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Geologic Analysis of the Upper Jurassic Cotton Valley Formation in Jefferson County, Mississippi

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By

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Geologic analysis of the Upper Jurassic Cotton Valley Formation in Jefferson County, Mississippi

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Though the Cotton Valley Group is productive in Mississippi, Louisiana, and Texas, little is known about production potential of the Bossier Formation (Lower Cotton Valley Shale) in southwest Mississippi. The Bossier Formation in Jefferson County, Mississippi is an organic-poor, carbonate-rich mudrock with siliciclastic intervals. Examination of cuttings by petrographic and scanning electron microscopy revealed fractures that have been filled by calcite and pore-filling pyrite. Porosity exists within and around pyrite framboids, in unfilled fractures, and within peloid grains. Organic matter is rare in Lower Cotton Valley samples suggesting it is not self-sourcing. Total Organic Carbon (TOC) values are low (0.86-1.1% TOC) compared to the productive Haynesville Shale Formation (2.8% TOC). Porosity of the Lower Cotton Valley Shale is low (2.5-4.2%) compared to productive Haynesville Shale Formations (8-12%). With current technology and gas prices, the Lower Cotton Valley Shale in Jefferson County, Mississippi does not have production potential.

DEDICATION

I dedicate this work to my late grandfather, David K. Brooks. Dave, as his grandchildren knew him, preferred to list his profession as "independent oil well operator." He was the classic independent oil man, continuously hunting for the next big prospect, taking the dry holes in stride and always optimistic that the next well would be pay dirt.

Dave's love of geology (which was only surpassed by his love of golf) was infected upon me at an early age. We colored paper maps together and looked for shows on well logs. Some of my earliest childhood memories are of his office at One LeFleur Square in Jackson, Mississippi, flipping through Oil & Gas Journal while he talked to prospective investors and partners on the phone.

Though it was a constant background to my life, Dave never once pressured me to go into the oil business or geology, preferring instead for me to find my own path. Although I took a circuitous route, I have finally found my home in geology.

Thank you, Dave.

David K. Brooks, January 20, 1914-October 29, 2011

ACKNOWLEDGEMENTS

Without the support of my wife, Jacquline, my success in graduate school could not have been guaranteed. Her constant love and encouragement came in many forms; cupcakes for the graduate student's office, kisses, and motivational speeches that included phrases like "suck it up, buttercup." Thank you for making the last two and a half years survivable.

My mother, Beverly, has been my number one fan since I was born. If she ever for one moment doubted that I could be a success in my return to academia, she never let it show.

I would like to thank all of my professors, especially Dr. Brenda Kirkland and Dr. John Mylroie. "Dr. Brenda" understood that for me, academic pursuits came second behind being a good husband and new father. Her academic guidance was second to none and her kindness and understanding over yet another missed deadline due to a sick child was always appreciated. Dr. Mylroie taught me more about writing for science and presenting an effective argument than any thesis writing class could have. I owe them both a huge debt of gratitude.

Ray Helfrich, president of Bruxoil in Jackson, MS, and Mike Newport, former president of Mainland Resources, Houston, Texas were extremely helpful in providing much of the data on which this study is based.

I would especially like to thank Steve Walkinshaw, President of Vision Exploration in Madison, Mississippi for shedding light on the topic of this thesis when things seemed darkest.

The staff at I^2AT was a joy to work with. I enjoyed my time at the electron microscopy center enough to briefly consider a career in the field.

Robert Irvin at the Mississippi Department of Geology was very accommodating in the process of sample acquisition.

Finally, I would be remiss if I neglected to thank my fellow graduate students and basement dwellers, especially Ben, Geroux, Natalie, Moe, and Courtney.

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CHAPTER I

INTRODUCTION

The development of horizontal drilling and multi-stage hydraulic fracturing technologies over the last ten years have opened up previously unproductive shale formations for petroleum exploration. These low-permeability shale formations have until recently been viewed either as seals for underlying reservoirs or as the source rock for overlying high-permeability sandstone or carbonate formations. Many of the shale formations are self-sourcing, meaning that the organic matter needed to generate hydrocarbons is incorporated within the reservoir rock.

Variability in depositional environment leads to differences in the volume of organic matter, kerogen type, porosity, and permeability. These properties vary from formation to formation and often within the same formation. Due to the relative lack of research on the reservoir characteristics of shale gas formations, there is limited data with which to work when assessing a shale formation for hydrocarbon reservoir potential. There also exists wide-ranging confusion within both the academic community and industry with regard to naming the shale formations of the Lower Cotton Valley Group, including the Bossier Formation.

The Upper Jurassic, Kimmeridgian Age Haynesville Formation in the northern Gulf of Mexico basin is one of the most prolific natural gas reservoir formations in the continental United States (Hammes *et al*, 2011). The production potential of this unconventional, self-sourcing formation has been proven in Texas and Louisiana in the Haynesville-Bossier play with more than 2000 wells drilled (1500 completed) from 2008 to 2011 (Kaiser, 2012). This study focuses on the Lower Cotton Valley Schuler and Bossier Formations that overlie that Haynesville Formation in southwest Mississippi.

The Upper Jurassic, Tithonian Age Bossier Formation has also been the target of recent hydrocarbon exploration. While the Bossier Formation is not as productive as the Haynesville Formation due to lower Total Organic Carbon (TOC) and lower porosity, it is, in some areas, capable of being a commercially viable reservoir when modern horizontal drilling and hydraulic fracturing techniques are used (Hammes, 2011).

For the purposes of this study, an unconventional formation is defined as a formation that must be drilled horizontally and hydraulically fractured to obtain maximum production. Development costs in an unconventional shale formation are higher than a conventional well because of the additional costs of horizontal drilling and hydraulic fracturing. The Cotton Valley Group Bossier Formation in southwest Mississippi is, to date, essentially unexplored. Production from the Haynesville Formation and overlying Bossier Formation has been prolific in Texas, Louisiana, and Arkansas, but it has yet to be shown whether the Bossier Formation contains profitable levels of natural gas in areas farther to the east in southwest Mississippi.

The first horizontally-drilled and hydraulically fractured shale-gas wells were drilled in the Barnett Shale in the Ft. Worth Basin in the early 2000's (Soeder, 2011). Within a few years, other shale-gas plays began to be developed, including the Marcellus in Pennsylvania, the Eagle Ford in South Texas, the Woodford in Oklahoma, and the Bakken in the Williston Basin in North Dakota (Soeder, 2011). Shale-gas production has risen from 1293 billion cubic feet (Bcf) in 2007 to 7994 Bcf in 2011 while production from conventional gas resources has declined (Soeder, 2011).

The objective of this study is to examine the hydrocarbon production potential of the Cotton Valley Group in Jefferson County, which is in southwestern Mississippi (Fig 1). The Cotton Valley Group is comprised of the upper Shuler Formation and the lower Bossier Formation. Because the Cotton Valley Group is very deep in this area, approximately 20,000 feet (6100 m), the number of physical samples and geophysical data are limited, and no wells are currently producing from the Cotton Valley Group at this depth. This study seeks to test the hypothesis that the Cotton Valley Group, Bossier Formation in southwestern Mississippi may produce profitable amounts of gas if the technology for hydraulically fracturing and completing wells at a depth of more than 20,000 feet becomes available.

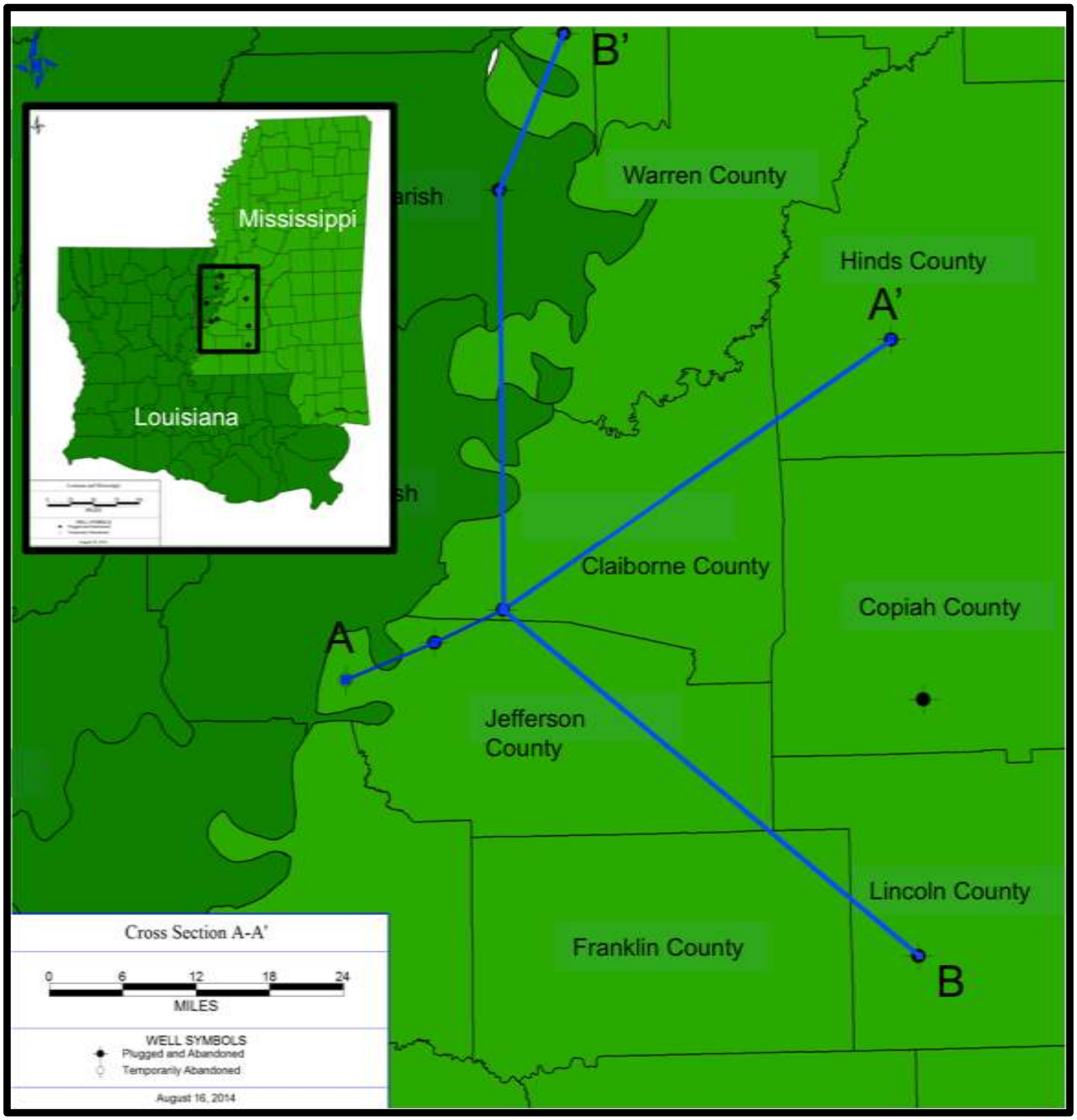

Figure 1 Study area.

Map of study area showing well and cross section locations.

In order to test the hypothesis that the Bossier Formation will contain profitable amounts of hydrocarbons, the formation's thickness, porosity, permeability, chemical composition, and thermal maturity will be determined. These findings will be compared with similar data from profitable Haynesville and Bossier Formation wells in Louisiana and Texas.

CHAPTER II

LITERATURE REVIEW

Geologic Setting

The Haynesville and Bossier Formations stretch from the East Texas Salt Basin, across the Sabine Uplift and North Louisiana Salt Basin, and into the Mississippi Interior Salt Basin (Hammes *et al*, 2011; Salvador, 1991). These features lie along the thick transitional crust of the northern Gulf of Mexico basin (Salvador, 1991; Mancini *et al*, 1999). The thick transitional crust is generally characterized by relatively shallow, well-defined basement highs with alternating lows (Sawyer *et al*, 1991). Wood and Walper (1974) state that the highs correspond with continental crust of near-normal thickness while the lows correspond with continental crust that thinned due to the initial breakup of Pangea and the opening of the Gulf of Mexico in the Late Triassic. Very little is known about the crust, or "basement," rocks that underlie the sediment and allochthonous salt in the majority of the Gulf of Mexico basin. This is due to several factors, including the difficulty of penetrating the salt with seismic surveys and the depth to drill to the basement (Sawyer *et al*, 1991). In west-central Mississippi, the basement rocks are Paleozoic igneous rocks associated with the opening of the Gulf of Mexico (Mancini *et al*, 1999).

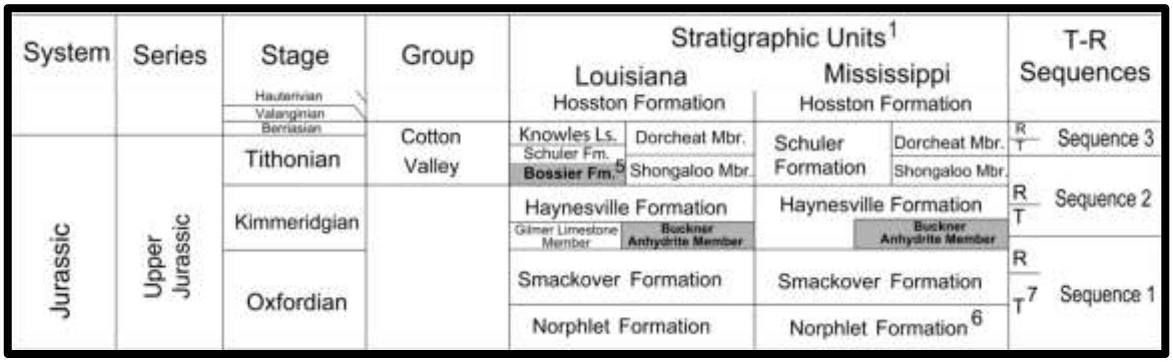

Figure 2 Stratigraphic column for Mississippi and Louisiana.

Louisiana and Mississippi stratigraphic column (modified form Mancini *et al,* 2008)

The known formations below the Haynesville and Bossier Formations begin with the Upper-Triassic, non-marine, siliciclastic Eagle Mills “red beds” Formation uncomfortably overlying the igneous basement rock (Salvador, 1991; Mancini *et al*, 2008) (Fig. 2). This formation varies in thickness from more than 2000 m in the grabens to a few meters, or absent, on the highs left behind during initial rifting of the Gulf of Mexico basin (Salvador, 1991; Wood, and Walper, 1974). Above the Eagle Mills Formation is an unconformity that encompasses much of the Early to Middle Jurassic (Salvador, 1991).

The deposition of the salt strata in the Gulf of Mexico basin is one of the most important features with regards to the location of oil and gas, due to salt tectonics (Salvador, 1991). The Louann Salt and Werner Anhydrate were deposited in large, (100-400 km in diameter), shallow basins that contained hypersaline water due to intermittent connectivity with the Pacific Ocean and limited inflow from rivers (Wood, and Walper, 1974). As the water evaporated, the Werner anhydrite precipitated around the periphery of the basins while the Louann Salt formed toward the interior (Salvador, 1991). The crust of the Gulf of Mexico continued to subside due to rifting during this time, which allowed for the thickness of the salt to exceed 5,000 m in some areas (Wood and Walper, 1974; Sawyer *et al*, 1991). In other areas, such as the Wiggins Uplift and Adams County High, little to no salt was deposited. Salt movement has not been recorded within the central potion of the study area in western Jefferson County, Mississippi (Fig 3).

Figure 3 Major Structural features of Mississippi

Structural features of Mississippi (Modified from Valentine *et al*, 2014). Note absence of salt features in Adams County High.

Depositional Environment

As the Gulf of Mexico basin continued to open and deepen, a series of transgressive-regressive events deposited the marine clastic sediments that constitute the bulk of the formations found in the Gulf of Mexico basin. During the Upper Jurassic, relative sea-level rises, combined with favorable climatic conditions, led to the deposition of marine-transgressive, black mudstones along the continental shelf (Hammes *et al.*, 2011). The basin was surrounded by carbonate shelves to the north and east with local carbonate platforms within the basin that had been created by basement structures and salt-cored domes. The basin periodically exhibited a restricted environment that led to reducing, anoxic conditions (Hammes *et al.*, 2011; Baria *et al.*, 1982). Organic-rich intervals allowed concentration between platforms and islands that provided anoxic conditions (Salvador, 1991). Preservation of organic material was assisted by rapidly rising sea level and high organic productivity (Hammes *et al.*, 2011).

The top of The Haynesville Formation is marked by the most landward extent of transgression coinciding with a Maximum Flooding Surface and backstepping of carbonates (Hammes *et al.,* 2011; Goldhammer, 1998). The Bossier Formation in Texas, Louisiana, and western Mississippi lie comfortably above the Haynesville Formation above the Maximum Flooding Surface (Salvador, 1991).

Regional Geology and Stratigraphy

The Kimmeridgian-age, Jurassic Haynesville Formation is underlain by the Louark Group, which includes the Smackover Formation and Gilmer Limestone (Hammes *et al*, 2011; Mancini *et al*, 2008; Salvador, 1991). The Haynesville Formation is overlain by the Tithonian-age Cotton Valley Group that includes the Bossier Shale, Knowles Limestone, and Schuler Formation (Mancini a *et al*, 2008). Along the northern Gulf of Mexico basin, the Haynesville Formation can be divided into the lower, evaporitic unit (Buckner Anhydrite) and an upper unit composed of terriginous clastics and carbonates (Haynesville Shale) (Salvador, 1991). The Buckner Anhydrite was deposited over the high-energy, shallow-water, upper Smackover, indicating that, as sea levels dropped briefly in the early Kimmeridgian, hypersaline lagoons formed where marine conditions had previously existed (Salvador, 1991).

The upper part of the Haynesville Formation was deposited in shallow-water, marine to intertidal, and supratidal littoral environments (Salvador, 1991; Hammes *et al.*, 2011). In southwest Mississippi, the upper Haynesville Formation is dominated by terriginous clastics deposited in such a manner that the ancestral Mississippi River delta can be inferred (Salvador, 1991).

In areas near the ancestral Mississippi River valley, the Bossier Formation is defined as a marine, regressive laminated mudstone with siliciclastic intervals (Hammes 2012). The more pure Bossier mudstones grade upward and updip into the thick sandstones of the Schuler Formation (Hammes 2012, Salvador 1991).

Mancini (2006) has reported 11 transgressive-regressive stratigraphic sequences in the interior salt basins of the central Gulf coastal plain. The earliest of the sequences contain the Norphlet, Smackover, and Haynesville Formations and Cotton Valley Group (Mancini *et al*, 2008). Each sequence consists of a transgressive system tract that deepens upward and a regressive system tract that shallows upward (Mancini *et al.*, 1999). Mancini (1999) also states that the formation of the Buckner Anhydrite was due to a brief regression that allowed for water to become hypersaline while trapped behind the Wiggins Arch. Above the Buckner Anhydrite, the Haynesville Formation varies in lithology from dark-gray to black calcareous shale (Mancini *et al.*, 1999).

Cotton Valley Group Lithofacies

The Upper Jurassic, Tithonian Stage to Lower Cretaceous, Barriesian Stage, Cotton Valley Group is composed of the upper Schuler Formation and the underlying Bossier Formation. The Schuler Formation can be further subdivided into the Upper Dorcheat and Lower Shongaloo Members (Mancini and Lindsey, 2002). In the East Texas Basin the Schuler Formation includes the Knowles Limestone. Though limited in extent, the Knowles Limestone is an important unit when present because it helps date the Cotton Valley Group (Salvador, 2001).

Moore (1983) mapped the sand percentages of the Cotton Valley Group. His work revealed a regressive depositional system, with depocenters in roughly the same area as the underlying Norphlet, Smackover and Haynesville depocenters. The ancestral Mississippi River delta complex influenced the western depocenter (Moore, 1983, Sydboten, and Bowen, 1987).

In central Mississippi, the Dorcheat member of the Schuler Formation consists of nearshore, varicolored shales, siltstones and white sandstones (Swain, 1944). In areas more basinward, the Dorcheat passes into dark-gray shell-bearing shales, limestones, and sandstones (Swain, 1944).

The lower Shongaloo Member of the Schuler Formation consists of red and red to green shales that are darker than the Dorcheat shales, red and white sandstones and conglomerates (Mancini and Lindsey, 2002). In basinward regions, dark gray shales and fossiliferous limestone becomes more prevalent (Swain, 1944)

At the type locality in the Bellevue oil field in Louisiana, the Bossier consists of dark gray to black, calcareous shale with layers of dark, argillaceous limestone, with sandstone beds near the top (Swain, 1944; Forgotson, 1954). Swain (1944) states "The Bossier Formation includes the marine, dark gray to black shale and sandstone, and the shoreward equivalents of these rocks beneath the Schuler Formation and above the Buckner Formation or its basinward equivalent."

Haynesville Shale Lithofacies

Throughout the extent of the formation in the Gulf Coastal Plain (horizontal and depth), the Haynesville Shale is highly variable in composition, consisting of clay, organic matter, siliceous silt, calcite cement, carbonate bioclasts, and calcite crystals (Hammes *et al.*, 2011). The siliceous and carbonate components tend to vary depending on the proximity to either carbonate shelves or areas of siliciclastic input such as deltaic systems (Hammes *et al.*, 2011). The clay minerals in the Haynesville Shale are mainly illite or mica, with small amounts of chlorite and kaolinite present (Hammes *et al.*, 2011). Most of the siliciclastic minerals are detrital quartz with trace amounts of feldspar, while the carbonate fraction is dominated by calcite with trace amounts of dolomite, ankerite, and siderite (Hammes *et al.*, 2011).

CHAPTER III

METHODS

Introduction

As previously stated, the objective of this study is to assess the hydrocarbon production potential of the Cotton Valley Group in Jefferson County, Mississippi. Several methods will be used to determine the formation's thickness, porosity, permeability, chemical composition, and thermal maturity. Gaining a thorough understanding of these parameters will give a better idea if the Cotton Valley Group in Jefferson County, Mississippi has the potential to be productive for hydrocarbons.

Sample and Data Acquisition

Borehole cuttings from a 200-ft interval of the Piazza #1 well in Jefferson County were obtained from the Mississippi Department of Environmental Quality (MDEQ) Environmental Geology Division's storage facility in Jackson, Mississippi. The Piazza #1 well was drilled in 1980 and is located six miles to the west northwest of the Burkley-Phillips #1 well from which a full suite of well logs have been obtained. Both wells penetrated an interval of mixed quartz sandstone, limestone, and carbonate mudrock at approximately the same depth, but were subsequently plugged and abandoned due to subsurface fluid pressures too great for the technology of the day to control.

Bruxoil Inc. and Mainland Resources have generously provided additional data. Bruxoil provided 2D seismic surveys and well logs from the Burkley-Phillips # 1 well, and Mainland resources provided a full geochemical workup on the core from Burkley-Phillips #1, which was carried out by Core Laboratories Inc. (CoreLab). Geochemical data included porosity, permeability, Total Organic Carbon (TOC), and thermal maturity.

Scanning Electron Microscopy (SEM)

Ten depths of cuttings of the 200-ft sample from Piazza #1 were initially chosen based on visual analysis using a low-power binocular microscope. Cuttings were chosen so as best to represent all the lithology types present within the study interval. Any anomalous cuttings were considered to be contamination either from more than 30 years of storage or were introduced from shallower formations as the drilling mud brought the cuttings to the surface. The anomalous cuttings were removed from the samples.

The cuttings from the Piazza #1 well were broken using sterile forceps to expose a fresh surface. The cuttings were then mounted onto a sterile stainless-steel stub using Conductive Lift-N-Press™ Adhesive Tabs. A platinum coating ($1.5x10^{-5}$ m thick) was applied with an EMS 150T ES high-resolution sputter coater. Selected samples were coated a second time with an additional $1.5x10^{-5}$ m of platinum if repeated imaging problems occurred.

Images of the well cuttings were taken using a Carl Zeiss EVO50VP Variable Pressure Scanning Electron Microscope and a JEOL JSM-6500F Field Emission Scanning Electron Microscope, both located at the Institute for Imaging and Analytical Technologies (I^2AT) at Mississippi State University. Elemental composition of the cuttings was determined using the Bruker Quantax 200 X Flash EDX Spectrometer System (LN2-free high speed 30mm2 SDD Detector) attached to the Carl Zeiss EVO50VP Variable Pressure Scanning Electron Microscope.

The images range in magnification from 10x to 35,000x. These images will be compared to SEM images from productive Haynesville and Bossier Formation wells from Louisiana and Texas to assess porosity and facies type.

