High Resolution Depositional Analysis of the Black River Group (Ordovician), Michigan Basin

Jennifer Elaine Schulz

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HIGH RESOLUTION DEPOSITIONAL ANALYSIS OF THE BLACK RIVER GROUP (ORDOVICIAN), MICHIGAN BASIN

by

Jennifer Elaine Schulz

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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Department of Geosciences
Advisor: G. Michael Grammer, Ph.D.

Western Michigan University
Kalamazoo, Michigan
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For my parents Gregory and Kelley Schulz.

Jennifer Elaine Schulz
HIGH RESOLUTION DEPOSITIONAL ANALYSIS OF THE BLACK RIVER GROUP (ORDOVICIAN), MICHIGAN BASIN

Jennifer Elaine Schulz, M.S.

Western Michigan University, 2011

The Ordovician Trenton and Black River carbonates of the Michigan Basin are significant hydrocarbon reservoirs that are characterized by hydrothermal dolomitization. Production has exceeded 132 million barrels of oil with forty new discoveries made in the past three years. The giant Albion-Scipio Trend is often used as a model for other prolific hydrothermal dolomite reservoirs around the world with current models focused on the structural control of reservoir quality dolomite.

Previous studies of the Black River Group have not delimited a well-constrained depositional model. This study integrates high-resolution core interpretations, whole core analysis, and thin section evaluation to determine how primary depositional fabric relates to reservoir quality, and show how the predictability of reservoir units can be enhanced through the application of a sequence stratigraphic framework. Highly interconnected bioturbated facies are a pervasive fabric in the Albion-Scipio Trend and act as highly permeable, dolomitizing fluid migration pathways that extend laterally away from the major fault and fracture zones. By characterizing and constraining the distribution of dolomitized reservoir facies with the Albion-Scipio Trend, predictive distribution models may lead to more targeted exploration in hydrothermal altered reservoirs around the world.
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CHAPTER I

INTRODUCTION

Summary of the Problem

The Ordovician Trenton and underlying Black River carbonates are regionally extensive units across eastern North America with considerable economic value; they are major oil and gas reservoirs in New York, Ohio, Michigan, Indiana, Illinois, and Ontario. The reservoir units of both the Trenton and Black River Groups are characterized by significant hydrothermal dolomitization (HTD), and many studies (Landes, 1946; Cohee, 1948; Ells, 1962; Buehner and Davis, 1969; Keith, 1986; Hurley and Budros, 1990; Wilson et al., 2001; Smith, 2006) have suggested that the HTD process is required for reservoir development. Current models of hydrothermal dolomite reservoirs define the distribution of reservoir quality dolomite as being controlled by the pattern of regional faults and fractures, with reservoirs located only very near the faults/fractures (Ives, 1960; Ells, 1962; Keith, 1986; Prouty, 1988; Hurley and Budros, 1990; Smith, 2006). Previous studies of the Trenton-Black River in the Michigan Basin have focused on the genesis of hydrothermal dolomite and structural-control of the HTD distribution related to hydrocarbon production (Keith, 1986; Taylor and Sibley, 1986; Prouty, 1988; Hurley and Budros, 1990; Smith, 2006); however, few studies have been made concerning depositional patterns and facies types of the Black River Group.
Fundamental Questions/Hypotheses

Previous investigations of the Trenton-Black River Groups (Ives, 1960; Keith, 1986; Taylor and Sibley, 1986; Hurley and Budros, 1990; Smith, 2006) have schematically illustrated a general trend of lateral variability in reservoir dolomite away from major fault zones. Therefore, reservoir distribution cannot be explained simply by the distribution of faults and fractures and it is hypothesized that it is likely related to depositional facies and their vertical stacking patterns. Furthermore, previous studies of the Trenton and Black River Groups have found that reservoirs exist only where the carbonates have been dolomitized (Landes, 1946; Cohee, 1948; Ells, 1962; Buehner and Davis, 1969; Keith, 1986; Hurley and Budros, 1990; Wilson et al., 2001; Smith, 2006). The goals of this study are to provide evidence of preferential dolomitization within primary depositional facies, to determine if these facies-controlled dolomitized zones are primary reservoir units, and to predict, through the use of analogs, how they may extend laterally away from the fault zones.

Objectives of the Study

The objectives of this study are to conduct a high resolution characterization of facies types in the Black River Group, south central Michigan, and create a first order depositional model. This study will further evaluate the relationship between primary depositional facies, their resulting fabrics and subsequent distribution of primary porosity and permeability (as a function of reservoir quality). This study will
also attempt to define the environmental control on dolomite distribution and reservoir quality, specifically how burrowing organisms affect depositional fabrics, and ultimately porosity and permeability.

To achieve these goals, detailed analysis of seven conventional subsurface cores located in major hydrothermal dolomite trends in south central Michigan were studied to determine lithology, texture, sedimentary structures, porosity types, and grain constituents, and to interpret depositional environments within the Black River Group. Additionally, a detailed characterization of burrow trace fossils (i.e. ichnology) was conducted to further aid in the interpretation of depositional environment. Integrating modern and ancient analogs in the reservoir characterization of the Black River Group (Michigan Basin) will better capture the vertical and lateral distribution of facies geometries and, in turn, the depositional system of the Albion-Scipio Trend.

Ordovician

Paleogeography

During the Middle Ordovician, the Michigan Basin was situated at approximately 25 degrees south latitude (Scotese and McKerrow, 1991) in the tropical to sub-tropical belt and covered by a shallow intra-craticonic sea (Figures 1 & 2). Areas of high carbonate production or "carbonate factories" are generally found in warm, shallow marine environments within the tropical zone (i.e. 30 degrees north and south latitude) (James, 1979). The Trenton and Black River Groups of the
Michigan Basin have been interpreted by other workers as open-marine, subtidal, shallow shelf/platform environments with deposition in water depths of 10 - 100 feet.

Figure 1. Global reconstruction of paleogeography during the Ordovician from the Scotese PALEOMAP Project. The Michigan Basin is located at approximately 25° south latitude in what is interpreted to be a tropical to sub-tropical environment (highlighted by box). Figure modified from the Scotese PALEOMAP Project (www.scotese.com).

(3 – 30 meters) (Keith, 1986; Hurley and Budros, 1990; McKerrow et al., 1991; Howell and van der Pluem, 1999). A humid paleoclimate for the Michigan Basin during this time was inferred by Morrow (1978), based on a distinct lack of evaporites. The eastern margin of North America, a component of the Laurentia supercontinent, collided with an island arc during the Ordovician resulting in the Taconic Orogeny (Scotese and McKerrow, 1991). Ash beds from the Taconic
Orogeny are found in Trenton-Black River rocks of the Michigan Basin and their equivalents across eastern North America (Huff et al., 1992).

Figure 2. Detailed view of Laurentia paleogeography during the Ordovician. Water depth in the Michigan Basin (circled) grades from shallow on the edges to deeper in the center of the basin (lighter to darker shades, respectively). Figure modified from Blakey Paleogeography and Geologic Evolution of North America (www4.nau.edu/geology/Blakey.html).
Sea Level

The relative frequency and amplitude of sea level fluctuation may vary greatly in response to continental glaciation (Read, 1998). Periods of extensive continental glaciation, or icehouse times, can experience eustatic sea level variations of 165 – 330 feet (50 – 100 meters), whereas periods of little continental glaciation, or greenhouse times, experience eustatic sea level changes of 30 feet or less (10 meters) (Read, 1998). Read (1998) classifies the Middle to Late Ordovician as a transitional period between greenhouse and icehouse cycles, and suggests it was a time of moderate sea level changes, on the order of 30 - 100 feet (10 - 30 meters). Read (1998) broadly categorized deposition on carbonate ramps during transitional times as being grainstone-dominated with lagoonal pellet dolomites and limestones forming the inner ramp and a marked absence of tidal flat facies. The general absence of tidal flats during the Ordovician suggests that sea level change was rapid, and reduced carbonate mud production diminished tidal flat sedimentation, resulting in diminished tidal flat progradation that was insufficient to keep pace with the migration of the shoreline (Read, 1998).

Ross and Ross (1992) also classify the Middle Ordovician as a transitional period with generally low amplitude sea levels fluctuations. Carbonate deposition was continuous on cratonic shelves with three to four shoaling upward cycles, indicating some minor sea level fluctuations occurred during this time. By Late Ordovician, Ross and Ross (1992) suggest that continental glaciation is prevalent in
upper latitudes, and six major transgressions and regressions are associated with
generally high amplitude eustatic sea levels.

Sea level fluctuations associated with transitional periods may not be evident
in the Trenton and Black River Groups of the Michigan Basin. The intra-cratonic
Michigan Basin was somewhat isolated from the Laurentia cratonic sea by several
arches and highlands (Ives, 1960; Ells, 1969) which may have dampened the effects
of eustatic sea level fluctuations.

Geologic Setting

The Black River and Trenton Groups (which are generally paired together by
petroleum geologists for convenience) are regionally extensive throughout the
Appalachian, Illinois, and Michigan Basins. Although they are distinctly different
groups/formations throughout the region, the Trenton and Black River Groups are not
always differentiated in the literature. In the Michigan Basin, the Trenton and Black
River are informally defined as formations in the subsurface (Catacosinos et al.,
2000).

The type sections of the Trenton and Black River are found near Trenton Falls
of Oneida County, New York and cliff exposures along the Black River in central
New York, respectively. In New York and Ontario, the Trenton and Black River are
designated as groups and are subdivided into a multitude of subunits; most of the
published literature refers to them as groups (Smith, 2006; Howell and van der
Pluijm, 1999; Hurley and Budros, 1990; Keith, 1988; Keith, 1986). Although there
are no formal subdivisions in the subsurface of the Michigan Basin, the Trenton and Black River are referred to as groups in this study.

Stratigraphy

The Trenton-Black River reach a depth of 11,000 feet (3,300 meters, basal Black River) in the central Michigan Basin and attain a maximum combined thickness of 1,000 feet (300 meters) in the eastern Basin, thinning to less than 400 feet (120 meters) in the western part of the Basin (Ives, 1960). The Trenton Group conformably overlies the Black River Group. The Black River Group is conformably underlain by the Glenwood Formation, a black-to-green shale which varies in thickness from 5 feet to 100 feet (1.5 to 30 meters) (Catacosinos et al., 1990; Prouty, 1988). The Trenton Group is overlain by 200 to 400 feet (60 to 120 meters) of the Utica and Collingwood Shales, which serves as a vertical seal for hydrocarbons (Hurley and Budros, 1990) (Figure 3).

Structure

The Michigan Basin is a nearly circular basin encompassing 122,000 square miles (316,000 square kilometers) of the Lower Peninsula of Michigan and parts of Wisconsin, Illinois and Ontario, Canada (Hurley and Budros, 1990; Howell and van der Pluijm, 1999). Significant, tectonically-driven basin-centered subsidence within the Michigan Basin began in the Early Ordovician, resulting in widespread shallow-water deposition. Eastward tilting toward the Taconic margin replaced basin-
centered subsidence in the Michigan Basin by the Middle Ordovician and dominated over eastern North America (Howell and van der Pluijm, 1999).

The Michigan Basin is bordered by several arches and other structural highs whose timing and genesis is somewhat enigmatic. The Basin is bounded to the west

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<td>Late Cincinnatian</td>
<td>Utica Shale</td>
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<td>460.9 Ma</td>
<td>Middle Mohawkian</td>
<td>Collingwood Shale</td>
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<td>Trenton Fm., Gr.</td>
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<td>Glenwood Fm.</td>
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Figure 3. Ordovician stratigraphy of the Michigan Basin. The Black River Group, which is informally referred to as the Black River Formation or Limestone, is the focus of this study. Figure modified after Catacosinos et al., 2000.
and north by the Wisconsin arch and the Wisconsin Highland or dome; the Canadian Shield to the north and north east; the Algonquin Arch and Findlay Arch to the east and south east; and the Kankakee Arch to the southwest (Catacosinos et al., 1990; Ells, 1969; Fisher et al., 1988) (Figure 4). The timing of the Findlay Arch is particularly ambiguous; Fisher (1969) places the Findlay Arch as a positive feature by the Late Ordovician, but later (Fisher et al., 1988) concludes that the Findlay Arch is post-Silurian. If the Findlay Arch is post-Silurian in origin, relatively open circulation with normal marine waters would be expected in the Michigan Basin versus somewhat more restricted circulation if the Arch developed by Late Ordovician time. The Logansport and Chatham sags on the Kankakee and Findlay Arches have also been identified as possible basin inlets during various periods of deposition (Ives, 1960), allowing for circulation with normal marine waters.

