MUDSTONE CHARACTERIZATION AND CLASSIFICATION AT A PROPOSED HUB SCALE CARBON SEQUESTRATION COMPLEX: KEMPER COUNTY, MISSISSIPPI, UNITED STATES

By

CONN L. R. WETHINGTON

Bachelor of Science in Geology
Oklahoma State University
Stillwater, OK
2017

Master of Science in Geology
Oklahoma State University
Stillwater, OK
2020

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Dissertation Approved:

Dr. Jack Pashin

Dissertation Adviser

Dr. Todd Halihan

Dr. Javier Vilcaez

Dr. Prem Bikkina

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Abstract:

The Mississippi Embayment in the US gulf coast plain and adjacent continental shelf present a vast resource for anthropogenic carbon capture and sequestration (CCS) opportunities from point sources to hub scale sequestration projects and are likely to be the site of many sequestration facilities in the coming decades. The current need to sequester anthropogenic CO_2 is no less than a thousand-fold of the current sequestration projects and saline reservoirs are a major target for injection operations both on and offshore. The Cretaceous and Tertiary strata within east-central Mississippi are proven to be world-class reservoirs, and have been characterized through the DOE CarbonSAFE Phase II (2017) and Phase III (2020) program and the drilling of 6 exploration wells. The drilling program and associated data led to a high-resolution stratigraphic delineation, reservoir and confinement characterization, and mudstone baffles, barriers, and seals classification of a 1.4 Gt resource within stacked reservoirs of multistory aggraded sandstone with a geometric mean permeability of 3.6 Darcy. The primary, secondary, and auxiliary reservoirs are the Paluxy Formation (Albian), Washita-Fredericksburg interval (Albian), and Lower Tuscaloosa Massive sand (Cenomanian) that internally contain mudstone baffles that are relatively thin and discontinuous through offset wells and the area of review and define reservoir heterogeneity. Thickly bedded aggraded paleosol deposits in the basal and upper Washita-Fredericksburg interval act as barriers to fluid flow and facilitate vertical plume confinement within the primary and secondary reservoirs. If fugitive CO_2 is to vertically escape out of the designated reservoirs the Lower Tuscaloosa sand will act as a storage buffer while also preventing significant CO_2 impingement at the reservoirs and seal interface. The major confining unit to the sequestration complex is the Marine Tuscaloosa shale (Cenomanian) that is clay rich and interpreted to have internal clinoform bedding morphology and was deposited as part of a eustatic rise in base level. The mudstone barriers and Marine Tuscaloosa seal have an absolute permeability on the order of 10-100 nD are regionally present, laterally continuous, and have implicit confinement to prevent significant amounts of CO_2 from escaping the designated sequestration reservoirs and contaminating the USDW in the Naheola and Nanafalia Formations.

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INTRODUCTION

Project Background

The United States Department of Energy, Southern Company, and the Southern States Energy Board have been in partnership to advance technology and promote best practices of carbon capture and geologic sequestration of anthropogenic CO_2 under the CarbonSAFE initiative. The Kemper County energy facility project began a second phase in 2017 that focused on geologic characterization and site qualification at a coal facility that is owned and operated by Mississippi Power a subsidiary of Southern Company, located in east central Mississippi. Phase 2 characterization of Cretaceous-Tertiary strata were facilitated through the drilling of 3 scientific wells located in a frontier region of the broader Mississippi Embayment and a subsequent phase 3 began in 2020 with the drilling of an additional 3 wells. Characterization has delineated a stratigraphic and depositional formwork that has identified a 1.4 Gt saline storage opportunity in world-class reservoirs defined by stacked sandstone reservoirs with Darcy scale permeability. The reservoirs are confined by mudstone with varying composition and geometry that were deposited in different depositional environments that define unique depositional architectures.

The chapters of this dissertation investigate the mudstone facies, facies association, and mudstone succession within the sequestration complex having an objective of understand how mudstone effects anthropogenic carbon sequestration complexes. Chapter 2 of this dissertation focuses on mudstone baffles and barriers within primary and secondary reservoirs and was published in Frontiers in Energy Research journal as an open access peer reviewed original research paper. Chapter 3 is a focus on the Marine Tuscaloosa shale as a regionally extensive confining unit with seal potential for a hub scale sequestration facility with a focus on depositional architecture and facies characterization. The paper will be submitted to the Elsevier's International Journal of Greenhouse Gas Control. The final paper in Chapter 4 focuses on defining a mudstone classification scheme that identifies and characterized differential scales of mudstone and their ability to confine and promote reservoir heterogeneity with storage complexes. The mudstone classification integrates mudstone thickness, continuity, areal extent, and quality as defining parameters to impeding an injectant and is the first of its kind to define and bridge gaps in communication associated with reservoir heterogeneity and compartmentalization. This work has been presented to the scientific community through local and international professional conferences in the form of posters and technical talks and has been awarded by the Geologic Society of America for research merit and featured in the AAPG Explorer.

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CHAPTER II

MUDSTONE BAFFLES AND BARRIERS IN LOWER CRETACEOUS STRATA AT A PROPOSED CO_2 STORAGE HUB IN KEMPER COUNTY, MISSISSIPPI, UNITED STATES

Abstract:

The Cretaceous and Tertiary deposits in Mississippi, Alabama, and the adjacent continental shelf constitute a widespread succession of sandstone, mudstone, and carbonate that has proven to be an important target for geologic CO_2 storage in the onshore Gulf of Mexico basin. Integrated analysis of stratigraphy, sedimentology, and reservoir properties based on cores and geophysical well logs indicates that the Paluxy Formation and Washita- Fredericksburg interval present gigatonne-class storage opportunities. The distribution, geometry, and composition of the area is a direct reflection of the original depositional environments, and understanding these factors is essential for understanding the geologic storage potential of the Paluxy Formation and Washita-Fredericksburg interval at the energy facility.

Geologic characterization of the Mississippi Embayment at the energy facility focused primarily on characterizing the confinement potential of the storage complex. Integration of core analyses and geophysical well logs has yielded a high-resolution stratigraphic analysis of storage reservoirs, baffles, barriers, and seals. Scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS), and quantitative X-ray diffraction (XRD) was used to characterize microfabric, pore types, and mineralogy within mudstones of the east-central Mississippi Embayment at the Kemper County energy facility. Mudstone beds in the Paluxy Formation and Washita-Fredericksburg interval have variable thickness and continuity. High water saturation in the Cretaceous mudstone units influences swelling smectite clays and mudrock permeability based on pulse decay analysis is 1-96 nD. These low permeability values indicate that the mudstone units are effective baffles, barriers, and confining intervals that make significant migration of injected CO_2 out of the storage complex unlikely. The numerous baffles and barriers within the target reservoir intervals, moreover, favor the retention of multiple CO_2 in plumes within the abundant stacked sandstone bodies.

Introduction

This project explored the confining potential of candidate geologic CO_2 sinks in Lower Cretaceous strata in the Gulf of Mexico Basin in east-central Mississippi at the Kemper County energy facility, which is being developed by Southern Company (Fig. 1). This research is sponsored by the Southern States Energy Board (SSEB) through the National Energy Laboratory of the U.S. Department of Energy's (DOE/NETL) CarbonSAFE program (Esposito, 2017; Riestenberg et al., 2019; Pashin et al., 2020). Plant Ratcliffe, also known as the Kemper County energy facility, was designed to include a large Integrated Gasification Combined Cycle (IGCC) coal plant (Reitze, 2012) and utilize a post combustion carbon capture unit, but because of echnical, regulatory, and market conditions is operating as a combined cycle natural gas power plant.

Reservoir strata under the energy facility house a gigatonne (Gt)-scale storage resource (1.4 Gt at 14% storage efficiency using method of Goodman et al., 2011) (Urban, 2020) and have the potential to host a regional storage hub for anthropogenic CO_2 emissions (Pashin et al., 2020). The facility is highly flexible, able to receive large volumes of CO_2 from local and regional sources and support a range of injection programs. The reservoirs are in multiple stacked sandstone units with geometric mean horizontal permeability of 3.9 Darcies; they have been interpreted as bedload-dominated fluvial deposits (Urban, 2020; Pashin et al., 2020). The bulk of the storage resource is in the Lower Cretaceous Paluxy Formation and Washita-Fredericksburg interval; numerous mudstone units define baffles and barriers separating the stacked sandstone bodies. The distribution, geometry, and composition of the mudstone units in the Paluxy Formation and Washita-Fredericksburg interval is hypothesized to be a product of the original depositional framework, and understanding these factors is essential for planning injection programs and determining the fate of CO_2 injected in the target sandstone units, which are confined by the mudstone layers. Indeed, the heterogeneity in the thickness and continuity of the mudstone is considered a fundamental control on where injected CO_2 plumes will flow and where hydraulic communication may exist among the stacked sandstone bodies.

Accordingly, the principal objectives of this research are to characterize Paluxy and Washita-Fredericksburg mudstone through stratigraphic analysis, sedimentologic analysis, and petrologic analysis. A classification of intraformational mudstone units was used that is based on the thickness and continuity of mudstone units (Wethington, 2020). Baffles locally confine CO_2, are on the order of 0.3-3 m (1-10 ft), and can be identified in geophysical well logs. Barriers are thicker, on the order of 3-30 m (10-100 ft), and are more likely to impede vertical CO_2 migration based on greater thickness and lateral extent. The baffles and barriers are fine-grained, clay-rich, have low carbonate content, and are characterized by variable thickness and continuity. Mudstone units within subsurface reservoirs are a key source of depositional and reservoir heterogeneity and affect storage efficiency, reservoir extent, and plume morphology (Neuzil, 1994; Downey, 1994; Doughty and Pruess, 2004; Bachu et al., 2007; Goodman et al., 2011; Cavanagh and Haszeldine, 2014). The stacked reservoirs at the Kemper County energy facility are hypothesized to support lateral plume growth over crossformational flow, and the high permeability helps limit pressure buildup during injection. The Kemper County energy facility is situated atop a world-class CO_2 storage complex and represents an important target for CO_2 sequestration in the United States that has exceptional potential for generational learning and transfer of concepts and technology to other sites.

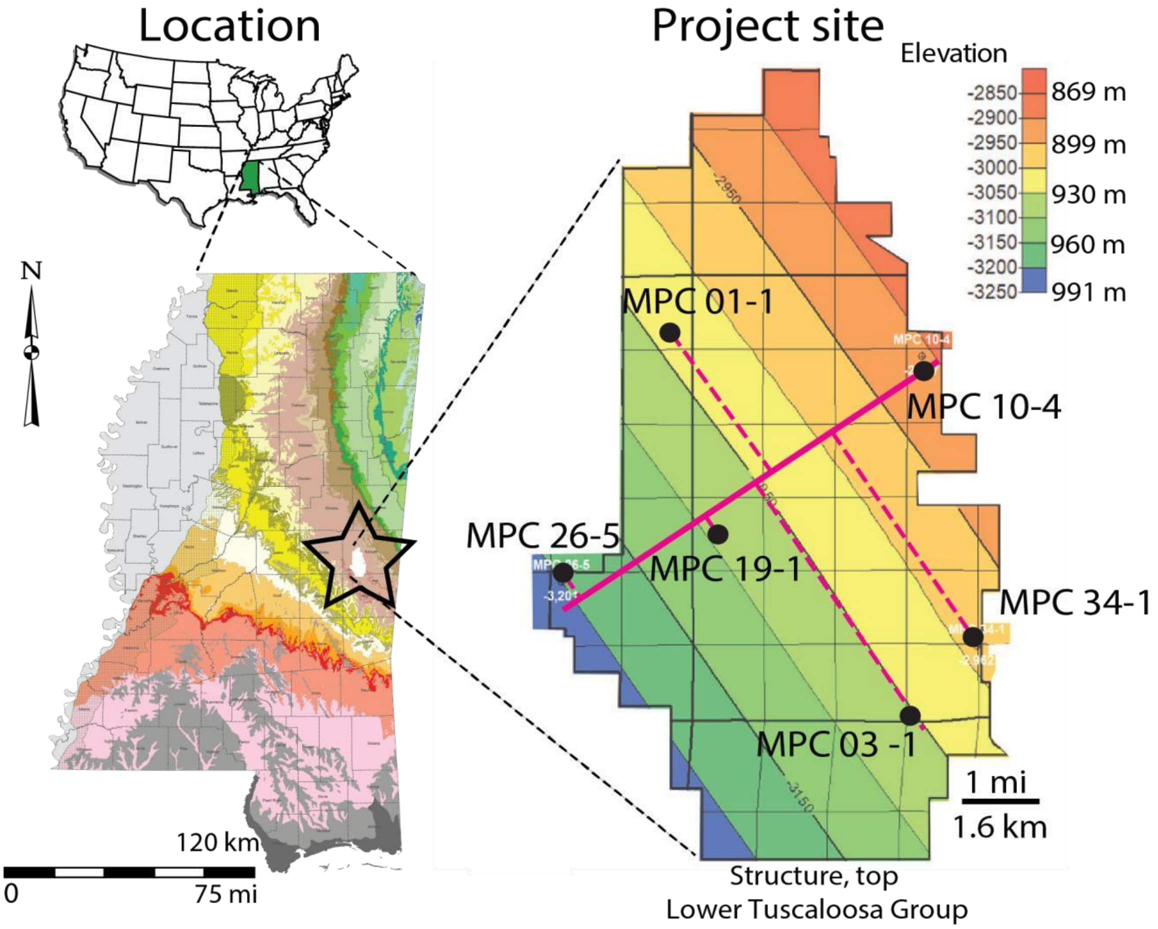


Figure 1. Location of study area. A) Map showing the Kemper County energy facility in eastcentral Mississippi. B) Structural contour map of the top of the lower Tuscaloosa Group showing locations of six exploratory boreholes and line of cross section (after Pashin et al., 2021).

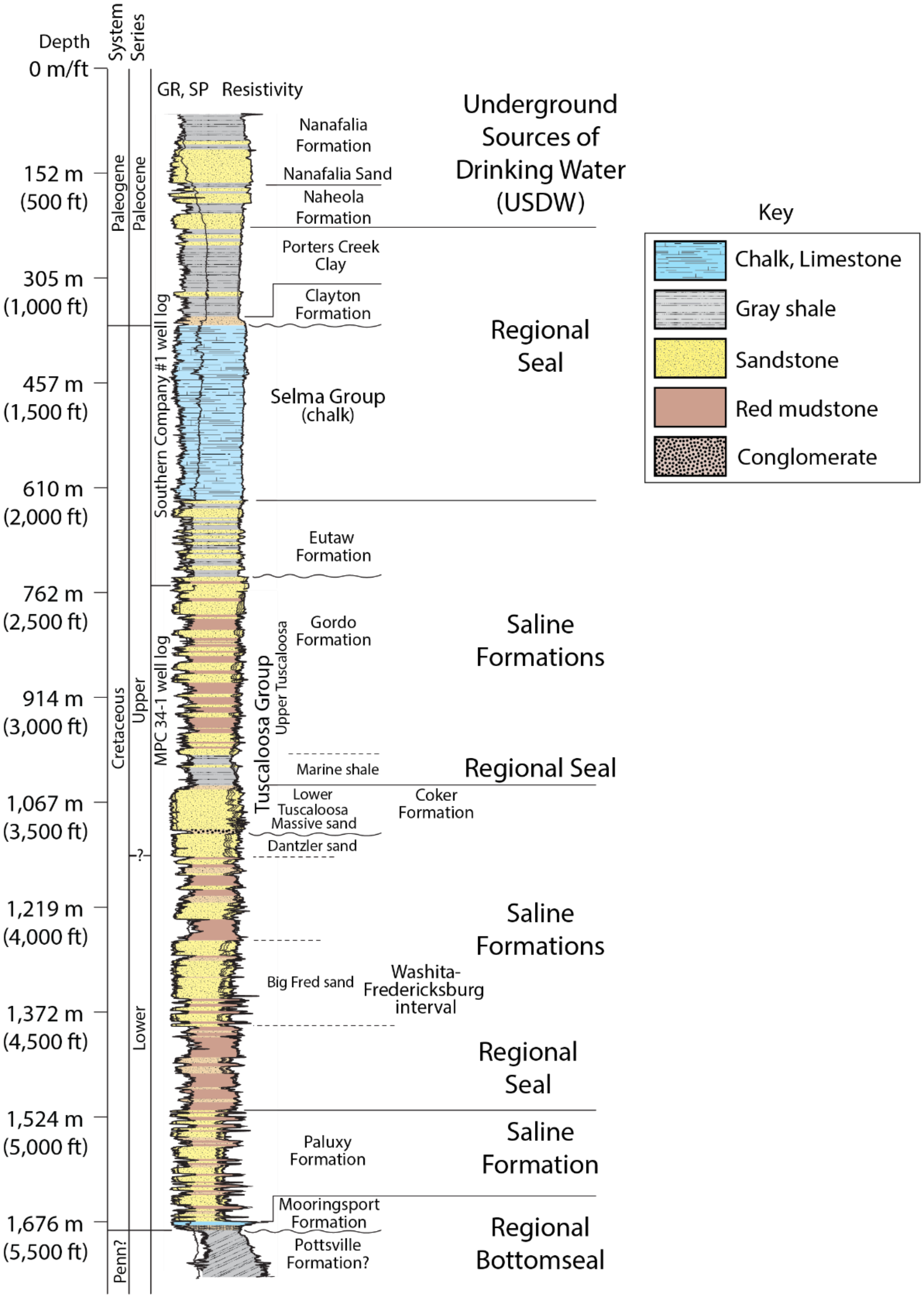


Figure 2. Composite stratigraphic section and geophysical well log of the Paleozoic-Mesozoic section at the Kemper County energy facility (after Pashin et al., 2020).

Geologic Setting

The Kemper County energy facility is in the eastern part of the Mississippi Embayment in east-central Mississippi, which began forming during Proterozoic-Cambrian Iapetan rifting (Thomas, 1991) and Mesozoic-Cenozoic extension associated with the opening of the Gulf of Mexico (Salvador, 1987). Post-Paleozoic strata dip regionally southwest above a subMesozoic angular unconformity (Cushing et al., 1964; Thomas et al., 1988; Pashin et al., 2008). The main storage targets are in Cretaceous deposits, and major sealing strata are developed in the Upper Cretaceous-Paleocene section of the Selma Group and the Porters Creek Clay. Underground sources of drinking water that need to be protected are in Paleogene strata of the Naheoloa and Nanafalia Formations. The Mississippi Embayment extends from 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 fringe of the embayment and thickens toward the south-southwest. Regional dip above the Paleozoic disconformity is < 1° (Sterns and Marcher, 1962; Pashin et al., 2008).

Cretaceous-Paleogene strata are preserved below the Kemper County energy facility and overlie an angular unconformity atop deformed Paleozoic strata of the Appalachian-Ouachita Orogen (Thomas, 1973, 1985, 1991; Hale-Ehrlich and Coleman, 1993; Pashin et al., 2008). The upper 38 m (125 ft) of the Paleozoic section has been penetrated by wells at the energy facility. 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 (Pashin et al., 2008, 2020). The Lower Cretaceous strata are restricted to the subsurface and are confined regionally by convergence of the sub-Mesozoic disconformity with the mudstone near the top of Washita-Fredericksburg interval. Upper Cretaceous strata of the Tuscaloosa Group disconformably overlie the Washita-Fredericksburg interval and contain basal conglomerate units that grade upward into poorly consolidated sand. These conglomerate and sandstone units make up the Massive sand of the lower Tuscaloosa Group. The overlying Marine Tuscaloosa shale is dominated by mudstone and claystone. The upper Tuscaloosa Group contains interbedded sandstone and mudstone. The Eutaw Formation disconformably overlies the Tuscaloosa Group and contains interbedded glauconitic sandstone and mudstone (Pashin et al., 2000). About 275 m (900 ft) of chalk assigned to the Selma Group caps the Upper Cretaceous section and is disconformably overlain by Paleocene-Eocene strata assigned to the Clayton Formation, Porters Creek Clay, Naheola Formation, and Nanafalia Formation (Rainwater, 1961; Wethington,2020). Together, the Selma Group and Porters Creek Clay form a thick (365 m; 1,200 ft) sealing section that defines the top of the CO_2 storage complex at the Kemper County energy facility. 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) in the study area (Fig. 2). Surface and near-surface deposits in the area of the Kemper energy facility are sand, clay, and lignite.

Material and Methods

Data were collected from six wells and selected cored intervals of the Cretaceous section in the MPC 26-5, MPC 34-1, MPC 10-4, MPC 19-1, and MPC 01-1 wells. Seventeen cores were recovered spanning 100.5 m (330 ft) from the Paluxy Formation, the WashitaFredericksburg interval, and the Tuscaloosa Group. The rocks were analyzed with respect to lithofacies and stratigraphic position. Lithofacies were defined and characterized based on rock type, texture, bedding, physical sedimentary structures, biogenic structures, and mineralogy.

The wells include a diverse suite of geophysical logs, including gamma ray, resistivity, density-neutron porosity, and spontaneous potential curves. Cores from the MPC 34-1 and MPC 10-4 cores were CT scanned in the original aluminum core sleeves prior to slabbing. Samples from the butt slabs of the cores were taken for thin sections, SEM billets, and bulk sampling for X-ray diffraction for mudstone samples from the MPC 26-5, MPC 34-1, and MPC 10-4 wells. Sample billets were ion milled for SEM/EDS analysis, and samples were crushed for semi-quantitative XRD analysis. Samples from the MPC 10-4 well were analyzed for total organic carbon content in gray mudstone in the Paluxy Formation.

Cores were described, photographed, and logged using standard stratigraphic and sedimentologic procedures. Graphic logs were constructed to document rock types, bedding contacts, sedimentary structures, and biological features. Grain size was characterized using the Wentworth scale (Wentworth, 1922). Intensity of bioturbation in CT images of the cores was characterized using the Bann bioturbation intensity index (MacEachern and Bann, 2008) and rock color was defined using the GSA Munsell color index (Munsell, 2009). Depositional environments were interpreted on the basis of rock types, grain size trends, bedding, sedimentary structures, fossils, and facies relationships. Samples of fine-grained rocks were taken from cores of the Paluxy Formation, Washita-Fredericksburg interval, and the Marine Tuscaloosa shale, and thin sections were milled to a thickness of 20 µm. The thin sections were vacuum impregnated with blue epoxy and stained with alizarin red and sodium cobaltinitrite to identify carbonate and feldspar. Descriptions and photography were done using a Leica DM EP and Olympus BX51 petrographic microscope. The grain size distribution 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 estimate the volume of clay and detrital grains, the comparison charts of Matthew et al. (1991) were used. Grain size percentages were then plotted in a ternary diagram (Picard, 1971) to characterize rock texture and determine facies characteristics.

Scanning electron microscopy (SEM) was performed on 12 mudstone samples using a FEI Quanta 600 FEG MK2 Environmental SEM. The samples were polished with a JEOL model IB-19500CP argon ion mill and plated with a gold-palladium alloy prior to imaging. The SEM is accompanied by a Bruker Quantax XFlash 6/60 unit with Quantax Esprit software for energy dispersive X-ray spectroscopy (EDS) analysis, which aided in mineral identification. The SEM samples have a corresponding thin sections that enable comparison of the features observed under transmitted light with those observed by SEM and EDS. Compositional data were used to supplement thin sections descriptions and characterization of mineralogy, micro fabric/texture, and pore systems were plotted in a pore system ternary diagram (Loucks et al., 2012).

Semi-quantitative x-ray diffraction (XRD) data were gathered for two samples (Table 1) from the MPC 34-1 and MPC 10-4 wells from the Paluxy Formation the samples correspond to thin sections and SEM images. XRD analysis was performed to determine the mineralogy of the mudrocks with respect to weight percent, including clay species. 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 shipped to Impac Exploration Services, and minerals were identified from the pattern of XRD peaks, and the percentage of each mineral was estimated by Rietveld analysis using the methods of Moore and Reynolds (1989).

Total carbon (TC) and sulfur content were determined for one sample from well MPC 10-4 from the Paluxy Formation (Table 2). Sample was selected based on the availability of associated thin section, SEM, and XRD data. The sample was crushed with a ceramic mortar and pestle and dried in glass dishes inside a Lab Companion scientific oven for 96 hours at a temperature of 45°C then re-crushed and dried for 48 hours at a temperature of 45°C. Sample size was greater than 100 mg and analyzed in an Eltra Carbon-Sulfur Determinator with two repeats. A standard sample was used for calibration before and after measuring each sample. The carbon standard TC4007 sample, which is certified at 7.3 % TOC, was used for standardization and calibration. Testing of the carbon standard established a maximum error of 0.23 %. TC was determined by combustion and total inorganic carbon (TIC) was measured by acidizing the samples to dissolve carbonate. Total organic content (TOC) was then calculated by subtracting TIC from TC.

Pulse-decay permeability testing of core plugs obtained from Lower Cretaceous mudstone in the MPC-19-1 well was performed by the Stratum core laboratory. The plugs were drilled from butt slabs of the core.. The testing was performed with air under a net confining stress of 10.3 MPa (1,500 psig). The core plugs have a diameter of 3.8 cm and length ranging between 3.2 and 4.5 cm and were placed in screened nickel-teflon sleeves for testing. The testing was performed on the samples on an as-received basis because high water content and fluid sensitivity precluded cleaning or drying prior to analysis.

Results

Stratigraphic Cross Section

The composite cross section based on the six well logs demonstrates complex spatial relationships among the mudstone and sandstone units and the nature of stratigraphic boundaries in the study interval (Fig. 3). Correlations are dependent on stratigraphic position relative to a datum at the top of the lower Tuscaloosa Group, log curves, and depositional architecture. The sandstone and mudstone units have variable thickness and lateral extent throughout the cross section, with sandstone units clustered in the Paluxy Formation and the Big Fred sand of the Washita-Fredericksburg interval. Facies relationships are complex in the Paluxy Formation, where the basal sandstone units onlap Mooringsport limestone toward the northeast, and shallower sandstone units have variable thickness and geometry ranging from lensoid and tabular to continuous. The mudstone units are also geometrically complex, filling the gaps between the sandstone bodies. The Washita-Fredericksburg interval contains the greatest concentration and continuity of sandstone and conversely the least amount of mudstone in the middle of the interval, specifically the Big Fred sand, whereas the lower and upper parts of the interval are dominated by mudstone containing lensoid sandstone units with variable thickness and continuity. The Dantzler sand forms the top of the Washita Fredericksburg interval and has undulatory basal and upper contacts. The Dantzler is disconformably overlain by the Massive sand of the lower Tuscaloosa Group, which has an undulatory basal contact and a relatively smooth upper contact, which was used as a datum to build the cross section.

The Paluxy Formation contains approximately 18 small-scale mudstone baffles per well that are on the scale of 0.3 m (1 ft) thick. Five of the baffles were correlated among most or all of the wells. There are approximately 3 mudstone barriers per well in the Paluxy Formation that are 3-10 m (10-30 ft) thick and can be correlated across the study area. The Washita-Fredericksburg interval contains 18 small-scale baffles per well with one correlatable mudstone package in the upper Big Fred sand and a moderately correlatable baffle in the upper Washita-Fredericksburg interval. There are 11 thicker mudstone barriers (>3 m; 10 ft) within the Washita-Fredericksburg interval; 8 of the barriers can be considered moderate due to incomplete lateral continuity and occurring at the same stratigraphic and structural interval between multiple wells. The lower Washita-Fredericksburg interval contains 4 barriers, the Big Fred sand contains 1, and 3 within the upper Washita-Fredericksburg interval. There is an occurrence of very thick baffle (>30m; 100 ft) in the upper Washita-Fredericksburg interval in the downdip MPC 26-5 well, but does not maintain thickness across the study area and correlates with thinner barriers updip. In general, the Paluxy Formation mudstone units are thin, have limited continuity, and are thus considered baffles that contribute to reservoir heterogeneity. Basal Washita-Fredericksburg mudstone units are generally thicker (>3 m), more numerous, and maintain more uniform thickness in the study area. The Big Fred sand within the Washita-Fredericksburg interval contains mainly thin mudstone layers, and the baffles may be discontinuous and are capped by a series of thicker and more widespread barriers in the upper Washita-Fredericksburg interval.

