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Modification of Pore Geometry and Petrophysical Characteristics of the Upper Jurassic Smackover Formation Thrombolite Reservoirs after Dolomitization

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ABSTRACT

The Upper Jurassic Smackover Formation thrombolite facies is a prolific reservoir in southwestern Alabama. Most of the Smackover Formation thrombolite facies discovered so far were dolomitized, and the original depositional characteristics of the rock are obscured. However, the thrombolite facies at Little Cedar Creek Field (LCCF) were only lightly dolomitized, and most of its depositional texture is well preserved.

Diagenesis caused important changes in the Smackover Formation thrombolite reservoir in LCCF. During the dolomitization process, the grains and early calcite cements were progressively replaced by dolomite crystals, whereas some of the remaining calcite was progressively dissolved, and intercrystalline porosity was generated. This process also caused the number of meso- and macropores to increase, and pore geometry and pore-throat size became more homogeneous.

The southern portion of the Smackover Formation thrombolite at LCCF is only partially dolomitized, and its porosity and permeability values are higher than coeval limestone units, varying from less than 10% to 15–20% porosity on average, and from less than 50 md to 100–600 md permeability on average (less than 10 md to 50–250 md for the geometric mean). The thrombolite units at Appleton and Vocation fields are intensely dolomitized. Their petrophysical characteristics are more homogeneous vertically and laterally, and they also have higher porosity and permeability values (average of 175–356 md of permeability and 13–17% of porosity) than those of the partially or non-dolomitized thrombolite at LCCF.

This study shows that increasing dolomitization improved reservoir quality of Smackover Formation thrombolite units in southwestern Alabama by modifying its pore system.

INTRODUCTION

Depositional facies are responsible for high quality reservoirs within the Smackover Formation (Gulf of Mexico, USA), but diagenesis has played an important role in enhancing or reducing their porosity and permeability. Thrombolite and ooid grainstone are the two most prolific reservoir facies of the Smackover Formation (Benson and Mancini, 1999; Kopaska-Merkel and Mann, 1991; Mancini et al., 1991, 2006). Calcite cementation, dolomitization and dissolution are the main diagenetic processes causing modification in these reservoirs (Benson and Mancini, 1999; Benson, 1988; Kopaska-Merkel and Mann, 1991; Mancini et al., 1991; Moore and Druckman, 1981; Prather, 1992b).

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The thrombolite unit of the Smackover Formation at Little Cedar Creek Field, in Alabama, USA (Fig. 1), has only a minor amount of dolomite, and most of its depositional texture is well preserved, making Little Cedar Creek Field an interesting location to study facies distribution and diagenetic alteration. Smackover Formation thrombolitic reservoir facies in several other fields were intensely dolomitized (Barrett, 1986; Benson and Mancini, 1999; Mancini et al., 1991; Prather, 1992b), and the depositional characteristics of these rocks were partially or wholly obscured. Appleton and Vocation fields, also located in Alabama (Fig. 1), are geographically close to Little Cedar Creek Field and they have intensely dolomitized thrombolite reservoirs.

Pore geometry characterization comprised measurements of pore size (maximum diameter), roughness (perimeter over area), and elongation (maximum diameter over minimum diameter). Pore-throat geometry characterization was done through capillary pressure measurements. By comparing the percentage of macropores, mesopores, and micropores, the variation in roughness and elongation values, and pore-throat geometry distribution on each sample, it was possible to recognize distinct pore system

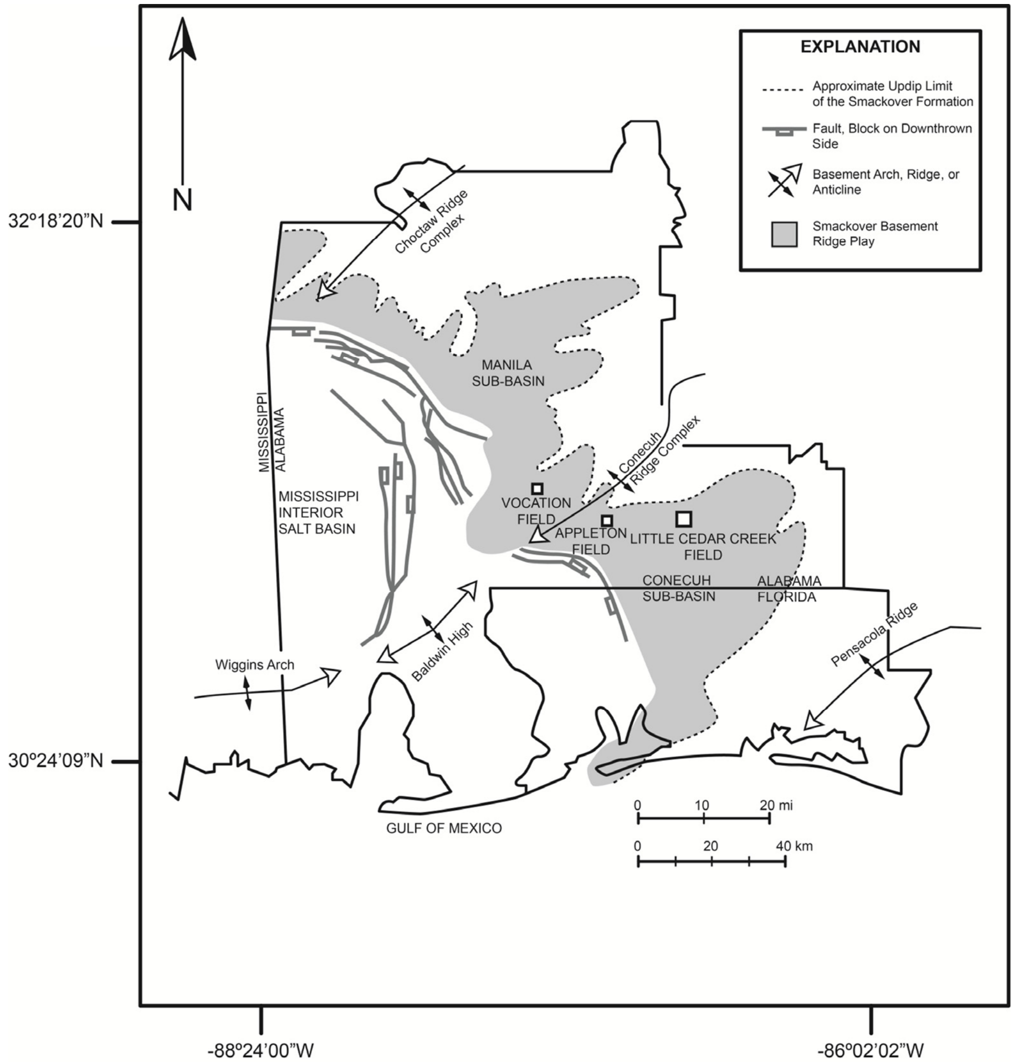


Figure 1. Location map of Conecuh Sub-Basin and Little Cedar Creek, Appleton, and Vocation fields, southwestern Alabama, U.S.A. (modified after Mancini et al., 2008). The updip basement ridge play is defined as the area between the updip limit of Smackover deposition and the regional peripheral fault trend. The play is characterized by thin or absent Jurassic salt and hydrocarbon-bearing structures (Mancini et al., 1991).

characteristics after dolomitization. This paper discusses the relationship between rock texture, pore geometry, pore-throat size distribution, and petrophysical properties of Smackover Formation thrombolite reservoirs with varying degrees of dolomitization.

GEOLOGICAL SETTING

Among other settings, the Upper Jurassic (Oxfordian) Smackover Formation records carbonate platform deposition. Local variations in topography were produced by pre-Jurassic salients or salt tectonics (Ahr, 1973; Driskill et al., 1988). Paleozoic ridges and Mesozoic horst blocks produced a number of paleohighs in the eastern Gulf of Mexico that separated southwest Alabama into a series of sub-basins or embayments (Benson, 1988; Mancini and Benson, 1980; Prather, 1992). The Conecuh Ridge separates the Manila Sub-Basin from the Conecuh Sub-Basin, which is bordered to the southeast by the Pensacola Ridge (Fig. 1).

The Oxfordian was characterized by a widespread sea level rise that progressively affected larger parts of the Gulf of Mexico Basin and surrounding areas (Salvador, 1987). At least four Upper Jurassic (Oxfordian) to Lower Cretaceous (Valanginian) transgressive to regressive (T–R) sequences extended across the Gulf Coast and the offshore northeastern Gulf of Mexico region (Mancini et al., 2008). Various authors have subdivided the Smackover into one, two, and three different transgressive and regressive cycles (Mancini et al., 1990; Wade and Moore, 1993; Heydari and Baria, 2006; Baria et al., 2008). In this paper the Smackover Formation (Fig. 2) is sub-divided into two systems tracts. The lower and middle Smackover Formation compose a transgressive systems tract (TST). Microbial reefs developed in the TST, and their growth ended before the maximum flooding zone (MFZ) that is characterized by a marine condensed section composed of relatively deep subtidal carbonate mudstone. The upper Smackover Formation (oncoid, peloid and ooid grainstone to wackestone, and local thrombolite buildups) represents the subsequent highstand systems tract (HST) (Mancini et al., 1990).

Smackover Formation Reefs

Smackover Formation reefs occur from Arkansas to Florida as elongate features, 1 to 70 m (3 to 210 ft) thick, and several square kilometers in map view (Baria et al., 1982). The reefs were constructed by cyanobacteria (thrombolite buildups) or a more diverse sponge and coral-algal assemblage. Smackover reef diversity is higher in southern Arkansas and northern Louisiana than in Alabama and Florida, where its depositional environment was more restricted (Baria et al., 1982). The reefs developed seaward of oolite shoals on three types of paleostructures that created subtle topographic relief: (1) basement ridges, (2) faulted basement highs, and (3) salt-cored paleo-structures (Baria et al., 1982). However, the microbial reefs in the Little