Petrographic Microscopy

Spectrum Petrographics prepared selected cuttings. Samples were selected after examination under low-power binocular microscope in order to give as much information about the study interval within budgetary constraints. The thin sections were visually analyzed for porosity and facies type. After the examination, approximately half of each thin section was stained for 30 seconds with a mixture of Alizarine Red-S in 2% HCl, which gives a red coloration to calcite, confirming the presence of calcite.

Well Log Correlation

The well log from the Burkley-Phillips #1 well was correlated with well logs from surrounding wells that have also penetrated the Cotton Valley Group to build a cross-section using IHS Petra software. Building an accurate cross-section helped to determine the thickness of the Lower Cotton Valley Formation as well as helped to establish the depositional environment.

Geochemical Data

Mainland Resources, Houston, Texas, provided geochemical data from the Burkley-Phillips #1 well. Core Laboratories performed a complete geochemical workup on a sample of the core from 20,428-20,434 feet deep. Data included Source Rock Analysis using Rock Eval pyrolysis to determine Total Organic Carbon (TOC) and thermal maturity as well as CMS-300 Conventional Plug Analysis to determine porosity and permeability.

CHAPTER IV

RESULTS

Scanning Electron Microscopy

Cuttings from the Piazza No. 1 well were analyzed for porosity, lithology, and morphology of clay minerals and presence of organic matter. Mudstone cuttings were chosen for SEM analysis based on identification under a low-power microscope. Energy Dispersive X-ray Spectroscopy (EDX) was used to confirm lithology and clay type. Due to the platinum coating on the samples, the EDX spectrum consistently shows a large, unlabeled peak of platinum. Little visible porosity was noted in any of the samples with most porosity found in an around pyrite framboids and in limited pockets of lightly compacted, authigenic clay minerals. Many fractures had been filled with pore-filling pyrite. Organic matter was very limited and only readily identifiable in one cutting.

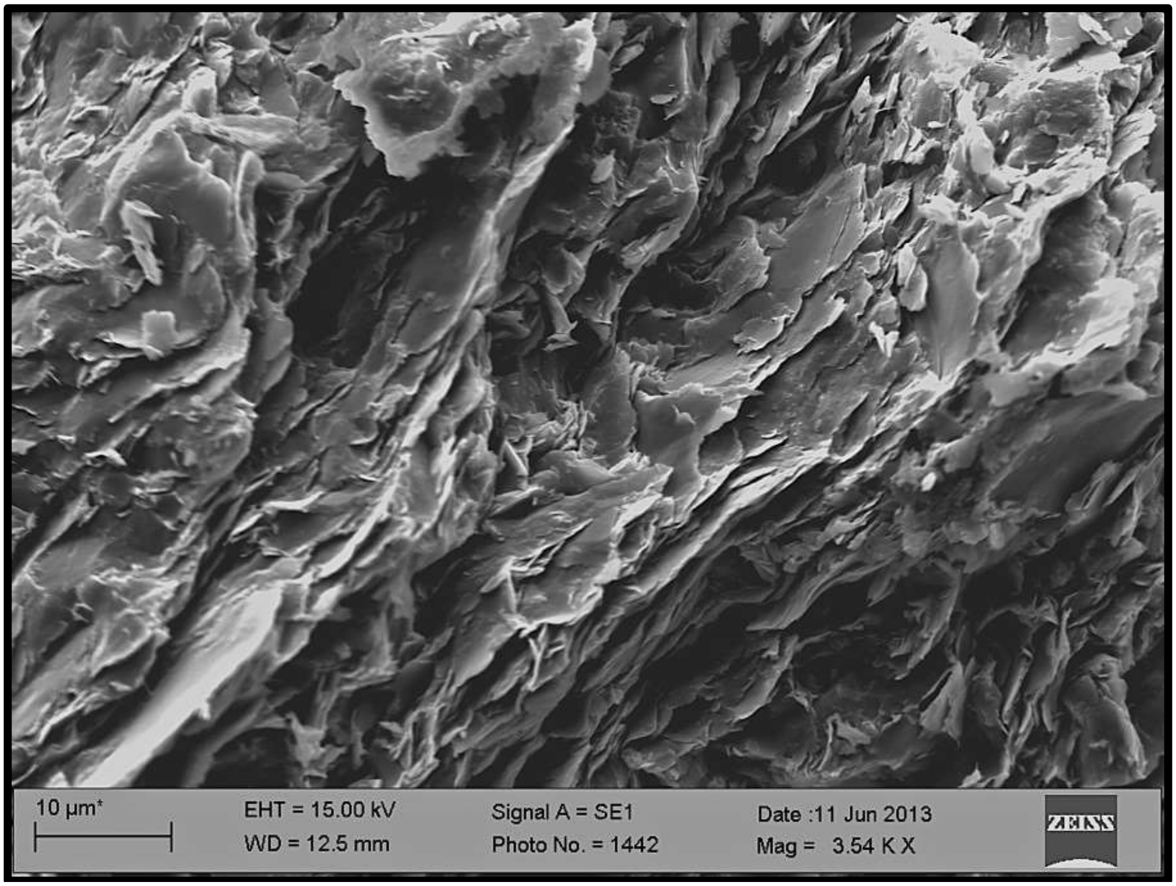

Figure 4 Sample from 19,740-19,769 feet. Electron micrograph of laminated, detrital illite

The cuttings from 19,740 to 19,769 feet are primarily compacted, detrital clay minerals (Fig. 4, Fig. 5). The morphology of the clay particles in this interval indicates illite, which is supported by EDX data (Fig. 6). Very little porosity is present and pyrite framboids are absent.

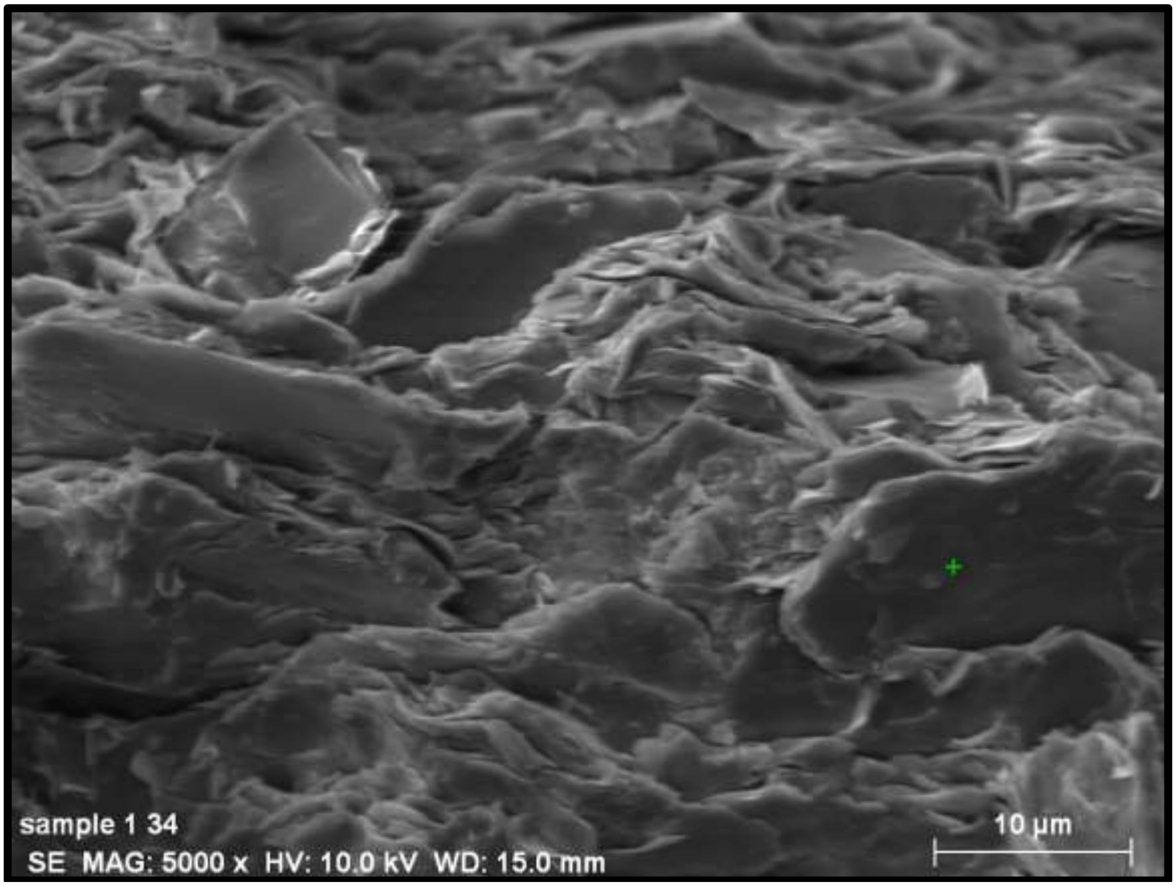

Figure 5 Sample from 19,740-19,769 feet. Electron micrograph of laminated, detrital illite

Green symbol marks point of focus for EDX analysis (Fig. 6).

The cuttings from 19,800 to 19,829 feet contained a mixture of smectite and illite, with smectite being the dominant clay mineral. The morphology of illite and smectite can be similar. The presence of sodium in the EDX data was used to determine the type of clay mineral; if sodium was present the clay mineral was determined to be smectite (Fig. 7), if it was absent it was determined to be illite (Fig. 6).

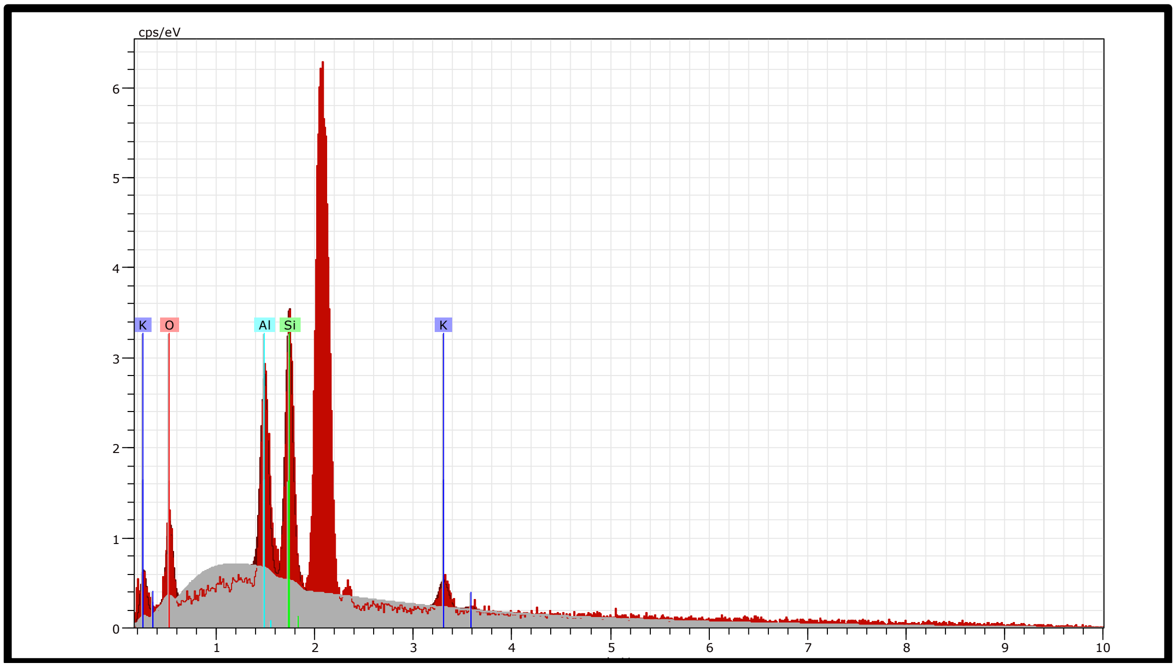

Figure 6 Sample from 19,740-19,769 feet. Energy Dispersive X-Ray Spectrum of illite.

Peaks are oxygen (O), potassium (K), aluminum (Al), and silicon (Si). Large unlabeled peak is due to platinum coating.

From 19,920 to 19,949 feet the cuttings were observed to have characteristics of carbonate rock with occasional siliciclastic grains. The cuttings contained numerous dolomite crystals (Fig. 9). These crystals had peaks of magnesium, iron, and calcite on the EDX spectrum (Fig. 10). The dolomite crystals were found in a micrite matrix with some pore spaces and fracturing around the dolomite crystals. Limited quantities of pyrite framboids were found in this interval. The siliciclastic cuttings were identified visually due to the presence of conchoidal fractures (Fig. 11) and confirmed by positive identification from the EDX spectrum (Fig 12). Quartz grains were supported in a micrite matrix. The quartz cuttings did not show any signs of porosity or fractures. Clay minerals were absent in the cuttings that were selected for this interval.

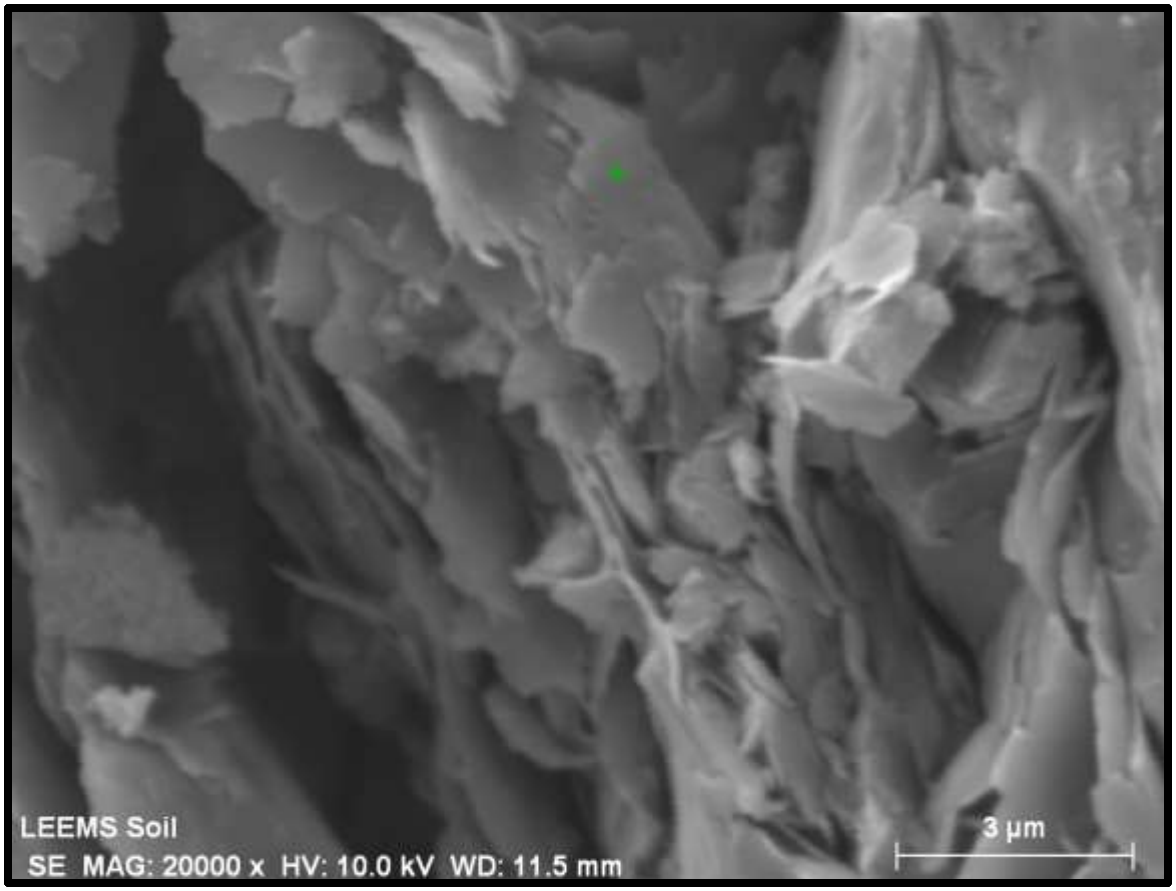

Figure 7 Sample from 19,800-19,829 feet. Electron photomicrograph of smectite. Green symbol marks point of focus for EDX analysis

The cuttings from 19,950 to 20,279 continued to show a mixture of calcite and quartz with a few clay minerals present as well. The clay minerals showed signs of embedded calcite or dolomite crystals in the form of rhombohedral voids (Fig. 13). The voids were likely caused by picking, or loss of grain, when the sample was prepared for imaging. Some porosity was found in the calcareous cuttings from 20,250 to 20,279 feet in the form of voids in the micrite matrix (Fig. 14) as well as limited fractures around calcite crystals (Fig. 15). The EDX spectrum (Fig. 16) shows peaks for calcium (Ca), carbon (C), and oxygen (O).

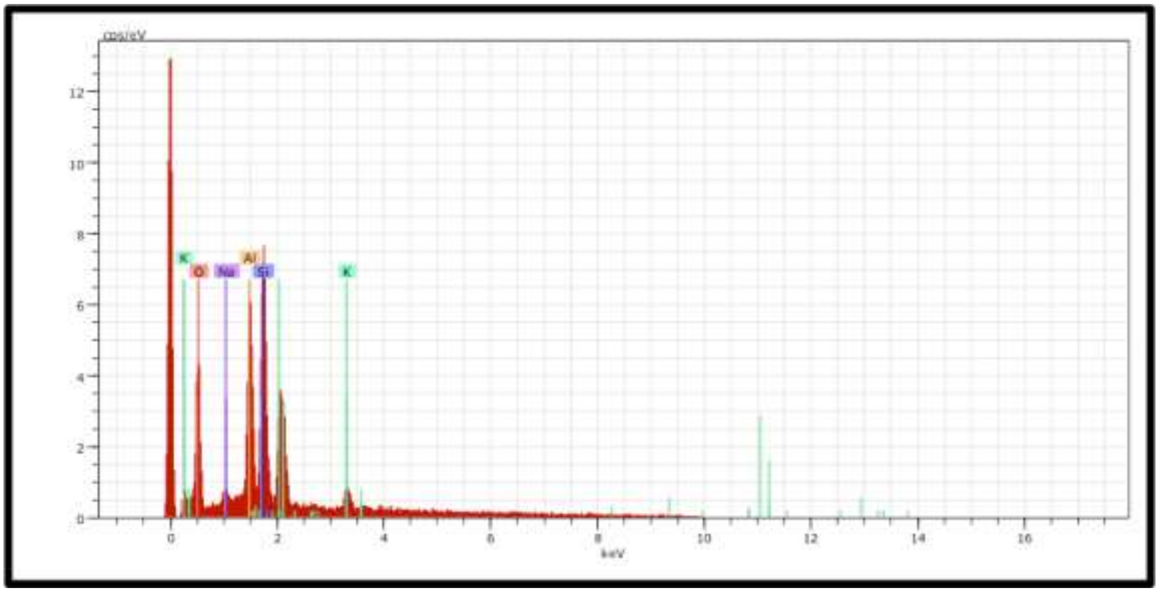

Figure 8 Sample from 19,800-19,829 feet. Energy Dispersive X-Ray Spectrum of smectite.

Significant peaks are Al, Si, Na, K, and O. Unlabeled peak is due to platinum coating.

The interval from 20,280-20,309 feet shows a varied composition that ranges from quartz to clay minerals with limited carbonate minerals present. This interval shows signs of porosity and possible organic matter in several of the cuttings. Porosity was noted in several cuttings in association with loosely compacted authigenic clay minerals. Pore-filling pyrite was present in many of the fractures. Cement varied between cuttings from quartz to calcite.

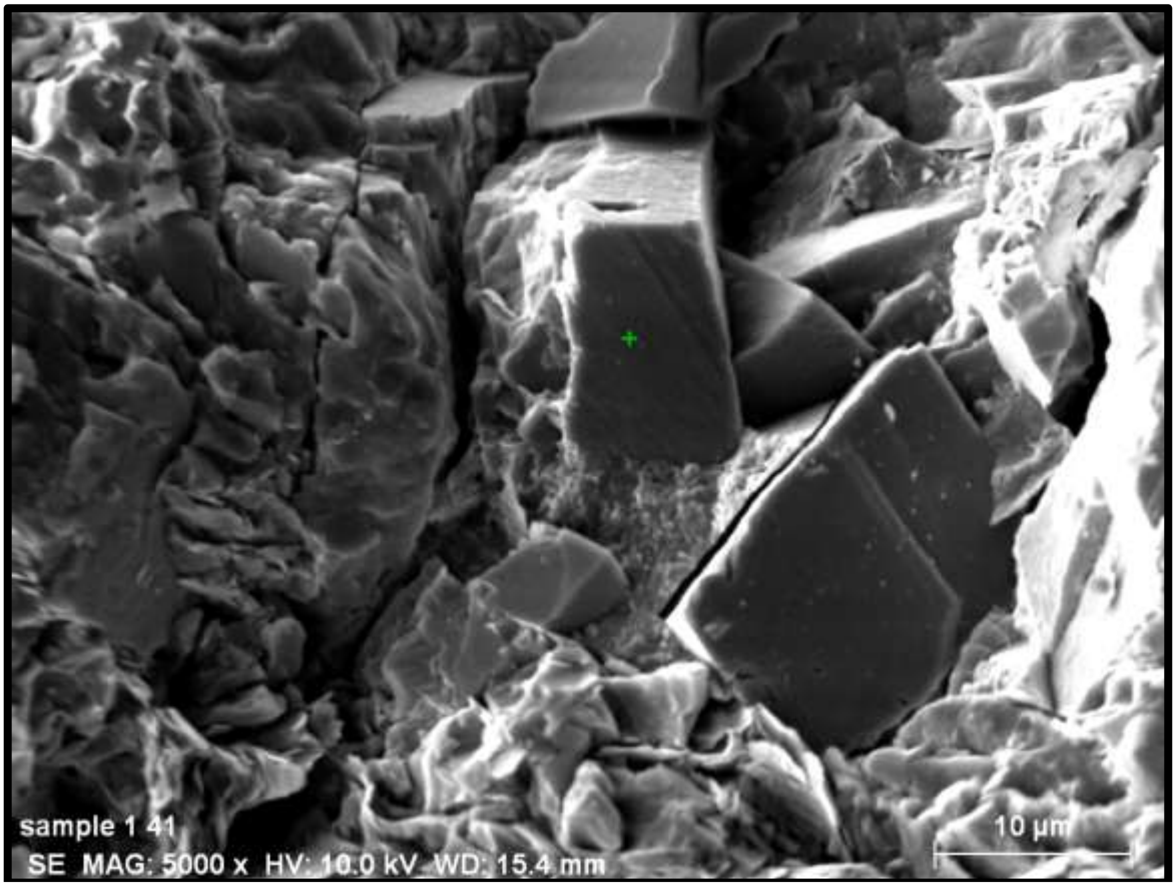

Figure 9 Sample from 19,920-19,949 feet. Electron micrograph of dolomite crystals cemented in calcite.

Green symbol marks point of focus for EDX analysis.

Circular patches of rough to amorphous material were interpreted as organic matter, possibly some form of microfossil. These circular patches were present on and around several quartz grains (Fig. 17). Porosity was present within the organic matter. The organic matter was found on quartz grains, often in groups (Fig. 18). This organic matter was highly localized and not present throughout the interval or throughout individual cuttings.

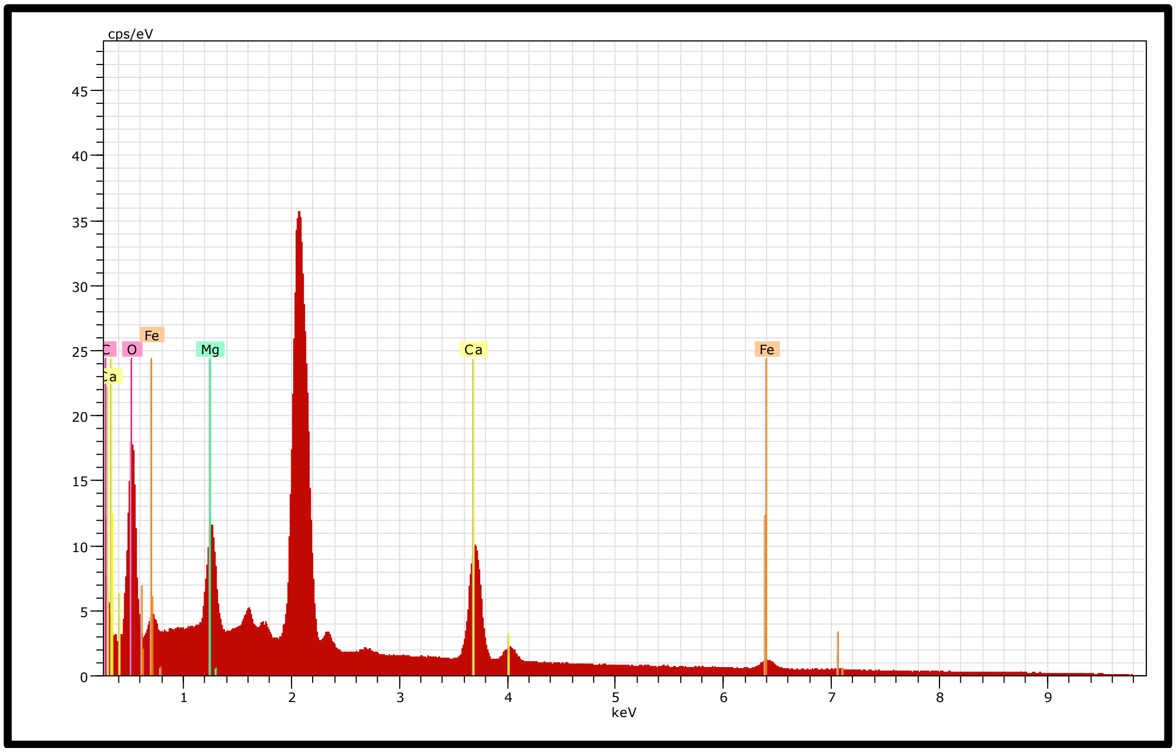

Figure 10 Sample from 19,920-19,949 feet. Energy Dispersive X-Ray Spectrum of dolomite.