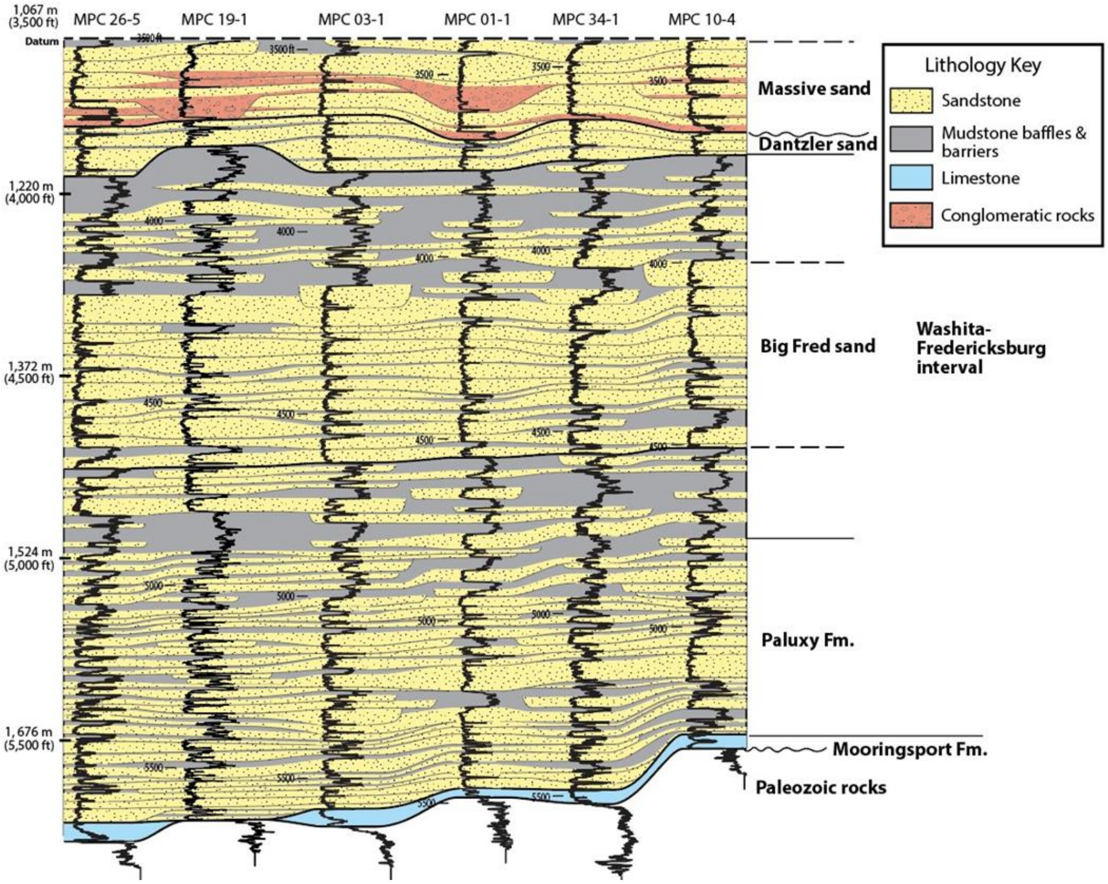


Figure 3. Stratigraphic cross section showing correlation of Paluxy and WashitaFredericksburg strata using gamma logs (after Pashin et al., 2021).

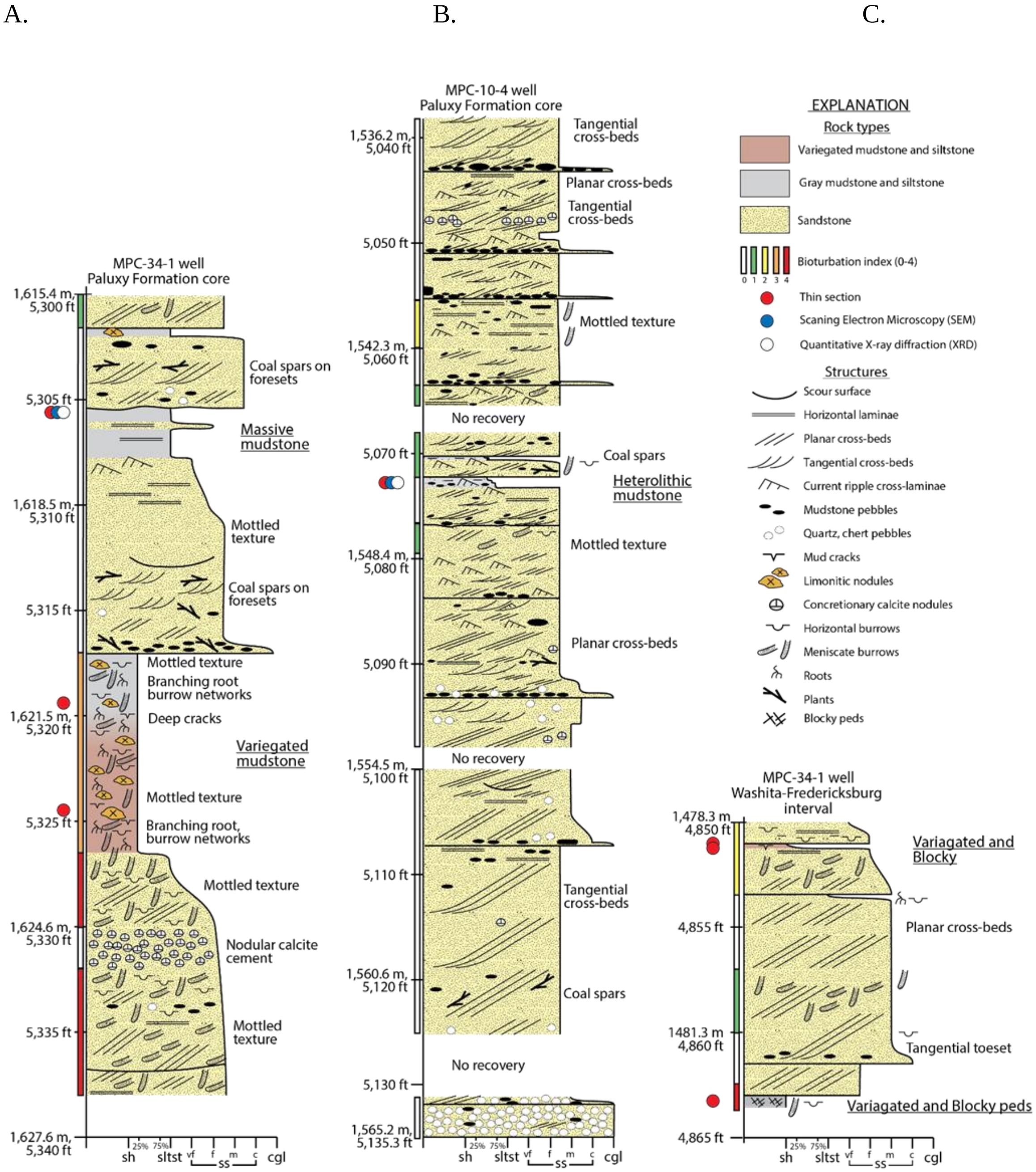


Figure 4. Graphic core logs from the Kemper County energy facility showing rock types, sedimentary structures, biogenic structures, diagenetic structures, and bioturbation index (modified from Pashin et al., 2020) (A) Graphic core log of the Paluxy Formation in the MPC 34-

1 well. (B) Graphic core logs of the Paluxy Formation in the MPC 10-4 well. (C) Graphic core log of the Washita-Fredericksburg interval in the MPC 34-1 well.

Mudstone Lithofacies

Mudstone in the Paluxy Formation and Washita-Fredericksburg interval is typically sandy, contains diverse sedimentary, biogenic, pedogenic, and authigenic structures. The mudstone was pliable at the time of core recovery and remains highly reactive with water. This section describes the characteristics of individual mudstone facies recognized in the cores and lithofacies naming is based on hand sample features.

About 2.7 m (9 ft) of the variegated mudstone facies was cored in the Paluxy Formation in well MPC 34-1 at a depth of 1,620.3-1,623 m (Fig. 4A). This facies appears to be the most typical component of the lower Cretaceous mudstone units at the Kemper County energy facility. The mudstone in this core is between two fining-upward sandstone units; it has a gradational lower contact and a sharp upper contact. The facies is texturally a sandy mudstone to clayey sandstone. It is characterized by variegated light bluish gray, with moderate yellow, and mixed grayish and moderate red colors throughout. Sedimentary structures include branching rootlets, desiccation cracks, and horizontal and vertical burrow networks that give this facies a mottled texture. Irregular sesquioxide nodules that are up to cobble size are common and weather with yellowish hues. Many of the nodules are not visible in hand sample but are readily observed in CT images because of high iron concentration, which increases rock density. Burrow mottling and adhesive meniscate burrows are common in this facies, and the bioturbation index is typically 3 (Fig. 5A).

The massive mudstone facies was cored in the Paluxy Formation in the MPC 34-1 well (Fig. 4A), and is not as common as the variegated mudstone described above. The massive mudstone is up to 0.3 m (1 ft) thick, and is predominantly structureless silty claystone with some faint horizontal laminae. The color ranges from very light gray to greenish gray and moderate greenish yellow, and the facies contain sesquioxide nodules resembling limonite that give this rock a greenish yellow tint (Fig. 5B). This facies contains no apparent bioturbation.

Heterolithic mudstone occurs in two intervals in the Paluxy Formation in the MPC 10-4 well and is preserved as thin intervals within a multistorey sandstone unit (Fig 4B). The facies has a net thickness of 0.5 m (1.5 ft) and is characterized by an erosional basal contact mantled with mudstone pebble conglomerate that grades upward into thinly interbedded clay-rich siltstone, sandy mudstone, and light gray, very fine-grained sandstone. In the sandstone layers, current ripple cross-laminae are succeeded by horizontal laminae and quartz-rich siltstone; no bioturbation was observed (Fig. 5C).

The variegated and blocky mudstone facies is in the basal Washita-Fredericksburg interval in the MPC 34-1 (Fig 4C) is approximately 1.2 m (4 ft) thick. The facies is thickly interbedded with very light gray sandstone and is a variegated moderate reddish-brown mudstone containing black streaks of organic matter (Fig. 5D). The base of the mudstone is light gray and contains desiccation cracks and some horizontal laminae. The mudstone contains blocky peds and includes a sand filled dike at the bottom of the facies (Fig. 5E). Some of the peds in the mudstone contain pedogenic slickensides. In general, the bioturbation index is 2-4, and vertical and horizontal burrows are present.

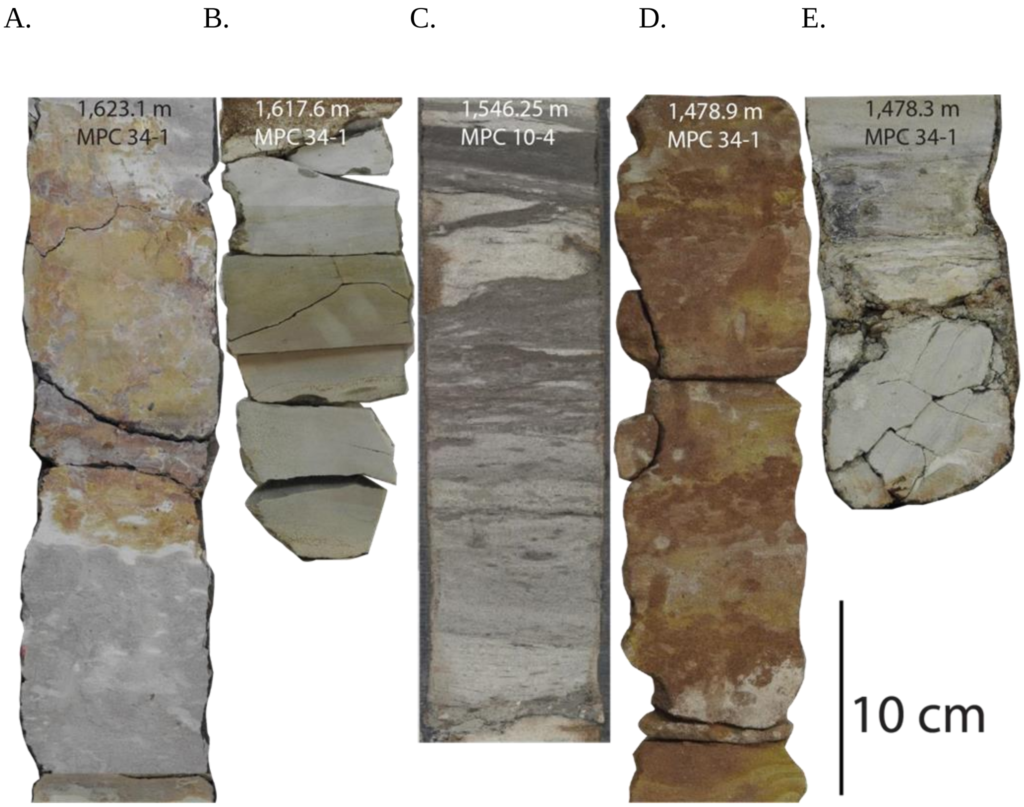
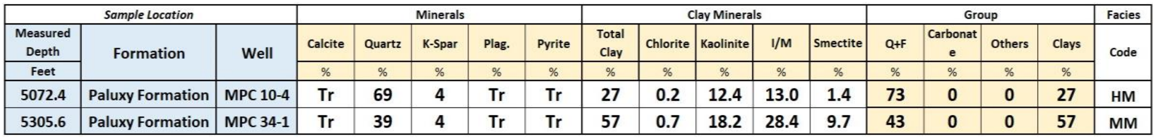


Figure 5. – Core photographs of mudstone-bearing rocks in the Paluxy Formation and the WashitaFredericksburg interval in the MPC 10-4 and MPC 34-1 wells. (A) Variegated mudstone facies, 1,623.1 m (5,325 ft) in the MPC 34-1 well. (B) Massive mudstone facies, 1,617.6 m (5,307 ft) in the MPC 34-1 well. (C) Heterolithic mudstone facies, 1546.25 m (5073 ft), in the MPC 10-4 well. D) Variegated and blocky mudstone facies, 1,478.9 m (4,852 ft), with interbedded sandstone and variegated color in the MPC 34-1, Washita-Fredericksburg interval. (E) Blocky gray peds in the variegated and blocky mudstone facies 1,478.3 m (4,850 ft), in the MPC 34-1, WashitaFredericksburg interval.

Mudstone Petrography

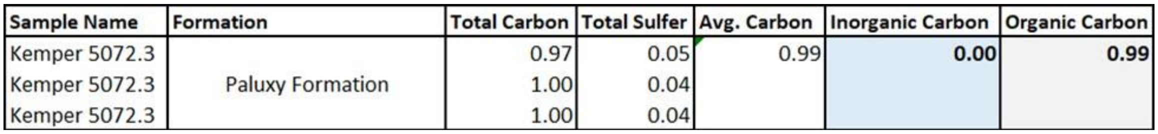
Mudstone petrography is discussed with respect to stratigraphic position and facies with emphasis on mudstone fabric, composition, porosity type and diagenetic features. X- ray diffraction data from mudstone in the Paluxy Formation are shown in Table 1 and organic content data are shown in Table 2.

Table 1. X-ray diffraction mineralogy of mudstone from the Paluxy Formation. Facies key: HM = Heterolithic mudstone and MM = Massive mudstone.



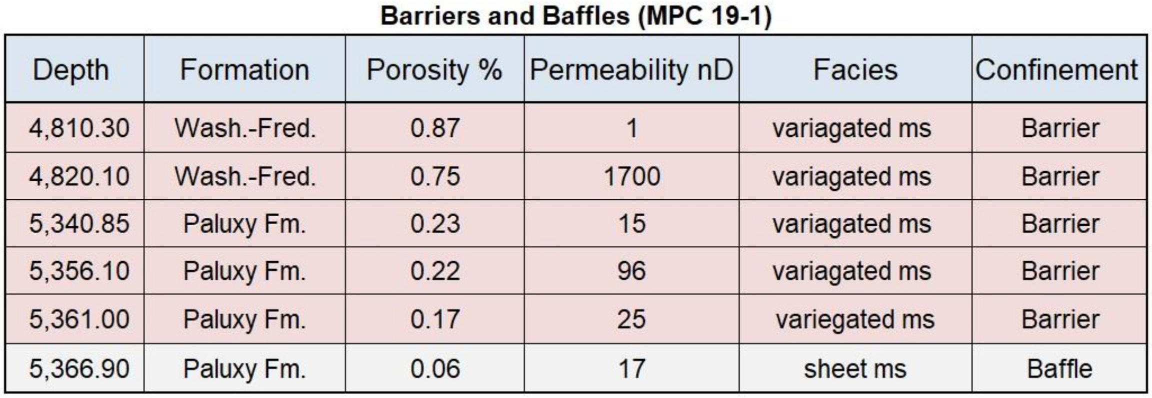
Sample Location			Minerals					Clay Minerals					Group				Facies
Measured Depth	Formation	Well	Calcite	Quartz	K-Spar	Plag.	Pyrite	Total Clay	Chlorite	Kaolinite	I/M	Smectite	Q+F	Carbonate	Others	Clays	Code
Feet			%	%	%	%	%	%	%	%	%	%	%	%	%	%	
5072.4	Paluxy Formation	MPC 10-4	Tr	69	4	Tr	Tr	27	0.2	12.4	13.0	1.4	73	0	0	27	HM
5305.6	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 2. Carbon analysis results from the MPC 10-4 well, Kemper County energy facility.



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			

Table 3. Porosity and pressure decay permeability of baffles and barriers in the MPC 19-1 well.



Barriers and Baffles (MPC 19-1)

Depth	Formation	Porosity %	Permeability nD	Facies	Confinement
4,810.30	Wash.-Fred.	0.87	1	variagated ms	Barrier
4,820.10	Wash.-Fred.	0.75	1700	variagated ms	Barrier
5,340.85	Paluxy Fm.	0.23	15	variagated ms	Barrier
5,356.10	Paluxy Fm.	0.22	96	variagated ms	Barrier
5,361.00	Paluxy Fm.	0.17	25	variegated ms	Barrier
5,366.90	Paluxy Fm.	0.06	17	sheet ms	Baffle

Mudstone Fabric and Composition

The variegated mudstone facies of the Paluxy Formation contains sandy mudstone with some calcite cement. The sample contains quartz grains floating in clay-rich matrix and includes many clay-size quartz clasts (Fig. 6). Quartz is the most abundant grain type, and accessory minerals include muscovite and biotite, sparse pyrite framboids, and isolated zircon crystals. The thin sections contain no apparent porosity since intergranular pores are occluded by fine-grained particles, organic matter, and calcite cement.

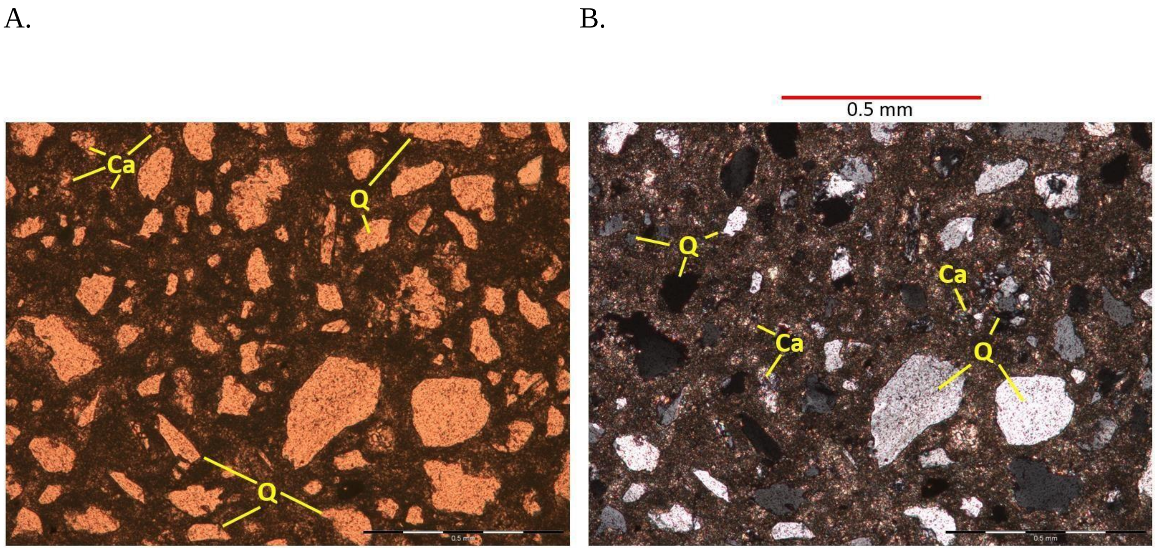


Figure 6. – Thin section image of variegated mudstone from the MPC 34-1 well, Paluxy Formation, 1621.5 m (5319.9 ft). A) Plane-polarized light (PPL) photomicrograph with calcite (Ca) and Quartz (Q). B) Cross- polarized light (CPL) photomicrograph.

On the basis of XRD, the massive mudstone facies of the Paluxy Formation is a silty claystone with 57 percent clay minerals consisting of 18.2% kaolinite, 28.4% illite, and 9.7% smectite (Table 1). The sample contains 39.0% quartz and only 4.0% feldspar. The thin section shows weak laminae and abundant silt and clay-size grains (Fig. 7A and B). Accessory grains include zircon, pyrite, muscovite, and biotite with micas that are typically elongate with bedding. In SEM images, most pores appear to be artifacts of desiccation and perhaps freezing of the sample, the artifacts contour grains and parallel bedding, the only primary pores observed are isolated intraparticle pores associated with fluid inclusions in quartz grains (Fig. 7C and D).

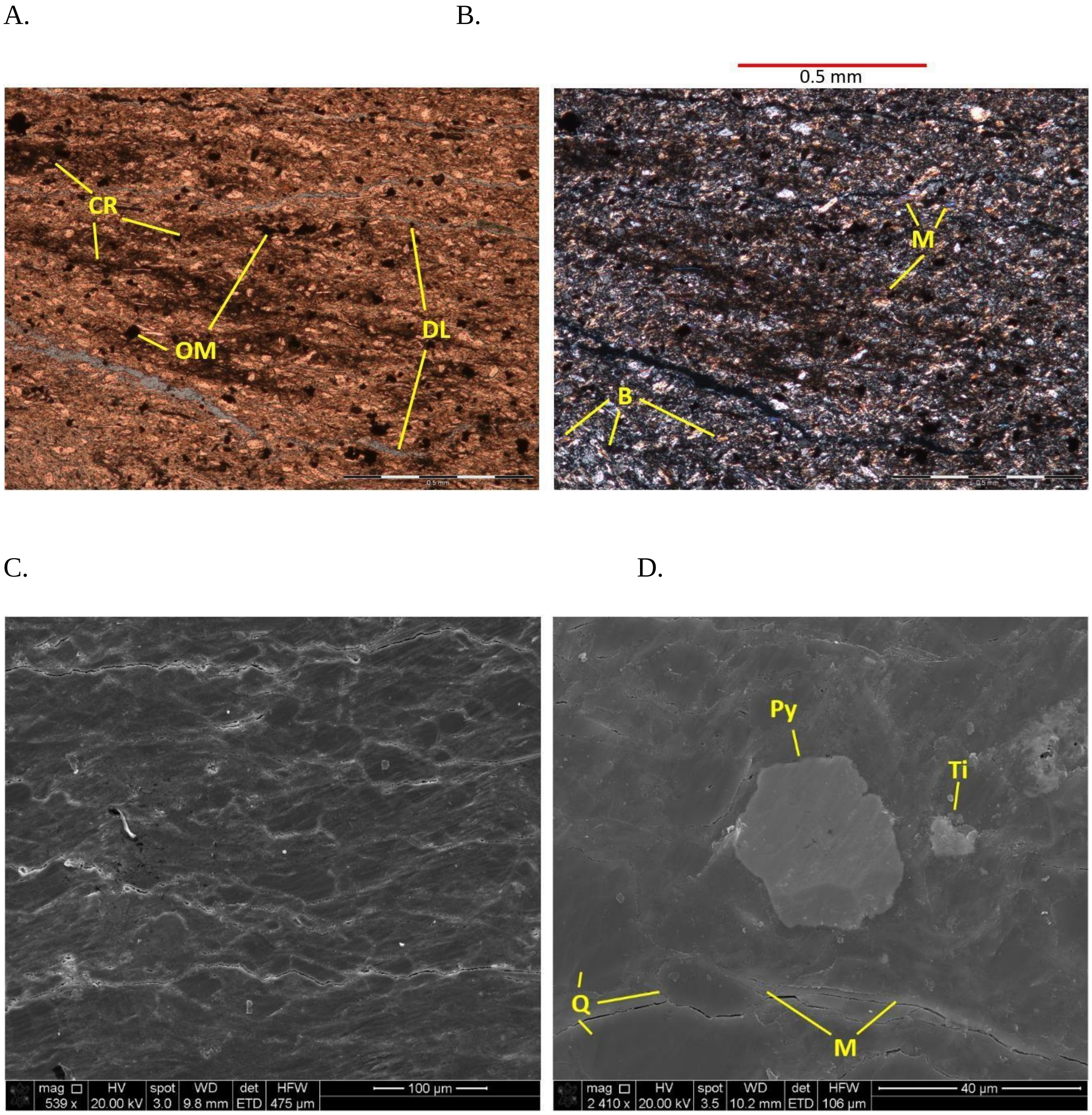


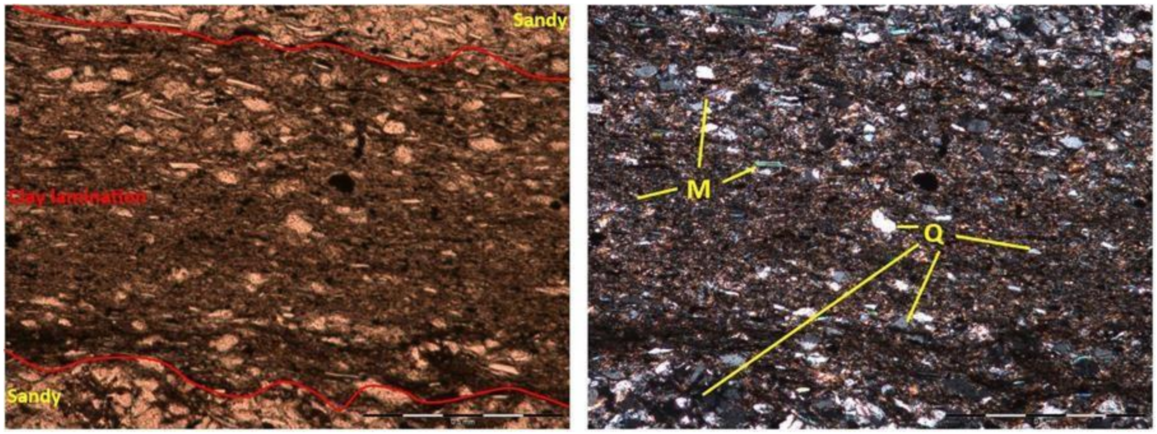
Figure 7. – Thin section of the massive mudstone facies in the Paluxy Formation, MPC 34-1 well, 1617.1 m (5305.5 ft). (A) PPL photomicrograph showing clay-rich lenses (CR), organic matter (OM), and fissures or delamination (DL) along bedding. (B) CPL photomicrograph showing abundant muscovite (M) and less common biotite (B) grains. SEM image of the massive mudstone facies imaged perpendicular to bedding, from the Paluxy Formation MPC 34-1 well, 5305.6 ft. (C) There is a lack of authigenic pores. (D) SEM/EDS image showing muscovite (M)

parallel to bedding, pyrite (Py), quartz (Q), and an accessory mineral rich in titanium (Ti), possibly rutile or anatase.

The heterolithic mudstone facies in the Paluxy Formation is a sandy mudstone with clay laminae. The facies contains 27% clay minerals, 39% quartz, and 4% potassium feldspar (Table 1).This facies has abundant clay laminae and ripple cross-laminae in hand sample, and in thin section, the laminae are inversely graded (Fig. 8A and B). Accessory minerals include muscovite, biotite, zircon and pyrite framboids. This facies contains up to 1% TOC and no inorganic carbon (Table 2). Bed-parallel and grain-contouring cracks reflect desiccation of the sample during exposure to atmospheric conditions following recovery. Primary interparticle pores are rare and have diameter on the order of 1 µm, and are partially occluded by clay-size pyrite cubes and kaolinite booklets (Fig. 8C and D).