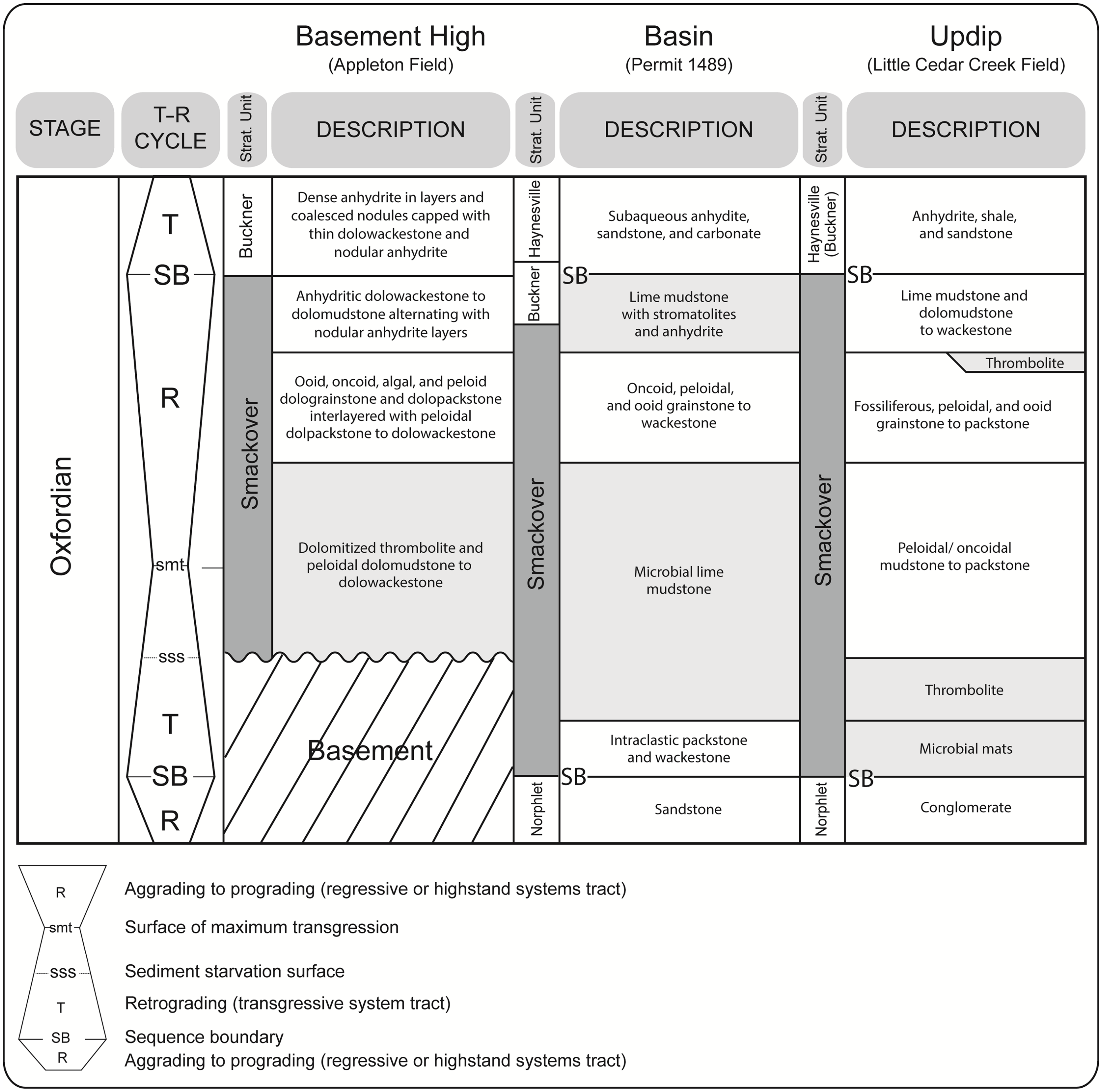


Figure 2. Upper Jurassic (Oxfordian) Smackover Formation sequence stratigraphy, including Appleton Field and Little Cedar Creek Field areas (modified after Mancini et al., 2008).

Cedar Creek Field area developed in nearshore, shallow subtidal and strandline settings along the updip margin of the Smackover Formation rather than on Paleozoic basement paleohighs (Koralegadara and Parcell, 2008; Mancini et al., 2006, 2008).

Smackover Formation Thrombolite Reservoir at Little Cedar Creek Field

Little Cedar Creek Field (Figs. 1 and 3), discovered in 1994, contains significant oil accumulation in two zones in the Upper Jurassic Smackover Formation: a lower thrombolite facies reservoir and an upper ooid-oncoid-peloid grainstone to packstone facies reservoir (Heydari and Baria, 2005; Mancini et al., 2006, 2008; Ridgway, 2010; Al Haddad and Mancini, 2013; Tonietto and Pope, 2013). The thrombolite reservoir facies in Little Cedar Creek Field is approximately 42 km (26 mi) long, 5 to 11 km (3 to 7 mi) wide and from 9 to 21 m (30 to 70 ft) thick, oriented along a NE–SW trend (Fig. 5A). The thrombolite facies has a clotted, mottled and nodular texture, with rare domal and branching structures. The thrombolite facies includes abundant peloids, with minor amounts of skeletal fragments of benthic foraminifera and ostracods. Dolomite can compose as much as 30% of the thrombolite facies (it is vertically variable) and its occurrence gradually decreases from south to north, being absent from near

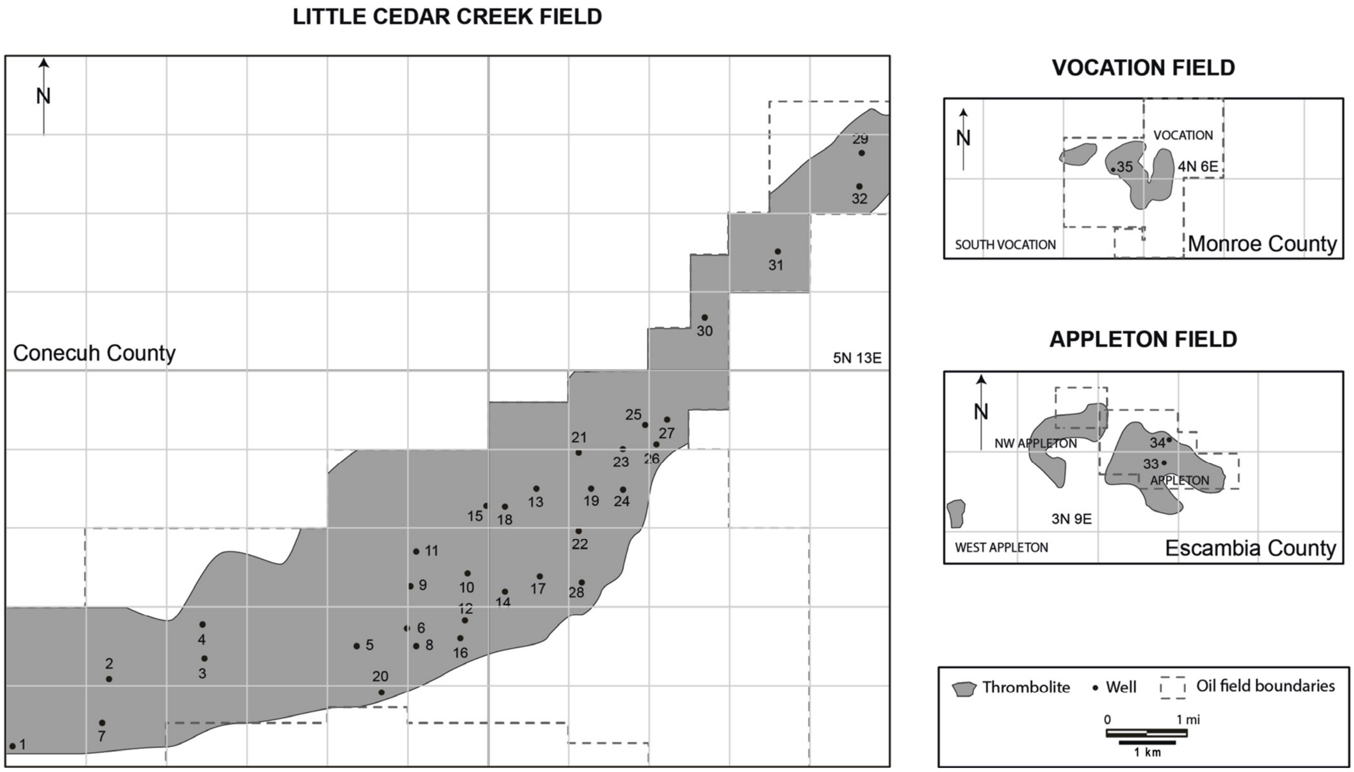


Figure 3. Thrombolite unit at Little Cedar Creek, Appleton, and Vocation fields with the location and identification of the wells (modified after Tonietto and Pope, 2013; Llinás, 2004). Well identification: well 1 (permit 11963), well 2 (permit 13177), well 3 (permit 13439), well 4 (permit 13510), well 5 (permit 13697), well 6 (permit 13746), well 7 (permit 13907), well 8 (permit 14069–B), well 9 (permit 14112), well 10 (permit 14114), well 11 (permit 14301–B), well 12 (permit 14309), well 13 (permit 14325), well 14 (permit 14545), well 15 (permit 14646–B), well 16 (permit 14652–B), well 17 (permit 14965), well 18 (permit 15000), well 19 (permit 15159–B), well 20 (permit 15165), well 21 (permit 15263–B), well 22 (permit 15357), well 23 (permit 15413), well 24 (permit 15418), well 25 (permit 15493), well 26 (permit 15496–B), well 27 (permit 15497), well 28 (permit 15731), well 29 (permit 16053), well 30 (permit 16115), well 31 (permit 16135), well 32 (permit 16238–B), well 33 (permit 3986), well 34 (permit 4835–B), and well 35 (permit 1599).

the center to the northeast portion of the field (Figs. 4B and 5). The amount of dolomite was visually estimated through petrographic analysis.

The pore types in the thrombolite are primary growth framework vugs and intergranular, and secondary diagenetic vugs (primary growth framework vugs enlarged by dissolution), intercrystalline porosity (when calcite cement crystals or dolomite crystals have pore space among them) and fractures. Petrophysical characteristics are highly variable laterally and vertically inside the thrombolite. In limestone thrombolite, core-plug analysis indicates that porosity values vary from 3 to 19% (Fig. 4C), and permeability values vary from less than 1 to 100 md, with rare values as high as 500 md. Large diagenetic vugs and fractures can cause local permeability values to be 1 to 4 darcys, rarely as much as 7 darcys. In partially dolomitized intervals of the thrombolite, porosity varies from 10 to 21% and permeability generally varies from 150 to 850 md, but is locally as much as 1200 md (Fig. 4D).

Smackover Formation Thrombolite at Appleton and Vocation Fields

Appleton Field, located on the western margin of the Conecuh Sub-Basin and on the eastern flank on the Conecuh Ridge (Figs. 1 and 3), was discovered in 1983 in a well drilled on the top of a paleotopographic structure. Reservoir-grade porosity at Appleton Field occurs in the thrombolite and in oolitic, oncoidal, and peloidal grainstone and packstone in the upper Smackover Formation (Mancini et al., 2000). Porosity in the thrombolite is a mixture of primary growth framework vuggy porosity overprinted by secondary intercrystalline and vuggy porosity. Porosity in the microbial thrombolite ranges from 9.5 to 25.3% and averages 16.9%, whereas permeability ranges from 1.1 to 4106 md and averages 356 md (Benson et al., 1997).

Vocation Field, located in the southeastern margin of the Manila Sub-Basin along the western flank of the Conecuh Ridge (Figs. 1 and 3), was discovered in 1971. A thrombolite reservoir occurs in the lower part of the Smackover Formation, deposited on the flank of a paleohigh. Pore types are vugs, interparticle, and fracture pores (Llinás, 2002). Porosity ranges between 8 and 20%, with an average of 13%, whereas permeability ranges from 30 to 410 md, with an average of 175 md.

METHODS

Structures and macrotextures, porous intervals, and pore size were documented from cores of 32 wells from Little Cedar Creek Field, 2 wells from Appleton Field, and 1 well from Vocation Field (Fig. 3). Samples include 153 plugs (2.5 cm [1 in] diameter) taken in a variety of textures and porosity features. Porosity and permeability measurements were determined from 115 plugs, and capillary pressure measurements by mercury injection were performed on 30 plugs. 320 pre-existing porosity and permeability analyses (plug analyses made by Midroc Operating Company) also were compared with the data generated in this study.