Previous Studies

Michigan Basin Regional Geology

Regionally, the Trenton and Black River Groups, in the Michigan Basin, are comprised of dense brown to gray crystalline carbonate (Cohee, 1948; Buehner and Davis, 1969; Ives, 1960) which may be limestone or dolomite in the southwestern and south central Michigan Basin. Dolomite is the dominant lithology in the western and extreme southwestern parts of the Basin (Ives, 1960) (Figure 5). Although dolomitization is pervasive, bedding structures and large fossil fragments are often preserved (Buehner and Davis, 1969). Thickness the Black River Group ranges from
45 to 150 meters (150 – 500 ft) and thickens to the southern and eastern portions of the Basin while the Trenton Group attains a maximum thickness of 170 meters (550 ft) (Catacosinos et al., 1990).

Figure 4. Generalized structure map of the Michigan Basin illustrating the position of major structural highlands, arches and sags during the Ordovician affecting sedimentation and circulation with open marine waters. Figure modified after Ives, 1960 and Ells, 1969.
Figure 5. Regional distribution of Trenton-Black River limestone and dolomite. Fault-controlled Trenton-Black River fields are also labeled. Figure modified from Landes, 1970.

Rock Types

**Trenton Group**

The dominant rock types in the Trenton Group are mudstones and crinoidal wackestones to packstones with current laminations interpreted as representing winnowing during storms (Hurley and Budros, 1990). Wilson *et al.* (2001) state that the Trenton and Black River are quite similar in the subsurface with the Trenton exhibiting more faunal diversity (echinoderms, brachiopods, bryozoans, ostracods,
trilobites, conodonts, and rare corals). Overlying the Trenton is the Utica shale, which is part of the Cincinnatian Group (Ives, 1960).

**Black River Group**

Previous work has shown that allochems are commonly limited in the Black River Group to pelletal grainstones and micritic mudstones with chert nodules, intense burrowing and dark shale laminae (Wilson *et al.*, 2001; Hurley and Budros, 1990; Ives, 1960). The lower Black River includes a target hydrocarbon interval known as the Van Wert zone. This zone is interpreted by previous workers as a dolomitized, laminated to cross-bedded crinoidal wackestone. The Van Wert is overlain and underlain by burrowed mudstones and wackestones, which generally display dolomite development restricted to the burrows (Hurley and Budros, 1990).

Ives (1960) states that the top of the Black River was picked on the top of a "black carbonaceous dolomitic shale bed" (e.g. Black River Shale) that is laterally extensive throughout the Basin. Wilson *et al.* (2001) suggest that the two laterally extensive gamma-ray markers that delineate the Trenton and Black River contact are metabentonites originating from volcanic activity associated with the Taconic Orogeny of eastern North America. The most persistent gamma-ray marker in the Michigan Basin is referred to as the Black River Shale, which is believed to be equivalent to the Millbrig metabentonite of Kentucky and Virginia (Wilson *et al.*, 2001; Pope and Read, 1997) (Figure 6). In a study by Hurley and Budros (1990),
however, spectral gamma-ray analysis indicated a low uranium and thorium and high potassium content, which is an atypical chemical signature for a volcanic ash. They

Figure 6. Type log from the Albion-Scipio trend displaying gamma-ray on the left and compensated neutron on the right. Note the Black River Shale is the most identifiable gamma-ray marker and is persistent throughout the Michigan Basin. Footages are in feet on the far left. See Figure 29 for well location.
suggested that the shales in the Black River have either undergone extreme chemical alteration or that there origin is marine. Huff et al., (1992) state that the Millbrig and other Ordovician ash beds have been altered to potassium-rich clay beds or K-bentonites; they further suggest that the Millbrig is the same ash event as the “Big Bentonite” seen in Europe. If the Millbrig event is recorded in Europe, an estimated 620 miles (1,000 kilometers) away from the Taconic front (Scotese and McKerrow, 1991), it is reasonable to assume that the potassium-rich Black River Shale (approximately 500 miles (800 kilometers) from Taconic front) is the Millbrig equivalent in the Michigan Basin and therefore a time-correlative (chronostratigraphic) surface throughout the Basin.

Dolomite

Four types of dolomite in the Trenton-Black River Groups have been described by other workers in the Michigan Basin (Prouty, 1988; Keith, 1988; Fara and Keith, 1988; Taylor and Sibley, 1986), based on petrography and geochemistry: 1) cap dolomite, 2) regional or early diagenetic dolomite, 3) fracture dolomite, and 4) baroque or saddle dolomite. The cap dolomite is iron rich and occurs in the uppermost 50 feet (15 meters) of the Trenton; it is generally characterized by a non-porous, finely crystalline dolomite and contains recognizable allochems. The genesis of the regional dolomite is a subject of much confusion. Taylor and Sibley (1986) describe the regional dolomite as being similar to the cap dolomite, but without the high iron content, while Fara and Keith (1988) suggest that the regional dolomite is
similar petrographically to fracture-related dolomite described by Taylor and Sibley (1986). Hurley and Budros (1990) do not associate the regional dolomite with the Albion-Scipio trend although it is present in the Trenton-Black River in the western and southwestern part of Michigan. Fracture dolomite occurs in conjunction with linear fault trends such as Albion-Scipio and Stoney Point fields of Michigan; it is generally characterized by coarse-grained crystalline dolomite, undulose extinction under cross-polarized light, and intercrystalline porosity. The fourth type of dolomite in the Michigan Basin is a white, coarsely crystalline saddle or baroque dolomite found in fractures, which some authors include with the fracture dolomite. Saddle dolomite is coarse-grained, with a curved crystal face and sweeping extinction petrographically (Taylor and Sibley, 1986). Fractures, vugs, and molds are often lined or occluded by saddle dolomite. Due to the pervasive occurrence of different dolomitic facies, understanding dolomitization may be a critical component in characterizing reservoir development in the Trenton-Black River Groups.

Reservoir Characteristics

Previous studies of the Trenton and Black River Groups have found that reservoirs exist only where carbonates have been dolomitized (Landes, 1946; Cohee, 1948; Ells, 1962; Buehner and Davis, 1969; Keith, 1986; Hurley and Budros, 1990; Wilson et al., 2001; Smith, 2006). Reservoir quality dolomite is generally coarsely crystalline with abundant fracture, vuggy, and intercrystalline porosity. Porosities generally range from two to five percent with four percent or greater being considered
"high-porosity" (Hurley and Budros, 1990). Permeability measurements are erratic, ranging from 0.1 to 8,000 millidarcies due to fractures, vugs, and cavernous porosity but are generally less than ten millidarcies (Hurley and Budros, 1990; Buehner and Davis, 1969).

The lower Black River includes a zone of increased porosity and permeability, the Van Wert zone discussed previously. The Van Wert zone is frequently productive, with well-developed porosities of 3 to 5 percent and permeabilities of 10 millidarcies in the southern part of Stoney Point and Albion-Scipio Fields (Hurley and Budros, 1990).

Distribution of reservoir quality dolomite is controlled by a series of en echelon faults, which are associated with a larger scale wrench fault system (Landes, 1946; Cohee, 1948; Ells, 1962; Buehner and Davis, 1969; Keith, 1986; Hurley and Budros, 1990; Wilson et al., 2001) (Figure 7)

Depositional Environment

Although the Hurley and Budros (1990) study is an excellent summary of the Albion-Scipio Field and the Trenton and Black River Groups, only generalized information regarding environments of deposition is presented. The depositional environment of the Trenton-Black River has been interpreted as subtidal, shallow-shelf, open-marine, and within the photic zone (Hurley and Budros, 1990; Howell and van der Pluijm, 1999; Keith, 1986). Trenton-Black River equivalent facies in the Appalachian Basin were studied by Pope and Read (1997) to better understand the
tectonic influences on carbonate ramp deposition. By analyzing the facies in high-resolution, they were able to provide a more comprehensive review of the regional depositional environment and sequence stratigraphy than previous studies. To achieve this end, Pope and Read (1997) incorporated outcrop data and conventional subsurface cores, which were used to delineate lithologies and sedimentary structures at the centimeter scale. These observations were then tied back (i.e. ground-truth) to

Figure 7. Structure map of Trenton top illustrating *en echelon* synclinal traces. The *en echelon* synclinal traces are an expression of basement wrench faulting. Note the dry holes (open circles) that step out from the producing wells (solid circles) on the fault zones. Structural contours are 10 foot interval (subsea). Redrafted from Hurley and Budros, 1990.
wireline logs in order to characterize the heterogeneities of potential reservoir facies. This study will employ a similar approach.

Field(s) Development History

The Lima-Indiana Trend of Ohio and Indiana, discovered in 1884, was the first major Trenton-Black River play. Over half of the production in the Lima-Indiana trend is related to dolomitization along the Bowling Green Fault zone (Keith, 1986). Dolomitization along the Bowling Green Fault is similar to the Albion-Scipio and Stoney Point fields in Michigan (Hurley and Budros, 1990).

The Deerfield field was the first Trenton discovery (1920) in Michigan. Porosity was developed only where dolomitized and initial production rates varied from 5 to 500 barrels of oil per day (Ives, 1960). The next major discovery, in 1954, was the Northville Pool (Ives, 1960). The first well in Northville was completed flowing natural at 200 barrels of oil an hour. Thirty-two wells had been completed by 1959, with approximately 80% of the production still from the discovery well (Ives, 1960). Ives (1960) further noted that the major Trenton and Black River fields in south Michigan occurred in conjunction with structural features trending north and northwest.

Natural gas was discovered in the Black River Group of central New York in 1986 (Smith, 2006). Smith (2006) reports that 20 new Trenton-Black River fields in the past decade have been discovered in elongate, linear trends of discontinuous dolomite reservoirs similar to fields in Michigan (Figure 8).
Albion-Scipio Trend

The Albion-Scipio field, discovered in 1956, is a north-northwest fracture-controlled trend approximately 30 miles (56 km) long and three quarters of a mile wide (Ives, 1960; Ells, 1962, Prouty, 1988) (Figures 9 & 10). In the early development of the field, well locations were chosen based on gravity surveys or “hunches”. The discovery well for the trend was a “non-technical location” drilled between two gravity highs (Ives, 1960; Ells, 1962). The Albion-Scipio trend was initially extended by “controlled random drilling,” or trendology, along a line projected from the southern Scipio field to the northern Albion field (Buehner and Davis, 1969; Ells, 1962). The field was divided into three separate pools: Albion

Figure 8. Generalized distribution of Trenton-Black River fault-controlled hydrothermal dolomite fields in eastern North America. Image modified after Smith, 2006.
Figure 9. Map of all oil and gas production (through 2005) in the state of Michigan. The Albion-Scipio Trend (circled) is an elongate, linear field approximately 30 miles in length. Map modified from the Michigan Department of Environmental Quality (www.michigan.gov/deq).
Figure 10. Structure map of the southern portion of the Albion-Scipio trend. Note the elongate, linear nature of the trend, which is related to basement wrench faulting. Figure redrafted from Hurley and Budros, 1990.
Pool in the north, Scipio Pool in the south, and the Pulaski Pool in the middle (Ives, 1960). The Albion-Scipio field gained national attention in 1957 when Ohio Oil Company’s Stephens #1 well “blew out of control for 25 hours” (Ives, 1960). Attempts to shut in the well caused cratering at the surface. There was an estimated loss of 4,000 barrels of oil and 15,000 MCF of gas before the well was killed with salt water (Ives, 1960). Cumulative production in the trend has surpassed 132 million barrels of oil and 230 BCF of gas (Wylie et al., 2004).

The Albion-Scipio trend is a dolomitic reservoir with a stratigraphic trap where tight regional limestone forms a lateral seal and is sealed vertically by a combination of cap dolomite, unaltered limestone, and the Utica Shale (Buehner and Davis, 1969; Hurley and Budros, 1990).

Structural Control

Ells (1962) suggested that the linear pools of the Albion-Scipio trend are located above deep seated basement faults. A series of synclinal depressions or sags are associated with each of the fractured reservoir zones and production from the Trenton and Black River carbonates is then related to dolomitization along the fault/fracture planes (Figure 11). Intermittent reactivation of basement-controlled wrench faults throughout the Paleozoic created a series of en echelon synclinal sags that occur in association with segments of the faults (Hurley and Budros, 1990). The Trenton-Black River reservoirs of the Appalachian Basin in New York display a
similar trend of dolomitization along narrow, elongate, *en echelon* sags related to basement wrench faults (Smith, 2006).