Peaks indicate calcium (Ca), iron (Fe), magnesium (Mg), and oxygen (O) are present at that point. Unlabeled peak is due to platinum coating.

Rutile (TiO_2) crystals were also present in the 20,280 to 20,309 foot deep interval. The needle-like crystals were found growing out of quartz, suggesting the formation of rutilated quartz (Fig 19). The EDX spectrum showed peaks of titanium (Ti), oxygen (O), aluminum (Al), and silicon (Si). The silicon peak is likely bleed-over from the surrounding quartz (Fig. 20). Porosity, primarily in the form of webby, non-compacted clay minerals was present in several cuttings in the interval between 20,280 to 20,309 feet (Fig. 21).

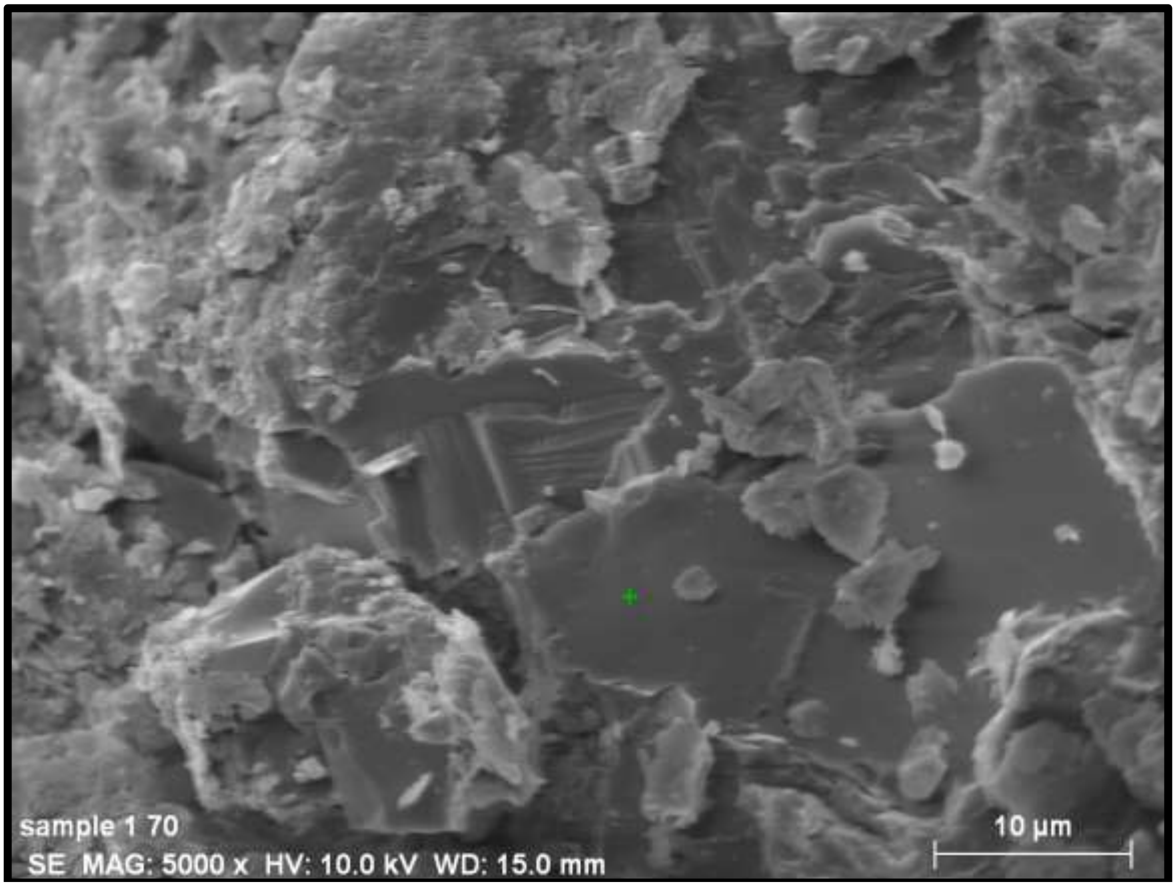

Figure 11 Sample from 19,920-19,949 feet. Electron micrograph of quartz. Green symbol marks point of focus for EDX analysis.

The interval between 20,310 and 20,489 feet was composed of the same homogenous carbonate, mudstone, and detrital quartz grains as imaged from 20,280 to 20,309 feet deep.

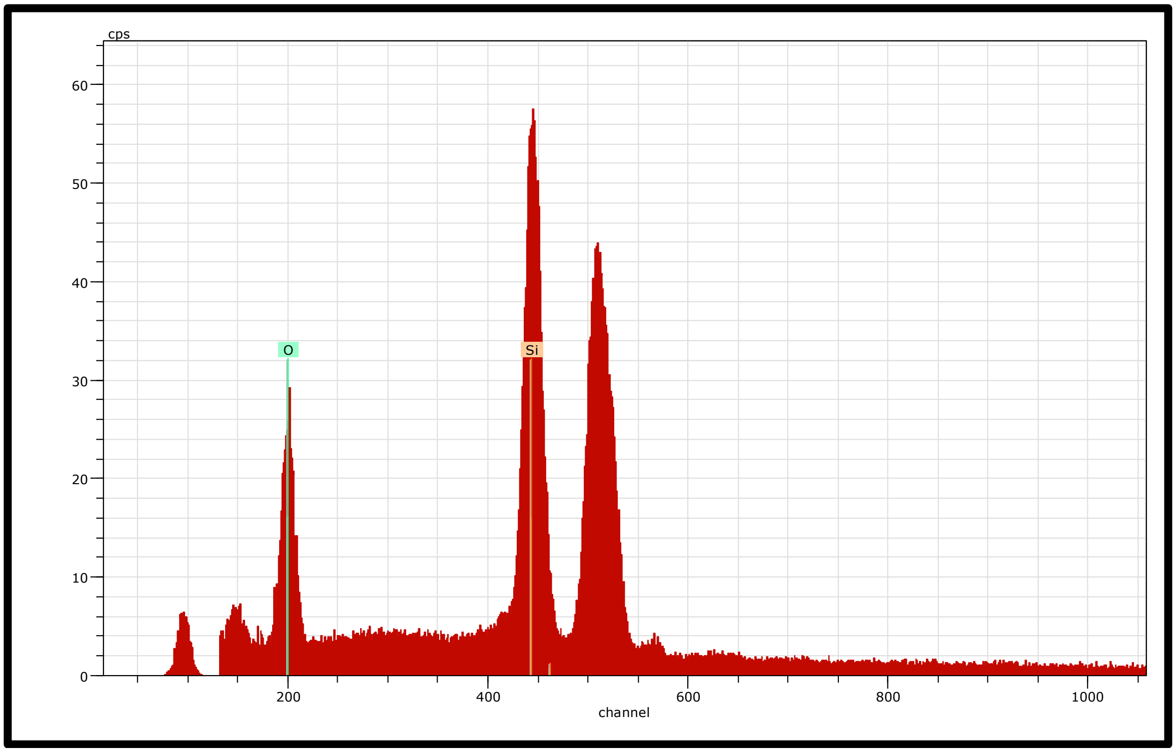

Figure 12 Sample from 19,920-19,949 feet. Energy Dispersive X-Ray Spectrum of quartz.

Silicon (Si) and oxygen (O) are primary peaks. Unleabled peak is platinum coating on sample.

From 20,490 to 20,700 feet, the cuttings are almost exclusively well-laminated, detrital illite, with dolomite crystal inclusions (Fig. 22). Limited kaolinite was also present below 20,600 feet. Kaolinite was identified in this interval by its typical stacked, pseudohexagonal plates (Fig. 23). Porosity below 20,490 feet was extremely limited and not apparent in any of the imaged cuttings.

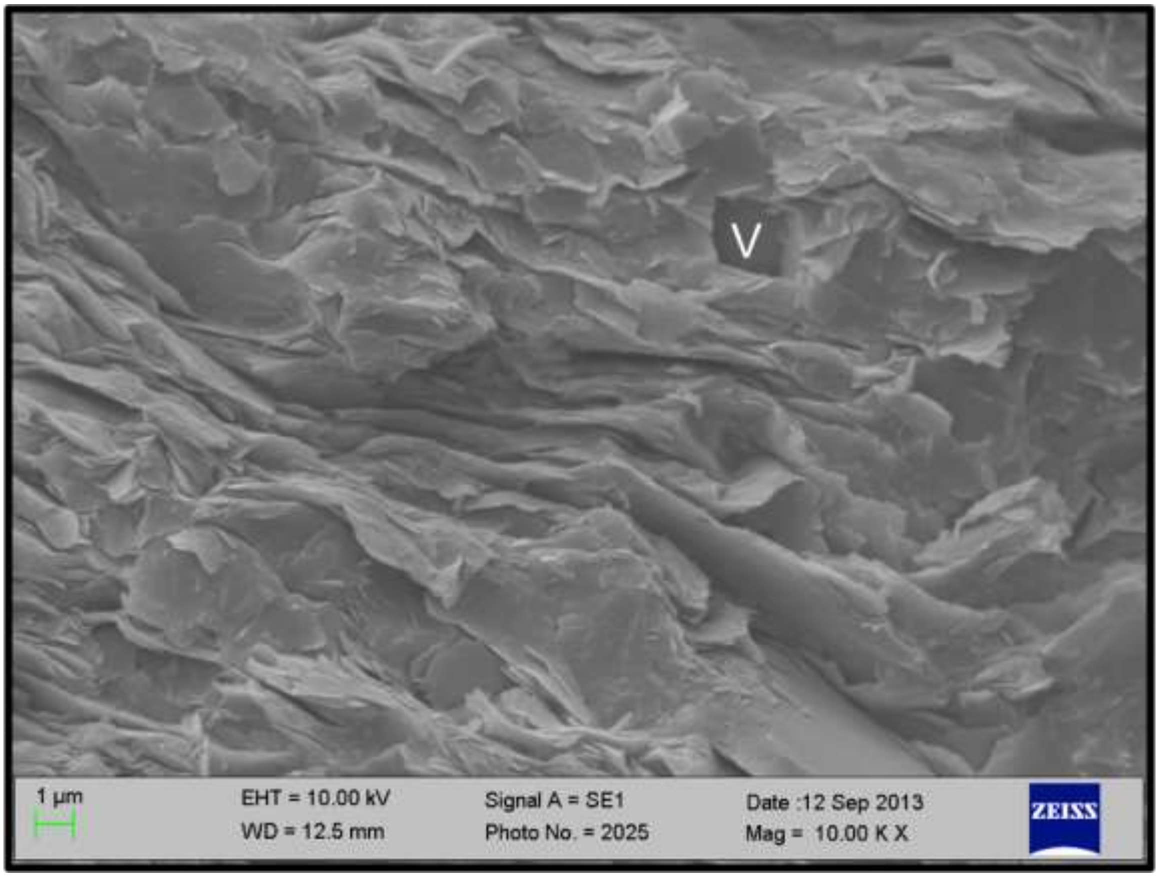

Figure 13 Sample from 20,130-20,159 feet. Electron micrograph of clay minerals. Note rhombohedral void (V) left by picked calcite or dolomite crystal.

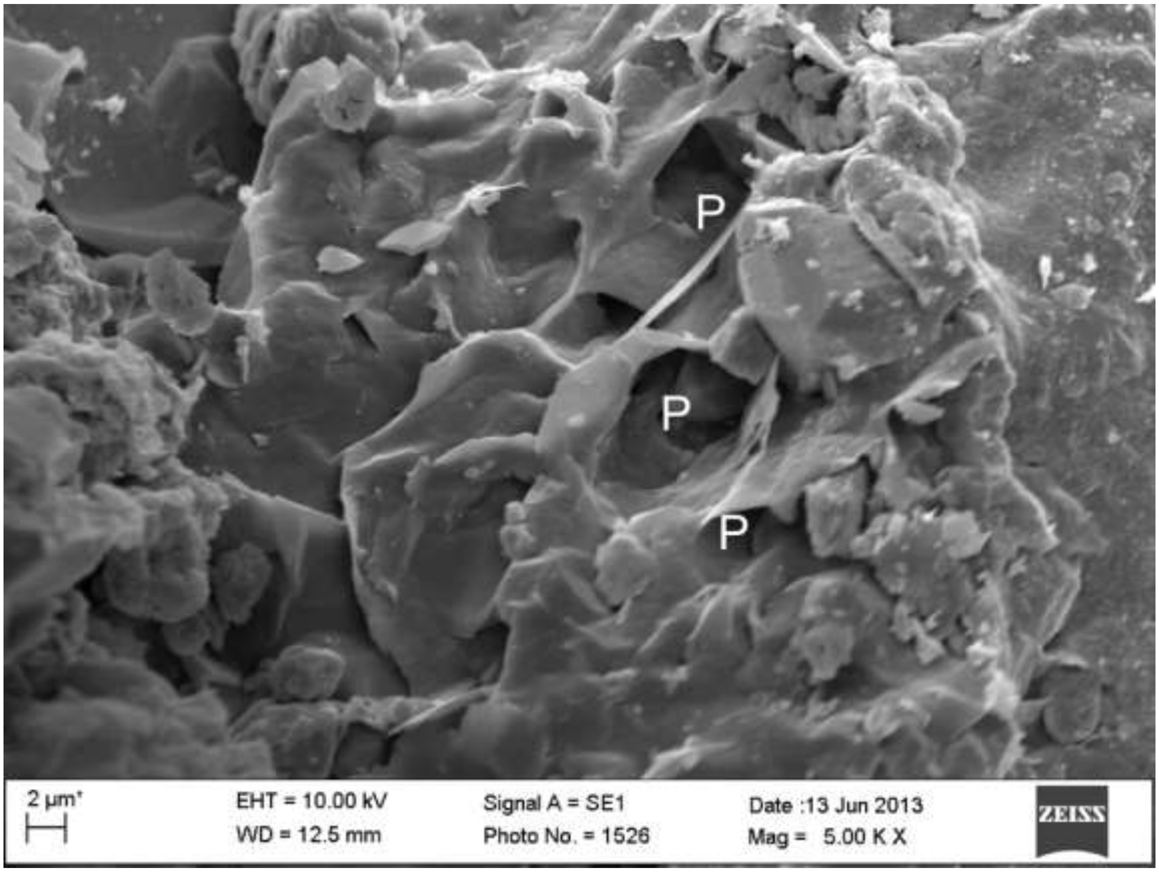

Figure 14 Sample from 20,130-20,159 feet. Electron micrograph of porous micrite. Note pore spaces (P).

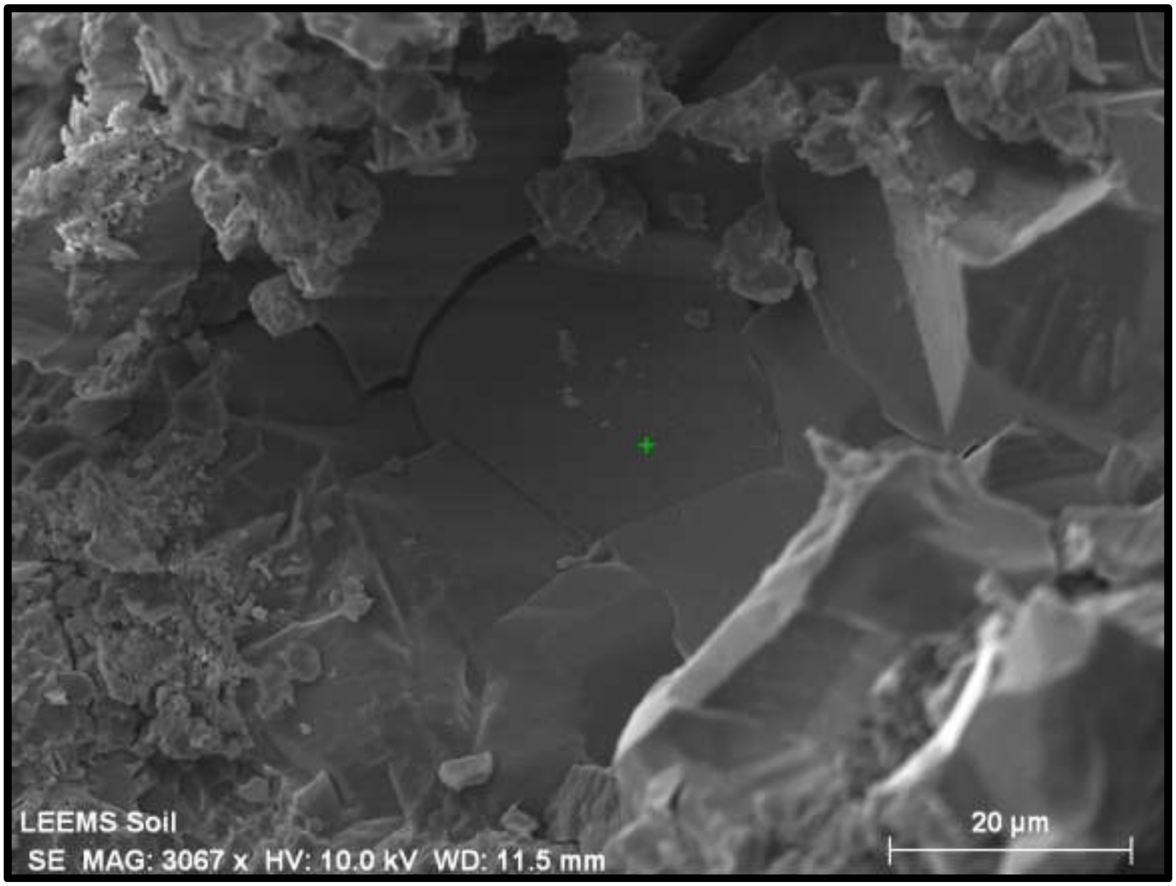

Figure 15 Sample from 20,250-20,279 feet. Electron micrograph of calcite.

Green symbol marks point of focus for EDX analysis.

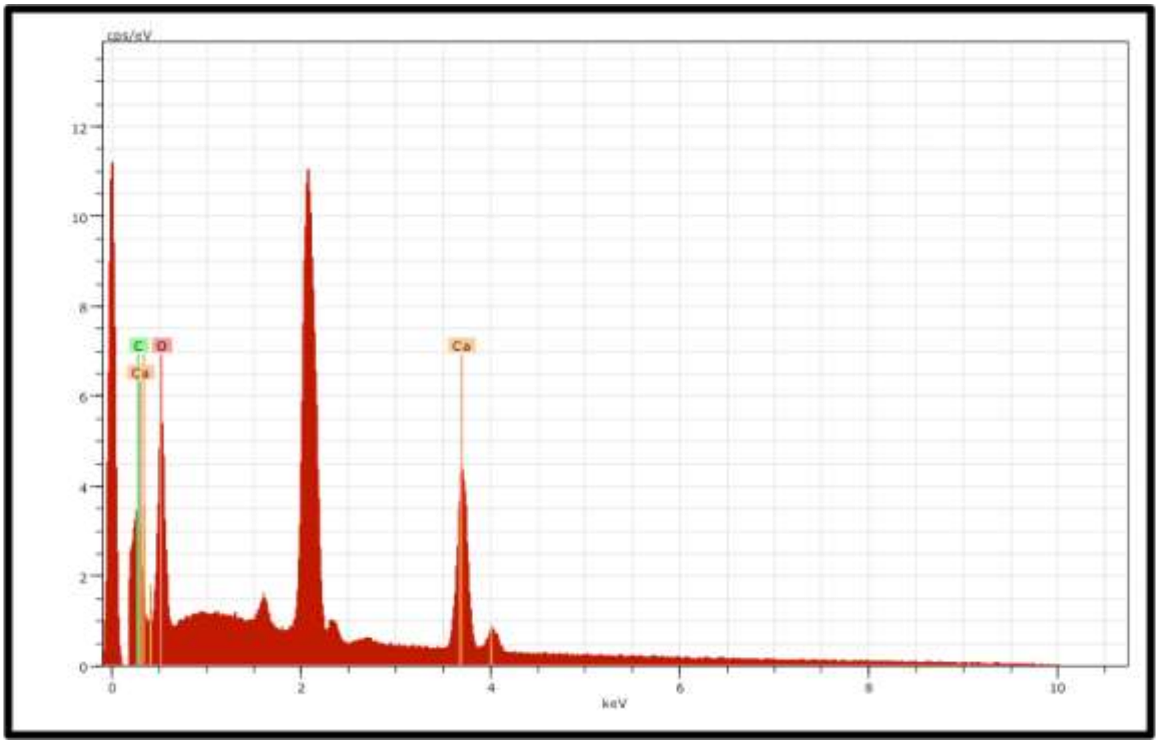

Figure 16 Sample from 20,250-20,279 feet. Energy Dispersive X-Ray Spectrum of calcite.

Notable Peaks are calcium (Ca), carbon (C), and oxygen (O). Unlabeled peak is due to platinum coating.

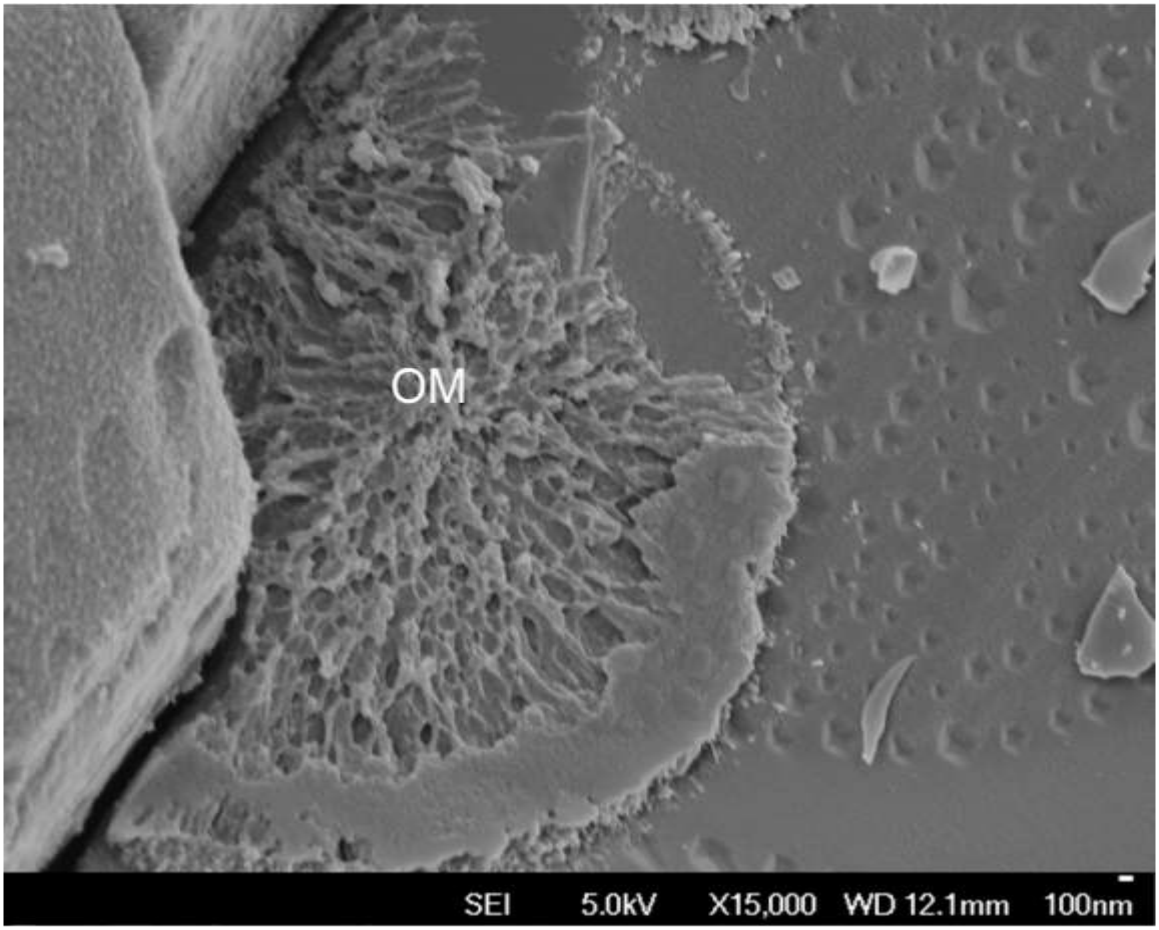

Figure 17 Sample from 20,280-20,309 feet. Electron micrograph of organic matter on quartz crystal.