A.

B.



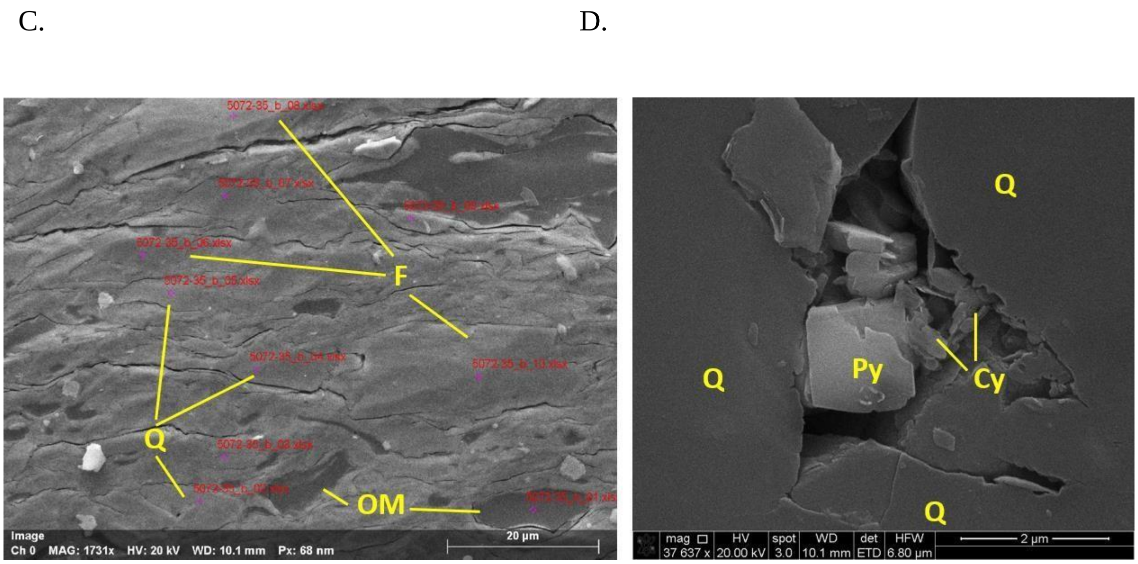


Figure 8. – Thin section photomicrographs of the heterolithic mudstone facies, Paluxy Formation, MPC 10-4 well, 1546.1 m (5072.35 ft). (A) PPL photomicrograph with inversely graded laminar and faint ripple cross-laminae. Thin section in plane polarized light. (B) CPL microphotograph image showing imbricated quartz (Q) and muscovite (M). SEM image of heterolithic mudstone facies, sandy mudstone, Paluxy Formation MPC 10-4 well, 1546.1 m (5072.35 ft). (C) SEM image showing micro cracks parallel to bedding and contouring grains quartz (Q), potassium feldspar (F), and organic matter (OM). (D) SEM image of a primary

The variegated and blocky mudstone facies is sandy to silty mudstone containing approximately 30% clay, 38% sand, and 32% silt. The coarsest grains are fine sand-size quartz and mica grains, the sample is cemented by calcite and pseudo cement clay (Fig. 9A and B). Feldspar, microcline, albite, and biotite are accessory minerals. The matrix is abundant in silt- and clay-sized particles. Bioturbation is associated with poor bimodal grain sorting and chaotic bedding (Fig. 9C and D). Intergranular space has largely been occluded by carbonate cement and clay-size matrix. Accessory minerals include zircon, pyrite, muscovite, biotite, and opaque minerals.

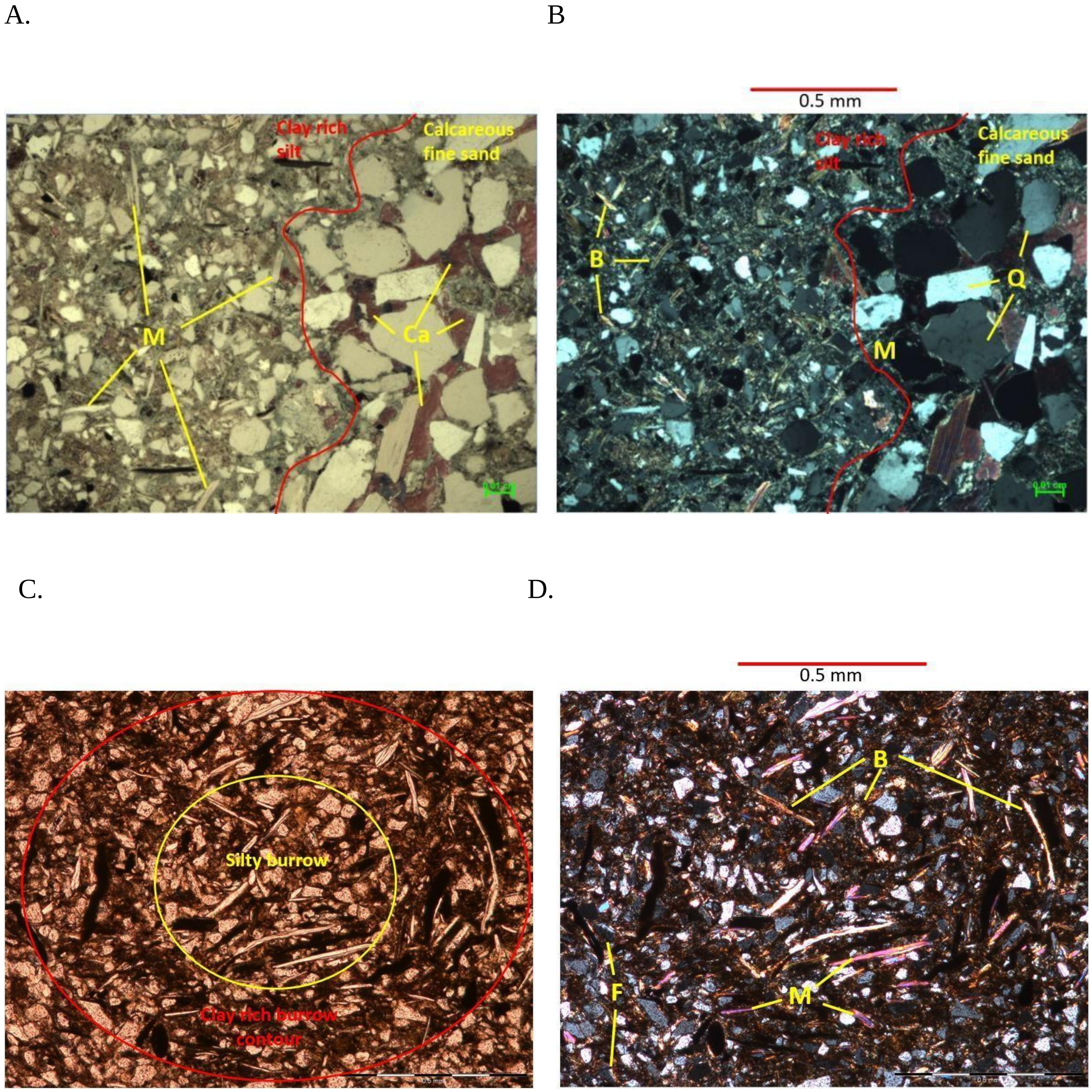


Figure 9. – Variegated and blocky mudstone facies from the Washita-Fredericksburg interval, MPC 34-1 well 1482.2 m (4863.0 ft). (A) PPL photomicrograph showing distinct contact between finegrained and coarser lithologies due to burrowing. (B) CPL image showing quartz, mica, and minor amounts of biotite. Variegated and blocky mudstone facies, clay rich thin section, from the WashitaFredericksburg interval in the MPC 34-1 well, 1478.5 m (4850.6 ft). (C) PPL image

showing a clayrich, lined horizontal burrow. (D) CPL microphotograph showing muscovite (M) and biotite (B) with some albite and microcline silt (F) with chaotic sorting.

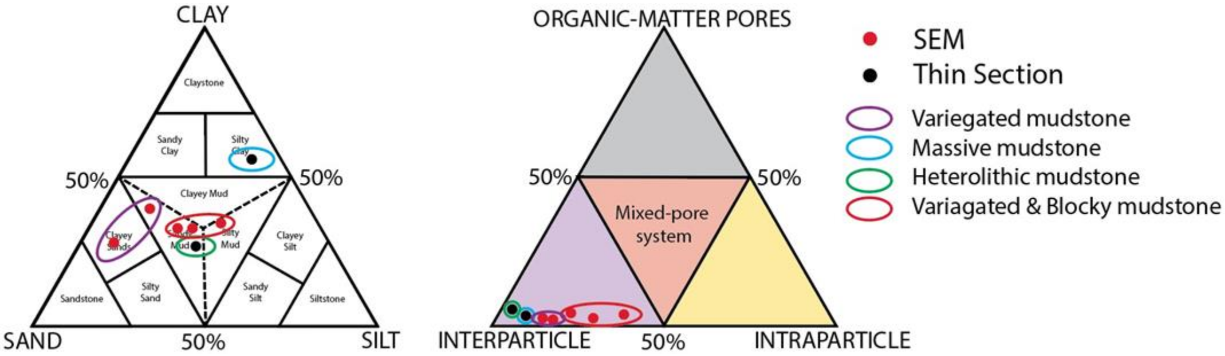


Figure 10. – Ternary plots showing mudrock composition and pore types in the Paluxy Formation (purple, blue, and green circle) and Washita-Fredericksburg interval. A) Mudrock classification based on grain size and XRD mineralogical analysis. B) Pore system analysis from petrographic analysis of mudstone.

Mudstone in the Paluxy Formation and Washita-Fredericksburg interval is mixed with variable amounts of sand, silt, and clay minerals that give each facies a distinct textural and chemical maturity profile (Fig. 10). The sandiest facies is the variegated mudstone, which contains abundant bioturbation and rootlets that resulted in differential textures within a single sample with little carbonate cement in coarser grained laminae. The heterolithic mudstone is largely matrix supported with abundant clay rich laminae and primary pores that are partially occluded by authigenic minerals. The massive mudstone facies is texturally mature with greater that 50% clay minerals in a matrix-supported rock that contains relatively few sand-sized particles and only trace amounts of carbonate cement (<1%). The variegated and blocky mudstone in the Washita-Fredericksburg interval contains abundant sand- and siltsize particles that are associated with burrows and are partially cemented with calcite. The mudstone intervals within the multi-storey sandstone reservoirs contain little organic matter, and intraparticle primary pores are associated with silty to sandy laminae and commonly have partial fills composed of clay, authigenic pyrite, and carbonate.

The results of pulse-decay permeability analysis indicate that nanodarcy-class permeability is typical. Permeability values range from 1 to 1,700 nD (Table 3). Three of the samples have values between 15 and 25 nD, indicating that the mudstone has significant confining potential. The 1,700 nD sample appears similar visually to the other samples, and the high value appears exceptional and may reflect either a fracture in the sample or imperfect sealing of the core plug in the sleeve.

Discussion

Depositional Environments

Mudstone in the Paluxy Formation and Washita-Fredericksburg interval represents finegrained deposits associated with bedload-dominated fluvial depositional systems (Pashin et al., 2020; Urban, 2020; Wethington, 2020; Folaranmi, 2015) and resemble a broad range of modern and ancient sandy braided stream deposits (e.g., Miall, 1977; Cant and Walker, 1978; Blodgett and Stanley, 1980; Bridge and Lunt, 2006). Analysis of the sandstone cores indicates that these systems were dominated by channels with transverse bars, and where FMI logs facilitate paleocurrent analysis, results indicates that the streams at least locally flowed northwest, parallel to strike of the margin of the Mississippi Embayment (Pashin et al., 2020). The upper parts of the sandstone and the adjacent sandy mudstone contains root systems and adhesive meniscate burrows (Figs. 4, 5), which are typically formed by insects (Hasiotis, 2002), and these structures are interpreted primarily as the products of transverse bars. Root systems, burrow networks, sesquioxide nodules, desiccation cracks, and blocky peds combined with reddened sediment and low organic content, save for scattered coalified plant fragments, provide evidence for stabilization of sediment in oxidizing environments, and these features are typical of spodic paleosols that form in transverse bars and in interfluves in semi-humid to environments (Brewer, 1980; Retallack, 1990).

The heterolithic facies in the Paluxy Formation is developed principally within multistorey sandstone units and is interpreted as a bar-top deposit that formed in association with transverse and tangential bars. The interstratification of mud and sandstone provides evidence for episodic flows that occurred when the tops of bars were submerged, load structures record fluidized sediment, and the mudstone layers record waning flow and slack-water conditions. Most of these deposits probably formed during flood stage and resemble the sheet-flow deposits described by Hampton and Horton (2007) from bar tops and interfluves.

The paleosols in the variegated, variegated and blocky, and massive mudstone facies have varying degrees of maturity and some degree of soil horizonation. Where the sandstone transitions upward to mudstone, the paleosols are dominated by burrows and contain relict sedimentary structures, including laminae and cross-strata and are interpreted as transitional between the C and B horizon. Sand content generally decreases upward, and sesquioxide nodules are best developed in variegated sandy mudstone containing abundant root traces and burrows characteristic of a lower B horizon. Inversely graded sand layers may be a product of traction during sediment accumulation or may reflect mixing of sediment in the soil profile by burrowing organisms and root systems. The upper parts of the paleosol layers are characterized by blocky peds with pedogenic slickensides and appear to represent the upper part of the B horizon; localized laminae may in places represent remnants of surface layers. Overall, the variable successions of primary sedimentary, pedogenic, and biogenic structures indicate that the thicker mudstone successions represent composites of multiple stacked paleosols, and this stacking is a significant source of heterogeneity of in the baffles and barriers. Conglomeratic layers containing mudstone pebbles indicate that many of these soil layers were prone to erosion and resedimentation. These layers are most common at the bases of the sandstone units and help define individual sandstone storeys.

Implications of Mudstone Baffles and Barriers

Paluxy Formation mudstone facies vary in composition but in general are sandy to silty mudstone that are rich in clay. The dominant primary pore type is interparticle porosity associated with silty and sandy laminae and lenses, and this porosity appears to be poorly interconnected. The cracks that parallel bedding or contour and follow grain boundaries appear to be mainly secondary fractures that formed during core retrieval, preservation, and storage and reflect desiccation of mudrock with swellable clay and high water saturation that have underwent atmospheric stress. The low permeability of the mudstone units (1 nD-1µD) relative to the sandstone units (multi-Darcy) favors confinement of CO_2 within the sandstone layers where mudstone units maintain lateral continuity (Fig. 3). The high clay content, which is dominated by water-sensitive kaolinite and smectite, contributes to low mudstone permeability.

The scale of heterogeneity in the thickness and continuity of the mudstone baffles and barriers (Fig. 3) is a direct reflection of the original depositional systems where aggradation, episodic flooding, and shifting of fluvial systems facilitated mud deposition and the preservation of paleosols. Erosional process like channeling and exposure determined where discontinuities formed in the mudstone layers. Paluxy Formation mudstone beds are typically on the order of 0.3 m (1 ft) thick and have an upper thickness limit of about 9 m (30 ft). The lower and upper parts of the Washita-Fredericksburg interval contains significant mudstone units with respect abundance and thickness. There is an average of 18 baffles on the order of 0.3 m (1 ft) thick and 11 barriers on the order of 3 m (10 ft) in each well, and the thickness of individual mudstone units locally approaches 30 m (100 ft). Mudstone barriers in the lower Washita-Fredericksburg interval are thick and widespread enough to prevent significant hydraulic communication between the Paluxy

Formation and the Big Fred sand. The barriers in the upper Washita-Fredericksburg interval will likely impede migration of CO_2 into shallower strata. Indeed, the high salinity of fluid in the Paluxy and Washita-Fredericksburg (60,000-110,000 mg/L TDS) relative to shallower strata (≤ 20,000 mg/L TDS) (Pashin et al., 2020) points toward hydraulic isolation of the Lower Cretaceous sandstone units. Baffles will likely help keep injected CO_2 in the target sandstone layers and promote lateral plume migration while impeding vertical migration of CO_2 into shallower sandstone layers where discontinuities exist in the mudstone layers (Fig. 11).

Regionally, restriction of the Lower Cretaceous section to the subsurface and convergence of the sub-Mesozoic disconformity with the mudstone at the top of the Washita-Fredericksburg interval forms a natural stratigraphic trap for CO_2 as the reservoir sandstone and confining mudstone units onlap the disconformity. Within the Kemper County Energy facility, lateral confinement is not apparent, but the low reservoir dip (<1°) indicates that injected CO_2 would form subsymmetrical plumes with limited updip migration. Facies heterogeneity in the sandstone-mudstone succession is hypothesized to have a stronger impact on plume geometry than any structural factor. Furthermore, it is hypothesized that only fugitive CO_2 that is injected in the Big Fred sand and deeper strata would migrate into the Massive sand of lower Tuscaloosa Group, and the Marine Tuscaloosa shale and the major sealing stratum formed by the chalk of the Selma Group and the mudstone of the Porters Creek Clay would ensure protection of the USDWs in the Naheola and Nanafalia Formations (Fig. 2). In addition, the sandstone units separating the baffles and barriers in the Lower Cretaceous section would likely capture fugitive CO_2, thereby providing additional protection of the shallow USDWs. Ongoing research designed to test this hypothesis is focusing on developing flow models that incorporate the framework put forth in this paper and use scaling of heterogeneity based on the depositional architecture and its modern and ancient analogs to provide a rational prediction of how CO_2 will migrate and be confined in the storage complex at the Kemper County energy facility.

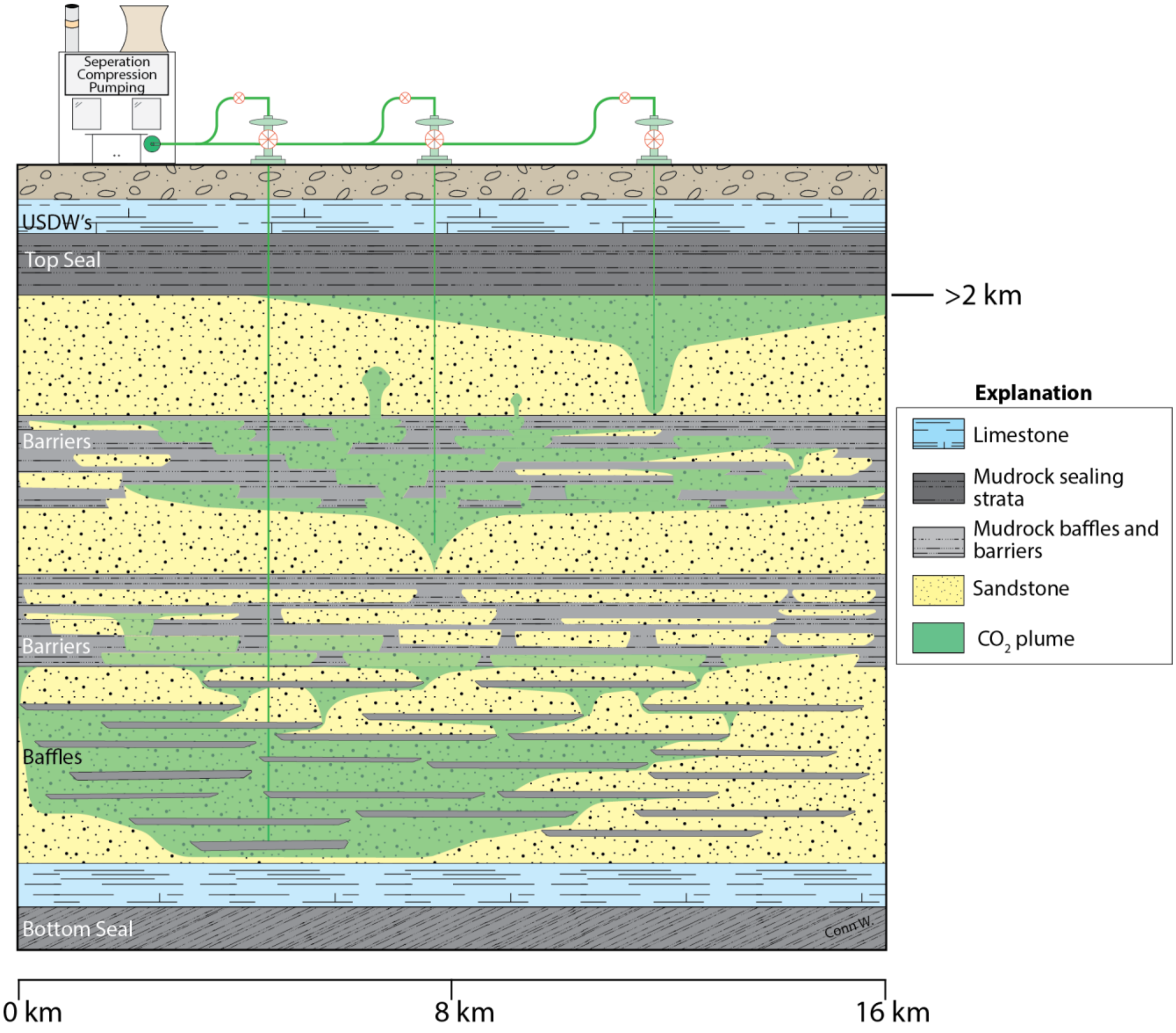


Figure 11. Conceptual model on mudstone baffles and barriers that define heterogeneous reservoirs.

Conclusions

With a storage resource of about 1.4 Gt in stacked sandstone reservoirs overlain by thick, continuous sealing strata that protect USDWs, the Kemper County energy facility provides the basis for a major geologic CO_2 storage complex with capacity to serve as a regional storage hub. The bulk of this resource is in highly permeable sandstone in the Paluxy Formation and the Big

Fred sand of the Washita-Fredericksburg interval, which contain numerous mudstone baffles and barriers that help confine the objective sandstone bodies. The mudstone is matrix supported and rich in clay, silt, and sand and is characterized by fluidsensitive kaolinite and smectite with high water saturation; permeability is on the order of 10 nD in the claystone. The target sandstone reservoirs were deposited in bedload-dominated fluvial deposits, and the mudstone baffles and barriers are principally bar-top deposits and paleosols. Mudstone conglomerate layers form secondary baffles within multistorey sandstone bodies. The numerous baffles within the target reservoir units in the Lower Cretaceous section are hypothesized to help contain injected CO_2 in the stacked sandstone units. Barriers are concentrated in the basal part of the Washita-Fredericksburg interval, separating Paluxy reservoirs from the Big Fred sand, and in the upper part of the WashitaFredericksburg, separating the Big Fred sand from the Dantzler sand. These barriers have potential to confine injected CO_2 within the target sandstone intervals, with plumes flattening at the bases of the baffles and barriers and smaller secondary plumes occurring where gaps exist in the mudstone layers. In the event that fugitive CO_2 migrates into shallower strata, that CO_2 would be contained in Upper Cretaceous strata, which contain many additional sandstone intervals, as well as numerous mudstone units, including the Marine Tuscaloosa shale. In the unlikely event that fugitive CO_2 migrates above the Marine Tuscaloosa, the thick sealing section formed by the Selma Group chalk and Porters Creek Clay ensures that CO_2 remains in the storage complex and the shallow USDWs of the Naheola and Nanfalia formations are protected.

CHAPTER III

CHARACTERIZATION OF A MARINE MUDSTONE CONFINING UNIT AT A PROPOSED CO_2 STORAGE HUB: KEMPER COUNTY ENERGY FACILITY, MISSISSIPPI, USA

Abstract:

Cretaceous and Tertiary strata in Mississippi, Alabama, and the adjacent continental shelf constitute a widespread succession of sandstone, mudstone, and carbonate that have proven to be important objectives for deployment of geologic CO_2 storage technology in saline formations. Analysis of stratigraphy, sedimentology, and reservoir properties indicates that the Paluxy Formation, Washita-Fredericksburg interval, and lower Tuscaloosa Group present a 1.4 gigatonne storage opportunity at the Kemper County energy facility in east-central Mississippi. The Marine Tuscaloosa shale is a widespread reservoir seal in the deep subsurface of Mississippi and Alabama, but the shale is relatively thin and was deposited closer to shore in the area of the energy facility, and so detailed characterization is required to understand the confining potential of the shale.

Geologic characterization of the Marine Tuscaloosa shale at the storage complex includes integrated analysis of geophysical well logs and core that have yielded a multiscale analysis of confining strata in the storage complex. Scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS), quantitative X-ray diffraction (XRD), and permeability analyses from core were used to characterize microfabric, pore types, mineralogy

and fluid properties within mudstone of the east-central Mississippi Embayment. This characterization has importance for identifying potential migration of fugitive CO_2 into or across the shale. Results indicate that mudstone in the Marine Tuscaloosa shale is an effective confining unit that is a key component of the storage complex in Kemper County. High water saturation in the Marine Tuscaloosa shale units promotes rock ductility and contributes to low permeability, which is on the order of 10-100 nD. Accordingly, the Marine Tuscaloosa shale is interpreted to prevent significant cross-stratal migration of injected CO_2 from deeper sandstone reservoirs and constitutes an important layer of protection intervening between those reservoirs and additional confining layers protecting the underground sources of drinking water in the study area.

Introduction

Confining units are essential components of a CO_2 storage complex, and characterizing these units is important for developing storage strategies (Li et al., 2005). Indeed, confining unit characterization can be conducted in concert with reservoir characterization to develop the best possible understanding of storage complex architecture and behavior (Wethington et al., 2022; Finley et al., 2013). This paper focuses on characterization of the Marine Tuscaloosa shale (Upper Cretaceous) at the Kemper County energy facility, which is a major storage site being developed under the U.S. Department of Energy National Energy Technology Laboratory CarbonSAFE program (Pashin et al., 2020).

Plant Ratcliffe in Kemper County, Mississippi was designed by Southern Company, and the 53-mi^2 (137km^2) area around the plant is referred to as the Kemper County energy facility (Fig. 1). The energy facility is situated atop a thick succession of Mesozoic-Cenozoic strata that has gigatonne-class CO_2 storage potential (Esposito, 2017; Riestenberg et al., 2019, Wethington et al., 2022) (Figs. 2, 3). The Kemper County energy facility was initially designed to include a large coal gasification power plant (Reitze, 2012) employing post-combustion carbon capture technology, but due to market conditions, technical, and regulatory factors, the power plant is operating as a combined cycle natural gas plant. Reservoir strata under the energy facility define a gigatonne-scale storage resource (P_{50} = 1.4 Gt) (Urban, 2020) that has the potential to sequester anthropogenic CO_2 emissions on a regional scale (Pashin et al., 2020). The storage complex can therefore support a range of injection programs and is being considered as a regional storage hub.

Saline reservoir strata in Lower Cretaceous and Upper Cretaceous strata below the Marine Tuscaloosa constitute numerous stacked sandstone units with geometric mean permeability of 3.9 Darcies and have been interpreted principally as bedload-dominated fluvial deposits (Pashin et al., 2020, Urban, 2020). The primary storage resource is in the Lower Cretaceous Paluxy Formation (Albian) and the overlying Washita-Fredericksburg interval (Albian), and additional resources are in the Upper Cretaceous Massive sand of the lower Tuscaloosa Group (Cenomanian) (Mancini and Puckett, 2000). Numerous intraformational mudstone layers separate sandstone beds in the Paluxy Formation and the Washita-Fredericksburg interval and define a system of reservoir baffles and barriers (Wethington et al., 2022). The lower Tuscaloosa Group is overlain by a major mudstone known as the Marine Tuscaloosa shale that is composed of claystone with interbedded siltstone and sandstone. The depositional framework of the marine shale is complex and is hypothesized to control how the shale functions as a confining unit. The Marine shale is a major petroleum reservoir seal in the deep subsurface of Mississippi and Alabama (Galicki, 1986; Mancini et al., 1987) and has been proven as a reservoir seal for CO_2 storage in southern Mississippi (Koperna et al., 2009; Petrusak et al., 2009) but is thinner and contains numerous sandy interbeds at the Kemper County energy facility.

