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of the Jurassic Smackover formation at Little
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**LITHOFACIES DISTRIBUTION AND DIAGENETIC
OVERPRINT OF THE JURASSIC SMACKOVER FORMATION
AT LITTLE CEDAR CREEK FIELD, CONECUH COUNTY, ALABAMA**

A Thesis by

Peter Wheiland

Bachelor of Science, University of Wisconsin-Oshkosh, 2012

Submitted to the Department of Geology
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Earth, Environmental and Physical Sciences.

Dr. William Parcell, Committee Chair

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Dr. James Bann, Committee Member

ABSTRACT

Upper Jurassic microbial carbonate buildups are proven petroleum reservoirs in southwest Alabama, including at Appleton, Vocation and Little Cedar Creek Fields. For the past 30 years, extensive effort has been applied to describing these microbial fabrics because of their influence on reservoir quality variability. The Smackover Formation at Little Cedar Creek Field in Conecuh County displays microbial lithofacies and reservoirs in a largely undolomitized state. These strata are an ideal dataset to characterize original microbial textures, providing more pristine information to interpret depositional environments and determine the extent that original depositional fabric controlled final reservoir quality. Various classifications of microbial fabrics have also provided models for interpreting depositional history and stratigraphic position of these buildups.

This study recognizes five lithofacies in the Smackover Formation: a lower laminated mudstone, a peloidal packstone, a microbial bindstone, a laminated mudstone, and an ooid grainstone. Of the previously published models, Heydari and Baria (2005) provide the best characterization of the units found in Little Cedar Creek. This study enhances the Heydari and Baria (2005) and Mancini et. al. (2008) models by integrating new wells and data gathered in the decade since the model was proposed.

TABLE OF CONTENTS

Chapter	Page
1. INTRODUCTION.....	1
2. GEOLOGIC SETTING	
2.1 LOCATION.....	3
2.2 GEOLOGIC HISTORY.....	5
2.3 PETROLEUM EXPLORATION/FIELD HISTORY.....	7
3. REGIONAL STRATIGRAPHY.....	9
4. METHODOLOGY.....	12
5. RESULTS	
5.1 LITHOFACIES.....	14
5.2 DIAGENESIS.....	26
6. DISCUSSION	
6.1 COMPARISON WITH OTHER STUDIES.....	32
6.2 SEQUENCE OF DEPOSITION.....	35
6.3 VARIANCE ON LITHOFACIES.....	37
6.4 DIAGENETIC ALTERATION.....	39
7. CONCLUSION.....	41
ACKNOWLEDGEMENTS.....	42
REFERENCES.....	43

CHAPTER 1 INTRODUCTION

Little Cedar Creek Field is an oil field in Southwest Alabama that produces out of the Upper Jurassic (Oxfordian) Smackover Formation. The Smackover units in southwest Alabama developed a carbonate ramp whose productive zones are largely microbial in origin (Ahr 1973, Heydari and Baria 2005, Mancini et. al. 2008). These microbial structures are dominated by thrombolitic texture (microbial structure with clotted internal fabrics) (Kennard and James 1986, Kopaska-Merkel 2003).

Petroleum exploration before discovery of Little Cedar Creek Field focused on finding topographic highs in the underlying Norphlet Formation and basement rock, as these highs would be a preferred location of microbial growth. For example, extreme paleotopographic relief, as found at Vocation Field, Monroe County, would break the surface of the water, and so the microbial reefs would form along the flanks.

Conversely, less extreme topographic highs such as found at Appleton Field, Escambia County, would remain submerged throughout deposition of the Smackover Formation, permitting microbial growth along the top and flanks of the high (Parcell 2002). With Little Cedar Creek Field it was recognized that microbial buildups could develop in bathymetric settings other than paleotopographic highs in the bedrock (Mancini et. al. 2006).

To date, the Little Cedar Creek Field is unique to microbial reservoirs in southwest Alabama, as the buildups do not occur on paleotopographic highs of the Norphlet Formation, but in a shallow, subtidal inner ramp setting, close to shore (Mancini et. al. 2008). Little Cedar Creek Field also differs from nearby fields in that

Little Cedar Creek has comparatively little dolomitization and most of the field has only experienced diagenetic alteration (Parcell 2002). Because of this, Little Cedar Creek Field is thought to retain much more original depositional textures useful for the study of microbial reefs found within the Smackover Formation. Little Cedar Creek is one of the largest and most productive Smackover fields in the Northern U.S Gulf Coast, and study of its formation is important for future exploration of fields of this type (Heydari and Baria 2006).

Two major studies of the field, conducted by Heydari and Baria (2005) and Mancini et. al. (2008), have created models of deposition and stratigraphic columns. These studies were created when only the western region of the field was being drilled. The two-reservoir system is well defined in the western region of the field, and can be easily picked out in density-porosity logs. Since these studies were published, the field has expanded considerably to the east and northeast. Porosity logs are not as well defined and in particular the lower microbial reservoir is more sporadic. This study examines the previous models and uses new well data from the expanded parts of the field to design an updated model of Smackover deposition at Little Cedar Creek Field.

This study examines core and thin sections from wells within Little Cedar Creek Field to develop a model of microbial reservoir development for the field. Core was analyzed from 11 wells, and petrographic analysis from thin sections from 10 wells. Comparisons were made to existing published models and revised and updated for the new additional wells across the field.

CHAPTER 2 GEOLOGIC SETTING

2.1 Location

The Little Cedar Creek Field (LCCF) is an oil producing field in Conecuh County, Alabama, approximately 10 miles southeast of the city of Evergreen. The producing Upper Jurassic Smackover Formation has been interpreted to have been located in the Conecuh Embayment within the Conecuh Subbasin (Heydari and Baria 2005, Mancini et. al. 2008). The embayment was part of a larger carbonate ramp that covers the present-day eastern Gulf Coastal Plain (Parcell 2002) [Figure 1]. The Conecuh Subbasin is bounded to the northwest by the Conecuh Ridge Complex, to the southwest by a series of faults, and to the southeast by the Pensacola Ridge (Mancini et. al. 2008).

The Oxfordian Smackover Formation was deposited during the opening of the Gulf of Mexico, which began in the Triassic Period. During the late Triassic, extensional tectonics related to the breakup of Pangaea created a series of basins across the northern Gulf Coast. Structural highs separated the basins from each other and from the proto-Gulf of Mexico (Heydari & Baria 2005). The ramp is separated into an inner and outer ramp by the Wiggins Arch (Parcell 2002).

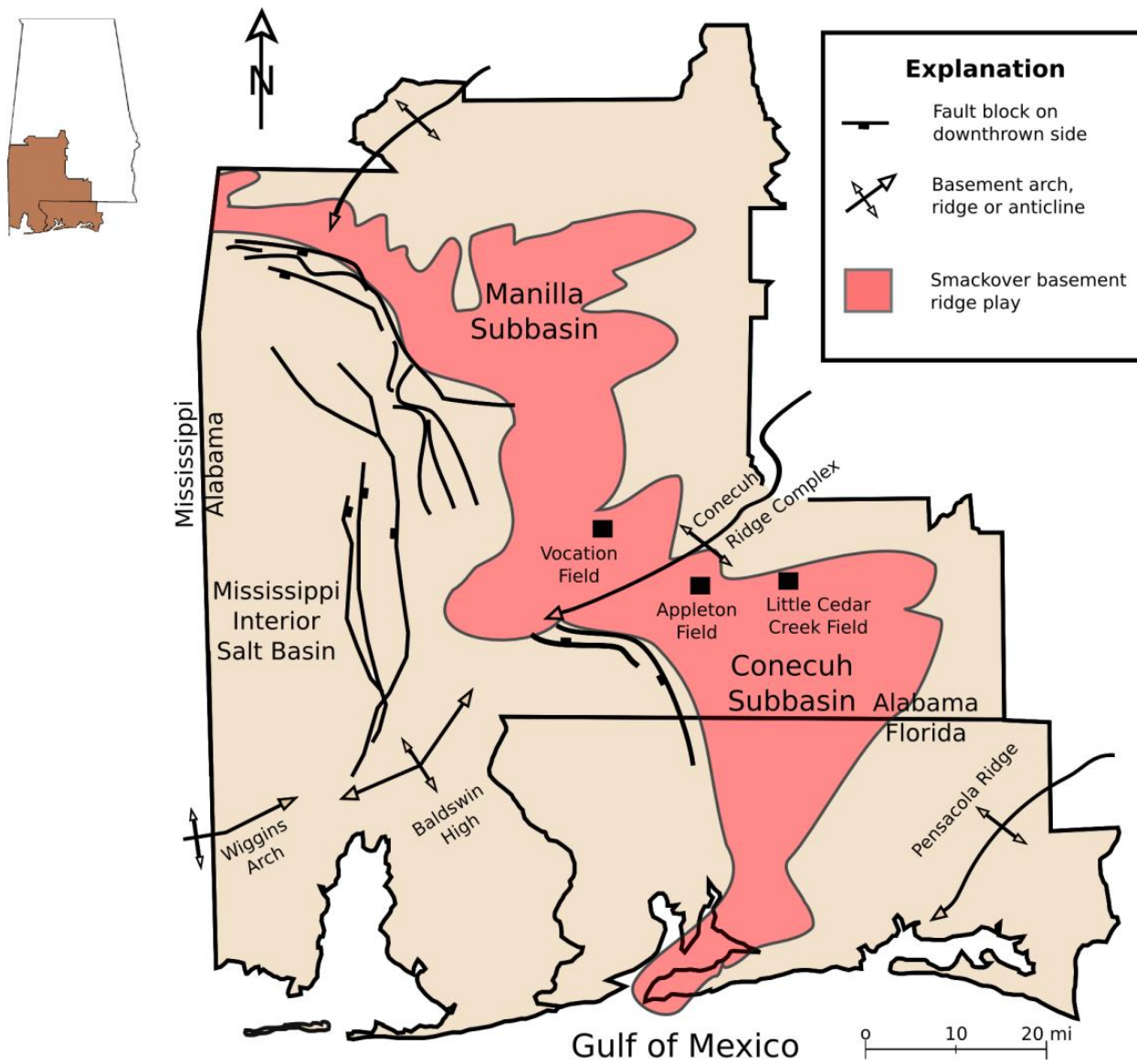


Figure 1: Map of southwest Alabama, showing location of Conecuh Subbasin, as well as the Vocation, Appleton, and Little Cedar Creek Fields (Modified from Mancini et al 2008).

2.2 Geologic History

The Smackover carbonates developed during a rapid transgression of the sea onto an eroded Norphlet Formation, represented in many places by a conglomerate lithofacies. The Smackover lithofacies developed a typical carbonate ramp succession with microbial reefs occurring both near shore and on paleo highs further from shore.

An earlier regression of the sea led to erosion of the top of the Norphlet Formation, in some cases being completely removed from the tops of paleotopographic highs in the bedrock [Figure 2]. During the subsequent transgression, the region was covered with the Smackover. Topographic lows were covered by the Lower Smackover lime mudstone and the highs were blanketed with grainstones and packstones. Earlier studies of Smackover microbial reservoir lithofacies at Appleton and Vocation Fields in southwest Alabama determined that microbial buildups developed primarily on paleotopographic highs in the bedrock (Parcell 2000, Mancini et. al. 2004, Mancini et. al. 2008). These types of reefs formed in less than nine meters (30 ft) of water (Mancini et. al. 2008).