Rough to amorphous material interpreted as organic matter (OM).

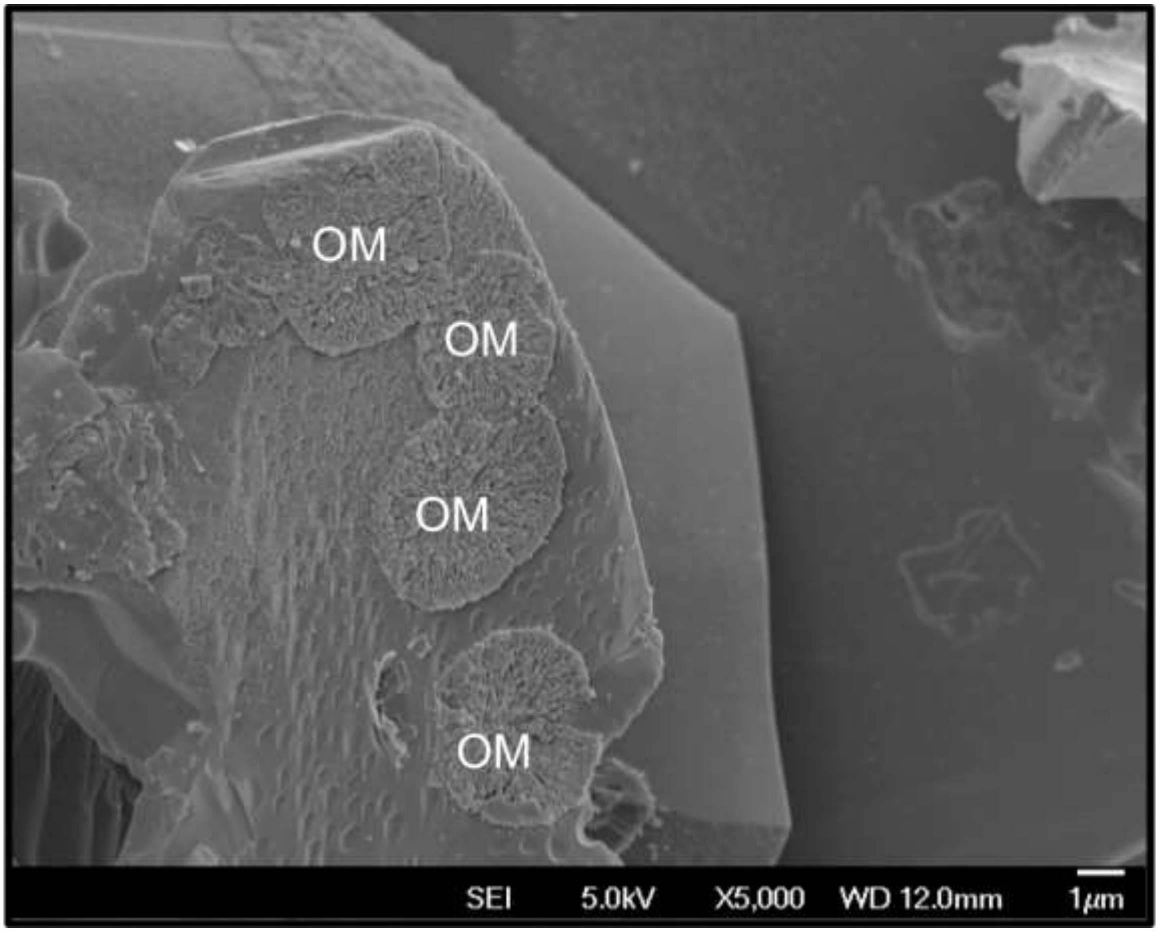

Figure 18 Sample form 20,280-20,309 feet. Electron micrograph of organic matter on quartz crystal.

Grouping of rough to amorphous material interpreted as organic matter (OM).

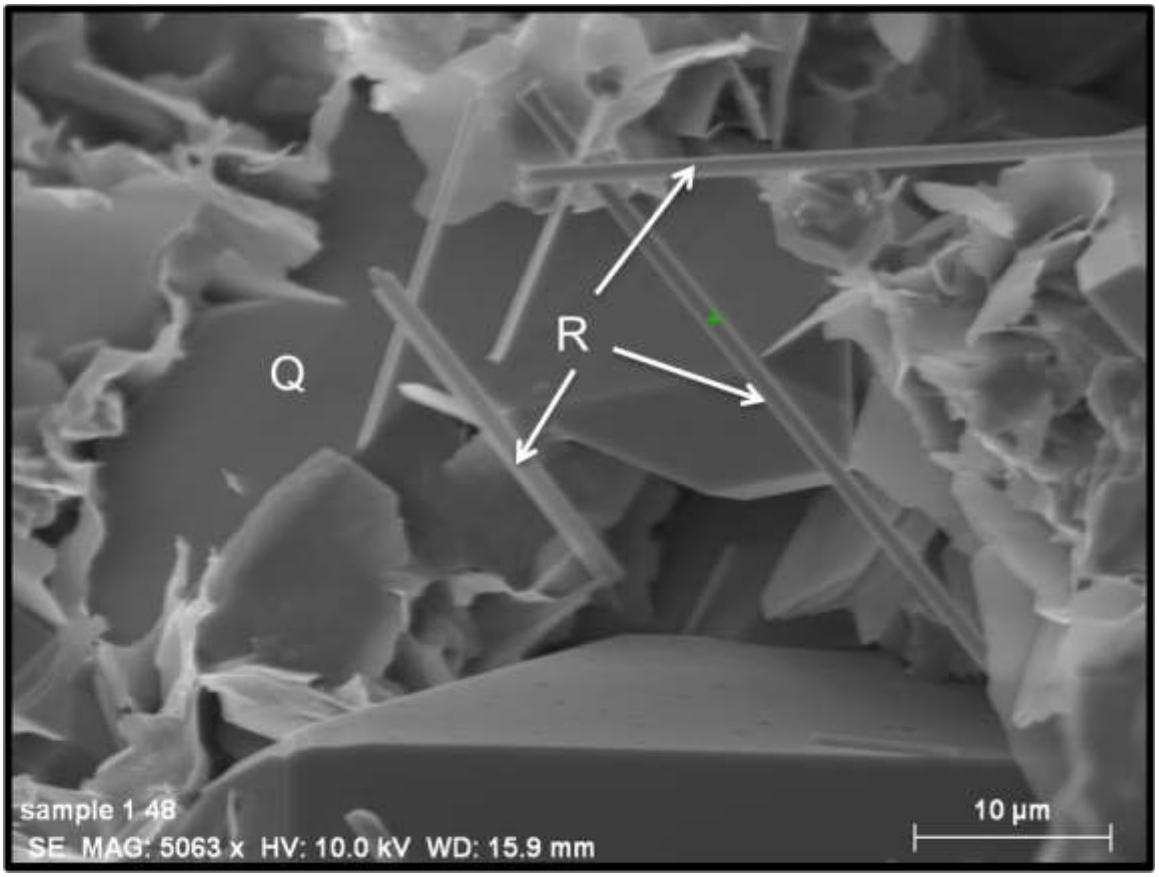

Figure 19 Sample from 20,280-20,309 feet. Electron micrograph of rutile crystals.

Rutile crystals (R), quartz (Q), and clay minerals. Green symbol marks point of focus for EDX analysis.

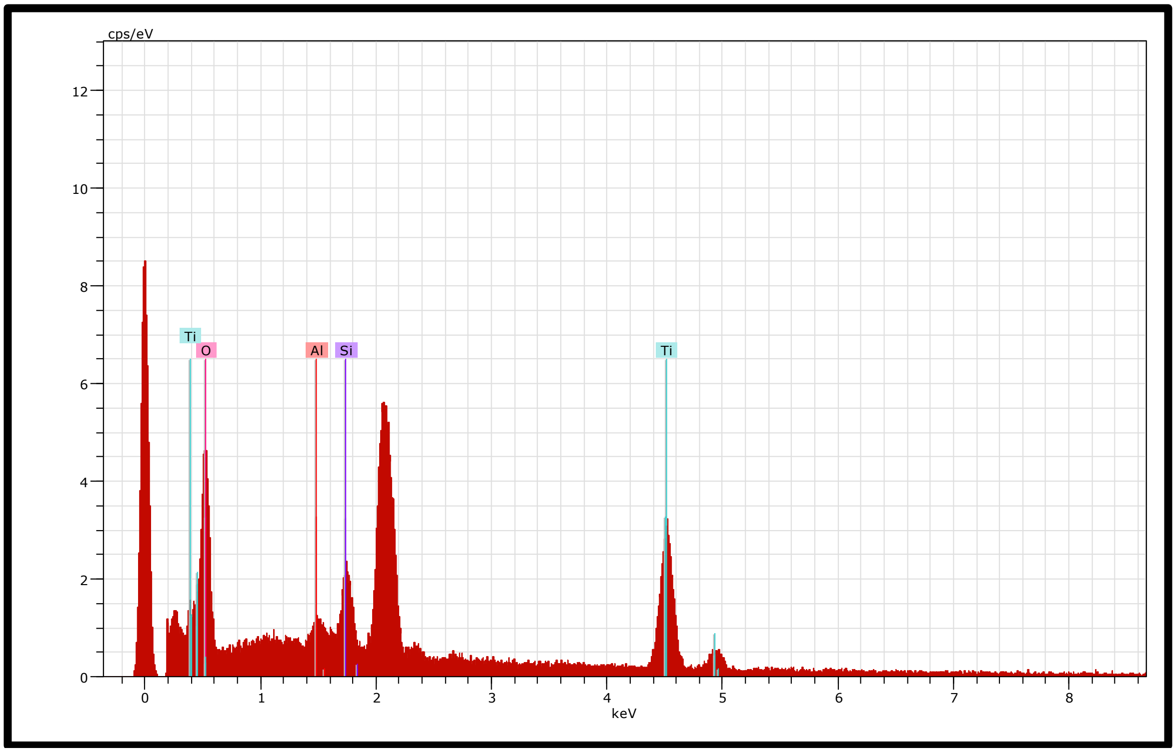

Figure 20 Sample from 20,280-20,309 feet. Energy Dispersive X-Ray Spectrum of rutile.

Notable peaks are titanium (Ti), and oxygen (O). Silicon (Si) peak is bleed over from nearby quartz. Aluminum (Al) peak is likely from clay minerals. Unlabeled peak is due to platinum coating.

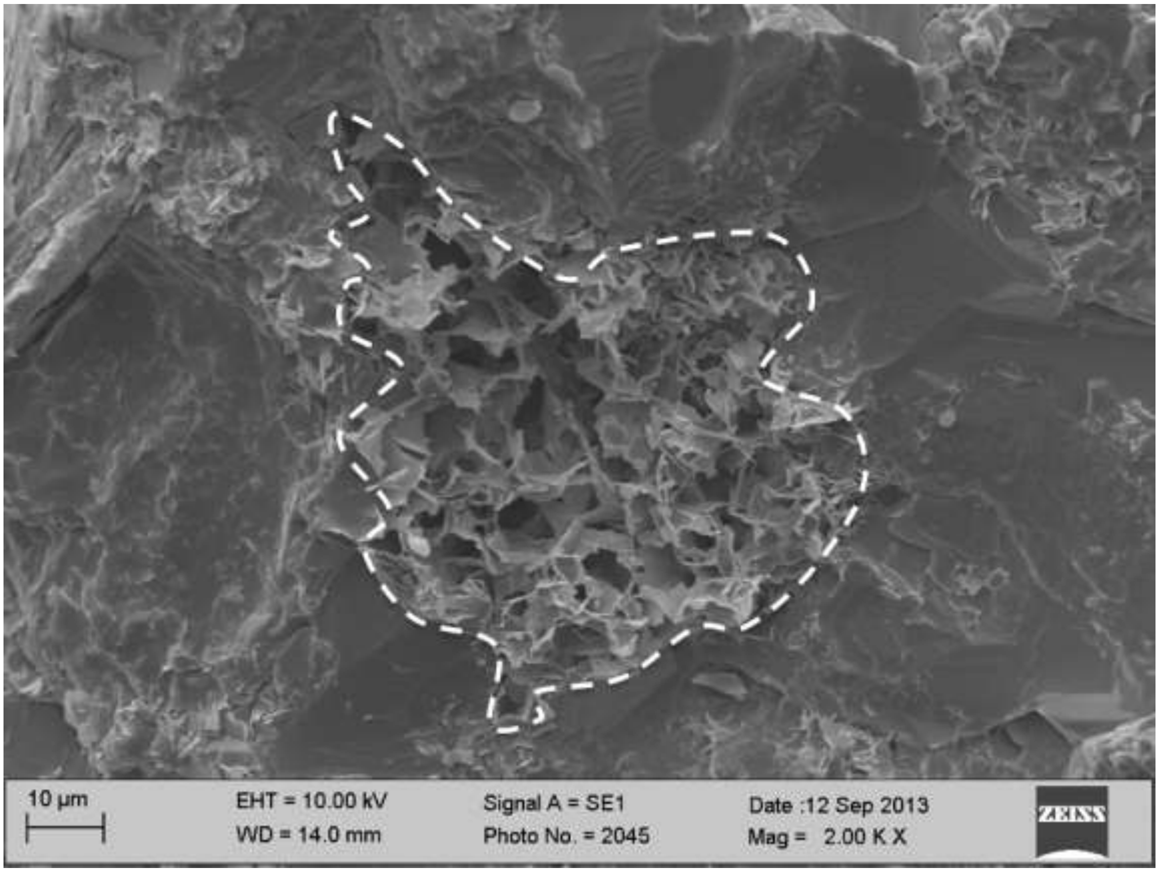

Figure 21 Sample from 20,280-20,309 feet. Electron micrograph of porosity.

Webby, authigenic clay minerals (outlined) filling in a pore space, but preserving some porosity.

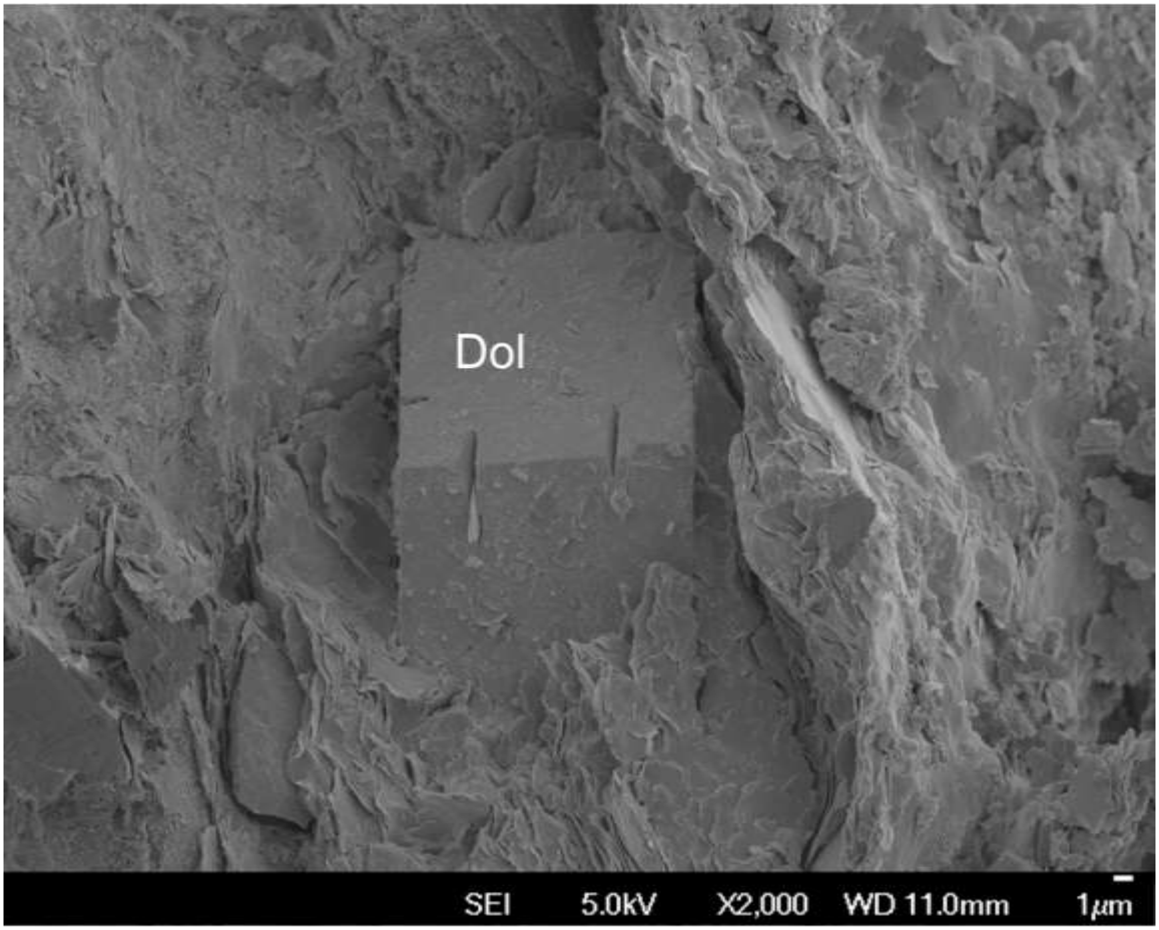

Figure 22 Sample from 20,600- 20,629 feet. Electron micrograph of illite with dolomite.

Compacted detrital illite with imbedded dolomite crystal (Dol).

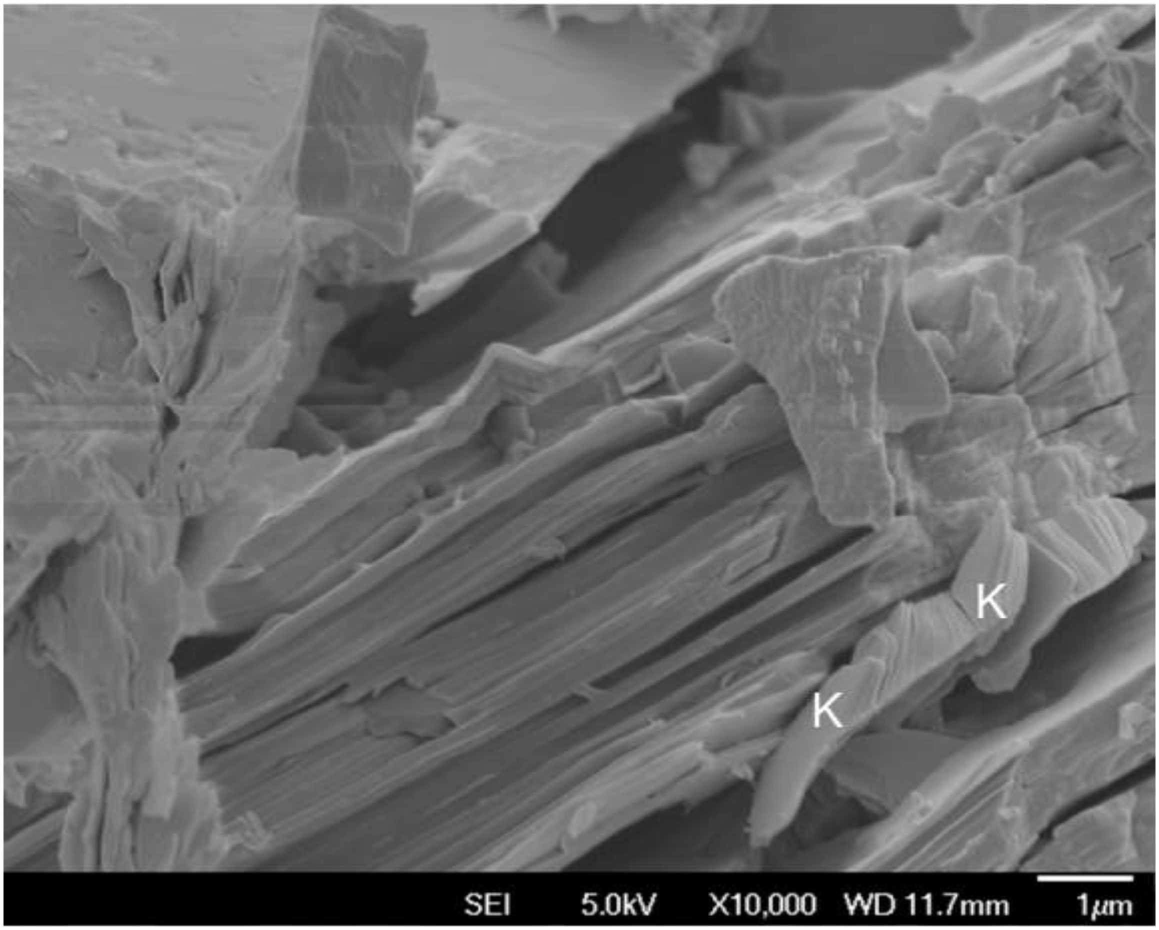

Figure 23 Sample from 20,600- 20,629 feet. Electron micrograph of clay minerals. Unidentified well laminated clay minerals and pseudohexagonal, stacked kaolinite (K).

Petrographic Microscopy

The cuttings comprising each thin section were assessed for porosity, fractures, matrix composition, and lithology. Composition varied greatly with depth. Quartz sandstone and detrital quartz grains cemented in authigenic quartz and clay minerals made up the bulk of the upper half of the studied interval. There was a middle interval that was largely composed of carbonates, mainly skeletal packstone, and grainstone. The deepest section was primarily composed of laminated, detrital clay minerals with dolomite inclusions (Table 1, Fig 24).

Table 1 Thin section composition

Cutting Interval (feet)	% Quartz Sandstone	% Calcite	% Mudstone
19,740-19,769	80	10	10
19,800-19,829	90	10	0
19,890-19,919	80	20	0
19,920-19,949	80	20	0
20,280-20309	60	30	10
20430-20,459	20	80	0
20,520-20,549	50	20	30
20,600-20,639	10	0	90
20,690-20,699	0	0	100

Quartz sandstone includes all cuttings primarily composed of quartz. Calcite includes all packstones, wackstones, and grainstones. Mudstone includes all calcareous mudstone and detrital, authigenic clay minerals, and mineral rich-mudstone

The uppermost interval (19,740 to 19,769 feet) of the study section contained a mix of 80% detrital quartz grains cemented in authigenic quartz and clay minerals, 10% packstone, and 10% carbonate mudstone (Fig. 25). Pyrite framboids and pore-filling pyrite are abundant and pyrite has replaced calcite in some skeletal grains (Fig. 26). Porosity was limited and primarily found within pyrite framboids.

