Tuscaloosa Sandstones, Central Louisiana, U.S.A.

Shirley P. Dutton, Marilyn E. Hutton, William A. Ambrose, A. Taylor Childers, and Robert G. Loucks

Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, University Station, Box X, Austin, Texas 78713–8924, U.S.A.

ABSTRACT

Thick, continuous chlorite coats on detrital grains in some Upper Cretaceous Tuscaloosa sandstones preserve porosity by inhibiting quartz cementation, but sandstones with discontinuous, incomplete chlorite coats are extensively cemented by quartz. The percentage of chlorite-coat coverage on detrital grains was quantified and compared to porosity and permeability to determine what completeness of grain coatings is necessary to reduce quartz cementation and preserve reservoir quality in hot (>275°F [>135°C]), deeply buried (>14,000 ft [>4.3 km]) Tuscaloosa sandstones in central Louisiana.

Petrographic analysis of 141 samples from central Louisiana documented composition, diagenesis, and reservoir quality in fluvial and deltaic Tuscaloosa sandstones having the same provenance. Most sandstones are sublitharenites, with an average composition of 86% quartz, 1% feldspar, and 13% rock fragments ($Q_{86}F_1R_{13}$); average grain size is upper fine grained (2.44 phi [0.184 mm]). Porosity, permeability, and chlorite-cement volume all have bimodal distributions. Twelve samples with a wide range of porosity and permeability were selected for quantification of chlorite grain-coat coverage on detrital quartz grains, measuring 50 grains per sample. Chlorite-coat coverage ranges from 29 to 95%, and chlorite-cement volume in these samples covaries from 2.5 to 10%. Significant correlations exist between chlorite-coat coverage and volume of chlorite cement, quartz cement, porosity, and permeability. Tuscaloosa sandstones with ≥80% chlorite-coat coverage (≥8% chlorite-cement volume) retain high porosity (20–29%) and permeability (10–1249 md) at temperatures of 275° to 420°F (135° to 215°C) by inhibiting quartz cementation. An estimated 25% of the Tuscaloosa sandstones in central Louisiana contain such extensive chlorite-coat coverage. Grain size and volcanic-rock-fragment content are the most important factors in determining chlorite-coat growth and reservoir quality in Tuscaloosa sandstones in central Louisiana.

Reservoir quality in Tuscaloosa sandstones is also influenced by the presence of carbonate concretions that completely occlude porosity within the cemented zones. The presence of thick, continuous chlorite coats did not inhibit later precipitation of carbonate cement. The concretions, which have an average measured thickness of 0.8 ft (0.23 m), degrade reservoir quality in 5% of the total thickness of the Tuscaloosa sandstones in central Louisiana. Although one cannot predict chlorite-coat coverage or the presence of calcite concretions on a foot-by-foot basis, a risk estimate can be assigned for encountering good reservoir quality.

INTRODUCTION

Sandstones of the Upper Cretaceous Tuscaloosa Formation produce oil and gas in Louisiana and Mississippi and are exploration targets in the northern Gulf of Mexico. Tuscaloosa reservoirs in central Louisiana (Fig. 1) were deposited in lowstand incised-valley systems and highstand deltaic systems (Woolf, 2012; Ambrose et al., 2015). Some of the Tuscaloosa sandstones in central Louisiana retain anomalously good reservoir quality (porosity ≥ 20% and permeability ≥ 10 md) (Fig. 2A) at depths > 14,000 ft (>4.3 m) and temperatures > 275°F (>135°C) (Fig. 2B). Porosity is preserved in these sandstones by the presence of robust, continuous chlorite coats that formed around detrital grains and inhibited later quartz cementation (Thomson, 1979; Smith, 1981, 1985; Pittman et al., 1992). However, other Tuscaloosa sandstones at the same depth and temperature are tightly cemented by quartz or calcite. This paper examines variable distribution of chlorite coats and reservoir quality in Tuscaloosa sandstones in central Louisiana, within an area of uniform provenance and similar burial histories. The goals are to (1) identify which sandstones developed continuous chlorite coats and retained good reservoir quality, (2) determine what percentage of chlorite coverage is necessary to inhibit quartz cementation in Tuscaloosa sandstones, and (3) estimate the percentage of Tuscaloosa sandstones in the study area that have sufficient chlorite-coat

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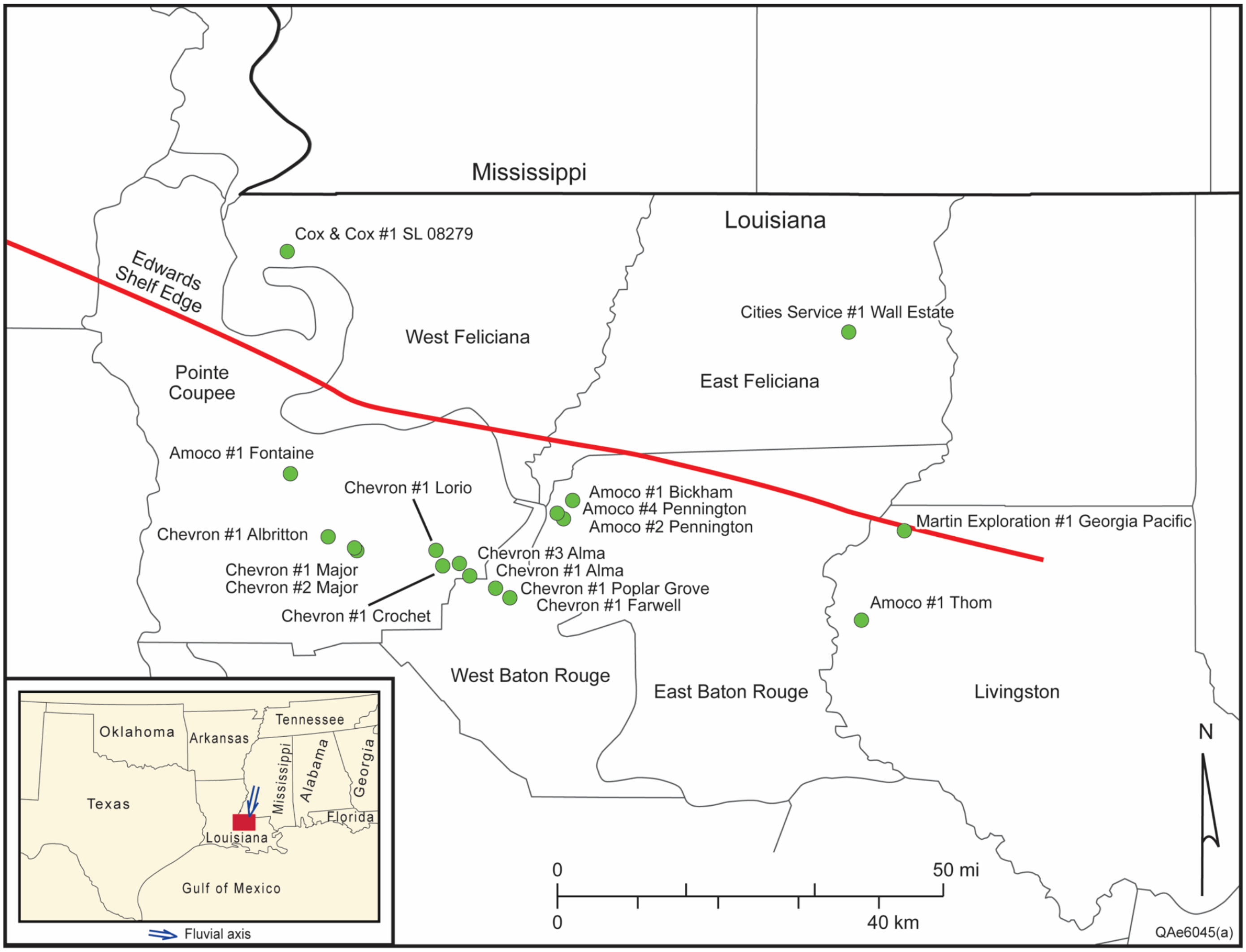


Figure 1. Location of 17 wells used in investigation of reservoir quality of Tuscaloosa sandstones in central Louisiana. Petrographic and core-analysis data were collected from all wells except the Chevron #1 Alma well, which only has core-analysis data. Inset map shows the study area within the northwest Gulf of Mexico Basin and the Tuscaloosa fluvial axis that carried sediment to central Louisiana. Orientation of fluvial axis based on work of Berg (1982), Smith (1985), Dubiel et al. (2003), and Woolf (2012).

coverage to retain good porosity and permeability. A further goal is to quantify the percentage of Tuscaloosa sandstones that are tightly cemented by calcite.

In this study we characterize the detrital mineral composition, diagenesis, and reservoir quality of Tuscaloosa sandstones from central Louisiana. Petrographic and reservoir-quality (porosity and permeability) data were collected from 17 wells in central Louisiana (Fig. 1), from samples buried to depths of 14,095 to 21,197 ft (4296 to 6460 m) and temperatures of 277 to 418°F (136 to 214°C). Tuscaloosa sandstones in central Louisiana were deposited in fluvial environments within lowstand incised-valley systems and in shallow-marine deltaic environments in transgressive and highstand systems (Barrell, 1997; Woolf, 2012; Ambrose et al., 2015). Farther downdip, Tuscaloosa sandstones were deposited on the slope and basin floor in the deepwater Gulf of Mexico (Woolf, 2012; Snedden et al., 2016). Understanding the controls on porosity and permeability in onshore Tuscaloosa sandstones could aid in predicting reservoir quality in deepwater Tuscaloosa sandstones deposited on the basin floor, which have been penetrated in deep Gulf of Mexico wells.