Standard petrographic description of 153 thin sections, 40 of which were stained with Alizarin Red–S and potassium ferricyanide (Dickson, 1966), were used to characterize microfabrics,

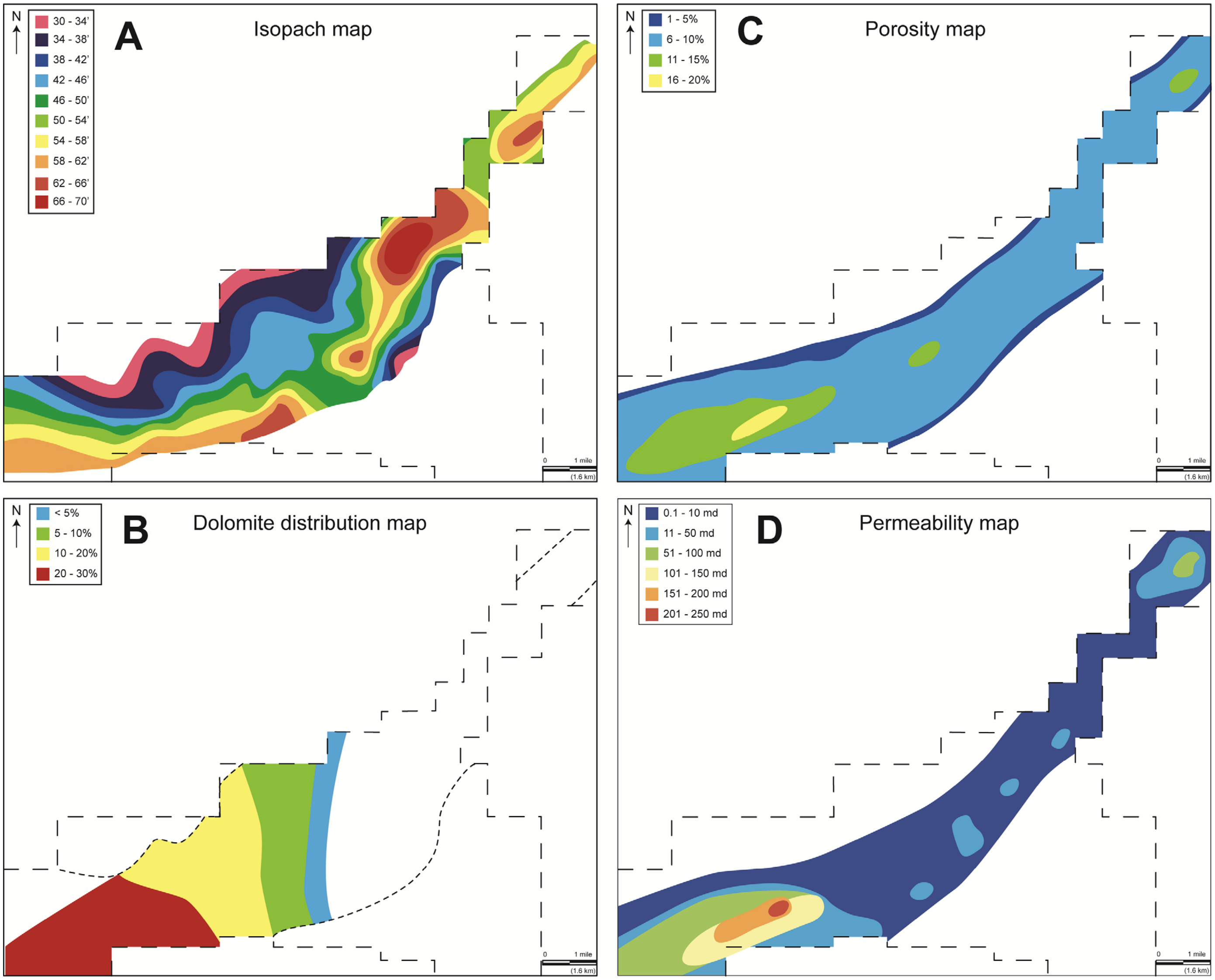


Figure 4. Thrombolite reservoir, Little Cedar Creek Field. (A) Isopach map of the thrombolite reservoir. (B) Map of dolomite distribution in the thrombolite reservoir. The dolomite content is vertically variable, and this map shows the maximum dolomite content observed in the samples of each well. (C) Map of average porosity of the thrombolite reservoir based on petrophysical analysis. (D) Map of permeability geometric mean of the thrombolite reservoir based on petrophysical analysis (modified after Tonietto and Pope, 2013).

diagenetic features, porosity and visual estimate of dolomite content.

Pore geometry analysis in 2D was performed on 50 thin section images using the Image-Pro Premier® software to determine the pore segmentation and analyze each pore as a separate object. The number of pores measured in each thin section varied from 1000 to 20,000. Area, perimeter, and maximum and minimum diameter were measured for each pore. Percentage of micropores (<50 µm diameter), mesopores (50–100 µm diameter), and macropores (>100 µm diameter), as well as roughness (perimeter over area) and elongation (maximum diameter over minimum diameter) of each pore was calculated. Pore geometry analysis in 3D was performed on two plugs using X-ray computed tomography images and the Avizo® software to render volumes in voxel units (resolution of 22 µm), to determine pore segmentation, and to separate and analyze the pores. The number of pores measured in each volume was 188,783 and 278,944, respectively. Percentage of pore volume and the number of micro-, meso-, and macropores were calculated for each sample.

RESULTS

Petrography and Pore Types

Changes in the rock texture after the dolomitization process are described here. The Smackover Formation thrombolite depositional texture in Little Cedar Creek Field consists predominantly of peloids with some bioclasts. Early diagenetic marine calcite cement rims the grains (mainly peloids and peloid clusters). The dolomite crystals replace grains and calcite cements, locally growing into the pore space (Fig. 6). Dolomite formed a new framework, where calcite was progressively dissolved. As a result, depositional grains and early diagenetic cements disappeared and a new texture formed, where dolomite crystals dominate (Fig. 7).

Primary macropores in the Little Cedar Creek Field thrombolite consist mainly of growth framework vugs and intergranular porosity, both reduced by early diagenetic marine cements, and then locally enlarged by dissolution. After dolomitization a significant modification in pore size and geometry occurred, with

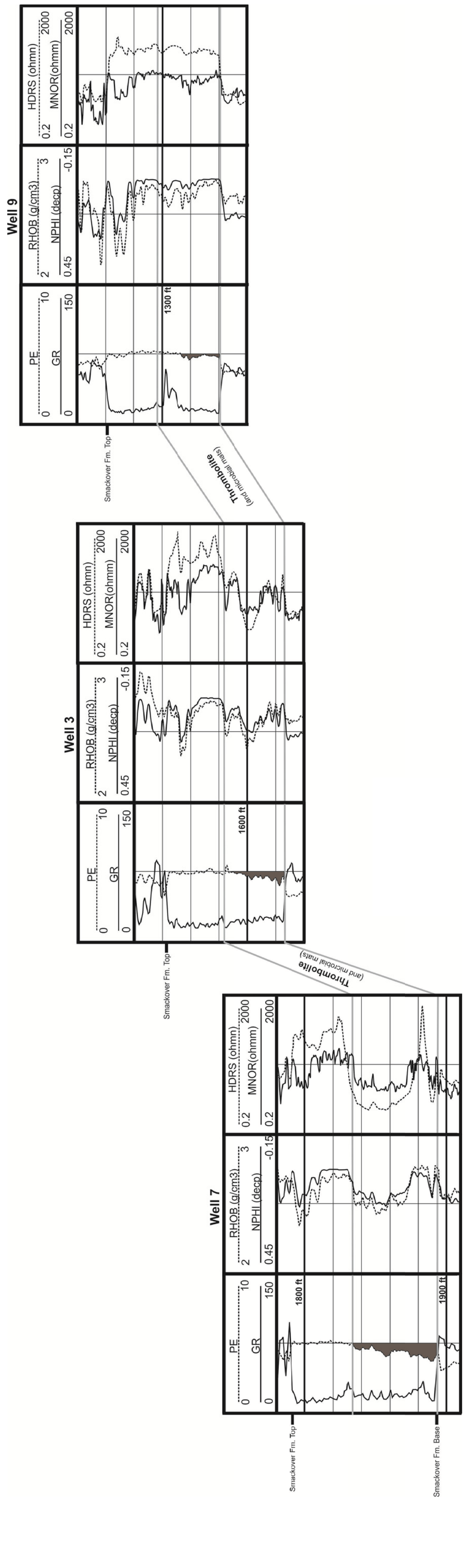


Figure 5. Cross section at the southern portion of Little Cedar Creek Field (wells 7, 3, and 9), SW–NE direction (see location of the wells on Figure 4). Logs: gamma ray (GR), photoelectric effect (PE), bulk density (RHOB), neutron porosity (NPHI), deep resistivity (HDRS), and micronormal (MNOR). The presence of dolomite (gray shading) caused the PE curve to deviate from 5, the typical value of calcite, to lower values (the PE value for dolomite is 3).

the primary porosity having been replaced by secondary intercrystalline pores.

The number of macropores and mesopores increased after dolomitization in the Smackover Formation thrombolite reservoirs (Figs. 8 and 9). A crossplot of the average roughness (perimeter over area) and elongation (maximum diameter over minimum diameter) of the macropores and mesopores in each thin section (Fig. 10) shows that there is less variation in pore geometry with increasing dolomitization level in the samples. This means that the pores became geometrically more homogeneous after the dolomitization process and this new characteristic of the pore space may have been generated because dolomite crystals grow in a regular shape and a more or less regular spatial distribution, transferring this regularity to the intercrystalline pores.

In the calcitic thrombolite, dominant pore types are isolated vugs, connected vugs (commonly enlarged by dissolution), intergranular (among peloids and peloid clusters), and intercrystalline (between calcite cement crystals). In the partially dolomitized thrombolite, dominant pore types are intercrystalline (between dolomite and calcite crystals) and vugs. In the dolomitized thrombolite, dominant pore types are intercrystalline (between dolomite crystals) and connected vugs (Fig. 11). In the center to the northern portion of the Smackover Formation thrombolite reservoir in Little Cedar Creek Field, a different diagenetic process locally affected the pore system. This process consisted of partial dissolution of the rock and the growth of very fine calcite crystals, resulting in intercrystalline porosity (Fig. 11D).

Capillary Pressure

Capillary pressure analysis in the calcitic, partially dolomitized, and completely dolomitized thrombolite shows distinct patterns of pore-throat size distribution for distinct types of dominant porosity (Fig. 12). In partially to intensely dolomitized Smackover Formation thrombolite, a combination of vuggy and intercrystalline porosity is very common. When intercrystalline pores dominate, pore-throat size distribution is concentrated between 0.1 and 15 µm. When connected vugs dominate, pore-throat size distribution is concentrated between 1 and 215 µm.