Previous studies have concluded that fluids migrate upward along deep-seated fault planes causing dolomitization in the Trenton and Black River Groups (Landes, 1946; Prouty, 1988; Hurley and Budros, 1990; Smith, 2006) (Figure 12). According to these studies, pressurized, high-temperature fluids rose rapidly along the fault planes before reaching lower-permeability zones in the upper Trenton and Utica Shale, which caused lateral flow into the Black River. Fault-controlled dolomitization in New York, Ohio, Michigan, and Ontario has been interpreted as occurring during the Late Ordovician or Early Silurian and is unequivocally hydrothermal in origin (Smith, 2006).
Figure 11. Schematic structural cross section depicting lateral variability of dolomitization and the synclinal sag on the top of the Trenton. Figure modified after Hurley and Budros, 1990.
Figure 12. Schematic diagram illustrating dolomitizing fluids moving vertically along basement wrench faults and laterally, to varying extents, in the Trenton and Black River Limestones. Lateral migration of dolomitizing fluids may be related to enhanced porosity and permeability in primary depositional facies. Figure redrafted from Hurley and Budros, 1990.
CHAPTER II

METHODS

Core Descriptions

Sixty-eight cores in the Trenton and Black River Groups were available at the Michigan Geological Repository for Research and Education (MGRRE). Seven cores, totaling 624 linear feet (190 meters), were chosen for this study based on stratigraphic interval (i.e. Black River Group), geographic or spatial distribution on hypothesized depositional strike and dip, condition of core and availability of corresponding petrophysical data (Figures 13, 14, & Table 1). The spatial distribution of cores was somewhat limited due to the nature of Black River production along narrow elongate-linear fault trends. High-resolution core descriptions were performed at a centimeter scale to determine lithology, texture, grain types, sedimentary structures, porosity types (both primary and secondary), and diagenetic features (i.e. saddle dolomite fracture, vug, and mold fills) (Appendix A). The GSA standard color chart was used to describe the wet color of rocks and the colors are noted in Appendix A. Pore types were described using the classification system of Choquette and Pray (1970), while rock types were described based on Dunham’s classification of carbonate rocks (Dunham, 1962). Additionally, analysis
of fifteen thin sections from key facies and other zones of interest were made to enhance the accuracy of descriptions when grain constituents were not

Figure 13. Map displaying the spatial locations of Trenton-Black River cores available at MGRRE. The squares represent Black River cores used in this study, while the circles represent Trenton cores.
Figure 14. Vertical distribution of Black River core data in studied wells. Wells are hung stratigraphically on the Black River Shale which serves as a datum. Footage scale on the left is in 5 foot intervals and corresponds to the vertical distance from the Black River Shale. (Hergert #2, permit #22196; Skinner #1, permit #21833; Buehrer #1, permit #21064; Hall #1-13, permit #36834; Timm-Kennedy #1-14, permit #30137, abbreviated TK; Tolle #1-33, permit #37507; Warner-Fouty #9-8, permit #41359, abbreviated W-F).
distinguishable in hand specimen (Appendix C). All thin sections were impregnated with blue epoxy to highlight pore spaces and alizarin red-S was applied to half of each slide to stain for calcite. Thin sections were analyzed using a broad field Leica M240 petrographic microscope and digital camera. Descriptions of all core data analyzed were then drafted in a chart format using Adobe Illustrator® and modeled after the American Association of Petroleum Geologists (AAPG) Sample Examination Manual (Swanson, 1989).

<table>
<thead>
<tr>
<th>Permit #</th>
<th>Well Name</th>
<th>Abbreviation</th>
<th>Footage (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21064</td>
<td>Buehrer #1</td>
<td>B</td>
<td>105</td>
</tr>
<tr>
<td>21833</td>
<td>Skinner #1</td>
<td>S</td>
<td>125</td>
</tr>
<tr>
<td>22196</td>
<td>McClure-Hergert #2</td>
<td>MH</td>
<td>170</td>
</tr>
<tr>
<td>36384</td>
<td>Hall #1-13</td>
<td>H</td>
<td>51</td>
</tr>
<tr>
<td>41359</td>
<td>Warner-Fouty #9-8</td>
<td>WF</td>
<td>23</td>
</tr>
<tr>
<td>37507</td>
<td>Tolle #1-33</td>
<td>T</td>
<td>30</td>
</tr>
<tr>
<td>30137</td>
<td>Timm-Kennedy #1-14</td>
<td>TK</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 1. Wells used in this study listed with their permit numbers, linear footage examined, and abbreviation of well name.

Ichnology

Bioturbation of sediments is a characteristic feature of carbonate shelves and platforms causing heterogeneity in the distribution of primary porosity and
permeability and is a controlling factor of diagenesis and therefore reservoir potential (Flugel, 2004). Two ichnofacies (i.e. a group of distinctive trace fossils that represent certain facies or bathymetric zones) were identified based on classifications of Ekdale et al. (1984). Trace fossils (burrows) were assigned to the *Cruziana* or *Skolithos* ichnofacies based on burrow geometry, orientation, degree of bioturbation, and variations in burrow fill material (Figure 15). Measuring or estimating the degree of bioturbation is a difficult task due to size, geometry, and diagenetic alteration of burrows as observed in core. Although Taylor and Goldring (1993) state that early classification schemes measuring percentage area of primary fabric destruction or percentage of bioturbation may not be as accurate as methods which measure bioturbation as a volume, they are generally sufficient since a volumetric measurement of bioturbation can be very difficult to determine.

The more descriptive classification scheme presented by Taylor and Goldring (1993) is used as a guide in this study (Table 2). Although Taylor and Goldring (1993) assign a percentage value (to describe the degree of bioturbation) and a descriptive classification, only a descriptive classification was used in this study owing to the difficulty of identifying burrows in core and the diagenetic overprint of dolomitization. Four distinct burrow types were described, using the classification scheme modified from Taylor and Goldring (1993) (Table 3). This additional description of the burrows is a necessary addition to the Dunham classification, which describes carbonate rocks based on depositional texture alone (i.e. mud or matrix
Figure 15. Schematic diagram displaying burrow traces from the *Cruziana* ichnofacies (A) and *Skolithos* Ichnofacies (B). *Cruziana* (A) type burrows are found in medium to low energy environments between fair- and storm weather wave base (Ekdale *et al.*, 1984). *Skolithos* (B) type burrows are characteristic of near shore, high-energy marine environments (Ekdale *et al.*, 1984). *Cruziana* burrows were identified in Facies 1, 2, 3, and 6. *Skolithos* burrows were identified in Facies 1 and 6. Image modified after Ekdale *et al.*, 1984.
<table>
<thead>
<tr>
<th>Term</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparse</td>
<td>Distinct bedding with few discrete traces</td>
</tr>
<tr>
<td>Moderate</td>
<td>Some bedding re-working but still discernable, discrete traces rarely overlapping</td>
</tr>
<tr>
<td>Intense</td>
<td>Bedding completely disturbed, later discrete burrows</td>
</tr>
<tr>
<td>Total</td>
<td>Total sediment reworking</td>
</tr>
</tbody>
</table>

Table 2. Chart describing terminology used to aid in burrow descriptions. Modified after Taylor and Goldring, 1993.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burrow Type 1</td>
<td>Horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite or calcite</td>
</tr>
<tr>
<td>Burrow Type 2</td>
<td>Intense to total bioturbation, later sparse discrete cylindrical and vertical (2 mm) burrows, stylobeding common</td>
</tr>
<tr>
<td>Burrow Type 3</td>
<td>Moderate to intense discrete horizontal and cylindrical burrows (2 mm – 15 mm)</td>
</tr>
<tr>
<td>Burrow Type 4</td>
<td>Moderate to dense cylindrical burrows (2 mm – 4 cm), with wispy/sutured burrow-bounding stylolites creating a burrow-brecciated fabric</td>
</tr>
</tbody>
</table>

Table 3. Chart describing the different burrow types identified in core.

**Whole Core Analysis**

Full diameter whole core analyses were available for all seven cores used in this study. Full diameter analyses, compared to plug or sidewall core analyses, are ideal when studying carbonates as the larger sample size (the full diameter of the
conventional core) will better reflect the inherent heterogeneities in carbonate rocks. Typically, a 0.33-foot (vertical) sample is measured once every foot and a sample number is assigned to each foot or depth interval examined. Core Laboratories Inc., Hycalog (Hergert #2), and Marathon Oil Company’s Petroleum Research Group (Warner-Fouty #9-8) performed the core analyses, which included permeability (maximum and vertical), percent porosity, residual saturation percent (oil and water), and bulk density. Bulk densities were used to determine limestone and dolomite lithologies (acid testing was used when bulk density did not give a clear indication of lithology). Maximum permeability and percent porosity were entered on a comma-delimited spreadsheet and imported to Petra to be viewed as digital curves.

**Wireline Logs**

All seven cores had a gamma ray log and either a compensated neutron log or a neutron (API) log. Both types of neutron logs are a measure of energy lost when neutrons collide with formation materials; in a neutron (API) log the energy lost is recorded as “counts” where a higher value correlates to lower porosity values while compensated neutron logs are recorded in limestone porosity percent units (Asquith and Gibson, 1982; Doveton, 1994). For each well, raster log tiff images of the wireline logs were calibrated in Petra; the gamma ray and neutron tracks were digitized and displayed with porosity and permeability from whole core analysis. Facies and burrow types from core descriptions were plotted along with wireline logs and core analysis data in order to observe and interpret any trends.
Data Limitations

The initial data set was chosen based on geographic location within the Albion-Scipio trend. Primary concerns of the core selection process were how much of the cored intervals overlapped stratigraphically, and their geographic distribution along a hypothesized depositional strike and dip. Although MGRRE has an inventory of sixty-eight conventional cores available in the Trenton-Black River, most of these wells were cored only through the Trenton Group. This conflict is due to the fact that petroleum geologists did not always differentiate the two Groups in well records and driller’s reports. The cored interval, in relation to stratigraphic interval, was determined in this study, by comparing the driller’s reports and wireline logs. If the cored interval indicated on the driller’s report fell within the Black River Group (as determined from log raster image) the well was then cross-referenced in the MGRRE Core Inventory to determine the footages available at MGRRE. A type log was selected on which the Black River cores were hung stratigraphically on the Black River Shale so that the distribution of the cored intervals could easily be viewed (refer to Figure 14).

Accurately labeled core is a requirement for any high-resolution core descriptions needed to identify facies, vertical stacking patterns of facies, and depositional environment. Cores should be labeled sequentially in one-foot intervals and show some indication of which direction is the top of each piece. When footages were not labeled, whole core analysis reports were used to determine sequential footage. Ideally, a whole core analysis will take 0.33-foot samples at every foot and
label each piece sampled with a sample number; often the sample analyzed will be discarded. Sample numbers can then be used to accurately reconstruct depths (Lucia, 1999). In the Buehrer #1 well, for example, samples were taken at seemingly random intervals making it difficult to reconstruct the footage accurately. Further complications are encountered when sample numbers (which correspond to whole core analysis) from the cores are missing or unreadable. When this problem occurred, footages were reconstructed as precisely as possible based on labeled pieces above and below the section in question.
CHAPTER III

LITHOFACIES

Seven cores (total of 624 linear feet) covering portions of the Black River Group in south central Michigan were examined and six lithofacies were identified. Facies were defined based on texture, grain types, faunal diversity and sedimentary structures. Individual facies and associated interpretations of water depth and energy levels were used to interpret specific depositional environments. Facies were delineated on primary depositional structures and allochems, which may have been subsequently altered during diagenesis. Dunham’s classification was used to describe the texture and grain constituents, although it does not allow for detailed classification of burrowed rocks. Further detailed descriptions of burrow types were essential since approximately 80% of the cored interval exhibited burrowing. Four main burrow types were defined based on burrow orientation, size, fill, and associated bounding features (e.g. stylolites). Burrows were further classified into the ichnofacies *Cruziana* and *Skolithos*, as defined by Ekdale *et al.* (1984) to aid in environmental interpretations. Facies are described below as depositional divisions on a ramp setting (i.e. ramp sub-environments).

Facies 1 - Burrow-mottled Mudstone to Wackestone – Mid to Outer Ramp

*Observations:* Facies 1 consists of moderately to totally burrowed-mottled mudstone to wackestone, with less than 10 percent peloids and sparse (less than 10
percent) skeletal debris containing bryozoans, trilobites, undifferentiated shelly fragments and less common gastropods and crinoids. Grain sizes range from fine-(0.125 mm) to very coarse-grained (2 mm) carbonate sand. Burrow types 1, 2, and 4 are associated with this facies. Burrow Type 1 is moderately to densely burrowed with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) *Cruziana* burrows. These burrows are filled with coarsely crystalline dolomite/calcite or micritized skeletal grains. Burrow Type 2 is generally associated with mudstones and is stylobedded and stylomottled. Stylobeding and stylomottling (after Flugel, 2004) occur when stylolites take on a laminated appearance due to swarms of parallel solution seams and when patchy enrichment of insoluble material has grown at solution interfaces, respectively (Flugel, 2004). Stylomottling was commonly observed at burrow boundaries. Cylindrical (2 mm) *Cruziana*-type burrows are common while vertical (2 mm) *Skolithos* burrows are rare. Burrow type 3 is composed of discrete horizontal and cylindrical *Cruziana*-type burrows (2 – 15 mm); burrows are characterized by coarsely crystalline dolomite often in a limestone matrix (Figures 16-18).

**Interpretations:** Abundance of horizontally oriented *Cruziana* type burrows indicates low water energy at the time of deposition (Ekdale et al., 1984). The *Cruziana* ichnofacies is common in shallow epeiric seas typically between fair- and storm-weather wave base. Intense burrowing has often destroyed any original sedimentary structures indicating total bioturbation (Ekdale et al., 1984). Tubular tempestites (Wanless et al., 1988), or forced burrow-fillings of coarser-grained storm
related sediment, are also common. Sparse skeletal debris and muddier matrix sediments suggest quiet water deposition in an outer ramp environment.

