Comparing The Depositional Environments Of The Upper Smackover Formation In Southwestern Clarke County, Mississippi And Brooklyn/ Little Cedar Creek Field, Alabama

Elsie Ekene Okoye
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COMPARING THE DEPOSITIONAL ENVIRONMENT OF THE UPPER SMACKOVER FORMATION IN SOUTHWESTERN CLARKE COUNTY, MISSISSIPPI AND BROOKLYN/LITTLE CEDAR CREEK FIELD, ALABAMA

A Thesis
presented in partial fulfillment of requirements
for the degree of Master of Science
in the Department of Geology and Geological Engineering
The University of Mississippi

by

ELSIE E. OKOYE

August 2017
ABSTRACT

This research evaluated the depositional settings of the upper Smackover Formation in southwestern Clarke County (SCC), Mississippi and compared its facies to those of the Brooklyn and Little Cedar Creek Fields (BF/LCC) in Conecuh and Escambia Counties, Alabama. The Smackover Formation has been a prolific oil producing formation in the Gulf of Mexico since its discovery in Union County, Arkansas in 1937. The discovery of the LCC in 1994 and the BF in 2007 has generated additional interest in the Smackover. The BF/ LCC occur near the updip limit of the Upper Jurassic (Oxfordian) Smackover Formation. These fields produce from oolitic/oolmoldic stratigraphically trapped reservoirs in the upper Smackover Formation. In SCC, the Smackover extends farther updip than in the BF/LCC. SCC also has several small oil fields that have produced from the Smackover Formation since 1976. This research used resistivity well logs and core analyses of SCC fields and selected four fields with the most oolites and therefore, the highest potential for similarity to production in the BF/LCC. The resistivity logs and core analyses of these four fields were used to construct structure contour maps and cross-sections for each field, illustrating the Smackover facies in the region. Higher resolution resistivity logs and core analyses from the BF/LCC were also used to construct cross sections of that area. Lithofacies and logfacies were defined for the research and used to compare the BF/LCC and SCC. Interpretation of the cross sections and maps showed that the BF/LCC and SCC have similar depositional settings and also similar lithofacies/depositional sequence. The difference between the study areas are: a lack of mudstones lithofacies in the BF/LCC; differences in thickness of the upper Smackover and; differences in logfacies. The BF/LCC and SCC have
substantial similarities in their depositional environment and sequence with the East Nancy field in SCC showing the most similarities to the BF/LCC.
DEDICATION

I thank God for His grace and favor in completing this thesis. I am thankful for the love and support of my friends, family and the geology and geological engineering department at Ole Miss. In particular, I want to thank my sisters and my dear friend, Imran, for being there for me and encouraging me through the entire process. This is dedicated to you all.
LIST OF ABBREVIATIONS AND SYMBOLS

BF/LCC- Brooklyn and Little Cedar Creek Fields

SCC- Southwestern Clarke County

Wackestone- lithology dominated by dense and vuggy limestone

Grainstone- lithology dominated by oolitic and oomolodic limestone

Mudstone- lithology dominated by dolomite or dolo- limestone
ACKNOWLEDGMENTS

My deepest appreciation goes to my advisor, Dr. Greg Easson, for working hard to find data for my research both from academic contacts and from the dusty storage rooms on Jackson avenue. Thank you to my committee members, Dr. Zachos and Dr. Platt for your great inputs, suggestions and help with engineering formatting and ArcGIS. Thank you to the Department of Geology and Geological Engineering for countless financial support opportunities and friendly words of encouragement.

In addition, I thank Dr. Larry Baria from Jurasearch for his generous supply of Little Cedar Creek/ Brooklyn Fields logs and core.

Lastly, I acknowledge my fellow graduate students for their quirks and smiles. This thesis couldn't have been the same without you.
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................. ii-iii
DEDICATION.............................................................................................................. iv
LIST OF ABBREVIATIONS AND SYMBOLS.............................................................. v
ACKNOWLEDGMENTS.............................................................................................. vi
LIST OF TABLES........................................................................................................ viii
LIST OF FIGURES...................................................................................................... ix- xi
INTRODUCTION....................................................................................................... 1-3
LITERATURE REVIEW/ BACKGROUND.................................................................... 4-14
METHODOLOGY....................................................................................................... 15-41
RESULTS/ DISCUSSION .......................................................................................... 42-52
CONCLUSION.......................................................................................................... 53-54
REFERENCES......................................................................................................... 55-60
APPENDIX............................................................................................................... 61-68
VITA......................................................................................................................... 69
LIST OF TABLES

1. The Smackover lithofacies in the Little Cedar Creek field and their accompanying descriptions................................................................. 13

2. The West Nancy field well information, southwestern Clarke County, MS .......... 22-23

3. The Nancy field well information, southwestern Clarke County, MS .................. 23

4. The East Nancy field well information, southwestern Clarke County, MS ............ 23

5. The Watts Creek field well information, southwestern Clarke County, MS .......... 23-24

APPENDIX A

Example Southwester Clarke County Well Data ................................................................. 63
LIST OF FIGURES

1. Map of Alabama and Mississippi showing the updip limit of Smackover Formation intersecting Conecuh and Escambia Counties, Alabama and Clarke County, Mississippi.............................................................................................................. 2

2. Jurassic stratigraphy of the northern Gulf of Mexico and map of Clarke County, MS showing oil production with prevalent Smackover production in the southwest. Map adapted from Champlin (2000) ......................................................... 3

3. Map of the Gulf of Mexico showing major structural features. Map adapted from Garrison and Martin (1973) ........................................................................................................................................................................ 6

4. Map of the basins and embayments of the northern Gulf of Mexico .................. 10

5. Cross section lines in Brooklyn and Little Cedar Creek Fields............................ 18

6. Brooklyn/ Little Cedar Creek Field cross section from 16663(W)-16606(E) ....... 19

7. Brooklyn/ Little Cedar Creek Field cross section from 16708(N) - 16727(S) ....... 20

8. Brooklyn/ Little Cedar Creek Field cross section from 16748-B(N) - 16827(S) .... 21

9. Structure contour map of the top of the upper Smackover Formation in southwestern Clarke County, MS ................................................................. 27

10. Structure contour map of the top of the Brown Dense/ lower Smackover Formation in southwestern Clarke County, MS ................................................. 28