GEOLOGIC SETTING

Sandstone reservoirs of the Upper Cretaceous Tuscaloosa Formation occur along the Lower Cretaceous paleo-shelf edge of the Gulf of Mexico in central Louisiana (Thomson, 1979). The lower Tuscaloosa Formation in this area is divided into two main intervals: (1) a lower section, commonly >1000 ft (>305 m) thick, composed of highstand, shallow-marine deposits that grade upward from deepwater slope deposits, and (2) an overlying sandstone-rich section (up to 700 ft [213 m] thick), consisting of lowstand incised-valley fill, primarily fluvial deposits (Ambrose et al., 2015). Tuscaloosa incised valley-fill systems in central Louisiana record deep incision (up to ~400 ft [~122 m]) into highstand deltaic complexes. The lower half of the valley succession typically is composed of coarse-grained and conglomeratic braided-stream systems that grade upward into mixed-load meander belt deposits, which are in turn overlain by a regionally continuous (10 to 25 ft [3 to 7.6 m]) mudstone interval recording valley inundation and development of estuarine systems (Ambrose et al., 2015). The incised-valley interval is overlain by a shaly 500 to 800 ft (152 to 244 m) section, the Tuscaloosa

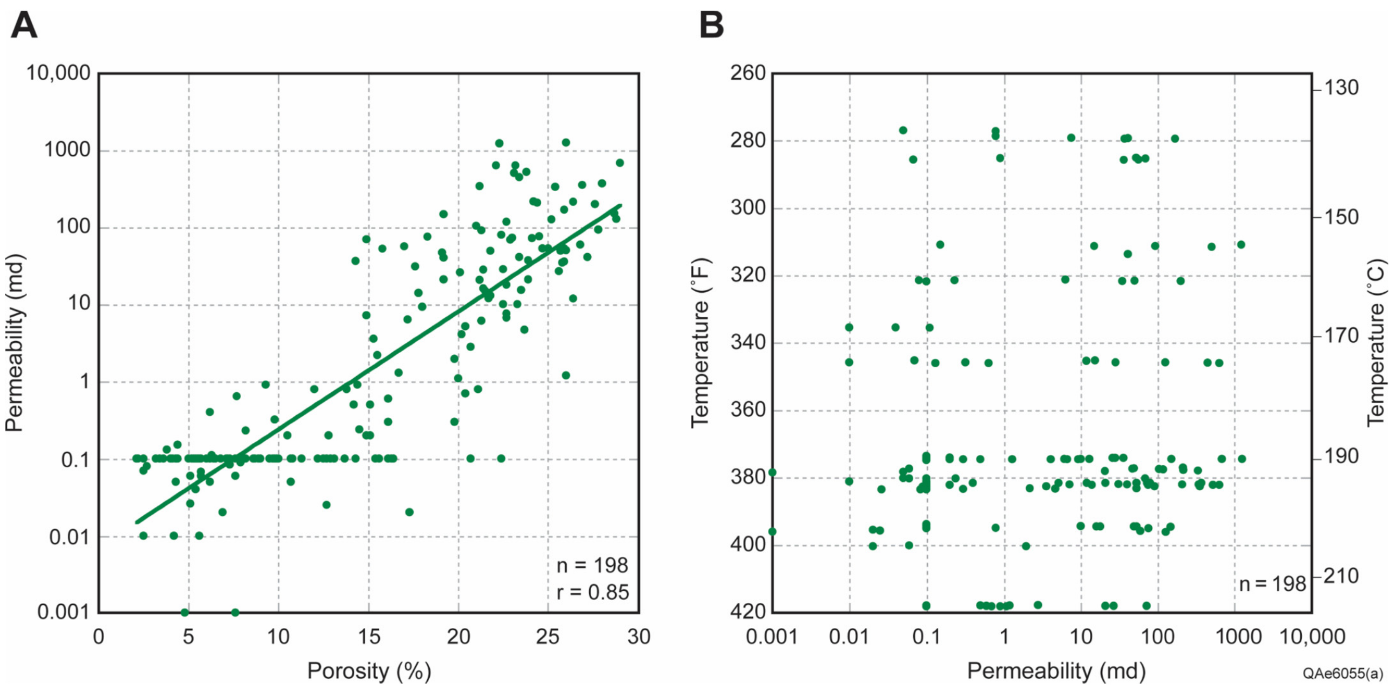


Figure 2. Reservoir quality in Tuscaloosa sandstones from central Louisiana. (A) Porosity versus permeability relationship. Routine core-analysis permeability measurements that were collected when the cores were first cut had a lower measurement limit of 0.1 md. (B) Permeability versus temperature plot. Some sandstones retain high permeability at high temperatures because continuous chlorite coats on detrital grains preserved intergranular porosity by inhibiting quartz cementation.

Marine Shale, within the middle Tuscaloosa Formation (Dubiel et al., 2003).

The study by Ambrose et al. (2015) of Tuscaloosa sandstones in central Louisiana documented sequence-stratigraphic and depositional controls on original porosity and permeability. The best original reservoir quality prior to diagenesis occurs in sandy, non-conglomeratic bedload-fluvial deposits within the incised valley systems and in proximal-delta-front sandstones at the top of highstand progradational successions (Ambrose et al., 2015).

Regional mapping of Tuscaloosa sandstone depocenters (Berg, 1982; Smith, 1985; Sohl et al., 1991; Dubiel et al., 2003) suggests that Tuscaloosa sandstones in central Louisiana were derived from the north and northeast, in the vicinity of the Monroe Uplift in northern Louisiana and the Jackson Dome in Mississippi (Dubiel et al., 2003). Volcanic rock fragments (VRFs) in the Tuscaloosa Formation are interpreted to be fragments of ultrabasic volcanics and volcaniclastics (Thomson, 1979). Harrelson (1981) used stratigraphic data to interpret the timing of extrusive volcanism and subsequent erosion of mafic igneous rocks at Jackson Dome. Harrelson (1981) concluded that erosion of Jackson Dome began during Tuscaloosa time and created abundant volcaniclastic deposits through Eutaw (late Turonian) time. Harrelson's (1981) interpretation of the timing of volcanism in the Jackson Dome and its location relative to the central Louisiana Tuscaloosa sandstones suggests that this area was the source of the VRFs in the Tuscaloosa Formation.

Lower Tuscaloosa sandstones in central Louisiana are interpreted to be at or near their maximum burial depths of 14,000 to 21,000 ft (4.3 to 6.5 km) and temperatures of 275 to 400°F (135 to 205°C). Tuscaloosa sandstones in the southern part of the study area are deeper and hotter than those to the north because they were deposited basinward of the underlying Edwards shelf edge (Fig. 1) (Dubiel et al., 2003). More accommodation space was available for thicker sediment to be deposited in this area of growth faulting (Dubiel et al., 2003).

METHODS

Composition of Tuscaloosa sandstones in central Louisiana was determined by point counts of 141 thin sections from 16 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). Grain size and sorting were determined by measuring the long diameter of 100 competent grains (quartz and feldspar) per thin section. Core-analysis data are available for 115 of the Tuscaloosa thin-section samples. 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. Core descriptions and facies interpretations (Ambrose et al., 2015) provided a sequence-stratigraphic and depositional-systems framework for interpreting reservoir-quality data.

Chlorite-coat quantification was done on 12 Tuscaloosa thin-sections from central Louisiana using the program JMicroVision (v. 1.27) and a digital drawing tablet and stylus. The 12 samples came from 6 different wells. For each well, one sample was selected having a higher volume of chlorite measured in thin-section point counts and the other sample having a lower volume of chlorite. Volume of chlorite determined from point counts in these samples ranges from 2.5 to 10% of the whole-rock volume. Chlorite-coat coverage was measured on 50 quartz grains in each thin section. Photomicrographs were taken of 10 areas scattered across the entire thin section, and 5 randomly selected quartz grains were measured in each photograph. For each grain, we used the following procedure: (1) measure the grain circumference, (2) measure the lengths of any parts of the grain that are in contact with other grains and thus not available for chlorite-cement coating, and (3) measure the lengths of chlorite coatings on the grain surface. Chlorite-coat coverage was calculated as: (sum of chlorite-coated lengths) ÷ (grain diameter – sum of grain-contact lengths).

Representative sandstone samples with continuous chlorite coats and good reservoir quality were prepared by argon-ion milling for viewing in a scanning electron microscope (SEM). 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. Epoxy-impregnated samples were used for porous sandstones that were too poorly lithified to be ion-milled without grain plucking.

The thickness and distribution of tightly calcite-cemented layers were quantified in seven Tuscaloosa sandstones cores in central Louisiana. These cemented layers are sandstone intervals that contain more than approximately 10% total volume of authigenic carbonate and have low porosity and permeability. The cemented layers were identified in cores by their color, smooth texture, and response to HCl, and the thickness of each concretion in the cores was measured.

