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STRATIGRAPHIC, GEOCHEMICAL, AND WELL LOG ANALYSIS OF THE WOLFCAMP-D UNCONVENTIONAL PLAY IN THE CENTRAL MIDLAND BASIN, TEXAS

Patrick Thomas Ryan

University of Kentucky, ryanp3435@gmail.com
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Patrick Thomas Ryan, Student

Dr. Michael M. McGlue, Major Professor

Dr. Edward E. Woolery, Director of Graduate Studies
A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in the College of Arts and Sciences at the University of Kentucky

By
Patrick Thomas Ryan
Lexington, Kentucky

Director: Dr. Michael M. McGlue, Pioneer Professor of Earth and Environmental Sciences
Lexington, Kentucky
2016

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ABSTRACT OF THESIS

STRATIGRAPHIC, GEOCHEMICAL, AND WELL LOG ANALYSIS OF THE WOLFCAMP-D UNCONVENTIONAL PLAY IN THE CENTRAL MIDLAND BASIN, TEXAS

This M.S. thesis utilizes diverse subsurface datasets from the central Midland Basin, a recently reinvigorated petroleum producing region, to better understand the depositional history of the prospective Wolfcamp-D interval. An integrated set of methods were applied to ~320 ft of drill core from Midland County (Texas). Elemental chemostratigraphy collected via x-ray fluorescence highlights the pervasive fine-scale variability in the stratigraphy of the core, and aided in the classification of three different mudrock facies types. Organic-rich, siliceous mudrocks are cyclically interbedded with aluminum-rich mudrocks and carbonates throughout the Wolfcamp-D. Trace metal correlations with total organic carbon indicate slow bottom-water recharge from the open ocean, and that the Midland Basin was at times strongly anoxic during the deposition of black mudrocks. The changes in depositional environment associated with these different lithofacies are interpreted to have been driven by glacioeustatic sea level change, as well as shifts in global and regional climate that occurred during the Late Pennsylvanian. The repetitively stacked lithofacies are therefore consistent with a deep-basin cyclothem depositional motif and share some commonalities with well-studied shelf cycloths. The results hold important implications for unconventional reservoir characterization of basin-center shale plays in the Permian Basin.

KEYWORDS: Mudrocks, Unconventional Petroleum Reservoirs, Chemostratigraphy, Lithofacies, Cycloths

Patrick T. Ryan
12/01/2016
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By

Patrick Ryan

Dr. Michael M. McGlue
Director of Thesis

Dr. Edward Woolery
Director of Graduate Studies

December 8th, 2016

Date
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CHAPTER ONE: INTRODUCTION

In recent years, the Midland Basin of the southwestern United States has received renewed interest as an unconventional petroleum-producing region (Waite and Read, 2014). The Midland Basin is the eastern sub-basin of the Greater Permian Basin (GPB) in western Texas and southeastern New Mexico (Frenzel et al., 1988). The GPB and the Midland Basin have historically housed prolific conventional petroleum plays, with exploration and development focused on sandstone reservoirs within the Spraberry Formation, and on porous platform carbonates such as the Strawn Formation (Saller et al., 1994; Hamlin and Baumgardner, 2012). Advances in horizontal drilling, combined with improvements in hydraulic fracturing technology, have made many new unconventional resource plays viable in the United States (Waite and Reed, 2014; Waite et al., 2015; Gaswirth et al., 2016). These new unconventional plays require the artificial manufacture of porosity and permeability in organic-rich mudrocks through hydraulic fracturing. In the case of the Midland Basin, the stacked pay zones in the upper Pennsylvanian and lower Permian sections are valuable unconventional targets. The U.S. Geological Survey estimates a technically recoverable resource of ~20 billion barrels of oil and 16 trillion cubic feet of gas (Gaswirth et al., 2016) from the stacked Wolfcamp play, and estimates from operators in the region suggest that these values may indeed be conservative. Petroleum production from the GPB has surged in the last several years, facilitated by technological advances. Increases in production have come mostly from the Spraberry, Wolfcamp, and Bone Spring Formations. Production from these three formations has increased from 140,000 barrels per day (bbl/d) in 2007 to 600,000 bbl/d in 2013 (Budzik and Perrin, 2014). Since the downturn in crude petroleum prices (beginning
in 2014), the Permian Basin has remained one of the most productive unconventional plays in the United States. As drilling activity has decreased, operators have been able to increase the productivity of new wells. Overall, despite fewer new wells being drilled in the GPB, more oil and gas is being produced from the basin than in the past (Energy Information Administration, 2016). Despite this clear interest in the GPB, there are limited publicly available publications that describe the Paleozoic geology of the basin, due to the proprietary status of most subsurface datasets. Time-equivalent strata that has been exposed at the surface in outcrop in the Guadalupe and Sacramento Mountains of New Mexico have been extensively studied, but these rocks are mostly platform carbonates, and therefore lack deepwater mudrocks that form the key unconventional petroleum targets (Soreghan, 1994; Soreghan and Giles, 1999; Waite and Henk, 2014).

The Wolfcamp-D (WC-D) is the lowest stratigraphic interval of the stacked Wolfcamp unconventional petroleum play (Hamlin and Baumgardner, 2012). The shallow upper Wolfcamp reservoir intervals (A, B and C) have received much more attention in the literature, but a handful of studies provide some basic insights on the character of rocks associated with this enigmatic deep “D” interval. The WC-D is a package of predominantly siliciclastic sediment that thins to the north and west, with sediment source points located in the east and south (Frenzel et al., 1988). The WC-D stratigraphy varies significantly across the basin, with more siliciclastic rocks in the center, and greater calcareous rocks along the margins (Hamlin and Baumgardner, 2012). The WC-D is also significantly different from the upper Wolfcamp strata. The basinal WC-D is mostly siliceous mudrocks with thin interbedded carbonates, whereas the upper Wolfcamp intervals are comprised of calcareous mudrocks with interbedded carbonates.
(Hamlin and Baumgardner, 2012). The upper Wolfcamp sediments are quite thick, as they were deposited in the early Permian when the basin was influenced by rapid subsidence (Horak, 1985; Walker et al., 1995). The recently completed U.S. Geological Survey resource assessment splits the Wolfcamp play up as the A, B, C and D sub-members. The estimate from that report is that the mean recoverable resources from the deep WC-D are 4,920 million barrels of oil, 3,936 billion cubic feet of gas, and 394 million barrels of natural gas liquids (Gaswirth et al., 2016).

The age of the WC-D has been a topic of speculation, but recent work on conodont biostratigraphy suggests that the unit is most likely Late Pennsylvanian in age (Kohn et al., 2016). During the Late Paleozoic, and in particular the Late Pennsylvanian, fluctuations in sea level resulted in the deposition of cyclic packages of rocks called “cyclothsms” that have long been recognized and mapped in many basins worldwide (Soreghan and Giles, 1999; Eros et al., 2012; van den Belt et al., 2015). Prominent and well-studied examples of shelf cyclothsms come from exposures in Kentucky, Kansas, and Oklahoma (Boardman and Heckel, 1989; Heckel, 1994; Heckel, 2008; Greb et al., 2008). Most studies of cyclic deposition during the Late Paleozoic have focused on paralic and carbonate platform settings (Saller et al., 1999; Heckel, 2008; Eros et al., 2012). Heckel (1994) speculated that deep marine conditions in the Midland Basin during the Late Pennsylvanian may have produced an unusual condensed variant of cyclothem that shared some genetic relations with shelf cyclothsms, but the data necessary to test this hypothesis were heretofore unavailable.

This study is the first to closely consider the potential of WC-D as a unit containing deep basin cyclothsms, making use of proprietary subsurface datasets
collected by Pioneer Natural Resources. The principle hypothesis for this study is that glacioeustatic sea level variability and associated changes in global climate explain lithofacies types and stacking patterns in the WC-D. Two previous studies have informed the development of this hypothesis. The regional conceptual cross-section and depositional motif discussed in Heckel (1994) suggests that deepwater cyclothsems may indeed be present in the Midland Basin, and therefore the development of these rocks must share a common heritage with the shelf cyclothsems of the mid-continent, albeit with deposition occurring under much different environmental and oceanographic gradients. A more recent study by Baldwin (2016) confirmed the presence of cyclic strata in the southern end of the Midland Basin in Upton County, and the data described in that study implied an important role for sea level change as a control on facies distributions and petroleum source-rock development. To evaluate this hypothesis and develop a conceptual depositional model for WC-D, a detailed understanding of the stratigraphy of the interval is required. To attain this goal, this study pursued a variety of geochemical, lithostratigraphic, sedimentological, and petrophysical analyses on a drill core from Midland County, which is situated in the axis of the Midland Basin, near its geographic center in Late Pennsylvanian time. The location of the core in the Midland Basin relative to important geologic features of the region is displayed in Figure 1.1. The development of these data sets allowed for lithofacies to be defined by unique physical sedimentological features and geochemical characteristics. Once lithofacies were defined, changes in the abundance of lithofacies in vertical section, as well as the stacking patterns, provide further insights into changes to the environment of deposition. Geochemical indicators also provide insights regard the oxygenation state of the basin,
and the rate of recharge of bottom waters. These same datasets also provide valuable
information for improving unconventional reservoir characterization.

The applied and academic motivations for this research are integrally linked. In
order to better understand and delineate potential unconventional petroleum reservoirs, a
more holistic understanding of the conditions that influenced WC-D deposition are
required. Today, Pioneer Natural Resources and other petroleum exploration companies
have a growing interest in the WC-D as an unconventional oil play (Jacobs, 2013; Waite
et al., 2015). Optimal exploitation of the WC-D requires a comprehensive understanding
of depositional environment and history of the interval, especially considering how
distinct these rocks are in comparison to the overlying Wolfcampian and Leonardian
basinal deposits (Waite et al., 2015). Although cyclothem have been studied extensively
in North America and worldwide, the details of the controls on cyclothsms forming in
deep-water settings remains poorly constrained; insights from the WC-D hold potential to
address this knowledge gap in a rigorous way (Boardman and Heckel, 1989; Greb et al.,
2008; Heckel, 2008; Eros et al., 2012).
Figure 1.1 Physiographic Features of the Midland Basin Region. Map showing the location the Midland county core and important geographic features that notionally influenced deposition of the WC-D. These include the Central Basin Platform, the Eastern Shelf, the Horseshoe Atoll, and Ozona Arch. Other major elements of the Greater Permian Basin are the Southern Shelf, the Marathon-Ouachita Orogenic Belt, and the Delaware Basin. Cores from Martin and Upton Counties were also donated as part of the same project, but these are discussed in detail elsewhere (e.g., Baldwin, 2016; Perlman, in prep).
CHAPTER TWO: BACKGROUND

2.1 Tectonic Setting

Located in western Texas and extending into south-eastern New Mexico, the Greater Permian Basin (GPB) covers approximately 115,000 mi\(^2\) (Frenzel et al., 1988; Yang and Dorobek, 1995). Figure 1.1 is a stylized representation of the physiographic features associated with the Midland Basin, and Figure 2.1 provides a broad perspective on the paleogeography of western North America at ~300 Ma (modified after Blakey, 2013). Within the GPB there are three depocenters: (1) the Midland Basin; (2) the Delaware Basin; and (3) the Val Verde Basin. The relatively deep Delaware Basin is separated from the shallower Midland Basin to the east by the fault bounded and uplifted Central Basin Platform (CBP) (Frenzel et al., 1988; Schumaker, 1992; Atchley et al., 1999). The GPB is bounded to the south by the Southern Shelf and ultimately the Marathon-Ouachita fold-and-thrust belt. To the east, the GPB is bounded by the Bend Arch, which is part of the Llano Uplift (Frenzel et al., 1988). To the north, the GPB is separated from the Palo Duro Basin by the Matador Arch. The western margin of the Delaware and the GPB is defined by the Diablo Platform, and the associated Sacramento and Guadalupe Mountains. The Sheffield Channel, to the south of the CBP, connects the Midland and Val Verde Basins to the Delaware Basin. The Delaware Basin is connected to the Panthalassic Ocean via the Hovey Channel to the southwest (Galley, 1958; Frenzel et al., 1988).

The morphology of Midland Basin during the Late Pennsylvanian was asymmetric, with a steep slope along the western margin associated with the CBP, and a broad, low relief Eastern Shelf to the east (Galley, 1958; Frenzel et al., 1988; Mazzullo and Reid, 1989). To the south, the Midland Basin is separated from the Val Verde Basin by the Ozona
Arch (Figure 1.1). In the northern axis of the Midland Basin, a carbonate buildup called the Horseshoe Atoll formed a persistent paleo-high (Hamlin and Baumgardner, 2012). The CBP and the Ozona Arch were reef-capped, basement involved uplifts. Both uplifts formed during the Late Mississippian, related to the Ouachita-Marathon orogeny and the formation of the Ancestral Rocky Mountains (Schumaker, 1992).

The GPB, including the Midland Basin, has been influenced by multiple tectonic events throughout the Phanerozoic. Figure 2.2 shows relative basement mobility profiles for various structural features of the GPB region since the Precambrian. From the end of the Precambrian to the Mississippian, the Tobosa Basin persisted as a shallow, semicircular sag basin undergoing passive margin-type subsidence (Horak, 1985; Frenzel et al., 1988; Atchley et al. 1999). During the Late Mississippian, the Tobosa Basin was differentiated into the Delaware and Midland Basins, owing to the Marathon-Ouachita orogeny. High-angle, basement-involved faulting created structural highs such as the CBP that split up the Tobosa Basin into a series of basins and uplifts (Frenzel et al., 1988; Shumaker, 1992). This increased tectonic activity, and therefore the greater lateral stratal heterogeneity, within the GPB is contemporaneous with deposition of the Absaroka sequence (Sloss, 1988). The WC-D is thought to be between 309 and 299 Ma of age, and therefore deposited as part of the Lower Absaroka I sequence. This age range is based on well log correlations to fusulinid biostratigraphy completed on shelf carbonates (Sloss, 1988; Waite and Reed, 2014) and has been partially confirmed by conodont biofacies analysis (Kohn et al., 2016).

Maximum subsidence in the Midland Basin took place during the Permian, resulting in the deposition of a comparatively thick package of Permian strata (Matchus and Jones, 1984; Frenzel et al., 1988). In Figure 2.2, this tectonic phase is referred to as
“Permian Basin”, but technically the period is when the basin was part of a complex orogenic foreland. The Val Verde Basin was the foredeep associated with the Ouachita-Marathon orogeny, and the Ozona Arch was likely the flexural forebulge (Horak, 1985; Atchley et al., 1999).