11. Structure contour map of the top of the Norphlet Formation in southwestern Clarke County, MS .................................................................................. 29
12. Isopach of the upper Smackover Formation in southwestern Clarke County, MS showing regions of paleohighs concordant with the oil fields selected for cross sections ................................................................. 30

13. Cross section lines in the Smackover producing fields, southwestern Clarke County, MS ................................................................. 31

14. Cross section line A-B in the West Nancy field, southwestern Clarke County, MS ................................................................. 32

15. Cross section A(N) – B(S) in the West Nancy field, southwestern Clarke County, MS ................................................................. 33

16. Cross section line C-D in the Nancy field, southwestern Clarke County, MS .... 34

17. Cross section C(N) - D(S) in the Nancy field, southwestern Clarke County, MS ................................................................. 35

18. Cross section line E-F in the East Nancy field, southwestern Clarke County, MS ................................................................. 36

19. Cross section E(N) - F(S) in the East Nancy field, southwestern Clarke County, MS ................................................................. 37

20. Cross section line G-H in the Watts Creek field, southwestern Clarke County, MS ................................................................. 38

21. Cross section G(N) - H(S) in the Watts Creek field, southwestern Clarke County, MS ................................................................. 39

22. Prototype log of well API 2302320183 in the West Nancy field showing the
lithofacies in the upper Smackover formation, southwestern Clarke County, MS ................................................................. 40

23. Comparing logfacies from well API 2302320183 in the West Nancy Field, southwestern Clarke County, MS and well permit number 16827 in the Brooklyn/Little Cedar Creek Field, AL ................................................................. 41

24. Structure contour map of the top of the upper Smackover Formation showing the outline of selected fields in southwestern Clarke County, MS ........................................... 44

25. Structure contour map of the top of the Brown Dense/ lower Smackover Formation showing the outline of selected fields in southwestern Clarke County, MS ............. 45

26. Structure contour map of the top of the Norphlet Formation showing the outline of selected fields in southwestern Clarke County, MS ...................................................... 46

APPENDIX B

Example Scoutcard of well 2302320554................................................................. 65

Example Core Analysis of well 2302320712............................................................. 66

Example Smackover Formation section in Oxley log of well 230232020............. 67

Grainstone Lithofacies description in SCC, using (a) The Smackover section of Oxley log for well 2302320183, compared to the BF/LCC, using (b) Core analysis report for well permit 16827 ................................................................. 68
INTRODUCTION

This research evaluated the depositional setting of the upper Smackover Formation in southwestern Clarke County (SCC), Mississippi and compared its facies to those of the Brooklyn and Little Cedar Creek Fields (BF/LCC) in Conecuh and Escambia Counties, Alabama. The Smackover of SCC is poorly studied compared to the well-researched Smackover of the BF/LCC. However, both of these two study areas lie near the updip limit of the Smackover Formation making for potential similarities in their depositional settings (Figure 1).

The Smackover Formation has been a prolific oil producing formation in the Gulf of Mexico since its discovery in Union County, Arkansas in 1937 (Philips, 2013). The discovery of the LCC in 1994 and the BF in 2007 has generated additional interest in the Smackover (Mancini et al., 1992). The BF/LCC produces from oolitic/oolmoldic stratigraphic trapped reservoirs in the upper member of the Jurassic (Oxfordian) Smackover Formation (Mancini et al., 1992). In southwestern Clarke County, there are several small oil fields that produce from the Smackover Formation (Galicki, 1986) (Figure 2). This research examined and correlated archival well logs and core analyses, to construct a series of maps and cross-sections that illustrate the upper Smackover facies in the regions so as to compare the depositional settings in southern Alabama with those of southern Clarke County, Mississippi.
Figure 1: Map of Alabama and Mississippi showing the updip limit of Smackover Formation intersecting Conecuh and Escambia Counties, Alabama and Clarke County, Mississippi.
Figure 2: Jurassic stratigraphy of the northern Gulf of Mexico and map of Clarke County, MS showing oil production with prevalent Smackover production in the southwest. Map adapted from Champlin (2000)
Geologic History of the Gulf of Mexico

The Gulf of Mexico is a divergent margin which covers an area of about 1.5 million square kilometers and opens to the Atlantic Ocean and Caribbean Sea (Mancini et al., 2005; Meyerhoff, 1967; Wilhelm and Ewing, 1972). To the southeast, the Gulf of Mexico is confined into two narrow passages: the Straits of Florida and the Yucatan Channel (Figure 3). The Gulf of Mexico is theorized to have formed within the Pennsylvanian-Permian (Garrison and Martin, 1973; Murray, 1966; Halbouty, 1967; Kirkland and Gerhard, 1971).

Mesozoic-Paleogene Geologic History of the Northern Gulf of Mexico

The northern continental margin of the Gulf of Mexico is marked by the Texas, Louisiana and Mississippi state lines (Figure 3). In the Early to Late Jurassic, thick beds of salt were precipitated in shallow basins around the gulf margins (Murray, 1966; Halbouty, 1967; Kirkland and Gerhard, 1971). These Jurassic salt structures are restricted to the northern gulf area by growth faults which cause the distortion and uplift of the structures.

In the Early Cretaceous, organic reefs grew and flourished in the northwestern regions of the gulf (Garrison and Martin, 1973). At the end of the Mesozoic, the Gulf of Mexico basin
subsided while sedimentation continued filling the northern part of the gulf and overwhelming the northern reefs. In the Paleogene, clastic terrigenous material from the coastal plains prograded south into the basin (Hardin, 1962).

The Gulf of Mexico considerably reduced in size at the end of the Cretaceous Period due to an influx of terrigenous sediments in its northern sector. During this northern sediment deposition, the Florida and Yucatan confining platforms continued their upward growth, in pace with the thermal subsidence in the rest of the Gulf, and maintained their tops near sea level. The gulf’s continental margin has therefore been divided into two geological provinces: shallow carbonate banks in the southeastern region and terrigenous embayments in the northwestern region.
Figure 3: Map of the Gulf of Mexico showing major structural features. Map adapted from Garrison and Martin (1973).
Jurassic Geologic History and Stratigraphy of the Gulf of Mexico

The Jurassic age lithostratigraphic units of the Gulf of Mexico include the Louann Salt, the Norphlet, the Smackover, the Buckner and the Haynesville Formations as well as the Cotton Valley Group (Figure 2). These units make up a mega-sequence bounded by a basal tectonic breakup unconformity and on top by the Prominentintra- Valanginian unconformity— the record of termination of seafloor spreading in the Gulf (Dobson and Buffler, 1997; Galloway, 2008; Marton and Buffler, 1999; Salvador, 1991b; Todd and Mitchum, 1977; Winker and Buffler, 1988, Wu et al., 1990).