A burial-history model of the Chevron #1 Lorio well (Fig.1) in Pointe Coupee Parish, Louisiana, was created using the program Genesis 5.71 (ZetaWare, 2009) to characterize burial history of onshore Tuscaloosa sandstones in the central Louisiana study area south of the Edwards shelf margin. Values of vitrinite reflectance equivalent (R_{oe}), an indicator of thermal maturity, were calculated in the burial-history model using the Lawrence Livermore National Laboratory (LLNL) vitrinite maturation model (Sweeney and Burnham, 1990). No measured vitrinite-reflectance data were available for model calibration.

SANDSTONE COMPOSITION AND DIAGENESIS

Petrographic properties of Tuscaloosa sandstones in central Louisiana, including grain size, detrital mineral composition, and diagenesis, were quantified and correlated with reservoir quality. Average grain size of Tuscaloosa sandstones in this study is upper fine grained (2.44 phi [0.184 mm]), and most of the samples are well sorted (0.35 to 0.5 phi standard deviation, as defined by Folk [1974]). Most Tuscaloosa sandstones in central Louisiana are sublitharenites, with an average composition of 86% quartz, 1% feldspar, and 13% rock fragments ($Q_{86}F_1R_{13}$). Basic VRFs are the most common lithic grains in central Louisiana (average whole-rock volume of 5.4%), followed by metamorphic and sedimentary rock fragments, mainly chert. Many VRFs are partly to completely dissolved and some are replaced by authigenic chlorite. The VRFs are interpreted to be fragments of ultrabasic volcanics and volcaniclastics derived from Cretaceous volcanic activity (Thomson, 1979; Harrelson, 1981).

Diagenesis plays a critical role in reservoir quality of the Tuscaloosa sandstones in central Louisiana. The first authigenic cement on many Tuscaloosa detrital grains is a thin, discontinuous layer of leucoxene (Fig. 3), a microcrystalline titanium oxide that is common in VRF–rich sediments (Folk, 1974). Authigenic chlorite, oriented perpendicular to the underlying detrital grains, is the next cement on most grains (Fig. 3). Chlorite forms robust, continuous coats on many detrital grains in Tuscaloosa sandstones from central Louisiana (Fig. 4A). The coats are 7 to 10 microns (0.007 to 0.01 mm) thick. The volume of chlorite cement, determined by thin-section point counts, varies from 0 to 14.5%. Chlorite-cement volume ranges from 0 to >10% at all burial depths and temperatures in the study area. As viewed in argon-ion-milled samples in SEM, chlorite occurs as thin, elongate crystals growing perpendicular to the detrital grains (Fig. 5). Small (0.6 μm), anhedral quartz overgrowths were observed in gaps between densely packed chlorite crystals oriented perpendicular to detrital grains (Fig. 5B), similar to those described by Ajdukiewicz and Larese (2012). The quartz overgrowths do not grow out beyond the chlorite coats because the clays prevent them from coalescing (Ajdukiewicz and Larese, 2012). Dissolution of VRFs is interpreted to be the source of the ions in these clay coats (Thomson, 1979; Smith, 1985; Pittman et al., 1992; Bloch et al., 2002). Work by Ryan and Reynolds (1996)

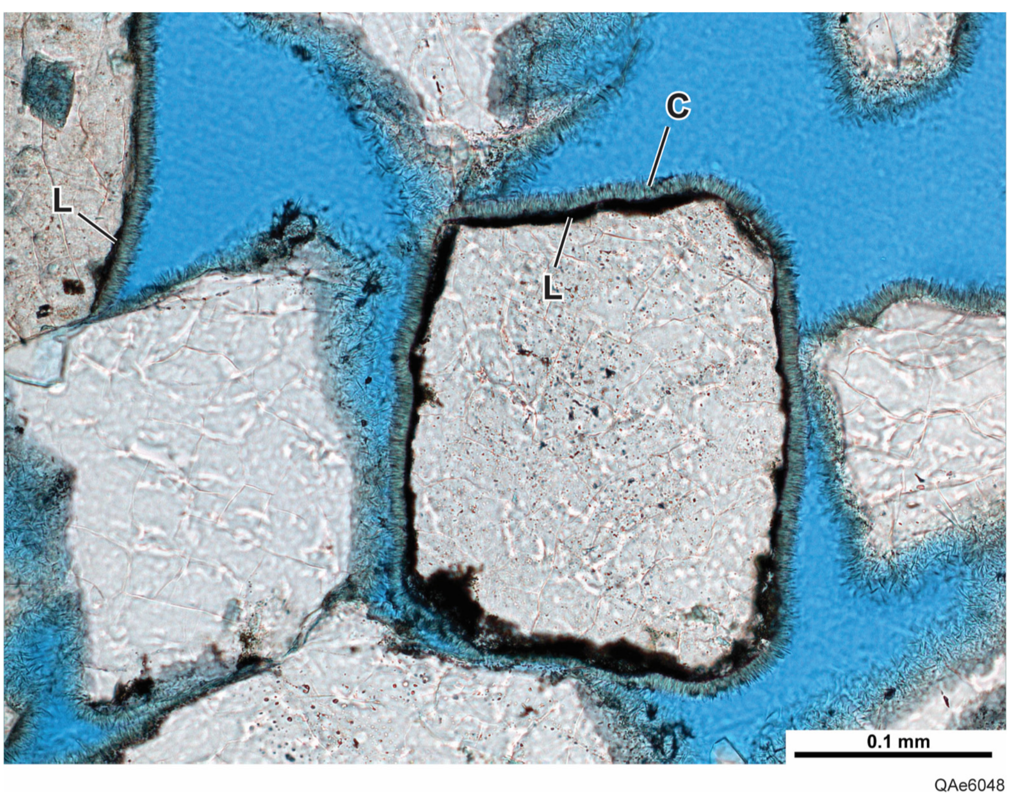
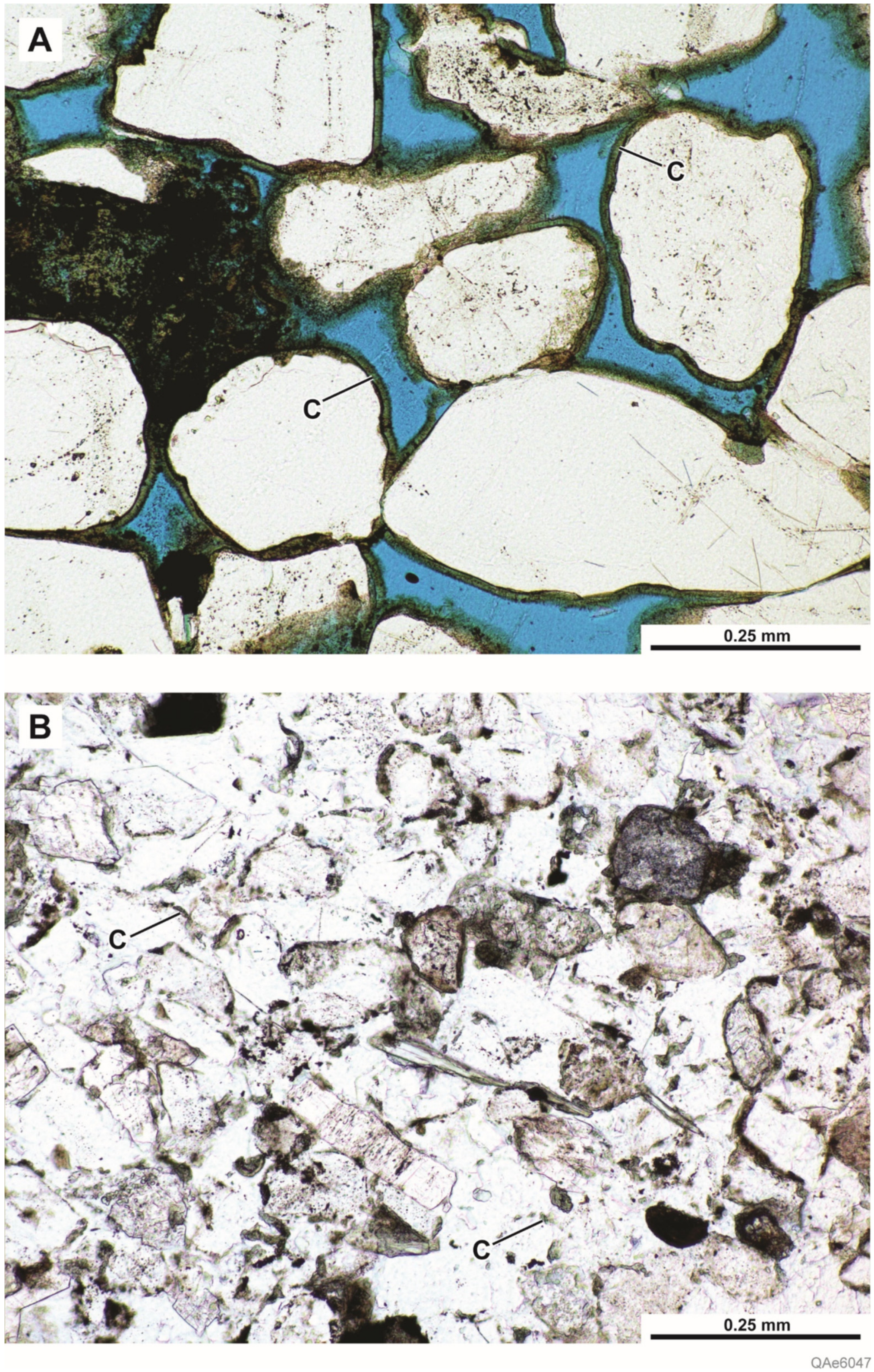


Figure 3. Early leucoxene cement (black, labeled L) on detrital grains in the Cox & Cox #1 SL 08279 well, West Feliciana Parish, Louisiana, from a depth of 14,706 ft (4482.4 m). Leucoxene is overlain by chlorite cement (C). Plane-polarized light.