Samples with isolated vugs as the dominant pore type have low pore-throat size values (Fig. 12A), with a maximum pore-throat size of 3.7 µm and average of 0.22 ± 0.16 µm. Connectivity between the vugs is poor, and cementation is very high (Fig. 11A). Few samples have intergranular porosity as the main pore type. Peloids are less clustered, and the rock texture is similar to a grainstone (Fig. 11B). Vugs also occur, causing larger pore-throat sizes as high as 201.3 µm, and the average mean is 7.8 ± 3.8 µm (Fig. 12B). When connected vugs dominate, pore-throats are larger (Figs. 12C and 12D, and two curves on Figure 13E), with maximum pore-throat size of 215 µm, and average mean from 11.5 ± 7.1 µm to 30.9 ± 5 µm. In the samples with intercrystalline porosity as the dominant pore type, the maximum pore-throat size is 80.5 µm, and when vugs occur they can be as high as 199.5 µm. The average mean of pore-throat size varies from 4.7 ± 2.3 µm to 7.2 ± 2.1 µm. A summary of pore-throat size distribution based on capillary pressure of 30 samples is shown on Table 1.

The difference in pore-throat size distribution can also be visualized through capillary pressure curves (Fig. 13). The samples with isolated vugs are the less efficient rock type in the reservoir, because connectivity between the vugs is poor, and the entry or displacement pressure is very high (Fig. 13A). Capillary pressure values in samples with connected vugs as the dominant pore type are lower than capillary pressure values in samples with intercrystalline porosity as the dominant pore type (Figs. 13C and 13D). Capillary pressure curves of the thrombolites

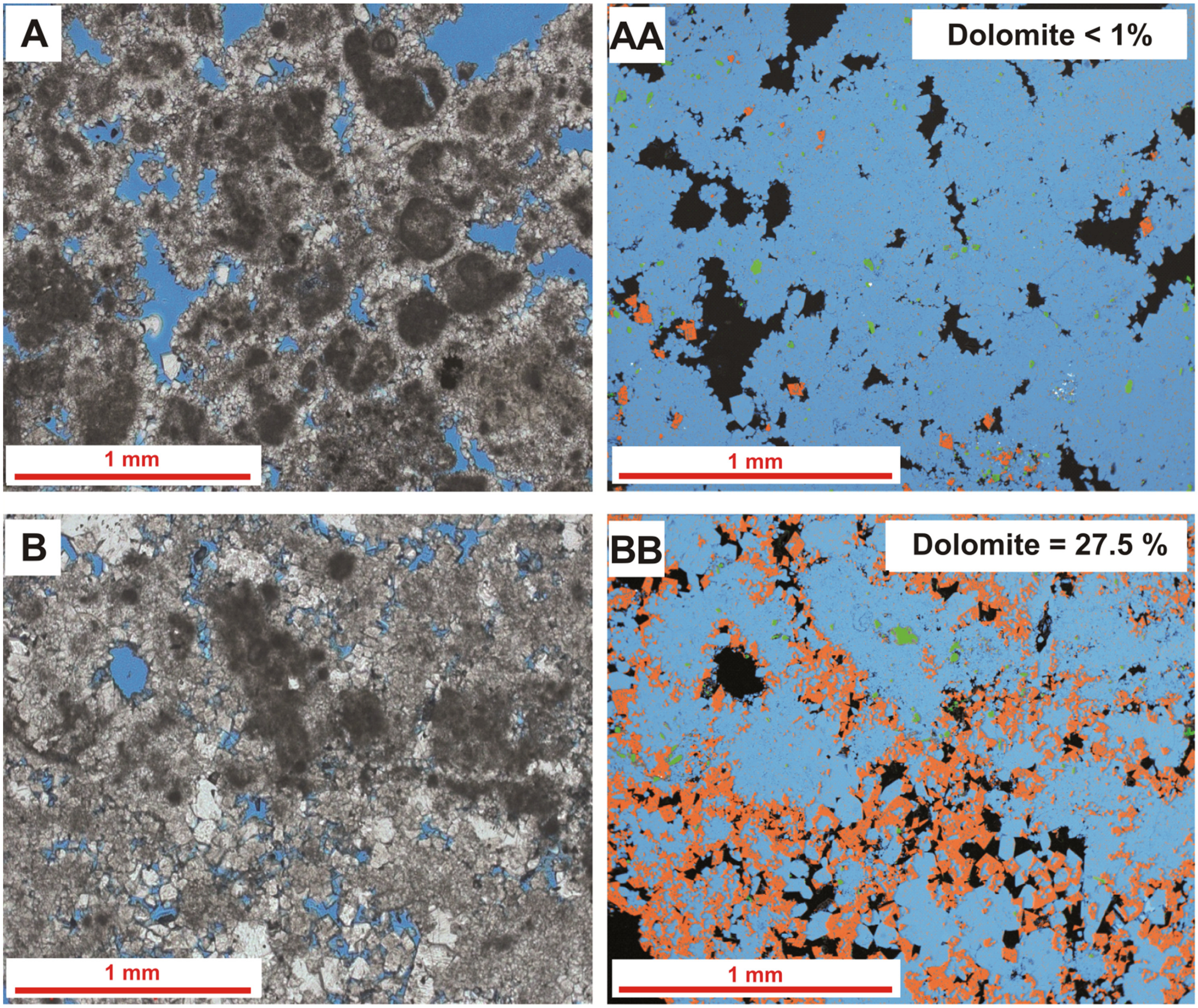


Figure 6. (A) Plane-polarized photomicrography of the thrombolite, Little Cedar Creek Field. Dolomite is not significant. Well 1, 11,900.2 ft. (B) Plane-polarized photomicrography of partially dolomitized thrombolite, Little Cedar Creek Field. The dolomite crystals replace grains and calcite cements, locally growing into the pore space. Well 5, 11,500.9 ft. (AA & BB) Images paired with images A and B, respectively. Colored X-ray compositional map made by the combination of X-ray maps of three elements: Ca, Si, and Mg. Calcite = blue, dolomite = orange, quartz = green, and black = pore space.

indicate that intercrystalline porosity increases entry pressure values by reducing pore-throat radius (Fig. 13B).

The difference in pore geometry (size, shape, and connection) among a non-dolomitized and a completely dolomitized thrombolite of Smackover Formation can also be visualized on computed microtomography images (Fig. 14), where the pore system is shown in 3D. As in the 2D analysis, the 3D also showed that in the non-dolomitized thrombolite the number of micropores are higher than in the dolomitized one. The resolution of the microtomography images are approximately 22 µm, so pores smaller than this and most of the pore throats were not detected. To estimate the amount of porosity below the resolution of the microtomography, the porosity obtained by petrophysical analysis was compared with the one obtained by image analysis. The difference between them corresponds to the estimated microporosity (Table 2).

Petrophysical Properties

As a result of the changes in rock texture and pore system geometry produced by diagenesis, petrophysical properties of the Smackover thrombolites also changed. The limestone thrombolite in Little Cedar Creek Field has large variation of petrophysical properties vertically, where high porosity and permeability values depend on the presence of a larger number of growth framework and diagenetic vugs (Fig. 15A). The dolomitized thrombolite in Appleton and Vocation fields has more homogeneous petrophysical properties vertically, being associated with abundant intercrystalline pores. It also has higher average porosity and permeability values than the limestone thrombolite of Little Cedar Creek Field (Fig. 15B).

Porosity-permeability crossplots (Fig. 16) show that limestone thrombolite has a greater range of values, from very low to

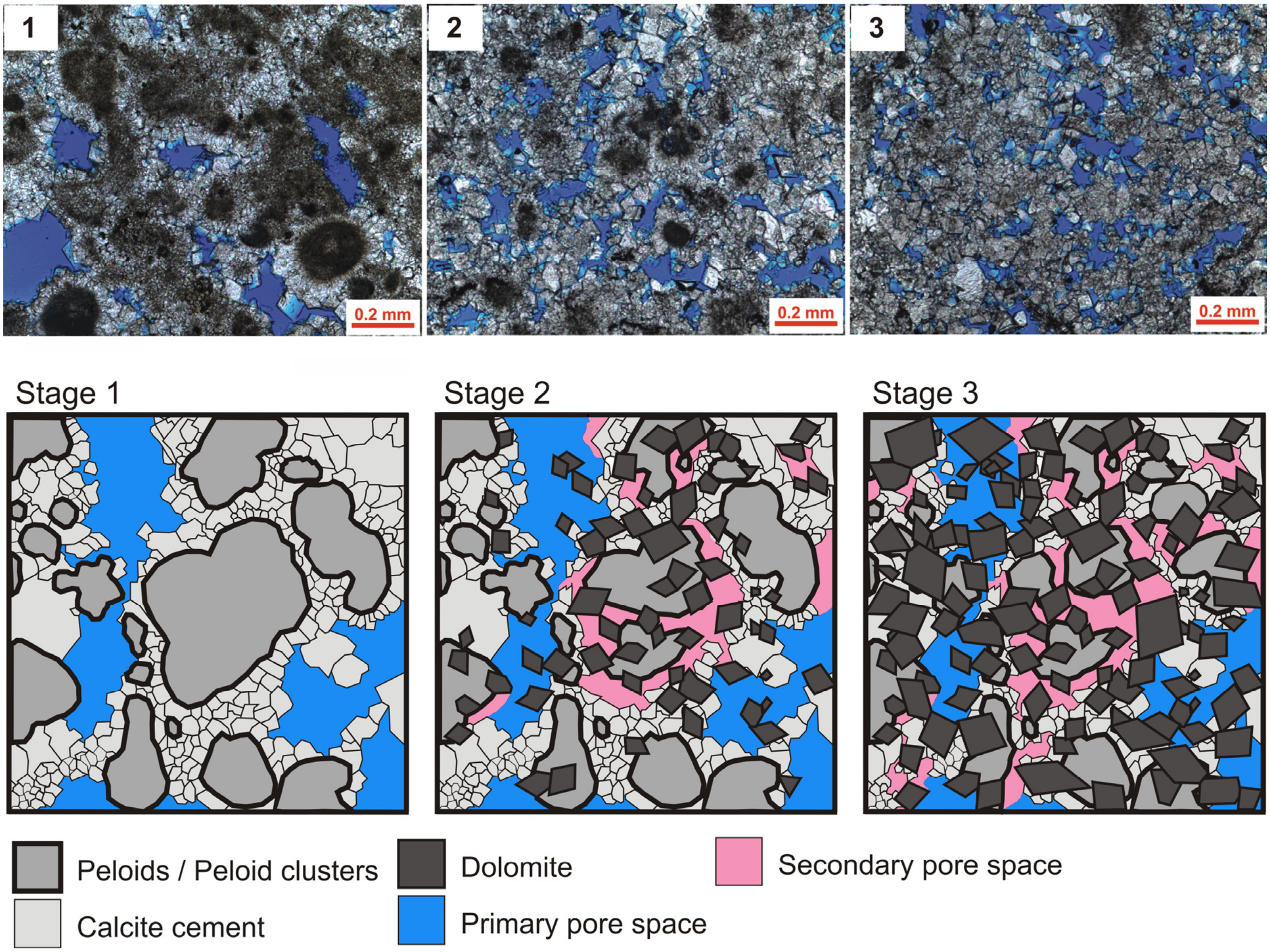


Figure 7. (Top) Photomicrographs showing the thrombolite unit at Little Cedar Creek Field with distinct levels of dolomitization: (1) No dolomitization, (2) little dolomitization, and (3) abundant dolomitization. The depositional texture (micritic peloidal grains and clusters rimmed by marine and early burial calcite cements) gradually disappears with increasing dolomitization. (Bottom) Schematic drawing of Smackover Formation thrombolite unit at Little Cedar Creek Field with distinct degrees of dolomitization and calcite dissolution. Stage 1—Thrombolite depositional texture. Vugs are the main pore type. Stage 2—Dolomite crystals start to replace calcite and grow in the pore space. Grains and calcite cement are partially dissolved. Stage 3—Higher dolomitization level. Intercrystalline porosity became the main pore type. The number of macro and mesopores are higher, but large vugs are less common.

very high porosity (3 to 22%) and permeability (<0.1 to 4000 md), whereas the partially dolomitized and totally dolomitized thrombolite have mainly high values of porosity and permeability (generally porosity > 10% and permeability > 10 md), but permeability values greater than 1000 md are less common. Intervals with large connected vugs have very high permeability values (>1000 md), but these intervals are laterally discontinuous in the reservoir.

