MUDSTONE CHARACTERIZATION AT A WORLD-CLASS CO_2 STORAGE SITE: KEMPER COUNTY ENERGY FACILITY, KEMPER COUNTY, MISSISSIPPI

By

CONN LEBONN ROBERT WETHINGTON

Bachelor of Science in Geology

Oklahoma State University

Stillwater, Oklahoma

2016

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2020

MUDSTONE CHARACTERIZATION AT A WORLD-CLASS CO_2 STORAGE SITE: KEMPER COUNTY ENERGY FACILITY, KEMPER COUNTY, MISSISSIPPI

Thesis Approved:

Dr. Jacob "Jack" Pashin

Thesis Adviser

Dr. James "Jim" Puckette

Dr. Natascha Riedinger

ACKNOWLEDGEMENTS

I would like to thank my wonderful wife Jamar, who I met at the University of New Mexico, who introduced me to geology and has been a constant reminder to appreciate our shared natural home we call Earth. Without her I would have never found my love for studying spatial and temporal changes to our solar system. Jamar has been by my side unwavering for over a decade and I look forward to our future together.

I would also like to thank my grandparents who have always supported me through my academic career and told me from a young age that schooling was important and to cherish the process of learning. I would especially like to thank my mother and Navajo grandmother who would take me hunting for Cretaceous fossils on the Navajo, Chaco Slope. I would “help” herd sheep and tend to animals with the main intent of finding interesting rocks, fossils and minerals then bring them to my grandmother and listen to her tell me interesting stories of ancient life that used to roam the badlands.

Dr. Jim Puckette is an important figure in my academic career at Oklahoma State University. He is selfless and a true humanitarian who gives more effort to improving the lives of others than anyone who I have ever met. When planning to transfer from UNM I visited the Noble Research Center and during my anxious visit I met Dr. Puckette who effortlessly sat down with me and talked about the program and helped build me a new academic plan. Dr. Puckette is a reminder to me that it is important to help out others when you can, and it doesn’t take much effort to make a lasting impression. After several years at OSU I came to realize that my story is not an original one, Dr. Puckette is the gem of the department and fully dedicates himself to the Cowboy community.

Dr. Jack Pashin is a champion for my academic career and my most influential mentor. Our work at Kemper, Mississippi has received recognition at the GSA national conference, award at the GSA 53rd joint section meeting, the Oklahoma Geologic Society, and featured in the AAPG EXPLORER. Our partnership began during my undergraduate career when I introduced myself and asked to work an independent research project with him. We worked two outcrops of the Devonian, Woodford shale where we built a rapport on geology and general philosophy. When I began looking at graduate programs and after months of apprehension, I again asked Dr. Pashin if he would be willing to bring me onboard and within 5 minutes I found a new home. It was a pivotal point in my career and a moment I will never forget. He has taught me to take a holistic approach to my work and to improve my geologic knowledge daily. During a workshop at the Alabama geologic survey, a fellow participant summed up Dr. Pashin by saying “He is just a happy guy who knows his rocks and likes to talk about ‘em.”, and I find it accurate. I greatly appreciate all the help and patience I have received from Dr. Pashin and I look forward to working with him for my dissertation.

Thank you for all your help over the years your actions have greatly influenced me and helped me on my journey through life.

Acknowledgements reflect the views of the author and are not endorsed by committee members or Oklahoma State University.

Name: CONN L. R. WETHINGTON

Date of Degree: DECEMBER, 2020

Title of Study: MUDSTONE CHARACTERIZATION AT A WORLD-CLASS CO_2 STORAGE SITE: KEMPER COUNTY ENERGY FACILITY, KEMPER COUNTY, MISSISSIPPI

Major Field: MASTERS OF SCIENCE GEOLOGY

Abstract: The Cretaceous and Tertiary deposits in Alabama, Mississippi, and the adjacent continental shelf constitutes a widespread succession of sandstone and shale that have proven to be an important target for geologic CO_2 storage in the onshore Gulf Coast basin. An integrated analysis of stratigraphy, sedimentology, and reservoir properties based on cores and geophysical well logs indicates that the Paluxy Formation, Washita-Fredericksburg interval, and the Lower Tuscaloosa Group present a gigatonne-class storage opportunity. Research sponsored by the U.S. Department of Energy and the Southern States Energy Board in south Alabama as part of the SECARB Anthropogenic Test in the Citronelle Field established the Paluxy as a safe and permanent carbon storage objective. The knowledge gained at Citronelle Field is being transferred to east-central Mississippi as part of the ECO_2S CarbonSAFE project at the Kemper County Energy Facility. Geologic characterization of the Mississippi Embayment at the Kemper County Energy Facility focused primarily on delineating a stratigraphic framework with an emphasis on seal-rock analysis. Integration of core analyses and geophysical well logs has yielded a high-resolution stratigraphic analysis of the targeted CO_2 storage reservoirs, baffles, barriers, and seals. Scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS) was used to characterize microfabric, mineralogy, and pore types within mudstone of the east-central Mississippi Embayment at the Kemper County Energy Facility. This characterization has two-fold importance: (1) to characterize free and adsorbed storage potential and (2) to characterize potential migration of CO_2 into mudstone baffling layers and seals by capillary processes and diffusion, which promote leakage from the primary injection targets. Mudstone in the Tuscaloosa Group supports adsorption and free storage in organic matter and smectitic mudrock. Mudstone in the Paluxy Formation and Washita-Fredericksburg interval lacks significant organic matter, and free storage and adsorption is in mudrock. High water saturation in the Cretaceous mudstone units helps keep capillary entry pressure high, and mudrock permeability is on the order of 1-100 nD. These low permeability values indicate that the mudstone units are effective baffles, barriers, and seals that make significant migration of injected CO_2 out of the storage complex unlikely.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Purpose

Southern Company and the United States Department of Energy have been in partnership to advance the Clean Coal Power Initiative II (CCPI II), which is the program that assisted in building the Kemper County energy facility in east-central Mississippi, which was intended to include a large coal gasification plant (Reitze, 2012) and has potential to serve as a storage hub for anthropogenic CO_2 emissions in the United States (Pashin et al., 2020). The CarbonSAFE program was initiated by the U.S. Department of Energy to explore options to reduce greenhouses gasses utilizing carbon capture and sequestration (CCS) technology at sites like the Kemper County Energy Facility, which are favorable for early commercial deployment of this technology (Esposito, 2017).

Geologic storage of CO_2 via underground injection into saline formations is a viable technology that is suitable for the storage of large volumes of supercritical CO_2 (Lackner, 2003). Saline formation storage requires the consideration of many geologic factors (e.g., geologic stability, depth, presence of a seal, reservoir continuity, reservoir and seal thickness, rock composition, rock strength, porosity, and permeability) that need to be evaluated prior to the implementation of a large-scale injection program. The objective of this research is to apply a range of geologic principles and techniques for site characterization to support the geologic qualification of saline formations as carbon sinks at the Kemper County energy facility as a partial fulfillment of establishing a CO_2 Storage complex. The concept of CO_2 sequestration has a foundation in enhanced oil recovery (EOR) projects beginning in the 1970's in the Permian Basin, in which CO_2 has been sourced, piped, and injected from natural sources (Graham et al., 1980). CO_2-EOR technology showed the potential for storing large volumes of CO_2 in the subsurface. In 1996, this led to the first commercial storage project without associated EOR in a saline formation above the Sleipner gas-condensate field in the North Sea (Chadwick et al., 2004). In 2004, another notable North Sea project began at the K12-B gas field, where produced CO_2 was separated from a gas stream and was reinjected into the reservoir from which it came (Vandeweijer et al., 2011). These industrial scale projects have helped pave the way for using subsurface storage of CO_2 for mitigating greenhouses gas emissions from industrial sources, and that technology and proof of concept can be translated to coal-fired power plants.

Project Summary

The two hypotheses tested as part of this research thesis are: (1) baffles, barriers, and seals can be categorized on the basis of mudstone thickness; (2) mudstone can be characterized as having low porosity and permeability and forms effective baffles, barriers, and seals that limit CO_2 migration. This study has defined and characterized the stratigraphic architecture of the carbon storage complex at the Kemper County energy facility. Stratigraphic characterization includes correlation of strata on the basis of geophysical well logs. Identification of stacked sandstone reservoirs and mudstone seals will provide information to help select injection zones and predict patterns of lateral and cross-formational CO_2 migration.

Kemper County Energy Facility

The CarbonSAFE program began in 2016 when the National Energy Technology Laboratory of the U.S. Department of Energy partnered with the Southern States Energy Board and Southern Company to determine the feasibility of placing an industrial scale CO_2

sequestration complex at the Kemper County energy facility near Meridian, Mississippi. Kemper County, Mississippi was an obvious location because Mississippi Power Company, a subsidiary of Southern Company, was already invested in building an Integrated Gasification Combined Cycle (IGCC) plant with CO_2 capture capability intended to supply southern Mississippi oil fields CO_2 for EOR, with potential storage of excess CO_2 in the saline formations at or near the energy facility (Pashin et al., 2008) (Fig. 1).

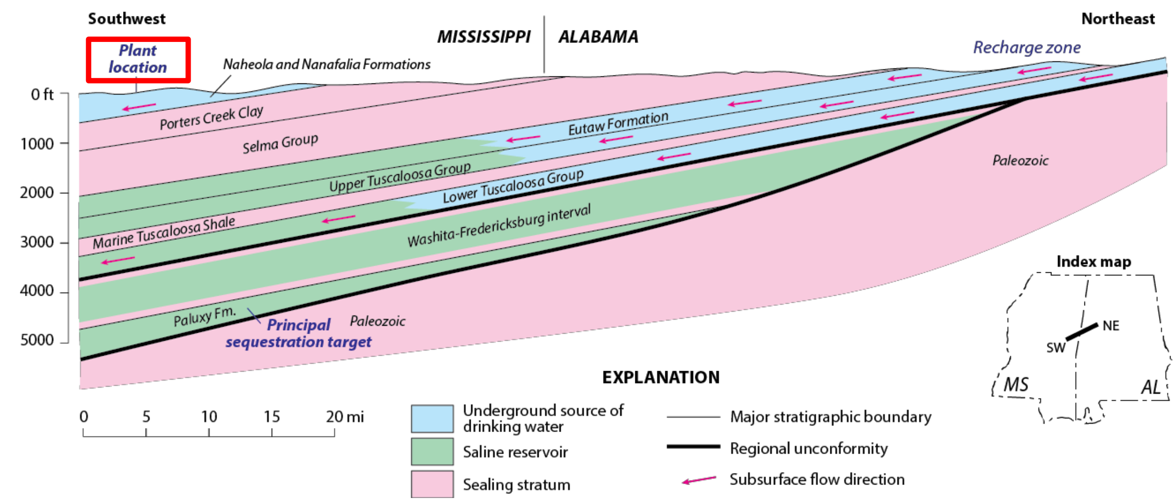


Figure 1. – Regional stratigraphic cross-section with strata identified as being an underground source of drinking water (USDW), sealing strata, or saline reservoir; Saline reservoirs are a potential CO_2 sink for an industrial scale CCS project (modified from Pashin et al., 2008).

A preliminary geologic evaluation was conducted to assist in permitting of the coal gasification plant (Pashin et al., 2008). The data set consisted of 20 geophysical well logs and well sample descriptions. Seismic profiles published by Amoco Production Company at the Appalachian-Ouachita juncture (Hale-Erlich and Coleman, 1993) were reinterpreted and were critical for characterizing the geology of the plant area. Pashin et al. (2008) concluded that there was a pre-feasibility potential to sequester 4-22 megatonnes of CO_2 per square mile in Cretaceous sandstone. Deeper Paleozoic units were also studied because they may provide additional storage potential aside from the Mesozoic and Cenozoic strata of primary investigation at the Kemper County energy facility (Fig. 2). In 2017, three scientific exploratory wells, MPC 26-5, MPC 34-1, and MPC 10-4, were drilled to a total depth of 5,877 ft, 5,748 ft, and 5,440 ft, respectively. The wells penetrate the uppermost part of the Paleozoic section and are located on the periphery of the acreage surrounding the Kemper Energy Facility that includes approximately 53 square miles, and data from these wells form the basis of this study (Fig. 3).

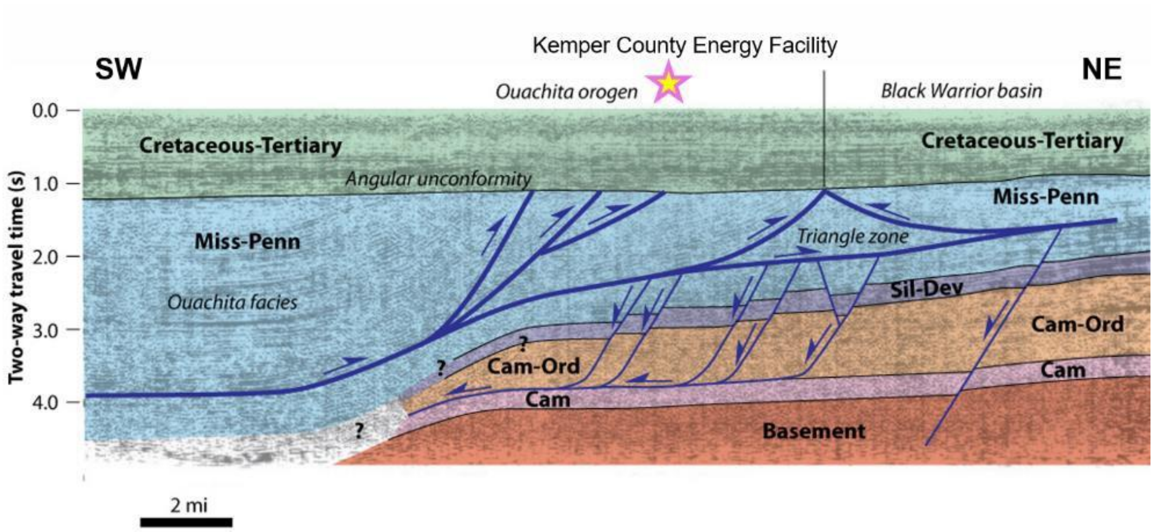


Figure 2. – Seismic cross-section SW–NE, of Paleozoic through Cenozoic strata under the Kemper County energy facility with the relatively flat Cenozoic through Mesozoic targeted strata for CO_2 storage (modified from Hale-Erlich and Coleman, 1993; Pashin et al., 2008).

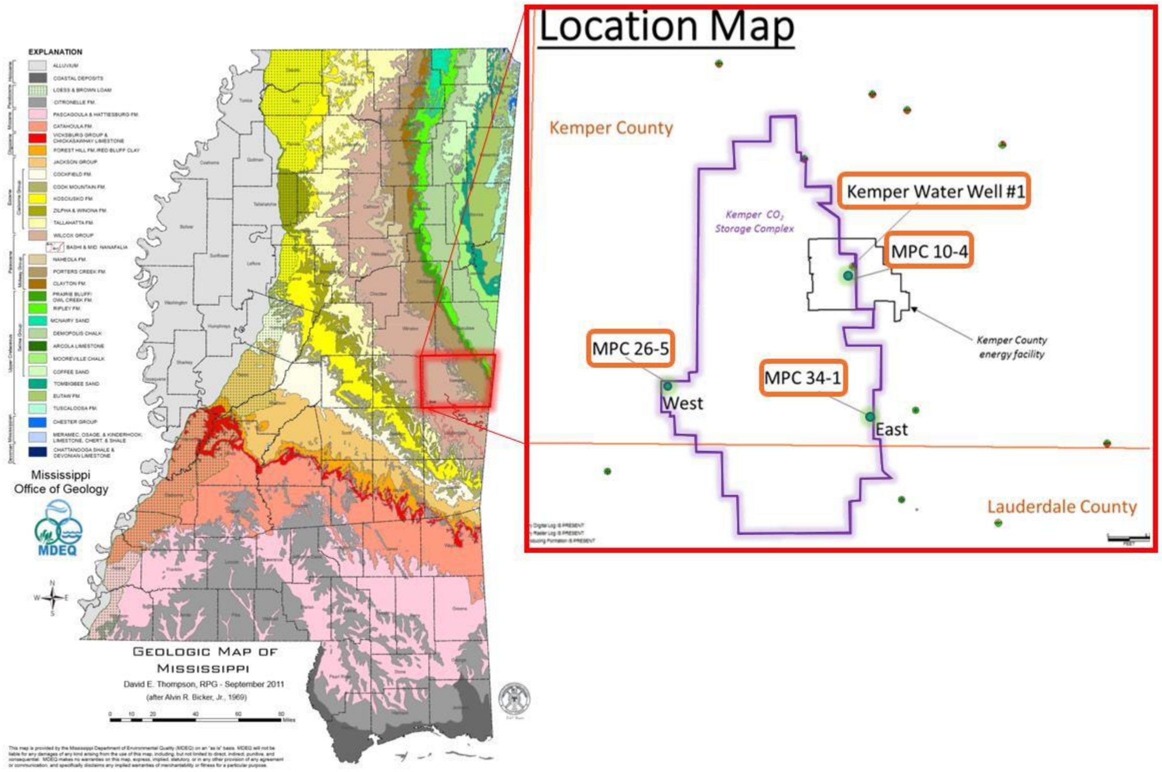


Figure 3. – Kemper County energy facility in Kemper County, Mississippi with acreage and three exploratory wells MPC 26-5, MPC10-4, and MPC 34-1 (geologic map after Bicker, 1969).

CHAPTER II

GEOLOGIC SETTING

Mississippi Embayment

The Kemper County energy facility is near the eastern margin of the Mississippi Embayment in east-central Mississippi (Fig. 4). The Mississippi Embayment contains Mesozoic and Cenozoic deposits that extend inland to the north and northeast of the Gulf of Mexico and are an extension of the Gulf Coastal Plain. The Mississippi Embayment extends from the fall line of the Mississippi Valley in southern Illinois to the Gulf of Mexico coastal plain in Louisiana, Mississippi, and Alabama; it lies west of the Nashville Dome and east of the Ozark Dome (Kolata et al., 1981; Abert, et al., 2016). Sediment fill in the embayment ranges in thickness from a feather-edge along the fringes of the embayment and thickens toward the south-southwest to more than 5,000 feet in southwest Mississippi. Regional dip is < 1° or approximately 30 feet per mile on the east flank of the embayment (Sterns and Marcher, 1962, Pashin et al., 2008). Figure 4 shows the geometry and thickness of the sediment fill in the Mississippi Embayment with respect to the Kemper County energy facility.

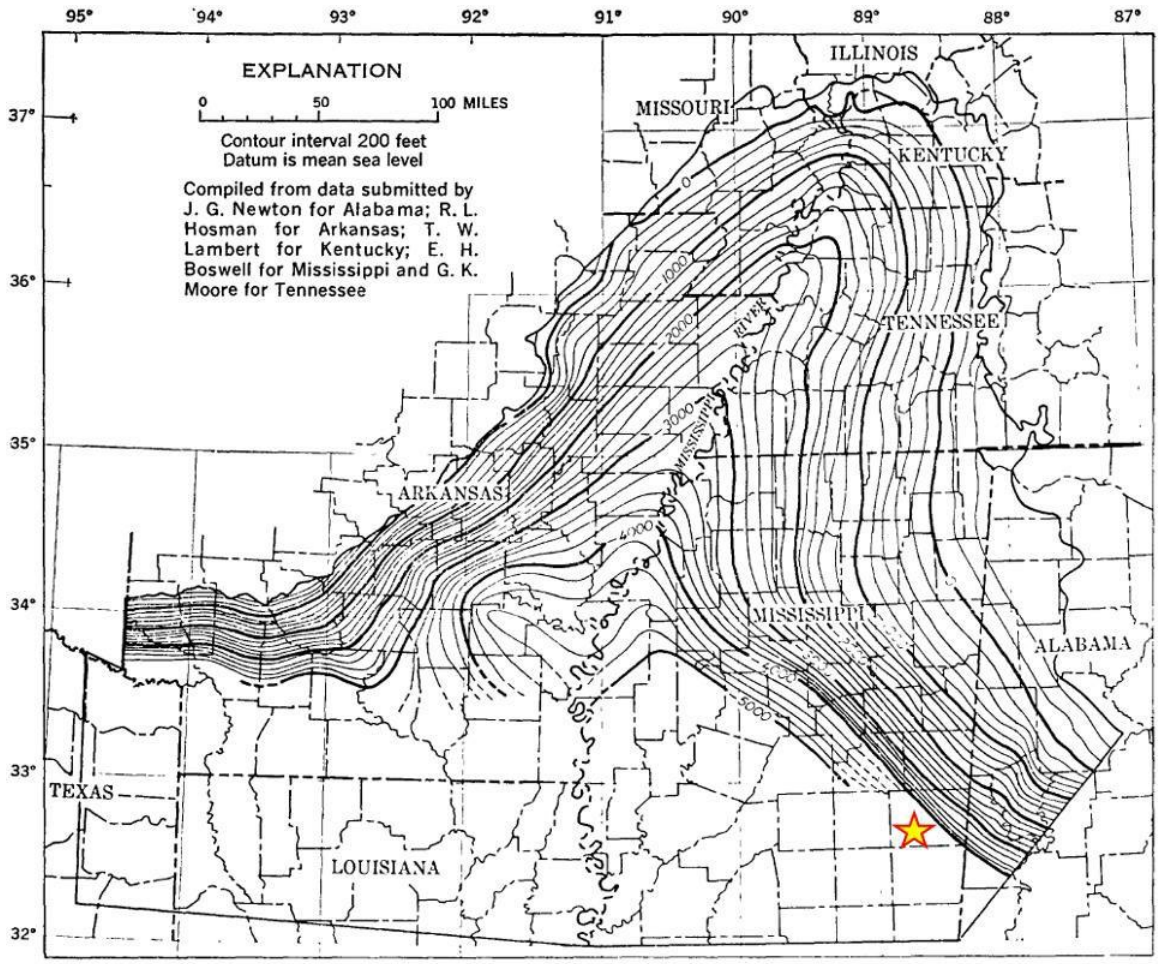


Figure 4. – Bold outer line denotes the inland extend of the Mississippi Embayment. Gold star denotes the location of the Kemper County energy facility (modified from Cushing et al., 1964)

Stratigraphic Framework

Cambrian through Paleogene strata are preserved below the Kemper County energy facility. Cambrian strata are thought to overlie crystalline basement in this area (Thomas, 1991). The energy facility is situated in the area of the Appalachian and Ouachita orogenic juncture (Thomas, 1985), and Paleozoic strata in this area have been referred to as the Appalachian-Ouachita orogenic facies (a.k.a., Ouachita facies) (Thomas, 1973, 1985; Pashin et al., 2008; Riestengberg, 2018). Only the upper 125 feet of the Paleozoic section has been penetrated by wells in the study area. An angular unconformity separates the Paleozoic and the Mesozoic section, representing a depositional hiatus from the Pennsylvanian to the Early Cretaceous (Pashin et al., 2008). The Appalachian-Ouachita juncture in Kemper County has been interpreted to include positive flower structures that lie east of the coal facility (Hale-Erlich and Coleman, 1993). The unconformity atop the Paleozoic section dips gently southwest with the Mesozoic-Cenozoic strata in Kemper County (Pashin et al., 2008, 2020).

The Mesozoic-Cenozoic section at the Kemper facility is illustrated in a composite geophysical well log (Fig. 5). Subhorizontal Lower Cretaceous strata overlie the angular unconformity and constitute a thick succession dominated by siliciclastic deposits. These strata are assigned to the Mooringsport Formation, the Paluxy Formation, and the Washita-Fredericksburg interval (Mancini and Puckett, 2002; Pashin et al., 2008, 2020).

Upper Cretaceous strata of the Tuscaloosa Group disconformably overlie the Washita-Fredericksburg interval (Mancini and Puckett, 2005). The lower Tuscaloosa Group (Coker Formation) at the Kemper County energy facility constitutes the Massive sand, which consists of a basal conglomerate that is overlain by poorly consolidated sand. The overlying Marine Tuscaloosa shale forms the base of the Gordo Formation of the Tuscaloosa Group and is dominated by mudstone. The upper part of the Gordo Formation, commonly identified in the subsurface as the upper Tuscaloosa Group, is dominated by interbedded sandstone and mudstone. The Eutaw Formation disconformably overlies the Tuscaloosa Group and contains interbedded sandstone and mudstone; glauconitic sandstone is the signature rock type in the Eutaw (Pashin et al., 2000).

Up to 900 feet of chalk assigned to the Selma Group caps the Upper Cretaceous section and is unconformably overlain by Paleocene-Eocene strata assigned to the Porters Creek Clay, Naheola Formation, and Nanafalia Formation (Rainwater, 1961). The Nanafalia Formation is the youngest unit in the study area and is included in the Wilcox Group (Paleocene-Eocene) (Bicker, 1969). The base of the Nanafalia Formation is a thick, fresh water-bearing sand called the Nanafalia Sand, which is the principal underground source of drinking water (USDW) and the principal groundwater protection objective in the study area. Surface and near-surface deposits in the area of the Kemper energy facility are sand, clay, and the lignite that was intended to fuel the coal gasifier at the energy facility.

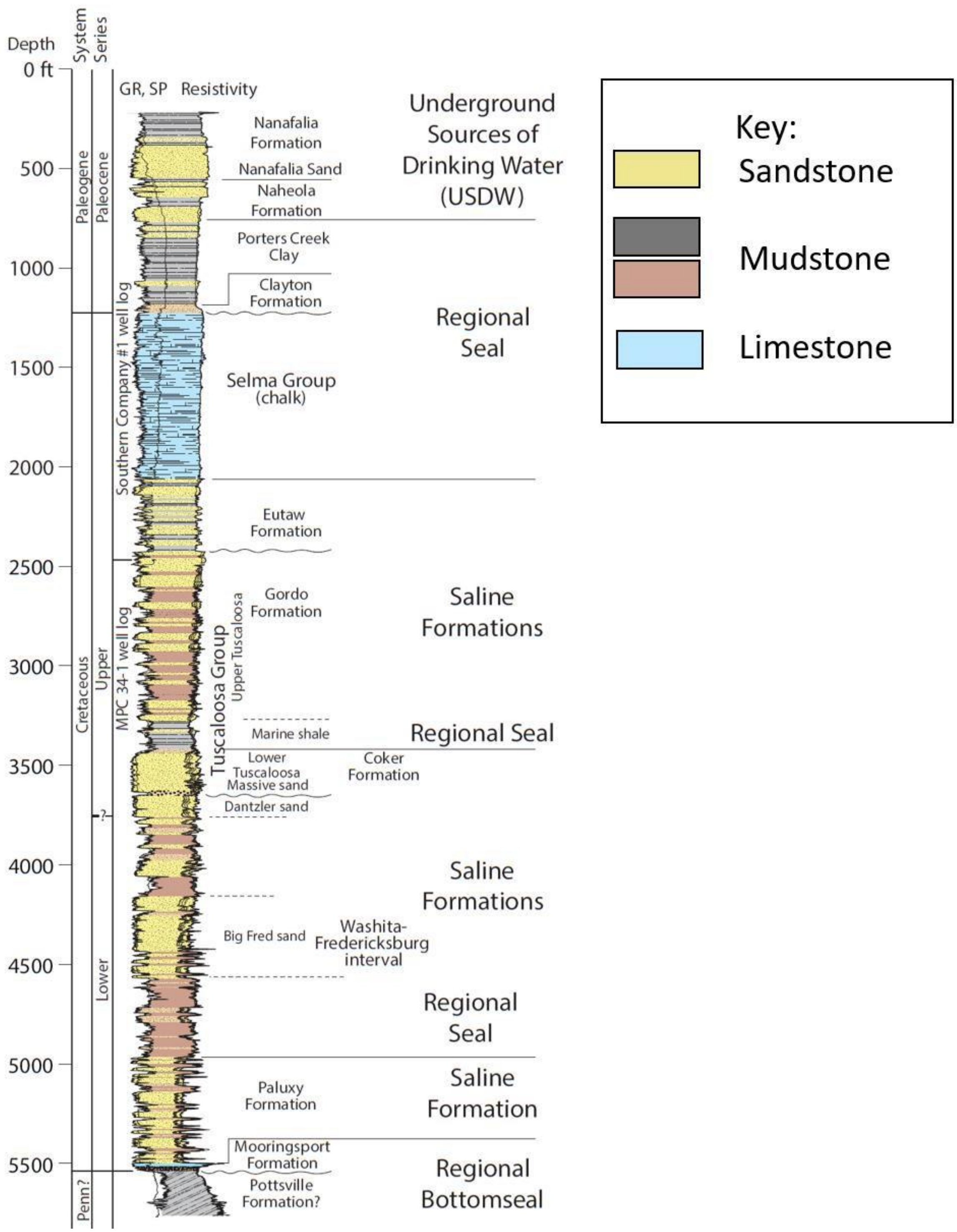


Figure 5. – Composite well log showing the Mesozoic-Cenozoic section at the Kemper County energy facility (after Pashin et al., 2020).