Figure 4. Photomicrographs of Tuscaloosa sandstones from central Louisiana. (A) Continuous chlorite coats (C) on detrital grains preserved intergranular porosity by inhibiting quartz cementation. Sample from Amoco #2 Pennington well, East Baton Rouge Parish, bedload fluvial-channel deposit from 16,584 ft (6074 m). Porosity = 27.6% and permeability = 199 md. (B) Tuscaloosa sandstone tightly cemented by quartz; chlorite coats (C) are small and incomplete. Sample from Chevron #1 Lorio well, Pointe Coupee Parish, transgressive deposit from 20,462 ft (6236.8 m). Porosity = 5.4% and permeability = 0.1 md.



indicates that the chlorite probably formed during burial diagenesis by transformation of an early Fe–rich serpentine clay precursor such as odinite or bertheirine (Worden and Morad, 2003). The serpentine precursor was altered to chlorite through a serpentine/chlorite mixed-layer-clay intermediate that exhibits decreasing serpentine layers with depth (Ryan and Reynolds, 1996).

Quartz cement forms overgrowths and outgrowths on detrital grains that lacked continuous chlorite coats (Fig. 4B). Breaks in the chlorite coats allowed quartz cement to nucleate and grow into the pore space (Fig. 5A). Quartz is the most abundant authigenic cement in Tuscaloosa sandstones in central Louisiana, having an average volume of 6.2% of whole-rock volume and

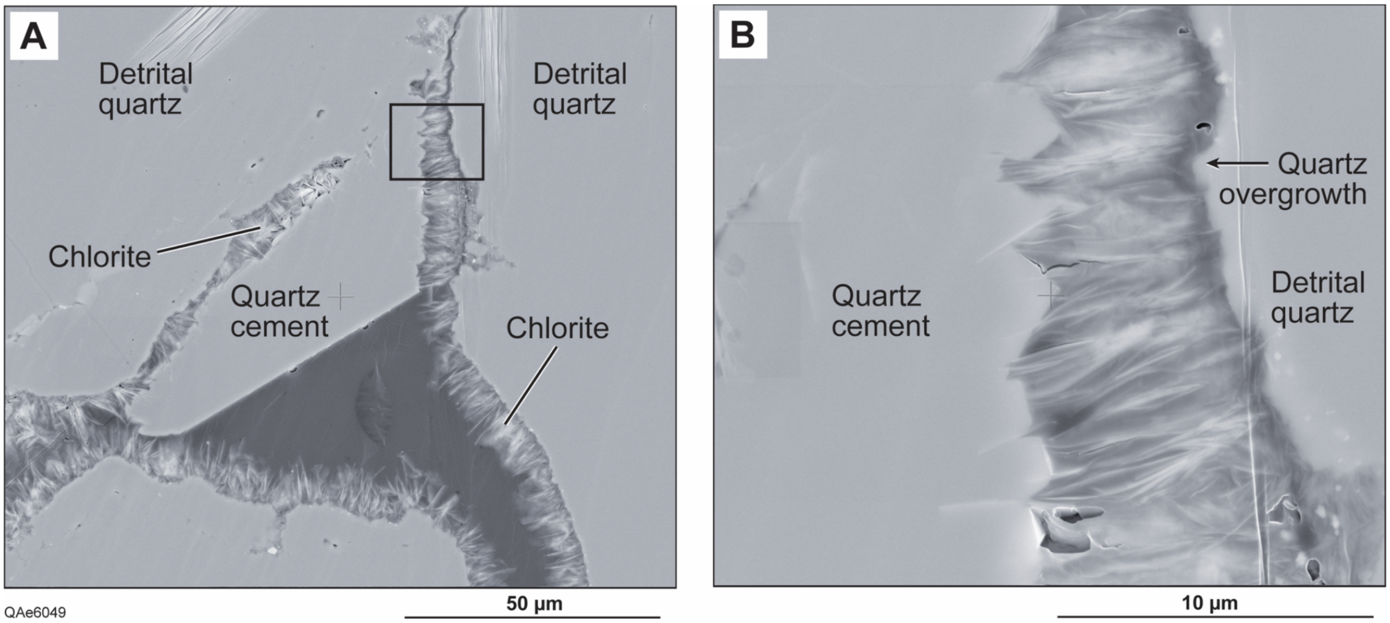


Figure 5. Images of an argon-ion-milled sample of Tuscaloosa sandstone from 18,831 ft (5739 m), Amoco #1 Fontaine well, Pointe Coupee Parish, Louisiana. (A) Chlorite coats on detrital grains inhibited quartz cement, but quartz cement precipitated at a gap in the chlorite coat and extended into the pore space. Box shows area of Figure 5B. (B) Small quartz overgrowths (example shown by arrow) developed on detrital quartz grain surface between clay flakes. SEM images taken by Patrick Smith.

ranging from 0 to 20.5%. Some of the samples with low volumes of quartz cement contain continuous chlorite coats that inhibited quartz cementation (Figs. 3 and 4A), and others are tightly cemented by carbonate. As will be demonstrated, Tuscaloosa sandstones that contain a large volume of quartz cement (Fig. 4B) had incomplete chlorite coats that were not sufficiently thick and continuous to inhibit quartz cementation at temperatures >250°F (>120°C).

Calcite, Fe–calcite, and ankerite are the main authigenic carbonate minerals in the Tuscaloosa sandstones. Authigenic calcite and Fe–calcite have an average combined volume of 5.7%, and the volume of authigenic ankerite is 0.8%. Calcite and Fe-calcite occur in primary, intergranular pores and as grain replacements of unstable grains, predominantly VRFs and feldspars. Calcite and Fe–calcite precipitated after quartz cementation had begun. Much of the carbonate cement was concentrated in concretions, or tightly cemented zones within less cemented sandstones. Where chlorite coats had prevented quartz cementation, carbonate cement precipitated directly on top of chlorite because chlorite did not inhibit precipitation of the carbonate. Quartz cementation continued as temperatures increased. Sandstones with the thickest, most continuous chlorite coats continued to inhibit quartz cementation even at temperatures >375°F (>190°C), retaining primary porosity. Late authigenic ankerite mainly occurs as a grain-replacement mineral, particularly of plagioclase feldspar grains and chert. This diagenetic sequence is similar to what has been interpreted in previous studies of Tuscaloosa sandstones (Thomson, 1979; Smith, 1981, 1985; Pittman et al., 1992).

The 1D burial-history model for the Chevron #1 Lorio well (Fig. 6) calculated an estimated R_{oe} of 2.4% in Tuscaloosa sandstones at a depth of 20,470 ft (6239 m) and a temperature of 405°F (207°C). This depth is within the cored interval with petrographic data used in this study. The model indicates that lower Tuscaloosa sandstones in the Lorio well have been at temperatures greater than 212°F (100°C) for 60 to 64 million years, since the early Paleogene (Fig. 6).

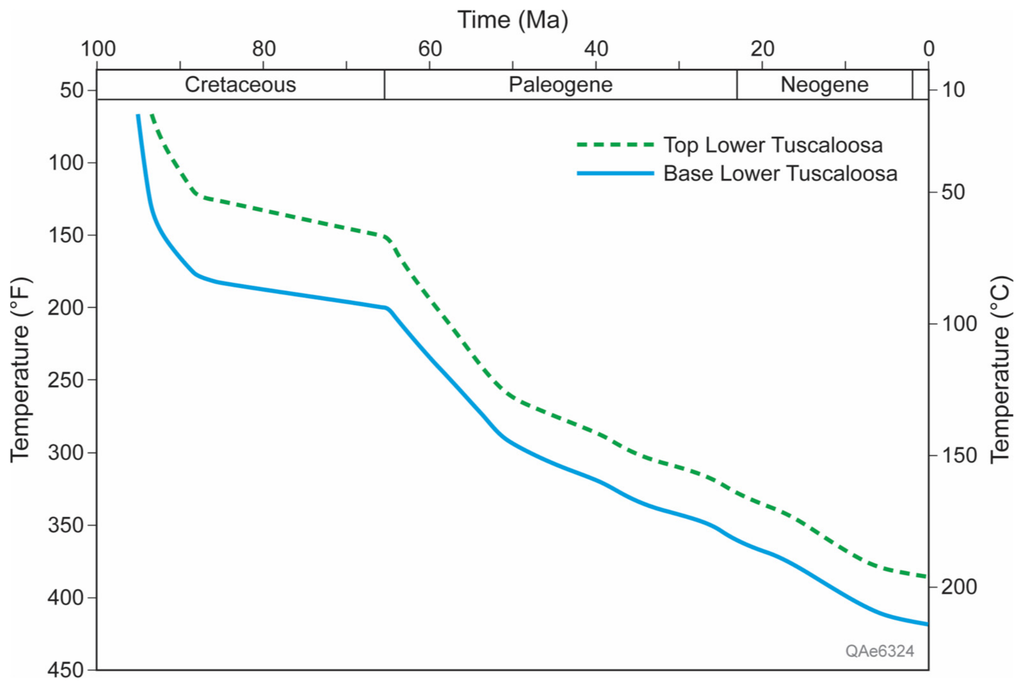
CHLORITE-CEMENT DISTRIBUTION AND RESERVOIR QUALITY

A characteristic of many Tuscaloosa sandstones in central Louisiana is the presence of thick, continuous chlorite coats that inhibited quartz cementation and preserved reservoir quality (Figs. 3 and 4A). The percentage of chlorite-coat coverage on quartz grains was not quantified in previous studies of Tuscaloosa sandstones, but studies of other formations show the importance of measuring the 2D proportion of chlorite coatings on grains (Taylor et al., 2004; Tobin, 2004; Ajdukiewicz et al., 2010). Using reservoir-quality modeling software, Tobin (2004) 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 Jurassic Norphlet sandstone needed to be 99% complete to retard quartz cement at temperatures of 392°F to 430°F (200°C to 220°C). Where Norphlet chlorite rims are only 92% complete, quartz cement fills the primary pores (Taylor et al., 2004). The aim of this study is to determine what percentage of the exposed surface area of detrital quartz grains must be covered by chlorite to inhibit quartz cementation in these Tuscaloosa sandstones.