The Little Cedar Creek Field is unique to date in that microbial buildups developed upon carbonate muds and sands along the inner ramp, as opposed to developing on hard basement rock along paleotopographic highs. Little Cedar Creek developed in an estimated three meters (10 ft.) depth and approximately five kilometers (three miles) from the paleoshoreline (Mancini et. al. 2008).

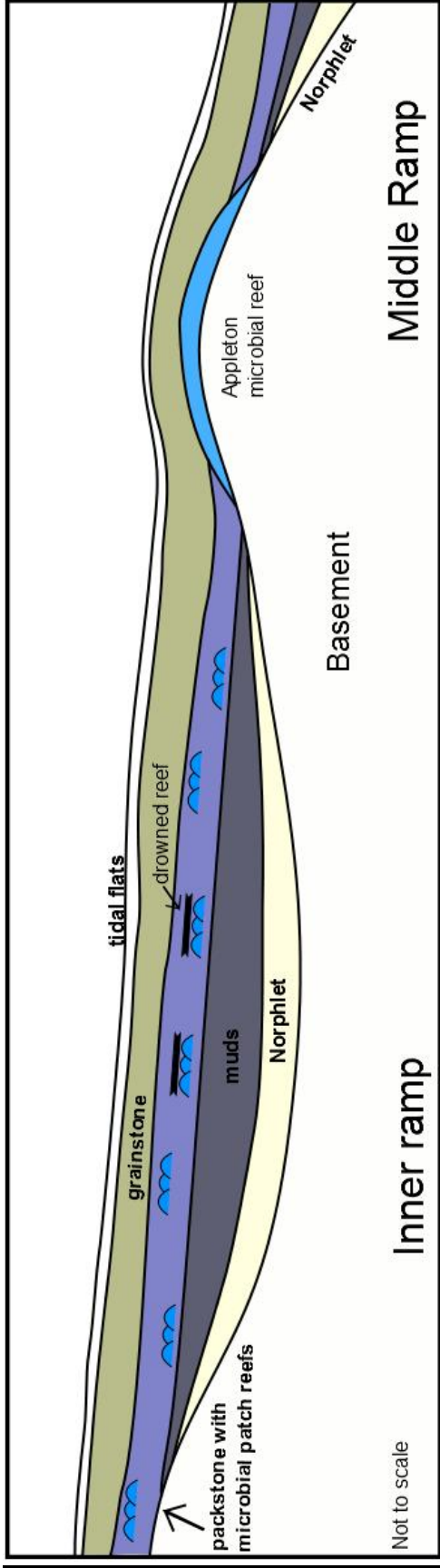


Figure 2: Stylized cross section, showing position of units within Little Cedar Creek Field as well as Appleton-style reef (modified from Mancini et. al. 2008).

2.3 Petroleum Exploration/Field History

Little Cedar Creek Field was discovered in 1994 by the Hunt Oil Company, with the drilling of the Cedar Creek Land and Timber Company 30-1 #1, which attained a flow rate of 108 barrels of oil per day of 46 degree API gravity oil (Mancini et. al. 2006) and 49,000 cubic feet of gas per day [Figure 3]. The field was later taken over by Midroc Operating Company, and a second well was drilled in 2000 and tested at 250 BOPD. A third well was drilled in 2003 and was the first well cored. Study of this core revealed that the field was not built up on a paleotopographic high, but along the stratigraphic updip limit of the Smackover (Mancini et. al. 2008).

The field was unitized in December 2004, and as of October 2014, has produced over 18.5 million barrels of oil and almost 23 billion cubic feet of gas, making it the number one oil producing field in the state (gsa.state). The Smackover in Little Cedar Creek resides at depths of approximately 3048-3650 m (10,000-12,000 ft). As of April 3rd, 2014 the field is approximately 10,050.96 acres (State Oil and Gas Board Docket) [Figure 3].

Although source-rock analysis of the lime mudstones and dolomudstones show enough total organic carbon content and thermal alteration, they are not thick enough to develop sufficient hydrocarbons for commercial production. It is hypothesized that the hydrocarbons most likely migrated from deeper within the Conecuh Subbasin center. (Mancini et. al. 2006).

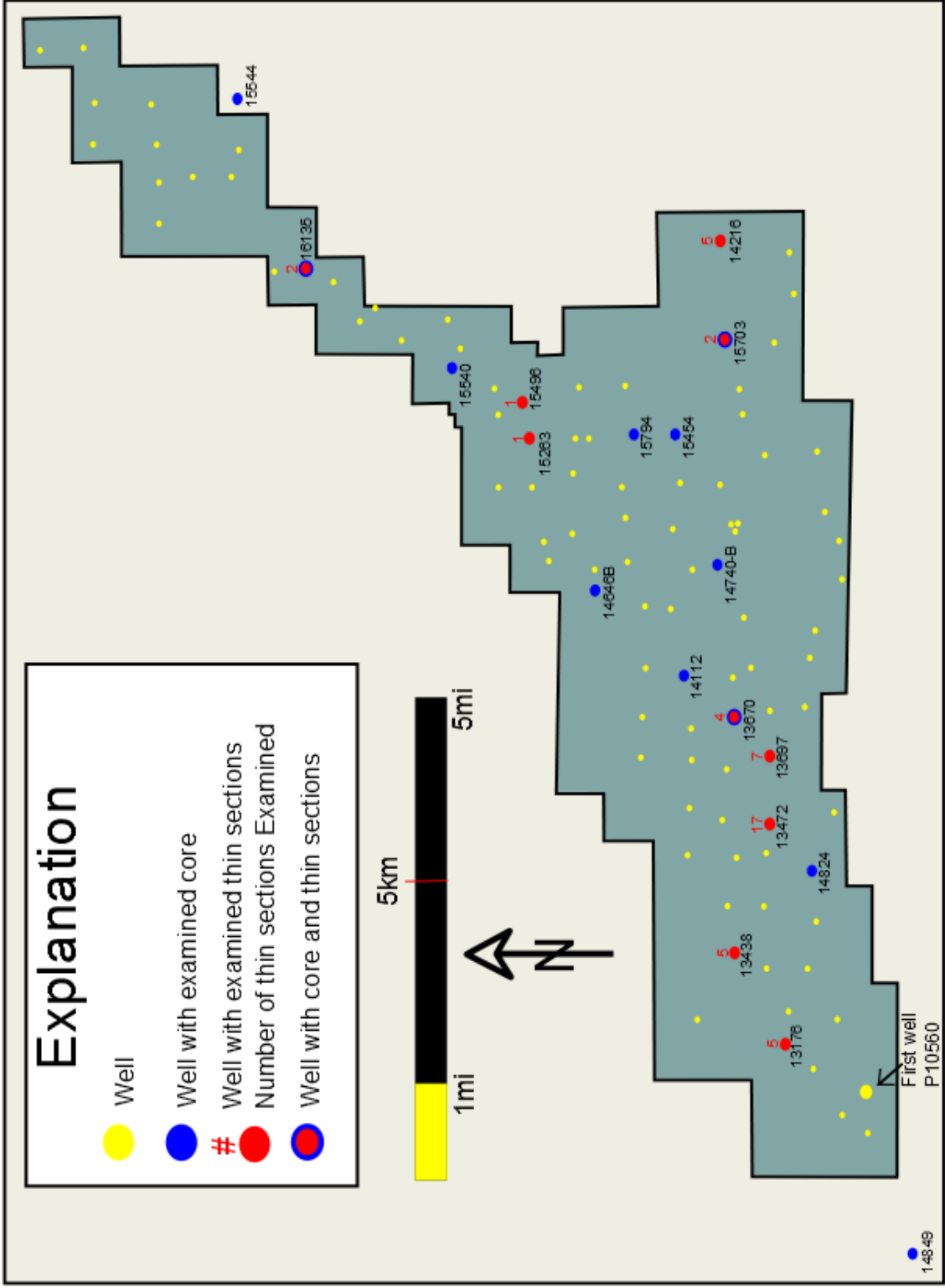


Figure 3: Map of Little Cedar Creek Field. Early studies focused on the older western region of the field. This study expands on those previous works by incorporating data from newer wells to the east and northeast (Modified from gsa.state).

CHAPTER 3 REGIONAL STRATIGRAPHY

The three stratigraphic formations of interest in the Little Cedar Creek Field are (in rising stratigraphic level) the Norphlet Formation, the Smackover, and the Haynesville Formation [Figure 4] (Mancini et. al. 2008).

The Norphlet is a conglomeratic sandstone considered to be a continental siliciclastic deposit formed in an arid climate (Kopaska-Merkel 2003). Continental alluvial, fluvial and eolian deposits have been identified within the Norphlet, and marine sandstone shoreface lithofacies have been identified in parts of the northeastern Gulf of Mexico. This marine lithofacies, where present, is interpreted as a reworking of the continental lithofacies during the same transgression that deposited early Smackover (Mancini 2010).

The Smackover is a carbonate ramp, and represents the majority of a transgressive-regressive cycle. At Little Cedar Creek it ranges in thickness from 70 to 110 feet (Mancini et. al. 2006). It is predominantly carbonate mudstone within the valley and low-lying areas, and grainstone along topographic highs and near the shore. The Smackover is microbially influenced throughout the region in the form of microbially dominated bioherms (Kopaska-Merkel 2003). At Little Cedar Creek, the patch reefs and bioherms form a lower reservoir, and the grainstone lithofacies forms an upper reservoir (Mancini et. al. 2006). Although most Smackover fields have these two lithofacies, they are usually laid one on top of the other. At Little Cedar Creek Field these two reservoir lithofacies are hydraulically disconnected by a dense mudstone to packstone lithofacies.

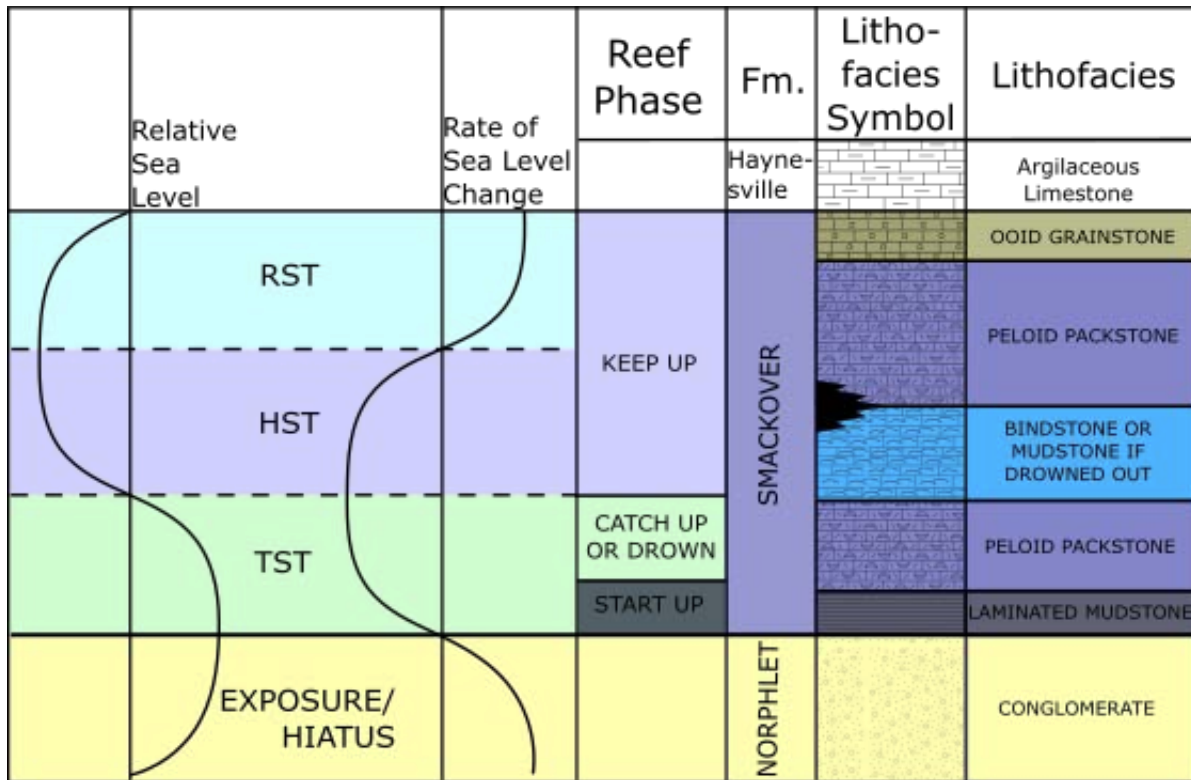


Figure 4: Stratigraphic column, including conceptual model depicting sea level position and rate of sea level change. Abbreviations are as follows: TST (transgressive systems tracts), HST (highstand systems tract), LST (lowstand systems tract)