Structure and Tectonics

The formation of the Mississippi Embayment has been episodic and arguably began during late Proterozoic-Cambrian Iapetan rifting. Early evolution of the embayment included conjugate basement faulting that resulted in development of the Mississippi Valley Graben (Thomas, 1991). Appalachian-Ouachita orogenesis is thought to have resulted in Paleozoic positive flower structures within the Kemper County transpressional zone located east of the plant location (Hale Erlich and Coleman, 1993). Paleozoic orogenesis was followed by Mesozoic rifting and drifting associated with the opening of the Gulf of Mexico and formation of the Mississippi Embayment (Salvador, 1987). The post-Paleozoic stratigraphy dips gently southwest above the sub-Mesozoic angular unconformity (Pashin, 2008). The angular unconformity and suprajacent strata dip southwest at a fraction of a degree (< 0.005°) based on the maps of Pashin et al. (2008).

.

CHAPTER III

METHODOLOGY

This study is focused on the mudstone confining units at a carbon storage complex. Data were collected as part of a multi-scale investigation and were integrated to help qualify the mudstone units as baffles, barriers, and seals to CO_2 migration. The data are from three exploratory wells that were drilled in Kemper County, Mississippi at the Kemper County energy facility between June and August 2017. Cores were retrieved from selected intervals of the Cretaceous section in the MPC 26-5, MPC 34-1, and the MPC 10-4 wells. The wells have a diverse suite of geophysical logs including gamma ray, resistivity, density-neutron porosity, and spontaneous potential curves. The MPC 34-1 and MPC 10-4 cores were CT scanned in the original core sleeves prior to slabbing. Thin sections were made for all three wells, and sample billets were made for SEM/EDS analysis, and samples were crushed for semi-quantitative XRD analysis. Only the MPC 10-4 well was analyzed for TOC content as it is the well that cored the Marine Tuscaloosa shale. Cored intervals with corresponding measured depths and formations are given in table 1.

Geophysical Well Log Analysis

Geophysical well logs for the three wells were analyzed for lithologic identification, core to well log depth calibration, well to well correlation, and analysis of stratigraphic relationships and facies patterns. The geophysical well logs were run by Schlumberger between June and August 2017, and the curves used for this study are gamma ray, resistivity, density porosity, and spontaneous potential. Calibration of core to well log was based on gamma ray and core gamma ray readings that were provided by Weatherford Laboratories in Houston, Texas.

Rock types and basic stratigraphic relationships were determined by conventional well log analysis and the comparison of multiple curves to determine the difference between mudstone, sandstone, and limestone. The core gamma ray was used to correlate cored depth to measured depth in well logs and to correlate core properties to well log responses to build a petrofacies model (e.g., Watney et al., 1999). This was facilitated by Petra software and LAS files. The petrofacies analysis employed a gamma ray cutoff of 75 API units, which served as a shale baseline, and SP signature. Strata were then correlated to identify formation tops, assess continuity, thickness, depositional dip, and stratigraphic hierarchy. Correlations of logs from the three wells were used to build a stratigraphic cross-section for identifying reservoir intervals and confining intervals.

The analysis of mudstones within the sequestration complex was focused on developing a categorical scheme of mudstone confining strata. There is a lack of unifying definitions for natural confining strata with respect to geologic reservoirs and the following definitions are used for the purposes of this report. A geologic baffle is laterally discontinuous within a resevoir, is often subseismic, and can effect flow within a reservoir (Chen et al., 2017). A geologic barrier has low permeability that results in reservoir compartmentalization (Rahimpour-Bonab et al., 2014). A seal is regionally extensive (Aplin, and Macquaker, 2011) and confines reservoirs over geologic time (Knott, 1993). The scheme in this thesis integrates these definitions of baffles, barriers, and seals with thickness constraints. Beds with thickness ranging 1-9 ft were classified as baffles, those with thickness of 10-99 ft were classified as barriers, and thicker than 100 ft were classified as potential seals. Other work on baffles, barriers, and seals have overlapping definitions and are generally concerned with determining if an economic resource is present within subsurface or how a reservoir or development plan is going to perform with internal retarding stratum. This proposed method helps to focus the scope of investigation to the confining strata within a sequestration complex that can later be integrated with rock quality.

Core Description and Depositional Environments

Cores were described, photographed, and logged using standard stratigraphic and sedimentologic procedures. Graphic logs were constructed to identify rock types, bedding contacts, sedimentary structures, and biological features. Grain size was characterized using the Wentworth scale (Wentworth, 1922), a hand lens, and a grain-size comparator. The intensity of bioturbation was characterized using the Bann bioturbation intensity index (Bann et al., 2005). Coupled with CT imaging, and a generalized permeability index based on the degree of mud filtrate staining of the cores was applied (Fig. 6), with the original sand without mud filtrate being white. Samples from the butt slabs of the cores were taken for further analysis.

The in situe reservoirs, baffles, barriers, and seals internal architecture reflect the original depositional environment with distinct processes and energy regimens. The heterogeneity of the storage complex can be better understood when the original depositional environment is appreciated by proving a predictive framework utilizing modern analogs. Modern analogs help to build conceptual models with respect to scale, sedimentation, and lithostratigraphic morphology. Comparative sedimentology and literature review were the primary methods used to determine depositional environments. Interpreted depositional environments are supported by sedimentary structures, fabrics, fossils, lithostratigraphy from cross-sections, and isopach mapping. This integrated approach allowed a reasonable interpretation of proposed analogs.

Table 1. – The three investigated wells MPC 26-5, MCP 34-1, and MPC 10-4 with total recovered core; with respective recovered core intervals and respective formation.

MPC 26-5:	18 ft recovered		
Core	**Depth**		**Formation**
core 1 - 1/2	3588.50	3590.00	Gordo Formation (Tuscaloosa Marine shale)
core 1 - 2/2	3590.00	3592.00	Gordo Formation (Tuscaloosa Marine shale)
core 2 - 1/4	3645.00	3648.00	Coker Formation (lower Tuscaloosa Group)
core 2 - 2/4	3648.00	3651.00	Coker Formation (lower Tuscaloosa Group)
core 2 - 3/4	3651.00	3653.00	Coker Formation (lower Tuscaloosa Group)
core 2 - 4/4	3653.00	3654.00	Coker Formation (lower Tuscaloosa Group)
core 3 - 1/2	4331.00	4333.00	Washita-Fredericksburg interval (Big Fred sand)
core 3 - 2/2	4333.00	4334.80	Washita-Fredericksburg interval (Big Fred sand)
MPC 34-1 :	50.94 ft recovered		
Core	**Depth**		**Formation**
core 1 - 1/3	4850.00	4853.10	Washita-Fredericksburg interval
core 1 - 2/3	4853.10	4861.15	Washita-Fredericksburg interval
core 1 - 3/3	4861.15	4863.05	Washita-Fredericksburg interval
core 2 - 1/1	5300.00	5307.00	Paluxy Formation
core 3 - 1/4	5307.00	5316.00	Paluxy Formation
core 3 - 2/4	5316.00	5325.19	Paluxy Formation
core 3 - 3/4	5325.19	5334.25	Paluxy Formation
core 3 - 4/4	5334.25	5337.89	Paluxy Formation
MPC 10-4:	122.75 ft recovered		
Core	**Depth**		**Formation**
core 1 - 1/4	3170.00	3179.07	Gordo Formation (Tuscaloosa Marine shale)
core 1 - 2/4	3179.07	3188.09	Gordo Formation (Tuscaloosa Marine shale)
core 1 - 3/4	3188.09	3196.40	Gordo Formation (Tuscaloosa Marine shale)
core 1 - 4/4	3196.4	3196.92	Gordo Formation (Tuscaloosa Marine shale)
core 2 - 1/1	3200.00	3207.65	Gordo Formation (Tuscaloosa Marine shale)
core 3 - 1/4	5038.00	5047.07	Paluxy Formation
core 3 - 2/4	5047.07	5056.11	Paluxy Formation
core 3 - 3/4	5056.11	5065.21	Paluxy Formation
core 3 - 4/4	5065.21	5065.69	Paluxy Formation
core 4 - 1/4	5068.00	5077.02	Paluxy Formation
core 4 - 2/4	5077.02	5086.04	Paluxy Formation
core 4 - 3/4	5086.04	5095.05	Paluxy Formation
core 4 - 4/4	5098.05	5098.44	Paluxy Formation
core 5 - 1/4	5100.00	5108.94	Paluxy Formation
core 5 - 2/4	5108.94	5117.97	Paluxy Formation
core 5 - 3/4	5117.97	5125.03	Paluxy Formation
core 5 - 4/4	5125.03	5125.5	Paluxy Formation
core 6 - 1/1	5131.00	5135.55	Paluxy Formation

Figure 6. – General permeability index based on core staining.

Thin Section Description

Samples of fine-grained rocks, mainly mudstone, were taken from cores of the Paluxy Formation, Washita-Fredericksburg interval, and the Marine Tuscaloosa shale. The samples were then sent to Wagner Petrographic to make thin sections with a thickness of 20 µm for the mudstone samples. The thin sections were vacuum impregnated with blue epoxy and were stained with alizarin red to identify calcite and sodium cobaltinitrite to identify potassium feldspar and ferroan calcite. The thin sections were described and photographed using an Olympus BX51 petrographic microscope. The thin sections were analyzed on a Leica DM EP polarized microscope that was calibrated with a Nikon petrographic micrometer for grain-size measurement. The grain size in the mudstone in each thin section was used to build a microfacies description that includes clay, quartz, feldspar, accessory grains, cement, fabric, and porosity. To visually determine approximate volumes of clay and detrital grains, the comparison charts of Mathew et al. (1991) were used (Fig. 7B). Grain size percentages were then plotted in a ternary diagram (Picard, 1971) to characterize sand, silt, and clay content (Fig. 7A).

SEM descriptions were used to characterize the pore systems in the mudrocks; data on interparticle pores, intraparticle pores in minerals, and intraparticle pores in organic matter were plotted in a ternary diagram based on Loucks et al. (2012) (Fig. 8).

Scanning Electron Microscopy and Energy-Dispersive X-ray Spectroscopy

Scanning electron microscopy was performed on 12 samples using a FEI Quanta 600 FEG MK2 Environmental Scanning Electron Microscope (SEM). The SEM was accompanied by a Bruker Quantax XFlash 6/60 unit with Quantax Esprit software for energy dispersive X-ray spectroscopy (EDS) analysis. The samples selected have a corresponding thin section that enabled comparison of the features observed under transmitted light with those observed by SEM. The samples were first cut into small tabs with a tile/rock saw and were later polished with a JEOL model IB-19500CP argon ion mill to facilitate SEM imaging of smooth surfaces. The samples were then mounted on studs and coated with a gold-palladium alloy to help reduce charging artifacts in the SEM images.

Microfabric, mineralogy, and pore types in each sample were described and characterized. EDS was used to determine elemental composition, and hence the mineralogy of particles within the samples. Compositional data were used to supplement thin sections and were then plotted on a Picard (1971) ternary diagram to classify the mudrocks texture (Fig. 7). The pore system was then analyzed and graphed in a Loucks pore system analysis ternary diagram (Loucks et al., 2012) (Fig. 8).

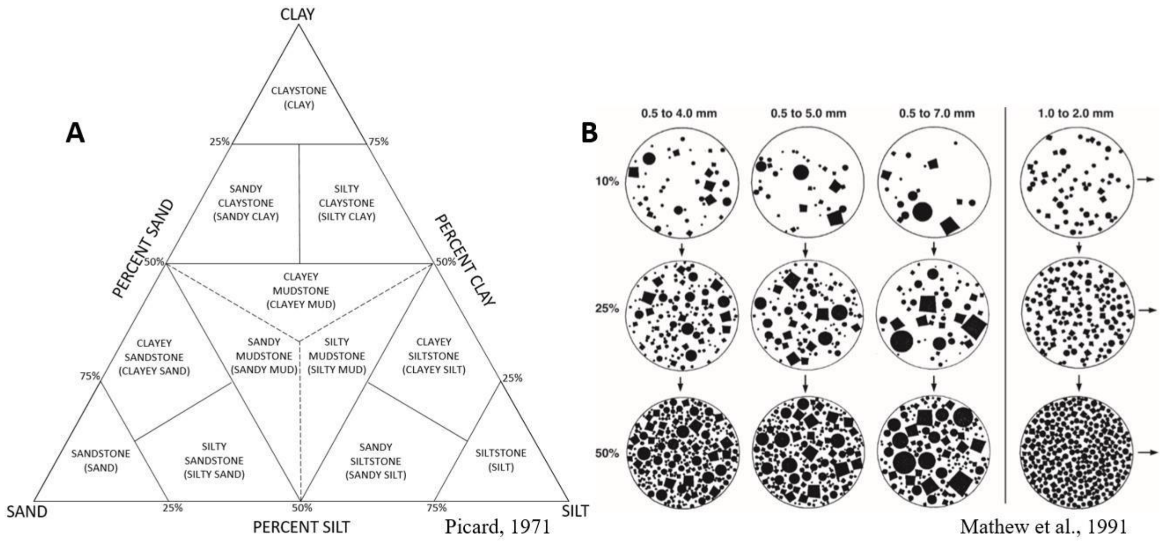


Figure 7. – Tools utilized for petrographic characterization of mudstone. A) Ternary diagram for fine-grained rocks (Picard, 1971). B) Graphical comparator used to approximate particle size and percentage (Mathew et al., 1991).

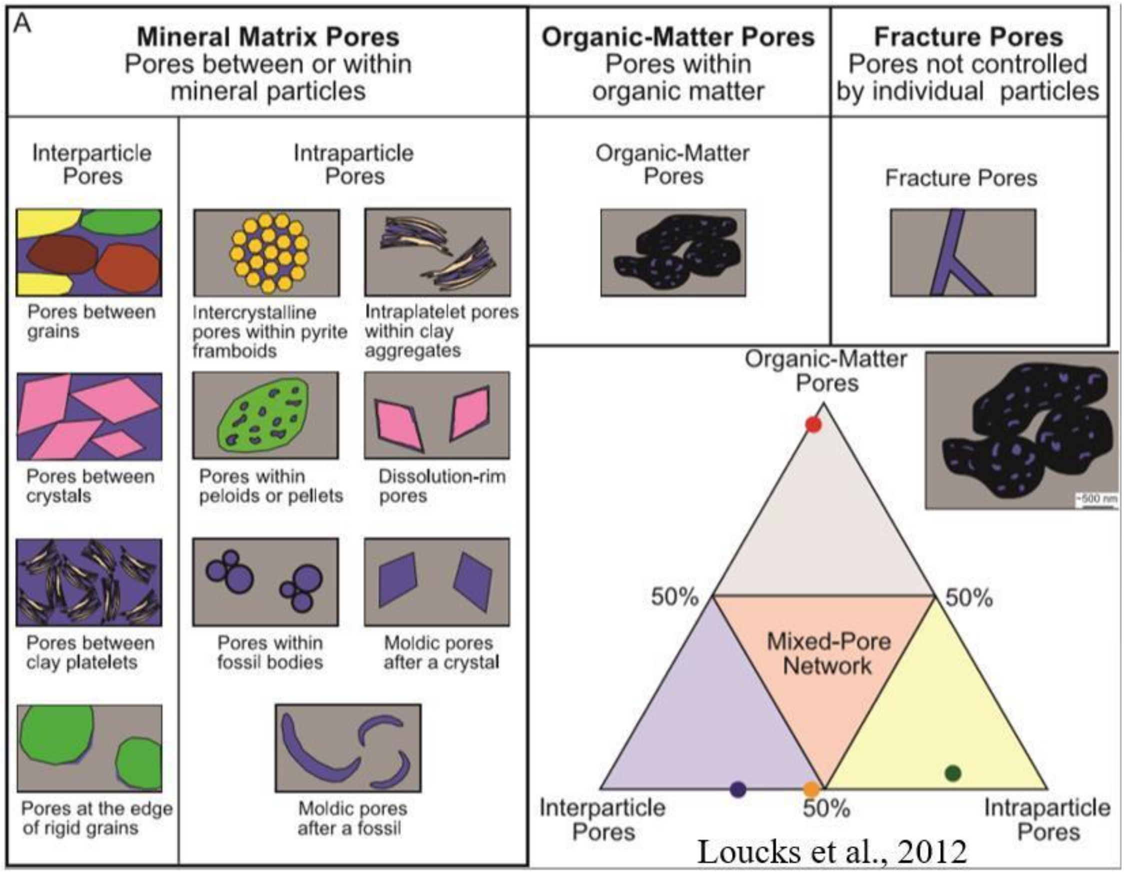


Figure 8. – Pore types and porosity classification for mudrocks (Loucks et al, 2012).

X-ray Diffraction Analysis

Semi-quantitative x-ray diffraction (XRD) data were gathered for 11 samples (Table 2). XRD analysis was performed to determine mudrock mineralogy, including clay species. The samples are from the Paluxy Formation and the Marine Tuscaloosa shale. Samples used for XRD analysis have corresponding thin sections and SEM images. The samples were extracted from butt slabs of the cores, ground with a ceramic mortar and pestle, and then dried in glass dishes inside a Lab Companion scientific oven for 72 hours at a temperature of 40°C. The samples were then weighed on a Mettler Toledo scientific scale to ensure a mass greater than 15 grams was available for analysis. The samples were then placed in labeled plastic specimen bags and shipped to Impac Exploration Services in Midland, Texas for analysis. Minerals were identified from the pattern of XRD peaks, and the percentages of each mineral were estimated by Rietveld analysis.

Table 2. – Samples taken for x-ray diffraction (XRD). The samples respective depth, corresponding formation, sample type, corresponding well, and weight.

Measured Depth	Formation	Sample Type	Well	Approximate weight (grams)
Feet				
3177.00	Gordo Formation (Tuscaloosa Marine shale)	Powder	MPC 10-4	23g
3190.50	Gordo Formation (Tuscaloosa Marine shale)	Powder	MPC 10-4	21g
3191.83	Gordo Formation (Tuscaloosa Marine shale)	Powder	MPC 10-4	25g
3196.30	Gordo Formation (Tuscaloosa Marine shale)	Powder	MPC 10-4	20g
3206.90	Gordo Formation (Tuscaloosa Marine shale)	Powder	MPC 10-4	21g
5072.35	Paluxy Formation	Powder	MPC 10-4	25g
3589.00	Coker Formation (lower Tuscaloosa Group)	Powder	MPC 26-5	21g
3590.00	Coker Formation (lower Tuscaloosa Group)	Powder	MPC 26-5	28g
3590.50	Coker Formation (lower Tuscaloosa Group)	Powder	MPC 26-5	25g
3592.00	Coker Formation (lower Tuscaloosa Group)	Powder	MPC 26-5	19g
5305.60	Paluxy Formation	Powder	MPC 34-1	21g

Total Organic Carbon Analysis

Total organic carbon (TOC) content was determined for six samples from well MPC 10-4. Five samples were run from the Marine Tuscaloosa shale, and one sample was run from the Paluxy Formation (Table 3). Samples were selected based on the availability of associated thin section, SEM, and XRD data. The samples were crushed with a ceramic mortar and pestle and then dried in glass dishes inside a Lab Companion scientific oven for 96 hours at a temperature of 45°C. The samples were then re-crushed with a mortar and pestle then dried in glass dishes inside a Lab Companion scientific oven for 48 hours at a temperature of 45°C, to ensure the sample was uniform in grain size and that that sample was completely dry prior to analysis. The samples were then analyzed in an Eltra Carbon-Sulfur Determinator. Sample size was greater than 100 mg, and each sample was run three times to get a representative average for the sample. Total carbon was determined by combustion using Eltra Carbon-Sulfer Determinator, and total inorganic carbon was measured by acidification of the sample prior to the combustion process. TOC content was then calculated by subtracting total inorganic carbon from total carbon. A standard sample was measured for calibration before and after measuring each sample. The carbon standard TC4007 sample, which is certified at 7.3 weight percent TOC was used for standardization and calibration. Testing of the carbon standard established a maximum error of 0.23 weight percent or a maximum percent error of 3.2%.

Table 3. – Samples used for TOC analysis from the MPC 10-4 well.

Sample Name	Formation
Kemper 5072.3 Kemper 5072.3 Kemper 5072.3	Paluxy Formation
Kemper 3190.5 Kemper 3190.5 Kemper 3190.5	Gordo Formation (Marine Tuscaloosa shale)
Kemper 3191.8 Kemper 3191.8 Kemper 3191.8	Gordo Formation (Marine Tuscaloosa shale)
Kemper 3196.3 Kemper 3196.3 Kemper 3196.3	Gordo Formation (Marine Tuscaloosa shale)
Kemper 3177.0 Kemper 3177.0 Kemper 3177.0	Gordo Formation (Marine Tuscaloosa shale)
Kemper 3206.9 Kemper 3206.9 Kemper 3206.9	Gordo Formation (Marine Tuscaloosa shale)

CHAPTER IV

RESULTS

SUBSURFACE ANALYSIS

Subsurface analysis was performed from the base of the Paluxy Formation through the top of the Porters Creek Clay. The purposes of the subsurface well log analysis is to identify the amount of mudstone in each section and classify them as potential baffles, barriers, or seals within the sequestration complex based on mudstone thickness alone. This original scheme does not factor in the quality of the baffle, barrier, or seal with respect to mineralogy or definitive lateral continuity. Bed thickness was assessed on a logarithmic scale. This scheme evaluates mudstone thickness based on the shale baseline in gamma ray logs. The stratigraphic architecture and interpretation of possible correlatable baffles, barriers, and seals shown in figure 9.

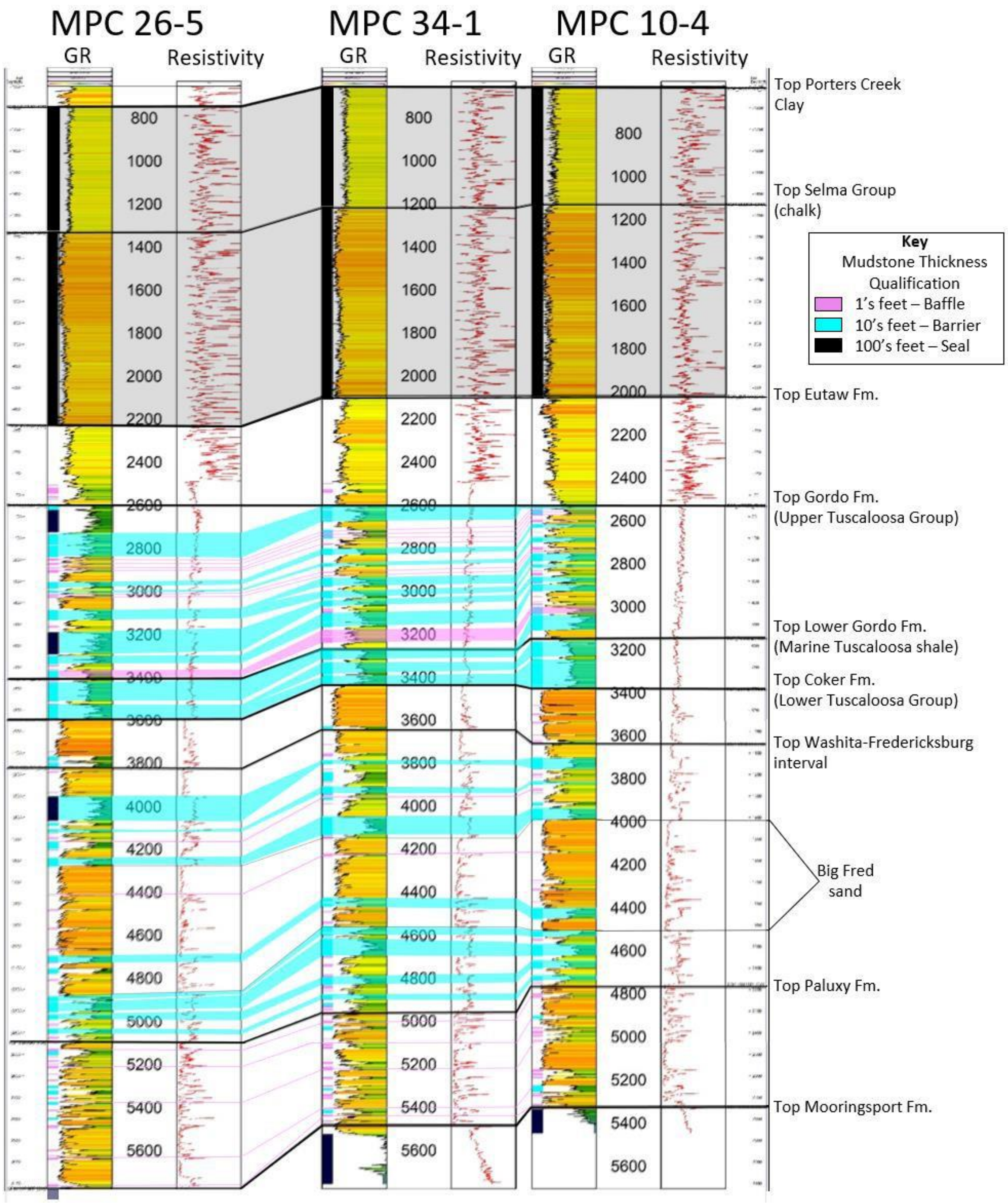


Figure 9. – The Kemper stratigraphic cross-section with wells MPC 26-5, MPC 34-1, and MPC 10-4 from left to right. Mudstones are shown in green with greater than 75 API, pink indicates thickness baffles on the 1's of foot scale, blue on the 10's of foot scale, and black greater than 100 continuous feet of mudstone. The interpreted correlation of baffles, barriers, and seals in ascending order with 5 baffles in the Paluxy Fm., 2 baffles and 8 barriers in the Washita-Fredericksburg interval, 7 baffles and 8 barriers in the Tuscaloosa Group, and 1 seal in the combined Selma Group through the Porters Creek Clay Fm.

Baffles, Barriers, and Seals

The Paluxy Formation on average contains 18 weak baffles per well with a possibility of 5 correlatable baffles on the scale of 1 ft thick and include an average of 3 weak non correlatable barriers on the 10's of feet scale with a maximum thickness of 30 ft, and averaging 15 ft.

The Washita-Fredericksburg interval has an average of 18 weak baffles with one correlatable mudstone package in the Big Fred sand, and one correlatable package in the upper Washita-Fredericksburg interval. There is an average of 11 barriers within the Washita-Fredericksburg interval up through the Dantzler sand; 8 of the barriers can be considered moderate due to the ability to be correlated. The lower Washita-Fredericksburg interval has 4 correlatable barriers, the Big Fred Sand has 1, and the upper Washita-Fredericksburg interval has 3 correlatable barriers. There is an occurrence of a thickness seal in the upper Washita-Fredericksburg interval, on the order of 100 feet thick, that is correlatable to baffles and is therefore categorized as a baffle.

The Coker Formation (lower Tuscaloosa Group) has an average of 3 weak baffles typically less than 5 feet thick. The baffles are identified by gamma-ray values above 75 API units. The base of the unit has a correlatable gamma ray that is a conglomeratic interval composed of mudstone, chert, and metamorphic clasts, and is not characterized as a baffle.

The Gordo Formation contains an average of 18 baffles with 7 being correlatable, and 15 barriers, 8 of which are correlatable. The barriers can be characterized as robust that approach the thickness of a seal on the order of 100's of feet down dip. In the updip correlation the mudstones have sand stringers that divide, up dip, mudstone beds.

The Eutaw Formation has an average of 4 weak baffles in the basal part of the section, none of which are correlatable. The Eutaw is succeeded by the Selma Group, a chalk that is a robust up-section seal on the order of 100's of feet and averages 891 ft thick. The Porters Creek

Clay caps the Selma Group and is over 500 feet thick. For the purposes of this report it is correlated with the Selma Group that together are over 1400 feet thick and are considered a robust seal to the entire sequestration complex.