In the Early Jurassic, initial subsidence in the Gulf formed a shallow basin that was followed by the deposition of nearly pure halite of the Louann Salt (Galloway, 2008). The Louann Salt deposits reached as far as the northern and southern margins of the Gulf.

In the Oxfordian, Louann salt deposition was replaced by deposition of the Norphlet Formation (Salvador, 1991a). The Norphlet is a siliciclastic sequence that was deposited disconformably above the Louann as a relatively thin, widespread bed. In the northeastern Gulf margin, the Norphlet deposition was thicker, up to 300 feet, because of the alluvial fan and delta systems that created local depocenters for the transgressing deposits (Galloway, 2008). The Norphlet deposition coincided with a period of aridity as is evident from eolian sabkha and playa deposits.

Oxfordian transgression onto the Gulf margin continued with the deposition of the Smackover, the Buckner, and the Haynesville formations, the first carbonate- dominated depositional episode in the Gulf of Mexico. They are bounded by underlying and overlying transgressive flood surfaces (Galloway, 2008; Mancini and Puckett, 2005; Salvador, 1991b).
These formations were deposited as dark, fine-grained, carbonate ramp sediments overlain by ramp-edge grain shoals that formed broad shoal systems around the northwest part of the Gulf of Mexico.

Deposition of the Cotton Valley Formation, in the Late Jurassic, came as an abrupt override of the transgressive episode of the Haynesville (Salvador, 1991b). In the northern Gulf, the overriding change from carbonates of the Haynesville to the siliciclastics of the Cotton Valley indicates continental uplift and climate change.

**Depositional History of the Smackover Formation in the Gulf of Mexico**

The Smackover Formation is a carbonate facies that dips about 1 degree to the south and southwest. It grades laterally into an evaporite facies in parts of the Mississippi Interior Salt Basin and is dissected by extensional faults and grabens in the northern Gulf of Mexico. The Smackover lies between the Norphlet Formation and the Haynesville Formation and was deposited on a ramp surface during the major Jurassic marine transgression in the Gulf (Mancini et al., 2005). Deposition during this transgression resulted in thermal subsidence due to crustal cooling. The Smackover consists of laminated and microbial lime mudstone, peloidal wackestone and packstone, microbial boundstone, ooids, oncoidal packstone, and grainstone interbedded with lime mudstone and is unofficially divided into upper, middle and lower regions (Mancini et al., 2005).

The lower Smackover is commonly called the Brown Dense Limestone. It is an important petroleum source rock in the Mississippi Interior Salt Basin. The Brown Dense was deposited in a deep-shelf environment and is a uniform limestone composed of organic-rich mudstone with regions of porosity in the form of sandstone lenses, carbonate porosity, and fractures (Philips,
The Brown Dense is the source of oil and gas for the Upper and Middle Smackover as well as the underlying Norphlet Sandstone.

The middle Smackover consists of sandstones and sandy limestone with deposition related to the ancient Mississippi River (Ridgway, 2010). It also grades upward from lateral sabkhas, ooid grainstones, peloids, thrombolitic boundstones, to algal boundstones.

The upper Smackover accumulated on a shallow oceanic ramp with varying bottom agitations. It grades upward from algal lateral sabkhas, ooid grainstones, peloids, thrombolitic boundstones, to algal boundstones (Philips, 2013). The Upper Smackover’s algal facies are recognized for having good porosity and inter-dolomite-rhomb-permeability when dolomitized.

**Smackover in Eastern Mississippi and Southwestern Alabama**

The Smackover in eastern Mississippi and southwestern Alabama is defined by Paleozoic ridges and Mesozoic horst blocks which separate the area into a series of embayments with different lithologies and porosity types (Benson, 1988). The principal paleo-highs influencing the Smackover deposition in the area are the: Choctaw Ridge, Conecuh Ridge, Wiggins Arch and Baldwin high. These highs separate the Mississippi Interior Salt Basin, The Manila Embayment and the Conecuh Embayment (Figure 4).
Smackover in Eastern Mississippi

Eastern Mississippi falls within the Mississippi Interior Salt Basin, an area that had an overall low-energy subtidal setting during deposition of the Smackover Formation. The lower Smackover is characterized by laminated mudstones that grade into shoaling upward cycles of peloidal wackestone/packstones, laminated mudstone and partially dolomitized oolitic grainstone deposited in a high-energy shoal environment (Mancini and Benson, 1984). The greatest porosity in the Mississippi Interior Salt Basin is secondary porosity in oolitic grainstones of the Smackover Formation (Mancini and Benson, 1984).
Smackover Oil Fields of Clarke County, Eastern Mississippi

Clarke County is located in southeastern Mississippi along the northeast flank of the Mississippi Interior Salt Basin. In Clarke County, the Smackover Formation extends farther updip than anywhere else in Mississippi and southwestern Alabama (Badon, 1973; Dickinson, 1962). Clarke County is dotted with small fields producing from the Smackover with its greatest abundance of fields in the southwestern part of the county (Figure 2). The Smackover deposition however has not been extensively studied in Clarke County. In Clarke County, Smackover producing oil fields include the: Addie Mae, Mike Creek, Sumrall, Harmony South, Garland Creek, Stage Coach Road, Fluffer Creek, Pachuta Creek, Nancy West, Nancy East, Nancy, Goodwater, Prairie Branch, Turkey Creek, Harmony, Shubuta, Barnett, Watts Creek and Shubuta North fields.

In southwestern Clarke County, the lower smackover is composed of tan silty limestone with oolitic and anhydrite lenses (Dickinson, 1962). The middle Smackover is defined by a conglomerate and siltstone unit. The upper Smackover is made up of gray dense limestone with an anhydrite lens near the middle and oolitic and silty intervals.