The Laramide orogeny followed an extended interval of tectonic quiescence during the Mesozoic. The tectonic events after the Permian had relatively little structural impact on the Midland Basin, but resulted in permanent uplift above sea level and exposure of Paleozoic strata to west in the Sacramento and Guadalupe Mountains. The crustal thinning and volcanism associated with the “Volcanic” and “Basin and Range” phases provided additional heat flow to the southwestern margin of the GPB (Figure 2.2). Associated faulting exposed the up-dip equivalents of many GPB intervals in the Sacramento and Guadalupe Mountains (Horak, 1985; Atchley et al., 1999).

2.2 Depositional History

Sediment accumulation within the GPB from the Paleozoic through the Mesozoic reflects the complex interaction of tectonics and climate, resulting in extensive temporal and spatial depositional heterogeneity. These environmental gradients resulted in a mixed siliciclastic and carbonate system that consisted of a variety of shales, sandstones, carbonates, and evaporates. There is limited information on the Precambrian basement underlying the GPB, due to a relative paucity of wells drilled into the pre-Paleozoic rocks. Based on the existing data available in literature, the GPB is underlain with a mixture of igneous, volcanic, and metasedimentary rocks (Frenzel et al., 1988). One well bore that
penetrated Precambrian basement beneath the CBP encountered a layered, gabbro intrusion (Hoover et al., 1985; Frenzel et al., 1988).

Early and Middle Cambrian strata are not present in the GPB. Therefore, the initiation of Paleozoic deposition in the ancestral Tobosa Basin is marked by the Late Cambrian Hickory Sandstone Member of the Riley Formation, deposited unconformably on top of the Precambrian basement (Frenzel et al., 1988). Ordovician deposition consisted of the Ellenburger Group, Simpson Group, and Montoya Formation in chronostratigraphic order. The Ellenburger Group and Montoya Formation are predominately limestones and dolomites, whereas the Simpson is a mixture of alternating sandstones, limestones, and green shales (Frenzel et al., 1988; Galley, 1958). The lithology of the early Silurian Fusselman Formation reflects the orientation of an ancient shelf margin at this time. The carbonates of this formation are predominantly composed of limestone in the southeast of the GPB, and they become more dolomitic to the northwest. Later in the Silurian, deposition was influenced by the same paleogeography, with carbonate deposition on the shelf and the shales of the Wristen Formation in the basin (Frenzel et al., 1988). The deposition of the Woodford Shale, in the Late Devonian to Early Mississippian, represents a marine transgression across the shallow shelf. This follows a regional unconformity at the base of the Kaskaskia sequence (Sloss, 1963; Frenzel et al., 1988; Waite and Henk, 2014).

The Mississippian-aged stratigraphy reflects a transition in the tectonics influencing the basin. Post Woodford, Early Mississippian deposition was predominantly limestones, reflecting continued passive margin subsidence. As the epeirogenic deformation that ultimately differentiated the Tabosa Basin into the Midland and Delaware
Basins began, the depositional regime shifted. Terrigenous input increased, resulting in a higher proportion of shales, siltstones, and sandstones (Frenzel et al., 1988). The top of the Mississippian also represents the end of the Kaskaskia sequence (Sloss, 1963; Waite and Henk, 2014).

Pennsylvanian deposition across the GPB is extremely heterogeneous due to the continuation of structural differentiation, and the influence of a dynamic global climate on base level. On the uplifted blocks such as the Central Basin Platform (CBP), limestones of the Strawn, Canyon, and Cisco Formations were deposited during highstands; periodic exposure occurred during lowstands (Saller et al., 1994). The Eastern Shelf at this time was primarily a mixed siliciclastic ramp with carbonate shoals (Brown et al., 1990; Frenzel et al., 1988). Based on well log correlations, the Wolfcamp-D (WC-D) is the basinal, down-dip equivalent of the upper Strawn, Cisco and Canyon Formations on the shelves rimming the Midland Basin (Frenzel et al., 1988; Waite and Reed, 2014). The WC-D is sometimes referred to the Cline Shale or simply the Pennsylvanian shale (Jacobs, 2013). Figure 2.3 shows the correlation of chronostratigraphy and platform deposits to the basinal formations (Waite and Reed, 2014).

During Wolfcampian time, at the beginning of the Permian, basinal deposition consisted of grey mudrocks and black shales. By contrast, carbonate deposition took place contemporaneously on the CBP, until transitioning into the upper Wolfcamp detrital unit (Matchus and Jones, 1984; Saller et al., 1994, 1999). On the Eastern Shelf, early Wolfcampian deposition was primarily siliciclastic in nature, creating a distally steepening ramp that prograded into the basin, before later transitioning into a true carbonate platform (Matchus and Jones, 1984; Frenzel et al., 1988). Leonardian basinal deposits included the
Dean and Spraberry sandstones, which form historically significant conventional petroleum reservoirs, and intervening carbonaceous mudrocks (Matchus and Jones, 1984; Frenzel et al., 1988). Guadalupian strata consists of a variety of carbonates that thicken toward the basin margins. By Ochoan time, 260 to 251 Ma, most of the available accommodation was filled, and the GPB became an evaporate pan (Frenzel et al., 1988).

2.3 Paleoclimate and Paleoceanography

For approximately 70 million years during the late Paleozoic, the Earth was in a long-term ice house climate. The late Paleozoic ice age (LPIA) is the first global ice house with significant terrestrial vegetation (Soreghan, 1994; Cleal and Thomas, 2008; Montañez and Poulsen, 2013). Glacial and periglacial sedimentation has been recognized in the rock record from sedimentary basins across Gondwana during the late Paleozoic (Feilding et al., 2008a, 2008b; Isbell et al., 2012). Far field effects on sedimentation within paralic and nearshore marine environments, due to glacial eustatic sea level changes, have been widely documented in basins across Euramerica (Boardman and Heckel, 1989; Rasbury et al., 1998; Saller et al., 1999a; Heckel, 2008; Greb et al., 2009; Eros et al., 2012; van den Belt et al., 2015). Figure 2.4 shows a review of the research on the LPIA, and how various environmental proxies have been used to track glaciation in space and time (Montañez and Poulsen, 2013).

Assuming correlations to shelf biostratigraphy are accurate, the WC-D was deposited during the Desmoinesian, Missourian, and Virgilian North American stages, and therefore contemporaneous with high-frequency, high-amplitude glacial eustatic sea cycles of the LPIA (Ross and Ross, 1987; Rygel et al., 2008; Montañez and Poulsen,
2013; Waite et al., 2014). The LPIA was composed of a series of shorter ice ages, each several million years long, separated by similarly long climate intervals marked by relatively temperate conditions (Fielding et al., 2008a, 2008b; Isbell et al., 2012; Montañez and Poulsen, 2013). The timing and local impacts of each ice age is uncertain, due to the diachronous nature of global climate change and the difficulty of dating Paleozoic sediments of a variety of different lithologies (Isbell et al., 2012). Sea level varied significantly, with estimates for glacioeustatic fluctuations ranging between 20 and 150 m (Rygel et al., 2008). The CBP was regularly exposed during sea level low stands during the Late Pennsylvanian and Early Permian (Saller et al., 1994; Saller et al., 1999).

During the deposition of the Strawn, Cisco, Canyon and Wolfcamp Formations on the CBP, 87 stratigraphic cycles have been identified, and most are bounded at the base by a subaerial exposure surface (Saller et al., 1994, 1999a, 1999b). Uranium-lead dating of pedogenic carbonates that developed on these exposure surfaces indicate an average cycle length of ~143 ±64 ka, using linear interpolation, similar to the shorter eccentricity Milankovitch cycle (Rasbury et al., 1998).

If available age data are indeed correct, then the deposition of the WC-D appears to have occurred during a period of less extensive glaciation across Gondwana and Euramerica (Isbell et al., 2003; Fielding et al., 2008). Based upon the integration of data from many investigations in northern Gondwana and Panthalassan-margin basins, the deposition of the WC-D occurred primarily between the Glacial II and Glacial III intervals of Isbell et al. (2003). In comparison, the WC-D was also deposited between the glacial intervals of C4 and P1 of eastern Australia (Fielding et al., 2008b). However, a lack of direct sedimentological evidence for glaciation does not necessarily mean there
was no glacial ice at that time. Landforms and sediments created by glacial processes are predisposed to subsequent reworking by later glaciations. The last, largest glaciation has the best chance of preservation in the rock record, creating an implicit bias when studying these environments (Soreghan et al., 2014). Within the multi-million year ice ages, and intervening temperate periods, orbital eccentricity controlled higher frequency glacial-interglacial changes to environments of deposition resulted in cyclic strata often referred to as “cyclothems” (Boardman and Heckel, 1989; Algeo and Heckel, 2008; Heckel, 2008).

The shifting global climate during the Desmoinesian to Virgilian of North America had a pronounced impact on global atmospheric circulation and precipitation patterns (Tabor and Poulsen, 2008; Horton et al., 2012; Heavens et al., 2015). The generalized model features a contraction in the range of the inter-tropical convergence zone (ITCZ), and for the subtropical arid belts to move towards the equator during glacial intervals (Soreghan, 1994; Tabor and Poulsen, 2008). The Midland Basin during the Late Pennsylvanian was located at approximately 5º North, and would have experienced a cooler, drier climate during glacial intervals (Tabor and Poulsen, 2008; Montañez and Poulsen, 2013; Heavens et al., 2015). The formation of Pangea is hypothesized to have created a monsoonal circulation pattern driven by differential heating of the super continent and Panthalassa, the global ocean. Given the tropical location of the Midland Basin, a monsoonal circulation pattern could have had a significant impact on deposition through a variety of mechanisms (Ruddiman, 2001; Algeo and Heckel, 2008; Montañez and Poulsen, 2013).
Modeling of late Paleozoic climate and precipitation patterns shows a high degree of variability depending on the assumptions used in determining the initial conditions for a given model (Horton et al., 2012; Heavens et al., 2015). Moisture availability influenced by the interglacial transgression(s) onto the continental shelf during high stands was found to be one of primary controls on annual precipitation in western equatorial Pangea (Heavens et al., 2015). A specific scenario of interest is the impact of low latitude, high-elevation glaciation on global circulation patterns. Geologic evidence for alpine glaciation during the early Permian in the ancestral Rocky Mountains has been found, but precise age control is not available (Soreghan et al., 2014). The Late Pennsylvanian appears to have been a relatively temperate interval during the LPIA, which was followed by the maximum extent of late Paleozoic glaciation. Therefore, low latitude upland glaciation was likely not a critical factor influencing precipitation patterns during deposition of the WC-D (Montañez and Poulsen, 2013; Soreghan et al., 2014; Heavens, 2015). Weak or intermittent monsoonal precipitation over western equatorial Pangea, modulated by glacial-eustatic cyclicity, rather than proximal alpine glaciers, was the most likely control on rainfall and runoff to the Midland depositional system. Greater annual precipitation and stronger monsoons most likely occurred during inter-glacials (sea level high stands), with weaker monsoons and overall less precipitation during glacial intervals (sea level low stands) (Heavens et al., 2015).

The Midland Basin was part of the Greater Permian Basin Seaway, which served as a connection between the Late Pennsylvanian Midcontinent Sea (LPMS) and the open Panthalassic Ocean. The LPMS was an epeiric sea that covered much of the North American midcontinent, and allowed for the cyclic deposition of marine strata across
what is now the U.S. Midwest (Algeo and Heckel, 2008). Widespread benthic anoxia within the sea is in evidence by black shale deposition on the Kansas shelf, and this condition was facilitated by unique set of environmental factors (Algeo et al., 2008; Algeo and Heckel, 2008; Heckel, 2008). High terrestrial runoff into a relatively shallow, landlocked basin contributed to a strong pycnocline, driven by differences in salinity and temperature. The circulation within the LPMS involved the exchange of sub-pycnocline waters from the Panthalassic Ocean, via a serpentine path that included the GPB (Algeo et al., 2008; Algeo and Heckel, 2008). These deeper waters were preconditioned to be denitrified and oxygen deficient, due to upwelling-driven primary productivity in the equatorial Panthalassic Ocean, similar to the modern eastern equatorial Pacific (Algeo et al., 2008; Algeo and Heckel, 2008). Modeling of tides within the LPMS indicates a predominantly micro-tidal setting, with some exceptions. The Eastern Shelf of the Midland Basin is one such area where tides may have been in the low meso-tidal range (Wells et al., 2007).
Figure 2.1. Paleogeography of the Midcontinent and Southwest of North America at ~300 Ma (modified from Blakey, 2013). This map shows the major physiographic features that influenced deposition in the GPB during the Late Pennsylvanian. The black rectangle marks the location of the GPB. To the (modern) southwest of the GPB is the connection to the Panthalassic Ocean. To the southeast are the Central Pangean Mountains. To the north and east, covering the U.S. Midwest, is the LPMS. To the northwest of the GPB are the Ancestral Rocky Mountains. See Figure 1.1 for a detailed overview of the geological features of the Midland Basin, and a comparison of modern to paleo-north.
Figure 2.2. Tectonic History and Basement Mobility of the Greater Permian Basin Region. The profiles trace the top of the Precambrian basement, relative to modern sea level, for various structural elements within the GPB. The Midland Basin is the thick, black line, whereas the CBP, Eastern Shelf, and Delaware Basins are the dark grey lines. The timing of tectonic phases are shown by the dark grey rectangles. The Pennsylvanian period is highlighted in light grey, coinciding with the Hercynian Collision phase (modified from Horak, 1985 and Walker et al., 1995).
Figure 2.3. Regional Stratigraphy of the Midland Basin (modified from Waite and Reed, 2014). The regional stratigraphy of the Midland Basin, associated chronostratigraphy, sequence sets, and an interpreted sea level curve (Sloss, 1969; Ross and Ross, 1987). The basal Wolfcamp interval is the focus of this study, and it lays directly on top of the Lower Strawn carbonate. The studied interval is believed to capture the transition from the Lower Absaroka 1.3 to 1.4. The equivalent up-dip formations on the CBP and Eastern Shelf are the Upper Strawn, the Canyon and Cisco Formations. The platform formation names are noted in parentheses in the Chronostratigraphy column.
The ice house conditions during the Late Paleozoic (Mississippian through Permian) have elicited a great deal of research and utilized a wide variety of methods. This figure summarizes several other review papers on the subject. For the purposes of this study, the period of interest is approximately 299-309 Ma (Desmoinesian to Virgilian of the North American stages). This interval represents, based on this wide array of research, a long-term warming period in the Late Pennsylvanian ice house, with shorter term glacial-interglacial cycles contained within it. Maximum ice house conditions prevailed during the subsequent early Permian, before the world-wide climate transitioned into a long-term greenhouse.
CHAPTER THREE: METHODS

An integrated, hierarchical set of methods was utilized to characterize the stratigraphy of the WC-D and the overlying Wolfcamp-C2 (WC-C2). Lithostratigraphic descriptions of ~320 ft of core were used in combination with well logs and integrated with a variety of geochemical analyses completed at the University of Kentucky. This approach was used to delineate facies types within the WC-D, which was the first step in creating an interpretation of changes to environment of deposition and to test hypotheses related to conditions that facilitated organic enrichment and petroleum source-rock development. Table 3.1 summarizes the various methodologies employed, including sampling intervals, total number of samples, and where appropriate, which laboratory conducted the analysis set. Pioneer Natural Resources (PXD) donated the two-thirds “working” portion of a 4-inch diameter core from Midland County, Texas. The core was delivered in 115 boxes, and a number of subsamples had been removed for analyses by subcontractors. Recovered core quality was reduced due to the contrast in hardness between the mudrocks and carbonates, which resulted in some sections of the core being highly fragmented. Fractures due to decompression during extraction were common, and also reduced the quality of the core significantly in some zones. Short, full-diameter sections were also included in the delivered core; these cores were apparently omitted from the slabbing and polishing process by PXD contractors. Based on comparing the depths labeled on the boxes, high-resolution photos of the one-third archive portion, and the state of delivered core, a significant amount section was missing. There were 18.2% fewer XRF analysis points than there theoretically should be for 320 feet of continuous core, with a two inch sample interval (1620 points, versus 1915). The missing lengths
were predominately short, typically 6-18 in long, and pervasive throughout the Wolfcamp intervals of the core.