DISCUSSION

Dolomitization accompanied by calcite dissolution caused significant changes in rock texture, pore geometry, and pore-throat size distribution in the Smackover Formation thrombolite unit in southwestern Alabama, also resulting in changes of the petrophysical characteristics in its reservoirs. The reason calcite dissolution occurs during or just after dolomitization is not clear.

Dissolution of relict calcite following dolomitization is necessary if the carbonate was added to the rock from an outside source (Murray, 1960). Growth of a dolomite rhomb would involve: (1) addition of magnesium from outside the system and (2) dissolution of some calcite from outside the volume of dolomite rhomb growth to provide the necessary carbonate for filling the pore space within the volume of dolomite rhomb. If insufficient carbonate is available, calcite dissolution must accompany growth of dolomite, thus forming and redistributing porosity.

The process of dolomite concentration by dissolution of the last remaining calcite from between the replacement dolomite crystals would enhance porosity and permeability, creating good reservoir rocks. This, along with the tetrahedral and sheet-like geometry of dolomite intercrystalline pore throats is probably the main reason dolostone has higher permeability than limestone with the same porosity (Ahr, 2008).

An example of dolomitization and calcite dissolution processes associated with high reservoir quality occurs in the Lower Ordovician Arbuckle Group microbialites (Franseen et al., 2003; Warusavitharana and Parcell, 2013; Gao et al., 1992). In central Missouri and Kansas, the Arbuckle Group microbialites consist

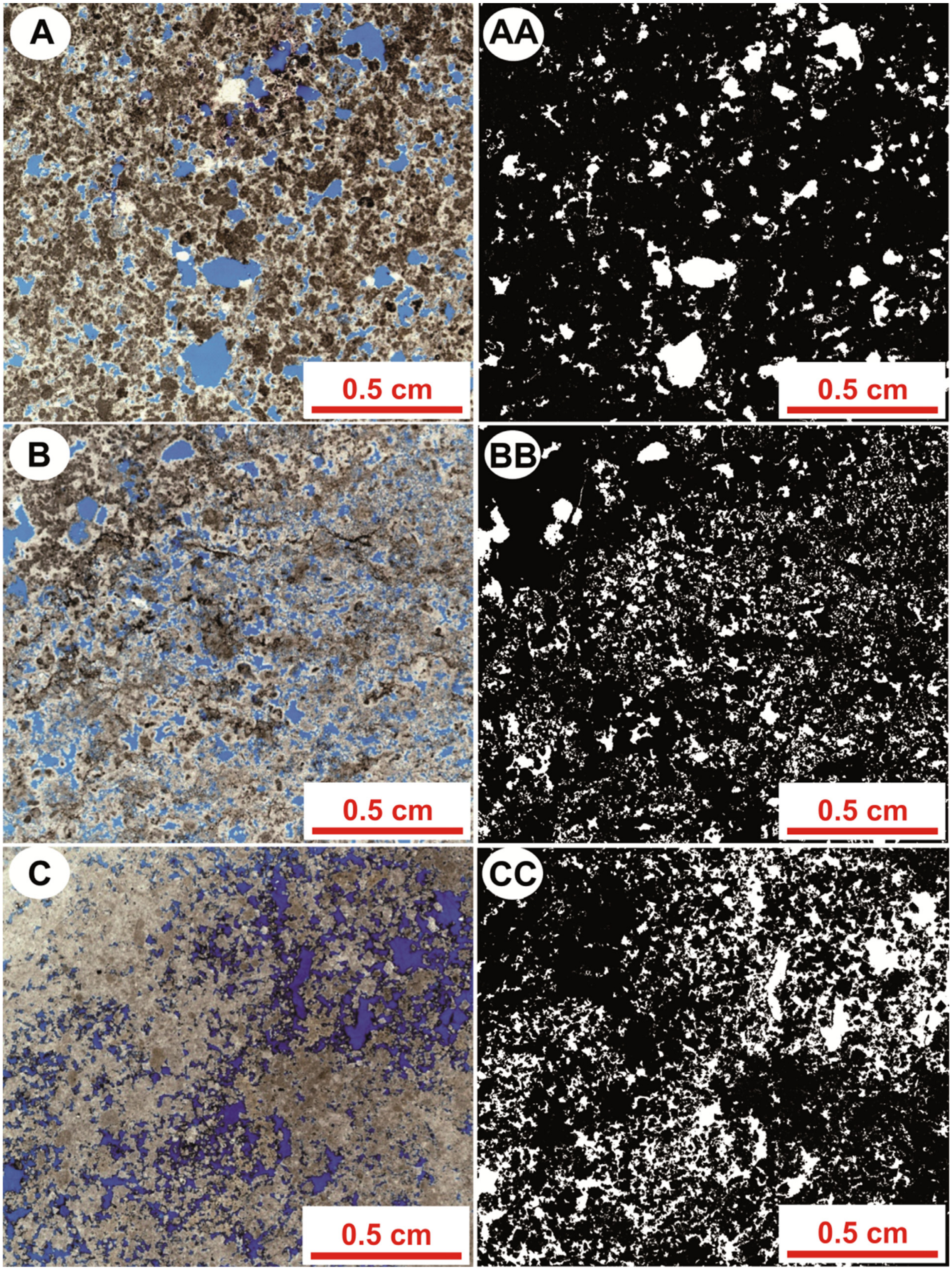


Figure 8. Smackover Formation thrombolite reservoir. The figures on the left are plane polarized petrographic images, where the pores are highlighted by blue epoxy. The figures on the right, paired with the images on the left, are binary images, where the pore system is highlighted in white. (A & AA) Limestone thrombolite. Intergranular and depositional growth framework vugs. Little Cedar Creek Field, well 2, 11,771 ft, porosity = 12%, and permeability = 77 md. (B & BB) Partially dolomitized thrombolite. Some of the depositional texture (peloids) is still preserved, but intercrystalline porosity was created. Little Cedar Creek Field, well 2, 11,787.9 ft, porosity = 16%, and permeability = 95.9 md. (C & CC) Dolomitized thrombolite. Intercrystalline and vuggy porosity. No depositional texture preserved. Appleton Field, well 34, 13,149.4 ft, porosity = 18%, and and permeability = 786 md.

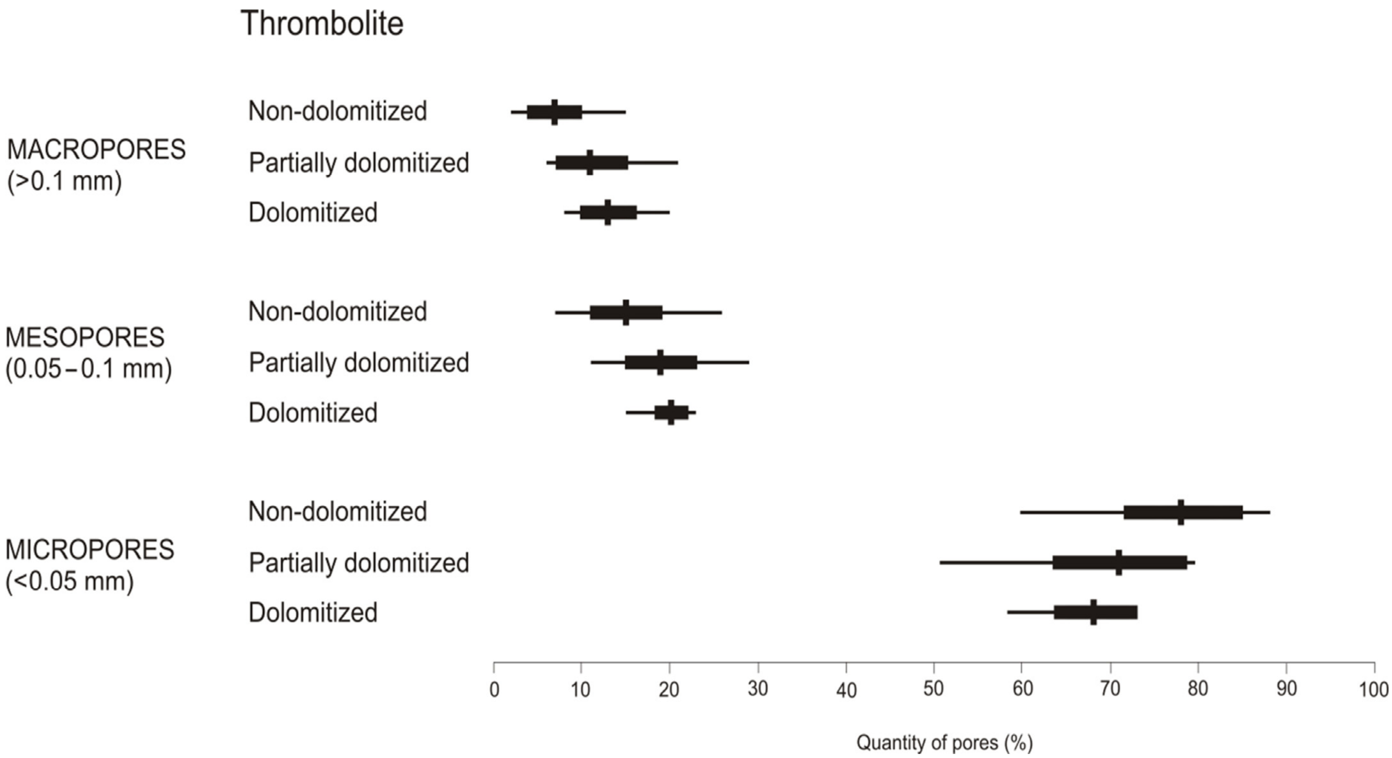
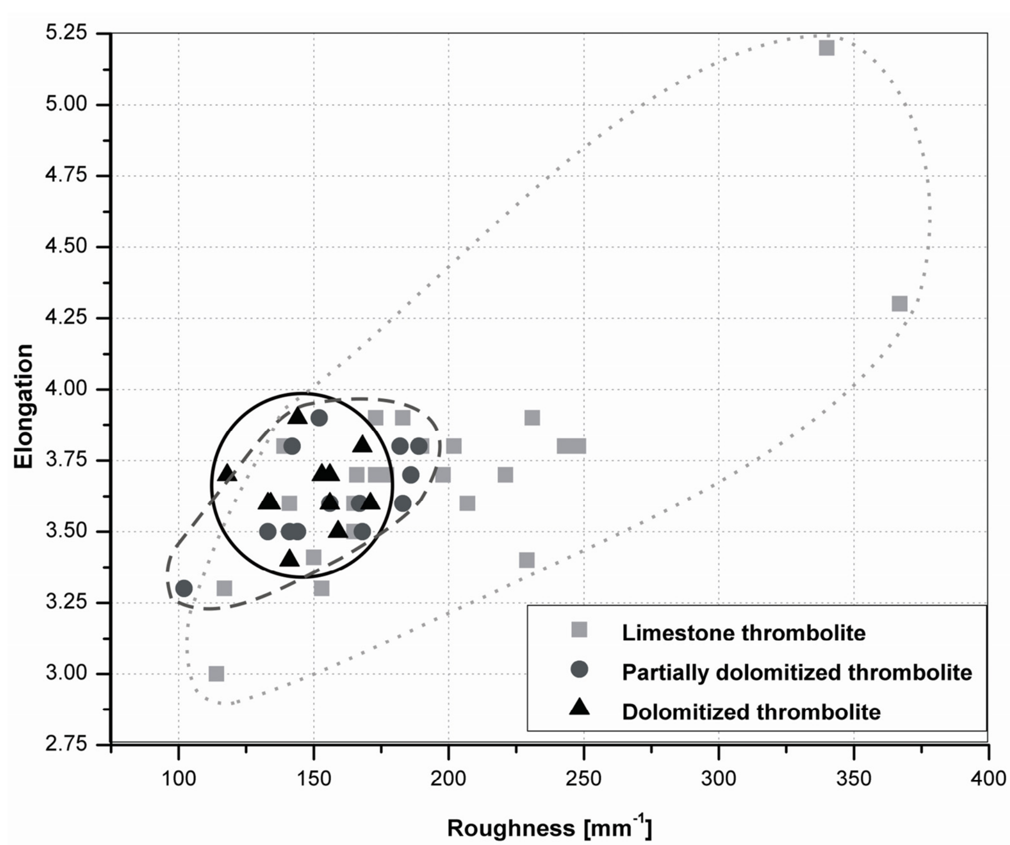