Figure 16. Facies 1 – Burrow-mottled Mudstone to Wackestone (Core Photographs). A: Burrow-mottled mudstone with boring (Bg), fine laminations present where burrowing was less intense; B) Burrow-mottled mudstone with dense burrowing (Bw) that are bounded by stylolites, scale in centimeters.
Figure 17. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A: Facies 1, burrow-mottled mudstone with borings (Bg). Borings are filled with courser (than matrix) crystalline dolomite, undifferentiated micritized grains, and skeletal grains. B: Facies 1, tubular tempestites (Tt) in mudstone, grains have been partially micritized and include brachiopods (Bh), and bryozoans (Bry).
Figure 18. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A & B: Facies 1, burrow-mottled mudstone displaying excellent intercrystalline porosity in burrows (Bw). Approximate location of burrows are shown by ellipses.
Facies 2 - Crinoidal Grainstone – Mid Ramp (Proximal)

Observations: Facies 2 is composed primarily of crinoid fragments (70%) with syntaxial overgrowths that have grown in optical continuity with the crinoidal grains (Evamy and Shearman, 1965; Scholle and Ulmer-Scholle, 2003). Facies 2 contains both scattered bryozoans as well as zones of bryozoan rich wackestone-packstone that is intercalated in thin beds (approximately 2 cm in thickness). The bryozoans measure 3 – 10 mm in length and less than 2 mm in diameter and are lined or occluded by saddle dolomite and constitute approximately 10 percent of Facies 2. Dominant pore types include bryozoan molds (less than five percent), intercrystalline (less than one percent), and micro-porosity (less than one percent). The facies is locally bioturbated. Burrow Type 1 is observed in this facies. It is sparsely burrowed with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) Cruziana-type burrows. These burrows are filled with crinoid fragments (Figures 19 & 20).

Interpretations: A crinoidal grainstone with syntaxial overgrowths suggests that the bryozoan fragments found in this facies are deposited as disarticulated skeletal debris, not as a growth position bafflestone. It is likely that bryozoan baffles/bioherms exist nearby and these thin beds are storm events washing in the bryozoan fragments. Syntaxial overgrowths imply that mud was absent from the system during deposition (Evamy and Shearman, 1965); mud was likely winnowed by higher energy (storm) events (Buttler et al., 2007). Pervasive fabric destructive dolomitization causes difficulty in interpreting grain types. A crinoidal matrix is
Figure 19. Facies 2 – Crinoidal Grainstone (Core Photographs). A) Crinoidal Grainstone with burrows (Bw) and bryozoans (Bry) fragments creating moldic porosity when they are not occluded by dolomite. Bryozoan wackestone to mud-rich packstone – bryozoan (Bry) fragments create moldic porosity when they are not occluded by dolomite; B) Crinoidal Grainstone with bryozoans that are occluded by dolomite, scale in centimeters. Crinoids are difficult to distinguish by the naked eye (figure 20).
Figure 20. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. Facies 2, Crinoidal grainstone (dolomitized). Bryozoan molds (Bry) are partially occluded by dolomite (D). Crinoidal (E) grainstone is inferred from syntaxial overgrowths and irregular shaped grains.
interpreted based on irregular shaped grains, as seen using the white card technique (Dravis, 1990), and presence of syntaxial overgrowths, which are commonly associated with echinoderm fragments (Evamy and Shearman, 1965; Jones, 1989). In cross polarized light, the observed unit extinction or single-crystal extinction of the echinoderm fragments and their associated syntaxial overgrowths is also supports the interpretation of a crinoidal grainstone (Scholle and Ulmer-Scholle, 2003). Facies 2 is only present in two cores (McClure-Hergert #2, and Skinner #1) located approximately 1.5 miles (2.3 km) apart; suggesting that bryozoan build-ups, which contribute to deposition on the mid-ramp, are localized.

Facies 3 - Burrow-mottled Wackestone to Grainstone – Mid Ramp

Observations: Burrow-mottled wackestones to grainstones of Facies 3 display an increased faunal diversity (relative to Facies 1) with abundant crinoids, brachiopods, and bryozoans (these allochems make up approximately 50% of the skeletal debris, (Figures 21 & 22). Ostracods, bivalves, and gastropods are common (approximately 10% of skeletal debris) while tabulate corals are rare (less than 1% of skeletal debris), and peloids are sparse. Skeletal particles are commonly disarticulated and abraded, subangular to subrounded, and grain sizes range from fine carbonate sand (0.125 mm) to very coarse carbonate pebbles (64 mm). Burrow types 1, 3, and 4 are associated with this facies. Type 1 burrows display moderate to dense burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) Cruziana-type burrows. These burrows are filled with coarsely crystalline dolomite/calcite or micritized skeletal grains. Burrow type 3 is composed of discrete horizontal and cylindrical Cruziana-
Figure 21. Facies 3 – Burrow-mottled Wackestone to Grainstone (Core Photographs). A) Burrow-mottled wackestone with tubular tempestites (Tt); B) Burrow-mottled wackestone with bryozoans (Bry), brachiopods (Bh) and crinoids, gastropods, bivalves, and ostracods (visible under binocular scope), scale in centimeters.
Figure 22. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A: Facies 3, burrow-mottled wackestone, under cross-polarized light no skeletal debris is discernable. B: Thin section ‘C’ under cross-polarized light using white card technique (Dravis, 1990) brings out skeletal grain ghosts (echinoid fragments (E) and mollusk (M) shell fragments).
type burrows (2 – 15 mm); burrows are coarsely crystalline dolomite often in a limestone matrix. Burrow type 4 is characterized by moderate to dense cylindrical (2 mm – 4 cm) *Cruziana*-type burrows. Type 4 burrows have a nodular appearance with wispy and suture stylolites that can be burrow-bounding with thick accumulations of coarsely crystalline (sucrosic) dolomite between burrows. Intercrystalline and intergranular porosity (approximately 5 percent) was observed in the burrows.

**Interpretations:** The depositional environment of Facies 3 is interpreted as the mid-ramp. Increased biota diversity (compared to Facies 1) suggests normal, open marine conditions (Dodd and Stanton, 1981). An abundance of crinoids and brachiopods further implies normal marine conditions, as these organisms are stenohaline (requiring salinities of 30 to 40 parts per thousand) and cannot tolerate large fluctuations in salinity (Raup and Stanley, 1978). Bryozoans can tolerate a wide range of environments (i.e. freshwater, brackish, and marine), however, Dodd and Stanton (1981) state that they thrive best within normal marine salinities. The profusion of bryozoans in Facies 3 is, therefore, also suggestive of normal marine conditions. Tubular tempestites (Wanless *et al*., 1988), or storm fillings of coarser grained material, are common as well, similarly to those seen in Facies 1.

**Facies 4 - Skeletal Grainstone – Inner Ramp Shoal**

**Observations:** Facies 4 is comprised of undifferentiated skeletal grainstones composed of completely micritized skeletal grains, sparse peloids, and mud rip-up clasts (Figures 23-25). The destructive micritization of skeletal grains often obscures the original grain type. Identifiable grains in this facies include: crinoids/echinoids
Figure 23. Facies 4 – Skeletal Grainstone (Core Photographs). A) Crinoidal Skeletal Grainstone – fine-grained, well-sorted; B) Micritized Skeletal Grainstone – coarse-grained, poorly-sorted micritized (McG) skeletal grains and mud clasts (MC), scale in centimeters.
Figure 24. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A: Facies 4, skeletal grainstone – large mud clast (MC) in center is composed of mud, skeletal grains, and dolomite (see ‘B’ for magnified view), replacing dolomite is seen only in mud clasts. B: Enlarged view of ‘A’, skeletal fragments include mollusk shells (M), bryozoans (bry), echinoid fragments (E), and ostracods (O).
Figure 25. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A: Facies 4, skeletal grainstone composed primarily of crinoid (E) fragments with syntaxial overgrowths (S) and sparse mud clasts (MC). B: Image ‘A’ under cross-polarized light.
and brachiopods (approximately 65% of total skeletal material); and trilobites, ostracods, bivalves, and bryozoans (approximately 15% of skeletal fragments). The micritized grains are subangular to subrounded, moderately- to well-sorted, and grain sizes range from fine (0.125 mm) to medium (0.5 mm) carbonate sand. Rip-up clasts (average 0.2 mm in diameter) are composed of clasts of skeletal debris, peloids, and dolomitized mudstones. Dolomite replacement of mud, within rip-ups, is more extensive in rip-up clasts containing sparse to no skeletal debris. Dominant cement types are primarily micritic and saddle dolomite, in addition to syntaxial overgrowths of echinoderm fragments. A limited amount of calcite and marine phreatic cementation is present, but is not pervasive within this facies type and likely indicates early marine cementation. Sparse, localized, intervals with graded beds, laminations, and occasional cross-lamentations were observed but are not typical of this facies.

**Interpretations:** Facies 4 is interpreted to be a shallow (within wave base), high energy skeletal grainstone shoal deposited within the inner-ramp environment. The absence of mud-sized particles and abundance of rounded micritized grains suggests high-energy conditions with active wave or current agitation of sediments, which winnowed away finer particles (Flugel, 2004; Rupple and Walker, 1982). Since a ramp, by definition, has no break in slope, high-energy shoal deposits (e.g. Facies 4) form in the nearshore environment (Ahr, 1973). Stabilization of the shoal can occur in areas where agitation of the substrate has ceased; boring algal filaments can cause micritization and cementation of grains on the inactive and stabilized shoals (Dravis, 1979). Additionally, micritized and cemented grains that were ripped-up
during a storm event can be redistributed within both the active and inactive shoal environments.

**Facies 5 – Tempestites**

Facies 5 consists of storm related deposits, or tempestites. Two types of tempestites were observed in core and thus broken into subfacies 5A and 5B. Facies 5A is a distal (relative to shoreface) storm deposit, that is defined by hummocky-cross laminations. Whereas Facies 5B is a proximal (relative to shoreface) storm deposit characterized by very coarse to pebble sand grains, intraclasts and shell lags with sharp basal contacts.

**Facies 5A - Hummocky-cross laminated skeletal Grainstone - Tempestite**

*Observations:* Facies 5A is a very fine (0.125 – 0.063 mm) sand sized undifferentiated skeletal to peloidal (0.063 – 0.015 mm) grainstone that displays hummocky cross laminations, which are generally bounded by sutured stylolites (Figures 26 & 27). Hummocky-cross laminations exhibit low-angle, gently curved laminations with a hummock that is convex-up and a swale that is concave-up (Flugel, 2004). Hummocky-cross laminations are best developed in the Van Wert Zone and is best displayed in the Tolle 1-13 core (see appendix B pg. 54). Thin (5 mm – 5 cm) intercalations of fine- (0.125 mm) to very fine-grained (0.062 mm) sub-parallel fossils (shelly fragments) are common in mudstones (Figure 23) and were documented in the Black River interval examined in this study.
Interpretations: Storm deposits, or tempestites, are a common feature on carbonate ramp environments (Flugel, 2004; Kreisa, 1981; Wanless et al., 1988).

Figure 26. Facies SA – Tempestite facies (Core Photographs). A) Hummocky-cross laminated (HCS) peloidal grainstone; B) Hummocky-cross laminated peloidal grainstone with distal skeletal storm lag debris (dst) – skeletal debris is mostly mollusks and brachiopods, scale in centimeters.
Figure 27. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A & B: Facies 5A, Peloidal grainstone from hummocky cross stratified zone. Stratification is discernable at the lower magnification of image ‘A’.

Facies 5A is interpreted to have been deposited between fair- and storm-weather wave base (Aigner, 1985) on the mid- to outer-ramp environments. The hummocky cross stratification observed in this facies is characteristic of high-energy storm waves and currents (Bourgeois, 1980), which are preserved because background sedimentation is so quiet. Thin intercalations of fine-grained, sub-parallel shelly lags are commonly associated with more distal mid-ramp storm event sedimentation (Flugel, 2004).

Facies 5B – Intraclastic Grainstone – Tempestite

Observations: Facies 5B is an intraclastic grainstone containing rip-up clasts of lime and dolomitic mudstone (2 mm – 4 mm), peloids, and undifferentiated skeletal debris. Normal graded bedding can often be discerned occurring in conjunction with a sharp basal contact and a bioturbated top. These beds have a coarsely crystalline matrix in hand sample and generally occur just below the peritidal deposits of Facies 6. This facies is only observed in two cores, Hergert #2 (see appendix B, pg. 43) and Skinner #1 (Figure 28).