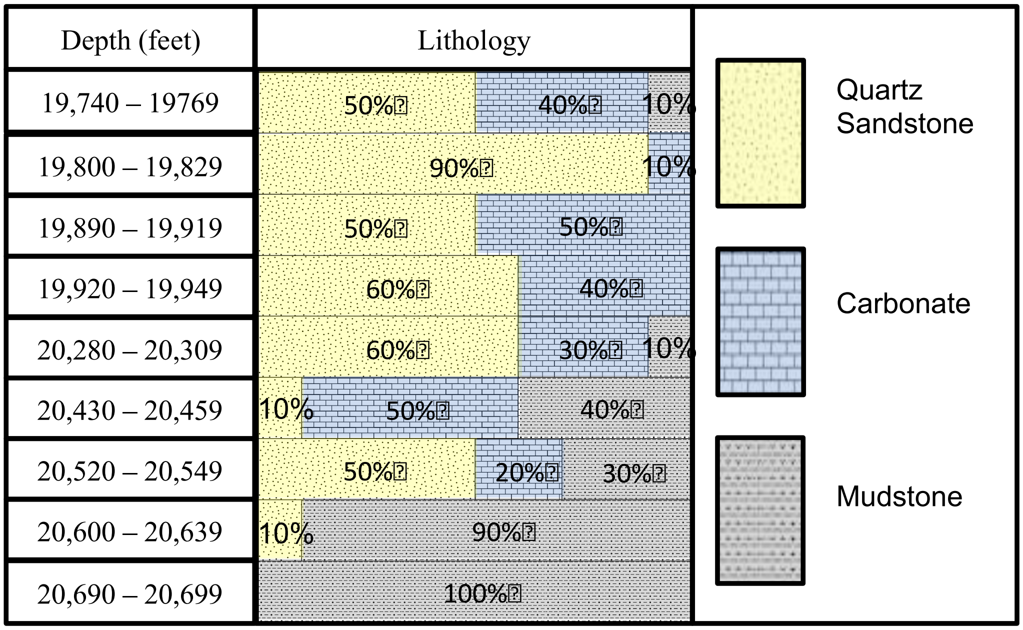

Figure 24 Thin section lithology

Chart showing percentages of lithology observed in each thin section. Overall trend from top to bottom is from a sandier section to a carbonate dominated section to a pure mud-dominated section.

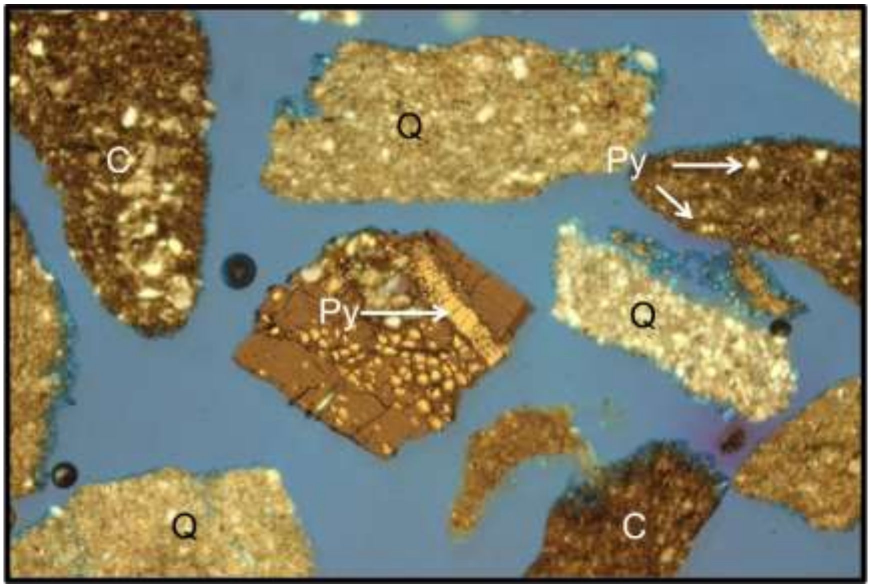

Figure 25 Sample from 19,740-19,769 feet.

Reflected light photomicrograph of an assortment of detrital quartz grains (Q) and claystone grains (C) with pyrite framboids. Pyrite fills fractures and pore spaces in some grains (Py). Field of view 3 mm.

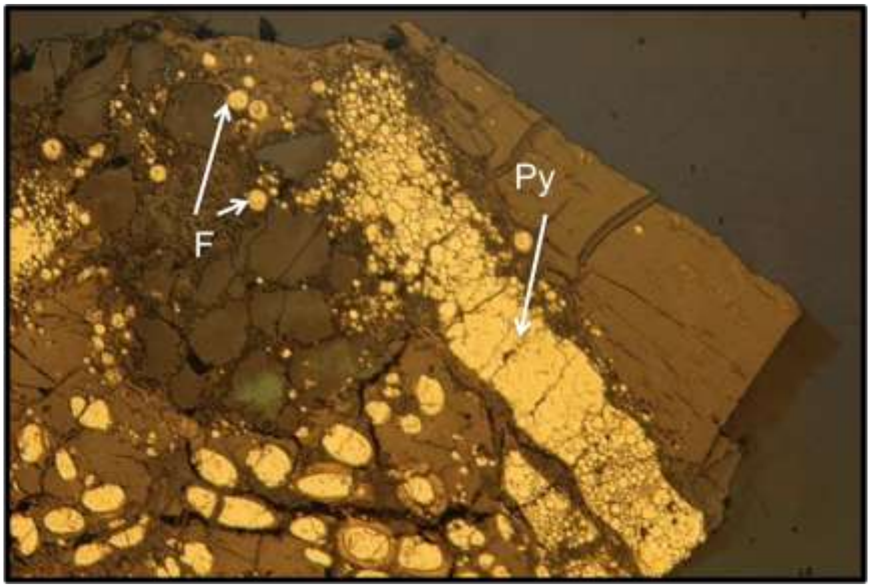

Figure 26 Sample from 19,740-19,769 feet.

Reflected light photomicrograph of pore-filling pyrite (Py) and pyrite framboids (F). Field of view 1.5 mm.

The interval from 19,890 to 19,919 feet contained 80% detrital quartz grains and 20% calcite grains cemented in micrite; bivalve shells and other shell fragments are present (Fig. 27). Porosity was not observed in the cuttings from this interval.

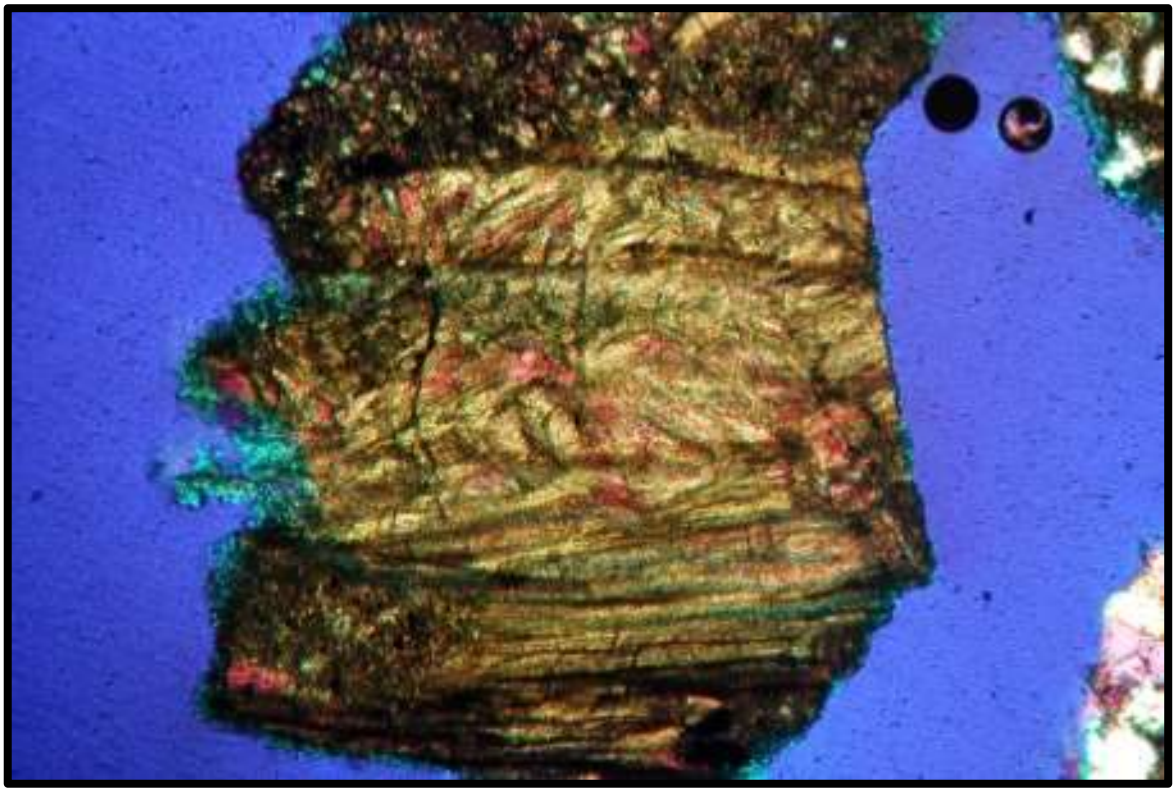

Figure 27	Sample from 19890-19919 feet. Transmitted light photomicrograph of bivalve shell.

Field of view 1.5 mm.

The middle portion of the study section from 19,920 to 20,549 feet consists of quartz sandstone, packstones, grainstones, carbonate mudstone, and clay minerals (Table 1). The lithology of the cuttings in this section became more mud-dominated with depth (Table 1). Limited intraparticle porosity was observed in skeletal grains within the packstone in the interval from 20,130-20,159 feet (Fig. 28). The interval from 20,280 to 20,309 feet showed more grainstone and packstone (Fig. 29), as well as some cuttings of laminated carbonate mudstone interbedded with pyrite (Fig 30). From 20,430 to 20,459 feet, grainstone was present as well as sparry calcite and dolomite crystals in a micrite and clay mineral matrix (Fig. 31). Also present in the 20,430 to 20,459 foot interval were uniserial foraminifera in a micrite matrix and some signs of porosity (Fig 32.).

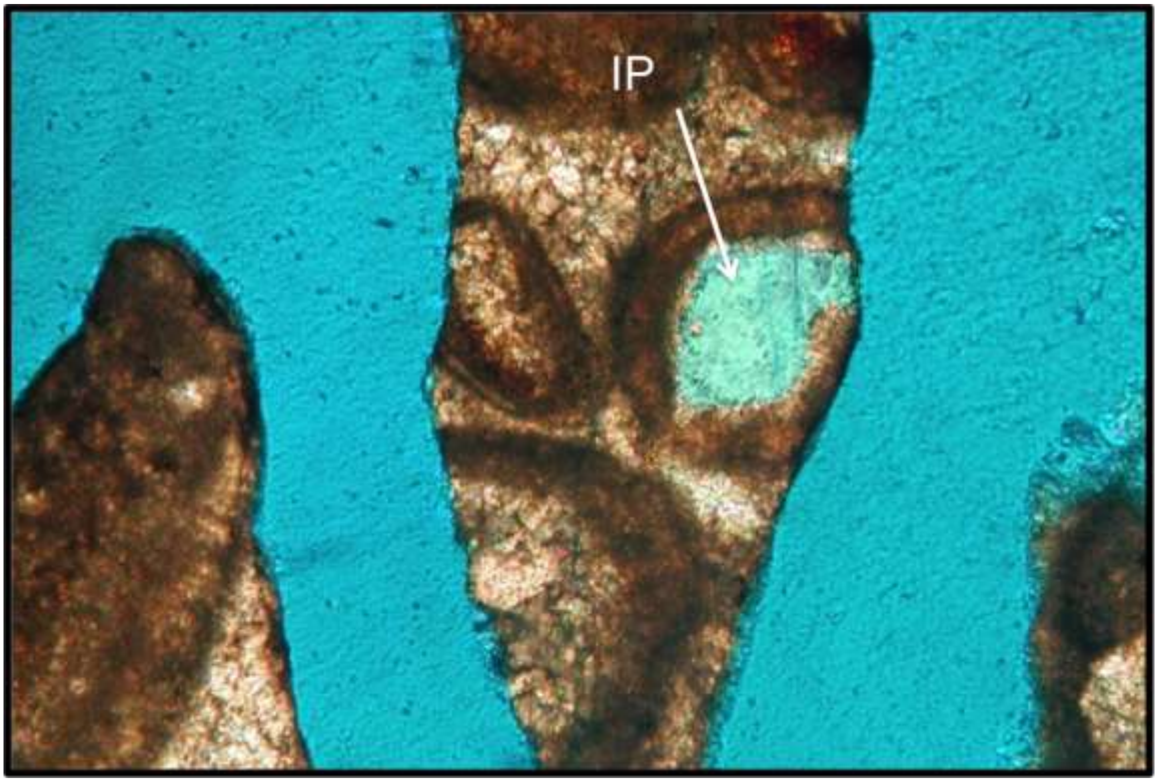

Figure 28 Sample from 20,130-20,159 feet. Transmitted light photomicrograph of porosity.

Intraparticle porosity (IP) in packstone. Field of view 3 mm.

From 20,430 to 20,699 feet calcite and sand decreased in abundance while mudstone increased to 100% at the bottom of the study section (Table 1). The thin section containing cuttings from the 20,520 to 20,549 foot interval contains 50% quartz grains, 30% mudstone with interbedded pyrite (Fig. 33) and 20% packstone cemented in micrite. Fractures in quartz grains have been filled with authigenic quartz (Fig. 34). The interval from 20,600 to 20,639 feet contains 90% carbonate mudstone and 10% detrital quartz sandstone grains with abundant pyrite laminated in the mudstone and filling fractures (Fig. 35). The deepest interval in the study, from 20,690 to 20,699 feet contained 100% carbonate mudstone interbedded with pyrite (Fig 36); pyrite partially filled fractures as well (Fig. 36). Abundant dolomite crystals were present as well as pore-filling pyrite (Fig. 37).

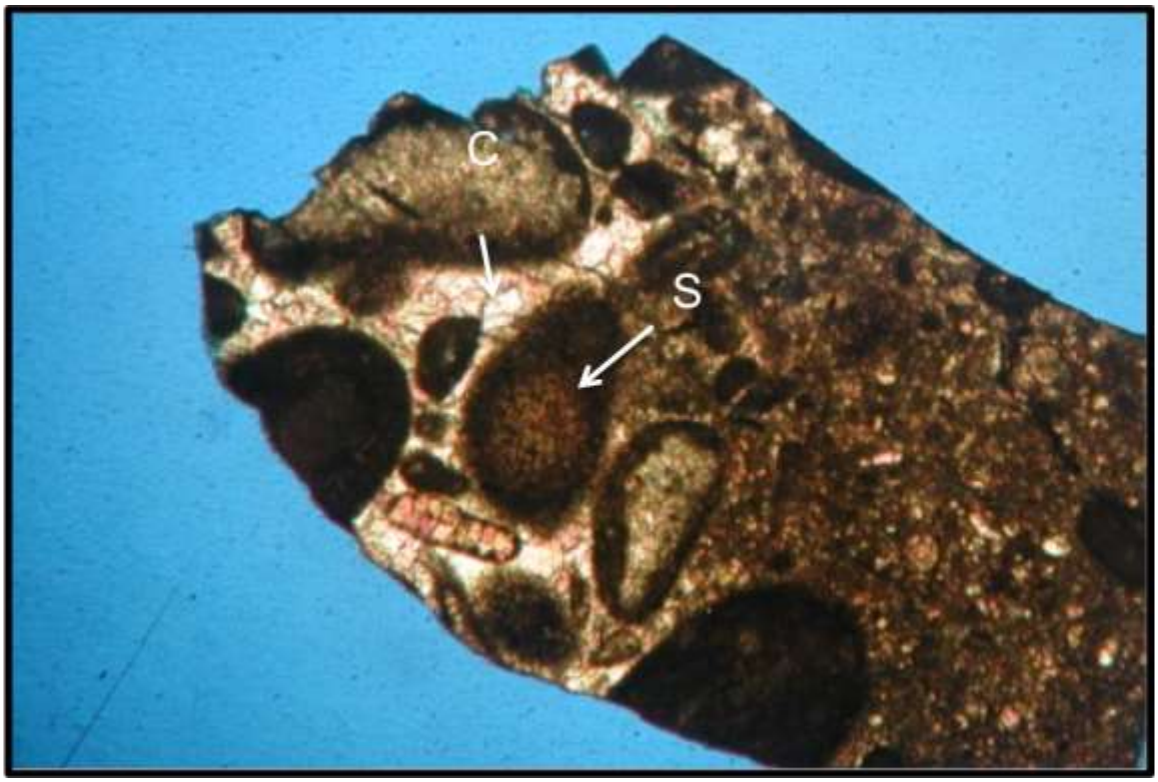

Figure 29 Sample from 20,280-20,309 feet. Transmitted light photomicrograph of packstone

Skeletal grains (S) cemented in calcite (C). Field of view 1.5 mm.

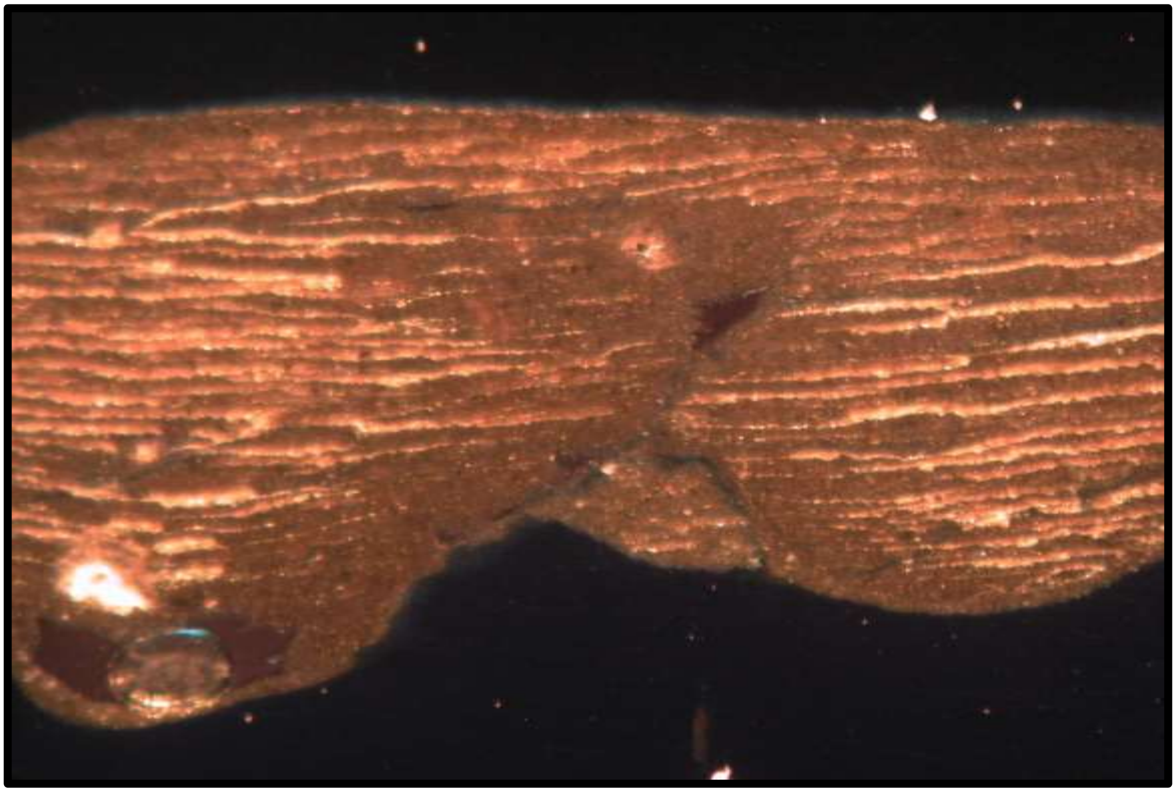

Figure 30 Sample from 20280-20309 feet. Reflected light photomicrograph of mudstone.

Pyrite (gold) interbedded with clay minerals (brown). Pyrite reflects a gold luster under direct light. Field of view 1.5 mm.

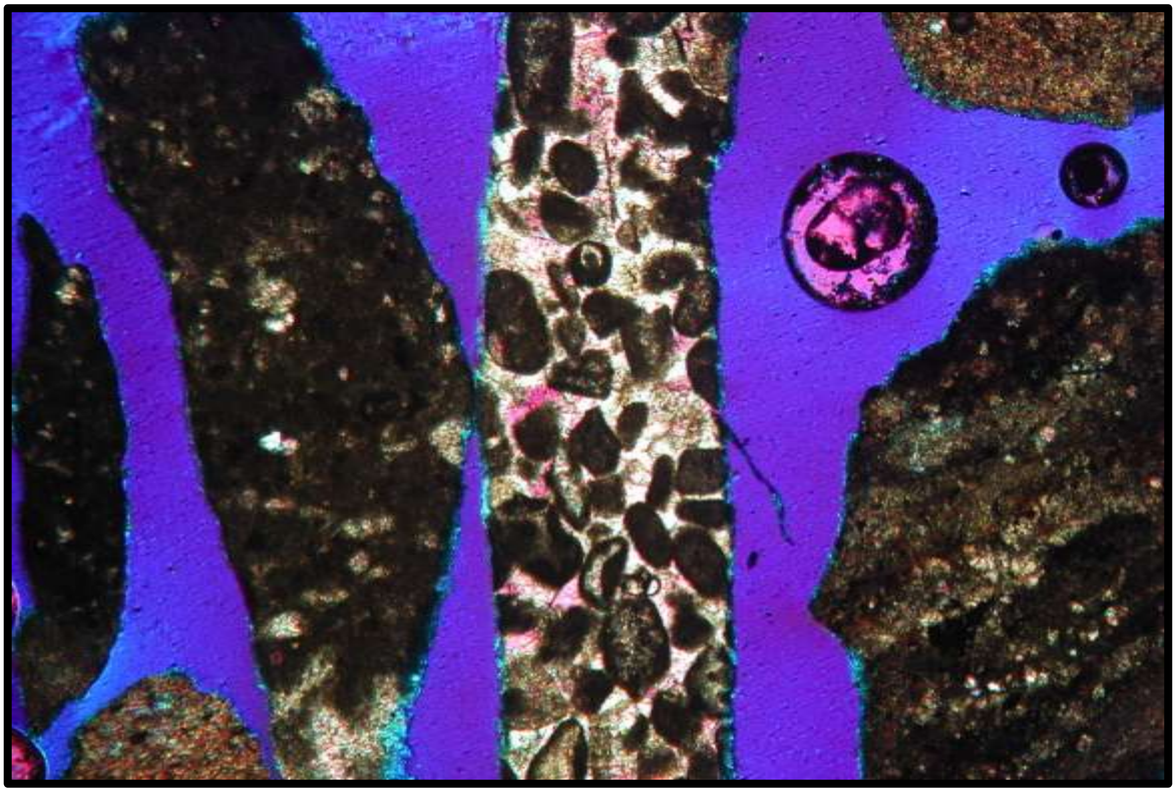

Figure 31 Sample from 20,430-20,459 feet. Transmitted light photomicrograph of carbonate rocks.

Skeletal grains cemented in sparry calcite (center) and packstone. Field of view 3 mm.

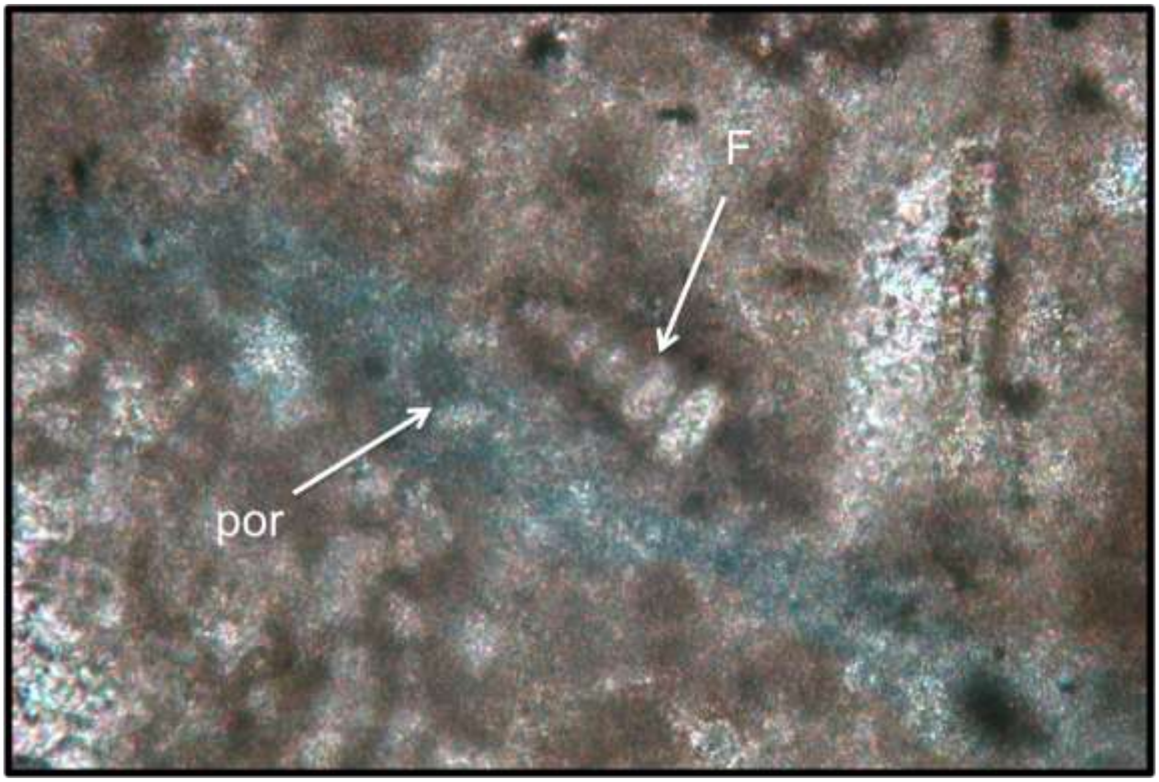

Figure 32 Sample from 20,430-20,459 feet. Transmitted light photomicrograph of porosity.