Accordingly, detailed geologic analysis is required to understand the confining potential of the Marine shale in this area and is the focus of this contribution. Indubitably, understanding the depositional framework and lithologic properties of confining strata is essential for planning injection programs and determining the fate of the injected CO_2. The thickness, continuity, heterogeneity, and hydraulic properties of mudstone are fundamental controls on containment of injected CO_2 and have value for predicting where and how hydraulic communication may take place within a storage complex (Wethington et al., 2022; Aplin and Macquaker, 2011). Therefore, the principal objectives of this research are to characterize the Marine Tuscaloosa shale through systematic stratigraphic, sedimentologic, and petrologic analysis.

The Marine Tuscaloosa shale beds are characterized on the thickness, continuity, reservoir properties, and areal extent of mudstone units (Wethington, 2020,). Baffles locally confine CO_2, are on the order of 0.3-3 m (1-10 ft), and can be identified in geophysical well logs. Barriers are thicker, on the order of 3-30 m (10-100 ft), and are more likely to impede vertical CO_2 migration and are correlatable at the field scale. Mudstone seals have thickness on the order of 30 m (100 ft) and are regionally extensive, preventing significant hydraulic communication and vertical migration of CO_2 (Wethington et al., 2022). Mudstone confining strata are ideally thick, continuous, fine-grained, clay-rich, have low permeability. Mudstone units within subsurface reservoirs are a key source of heterogeneity and affect storage efficiency, reservoir extent, and plume morphology (Neuzil, 1994; Downey, 1994; Doughty and Pruess, 2004; Bachu et al., 2007; Goodman et al., 2011; Cavanagh and Haszeldine, 2014). Major sealing strata, like the Marine Tuscaloosa shale, arguably correlate among sedimentary basins at the global scale and define a major marine transgressive unit. The stacked reservoirs at the Kemper County energy facility support lateral plume growth over cross-formational flow (Wethington et al., 2022), and the high permeability helps limit pressure buildup during injection. Furthermore, the baffles and barriers help to limit buoyant forces from fugitive CO_2 from impinging on the Marine Tuscaloosa shale. The Kemper County energy facility is situated atop world-class CO_2 storage reservoirs that are sealed by a thick areally extensive marine shale, chalk, and sandy claystone that defines a potential onshore storage hub that has remarkable potential for transfer of technology and concepts that can be applied to other CO_2 storage complexes across the world.

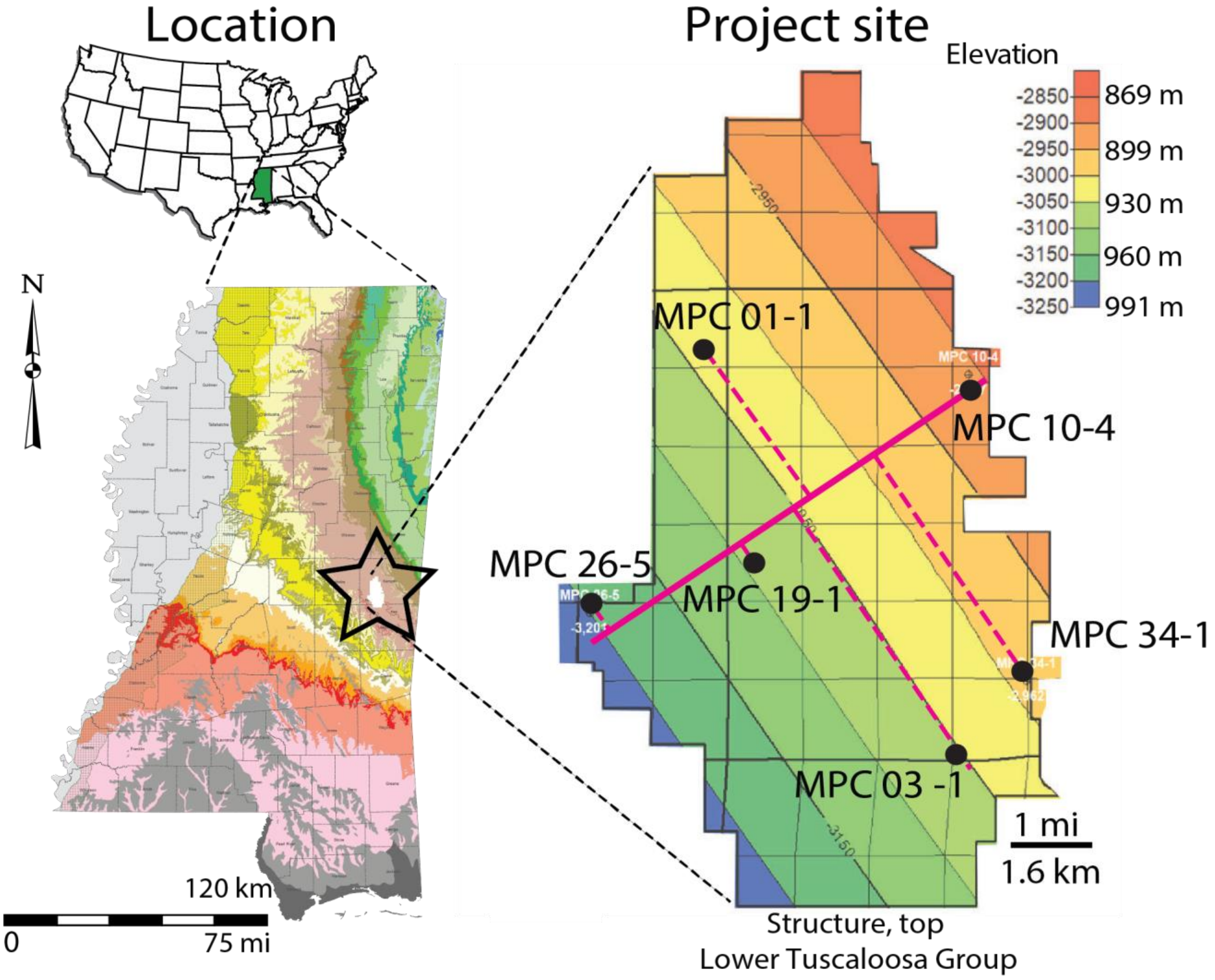


Figure 1. – A) Location map of the Kemper County energy facility located in east-central Mississippi (modified from Bicker, 1969). B) Structure map atop of the storage complex (top lower Tuscaloosa Group) and six scientific wells (after Pashin et al., 2021; Wethington et al., 2022).

Geologic Setting

The Kemper County energy facility is near the eastern margin of the Mississippi Embayment in east-central Mississippi. The embayment began forming during Proterozoic-Cambrian Iapetan rifting (Thomas, 1991) and was affected by Mesozoic-Cenozoic extension associated with formation of the Gulf of Mexico (Salvador, 1987). The embayment extends from southern Illinois to the Gulf of Mexico coastal plain in south-east Texas, Louisiana, Mississippi, and Alabama; it lies east of the Ozark Dome and west of the Nashville Dome (Kolata et al., 1981; Abert, et al., 2016). Sediment fill in the embayment thickens from the outcrop along the fringe of the embayment toward the axis, which is near the contemporary Mississippi River. Post-Paleozoic stratigraphy at the Kemper location dips regionally to the south southwest above a sub-Mesozoic angular disconformity at ~0.33° (Sterns and Marcher, 1962; Cushing et al., 1964; Pashin et al., 2008). The main storage targets are in Cretaceous strata, and confining intervals are preserved in Lower Cretaceous strata of the Paluxy Formation and Washita-Fredericksburg interval (Fig. 2). Upper Cretaceous confining strata include the Marine Tuscaloosa shale and chalk in the Selma Group, and Paleocene confining strata include the Porters Creek Clay. A thin (1.8 m; 8 ft) freshwater aquifer has recently been identified in sand at the top of the Eutaw Formation, and major underground sources of drinking water are extracted from poorly consolidated sand in the Paleogene Naheola and Nanafalia Formations.

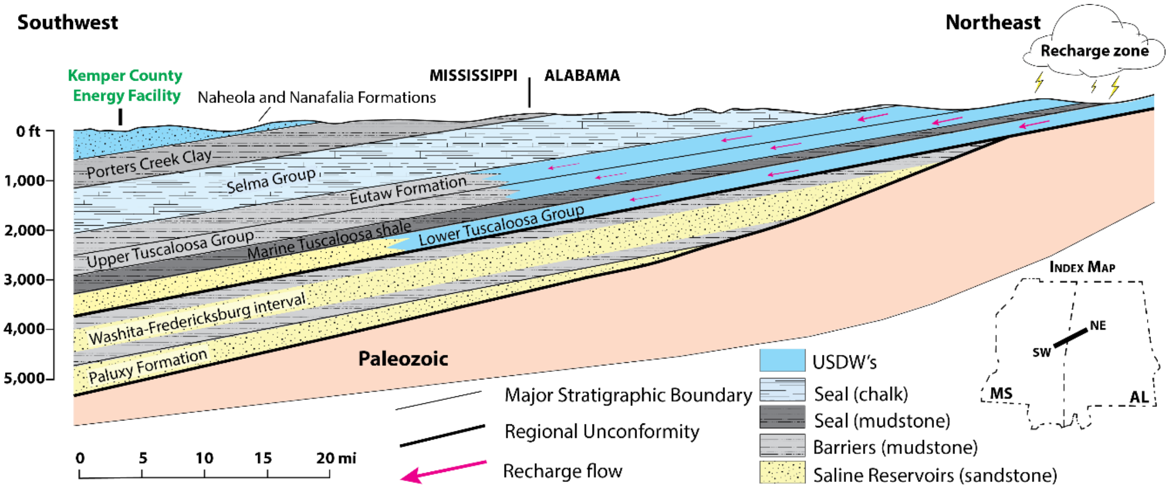


Figure 2. Regional structural cross section showing distribution of saline formations, underground sources of drinking water, and confining strata (after Pashin et al., 2008). Note that Lower Cretaceous strata form a sediment wedge that is confined to the subsurface, whereas younger strata crop out in the northeast where they accept meteoric recharge.

Cretaceous-Paleogene strata at the Kemper County energy facility sit atop an angular disconformity that is developed above deformed Paleozoic strata of the Appalachian-Ouachita Orogen (Thomas, 1973, 1985, 1991; Hale-Ehrlich and Coleman, 1993; Pashin et al., 2008; Riestenberg, 2019). The upper 38 m (125 ft) of the Paleozoic section has been penetrated by wells at the energy facility and is interpreted to be in Pennsylvanian shale of the Pottsville Formation and define a bottom seal for the sequestration complex (Fig. 3). Lower Cretaceous (Albian) strata overlie the angular unconformity and define a thick sedimentary succession that begins with a thin carbonate veneer in the Mooringsport Formation that is succeeded by siliciclastic deposits of the Paluxy Formation and the Washita-Fredericksburg interval (Pashin et al., 2008, 2020; Wethington et al., 2022). Upper Cretaceous strata of the Tuscaloosa Group (Cenomanian-Turonian) disconformably overlie the Dantzler sand (Albian), which forms the top of the Washita- Fredericksburg interval in this area, and uppermost Albian and lower Cenomanian strata are absent in the area of the energy facility. Basal Tuscaloosa conglomerate and conglomeratic sandstone that grades upward into poorly consolidated sand and mudstone constitute the Massive sand of the lower Tuscaloosa Group (Cenomanian). The overlying Marine Tuscaloosa shale (Turonian) is dominated by dark gray mudstone and claystone, and the upper Tuscaloosa Group (Turonian) contains interbedded sandstone and variegated mudstone more than 200 m thick. The Eutaw Formation (Coniacian-Santonian) disconformably overlies the Tuscaloosa Group and contains interbedded glauconitic sandstone and mudstone (Pashin et al., 2000). About 275 m of chalk assigned to the Selma Group caps the Upper Cretaceous section and is disconformably overlain by Paleocene-Eocene strata of the Clayton Formation, Porters Creek Clay, Naheola Formation, and Nanafalia Formation (Rainwater, 1961). The Nanafalia Formation is part of the Wilcox Group and is the youngest unit in the study area (Paleocene-Eocene) (Bicker, 1969).

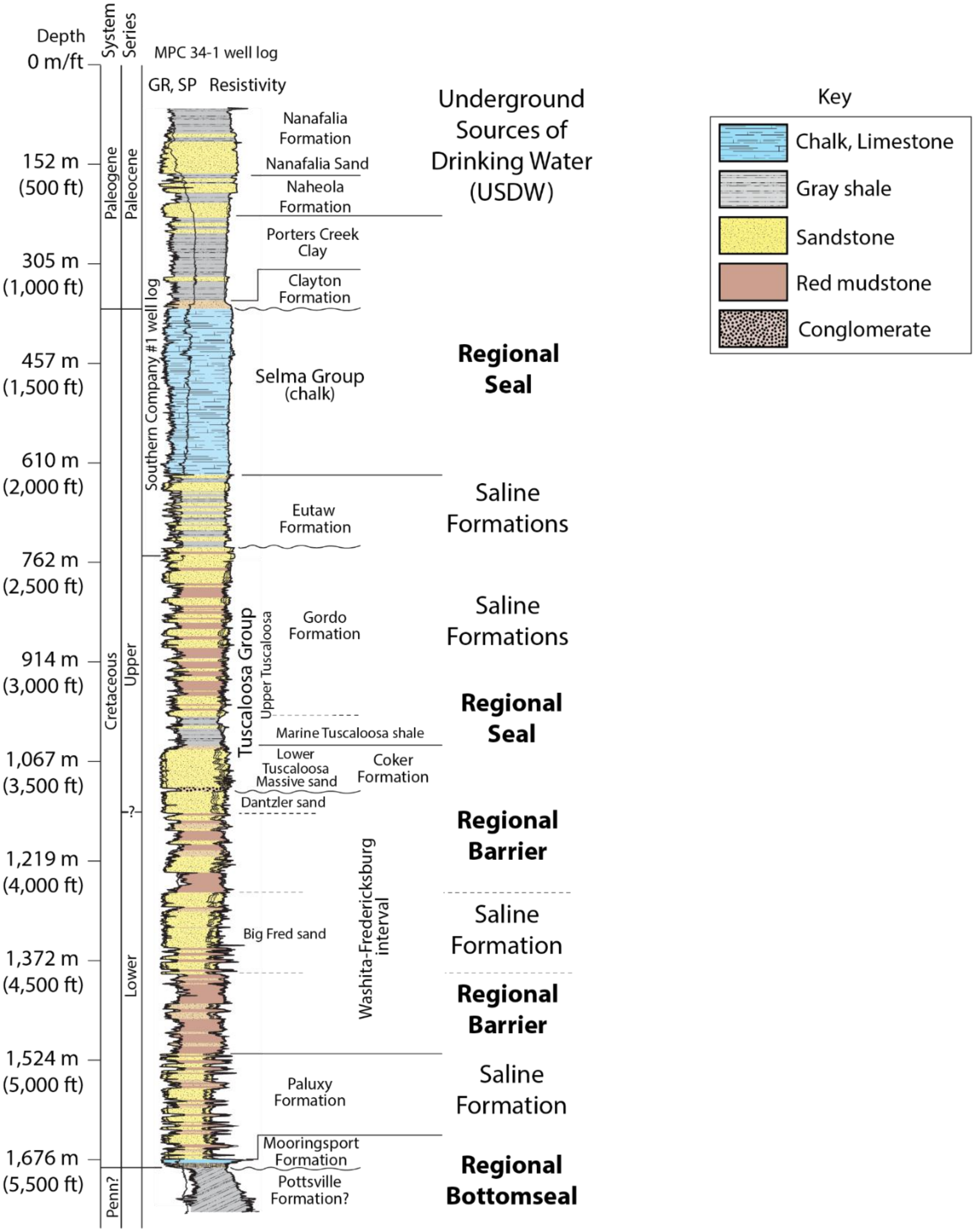


Figure 3. Composite stratigraphic section and geophysical well log of the Paleozoic-Paleogene section at the Kemper energy facility (after Pashin et al., 2020).

Material and Methods

Data were collected from six wells and selected cored intervals of Cretaceous section in the MPC 26-5 and MPC 10-4 wells. Two sections of core were recovered spanning 19.2 m (63 ft) from the Marine Tuscaloosa shale. The rocks are addressed with respect to lithofacies and stratigraphic position. Lithofacies are defined and characterized based on rock type, bedding, physical sedimentary structures, biogenic structures, and mineralogy. The wells include a diverse suite of geophysical logs including gamma ray, resistivity, density-neutron porosity, and spontaneous potential curves. Cores from the MPC 34-1 and MPC 10-4 cores were CT scanned in the original aluminum core sleeves prior to slabbing and aided in estimating bioturbation index and identifying bedding types and sedimentary structures.

Thin sections were made for mudstone samples from the MPC 26-5, and MPC 10-4 wells, sample billets were made and Argon ion milled for SEM/EDS analysis, and samples were crushed for semi-quantitative XRD analysis. Samples from the MPC 10-4 well were analyzed for total organic carbon (TOC) content in gray mudstone. Cores were described, photographed, and logged using standard stratigraphic and sedimentologic procedures. Graphic logs were constructed to document rock types, bedding contacts, sedimentary structures, and biological features. Grain size was characterized using the Wentworth scale (Wentworth, 1922). Intensity of bioturbation in CT images of the cores was characterized using the Bann bioturbation intensity index (MacEachern and Bann, 2008), and rock color was defined using the GSA Munsell color chart (Munsell, 2009). Samples from the butt slabs of the cores were taken for thin sections, SEM billets, and bulk sampling for X-ray diffraction and TOC content. Depositional environments were interpreted on the basis of rock types, grain size trends, bedding, sedimentary structures, fossils, and facies relationships. Samples of fine-grained rocks were taken from cores of the Marine Tuscaloosa shale, and thin sections were milled to a thickness of 20 µm. The thin sections were vacuum impregnated with blue epoxy and stained with alizarin red and sodium cobaltinitrite to identify carbonate and feldspar minerals. Descriptions and photography were made using Leica DM EP Olympus BX51 petrographic microscopes. The grain size distribution in the mudstone in each thin section was used to build a microfacies description that includes percentages of clay, quartz, feldspar, accessory grains, cement, fabric, and porosity. To estimate the volumes of clay and detrital grains, the comparison charts of Matthew et al. (1991) were used. Data were then plotted in a ternary diagram (Picard, 1971) to characterize rock textures and facies characteristics.

Scanning electron microscopy (SEM) was performed on 12 mudstone samples using a FEI Quanta 600 FEG MK2 Environmental SEM. The samples were polished with a JEOL model IB-19500CP argon ion mill and plated with a gold-palladium alloy prior to imaging. The SEM is accompanied by a Bruker Quantax XFlash 6/60 unit with Quantax Esprit software for energy dispersive X-ray spectroscopy (EDS), which aided in mineral identification. The SEM samples have corresponding thin sections that enable comparison of the features observed under transmitted light with those observed by SEM and EDS. Compositional data were used to supplement thin sections descriptions and characterization of mineralogy, microfabric/texture, and pore systems were plotted in a pore system ternary diagram (Loucks et al., 2012).

Semi-quantitative x-ray diffraction (XRD) data were gathered for 9 samples (Table 1) from the MPC 10-4 and MPC 26-5 wells from the Marine Tuscaloosa shale, the samples correspond to thin sections and SEM images. XRD analysis was performed to determine the mineralogy of the mudrocks with respect to weight percent, including clay species. 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 shipped to Impac Exploration Services, and minerals were identified from the pattern of XRD peaks, and the percentages of each mineral were estimated by Rietveld analysis using the methods of Moore and Reynolds (1989).

Total carbon (TC) and sulfur content were determined for five samples from well MPC 10-4 from the Marine Tuscaloosa shale (Table 2). The 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 dried in glass dishes inside a Lab Companion scientific oven for 96 hours at a temperature of 45°C then re-crushed and dried for 48 hours at a temperature of 45°C. Samples size was greater than 100 mg and analyzed in an Eltra Carbon-Sulfur Determinator with two repeats. A standard sample was used for calibration before and after measurement. The carbon standard TC4007 sample, which is certified at 7.3 % TOC, was used for calibration. Testing of the carbon standard established a maximum error of 0.23 %. TC was determined by combustion, and total inorganic carbon (TIC) was measured by acidizing the samples to dissolve carbonate. Total organic content (TOC) was then calculated by subtracting TIC from TC.

Mudstone permeability data were also gathered from the Marine Tuscaloosa shale in the MPC 10-4 well. Moisture equilibrated pressure decay permeability was performed on two crushed shale samples from the MPC 10-4, using a Core Labs Permeameter SMP-200 using the methods described by Achang et al. (2017, 2019) (Table 3). Routine core analysis targeted sandy and silty interbeds within the Marine Tuscaloosa section to determine an upper limit permeability value and testing was performed by Stratum Reservoir Laboratories (Table 4).

Results

Stratigraphic Cross Section

The composite cross section based on gamma ray logs from the six wells in the study area demonstrates the stratal architecture of the upper Washita-Fredericksburg interval, Dantzler sand, Massive sand of the Lower Tuscaloosa Group, Marine Tuscaloosa shale and the upper Tuscaloosa Group (Fig. 4). The six wells are ordered with respect to regional dip and the datum is a surface at or near the base of the Marine shale marked by elevated gamma count. Mudstone units have complex geometry in the upper Washita-Fredericksburg interval, and sandstone bodies are discontinuous. The Dantzler sand has variable thickness and extends across the study area. The unit has a sharp base that appears to mark a disconformity, and sandstone and thin mudstone beds within the Dantzler onlap the disconformity surface. The Massive sand (Cenomanian) disconformably overlies the Dantzler sand (Albian), and relief on the disconformity surface contributes to the variable thickness of the Dantzler. The Massive sand includes abundant conglomerate containing quartzite, vein quartz, and chert, and the basal disconformity truncates the upper part of the Dantzler sand. The conglomeratic strata grade upward into a poorly consolidated sandstone with a muddy zone near the top.

The Marine Tuscaloosa shale has a depositional framework that contrasts markedly with the surrounding strata. The shale is about 100 m thick and contains two distinctive parts (Fig. 4). Mudstone and sandstone beds likely define a clinoform geometry in the lower part of the shale and an onlapping geometry in the upper part. Clinform strata constitute nearly the full thickness of the Marine shale in the northeastern part of the cross section in the MPC 10-4 well, and these strata thin southwestward to 27 m in the MPC 26-5 well. In the MPC 10-4 well, individual mudstone layers are up to 30 m thick. As the sandstone layers converge, sandstone beds tend to be stacked in the distal toes of the clinoforms. Sandstone beds tend to thicken upward in the clinoform section, and a sandstone bed marking the top of the clinoform section reaches a maximum thickness of 9 m in the MPC 03-1 well.

Mudstone and sandstone units in the onlapping portion of the Marine Tuscaloosa shale have great lateral continuity and, are broadly undulatory, and onlap the clinoform section in the northeastern part of the cross section (Fig. 4). This part of the section thins northeastward above the steepest dipping part of the clinoform section. The thickest mudstone interval of 28 m is near the base of the onlapping section in the MPC 03-01 well. Sandstone beds generally thicken upward at the expense of mudstone. The widespread sandstone at the top of the onlapping section reaches a maximum thickness of 10 m in the MPC 01-1 well, and stacking of sandstone units in this well results in a sandstone-dominated interval that is about 50 m thick at the top of the Marine Tuscaloosa.

Stratal geometry in the upper Tuscaloosa Group resembles that in the upper part of the Washita-Fredericksburg interval (Fig. 4). A regionally extensive mudstone layer forms the base of the upper Tuscaloosa and reaches a maximum thickness of 30 m. The geometry and thickness of mudstone and sandstone higher in the section is complex and signals a return to the style of sedimentation that occurred late in Washita-Fredericksburg deposition.

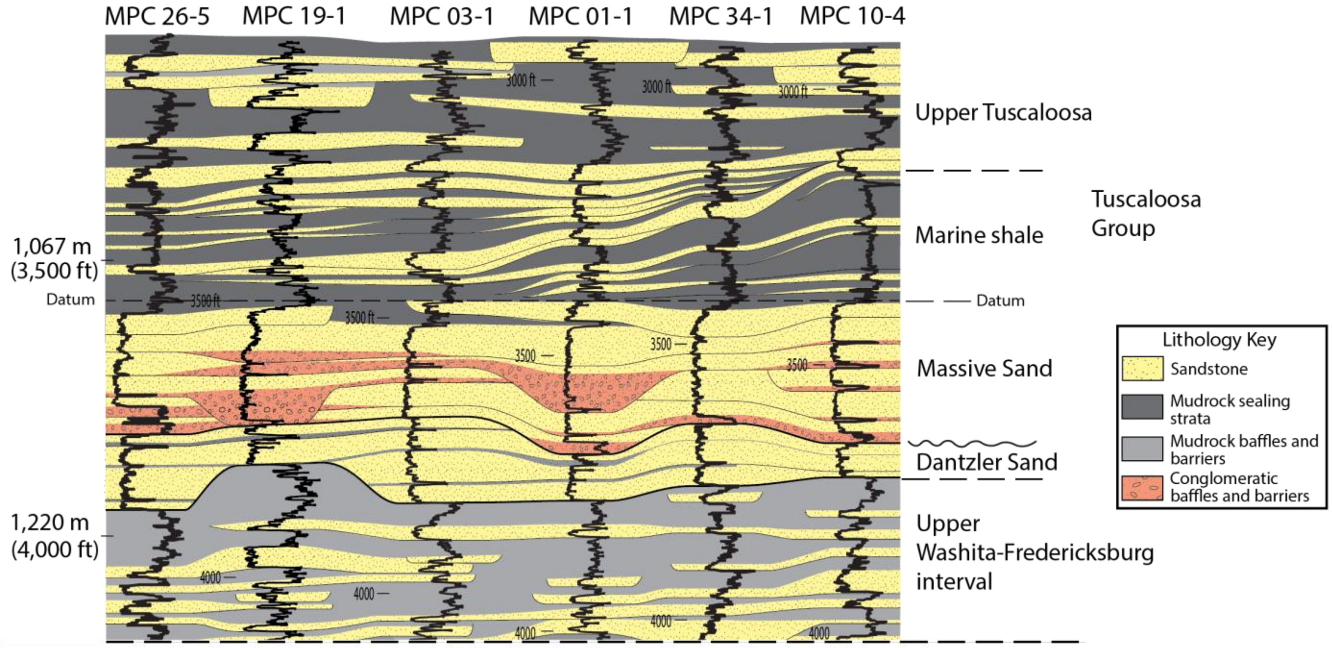


Figure 4. Composite cross section of six wells, correlations are with respect to mudstones using the gamma-ray curve (after Pashin et al., 2021).

Mudstone Lithofacies

The two cores recovered from the Marine Tuscaloosa shale are from different parts of the section. The core from the MPC 26-05 well (Fig. 5) is from the basal part of the shale below the radioactive section used as the datum for the cross section. The MPC 10-4 core, by contrast, is from the upper part of the clinoform section and includes part of the sandstone unit that defines the top of the Marine shale sequence. The MPC 26-5 core records only 1 m of section and is dominated by burrowed mudstone with pinstripe, lenticular, and wavy bedding. The MPC 10-4 core, by contrast, covers about 10 m of section and records an overall coarsening-upward succession containing a diversity of bedding types, sedimentary structures, and biogenic structures. The sandstone at the top of the core is glauconitic, horizontally laminated and contains abundant burrows and an accumulation of mollusc shells.