The Haynesville Formation caps the Smackover. The boundary between Smackover and Haynesville also represents the boundary between Oxfordian and Kimmeridgian stages of deposition (Mancini et. al. 2010). The lowest member, the Buckner, is composed of anhydrite and limestone in a tidal flat setting. The base of the Haynesville is a conformable sequence boundary (Mancini et. al. 2008), with the Buckner member representing the end of the regression, and the rest of the Haynesville shales and sandstones are representative of another transgressive cycle (Mancini 2010). The Buckner anhydrite beds at Little Cedar Creek are thin and discontinuous, and do not directly overlie the grainstone lithofacies of the Smackover. The Buckner argillaceous beds that do overlie the grainstone are considered the seal rocks for the upper reservoir (Mancini et. al. 2006).

CHAPTER 4 METHODOLOGY

Core was examined at the Geological Survey of Alabama in Tuscaloosa. This study examines 11 cores, as well as 49 thin sections from 10 wells [Figure 3]. Thin sections from adjacent wells were taken where applicable to maintain correlation between core and thin section.

Lithologic boundaries were determined and descriptions were taken of core. Core boundary depths were compared to geophysical logs [Figure 5]. Photos of all core examined were taken for later reference and study. Thin sections were examined using an Olympus BX50 petrographic microscope and described for mineralogy, grain size, textures, fabrics, cements, and fossil content. Images were taken using an Olympus DP10 microscope camera.

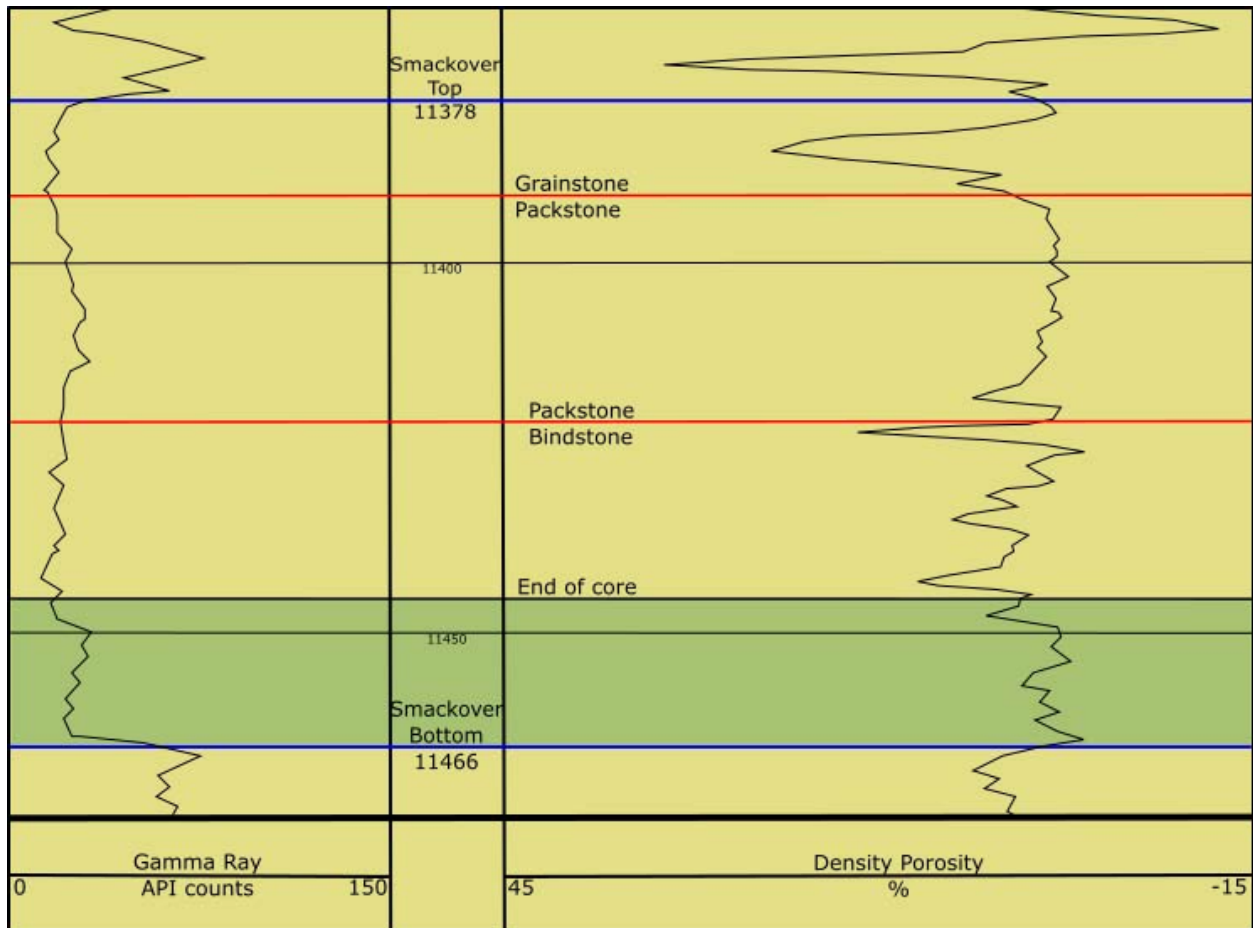


Figure 5: Sample of geophysical log work. Well P13670. Labeled for Smackover depth and lithofacies boundaries. Lithofacies boundaries were determined via core and thin sections where available, and adjusted to geophysical log depths. Where core was incomplete, it is shown.

CHAPTER 5 RESULTS

5.1 Lithofacies

From analysis of core, thin sections and geophysical logs, five major lithofacies are identified. These lithofacies are: lower laminated mudstone, peloidal packstone, microbial bindstone, laminated mudstone, and ooid grainstone [Figure 4]. These are idealized lithofacies with often extended gradational boundaries. Patches of microbial deposition was also noted throughout almost the entire Smackover thickness in the majority of wells. Pockets or bands of microbial growth are interfingered within the packstone, as well as the lower parts of the grainstone and upper parts of the lower mudstone. They vary from previous lithofacies described by Heydari and Baria (2005) and Mancini et. al. (2008). Numerous diagenetic alterations also were noted, including multiple phases of cement, dissolution, recrystallization, and physical and chemical compaction.

Lithofacies (F-1) is a mudstone to wackestone and typically rests unconformably upon the Norphlet conglomerate [Figure 6]. It is composed of wavy lamination on the bottom and grades into horizontal laminations on top, although the lithofacies may appear massive in parts. Microbial binding can be present, although from visual inspection diagenetic recrystallization and dolomitization can damage original microstructures.

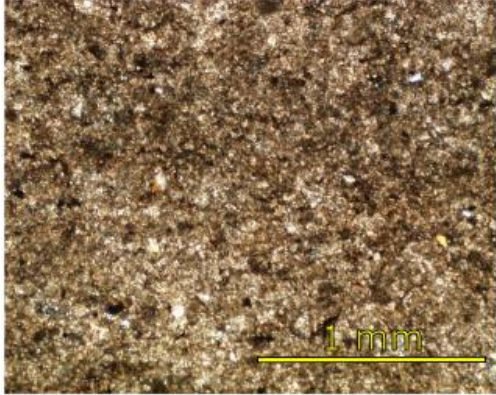


Figure 6: F-1 Laminated Mudstone. This is the stratigraphically lowest Smackover facies deposited, and it lies unconformably upon the Norphlet. Thin section images from P13438 at 3536.5 m (11603 ft.) depth. Core images from P16135

The F-1 mudstone grades conformably into peloidal packstone lithofacies (F-2) dominated by micrite peloids $\sim\frac{1}{4}$ mm in size [Figure 7]. Micritized benthic foraminifera are commonly present in petrographic analysis and maintain their internal structures [Figure 8]. Microbial features such as mats and microbially bound grains are present, especially as the F-2 grades into the bindstone. Intergranular porosity by dissolution is often filled with rind cements [Figure 9] and to varying degrees by large mosaic calcite crystal growth [Figure 10]. Dolomite locally grows into the intergranular pore space, but typically does not reach larger than $\frac{1}{4}$ mm [Figure 11].

A microbial bindstone lithofacies (F-3) is the first and stratigraphically lower reservoir within the Smackover Formation at Little Cedar Creek [Figure 12]. Generally composed of a mix of peloids, pellets, and microbially bound grains as well as microbial mat textures. Larger microbial grains grow around and incorporate pellets within their matrix; although some microbially bound grains may have formed calcimicrobes. These microbially bound grains are often 1-10mm in size, and generally grow more horizontally than vertically. They universally have clotted internal textures. Different microbe species or assemblages may be present, as the clumps can take on a wide variety of features (strength of clotted fabric, resistance to dissolution, thickness of exterior walls, etc.). Porosity types include framework and intergranular (vuggy) porosity. Rind cement, if present, is very thin and does little to restrict porosity and permeability. Dolomite and mosaic calcite is rare within the bindstone lithofacies in most wells.