The Paluxy Fm. is dominated by baffles with few weak, uncorrelatable, barriers to CO_2 migration. The basal Washita-Fredericksburg has multiple correlatable barriers and then becomes mudstone lean in the Big Fred sand, which is a major storage objective (Pashin et al., 2020). The Big Fred sand contains 5 baffles and is capped by correlatable baffles that locally exceed 100 feet in thickness to qualify as a local thickness seal. The lower Tuscaloosa Group has a possible weak baffle that is correlatable at its base that thickens downdip, and is from a conglomeratic zone of mudstone, chert, and metamorphic clasts. The Gordo Formation, Marine Tuscaloosa shale, has the highest continuous gamma-ray signature in the stratigraphy. It is dominated by tight mudstone to claystone and has significant baffles that thicken to seal scale in correlatable downdip packages.

The most significant and robust seal to the entire complex is the undivided Selma Group chalk and Porters Creek Clay that is over 1000 feet thick. It is on the upper end of the proposed logarithmic thickness seal classification and easily qualifies it as a thickness seal to the entire lower storage complex protecting the USDW's above the Porters Creek Clay.

LITHOFACIES

Twelve cores spanning 192 ft of section were recovered from the Paluxy Formation, the Big Fred sand of the Washita-Fredericksburg interval, the Coker Formation (lower Tuscaloosa Group), and the lower Gordo Formation (Marine Tuscaloosa shale). The rocks will be discussed with respect to lithofacies and stratigraphic position. Lithofacies are defined and characterized based on rock types, bedding, physical sedimentary structures, and biogenic structures. The sandstone facies is the most abundant facies and is present within all of the cored formations. The most sandstone was recovered from the Paluxy Formation, which contains 7 distinct facies encompassing conglomerate, sandstone, and mudstone lithologies from the MPC 34-1 and MPC 10-4 wells. The Washita-Fredericksburg interval contains 3 distinctive sandstone facies and 1 mudstone facies in the MPC 34-1 (basal Washita-Fredericksburg) and MPC 26-5 (Big Fred sand) cores. The Coker Formation has 1 sandstone facies, and lower Gordo Formation (Marine Tuscaloosa shale) contains 2 sandstone/silt facies and 3 mudstone facies from the MPC 26-5 and MPC 10-4 cores.

Paluxy Formation

The Paluxy Formation contains conglomerate, sandstone, and mudstone. The cored intervals were from the MPC 10-4 and MPC 34-1 wells, and graphical core logs are shown in figures 10 and 11.

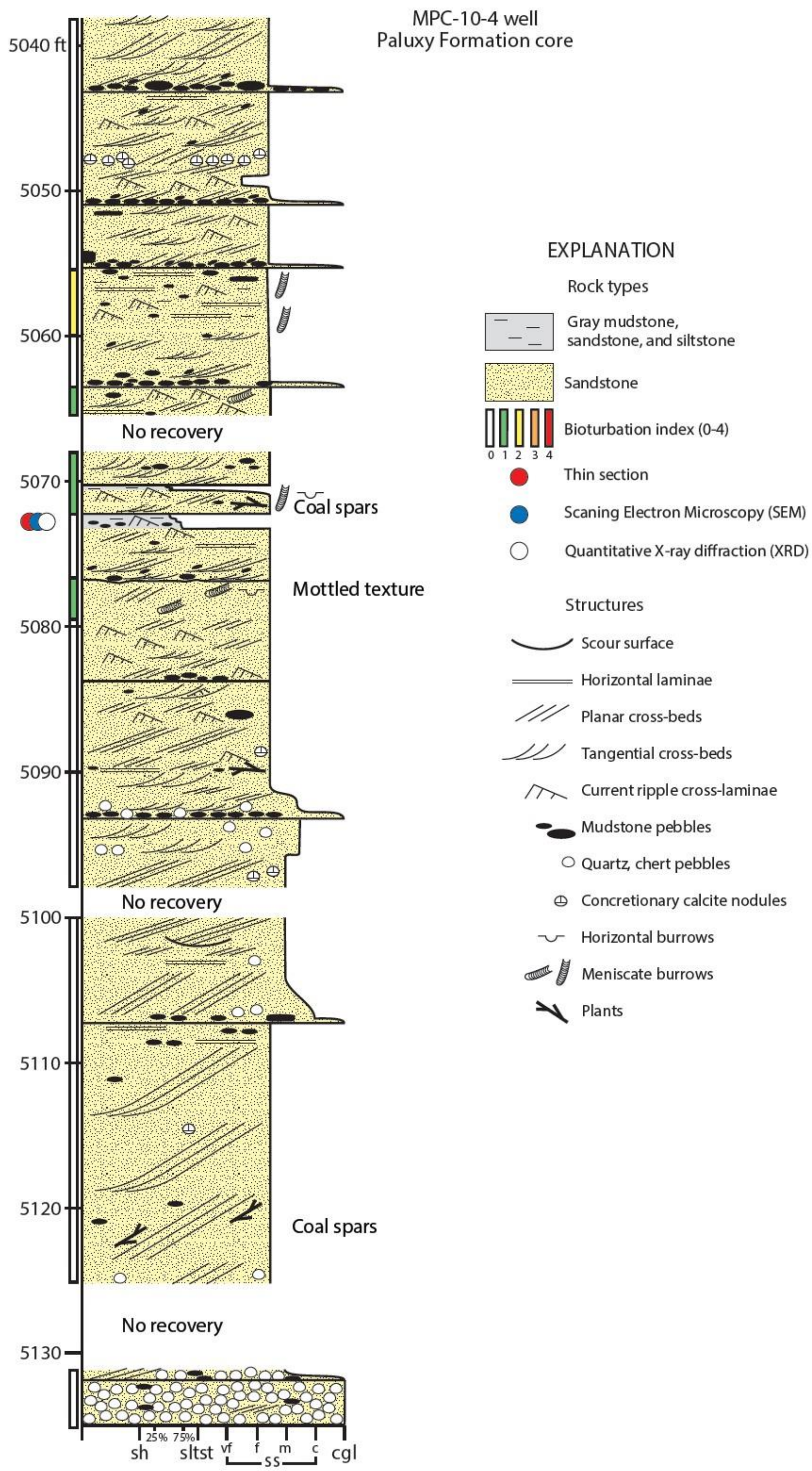


Figure 10. – Graphic core log of the Paluxy Formation from the MPC 10-4 well. Sedimentary features of the formation include scour surfaces, planar and tangential cross-beds, horizontal laminae, and current ripples. The measured section has a dominant lithology of medium sandstone, with conglomerate beds, and the occurrence of a mudstone bed (modified from Pashin et al., 2020).

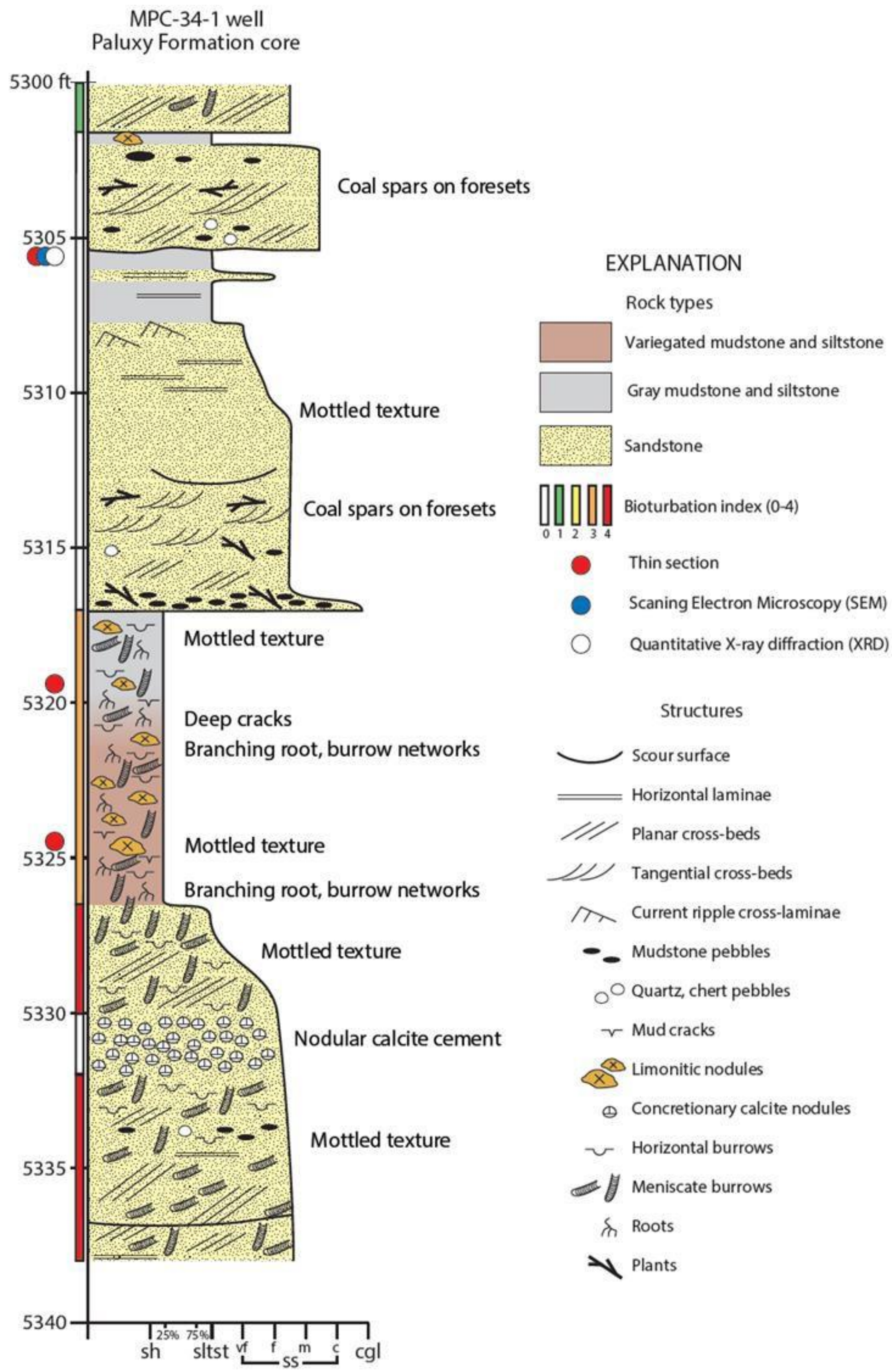


Figure 11. – Graphic core log of the Paluxy Formation from the MPC 34-1 well. The measured section is sandstone and mudstone lithology with the occurrence of a conglomerate bed. The section has bioturbation up to an index of 4 that produced texture mottling and destroyed primary sedimentary structures (modified from Pashin et al., 2020).

Conglomerate Lithofacies Characteristics

The conglomerate facies occur in the MPC 34-1 and MPC 10-4 wells within the Paluxy Formation. Clasts include pebbles to cobbles of mudstone, sandstone, and quartz, within a matrix of medium sand and in one case clayey sand.

Extraformational conglomerate is up to 4.5 feet thick in the MPC 10-4 well and contains mud and clay matrix with pebbles to cobbles of mudstone, quartz pebbles, and granules of sandstone that are subangular to well rounded. The extraformational conglomerate grades upward into fine- to medium-grained sandstone. This facies is largely clast supported and is the thickest succession of the conglomerate facies (Fig. 12A).

Intraformational conglomerate is clast supported, it is up to 6 inches thick in the MPC 10-4 core and generally contains well rounded pebble- to cobble-size mudstone clasts with minor amounts of quartz pebbles and plant material. The matrix is medium-grained sandstone. The conglomeratic beds grade into a fine- to medium-grained sandstone, and the clasts form lags at the toesets of cross-beds (Fig. 12B).

A.

B.

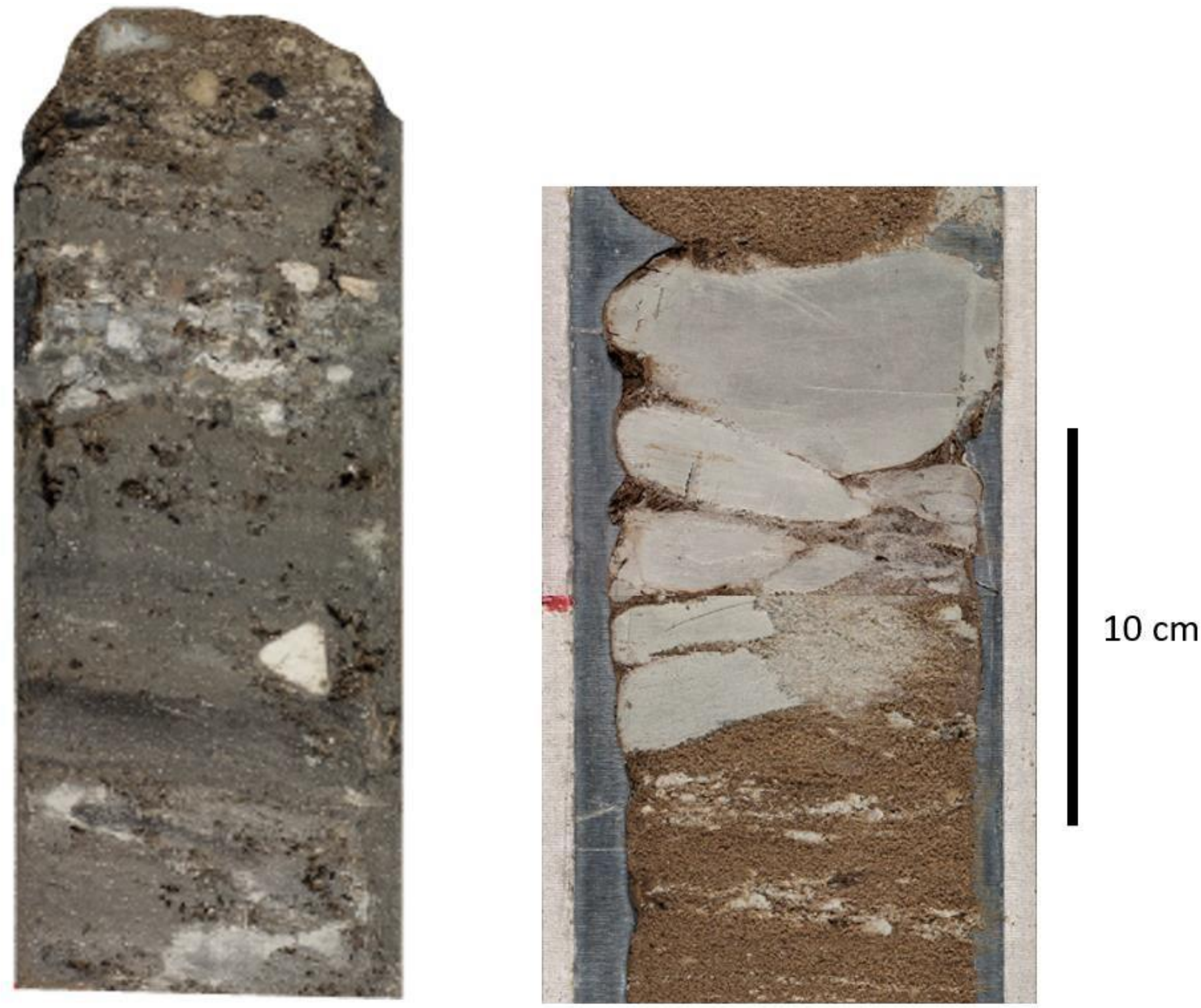


Figure 12. – Core photographs of conglomerate facies from the Paluxy Formation MPC 10-4 well. A) Extraformational conglomerate, 5131 ft measured depth, has quartz and mudstone pebbles with a clayey sand matrix. B) Intraformational conglomerate, 5043 ft measured depth, is clast supported and contains up to cobble-size mudstone clasts.

Sandstone Lithofacies Characteristics

Cross-bedded sandstone is the most common facies that was cored within Paluxy Formation. It was cored in the MPC 34-1and MPC 10-4 wells, is up to 5.5 ft thick, and is characterized by a sharp basal conglomerate contact that transitions to very fine- to medium-grained sandstone with planar cross-beds and some horizontal laminae in the toesets. The facies also contain minor amounts of mudstone chips, quartz pebbles, and coalified plant material along the cross-bed surfaces. Bioturbation is restricted to a few intervals, having a bioturbation index of 2-4 and consists mainly of vertical and horizontal meniscate burrows that disrupt sedimentary structures. (Fig. 13A).

The concretionary calcite facies is up to 2 ft thick, has gradational boundaries and is composed of medium-grained sandstone with no identifiable primary sedimentary structures. The unique identifier of this facies is the presence of uniformly sized concretionary calcite nodules. The concretions can be isolated or amalgamated and this facies is absent of identifiable bioturbation, possibly obscured from diagenetic overprinting (Fig. 13B).

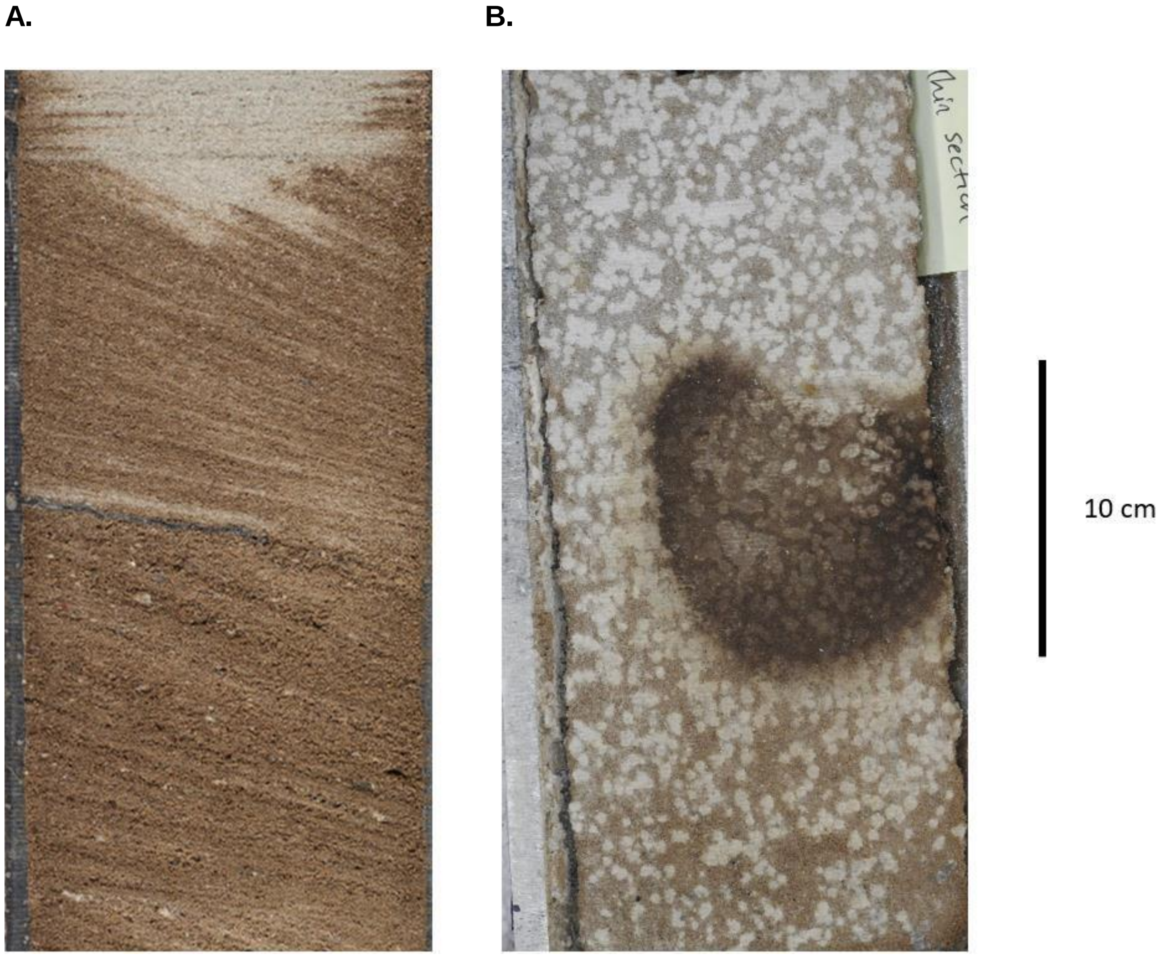


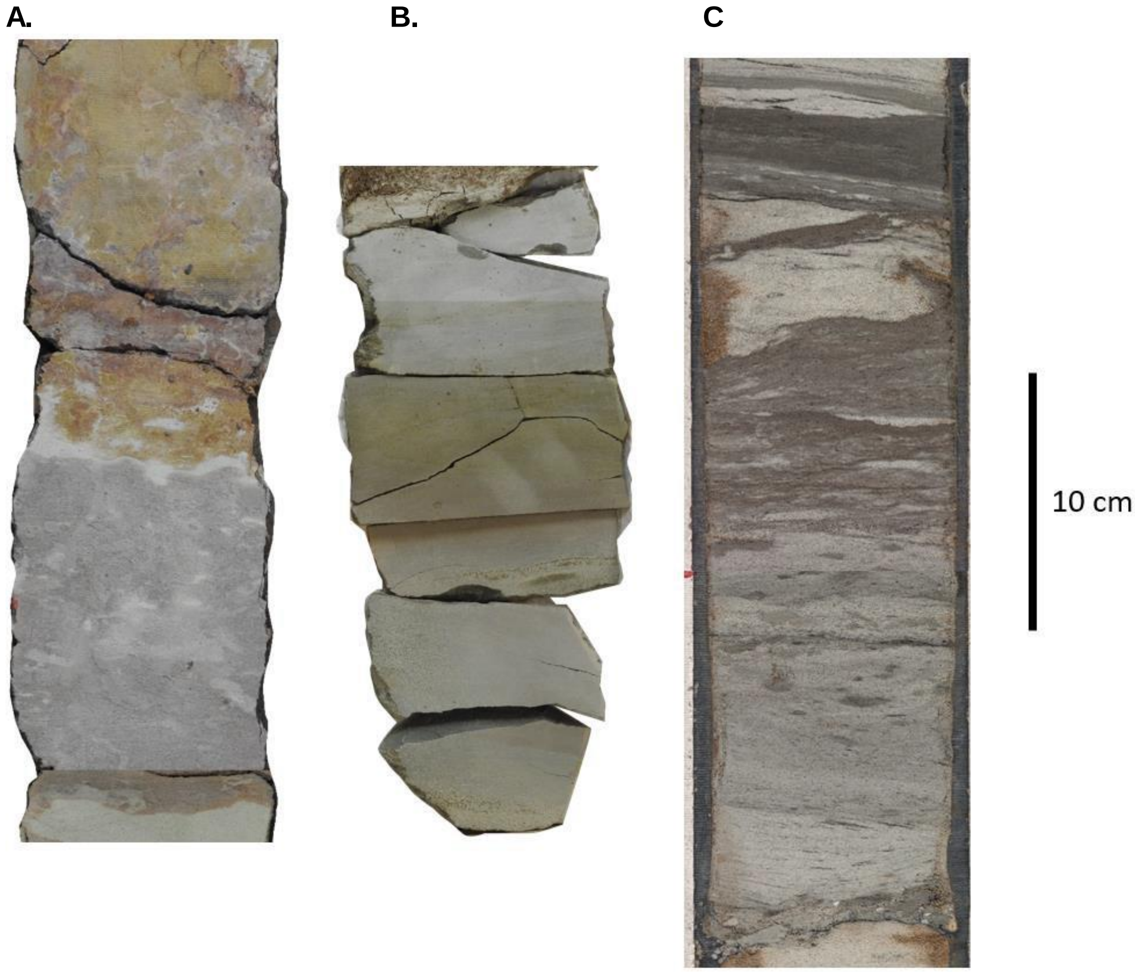
Figure 13. – Cross-bedded sandstone facies and concretionary calcite facies in the Paluxy Formation of well 34-1 and MPC 10-4 respectively. A) Cross-bedded sandstone lithofacies, 5091 ft measured depth, is the most abundant facies within the cored interval and consists of medium-grained sandstone with planar to planar-tangential cross-beds. B) Concretionary calcite facies, 5331 ft measured depth, is identified by an abundance of granule-sized nodules of concretionary calcite within medium-grained sandstone.

Mudstone Lithofacies Characteristics

The variegated mudstone facies is the deepest mudstone that was cored within the Paluxy Formation in well MPC 34-1, is approximately 9 feet thick, and is a sandy mudstone to clayey sandstone. It is characterized by variegated gray, orange, and pink colors throughout. Sedimentary structures include branching rootlets, desiccation cracks, and horizontal and vertical burrow networks that give this facies a mottled texture. The bioturbation index of this facies is 3 throughout (Fig. 14A).

The massive mudstone facies is up to a foot thick and is a massively bedded silty claystone with some faint horizontal laminae. The color ranges from gray to orange and pink. The facies contains a few possible limonitic nodules that give this rock an orange tint in some spots and no bioturbation is associated with this facies (Fig. 14B).

Heterolithic mudstone occurs in two intervals within the Paluxy Formation in well MPC 10-4 well and is significant in that it is the only mudstone facies associated with almost 95 feet of continuous core dominated by sandstone. The facies is 1.5 ft thick and is characterized by an erosional basal contact with mudstone pebble intraclasts and grades into clay-rich siltstone and sandy mudstone. There are current ripples and cross-laminae that are succeeded by horizontal laminae and quartz-rich siltstone. There are no apparent burrows associated with this facies (Fig. 14C).



.

Figure 14. – Variegated mudstone facies and massive mudstone facies in MPC 34-1 well and heterolithic mudstone facies in the MPC 10-4 well within the Paluxy Formation. A) Variegated mudstone facies, 5325 ft measured depth, has orange, red, purple, and gray coloring and a bioturbation index of 3 throughout. B) Massive mudstone facies, 5307 ft measured depth, is a silty claystone with no apparent bioturbation. C) Heterolithic mudstone facies, 5073 ft measured depth, is a silty-sandy mudstone with current ripples and cross-laminae and no apparent bioturbation.

Washita-Fredericksburg Interval

The Washita-Fredericksburg interval contains sandstone and mudstone. The cored intervals are from the MPC 26-5 well, which contains 4 feet from the Big Fred sand (Fig. 15), and the lower part of the Washita-Fredericksburg interval of the MPC 34-1 well, which spans 13 feet of section (Fig. 16).

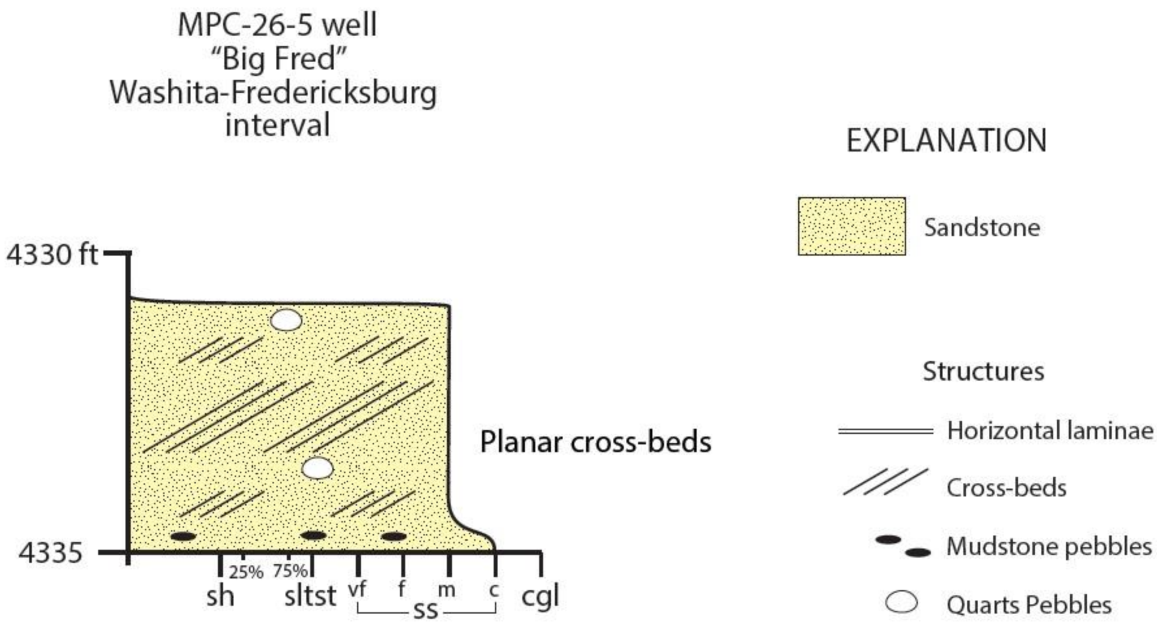


Figure 15. – Graphic core log of the Big Fred sand from the Washita-Fredericksburg interval from the MPC 26-5 well.