Interpretations: Facies 5B represents proximal tempestites deposited between storm wave base and fair weather wave base (the depth to which average daily waves will affect a substrate) during storm events within the inner-ramp environment. Shell pavement or lags formed through the transportation and mixing of bottom megafauna occurs in high-energy nearshore environments (Kreisa, 1981). Proximal deposits form in higher energy, are coarse-grained, and thicker then their distal cousins (Ainger, 1985). Proximal tempestites are characterized by very coarse (1 mm) sand
Figure 28. Facies 5B – Tempestite facies (Core Photographs). A & B) Intraclastic Grainstone with mud clast rip-ups (MC), peloids and undifferentiated skeletal debris, scale in centimeters.
grains to pebble (2 – 64 mm) grains within peloidal/skeletal wackestones to
grainstones (Flugel, 2004). Sharp basal contacts are indicators of erosion due to
storms and hurricanes (Ainger 1985; Ball et al., 1967). Intraclasts are likely related
to early marine cementation and the formation of hardgrounds (Flugel, 2004; Kreisa,
1981), which were later, ripped up possibly from tidal flat beaches.

Facies 6 - Peloidal Packstone to Grainstone – Inner Ramp/Peritidal

Observations: Facies 6 is a peloidal packstone to grainstone with sparse
cylindrical (Cruziana-type) and vertical (Skolithos) burrows. Peloids are fine- to very
fine-silt size (0.008 mm – 0.004 mm) and appear uniformly elongate and rounded in
thin sections and therefore may be fecal in origin. Moldic and fenestral porosity
(localized) are observed in less than five percent of these rocks. The molds and
fenestrae range in size from 1 – 10 mm and can be lined with dolomite. High
amplitude (up to 3 cm) suture stylolites (after Flugel, 2004) are common. Burrow
type 2 is identified in Facies 6 and is stylobedded exhibiting rare discernable vertical
(2 mm) Skolithos burrows. Intense bioturbation has almost completely reworked the
sediment making identification of individual burrow traces difficult (Figures 29 &
30).

Interpretations: Facies 6 is interpreted as being deposited in a peritidal
environment. It is likely the original depositional peritidal sediment was composed of
soft fecal pellets that were later compressed; in thin section, micritized peloids and
peloid relicts can be seen. Peritidal carbonates are defined as sediments that form
“around the tides” by Folk (1973). Flugel (2004) further classifies peritidal
Figure 29. Facies 6 – Peritidal (Core Photographs). A) Peloidal packstone with vertical burrows (Vb) and stylolites (Sty); B) Peloidal packstone with stylolites, very-fine silt sized peloids can be identified in thin section, scale in centimeters.
Figure 30. Photomicrographs impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A: Facies 6, peloidal grainstone. B: Peloidal grainstone with dolomite crystals (D) lining vugs (V) and molds.
carbonates as “deposits formed in supratidal, intertidal and shallow subtidal areas”. No definitive evidence of subaerial exposure, e.g. cyanobacterial mats, mudcracks, karsting, soil formation, etc., was observed within the core, suggesting a very shallow subtidal to lower intertidal environment of deposition. Although fenestrae are observed (less than five percent), Shinn (1983) cautions against basing environmental interpretations on fenestrae alone, as irregularly shaped voids (such as fenestrae) occur in both subtidal and supratidal grainstones. A study of Ordovician peritidal carbonates by Grover and Read (1978), also recognized that fenestrae of tidal flat deposition occur in conjunction with exposure/desiccation. Facies 6 lacks exposure/desiccation features suggesting an unexposed environment of deposition. The reworking of sediment by intense bioturbation and lack of cyanobacterial mats suggests that normal marine tidal waters (non-hypersaline) influenced the peritidal environment in this facies. Cyanobacterial mats are generally deposited in the supratidal and upper-intertidal environments where the water conditions are too harsh for most burrowers; the overwhelming evidence of bioturbation in Facies 6 is suggestive of a subtidal to very lower-intertidal depositional environment. Cyanobacteria mats and intense burrowing do not co-exist since the burrowers will feed on the cyanobacterial mats (documented in a study by Grover and Read, 1978). Facies 6 also exhibits a buff color (Light Olive Gray 5Y 5/2 in core descriptions, see Appendix A) resulting from oxidation, which Shinn (1983b) relates to peritidal deposition.
Facies Burrow type 1 Burrow type 2 Burrow type 3 Burrow type 4
Facies 1 Y Y Y Y
Facies 2 Y N N N
Facies 3 Y N Y Y
Facies 4 N N N N
Facies 5A N N N N
Facies 5B N N N N
Facies 6 N Y N N

Table 5. Chart showing which burrow types are present in the different facies.
CHAPTER IV

DISCUSSION

Reservoir characterization of carbonate rocks requires the integration of depositional, diagenetic, and petrophysical data at multiple levels (i.e. outcrop and subsurface studies) (Flugel, 2004; Grammer et al., 2004). A reservoir can be defined by its storage capacity and ability to recover hydrocarbons (Grier and Marschall, 1992). The quality of a reservoir is delineated by preserved primary porosity and associated permeability or enhancement (e.g. meteoric dissolution) and conversely by occlusion, in which, all effect the fluid flow. Because the depositional systems/facies are the primary control on reservoir characteristics (i.e. porosity, permeability, diagenesis), the main focus of this study relied on high-resolution core analysis and porosity and permeability data from core and wireline logs to reconstruct depositional systems.

It is important to note that reservoir quality, as a function of porosity, is dependent on the arrangement of pores and the way in which those pores are interconnected by the pore throats (Flugel, 2004). Additional studies of both the petrophysical properties and diagenesis in the Trenton-Black River would augment the current depositional analysis and aid in the development of a more detailed reservoir characterization.
Depositional Setting

Four depositional settings, or sub-environments, were recognized for the Black River group: the outer ramp, the mid-ramp, the inner ramp, and a peritidal zone (Figure 31). Carbonate ramps, as defined by Ahr (1973), are carbonate platforms with gently dipping slopes of less than one degree and no significant break in slope. According to the Ahr model, higher energy facies are deposited in a shallow, shoreward or proximal position and lower energy facies are deposited in a deeper, seaward or distal environment. Previous studies of carbonate ramps (Pope and Read, 1997; Read, 1980, 1998; Ahr, 1973; van Buchem et al., 2002; Dibenedetto and Grotzinger, 2005; Wright and Burchette, 1998; Lindsay et al., 2006; Irwin, 1965) have found a distribution of grainier (higher energy) facies in a proximal position and muddier (lower energy) facies that pass into relatively deeper environments without a significant break in slope.

By understanding the depositional system and vertical stacking pattern of facies at a higher resolution than previous studies have captured, an enhanced picture of the heterogeneities in hydrothermally dolomitized ramp reservoirs may be gained. Similar to the Ahr model, a depositional trend and vertical stacking pattern of muddy to grainy facies was observed in this study that is consistent with deposition along a low declivity ramp (Figure 32).
Figure 31. Idealized depositional model for the Black River carbonate ramp in south central Michigan Basin. The model illustrates a single time slice of deposition from the inner ramp, ramp crest (shoal), mid-ramp, and outer ramp. Depositional energy, sedimentary structures, and main carbonate textures determined from this study are depicted below each environment. Image modified after Flugel, 2004.
Figure 32. Location map of the 7 wells used in this study. Wells were chosen based on stratigraphic range, geographic location, condition of core and availability of corresponding petrophysical data. Hypothesized direction of depositional strike and dip are also displayed.
Outer to Mid-Ramp

Depositional Fabric

The outer ramp is characterized primarily by burrow-mottled mudstone and is observed in all cores in the study (see appendix B). Burrowed mudstones are frequently intercalated with thin, sub-parallel shelly lags interpreted as distal tempestites. Deposition of sediments in the outer ramp occurred between fair- and storm-weather wave base. Storm-weather wave base is defined as the depth to which storm waves affect sediments on the sea floor; in modern seas this zone ranges between 15 to 50 m (Aigner, 1985, Tucker and Wright, 1990). Outer ramp facies are diagenetically overprinted by stylomottled pressure solution structures, which Flugel (2004) defines as a patchy enrichment of insoluble material that has grown at solution interfaces. Generally occurring at burrow boundaries, these solution interfaces are accumulations of calcite while the burrows are dolomitized and create a nodular fabric. Other workers (Aigner, 1985; Wanless, 1979) have also noted that outer ramp environments are dominated by stylomottled pressure solution structures. Stylomottling, or non-sutured solution surfaces, create a nodular fabric that is associated with burrowing and dolomitization.

The mid-ramp represents normal marine conditions ideal for carbonate production as noted by a general increase in faunal diversity. Other workers (e.g. Ruppel and Jones, 2006; Dodd and Stanton, 1981; Choi and Simo, 1998) have noted that an increase in faunal diversity relative to outer ramp environments, or other semi-restricted environments, may be used as a proxy for normal marine conditions.
Conversely, a decrease in faunal diversity (relative to normal marine, or other non-restricted environments), when observed with accumulations of mud-sized sediment and scarce current structures, may be used as a proxy for lower energy, mid (distal) to outer ramp deposition. Concentrated zones of bryozoan debris, present in only two cores (McClure Hergert #2 and Skinner #; 2.4 km/1.5 mi apart), suggests that bryozoan thickets are localized along the mid-ramp, providing detrital material that is locally intercalated with crinoidal packstones and grainstones of nearby ramp crest shoals (see appendix B, pg. 48 and 74). Since at least 85% of the crinoidal materials observed in this study are associated with deposition in a high-energy shoal environment, logic suggests the bryozoan thickets occurred in close juxtaposition to the shoals.

Burrowing is a common feature in ramp environments (Enos, 1983) and is observed throughout the outer and mid-ramp in this study. Distally, there is a decrease in faunal diversity and an increase in burrowed mudstones, which are intercalated with thin, fine-grained tempestites. A decrease in faunal diversity distally may be caused by changes in the water chemistry or oxygen levels. Storm deposits, or tempestites, are a ubiquitous feature in carbonate ramp environments (Flugel, 2004; Kreisa, 1981; Wanless *et al.*, 1988; Burchette and Wright, 1992). Wanless *et al.* (1988) defines a tubular tempestite as forced burrow-fillings of coarser-grained storm related sediment. Since the ramp is highly burrowed and commonly affected by storms, tubular tempestites are a prominent fabric observed in the outer and mid-ramp environment. Hummocky cross laminations are most
common in the mid-ramp environment between fair- and storm weather wave base. Previous workers (Flugel, 2004; Aigner, 1985; Kreisa, 1981) have defined hummocky cross laminations (or stratification) as low angled, gently curved laminae which display a convex-upward hummock and a concave-upward swale. Hummocky cross laminations in carbonate sediments are generally developed in packstone to grainstones and range in thickness from 0.1 m – 2 m (0.5 ft – 7 ft) (Flugel, 2004). The Van Wert zone is the most notable hummocky-cross laminated tempestite in the Black River and can be as thick as half a meter (1.6 ft) (see appendix B, pg. 54).

**Reservoir Quality Associated with Fabric**

Pemberton and Gingras (2005) suggest that fossilized burrow fabrics are largely an overlooked reservoir, yet they are an essential factor in calculations of reservoir volume and performance. Burrowed facies account for 85 percent of the Black River Group evaluated in this study and thus special attention was paid to their reservoir properties. Burrow-fills (i.e. tubular tempestites; Wanless *et al.*., 1988) display the best developed porosity in the Black River, which is consistent with what has been documented by other workers in similar environments (Lindsay *et al.*, 2006; Pemberton and Gingras, 2005; Gingras *et al.*, 2004; Flugel, 2004; Scholle, and Ulmer-Scholle, 2003; Longman *et al.*, 1987).

Individual burrowed intervals in this study range in size from 2 mm to 4 cm (diameter) and exhibit average porosities and permeabilities of 2.5 percent and 2 millidarcies from whole core analyses. The low porosity and permeability values are
likely due to sample bias incorporated into whole core analysis, where samples are chosen at relatively low resolution (1-3 ft). Higher resolution (millimeter to centimeter scale) sampling of burrows versus matrix would provide a more accurate spread of permeability values and other reservoir calculations as burrow fill permeabilities are not uniformly distributed and generally differ from the matrix (Pemberton and Gingras, 2005, Gingras et al., 2004). Mini-permeameter measurements by Gingras et al., 2004, from the Upper Ordovician Bighorn Group facies (which includes the Red River Formation) in the Williston basin (depositionally analogous to the Trenton-Black River, Michigan Basin) exhibits an average matrix permeability of 1.65 millidarcies while average burrow permeability is 19.2 millidarcies. Thin sections examined in this study display greater porosity in the burrows than matrix, which suggests a high-resolution permeability study, would result in similar findings to the Gingras, et al., 2004 study (Figure 33). Additional studies of the Trenton-Black River by Thornton (2011, in progress) have yielded new data on variations in reservoir permeability. Using a mini-permeameter, Thornton was able to measure the permeability of Trenton-Black River cores at a centimeter scale and map variations of permeability in burrowed versus non-burrowed rocks (Figure 34).

**Geometry/Regional Extent**

The uniformity of sea-floor topography on low declivity ramps results in the prevalence of relatively thin, but widespread distribution of depositional facies that
grade continuously along the ramp without abrupt changes into adjacent facies (Aigner, 1985). Major storm events, creating hummocky cross laminations, have been documented (Wanless et al., 1988) to affect sedimentation over large areas (i.e.