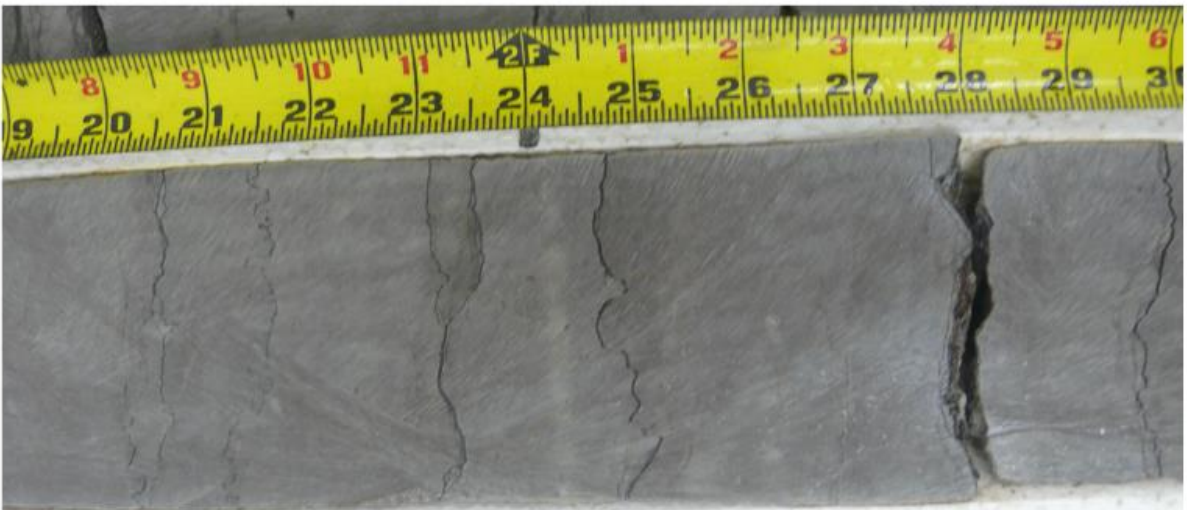
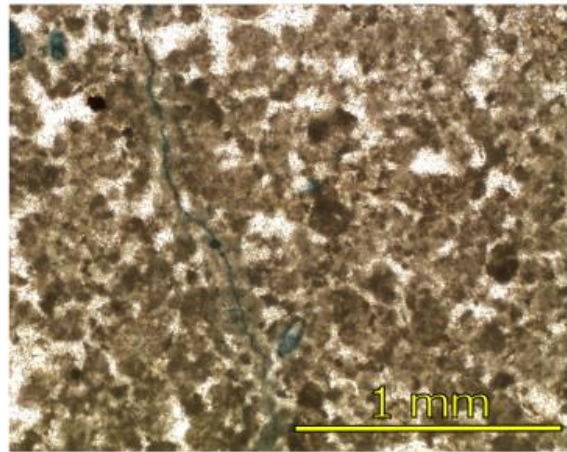
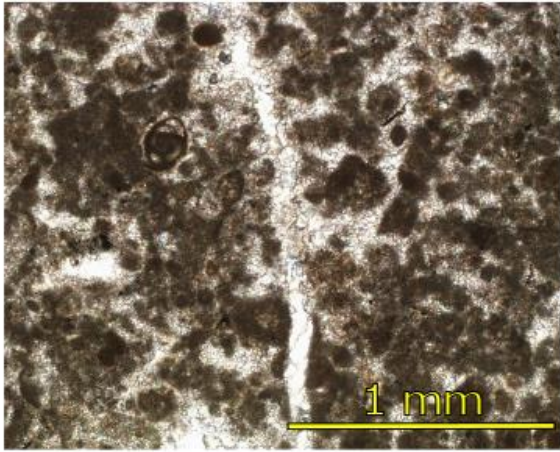


Figure 7: F-2 Packstone. This unit is identified by the abundance of peloids, generally 1/4mm in size. Benthic foraminifera are most abundant within this facies. Upper left thin section from P13472 at 3512 m (11522.5 ft.) depth. Upper right thin section from P13670 at 3488 m (11443 ft.) depth. Core is from P15703.

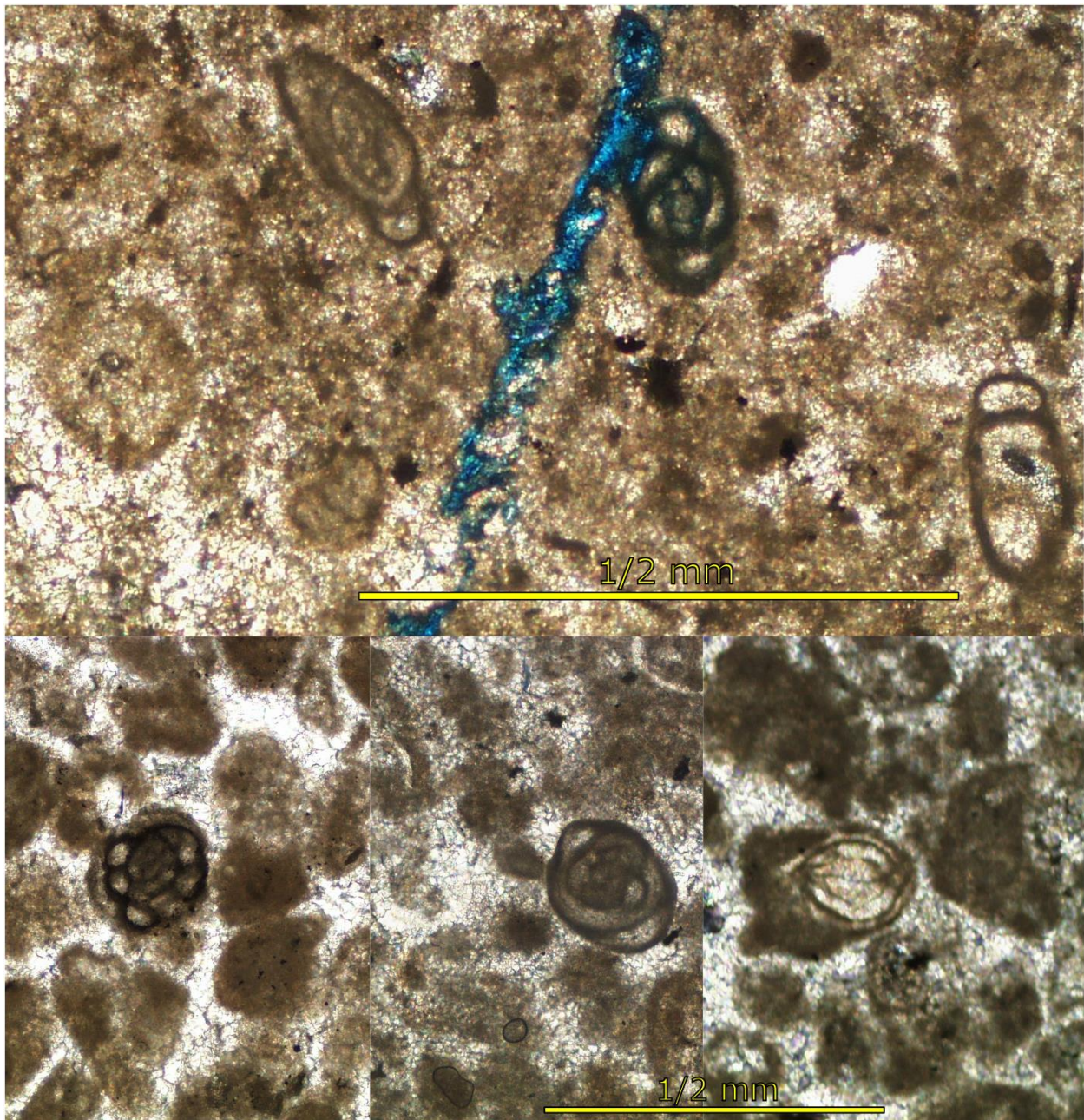


Figure 8: Benthic foraminifera. Although found in grainstone and bindstone facies, they are most common with the packstone. They are replaced but maintain their internal structures. Top image from P16135 at 3239 m (10627 ft.) depth, bottom images from P13472 at 3512 m (11522.5 ft.) depth.

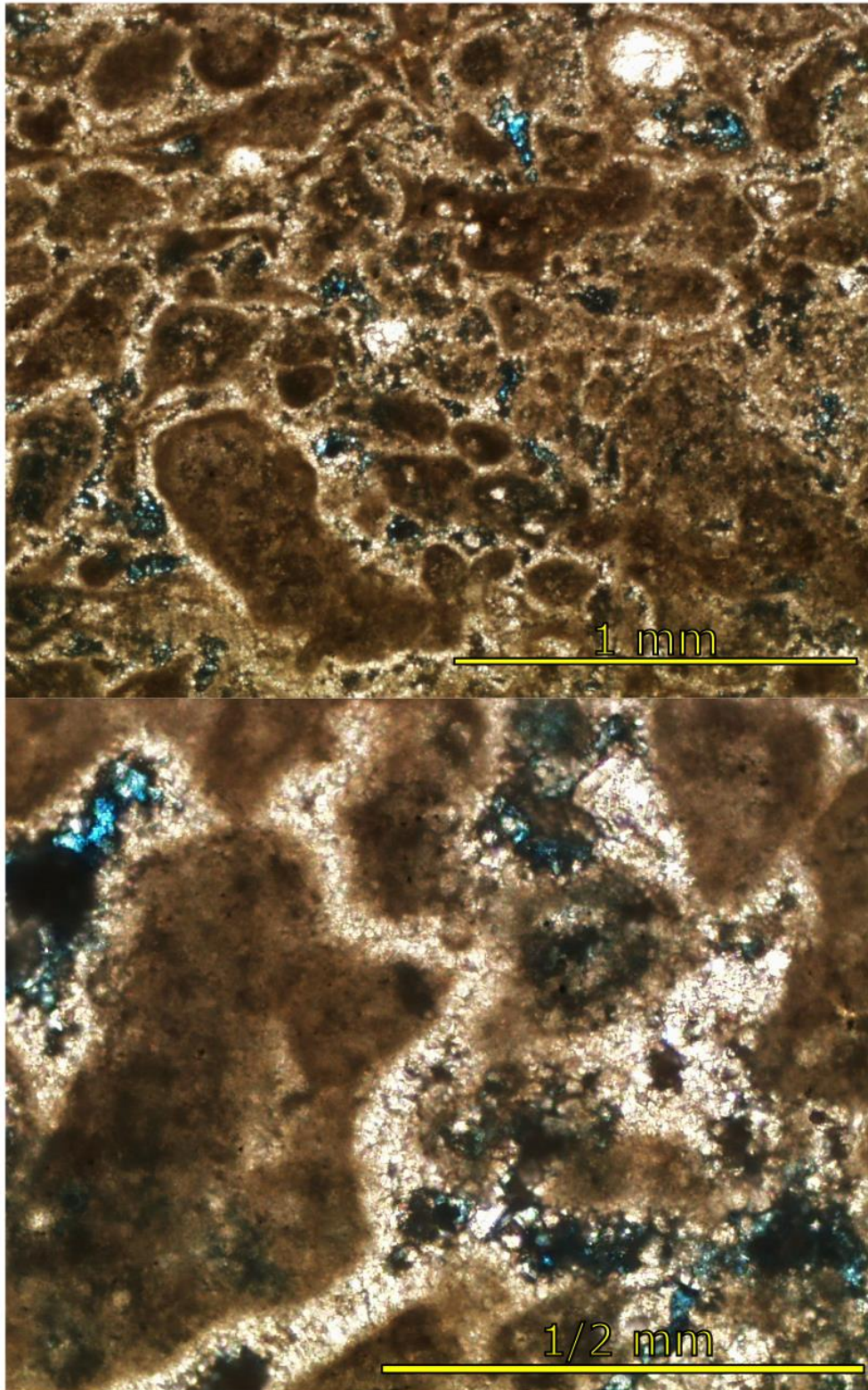


Figure 9: Calcite rind cement. In both images the light tan to white is the rind cement. It is an isopachous cement found in every thin section at all depths in every well. The grain size and cement thickness varied greatly between samples. Images from P13697 at 3495 m (11466 ft.) depth.