Uniserial foraminfera (F) cemented in micrite with porosity (por). Porosity appears blue. Field of view 0.75 mm.

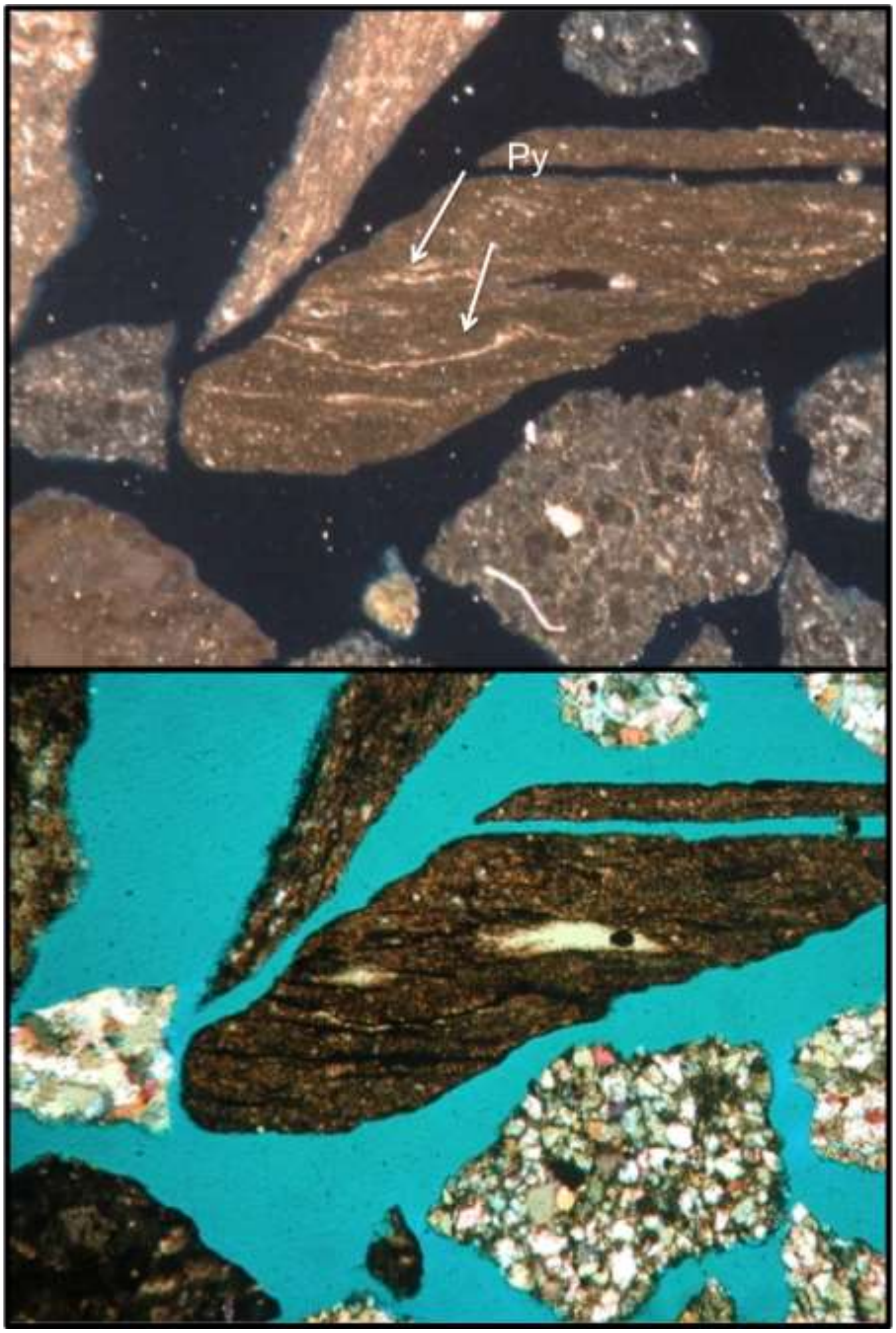

Figure 33 Sample from 20,520-20,549 feet. Photomicrograph of mudstone with pyrite.

Reflected light photomicrograph (top) of pyrite (Py) between mudstone layers. Field of view 3.0 mm. Transmitted light photomicrograph (bottom) of quartz sandstone and mudstone.

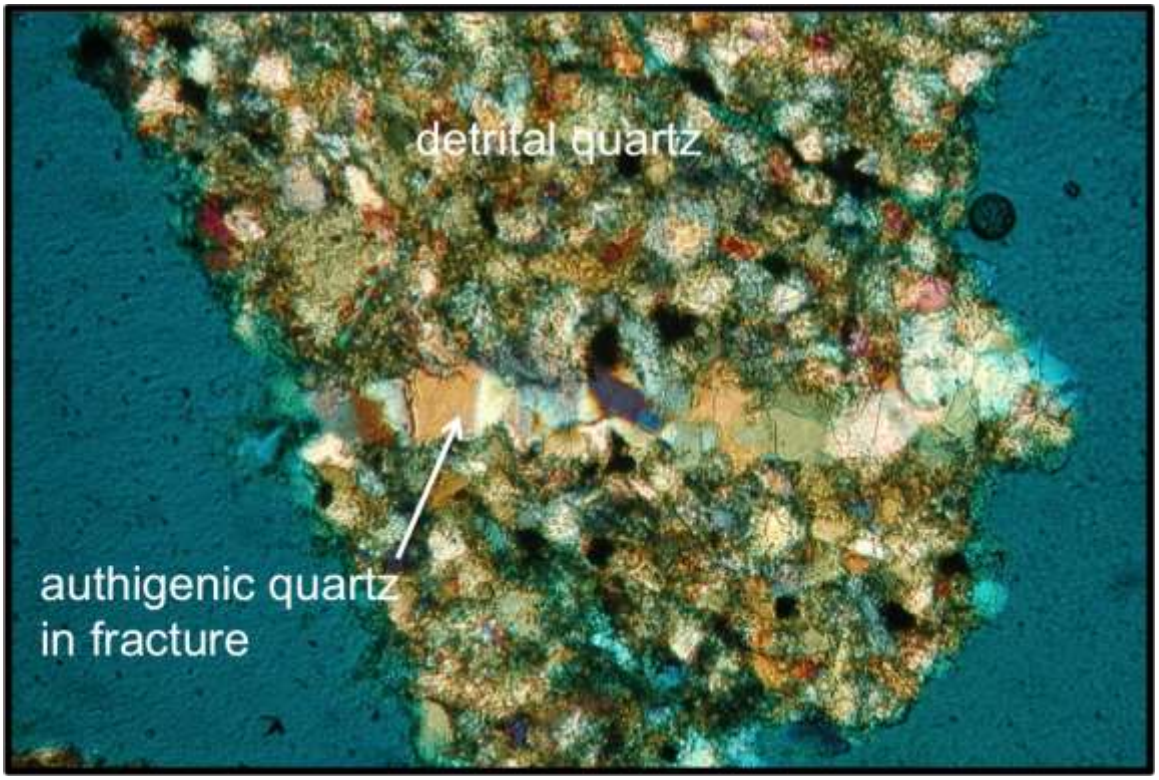

Figure 34 Sample from 20,520-20,549 feet. Transmitted light photomicrograph of sandstone.

Detrital quartz grains in sandstone with authigenic quartz filling fracture. Field of view 1.5 mm.

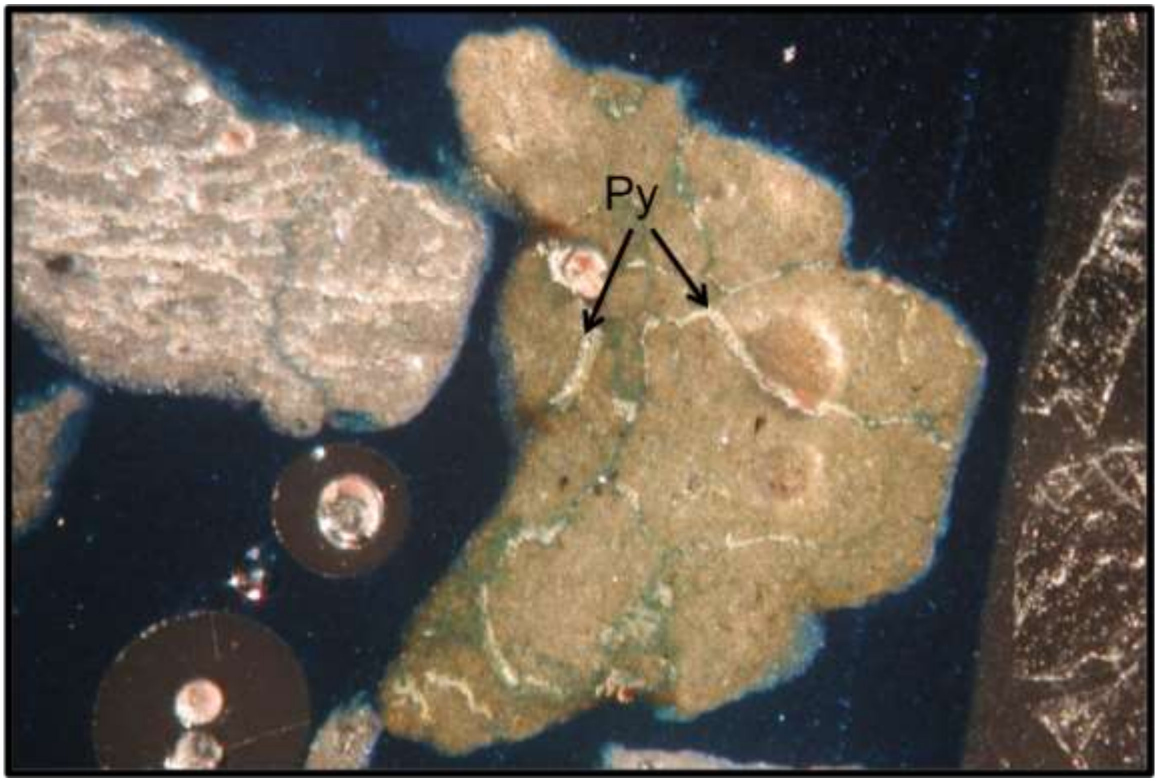

Figure 35 Sample from 20,600-20,639 feet. Reflected light photomicrograph of pyrite.

Pyrite (Py) has gold metallic luster in reflected light. Field of view 3 mm.

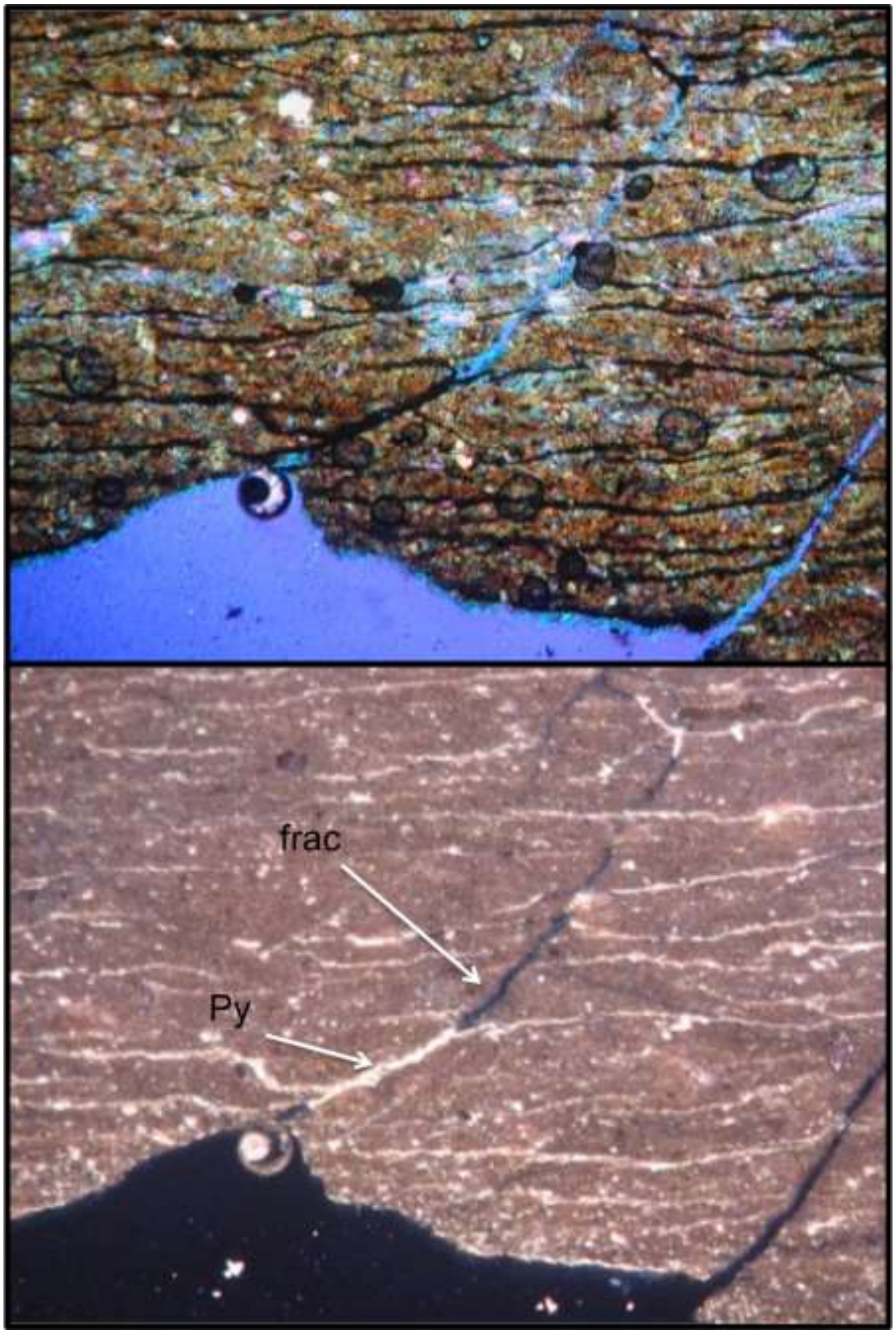

Figure 36 Sample from 20,690-20,699 feet. Photomicrograph of mudstone.

Transmitted light micrograph of fracture network in calcareous mudstone (top). Reflected light photomicrograph of abundant pyrite (pyr) filling fractures (frac) in calcareous mudstone (bottom). Field of view 1.5 mm.

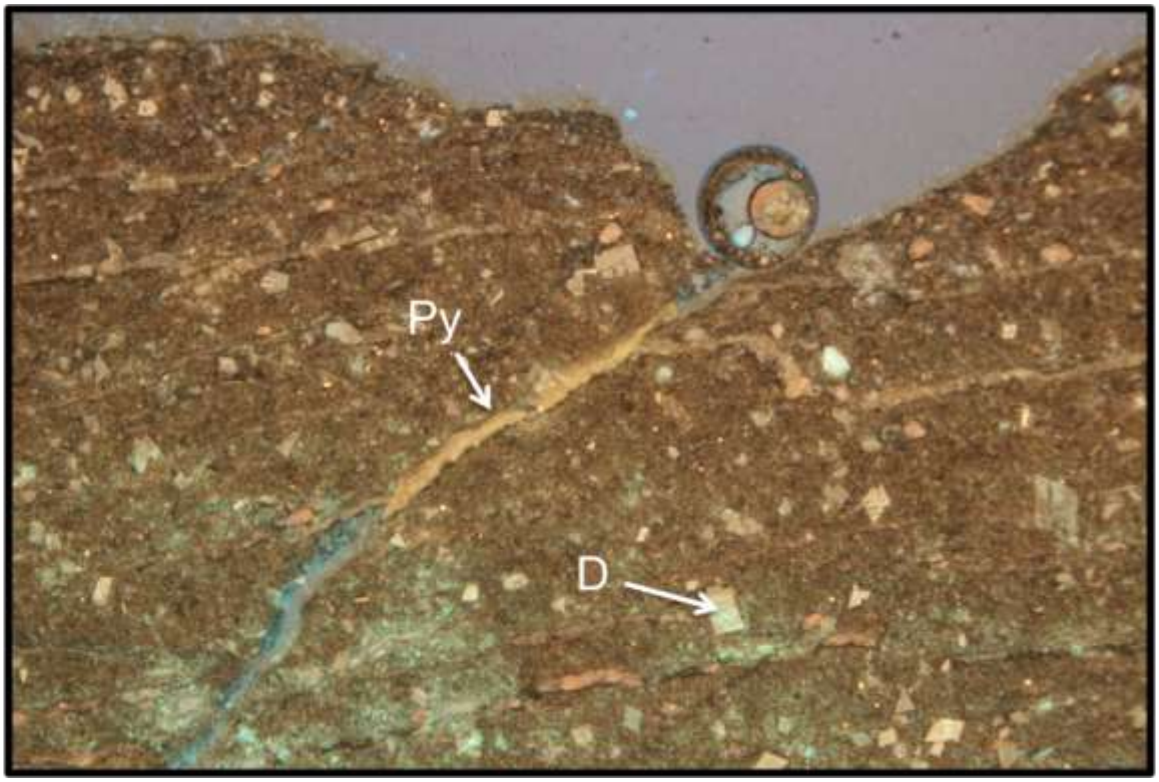

Figure 37 Sample from 20,690-20,699 feet. Photomicrograph of pore-filling pyrite.

Combined transmitted and reflected light micrograph of dolomite crystals (D) and authigenic pore filling pyrite (Py). Field of view 1.5 mm.

Well Logs

Mud Log

The mud log from the Burkley-Phillips #1 well was examined for lithology and any indication of hydrocarbons. Lithology ranged from a shaley limestone with sandstone pulses at the top of the Dorcheat Formation near 19,300 feet to a nearly pure mudrock with small amounts of sandstone and dolomite at the top of the Bossier Formation near 20,000 feet. Pyrite was noted throughout the studied interval.

The only indication of hydrocarbons, also known as a show, indicated on the mud log occurred from 19,670 to 19,700 feet (Fig. 38). The lithology in which the show occurred was composed of a slightly fossiliferous limestone with interstitial calcite. The show was poor, only indicating faint fluorescence in the cuttings., The logger makes note of faint hydrocarbon shows elsewhere in the log that may be due to gas the driller used to test the flow.

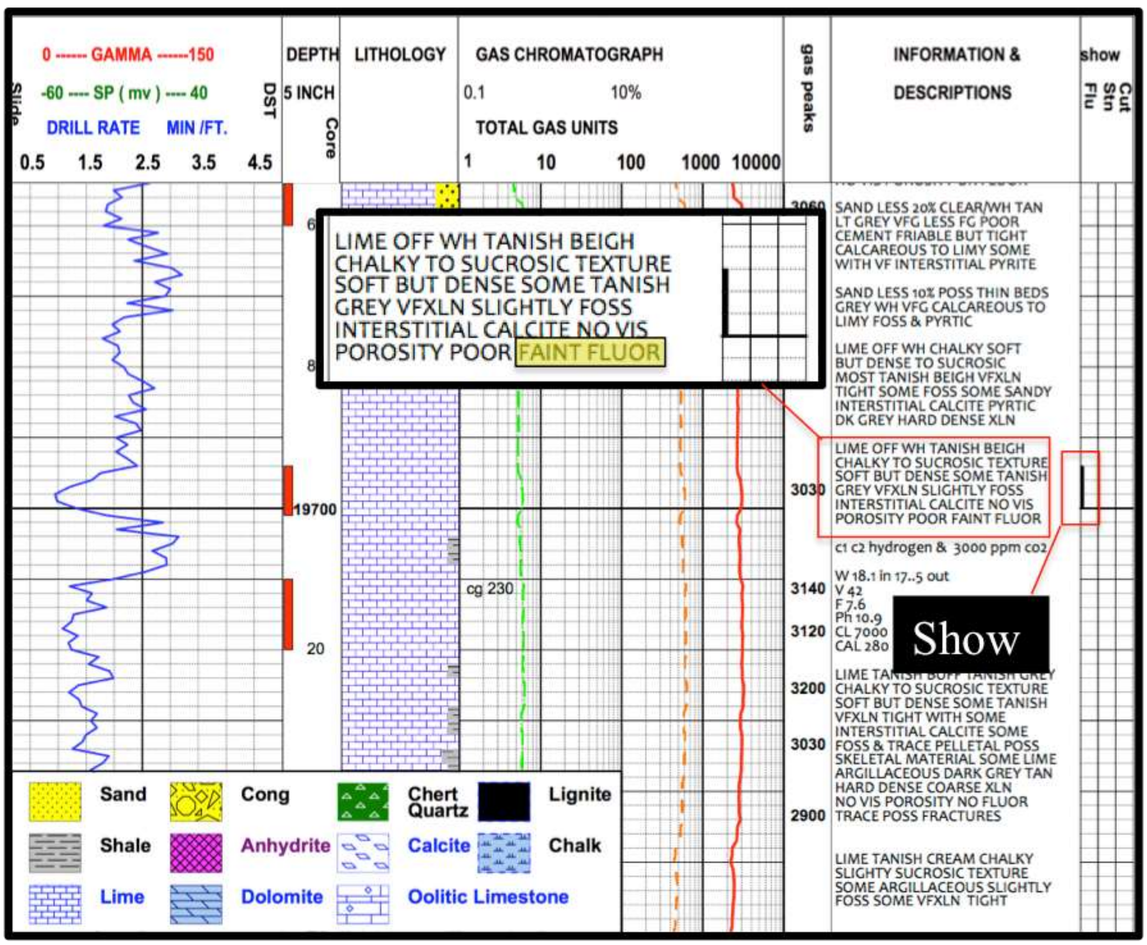

Figure 38 Burkley-Phillips #1 mud log show.

Mud log performed my J.M. Santone, Shreveport, Louisiana, courtesy of Vision Exploration LLC, Jackson, Mississippi. Faint florescence in limestone cuttings from 19,670 to 19,700 feet deep indicating presence of hydrocarbons.

The gas chromatograph log indicates the presence of methane and ethane. The logger makes notes of abundant CO_2. Intervals containing traces of H_2S are also noted.

Wireline Logs

Tiff images of scanned paper wireline well logs with gamma ray, spontaneous potential, and resistivity tracks were downloaded form the Mississippi Oil and Gas Board and Louisiana Department of Natural Resources websites. A composite Schlumberger Shale Gas Analysis log with lithology was provided by Mainland Resources, Inc. The gamma ray signature was the primary track that was used to define the top of the Dorcheat Member and Shongaloo Member of the Schuler Formation, and Bossier Formation in the study area.