Figure 33. Photomicrograph impregnated with blue epoxy to fill pore space and stained with Alizarin red to highlight calcite. A tubular tempestite is circled in black which displays intercrystalline porosity while little to no visual porosity can been indentified in the rest of the sample.
Figure 34. Burrow-enhanced permeability in Trenton-Black River (core photographs). Mini-permeameter measurements made on a 2 cm by 2 cm grid are overlain on a burrowed Black River core. Permeability in md is contoured on the rock surface. From Thronton, 2011 (in progress).

the Caicos Platform, approximately 430 square kilometers). Storm waves can penetrate to depths of 200 meters (650 ft) (Kreisa, 1981). A zone of hummocky cross stratification in the Albion-Scipio trend (the Van Wert zone), can be correlated from the Warner-Fouty 9-8 (see appendix B pg 50), Tolle #1-33 (see appendix B pg. 54), and Timm-Kennedy #1-14 (see appendix B, pg. 62) wells, approximately 89 kilometers (55 mi). The correlative zone of hummocky cross stratification suggests
that the ramp environment during Black River time was regionally extensive, and less than 200 meters (650 ft) deep, which can result in widespread development of tubular tempestites.

**Shoal and Inner Ramp**

**Depositional Fabric**

The ramp crest shoal sediments are composed of partially to completely micritized skeletal grains within a well-sorted, cross-laminated grainstone. The ramp shoal facies was deposited in a very shallow, high-energy subtidal setting between wave base and fair-weather wave base. A ramp, by definition, has no discernable break in slope, thus waves break in a proximal or near shore position resulting in the formation of shoal environments (Ahr, 1973; Aigner, 1985). Grainstone shoal facies in the Albion-Scipio trend are composed primarily of crinoids/echinoids and brachiopods (approximately 65%) although the original grains are often obscured by destructive micritization.

Micritization of grains can occur rapidly over inactive portions of the shoal, as documented by Dravis (1979). Stabilization of the shoal can occur in areas where agitation of the substrate has ceased; biota-mediated micritization and cementation of grains on the inactive and stabilized shoals (Dravis, 1979). Grammer *et al.* (1999), have established that cementation of ooid sand grains in water depths of 30 meters or more in the Bahamas can occur within eight months. Other workers have also noted similar trends in ramp crest (shoal) energy, water depth, and cementation or
micritization of the shoal environment (French and Kerans, 2004; Lindsay et al., 2006; Read, 1982; Dravis, 1979).

Facies 4 of the current study was identified as a skeletal grainstone shoal, dominated by micritized grains. An absence of mud-sized particles and abundance of round micritized grains is indicative of high-energy conditions, which winnowed away finer particles. As the active shoal shifted position, inactive portions would have stabilized through micritization and cementation of grains.

The inner ramp peritidal environment represents the most proximal or shoreward position of facies identified in the current study. Facies in the inner ramp environment are composed of bioturbated, peloidal packstones to grainstones (see appendix B for examples). The shoal crest acts to dampen the affect of wave activity; high peloidal content and low faunal diversity suggests a decrease in normal marine circulation (Lindsay et al., 2006). Grover and Read (1978) indicate that intense burrowing, when combined with a lack of cyanobacterial mats is related to non-hypersaline tidal waters.

Facies 6, the inner ramp – peritidal facies in the current study, is characterized by a low diversity of biota, and intense bioturbation. The combination of low diversity fauna and intense burrowing suggests an inlet or passageway through the ramp crest shoal, possibly due to migration of the shoal. Restricted portions of the peritidal zone exhibit chert nodules (most likely relicts of restricted sponge deposition, Enos, 1983), which are common in the uppermost part of the Black River.
Reservoir Quality Associated with Fabric

Reservoir quality of the inner ramp and ramp crest shoal is mixed depending on the amount of cementation. On average, porosity is 2% and permeability is less than 1 md. Early marine cementation of the packstones and grainstones makes the shoal more resistant to burrowing and wave processes that may create porosity (French and Kerans, 2004) through the formation of tubular tempestites if the material could be moved downdip along the ramp. Secondary porosity, developed as molds and fenestral pores, which are dominant pore types observed in the shoal and inner ramp, have been shown by Anselmetti et al. (2008) to have low permeability due to their non-connectivity of the pores in three dimensions. Further, pore space is often occluded by dolomite and anhydrite (see appendix B, pg. 96 as example).

Geometry/Regional Extent

The ramp shoal facies can be identified between wells along strike for 89 kilometers (55 mi) between the McClure-Hergert #2 and Timm-Kennedy #1-14 wells (figure 29) suggesting a widespread shoal complex developed in a strike orientation. The peritidal environment (inner ramp) is correlative in a dip direction for 6.6 kilometers (10 mi) between the McClure-Hergert #2 and Hall #1-13 wells (refer to Figure 31 for well locations). Uncertainty remains as to the subsurface continuity of these (and other) facies due to the fairly limited well and core control (see Figure 34). Increased prediction of the lateral continuity of facies in studies such as this with limited subsurface data can often be enhanced through the incorporation of analogs.
Analogs

One of the key facies in the Black River Group of the Albion-Scipio trend are the burrowed facies. The burrowed facies are present in every core examined in the study (see appendix B for examples). These burrow networks are important because they are often hydraulically filled with grainier sediments during storm events, have an extensive interconnected three-dimensional pore networks, and are preferentially dolomitized. Modern carbonate depositional environments are used as a comparison to better understand the processes that created fabrics seen in the Black River Group, Michigan Basin. Additionally, other Ordovician intracratonic basins can be evaluated for similarities both structurally and depositionally, in order to capture a robust understanding of how the primary depositional facies influence reservoir quality in the Black River Group, Michigan Basin.

Florida Bay

Florida Bay and the Florida reef tract are situated at approximately 25 degrees north latitude (sub-tropical) on a carbonate shelf extending 300 km (186 mi) south to southwest of Miami (Tucker and Wright, 1990) (Figure 35). Florida Bay is a triangular lagoon between the southern end of the Florida Peninsula and the Upper Florida Keys. The Bay (inner shelf) is connected to open marine waters through a series of tidal channels between the Keys, although the exchange of normal marine
water is relatively limited (Tucker and Wright, 2001; Enos and Perkins, 1977; Bathurst, 1971). Water temperatures of the Bay range from 15-40°C (59-104°F) while the shelf temperatures are 18-30°C (64-86°F) and salinities in Florida Bay can range from 6 to 58 ppt (Tucker and Wright, 1990; Bathurst, 1971). Deposition in Florida Bay is dominated by mud banks, which are commonly burrowed (Enos,
Depositional Fabric

As discussed previously, tubular tempestites, as defined by Wanless et al. (1988), are forced burrow-fillings of coarser-grained storm related sediment. Modern burrows in Florida Bay are back-filled rapidly once they become inactive (Shinn 1968). Modern Callianassa (a type of crustacean) burrows are considered to be analogous to the Thalassinoides burrow traces, (Wanless et al, 1988; Sheehan and Schiefelbein, 1984) which are common during the Ordovician (Gingras et al, 2004; Pemberton and Gingras, 2005; Sheehan and Schiefelbein, 1984). Coarse-grained sediments that are ejected by the burrower tend to make up backfilling materials, particularly in Callianassa type burrows, contributing to a porosity and permeability contrast with the matrix sediments (Morrow, 1978). Wanless et al (1988) concluded that a small storm will completely fill open burrows forcing excavation of new Callianassa burrows; storms generating energy levels high enough to fill open burrows can be expected, on average, every 5-8 years in sub-tropical zones (e.g. Florida, Bahamas, Caicos). Tedesco and Wanless (1991) have shown that Callianassa burrowers will eject finer grained sediment to the surface and pack coarser sediment in the side chambers of the burrow; when the chambers are filled in (from either storms or normal burrowing activity), a new burrow will be excavated (Figure 36). This constant reworking of sediments will destroy any evidence of primary, e.g. original, sedimentary structures with the exception of skeletal debris that
was too coarse for the burrowers to excavate (Tedesco and Wanless, 1991). Although coarse-grained skeletal debris may be preserved in the burrow galleries, it should not be used as a proxy for the energy level of the original depositional environment (Shinn, 1968). Fine-grained sediment expelled from the burrows may be winnowed away during storms or in the presence of bottom currents creating an overall coarsening of the sedimentary sequence (Tedesco and Wanless, 1991).

Figure 36. Examples of modern decapod crustacean Callianassa (made from a partial resin cast, left) and ancient Thalassinoides (right) burrows. Burrowing organisms can create extensive interconnected three-dimensional burrow galleries which may enhance permeability and play a significant role in reservoir quality. Scholle, P.A., Bebout, G.D., and Moore, C.H., 1983.

Reservoir Quality Associated with Fabric

Horizontal burrows of Callianassa (modern crustaceans) and Thalassinoides (ancient) traces can create extensive three-dimensional interconnected galleries
Burrow galleries act as fluid migration pathways resulting in preferential dolomitization in other ancient settings (Lindsay et al., 2006; Pemberton and Gingras, 2005; Gingras et al., 2004; Flugel, 2004; Scholle, and Ulmer-Scholle, 2003; Pu, and Qing, 2003; Longman et al., 1987; Wilson and Jordan, 1983; Wanless, 1979; Morrow, 1978; Porter and Fuller, 1959; Beales, 1953) similar to burrows in the Black River Group in the Albion-Scipio trend. Thornton (2011, in progress) measured Black River core using a mini-permeameter and recorded permeabilities from 1 to over 100 md in burrowed facies (see Figure 34), which supports the interpretations of the current study.

Figure 37. Schematic diagram illustrating tubular tempestites evolution. A) Normal burrowing conditions with coarse grained material packed in side chambers of burrow; B) storm infilling of burrow gallery; C) Re-excavation after a storm blocks off the burrow; D) multiple generations of storm infillings (tubular tempestites) of Callianassa burrows. Image from Tedesco and Wanless, 1991.
Geometry/Regional Extent.

The *Callianassa* burrow galleries can extend one to two meters into the substrate and create a network of burrows that are laterally extensive across hundreds of meters (Shinn, 1968; Wanless et al, 1988). The burrow mounds are densely packed, generally less than one meter apart (Shinn, 1968). These burrowed banks can then extend laterally along depositional strike for several kilometers (Enos, 1977). *Callianassa* burrows are common in lower intertidal to subtidal environments in water depths of up to 10 meters (35 ft) in Florida (Shinn, 1968). Since ramps commonly range from ten’s to hundred’s of kilometers in strike direction and several kilometers in dip direction (Flugel, 2004; Enos, 1983; Read, 1982), i.e., burrowed sediments can be extremely pervasive on epeiric carbonate ramps. Burrowing associated with the Van Wert storm bed (see appendix B, pg. 55) can be correlated 89 kilometers (55 miles) along depositional strike creating a considerable spatial area in which tubular tempestites are able to develop.

Bahamas

The modern Bahamas Platform is a sub-tropical carbonate platform (between 22° and 27° north latitude) and occupies an area of approximately 96,000 square kilometers (37,000 square miles) (Tucker and Wright, 1990; Bathurst, 1971) (Figure 38). Average water depth across the Great Bahama Bank is 7 to 10 m (10 – 33 ft) and temperatures on the bank average 22° C to 31° C (72° F to 89° F) (Bathurst, 1971). Salinities are generally normal marine (36 ppt) but can range as high as 46 ppt in
more restricted areas that lack tidal exchange with open marine waters (e.g., waters

just leeward of Andros Island). Easterly trade winds create a series of skeletal reefs
and shoals on the windward margins of the Bahamas platform. Burrowing and
peloidal sediments dominate the deposition on the leeward margins of the Bahamas
platform where the waters are relatively calm. Although Great Bahama Bank is an
isolated carbonate platform, it is comparable in facies distribution and geometry to
the low declivity ramp deposition of the Black River Group in the Michigan Basin.
Facies trends across the Bahama Banks are aerially extensive and generally grade

Figure 38. Satellite image of the Bahamas Platform. Lighter shades indicate shallow
water. Image courtesy of NASA.
continuously across the platform without abrupt changes similar to ramp deposition in epeiric sea settings (e.g., Michigan Basin during the Ordovician).

**Depositional Fabric**

The leeward (western) side of Andros Island (Great Bahama Platform) is a tidal flat extending 5 to 35 km (3 - 22 mi) with a muddy peloid-rich lagoon behind the tidal flat complex (Tucker and Wright, 1990). Behind Andros Island muddy peloidal sediment with extensive bioturbation covers approximately sixty percent of the platform (Figure 39). The tidal flat and the bioturbated peloidal sediment behind Andros are similar in both depositional facies and distribution to peritidal facies in this study (see appendix B, pg. 45). Increasing energy conditions across the platform (caused by fetch) creates a rim of skeletal packstones at the edge of the platform and an increased diversity in biota approaching the rim of the platform; similarly, an increased diversity of biota is observed in the mid-ramp approaching the skeletal grainstones of the ramp crest shoal in this study.