Smackover in Southwestern Alabama

The BF/LCC study area in southwestern Alabama lies within the Conecuh Embayment. In this embayment, the Smackover was deposited in a low energy setting. The lower Smackover is composed of dolomitized peloidal wackestone interbedded with laminated mudstone. The middle Smackover grades into dark laminated mudstones and the upper Smackover is characterized by peloidal wackestones and packstones (Mancini and Benson, 1984). Dolomitized ooid grainstones are found locally on paleohighs in the upper Smackover. These dolomitized
upper Smackover deposits show the greatest porosity in the form of secondary porosity including vuggy and moldic properties. Shoal-water grainstone deposits are absent in much of the Conecuh Embayment (Mancini and Benson, 1984).

**Brooklyn and Little Cedar Creek Fields**

The Little Cedar Creek field is a Smackover producing oil field located in southwestern Alabama, in the onshore area of the northeastern Gulf of Mexico. The Brooklyn field is a Smackover producing oil field located three miles south of the LCC. The Smackover oil reservoirs for the LCC and the BF are considered separate due to their differences in reservoir pressure. These oil fields are characterized by stratigraphic hydrocarbon traps controlled primarily by changes in depositional facies. They lie near the updip limit of the Smackover Formation in southeastern Conecuh and northern Escambia Counties, Alabama.

The Little Cedar Creek field was discovered in 1994 when Hunt Oil Company drilled a discovery well, with a total depth of 12,100 feet and was completed in the Upper Jurassic Smackover Formation as an oil producer (Ridgway, 2010 and Haddad, 2012). The initial flow rate of the field was 108 barrels of oil per day, however, as of May 2012, 12,500,000 barrels of oil have been produced from over 120 wells in the field (Haddad and Mancini, 2013; Haddad, 2012).

The Brooklyn field was discovered in 2007 by Sklar Exploration Company, LLC, which drilled just off the limit of the Little Cedar Creek field (Day, 2011). Initial production from the first well was averaged at 8 barrels of oil per day (Day, 2011). The third well drilled was three miles south of the LCC and showed significantly higher pressure, establishing the BF at initial testing of 531 barrels of oil per day (Day, 2011). In August 2013, a reported 53 producing wells
in the BF and a combined total of over 31.5 million barrels of oil was produced from both the LCC and the BF (Day, 2011).

The oil producing stratigraphy of the BF/LCC consists of three formations: the Haynesville, the Smackover, and the Norphlet Formations. The Norphlet is conglomeratic and consists of igneous and metamorphic clasts in a sandstone matrix. The Oxfordian Smackover disconformably overlies the Norphlet Formation and is conformably overlain by the Buckner Anhydrite. The Buckner Anhydrite is characterized by massive anhydrites with crystalline dolomite. The crystalline nature of the Buckner makes it a good hydrocarbon seal. The Kimmeridgian Haynesville overlies the Buckner and is composed of carbonates interbedded with shales and anhydrites.

The petroleum system at the LCC consists of seven distinct lithofacies in the Smackover, two of which are proven reservoirs. The seven lithofacies annotated by Mancini et al. (2008) are:

<table>
<thead>
<tr>
<th>Smackover Lithofacies (SL)</th>
<th>Description (role in LCC petroleum system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>lime mudstone-dolomudstone- wackestone (seal)</td>
</tr>
<tr>
<td>2</td>
<td>conglomeratic floatstone-rudstone</td>
</tr>
<tr>
<td>3</td>
<td>grainstone-packstone (reservoir)</td>
</tr>
<tr>
<td>4</td>
<td>lime wackestone-mudstone (seal)</td>
</tr>
<tr>
<td>5</td>
<td>microbially-influenced packstone-wackestone</td>
</tr>
<tr>
<td>6</td>
<td>thrombolite boundstone (reservoir)</td>
</tr>
<tr>
<td>7</td>
<td>lime mudstone-dolomudstone (seal)</td>
</tr>
</tbody>
</table>

Table 1: The Smackover lithofacies in the Little Cedar Creek field and their accompanying descriptions
The Smackover at the LCC lacks structural closure and all of its reservoirs are confined by stratigraphic traps. The SL-3 and SL-6 lithologies are the proven reservoirs and make the LCC a dual-reservoir petroleum system (Ridgway, 2010). These reservoirs are microbial and have void and vuggy pore types developed during deposition and by diagenetic solution enhancement. These pores make the reservoirs very permeable and therefore, very productive. SL-3 however, has vuggy and grain moldic pore types which makes it less permeable and therefore, less productive than SL-6. SL-3 and SL-6 are separated by a low permeability layer. The Smackover at the LCC also has its original depositional fabric preserved by lack of dolomitization.

SL-5 and SL-7 serve as the formation source made of algal and amorphous kerogen. These two lithofacies have a thermal history favorable for generation and preservation of hydrocarbons.
METHODOLOGY

The purpose of this research is to evaluate the depositional settings of the upper Smackover Formation in SCC, Mississippi and to compare it to the BF/LCC in Conecuh and Escambia Counties, Alabama. To accomplish this goal, a series of maps and cross sections were developed (Figures 5-21 and 24-26). These maps include structure contour maps of the top of the Smackover, top of the Brown Dense and top of the Norphlet Formations as well as an isopach map of the upper Smackover. Geologic cross sections for fields in SCC were developed by correlating well logs and core analyses. These cross sections were then compared to cross sections in the BF/LCC to determine their similarities in log signature and order of lithofacies.

Data

Well data for 204 wells in SCC and 122 wells in the BF/LCC were collected and compiled into an ArcGIS database. Well data from SCC were collected from the Mississippi Oil and Gas Board and the Mississippi Mineral Resources Institute. Well data in the BF/LCC were collected from the State Oil and Gas Board of Alabama. Data collected includes: longitude, latitude, API numbers, permit numbers, well names, well types, operator names, field names, resistivity logs, lithologic logs, scoutcards, core analysis reports available, Oxley lithologic logs,
township, range, section, top of the upper Smackover, top of the Brown Dense/lower Smackover and top of the Norphlet (Appendix A and B).

Southwestern Clarke County

In SCC, fifteen of the wells collected were used to develop four cross sections within four of the fields present in SCC. The primary data used were resistivity logs, Oxley lithologic logs and core analysis reports. The resistivity logs used included: normal and laterolog deep, medium and shallow induction resistivity logs. Resistivity logs measure the electric resistance of a formation. Laterologs are more accurate in higher resistivity formations and normal induction logs are more accurate in low-medium induction formations (Doll, 1949). Laterologs have a finer vertical resolution than normal induction logs, with a vertical resolution of approximately 3 feet while a normal induction resistivity log can have a maximum vertical resolution of about 6 feet (Crain, 2015). Resistivity logs also give information on hydrocarbon presences in a well by showing a high resistivity reading for the deep log curve as well as separation between the deep and medium log curves (Schroeder, 2004). Separation between the deep and medium log curves means the formation fluid present in a well is different from the drilling fluid (Schroeder, 2004). Depending on the type of drilling fluid used (such as oil based or water based), the formation fluid can then be confirmed as a hydrocarbon.