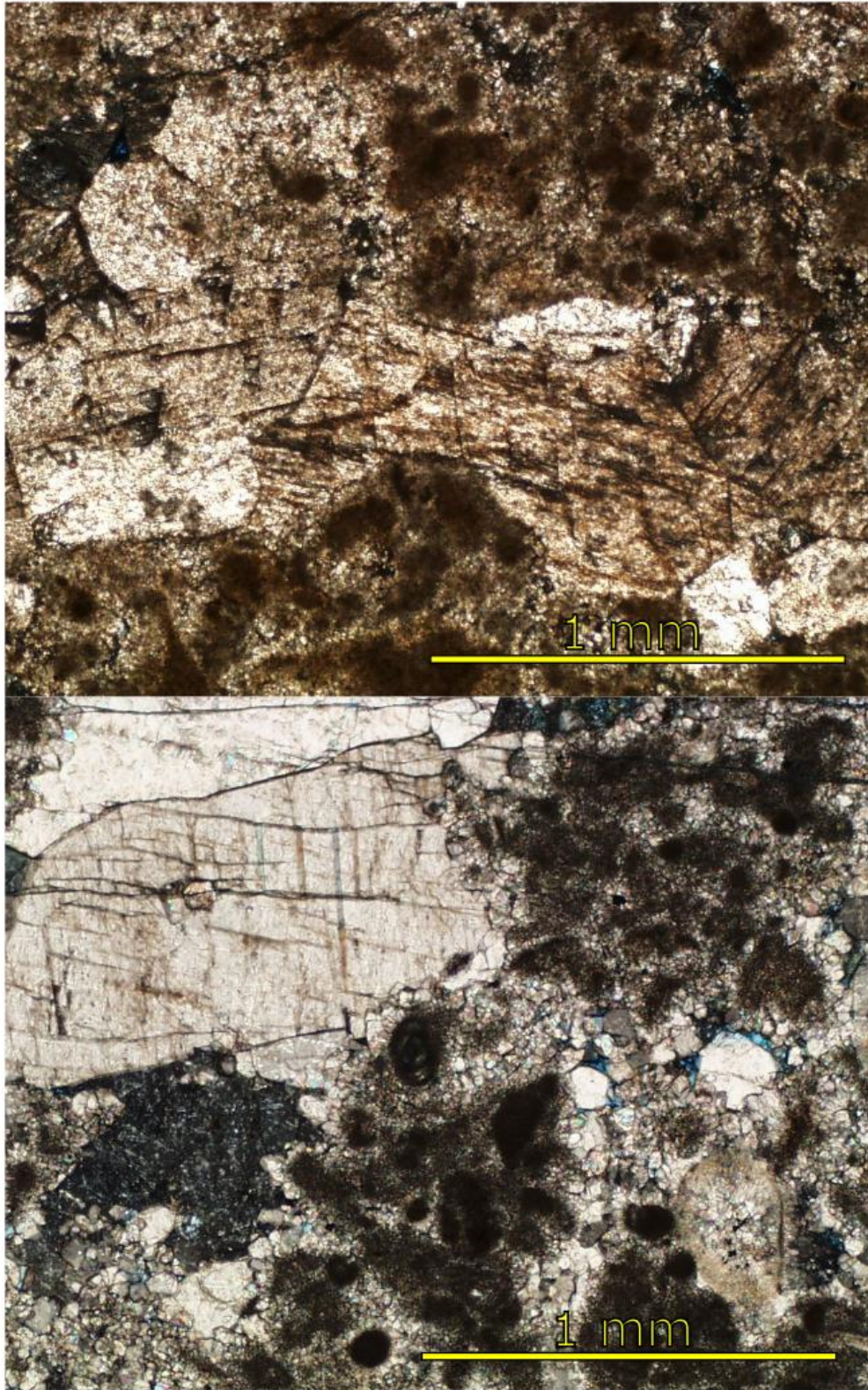


Figure 10: Mosaic calcite. Large crystals of calcite were one of the last cements to grow. They are most noticeable where vuggy pore space is abundant. They significantly reduce both porosity and permeability where present. Lower image from P13472 at 3517 m (11539 ft.) depth.

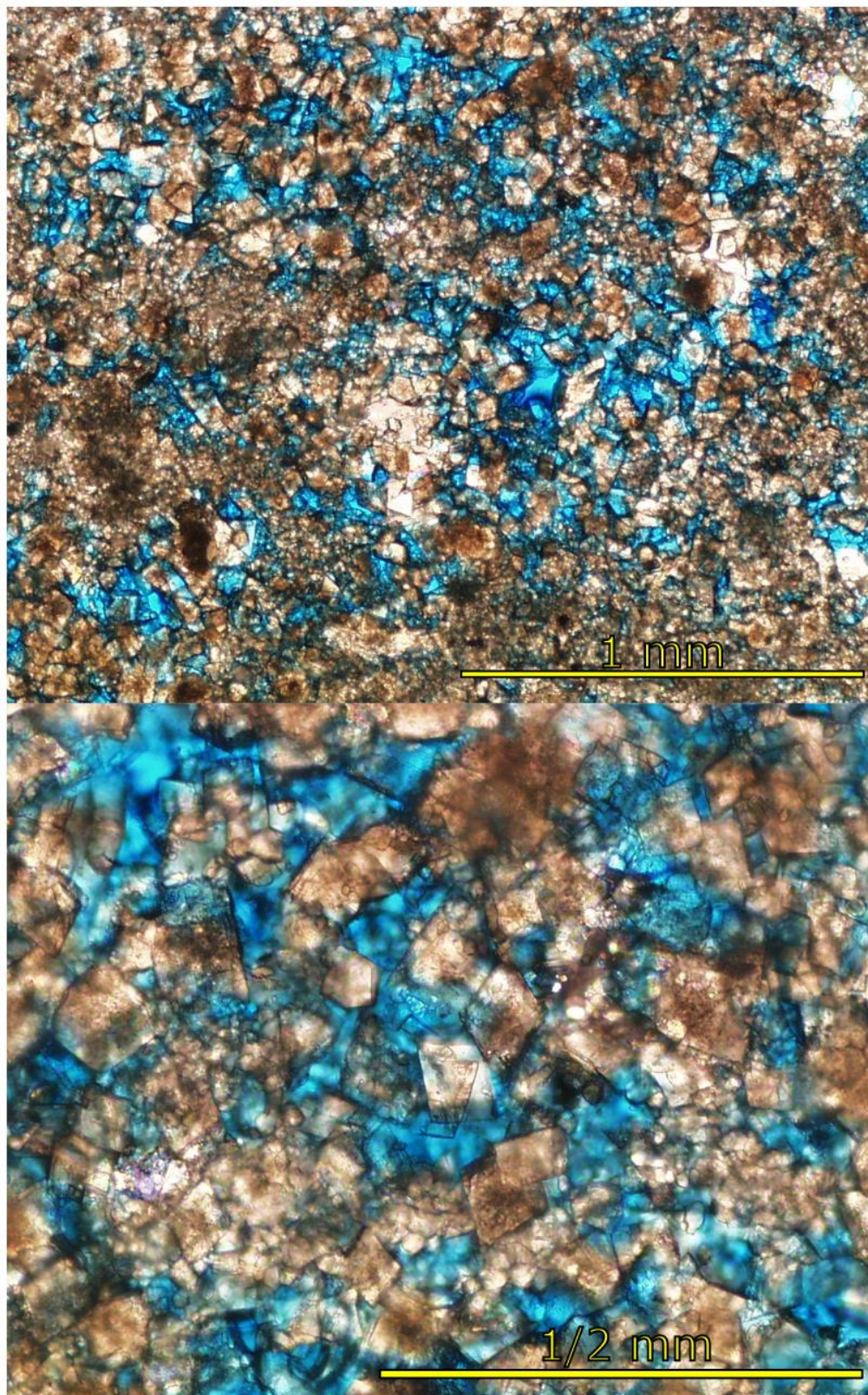


Figure 11: Dolomite rhombs. Dolomite is sparse within Little Cedar Creek wells. It typically forms as a cluster of crystals within a pore. Images from P13472 at 3526.5 m (11570 ft) depth.



Figure 12: F-3 Bindstone. Microbial in origin and generally found as patch reefs that in core are observed as thin units that interfinger within other units. Occasionally these reefs will grow to dominate an area, which is represented in core with multiple feet of intense microbial fabric within the rock. Thin section images from P13697 at 3525 m (11566 ft.) depth.

A laminated mudstone (F-4) is composed of dark, laminated carbonate mudstone. It contains no fossils and only minor recrystallization. No dissolution or cements are present in this lithofacies. It was not present in studied cores east of P13670.

The last Smackover lithofacies, composing the upper reservoir is a peloid-oid grainstone (F-5) [Figure 13]. It is composed of peloids as well as ooids generally $\frac{1}{2}$ mm to $\frac{3}{4}$ mm. Coated grains and grapestones are common in some wells [Figure 14]. Fossils include foraminifera, ostracods, and more rarely gastropods and bivalves. In general, microbial features in this lithofacies are rare, but are more likely to occur in the eastern and northeastern regions of the field where the strong distinction between lithofacies begins to break down. Intergranular and moldic pores make up porosity in the grainstone lithofacies, with ooid and fossil molds maintaining some degree of internal structures. Rind cement is often minimal and does little to fill pores or restrict permeability.

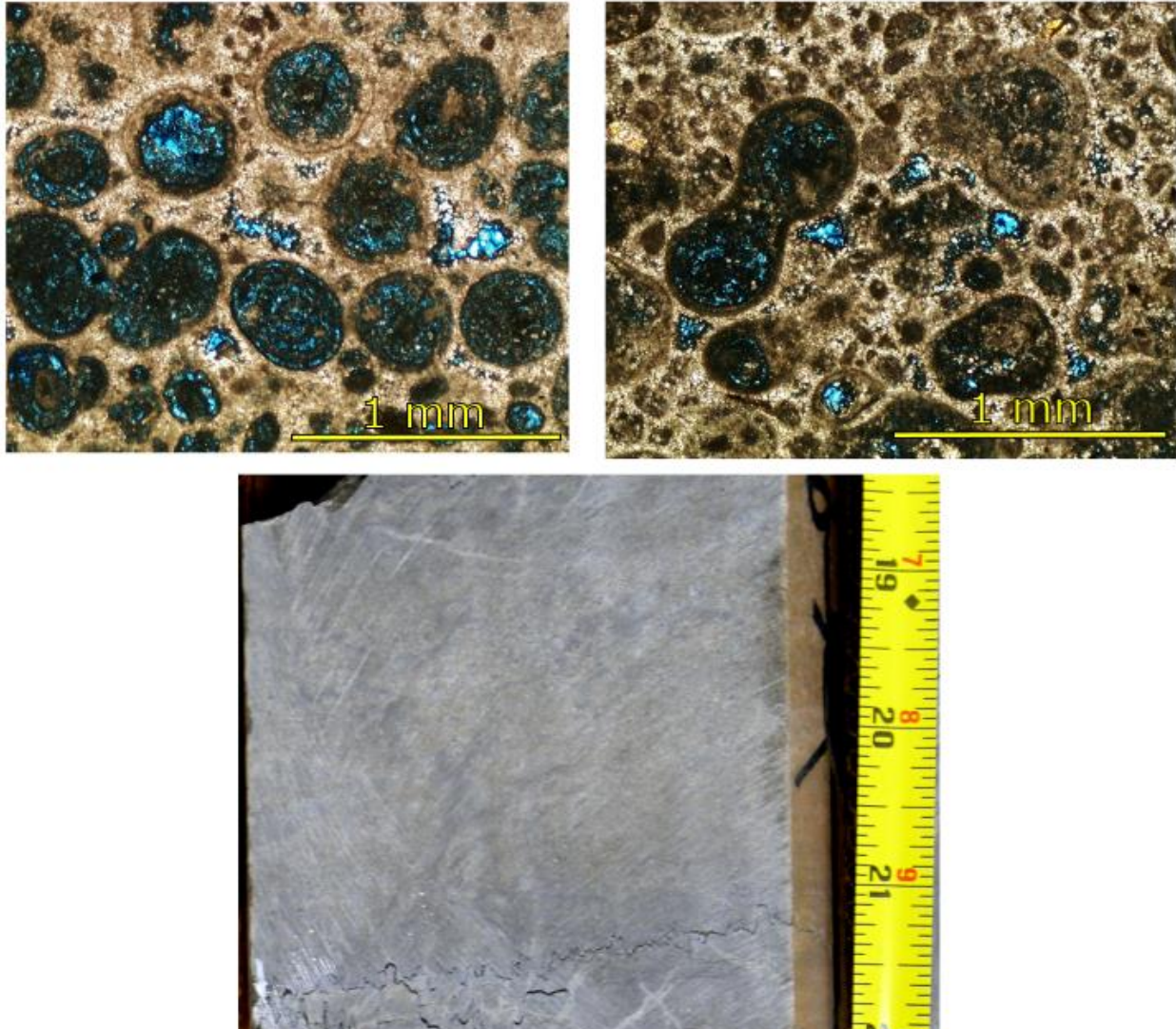


Figure 13: F-5 Grainstone. This facies is characterized by an abundance of ooids and grapestones. The two main porosity types are intergranular and moldic. Thin sections from P13438 at 3523.5 m (11560 ft.) depth. Core image from P14824.