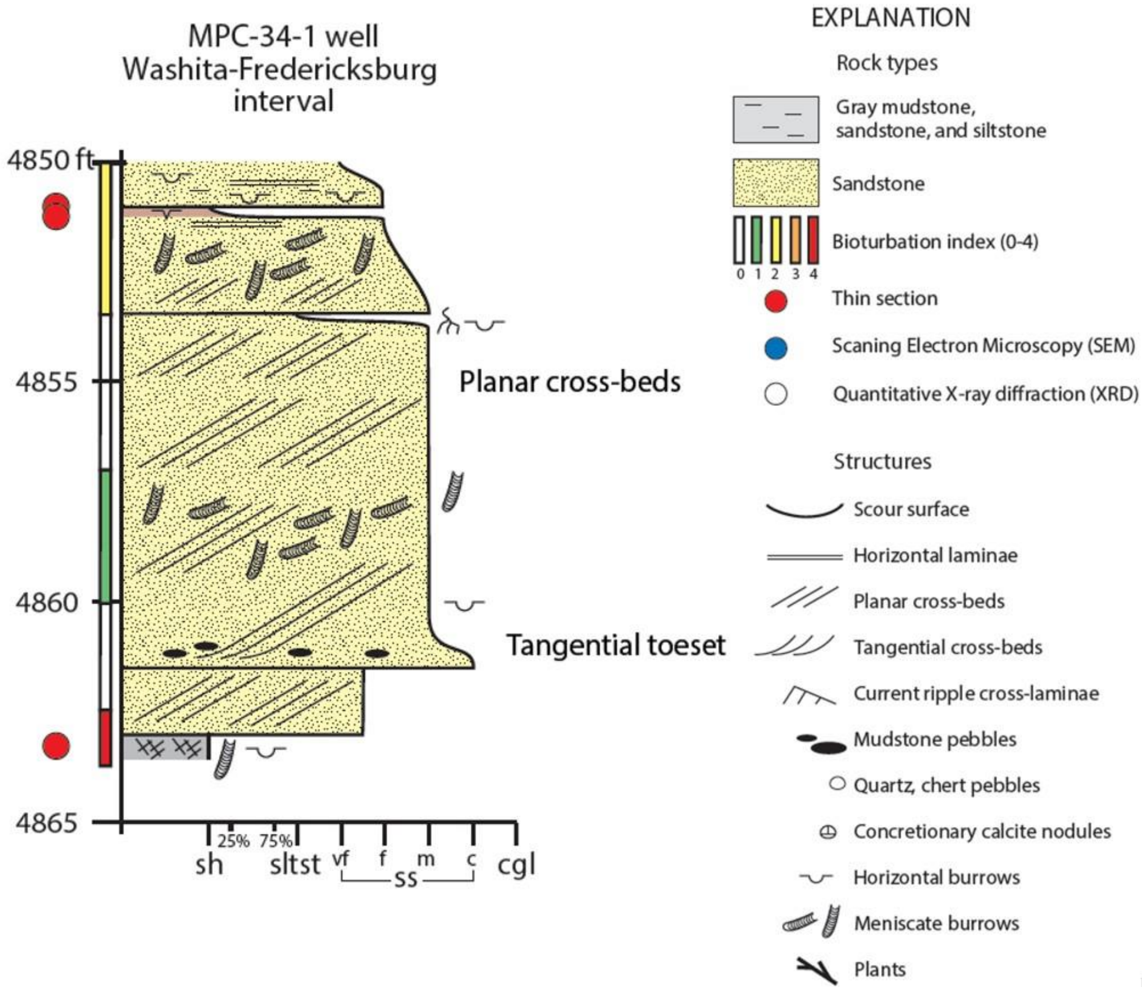


Figure 16. – Graphic core log of the Washita-Fredericksburg interval from the MPC 34-1 well (modified from Pashin et al., 2020).

Sandstone Lithofacies Characteristics

The cross-bedded sandstone facies in the Washita-Fredericksburg interval is in the lower portion of the Washita-Fredericksburg interval in the MPC 34-1 well and is characterized by fine- to medium-grained sandstone up to 4 ft thick with scattered purple and red variegation of color. Sedimentary structures include planar cross-beds, and no bioturbation is present (Fig. 17A).

The burrowed sandstone facies in the lower Washita-Fredericksburg contains medium- to fine-grained sandstone, up to 2 ft thick, with meniscate burrows and has a bioturbation index of 2 or less. Trace fossils include meniscate and horizontal burrows with minor overlap among burrows; cross-bedding is only mildly disturbed (Fig. 17B).

The Big-Fred sand of the Washita-Fredericksburg interval contains medium-grained white sandstone and few well rounded quartz pebbles. Core was from the MPC 26-5 and sedimentary features were not preserved well due to the core being liquified in the core barrel.

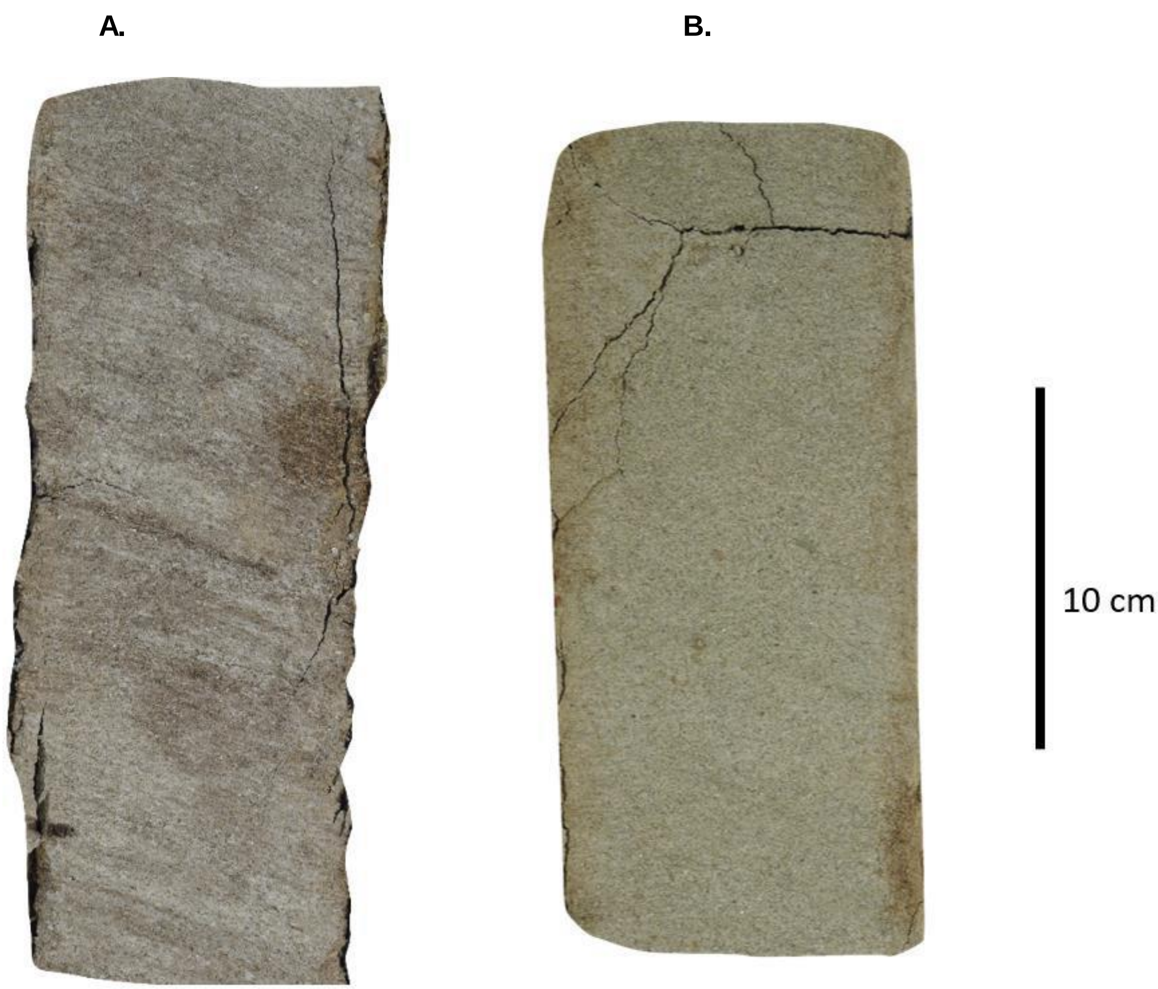


Figure 17. – Photographs of sandstone facies in the basal Washita-Fredericksburg interval of the MPC 34-1 well. A) Washita-Fredericksburg cross-bedded facies, 4859 ft measured depth, is characterized as a fine- to medium-grained, variegated sandstone. B) Washita-Fredericksburg burrowed sandstone facies, 4855 ft measured depth, is characterized as a medium- to fine-grained sandstone with cross-beds that are commonly disturbed by bioturbation.

Mudstone Lithofacies Characteristics

The variegated and blocky mudstone facies is in the basal Washita-Fredericksburg interval is approximately 12 feet thick and interbedded with sandstone. The color is red to purple and light gray with black streaks, desiccation cracks, and horizontal laminae. It contains blocky peds, and includes a sand filled dike at the bottom of the facies. The facies bioturbation index is 2-4, having common occurrence of vertical and horizontal burrows that overlap and disturb sedimentary features and bedding (Fig. 18).

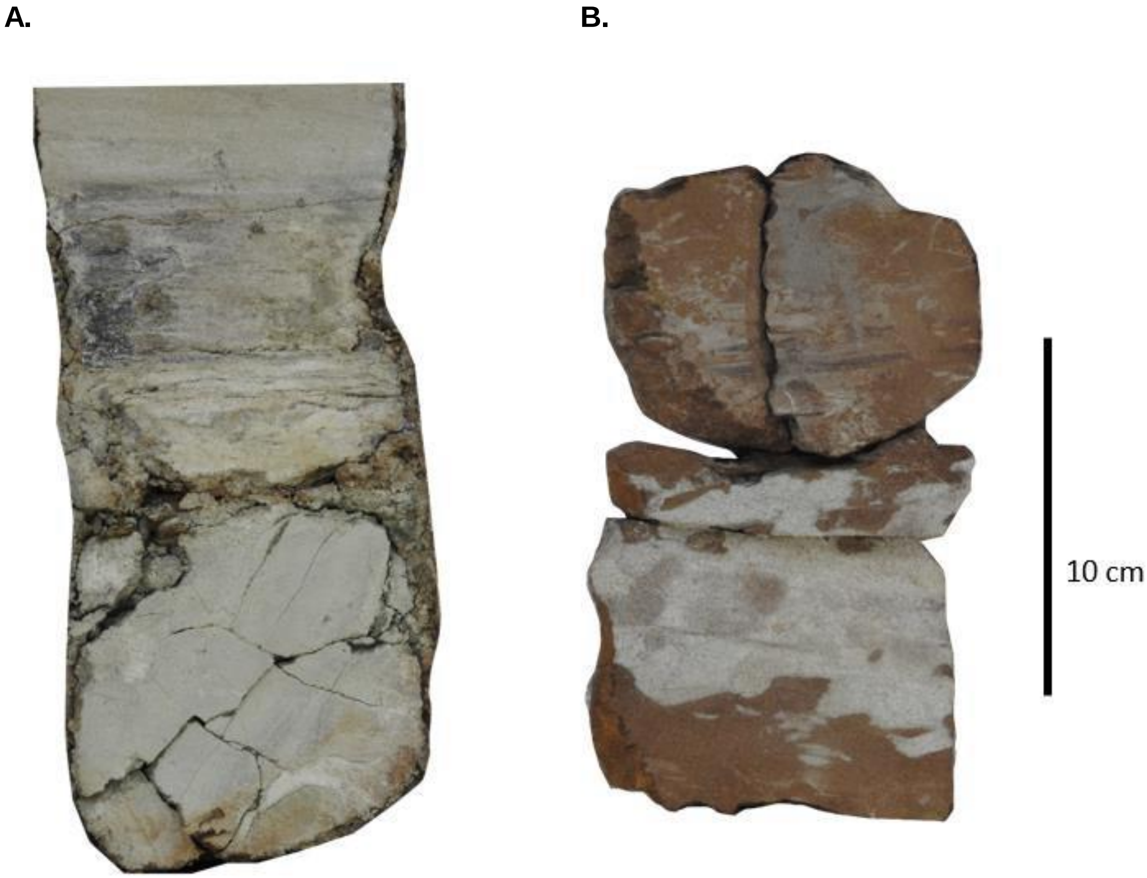


Figure 18. – Variegated and blocks mudstone facies are interpreted to be paleosols within the basal Washita-Fredericksburg interval of the MPC 34-1 well. A) Mudstone, 4862 ft measured depth, that is interpreted to be a paleosol with blocky ped morphology. B) Mudstone, 4850 ft measured depth, with variegated color and a bioturbation index of 2.

Coker Formation (lower Tuscaloosa Group)

The Coker Formation (lower Tuscaloosa Group) core contains sandstone. The cored intervals were from the MPC 26-5 well and includes a section with 9 feet of sandstone (Fig. 19).

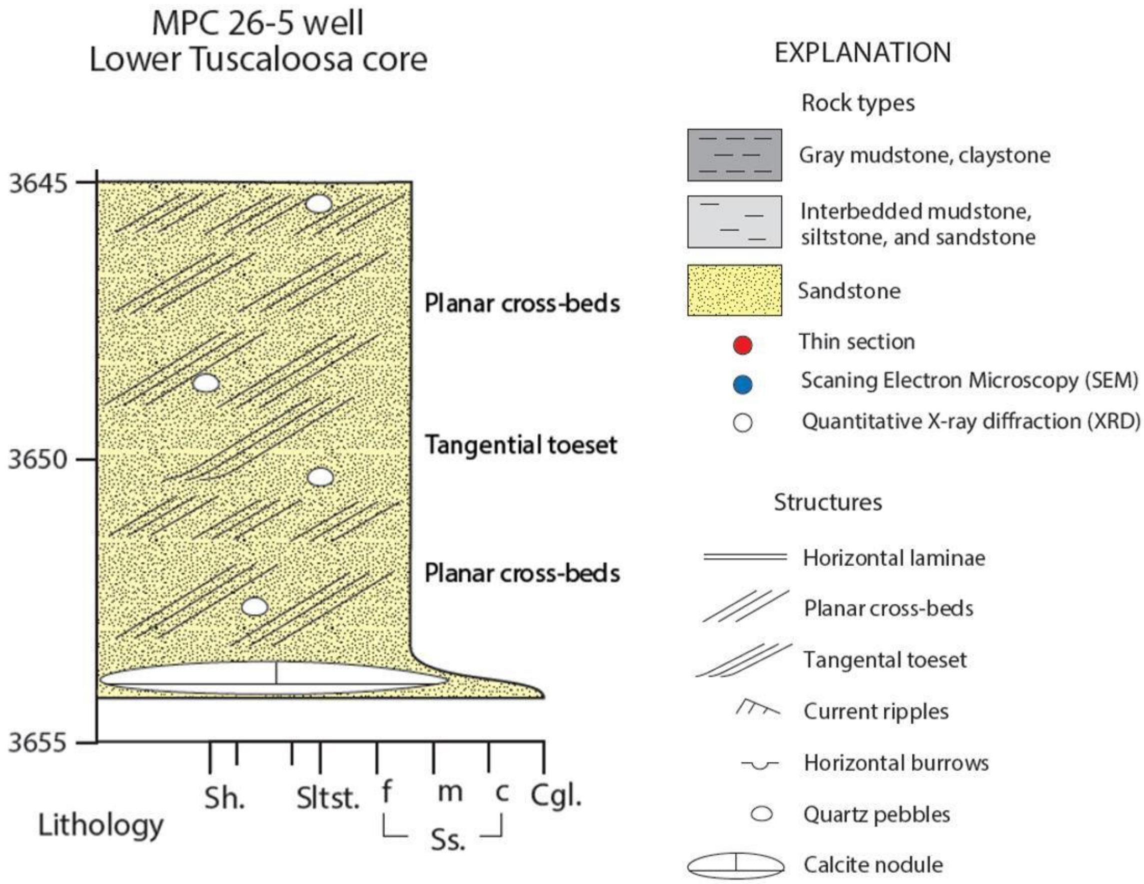


Figure 19. – Graphic core log of the Coker Formation (Lower Tuscaloosa) from the MPC 26-5 well. Lithology is sandstone with a large calcite concretion at the base.

Sandstone Lithofacies Characteristics

The Coker Formation (lower Tuscaloosa Group) core has one facies associated with it from the limited core that was recovered, the Coker sandstone facies, from the MPC 26-5 well.

Lithologically it is medium- to fine-grained sand with isolated, well rounded quartz pebbles and planar cross-beds. The base of the core contains a cobble-sized calcite concretion.

Gordo Formation (Marine Tuscaloosa shale)

The Marine Tuscaloosa shale contains dominantly mudstone interbedded with sandstone and siltstone. Core recovery was 3.5 ft from the MPC 26-5 well and 34.5 ft from the MPC 10-4 well (Fig. 20, 21).

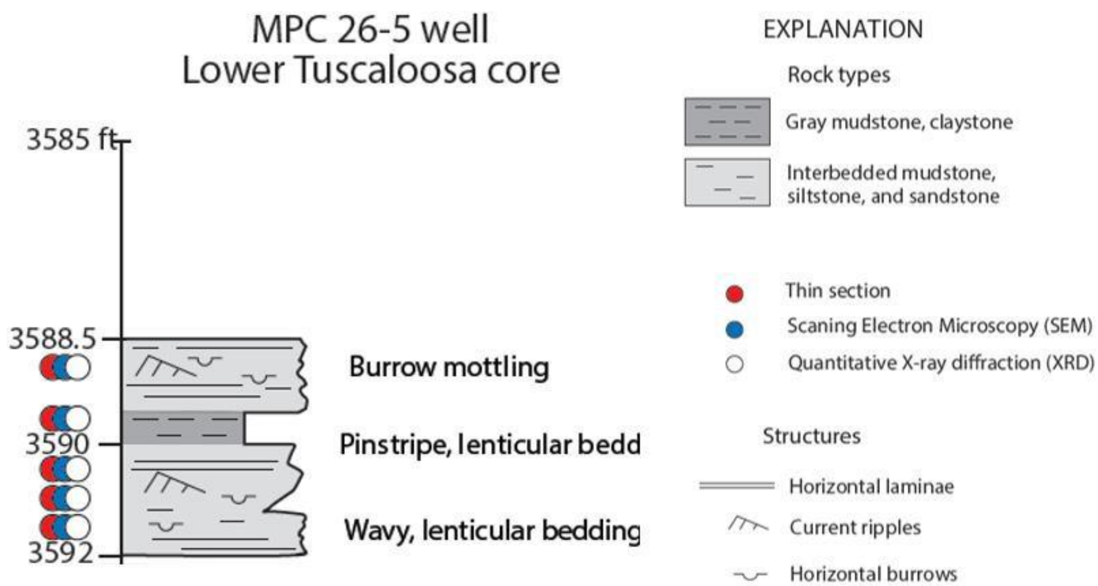


Figure 20. – Graphic core log of the lower Gordo Formation (Marine Tuscaloosa shale) in the MPC 26-5 well.

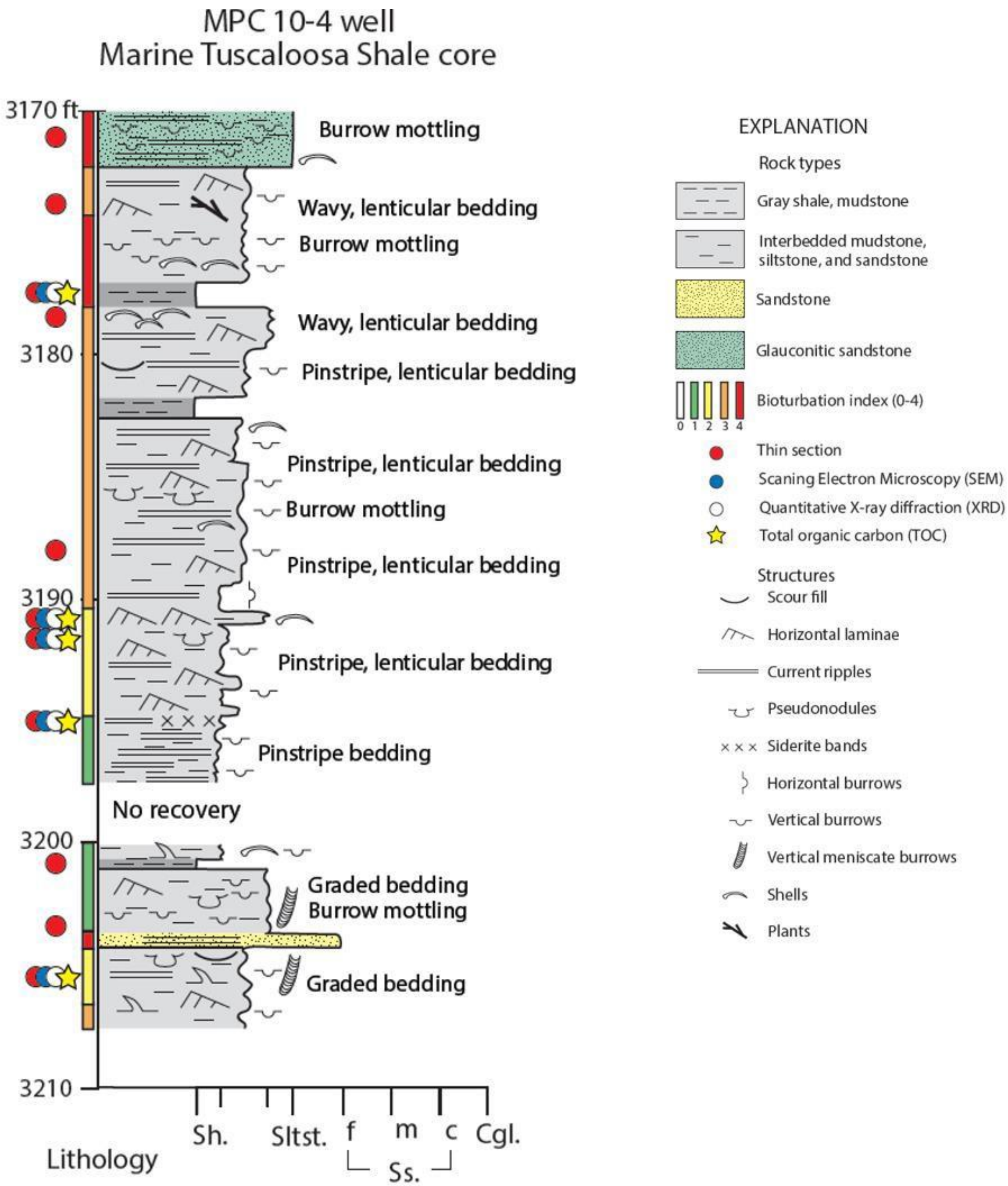


Figure 21. – Graphic core log of the Marine Tuscaloosa shale in the MPC 10-4 well (modified from Pashin et al., 2020).

Siltstone Lithofacies Characteristics

The graded muddy siltstone lithofacies is within the Marine Tuscaloosa shale in the lower part of the MPC 10-4 core and is dominantly coarse-grained siltstone with interbedded claystone. The siltstone contains normally graded beds at the centimeter scale with soft sediment deformation within the clayey beds that have pseudonodules resembling ball-and-pillow structures. There is localized burrowing and mottling with a bioturbation index of 1-4, having abundant vertical and horizontal burrows (Fig. 22A).

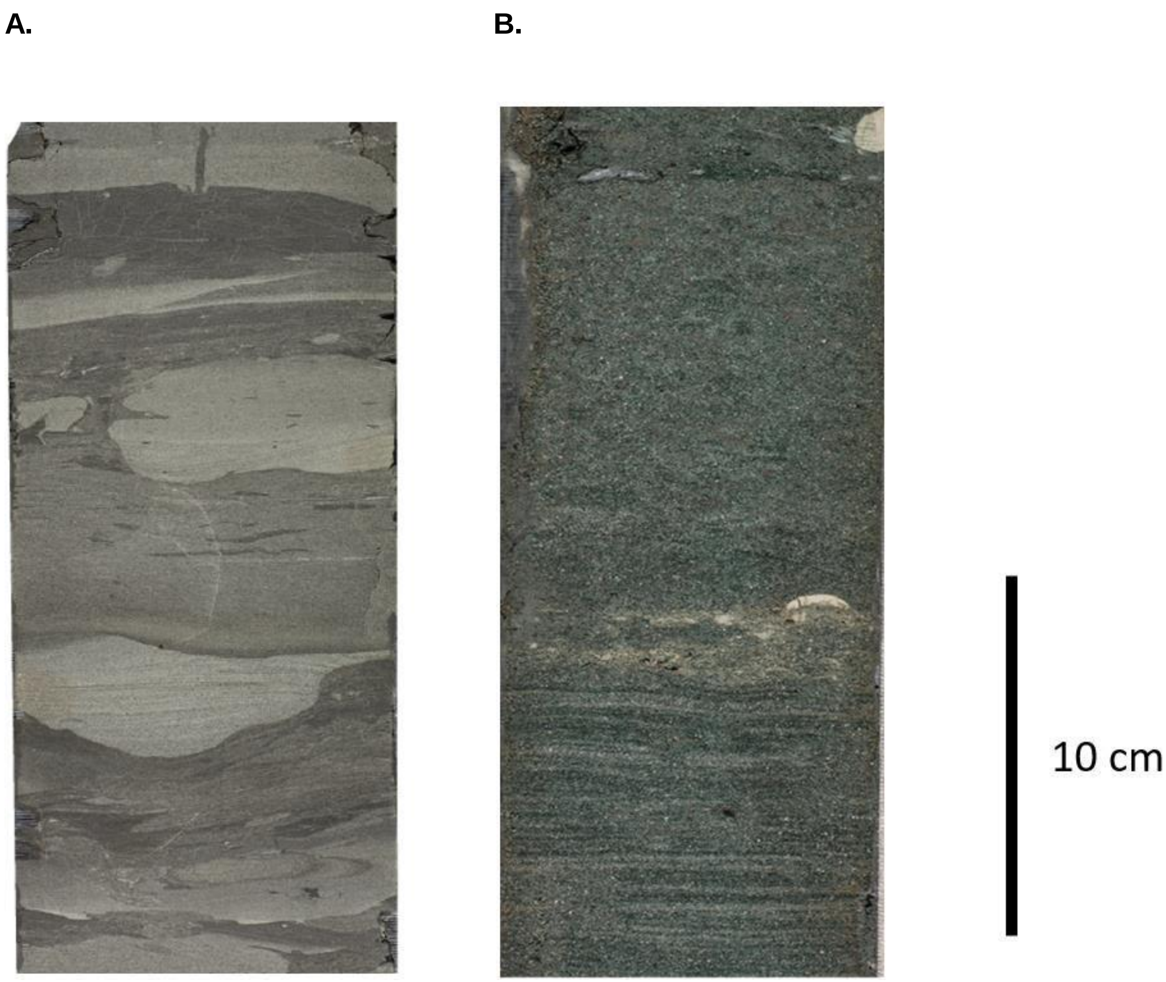


Figure 22. – Siltstone and sandstone facies of the Gordo Formation (Marine Tuscaloosa shale) from MPC 10-4 well. A) Graded muddy siltstone lithofacies, 3205 ft measured depth, has soft

sediment deformation and flame structures. B) Glauconitic sandstone lithofacies, 3172 ft measured depth, is associated with glauconitic sand and intense bioturbation with the inclusion of clay pebbles, marine fossils, and some horizontal laminae.

Mudstone Lithofacies Characteristics

The pinstriped claystone lithofacies is the thickest facies cored at approximately 15 feet thick and is characterized as a claystone with interbedded silt- fine-grained sand pinstripe bedding, with faint siltstone laminae. Clay laminae about 5 mm thick are intercalated with silt laminae that are about 2 mm thick. Sedimentary structures include horizontal laminae and current ripples within the siltier sections and pinstripe to lenticular bedding within the clay-rich section. There are common pyrite nodules. Bioturbation has an index of 1-3 with more bioturbation associated with silt-rich zones at the top of the facies, and there are localized silt layers that are significantly bioturbated; horizontal traces are commonly filled with silt and pyrite framboids. There are two occurrences of fragmented marine fossil beds interpreted to be dominantly molluscs (Fig. 23A).