Oxley lithologic logs were used to define SCC lithologies. The logs, developed from drill cuttings, showed lithologic symbols and corresponding detailed lithologic descriptions from the top of the Cotton Valley formation to the Norphlet within SCC. In Appendix B, the Smackover section in Oxley log for well API 2302320206 is shown. The log defines the Smackover in the well in two sections of hundred-foot intervals and one fifty-foot interval. The log descriptions
included: oolitic limestone, faint oil stains, slight sandy limestone, sparse anhydrite, dolomite, and calcarenitic limestone.

The core analysis reports in SCC were mostly from side-wall cores and so, defined short sections within the Smackover. In Appendix B, the example core analysis report for well API 2302320712 provides lithology for a 26 foot section of the Smackover in the well however; there are about 900 feet of Smackover recorded by the resistivity log of this well (Figure 17). Core analysis reports gave generalized lithologic information including: vuggy limestone, dense limestone, oolitic limestone, and dolomite (Appendix B).

**The Brooklyn/ Little Cedar Creek Fields**

In the BF/LCC, eleven of the wells collected were selected and used to develop three cross sections in north-south and west-east directions across the fields (Figures 5-8). The data used in the BF/LCC was with the primary objective of comparison to SCC; as such the type of logs available in SCC determined what was used in the BF/LCC. The logs used were resistivity logs including array induction logs. Array induction logs use several resistivity induction coils to account for different depths of investigation (Crain, 2015). Array induction logs are the newest contribution to resistivity logging, as such they have high vertical resolutions of four feet, two feet, and one foot, each with six depths of investigation including: 10, 20, 30, 60, 90, and 120 inches (Crain, 2015). Lithologic logs and core analysis reports were readily available in the BF/LCC and used to define the lithology in each well.
Figure 5: Cross section lines in Brooklyn and Little Cedar Creek Field
**Figure 6:** Brooklyn/ Little Cedar Creek Field cross section from 16663 (W) - 16606 (E)
Figure 7: Brooklyn/ Little Cedar Creek Field cross section from 16708(N) - 16727(S)
The mode of correlation in this research was by using lithofacies and logfacies. The lithofacies were defined by condensing lithology collected from core analyses and lithologic logs (Appendix B). Condensing of lithology involved disregarding thin interbedded changes in lithology and using the dominant lithology to group sections of the Smackover as modified: wackestones, grainstones, and mudstones. Dominantly dense and vuggy limestone sections were the wackestones. The mainly oolitic and oomolodic limestone sections were the grainstones and...
The dolomite or dolo-limestone sections were the mudstones. These lithofacies were color coded and represented on the cross sections.

The logfacies were defined for each field by correlating lithofacies with resistivity log signatures. Wells with corresponding resistivity logs, core analysis and lithologic logs were used as the prototype well for its corresponding field. An example in SCC is taken from well API 2302320183 in the West Nancy Field (Figure 22). This well has all three lithofacies in its Smackover formation section as such it is a good prototype for the wackestone, grainstone and mudstone logfacies in the West Nancy field. Logfacies were used to define the lithofacies in wells, within the same field, which did not have lithologic logs or core analysis. Tables 2-5 give info on all wells used for cross sections in SCC and the corresponding prototype well for each field. Core analyses and lithologic logs were available for all wells in the BF/LCC so logfacies were not used between wells for lithofacies identification.

Although logfacies varied between fields in SCC, general patterns were observed in SCC versus the BF/LCC. Logfacies in the West Nancy field were good examples of the general logfacies in SCC so they were compared to the general logfacies of the BF/LCC taken from well permit number 16827 (Figure 23).

<table>
<thead>
<tr>
<th>WELL API NUMBER</th>
<th>WELL TYPE</th>
<th>PLSS</th>
<th>LITHOLOGY INFORMATION AVAILABLE</th>
<th>WELL USED FOR LOG FACIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2302320219</td>
<td>OIL</td>
<td>T1N R14E SEC6</td>
<td>none</td>
<td>2302320183</td>
</tr>
<tr>
<td>2302320206</td>
<td>OIL</td>
<td>T1N R14E SEC6</td>
<td>Oxley lithologic log and core analysis</td>
<td>2302320206</td>
</tr>
<tr>
<td>2302320237</td>
<td>OIL</td>
<td>T1N R14E SEC6</td>
<td>none</td>
<td>2302320183</td>
</tr>
</tbody>
</table>
Table 2: The West Nancy field well information, southwestern Clarke County, MS

<table>
<thead>
<tr>
<th>WELL API NUMBER</th>
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Table 3: The Nancy field well information, southwestern Clarke County, MS

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Table 4: The East Nancy field well information, southwestern Clarke County, MS

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**Table 5**: The Watts Creek field well information, southwestern Clarke County, MS

**Cross Section Development**

Cross section wells were selected by type, quality and type of log available, depth reached in logs, and availability of corresponding core analysis report. The type of wells selected was primarily oil wells. Good quality resistivity logs were used in both the BF/LCC and SCC. The log depth preferred for selected wells spanned the top of the Smackover to the top of the Norphlet.

**The Brooklyn/ Little Cedar Creek Fields**

The BF/LCC cross sections were oriented in a general longitudinal direction as well as perpendicular to the longitude cross section for coverage of the study area. Figure 6 was oriented in the general longitudinal direction and figures 7-8 are perpendicular to longitude, each intersecting figure 6 at different points. The cross section wells were spaced true to their onsite distance (Figures 6-8). The cross sections are hung in depth (negative elevation) and were vertically scaled with respect to the well with the thickest Smackover section in each cross section.
Southwestern Clarke County

In SCC, the fields selected for cross sections were based on paleotopographic expressions interpreted from the structure contour maps developed, and lithologic composition interpreted from Oxley lithologic logs (Figures 9-12). Oxley logs showed the four selected fields to have the thickest oolitic/oolmoldic section in the SCC area. This oolitic lithology shows potential for similar to the oolitic oil reservoirs of the BF/LCC. The paleotopographic expressions observed in the SCC fields have the potential for similarities to the paleohighs of the BF/LCC. Paleohighs in the BF/LCC have localized ooid grainstone deposits and high upper Smackover formation porosity (Mancini and Benson, 1984). These four SCC fields were therefore selected for their potential for similarity to the BF/LCC. The SCC fields include the: West Nancy, Nancy, East Nancy and Watts Creek Fields (Figure 13).