Figure 9. Percentage of micropores (<0.05 mm), mesopores (0.05–0.1 mm), and macropores (>0.1 mm) measured in 50 thrombolite thin sections from Little Cedar Creek, Appleton, and Vocation fields using the software Image-Pro Premier®. The number of pores measured in each thin section varied from 1000 to 20,000. Vertical bars are means, wide horizontal bars are plus/minus one standard deviation, and narrow horizontal bars are ranges. The percentage of micropores decreases with dolomitization, whereas the percentage of mesopores and macropores increases.

Figure 10. Crossplot of the mean value of roughness (perimeter over area) and elongation (maximum diameter over minimum diameter) of macropores and mesopores measured through thin section image analysis using the software Image-Pro Premier®. Samples from Little Cedar Creek, Appleton, and Vocation fields. There is less variation in pore geometry when the thrombolite is dolomitized.



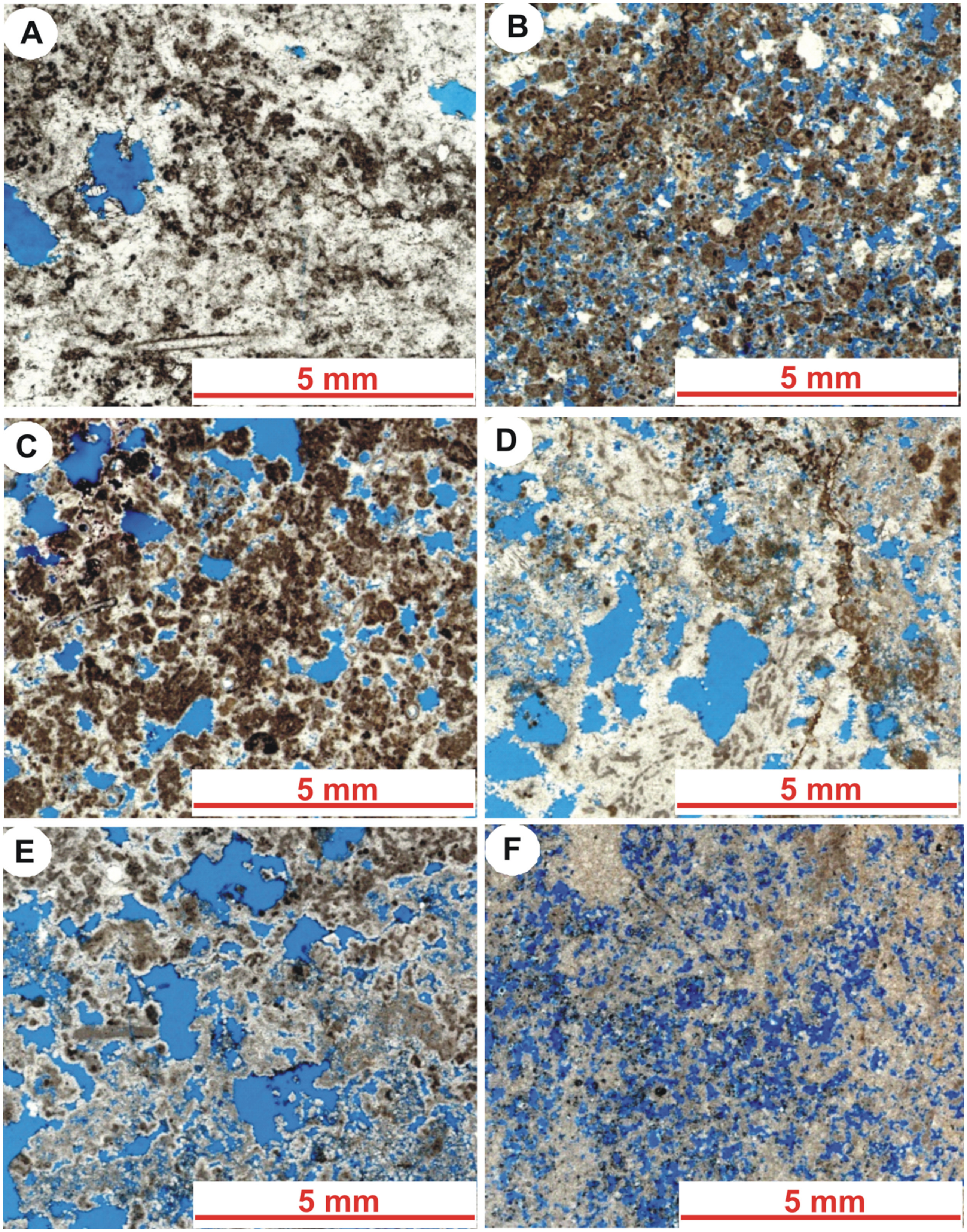


Figure 11. Photographs of pore types in Smackover Formation thrombolites. (A) Limestone thrombolite, isolated vugs. Little Cedar Creek Field, well 14, 11,314.7 ft, porosity = 7%, and permeability = 0.046 md. (B) Limestone thrombolite, intergranular and vuggy porosity. Little Cedar Creek Field, well 21, 11,249.3 ft, porosity = 10%, and permeability = 3.6 md. (C) Limestone thrombolite, connected vugs. Little Cedar Creek Field, well 2, 11,771 ft, porosity = 12%, and permeability = 77 md. (D) Limestone thrombolite, vuggy and intercrystalline porosity. Little Cedar Creek Field, well 21, 11,279.5 ft, porosity = 9%, and permeability = 16.6 md. (E) Partially dolomitized thrombolite, vuggy and intercrystalline porosity. Little Cedar Creek Field, well 3, 11,609.5 ft, porosity = 20%, and permeability = 1130 md. (F) Dolomitized thrombolite, intercrystalline porosity. Vocation Field, well 35, 14,182 ft, porosity = 12%, and permeability = 37.7 md.

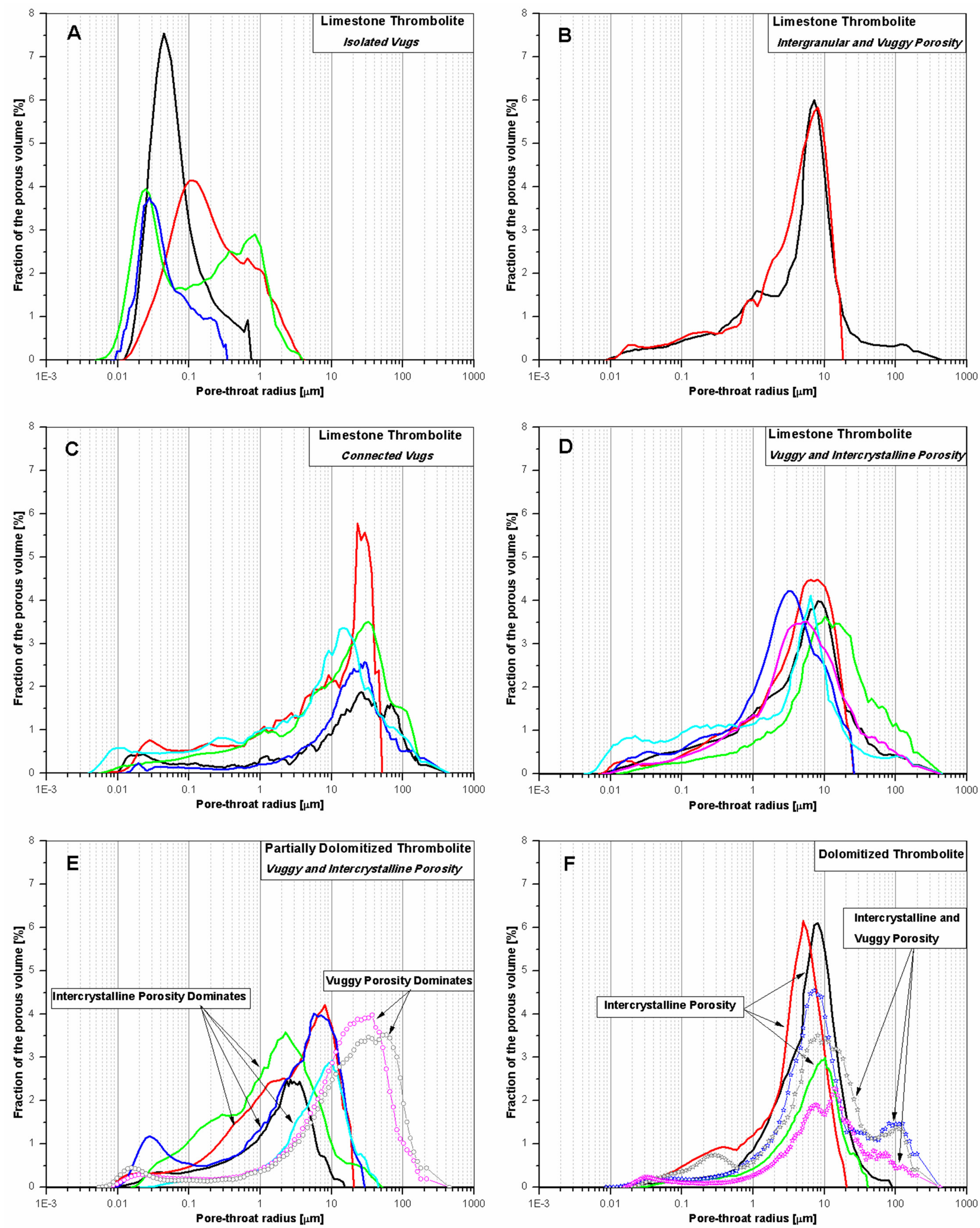


Figure 12. Fraction of the porous volume in percentage versus natural log of pore-throat radius in micrometers. Samples are grouped by lithology and dominant pore type. (A to D) Limestone thrombolite. (A) Isolated vugs. (B) Intergranular and vuggy porosity. (C) Connected vugs. (D) Vuggy and intercrystalline porosity. (E) Partially dolomitized thrombolite. Vuggy and intercrystalline porosity. (F) Dolomitized thrombolite. Intercrystalline and intercrystalline and vuggy porosity. Maximum and minimum values, and average mean of pore-throat size for these samples is shown on Table 1. Samples with connected vugs have bigger pore-throat values than samples with intercrystalline pores only.