The lenticular claystone lithofacies is a sandy claystone with coarse silt to fine sand laminae with lenticular to wavy bedding, silty horizontal laminae, and current ripples are common. This facies is also the most fossiliferous with coaly plant fragments and marine fossils, probably molluscs, occurring in the sandy interbeds up to 3 inches thick. The siltier and sandier interbeds also have the highest bioturbation index of 3-4 that results in burrow mottling (Fig. 23B).

The wavy mudstone lithofacies occurs in the Marine Tuscaloosa shale in the MPC 26-5 and MPC 10-4 well. It is characterized as a dark gray, clay rich mudstone with some coarse-grained silts to fine-grained sands within wavy to lenticular bedding and some horizontal laminae; the facies has a bioturbation index of 3 that begins to interfere with sedimentary structure (Fig. 23C).

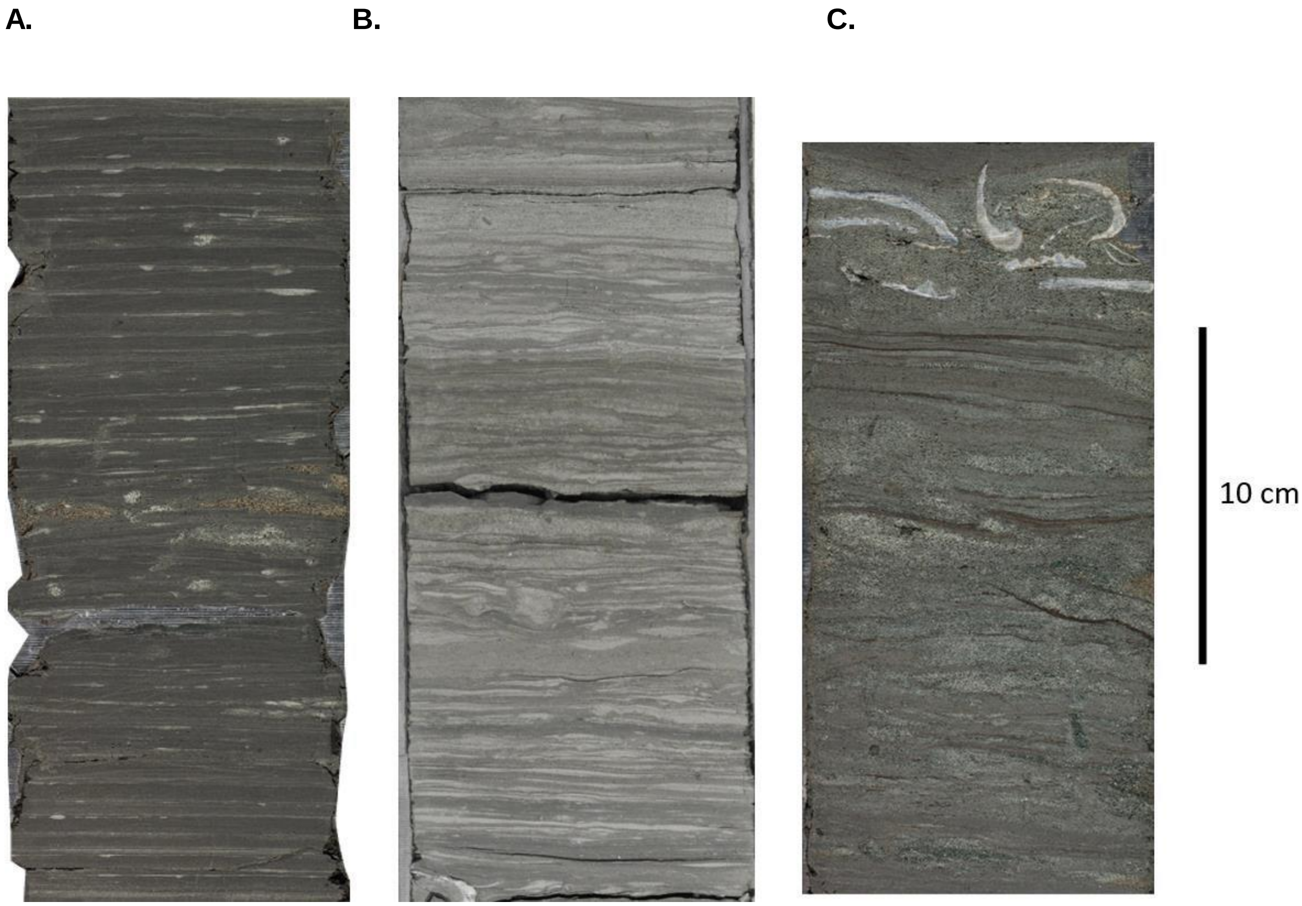


Figure 23. – Mudstone facies in the Gordo Formation (Marine Tuscaloosa shale) from the MPC 10-4 well. A) Pinstripe claystone lithofacies, 3195 ft measured depth, has rhythmic bedding with claystone laminae interbedded with siltstone laminae and is the thickest facies at approximately 15 ft. There are common pyrite rich beds and lenses and has a bioturbation index of 1-3. B) Lenticular claystone lithofacies, 3179 ft measured depth, has lenticular to pinstripe bedding with localized interbedded claystone. This facies contains coaly material, fragmented shales, and burrowing with a bioturbation index of 3. C) Wavy mudstone lithofacies, 3178 ft measured depth, has wavy to lenticular bedding and is rich in coarse silt and fine grains. Coalified plant material and marine fossils are present, and the facies has a bioturbation index of up to 4.

Sandstone Lithofacies Characteristics

The glauconitic sandstone lithofacies is uniquely characterized as a fine-grained glauconitic sandstone with some horizontal laminae, current ripples, shell fragments likely from molluscs. This facies also has a bioturbation index of 4, having frequent overlapping horizontal burrow traces that results in texture mottling. Clay pebbles occur in this facies, which only appears near the top of the core (Fig. 22B).

MUDSTONE PETROGRAPHY

Mudstone petrography is addressed with respect to stratigraphic position and facies. For each formation, mudstone fabric, composition, porosity and diagenetic features is discussed. X-ray diffraction data were gathered for mudstone in the Paluxy Formation and Marine Tuscaloosa shale (Table 4).

Table 4 – X-ray diffraction mineralogy of mudstone from the Paluxy and Marine Tuscaloosa shale. Facies key: GB = Graded muddy siltstone lithofacies, LB = Lenticular claystone lithofacies, PB = Pinstripe claystone lithofacies, WB = Wavy mudstone lithofacies, HM = Heterolithic mudstone, MM = Massive mudstone.

Sample location			Minerals					Clays						Grouped				Facies
Measured Depth	Formation	Well	Calcite	Quartz	K-Spar	Plag.	Pyrite	Total Clay	Chlorite	Kaolinite	I/M	Smectite	Q+F	Carbonates	Others	Clays	
Feet			%	%	%	%	%	%	%	%	%	%	%	%	%	%	
3177.00	Marine Tuscaloosa	MPC 10-4	1	26	7	2	2	62	2.0	34.2	9.9	15.8	35	1	2	62	GB
3190.50	Marine Tuscaloosa	MPC 10-4	1	28	7	1	1	62	1.5	35.4	21.1	4.0	36	1	1	62	LB
3191.83	Marine Tuscaloosa	MPC 10-4	2	32	7	1	1	57	2.3	36.0	16.6	2.1	40	2	1	57	LB
3196.30	Marine Tuscaloosa	MPC 10-4	1	38	6	1	Tr	54	0.5	9.4	11.1	33.0	45	1	0	54	PB
3206.90	Marine Tuscaloosa	MPC 10-4	Tr	49	4	1	1	45	2.1	15.5	1.0	26.4	54	0	1	45	GB
3589.00	Marine Tuscaloosa	MPC 26-5	Tr	62	6	1	Tr	31	0.6	19.7	3.2	7.4	69	0	0	31	WB
3590.00	Marine Tuscaloosa	MPC 26-5	Tr	44	4	1	Tr	51	1.9	24.2	12.5	12.4	49	0	0	51	WB
3590.50	Marine Tuscaloosa	MPC 26-5	Tr	57	5	1	Tr	37	0.3	31.7	1.2	3.8	63	0	0	37	WB
3592.00	Marine Tuscaloosa	MPC 26-5	Tr	49	5	1	Tr	45	1.6	36.0	6.2	1.2	55	0	0	45	WB
5072.35	Paluxy Formation	MPC 10-4	Tr	69	4	Tr	Tr	27	0.2	12.4	13.0	1.4	73	0	0	27	HM
5305.60	Paluxy Formation	MPC 34-1	Tr	39	4	Tr	Tr	57	0.7	18.2	28.4	9.7	43	0	0	57	MM

Table 5. – Samples used for TOC analysis from the MPC 10-4 well with results.

Sample Name	Formation	Total Carbon	Total Sulfer	Avg. Carbon	Inorganic Carbon	Organic Carbon
Kemper 5072.3	Paluxy Formation	0.97	0.05	0.99	**0.00**	**0.99**
Kemper 5072.3		1.00	0.04			
Kemper 5072.3		1.00	0.04			
Kemper 3190.5	Gordo Formation (Marine Tuscaloosa shale)	1.31	0.05	1.38	**0.27**	**1.11**
Kemper 3190.5		1.38	0.06			
Kemper 3190.5		1.46	0.06			
Kemper 3191.8	Gordo Formation (Marine Tuscaloosa shale)	1.21	0.09	1.18	**0.20**	**0.98**
Kemper 3191.8		1.21	0.08			
Kemper 3191.8		1.13	0.08			
Kemper 3196.3	Gordo Formation (Marine Tuscaloosa shale)	1.64	0.27	1.31	**0.07**	**1.24**
Kemper 3196.3		1.11	0.28			
Kemper 3196.3		1.19	0.06			
Kemper 3177.0	Gordo Formation (Marine Tuscaloosa shale)	13.44	0.57	13.68	**0.38**	**13.30**
Kemper 3177.0		13.78	0.59			
Kemper 3177.0		13.83	0.57			
Kemper 3206.9	Gordo Formation (Marine Tuscaloosa shale)	1.09	0.82	0.94	**0.03**	**0.91**
Kemper 3206.9		0.86	0.82			
Kemper 3206.9		0.86	0.83			

Mudstone Fabric and Composition

Paluxy Formation

The variegated mudstone facies of the Paluxy Formation is characterized as a sandy mudstone with calcite cement. This facies is bordering a claystone due to the abundance of clay and based on measured particle size; without quantitative XRD definitive classification is interpretive. The sample contains quartz grains floating in clay-rich matrix and includes many clay-size quartz clasts. Quartz is the most abundant grain, and the sample is lean in feldspar. Accessory minerals include muscovite and biotite, occasional pyrite framboids, and isolated zircon crystals. All visible pore space has been occluded by fines, organic material, and calcite cement (Fig. 24).

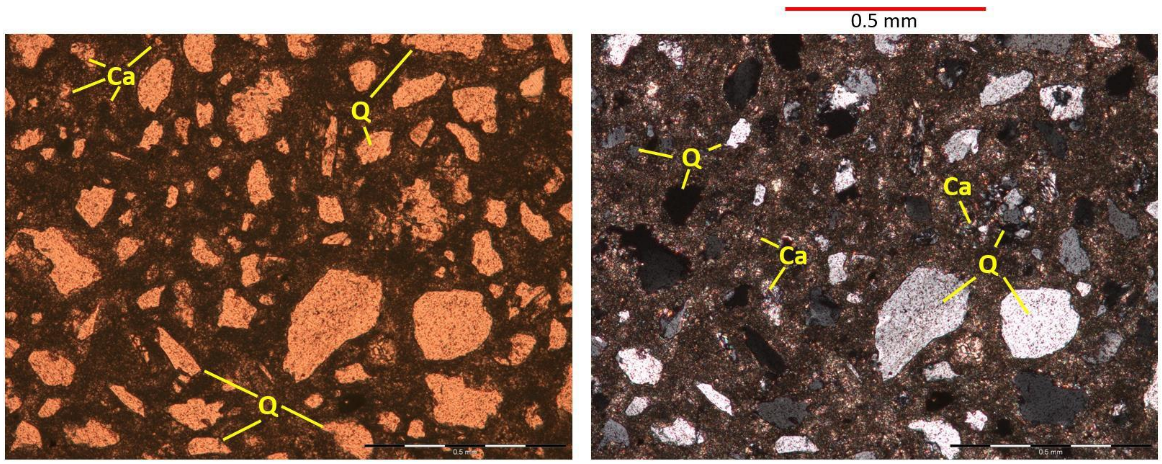
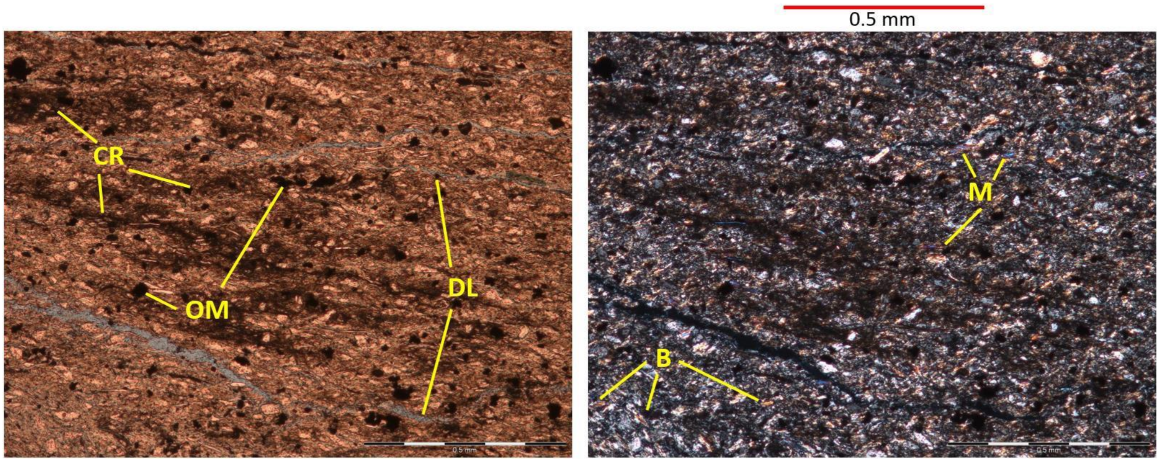


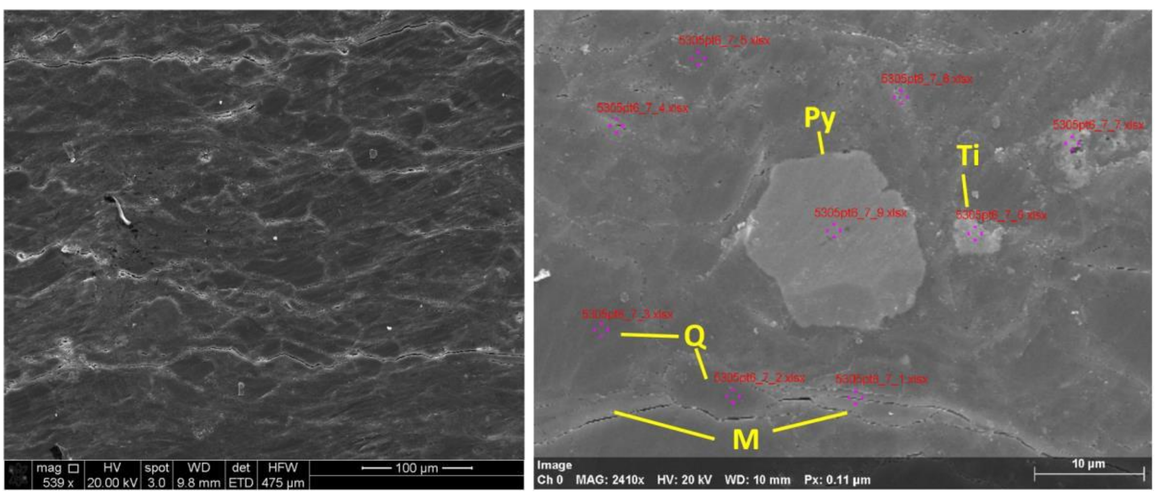
Figure 24. – Thin section image of variegated mudstone facies from the MPC 34-1 well within the Paluxy Formation at 5319.9 ft measured depth. The thin sections reveal no visible porosity and abundant clay. Pores that once existed are filled with carbonate cement (Ca). Quartz (Q) is the most abundant grain and is typically very fine-grained and smaller. This thin section is from a massively bedded, structureless, sandy mudstone. Left: plane-polarized light (PPL). Right: cross-polarized light (CPL).

Paluxy massive mudstone facies from XRD is a silty claystone with 57 percent clay consisting of 18.2% kaolinite, 28.4% illite, and 9.7% smectite. The sample contains 39.0% quartz and only 4.0% feldspar (Table 4). The thin section has weak laminae with silt being the most common grain size above clay sized grains (Fig. 25). Accessory grains include muscovite, biotite, zircon, and pyrite. In SEM images pores appear to be artifacts due to desiccation and freezing of the sample, and the visible pores are intraparticle associated with fluid inclusions in quartz grains (Fig. 26).



A. B.

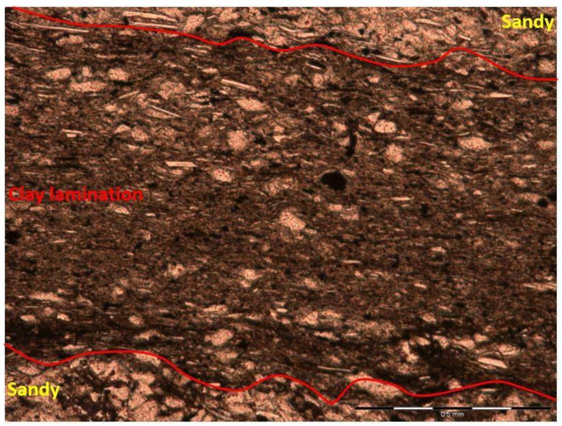
Figure 25. – Thin section image of massive mudstone facies from the MPC 34-1 well in the Paluxy Formation at 5305.5 ft measured depth. A) Plane-polarized light microphotograph showing clay rich lenses (CR) and blotchy organic material (OM), and fissures or delamination parallel and subparallel to bedding (DL). B) Cross-polarized light photomicrograph showing abundant muscovite (M) and lesser amount of biotite (B)grains that are typically elongate parallel to subparallel to bedding. The thin section is a weakly laminated silty claystone.



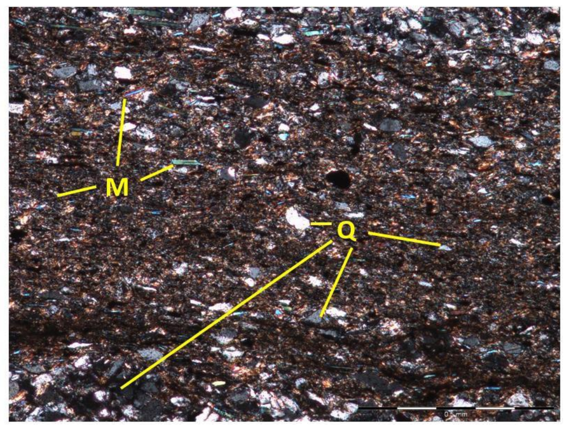
A. B.

Figure 26. – SEM image of massive mudstone facies from the MPC 34-1 well in the Paluxy Formation at 5305.6 ft measured depth. A) The SEM thin section is a massively bedded silty claystone. Porosity is bed-parallel fracture porosity due to desiccation of the sample. B) SEM/EDS with muscovite (M) parallel to bedding, trace amounts of pyrite (Py), quartz (Q), which is the most abundant grain and typically slightly darker than the surrounding grains in SEM images, and the accessory mineral rich in titanium possibly titanium oxide (Ti).

The heterolithic mudstone facies of the Paluxy Formation is a sandy mudstone as classified from quantified XRD with 27% clay, 39% quartz and, 4% potassium feldspar (Table 4). This facies has abundant clay laminae in hand sample as well as in thin section. Accessory minerals include muscovite (Fig. 27), biotite, some zircon and pyrite framboids. This facies contains up to 1% TOC and no inorganic carbon (Table 5). Bed-parallel cracks are apparently due to the desiccation of the sample. Interparticle primary pores are very rare, have diameters on the order of 1 micron, and are partially occluded with clay-size particles (Fig. 28).

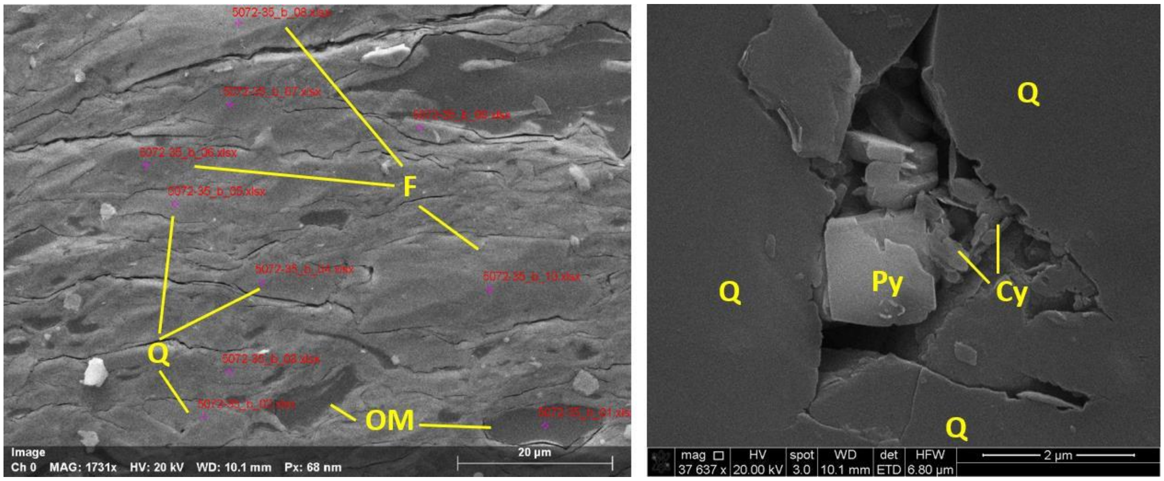


A.



B.

Figure 27. – Thin section of Paluxy Formation heterolithic mudstone facies from the MPC 10-4 well at 5072.35 ft measured depth. The sample is characterized as a sandy mudstone with clay laminae. The sample is normally oriented and has inverse grading indicative of traction deposition with some faint ripple cross-laminae. A) Thin section in plane polarized light shows that there is no visible porosity, and the sample contains clay laminae. B) Cross-polarized light image showing that the most abundant grain type is quartz (Q) with muscovite (M) that is parallel to subparallel to bedding. The grains are imbricated, with cross-laminae that steepen upward.



A. B.

Figure 28. – SEM image of Paluxy Formation heterolithic mudstone facies the MPC 10-4 well at 5072.35 ft measured depth. The sample is sandy mudstone dominated by interparticle pores within the sandy areas. A) SEM/EDS image showing microcracks parallel to sub parallel to bedding and contouring grains due to desiccation of the sample. Quartz (Q) is the most abundant grain type with minor amounts of potassium feldspar (F) and organic material (OM), likely plant fragments lacking cell lumens. B) SEM image showing primary porosity between quartz grains (Q), authigenic clay (Cy) interpreted to be kaolinite, and pyrite cube (Py).

Paluxy Fm. mudstones vary in clay, silt, and sand content but in general is the sandiest mudstones cored. The dominant primary pore type is interparticle porosity associated with silty and sandy laminae and lenses. The cracks that parallel bedding or follow grain boundaries appear to be secondary fractures that formed during core retrieval, preservation, and storage and are not accounted for as a source of porosity (Fig. 29).

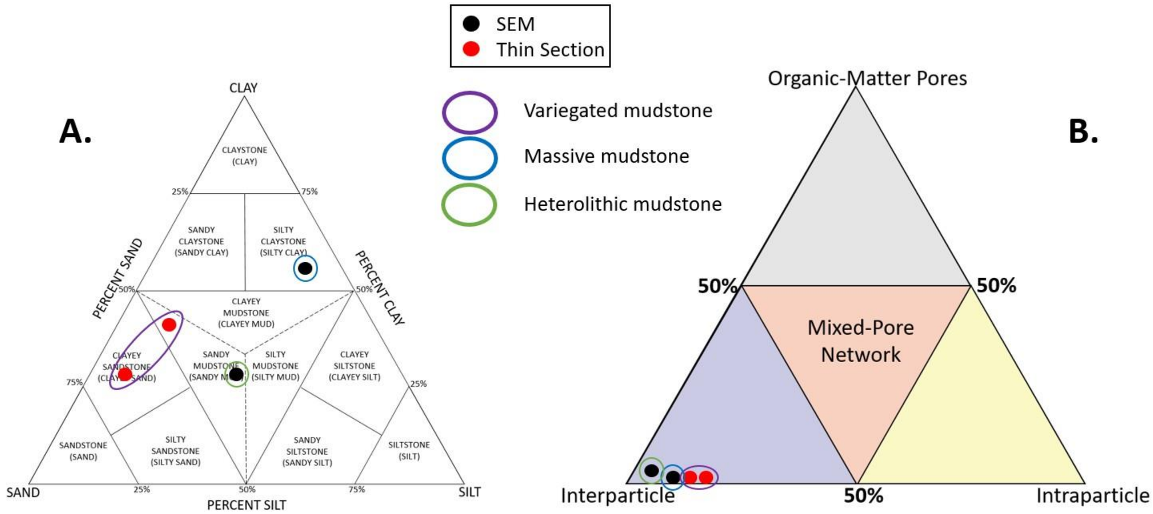
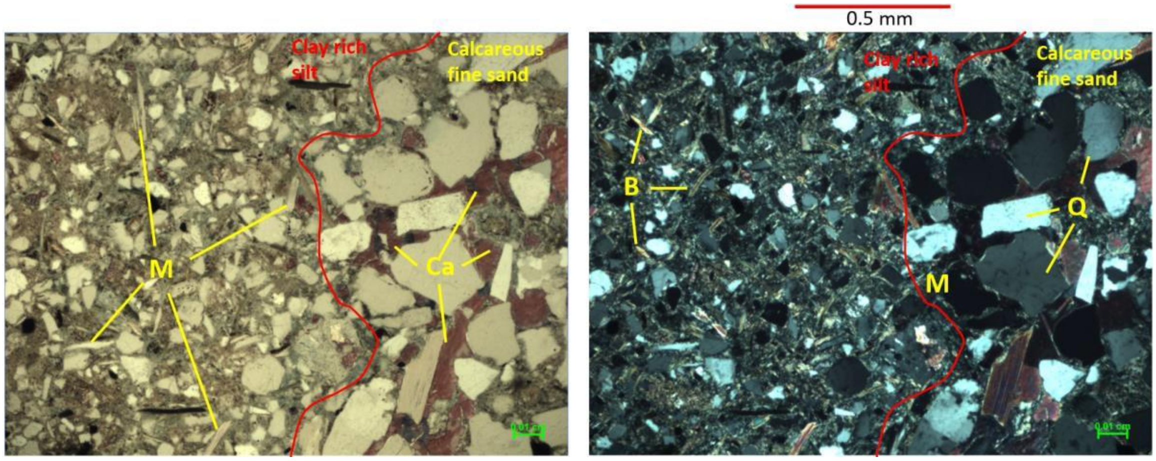


Figure 29. – Ternary plots showing composition and pore types in mudstone of the Paluxy Formation. A) Mudrock classification based on grain size and XRD mineralogical analysis; B) Pore system analysis, for Paluxy mudstone facies denoted by purple, blue and green circles.