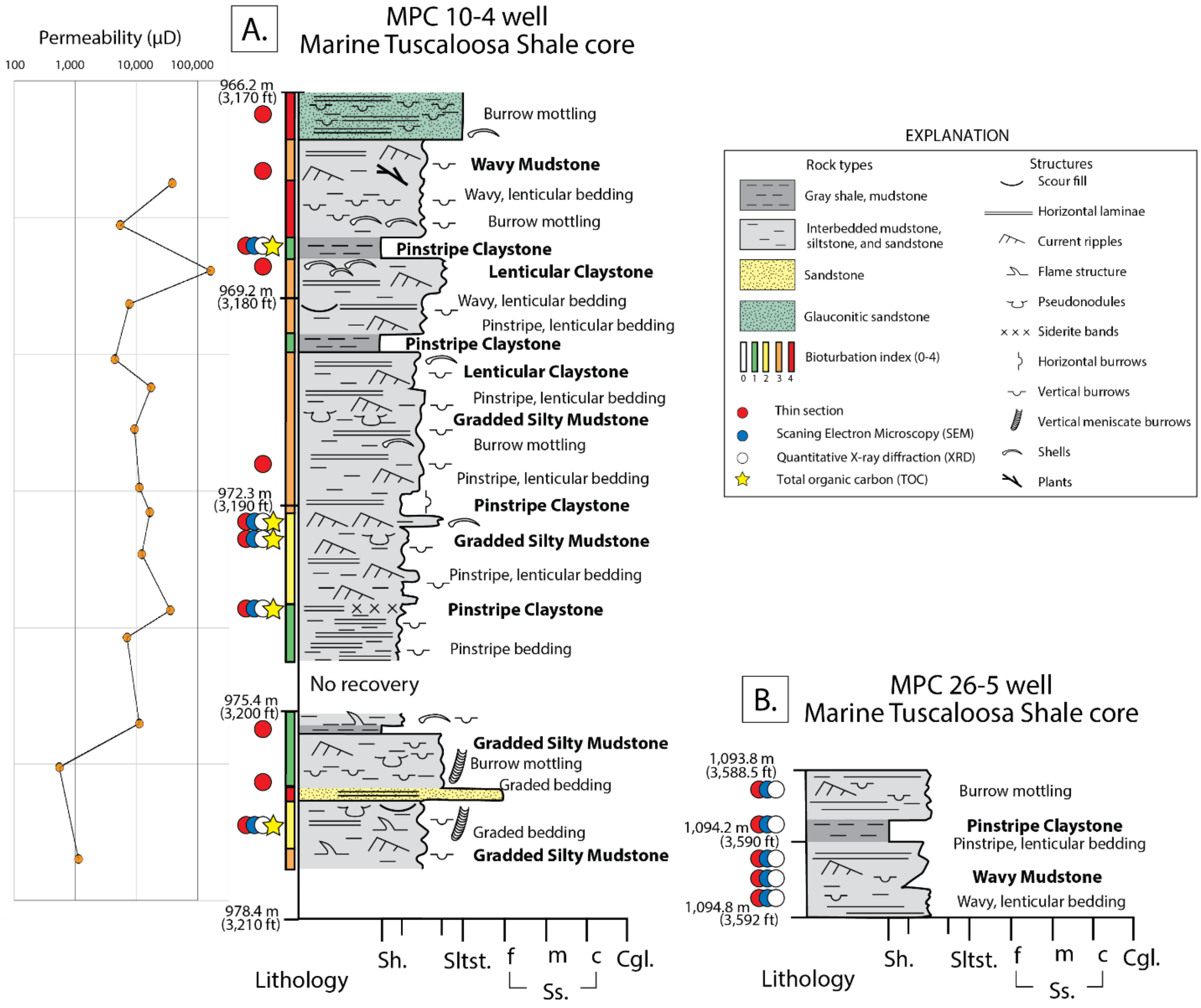


Figure 5. – Graphic core logs of the Marine Tuscaloosa shale at the Kemper County energy facility showing rock types, sedimentary structures, biogenic structures, diagenetic structures, and bioturbation index. A) Graphic core log of the MPC 10-4 well and permeability measured by routine core analysis (modified from Pashin et al., 2020). B) Graphic core log of the MPC 26-5 well showing sample locations.

The cores contain four distinctive lithofacies called the 1) graded silty mudstone lithofacies, 2) pinstripe claystone lithofacies, 3) the lenticular claystone lithofacies, and 4) the wavy mudstone lithofacies (Fig. 5). The graded silty mudstone lithofacies is dominantly coarse-grained siltstone with interbedded claystone. The siltstone constitutes thin, normally graded beds with soft sediment deformation structures, including pseudonodules resembling small-scale ball-and-pillow structures and flame structures (Fig. 6A). Burrowing is localized, resulting in a bioturbation index of 1-4, and the facies contains numerous vertical and horizontal burrows.

The pinstripe claystone lithofacies is the thickest facies spanning approximately 4.5 m of section in the middle part of the MPC 10-4 core and is characterized as claystone interbedded with pinstripe laminae of quartz silt and sand. Clay laminae about 5 mm thick are intercalated with silt laminae that are about 2 mm thick. Sedimentary structures include horizontal pinstripe laminae and solitary current ripples. Pyrite nodules are common in this facies. Bioturbation has an index of 1-3, with increased bioturbation associated with silt-rich zones at the top of the facies; localized silt layers are significantly bioturbated. Horizontal traces are commonly filled with silt and framoidal pyrite (Fig. 6B). Two layers containing fragmented mollusc shells were identified in this part of the mudstone (Fig. 5A).

The lenticular claystone lithofacies contains sandy claystone with laminae of coarse silt to fine sand. Lenticular to wavy bedding, silty horizontal laminae, and current ripples are common. The facies is fossiliferous, containing coaly plant fragments and mollusc shells, which occur in sandy beds that are up to 8 cm (3 in) thick. The silty and sandy beds have a bioturbation index of 3-4 that is expressed as burrow mottling (Fig. 6C).

The wavy mudstone lithofacies occurs in the MPC 26-5 and MPC 10-4 cores. It is characterized as a dark gray, clay rich mudstone with some coarse-grained silt to fine-grained sand layers that form wavy to lenticular beds. Current ripple cross-laminae and horizontal laminae are the most common sedimentary structures; the facies has a bioturbation index of 3, and the burrows disrupt the sedimentary structures. Accumulations of disarticulated shells are preserved in the sandy interbeds (Fig. 6D). In the MPC 10-4 core, this facies becomes increasingly sandy and is dominated by lenticular bedded sandstone just below the glauconitic sandstone in the uppermost part of the core.

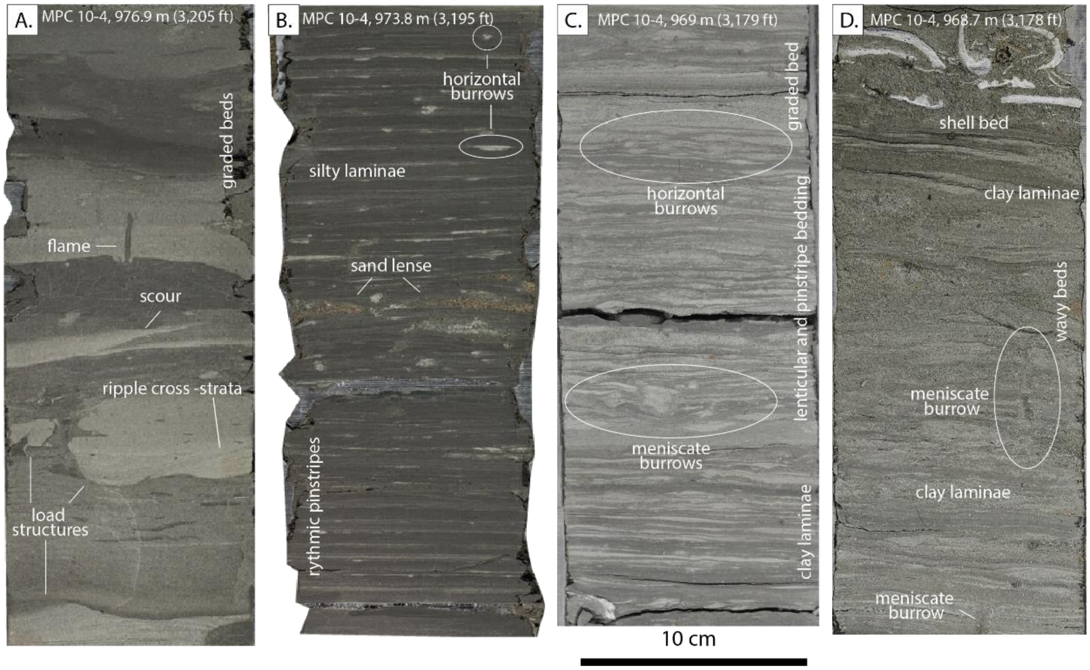


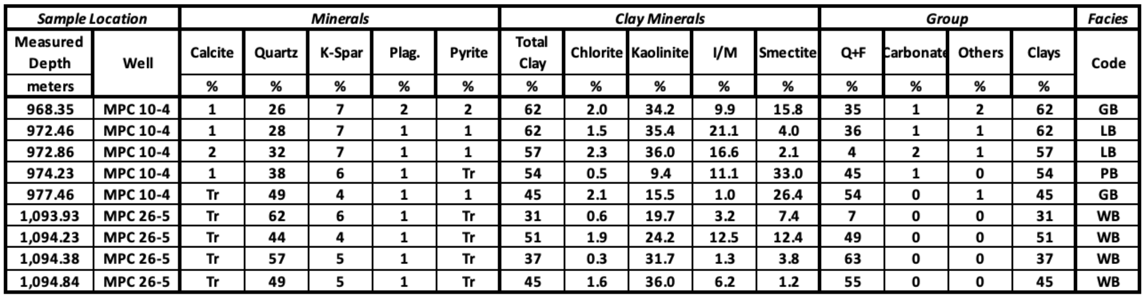
Figure 6. – Core photographs of the Marine Tuscaloosa shale, MPC 10-4 well. A) Graded silty mudstone lithofacies showing soft-sediment deformation and flame structures, 976.9 m (3,205 ft). B) Pinstripe claystone lithofacies contains rhythmic bedding with claystone interlaminated with siltstone, 973.8 m (3,195 ft). C) Lenticular claystone lithofacies showing wavy, lenticular and pinstripe bedding, 969 m (3,179 ft). D) Wavy mudstone lithofacies showing wavy to lenticular bedding and a shell accumulation, 968.7 m (3,178 ft).

Mudstone Petrography

Marine Tuscaloosa shale petrography has been characterized in terms of stratigraphic position, facies, and facies succession with an emphasis on mudstone textures, composition, mineralogy, pore type, diagenetic features, carbon content, and permeability. Semiquantitative x-ray diffraction data collected from 9 samples are given in Table 1, and total carbon content from 5 samples is given in Table 2, moisture equilibrated crushed shale permeability measurements from

2 samples are in Table 3, and routine core analysis data from 15 samples are in Table 4. Moisture equilibrated pressure decay permeability is interpreted to have a permeability 12 and 64 nD from the exponential segment of the pressure decay curve after Pashin et al., 2020 (Fig. 7). These numbers are similar to results of pulse decay permeability analysis of Paluxy and Washita-Fredericksburg mudstone (Wethington et al., 2022). Permeability measurements were attempted on additional samples, but permeability is sufficiently low that the permeameter could not resolve a pressure decay curve—the samples effectively behaved like the glass beads used to zero the permeameter (Pashin et al., 2020). Routine core analysis performed on 1-inch plugs drilled parallel to bedding indicate permeability ranging from 0.5 to 162 mD, with values on the order of 10 mD being common, which demonstrates a strong contrast between mudstone and the siltstone-sandstone beds.

Table 1. X-ray diffraction mineralogy of mudstone from the Marine Tuscaloosa shale. Facies key: WB = wavy mudstone lithofacies, GB = graded silty mudstone lithofacies, PB = Pinstripe claystone lithofacies, LB = Lenticular claystone lithofacies.



Sample Location		*Minerals*					*Clay Minerals*					*Group*				*Facies*
Measured Depth	Well	Calcite	Quartz	K-Spar	Plag.	Pyrite	Total Clay	Chlorite	Kaolinite	I/M	Smectite	Q+F	Carbonate	Others	Clays	Code
meters		%	%	%	%	%	%	%	%	%	%	%	%	%	%	
968.35	MPC 10-4	1	26	7	2	2	62	2.0	34.2	9.9	15.8	35	1	2	62	GB
972.46	MPC 10-4	1	28	7	1	1	62	1.5	35.4	21.1	4.0	36	1	1	62	LB
972.86	MPC 10-4	2	32	7	1	1	57	2.3	36.0	16.6	2.1	4	2	1	57	LB
974.23	MPC 10-4	1	38	6	1	Tr	54	0.5	9.4	11.1	33.0	45	1	0	54	PB
977.46	MPC 10-4	Tr	49	4	1	1	45	2.1	15.5	1.0	26.4	54	0	1	45	GB
1,093.93	MPC 26-5	Tr	62	6	1	Tr	31	0.6	19.7	3.2	7.4	7	0	0	31	WB
1,094.23	MPC 26-5	Tr	44	4	1	Tr	51	1.9	24.2	12.5	12.4	49	0	0	51	WB
1,094.38	MPC 26-5	Tr	57	5	1	Tr	37	0.3	31.7	1.3	3.8	63	0	0	37	WB
1,094.84	MPC 26-5	Tr	49	5	1	Tr	45	1.6	36.0	6.2	1.2	55	0	0	45	WB

Table 2. Carbon analysis results from the MPC 10-4 well, Kemper County energy facility. Facies key: GB = graded silty mudstone lithofacies, PB = Pinstripe claystone lithofacies, and LB = Lenticular claystone lithofacies.

Sample Location		***Sample Content***					***Facies***
Measured Depth	**Well**	**Total Carbon**	**Total Solfur**	**Avg. Carbon**	**Inorganic Carbon**	**Organic Carbon**	**Code**
meters		**%**	**%**	**%**			
972.46	**MPC 10-4**	**1.31**	**0.05**	**1.38**	**0.27**	**1.11**	**LB**
		1.38	**0.06**				
		1.46	**0.06**				
972.86	**MPC 10-4**	**1.21**	**0.09**	**1.18**	**0.2**	**0.98**	**LB**
		1.21	**0.08**				
		1.13	**0.08**				
974.23	**MPC 10-4**	**1.64**	**0.27**	**1.31**	**0.07**	**1.24**	**PB**
		1.11	**0.28**				
		1.19	**0.06**				
968.35	**MPC 10-4**	**13.44**	**0.57**	**13.68**	**0.38**	**13.30**	**GB**
		13.78	**0.59**				
		13.83	**0.57**				
977.46	**MPC 10-4**	**1.09**	**0.82**	**0.94**	**0.03**	**0.90**	**GB**
		0.86	**0.82**				
		0.86	**0.83**				

Table 3. Moisture equilibrated pressure decay permeability from the MPC 10-4 well. GB = graded silty mudstone lithofacies

Sample Location		***Pressure Decay***	***Facies***
Measured Depth	**Well**	**Permeability**	**Code**
meters		**(µD)**	
977.18	**MPC 10-4**	**0.0124**	**GB**
977.49	**MPC 10-4**	**0.0644**	**GB**

Table 4. Porosity and permeability from the Marine Tuscaloosa shale determined from routine core analysis. GB = graded silty mudstone lithofacies, PB = Pinstripe claystone lithofacies, LB = Lenticular claystone, lithofacies WB = wavy mudstone lithofacies.

Sample Location		***Routine Core Analysis***		***Facies***
Measured Depth	**Well**	**Porosity**	**Permeability**	**Code**
meters		**%**	**(μD)**	
967.50	**MPC 10-4**	**28.1**	**38,100**	**LB**
968.11	**MPC 10-4**	**24.9**	**5,430**	**WB**
968.78	**MPC 10-4**	**33.9**	**162,000**	**WB**
969.26	**MPC 10-4**	**27.0**	**7,590**	**PB**
970.07	**MPC 10-4**	**25.0**	**4,450**	**PB**
970.48	**MPC 10-4**	**25.8**	**17,200**	**PB**
971.09	**MPC 10-4**	**27.4**	**9,290**	**LB**
971.95	**MPC 10-4**	**26.9**	**11,200**	**LB**
972.31	**MPC 10-4**	**24.7**	**16,500**	**PB**
972.92	**MPC 10-4**	**24.2**	**12,200**	**LB**
973.74	**MPC 10-4**	**26.5**	**35,600**	**GB**
974.14	**MPC 10-4**	**23.8**	**6,990**	**PB**
975.41	**MPC 10-4**	**22.6**	**11,100**	**GB**
976.05	**MPC 10-4**	**23.1**	**544**	**GB**
977.39	**MPC 10-4**	**21.2**	**1,120**	**GB**

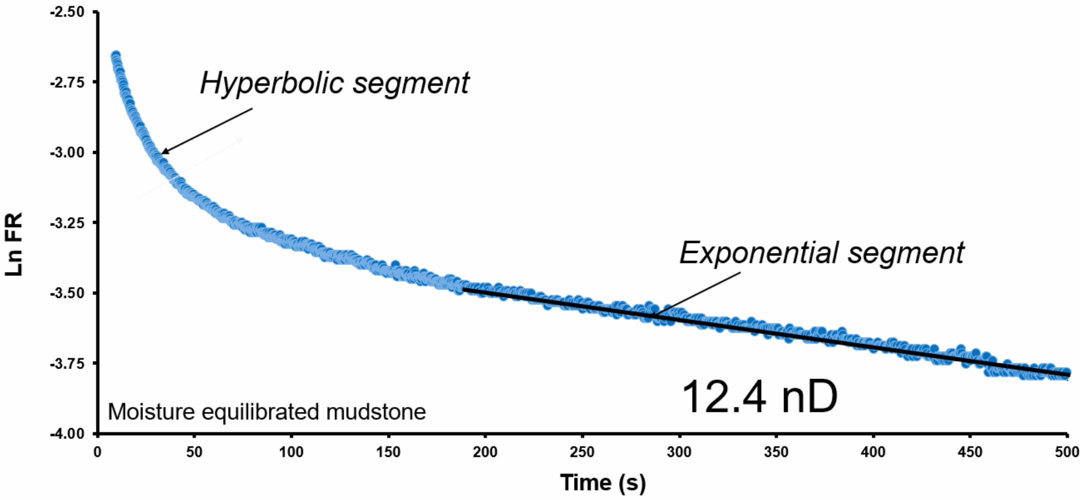


Figure 7. Moisture equilibrated pressure decay permeability from the graded silty mudstone lithofacies of the Marine Tuscaloosa shale (after Pashin et al.,2020).

Mudstone Fabric and Composition

The graded silty mudstone lithofacies of the Marine Tuscaloosa shale contains two distinct rock types; The lower portion is clayey mudstone (<50% clay), and the upper portion is silty claystone (>50% clay). The clayey mudstone contains clay laminae and sparse intraparticle porosity associated with partially dissolved feldspar and fractured quartz silt grains. The silty claystone locally is structureless and lacks visible pores, likely due to high clay content (Fig. 8A and B). Clay mineralogy in the clayey mudstone is 36.0% kaolinite, 6.2% illite, 1.3% smectite, and 1.6% chlorite and is accompanied by approximately 1% of authigenic pyrite an up to 1 % organic carbon (Table 1 and 2). The bioturbation index of the clayey mudstone and the silty claystone is 2 toward the base and 1 at the top. The dominant pore types within this facies are intraparticle (feldspar and mics) and intercrystalline (pyrite framboids) pores. In SEM images, pores are associated with pyrite cubes and framboids and also occur in organic matter and appear as small slits. (Fig. 8C and D). The silty to fine sand interbeds are the principal source of permeability (Table 4) and in general, the porosity and permeability is low within this facies.

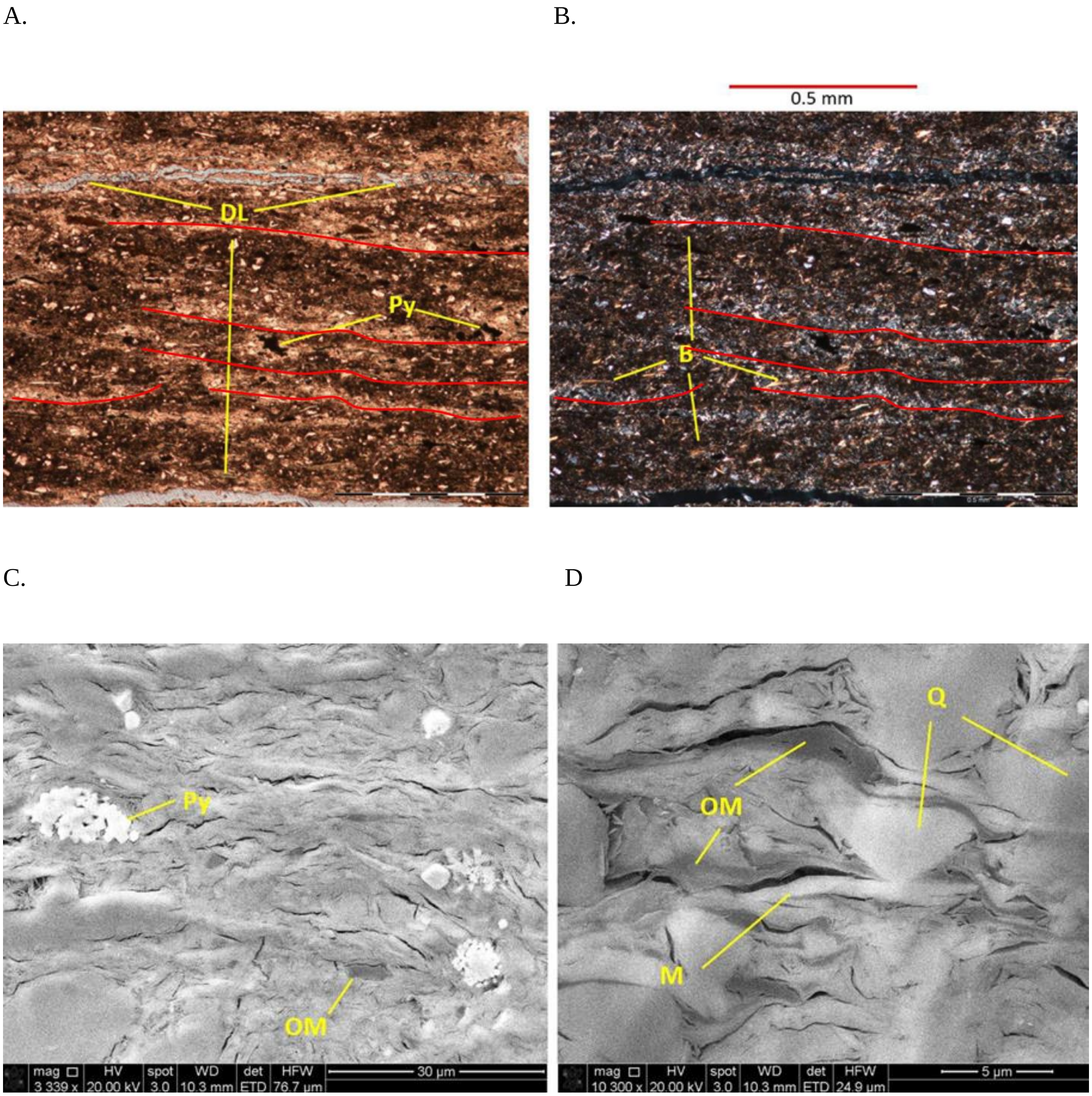


Figure 8. – Thin section photomicrographs and SEM images of the graded mudstone lithofacies from the MPC 10-4 well, 977.5 m (3206.9 ft). A) Silty claystone with clay-rich matrix and ripple

cross-laminae. Opaque minerals are pyrite (Py). B) Cross-polarized light thin section showing ripple cross-laminae and an abundance of biotite (B), which is as coarse as fine sand. Other grains include quartz and minor amounts of plagioclase, zircon, and glauconite. C) Clay-rich mudstone with pyrite (Py) famboids and cubes at different scales and associated intracrystalline porosity. Porosity slits in clay matrix is apparently artificial due to desiccation. D) Silt-size quartz, mica, and clay. Note slit pores from desication of the clay particles.

The pinstripe claystone lithofacies of the Marine Tuscaloosa shale is characterized as silty claystone. This facies contains approximately 54-62% clay minerals based on XRD results. The concentration of clay species ranges from 34-36% kaolinite, ≤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 1). This facies has pyrite content up to 2% and organic content up to 13.3% (Table 2), which are the highest values in any mudrock examined in this study. In thin section, the microfacies ranges from claystone with pinstripe and lenticular siltstone laminae to poorly bedded claystone with dispersed organic particles (Fig. 9A and B). This facies also contains a spinose palynomorph with intraparticle porosity (Fig. 9C and D). The pore system of this facies includes intercrystalline porosity in pyrite framboids and porosity in organic matter (Fig. 12).

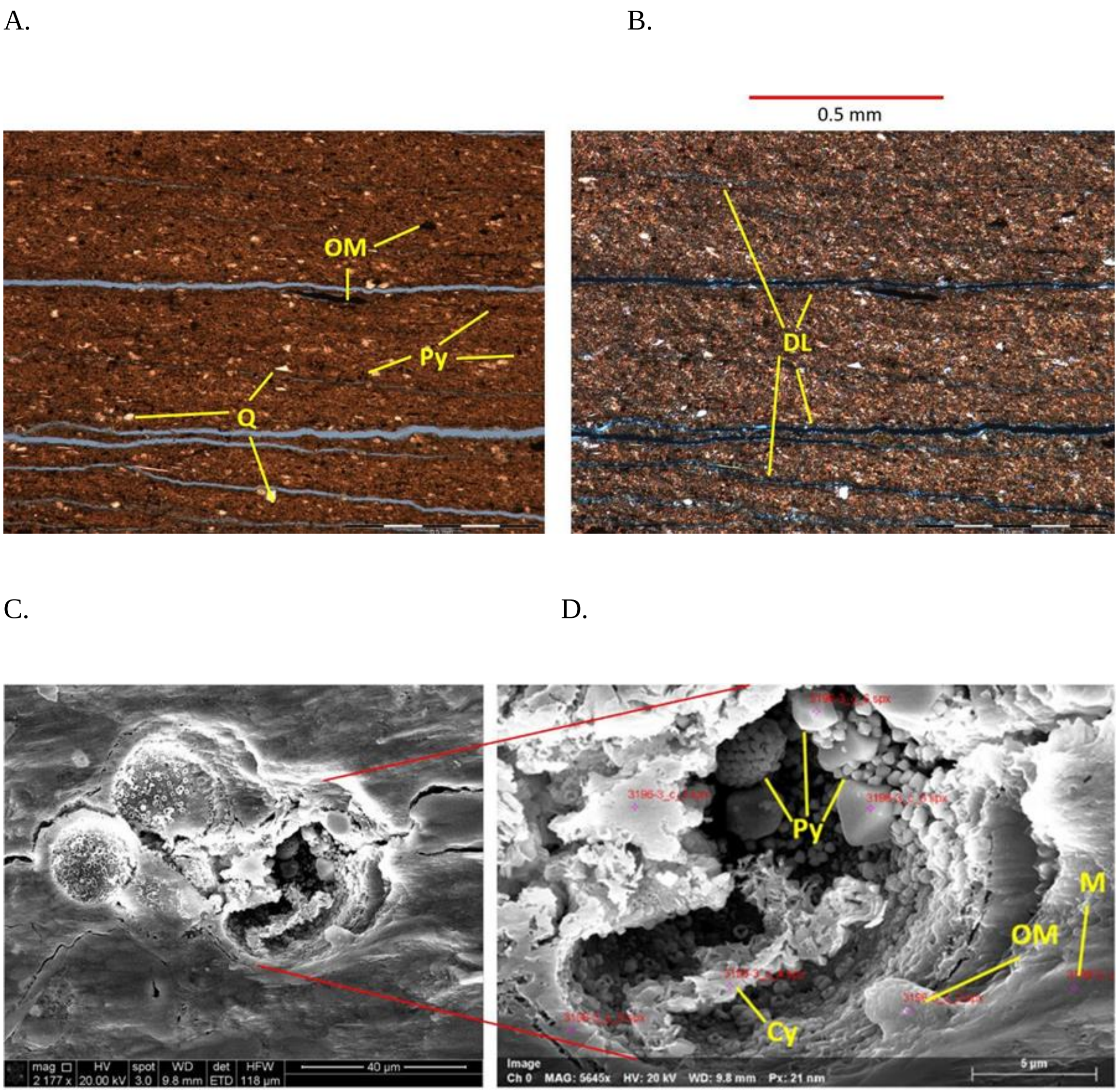


Figure 9. Thin section photomicrographs of the pinstripe claystone lithofacies of the Marine Tuscaloosa shale, MPC 10-4 well, 372 m (3188.8 ft). A) Plane polarized light image with abundant quartz silt (Q), rounded and platy organic matter (OM), and pyrite (Py). B) Thin section in cross-polarized light showing current ripple cross-strata. Argon ion miller SEM images of spinose palynomorph, in the MPC 10-4 well, 974.2 m (3196.3 ft). C) Sample showing a cluster of spinose palynomorphs. D) Inset of “C” showing authigenic pyrite (Py) and clay (Cy), along the internal margin of an organic-lined pore that defines the palynomorph (OM).