The highest resolution dataset is the lithostratigraphy, generated through core logging following the methods described by Campbell (1967), Bohacs (1990), and Bohacs et al. (2014). The lithostratigraphy provides information about the depositional environment of the WC-D based on color, bedding, grain size, physical sedimentary structures, texture, and mineralogy of the rock. Qualitative observations regarding fossil abundance, type, and preservation were recorded along with lithofacies characteristics. Macroscopic fossil content was classified using a descriptive scale: Rare/Absent, Occasional, Frequent, Common, and Abundant. Lithology and grain size were determined by reaction with dilute acid, the energy dispersive x-ray fluorescence dataset (see below), and macroscopic examination of hand samples. Macroscopic observations were supplemented with petrographic analysis of thin sections made by CoreLab, provided to the project by PXD. For intervals not represented by the preexisting thin sections, a DinoLite™ handheld digital microscope was utilized. Limestone gravity flow deposits and other carbonates were classified using Dunham’s textural classification scheme (Dunham, 1962; Flügel, 2004). All observations were recorded in an MS Excel® table, and incrementally transferred to a master stratigraphic column kept in an Adobe Illustrator® document. The lithostratigraphy provided guidance in sampling for the geochemical analyses.

Wireline well logs collected by Weatherford were provided for this project by PXD as raster files or as Log ASCII Standard (LAS) files. The log curves of greatest interest for the integrated stratigraphic analysis were gamma ray, resistivity, bulk density,
neutron porosity, and the caliper (Meyer and Nederlof, 1984). Log curves were plotted on scales appropriate for the lithologies of interest (A. Reynolds, personal communication, 2015). The logged depths were adjusted via manual peak matching to match the cored depths. The second highest resolution dataset was the inorganic elemental chemostratigraphy, generated by energy dispersive x-ray fluorescence (ED-XRF). High resolution images of the “archive” one-third slab of the core were used as a general guide for placing sample locations on our cores, due to the quality of the two-thirds sections. The “working” two-thirds slabs were measured and marked in two inch increments with orange labels for analysis. Figure 3.1A shows a measured and marked box of Midland County core. The analyses were conducted using two Bruker Tracer IV-SD™ hand-held energy dispersive x-ray fluorosscopes, following procedures modified from Rowe et al. (2012). Both devices were outfitted with a 40 kilo electron volts (keV) and 60 micro amperes (µA) x-ray tube. A 90 second dwell time was used for each ED-XRF scan, in order to maximize the signal to noise ratio and improve data quality. Separate scans for major and trace elements were run at each measured and marked point. The analysis of the core proceeded from the base (319.167 ft) to the top of the core (0 ft). Our initial XRF device was used for depths 319.167 ft to 183.165 ft, and 173.165 ft to 165.000 ft, whereas the second XRF was used for all other intervals. Scans for major elements (atomic numbers 11 through 26) with the first device were run at 15.00 keV and 40.00 µA, with a 9 torr or more vacuum in place. The major element tube settings for the second device were 15.00 keV, and 41.00 µA. For the trace elements (atomic numbers 27 through 51) with the first device, the samples were run at 40.00 keV and 15.20 µA, without a vacuum. The trace element tube settings for the second device were 40.00 keV, and 35.00 µA. A
summary of the device settings are listed in Table 3.2. The differences in the tube settings were due to adjustments to the analog-to-digital converter interface of the second ED-XRF, in order to bring the beam length and counts per second into the appropriate ranges (B. Kaiser, personal communication, 2014). Figure 3.1b illustrates the setup of the ED-XRF device and associated peripheral equipment.

The elemental values collected with the ED-XRF can be used as indicators for mineralogy, and are therefore helpful in delineating facies types. This is particularly useful when analyzing mudrocks and shales, as visual examinations by themselves may not be sufficient in distinguishing the variability in mudrock composition (Rowe et al. 2012). Trace metal concentrations, when compared to total organic carbon (TOC), provide possible inferences into bottom water conditions and oceanographic circulation patterns (Algeo and Rowe, 2012). Advances in ED-XRF hardware and software have helped reduce instrument size and improved detection limits. The appeal of using an ED-XRF is the significant increase in the number of samples that can be scanned in a given amount of time, as well as the non-destructive nature of the analysis. This is due to the reduced amount of sample prep required to scan slabbed core, as opposed to pressing pucks or creating fused glass disks for wavelength-dispersive XRF (Rowe et al., 2012).

Consistency and data quality were ensured by running a pressed pellet of an international carbonaceous shale standard (SARM 41), for both majors and traces. The standard was run whenever the instrument was initialized, or when the settings were changed (Ring, 1989). The raw counts were converted into elemental weight percentages utilizing Bruker’s proprietary software and empirical calibrations, as described in Rowe et al. (2012). The limits for these empirical calibrations are listed in Table 3.3 for major
elements (MA1.cfz) and Table 3.4 for trace elements (TR2.cfz). The major element calibration is applicable to the reported elements lighter than and including iron, but the calibration reports some heavier elements. The inverse is true for the trace element calibration, which is applicable to the reported elements heavier than iron. The empirical calibrations were made by comparing the results from multiple analytical methods, as applied to suite of 90 mudrocks of varying compositions (Rowe et al., 2012). The accuracy of the instrument is reduced for elements at the low end of the detection spectrum. This is relevant to this study as Mg is the second lightest major element reported and is significant rock forming element for certain carbonates.

Principle component analysis (PCA) was applied to elemental abundance values for elements that were the most pertinent mineralogical and environmental metrics: Al, Ca, Cr, Fe, K, Mo, S, Si, and Ti. The analysis was conducted using PAST3, a publicly available multivariate statistical computer software package for stratigraphic and paleontological data (Hammer et al., 2001). New interrelationships may be recognized by reducing many variables down to a few hypothetical variable “components” that account for most of the variance in the dataset, which is the basis of PCA. As part of the analysis, each variable is normalized, so differences in units do not influence the calculations (Harper, 1999).

Additional geochemical datasets were compiled utilizing a variety of methods for discrete subsamples from the Midland County core. Pioneer Natural Resources provided LECO total organic carbon values (n=39), and associated Rock-Eval pyrolysis data (n=32), that had previously been collected by industrial contract laboratories (McCarthy et al., 2011). In order to supplement the existing organic geochemical data, 42 subsamples from
the length of the core were crushed, powdered, and sieved before being sent to the University of Utah SIFER (Stable Isotope Ratio Facility for Environmental Research) laboratory. Additionally, 29 samples were taken from a 10 foot interval (185-175 ft) to produce a high resolution organic isotope geochemical dataset across a single interpreted cycle. To remove carbonate minerals, the powdered samples were leached with hydrochloric acid, until the resulting slurry was free of the dissolution reaction, and then washed with distilled water (Connin et al., 1997). The analyses utilized an elemental analyzer, coupled with isotope ratio mass spectrometer, configured for carbon and nitrogen (EA-IRMS-CN). The results provided stable isotope values for carbon ($\delta^{13}C_{\text{ORG}}$) and nitrogen ($\delta^{15}N_{\text{ORG}}$). The same analyses also provided total organic carbon (TOC), total nitrogen, and the carbon to nitrogen ratio (C:N). Stable isotope data is presented using delta ($\delta$) notation, which represents the difference between the isotopic ratio of a sample and an internationally accepted standard, per thousand or per-mille ($\%$). This is calculated using the following formula:

$$\delta_{(sa)} = \frac{R_{(sa)} - R_{(st)}}{R_{(st)}} \times 1000$$

Where $R_{(sa)}$ is the isotopic ratio of the sample (either $^{13}C/^{12}C$ or $^{15}N/^{14}N$), and $R_{(st)}$ is the isotopic ratio of the appropriate standard. In this study, the standards consisted of either Vienna Pee Dee Belemnite (VPDB) for carbon, and atmospheric air (AIR) for nitrogen (Bowen, 1991).

The molar carbon to nitrogen ratio (C:N) is an indicator of the provenance of organic matter. Land plants typically display C:N in excess of 20, whereas marine algae have C:N ratios less than 10 (Meyers, 1997). Values for C:N within the terrigenous range may be derived from marine algae due to preferential bacterial destruction of algal lipids
and proteins, or from nitrogen limited algal production (Meyers, 1997; Algeo et al., 2008). To distinguish the source of organic matter, C:N data is often plotted versus $\delta^{13}\text{C}_{\text{ORG}}$. The fractionation of carbon is different for the various photosynthesis pathways, therefore $\delta^{13}\text{C}_{\text{ORG}}$ can help determine the plant type that is source of the organic material (Meyers, 1997). Stable isotope values for organic carbon from marine sediments are also influenced by a number of factors that control the isotopic composition of dissolved inorganic carbon (DIC) in the water column (Bowen, 1991). The solubility of carbon dioxide in water is controlled by water temperature, whereas water pH influences the dominant molecular form of DIC used in photosynthesis. The rate of removal of DIC from the water column by primary productivity, and the recycling of $^{13}$C depleted bottom waters can both result in $\delta^{13}\text{C}_{\text{ORG}}{\%}$ excursions (Cohen, 2003).

Nitrogen isotope values provide possible insights into the nitrogen cycle within the basin. As the nitrogen cycle is complex, there are many factors that may result in nitrogen isotope excursions (Meyers, 1997). Fundamentally, any factor that impacts the rate of primary production or the dominant type of flora responsible for primary production will affect nitrogen isotope values. Such factors include changes in the supply of dissolved inorganic nitrogen, changes in mixing, and changes in water pH. Surface water processes influence denitrification in the bottom waters, further complicating the interpretation of nitrogen isotopes from sediments (Cohen, 2003; Algeo et al., 2008).

Organic petrography was conducted to identify the relative abundance of maceral types. Organic petrography provides a visual method for assessing the source of the organic material, which can be useful for comparison with the analytical chemistry methods. To this end, subsamples were coarsely crushed, sieved, mixed with epoxy, and then placed in
ring molds. Once the epoxy hardened, the resulting pucks were polished and oiled. Point counts (n=500) are conducted under white and fluorescent light utilizing a specialized reflected light microscope at the Kentucky Geological Survey (Ting, 1978; Chapman et al., 2015).

Thirty bulk carbonate subsamples were processed by SIRFER for stable isotope values for oxygen (δ^{18}O_{\text{CARB}} \text{‰}) and carbon (δ^{13}C_{\text{CARB}} \text{‰}). Analyses were conducted using a Thermo Fisher Scientific GasBench II coupled with a ConFlow IV interface and a MAT 253 mass spectrometer. Carbon isotopes from carbonate should reflect changes in the isotopic composition of dissolved inorganic carbon (DIC) in ocean water due to changes in global carbon cycle. Isotopic values for carbonate also reflect changes in the surface water temperature where the carbonate was precipitated, due to the inverse relationship between the solubility of carbon dioxide and water temperature (Saltzman and Thomas, 2012). When interpreting bulk isotope values for allochthonous carbonate deposits there are a wide range of qualifications and conditions that must be considered. Various organisms that deposit carbonate have vital effects that impact stable isotope values. The use of bulk samples is a hindrance to determining if an excursions is due to changes in the isotopic composition of DIC in ocean water, a change in the dominant fauna, or both. Additionally, there are a wide variety of diagenetic processes that will alter carbonate stable isotope values, obscuring the primary environmental signal. Due to these complexities the use of carbonate stable isotopes in study are most valuable for an initial comparison of the dolomites versus the gravity flow limestones (Keith and Weber, 1964; Saltzman and Thomas, 2012).
### Table 3.1 Midland County Core Datasets

<table>
<thead>
<tr>
<th>Data Set (s)</th>
<th>Method (s)</th>
<th>Resolution</th>
<th>Samples (n)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithostratigraphy</td>
<td>Core Logging</td>
<td>Lamination Scale</td>
<td>n/a</td>
<td>P. Ryan</td>
</tr>
<tr>
<td>Elemental Weight % (Major and Trace)</td>
<td>ED-XRF</td>
<td>2 inches</td>
<td>n=1579</td>
<td>P. Ryan and others</td>
</tr>
<tr>
<td>GR, RES, ROHB, and NPOR</td>
<td>Wireline tools</td>
<td>6 inches</td>
<td>n=639</td>
<td>PXD Subcontractors</td>
</tr>
<tr>
<td>TOC</td>
<td>EA-IRMS-CN, LECO</td>
<td>~3 feet</td>
<td>n=42</td>
<td>Utah SIRFER Lab</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>n=39</td>
<td>PXD Subcontractors</td>
</tr>
<tr>
<td>Organic δ¹³C, δ¹⁵N, and C:N</td>
<td>EA-IRMS-CN</td>
<td>~5 feet</td>
<td>n=42</td>
<td>Utah SIRFER</td>
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<tr>
<td>S1, S2, S3, H.I., O.I., P.I., and Tmax</td>
<td>Rock Eval</td>
<td>~10 feet</td>
<td>n=32</td>
<td>PXD Subcontractors</td>
</tr>
<tr>
<td>Bulk carbonate δ¹⁸O and δ¹³C</td>
<td>Gasbench-CO</td>
<td>Subsamples</td>
<td>n=30</td>
<td>Utah SIRFER Lab</td>
</tr>
<tr>
<td>Maceral Abundances</td>
<td>Organic Petrography</td>
<td>Subsamples</td>
<td>n=18</td>
<td>A. Eliopoulos and C. Eble (KGS)</td>
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### Table 3.2 ED-XRF Settings