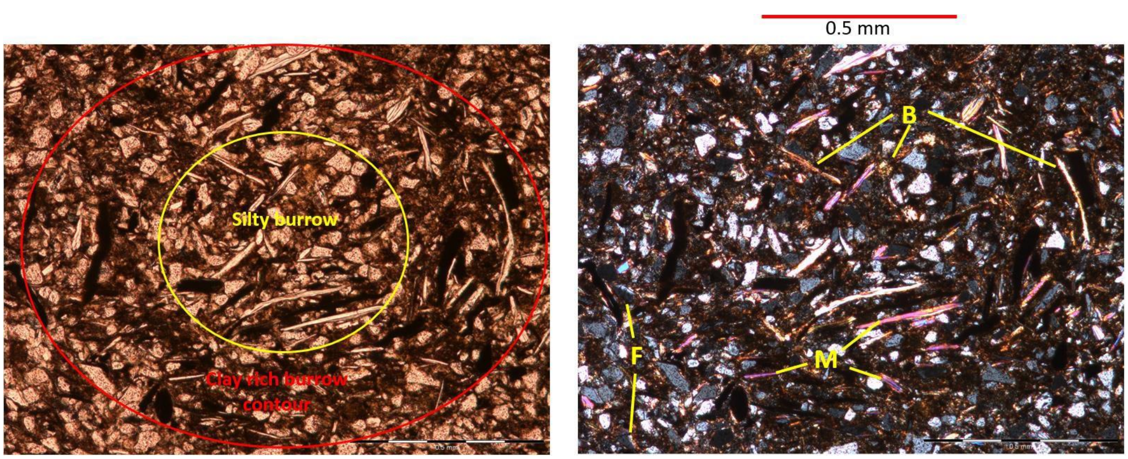
Washita-Fredericksburg Interval

The variegated and blocky mudstone facies of the Washita-Fredericksburg interval in thin section is a clay-rich, sandy to silty mudstone with about 30% percent clay, 38% sand, and 32% silt (Fig. 32). The sands have an upper grain size limit of fine sand with irregular calcareous cementation that can be characterized as a sandy to silty mudstone, with an abundance of mica accessory minerals. The thin section samples are typically massively bedded with micro scale-bimodal distribution with clay rich areas being occluded of visible porosity by fines (Fig. 30). Clay lean areas are occluded of porosity by carbonate cement. There is evidence of bioturbation even in thin section with clay rich interbeds (Fig. 31). There is no visible porosity as all the pores are occluded by fines, silica, or calcite cement. Accessory minerals include zircon, pyrite, opaque minerals, muscovite, and biotite. Feldspar is rare and includes microcline and albite. Interparticle pores largely appear to be an artifact of grain plucking during thin section preparation.



A. B.

Figure 30. – Thin section of variegated and blocky mudstone facies from the MPC 34-1 well in the Washita-Fredericksburg interval at 4863.0 ft measured depth. Larger grains are mostly quartz and mica and the matrix is silt- and clay-sized particles and calcite cement. A) Plane-polarized light photomicrograph showing the vertical contact between lithologic zones. Clay-rich silt, calcareous fine sand, and mica grains that show no preferred bedding direction due to convolute bedding probably represent fill in a burrow, crack, or root-void. B) Cross-polarized light photomicrograph showing quartz, mica, and minor amounts of biotite that are smaller than muscovite. The thin section can be characterized as silty mudstone with calcareous fine sand. The coarser-grained sediment is cemented by calcite that occludes visible porosity.



A. B.

Figure 31. – Thin section variegated and blocky mudstone facies from the MPC 34-1 well within the Washita-Fredericksburg interval at 4850.6 ft measured depth. This facies lacks visible porosity and is characterized as a clay-rich sandy mudstone. A) Plane-polarized light image showing the cross-section of a clay-rich, lined horizontal burrow. B) Cross-polarized image showing the abundance of muscovite (M) and biotite (B) with moderate amounts of albite and microcline, typically silt sized.

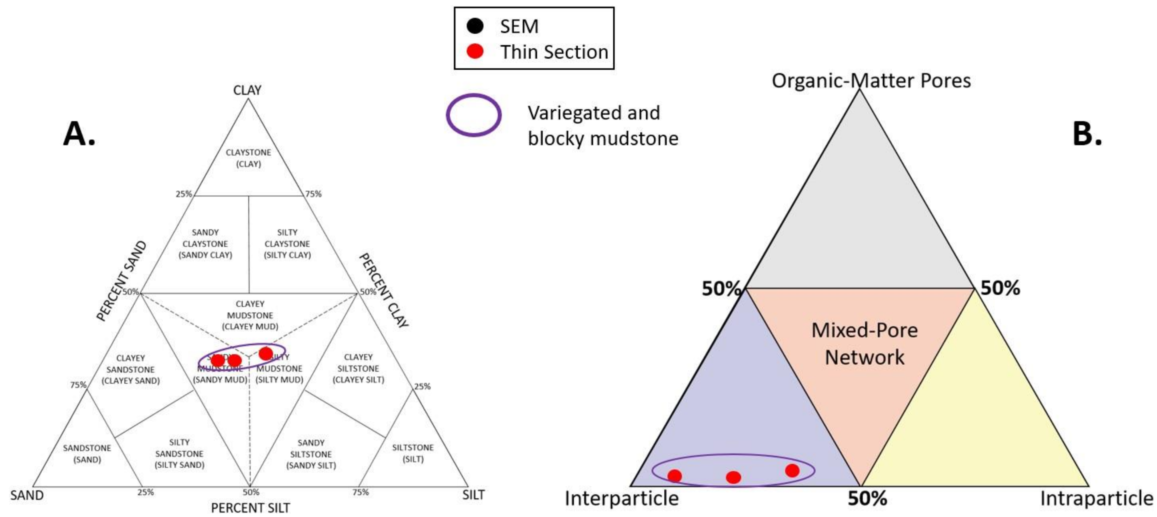
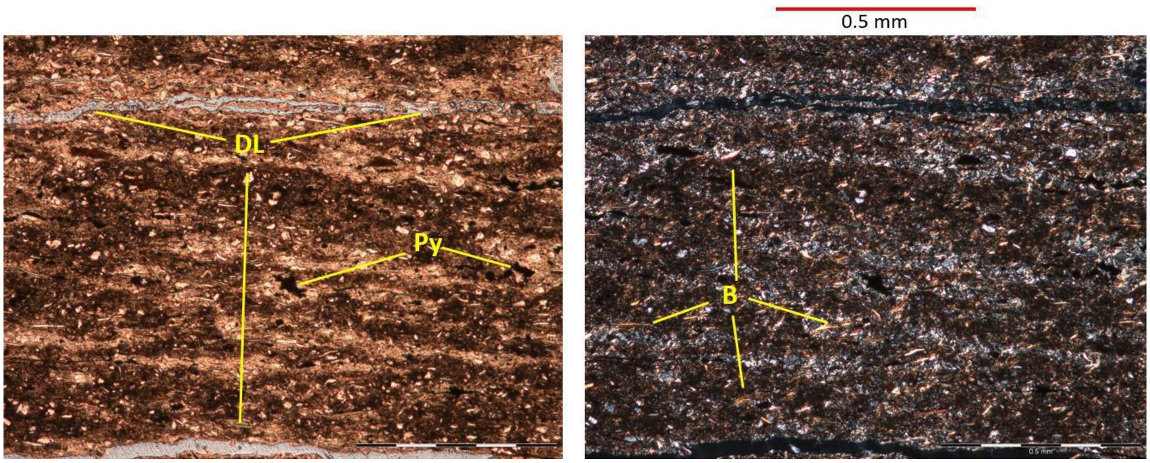


Figure 32. – Ternary plots of composition and pore type in the basal Washita-Fredericksburg interval. A) Classification based on grain size; B) Pore system analysis for the variegated and blocky mudstone facies denoted by the purple oval. The pore system analysis is absolute and it should be noted that there is negligible porosity within this facies.

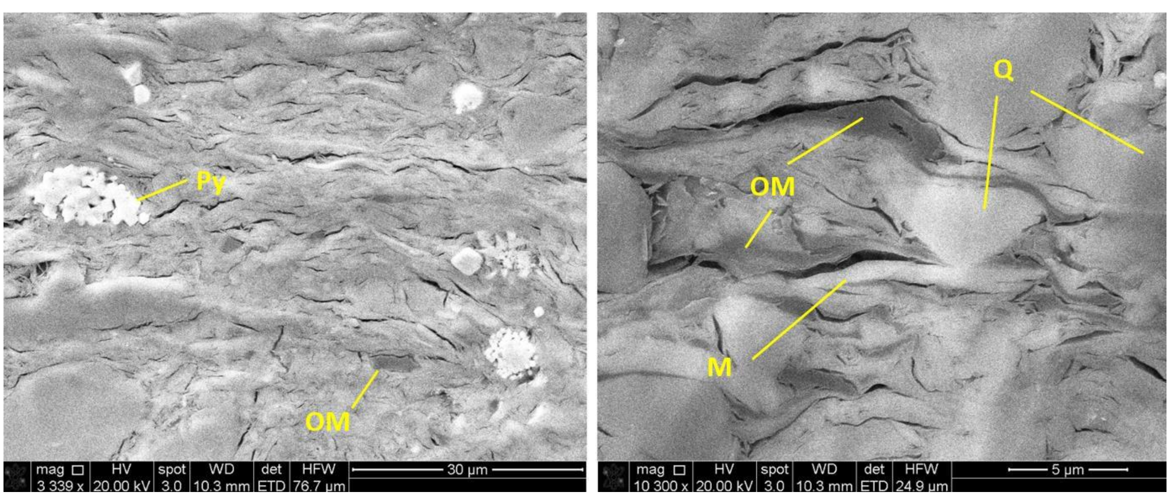
Marine Tuscaloosa shale

The graded mudstone lithofacies contains two distinct rock types; at the base of the facies, the rock is a clayey mudstone (<50% clay) and the upper portion is a silty claystone (>50% clay). The clayey mudstone has clay laminae and rare intraparticle porosity associated with partially dissolved feldspars and fractured quartz silt grains. The silty claystone is massively bedded and lacks apparent pores, likely due to the high clay content (Fig. 33). Clay mineralogy in the clayey mudstone is 36.0% kaolinite, 6.2% illite, 1.3% smectite, and 1.6% chlorite (Table 4). The bioturbation index of the clayey mudstone and the silty claystone is, 2 toward the base and 1 at the top, which likely reflects marginally inhospitable conditions within a predominantly suspension settling environment. The dominant pore system within this facies is intraparticle because in SEM more pores are associated with pyrite cubes and framboids than the small slits within organic matter (Fig. 34). Also based on XRD results pyrite makes up approximately 1% of the rock composition while organic content of the facies is 0.90 wt% (Table 4, 3). In general, the volume of pores is very low within this facies noted by the weight percent of organic matter and pyrite.



A. B.

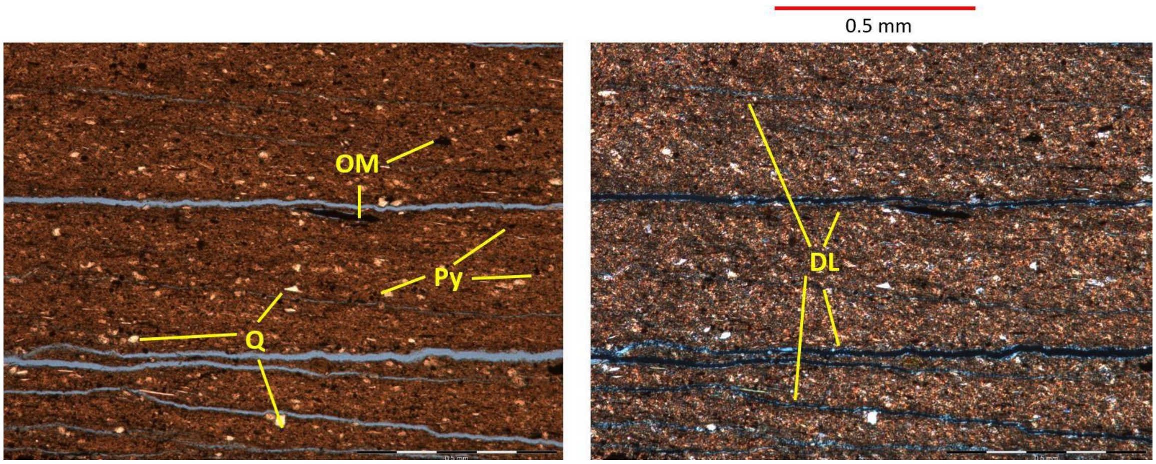
Figure 33. – Thin section of the graded mudstone lithofacies from the MPC 10-4 well of the lower Gordo Formation at 3206.9 measured depth. This sample is classified as a silty claystone. A) Silty claystone with a clay-rich matrix having ripple cross-laminae. Opaque minerals are abundant and interpreted to be pyrite (Py). B) Cross-polarized light thin section showing ripple cross-laminae and the abundance of parallel to subparallel bedded biotite (B), that are the largest grains having an upper limit of fine sand size. Other grains are typically silt sized with an abundance of quartz and very few plagioclase feldspars, zircons, and glauconite.



A. B.

Figure 34. – SEM image of graded mudstone lithofacies from the MPC 10-4 well of the lower Gordo Formation at 3206.9 measured depth. A) Laminated intervals of clay rich matrix with pyrite (Py) famboids at different scales and associated intraparticle porosity. Porosity is artificial due to sample desiccation, identified by pores being elongate, parallel to bedding, and contouring grains. B) SEM matrix desiccation and organic material. There is abundant silt sized quartz grains and mica that are parallel to the bedding plain.

The pinstripe claystone lithofacies of the Marine Tuscaloosa shale is characterized as a silty claystone. This facies has approximately 54-62% clay minerals, from tested samples, as estimated from XRD results. The clay species and concentration ranges from kaolinite 34-36%, up to 16% smectite, 10-21% illite, and 2% chlorite. The mudstone is also composed of 1-2% calcite, 6-7% potassium feldspar, 1-2% plagioclase and 1-2% pyrite (Table 4). This facies has the highest pyrite content of up to 2% and has the highest organic content up to 13.3 wt%. In thin section the microfacies ranges from claystone with wavy laminae of silt (Fig. 35) to poorly bedded with few localized concentrated laminae of clay and organic material (Fig. 36). This facies also has a peculiar fossil associated with it that is interpreted to be a spinose palynomorph that has intraparticle porosity (Fig. 37). The pore system of this facies is primarily intraparticle porosity associated with the pyrite framboids, and porosity within organic material (Fig. 38 and 39). Since this facies has the highest organic content and the organic content has pores, the pore system is interpreted to slightly favor organic-matter pores over intraparticle pores of pyrite.

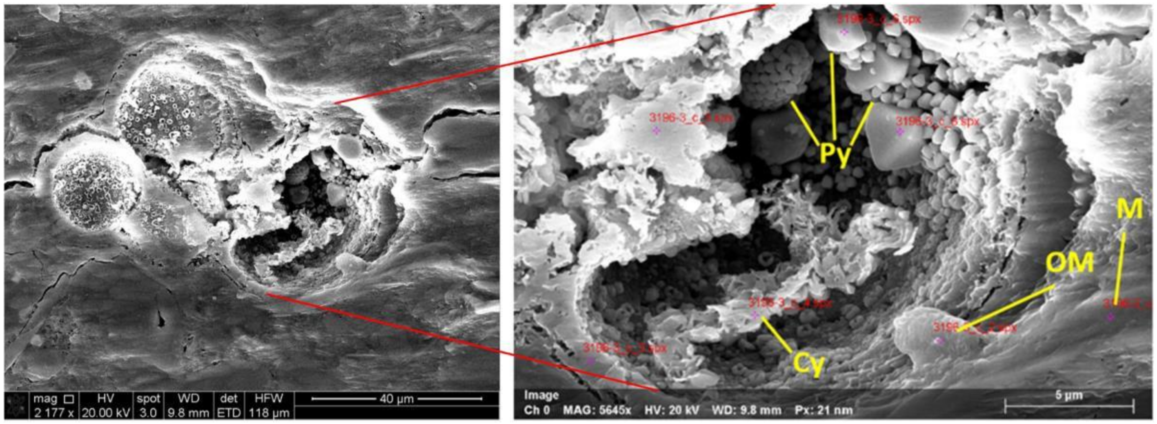


A. B.

Figure 35. – Thin section of pinstripe claystone lithofacies from the MPC 10-4 well of the Marine Tuscaloosa shale at 3188.8 feet measured depth. Mudstone facies 10 is a claystone with siltstone laminae. A) Plane polarized light image with abundant quartz silt (Q), blotchy and platy organic matter (OM), and opaque minerals interpreted as pyrite (Py). B) Thin section in cross-polarized light with ripple cross-strata visible between claystone delaminations (DL).

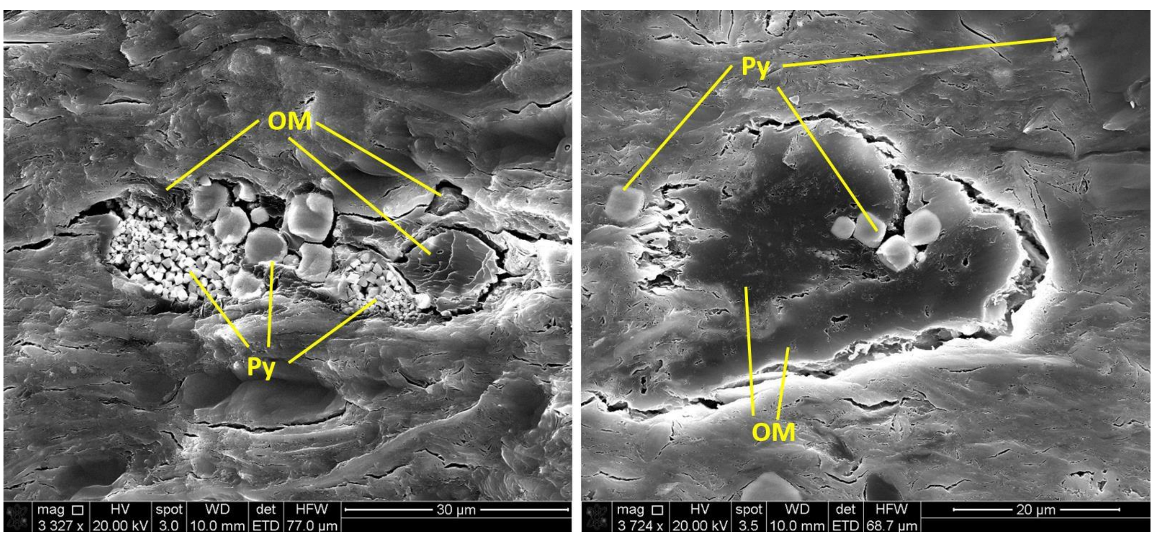
A. B.

Figure 36. – Thin section image of pinstripe claystone lithofacies from the MPC 10-4 well of the Marine Tuscaloosa shale at 3177.0 measured depth. This facies is a massively bedded silty claystone. A) Biotite (B) constitutes the largest grains within a silt-clay matrix. B) Pyrite (Py) grains are common in thin section.



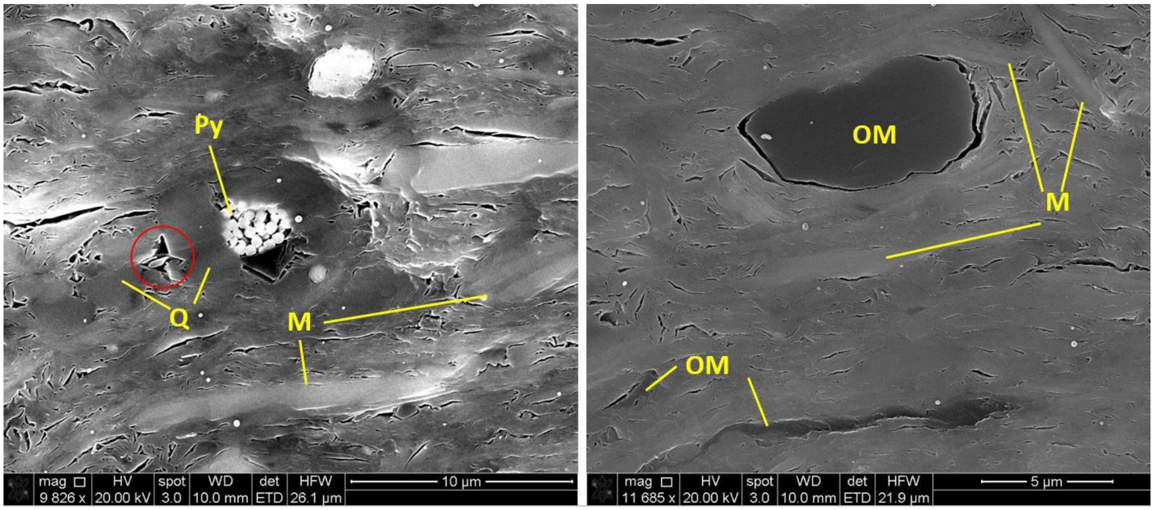
A. B.

Figure 37. – Spinose palynomorph SEM imaged within pinstripe claystone lithofacies from the MPC 10-4 well at 3196.3 ft measured depth. The facies is associated with the lowest bioturbation index of 1 in the lower Gordo Formation (Marine Tuscaloosa shale). A) Ion milled sample showing remnant cluster of spinose palynomorphs. B) Inset of "A" showing authigenic pyrite (Py) and clay (Cy), along the margin of an organic-lined pore (OM).



A. B.

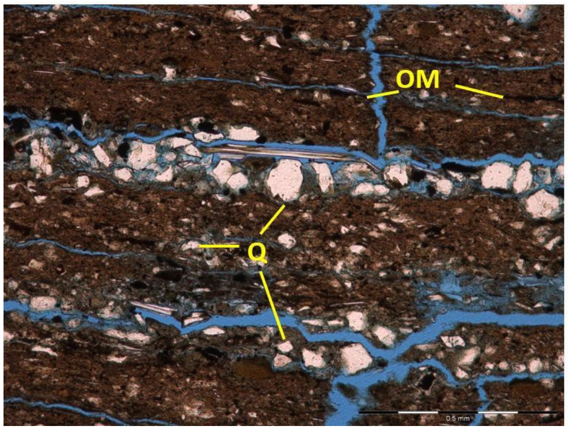
Figure 38. – SEM image of pinstripe claystone lithofacies from the MPC 10-4 well of the lower Gordo Formation at 3177.0 measured depth. A) Pyrite (Py) at three different scales and morphologies, framboidal, cubic, and rounded grains all with pores between individual crystals. Spheroidal organic material (OM), within a clay rich matrix with fissures that contour grains and organic material due to desiccation. B) SEM of organic matter (OM) with intraparticle porosity, subhedral pyrite (Py) cubes and framboids, upper right, and desiccation fissure that follows the margins of grains and organic material (OM).



A. B.

Figure 39. – SEM image of pinstripe claystone lithofacies from the MPC 10-4 well of the Marine Tuscaloosa shale at 3190.5 ft measured depth. A) Pyrite framboids and intraframboid porosity, mica grains that are not visible in thin section, and a large primary pore between silt grains (very rare in occurrence). B) SEM image of spheroidal organic particle (OM) and linear kerogen possibly a plant cuticle, common mica grains (M**)** and desiccation-related fissure pores that follow the edges of grains and organic material.

Lenticular claystone lithofacies of the Marine Tuscaloosa shale is characterized as a sandy claystone having clay content greater than 50% (Table 4) and thin laminae of fine-grained sandstone. Accessory minerals include an abundance of muscovite and biotite, the rare occurrence of glauconite, rare zircons, and pyrite in burrows. Organic material is common within the clay matrix and makes up approximately 1 wt% of the rock (Table 5) and appear elongate and spheroidal (Fig. 40). There is no visible porosity within the clay matrix. The mudstone has limited intergranular porosity that is associated with the fine sand and silt laminae and is dominated by intraparticle pores associated within partially dissolved grains.



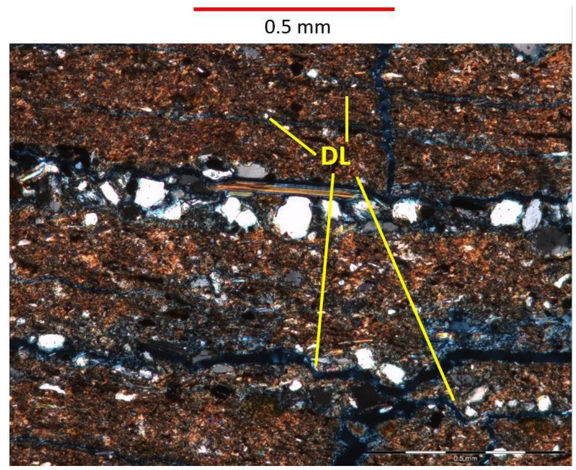
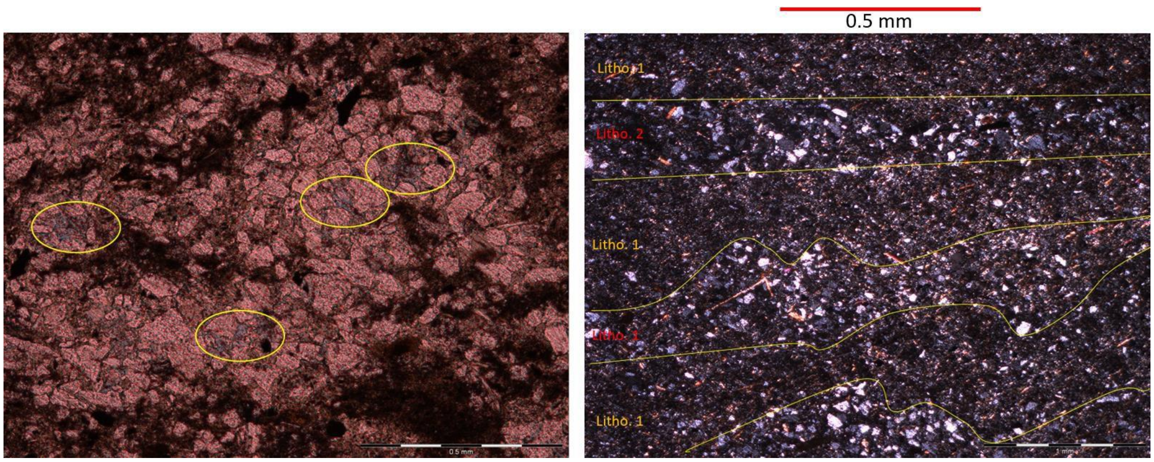


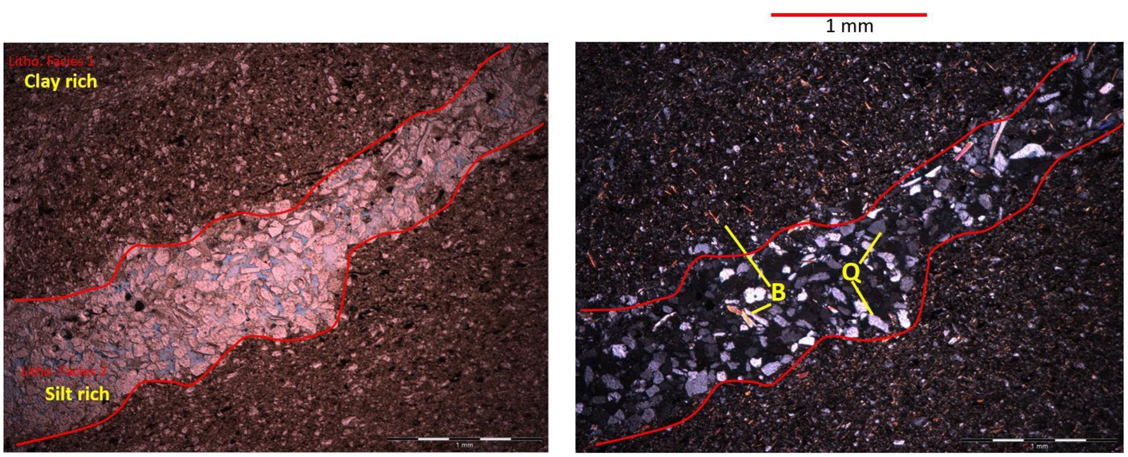
Figure 40. – Thin section image of the lenticular claystone lithofacies from the MPC 10-4 well of the Marine Tuscaloosa shale at 3178.4 ft measured depth. The mudstone is classified as a sandy claystone with siltstone and sandstone laminae. A) Thin section image in plane polarized light of claystone with quartz (Q) and organic particles (OM), the organic matter define ripple cross-laminae. B) Thin section in cross-polarized light that shows parting of the claystone along laminae (DL).

The wavy mudstone lithofacies of the Marine Tuscaloosa shale ranges between a clayey siltstone and silty claystone. The clay mineralogy content ranges from 31-51 wt% and is dominantly kaolinite with 20-36 wt% (Table 4). The mudstone contains parallel to subparallel laminae of coarse silt to very fine sand (Fig. 41). Horizontal and vertical burrows are filled with coarse silt to fine sand and contain less clay than the adjacent mudstones. Overall, clay content decreases upsection as bioturbation increases. The visible porosity in thin section is interparticle confined to silty laminae and burrows (Fig. 42) and some intraparticle porosity exists due to partially dissolved feldspar grains. At micron scale the pores are in organic material and are interparticle pores. The organic pores are commonly filled with interstitial matrix of silt and clay sized fragments (Fig. 43 and 44). More interparticle porosity than organic matter porosity is visible in thin section. Overall porosity is very low and does not appear to be well interconnected across bedding within the silty claystone.