Cross section lines in SCC were based on wells within each of the selected fields with the best available data (Figure 14-21). The cross section wells are spaced true to their onsite distances. The cross sections are hung in depth (negative elevation) and vertically scaled with respect to the well with the thickest Smackover section in each cross section.

Information in Cross Sections

Cross sections in both SCC and BF/LCC show: the top of the upper Smackover, the top of the Brown Dense, the top of the Norphlet, a resistivity log curve of the Smackover section in each well, perforated zones (where available) and sections of correlated lithofacies (Figures 5-8 and 13-21). The tops of the formations were determined by their resistivity log signatures. These top picks were compared to the tops shown in lithologic logs to ensure consistency in the log picks. Depths to the top of the Brown Dense and the Norphlet were not consistently reached in
drilling. These depths were also not consistently highlighted in the lithologic logs so adequate representation of the Brown Dense and the Norphlet was less than the representation of the upper Smackover. The perforated zones represented in the cross sections are listed values from the scout cards in SCC (Appendix B). They were included for comparison to the resistivity signatures that show potential for oil. In resistivity logs with multiple coils (such as normal induction logs with deep, medium and shallow coils), hydrocarbon presence can be depicted by separation between the log curves as seen in the log signature of perforated zones in the cross sections (Figures 15, 17, 19, and 21).
Figure 9: Structure contour map of the top of the upper Smackover Formation in southwestern Clarke County, MS
Figure 10: Structure contour map of the top of the Brown Dense/ lower Smackover Formation in southwestern Clarke County, MS
Figure 11: Structure contour map of the top of the Norphlet Formation in southwestern Clarke County, MS
**Figure 12:** Isopach of the upper Smackover Formation in southwestern Clarke County, MS showing regions of paleohighs concordant with the oil fields selected for cross sections
Figure 13: Cross section lines in the Smackover producing fields, southwestern Clarke County, MS
Figure 14: Cross section line A-B in the West Nancy field, southwestern Clarke County, MS
Figure 15: Cross section A (N) – B(S) in the West Nancy field, southwestern Clarke County, MS
**Figure 16**: Cross section line C-D in the Nancy field, southwestern Clarke County, MS
Figure 17: Cross section C(N) - D(S) in the Nancy field, southwestern Clarke County, MS
Figure 18: Cross section line E-F in the East Nancy field, southwestern Clarke County, MS
Figure 19: Cross section E(N) - F(S) in the East Nancy field, southwestern Clarke County, MS
Figure 20: Cross section line G-H in the Watts Creek field, southwestern Clarke County, MS
Figure 21: Cross section G(N) - H(S) in the Watts Creek field, southwestern Clarke County, MS
**Figure 22:** Prototype log of well API 2302320183 in the West Nancy field showing the lithofacies in the upper Smackover formation, southwestern Clarke County, MS.
Figure 23: Comparing logfacies from well API 2302320183 in the West Nancy field, southwestern Clarke County, MS and well permit number 16827 in the Brooklyn/Little Cedar Creek Fields, AL
RESULTS AND DISCUSSION

Reconstruction of Depositional Environment of the upper Smackover in Southwestern
Clarke County

Depositional surface, Paleohighs, Depositional energy and Faulting

This research constructed a series of maps to understand the trends and patterns of the Smackover in SCC. A structural contour map of the unofficial middle Smackover was not developed in this research because this unit was not distinct in the data available in the study areas. The Brown Dense was defined as the depositional surface of the upper Smackover and was represented by a structure contour map (Figure 10). In the structure contour map of the top of the Brown Dense, indications of paleohighs were observed in all of the fields selected with the least indication of a paleohigh observed in the West Nancy field, due to limitations in data availability (Figure 25). These paleohigh indications are defined as contour closures with decreasing numerical values since the maps are contoured depths. The paleohigh indications were also observed in the structure contour map of the top of the Norphlet formation (Figure 26). The consistent expression of paleohighs from the Brown Dense to the Norphlet gives the indication that these paleohighs existed before the deposition of the Smackover and the Norphlet Formations. These paleohighs could have been shallower seas with higher wave and therefore,
localized areas of higher energy; increased oxygen circulation and, higher potential for bioactivity. This bioactivity could include the formation of carbonate dominated shells and fragments which could serve as oolite nucleus, resulting in the potential for increased ooid grainstone deposition. The carbonate shells could also be dissolved to form moldic porosity.

Faulting was interpreted in the southeastern part of the study area as observed in the structure contour maps (Figures 24-26). This fault was oriented in a northeast-southwest direction. This fault was observed from the top of the Smackover to the top of the Norphlet as such; faulting is interpreted to be post depositional and therefore did not impact the deposition of the upper Smackover (Figures 24-26).
Figure 24: Structure contour map of the top of the upper Smackover Formation showing the outline of selected fields in southwestern Clarke County, MS
Figure 25: Structure contour map of the top of the Brown Dense/ lower Smackover Formation showing the outline of selected fields in southwestern Clarke County, MS
Figure 26: Structure contour map of the top of the Norphlet Formation showing the outline of selected fields in southwestern Clarke County, MS
Lithofacies/ Depositional Sequence

Southwestern Clarke County

The depositional sequence of the study areas was interpreted from the cross sections developed. In SCC, the cross section lines have a general northwest to southeast orientation within each field (Figures 14-21). The vertical scale of the cross sections was set at 1 inch representing 450 feet for each field with the exception of the West Nancy field which had a scale of 1 inch representing 150 feet due to the thickness of the Smackover section available in its wells.