CHLORITE-COAT COVERAGE

The percentage of chlorite-coat coverage on quartz grains was measured on 50 grains in 12 Tuscaloosa sandstone samples from central Louisiana. Average chlorite-coat coverage in these 12 samples ranges from 29 to 95% (Fig. 7A and Table 1). Chlorite-coat coverage on the 600 individual measured grains in the samples ranges from 2.3 to 100% and has a bimodal distribution (Fig. 7B). The greatest number of grains contain >90% coverage, but a smaller population of grains contains 20 to 30% chlorite-coat coverage (Fig. 7B). Average chlorite-coat coverage is significantly correlated with both porosity (Fig. 8A) and permeability (Fig. 8B), as well as inversely correlated with volume of quartz cement (Fig. 9). Of the 12 samples with measured

Figure 6. Burial-history curves showing temperature through time for the lower Tuscaloosa Formation in the Chevron #1 Lorio well, Pointe Coupee Parish, Louisiana. Well location shown in Figure 1.



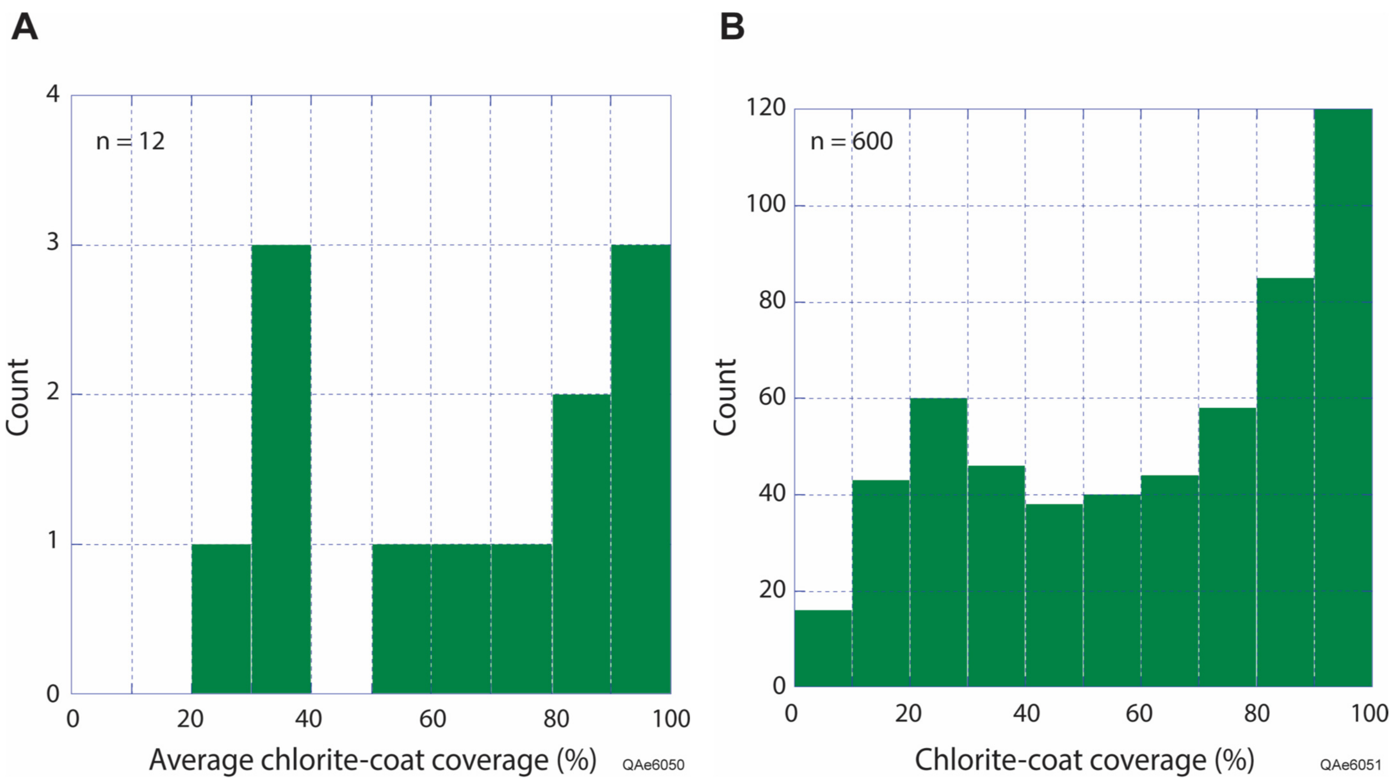


Figure 7. The percentage of chlorite-coat coverage on quartz grains was measured on 50 grains in 12 Tuscaloosa samples from central Louisiana. See Table 1 for well names and depths of the samples. (A) Histogram of average chlorite-coat coverage in the 12 samples. (B) Histogram of chlorite-coat coverage measured on all 600 quartz grains in the 12 samples.

chlorite-coat coverage, the 8 sandstones that contain >50% chlorite-coat coverage retain higher porosity and permeability by inhibiting quartz cementation. These 8 samples, which have porosity ranging from 15.3 to 27.6% and permeability from 4 to 1249 md (Table 1), contain an average of 3.4% quartz cement and 81% chlorite-coat coverage. In samples with less than 50% chlorite-coat coverage (average = 32% coverage), which have porosity ranging from 5.4 to 15.1% and permeability from 0.1 to 0.3 md, quartz cement fills an average of 13% of the primary pore space.

It is difficult to identify the controls on chlorite-coat coverage in Tuscaloosa sandstones in this small sample set. The

Table 1. Chlorite-coat coverage was measured in 12 Tuscaloosa sandstone samples from central Louisiana. Well locations shown in Figure 1. The percentages of quartz cement, chlorite cement, and volcanic rock fragments are whole-rock volumes.

Well	Depth (ft)	Facies	Grain size (phi)	Temperature (°F / °C)	Grain Coating (%)	Chlorite cement volume (%)	Quartz cement volume (%)	Volcanic rock fragments (%)	Porosity (%)	Permea-bility (md)
Amoco #1 Fontaine	18830.8	LST Upper fluvial channel	1.81	346 / 174	29	2.5	17	3.5	9.8	0.32
Amoco #1 Fontaine	18831.8	LST Upper fluvial channel	2.04	346 / 174	85	6	2	13.5	22.5	28.5
Amoco #2 Pennington	16584.0	LST Bedload fluvial channel	1.84	322 / 161	94	9	2	3	27.6	199.3
Amoco #2 Pennington	16594.0	LST Bedload fluvial channel	2.47	322 / 161	34	5.5	8.5	7	8.7	0.1
Chevron #1 Crochet	19928.1	HST Channel mouth bar	1.91	375 / 191	67	10	3	4.5	26	1249
Chevron #1 Crochet	19941.5	HST Channel mouth bar	2.20	375 / 191	34	3.5	9	13	15.1	0.2
Chevron #1 Lorio	20434.0	HST Channel mouth bar	2.21	382 / 194	76	8.5	1.5	2.5	21.2	342
Chevron #1 Lorio	20462.0	TST Transgressive deposits	3.10	383 / 195	30	3	17.5	4	5.4	0.1
Chevron #1 Poplar Grove	20266.0	TST Transgressive deposits	2.81	383 / 195	81	7.5	11.5	2	15.3	3.57
Chevron #1 Poplar Grove	20268.0	HST Channel mouth bar	2.23	383 / 195	95	7	2	6.5	26.9	352.41
Chevron #3 Alma	20136.0	TST Transgressive deposits	2.11	377 / 192	58	8.5	3.5	2.5	21.8	49.2
Chevron #3 Alma	20181.0	HST Proximal delta front	2.22	378 / 192	90	9	1.5	5	25.4	334.3

paired samples (each pair includes one high-chlorite and one low-chlorite sample from each well) all have the same provenance, although they are from a range of depths and temperatures (Table 1). In 4 sample pairs, the coarser-grained sample has a higher percentage of chlorite-coat coverage than does the finer-grained sample from the same well (Table 1). Because fine-grained sandstones have a higher surface area than do coarse-grained sandstones, perhaps the same volume of components could form more complete chlorite coats in the coarser-grained samples than in the finer-grained ones. However, in the Amoco #1 Fontaine and the Chevron #3 Alma wells, the finer-grained samples contain a higher percentage of chlorite-coat coverage (Table 1). In both of these cases, the samples having a higher volume of VRFs contain the higher percentage of chlorite-coat coverage. However, there is not a significant correlation between measured chlorite-coat coverage and either grain size or VRF content in these 12 thin sections.