The lenticular claystone lithofacies of the Marine Tuscaloosa shale is a sandy claystone having clay content greater than 50% being composed of approximately 2% chlorite, 36% kaolinite, 17% mixed-layer illite-smectite, and 2% smectite (Table 1) and containing thin laminae and lenses of fine-grained sand. Accessory minerals include muscovite, biotite, glauconite, pyrite, and zircon. Organic matter is common in the clay matrix, making up approximately 1% of the rock (Table 2), and is preserved as spheroidal to elongate particles. There is no visible porosity within the clay matrix. The mudstone contains limited intergranular porosity within the fine sand and silt laminae (Fig. 10A and B).

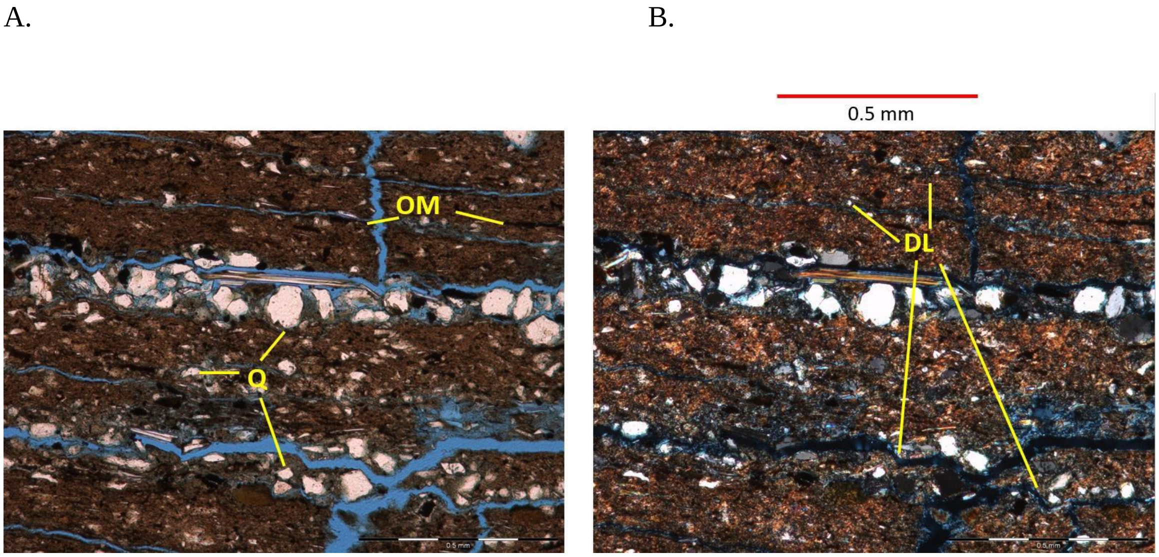


Figure 10. – Thin section images of the lenticular claystone lithofacies, Marine Tuscaloosa shale, MPC 10-4 well, 969 m (3178.4 ft). The mudstone is classified as sandy claystone with siltstone and sandstone laminae. A) Thin section image in plane polarized light of claystone containing quartz (Q) and organic particles (OM). Organic matter is dispersed in current ripple cross-laminae. B) Thin section in cross-polarized light that shows parting of the claystone along laminae (DL).

The wavy mudstone lithofacies ranges in composition between clayey siltstone and silty claystone. Clay content ranges from 31-51% and is dominantly kaolinite (20-36%) with trace amounts of pyrite and no detectable carbonate (Table 1). The mudstone contains parallel to subparallel laminae of coarse silt to very fine sand (Fig. 11A and B). Horizontal and vertical burrows are filled with coarse silt to fine sand and contain less clay than the adjacent mudstone. Overall, clay content decreases upward in section as bioturbation increases. Interparticle porosity was observed in thin section and is confined to silty laminae and burrows (Fig. 11A). Some intraparticle porosity exists in vacuolized feldspar grains. In SEM images, pores were observed in organic matter and between silicate grains. The organic pores are commonly filled partially with silt and clay (Figs. 11C and D). Interparticle porosity is the dominant pore type in this sample (Fig. 12).

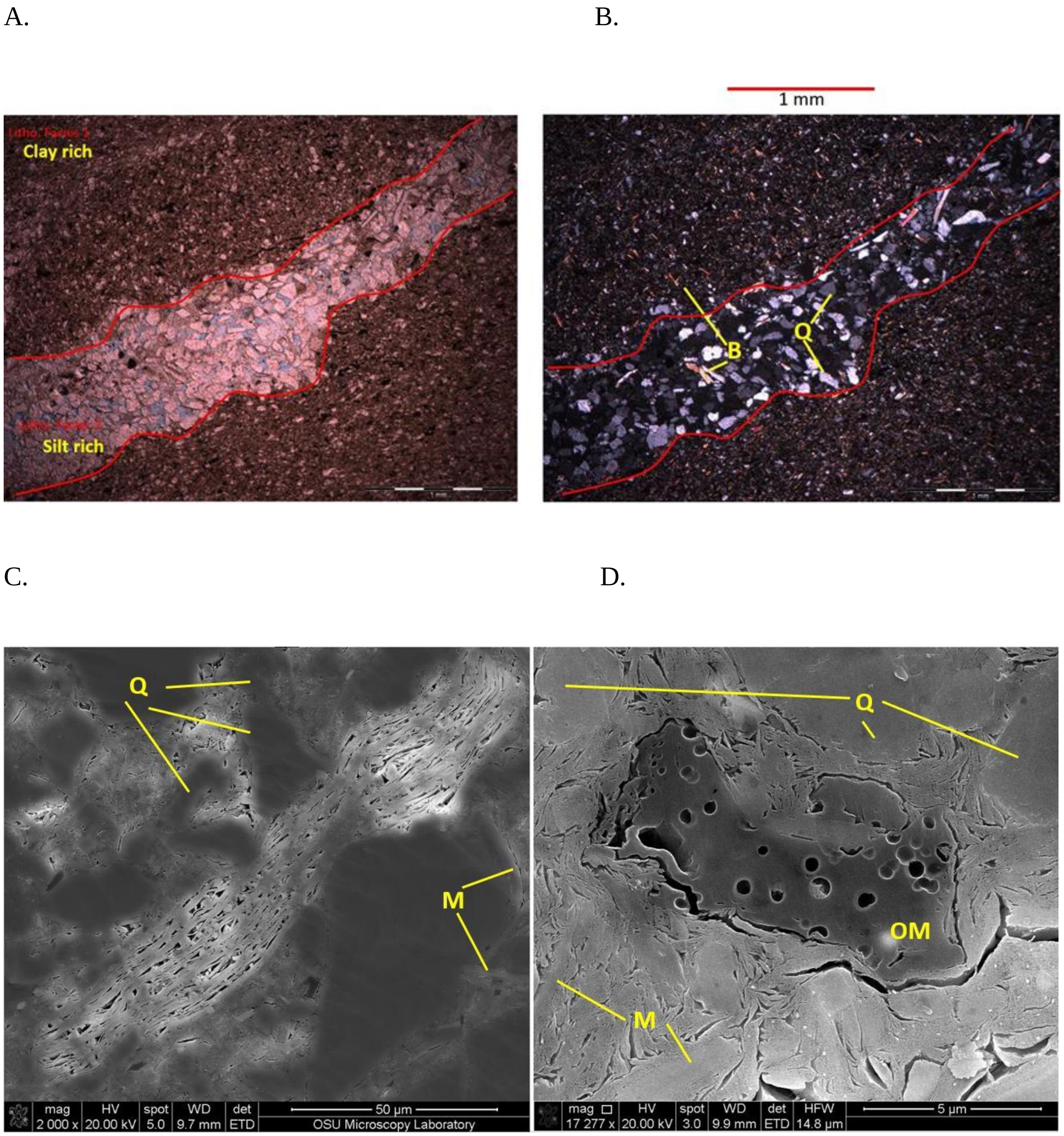


Figure 11. – Photomicrographs of the wavy mudstone lithofacies in the Marine Tuscaloosa shale, MPC 26-5 well, 1,093.8 m (3,588.6 ft). A) Plane polarized light thin section image showing clayey mudstone containing an irregular siltstone lamina with interparticle porosity. B) Cross-polarized image showing abundant silt to fine sand-size quartz (Q) and biotite (B) in the irregular siltstone lamina. SEM images of organic matter in the MPC 26-5 well, 1,094.5 m (3,590.5 ft). C)

Woody plant fragment with open cell lumens. D) Organic particle (OM) in clay, organic porosity forms subcircular vacuoles.

The Marine Tuscaloosa shale from the cored intervals generally contains silty claystone (Fig. 12A). Sand content and grain size generally increase upward in the shale, and porosity is concentrated in siltstone and sandstone interbeds. The visible pore types are varied with respect to facies and content of sand, silt, clay, and organic material with the wavy mudstone having mostly interparticle primary porosity, lenticular and graded lithofacies have pores within authigenic pyrite. The pinstripe claystone is dominantly claystone containing dispersed organic matter (Fig. 12).

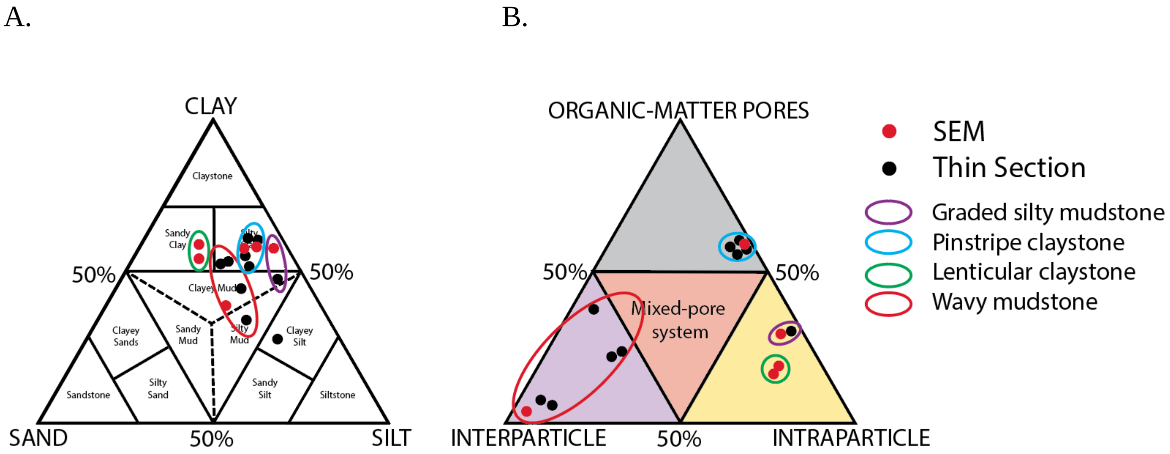


Figure 12. – Lithologic and pore system classification of the Marine Tuscaloosa shale at the Kemper County energy facility. A) Lithologic classification based on grain size. B) Pore system analysis showing variation of pore type in mudstone. Fissure pores related to sample desiccation were excluded from analysis.

Discussion

Depositional Environments

The base of the Tuscaloosa Group is a regional disconformity that marks the beginning of a major marine transgression during the Late Cretaceous (Cenomanian) (e.g., Mancini et al, 1987; Petty, 1997; Mancini and Puckette, 2003). The Massive sand of the lower Tuscaloosa Group is interpreted to include fluvial and tidally influenced marginal-marine strata (Mancini et al., 1987; Raymond and Pashin, 2005). The conglomerate and sandstone that forms the bulk of the Massive sand at the Kemper County energy facility has been interpreted as a bedload-dominated fluvial deposit, and the sandstone and mudstone in the upper part of the Massive sand has been interpreted as a marginal marine deposit (Urban, 2020; Pashin et al., 2020).

The Marine Tuscaloosa shale is a regionally extensive marine deposit that has historically been interpreted to represent the establishment of prodeltaic and shelf environments near the Cenomanian-Turonian boundary (Mancini et. al, 1987; Mancini et al., 1996; Petty, 1997; Mancini and Puckett, 2003; Lowery et al., 2017). The Marine shale in the MPC 26-5 core (Fig. 5) is from the basal part of the unit and is interpreted as a transgressive deposit that is effectively in facies relationship with the uppermost part of the Massive sand. The weakly radioactive marker that was used as a datum for the stratigraphic cross section (Fig. 4) is interpreted as a condensed section similar to that identified by Mancini et al. (1996), which records marine flooding of the region as the rate of marine transgression approached a maximum. The clinoform portion of the Marine shale, by contrast, records an increase in sedimentation rate and progradation of sediment into the basin during a relative highstand of sea level; this is reflected in the overall coarsening upward of the section in the MPC 10-4 core. The horizontally laminated glauconitic sandstone at the top of the MPC 10-4 core has been interpreted as a beach or shoreface deposit at the top of the Marine Tuscaloosa shale (Pashin et al., 2020), and the height of the clinoforms indicates that, while the northeastern part of the study area was at or near the shoreline, water depth in the southwestern part of the study area was greater than 55 m. The top of the clinoform section is interpreted as a lowstand surface, and the onlapping portion of the Marine shale records a subsequent marine transgression during which the area around the energy facility was filled with sediment to sea level. Upper Tuscaloosa deposits at the energy facility are dominated by sandstone interpreted as fluvial deposits and red mudstone interpreted as interfluvial paleosols (Pashin et al., 2021). These deposits signify terrestrialization of the region during a late Cenomanian - Turonian highstand and the establishment of coastal plain depositional environments that were similar to those that prevailed during Early Cretaceous (Albian) Washita-Fredericksburg deposition.

Lithofacies at the Kemper County energy facility give insight into depositional processes and environments during Marine Tuscaloosa deposition. The overall facies succession in the MPC 10-4 core progresses from the graded muddy siltstone to the pinstripe claystone to the lenticular claystone and then the wavy mudstone, which is capped by glauconitic sandstone (Fig. 5). The facies association of pinstripe, lenticular, wavy, and laminated siltstone-sandstone beds are characteristic of tidal environments and demonstrates an overall shoaling upward succession (Reineck and Sing, 2012). Current ripple cross-laminae in these deposits appear unidirectional (Fig. 8), indicating deposition by a dominant tidal current. The graded muddy siltstone lithofacies is interpreted to represent subtidal storm deposits or other types of event beds formed with episodic currents. The sand and silt loaded less dense and fluid argillaceous sediment, resulting in soft-sediment deformation (Fig. 6A). The fine grain size and grading indicate that sedimentation was principally by suspension settling after major flow events.

Overlying the graded muddy siltstone is the pinstripe claystone lithofacies, which contains claystone with fine silt horizontal laminae. These rhythmic laminae are typical of tidal rhythmites (Kvale et al., 1989; Kvale, 2012). The rhythmic strata are dominated by thin laminae of silt and sand overlain by ripple cross-laminated claystone and mudstone (Fig. 9). This texture indicates that the mudstone layers formed principally by ripple migration, which is common in what appears in hand sample as laminated shale (Schieber, 1994; Schieber et al., 1998). The pinstripe claystone facies apparently formed shoreward of the graded muddy siltstone, and the absence of desiccation cracks and root structures suggests it is a subtidal or lower intertidal facies.

The pinstripe claystone lithofacies grades into the lenticular claystone lithofacies and the wavy mudstone lithofacies. The lenticular claystone facies contains concentrations of disarticulated marine shell fragments, which are interpreted to have been deposited by storms and tidal currents. The abundant lenticular and wavy bedding in these facies, along with burrows and shell fragments, is typical of tidal flat deposits and was probably deposited in the intertidal zone (van Straaten, 1954; Klein, 1977; Reineck and Singh, 2012; Daidu, 2013). The glauconitic sandstone that caps the MPC 10-4 core is interpreted as a beach-shoreface deposit, and the Marine Tuscaloosa shoreline appears to be part of a tide-dominated coastal system with crescentic beach-barrier systems, which is typical of mesotidal shorelines around the world (e.g., Coleman and Wright, 1975; Reineck and Singh, 2012; Goodbred and Saito, 2012).

Implications for sealing Strata

The Marine Tuscaloosa shale was evaluated for its potential as a regionally extensive seal for the carbon storage complex at the Kemper County energy facility, and is the mudstone section that was studied in greatest detail. The Marine shale at the energy contains a complex succession of mudstone, siltstone, and sandstone. The shale is the product of an initial marine transgression that began during Cenomanian time with lower Tuscaloosa deposition, a weakly to moderately radioactive condensed section near the Cenomanian-Turonian boundary, a clinoform progradational succession that thins southwestward and records a relative highstand, and a late-stage transgressive succession that onlaps the clinoform strata (Fig. 4). A subsequent highstand culminated in terrestrialization of the region and the deposition of upper Tuscaloosa redbeds. The complex interlayering of mudstone, siltstone and sandstone in the Marine shale at the energy facility stands in stark contrast to the thick mudstone deeper in the basin that is a proven reservoir seal (Galicki et al., 1986; Mancini et al., 1987; Koperna et al., 2009).

The MPC 26-5 core is from part of the basal transgressive succession, whereas the MPC 10-4 core is from the upper part of the highstand succession. Both cores contain interbedded mudstone, siltstone, and sandstone (Fig. 5), and geophysical well logs indicate that sandstone deposited at the toe of the clinoforms is locally present within only 5 m of the condensed section (Fig. 4). The mudstone is rich in clay, and the pore system is largely poorly interconnected intraparticle porosity. The four mudstone facies in the MPC 10-4 core are associated with a general upward increase in silt and sand content, intraclast frequency, and bioturbation index, reflecting a transition from offshore to tidally dominated shore-zone environments. Organic carbon content displays a general inverse relationship to the intensity of bioturbation, and organic matter and clay surfaces provide adsorption sites for fugitive CO_2.

The pressure decay permeability values of 12 and 64 nD are comparable to those performed in the Paluxy Formation and Washita-Fredericksburg interval by Stratum Reservoir (Wethington et al., 2022) and thus appear representative of Cretaceous mudrocks in the study area. Routine analysis of core plugs with silty to sandy interbeds indicates permeability of 0.5-162.0 mD, indicating that the siltstone and sandstone layers have the ability to conduct fluid. The desiccation fissures observed in SEM likely further affected routine core analysis. These results indicate that the mudstone layers have extremely low permeability and impede cross-stratal flow, whereas the siltstone-sandstone layers are capable of conducting flow parallel to bedding. This indicates that the behavior of the Marine Tuscaloosa shale at the Kemper County energy facility as a confining interval is complex and warrants more advanced study.

Paluxy and Washita-Fredericksburg strata form a subsurface sediment wedge that is confined in large part by the mudstone in the upper part of the Washita-Fredericksburg interval (Fig. 3), and thus contains the highest priority injection targets at the Kemper County energy facility. The Massive sand of the Lower Tuscaloosa Group contains only 13% (183 Mt) of the storage resource at the energy facility (Urban, 2020; Pashin et al.., 2020) and contains fresh water to the northeast, where it receives fresh water recharge (Pashin et al., 2008), making it a lower priority objective for storage. Wethington et al. (2022) found that injection in the Paluxy Formation and Washita-Fredericksburg interval would result in no more than minor amounts of fugitive CO_2 reaching the lower Tuscaloosa Group and the Marine shale. Therefore, any fugitive CO_2 reaching the Marine shale would likely be adsorbed in mudstone or absorbed by the siltstone-sandstone layers. The widespread mudstone at the base of the upper Tuscaloosa Group (Fig. 4), moreover, provides an added layer of protection that ensures little if any CO_2 would migrate out of the storage complex and that USDWs are protected.

Conclusions

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 Gt. There are no apparent escape mechanisms, such as faults that breach barriers and seals. The priority reservoirs within the storage complex are the Paluxy Formation and the Big Fred sand in the Washita-Fredericksburg interval that contain numerous mudstone baffles and barriers that help confine CO_2 in the injection zones. This depositional architecture reduces the likelihood of fugitive CO_2 impinging on the Marine Tuscaloosa shale, which intervenes between the storage and shallower confining units protecting the USDWs. The major marine transgressive surface is a regionally extensive marine shale that was deposited during a globally recorded event that is clay rich with interbedded sandstone. The Marine Tuscaloosa shale is a thick mudstone deposit that approaches 75 m (238 ft) thick and records the aggregation of 10s of meters of continuous mudstone and claystone interbeds that are regionally correlatable across the broader Mississippi embayment. The claystone interbeds have a permeability on the order of 10-100 nD and are continuous across the region. Internally the sandstone beds are potentially laterally conductive but lack significant cross-stratal connectivity that would have a detrimental impact on seal quality. However, more research is required to understand the performance of the storage complex through flow simulations in each of the proposed reservoirs and comprehensive well testing as the site continues to be developed. The Kemper County energy facility is situated atop a world-class CO_2 storage complex that has significant potential for generational learning about storage technology and operations.

CHAPTER IV

BAFFLES, BARRIERS, AND SEALS: CLASSIFICATION OF MUDSTONE CONFINING LAYERS FOR CARBON STORAGE

Abstract

A classification of confining layers composed of siliciclastic mudstone was developed to fill a need for more effective characterization of geologic CO_2 storage opportunities. Limited research on mudstone confining beds in carbon capture and sequestration (CCS) systems has been published, and no consistent definition of the scaling relationships of mudstone deposits exists. The extent of effective confining layers is directly proportional to the total volume of CO_2 injected, reservoir extent and architecture, and plume geometry. Seals are typically thick confining intervals of regional to interregional extent that define the upper boundaries of storage complexes. At a minimum, an effective seal must exceed the lateral extent of a CO_2 storage complex by a large margin to minimize the risk of injectant migrating into underground sources of drinking water. Within a storage complex, laterally extensive barriers have the ability to impede cross-formational migration of CO_2 by bounding individual or stacked plumes. Intraformational baffles, by contrast, have limited thickness and continuity but are an important component of reservoir heterogeneity that increases reservoir efficiency by helping concentrate CO_2 within buoyant plumes.

Integration of seismic reflection surveys, geophysical well logs, and core analyses facilitates characterization of confining intervals at high resolution within prospective CO_2 storage complexes. Seismic reflection data provide primary control on the lateral continuity of bedding, and thus the lateral extent and heterogeneity of reservoir strata and confining strata; therefore, seismic data in combination with other geological data are key to delineating a candidate storage complex. Well logs are instrumental for correlating reservoirs and confining beds, characterizing lateral heterogeneity, and quantifying fundamental reservoir parameters, such as porosity. Core analysis is important for characterizing the depositional framework of reservoirs and confining beds, as well as determining properties such as permeability and fluid saturation. Thin section and SEM petrology facilitates facies classification, pore typing, and x-ray diffraction and x-ray fluorescence are critical for mineral identification and quantification of clay minerals in confining layers. This conceptual classification and approach has broad utility for site screening and development. Indeed, CCS prospecting and development must incorporate a range of scales of investigation to successfully deploy technology and manage risk.

Introduction:

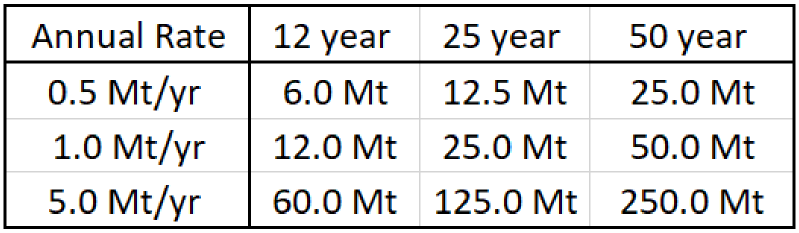
Efforts to reduce CO_2 emissions necessitate the safe implementation of subsurface geologic storage over the next century (Jackson et al., 2017, Middleton et al., 2020). A critical concern is the efficacy of long-term sequestration projects and the potential for migration of CO_2 out of storage complexes, posing risk to underground sources of drinking water and soil (Le et al,. 2010). To meet and exceed expectation, the CCS community must recognize gaps in understanding of how a large volume of injected CO_2 (>1 Mt) will behave over half a century or longer and whether a given industrial or hub-scale injection program can be performed safely (Pruess and Nordbotten, 2011). To understand and predict how a plume will evolve over the life of a project, including post-injection plume stabilization, there must first be an understanding of the depositional architecture of the reservoirs and confining beds that define the storage complex.

Current approaches utilize gridded, geocellular, and meshed simulations that give insight into plume migration, shape, and ultimate trapping mechanism for CO_2 (Bandilla et al., 2014). A degree of uncertainty exists about the ability to delineate and characterize single and stacked storage opportunities that accurately reflect the geology of a storage complex and ultimately control fluid flow. Large reservoirs (>100 km^2) with permeability on the order of 100->1,000 mD are premium objectives for sequestration, but diligence is commonly incomplete in defining and characterizing non-reservoir rock types, such as mudstone, that are a key source of heterogeneity that affects injectivity, reservoir efficiency, and plume morphology (Shukla et al., 2010).

There is no widely used classification terminology for mudstone beds based on thickness and spatial distribution that provides a common language for the evaluation of confining layers in geologic storage complexes and petroleum reservoirs, although a useful classification was described by Wethington et al. (2022) for a Cretaceous storage complex in the Gulf of Mexico coastal plain. Confinement must account for the total volume of injectant over the life of a project and can be determined based on an annual injection rate and the number of years of injection. In the USA, for example, the smallest injection programs taking full advantage of 45Q tax credits at a point source facility are currently 0.5Mt/yr over a 12-yr claim period, which equates to 6 Mt of CO_2 injected. At the other end of the scale, an industrial facility injecting 1 Mt/yr, or hub facility injecting 5 Mt/yr over 12-50 years, yields a range of 12-250 Mt of CO_2 that must be stored and monitored (Table 1). An important unknown is how commercial storage programs will perform relative to pre-injection assessments of storage resource, capacity, and reservoir simulation results.

The classification of mudstone confining beds used in this paper identifies and categorizes mudstone confinement in a way that integrates multiple scales of data acquisition, mudstone facies variability, stabilized post-injection plume geometry, and CO_2 migration. Heirarchical classification of confining layers into baffles, barriers, and seals is intended to assist in carbon sequestration prospecting at the basin and storage complex scales. This system incorporates a common language that can be shared among geologists, reservoir modelers, and engineers to help promote consistent communication and application of best practices. The method applied utilizes the scopes, and scales of investigation, and data resolution to characterize confinement when defining and determining the behavior of storage complexes.

Table 1. Volume of CO_2 intended to be sequestered over the life cycle of an injection program based on annual rate and duration of injection program.



Annual Rate	12 year	25 year	50 year
0.5 Mt/yr	6.0 Mt	12.5 Mt	25.0 Mt
1.0 Mt/yr	12.0 Mt	25.0 Mt	50.0 Mt
5.0 Mt/yr	60.0 Mt	125.0 Mt	250.0 Mt

Classically described Mudstone and Seals:

Mudstone is a loose term that describes a spectrum fine-grained sedimentary rocks, such as claystone, shale, argillaceous siltstone, micrite, etc., which contain varying amounts of clay, silica, and carbonate (Dunham, 1962; Macquaker, 2003; Loucks et al., 2012; Miliken, 2014). Siliciclastic mudstone is composed of a mixture of clay, silt, and sand grains and usually contains some amount of carbonate, organic carbon, and a range of organic, calcareous, and phosphatic fossils (Lazar et al., 2015). Mudrocks are generally matrix-supported and susceptible to mechanical and chemical compaction; they therefore have lower porosity and permeability than traditional sandstone and carbonate reservoir strata (Milliken and Day-Stirrat, 2013). Mudstone can form in a very broad range of depositional environments, and large volumes of mudstone are associated with soil profiles, interfluvial deposits, lacustrine deposits, and marine deposits.