In the West Nancy field, three of the four wells in the cross section are not drilled into the Brown Dense (Figures 14-15). The fourth well extends into the Brown Dense but does not reach the top of the Norphlet formation. The cross section shows a Smackover lithofacies order of mudstones overlain by wackestones and then by grainstones. This lithofacies order gives the indication of shallowing water and therefore increasing depositional energy towards the top of the Smackover; a reduction in fine-grained matrix is observed from a mudstone to wackestone to grainstone lithofacies. This increase in depositional energy could be due to deposition in a regression. In the upper Smackover section of the West Nancy field, available data show a thickness range from 150-450 feet. The upper Smackover lithofacies are wackestones overlain by grainstones. Perforation and therefore potential production is also observed in the grainstones of the upper Smackover. These grainstones show a maximum thickness of 300 feet (Figure 15).

In the Nancy field, all the cross section wells are drilled to the top of the Norphlet Formation as such the entire Smackover section is represented (Figures 16-17). The upper Smackover lithofacies in the Nancy field shows a cycle of mudstones, wackestones and
grainstones underlying another cycle of mudstones overlain by wackestones and then by grainstones. This lithofacies order, observed only in the Nancy field, could be interpreted as two regressive sequences. However, due to the thickness of the underlying mudstone-grainstone sequence compared to the overlying mudstone-grainstone sequence, the lithofacies probably represent minor agitations in a regression sequence. The upper Smackover in the Nancy field averages 450 foot thickness and the grainstones show a maximum thickness of about 200 feet. In the Nancy field, production is observed in well 2302320272 within the Brown Dense (Figure 17). However, the deep and medium curves of the laterolog of the same well showed separation indicating the possible presence of hydrocarbons in the upper Smackover grainstones.

In the East Nancy field, the upper Smackover is represented in three of the four cross section wells (Figures 18-19). In this cross section, an indication of a paleohigh is represented by the top of the Smackover occurring at a shallower depth in the two central wells compared to the two outer cross section wells. In central wells 2302320091 and 2302320035, the top of the Smackover occurs at 13238.8 feet and 13282 feet respectively while in outer wells 2302320046 and 2302320064, the top of the Smackover occurs at 13290 feet and 13311 feet respectively (Figure 19). This paleohigh indication is supported by the thinner upper Smackover section in the central wells compared to the outer well 2302320046 in the northwest of the cross section. The East Nancy field cross section line potentially intersects the paleohigh within this field. The East Nancy field lithofacies include mudstones overlain by wackestone and then by grainstone following the order observed in the previous fields. Consistent perforation is observed in the grainstone of the upper Smackover of all four wells in this cross section. The upper Smackover averages about 400 feet in the East Nancy field and grainstone at the top of the upper Smackover section averages about 200 feet.
In the Watts Creek field, the upper Smackover lithofacies are mudstones overlain by wackestones (Figures 20-21). The thickest section of the upper Smackover in SCC is observed in this field with a maximum thickness of about 700 feet towards the east. In the isopach map, the Watts Creek field is confirmed to be within a region of thick upper Smackover deposits (Figure 12). Although the Watts Creek field showed indications of a paleohigh, interpreted from the structure contour maps, and oolitic composition, interpreted from Oxley lithologic logs, this field is potentially not similar to the paleohighs of the BF/LCC (Figures 24-26). Sediments deposited on a paleohigh are expected to thin on the paleohigh and thicken into the basin. Since the Watts Creek field has some of the thickest deposits of the upper Smackover in SCC, the field is discounted as a paleohigh and therefore bares the least similarity, of the four selected SCC fields, to the paleohighs of the BF/LCC.

Brooklyn/Little Cedar Creek Field

In the BF/LCC, the vertical scale of the cross sections was set at 1 inch representing 100 feet (Figures 5-8). The upper Smackover lithofacies in the longitudinal cross section line showed primarily wackestones with mudstone interbeds close to the bottom of the section and grainstone interbeds close to the top of the section (Figure 6). Anhydrites were also observed at the top of the Smackover section. This BF/LCC lithofacies sequence probably resulted from deposition during a regression. The upper Smackover, in this longitudinal cross section, averages 150 feet with grainstone beds at a maximum of 20 foot thickness (Figure 6).

The second cross section line is taken perpendicular to the longitude (Figure 7). The upper Smackover lithofacies in this cross section are wackestones overlain by grainstones
interbedded with anhydrites. The upper Smackover averages about 100 foot thickness with grainstone beds ranging from 5-20 feet thick.

The third BF/LCC cross section line is also taken in a general direction perpendicular to the longitude (Figure 8). The upper Smackover in this cross section shows wackestones, with sparse mudstones interbeds, overlain by grainstones interbedded with anhydrites. The upper Smackover thickness is about 150 feet with grainstones of 50 feet maximum thickness.

**Comparing the Brooklyn/ Little Cedar Creek Fields to Southwestern Clarke County**

Similarities and differences were observed between the BF/LCC and SCC. In the BF/LCC, the Smackover Formation was deposited in a transgressive-regressive sequence on a ramp surface punctuated by paleohighs (Benson, 1988). The deposition of the upper Smackover in the BF/LCC was during a regression as is evident by the lithofacies sequence of wackestones interbedded with sparse mudstones and overlain by grainstones interbedded with anhydrites (Figures 6-8). This depositional setting is similar to that which was interpreted for SCC from the structure contour maps (Figures 9-11).

In the SCC selected fields, the Smackover was about 950 feet thick with the upper Smackover averaging about 450 feet in thickness and grainstone sections averaging about 200 feet in thickness (Figure 15, 17, 19 and 21). In the BF/LCC, the Smackover was about 200 feet thick with the upper Smackover averaging about 150 feet in thickness and grainstones averaging about 20 feet thick (Figures 6-8). This difference in thickness of the upper Smackover could be due to differences in the definition of this informal upper Smackover member between the two study areas. The thickness differences could also be due to the Smackover extending further
updip in SCC as opposed to the BF/LCC (Figure 1) (Badon, 1973; Dickinson, 1962). This could mean that SCC was deposited in a region of greater deposition than the BF/LCC.