A statistically significant correlation does exist between average chlorite-coat coverage measured in the 12 samples and the volume of chlorite cement determined from thin-section point counts of these samples ($r = 0.76$) (Fig. 10). Significant correlation between chlorite-coat coverage and total volume of chlorite cement can occur because the chlorite cement in Tuscaloosa sandstones in central Louisiana forms predominantly as coats on the surface of grains (Fig. 4A), and chlorite cement does not extend out into the center of pores. Therefore, whole-rock volume of chlorite cement measured in the large thin-section dataset ($n = 141$) can be compared with various parameters to identify controls on chlorite-coat coverage in Tuscaloosa sandstones. Although there is a lot of scatter in the relationships, significant positive correlation exists between volume of chlorite cement and VRF content ($r = 0.33$) and grain size ($r = 0.27$) and inverse correlation with the volume of quartz cement ($r = -0.31$). Thus, VRF content and grain size apparently are the most important factors in determining chlorite-coat coverage and reservoir quality in Tuscaloosa sandstones. Models by Tobin (2004) showed that the amount of clay-coat coverage needed to inhibit quartz cementation depends on grain size, such that fine-grained sandstones require more complete grain coverage than coarse-grained sandstones to preserve good reservoir quality.

As noted by Bloch et al. (2002), chlorite-coat coverage in Tuscaloosa sandstones does not vary with depositional environment but is instead an example of provenance-controlled chlorite coats. The 12 samples with measured chlorite-coat coverage in this study are from fluvial-channel (4), channel-mouth-bar (4), proximal-delta-front (1), and transgressive (3) depositional environments (Table 1). Fluvial-channel sandstones have chlorite coverage that ranges from 29 to 94%, channel-mouth-bar deposits from 34 to 95%, and transgressive deposits from 30 to 81% (Table 1). Chlorite volume also shows little variation with sequence stratigraphic setting in the larger thin-section dataset. Chlorite is somewhat more abundant in lowstand systems tract (LST) fluvial deposits (average = 5.9%) than in highstand systems tract (HST) deltaic deposits (4.7%) or in transgressive systems tract (TST) deposits (4.9%). There is more variation in the volume of chlorite cement with depositional environment. Samples of medial-delta-front (7.4%), storm (7.2%), bedload-fluvial-channel (6.6%), fluvial-channel (Fig. 11) (6.2%), and channel-mouth-bar (5.5%) deposits contain the greatest volumes of chlorite cement (>5% average whole-rock volume). Samples of transgressive (4.9%), proximal-delta-front (4.4%), distributary-channel (3.6%), delta-front-splay/distal-delta-front (2.3%) deposits contain smaller average volumes of chlorite cement (<5%). However, within each depositional environment, variations in chlorite-cement volume and reservoir quality occur on a foot-by-foot basis (Fig. 11).

The volume of chlorite cement measured in the thin sections can provide an estimate of the percentage of Tuscaloosa sandstones in central Louisiana that contain sufficient chlorite to

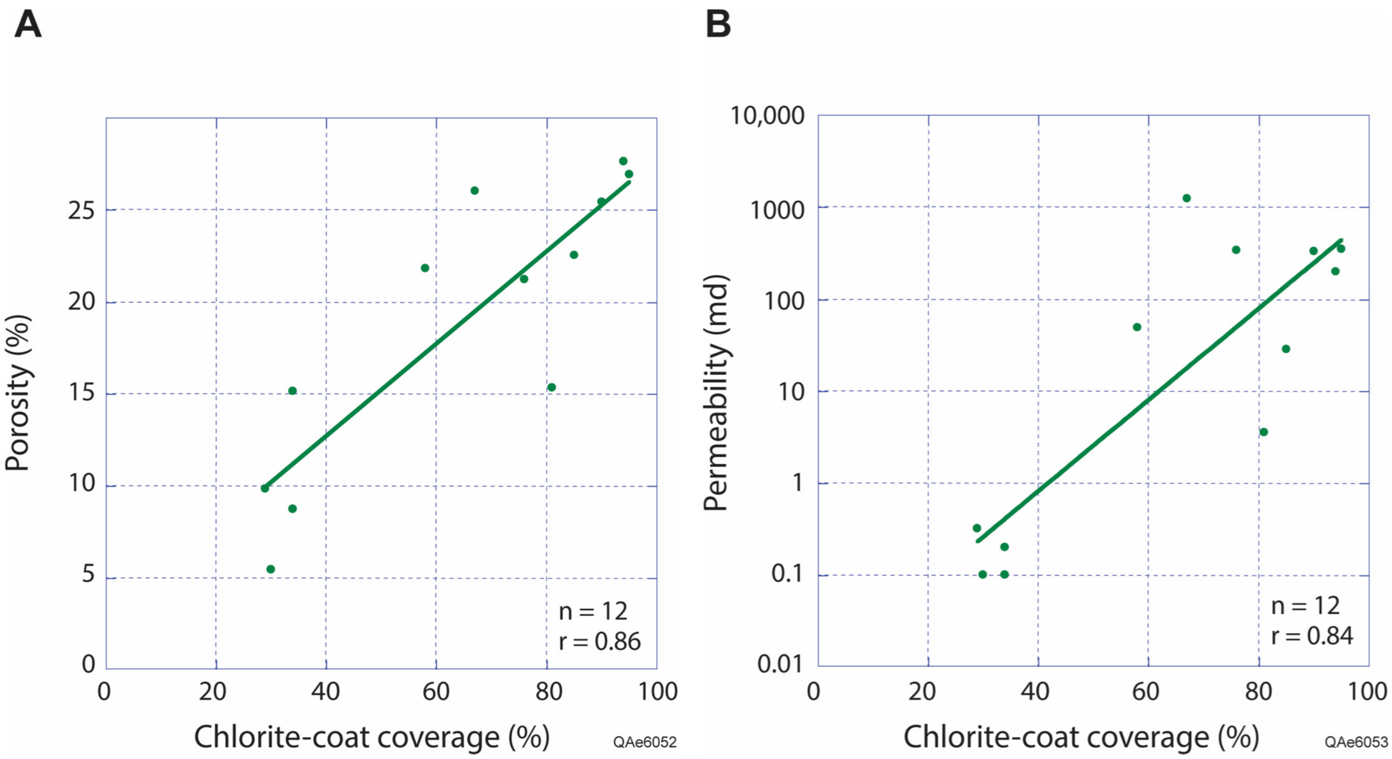


Figure 8. Correlations between chlorite-coat coverage and (A) porosimeter porosity and (B) permeability in 12 samples from central Louisiana.

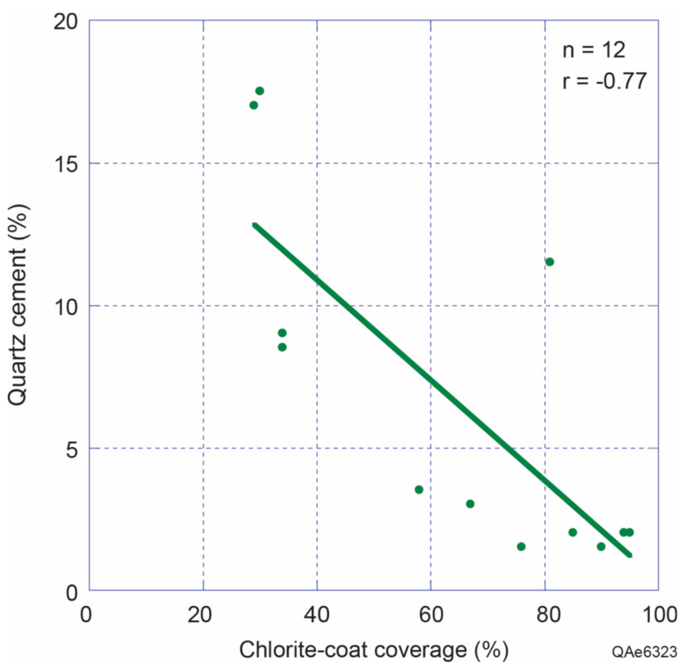


Figure 9. Inverse correlation between chlorite-coat coverage and quartz-cement volume in the 12 Tuscaloosa sandstone samples from central Louisiana.

inhibit quartz cementation and preserve good porosity and permeability at high temperatures. The highest porosity (≥20%) and permeability (≥10 md) in Tuscaloosa sandstones in central Louisiana (Fig. 2A) mainly occur in sandstones that contain ≥8% chlorite cement volume. Approximately 25% of the Tuscaloosa thin-section samples in central Louisiana have ≥8% chlorite cement and retain such good reservoir quality. These samples are currently at temperatures ranging from 275 to 420ºF (135 to 215ºC) (Fig. 2) and would normally be expected to contain abundant quartz cement, resulting in poorer reservoir quality, if they did not contain chlorite coats.