Mudstone quality includes limiting capacity (i.e., permeability) and failure point to retain a given amount of buoyant CO_2 that impinges on a confining bed; this can be quantified by the maximum column height (h_{max}) of buoyant CO_2. Equation 1, shows that maximum column height is directly proportional to the difference of the threshold pressure of the seal (Pth) and the reservoir (P_{thres}) and is inversely proportional to the difference in formation water density (ρ_{fw}) and CO_2 density (ρ_{CO2}) multiplied by hydrostatic pressure gradient (P_h; 0.43->0.50 psi/ft), which varies as a function of brine saturation and hydraulic setting (Kivor et al., 2002)**,**

$$h_{max} = (P_{th} – P_{thres}) / ((\rho_{fw} – \rho_{CO2}) * P_h) \quad (1)$$

Equation 1. Critical height of bouyant CO_2 and threshold pressure of a geologic seal (after Kivor et al., 2002).

Capillary entry pressure measurements can be used to determine threshold pressure (P_{th}). When the buoyancy pressure of CO_2 is greater than the capillary entry pressure of a mudstone, CO_2 has the ability to enter the mudstone. Where buoyancy pressure is greater than threshold pressure, cross-formational migration of CO_2 can occur. Therefore, the column height of CO_2 must exert a force less than the capillary entry pressure at least in the upper part of the confining bed to maintain seal integrity.

A seal also is defined by its ability to areally confine an injectant, and reservoir seals have classically been characterized as at least as laterally extensive as the confined oil and gas accumulations (Aplin and Macquaker, 2011). An effective seal lacks transmissive faults and fractures and confines reservoirs over geologic time (Knott, 1993; Shukla et al., 2010; Meng et al., 2020). These criteria underscore the importance of seal thickness, areal extent, and location of potential spillpoints relative to plume geometry. Thickness, continuity, and areal extent are all factors determined in the original depositional system and modified by penecontemporaneous or subsequent faulting, fracturing and diagenesis. Analysis of depositional systems in the Gippsland Basin in Australia was used to determine CO_2 storage potential and gives insight into the scale of confinement provided by various depositional systems (Figures 1 and 2) (Root, 2007). The thickest and most continuous mudstone units include lacustrine, back-barrier lagoon, tidal flat, and prodelta deposits (Figure 1). The most areally extensive mudstone deposits also correlate with seal quality from calculated threshold pressure (Figure 2) and implies that widespread mudstone depositional environments provide for significant mudstone accumulation both vertically and laterally.

Confinement by mudstone can be assessed from many quality parameters such as bulk composition, mineral content, texture, ductility, and membrane capacity, but also need to integrate mudstone geometry across an area of interest and the likelihood of areal coverage sufficient to confine CO_2 within a storage complex. A mudstone of subseal quality or areal extent and continuity should be termed a barrier that has the ability to impede vertical hydrologic connectivity, resulting in vertical and potentially lateral compartmentalization of the storage complex (Bonab et al., 2014; Wethington et al., 2022). Barriers can be thick and widespread enough to be considered a definable geologic unit, leaving discontinuous intraformational mudstone layers within the reservoir to be termed baffles. In essence, baffles affect fluid flow within a reservoir and are an important component of reservoir heterogeneity.

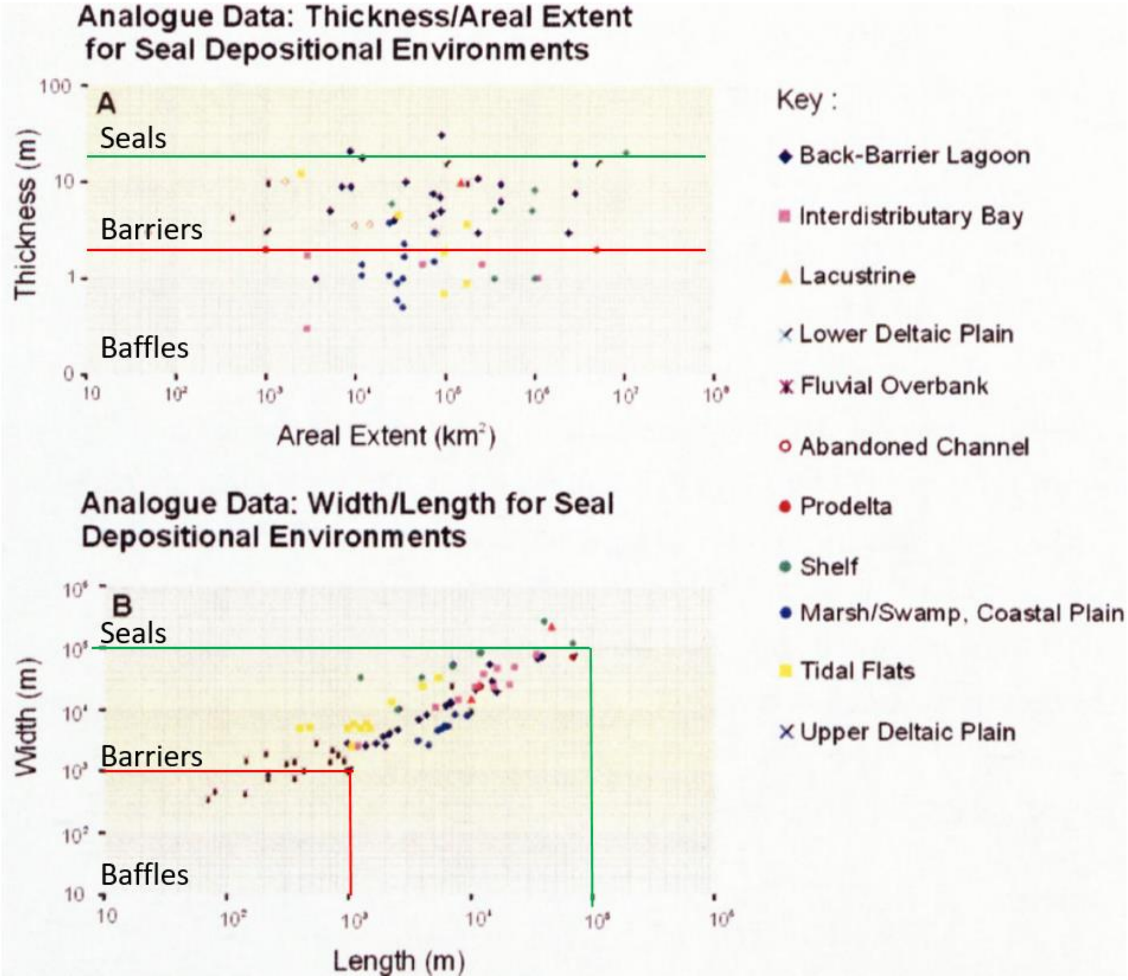
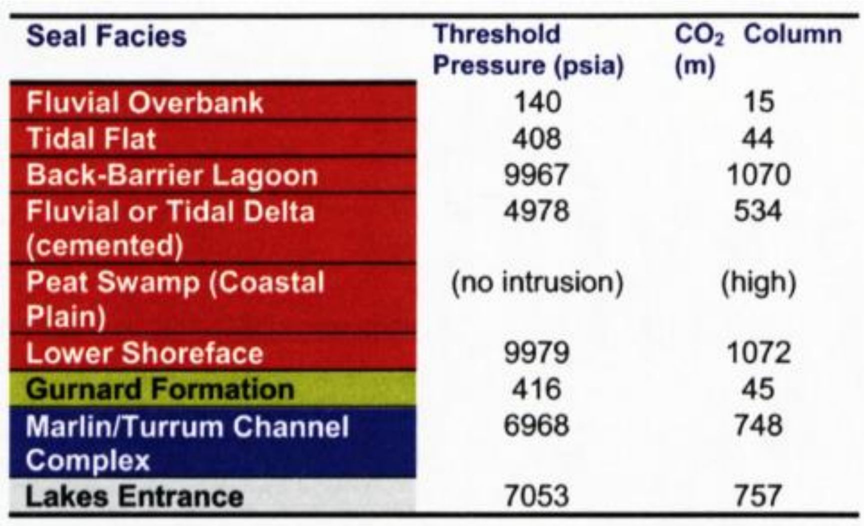


Figure 1. A) Mudstone thickness with respect to depositional environemnt. B) Mudstone length and width parameters of different depositional environments (after Root, 2007).



Seal Facies	Threshold Pressure (psia)	CO_2 Column (m)
Fluvial Overbank	140	15
Tidal Flat	408	44
Back-Barrier Lagoon	9967	1070
Fluvial or Tidal Delta (cemented)	4978	534
Peat Swamp (Coastal Plain)	(no intrusion)	(high)
Lower Shoreface	9979	1072
Gurnard Formation	416	45
Marlin/Turrum Channel Complex	6968	748
Lakes Entrance	7053	757

Figure 2. Column heigth of differned mudstone depostional envornments in Gippsland, Australia (after Root, 2007).

Material and Methods

A hierarchal classification of mudstone beds as confining units was composed on the bases of the sealing and confinement potential of a mudstone layer is ultimately defined by the size of the storage complex and the total amount of CO_2 to be stored. The total volume of CO_2 is therefore defined by the annual storage rate of CO_2 and the life cycle of the injection program.

Storage complex identification and characterization is limited by the resolution of the data available to constrain the reservoir architecture, which is a direct reflection of the depositional system and structural evolution. Data types that can be used include a combination of seismic surveys, outcrop data, geophysical well logs, cuttings, and core analyses, each of which have their own benefits and limitations for characterization. Accordingly, an integrative approach forms the foundation for this classification. A hierarchy based on orders of magnitude of scale can be utilized that employs core evaluation at lamina and bed resolution (~1 cm-10 m) and well log analysis, which has resolution of approximately 2.5 ft (0.8 m). Well penetrations are basic control points that can be at 40-acre (1,320 ft; 402 m) or closer spacing, which is common in oil fields, or greater than 1 mi spacing, which is common in natural gas fields and CO_2 storage programs. Most geophysical logging programs provide SP, resistivity, gamma ray, density, and neutron logs for interpretation. The coarsest data sets are from wildcat wells in frontier exploration areas. Seismic lines typically have vertical resolution of 30-60 ft (quarter wavelet). Each of these scales of investigation affects the ability to characterize and define potential containment, reservoir capacity, and plume geometry.

The classification divides confining mudstone units into three basic categories based on observations that can be made from analysis of cores, geophysical well logs, and seismic data: 1) baffles, 2) barriers, and 3) seals. The concept of hierarchal and scaling relationship of mudstones and implied confinement is based on observations at the Kemper County energy facility, a proposed regional storage hub in the Gulf of Mexico coastal plain in Mississippi (Wethington, 2020; Wethington et al., 2022), and this paper also uses relevant examples from the literature that illustrate key points. Analytical techniques include analysis of texture and composition in hand sample, thin section, scanning electron (SEM) microscope images, and x-ray diffraction (XRD). Geophysical well logs, and particularly gamma-ray logs, were used to identify and determine the thickness of mudstone, and correlation of well logs was used to assess lateral extent. Seismic data were used to assist in the identification of barriers and seals and determining thickness and lateral extent.

Classification

Measurements of bed thickness and lateral extent tend to form log-normal statistical populations regardless of rock type (e.g., Sylvester, 2007; Eide et al., 2014), and thus provides a natural basis for recognition of baffles, barriers, and seals based on orders of magnitude of bed thickness and continuity. Baffles were identified in cores and well logs and have gamma count higher than 75

API units. Baffles are less than 10 ft (3 m) thick, and can form single or composite beds that are internally bedded and laminated. Barriers were identified in hand sample and well logs and characterized in thin section, SEM, and XRD. They have elevated gamma count (>75 API units) and thickness ranging from 10-100 ft (3-30 m), and thus can be characterized using well logs and more imprecisely using seismic data. Barriers can be correlated among wells and can have similar geophysical well log patterns; they commonly extend laterally >10 mi (16 km). Seals are continuous mudstone deposits that are thicker than 100 ft (30 m) and can in places approach 1,000 ft (300 m) in thickness. Seals can be identified in core, well logs, and seismic surveys.

Baffles:

Mudstone baffles are typically thinner than 10 ft (3 m) and can constitute laminae to very thick beds of mudstone; they can be identified in cores (Figure 3) and geophysical well logs. Baffles characteristically lack clear continuity and so correlating baffles among wells regardless of spacing is commonly uncertain (Figure 4). The areal extent of baffling mudstone layers is typically on the order of 100 to 1,000,000 ft^2 (0.002-23 acres), thus baffles can be considered as a key component of interwell heterogeneity. Baffling mudstone can be sandy and silty, having variable clay content, and typically has permeability between 10 nD and 10 µD. Determining the areal extent of baffles is limited by the resolution of well control, and baffles are typically subseismic features. Analogs of discontinuous mud layers from corresponding depositional systems arguably follow a log normal distribution (Figure 5) and can be used to scale baffles for gridded, meshed, or geocellular reservoir simulations. Areal extent and stratigraphic distribution also can be interpreted based on statistical analysis of the vertical frequency per unit area in a set of correlated well logs.

Baffles can locally help confine and impede the growth of a CO_2 plume and can contribute positively to reservoir efficiency. Baffles locally impede vertical coning and pancaking, leading to increased primary and residual saturation of CO_2 below the mudstone layers, thereby allowing more of the plume to contact the reservoir. Intraformational mudstone baffles can form in a broad range of fluvial, interfluvial, and marine depositional environments, including paleosols, flood-basin and bayfill deposits, crevasse splays, muddy channel lags and plugs, and can include muddy drapes within and between sand sheets and sandy bedforms (Figure 6) (Stanistreet and Stollhofen, 2002; Wilson et al., 2013; Schneider et al., 2021; Jonk et al., 2022; Wethington et al, 2022).

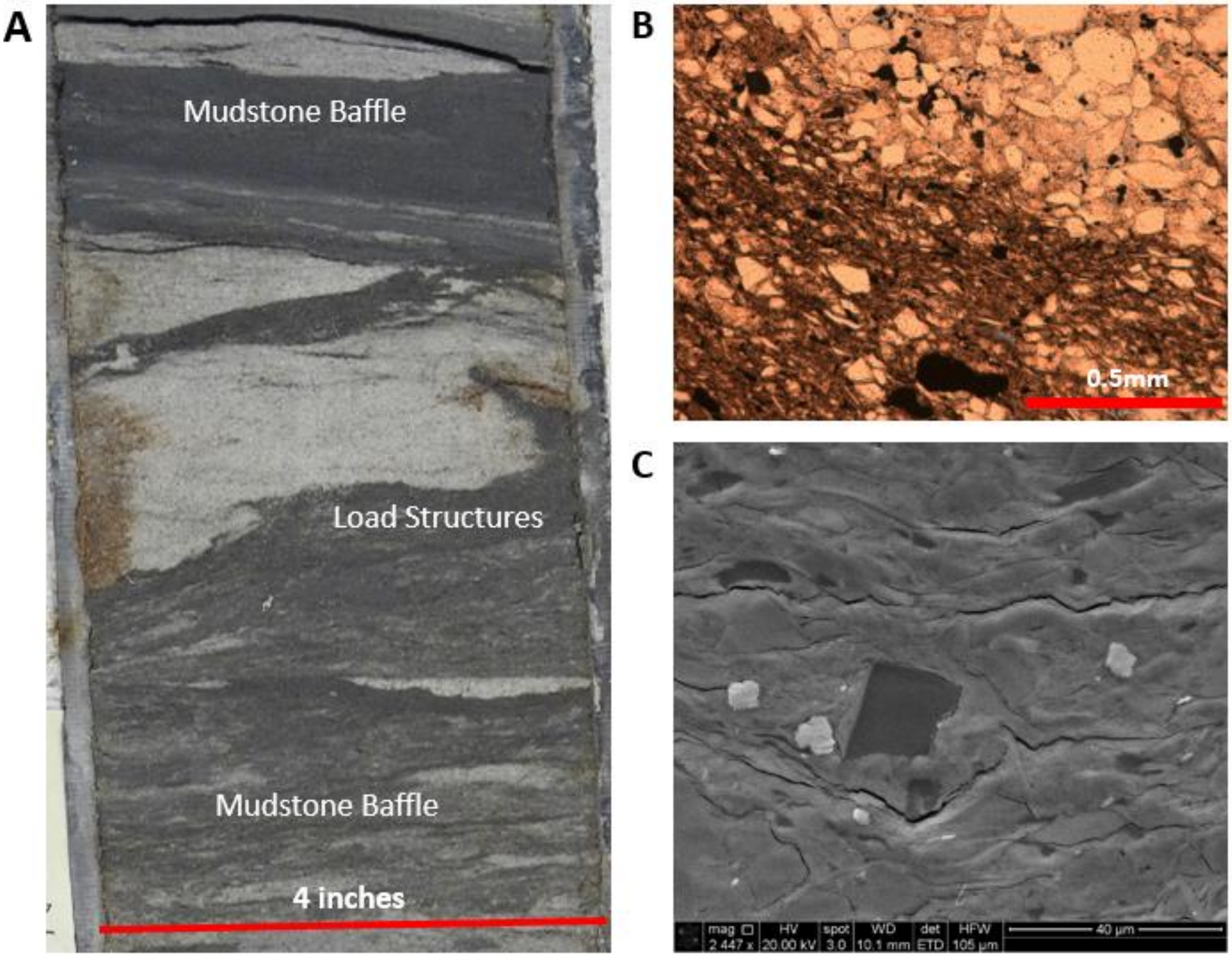


Figure 3. Fluvial heterolithioc mudstone baffle interpreted to be a fluvial sheet flood deposit imaged in core, thin section and SEM (after Wethington et al., 2022).

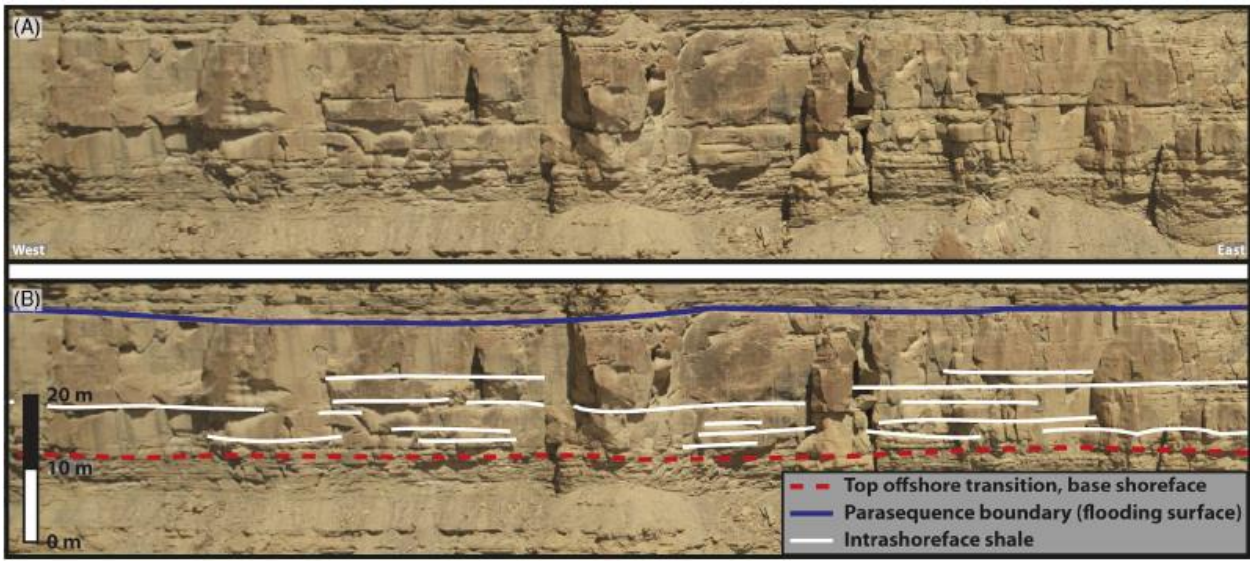


Figure 4. A. Uninterpreted and B. interpreted photograph showing mudstone baffles within a shallow wave-dominated marine shoreline sandstone. Note the lateral discontinuity of the shale layers (white) (after Eide et al., 2014).

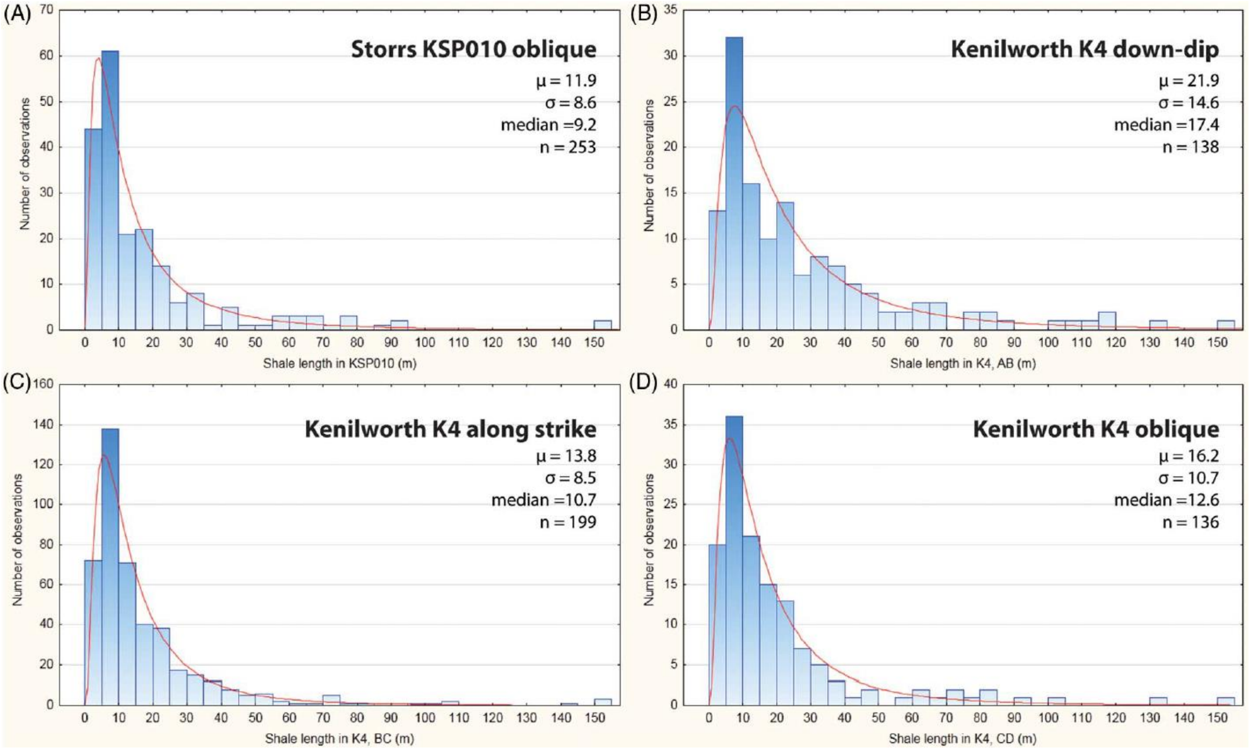


Figure 5. Log-normal distribution of mudstone length defining baffles being laterally discontinuous mudstones, from a shallow marine wave dominated sandstone (after Eide et al., 2014).

Barriers:

Mudstone barrier thickness is typically on the order of 10-100 ft (3-30 m) and thus constitutes very thick, or massive beds. Barriers are laterally continuous and can be correlated among multiple wells. Barriers are readily recognized in cores, geophysical well logs, and thick barriers may be imaged in seismic surveys. Barriers are laterally extensive, covering on the order of 10 to >100 mi^2. As in baffles, mudstone in barriers can contain variable amounts of sand, silt, and clay and are a reflection of depositional environment and tectonic history (Figure 6). Common depositional environments include a broad range of alluvial plain, interfluvial, lacustrine, back-barrier, deltaic, and shelf settings (MacDonald and Halland, 1993; McCarthy et al., 1997; Andsbjerg, 2004; Johnson and Graham, 2004; Plint, 2014; Pashin et al., 2020; Wethington et al., 2022). Mudstone barriers can be internally heterogeneous, and so permeability within these units can vary from ~10 nD to 100 µD, reflecting internal variation of rock type, bedding, and sedimentary structure (Figure 7).

Barriers can be significant sources of heterogeneity in a storage complex and commonly separate stacked reservoirs (Figure 8). The defining qualification of a barrier is the potential to significantly affect the migration and geometry of a CO_2 plume and impede cross-formational flow across a significant area. Barriers also lack the ability to provide confinement across a CO_2 storage complex because of incomplete areal coverage or insufficient permeability and capillary properties. Barriers are more robust than baffles, which are a component of heterogeneity that affects storage efficiency, but do not qualify as seals, which can confine large volumes of fluids over large areas. Rather, barriers help define individual reservoir and confining objectives within a storage complex but do not provide the sealing capacity that gives confidence that underground sources of drinking water are sufficiently protected from migration of fugitive CO_2.

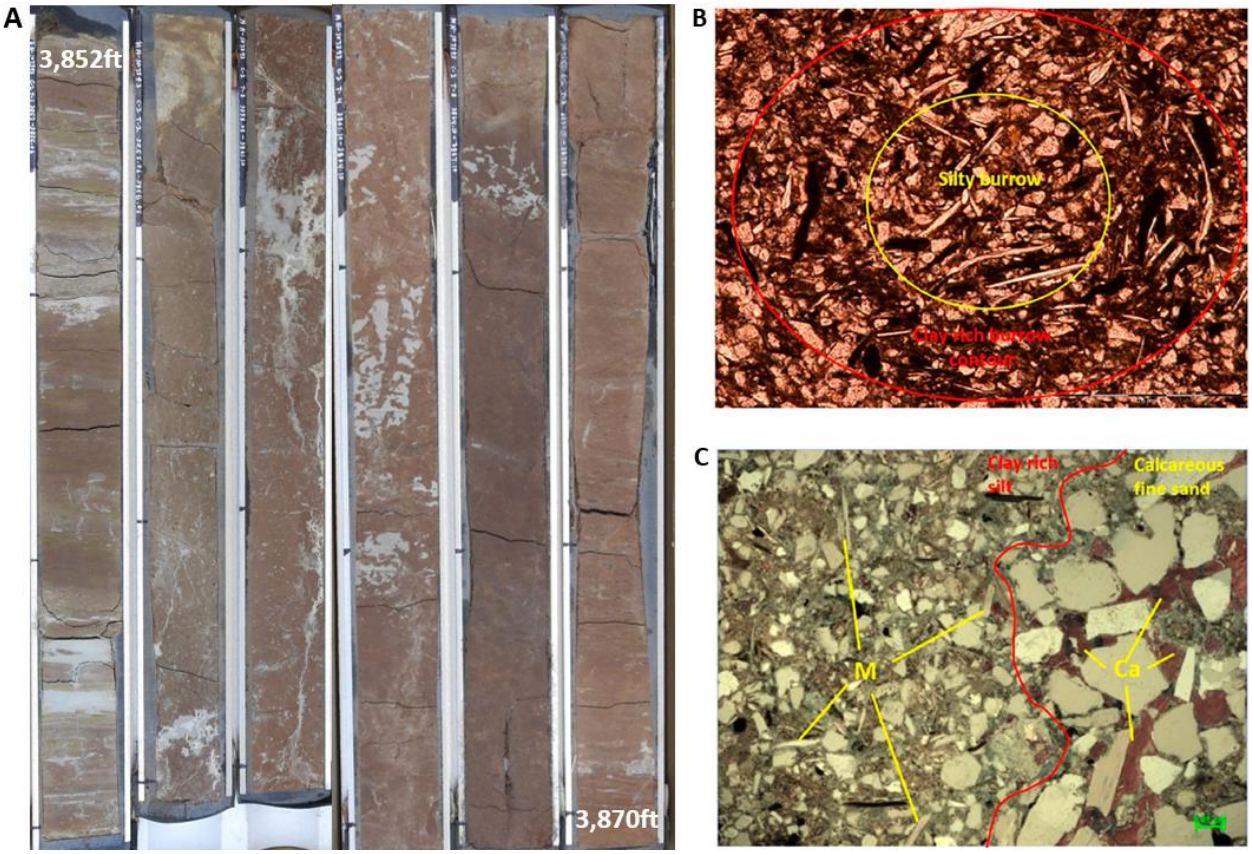


Figure 6. Thickly bedded Paleosol barrier from the Cretaceous, basil Washita- Fredericksburg interval, from the Mississippi embayment in Kemper County Mississippi (after Wethington, 2020).