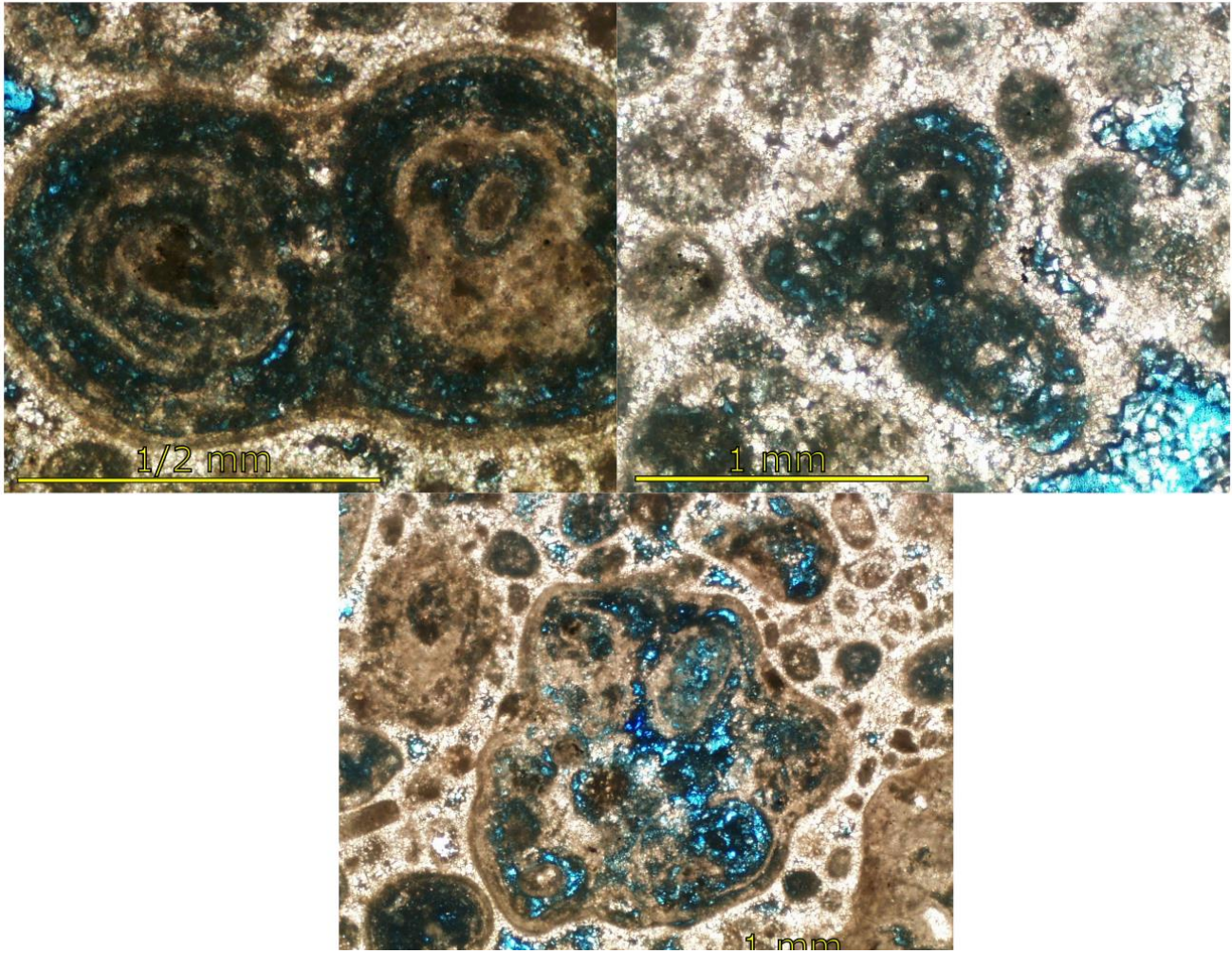


Figure 14: The top two images are grapestones of ooids. The bottom image is a microbially-bound grain. Microbial activity was noted within the grainstone lithofacies. Upper left and bottom images are from P13438 at 3523.5 m (11560 ft) depth. Upper right image is from P13176 at 3584 m (11759 ft) depth.

5.2 Diagenesis

Little Cedar Creek Field has undergone numerous diagenetic alterations, including fabric selective and wholesale dissolution, multiple phases of cementation, dolomitization, recrystallization, and physical and chemical compaction. A field's location within the basin and relative to the Smackover updip limit had a dramatic effect on diagenetic effects within its lithofacies (Benson and Mancini 1999). Lithofacies have been altered to various degrees throughout the field, and some have avoided all or part of these processes.

Dissolution occurred in multiple forms, but was typically facies selective (Mancini and Benson 1980). Generally mud and laminated muddy lithofacies are least dissolved, most likely relating to the low permeability of the lithofacies. Sections with a larger content of coarser grains (ooids, peloids, skeletal fragments, etc.) tended to be most dissolved. The upper grainstone reservoir experienced significant moldic porosity, especially within the ooid grains [Figure 15]. Fabric selective dissolution occurred strongest within the bindstone lithofacies. All lithofacies save the mudstones experienced wholesale dissolution in at least some parts. Vuggy pores were common within the grainstone and parts of the packstone.

There are multiple phases of cementation in the Smackover. The earliest diagenetic cement is fibrous calcite cement [Figure 16]. Fibrous grains typically less than ¼ mm were found rimming grains. It was rarely found within thin section, suggesting that it either rarely developed or that it was easily dissolved. Where present, it is the first cement phase and developed directly on grains.

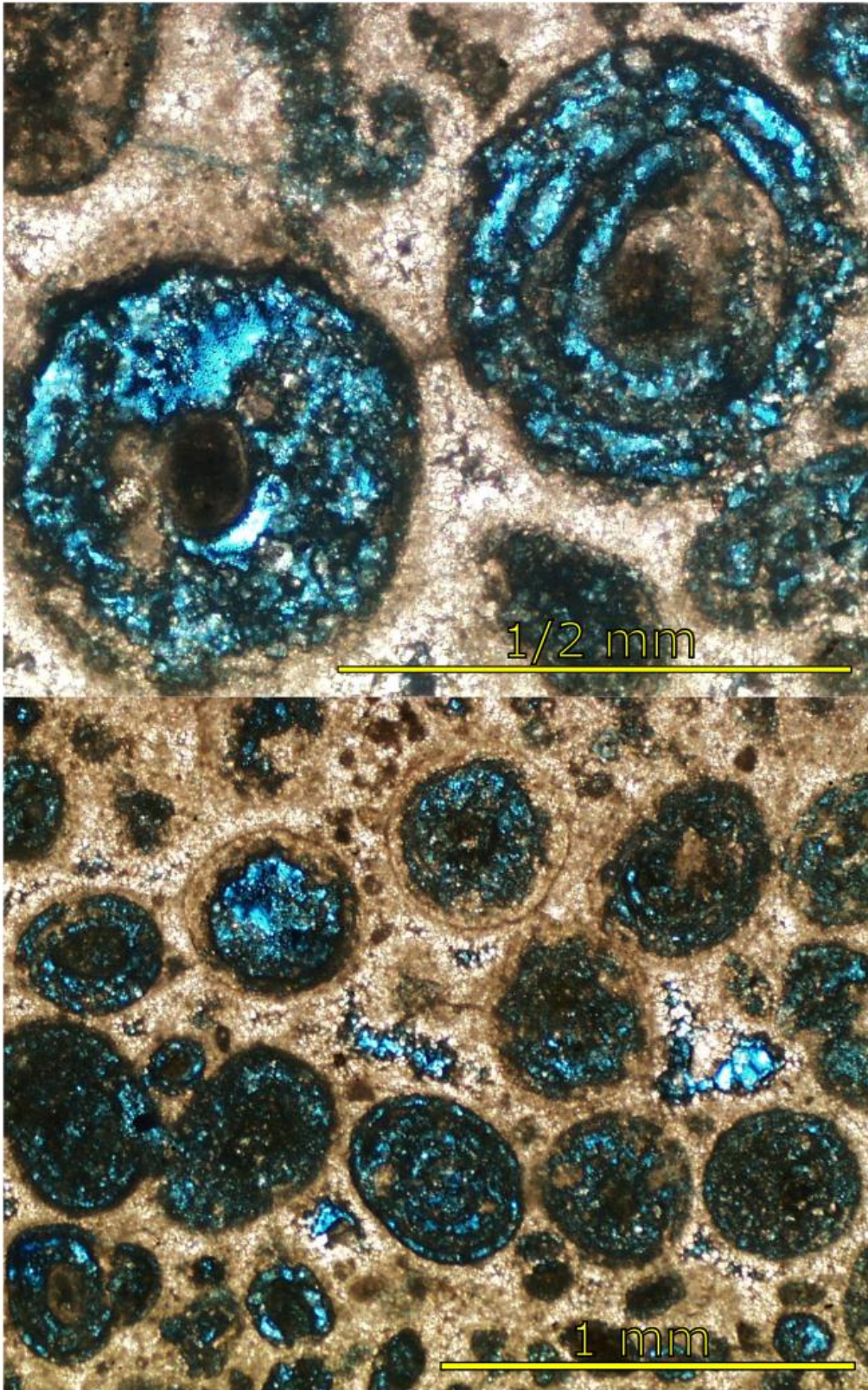


Figure 15: Moldic pores of ooids. Although moldic pores were occasionally found in the upper parts of the packstone and in the bindstone, it is the grainstone that benefited most from this dissolution. Images from P13438 at 3523.5 m (11560 ft) depth.