Chlorite coats that cover ≥80% of the exposed grain surface inhibited quartz cementation and preserved good reservoir quality in Tuscaloosa sandstones in central Louisiana. In contrast, Norphlet sandstones require ≥98% chlorite-coat coverage to prevent extensive quartz cementation and preserve reservoir quality (Taylor et al., 2004; Tobin, 2004). Norphlet sandstones in Mobil Bay, offshore Alabama, are currently at temperatures of 392° to 428°F (200° to 220°C) and have been hotter than 212°F (100°C) for the past 100 million years (Taylor et al., 2004). The Tuscaloosa sandstones in central Louisiana are at cooler temperatures of 275° to 420°F (135° to 215°C) and have been at temperatures >212°F (>100°C) for the past 60 million years. The higher thermal maturity of the Norphlet Formation probably explains why more complete chlorite coverage is necessary to preserve reservoir quality in Norphlet sandstones compared to Tuscaloosa sandstones. Work by Tobin (2004) indicates that at lower temperatures, quartz-cement nucleation can be effectively suppressed by less complete chlorite-coat coverage.

CARBONATE-CEMENT DISTRIBUTION AND RESERVOIR QUALITY

Carbonate cement also has a large impact on reservoir quality in Tuscaloosa sandstones. Much of the calcite and Fe–calcite cement in the Tuscaloosa occur as concretions, where porosity is completely occluded within the cemented zone. There are generally sharp boundaries at the edge of the concretions that can be seen in core (Fig. 12), as well as in thin section (Fig. 13). The presence of thick, continuous chlorite coats did not inhibit precipitation of the carbonate cement. Some chlorite coats that are

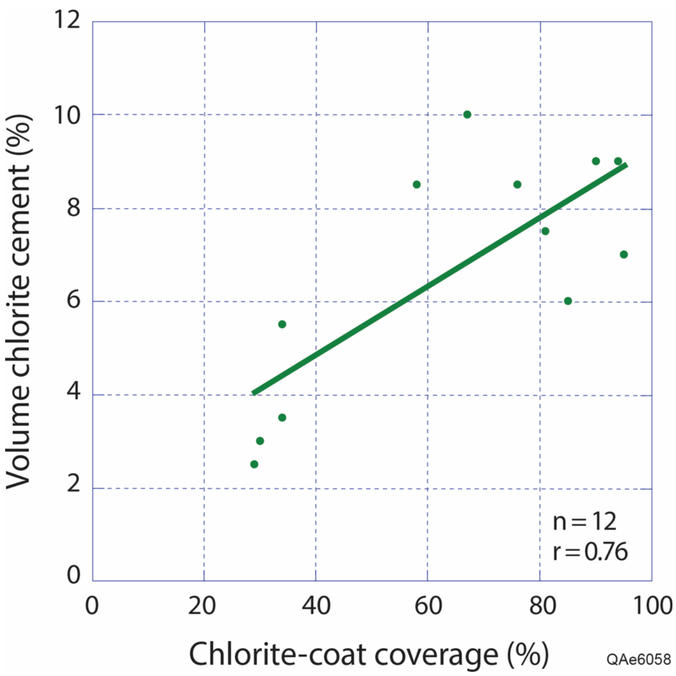


Figure 10. Correlation between chlorite-coat coverage and chlorite-cement volume in the 12 Tuscaloosa sandstone samples from central Louisiana. This correlation exists because chlorite cement forms only as coats on the surface of grains and does not extend out into the center of pores.

covered by carbonate cement can be difficult to see in thin section because of overlap within the thickness of the thin section. As a result, the volume of chlorite cement determined by point counts in samples with extensive authigenic carbonate may underestimate the volume of chlorite.

The calcite-cemented zones in seven Tuscaloosa cores in central Louisiana range from 0.2 to 5.1 ft (0.0 to 1.6 m) thick, and the average thickness is 0.8 ft (0.23 m). The percent of calcite-cemented sandstones out of total sandstone thickness (i.e., not counting thickness of shale layers) ranges from 1 to 17% and averages 5%. Therefore, approximately 5% of the total thickness of Tuscaloosa sandstones in these cores is extensively cemented by calcite and has little or no remaining porosity. The lateral extent of concretions cannot be seen in core, so it is not possible to determine how large they are. Because the concretions average only 0.8 ft (0.23 m) thick in the core, we estimate that they are probably only a few feet in lateral extent, or less.

Calcite-cemented layers in Tuscaloosa sandstones occur in fluvial, deltaic, and transgressive deposits. They are most common in the delta-front and fluvial-channel facies, but it is not possible to predict the exact location or particular zones that are cemented. Therefore, devising an exploration strategy to avoid calcite concretions would be difficult, but a risk estimate can be assigned, indicating that 5% of the Tuscaloosa sandstones in central Louisiana will have poor reservoir quality because of calcite concretions.

CONCLUSIONS

Diagenesis has a large influence on reservoir quality in Tuscaloosa sandstones. Robust and continuous chlorite grain coatings retard quartz cementation and preserve reservoir quality, but chlorite cement does not inhibit carbonate cementation. Chlorite-coat coverage was quantified in 12 Tuscaloosa sandstone samples from central Louisiana, an area of uniform provenance. Chlorite-coat coverage ranges from 29 to 95%. Because there is a statistically significant correlation between chlorite-coat coverage and volume of chlorite cement, the larger thin-section dataset (141 samples) was used to estimate the percentage of Tuscaloosa sandstones in central Louisiana that contain sufficient chlorite to inhibit quartz cementation and preserve good reservoir quality at temperatures of 275 to 420°F (135 to 215°C). The highest porosity (≥20%) and permeability (≥10 md) in Tuscaloosa sandstones in central Louisiana occurs in sandstones that contain ≥8% chlorite cement volume, which is equivalent to 80% chlorite-coat coverage. Approximately 25% of the Tuscaloosa thin-section samples in the study area have ≥8% chlorite cement and retain such good reservoir quality. Chlorite-cement volume in Tuscaloosa sandstones is most extensive in coarser-grained sandstones and in sandstones that contain higher volumes of VRFs.

Chlorite cement occurs in samples from all systems tracts, but it is somewhat more abundant in LST fluvial deposits (average = 5.9%) than in HST deltaic deposits (4.7%) or in TST deposits (4.9%). There is more variation in the volume of chlorite cement with depositional environment. Samples of medial-delta-front (7.4%), bedload-fluvial-channel (6.6%), fluvial-channel (6.2%), and channel-mouth-bar (5.5%) deposits contain the greatest volumes of chlorite cement (>5% average whole-rock volume). Samples of transgressive (4.9%), proximal-delta-front (4.4%), distributary-channel (3.6%), and distal-delta-front (2.3%) deposits contain smaller average volumes of chlorite cement (<5%).

Approximately 5% of the Tuscaloosa sandstone thickness in central Louisiana is tightly cemented by calcite. These cemented zones, which contain >10% calcite, range in thickness from 0.2 to 5.1 ft (0.0 to 1.6 m) and have an average thickness of 0.8 ft (0.23 m). Calcite-cemented layers occur in fluvial, deltaic, and transgressive deposits. They are most common in distal- and proximal-delta-front sandstones, but it is not possible to predict the exact location of zones that are cemented. Therefore, devising an exploration strategy to avoid calcite concretions would be difficult, but a risk estimate can be assigned, indicating that 5% of the Tuscaloosa sandstones in central Louisiana will have poor reservoir quality because of calcite concretions.

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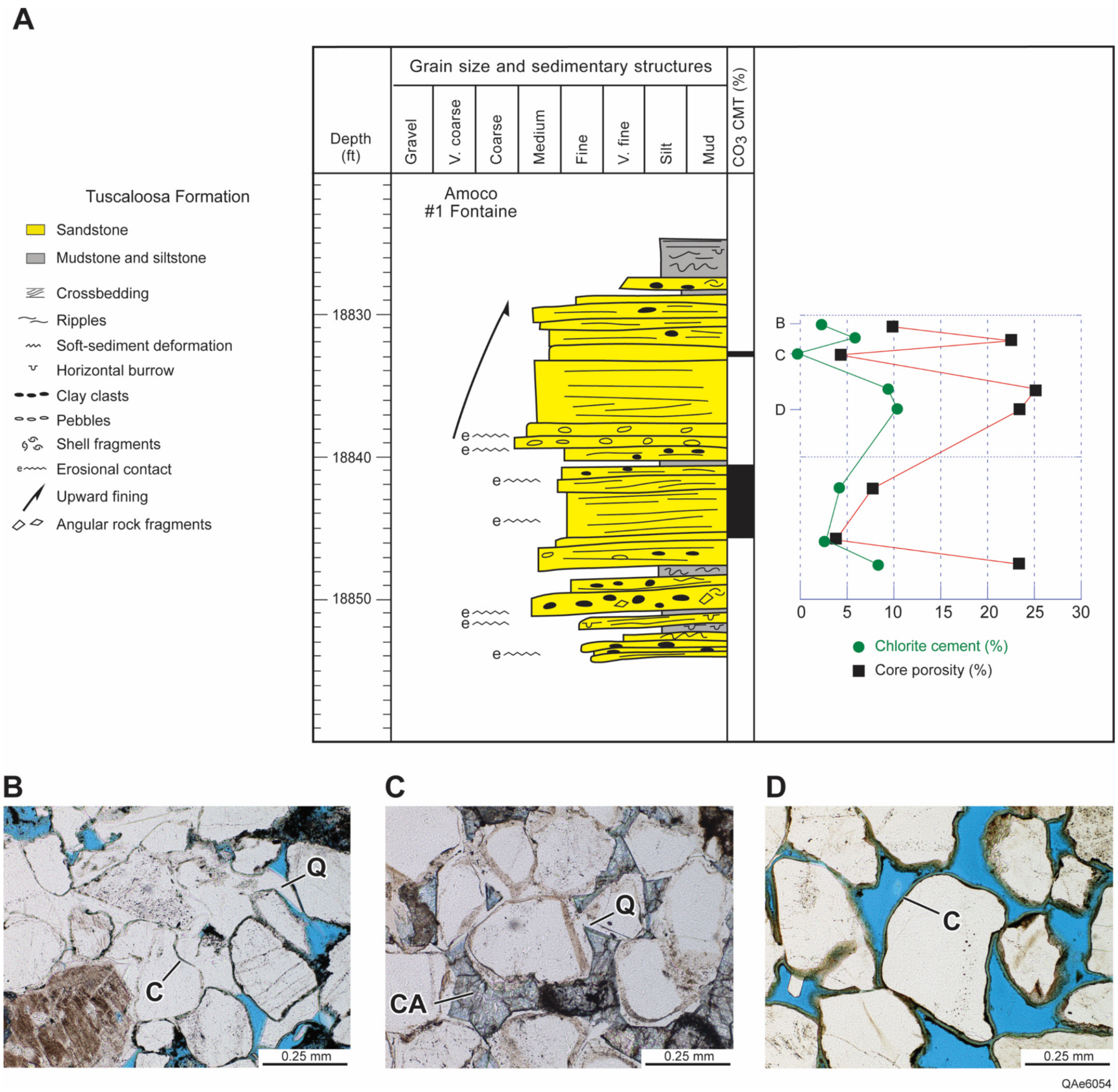