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<th>Majors</th>
<th>Traces</th>
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<tr>
<td>“First” (Loaner)</td>
<td>15.00 keV, 40.00 µA</td>
<td>40.00 keV, 14.20 µA</td>
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<td>“Second” (New Tube)</td>
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<td>40.00 keV, 35.00 µA</td>
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<td>Filter #1-(No filter)</td>
<td>Filter #2-(0.001”Ti/0.012”Al beam filter)</td>
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<tr>
<td></td>
<td>Pulse Length 200</td>
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Table 3.3 Majors Calibration Limits

<table>
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<th>Element</th>
<th>Symbol</th>
<th>Atomic No.</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>11</td>
<td>964 ppm</td>
<td>8606 ppm</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>12</td>
<td>2412 ppm</td>
<td>10.25%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>13</td>
<td>9103 ppm</td>
<td>13.07%</td>
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<tr>
<td>Silica</td>
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<td>14</td>
<td>3.75%</td>
<td>38.20%</td>
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<tr>
<td>Phosphorous</td>
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<td>87 ppm</td>
<td>9819 ppm</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>16</td>
<td>200 ppm</td>
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</tr>
<tr>
<td>Potassium</td>
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<td>Calcium</td>
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<td>20</td>
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<td>34.66%</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
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<td>479 ppm</td>
<td>5336 ppm</td>
</tr>
<tr>
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<td>22 ppm</td>
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<td>Chrome</td>
<td>Cr</td>
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<td>10 ppm</td>
<td>295 ppm</td>
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<tr>
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<td>Iron</td>
<td>Fe</td>
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<td>Cobalt</td>
<td>Co</td>
<td>27</td>
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<td>46.8 ppm</td>
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<tr>
<td>Nickel</td>
<td>Ni</td>
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<td>14 ppm</td>
<td>302 ppm</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>29</td>
<td>5 ppm</td>
<td>429 ppm</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>30</td>
<td>20 ppm</td>
<td>836 ppm</td>
</tr>
<tr>
<td>Barium</td>
<td>Ba</td>
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<td>1.50%</td>
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Table 3.4 Traces Calibration Limits

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<th>Atomic No.</th>
<th>Minimum</th>
<th>Maximum</th>
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<tbody>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>20</td>
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<td>34.66%</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
<td>22</td>
<td>479 ppm</td>
<td>5336 ppm</td>
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<tr>
<td>Chrome</td>
<td>Cr</td>
<td>24</td>
<td>10 ppm</td>
<td>295 ppm</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn</td>
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<td>77 ppm</td>
<td>1239 ppm</td>
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<tr>
<td>Iron</td>
<td>Fe</td>
<td>26</td>
<td>4267 ppm</td>
<td>6.53%</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Co</td>
<td>27</td>
<td>1.4 ppm</td>
<td>46.8 ppm</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni</td>
<td>28</td>
<td>14 ppm</td>
<td>302 ppm</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>29</td>
<td>5 ppm</td>
<td>429 ppm</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>30</td>
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<td>&lt;1 ppm</td>
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<td>41</td>
<td>2 ppm</td>
<td>16 ppm</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Mo</td>
<td>42</td>
<td>&lt;1 ppm</td>
<td>166 ppm</td>
</tr>
<tr>
<td>Tin</td>
<td>Sn</td>
<td>50</td>
<td>&lt;1 ppm</td>
<td>14 ppm</td>
</tr>
<tr>
<td>Antimony</td>
<td>Sb</td>
<td>51</td>
<td>&lt;1 ppm</td>
<td>47.1 ppm</td>
</tr>
<tr>
<td>Barium</td>
<td>Ba</td>
<td>56</td>
<td>30 ppm</td>
<td>1.50%</td>
</tr>
<tr>
<td>Lead</td>
<td>Pb</td>
<td>82</td>
<td>&lt;1 ppm</td>
<td>28 ppm</td>
</tr>
<tr>
<td>Thorium</td>
<td>Th</td>
<td>90</td>
<td>2 ppm</td>
<td>14 ppm</td>
</tr>
<tr>
<td>Uranium</td>
<td>U</td>
<td>92</td>
<td>1 ppm</td>
<td>51 ppm</td>
</tr>
</tbody>
</table>
Figure 3.1. Labeled Core Box and Instrument Setup for ED-XRF
(A) Photograph of a box of the Midland County core measured and marked with orange stickers for analysis with the ED-XRF. Note the section that has been removed by a corporate contract laboratory, and replaced with a blue foam spacer. (B) Image of the Bruker Tracer IV-SD handheld ED-XRF in use. The plexiglas box supports longer, heavier sections of core to protect the XRF device.
CHAPTER FOUR: RESULTS

4.1 Lithofacies

The objectives of the coring campaign conducted by Pioneer Natural Resources was to recover continuous core from the lower Wolfcamp interval. Based on petrophysical analyses conducted by that company, the Midland County core is known to have captured three stratigraphic units: the Strawn Formation, the Wolfcamp D (WC-D), and the Wolfcamp C2 (WC-C2). In this study, seven lithofacies have been identified within the WC-D and WC-C2, which are a mixture of siliciclastic mudrocks and carbonates. The Strawn Formation contains a variety of carbonate lithofacies, but since this formation is not an unconventional petroleum target, it will not be addressed in extensive detail in this study. There is significant vertical variability in the distribution of lithofacies throughout the lower Wolfcamp section (Figure 4.1).

Three different mudrock lithofacies have been recognized in the core, including a grey mudrock (GMR) and two variants of black mudrock (BMR-1 and BMR-2). In terms of relative abundance, GMR is the most common lithofacies type present throughout the lower Wolfcamp intervals in the Midland County core (Figure 4.1). However, from the perspective of reservoir characterization, the BMR-1 stands out for its potential for unconventional petroleum resources. These lithofacies in the Midland County core are similar to those found in a core from Upton County, and descriptions of those facies were used as a guide in characterizing the lithofacies in the Midland County Core (Baldwin, 2016).

One prominent means by which the black mudrock lithofacies can be distinguished and differentiated is by inorganic and organic geochemical tools. These
geochemical differences are important, because BMR-1 and BMR-2 are often difficult to distinguish in hand sample. The major element geochemical profile for BRM-1 is typified by high silicon (>26%), low aluminum (<6%), and low calcium (<4.5%) (Figure 4.2). Total organic carbon (TOC) content for BMR-1 ranges from 2.17 wt. % to 7.83 wt. %, with a mean %TOC of 5.15. Additionally, BMR-1 has relatively high concentrations of the trace metals molybdenum, chromium, and vanadium (Supplemental Table 1 and Figure 4.3). In establishing chemical traits for the different black mudrocks, the major element (%Si, %Al, %Ca) cutoffs listed above were treated chiefly as an interpretive guide. In other words, the geochemical tools hold the strongest power when used in conjunction with the lithostratigraphic and physical facies characteristics. This data integration method mandates that individual maximum and minimum elemental values may be slightly higher or lower than the cutoffs we used in the analysis (Supplemental Table 1). In hand sample, BMR-1 ranges in color from very dark grey to black, and it is mainly massively bedded and ungraded. Although evidence of bedding is uncommon, parallel-to-subparallel thin beds and laminations are occasionally present in the BMR-1 facies (Figure 4.4). A distinguishing characteristic of BMR-1 is the presence of phosphate nodules, which are common in many beds and express a round, lenticular, or flattened morphology. The phosphate nodules can be wider than the diameter of the core (4 inches), but they are usually much thinner, and can be less than a 1 inch thick. Often, the phosphate nodules appear flattened, and can resemble thin beds or laminations that span the full width of the core. Less compacted oval-shaped phosphate nodules are occasionally present, and different nodule morphologies may appear together in the same beds of BMR-1. Due to the size of the nodules, they were sometimes scanned by the XRF
during routine operation. The nodules are highly enriched in phosphorous, and relatively enriched in calcium and magnesium in comparison to the black mudrock matrix that surrounds them. In thin-section, a distinguishing characteristic of BMR-1 is the presence of faint, mm-scale laminations made of silt and sand size Tasmanites cysts that are filled with recrystallized biogenic quartz. Similar Tasmanites were encountered in BMR-1 within the Upton County core, though in many cases these quartz-filled cysts were dispersed throughout the fine-grained matrix and lacked any suggestion of a bedding fabric (Baldwin, 2016) (Figure 4.4). Beds of BMR-1 are up to 5 ft thick at the maximum, and they can be as thin as a few inches thick. Mineralized fractures, both horizontal and vertical oriented, also occasionally occur in BMR-1 beds.

We interpret the BMR-1 facies type to have been deposited by suspension fallout (gravitational settling) in a basin with relatively slow sedimentation rates. Patterns of elevated TOC indicate that the bottom waters of the basin were anoxic to euxinic, which aided in the preservation of organic matter. The presence of phosphate nodules is interpreted to be the result of high primary productivity in the basin during deposition, which may be related to circulation patterns and upwelling, which would have assisted in nutrient flux to surface waters and ultimately the deposition of TOC-rich rocks (Algeo et al., 2008). The abundance of flattened and silica filled Tasmanites cysts also indicate elevated productivity (Schieber, 1996; Schieber et al., 2000). It is plausible that elevated production exerted a feedback on bottom water anoxia, as available oxygen on the sea floor was consumed due to decomposition of abundant labile organic material that had settled from the photic zone. With only a few exceptions, beds of BMR-1 are massive; only occasional faint laminations were discovered. The scarcity of fine laminations and
absence of fissility result in the facies being classified as a mudrock instead of a shale. To be classified as a true shale, the facies would need to exhibit pervasive macroscopic laminations and fissility, similar to the Devonian Ohio Shale of eastern Kentucky (Ettensohn et al., 1988; Potter et al., 2005). The discontinuous or planar laminations of quartz-filled *Tasmanites* cysts do not appear to impart fissility to the vast majority BMR-1 beds.

The second and more abundant black mudrock facies type (BMR-2) is characterized by a different chemical composition than BMR-1. The geochemistry of the BMR-2 lithofacies is defined by <26% silicon, >6% aluminum, or >4.5% calcium (Figure 4.2). Additionally, BMR-2 is not as enriched in the trace metals molybdenum (µ=17.10 ppm), chromium, and vanadium as BMR-1 (Supplemental Table 1; Figures 4.2, 4.3, and 4.5). Furthermore, BMR-2 exhibits a mean wt. % TOC of 3.81, which is lower than that of BMR-1 (µ=5.15 wt. %). However, the range of %TOC values for BMR-2 is quite wide, with values at higher and lower extremes than the BMR-1. In hand sample, BMR-2 appears very dark grey to black, but it is often discernably lighter in color than BMR-1. Most often, BMR-2 exhibits massive bedding characteristics; where present, visible internal structures are limited to parallel-to-subparallel, continuous-to-discontinuous laminations. In contrast to BMR-1, phosphate nodules are relatively uncommon in BMR-2. An important difference between BMR-1 and BMR-2 is the macrofossil content. Whereas carbonate fossils (or fossil hash) of shelf fauna or algae are entirely absent from BMR-1, they can be common in BMR-2 (Figure 4.5). Macrofossils in BMR-2 are often coated or replaced by pyrite. In thin section, BMR-2 is distinguished from BMR-1 by a difference in depositional fabric. Whereas BMR-1 has continuous-to-discontinuous
laminations, BMR-2 displays a more disrupted and massive texture with occasional
evidence of burrowing. There are abundant silt to sand sized silica-filled *Tasmanites* in
BMR-2, but these cysts do not form discrete laminations to the same degree as in BMR-1. The textural distinctions between BMR-1 and BMR-2 are consistent with the findings
of Baldwin (2016) in a lower Wolfcamp core from Upton County, Texas.

The BMR-2 facies type is interpreted to have been deposited by suspension
fallout in a marine basin characterized by slow sedimentation rates and elevated primary
productivity. However, the environmental conditions that resulted in BMR-2 deposition
appear to differ from those that resulted in BMR-1, in that bottom water anoxia was
apparently not as pronounced or as pervasive, which would have influenced the
preservation of organic matter within the mudrock matrix. The main evidence in support
of this interpretation are organic carbon and trace metal content (Supplemental Table 1),
which are markedly lower than BMR-1. The absence of phosphate nodules may indicate
lower production rates than those that prevailed during BMR-1 deposition, or perhaps an
absence of nutrient fertilization driven by upwelling. The disrupted microfabric of BMR-2
is interpreted to have resulted from bioturbation, very likely indicating the presence of
soft-bodied infauna (Hoffman et al., 1998). The presence of infaunal organisms suggests
that oxygen stress was less severe during the deposition of BMR-2 relative to the
environment of BMR-1. Beds of BMR-2 range from less than 1 ft to up to 8 ft thick. Both
horizontal and vertical mineralized fractures also occur in BMR-2 beds.

The grey mudrock facies type (GMR) is light-to-medium grey, and occasionally
tan in color. The inorganic elemental composition of GMR is defined by a relatively low
silicon content (µ=22.74 wt.%), high aluminum (µ=5.99 wt.%), and high calcium content
(μ=5.16 wt.%). The TOC content of GMR is low in comparison to the BMR lithofacies types, with a range from 0.79 to 3.15 and a mean of 1.69 wt.%. (Supplemental Table 1, Figures 4.2 and 4.3). Perhaps the most distinguishing characteristic of the GMR facies is its abundance and diversity of macrofossils, which far exceeds even that of BMR-2, not to mention the barren BMR-1 (Figure 4.5). The fossil content of GMR often consists of fragmented, sand-sized shell hash. In cases where shells are reasonably well-preserved, we have identified several types of bivalves, echinoderms, gastropods, and fragments of coral. On a relative basis, the shells within the GMR facies type are not pyritized as often as they are in BMR-2, but replacement pyrite does appear in several intervals. Pyritized burrows, as well as burrows distinguished by mineralogical differences between the burrow walls and the surrounding mud matrix, are common in GMR. Bioturbation and trace fossils are pervasive throughout GMR, with clear evidence present on bedding planes exposed by decompression fracturing. Due to the bioturbation, the GMR facies rarely contains well-defined laminations and massive bedding characteristics prevail. Scoured, sharp, and well-defined bedding planes comprised of abundant skeletal fragments above a basal contact are the most prominent physical sedimentary structures in the GMR facies type.

The depositional mechanism for the GMR facies is interpreted as a combination of suspension settling and low-concentration turbidity currents. The evidence for turbidity current activity include the sharp-basal contacts and re-sedimented coarse skeletal material. There are examples of both coarse lags enriched in skeletal fragments created by scouring currents, as well as graded thin-beds deposited from waning turbidity flows. The average values for %Al, %K, and %Ti are higher in GMR than those of
BMR-1 and BMR-2, which indicate greater input of terrigenous clay minerals. Titanium in particular is only found in the weathered products of continental rocks (Tribovillard et al., 2006), whereas potassium and aluminum are frequently associated with clay minerals like illite. High relative %Ca in the GMR beds is best explained by flushing of shelf carbonates (both fine muds and coarser allochems) into the basin, most likely from the Central Basin Platform (Figure 1.1).