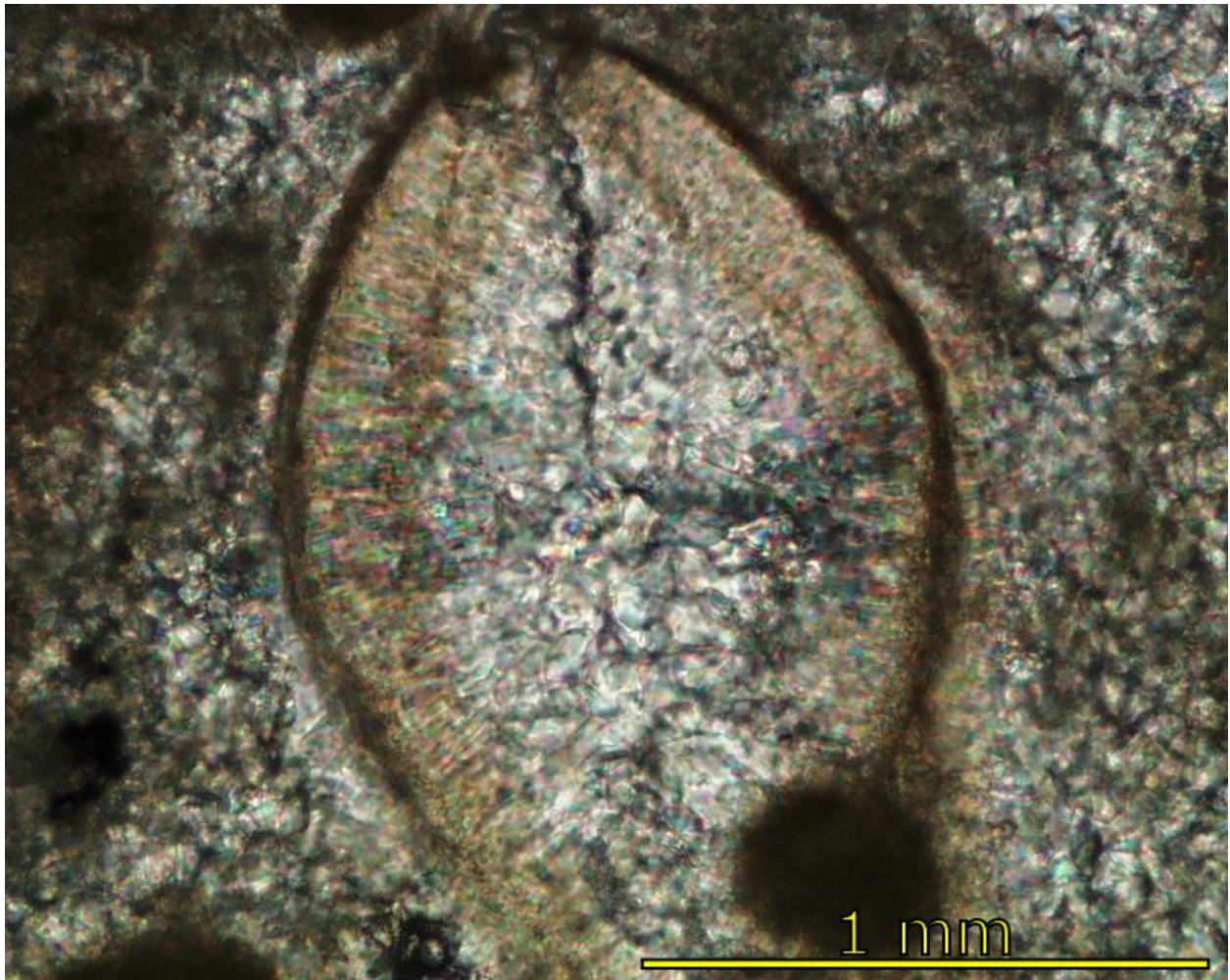


Figure 16: Ostracod with fibrous calcite cement. An early phase of cement, it was very rare within Little Cedar Creek wells. It may have formed before a dissolution phase and been washed out prior to the rind cement. Here, the rind cement formed on top of the fibrous cement and filled in the remaining pore space. From P13472 at 3517 m (11539 ft) depth.

Another cement phase was isopachous calcite rind cement that fringes grains [Figure 9]. It was ubiquitous in every sample in every well. The thickness of the cement is variable across both wells and section depth. It is notable that the cement does not build into pore space; it simply develops a rind or coating around each grain. Sections with small pore spaces and dense clusters of small grains have a greater portion of intergranular pore fill, while grainstones with large grains and thus large intergranular pore spaces have a much smaller reduction in porosity and permeability due to rind cement.

The most restrictive form of cementation is large grain mosaic calcite growth [Figure 10]. One of the key features of this cement is its large size, occasionally growing multiple millimeters. When present, mosaic calcite greatly reduces porosity and permeability within a rock, restricting even large vuggy pores. This cement is found throughout the section, but is more prominent where vuggy porosity is more plentiful and pores are large.

Compared to other Smackover oil fields in Alabama, Little Cedar Creek Field has experienced relatively little dolomitization. Dolomite occurred in two forms: It replaced other carbonates in the framework, and it formed as euhedral rhombs within pore space [Figure 11]. Dolomite replacement increased porosity, but also destroyed original fabrics and textures in the process. Rhomb growth filled in intergranular and vuggy pore space, but produced crystals that were rarely larger than ¼ mm. Neither form of dolomite is particularly prevalent within Little Cedar Creek Field.

Also present to varying degrees are signs of physical and chemical compaction. Stylolites were found in all lithofacies, but are most commonly present within the F-2

packstone lithofacies [Figure 17]. Specifically, they formed best where the packstone grades into or out of muddy sections. Calcite, quartz, and anhydrite grains were found embedded within stylolites. Fractures are also noted within both core and thin sections. Some have been filled in with cement, but many remain open.

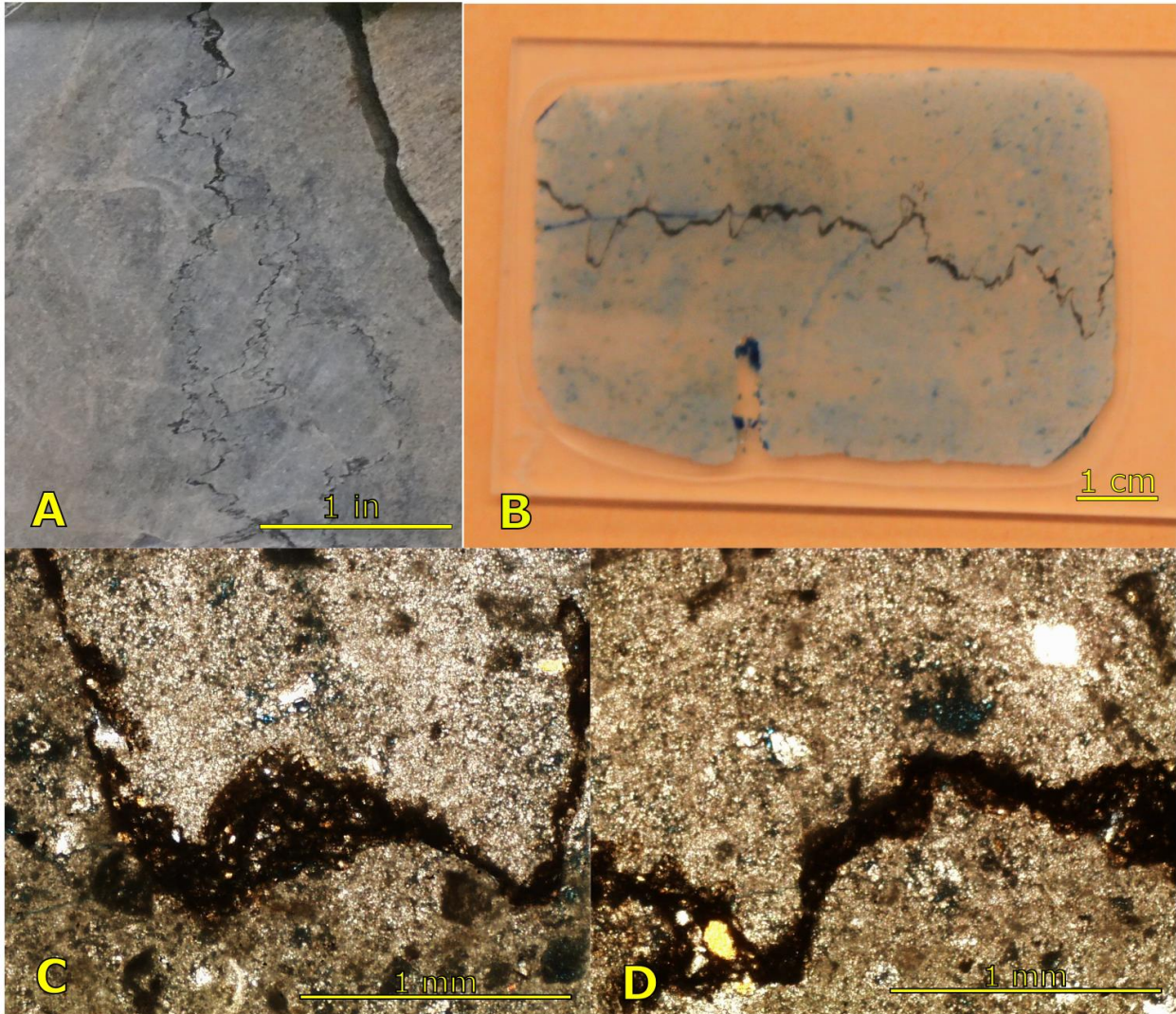


Figure 17: Stylolites: A is a core photo from P15454 at 3405 m (11171 ft) depth. B is a macro image of a thin section with a stylolite running down the middle from P14216 at 3416 m (11208 ft) depth. C and D are petrographic views of the same thin section. Notice the grains within the wider parts of the stylolite in C and D. While most are calcite, the large yellow grain in the lower left corner of D is a quartz grain. Quartz, although rarely identified in the rock, was often found within well-developed stylolites.

CHAPTER 6 DISCUSSION

6.1 Comparison with Other Studies

The lithofacies described previous and the characteristics of them are suggestive of an evolving environment of deposition. Lithofacies grade into other lithofacies based on water depth and associated energy levels. Microbial reefs are patch reefs and during deposition constantly competed with both inorganic and other forms of organic deposition.

It is generally accepted that the Smackover formed on a carbonate ramp (Ahr 1973), but previous investigations of depositional lithofacies has produced a variety of interpretations within Little Cedar Creek. Mancini et. al. (2008) and Heydari and Baria (2005) produced two unique stratigraphic columns and distinct hypotheses on the nature of Smackover deposition at Little Cedar Creek. Mancini et. al. (2008) proposed a full transgression-regression cycle, while Heydari and Baria (2005) proposed a transgression and highstand model. Many new wells have been drilled since the release of these studies and this study attempts to expand upon these models given the new data in the eastern and northeastern regions of the field.

Mancini et. al. (2008) explains the distribution of lithofacies as being deposited during one full transgressive- regressive cycle with the lower lithofacies building through the transgression, and reaching maximum transgression shortly after the microbial reef drowned. As the subsequent regression progressed, the upper nearshore lithofacies swept through the region depositing the upper reservoir just prior to the deposition of the sabkha salts and shales of the Buckner Member of the Haynesville Formation.

In the Mancini et. al. (2008) model, the Little Cedar Creek stratigraphic column is separated into six lithofacies. The transgressive phase is represented (in stratigraphic progression) by a lime mudstone/dolomudstone to wackestone, a clotted peloidal thrombolitic boundstone, a microbially influenced mottled packstone to lime mudstone, and a microstylolitic mudstone. The transition from a transgressive to a regressive phase occurs during deposition of the microstylolitic mudstone. An upper mudstone, peloidal ooid grainstone to wackestone, and lime mudstone and dolomudstone to wackestone comprises the units deposited during the regressive phase. The thrombolite boundstone and the peloid ooid grainstone lithofacies are the reservoirs lithofacies, whereas seal rock lithofacies are comprised of the lower mudstone and dolomudstone, the microstylolitic mudstone, and the upper lime mudstone to dolomudstone.

In contrast, Heydari and Baria (2005) developed a model of only transgression and highstand. In this model, the Smackover reefs never drowned, but kept up with rising sea level. Upon reaching highstand, nearshore lithofacies then prograded the reefs as relative sea level was lowered.