Figure 11. (A) Chlorite-cement volume and core-analysis porosity vary on a foot-by-foot basis in a fluvial-channel sandstone from the Amoco #1 Fontaine well, Pointe Coupee Parish, Louisiana. Core description from Ambrose et al. (2015). Photomicrographs are from depths labeled B, C, and D. (B) Abundant quartz cement (Q) and discontinuous chlorite coats (C) in a sample from 18,830 ft (5739 m). Porosity = 9.8% and permeability = 0.32 md. Plane-polarized light. (C) Fe–calcite (CA) precipitated after quartz cement (Q) in a sample from 18,832 ft (5740 m). Porosity = 4.2% and permeability = 0.01 md. Plane polarized light. (D) Continuous chlorite coats (C) on detrital grains inhibited quartz cementation in a sample from 18,836 ft (5741 m). Porosity = 23.4% and permeability = 446 md. Plane-polarized light.

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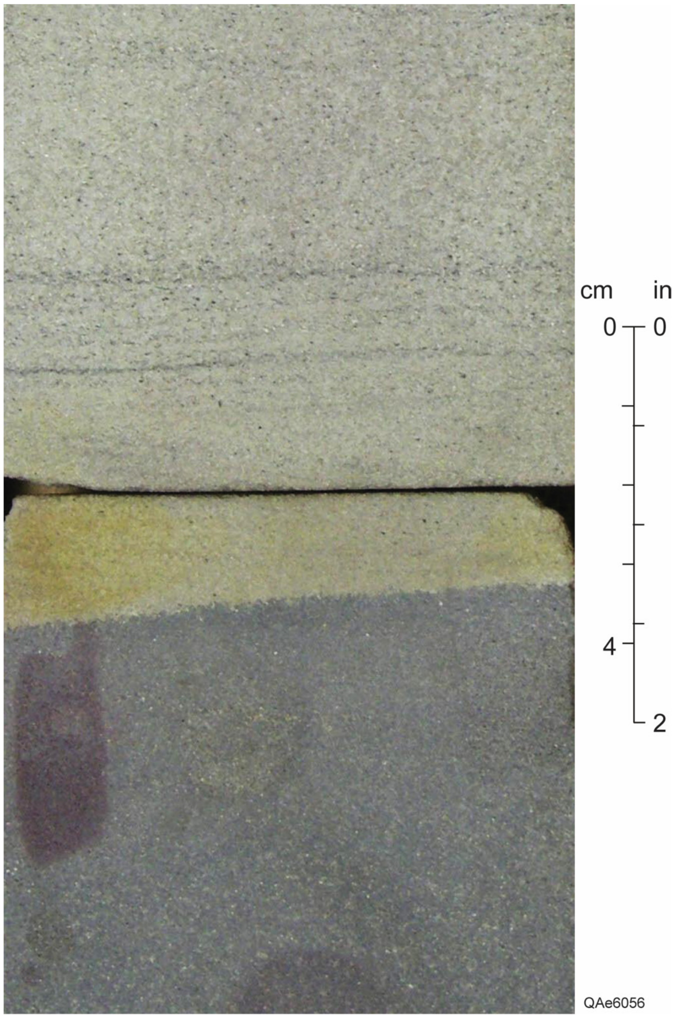

Figure 12. Sandstone layer (dark gray) cemented by calcite in a channel-mouth-bar deposit from the Chevron #1 Crochet well, Pointe Coupee Parish, Louisiana, at a depth of 19,934 ft (6075 m).

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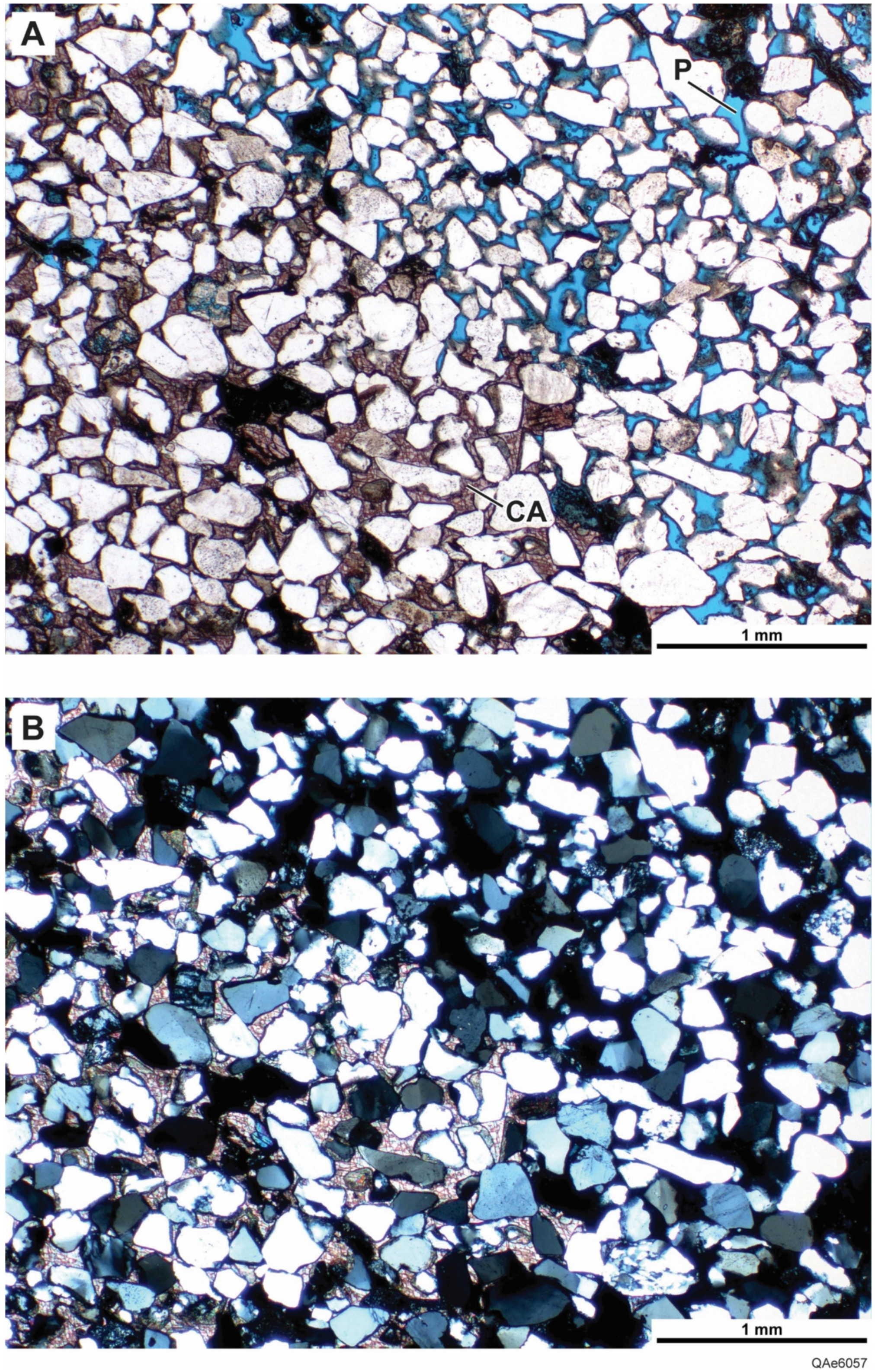

Figure 13. (A) Calcite cement (CA) is localized in a tightly cemented concretion (lower left side of photo); abundant porosity (P) remains in the rest of the sandstone (upper right side of photo). Sample is from the Amoco #2 Pennington well, East Baton Rouge Parish, Louisiana, from a depth of 16,575 ft (5052 m). Plane-polarized light. (B) Crossed-polarized light.