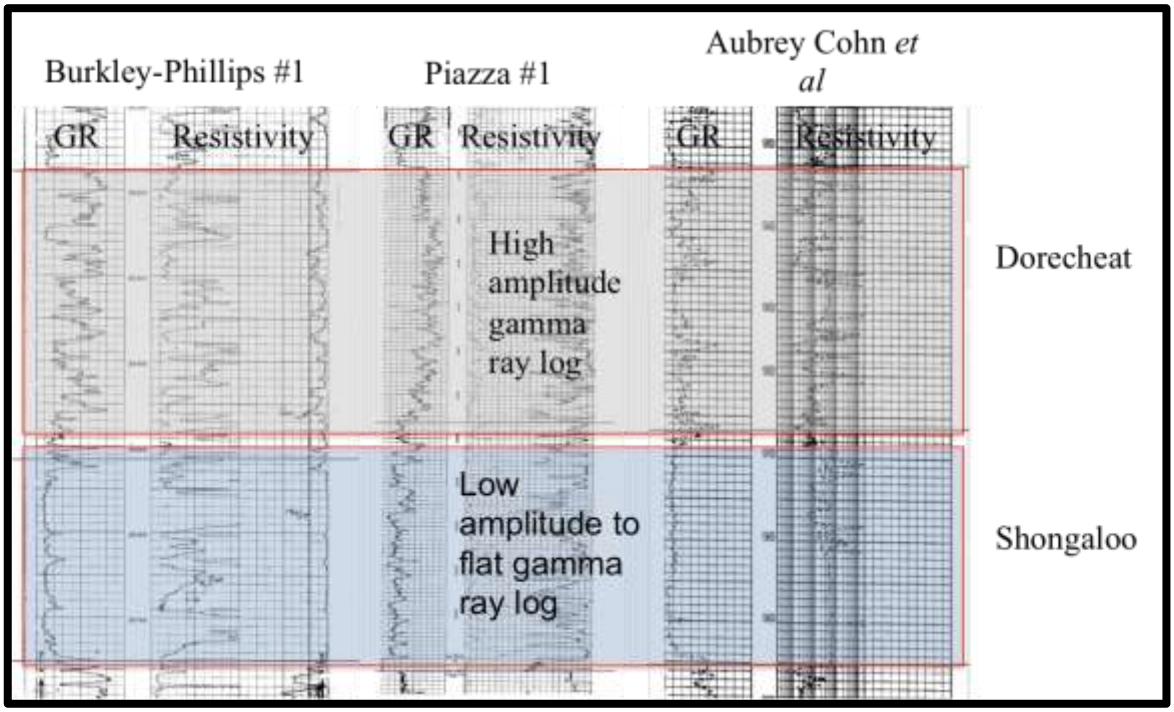

Figure 39 Gamma ray (GR) log signatures.

The Dorcheat Member shows a high-amplitude, gamma ray log with many sharp peaks compared to the low-amplitude, mostly flat gamma ray log of the Shongaloo Member.

Formation tops were picked based on the scout cards[1] associated with the Aubrey Cohn et al. and Piazza #1 wells. The Aubrey Cohn *et al.* and the Burkley-Phillips #1 well had nearly identical and easily identifiable gamma ray signatures for the Dorcheat Member, Shongaloo Member and the top of the Bossier Formation (Fig. 39). The Piazza #1 had a thickened Schuler Formation section compared to the condensed Burkley-Phillips #1 and Aubrey Cohn *et al.* Schuler Formation sections. This thickening can be

[1] A brief report about a well from the time it is permitted through drilling and completion. A scout ticket typically includes the location, total depth, logs run, production status, and formation tops. (Pirie, 2014)

seen on a cross-section that has been flattened on the top of the Dorcheat Member of the Schuler Formation (Fig 40).

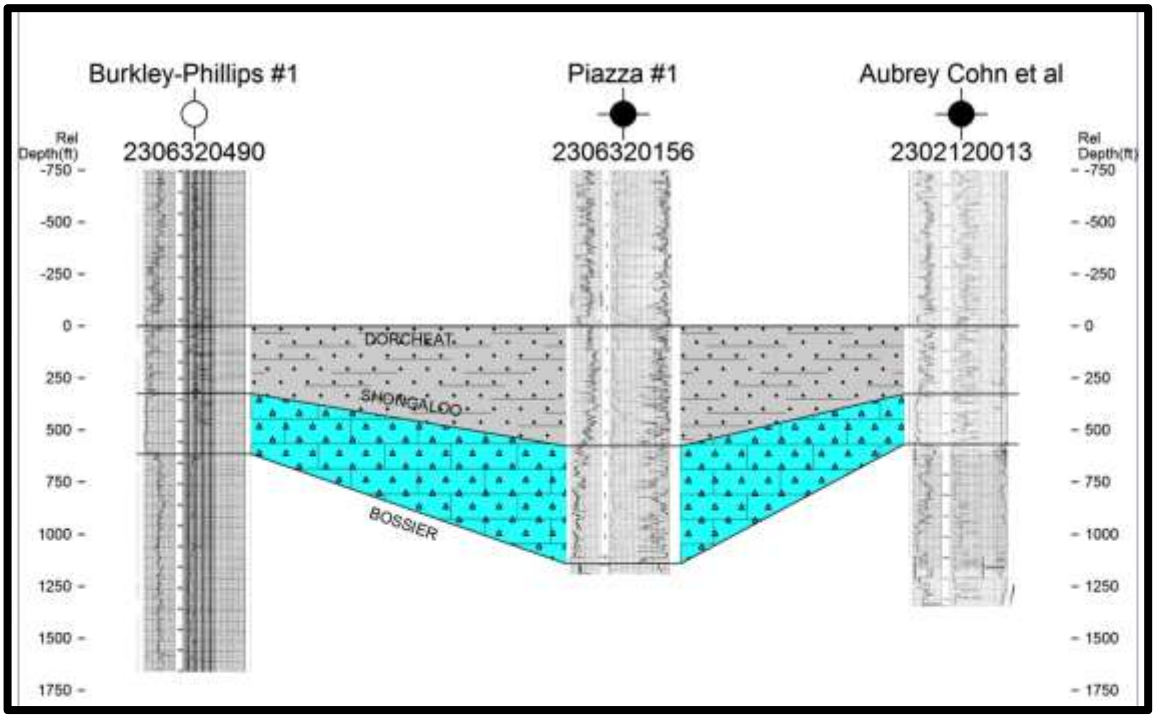

Figure 40 Stratigraphic cross section flattened on top of Dorcheat Member

Piazza #1 shows a thickened Schuler Formation (Dorcheat and Shongaloo Members).

Burkley-Phillips #1 Core

Geochemical Results

Mainland Resources Inc. of Houston, Texas provided geochemical data. Core Laboratories conducted a full geochemical workup using Rock Eval Pyrolysis on a full core taken from 20,420 to 20,441 feet deep within the Bossier Formation (Table 2). During Rock Eval Pyrolysis, a sample is heated in an inert atmosphere. During heating, hydrocarbons already present (S1) are volatilized and measured followed by kerogen in place (S2). CO_2 generated during heating is recorded as the third peak (S3) (Peters and Cassa, 1994).

Within the cored interval, Total Organic Carbon (TOC) ranged from 0.86% to 1.1%. Free hydrocarbons (S1) were 0.02 mg hydrocarbons/g for all samples. Hydrocarbons generated through thermal cracking of nonvolatile organic matter (S2) ranged from 0.09 to 0.1 mg hydrocarbons/g. The amount of CO_2 per gram of rock (S2) ranged from 0.06 mg CO_2/g to 1.33 mg CO_2/g.

Table 2 Burkley-Phillips #1 core geochemical report.

Depth ft.	Sample Wt. mg	TOC wt% HC	S1 mg HC/g	S2 mg HC/g	S3 mg CO2/g
20427.8	99.5	1.1	0.02	0.1	0.06
20431.7	100.3	0.86	0.02	0.1	0.06
20434	99	1.02	0.02	0.09	1.33

Depth ft.	Tmax ° C	HI S2x100/TOC	OI S3x100/TOC	PI (S1/(S1+S2))
20427.8	364.3	9.09090909	5.45454545	0.16666667
20431.7	371.4	11.627907	6.97674419	0.16666667
20434	438.3	8.82352941	130.392157	0.18181818

Note high S3 readings for the sample from 20,434 feet deep.

T_{max}, the temperature at which the maximum amount of S2 hydrocarbons are generated during Rock-Eval pyrolysis (Peters and Cassa, 1994), ranged from 364.3° C to 438.3° C, which places the thermal maturation of the organic matter present in the early mature stage (Tissot and Welte, 1984).

Porosity and Permeability

Porosity in the cored section ranged from 2.47% to 4.23% (Table 3). Permeability ranged from below the measuring threshold of the machine to 0.0002 md. No oil was found in pores.

Table 3 Burkley-Phillips #1 porosity and permeability

Depth (ft)	Stress (psig)	Porosity (%)	Klinkenberg (md)	Kair (md)	b(air) psi
20419.00	1200	2.58	NA	NA	NA
20423.00	1200	2.47	.0001	.0005	323.19
20429.90	1200	4.23	.0002	.001	245.88

Depth (ft)	Beta ft(-1)	Alpha (microns)	Oil % Pore Volume	Water	Density (g/cm3)
20419.00	NA	NA	0.0	34.4	2.692
20423.00	2.01E+18	3.57E+05	0.0	41.1	2.700
20429.90	2.41E+17	1.31E+05	0.0	33.7	2.718

Permeability was below the measurement range of the testing equipment for the sample from 20,419 feet deep for both Klinkenberg and Kair permeability.

Bottom Hole Temperature

Bottom hole temperatures were recorded on the well logs for the Aubrey Cohn *et al.* and Burkley-Phillips #1 well. The Piazza #1 well did not have a recorded bottom hole temperature. The bottom hole temperature for the Aubrey Cohn *et al.* well was 400° F (204° C). The bottom hole temperature for the Burkley-Phillips #1 well was 409° F (209° C). The temperatures recorded are at the upper end of the dry gas window (300-430° F, 150-220° C) for thermal maturation (Tissot and Welte, 1984).

Cross Sections

Raster well logs from seven key wells in the study area were loaded into IHS Petra and depth calibrated. The depth calibrated well logs were used to create two cross sections (Fig. 1).

The structural A-A’ cross section shows a general updip direction from the southwest to the northeast, with a dip at the Aubrey Cohn *et al.* well (Fig 41). The Dorcheat Member and Shongaloo Member thinned over the Burkley-Phillips #1 and Aubrey Cohn *et al.* wells compared to the Piazza #1 and McNair *et al.* #1 wells (Fig. 42).

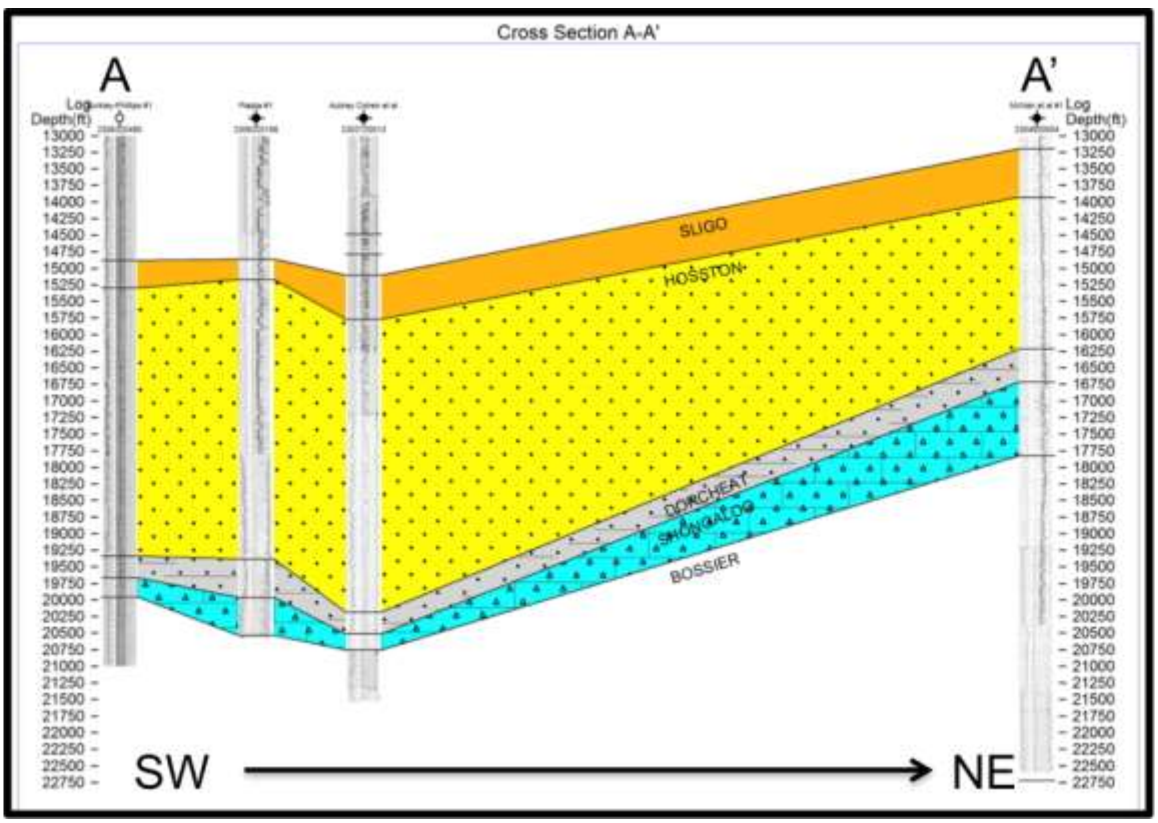

Figure 41 A-A’ structural cross section

Updip for all formations shown is generally southwest to northeast, with a dip at the Aubrey Cohn *et al.* well.

When flattened on the top of the Dorcheat Formation, the A-A’ cross section indicates that the area around the Burkley-Phillips #1 and the Aubrey Cohn *et al.* wells were elevated compared to the Piazza #1 and the McNair *et al.* #1 during Cotton Valley Group deposition (Fig 6).

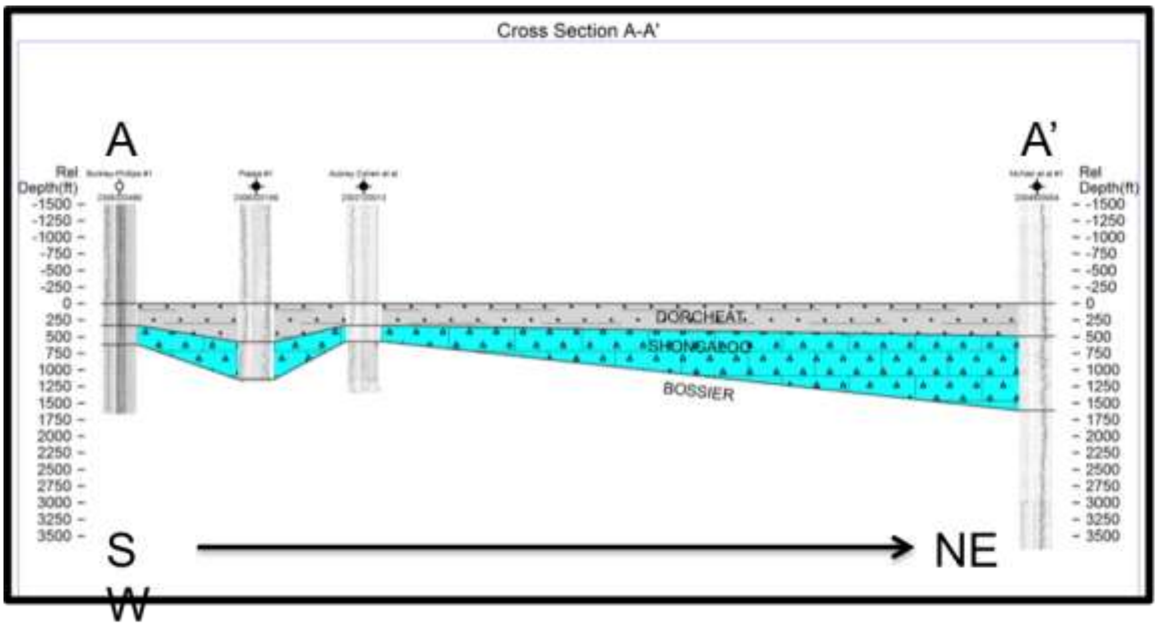

Figure 42 A-A’ structural cross section.

Cross section flattened on the top of the Dorcheat Member indicating paleo-lows in area of Piazza #1 and McNair *et al* #1 wells.

The movement of basement features since Cotton Valley Group deposition is apparent on a three well cross section comprised of the Burkley-Phillips #1 well, Piazza #1 well and Aubrey Cohn *et al* well. The structural cross section shows a thickened Schuler Formation at the Piazza #1 well compared to the wells to the northeast and southwest (Fig. 43). The stratigraphic cross section, when flattened on the top of the

Dorcheat Member, shows the paleo-low that likely existed during the time of Cotton Valley Group deposition (Fig. 44).

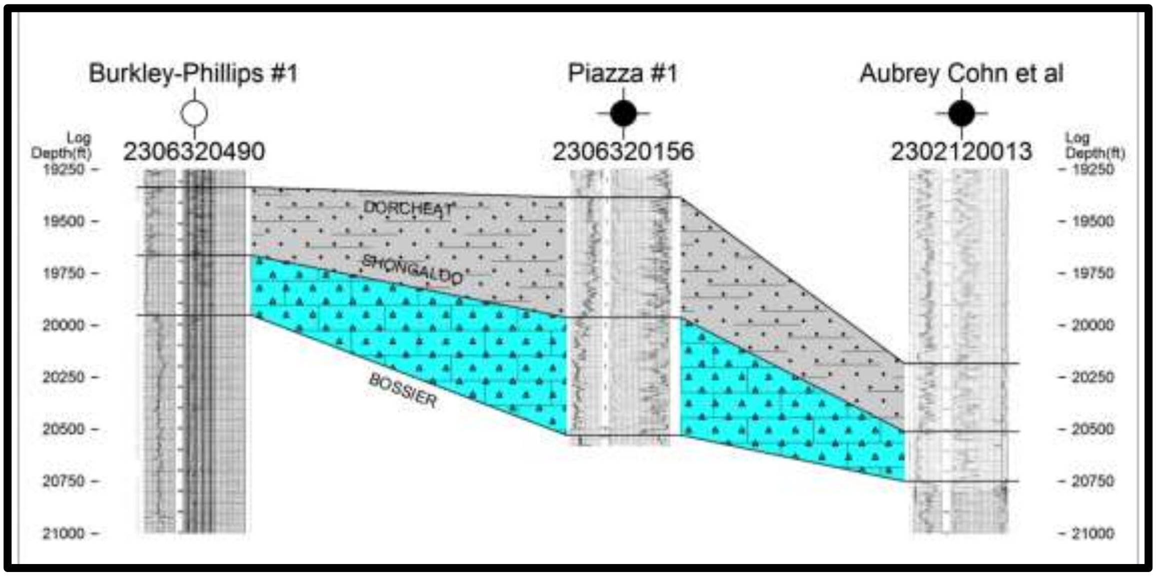

Figure 43 Three well structural cross section from A-A'.

Present day structure of the Cotton Valley Group.

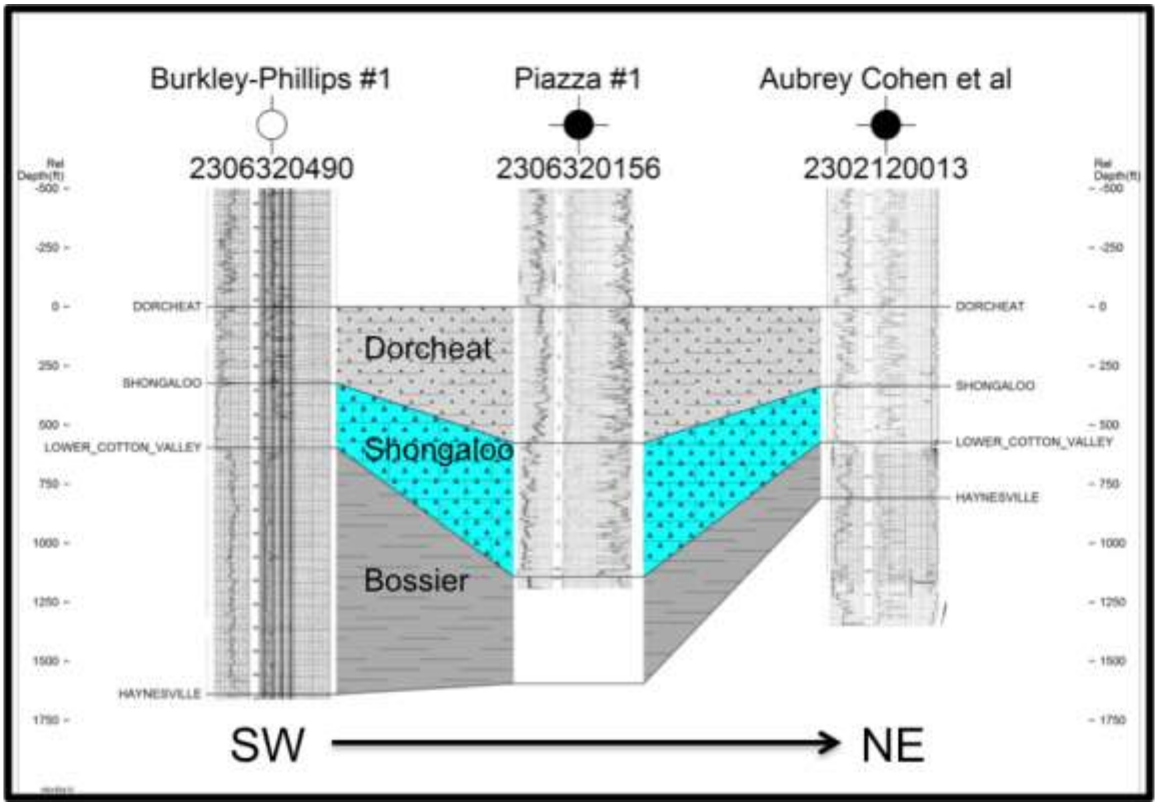

Figure 44 Three well stratigraphic cross section from A-A'.

Paleo-low at the time of deposition in the vicinity of the Piazza #1 well leads to thickened Cotton Valley Group.

The cross section from B-B' runs roughly south to north from Lincoln County, Mississippi through Madison Parish, Louisiana, terminating in Issaquena County, Mississippi (Fig 1). The structural cross section indicates a general up-dip direction in the Cotton Valley Group from south to north, with a peak on the Wall #1 well in Madison Parish, Louisiana (Fig 45). When flattened on the top of the Dorcheat Member of the Cotton Valley Formation, the paleo-lows, based on formation thickness, are in the area of the Wall # 1 well and the Aubrey Cohn *et al.* well during Cotton Valley Group deposition (Fig. 46).

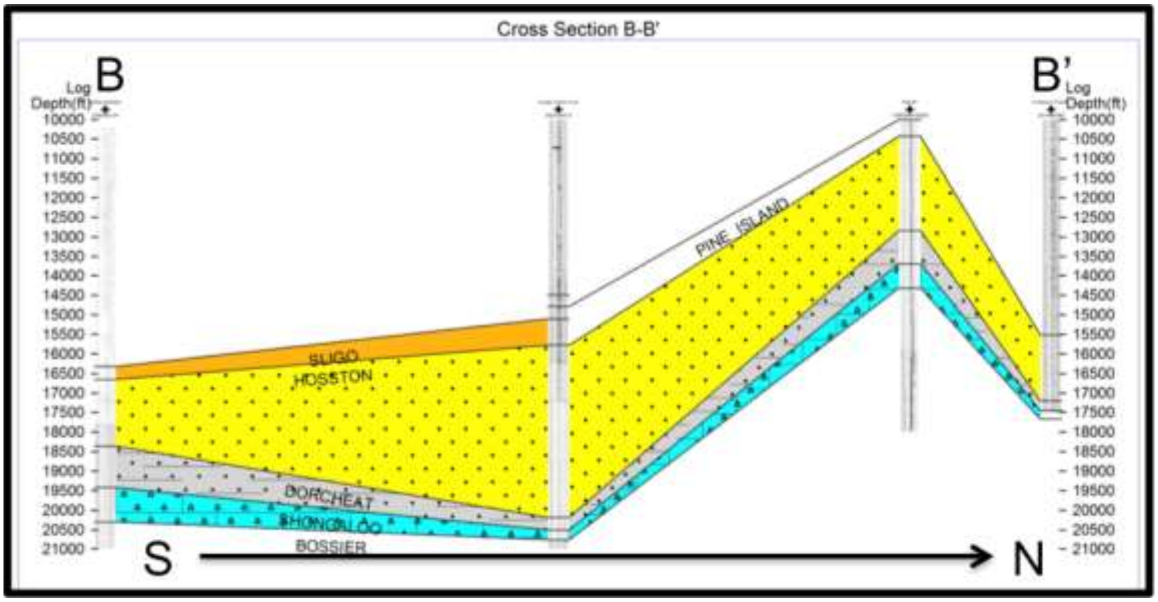

Figure 45 B-B' structural cross section

Wall #1 well marks present day high point of Cotton Valley Formation within the study area.