Ooid sand shoals commonly develop along portions of the platform margins as a result of tidal flow and wave-generated currents, which constantly agitate the sediments and create ooids (Harris, 1979). Dravis (1979) has shown that submarine cementation and surficial hardground formation of oolitic sediments can be a widespread and rapid diagenetic occurrence resulting in stabilization of shoals and occlusion of porosity. The skeletal grainstone shoal observed in this study (Facies 4) displays evidence of marine cementation and micritization of grains suggesting shoal
Figure 39. Facies map of the Bahamas Platform and South Florida. Note that approximately 60% of Great Bahama Bank is covered by muddy pelletal sediment. Image modified from Enos and Perkins, 1976.

Storm infillings of modern burrow structures (*Callianassa*), first observed on the Bahamas Platform, have been related to the Paleozoic *Thalassinoides* burrow trace (Shinn, 1968; Wanless et al., 1988; Gingras et al., 2004), which are observed in the current study. Studies by Shinn (1968) and Tedesco and Wanless (1991), have demonstrated that *Callianassa* burrow structures can be densely concentrated (within meters of one another) in peritidal areas and extend one to two meters into the
substrate (Figure 40). Peritidal facies observed in the Albion-Scipio trend (Facies 6)

Figure 40. A) Callianassa burrow mounds exposed during a spring low tide on Long Key, Florida; B & C) Underwater photographs of Callianassa burrow mounds. Note the density in which the organisms build their burrows. Photographs courtesy of G. Michael Grammer and W. B. Harrison III.

were subjected to intense bioturbation that obliterated all structures, comparable to intense bioturbation observed today in South Florida peritidal environments.

Reservoir Quality Associated with Fabric

Dravis (1979) has demonstrated that early diagenetic modification to modern oolitic sand shoals is related to porosity and permeability trends and may be
analogous to reservoir quality in ancient sand shoals of various composition. Shoal facies in the current study (Facies 4) exhibit evidence of diagenetic modification that, in general, decreases porosity and permeability.

Densely packed three dimensional *Callianassa* burrow galleries (tubular tempestites) are considered a modern analog to the Paleozoic *Thalassinoides* by other workers (Shinn, 1968; Wanless et al., 1988; Gingras et al., 2004; Sheehan and Schiefelbein, 1984). High resolution sampling of ancient burrow galleries, in core, by Gingras et al. (2004) have demonstrated that permeabilities of tubular tempestites can be up to twenty times greater then permeability averaged over the entire sample. Visual porosity, observed in Black River cores and thin sections, increased sharply in moderately burrowed facies (Figures 18, 21, and 33).

**Geometry/Regional Extent**

Modern shoals on the Bahama Banks can range from 2 – 4 km (1.2 – 2.5 mi) wide and extend, discontinuously, nearly 70 km (44 mi) (Harris, 1979). It is reasonable to assume the shoal environment of the Albion-Scipio during Black River time may also have extended, discontinuously, approximately 89 km (55 mi) between the McClure Hergert and Timm-Kennedy wells in this study (see appendix B for examples).

Burrowed fabrics are pervasive throughout the Bahaman Platform. Approximately 60% of Great Bahama Bank is composed of pelleted and peloidal sediments (Enos and Perkins, 1976) and tubular tempestites. Burrowed sediments are
a ubiquitous fabric throughout the Black River Group and account for approximately 85% of facies observed in the cores of this study. The calm waters in the lee of Andros are conducive to carbonate mud generation by burrowing organisms. By comparison, the lower energy conditions of the outer ramp and of the peritidal environment in the study area (where energy is dampened by the skeletal shoal) generated fabrics similar to those observed over approximately 60% of Great Bahama Bank (refer to Figure 38).

Williston Basin

The Williston Basin is an intracratonic basin similar to the Michigan Basin during the Paleozoic, and the Ordovician Red River Formation is depositionally analogous to the Trenton-Black River (Peterson and MacCary, 1987; Longman et al., 1987; Porter and Fuller, 1959) (Figures 41 & 42). The Red River package ranges in thickness from 150 to 215 meters (500 - 700 ft) and burrowed members within the formation can range in thickness from 9 to 90 meters (30 - 300 ft) (Peterson and MacCary, 1987; Longman et al., 1987).

Depositional Fabric

The Red River Formation in the Williston Basin (Ordovician) is split into three shoaling upwards units: A, B, and C (Longman, 1987; Kohm and Louden, 1982). The “C” unit, 90 – 140 m (300 – 400 ft) thick, is economically the most important and is divided into a burrowed, laminated, and anhydrite member (Kohm

Figure 41. Location of the Williston Basin. Basin edge is defined by the finely
dashed line. The Williston Basin also extends northward into Manitoba

the “C” burrowed member accounts for almost 50 percent of reserves in the Red
River “C”, and is a primary target for exploration and production.

*Thalassinoides* burrow traces are recognized throughout the Paleozoic,
particularly the Ordovician, as composing much of the bioturbated carbonate shelf
deposits seen in the Great Basin (Sheehan and Schiefelbein, 1984), Williston Basin
(northern Great Plains) (Gingras et al., 2004; Pemberton and Gingras, 2005), and the
Michigan Basin.
### Reservoir Quality Associated with Fabric

The Red River Formation typifies diagenetic heterogeneities induced by burrowing (i.e. mottling); matrix permeabilities consistently average less than 2 md
while burrow permeabilities fluctuate widely and average 19 md (Gingras et al, 2004; Pemberton and Gingras, 2005, Longman et al., 1987). A similar trend is observed in the burrowed Black River group where the average permeability (from whole core analysis) is less than 2 md while permeability (from mini-permeameter) in a burrow can be above 100 md (Thornton, 2011 in progress) (see Figure 34).

Geometry/Regional Extent

Burrow-mottled limestones and dolomites can be extensive both vertically and laterally. Burrowed facies of the Red River Formation, Williston Basin, have been observed to extend tens of kilometers laterally and reach thicknesses of ten meters (Pemberton and Gingras, 2005); similar trends are observed in the Albion-Scipio trend in the Michigan Basin.

Limitations

Tie to Wireline Logs

Reservoir characterization projects attempt to correlate rocks and their associated facies to wireline logs as a tool to increase predictability of reservoir units. The vertical succession of depositional facies in the Black River is reasonably consistent, but few well-defined patterns of those facies may be gleaned from wireline logs alone. The lack of well-defined wireline log patterns may be related to multiple generations of extensive dolomitization and diagenesis. The most consistent marker in wireline log is the Black River Shale, which can be correlated across all wells used in this study. Hurley and Budros (1990) further subdivide the Trenton and
Black River Groups into layers “A” through “N” based on gamma-ray markers of compacted shales (millimeters to 15 cm thick). The subtlety of these markers in the study area makes this subdivision problematic to reproduce with any consistency and consequently was not used in this study.

**Problems Constructing Sequence Stratigraphic Framework from Albion-Scipio Data**

Sequence stratigraphy, as defined by Posamentier and James (1993) and Vail *et al.* (1977), is a study of rock relationships that occur within a chronostratigraphic framework of cyclic, genetically related units which are bounded by unconformities and their correlative conformities. A sequence stratigraphic framework can be established by identifying an ideal vertical succession (i.e. stacking pattern) of depositional facies and thereby delineating time correlative surfaces. The vertical succession of facies represent a shallowing upward cycle of depositional facies and can be used to infer changes in relative sea level in tectonically stable intracratonic seas (Ross and Ross, 1996). A second approach to sequence stratigraphy infers sea level fluctuations from the assemblages of shelly benthic fossils and their associated water depths (Ross and Ross, 1996). By differentiating depositional packages (i.e. vertical succession of facies) which form during a rise of sea level one can better predict lateral changes in facies type and geometry that may be expected in shoreward and basinward directions by applying Walther’s Law (e.g., facies that are found laterally adjacent will also be vertically adjacent).
Difficulties in the Michigan Basin

A multitude of factors create difficulty in building a sequence stratigraphic framework in the Michigan Basin: 1) A lack of well-defined exposure surfaces and tidal flat facies that normally delimit the upper boundary of each shallowing upward depositional sequence; 2) Accommodation space is not always filled (i.e. the rocks were not always exposed during a sea level lowstand); 3) Facies grade gradually into one another without abrupt contacts; and 4) Intense and pervasive dolomitization and subsequent recrystallization obscures original texture of fossil assemblages making chronostratigraphic correlations based upon the fossil assemblages problematic.

High frequency sequences (one vertical succession of facies) can be picked in individual wells based on vertical stacking patterns of facies, but cannot be correlated with any degree of certainty when core data does not overlap stratigraphically. Additionally, because well control is limited due to the elongate, linear nature of the Albion-Scipio trend and the oil water contact, the current interpretation of the sequence stratigraphic framework is data-constrained and may be refined as additional data become available.

Comparison to Williston Basin

The Williston Basin is the primary analog for the Michigan Basin during Black River time. Structural and depositional similarities between the two Basins allow for reasonable comparison of the intensely burrowed Red River Dolomites (Williston) and the Black River Group (Michigan). The Williston Basin can be used
as a proxy in the Michigan Basin to help refine some of the sequence stratigraphic
limitations encountered in the Black River Group.

The Williston Basin is an irregular or elliptical intracratonic basin covering an
area of 345,000 square kilometers (133,000 square miles) in North Dakota, South
Dakota, Montana and Canadian provinces of Manitoba and Saskatchewan (northern
Great Plains) (Gerhard et al., 1990). The basin is bounded in the east-southeast by
the Transcontinental Arch/ Siouxia uplift, the Bowdoin Dome, Black Hills Uplift and
Miles City Arch to the west-southwest, and the Canadian Shield to the North; no
structural sags or inlets to open marine waters, however, are reported during the
middle Ordovician (Gerhard et al., 1982; Peterson and MacCary, 1987) (Figure 43).

Sedimentation in the Williston Basin was, more or less continuous throughout
the Phanerozoic, and dominated by carbonate deposition during the Paleozoic
(Gerhard et al., 1982). Onset of basin subsidence, which is thought to be during the
Ordovician, initiated a transgression that was continuous into Silurian time (LoBue,
1982). Initial subsidence in the Williston Basin is also thought to be related to
Appalachian Orogenic activity (Gerhard et al., 1990).

In comparison, the Michigan Basin is an undeformed intracratonic basin
occupying approximately 207,000 square kilometers (80,000 square mi) and 5
kilometers (3 mi) deep. Basin-centered subsidence was initiated during the
Ordovician followed by regional eastward tilting into the Silurian (Howell and van der Pluijm, 1990, Catacosinos et al., 1990). Howell and van der Pluijm (1990), further state initial subsidence was related to Appalachian orogenic activity (Taconic Orogeny) during the Middle Ordovician. The Basin is bounded in the south-southeast by the Findlay-Algonquin arches, the Kankakee arch to the southwest, the Wisconsin arch to the west, and the Canadian Shield to the north (Catacosinos et al., 1990; Hurley and Budros, 1990) (Figure 44). The Logansport sag on the Kankakee arch

Figure 43. Map of the Williston Basin illustrating the locations of various structural arches and uplifts during the Ordovician. Image modified after Peterson and MacCary, 1987.
and the Chatham sag on the Findlay arch are thought to represent inlets to normal marine waters (Ives, 1960).

Figure 44. Conceptual map of the Michigan Basin during the Ordovician. The Logansport and Chatham Sags are proposed as inlets to open marine waters. Image modified after Ives, 1960.
Deposition of the Red River Formation is considered to be a series of "brining-upward" sequences composed of burrowed skeletal wackestones to packstones, laminated mudstones, and bedded anhydrite, which were all deposited in a subtidal setting (Longman et al., 1987). A "brining-upward" sequence of carbonates occurs during deposition in progressively more saline waters; the brines were most likely contemporaneous with deposition of the Red River "C" anhydrite (Longman et al., 1987). Longman et al. (1987) further state that deposition occurred in an arid, relatively restricted environment.

Little to no evaporite sequences are reported in the Black River of the Michigan Basin (or their equivalents in eastern North America) by other workers (Smith, 2006; Wilson et al., 2001; Pope and Read, 1997; Catacosinos et al., 1990; Hurley and Budros, 1990; Keith, 1988; Keith 1986), which is consistent with findings in the current study. In contrast, evaporite deposition is prevalent throughout the Red River of the Williston Basin (Longman et al., 1987). The disparity suggests a more restricted depositional environment in the Red River (Williston Basin) versus the Black River (Michigan Basin). Indeed, previous investigations of Black River fossil assemblages have concluded that deposition was predominantly normal marine with a wide array of biota including bryozoans, brachiopods, echinoderms, ostracods, conodonts, trilobites, bivalves, and gastropods (Wilson et al., 2001; Hurley and Budros, 1990).