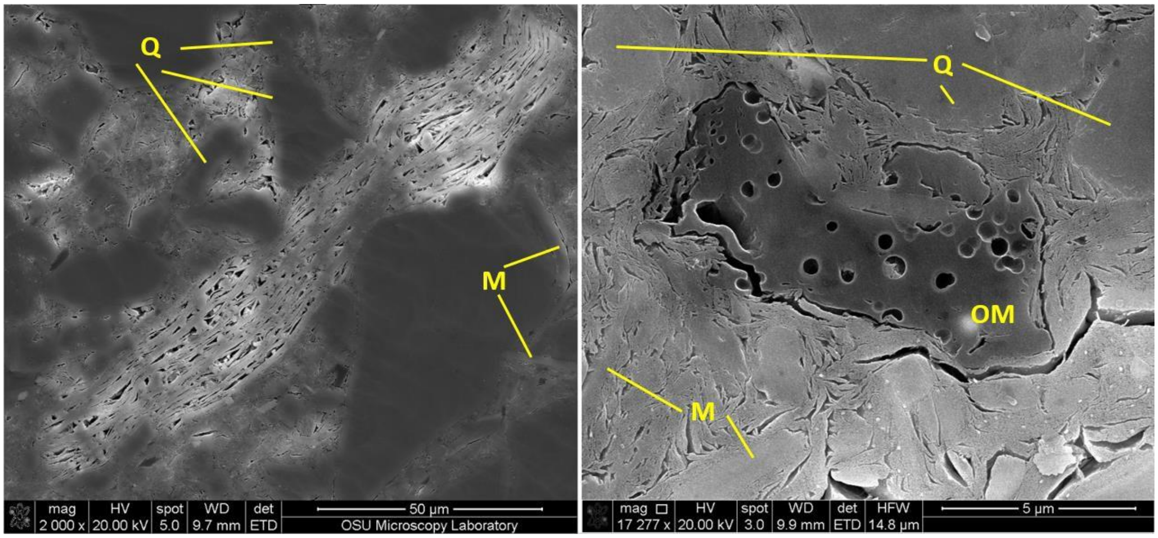
A. B.

Figure 41. – Thin section of wavy mudstone lithofacies within the MPC 26-5 well of the Marine Tuscaloosa shale 3590.0 ft measured depth. A) Visible porosity within the clay lean and fine sand interbeds (yellow circle), dark clots could possibly be remnant fecal pellets. B) Silt rich claystone with wavy to planar silty laminae.



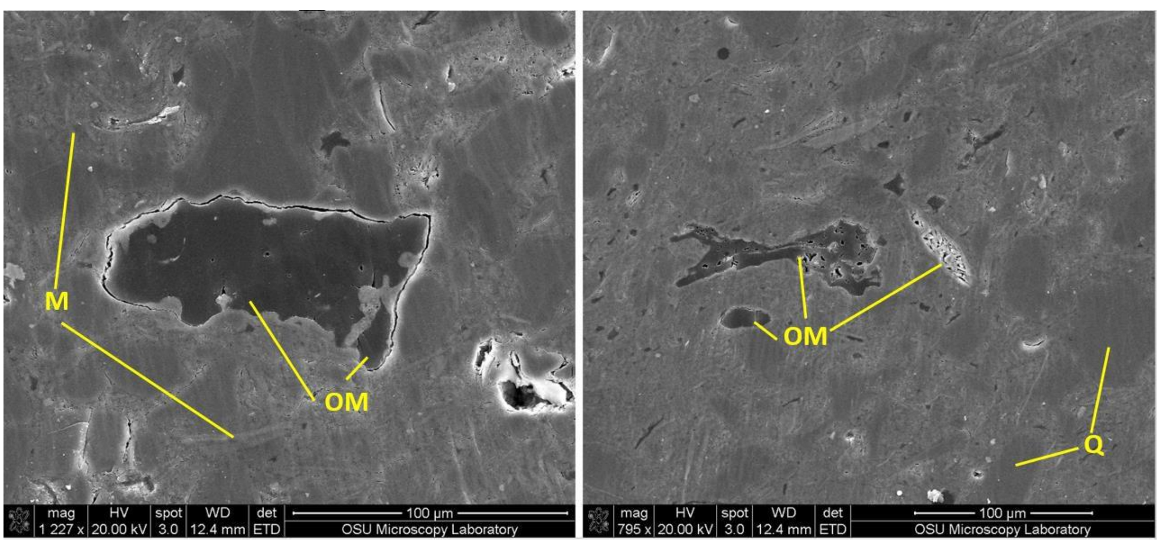
A. B.

Figure 42. – Wavy mudstone lithofacies from the MPC 26-5 well in the Marine Tuscaloosa shale at 3588.6 measured depth. A) Plane polarized light thin section with a clay rich siltstone with wavy laminations of coarse silt to fine sand. Porosity is confined to the wavy laminae of the coarser sediment. B) Mineralogically there is abundant silt to fine sand-size quartz (Q) and biotite (B). The facies can generally be characterized as a clayey mudstone.



A. B.

Figure 43. – SEM image of wavy mudstone lithofacies from the MPC 26-5 well within the lower Marine Tuscaloosa shale. This facies is characterized as a clayey mudstone. A) Woody plant fragment with intraparticle porosity associated with compacted cell lumens. There are abundant quartz (Q) and mica (M) grains. B) Organic particle (OM) within kaolinitic clay matrix. Intraparticle porosity within organic particle is interpreted as microbial boring.



A. B.

Figure 44. – Wavy mudstone lithofacies, imaged under SEM, within the MPC 26-5 well of the Marine Tuscaloosa shale at 3590.0 ft measured depth. A) Organic material with some intraparticle porosity (OM), abundant mica (M) grains imbedded within the mudstone matrix and a large pore resulting from propping. B) Organic material with intraparticle porosity with approximately 5-micron aperture (OM). Intraparticle splinter porosity associated with compressed plant cell lumens normal to bedding (OM), and the abundance of silt-size quartz grains (Q).

The Marine Tuscaloosa shale from the cored interval is generally a claystone lithology and mineralogy with the exception of the wavy mudstone lithofacies (Fig. 45A). There is a general trend of an increase in grain size and an increase in the volume of sand sized grains with ascending facies. The profile has an overall shoaling up succession of mudstones. The visible pore system types are varied with silty and sandy facies favoring inter and intraparticle porosity and the pinstripe claystone lithofacies favors organic matter porosity due to the high organic carbon content (Fig. 45B).

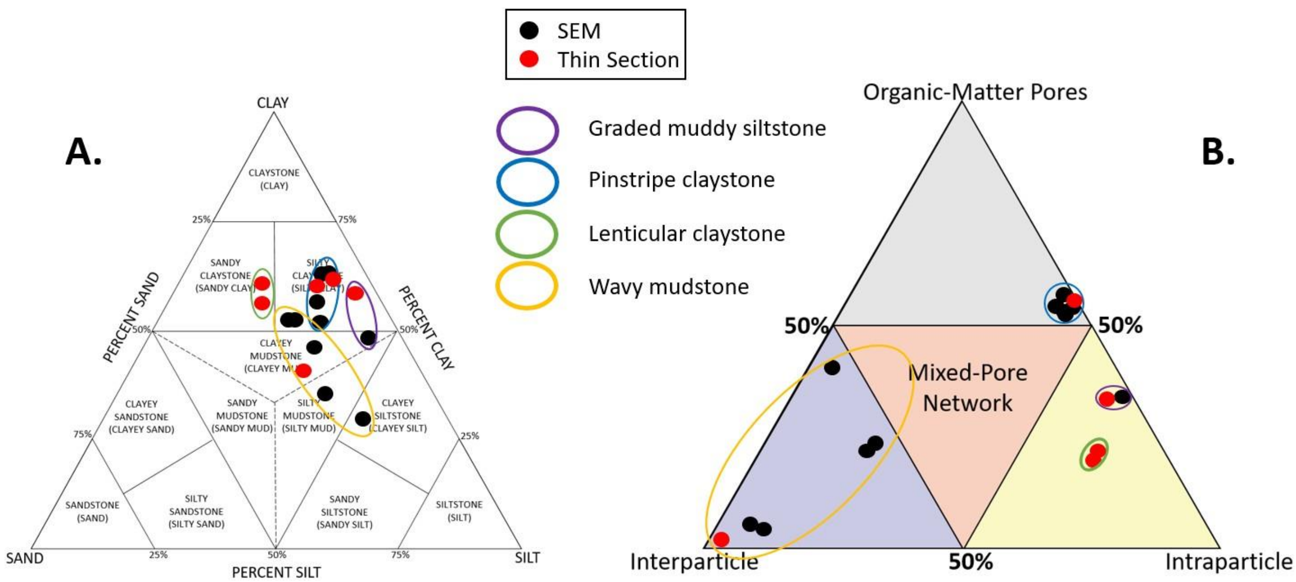


Figure 45. – Marine Tuscaloosa shale facies characterization for mudstone analysis A) Classification based on grain size. B) Pore system analysis for mudstones normalized to account for authentic pores.

CHAPTER V

DISCUSSION

Mudstone Sealing Strata Characterization

Sealing strata within the Kemper storage complex are varied with respect to formation and stratigraphic position. The data that were collected from core and geophysical well logs favor the basal Washita-Fredericksburg interval as a robust barrier. From petrographic analysis the lithology is sandy/silty mudstone with about 30 percent clay minerals and clay-size clasts of other minerals. Geophysical well logs indicate there are 5 stacked barriers on the scale of 10's of feet thick that are interbedded by baffles on the order of 1 foot thick. The mudstone section at the top of the Washita-Fredericksburg interval is also a significant barrier above the Big Fred sand, considering the mudstone is up to 100 feet thick with 3 correlatable barriers and several mudstone baffles.

The Marine Tuscaloosa shale was evaluated for its potential as a regionally extensive seal to the carbon sequestration complex at the Kemper County energy facility, and is the mudstone section that was studied in greatest detail. The graded muddy siltstone lithofacies is rich in clay mineralogy and the pore system in largely intraparticle porosity within pyrite crystals. It was also the second coarsest grained mudstone within the Marine Tuscaloosa shale behind the wavy mudstone lithofacies. The mudstone facies are stacked in ascending order, graded muddy siltstone, pinstripe claystone, lenticular claystone, and wavy mudstone and the general stacking reflects the trend of an increase in grain size, clast volume, and bioturbation index. The organic carbon content within the Marine Tuscaloosa shale ranges in values of 0.9-13.3 wt%. Organic carbon content displays a general inverse relationship with bioturbation and increases as bioturbation decreases. The stacked facies also reflect deposition within an increasing energy regime. The lower part of the cored section is dominated by suspension settling and the upper portion contains abundant ripples, with a predominance of pinstripe and lenticular bedding indicating tidal action. When addressing the quantified XRD data, and thin section analysis for the mudstone of the Marine Tuscaloosa shale, with the exception of the wavy mudstone lithofacies, they can be reasonably qualified as claystone having intraparticle pores associated with vacuolized organic matter and authigenic pyrite. They are also composed of more than 50 wt% clay mineralogy, with the graded muddy siltstone being only 45 wt% clay, but when factoring in grain size it would be reasonable that at least 6% of the quartz grains would be clay sized.

The Marine Tuscaloosa shale is over 150 ft thick in the study area and while the pinstripe claystone lithofacies was the most dominant within the cored interval, the statistical facies distribution through the entire Marine Tuscaloosa shale is unknown. This has important implications pertaining to the rock quality and sealing capacity. The pinstripe claystone lithofacies is more favorable for low permeability and sealing capacity than the graded siltstone or wavy mudstone lithofacies, due to high clay composition and interbedded claystone. Pashin et al. (2020) reported permeability data for the Marine Tuscaloosa shale ranging from 12-64 nD as reported from helium pressure decay permeability analysis. The samples were taken from the graded muddy siltstone lithofacies (12.4 nD) and the wavy mudstone lithofacies (64.4 nD). The permeability sampling was taken from coarser grained facies and the relatively high permeability values can be attributed to the samples drying and creating desiccation fissures, as seen in SEM, as well as the increased in grain size. The desiccation features likely increase the permeability of the mudstones and are likely higher than in situ mudstones, that are water saturated and under lithostatic pressure. The evidence supports the Marine Tuscaloosa shale as a possible seal to the sequestration complex at the Kemper County energy facility when factoring in mudstone thickness, high clay content, and correlatability.

The major topseal to the entire complex is the chalk of the Selma Group combined with the argillaceous Porters Creek Clay Formation, which together are over 1400 feet thick and protect the underground sources of drinking water in the Paleocene-age Nanafalia Sand. Moreover, the Selma Group chalk has been modeled to become less permeable over time when exposed to CO_2 (Zhang el al., 2017) and the Porters Creek Clay is a proven seal to petroleum resources from fractured chalk reservoirs in the nearby Gilbertown Field, Choctaw County, southwest Alabama (Pashin et al., 1998).

Depositional Environment Interpretation

Paluxy Formation

Conglomerate

The conglomerate facies in the Paluxy Formation (Fig. 12) resemble that of lag deposits, and channel fills reported by Miall (1977) in the Saskatchewan River. They mark the bases of channels as well as the beginning of vertical accretion episodes (Miall, 1985). Conglomerate facies are different with respect to depositional energy and sediment sourcing but are variations of the same geologic process of channel migration and fluctuations in water energy. The environment of deposition is interpreted to be channel bottoms (Miall, 1978; Allen, 1983). The mudstone clasts are interpreted to be derived locally by erosion and reworking of older sediment. The quartz pebbles appear to be sourced remotely from headwaters in igneous and metamorphic terranes, such as the Appalachian Orogen, and from chert derived from denudation of carbonate rocks in the Appalachian thrust belt and the nearby sedimentary basins (Urban, 2020).

Sandstone

Sandstone facies of the Paluxy Formation (Fig. 13) can be tied to subenvironments within a bedload-dominated fluvial system. Cross-bedded sandstone contains bioturbation and has implications for biologic hospitability that likely took place in channel margins or moribund longitudinal and transverse bars followed by channel migration and abandonment. Concretionary calcite lithofacies is straddled by the cross-bedded lithofacies and falls within the same sand subenvironment except that it underwent diagenetic alteration associated with precipitation of concretionary calcite.

Mudstone

Variegated Mudstone facies and the Massive mudstone facies in the Paluxy Formation are interpreted to have formed as paleosols due to the presence of slickensides and carbonate particles including the rootlets and orange coloring likely from iron staining. The variegated Mudstone facies (Fig. 14A) is interpreted as a weakly to moderately developed spodosol equivalent to the Bt horizon (Retallack, 1988; Mack et al., 1993) that can be classified as part of a B-II sesquioxidic soil profile (Retallack,1988; Machette, 1985; Giles et al., 1966) because it contains abundant bioturbation, root traces, desiccation cracks, and minor organic material. The variegated mudstone lithofacies and the massive mudstone lithofacies are desiccated, and it is a reasonable interpretation that the deposits were episodically inundated, exposed, and then desiccated (Retallack, 1988) possibly within an intrafluvial drainage system with locally weathered and reworked sediment (Muller et al., 2004). An indicator of this interpreted environment is the aggregational nature of the paleosol, up to 10 feet thick, being thoroughly bioturbated with deep desiccation cracks. The massive mudstone facies (Fig. 14B) is interpreted as a protosol (Mack et al., 1993) with slight oxidation and of a silty claystone composed of more than 50 percent in clay, primarily kaolinite, illite and smectite. This facies is likely a sheet-flood deposit atop a bar or at the margins of the braided river (Rust, 1981) and reflects seasonal fluctuation in precipitation and stream levels resulting in avulsion of fine-grained sediments over channel banks (Tabor and Myers, 2015). The heterolithic mudstone facies (Fig. 14C) is a sandy mudstone that is interpreted to be a minor sheet flood deposit atop a longitudinal bar due episodic waning flood events (Miall, 1977; 1978).Overall, the Paluxy Formation can be interpreted to be deposited within a braided fluvial system. There is an abundance of medium-grained and coarser sandstone and a lack of significant interbedded mudstone suggesting deposition associated with bedload transport, with sustainable sediment supply (Freidkin, 1945; Schlager, 2004, 2010). Sediment is largely recycled medium-size quartz grains, and local sediment sourcing from erosion of muddy deposits is evidenced in the conglomerate facies that marks the bases of the individual sandstone storeys. Mudstones are interpreted to represent flooding events and paleosol development and are sub environments that are located either on the margins of the fluvial channels or in interfluves (Friedkin, 1945; Miall, 2014).

Analogs

Modern process analogs for the Paluxy Formation, which is the primary reservoir for the sequestration complex have been proposed by Folaranmi (2015) and include the South Saskatchewan River in Canada, Cooper's Creek in central Australia, and the Ganges River in India (Fig. 46-48).

Miall (1978), described different braided river deposits and identified the South Saskatchewan River as being dominated by sand cycles. The vertical profile is similar to that of the Paluxy, as both have sharp basal contacts, a basal conglomerate facies, and cyclic deposits of sandstone with fining upward sequences that are in places capped by silty sand and mud. This fits the basic description of the Paluxy Fm., which contains a basal conglomerate facies interpreted to be basal channel fill and is succeeded by fine- to medium-grained sand locally capped by paleosol or silty sandstone and mudstone. An unmet condition in the analog is the interpreted climate during Paluxy deposition, which was interpreted to be semi-arid to sub-humid at Citronelle Field as described by Folaranmi (2015) based on interpreted calcic vertisols. The Kemper location during the Paluxy deposition can be interpreted to be sub- to semi-humid climate due to the lack of major pedogenic carbonate, which stands in contrast to the Paluxy Fm. in southwest Alabama (Folaranmi, 2015). The criteria of scale is also uncertain at this time due to the lack of well control and the Saskatchewan River being on the scale of 100's of meters wide at the primary river channel is a reasonable analog for individual channel width within the greater Paluxy Fm. costal braid plain (Fig. 46).

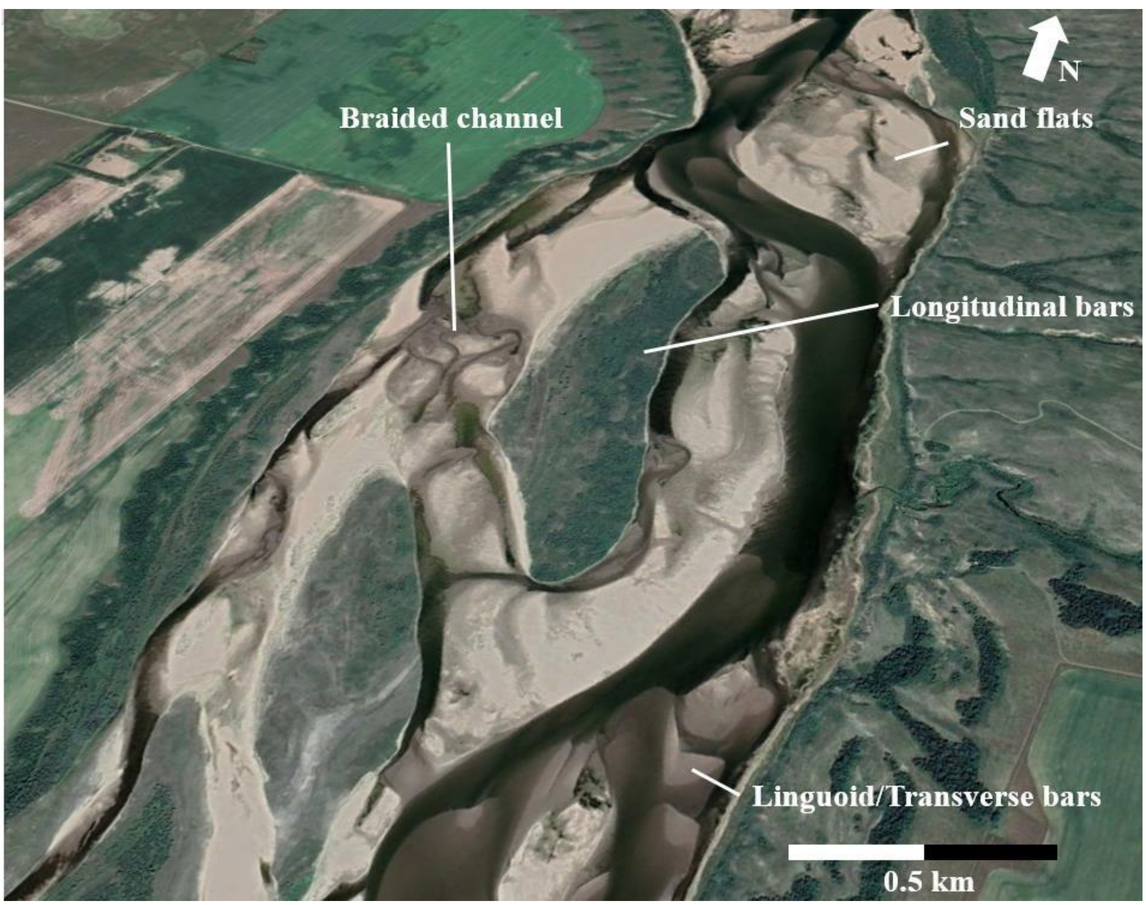


Figure 46. – The Saskatchewan River in Canada is similar to the Paluxy Formation with respect to sedimentary structures (modified from Google Earth, 2018).

Rust (1981) described the central Australia's Cooper's Creek in the Lake Eyre Basin as large, ephemeral multi-channel fluvial system, being on the scale of 10's of kilometers in width (Fig. 47). A strong similarity between the Paluxy Fm. and Cooper's Creek systems is the development of large braid plains composed of sand, silt, and clay. Both systems' overbanks are lean in silt compared to the sand and clay fraction. There is also a similarity in the two systems in that there are thick mudstones deposits on the meter scale with abundant rootlets and bioturbation that have produced a texture much like the variegated mudstone lithofacies. Cooper's Creek analog contains two primary systems a contemporary anastomosing system over a significant ancient broad braided fluvial plain. The ancient fluvial braided plain is on the order of 10's of kilometers wide and is a good analog to the breadth of the Paluxy braid plain. The evidence seems to support potential overprinting systems at the Kemper location like the Cooper's Creek location. When integrating paleocurrents from an FMI study from Pashin (2020) that showed the Paluxy was flowing perpendicular to regional dip it is reasonable to assume that at some point the channels flowed parallel to regional dip over the approximate span of 2 m.y. during which the Paluxy Formation was deposited (Mancini and Puckett, 2002).

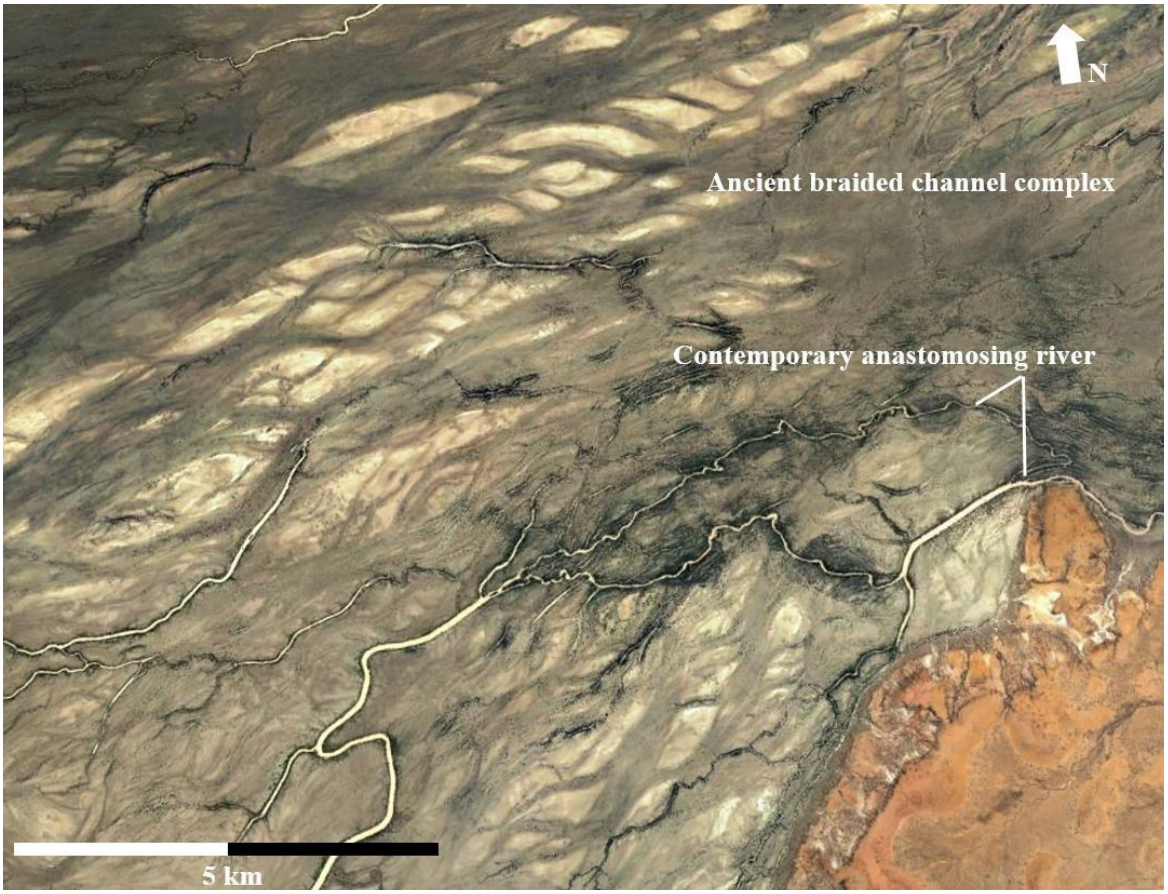


Figure 47. – The Cooper's Creek analog with an ancient braided river system, overprinted by anastomosing contemporary river system, that is the scale of 10's of kilometers wide and is a geomorphologic analog for the breadth of the Paluxy system (modified from Google Earth, 2018).

The Ganges River analog is intriguing in that there is some oxidized sediment, but the sediment is generally gray to dark gray. Also the sands are light, nearly white, unlike most of the Paluxy strata cored for the Folaranmi (2015) study which are highly oxidized. Also there are extensive gravels within the Ganges system, which is a significant difference from the Kemper Paluxy system. The Ganges River is a geomorphologic example showing the distinction of active channels and inactive bars, with vegetation and soil formation on longitudinal bars and in interfluves (Fig. 48)

Figure 48 – The Ganges River, India modern day geomorphologic analog with annotation (from Folaranmi, 2015), scale at the Ganges is on the kilometer scale and approximately 4 km wide at its widest within the image.

Fundamentally, deposition of the Paluxy Formation was in an area with low relief, approximately 10 to 15 feet, in a temperate climate regime being sub- to semi-humid at Kemper or semi-arid to sub-humid for the Folaranmi (2015) Citronelle Field study. The environment geomorphologically was likely similar to that of the Ganges River system and likely had episodic development with overprinting of braided fluvial channels on a broad braid plain as in the case of the Cooper's Creek with the sediment supply associated with the Saskatchewan River system.

Washita-Fredericksburg Interval

Sandstone facies of the Washita-Fredericksburg interval are interpreted to represent fluvial sand deposited mainly in the upper flow regime of a fluvial system on the basis of horizontal laminae and planar cross-beds (Miall 1985; 1977; Fielding, 2006). The environment is similar to that of the Paluxy Fm. with similar physical and biologic structures. The cross-bedded sandstone facies is likely from transverse bar deposition and the bioturbated facies is likely formed atop longitudinal bars or in interfluves. The Big Fred sand is interpreted to have been deposited as transverse bars and was cross-stratified with pebbles distributed along the bedding plains.

Variegated and blocky mudstone of the basal Washita-Fredericksburg is interpreted to represent paleosols. The bioturbation index of the mudstone, 2-4, with the inclusion of mild oxidation features with an overall blocky ped morphology (Birkeland, 1984) is characteristic of the Bt-I soil horizon (Guthrie and Witty, 1982; Retallack, 1988; Machette, 1985; Giles et al., 1966). The variegated and blocky mudstone facies is similar to that of variegated mudstone facies from the Paluxy Fm. but is overall less well developed. The depositional environment is interpreted to be longitudinal bar within a bedload-dominated fluvial system.