The logfacies in the BF/LCC and SCC also showed considerable differences (Figure 23). The log signatures for grainstone, wackestone and mudstone lithofacies in SCC show little to no similarities to those of the BF/LCC. These differences could be due to the thin interbedded changes in lithology that were disregarded in the grouping of lithofacies using only dominant lithology. An example of comparing grainstone defined in the BF/LCC and SCC uses Oxley lithologic log for SCC and core analysis for the BF/LCC (Appendix B). In SCC, the Oxley log of well API 2302320183 shows a 150 foot section of the Smackover grouped as a grainstone (Appendix B). This grainstone section shows lithology including chert and small dolomite crystals however, since the section is dominantly composed of oolites; it is defined as a grainstone. Comparatively, core analysis from the BF/LCC for well permit number 16827 shows a 14 foot section grouped as a grainstone (Appendix B). This BF/LCC grainstone section shows a consistent description of the lithology as dominantly oolitic with minor changes in lithologic color. The interbedded changes in lithology in SCC compared to the BF/LCC could account for the variations in resistivity log signatures in SCC compared to the BF/LCC. Another reason for the difference in logfacies could be due to disparities in the quality and vertical resolution of resistivity logs available in both areas. In the BF/LCC, array induction tools with finer vertical resolutions of 4 feet, 2 feet, and 1 foot, each with six depths of investigation including: 10, 20, 30, 60, 90, and 120 inches were used. In SCC, older resistivity logging tool such as laterolog and normal induction logs with considerably coarser vertical resolutions of about 3 feet for laterologs and a maximum of about 6 feet for normal induction logs were used.
In comparing the lithofacies order in the BF/LCC and SCC, a general lithofacies order of mudstones overlain by wackestone and then by grainstones was observed in the West Nancy and the East Nancy fields in SCC. The Nancy field had a sequence of mudstone overlain by wackestone and grainstone underlying a repeat sequence of mudstone overlain by wackestone and then grainstone. The Watts Creek field had only mudstones overlying grainstones. In the BF/LCC, a general sequence of wackestones with sparse mudstone interbeds overlain by grainstones interbedded with anhydrites was observed. The BF/LCC and SCC lithofacies order were similar however; the BF/LCC lacked the extent of mudstone lithofacies observed in SCC. Mudstone lithofacies, as defined by this research, represent sections of Smackover predominantly composed of dolomites or dolomitized lithology. Mudstones are mud-supported rocks with less than 10 percent grains while wackestones are also mud-supported but contain over 10 percent grains (Dunham, 1962). Grainstones are grain-supported with little mud. The lack of grains in mudstones compared to wackestones indicates potential deposition in deeper waters than wackestones. Mudstones are observed at the bottom of the upper Smackover sequence in both SCC and the BF/LCC as such, the two study areas potentially underwent initial deposition of the upper Smackover in deep marine environments. However, since mudstones are more abundant in SCC compared to the BF/LCC, SCC potentially underwent a longer period of the upper Smackover deposition in deep marines compared to the BF/LCC. Further research into the comparison of the BF/LCC and SCC could focus on the East Nancy field for SCC because this field has the least mudstone lithofacies and therefore the highest potential for similarity to the BF/LCC (Figure 19).
CONCLUSION

The purpose of this research was to evaluate the depositional settings of the upper Smackover Formation in SCC, Mississippi and to compare it to the BF/LCC in Conecuh and Escambia Counties, Alabama. In evaluating the depositional setting of the upper Smackover Formation in SCC, the Brown Dense was defined as the depositional surface for the upper Smackover. This Brown Dense depositional surface was a ramp punctuated by paleohighs as indicated by the structure contour maps (Figures 9-11). Deposition of the upper Smackover was during a regressive sequence as is evident by the lithofacies sequence of mudstone to grainstone. Faulting in SCC occurred after the deposition of the Jurassic Smackover formation as is evident by the fault in the southeast of SCC which faults from the Norphlet through to the top of the Smackover.

In comparing the BF/LCC and SCC, similarities and difference were observed. In the BF/LCC, the Smackover was deposited in a transgressive-regressive sequence on a ramp surface punctuated by paleohighs (Benson, 1988). The deposition of the upper Smackover in the BF/LCC was during a regression as is evident by the lithofacies sequence of wackestones interbedded with sparse mudstones and overlain by grainstones interbedded with anhydrites (Figures 6-8). This depositional sequence and setting is similar to that interpreted for SCC.

The BF/LCC showed difference from SCC in its sparse mudstone lithofacies however, the East Nancy field in SCC had the least mudstone lithofacies of the selected fields and could
potentially be similar to the BF/LCC. Differences in the thickness of the upper Smackover in the BF/LCC compared to that of SCC was also observed and accounted to the Smackover extending further updip in SCC compared to the BF/LCC as such, SCC was potentially an area of greater Smackover deposition (Figure 1). The final difference was in logfacies of the BF/LCC compared to SCC. These logfacies differences could be due to interbedded difference in lithology obscured by the generalized grouping of lithofacies. The logfacies differences could also be due to disparities in the quality and vertical resolution of resistivity logs available in both areas.

The BF/LCC and SCC have similar depositional settings and sequences. The East Nancy field in SCC showed the most similarity to the BF/LCC with features including:

1. The paleohigh observed in structure contour maps, isopach and cross section (Figure 9-12 and 19).
2. Thinner Smackover Formation deposits over the paleohigh observed in the isopach map and cross section (Figure 12 and 19).
3. Lithofacies order of relatively thin mudstones overlain by wackestones and then by grainstones observed in cross section (Figure 19).
4. Relatively sparse mudstone lithofacies observed in cross section (Figure 19).

Further research into comparing the BF/LCC and SCC should focus on the East Nancy field. That study will require analysis of core in the East Nancy field for more detailed lithologic study in the form of petrographic analysis. The study could also benefit from examination of other types of logs in both study areas, as they become available in SCC, for better comparison of the features of the BF/LCC and SCC.
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APPENDIX A: Example Southwestern Clarke County Well Data
## Example Table of Southwestern Clarke County Well Data

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APPENDIX B: Example Scoutcard, Core Analysis, the Smackover section of Oxley log and Comparing Grainstone Lithofacies in the BF/LCC and SCC using core analysis and Oxley logs
Example Scoutcard of well 2302320554
Example Core Analysis of well 2302320712
Example Smackover Formation section in Oxley log of well 2302320206
(a) Smackover section of Oxley log of well 2302320183

(b) core analysis report for well permit 16827

Grainstone Lithofacies description in SCC, using (a) the Smackover section of Oxley log for well 2302320183, compared to the BF/LCC, using (b) core analysis report for well permit 16827
VITA

EDUCATION

December 2013   Bachelors' of Science in Geological Engineering at the University of Mississippi

WORK EXPERIENCE

January- May 2017  Instructor of Environmental Geology at the University of Mississippi

June- August 2015  Petroleum Exploration Management Intern at the Nigerian National Petroleum Company (NNPC)