The limestones present in the upper portion of the Midland County core (WC-C2 and WC-D) are best described as grainstones, according to Dunham’s classification, due to the abundance of coarse carbonate allochems that dominates the fabric, combined with a paucity of mud matrix (Dunham, 1962). The inorganic chemical composition of the GNST facies is enriched in calcium (µ=17.99 wt.%) and contains intermediate concentrations of silicon (µ=14.16 wt.%) and low concentrations of aluminum (µ=2.65 wt.%). In hand sample, beds of the grainstone facies type (GNST) appear either massive or normally graded with pronounced scours along basal contacts. In some instances, thin wavy laminae that consist of siliciclastic clay and silt may be interbedded with thin GNST. Examination of hand samples using a Dino-Lite® digital microscope shows that the size of individual allochems that comprise the GNST are typically greater than ~62.5 microns in diameter. Identifying the organisms that produced the individual grains of the GNST facies type is not possible, however, because the skeletal material has been fragmented and abraded into a nearly uniform carbonate sand. Pyrite laminations within the grainstone beds are a common occurrence. The tops of the grainstone intervals are often bioturbated, and burrows are made obvious by the color and textural contrast between the limestone and overlying mudrock. In the Midland County core, GNST facies
occurs as very thin beds, often < 2 inches thick. This pattern results in only a small fraction of the total Wolfcamp section being classified as GNST (Figure 4.1).

The deposition of the GNST facies type is interpreted to be the result of low concentration turbidity currents that are composed of carbonate debris from the shelf. Thus, GNST represent re-sedimented allochthonous carbonates. The scoured bases, massive or normal grading, and occasional wavy laminae of the GNST beds are consistent with the Bouma sequence model for low-density turbidites (Shanmugam, 1997). Examples of the GNST facies type, which illustrate these important depositional textures, are shown in Figure 4.6.

The dolostone facies (DOL) is characterized by its massive, crypto-crystalline internal texture and relative enrichment in magnesium ($\mu$=3.53 wt.%). Based on x-ray diffraction (XRD) analyses conducted by Core Laboratories, the DOL beds consist of ~13 to 67 wt. % dolomite, and ~4 to 13 wt. % calcite. In terms of chemical composition, DOL facies is enriched in calcium ($\mu$=17.08 wt.%), with relatively low silicon ($\mu$=10.75 wt.%) and aluminum ($\mu$=3.26 wt.%) content. When examined with a Dino-Lite® digital microscope, hand samples of the DOL facies type appears to be composed chiefly of interlocking crystalline cement. Macrofossils and evidence of burrowing are rare or absent in most DOL facies type intervals, with the exception of the DOL bed at 91 ft (Supplemental Figure 2). The DOL bed at 91 ft in the core is notable as it is relatively thin, has evidence of burrows, and includes carbonate macrofossils. The beds of the DOL facies type range from 0.5 to 3 ft in thickness. In most cases, the assessment of the DOL facies type was impaired by particularly poor core recovery above and below DOL.
intervals, which obfuscates the examination of the transitions into and out of the DOL deposition.

The DOL intervals are interpreted to be subaqueous hardgrounds that formed during periods with extremely slow sediment accumulation. Hardgrounds cements are precipitated from seawater circulating through the top layer of sediment, which implies a burial diagenesis origin (Flügel, 2004). Aragonite and high-magnesium calcite are common chemical precipitates in hardgrounds, which are typically altered by diagenesis to calcite and dolomite. Post-depositional diagenesis may also play a role in altering the cement to dolomite during burial. There are many other models for the dolomitization, all of which involve the mixing of chemically disparate fluids that result in cation exchange. The fluids involved are typically meteoric waters, or highly saline brines interacting with marine pore waters in the limestone rocks. These models are most applicable to carbonate platforms, where there is sufficient hydrological head to facilitate the advection of the pore fluids, and most are not relevant to a deep basin environment (Flügel, 2004). Burial dolomitization is an alternative model, with pore waters enriched in Mg\(^{2+}\) (by the conversion of smectite to illite in muds) are expelled during dewatering (Flügel, 2004).

A minor facies type in the Midland County core, but much more prevalent in the Upton County Core, is what Baldwin (2016) referred to as the Mixed facies type. The Mixed facies consists of convoluted laminations, thin beds, and allochems or intraclasts of carbonate admixed within a matrix BMR-2. An example of the Mixed facies from core is shown in Figure 4.7. The inorganic chemical composition of the Mixed facies are therefore similar to BMR-2, and show enrichment in %Ca, and variable %Al, %K and %Ti. The trace metal concentrations of the mixed facies type are similar to BMR-2. The
only occurrence of the Mixed facies type is a 10-inch interval (8.35-9.668 ft) within the WC-C2 interval.

The depositional mechanism responsible for the genesis of the Mixed facies type is interpreted to be soft-sediment deformation (Baldwin, 2016). Soft sediment deformation in allochthonous, basinal carbonates from the early Permian in the Midland basin have been recognized by others, but those authors did not propose a clear mechanism for formation (Hobson et al., 1985). There is a wide variety of soft sediment mechanisms identified in other systems, which required extensive outcrop, or 3D seismic to identify (Silva and Booth, 1985; Alves, 2015). Toe thrusting driven by creep up-dip is a possible deformation mechanism, given the distance of the coring location from fault-bounded uplifts (Schlager and Reijmer, 2009). Another possible mechanism for the deformation is seismicity, given the relative proximity to an active orogeny, and deposition in a complex foreland (Horak, 1985; Atchley et al. 1999, Ettensohn et al., 2011). Positive identification of earthquake-induced liquification requires further study and better spatial coverage with the datasets, but considering the basin center, low-relief position of the Midland County core site, this mechanism cannot be discounted.

The final facies type identified within the lower Wolfcamp sections of the Midland County core are Diagenetic Mineralized Beds (DMB), which are thin beds characterized by abundant authigenic and digenetic minerals, including pyrite, phosphate, and glauconite. Examples of the DMB facies type from core photos are shown in Figure 4.7. Within packages of DMB, coarse lags of calcareous and pyritized skeletal fragments are often present. These beds lie directly on top of sharp or scoured surfaces and the phosphate nodules in these beds may have angular facets, indicating transport and
reworking. The DMB’s are very thin (<1-6 in thick), and occur intercalated with black mudrock intervals. Two of the DMB’s occur near the bottom of the WC-D (~261 and 245 ft), while another is present near the middle of the WC-D (~144 ft).

Diagenetic or authigenic minerals are known to form at the sediment water interface, as well as during shallow burial within black shales (Schieber, 1998). There are multiple pathways for the formation of iron sulfides like pyrite in black mudrocks or shales (Schieber, 2011). The pyrite found within the WC-D is pelodial in nature, or it forms as a replacement of calcareous skeletal fragments (Schieber, 2011; Baldwin, 2016). Phosphate nodules are associated with high productivity, and the export of phosphorus from the water column to the deposited sediment. The nodules also often nucleate around phosphatic skeletal fragments (Schieber, 1998; Li and Schieber, 2015). Glauconite formation is thought to occur in mid-shelf environments, with slow sediment accumulation rates, during shallow burial, or during diagenesis (Chafetz and Reid, 2000).

Scouring currents along the sea floor remove fines (clays, silt, and organic material), and leave behind lags of coarse material. In anoxic muddy depositional environments, the coarse mineral fraction is often composed of diagenetic minerals. The coarse minerals are left behind by winnowing currents as a lag, despite forming from different geochemical processes (Schieber, 1998).

4.2 Lithostratigraphy

Basic formation tops were provided with the Midland County core data suite that was delivered to us by Pioneer Natural Resources. Petrophysical data were used to split up the core into three formations, which (from oldest to youngest) include the Strawn
Formation, Wolfcamp-D (WC-D), and the Wolfcamp-C2 (WC-C2). In the Midland County core, the Strawn Formation makes up the base of interval, from 320 to 263 ft (~57 ft long). Overlying the Strawn Formation is the WC-D, from 263-15.5 ft (~247.5 ft long). Ultimately, the upper 15.5 ft of the core are the WC-C2. According to available fusulinid biostratigraphy and basin-wide well log correlations completed by Pioneer Natural Resources scientists, the Strawn interval captured at the base of the Midland County core is believed to be early Desmionesian age (Waite et al., 2015). The WC-D was deposited from the later Desmionesian, Missourian and into the Virgilian, making it equivalent to the upper Strawn, Canyon and Cisco Formations on the shelf. The WC-C2 is likely to be of earliest Wolfcampian age (Waite et al., 2015; Figure 2.3). As part of this study, the WC-D has been divided into three sub-units based on vertical changes in lithofacies abundances and stacking patterns. The sub-intervals are herein named the Lower (263 to 186 ft), Middle (186 to 100 ft) and Upper WC-D (100 to 15.5 ft).

The Strawn Formation in the Midland County core consists of a variety of shelf carbonates (mudstones, wackestones, and packstones) with occasional argillaceous interlaminations. Nodular, wavy-parallel, and wavy-non-parallel bedding are the most common depositional fabrics. Chert nodules, as well as macro-skeletal fragments from echinoderms, bryozoans, foraminifera, and brachiopods, are pervasive throughout the Strawn. The top of the Strawn at 263 ft in the core is marked by an abrupt facies transition from carbonates to mudrocks, which is likewise reflected in a significant positive shift in gamma ray signature (Supplemental Figure 2).

The lower WC-D lies directly above the Strawn. The Lower WC-D interval is ~80 ft thick (263 - 183 ft). The top of the Strawn is marked by a scoured surface that contains
a mixture of both pyritized and unaltered carbonate skeletal fragments within a bed of BMR-2. The basal ~24 ft of the Lower WC-D is unique in that it includes two DOL beds and two thin DMB beds (Supplemental Figure 2). Otherwise, it is composed of interbedded BMR-2 and GMR that vary in thickness from 1 to 8 ft. There is a relatively thick interval of DOL (~3 ft) at 225 ft in the core and two thinner DOL intervals within the bottom 16 ft of the WC-D. Altogether, this results in the Lower WC-D having the highest proportion of DOL of the Wolfcamp intervals in the core (7.7%; Figure 4.1). There are 25 ft of fossiliferous GMR near the top of the Lower WC-D, with multiple lags of skeletal fragments and glauconite. This interval is capped by the first occurrence of the GNST facies (Supplemental Figure 2). This thick package of GMR forms the transition between the Lower and Middle WC-D, because it separates two different lithofacies stacking patterns. The Lower WC-D is GMR rich (67.2%), and has the least BMR-1 (2.7%) of the WC-D sub intervals (Figure 4.1).

The Middle WC-D is found from 183 to 100 ft in the core (~83 ft total length). The stratal stacking pattern changes significantly when moving from the Lower into the Middle WC-D. The Middle WC-D is marked by a higher abundance of BMR-1 and a more systematic vertical succession of facies types. The Middle WC-D consists of ~24% BMR-1, which is the most of the Wolfcamp sub intervals (Figure 4.1). The typical vertical facies succession is 15 to 20 ft thick, and there are five repetitions of these cycles in the Middle WC-D. Each lithofacies succession is comprised of BMR-1 overlain by BMR-2, which transitions into GMR. Within the GMR intervals, there are intercalated beds of DOL and GNST that are typically less than <3 ft thick. Not every interval includes both the DOL and GNST beds, but each succession does always include at least
one of these carbonate facies types. Most of the grainstones in the Middle WC-D are thin and separated from one another by at least 2 ft of GMR. The regular repetitive sequence of facies types, and close spacing of black mud rock bedsets (BMR-1 overlain and underlain by BMR-2) is the defining characteristic of the Middle WC-D.

The Upper WC-D is from 99.835 to 15.5 ft of the Midland County core (~84 ft in length). The defining characteristic of Upper WC-D is that it contains the lowest proportion of GMR, and the highest proportion of BMR-2 for the WC-D sub-intervals (Figure 4.1). Like the Lower WC-D, the Upper WC-D is separated from the Middle WC-D by a thick (~32ft) bedset dominantly comprised of GMR, with several thin interbeds of BMR-1, BMR-2, DOL, and GNST. The two DOL beds in this interval account for all of the DOL within the Upper WC-D. Above the transitional bed at 55 ft, the Upper WC-D mostly consists of BMR-1 and BMR-2. The top of the Upper WC-D is split by a bedset from 39 to 27 ft, composed of GMR, four GNST beds, and minor intercalated BMR-2. The black mudrocks (BMR-1 and BMR-2) of the Upper WC-D are relatively continuous (~10 to 20 ft), lacking GMR, GNST and DOL interbeds, which are common in the Middle WC-D.

The WC-C2 section of the Midland County core is only 15.5 ft long and it mainly consists of interlayered GMR and BMR-2. The only occurrence of the Mixed facies type in the Midland Basin core is in the WC-C2, and it is less than ~1 ft thick. Due to the limited section captured in core, no generalization about repetitive patterns in lithofacies deposition in the interval can be made in this study.

Marked changes in facies abundances and vertical stacking patterns characterize WC-D in the Midland County core. The Lower WC-D is dominated by GMR, and this
interval has the highest proportion of DOL. The Middle WC-D has the greatest proportion of BMR-1, and has the most regularly repetitive cycles of facies types. The Upper WC-D is represented by an increase in the number of BMR-2 beds, and indistinct facies stacking. The WC-C2 interval is short, but appears to follow the same trend as the Upper WC-D, with a higher proportion of BMR-2 and a paucity of BMR-1 (Figure 4.1).

4.3 Geochemistry

The high-resolution XRF analysis resulted in 1,620 sample points and 3,240 total major and trace element analyses. The 2-inch sampling interval allowed for the examination of the highly variable, interbedded lithofacies, which are sometimes hard to distinguish with macroscopic core examination. The geochemical data collected for this study correlates well with the physical lithofacies characteristics, as well with the wireline logs (Supplemental Table 1, and Supplemental Figure 1).

The major elements of main concern are aluminum, calcium, iron, magnesium, potassium, silicon, sulfur, and titanium, as they are important constituents of the common rock forming minerals (clays, calcite, dolomite, feldspars, ferromagnesian silicates, pyrite, and quartz). The trace metals that are known to be sensitive to changes in the redox conditions (Mo, Cr and V) were also evaluated (Tribovillard et al., 2006; Algeo and Rowe, 2012).

Examination of univariate chemostratigraphic plots (elemental abundance versus depth) shows high frequency variability throughout the upper 263 ft of the Midland County core (Supplemental Figure 1). This variability is best illustrated by the curves for
Al, Si, Ca, Mg, Mo, and TOC. The highest frequency variability occurs from 186 to 86 ft, which equates to the Middle WC-D.