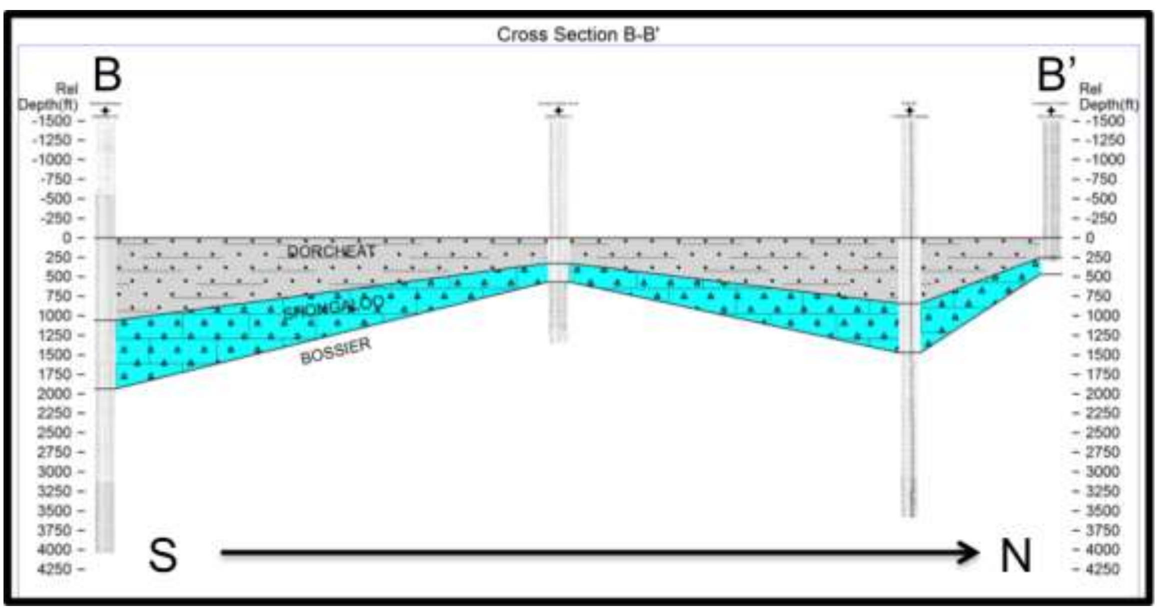

Figure 46 B-B' Stratigraphic cross section.

Cross section shows paleo-lows to the north and south of the Aubrey Cohn *et al.* well.

CHAPTER V

DISCUSSION

Sequence Stratigraphy

Analysis of the thin sections and well logs helped aid in the proper placement of the studied Cotton Valley Group interval in the sequence stratigraphic model (Fig. 47). The general trend in the studied interval was coarsening upward, indicating a gradual movement to a higher-energy environment as sediment was deposited. The Piazza #1 well penetrated the well-laminated, calcareous mudstone of the Bossier Formation at its maximum depth of 20,699 feet. According to the sequence stratigraphic model set forth by Hammes *et al* (2011) the contact between the Haynesville and Bossier Formations is placed at the Maximum Flooding Surface (MFS) immediately above the transgressive Haynesville Formation.

The Cotton Valley Group was deposited as part of a Highstand System Tract (HST). As sea level continued to fall, the low-energy Bossier Formation mudstones and shales coarsened upward into the packstones of the Shongaloo Member and the sandstones and mudstones of the Dorcheat Member. Siliciclastic intervals and abrupt changes in lithology within the Schuler Formation may have been caused by the proximity of the study area to the ancestral Mississippi River delta system (Moore, 1983).

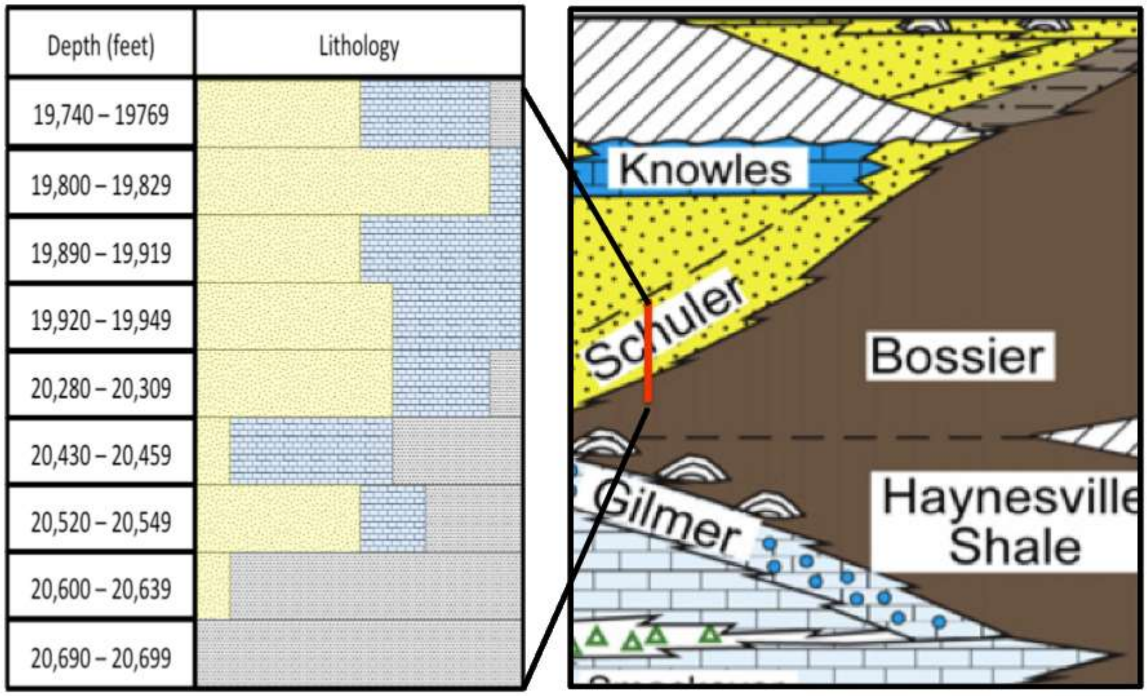

Figure 47 Study interval location in sequence stratigraphic framework.

The study interval from the Piazza #1 well (red vertical line) fits in the Bossier and Schuler Formations above the maximum flooding surface that separates the Haynesville and Bossier Formations (Modified from Hammes and Frebourg, 2012).

Electron Microscopy Analysis

Because shale samples were preferentially chosen for imaging with the scanning electron microscope as opposed to sandstone or carbonate samples, the results do not aid in describing the general lithology of the studied interval or its placement in the sequence stratigraphic framework. The results do aid in identification of the type of clay minerals present as well as indications of porosity within the clay-rich units. Also, the pyrite framboids could be imaged and porosity around framboids easily identified. Other minerals such as rutile were noted in limited quantities and positively identified using the Energy Dispersive X-Ray (EDX) spectrum.

Illite is the dominant clay mineral found in the cuttings from the Piazza #1 well. The morphology of the illite was laminated, which was interpreted as being of detrital origin (Fig. 4). Laminated, detrital smectite (Fig. 7) and trace amounts of kaolinite (Fig. 23) were also identified. Very little porosity was found in association with clay minerals, with notable porosity occurring in only a few instances where authigenic, webby clay minerals fill pore spaces (Fig. 21). Pyrite was found at all depths. Pyrite framboids were usually found in clusters, thereby creating porosity between framboids due to their roughly spherical shape.

Rutile (TiO_2) crystals were found in one cutting and verified with the EDX spectrometer (fig. 19, 20). The rutile could be detrital, digenetic, or authigenic, though cases of authigenic rutile in sedimentary rocks are very rare. Its presence suggests that there may have been hydrothermal activity in the Cotton Valley Group (Meinhold, 2010). Alternatively, the authigenic formation of rutile could be due to basinal brines.

Petrographic Microscopy Analysis

Examination of the thin sections from the Piazza #1 well, revealed several aspects of the units studied. First, porosity was very limited; second, pyrite was abundant in framboids and filling pores and fractures; third, the lithology of each depth range is somewhat uncertain given the variables of examining cuttings as opposed to core.

The porosity was very limited in the majority of the cuttings, regardless of depth, matrix lithology, or cement type. Porosity was observed in the thin sections from 20,130-20,159 feet in intra-peloidal voids in the packstone from (Fig. 28). Porosity was also observed in the lowest depth from which cuttings were available, 20,690-20,699 feet, where it occurred in fractures in the laminated mudstone of the Bossier Formation. Additionally, porosity occurred around pyrite framboids throughout the studied interval.

Pyrite was observed in every depth in the studied interval, both in framboids and pore-filling morphologies. Due to the rounded shape of pyrite framboids and their tendency to be found in clusters, they create porosity (Fig. 26). However, any positive effect in porosity caused by the framboids appeared to be negated by the presence of pore-filling pyrite (Fig. 26, 30, 33, 35, 36). Pore-filling pyrite was present in nearly all intervals in the studied section of the Piazza #1 well and noted in the mud log from the Burkley-Phillips #1 well.

It must also be noted that working with well cuttings is at best inexact and can involve the need to make an educated guess as to the dominant lithology for a particular depth. As drilling mud carries the cuttings to the surface, it can pick up cuttings from much shallower sections in the well bore. Each 30-foot interval contained many types of lithology. In some cases there was detrital quartz sandstone, authigenic quartz, calcareous mudstone, wackstone, and packstone within the same interval.

Well Logs

Burkley-Phillips #1 Mud Log

The hydrocarbon show that occurred in the mud log from 19,670-19,700 feet was noted as faint florescence in the loggers notes (Fig. 36). When the mud log and the Schlumberger Shale Gas Analysis well log were compared, a very faint hydrocarbon show was indicated at approximately the same depth on the Neutron Density/Porosity log. Considering that no other shows indicated on the mud log, even where the Neutron

Density/Porosity log indicate possible shows, the mud log hydrocarbon show may be considered an error.

The gas chromatograph on the mud log registered methane, ethane and iso-butane throughout the Bossier Formation. Because there are no spikes in the gas chromatograph in the Bossier Formation that would indicate drilling through a gas reservoir, the background gas is likely due to penetrating gas-bearing sand at a shallower depth.

Porosity and Permeability

The core from Burkley-Phillips # 1 was taken from within the Bossier Formation. Porosity ranged from 2.58-4.23%, with two of the three samples having approximately 2.5% porosity (Fig. 2). This compares poorly with the average Haynesville Formation reservoirs (8-16%) and Bossier Formation reservoirs (9-18%) in Texas and Louisiana (Mancini *et al* 2008). The low porosity of the Bossier Formation is likely due to compaction from over 20,000 feet of overburden as well as the layered morphology of the detrital illite that is the main component of the formation.

Permeability was less than 0.001 md for all samples, and one sample was below the measurement threshold for the machine (Table 2). This is several orders of magnitude lower than Haynesville and Bossier Formation reservoirs in Louisiana and Texas, which tend to have permeability measurements in the range of 1-400 md (Mancini *et al* 2008) . Such low permeability is due to compaction from overburden, as well as pyrite fills in fractures.

Low porosity and permeability would make production in an area such as this one difficult. Low porosity leaves very little room for hydrocarbons per volume of rock. In addition, low permeability reservoirs such as these would require expensive, multi-stage hydraulic fracturing. The depth of the potential reservoirs described herein would compound the cost.

Geochemical Analysis

Total Organic Carbon (TOC) ranged from 0.86-1.02% (Table 1). The TOC of the Bossier Formation in at the Burkley-Phillips #1 well is low compared to the productive Bossier Formation reservoirs in Louisiana and Texas, which have a TOC that ranges from 1- 8.5% (Hammes and Frébourg, 2012). Gas-prone source rocks generally have a TOC >0.5% (Hunt, 1996).

Other geochemical indices for the Bossier Formation at the Burkley-Phillips #1 well are also low. The Rock Eval analysis performed by Core Laboratories generated S1, S2, S3 values that are used to calculate the Hydrogen Index (HI), Oxygen Index (OI) and Production Index (PI) (Table 2). All indices were very low compared to productive shale gas formations, except for the S3 value for the sample from 20,434 feet deep, which was almost 20 times as high as S3 values for the sample two feet higher in the core. According to Emis and Kvenvolden (1986), abnormally high S3 readings can be caused by contamination of the sample, migrated oil or may be caused by ratios of small, inaccurate numbers.

The amount of hydrocarbons present in the sample (S1) from the Burkley-Phillips well was 0.02 mg HC/g in the cored interval. Values over 1 mg HC/g a normally considered indicative of an oil show. The amount of HC generated by thermally cracking nonvolatile organic matter (S2) ranged from 0.09-0.1 mg HC/g, indicated that all organic matter that was present within the rock had already been converted to hydrocarbons.

Typical shale gas reservoir formations have a HI of >150 mg HC/g (Slatt and Rodriguez, 2012). The samples from the Burkley Phillips #1 core had a HI of 8.8-11.2 mg HC/g.

T_{max} is similar to vitrinite reflectance, in that it assesses the maturation of organic matter in a sample. The T_{max} for the samples from Burkley-Phillips #1 ranged from 364.3° C to 438.4° C, which places the maturity in the under mature zone. When extremely small amounts of organic matter are present, the T_{max} values can be under-represented.

The sum of the geochemical data provided by Core Laboratories points to two possible scenarios: 1) the Bossier Formation in the vicinity of the Burkley-Phillips #1 well was largely void of organic matter during the time of deposition or 2) the Bossier Formation in Jefferson County, Mississippi was subjected to enough heat and pressure that all organic matter was thermally cracked to hydrocarbons and then volatilized out of the formation.

Cross Section Interpretation

The cross sections show both the present day formations (structural cross sections) and the relief of the basin at the time of deposition (stratigraphic cross sections). By comparing the two, areas of relative uplift and subsidence can be inferred. A thickened Cotton Valley Group represents deposition in a paleo-low while a condensed section was deposited over a paleo-high. By comparing the structural and stratigraphic cross sections, depositional history and movement of basement features can be assessed.

Present-day formation tops (Fig. 40) indicate that there has been uplift to the northeast toward the McNair *et al* #1 well. This uplift was likely caused by the activation of the Jackson Dome during the late Cretaceous Period (Salvador, 1991). A lower amplitude uplift occurred simultaneously to the southwest in the area of the Burkley-Phillips #1 well. This area is near a basement feature known as the Adams County High (Fig 2). Recent USGS research suggests that igneous activity in the Adams County High reactivated during the Late Cretaceous Period, which caused the slight uplift seen in the structural cross sections today (Fig. 42)(Valentine *et al*, 2014).

The B-B' structural cross section (Fig. 44) runs roughly south-north and shows that up to 3,000 feet of uplift occurred after the time of Cotton Valley Group deposition in the Upper Jurassic in the area of the Monroe Uplift. The stratigraphic cross section (Fig. 45) shows deposition of Cotton Valley Group is thickest basinward, tapers over the Adams County High, thickens again in the area of the present-day Monroe Uplift (Wall #1 well), and thins as it reaches the edge of the basin to the north.

Thermal Maturity Timing

Understanding the timing of hydrocarbon generation, expulsion, and migration can help to explain why certain areas are rich in hydrocarbons and other areas, such as the primary study area in Jefferson County, lack commercially profitable amounts of hydrocarbons. According to Mancini *et al* (2001) hydrocarbon maturation for the Upper Jurassic carbonate mudstones began in Cretaceous Period and continued into the Tertiary Period. Expulsion also began in the Cretaceous Period and ended in the Tertiary Period. Hydrocarbon migration was maximized during the late Cretaceous Period.

One way to graphically plot these data is to create a critical moment chart (Fig. 46). This chart shows the timing of source rock deposition hydrocarbon maturation, expulsion and plots the time of proposed reactivation of the Adams County High. If the Adams County High is an igneous intrusion that reactivated at the same time of the

Jackson Dome, 65-95 ma, then it could have led to elevated thermal gradients in the immediate area (Valentine *et al* 2014). The elevated thermal gradients could have led to rapid maturation, expulsion, and migration of hydrocarbons sourced from Jurassic source rock such as the Smackover, Haynesville, and Bossier formations.

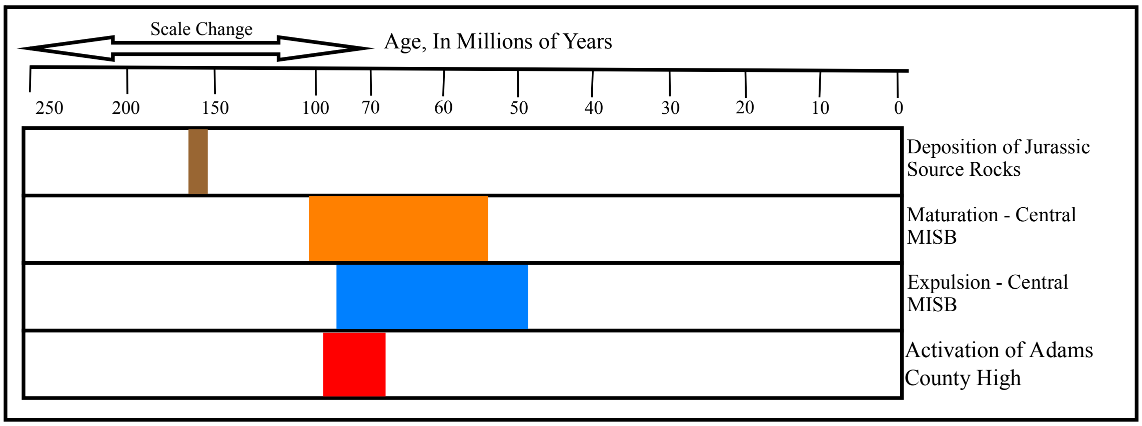

Figure 48 Critical moment chart for Jurassic source rocks.

Maturation and expulsion would rapidly cease in proximity to an igneous intrusion, such as a reactivated Adams County High.

There are many productive oil and gas fields on top of the Adams County High. However all of the production in the area is sourced from the Upper Cretaceous, Cenomanian Stage Tuscaloosa Formation and younger formations (Mississippi Department of Environmental Quality, 2014). The Tuscaloosa Formation did not enter the maturation window until the Tertiary Period, after the igneous activity in the area had ceased (Mancini *et al,* 2001). Based on the age of the formations producing in the area atop the Adams County High, as well as the accumulation of oil and gas fields in the same area, it appears as if the Adams County High created a broad dome for hydrocarbon accumulation before expulsion from tertiary reservoirs. Additionally, the accelerated maturation from the reactivation of the Adams County High did not negatively affect maturation of overlying Tertiary and younger sediments.

CHAPTER VI

CONCLUSIONS

The research performed in this project has led to three primary conclusions regarding the Bossier Formation in Jefferson County, Mississippi and the surrounding area.

- The Bossier Formation in Jefferson County, Mississippi was deposited in such a manner that very little organic matter was preserved.
- Porosity, permeability, and Total Organic Carbon in the Bossier Formation are very poor compared to productive shale reservoirs elsewhere in the Gulf of Mexico basin.
- Elevated thermal maturity and uplift of the Cotton Valley Group after deposition indicates the possibility of igneous activity in the Adams County High area in conjunction with the formation of the Jackson Dome.

CHAPTER VII

FUTURE RESEARCH

Data in the study area from within the Bossier Formation is very limited. The vast majority of the data compiled for this study came from well logs and cuttings that were originally produced over 30 years ago. Recent developments in seismic acquisition technology have made it possible to image basement features more accurately. A modern three-dimensional seismic study of the Adams County High area would yield valuable data and may aid in understanding how the Gulf of Mexico formed.

Additionally, a more in-depth study of the elevated thermal maturity in the Jurassic aged section of the Adams County High area would be extremely valuable. Valentine *et al.* (2014) conducted preliminary research as a part of their study of the Aptian age section in the Mississippi Salt Basin, but a study of the Jurassic age section could reveal more information. Much of this study could be completed using existing cores and cuttings to determine the aerial extent of the influence of the Adams County High. By determining how far away from the Adams County High thermal maturities are elevated, one could better determine where not to drill for deep hydrocarbon resources.

Finally, a core from the basement rock in the Adams County High would be invaluable. A core would reveal if the basement rock is similar to the Wiggins Arch, which is itself a remnant of the rifting of Africa from North America, or if the Adams

County High more closely resembles basement rock found elsewhere in the Gulf of Mexico basin.

REFERENCES

Baria, L. R., Stoudt, D. L., Harris, P. M., and Crevello, P. D., 1982, Upper Jurassic reefs of Smackover Formation, United States Gulf Coast. AAPG Bulletin, v. 66, p. 1449-1482.

Dahl, B., Bojesen-Koefoed, J., Holm, A., Justwan, H., Rasmussen, E., and Thomsen, E., 2004, A new approach to interpreting Rock-Eval S2 and TOC data for kerogen quality assessment: Organic Geochemistry, v. 35, p. 1461-1477.

Emeis, Kay-Christian, and Kvenvolden K.A., Shipboard organic geochemistry on JOIDES Resolution. Ocean Drilling Program, Texas A & M University, 1986.

Forgotson Jr, J. M., 1954, Regional stratigraphic analysis of Cotton Valley Group of upper Gulf coastal plain: AAPG Bulletin, v. 38, p. 2476-2499.

Gazzier C.A., Bograd, M.B.E., 1988. Structural features of Mississippi. Mississippi Department of Natural Resources Bureau of Geology. Scale 1:500,000.

Hammes, U., and Frébourg, G., 2012, Haynesville and Bossier mudrocks: A facies and sequence stratigraphic investigation, East Texas and Louisiana, USA: Marine and Petroleum Geology, v. 31, p. 8-26.

Hammes, U., Hamlin, H. S., and Ewing, T. E., 2011, Geologic analysis of the Upper Jurassic Haynesville Shale in east Texas and west Louisiana. AAPG bulletin, v. 95, p. 1643-1666.

Huc, A. Y. (1997). Petroleum geochemistry and geology: by JM Hunt. WH Freeman and Company, New York, 1996, i–xii+ 743 pp. ISBN 07167-2441-3 (hardcover).

Kaiser, M. J., 2012, Haynesville Shale Play Economic Analysis. Journal of Petroleum Science and Engineering, v. 82-83, p. 75-89.

Mancini, E. A., Li, P., Goddard, D. A., Ramirez, V., and Talukdar, S. C., 2008, Mesozoic (Upper Jurassic–Lower Cretaceous) deep gas reservoir play, central and eastern Gulf coastal plain. AAPG Bulletin, v. 92, p. 283-308.

Mancini, E. A., Puckett, T. M., Parcell, W. C., and Panetta, B. J., 1999, Topical reports 1 and 2, basin analysis of the Mississippi Interior salt basin and petroleum system modeling of the Jurassic Smackover Formation, eastern Gulf coastal plain. US Department of Energy Technical Report: Project Number DE-FG22-96BC14946,.

Mississippi Department of Environmental Quality, Mississippi County Oil and Gas Production Index Maps. http://geology.deq.ms.gov/energy/map.aspx, (accessed August 8, 2014)

Peters, K. E., and Cassa, M. R., 1994, Applied source rock geochemistry: Memoirs-American Association of Petroleum Geologists, p. 93-93.

Pirie, Gordon, 2014, Schlumberger Oilfield Glossary,http://www.glossary.oilfield.slb.com/ (accessed September 21, 2014).

Salvador A., 1991, Triassic-Jurassic, *in* Salvador, A. ed, The Gulf of Mexico Basin. Geological Society of America, The Geology of North America, v.J.

Sawyer, D. S., Buffler, R. T., Pilger Jr, R. H., 1991, *in* Salvador, A., The crust under the Gulf of Mexico Basin, The Gulf of Mexico Basin. Geological Society of America, The Geology of North America, v. J.

Soeder, D. J., 2012, The Successful Development of Shale Gas Resources in the United States. 41st Annual Eastern Section AAPG Meeting, Cleveland, Ohio.

Swain, F. M., 1944, Stratigraphy of Cotton Valley beds of northern Gulf coastal plain. AAPG Bulletin, v. 28, p. 577-614

Sydboten, B. D., Jr., and Bowen, R.L., 1987, Depositional environments and sedimentary tectonics of the subsurface Cotton Valley Group (Upper Jurassic), west-central Mississippi: Transactions of the Gulf Coast Association of Geological Societies, v. 37, p. 239-245.

Tissot, B.P. and D.H. Welte 1984. Petroleum formation and occurrence. 2nd Edition, Springer, New York. Waples, D.W. 1985. Geochemistry in Petroleum Exploration. Springer Verlag, Boston, 223 p.

Valentine, B. J., Hackley, P. C., Enomoto, C. B., Bove, A. M., Dulong, F. T., Lohr, C. D., and Scott, K. R., 2014, Organic petrology of the Aptian-age section in the downdip Mississippi Interior Salt Basin, Mississippi, USA: observations and preliminary implications for thermal maturation history: International Journal of Coal Geology, v. 131, p. 378-391

Wang, Q., Chen, X., Jha, A. N., and Rogers, H., 2014, Natural gas from shale formation – The evolution, evidences and challenges of shale gas revolution in United States: Renewable and Sustainable Energy Reviews, v. 30, p. 1-28

Wood, M. L., and Walper, J. L., 1974, The evolution of the interior Mesozoic basin and the Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions, v. 24, p. 31-41.