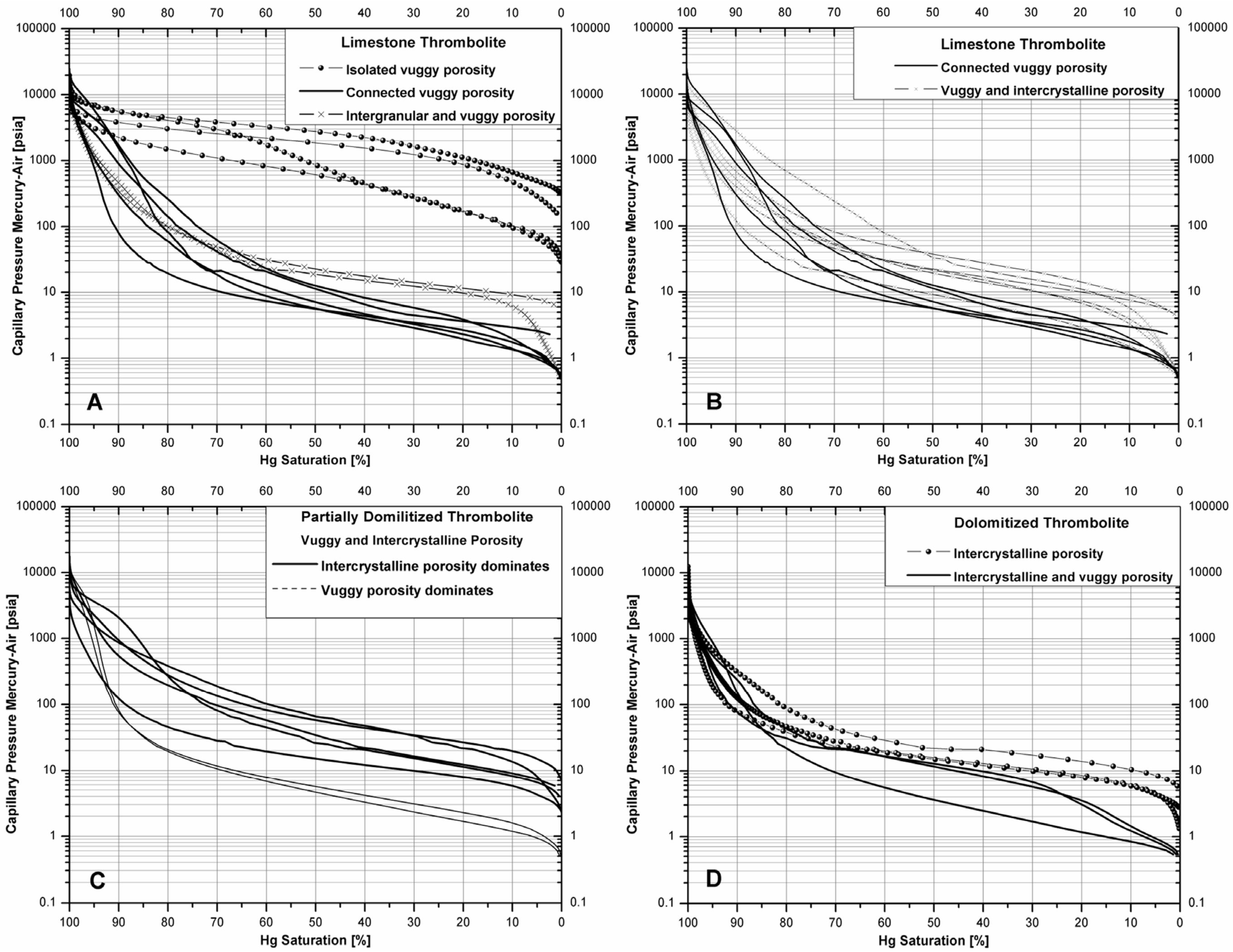


Figure 13. Capillary pressure curves of Smackover Formation thrombolite samples. The samples are grouped by lithology, pore type, and pore type abundance. Distinct dominant pore type(s) have distinct curve appearance, because pore-throat size is related to pore type. (A) Samples with isolated vugs as the dominant pore type have small pore-throat sizes and high entry pressure values. Samples with connected vugs have low capillary pressure and entry pressure values. Samples with vuggy and intergranular porosity have higher capillary pressure values when compared with samples with only vuggy porosity. (B) Samples with vuggy and intercrystalline porosity have higher capillary pressure values than samples with only vuggy porosity. (C) In partially dolomitized thrombolite samples, capillary pressure values are higher when intercrystalline porosity dominates over vuggy porosity. (D) In completely dolomitized thrombolite samples, capillary pressure values are higher when intercrystalline porosity is the major pore type, and vuggy porosity is not significant. Capillary pressure curves in B, C, and D show that samples with intercrystalline porosity as its dominant pore type present higher capillary pressure values, and consequently lower pore-throat sizes than samples with connected vugs as the dominant pore type.

Table 1. Mean values of pore-throat size distribution measured in capillary pressure curves of 30 samples. The samples were grouped by lithology and dominant pore type(s). When two dominant pore types occur, the one that is listed first is more abundant.

	Dominant pore type(s)	Mean of pore-throat size (µm)	Minimum pore-throat size (µm)	Maximum pore-throat size (µm)
Limestone thrombolite	Isolated vugs	0.218 ± 0.162	0.005	3.702
	Connected vugs	22.945 ± 6.508	0.006	215.003
	Intergranular / vug	7.760 ± 3.765	0.009	201.347
	Vug / intercrystalline	11.448 ± 7.135	0.005	213.656
Partially dolomitized thrombolite	Intercrystalline / vug	4.718 ± 2.355	0.006	45.799
	Vug / intercrystalline	30.897 ± 4.999	0.006	215.003
Dolomitized thrombolite	Intercrystalline	7.180 ± 2.148	0.009	80.534
	Intercrystalline / vug	22.243 ± 2.305	0.010	199.458

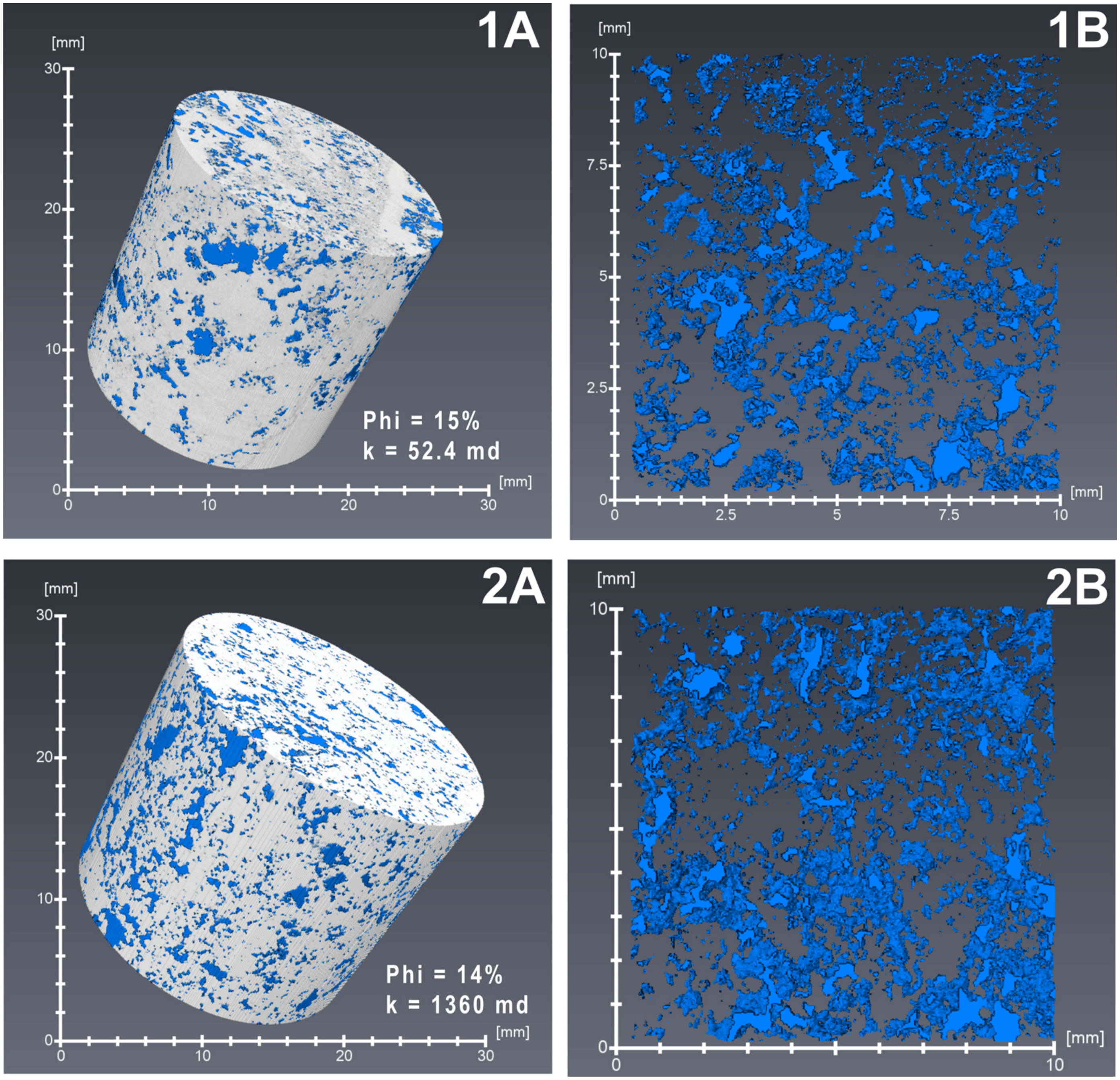


Figure 14. X-ray computed tomography volumes of two Smackover Formation thrombolite samples. It is possible to notice that in the dolomitized thrombolite vugs are better connected through a network of smaller pores. (1A) Non-dolomitized thrombolite (porosity in blue). Little Cedar Creek Field, well 10, 11,335.9 ft. (2A) Detail of the porosity in the same sample shown on 1A. (1B) Dolomitized thrombolite (porosity in blue). Vocation Field, well 35, 14,148 ft. (2B) Detail of the porosity in the same sample shown on 1B.

of dolomitized stromatolitic and thrombolitic facies, commonly with intercrystalline, vuggy, fenestral, and moldic pores. In Kansas, dolomitized Arbuckle stromatolites have porosity values up to 32% and permeability values up to 1500 md. Porosity in these rocks is related to depositional facies, early diagenesis, and dolomitization (Franseen et al., 2003). In southwestern Oklahoma, dolomitization and dissolution in the Arbuckle Group microbialites were early diagenetic events, producing abundant intercrystalline porosity, along with minor amounts of vuggy and fracture porosity (Gao et al., 1992).