Figure 7. Fluvial strata dominated by mudstone from the Permian-Triassic Beauford Group, Karoo Basin, South Africa, 240 m with individual mudstone beds on the order of 10 ft (3 m) thick and having broad lateral extent (after Wilson and Payebberg, 2013).

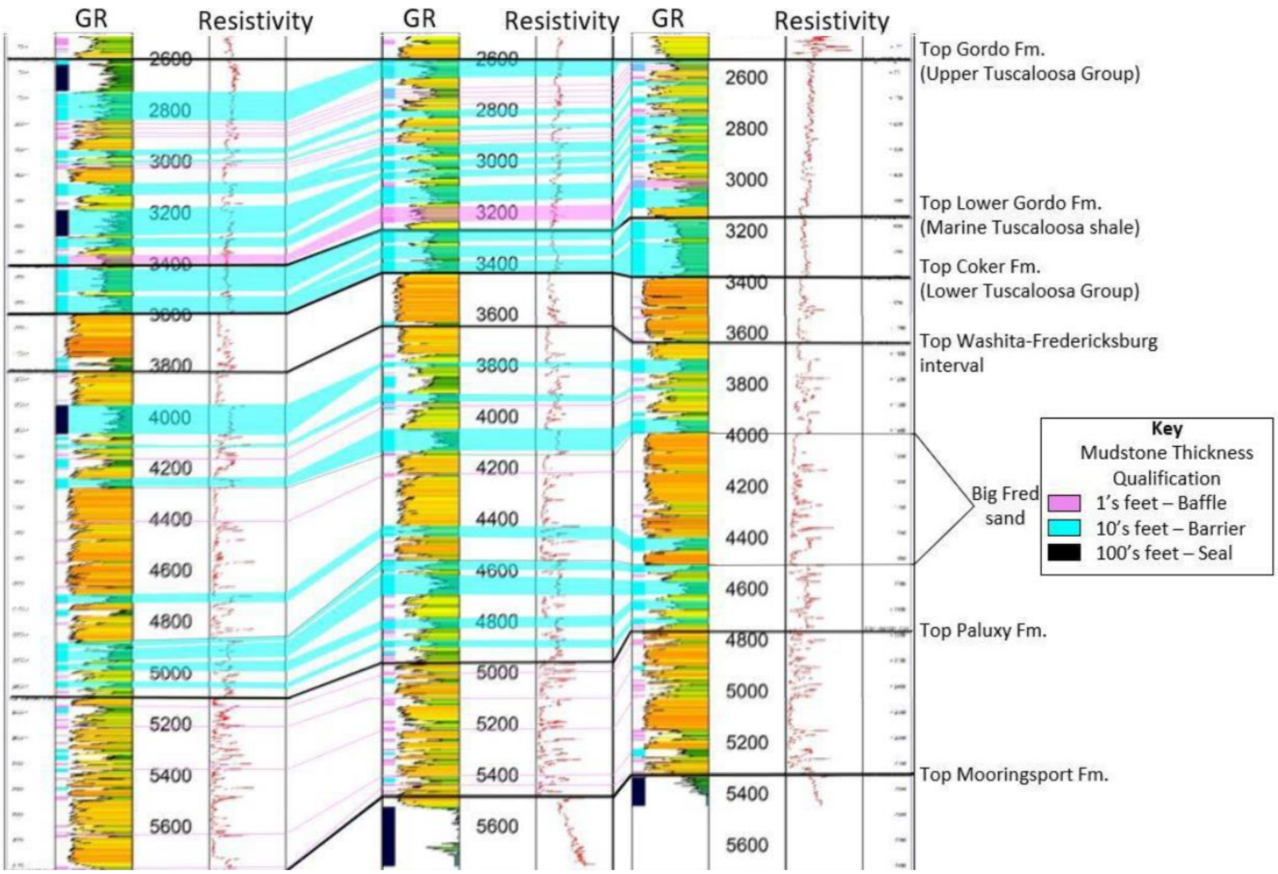


Figure 8. Mudstone barriers (blue) interstratified with bedload-dominated fluvial sandstone at a CarbonSAFE site in Kemper County, Mississippi (after Wethington, 2020).

Seals:

Mudstone seal thickness is on the order of 100-1,000 ft (>30 m) and can be defined as a thick, widespread geologic interval that is laterally continuous. Seals are commonly of regional to interregional extent (1,000 to >100,000 mi^2) and thus typically form distinctive stratigraphic markers that are readily recognized and correlated across regions (Figure 9, A and B). Seals can be identified in cores, well logs, outcrops, and are typically imaged clearly in seismic surveys. Seals have heterogeneity related to variations in clay, silt, and sand content that is typically a product of internal bedding (Figure 10). Sealing mudstone contains abundant claystone with permeability on the order of 10-100 nD that prevents cross-formational flow. Major discontinuities in these layers are typically structural rather than stratigraphic, and so folds, faults and transmissive natural fracture systems are the key limiting variables determining the extent of a potential storage complex (Figure 9C) (Pei et al., 2015; Meng et al., 2020).

Common depositional environments include a range of marine and lacustrine settings. Thick mudstone units associated with large lakes tend to form at the regional or basinal scale (Katz and Lin, 2014; Tanavsuu and Sarg, 2015; Nordsted et al., 2015), whereas marine units are commonly regional to interregional (Sloss, 1963; Haq et al., 1988; Catuneanu et al., 2009). Marine mudstone seals are typically associated with major marine transgressions and highstands (Figure 11) and include transgressive shelf deposits, including condensed sections, and progradational deltaic and beach-shoreface deposits, specifically prodelta-delta-front and beach-shoreface successions (Postma et al., 1995; Maceachern et al., 1999; Jonk et al., 2022).

The quality of a seal reflects depositional and structural architecture. Upscaling of porosity and permeability data from hand samples, cores, and well logs for reservoir simulation. Ultimately, a seal that confines a storage complex needs to maintain depositional and structural integrity in an area that exceeds the bounds of an area of review for a given storage program. Characterization of seals confining storage complexes, moreover, should be thorough enough to give operators and regulators confidence that the seal can readily confine the CO_2 column and that underground sources of drinking water are adequately protected.

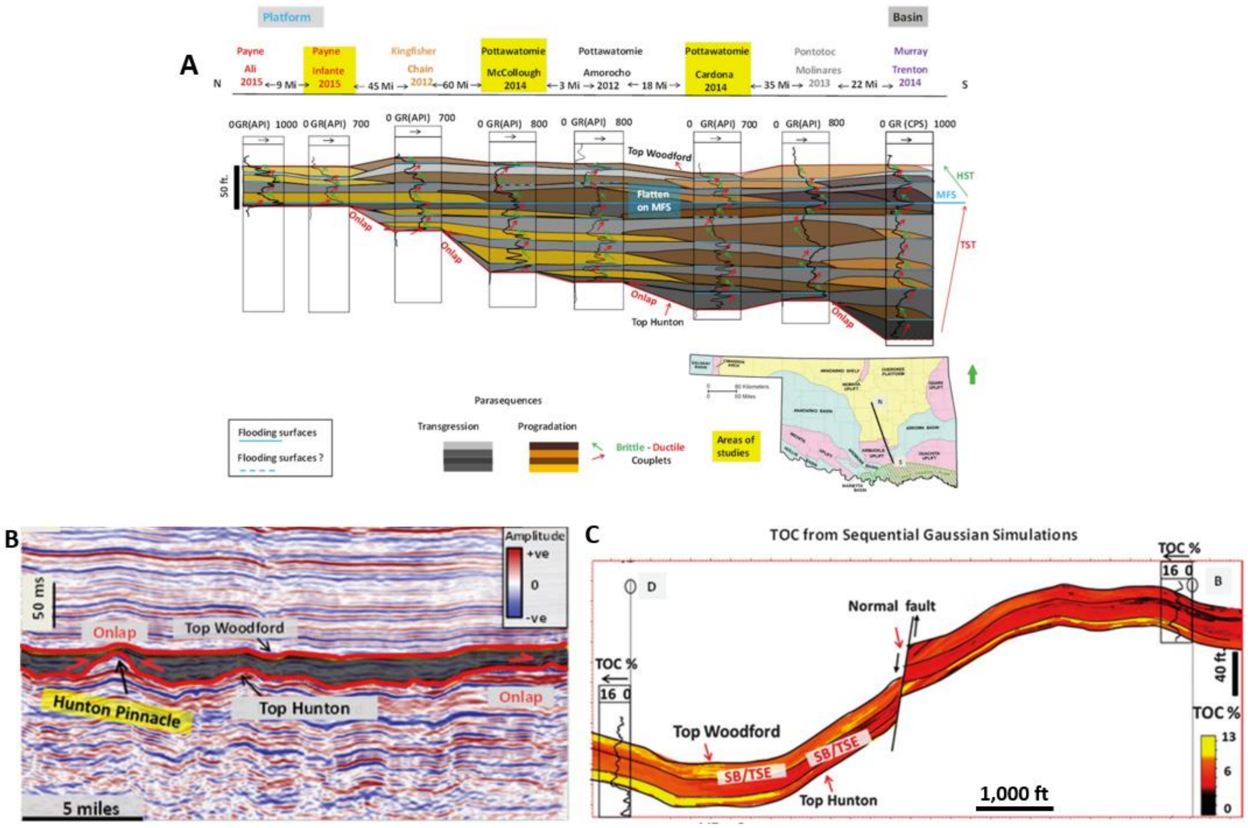


Figure 9. Regional Presence of the Devonian, Woodford shale (mudstone) in the US Midcontinent. A) Regional well log correlation of the Woodford and internal units associated with internal depositional packages. B) Seismic image showing variation of Woodford thickness associated with paleotopography on the sub-Woodford disconformity. C) Fault seal in the Woodford Shale (after Infante-Paez et al., 2017).

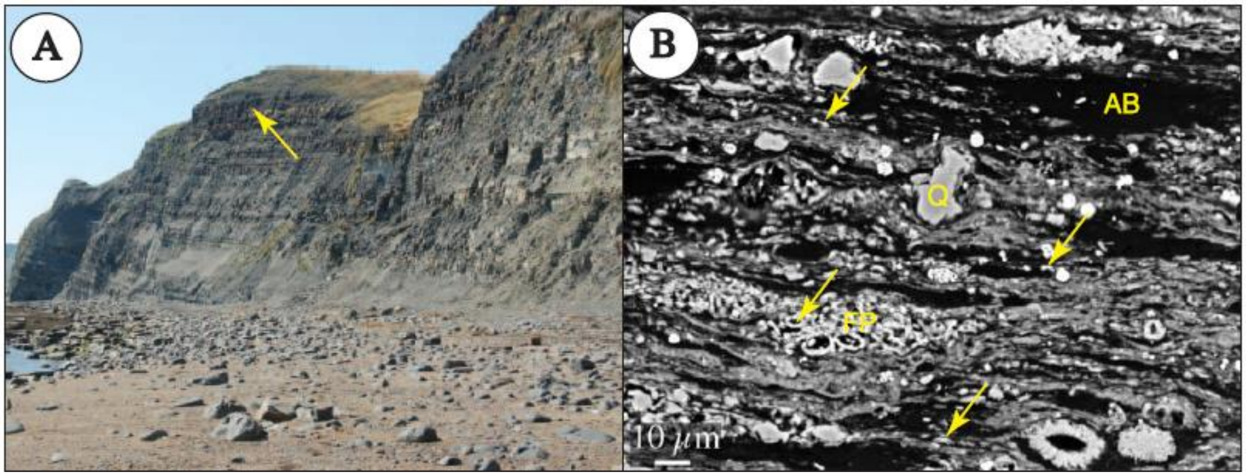


Figure 10. Jurassic, Kimmeridge Clay formation near Kimmeridge Bay, England. A) The shaley mudstone outcrop is ~100 ft (30m) thick and B) is siliciclastic rich with organic material and fossil cocoliths (after Aplin and Macquaker, 2011)

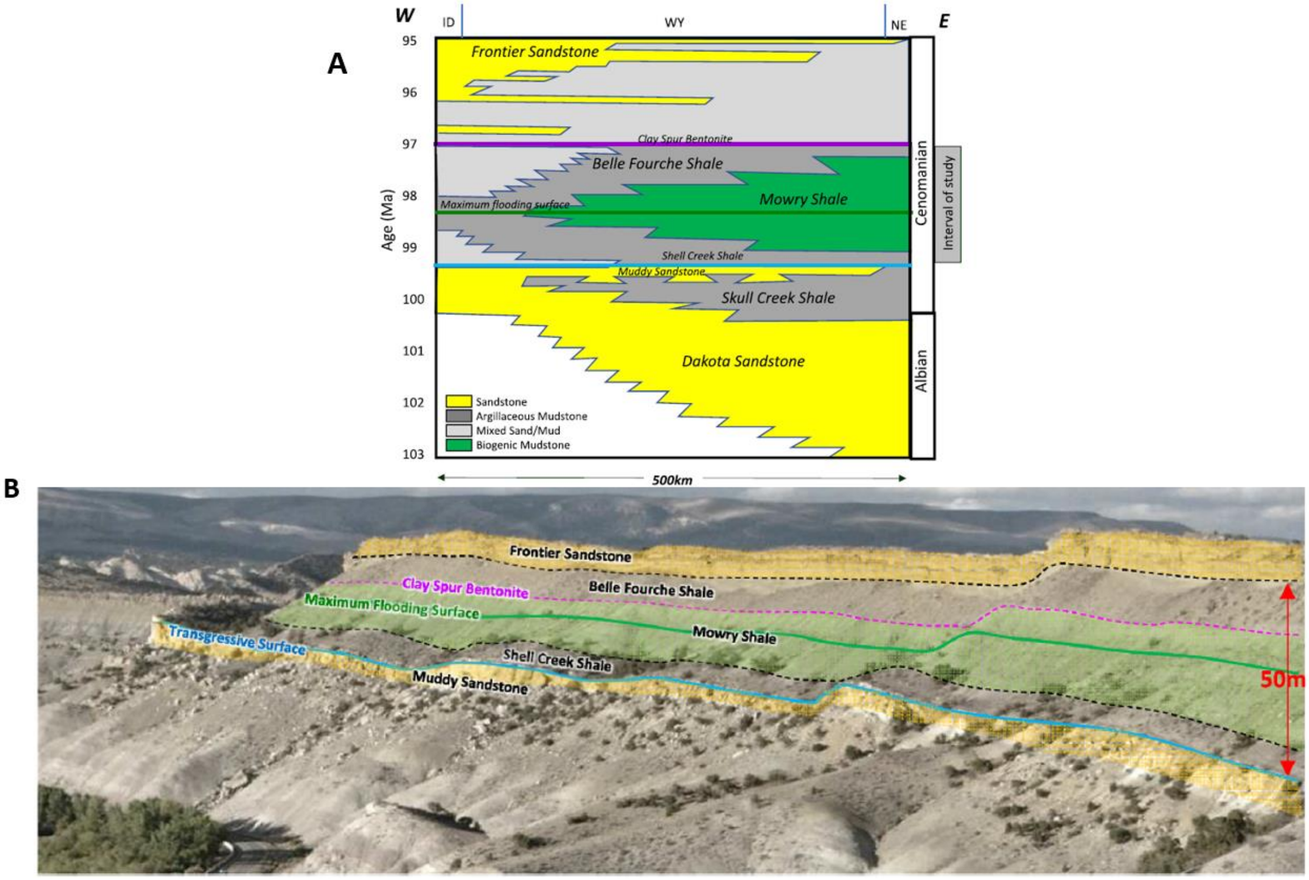


Figure 11. A) Transgressive and highstand deposition of sandstone and mudstone (Albian-Cenomanian) of the greater Wyoming region. B) Vernal outcrop of northeast Utah with >50 m of mudstone deposition associated with a marine transgression and subsequent regression (Jonk et al., 2022).

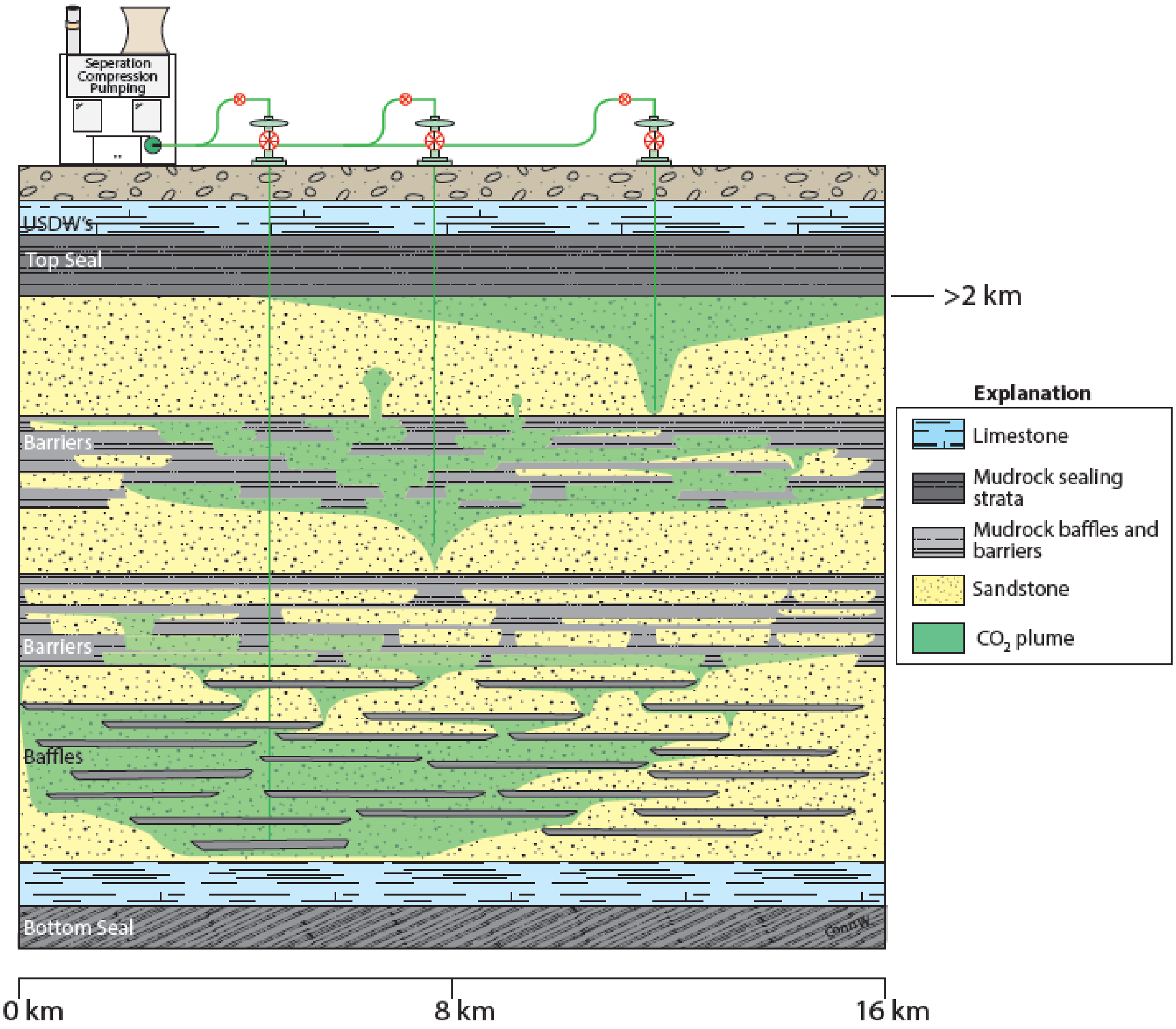


Figure 12. Conceptual model of baffles, barriers, and seals based on analysis of the CO_2 storage complex at Kemper County energy facility (Wethington et al., 2022).

Discussion

The classification of baffles, barriers, and seals put forth in this paper is based on the log-normal statistical distribution of bed thickness and lateral extent, which provides a natural basis for recognition and classification. Cores and geophysical well logs are critical for evaluating rock fabric and documenting the assemblages of rock type, texture, bedding, and sedimentary structures to identify depositional environments and understand confining bed architecture.

Geophysical well logs are a primary resource for correlation of confining beds and determining thickness and estimating lateral extent. Baffles are typically subseismic features, and so seismic reflection data are most useful for recognizing thick, widespread barriers and regionally extensive seals.

Baffles increase reservoir efficiency and promote residual trapping of CO_2 by enabling a CO_2 plume to contact more reservoir space than is possible in a homogeneous reservoir, which favors development of simple buoyant plumes and sill-like spreading of plumes below the overlying confining bed. Barriers may not confine a CO_2 plume over geologic time but have the ability to significantly impede the cross-formational flow of CO_2, thereby enabling management of multiple plumes within a storage complex. Accordingly, a stacked storage complex containing several well-defined barriers is a premium target for hub and industrial storage, and the presence of multiple storage objectives and confining beds provides flexibility with respect to where and how wells and completion zones are placed and where and how CO_2 is injected. Storage complexes must be large enough to confidently contain a commercial volume of injected CO_2 while ensuring protection underground sources of drinking water and surficial soil from migration of injectate (Figure 12). The ultimate topseal is the stratum that needs to ensure the safe and effective storage of a large volume and potentially thick gas column of anthropogenic CO_2 and needs to be assessed based on limiting factors associated with capillary and rock-mechanical properties. Seals are characteristically regionally to interregionally extensive mudstone units that are thick enough and of sufficient quality to confine a tall gas column and minimize the risk of migration of CO_2 into protected formation water.

Although this classification was defined using mudstone confining intervals as a vehicle, the work can be applied more broadly. Other confining rock types, such as tight carbonates and evaporates, can be analyzed using this approach. In addition, this approach could be applied to storage systems containing carbonates, as well as the siliciclastics emphasized in this paper.

Conclusions

The log-normal statistical distribution of the thickness and lateral extent of beds regardless of rock type provides a natural basis for the classification of mudstone confining units. Thus, mudstone confining beds are classified as baffles, barriers, and seals based on differing orders of magnitude of bed thickness and lateral extent. Baffles have thickness between on the order of 1-10 ft and lateral continuity on the order of 100-1,000,000 ft^2. Barriers, by contrast, have typical thickness on the order of 10-100 ft and are continuous over areas on the order of 10 to >100 mi^2. Seals tend to form regionally to interregionally extensive confining units with thickness of the order of 100-1,000 ft that at a minimum cover large parts of sedimentary basins and are distinctive stratigraphic markers that in many places can be correlated among multiple basins and even across continents.

Cores and geophysical well logs are used to characterize rock fabric and are essential for identifying depositional environments and understand understanding depositional architecture. Geophysical well logs are the principal tool for correlating and determining the thickness and lateral extent of confining beds. Baffles are commonly difficult to resolve confidently using seismic data, whereas major sealing formations have a distinctive signature in seismic surveys, which are important for documenting the lateral continuity and structural integrity of seals.

Baffles are an important component of intraformational heterogeneity that contribute to storage efficiency; they commonly represent localized depositional environments within fluvial and beach-shoreface depositional systems. Barriers, by contrast, are components of larger-scale depositional systems and form in a range of depositional environments, such as interfluves, interdistributary bays, lagoons, and parts of continental shelves. The tend to form primary confinement for individual reservoirs in stacked storage complexes but do not necessarily provide clear protection of underground sources of drinking water. Seals form in extremely widespread depositional environments and are commonly key stratigraphic markers associated with major relative and eustatic sea-level rises and highstands; they are characteristic of widespread delta-front, prodelta, shelf, and slope deposits. Seals, moreover, are thick enough and have capillary and mechanical properties that can confine a large, buoyant gas column and thus provide confidence that underground sources of drinking water will be protected from CO_2 storage activities.

CHAPTER V

CONCLUSIONS

The Cretaceous-Tertiary stratigraphy at the Kemper County Energy Facility dip to the south-south west into the broader Gulf of Mexico and define a stratigraphic trap at a proposed CCS complex in east-central Mississippi. The storage resource of 1.4 Gt supports the potential for a hub scale ($\geq$5 Mt/yr) sequestration opportunity with >3,000 ft (>900 m) of stratigraphy in play for sequestration operations. The primary and secondary reservoirs, the Paluxy Formation and Washita-Fredericksburg interval, are confined by regionally extensive stacked paleosols with individual beds being > 10 ft (>3 m) being composed of differential amounts of sand, silt, clay, and organic material and are characterized as barriers. The basal and upper Washita-Fredericksburg interval barriers compartmentalize the Paluxy Formation from the Washita-Fredericksburg reservoir and help to prevent large volumes of CO_2 from migrating upsection. The barriers are thought to allow access to two distinctly different reservoirs that enable a stacked storage program and allows for flexibility with respect to CO_2 sourcing and injection strategies. The Paluxy Formation is characterized as containing abundant intraformational mudstone baffles that promote residual trapping of CO_2 and have the ability to increase reservoir efficiencies by preventing plume coning and allowing more pore space to be contacted. The secondary reservoir, Washita-Fredericks interval, has fewer intraformational mudstone baffles and barriers and potentially has the ability to receive large rates of injection. The Lower Tuscaloosa Massive sand has intraformational conglomeratic baffles and barriers and should be used as a buffer reservoir for fugitive CO_2 that escape the primary and secondary reservoirs. The Massive sand used as buffer prevents significant impingement of CO_2 at the interface of the Marine Tuscaloosa shale that is characterized as a thick regionally present confining unit with sufficiently low permeability and clay content to prevent the vertical migration of CO_2 out of the storage complex ensuring the safety of USDW and surface soils.

The mudstone classification of confining intervals for sequestration play identification and characterizations is the first of its kind and assesses the differential thickness and areal extent of mudstones. Thin mudstones that lack significant correlation among wells are coined baffles. Baffles define reservoir heterogeneity and increase reservoir efficiency with implications of increasing residual trapping of CO_2. Mudstones on the order of >10 ft (3 m) that are present regionally to interregional have the ability to significantly confine vertical plume migration within a sequestration complex. Barriers also define compartmentalized reservoirs and should be identified within a potential prospect as an asset with two-fold importance: (1) helps define a sequestration complex with more opportunity for sequestration resource and (2) potentially allows a differential injection program that is favorable for different rates of CO_2 receipt. Areally extensive mudstone present across a basin or multiple basins on the order of > 100 ft (>30 m) characterize mudstone seals and should be extensive as to cover terminal plume migration and geometry with respect to injection rate and lifecycle to ensure the safe disposal of anthropogenic CO_2.

The research and results of the Kemper CarbonSAFE program have enabled the identification, characterization, and development of a mudstone classification that enables cross discipline communication by providing a common definition of the scale and capacities of confining units. The classification methods also have implications to the scaling of geocellular models and grid sizing that will ultimately need to be simulated in order to understand sequestration efficacy and attain an injection permit. Indeed, the work contained herein gives insight into the potential of a world-class and potentially worlds fist, large scale sequestration hub. There are more scientific questions to be asked and tested at the Kemper site and the facility will allow for generational learning and transfer of information and technology that will improve CCS practice to the global community through the work of other Sequestrians.

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VITA

Conn L. R. Wethington

Candidate for the Degree of

Doctor of Philosophy

Thesis: MUDSTONE CHARACTERIZATION AND CLASSIFICATION AT A PROPOSED HUB SCALE CARBON SEQUESTRATION COMPLEX: KEMPER COUNTY, MISSISSIPPI, UNITED STATES

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Geology at Oklahoma State University, Stillwater, Oklahoma in December, 2022.

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

Completed the requirements for the Bachelor of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in 2017.

Experience: Geologic exploration, stratigraphy, sedimentology, and formation evaluation
Chevron – Global Exploration and New Ventures; July 2022 – October 2022
Department of the Interior – Physical Scientist, Carbon Sequestration Specialist; August 2021 – Present
Oklahoma State University – Research Associate, Ph.D. Geology candidate August 2019 – 2022
Ascent Resources – Subsurface Petroleum Geologist; May – August 2019
Oklahoma State University – Research and Teaching Assistant, M.S. Geology May 2017– May 2019
GeoSync – Exploration & Strategic Services; May – August 2019
Research Experience in Carbon Sequestration – June 2017

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