Moving up the core from the top of the Strawn, the most significant trend is a gradual increase in %Al and %K, as more mudrocks are encountered in the strata. The rising trend of the %Al and %K curves is occasionally interrupted by abrupt deflections to lower values associated with the presence of DOL beds. Approximately half-way up the Lower WC-D (221 ft) sub-unit, the %Al and %K curves start to decline, and continue to do so until the transition at the base of the Middle WC-D sub-unit. Throughout the Lower WC-D, the %Ca curve repeatedly increases gradually until it spikes dramatically to higher values in association with DOL beds. Directly above DOL beds, %Ca is at a local minimum, and begins to gradually increase again, repeating the pattern. Over the length of the Lower WC-D sub-interval, %Si and %Ca curves inversely covary, but neither shows a pronounced long term trend (Supplemental Figure 1).

In the Middle WC-D, %Al and %K track each other closely, but any long-term trend is obscured by the high frequency variability. The curves for %Si and %Ca are much more variable within the Middle WC-D. If the abrupt spikes due to interbedded carbonates (DOL and GNST) are ignored, there are also subtle but significant trends in %Si, %Al, %K and %Ti. These curves have cyclic shifts in their ranges, reflecting the cycles in the stacking of lithofacies. The transitions from BMR-1 to BMR-2 and GMR are reflected in decreases of %Si while inversely %Al, %K, and %Ti increase. As the lithofacies cycle continues with the opposite progression (GMR, to BMR-2, then BMR-1) the reverse pattern in chemostratigraphy is observed, with %Si increasing while %Al, %K and %Ti decrease (Supplemental Figure 1).
At the transition into the Upper WC-D, the %Si curve becomes less variable, and takes on a weak long-term trend of decreasing values (from >30 wt. % to <20 wt. %). Upper WC-D shows a long-term increase in %Al and %K, and short-term variability of these elements declines in this interval (Supplemental Figure 1). In the upper portion of the Upper WC-D and into the WC-C2, there are three cycles where %Si values shift from high to low, following the facies changes. The %Si and %Al curves move gradually in opposing directions in the Upper WC-D, in contrast to the high-frequency shifts observed in these elements within the Middle WC-D. Besides the large abrupt spikes in %Ca that are associated with carbonate facies, the baseline weight percent values of %Ca gradually increase then decrease through the Upper WC-D. The %Mg curve is dominated by large spikes associated with the DOL intervals, but the amplitude of the spikes increase moving up section through the core.

The first two principle components determined by the principle component analysis (PCA) account for ~66% of the variance in the elemental geochemical data. The first principle component (PC1) accounted for 43.83% of the variance in the data set, and loaded positively for %Si, %Al, %K, and %Ti (Figure 4.10). Calcium showed a strong negative loading for PC1, whereas S had a weak negative loading and Fe a weak positive loading. Therefore, we interpret the PC1 curve chiefly as a proxy for siliciclastic (positive) and carbonate (negative) lithologies. The second principle component accounted for 22.45% of the variance in the data set, and showed a strong positive loading with the redox sensitive elements Mo, Cr, Fe and S. Additionally, PC2 has a strong negative loading for elements associated with terrigenous minerals (Al, K and Ti) and a weak negative loading for Ca. Therefore, we interpret PC2 as an indicator of
bottom water redox conditions, where strongly positive values indicate anoxic and potentially euxinic conditions, which are interpreted to be conducive to the preservation of organic matter (Figure 4.10).

The direction and periodicity of the shifts in the PC1 reflect changes in the major rock forming elements and therefore it tracks lithofacies stacking patterns. At the base of the Lower WC-D, the PC1 curve is erratic, due to the thin and highly variable lithofacies. Above 238 ft, the PC1 curve stabilizes, as the lithofacies are mostly GMR and BMR-2. There are strong negative deflections associated with carbonate beds, and weak negative deflections related to GMR intervals that are especially fossil rich (Supplemental Figure 3). The PC2 curve attains its highest positive values in the 24 ft above the Strawn, and is generally low for the rest of the Lower WC-D, with short and low-amplitude positive excursions associated with BMR-2 beds. In the Middle WC-D, the curves for PC1 and PC2 become more variable, with repetitive sequences of positive and negative deflections (Supplemental Figure 3). Strong positive deflections in both PC1 and PC2 are associated with BMR-1 beds, whereas negative deflections are associated with beds of the carbonate (DOL and GNST) facies. Beds of BMR-2 are associated with PC1 values close to zero, and low amplitude positive values for PC2, signifying slightly different redox conditions than those that existed during the deposition of BMR-1. The GMR facies type is reflected by gradual decreases from low positive to moderately negative values for both PC1 and PC2, again reflecting the abundance of finely comminuted fossil material that was mostly likely deposited under transient oxic conditions on the bottom of the Midland Basin sea floor. The Upper WC-D is characterized by similar patterns as in the Middle WC-D, but the periodic deflections in both curves are more gradual (Supplemental Figure 3).
The organic matter stable isotope data is presented as a cross plot of the carbon to nitrogen molar ratio (C:N) versus δ¹³C ‰, broken out by the different facies types (Figure 4.9). The values presented are from samples along the whole length of the core, as well as the high-resolution sample set from approximately 185 to 175 ft, spanning the boundary of the Lower and Middle WC-D. Most of the samples (~57%) have molar C:N of less than 10, indicative of a marine source for the organics (Meyers, 1997). Samples with C:N below 10 have a ~4‰ range in δ¹³C, between approximately -23‰ and -27‰. As C:N increases, there is an associated increase in the range of δ¹³C. Samples with C:N between 10 to 15 (n=18) have δ¹³C values between -21‰ and -27.5‰. Carbon-to-nitrogen ratios in excess of 15 have the widest spread in δ¹³C values (-15‰ to -30‰). By facies type, the BMR-1 has the highest average C:N (~17), BMR-2 is second highest with an average of ~13.5, and GMR samples had the lowest average ration of ~8.4. This may indicate that the BMR-1, and to a lesser extent BMR-2, have proportionally more terrigenous organic material. Alternatively, nitrogen may be depleted from the system during the deposition of these facies, which would drive C:N values artificially higher.

For example, nitrification may have been prevalent in the Midland Basin during the Late Pennsylvanian, as this process is known to take place in anoxic marine environments (Algeo et al., 2008). Nonetheless, Maceral point counting reveals a similar trend, with a primarily marine organic source, but an increasing terrestrial component in higher TOC samples. Inertinite is the most prevalent terrestrial maceral in samples with elevated terrestrial organic matter (Chapman et al., 2015). Differences in hydrodynamic sorting between inertinite and siliciclastic clay minerals may account for why BMR-1 and BMR-2 have low %Al and %K, but increased concentrations of terrestrial organics. The
refractory nature and low density of inertinite may allow for a greater distance of transportation, as compared to clay minerals (C. Eble personal communication, 2015).

The organics incorporated in the GMR facies type are more dominantly marine in their provenance signature.
Figure 4.1. Normalized Facies Abundances for Wolfcamp Subintervals. The relative proportion of each Wolfcamp sub-interval composed of each lithofacies type. The proportions are calculated using the facies type assigned to each XRF analysis point. (A) Wolfcamp-C2. (B) Upper Wolfcamp-D. (C) Middle Wolfcamp-D. (D) Lower Wolfcamp-D.
Figure 4.2. Aluminum versus Silicon Elemental Values
Cross plot of weight percent Al versus weight percent Si, broken down by facies type. The BMR-1 facies type has less than 6.0 wt. % Al, and overall highest %Si of the lithofacies types. By definition BMR-2 facies type contains high values of %Al, in excess of 6.0 wt. %. The BMR-2 points with less than 6.0 wt. %Al also generally have lower concentrations of silicon. The GMR facies type plots towards the bottom left, due to calcium dilution and the prevalence of finely fragmented fossil material.
Figure 4.3. Molybdenum (Mo) Concentration by Facies Type in the Wolfcamp-D Subinterval
Histograms of Mo concentrations, broken out by mudrock facies type and Wolfcamp-D subinterval. While there is simply not enough BMR-1 in the Lower WC-D to make a robust analysis, it is clear that within the Middle and Upper WC-D, BMR-1 trends to have higher concentration of Mo. The Mo concentrations within the GMR type are consistently much lower than those in BMR-2. These patterns can be attributed to sea level and bottom water anoxia. See text for details.
Figure 4.4. Major Facies Types in Hand Sample and Photomicrograph
Photographs of lithofacies types that make up the majority of the stratigraphy of Midland county core. Photos at top are photographs of the slabbed core, whereas photos at bottom are photomicrographs. From left to right, the facies are BMR-1, BMR-2, GMR, GNST, and DOL. The mudrock facies type photomicrographs are of thin sections taken on a transmitted light microscope, with plain light. The GNST and DOL facies types had no available thin sections, so the photographs of hand samples were taken with a Dino-Lite® handheld microscope instead.
Figure 4.5. Macrofossil Abundance Classification for Mudrock Facies Types
Top: The normalized percent of each mud rock facies type classified with a given macrofossil abundance, using categories assigned to each XRF analysis point.
Bottom: Examples of each macrofossil abundance classification, in core photos of GMR.
Figure 4.6 Examples of Grainstone Facies Type
Pictures of Grainstone (GNST) facies type from photographs of the archive portion of core. The core face is approximately 3 3/16 inches wide. Notice internal physical sedimentary textures consistent with deposition as calci-turbidites, such as normal grading, planar and wavy laminations, and diffuse, bioturbated upper contacts. (A) GNST from ~35 ft in the core with wavy and possible burrowed upper thin bed. (B) GNST from ~106.5 ft. (C) GNST from ~16 ft. (D) GNST from ~31 ft. See text for details.
Figure 4.7 Examples of the Mixed and Diagenetic Mineralized Bed Facies Types
(A) Mixed (heterolithic) facies type from ~9 ft in the core. Notice the thin distorted beds, which appear to have been sheared and over-turned. (B) A Diagenetic Mineralized Bed (DMB) from 245 ft in the core. Note how the phosphate nodules have angular faces, indicating possible transport and reworking. (C) A DMB from 143 ft in the core. In this case the DMB is a thin bed composed of pyrite.
Figure 4.8. Trace Metals Chromium (Cr) and Molybdenum (Mo) versus Total Organic Carbon (TOC)
Cross plots of Mo and Cr versus TOC, with linear regressions. These data represent a statistical sampling for the whole core, as well as a high-frequency sample set from ~175 to 185 ft. (A) TOC versus Mo for the entire core ($n=79$). (B) TOC vs. Cr for the entire core ($n=79$). C) TOC versus Mo for the high-frequency sample set between 175 to 185 ft. ($n=29$). (D) TOC versus Cr for the high frequency sampling set between 175 to 185 ft. ($n=29$). The data from the high frequency sample sets (C and D) are not included in the whole core plots, as not to bias the whole core regression calculations.
Figure 4.9. $\delta^{13}C$ $\%$ versus Carbon to Nitrogen Molar Ratio
Organic geochemical data broken out by facies. Plot includes data from sets of organic geochemical analyses (whole core length, and high resolution sample set from ~185 to 175 ft). Generally, lower C:N (<10) indicate a marine source for organic material. Ratios from 10 to 15 result from either a mixed source, or possibly diagenetic alteration. A primarily terrigenous source of organic material will result in a ratio greater than 15 (Meyers, 1997). The widest scatter is observed in the BMR-1 facies, which also contained the highest terrestrial maceral content in the Midland county core. However, denitrification may also impact the geochemistry.
Plots of loading coefficients by variables (elements) for the first two principle components, which explain the majority of the variance in the dataset. (A) Principle component 1 (PC-1), loads positively on the major mineral forming elements found in black mudrocks (e.g., Si), as well as the trace metals (Mo and Cr). (B) Principle component 2 (PC-2) loads strongly positively with the redox sensitive elements (Fe, S, Mo and Cr), and weakly with Si. The elements that are negatively loaded with PC2 imply higher runoff and less anoxic conditions in deep water.
CHAPTER FIVE: DISCUSSION