Coker Formation (lower Tuscaloosa Group)

The Massive Sand of the Lower Tuscaloosa Group changes regionally and in general has been broken into three units, a basal sandstone unit, interbedded sand and claystone unit, and the

Massive Sandstone unit. At the Kemper location, in general, it is a fining upward succession with a conglomeratic base, thinly bedded sandstone, and shale in the upper portion. The well log profile has a blocky sandstone profile and fits the geophysical well log expression of the Massive Sandstone unit of the Massive sand interval and has been interpreted as fluvial and stacked coastal barrier deposits (Mancini et al., 1987; Petty, 1997; Mancini and Puckett, 2003; Raymond and Pashin, 2005).

Gordo Formation (Marine Tuscaloosa shale)

The Marine Tuscaloosa shale is a major marine transgressive deposit associated with the upper Zuni sequence (Sloss, 1963) and has been interpreted to be an open marine shelf deposit (Mancini et. al, 1987; Petty, 1997). At the Kemper location the lithologic facies give greater insight into sub-environments within the open marine shelf interpretation. The ascending facies are stacked from the graded muddy siltstone lithofacies, to the pinstripe claystone lithofacies, lenticular claystone facies, wavy mudstone, and capped by a glauconitic sandstone. The facies association of pinstripe, lenticular, wavy, and laminated sandstone beds are interpreted to be sediments characteristically deposited within tidal environments (Reineck and Sing, 2012).

The graded muddy siltstone lithofacies is interpreted to be storm or current influenced deposits associated with an increase in sand and silt sedimentation. The influx of sand and silt dilute and load clay and silt beds that result in soft sediment deformation and develop pseudonodules of coarser-grained sediment. The facies being coarser-grained is associated with the lower tidal zone with sediments likely deposited by means of suspension settling. The grains are likely transported by bottom current velocities greater than 10cm/s, that shear sand and silt and transport them into the middle tidal flat (Klein 2012; Reineck and Wunderlich, 1960).

Overlying the graded muddy siltstone is the pinstripe claystone lithofacies that is a claystone with fine silt horizontal laminations that are interpreted to be middle tidal flat deposits. The rhythmic texture is a diagnostic feature of tidal rhythmites (Kvale, 2012). The rhythmic texture is dominated by clay and mud with silt and sand grains being subordinate and support an interpretation that the tidal flat was muddy (Klein, 2012).

The rhythmic pinstripe claystone lithofacies grades into the lenticular claystone lithofacies that contains disarticulated marine shell fragments consolidated into a bed, that have been interpreted to be transported from the subtidal to lower intertidal zone by storm action that brought an influx of coarser-grained sediment. The subtidal zone in general contains coarser-grained sediment and can be interpreted to be associated with bedload transport and deposition (Klein, 2012; Reineck and Singh, 2012).

The wavy mudstone lithofacies is characterized by an increase in sand and silt content as well as marine fossils and is interpreted as intertidal mud deposition and transported larger grains via bedload transport from offshore (Daidu, 2013). The glauconitic sandstone lithofacies caps the succession and is interpreted to be tide generated sandstones within the subtidal zone (Klein, 2012), possibly from a small destructive delta.

The interpreted environment is a muddy tidal flat, with some current and storm influence. The sub environments range from the subtidal to middle intertidal zone and are largely interpreted from sedimentary structures and grain size. The geomorphology of the Kemper coastline was likely a linear transgressive marine coastline fringing a delta system with no obvious thickness or structure anomalies when looking at isopach maps (Urban, 2020). The tidal range of the system was likely significant due to the facies associations and onlap of glauconitic sandstone onto intertidal rhythmites and could be classified as mesotidal (Klein, 2012; Boyd et al., 1992).

Analog

The proposed modern analog to the Kemper tidal system is that of the Wadden Sea of the Netherlands and northwest Germany (Fig. 49). Although Cretaceous seas were relatively large, wide, and shallow the North Sea analog is reasonable as it is tide-dominated with a wide shelf (Klein, 1977). The issue of scale, costal morphology, and sediment supply is interesting as there is a positive correlation between shelf width and increased tidal range and current velocities that have a direct influence of sediment transport and coastal evolution (Klein and Ryer, 1978).

Coastal morphology plays a vital role in sedimentation and tidal progradation. At this time the interpretation is that the Kemper coastline was relatively linear in comparison to the northern German coast that has significant barrier beaches, tidal deltas, and estuaries along a semi linear coast (Klein, 2012).

The correlation to tidal strength and shelf size likely favored a mesotidal range at the Kemper location. The sedimentologic structures composed of mixed sediments, dominantly mud sized particles to sand, form lenticular, wavy, laminated, and pinstripe textures that are diagnostic of tidal deposits and the process is time transgressive (Klein and Reyes, 1978). General lithologic trends are interpreted to be reasonably equivalent based on the nature of tidal systems. The sediments have a general relationship of becoming coarser-grained from the finest mud content at high tide, closest to shore, to an admixture of silt and mud in the intertidal region and sand and silt at the uppermost subtidal deposits (Hantzschel, 1955).

In general, the Wadden Sea is a reasonable analog to the Kemper location with respect to sedimentary structures, bedding, and lithology. Uncertainty in geologic interpretation and modeling will always raise the question to the amount of influence from adjacent tidal subenvironments. It is proposed that the lower section of the Marine Tuscaloosa shale which was cored and part of this study likely favored tidal progradation in the seaward direction on trend with the highstand deposition during Marine Tuscaloosa deposition. Understanding the interactions of base level change following a marine transgression and the balance with siliciclastic input and tidal forces leaves room for interpretation along strike and up-section of the cored interval. For the purposes of this study, a simple model reflects the need to integrate more data to further constrain a model of the Marine Tuscaloosa shale deposit.

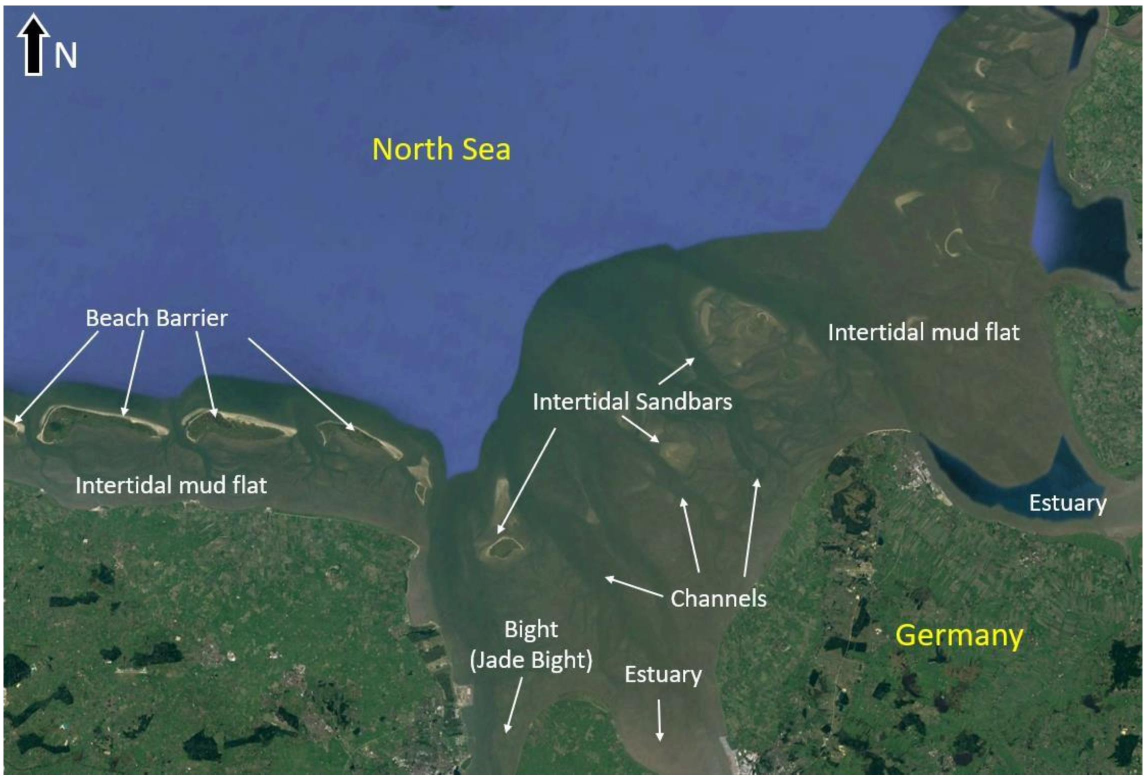


Figure 49. - Proposed analog of the tidal environment along the Wadden Sea and Germany. The depositional environment of the cored interval is interpreted to be a middle tidal flat environment.

Implications for Commercial Scale CO_2 Sequestration

The Kemper County Energy Facility sits in a structurally simple area that has gently dipping strata and significant CO_2 storage potential estimated at 1.4 gigatonnes (Urban, 2020; Pashin et al., 2020). One of the more complex problems associated with starting an injection program is managing reservoir facies heterogeneity, which is a direct reflection of stratigraphic architecture and the original depositional environment. The Paluxy Formation at Citronelle Field in southwest Alabama has been proven as a viable reservoir for sequestration (Koperna et al., 2013). From core, petrographic, and geophysical well log analysis, simple baffles have been identified, such as preferentially cemented sandstone laminae and cross-bed mud drapes that will locally confine CO_2 in paleo fluvial systems. Baffles that are identified in well logs as being on the scale of 1 foot in thickness they may impede CO_2 migration but are predicted to have limited lateral extent and intraformational sealing capacity. In the Big Fred sand of the Washita-Fredericksburg interval and the Massive Sand of the lower Tuscaloosa Group, there are few baffles and virtually no barriers, making vertical and lateral facies heterogeneity relatively simple.

The positives that are associated with injection into the Paluxy Fm. will be that the vertical baffles and weak barriers will help mitigate pressure buildup on the confining layer of the basal Washita-Fredericksburg interval, by promoting lateral migration of CO_2 and increasing reservoir efficiency. Since the depositional environment is interpreted to be fluvial and strata dip less than 1 degree or about 30 feet per mile, it is likely that the majority of channeling of CO_2 will be 180^O from regional dip, that is west and southwest toward the axis of the embayment and the Gulf of Mexico basin. Pashin et al. (2020) concluded on the basis of paleocurrent analysis that channeling and deposition were parallel to strike, but it is uncertain whether channeling, parallel to strike, applies to all or the majority of the sandstone storeys within the Paluxy Formation. Within the Paluxy Formation, the mixture of discontinuous sandstone units with mudstone baffles and barriers may contribute to localized reservoir compartmentalization and has a probability of resulting in a series of thin buoyant plumes of CO_2. The CO_2 plumes will likely be subcircular because of low bedding dip and be influenced by paleochannel patterns and will accumulate near the tops of amalgamated sandstone units due to CO_2 buoyancy. At this time paleocurrent variability for the entire Paluxy Fm. is unknown. Contrary to the Paluxy, the Big Fred sand and Massive Sand reservoirs have a blocky geophysical well log profile and may be able to accommodate higher rates of injection.

The Marine Tuscaloosa shale is dominated by low-permeability siltstone and claystone and is a sealing stratum in the upper part of the storage complex. The complex is dynamic in that with a combination of the Paluxy Fm. where long-term sustained injection can take place, there is a strong possibility for large volume and high rate injection into the Big Fred sand and Coker Formation (Massive Sand). However, more research and development is required to understand the performance and storage complex, and that is slated to be accomplished with the drilling and testing of additional wells as the CarbonSAFE program continues.

CHAPTER VI

CONCLUSION

The strata underneath the Kemper County energy facility has a P_{50} storage resource (1.4 Gt) that greatly exceeds the 50 Mt minimum volume of CO_2 desired for commercial-scale CO_2 sequestration. There are no apparent escape mechanisms, such as faults that breach seals. There are thick, continuous sections of sealing strata, such as the Marine Tuscaloosa shale and the Selma Group and Porters Creek Clay. The proposed reservoirs within the complex are the Paluxy Formation, Big Fred sand, and the Massive Sand. The depositional environment of the Paluxy Fm. is a broad coastal fluvial braid plain that is dominated by bedload deposition with multi-storey aggrading sandstone bodies. The stratigraphic architecture and environments of deposition give direct insight into the heterogeneity of prospective reservoirs, baffles, barriers, and seals. Discontinuous mudstone baffles will increase the efficiency of storage within the reservoir formations by locally confining buoyant CO_2 plumes. The Kemper storage complex includes multiple barriers to mitigate cross-formational flow, and a major chalk-claystone, seal is present between the targeted injection zones and the USDWs in the Nanafalia Formation and will protect the USDW. Assessment of sealing strata requires quantifying thickness and determining continuity as well as measuring fundamental rock properties, such as porosity and permeability. The basal Washita-Fredericksburg interval has multiple beds of mudstone on the order of 10's of feet thick that are characterized as silty to sandy mudstones with approximately 30 percent clay. When examining the sealing strata of the Big Fred sand there are several correlatable mudstone beds that are 10's of feet thick and one mudstone bed more than 100 feet thick. The lower

Tuscaloosa Group is capped by the Marine Tuscaloosa shale, which is one of the more significant potential seals in the storage complex. The Marine Tuscaloosa shale deposition on a muddy tidal environment associated with a major marine transgression is an interpretation supporting a potential seal that is regionally extensive, lean in carbonate, and is composed of claystone that favors high capillary entry pressure. Compositionally, the seal contains abundant water-saturated clay at in situ conditions and in general the SEM analysis revealed that there is only localized visible porosity that are not obviously interconnected. When the chalk of the Selma Group, a self-healing limestone more than 900 feet thick, is coupled with the Porters Creek Clay, a proven petroleum seal, the Kemper sealing strata appear to have high integrity.

The reservoir strata under the Kemper County energy facility have been evaluated as a gigatonne-scale storage complex with strata that can support a range of injection programs and have the capacity and permeability to serve as a regional storage hub. The data supports the facility as feasible and flexible with regard to issues of receiving differential volumes of CO_2 from multiple sources, proximity to CO2-EOR opportunities, and variations in supply of CO_2. The reservoirs have Darcy-scale permeability and a significant volume of stacked baffles, barriers, and seals within a geologically stable region. The reservoirs support lateral migration of CO_2, as to not build confining pressure, and significant cross-formation migration of injected CO_2 beyond the confines of the storage complex is unlikely. The Kemper County Energy Facility is situated atop world-class CO_2 sequestration strata and currently represents an important target for CO_2 sequestration within the United States of America, with exceptional potential for generational learning and transfer of technology to other sequestration sites.

REFERENCES

Abert, C.C., Marshak, S., and Larson, T.H., 2016, Geological and geophysical maps of the Illinois Basin-Ozark Dome region: Illinois State Geological Survey, Map 23, scale 1:500,000.

Allen, J.R.L., 1983, Studies in fluviatile sedimentation: bars, bar-complexes and sandstone sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders: Sedimentary Geology, v. 33, p. 237-293.

Aplin, A.C. and Macquaker, J.H., 2011, Mudstone diversity: Origin and implications for source, seal, and reservoir properties in petroleum systems: AAPG bulletin, v. 95, p. 2031-2059.

Bicker A. R., 1969, Geologic Map of Mississippi: Mississippi Department of Environmental Quality, Mississippi Office of Geology, scale 1:500,000.

Birkeland, P. W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Boyd, R., Dalrymple, R., and Zaitlin, B.A., 1992, Classification of clastic coastal depositional environments, Sedimentary Geology, v. 80, p. 139-150.

Campbell, C.V., 1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8, p. 7-26.

Chadwick, R.A., Zweigel, P., Gregersen, U., Kirby, G.A., Holloway, S., Johannessen, P.N., 2004, Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, northern North Sea: Energy, v. 29, p. 1371-1381.

Chen, L., Forsythe, J.C., Wilkinson, T., Winkelman, B., Meyer, J., Canas, J.A., Xu, W., Zuo, J.Y., Betancourt, S.S., Shan, D. and Hayden, R.S., 2017, A study of connectivity and baffles in a deepwater Gulf of Mexico reservoir linking downhole fluid analysis and geophysics: SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, p. 1210-1215.

Cushing, E.M., Boswell, E.H. and Hosman, R.L., 1964, General geology of the Mississippi Embayment, U.S. Geologic Survey Professional Paper 448-B, p. B9.

Daidu, F., Yuan, W. and Min, L., 2013, Classifications, sedimentary features and facies associations of tidal flats: Journal of Paleogeography, v. 2, p. 66-80.

Fielding, C.R., 2006, Upper flow regime sheets, lenses and scour fills: extending the range of architectural elements for fluvial sediment bodies: Sedimentary Geology, v. 190, p. 227-240.

Esposito, R., Riestenberg, D. and Gray, K.S., 2017. Establishing an Early CO_2 Storage Complex in Kemper County, Mississippi: Project ECO2S, Southern States Energy Board, U.S. Department of Energy, p. 6-10.

Fisher, W.L., 1969, Facies characterization of Gulf Coast Basin delta systems, with some Holocene analogues, Gulf Coast Association of Geological Societies Transactions, v. 19, p. 239-261.

Folaranmi, A. T., 2015, Geologic characterization of a saline reservoir for carbon sequestration: the Paluxy Formation, Citronelle Dome, Gulf of Mexico Basin, Alabama: Stillwater, Oklahoma State University: unpublished Master's thesis, p. 110.

Friedkin, J.F., 1945, A laboratory study of the meandering of alluvial rivers: United States Waterways Experiment Station, U.S. Corps of Engineers, p. 12-14.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Graham, B. D., Bowen, J. F., Duane, N. C., and Warden, G. D., 1980, Design and Implementation of a Levelland Unit CO_2 tertiary pilot: SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, Society of Petroleum Engineers, SPE-8831-MS, p. 211-212.

Guthrie, R. L., Witty, J. E., 1982, New designation for soil horizons and the new Soil Survey Manual: Soil Science Society of America Journal, v. 46, p. 443-444.

Hale-Erlich, W. S., and Coleman J. L., Jr., 1993, Ouachita-Appalachian juncture: A Paleozoic transpressional zone in the southeastern USA: AAPG Bulletin, v. 77, p. 552-568.

Häntzschel, W., 1955, Tidal flat deposits (Wattenschlick), The Society of Economic Paleontologists and Mineralogists (SEPM), Recent Marine Sediments special publication 4, AAPG data archives, p. 195-206.

Kvale, E.P., Archer, A.W. and Johnson, H.R., 1989, Daily, monthly, and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana, Geology, v. 4, p. 365-368.

Klein, G.D., 1977, Tidal circulation model for deposition of clastic sediment in epeiric and mioclinal shelf seas, Sedimentary Geology, v. 18, p. 1-12.

Klein, G.D., and Ryer, T.A., 1978, Tidal circulation patterns in Precambrian, Paleozoic, and Cretaceous epeiric and mioclinal shelf seas, Geological Society of America Bulletin, v. 89, p. 1050-1058.

Klein, G.D., 1998, Clastic tidalites — a partial retrospective view, The Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication 2012, Sedimentary Geology, AAPG Data Pages, p. 5-12.

Knott, S.D., 1993, Fault seal analysis in the North Sea: AAPG bulletin, v. 77, p. 778-792.

Kolata, D.R., Treworgy, J.D. and Masters, J.M., 1981, Structural framework of the Mississippi Embayment of southern Illinois: Illinois State Geological Survey, Circular 516, 38 p.

Koperna Jr, G.J., Kuuskraa, V., Riestenberg, D., Rhudy, R., Trautz, R., Hill, G. and Esposito, R., 2013, The SECARB anthropogenic test: status from the field, Energy Procedia 37, p. 6273-6286.

Lackner, K.S., 2003, A guide to CO_2 sequestration: Science, v. 300, p. 1677-1678.

Loucks, R.G, Reed, R.M., Ruppel, S.C., Hammes, U., 2012, Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores, AAPG Bulletin, v. 96, p. 1071-1098.

MacEachern, J.A., Bann, K.L., 2008, The role of ichnology in refining shallow marine facies models: Hampson, G.J., Steel, R.J., Burgess, P.B., Dalrymple, R.W. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy: SEPM Special Publication 90, p. 73–116.

Machette, M.N., 1985, Calcific soils of the southwestern United States. Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

Mack, G.H., James, W.C. and Monger, H.C., 1993, Classification of paleosols, Geological Society of America Bulletin, v. 105, p. 129-136.

Mancini, E. A., R. M. Mink, J. W. Payton, and B. L. Bearden, 1987, Environments of deposition and petroleum geology of Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: AAPG Bulletin, v. 71, p. 1128–1142.

Mancini, E.A. and Puckett, T.M., 2002, Transgressive-regressive cycles in Lower Cretaceous strata, Mississippi Interior Salt Basin area of the northeastern Gulf of Mexico, USA: Cretaceous Research, v. 23, p. 409-438.

Mancini, E. A., and T. M. Puckett, 2003, Petroleum potential of aggrading sandstones of transgressive-regressive cycles in the Mississippi-Alabama area: Gulf Coast Association of Geological Societies Transactions, v. 53, p. 527–536.

Mancini, E.A. and Puckett, T.M., 2005, Jurassic and Cretaceous transgressive-regressive (TR) cycles, northern Gulf of Mexico, USA: Stratigraphy, v. 2, p.31-48.

Matthew, A.J., Woods, A.J., and Oliver, C., 1991, Spots before the eyes: new comparison charts for visual percentage estimation in archaeological material: Recent Developments in Ceramic Petrology, v. 81, p. 221-263.

Miall, A.D. 1977. A review of the braided river depositional environment: Earth Science Reviews, v. 13, p. 1-62.

Miall, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary, 597-604, Fluvial Sedimentology. Memoir Canadian Society of Petroleum Geology, v. 5, p. 597-604.

Miall, A.D., 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits: Earth-Science Reviews, v. 22, p. 261-308.

Miall, A.D., 2014, Fluvial depositional systems: Springer, Berlin, Springer Geology, v. 14, p. 9-75.

Müller, R., Nystuen, J.P. and Wright, V.P., 2004, Pedogenic mud aggregates and paleosol development in ancient dryland river systems: criteria for interpreting alluvial mudrock origin and floodplain dynamics, Journal of Sedimentary Research, v. 74, p. 537-551.

Pashin, J. C., Raymond, D. E., Alabi, G. G., Groshong, R. H., Jr., and Guohai Jin, 2000, Revitalizing Gilbertown oil field: Characterization of fractured chalk and glauconitic sandstone reservoirs in an extensional fault system: Alabama Geological Survey Bulletin 168, 81 p.

Pashin, J. C., Hills, D. J., Kopaska-Merkel, D. C., and McIntyre, M. R., 2008, Geologic Evaluation of the Potential for CO_2 Sequestration in Kemper County, Mississippi: Final Report, Southern Company Contract 8-08-00142, 53 p.

Pashin, J. C., Urban, S., and Wethington, C., 2019, Geologic overview: Project ECO_2S, Kemper County Energy Facility: Atlanta, Georgia, SECARB Annual Stakeholders's Meeting, p. 19.

Pashin, J. C., Achang, Mercy, Martin, Sam, Urban, S. K., and Wethington, C. L. R., 2020, Commercial-scale CO_2 injection and optimization of storage capacity in the southeastern United States (Project $ECO2_S$, Kemper County energy facility, Mississippi): U.S. Department of Energy, National Energy Technology Laboratory Final Report (funded through the Southern States Energy Board and Advanced Resources International), contract DE-FE001055, p. 64.

Petty, A.J., 1997, Lower Tuscaloosa clastic facies distribution (Upper Cretaceous), Federal and State Waters, eastern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 47, p. 451-462.

Picard, M.D., 1971, Classification of fine-grained sedimentary rocks: Journal of Sedimentary Research, v. 41, p. 179-195.

Rahimpour-Bonab, H., Enayati-Bidgoli, A.H., Navidtalab, A. and Mehrabi, H., 2014, Appraisal of intra-reservoir barriers in the Permo-Triassic successions of the Central Persian Gulf, Offshore Iran: Geologica acta, v. 12, p. 87-107.

Rainwater, E. H., 1961, Outline of Geological History of Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 11, p. 43-45.

Raymond, D. E., and Pashin, J. C., 2005, Road log, in Raymond, D. E., ed., The Coker Formation of the Tuscaloosa Group in the Cottondale 7.5-minute quadrangle, Tuscaloosa County, Alabama: Alabama Geological Society Field Trip Guidebook, p. 34-50

Reineck, H.E. and Singh, I.B., 2012, Depositional sedimentary environments: with reference to terrigenous clastics, Springer Science & Business Media, p. 332-334.

Reitze, A.W., 2012, Carbon Capture and Storage Program's NEPA Compliance: Environmental Law Review, v. 42, p. 10853.

Retallack, G.J., 1988, Field recognition of paleosols: Geological Society of America Special Paper 216, p. 1-20.

Riestenberg, D., 2018, CarbonSAFE: Establishing an Early CO_2 Storage Complex in Kemper County, Mississippi: Project ECO_2S (No. DOE-SSEB-0029465-12), Southern States Energy Board, U.S Department of Energy, review meeting, 4,5 p.

Riestenberg, D., 2018b, Project ECO_2S: Characterization of a World Class Carbon Dioxide Storage Complex (No. DOE-SSEB-0029465-9), Southern States Energy Board.

Rust, B.R., 1981, Sedimentation in an arid-zone anastomosing fluvial system; Cooper's Creek, central Australia: Journal of Sedimentary Research, v. 51, p. 745-755.

Salvador, A., 1987, Late Triassic-Jurassic paleogeography and origin of Gulf of Mexico basin: AAPG Bulletin, v. 71, p. 419-451.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93-114.

Tabor, N.J. and Myers, T.S., 2015, Paleosols as indicators of paleoenvironment and paleoclimate, Annual Review of Earth and Planetary Sciences, v. 43, p. 333-361.

Thomas, W. A. 1973, Southwestern Appalachian structural system beneath the Gulf coastal plain: American Journal of Science, v. 273, p. 372-90.

Thomas, W.A., 1985, The Appalachian-Ouachita connection: Paleozoic orogenic belt at the southern margin of North America: Annual Review of Earth and Planetary Sciences, v.13, p. 175-199.

Thomas, W. A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, p. 415–431.

Urban, Stone, 2020, Geologic characterization of the Kemper County energy facility, Mississippi: A world-class site for CO_2 storage: Stillwater, Oklahoma State University, unpublished M.S. thesis, 70 p.

Vandeweijer, V., Van der Meer, B., Hofstee, C., Mulders, F., D'Hoore, D., Graven, H., 2011, Monitoring the CO_2 injection site: K12-B: Energy Procedia, v. 4, p. 5471-5478.

Watney, W.L., Guy, W.J., Doveton, J.H., Bhattacharya, S., Gerlach, P.M., Bohling, G.C. and Carr, T.R., 1999, A petrophysical tool for geologic/engineering reservoir characterization: Petrofacies Analysis, AAPG Memoir 71, Ch. 6.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: The Journal of Geology, v. 30, p. 377-392.

Zhang, L., Soong, Y. and Dilmore, R.M., 2017, Numerical investigation of Lower Tuscaloosa Sandstone and Selma Chalk caprock under geological CO_2 sequestration conditions: mineral precipitation and permeability evolution: Greenhouse Gases: Science and Technology, v.7, p. 988-1007.

VITA

Conn L. R. Wethington

Candidate for the Degree of

Master of Science

Thesis: MUDSTONE CHARACTERIZATION AT A WORLD-CLASS CO_2 STORE SITE:

KEMPER COUNTY ENERGY FACILITY, KEMPER COUNTY, MISSISSIPPI

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in December, 2020.

Completed the requirements for the Bachelor of Science in Geology at Oklahoma State University in Stillwater, Oklahoma in 2016.

Experience:

Summer 2020

- Oklahoma State University – Caney Fm. – Ardmore Basin, Oklahoma

Basin Analysis, structure & stratigraphic Architecture
Petrophysical characterization & basin modeling

Summer 2019

- Ascent Resources – Utica Fm. – Appalachian Basin, Ohio

Reservoir Optimization & Technology
Petrophysical characterization coupled with completion data for reservoir optimization

Summer 2018

- GeoSync – Exploration & Strategic Services

Prospect Generation – Mancos Fm. & Gallup Fm. – San Juan Basin, New Mexico
– Osage, Meramec, & Chester – Anadarko Basin, Oklahoma
Prospect building and basin analysis utilizing petrophysical logs & core data

Summer 2017

- Department of Energy (DOE) & Southern Company (Kemper Project)

Research Experience in Carbon Sequestration (RECS) – Mississippi embayment – Alabama & Mississippi
Core study, data integration (petrophysics, petrographic analysis, site characterization)

Professional Memberships: AAPG, GSA, SEPM, SEG, TGS, and OCGS