CONCLUSIONS

Diagenesis caused significant changes in rock texture, pore geometry, and pore-throat size distribution in the Smackover Formation thrombolite reservoirs in southwestern Alabama. Consequently, the petrophysical characteristics of the thrombolite unit also changed. During the dolomitization process, the grains and early calcite cements were progressively replaced by dolomite crystals, the remaining calcite was progressively dissolved, and intercrystalline porosity was generated. The number

Table 2. Results of X-ray computed microtomography analysis of the pore system in 3D in two samples.

	Non-dolomitized thrombolite	Dolomitized thrombolite
Porosity	12.2%	13.6%
Microporosity (22–50 μm)	0.15%	0.03%
Mesoporosity (50–100 μm)	0.29%	0.20%
Macroporosity (>100 μm)	99.56%	99.77%
Microporosity below resolution (ϕ Lab–ϕ Microtomography)	1.8%	0.4%
Average of Micropores (22–50 μm)	6.5 pores / mm^3	2.7 pores / mm^3
Average of Mesopores (50–100 μm)	3.7 pores / mm^3	4.6 pores / mm^3
Average of Macropores (>100 μm)	5 pores / mm^3	6.9 pores / mm^3

of meso- and macropores increased, and pore geometry became more homogeneous. Pore throats are smaller and more homogeneous in intercrystalline porosity (after dolomitization) than in connected vuggy porosity (depositional vugs, commonly enhanced by late dissolution).

The southern portion of the Smackover Formation thrombolite at Little Cedar Creek Field is partially dolomitized and porosity and permeability average values are higher in this portion of the field. The petrophysical properties in the partially dolomitized reservoir are more homogeneous vertically and laterally. Dolomitization accompanied by calcite dissolution generated intercrystalline porosity in the Smackover Formation thrombolite unit, resulting in improved reservoir quality at Little Cedar Creek (southern portion of the field), Appleton and Vocation fields, southwestern Alabama.

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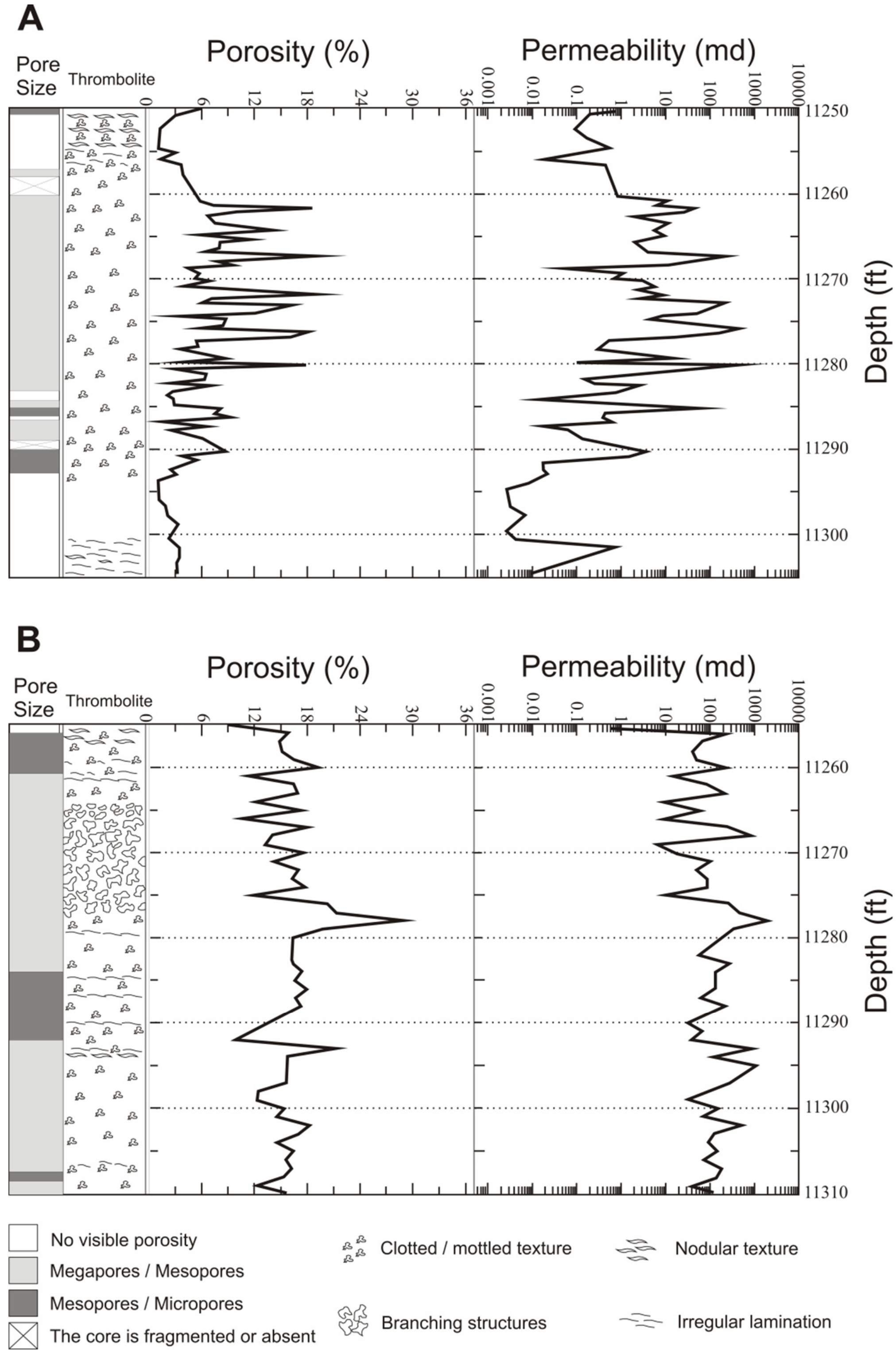

Figure 15. Correlation of core description and vertical porosity and permeability trends (petrophysical data from core plugs) of Smackover Formation thrombolite reservoirs. (A) Limestone thrombolite (no dolomization in this core). Little Cedar Creek Field, well 21. (B) Dolomitized microbial thrombolite. Appleton Field, well 33. Micropore corresponds to pore size smaller than or equal to 0.0625 mm (silt size), mesopore corresponds to pore size between 0.0625 mm and 4 mm (sand and granule size), and megapore corresponds to pore size larger than 4 mm (pebble size).

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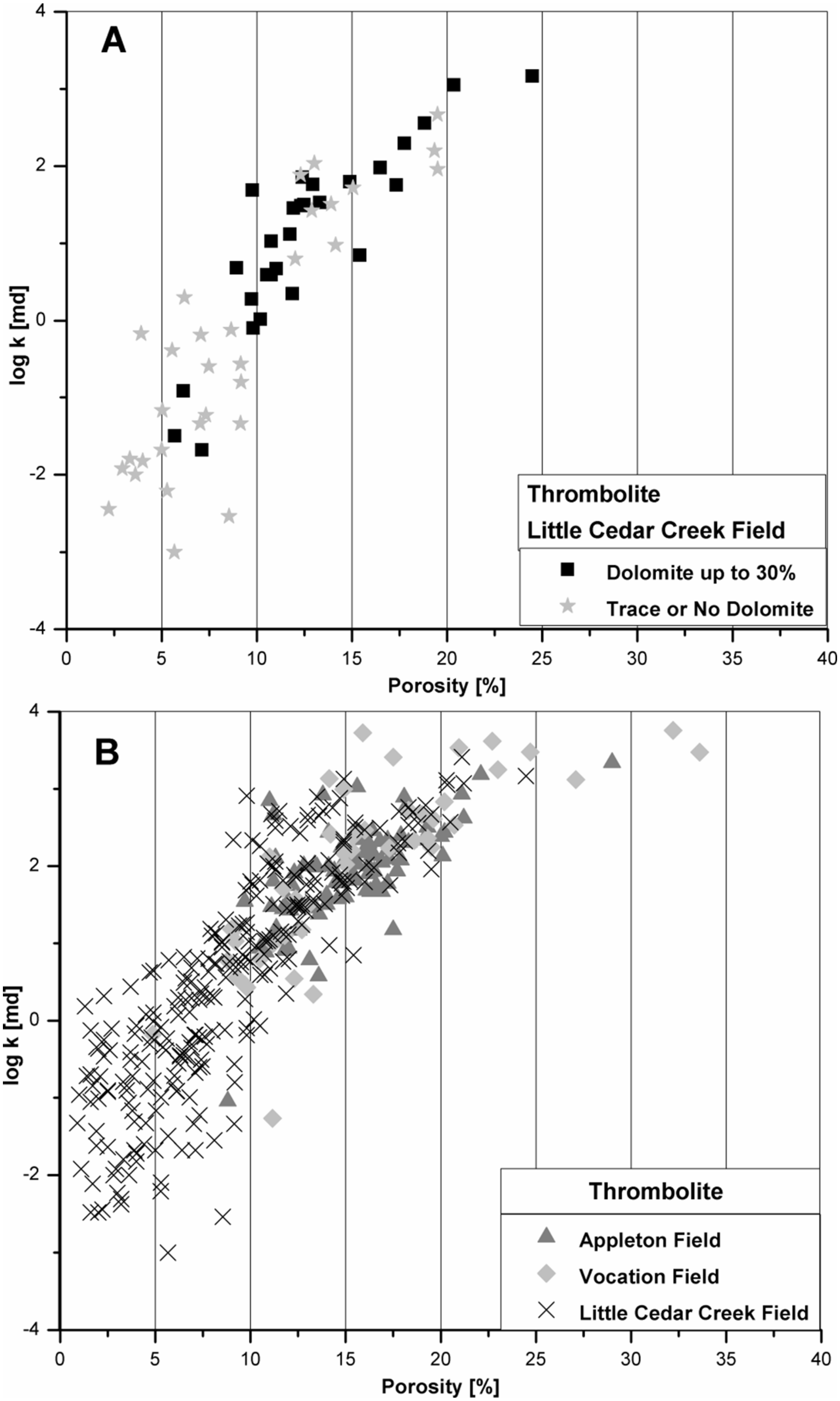

Figure 16. Porosity-permeability crossplots. (A) Thrombolite petrophysical data from Little Cedar Creek Field. (B) Thrombolite petrophysical data from Little Cedar Creek, Appleton, and Vocation fields. The thrombolite unit in Appleton and Vocation fields is intensely dolomitized. The partially or intensely dolomitized samples tend to have high porosity and permeability.

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