5.1 Controls on Lithofacies

The seven lithofacies types identified within the Midland County core were each deposited by a specific depositional mechanism, or multiple related depositional mechanisms. These facies types in the Midland county core are similar to what was encountered by Baldwin (2016) in Upton County, albeit with less diversity in the carbonate lithofacies that can be explained by differences in basin morphology. The influence of global climate on glacioeustatic sea level and regional precipitation patterns is interpreted to be the key control on cyclic changes in depositional processes in the center of the Midland Basin during the Late Pennsylvanian. Due to the applied motivation of this study for unconventional reservoir characterization, particular emphasis has been placed on the paleoenvironmental conditions that contributed to organic matter enrichment in these rocks. Individual lithofacies and stacked successions of lithofacies have been interpreted in the context of a eustatic sea level cycle, and placement of individual facies on the curve was considered in the context of environmental interpretations made by Algeo and Heckel (2008) for the mid-continent, Saller et al. (1994) for the CBP, and Baldwin (2016) for Upton County. Figure 5.1 is an idealized “type cycle” for the Middle WC-D, with lithofacies matching limbs of an individual glacioeustatic cycle. The proposed depositional mechanisms associated with each lithofacies are illustrated in Figure 5.2. Using the association of lithofacies types with specific positions on the sea level curve, a glacioeustatic curve for the WC-D has been interpreted, which is presented in Supplemental Figure 3.
We have interpreted Black Mudrock 1 (BMR-1) to represent sea level lowstands, based on several lines of geochemical and sedimentological evidence. The element molybdenum (Mo) is used in conjunction with total organic carbon (TOC) as an indicator of bottom water recharge in silled basins (Algeo and Rowe, 2012). It is conservative under oxygenated conditions, but is removed from the water column and incorporated into the organic fraction of sediment under conditions of anoxia (Vorlicek et al., 2004; Algeo and Maynard, 2008; Algeo and Rowe, 2012). If a strong correlation between TOC and Mo exists, then the slope of the regression line can be interpreted to be indicative of the rate of bottom water recharge, as has been done for a number of modern basins worldwide (Algeo and Rowe, 2012). Faster recharge will result in a higher rate of Mo to TOC enrichment, as bottom waters advected from the open ocean supply Mo to be sequestered in the sediment (Algeo and Rowe, 2012). In the WC-D, there is a strong correlation between the TOC and Mo, but the slope of the line is low and similar to the modern Black Sea (Figure 4.8; Algeo and Rowe, 2012). Conversely, published values for Late Pennsylvanian core black shales from the Kansas shelf, which have been widely interpreted as a hallmark of transgressions, indicate strong connectivity to the open ocean (Algeo and Heckel, 2008). Thus when the mid-continent region is flooded and at highstand, sea level in the Midland Basin must also be at highstand, but depositional processes favor gravity flows as the reef/shelf complex expands. The BMR-1 facies type has high %Si, and there are abundant phosphate nodules of a variety of morphologies (Supplemental Table 1). Phosphate nodules are often associated with upwelling-driven primary productivity (Delaney, 1998). Based on petrographic analysis and the presence of quartz-filled *Tasmanites*, the source for the silicon within the BMR-1 facies type is
dominantly biogenic and presumably recrystallized from the dissolution of radiolarians (Baldwin, 2016). Biogenic silica from marine organisms is mobilized and precipitated in algal cysts during diagenesis, and acts as a source for silt and sand-sized grains within black mudrocks and shales (Schieber, 1998). The BMR-1 facies type has low %Al, and %K, elements associated with terrigenous minerals such as clays (Supplemental Table 1). The reduction in siliciclastic mineral flux during lowstands can be explained by substantially reduced continental runoff, which would be expected with lower precipitation, as well as a greater transportation distance between the deep basin and the adjoining hinterland sediment sources. Modelling of global circulation patterns during the Late Pennsylvanian indicates that precipitation rates in western equatorial Pangea would have been dominantly influenced by moisture availability, controlled by marine transgression across the midcontinent, as well as surface temperatures (Heavens et al., 2015). Any monsoonal precipitation patterns associated with the formation of the supercontinent Pangea would have been inhibited by a reduction in the thermal contrast between the ocean and the supercontinent during glacial intervals. Additionally, upland glaciation of either the Central Pangean Mountains or the Ancestral Rockies would have suppressed a monsoonal circulation pattern from forming (Soreghan et al., 2014; Heavens et al., 2015). A more arid climate during glacial periods is likewise in accord with the conventional assumptions, which are based on a contraction of the intertropical convergence zone (ITCZ) due to an expansion of polar ice sheets (Soreghan, 1994). A lowstand-associated reduction in continental runoff during glacial maximums, as reflected in low BMR-1 clay content, is a key to our depositional model for lowstand enrichment in organics. Production, destruction, and dilution are the three factors that
control the organic enrichment of sedimentary rocks (Passey et al., 2010). Reduced continental runoff would both increase production and reduce dilution. Production would be increased by nutrient supply to the surface waters from upwelling. High continental runoff would plausibly create a low salinity layer on the surface of the Midland seaway, and therefore the potential for a strong halocline, which would reduce the potential for vertical mixing and nutrient flux to the photic zone. Conversely, reduced runoff would have the opposite effect, and potentially allow for the erosion of a weak salinity gradient in the water column. At the same time, lower surface temperatures could reduce the stability of the thermocline, resulting in weaker water column thermal stratification. Weaker stratification would allow for more upwelling-driven primary productivity, assuming a mechanism, such as favorable winds, was available to promote vertical movements of the water mass. The abundant phosphate nodules in BMR-1 are indicative of high primary productivity, driven by upwelling. Periodic, partial overturn of the water column by Ekman transport of surface waters is also a plausible mechanism driving overturn (Ruddiman, 2001). Monsoonal or zonal winds would could both have driven upwelling given the orientation of the basin at the time (Parrish and Peterson, 1988; Algeo and Heckel, 2008; Heavens et al., 2015). The physical formation of phosphate nodules happens under anoxic conditions via inorganic precipitation at the surface-water interface or pore waters during shallow burial (Burnett and Roe, 1983; Kidder, 1985). Reduced continental runoff would also minimized dilution by clays and other siliciclastic minerals, which is consistent with the low %Al, %K and %Ti in BMR-1.

The lowstand enrichment and burial of organic matter in the BMR-1 facies has been used to guide the interpretation of sea-level relationships with other facies types.
The Black Mudrock 2 facies type (BMR-2) usually brackets BMR-1 intervals stratigraphically, occurring directly below or above occurrences of BMR-1 (Figure 5.1). Therefore, we interpret the BMR-2 facies type to have been deposited during late falling stage and early rising stage of eustatic sea level. Many of the same environmental conditions that contributed to BMR-1 deposition would have been prevalent during BMR-2 deposition, but to an incrementally reduced degree (Figure 5.2). Modestly increased rates of precipitation and continental runoff would have contributed to higher %Al and %K values for BMR-2 (Supplemental Table 1). Sediment-laden interflows across the Eastern Shelf, driven by higher relative precipitation and freshwater influx are a possible mechanism for increased terrigenous mineral input to the central basin (Jaminski et al., 1998). The disrupted fabric of BMR-2 in thin section indicates possible bioturbation, which suggests that the pervasiveness of basin floor anoxia was different between the deposition of BMR-2 and BMR-1. Similarly, the average TOC wt. % for BMR-2 is lower than BMR-1. This is possibly due to bacterial decomposition, which is not possible in anoxic waters (Sageman et al., 2003). The maximum TOC values for BMR-2 are just as high as BMR-1, but the average TOC is substantially lower, which we interpret to be reflective of a marine environment marked by relatively high primary productivity, but lower overall preservation due to higher levels of oxygen on the sea floor, and a stronger dilution effect from the detrital clay influx. Phosphate nodules are present in BMR-2 but are not as abundant as in BMR-1, seemingly consistent with an environment marked by high production in the photic zone. This may indicate a decrease in upwelling driven primary productivity, relative to the environment of BMR-1. Increased dilution from siliciclastic minerals, increased destruction from bacterial
decomposition, and reduced upwelling primary productivity would all contribute to the lower average TOC values of BMR-2, as compared to BMR-1.

We interpret the Dolostone (DOL) facies to form during the maximum rate of sea level rise, as the central area of the basin would have likely been starved of sediment during a rapid transgression. The DOL facies type is interpreted to be cement grounds that formed via in situ cementation. Cement grounds form by the precipitation of high magnesium calcite and aragonite, due to the interaction of pore and bottom waters (Flügel, 2004). Concerning sea level fluctuations, the formation of dolomite is a complicated and contentious problem, and most formation models focus on carbonate platforms and alteration by meteoric fluids (Flügel, 2004; Al-Awadi et al., 2009). One model that is applicable to the deep basin is burial dolomitization, driven by the expulsion of pore waters enriched in Mg$^{2+}$ due to the transformation of clay minerals (Flügel, 2004). The presence of the un-dolomitized GNST facies raises the question of why some beds would be preferentially altered, if burial diagenesis was the dolomitization mechanism at work in this setting. More research is needed to address this important question, as well as to ascertain whether the DOL beds are regionally significant stratal marker beds.

During periods of sea level highstand (corresponding with interglacial climatic conditions), we interpret that the depositional regime was dominated by sediment export from the carbonate platform and by terrigenous sediment influx to the Midland Basin. During these phases, the main facies that were deposited are GMR and GNST. The GMR facies type is interpreted to be indicative of intermediate sea level rise, highstands, and initial regression or the falling stage of sea level. The gradational nature of transitions
from one mudrock facies type to another reflect incremental changes in the environment of deposition, associated with the gradual lowing of sea level due to the growth of ice sheets (Figure 5.1). The environmental conditions that drove organic enrichment in BMR-1 would be reversed during the deposition of GMR, resulting in the low organic matter content ($\mu=1.67$, TOC wt. %). The GMR facies type has elevated concentrations of elements associated with terrigenous clay minerals ($%\text{Al}, %\text{K}$ and $%\text{Ti}$), as well as increased macrofossil and $%\text{Ca}$ content (Figure 4.5; Supplemental Table 1). Greater precipitation in western equatorial Pangea during inter-glacials is expected to have increased runoff to the Midland Basin, which appears to have entrained clays and calcareous fossil fragments from the shelf, which ultimately allowed flows to transform into low concentration turbidity currents with a change in slope at the platform margin (Shanmugam, 1997; Heavens et al., 2015). Increased continental runoff would also have the effect of creating a stronger halocline, by creating a reduced salinity layer at the top of the water column, similar to the Late Pennsylvanian Midcontinent Sea as proposed by Algeo and Heckel (2008). The halocline would be also reinforced by an enhanced thermocline due to higher surface temperatures, overall reducing the likelihood of upwelling. The combination of increased terrigenous sediment flux, and a reduction in mixing-driven productivity would both contribute to the overall lower TOC content of the GMR facies type (Passey et al., 2010). Additionally, reworking of organic material appears to have increased, based on pervasive bioturbation in the GMR facies type, as the presence of infauna and bacterial decomposition are both associated with oxygenated bottom waters (Sageman et al., 2003).
The GNST facies type was encountered almost exclusively interbedded with GMR, suggesting that the deposition of the two facies types are intrinsically linked and may share similar causative mechanisms of formation (Figure 5.1). Highstand export of reef material from a carbonate platform is consistent with the classic model for carbonate sequence stratigraphy (Schlager et al., 1994). During periods of high sea level, the carbonate factory is active and the platform builds upward into the photic zone. Overstepping and wave action results in the export of carbonate from the platform to the adjacent basin (Schlager et al., 1994; Saller et al., 1999; Flügel, 2004). Additionally, the initiation of calci-turbidite deposition has been linked with the flooding of carbonate platforms in the Bahamas during the Quaternary. The export of carbonate to the basin as gravity flows is not possible during periods of low sea level, as productivity is limited, and the little sediment that is produced either is lithified quickly or removed (Jorry et al., 2010). In cycles where there are both DOL and GNST, the GNST facies type is typically stratigraphically above the DOL (Figure 5.1; Supplemental Figure 2). This stratigraphic relationship is consistent with the interpretation that DOL represents a period of maximum sea level rise, and the GNST facies type is indicative flooding of the carbonate platform. Exceptions to this rule may be due to effect of shorter period cycles on the environment of deposition.

The lowstand deposition of black mudrocks and organic enrichment is somewhat antithetical to the typical stratigraphic interpretation of black shales and mudrocks, which favor sea level highstands (Heckel, 2008; Passey et al., 2010). This model works well for a shelf depositional environment, such as the core black shale of Kansas, which have been interpreted to represent maximum sea level highs (Heckel, 1986; Algeo and Heckel,
The geochemistry of the core black shales from Kansas of Late Pennsylvanian age indicate strong connectivity to the open ocean (Algeo and Heckel, 2008). The Mo-TOC ratios observed in the WC-D indicate a low rate of recharge, indicating a different paleoceanographic circulation pattern during the deposition of organic rich facies (BMR-1 and BMR-2). The traditional highstand depositional model of organic black mudrocks, as an alternative to the model proposed in this, work creates additional complications which are less simple to reconcile. This is particularly true with respect to a mechanism for generating carbonate-laded gravity flows during sea level lowstands. (Supplemental Figure 2). Other models for black mudrock deposition focus on tectonism creating lateral and vertical changes in environmental gradients (Ettensohn et al., 1988). The contrast between the persistently deep-basin setting of the location of Midland County core during the Late Pennsylvanian, with the high frequency variability observed in the WC-D stratigraphy, indicates that changes at the tempo of glacial-eustatic sea level change were a more dominant control on facies than long-wavelength subsidence. Additionally, during the Late Pennsylvanian the Midland Basin was undergoing relatively slow and steady subsidence, as compared to the rapid rate of subsidence during the Permian (Figure 2.2)

5.2 Stratigraphic Evolution

There has been extensive study of cyclothem deposition across the world, as well as global climate variability during the Late Paleozoic Ice Age (LPIA), which is linked to these deposits (Boardman and Heckel, 1989; Rasbury et al., 1998; Saller et al., 1999; Feilding et al., 2008a, 2008b; Heckel, 2008; Greb et al., 2009; Eros et al., 2012; Isbell et al., 2012; Montañez and Poulsen, 2013; van den Belt et al., 2015). These two topics are
integrally related, as the changes in ice sheet volume directly controlled eustatic sea level (Montañez and Poulsen, 2013). Integrating our findings with the published literature on the LPIA and cyclothsems is important for fully contextualizing the cyclic stratigraphy of the WC-D. We interpret 12 cyclothsms in Midland County, though the expression of cycles varies with vertical position in the core (Supplemental Figure 3). Our interpretation rests on the influence of sea level fluctuations and changes in precipitation patterns as the key controls responsible for the deposition of cyclic packages of lithofacies successions within the Midland Basin. The relevance of many studies for providing context to the WC-D deposition is limited by a lack of strong published age control, and the narrow period of interest for this study (~10 Ma). As a result, the studies that have presented robust age control and focus on the Desmoinesian, Missourian, and Virgilian received the greatest consideration in providing context for the WC-D.

Several studies integrating well logs, core data, and petrographic analysis of the Strawn, Cisco, and Canyon formations on the Central Basin Platform (CBP) present robust evidence for subaerial exposure and identified 89 individual cycles (Saller et al., 1999). Radiometric dating on the CBP indicate a mean cycle length of 143 ± 64 ka during Desmoinian through Virgilian time, close to the 100 ka “short” eccentricity Milankovitch cycle (Rasbury et al., 1998). A detailed stratigraphic assessment of paralic onlap-offlap in the Donets Basin of Ukraine, combined with robust chronostratigraphy that is based on U-Pb dating of zircons in tonsteins indicate <400 ka cyclicity (Eros et al., 2012). The relatively uniform subsidence history of the Donets Basin during the Late Pennsylvanian allowed for correlations to 12 major North American mid-continent cyclothsms (Heckel, 2008; Eros et al., 2012). The Ross and Ross (1987) sea level curve for North America,
developed based on stratigraphic relationships, is still widely used and referenced in studies of the Late Pennsylvanian-Early Permian (Waite, 2015). The existing sea level curves have three major components in common. These commonalities include: (1) long-term transgression and increasing amplitude of sea level change during the Late Desmoinian into the Missourian; (2) maximum sea level variability and long-term highstand during the Missourian; and (3) initiation of long-term regression and reduction in sea level variability in the Late Missourian into the Early Virgilian (Ross and Ross, 187; Saller et al., 1999; Eros et al., 2012). We have interpreted sea level dynamics as recorded in the Midland Basin depocenter with these established trends in mind.

We interpret the Lower WC-D as an interval that records a long-term transgression, with two shorter sea-level cycles superimposed on the long wavelength trend. The very base of the Lower WC-D (263 to 239 ft) is interpreted as a transition from the deposition of the Strawn Formation, to a deep-water style of deposition (Supplemental Figure 3). Cycles 11 and 12 from 183 ft to 239 ft are interrupted to represent long-term sea level rise with two short reversals overprinted upon them. The facies abundances in Lower WC-D are consistent with a long-term rise in sea level, with rapid transitions between short-lived lowstands and the highstands. For example, the Lower WC-D has the highest proportion of the DOL facies and GMR in the core, which we believe reflect rapid transgressions and a deepening of paleobathymetry at the Midland county core site. Additionally the Lower WC-D has the lowest proportion of black mudrocks (BMR-1 and BMR-2) of the three sub intervals and the only GNST bed is near the very top of the Lower WC-D at 185 ft. The increase in sea level variability and the modest amplitude of sea level highstands is consistent with the curves from the CBP
(Saller et al., 1999), the Donets Basin onlap-offlap (Eros et al., 2012), and the Ross and Ross (1987) midcontinent curves.