Heydari and Baria (2005) separated the Smackover formation at Little Cedar Creek into seven lithofacies deposited during one transgression-regression cycle (starting with stratigraphically lowest): S-1) laminated peloid wackestone, S-2) bioturbated peloid packstone, S-3) microbial bindstone, S-4) laminated peloid wackestone-packstone, S-5) bioturbated peloid packstone, S-6) peloid-ooid grainstone, and S-7) red and/or green shale, sandstone, and conglomerate. The S-3 and S-6 lithofacies are the lower and upper reservoirs, respectively, while S-1, S-2, S-4, S-5, and S-7 lithofacies are typically low permeability seal rocks.

This study observes similar lithofacies to those classified by Heydari and Baria (2005). This study varies from Heydari and Baria (2005) in the following ways: The S-4 mudstone was not prevalent in the wells examined to the east and northeast. The S-7 siliciclastics are described as Smackover siliciclastics, but this study interprets the siliciclastics above the grainstone lithofacies to belong to the Buckner Member of the Haynesville Formation, with the Smackover grading into the Buckner to varying degrees depending on location. Finally, the S-2 and S-5 packstone lithofacies are thought to be one lithofacies, represented as the F-2 peloidal packstone lithofacies here.

This study interprets that the Smackover represents an entire transgressive-regressive sequence. It has two reservoir lithofacies, and seal rock lithofacies above and below each reservoir. The first lithofacies within the Smackover is a lime mudstone that unconformably deposited upon the low-lying areas of the Norphlet post-exposure. Stratigraphically above the lime mud is a peloidal packstone. The packstone lithofacies also contains numerous peloids, ostracods, benthic foraminifera, and bivalve fragments. This packstone lithofacies grades into a nearshore grainstone lithofacies, which is the upper reservoir. The upper reservoir lithofacies is characterized as a fossiliferous, peloidal, and ooid grainstone to packstone. Finally, the grainstone lithofacies graded into tidal flat salts and shales of the Haynesville Formation.

Intermittent through all lithofacies but especially the packstone, thrombolite patch reefs developed. Where the thrombolites developed significant thickness (on the order of feet to tens of feet), it creates the lower reservoir. The thrombolite reefs must outcompete deposition of the packstone lithofacies to achieve noticeable thickness. The reef must remain within the photic zone, and may occasionally drown out if it cannot

keep up with rising sea level. This occurred most often within the western region of the field. When the reef does drown out, it is often covered by a dense lime mudstone that is microstylolitic and can provide the seal for the top of the lower reservoir.

6.2 Sequence of Deposition

The Smackover is described as a carbonate ramp (Ahr 1973, Baria et. al. 1982, Mancini et. al. 2004). Characteristics of a carbonate ramp (as described by Ahr 1973) include:

1. Facies belts that parallel the shoreline
2. Progression of pelagic muds in the deepest parts and grading into grainstone near shore
3. Monotonous wedge-shaped deposits that thicken seaward
4. An absence of continuous reef trends. Instead, patch reefs are present locally.

These characteristics are present within the Smackover of Little Cedar Creek, with the facies belts shifting in response to relative sea level.

Norphlet exposure was followed by a fast transgression of the ocean, as evidenced by the sharp contact between the Norphlet and Smackover, as well as the first lithofacies of the Smackover being F-1 lime mud. The lime mud is interpreted as being low energy deep water facies.

The lime mudstone grades into the F-2 peloidal packstone. This packstone is rich in allochems and pellets. Evidence of microbial activity is fairly abundant. Microbial activity includes micritic envelopes, microbially bound grains, and rare grapestones.

The F-3 microbial patch reefs develop within the packstone lithofacies. The packstone and bindstone lithofacies occur in the same approximate water depth along

the ramp, and deposited at the same time. The microbial reef occasionally out-competes the packstone in the volume of deposition, leading to a distinct bindstone lithofacies in core. This happens to a much larger degree in the western region of the field than to the east. The east and northeast regions of the field often see interfingering of bindstone and packstone as opposed to tens of feet of microbial reef bounded above and below by packstone.

Occasionally, a reef may not develop or deposit quickly enough and drown. In this case, the F-4 laminated mudstone may develop over the drowned reef. This is most likely a condensed section of pelagic mud settling out of the water column. Although Heydari and Baria (2005) and Mancini et. al. (2008) often describe a mudstone lithofacies on top of the bindstone as multiple feet thick, in the eastern and northeastern regions of the field it is very thin (< 3 cm) or nonexistent.

Eventually, the transgression and highstand ends and relative sea level begins to regress slowly. Laminated mudstone lithofacies, if present, begin to progress back into a shallower lithofacies of peloidal packstone. Shell fragments and *Favreina* sp. pellets become more common, as well as foraminifera and rarely gastropods. The increase in metazoan life towards the top of the column suggests a possible return to near standard seawater chemistry.

As the regression continued, nearshore F-5 ooid-peloid grainstone lithofacies swept through the region from the north, leading the regression. This unit is fairly regional, and occasionally mixed with microbial lithofacies. As the regression continued, the region regressed into a sabkha, depositing salts, shales, and nearshore sandstone deposits that are the overlying Haynesville Formation.

6.3 Variance on Lithofacies

Nearly all lithofacies have some degree of microbial influence, and the Smackover at Little Cedar Creek contains a microbial patch reef (Heydari and Baria 2005). The wells on the western side of the field have well defined porosity and permeability signatures that Heydari and Baria (2005) used to help define their stratigraphic column. In the decade since that writing, the field has been expanded to the east and northeast. In these newer wells, the earlier lithofacies classifications and density signatures begin to break down and often seem to blend together. The F-3 bindstone lithofacies becomes less of a multiple feet thick unit, and instead interfingers within the F-2 packstone lithofacies.

The F-4 laminated mudstone is not observed in any wells in the eastern or northeastern regions of the field, although very thin units of dark mudstone are occasionally found interspersed within the upper Smackover. These units never exceed five centimeters thick, far less than the multiple feet of laminated mud described in the western part of the field. No direct correlation can be made between these thin black units and the F-4 laminated mudstone.

The reason for such variance across the field is due in part to the elevation of the Norphlet at the time of transgression. The field is located near the opening of the Conecuh Subbasin, and the western region of the field is furthest from the stratigraphic updip limit of the Smackover [Figure 1]. The western region of the field is deeper within the basin and most likely was lower than the eastern and northeastern regions of the field.

Because of the elevation variation, the fast transgression did not impact the field equally. The western region of the field would have been inundated much sooner than the eastern and northeastern regions of the field. A reef's ability to stay within the photic zone is paramount to its continued survival and growth. If the reef cannot keep up with rising sea level, it leaves the photic zone and drowns (Parcell 1999). The western reaches of the field would be more likely to drown out due to an extended transgression. Being deeper, that portion of the field that drowned would then develop pelagic mud settling out of suspension more than pellets and foraminifera. Between the buildup of mud and a slow regression, the environment would transition back into the F-4 packstone, but would most likely have far less microbial influence barring an invasion from a nearby microbial mound. This explains why the western region described by Heydari and Baria (2005) and Mancini et. al. (2008) have much thicker mudstone deposits overlying the microbial bindstone reef than what is observed in the east and northeast.

The eastern parts of the field would not have experienced the full transgression due to it being topographically higher. The reef would therefore never be in as deep of water as the western region, and would be far more likely to keep up with the remaining transgression. If the reef did drown, it would be near the highstand, and very little pelagic mud would be able to develop before the subsequent regression.

The northeastern region of the field is much higher than the rest of the field, and would avoid the early part of the transgression entirely. There is no deep water mudstone associated with the F-3 bindstone lithofacies in the northeastern region of the

field because that portion of the field never reached such depths after entering the zone of packstone deposition.

Although Heydari and Baria (2005) describe two packstone lithofacies and the bindstone lithofacies as separated into three distinct units, it is probable that they are part of the same depositional episode. The upper and lower packstone lithofacies are in fact one unit, representing an extended period of deposition. The microbial reef simply out-deposited the packstone occasionally, leading to a distinct bindstone lithofacies. Numerous pellets are found both around and within the microbial clumps of the bindstone lithofacies, suggesting that the microbial reef was building into and on top of the packstone lithofacies, essentially sharing the same water depth zone on the ramp.

6.4 Diagenetic Alteration

Reservoir quality within Smackover oil fields is often greater affected by depositional fabrics and facies than due to diagenetic overprint. Still, secondary effects do play a role in the final reservoir quality. Although Little Cedar Creek Field is better preserved than almost any other Smackover oil field, it has still experienced significant alterations to the originally deposited fabrics and textures.

The first alteration was the formation of fibrous calcite cement. This was exclusively a marine phase of cementation (Tonietto and Pope 2013). It was followed by the calcite rind cement, which is a marine and earliest burial cement. Next was the first of two phases of mosaic calcite growth. The first phase of mosaic calcite is a purely early burial phase (Tonietto and Pope 2013).

After the conclusion of mosaic calcite, physical and chemical compaction began (Tonietto and Pope 2013). Fractures are noted in a number of thin sections,

occasionally filled in with cement. Stylolites were noted at all depths and in all lithofacies.

Late in the sequence is burial dissolution. This phase penetrated many of the original grains. It is what created the moldic porosity within the ooids and grapestones in the grainstone lithofacies, as well as formed much of the pore space within microbially bound grains in the bindstone lithofacies. It is also probable to be the cause of vuggy pore formation. The end of the dissolution phase overlaps with the beginning of the dolomite growth and replacement phase (Tonietto and Pope 2013). Dolomite replacement, where present, aided in dissolution of the previously deposited rock. Dolomite rhomb formation also occurred at this time, but reduced porosity instead. The final major phase of alteration is the second phase of mosaic calcite. This phase seems to have similar properties and effects to the first phase, but is noted as being later by the inclusion of dolomite rhombs in a few of the grains.

The Buckner Member of the Haynesville Formation typically contains an anhydrite unit believed to be part of a tidal flat deposit. Because of the placement of the field within the basin, the Buckner at Little Cedar Creek Field is more of a continuous limestone (Getz 2012). The anhydrite beds of the Buckner Member are considered to be the source of the magnesium for brine reflux that created the intense dolomitization found at other Smackover oil fields. This brine reflux is also thought to be reason for oomoldic pores to be occluded with dolomite and anhydrite in other fields (Benson and Mancini 1999). The overlying Buckner Member being composed of limestone as opposed to anhydrite at Little Cedar Creek may be reason why the field has escaped such destructive alteration (Getz 2012).

CHAPTER 7 CONCLUSION

Among Smackover reservoirs in southwest Alabama, Little Cedar Creek Field provides a unique depositional setting. Although it produces out of microbial reef lithofacies similar to nearby fields such as Appleton and Vocation, the reefs at Little Cedar Creek developed on soft sediment close to the paleoshoreline as opposed to directly upon paleo highs further out in the basin. This study recognizes five lithofacies in the Smackover Formation: a lower laminated mudstone, a peloidal packstone, a microbial bindstone, a laminated mudstone, and an ooid grainstone.

Previous studies by Mancini et. al. (2008) and Heydari and Baria (2005) have focused on interpreting the environmental conditions that formed and characterized these carbonate lithofacies. Since these studies were conducted, the field has expanded considerably to the east and northeast. This study includes data from these new regions.

The Smackover Formation at Little Cedar Creek Field developed on a fairly proto-typical carbonate ramp, one with gradational zones of carbonate lithofacies with deep water mudstone in the basin and grainstone closer to shore. The facies parallel the shoreline and migrate with rising or falling relative sea level. These facies are locally disrupted by microbial patch reefs that occasionally grow upwards tens of feet thick, but which usually are on the scale of inches to a few feet thick.

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