The Middle WC-D is interpreted to represent deposition during a time of high sea level variability, both in magnitude and frequency. In the Midland Basin core this is reflected by having the most regular and repetitive lithofacies cycles. Within the Middle WC-D, there are five interpreted cyclothsms (Cycles #6-10, Supplemental Figure 3). Sea level lowstands for each cycle in the Middle WC-D are reflected by BMR-1, which is not expressed similarly in the other two sub-intervals. Three cycles include a DOL bed, and four have GNST beds, resulting in the Middle WC-D having the best-developed cyclic stratigraphy in our depositional model. This is consistent with the maximum sea level variability as expressed in the Ross and Ross (1987) and the Donets Basin curves (Eros et al., 2012) during the Missourian and early Virgilian. On the CBP, this manifests as a period of generally higher sea levels during the deposition of Canyon-aged strata (Saller et al., 1999).

The Upper WC-D contains five interpreted cycles (Cycles #1-5, Supplemental Figure 3). Cycles four and five contain thick bedsets comprised chiefly of GMR, which has the effect of creating long-wavelength sea level cycles. The Upper WC-D has the highest proportion of BMR-2 and much less BMR-1 compared to the Middle WC-D (Figure 4.1). Additionally the Upper WC-D sub-interval contains the least DOL facies. The changes in the lithofacies abundances and shifts in the style of cyclic deposition indicate that there were long-term changes in the environment of deposition. This is consistent with the curves presented by other authors, which show a reduction in the magnitude of maximum sea level moving into the later Virgilian (Ross and Ross, 1987;
Saller et al., 1999; Eros et al., 2012). The Wolfcamp-C2 is only represented by 15 ft of core, and it is therefore difficult to make interpretations about changes in cyclic deposition. Based on the literature, the icehouse climate is believed to have intensified during this time period, as there is the more abundant evidence for glacial deposition during the earliest Permian (Isbell et al., 2012; Montañez and Poulsen, 2013). This is notionally also a period marked by greater siliciclastic influx to the Midland deposystem from several sources, including the northeast and south, which likely changed the accommodation available in the basin. Overall, the findings of this study broadly correspond well with previous studies, with twelve interpreted cycles consistent with the major cyclothems of the midcontinent (Heckel, 2008) and the Donets Basin (Eros et al., 2012).

5.3 Petroleum Geology

The findings from this study have ramifications for understanding the unconventional hydrocarbon potential of the WC-D. Although many complex and interrelated geologic variables control unconventional reservoir productivity, stratigraphy and geochemistry provide key insights on potential targets. The identification of the best reservoir horizons is based on several factors, including but not limited to facies stacking, thickness patterns, organic enrichment, and an elemental geochemistry that is indicative of rocks amenable to a brittle response to hydraulic fracturing. The organic richness directly controls the hydrocarbon generation potential of the interval, and the elemental geochemistry has implications to the elastic properties of the rock (Passey et al., 2010; Sone and Zoback, 2013). Based on the organic richness and inorganic geochemical
composition of BMR-1, we interpret this facies to be the most prospective for unconventional oil reservoirs in the lower Wolfcamp of Midland County. BMR-1 appears to be a suitable candidate for hydraulic fracturing, due to its high %Si and low %Al content. With lower average TOC, higher %Al and %K, the BMR-2 facies would likely be more a more ductile rock, and potentially contain less hydrocarbons (Passey et al., 2010; Sone and Zoback, 2013). Beds of BMR-1 are often sandwiched by more ductile BMR-2, which could present a potential complication to how these reservoirs are completed, especially with respect to borehole stability.

Tilt meter and microseismic analyses indicate that hydraulically induced fractures propagate in the direction of the maximum stress, perpendicular to the least principle stress. This means that on average, at depths greater than 2000 ft, most fracture propagation will be vertical (Fisher and Warpinski, 2013). Additionally, fracture lengths are greatest in thick, homogenous formations and reduced by interlayered, lithological complex stratigraphy (Fisher and Warpinski, 2013). As fractures in the WC-D are likely to propagate vertically, the thickness and spacing of potential reservoir horizons, as well as the lithology and the thickness of beds intercalated with potential reservoir intervals, need to be considered. Greater depth of burial is associated with higher pressures, and higher pressures usually increase recovery volumes. In the case of the WC-D, overlying intervals have been successful production targets, and the pressure difference between the top and bottom of the WC-D in the center of the basin will likely have a minimal impact on production. The formation integrity of the horizontal drilling target is important to wellbore stability, as well-bore collapse while drilling could complicate and slow operations.
Considering all these factors, we interpret two potential landing zones of high interest for unconventional petroleum reservoirs. The primary target zone is from ~90 to 183 ft, which is mostly contained within the Middle WC-D. The Middle WC-D zone has a higher proportion of BMR-1, but the pay intervals are spaced out and isolated from one another. One option for targeting this zone would be to drill the GMR-GNST bedset at ~135 ft in the core, as the reservoir facies (BMR-1 and BMR-2) may be prone to well bore stability problems due to their mineralogical composition. The targeted bedset is centrally located, with roughly co-equal thicknesses of reservoir facies within ~50 ft above and below. Other non-reservoir intervals in the Middle WC-D have beds of the DOL facies, which are generally very hard (based on Leeb hardness measurements; O’Dell et al., unpublished) and may also cause issues for horizontal drilling. The secondary target zone is the upper portion of the Upper WC-D from 5 to 54 ft. This interval has a lower proportion of the BMR-1, but is less stratigraphically variable, which may be conducive the propagation of hydraulically induced fractures. The tradeoffs between more continuous BMR-2, versus more discreet and isolated BMR-1 with both hard and ductile lithofacies between unconventional reservoir intervals requires more investigation.
Figure 5.1. Idealized Type Cycle for the Middle WC-D
A single idealized cycle runs from the base of the BMR-1 bed, to the base of the next BMR-1 bed, representing a full wavelength of sea level change. The lithofacies are related to the limbs of the sea level curve: BMR-1 is interpreted to represent the maximum lowstand; BMR-2 for early rising sea level; GMR for continued rising sea level; DOL for maximum rate of sea level rise; GMR and intercalated GNST for high and early falling sea level; BMR-2 for late falling sea level. This repetitive pattern is most clearly expressed in the middle WC-D subinterval.
Figure 5.2. Depositional Model for the WC-D Derived from Integrated Stratigraphic Analysis

(A) Maximum lowstand and restriction of the Midland Basin. Low rates of continental runoff, combined with upwelling-driven productivity drives anoxia, and organic enrichment during the deposition of BMR-1. (B) Intermediate rising, or falling sea level, combined with moderately increased continental runoff, results in less pervasive and persistent anoxia and greater siliciclastic sediment flux during the deposition of the organic-rich but also Al-rich BMR-2. (C) The most rapid rise in sea level results in siliciclastic sediments being impounded nearshore. Fluid circulation and interactions result in in situ cementation and the development of diagenetic dolostones (DOL facies). (D) High sea level, combined with increased continental runoff results in shedding from the CBP and siliciclastic sediment input to deep water. Fresh water runoff increases the strength of water column stratification, preventing mixing. Shedding from the CBP resulting in the deposition of the GNST facies, and increased siliciclastic flux contributing to the deposition of the GMR facies.
CHAPTER SIX: CONCLUSIONS

The application of an integrated, hierarchical set of methods for this study has provided new insights into cyclic environmental and oceanographic changes that occurred during the deposition of the Wolfcamp-D (WC-D). Well log correlations to fusulinid-dated shelf carbonates indicate that the WC-D is likely Late Pennsylvanian (~299-309 Ma) in age, which is an interval of geologic time associated with high-frequency and high-amplitude sea level fluctuations (Heckel, 2008; Waite et al., 2015). Within the lower Wolfcamp section (D and C2) of the Midland County core, seven distinct facies types have been identified. Three of these facies are types of mudrock that vary with respect to chemistry, mineralogy, and fabric: (1) Black Mudrock 1 (BMR-1); (2) Black Mudrock 2 (BMR-2); and (3) Grey Mudrock (GMR). Two carbonate facies types, grainstones (GNST) and dolomite cement grounds (DOL), were also present in the Midland County core. The two other facies types, Mixed (heterolithic) and Digenetic Mineralized Beds, occur in only very small proportions in Midland County, but are of greater significance in cores of the WC-D in other locations in the basin.

- Each facies type has a unique chemical, mineralogical, and textural signature, which have been attributed to the depositional processes that led to their formation. Importantly, the facies have a typical stacking pattern (from stratigraphically low to high): BMR-1-BMR-2-GMR (+/- GNST, DOL)-BMR-2-BMR-1. The repetitive nature of this succession has been interpreted to indicate cyclic changes in the environment of deposition, specifically influenced by position on the sea level curve. The stacking patterns, abundance of each facies type, and geochemistry (especially organic enrichment) vary vertically, indicating long-term shifts in accommodation driven
dominantly by the amplitude of sea level. These long-term changes allowed the WC-D to be subdivided into three intervals: Lower, Middle and Upper WC-D.

- Within each sub-interval of the WC-D, there are several cycles of sea level apparent, based on the interpreted depositional environment associated with the facies types, and the stacking patterns of the lithofacies. This results in a total of 12 cycles through the WC-D, consistent with the major cyclothems of U.S. midcontinent and the Donets Basin of Ukraine (Heckel, 2008; Eros et al., 2012). In studies where robust age control makes time series analysis possible (van den Belt et al., 2015), the results have indicated that the development of cyclothems was driven by the influence of Earth’s orbital configuration (e.g., eccentricity) on sea level and glaciation. The most dominate orbital frequency as determined by time series analysis is dependent on the type of depositional environment (Rasbury et al., 1988; van den Belt et al., 2015). This study of WC-D is unique because it offers a view of cyclothem deposition in a deep, restricted marine basin, whereas most published studies on this topic have examined shelf limestones (U.S. midcontinent) or paralic swamps or other marine transitional environments marked by heavy siliciclastic influx (Heckel, 2008; Greb et al., 2009; Eros et al., 2012).

- Comparing the trace metal enrichment values for the WC-D black mudrocks to core shales from the Kansas shelf suggests a much slower rate of bottom water recharge in the Midland Basin versus the shallow, epeiric interior seaway. The interior seaway was connected to the open ocean by a proposed super estuarine circulation model (Algeo and Heckel, 2008). In order to reconcile this model with the Midland Basin as we understand it in Late Pennsylvanian time, we propose that BMR-1 was deposited during sea-level lowstands. This interpretation is consistent with insights provided by Mo-TOC
ratios, which indicate very slow bottom water recharge and an environment conducive to preserving abundant organic matter. The traditional model of sequence stratigraphy in mixed carbonate-siliciclastic basins is for highstand shedding of reef and slope material into the basin through mass wasting events, and siliciclastic mudrock deposition during lowstands. To reconcile this model with the slow bottom recharge rates, as implied by the Mo/TOC ratios, lowstand deposition of BMR-1 is most fitting and explains most of the data.

- Upwelling-driven primary productivity drove oxygen removal from bottom waters, which had already been preconditioned before being advected from the Panthalassic Ocean into the Midland seaway (Algeo and Heckel, 2008; Algeo et al., 2008). Climate modeling indicates that during sea level lowstands, precipitation over western tropical Pangea would have decreased due to a reduction in available moisture, and lower surface temperatures (Heavens et al., 2015). The lower freshwater input due to reduced precipitation coupled with colder surface waters appears to have weakened water column stratification and enhanced mixing. Additionally, the reduction in continental runoff would have contributed to a decrease in the transport of terrigenous sediment to the basin during lowstands, which is manifest in the low %Al, %Ti, and %K content of BMR-1. The other facies types fit reasonably well into this interpretation on other limbs of the sea level curve. The packages of GMR with interbedded GNST represents highstand shedding and gravity flow activity derived from the up-dip platform, and increased siliciclastic input from greater continental runoff during sea level highstands. The DOL facies type is hypothesized to have formed via *in situ* cementation when the rate of transgression reached its maximum, and siliciclastic sediments were impounded nearshore. The BMR-2 facies type is an intermediary facies type between BMR-1 and
GMR, representing the transition in the depositional regime. On the sea level, curve BMR-2 deposition occurs during early sea level rise, and at later stages of sea level fall, bracketing the maximum lowstands.

- For reservoir development, the goal is to maximize the volume of hydrocarbons produced through artificial stimulation of the interval by inducing fractures hydraulically via high-pressure injection. We interpret BMR-1 to be the most prolific potential unconventional reservoirs in the WC-D. Key factors influencing WC-D reservoirs are: (1) thickness of source-rock facies (BMR-1); (2) the vertical spacing of BMR-1 beds; (3) the brittleness and hardness of both the targeted intervals and intercalated lithologies; and (4) formation integrity of the target horizon, which is important to avoid wellbore stability complications. Given all of these factors, the best placement for lateral wells in the center of the Midland Basin is in the Middle WC-D. A secondary target for consideration is the upper portion of the Upper WC-D.

- The feasibility of the Middle WC-D as a production target depends on the propagation of fractures to the relatively isolated and thin BMR-1 intervals. The thin DOL and GNST beds individually may not constitute significant fracture barriers. However, several successive beds of GNST and GMR may collectively reduce the reach of induced fractures. The most significant “known unknown” impacting development of the Upper WC-D is the difference in fracability between BMR-1 and BMR-2. The Upper WC-D has more closely spaced organic-rich black mudrock, but a greater proportion of this is composed of the aluminum-rich BMR-2. Balancing the tradeoffs between targeting disparate BMR-1 intervals, or thicker BMR-2 packages requires more investigation. Geomechanical research may provide some answers, but the ideal solution may not be
determined until wells are drilled in each and the impact of other geologic and operational factors are taken into account.
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VITA
Patrick Thomas Ryan

Education
B.S. Earth Sciences (2012)
B.S. Finance (2012)
University of Maine

Experience
Graduate Research Assistant
Pioneer Paleoenvironments and Stratigraphy Lab
Department of Earth and Environmental Sciences
University of Kentucky, 40506

Graduate Teaching Assistant
Department of Earth and Environmental Sciences
University of Kentucky, 40506

Field Specialist (Mud Logger)
Geoservices: a Schlumberger Company
Uganda and Equatorial Guinea

Coastal Marine Geology Intern
Maine Geological Survey
State of Maine: Department of Agriculture, Conservation and Forestry, 04333

Antarctic Field Assistant
Climate Change Institute
University of Maine, 04469

Undergraduate Research Assistant
School of Earth and Climate Sciences
University of Maine, 04469