Although the Black River (Michigan Basin) and Red River (Williston Basin) carbonates were deposited in similar subtidal settings, it appears that the Williston
Basin was more restricted during the Ordovician (based on the presence of evaporites). The capping evaporites in the Red River suggest the depositional system shoaled to exposure. The Michigan Basin was likely connected to open marine waters through the Logansport and Chatham sags, which were tentatively identified as inlets by Ives (1960), reducing sea level drawdown and subsequent exposure for the Black River Group (Figure 41). Even though the Black River Group, Michigan Basin, lacks capping evaporites, a proxy sequence stratigraphic framework can be developed using the chronostratigraphic units of the Red River Dolomites, Williston Basin.

Conclusions
1. The Black River Group was deposited on a low declivity ramp with facies consistent with deposition from inner ramp and peritidal environments to outer ramp environments with storm deposits. The depositional model was developed through a detailed depositional analysis, which integrated high-resolution core description, whole core analysis data, and a study of thin sections over key surfaces and facies, to provide an integrated model more robust than published models for the Black River Group in the Michigan Basin.

2. Bioturbation of the primary depositional facies has a direct affect on porosity and permeability. Highly interconnected burrow galleries, which have been hydraulically packed with coarser-grained sediments (e.g. tubular tempestites), act as conduits for fluid migration and are a fundamental reservoir unit in the Black River Group in the
Albion-Scipio trend. Bioturbated facies can be aerially extensive on a ramp, extending one half to two meters into the substrate and ten's of kilometers laterally, during a given time slice.

3. Understanding spatial distribution and geometries of facies mosaics will enhance the predictability of fundamental reservoir units in the Black River. Currently, well control constrains the data to such a degree that constructing a sequence stratigraphic framework can be problematic, however, the current interpretation may be refined as additional data become available. Despite the current data limitations, an increased understanding of the Black River depositional system and how it migrates over time will aide in the identification and prediction of fundamental reservoir units thus impacting future development of the Albion-Scipio trend (Figure 45).

4. Comparison of the Black River Group with the depositionally similar Red River Dolomites in the Williston Basin indicates that the Michigan Basin was less restricted during the Ordovician than the Williston Basin. Nevertheless, a sequence stratigraphic framework developed for the Red River dolomites can be used as a proxy when identifying high frequency sequence boundaries in the Black River Group (Michigan Basin). The presence of capping evaporite facies in the Red River Dolomites suggests a depositional system, which shoaled to exposure, whereas the cycles did not shoal to exposure (except locally) in the Michigan Basin. It is likely that structural sags on the Kankakee and Algonquin-Findlay arches of the Michigan
Basin acted as inlets to open marine water, reducing (or eliminating) sea level drawdown to the point of exposure for the Black River Group in the Michigan Basin.

5. Based upon facies type and correlations in the Michigan Basin, Figure 45 is a proposed model to explain how the Black River Group, in the Albion-Scipio study area, migrates and changes through a transgressive and regressive cycle. Although facies in the Black River Group generally do not shoal up to exposure, making it difficult to define high frequency sequences, a proxy sequence stratigraphic framework from the Williston Basin it is a likely model to be applied in the Michigan Basin. The proposed model could make a significant difference in the predictability of some key reservoir facies, and should be evaluated further with additional studies across the Michigan Basin.
Figure 45. Proposed model of the sequence stratigraphic framework of the Black River Group, Michigan Basin. The green represents the key reservoir facies. As sea level raises, the key reservoir faces back steps (retrogrades) and as sea level falls, the reservoir facies steps out (progrades). This relationship is important to understand because you can, in turn, better predict the vertical and lateral distribution of the key reservoir facies.
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APPENDIX A

Core Descriptions
Abbreviations and definitions

<table>
<thead>
<tr>
<th>Pore types</th>
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<tr>
<td>BC  Intercrystalline</td>
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<tr>
<td>BU  Burrow/Boring</td>
</tr>
<tr>
<td>BP  Interparticle</td>
</tr>
<tr>
<td>FE  Fenestral</td>
</tr>
<tr>
<td>FR  Fracture</td>
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<tr>
<td>VUG  Vug</td>
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<tr>
<td>WC  Intracrystalline</td>
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<td>WP  Intraparticle</td>
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Pressure Solution definitions (from Flugel, 2004)

**Stylobedding:** Pseudo-bedding caused by parallel pressure solution

**Stylolaminated:** Laminated appearance due to swarms of parallel stylolites

**Stylonodular:** Nodules and lenses of densely packed grains separated by stylolites

**Stylomottled:** Patchy enrichment of insoluble stylocumulate

**Stylobreccoid:** Originates from selective pressure solution

**Stylocumulate:** Insoluble residue accumulated along a pressure-solution surface
McClure Oil Co., McClure-Hergert #2, Hillsdale County, Michigan
Permit # 22196
Cored Interval: 3892.0’ – 4062.0’

3898.6’-3905.5’: Limestone, Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Medium Dark Gray (N4), skeletal burrow-mottled wackestone to packstone (facies 3), intercalated undifferentiated skeletal grainstone, bryozoans/brachiopods/crinoids/gastropods, peloids, intraclasts, chert nodules, stylolites

3917.1’-3898.6’: Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled mudstone to wackestone (facies 1), intercalated skeletal packstone (bryozoans/brachiopods/crinoids/gastropods) and peloidal wackestone, stylolites, Burrow types 1 & 3: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite, discrete horizontal and cylindrical burrows (2 – 15 mm)

3918.5’ – 3917.1’: Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite

3917.5’: Fine-grained skeletal tempestite, 6 cm

3917.9’: Fine-grained skeletal tempestite, 5 mm

3919.6’ – 3918.5’: Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), micritized skeletal grainstone (facies 4), very coarse-grained, burrows are rare, Burrow type 4: sparse cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding

3924.2’ – 3919.6’: Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled wackestone to packstone (facies 3), crinoids/trilobites/bryozoans/bivalves, Burrow type 4: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding
3933.8' – 3924.2': Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris, *Burrow types 1, 3, & 4*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite, discrete horizontal and cylindrical burrows (2 – 15 mm), moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding

3924.9': Skeletal grainstone (facies 4), 6 cm

3926.2': Skeletal grainstone (facies 4), 1.5 cm

3932.2': Skeletal grainstone (facies 4), 2.5 cm

3933.5': Skeletal grainstone (facies 4), 1.5 cm

3939.2' – 3935.2': Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled wackestone to packstone (facies 3), crinoids/trilobites/bryozoans/bivalves, *Burrow type 4*: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding

3939.8' – 3940.3': Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled, micritized skeletal/peloidal packstone (facies 3), crinoids/trilobites/bryozoans/bivalves, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite

3939.8' – 3940.3': Dolomitic Limestone, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled wackestone to packstone (facies 3), bryozoans/brachiopods/crinoids/gastropods, stylolites, MO/VUG

3950.8'-3940.3': Limestone, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (crinoids/brachiopods/bryozoans), peloids, chert nodules (<4 cm), *Burrow types 3 & 4*: discrete horizontal and cylindrical burrows (2 – 15 mm), moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding

3940.6': Hardground

3946.1': Laminations (5 cm)
3946.9': Skeletal Grainstone (facies 4) (4 cm)

3953.3'-3950.8': Limestone, Olive Gray (5Y 4/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (bryozoans/brachiopods/crinoids), chert nodules (5 cm), stylolites, Burrow types 3 & 4: discrete horizontal and cylindrical burrows (2 - 15 mm), moderate to dense cylindrical burrows (2 mm - 4 cm), wispy/suture stylolites which can be burrow-bounding

3957.5'-3953.3': Limestone (3964.7'-3962.8': Dolomite), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), burrow-mottled wackestone to packstone (facies 3), with peloids, sparse skeletal debris (bryozoans/brachiopods/crinoids), intercalated with zones of skeletal grainstone, intraclasts, stylolites, Burrow types 1, 3, & 4: horizontal (2 - 4 cm) and cylindrical (1 - 5 mm) burrows, filled with coarsely crystalline dolomite/calcite, discrete horizontal and cylindrical burrows (2 - 15 mm), moderate to dense cylindrical burrows (2 mm - 4 cm), wispy/suture stylolites which can be burrow-bounding

3958.7' - 3957.5': Limestone, Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), crinoidal/micritized grainstone (facies 4), argillaceous seams <2 mm, intercalated with burrow-mottled mudstone (facies 1), mud rip-ups (1 mm - 1 cm), Burrow type 4: moderate to dense cylindrical burrows (2 mm - 4 cm), wispy/suture stylolites which can be burrow-bounding

3956.1': Micritized grainstone storm bed (5 mm)

3957.1': Graded storm bed (6 cm)

3962.7' - 3958.7': Limestone (3964.7'-3962.8': Dolomite), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), burrow-mottled mudstone to wackestone (facies 1), with peloids, sparse skeletal debris (bryozoans/brachiopods/crinoids), intercalated with zones of skeletal grainstone, intraclasts, stylolites, Burrow types 1, 3, & 4: horizontal (2 - 4 cm) and cylindrical (1 - 5 mm) burrows, filled with coarsely crystalline dolomite/calcite, discrete horizontal and cylindrical burrows (2 - 15 mm), moderate to dense cylindrical burrows (2 mm - 4 cm), wispy/suture stylolites which can be burrow-bounding

3961.2': Crinoidal/micritized skeletal grainstone (facies 4) with rip-up clasts

3964.0' - 3962.7': Dolomite, Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), crinoidal grainstone with bryozoans
(2 mm – 1 cm) (facies 4), Burrow type 1: horizontal (2 – 4 cm) and vertical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite

3964.7’ – 3964.0’: Dolomite, Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Light Gray (N7), Medium Gray (N5), peloidal packstone to grainstone (facies 6)

3967.0’-3964.7’: Dolomite, Olive Gray (5Y 4/1), Light Gray (N7), Medium Dark Gray (N4), burrow-mottled mudstone to wackestone with sparse skeletal debris (facies 1), bryozoans/brachiopods/crinoids, intraclasts, stylolites, MO, Burrow type 3: discrete horizontal and cylindrical burrows (2 – 15 mm), intercalated with coarse grain tempestites of cemented skeletal grainstone with mud rip-ups

3968.5’ – 3967.0’: Dolomite, Olive Gray (5Y 4/1), Light Gray (N7), Medium Dark Gray (N4), hummocky to intraclastic grainstone (facies 5A & 5B), crinoids/bryozoans/brachiopods/gastropods, rip-ups of mud (5 mm – 1 cm, suture/wispy stylolites, MO, Burrow type 1 (sparse): horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite

3971.9’-3971.6’: Dolomite, Medium Dark Gray (N4), Brownish Black (5YR 2/1), black mudstone (facies 1)

3972.9’-3970.3’: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Dark Gray (N3), peloidal packstone (facies 6) to intraclastic grainstone (facies 5B), rare vertical burrows, rip-ups and intraclasts, MO/FR

3974.4’ – 3972.9’: Dolomite, Olive Gray (5Y 4/1), Brownish Black (5YR 2/1), Light Gray (N7), Dark Gray (N3), mudstone to intraclastic grainstone (facies 5B), mud rip-ups (2 mm – 5 cm) which grade into crinoidal grainstone, Burrow type 1 (in mudstone): horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite

3977.8’-3974.4’: Dolomite, Olive Gray (5Y 4/1), Brownish Black (5YR 2/1), Light Gray (N7), Dark Gray (N3), burrow-mottled wackestone (facies 3), bryozoan/crinoids/brachiopods/trilobites/rare coral clasts, peloids, MO, Burrow type 1: horizontal (2 – 4 cm) and vertical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite

3978.4’-3977.8’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Light Gray (N7), bryozoan wackestone (facies 2), burrow-mottled, stylolites, MO, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite
3995.8'-3978.4': Dolomite, Light Olive Gray (5Y 5/2), Olive Black (5Y 2/1), Medium Dark Gray (N4), burrow-mottled mudstone to wackestone (facies 1), intercalated skeletal packstone to hummocky cross laminated grainstone (facies 5A) (bryozoans/brachiopods/crinoids), burrow-mottled, stylolites, MO/FR

3996.3' – 3995.8': Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), mudstone to bryozoan wackestone (facies 2), MO, oxidized

3996.7'-3996.3': Dolomite, Light Olive Gray (5Y 6/1), Light Gray (N7), Black (N1), bryozoan wackestone (facies 2), MO

3998.6'-3996.7': Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Grayish Black (N2), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (bryozoans/undifferentiated shelly fragments), peloidal, grainier burrow-fills, MO, intercalated with intraclastic grainstone (facies 5) zones (<5 cm) with mud rip-ups (5 mm – 1 cm)

3997.7'; 3996.8': Hardground/erosional surface

3999.8'-3998.6': Dolomite, Yellowish Gray (5Y 7/2), Light Gray (N7), peloidal packstone (facies 6), sparse skeletal debris, burrowed, MO, Burrow type 2: bioturbated with sparse cylindrical and vertical (2 mm) burrows, stylobedded

4001.3'-3999.8': Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Brownish Black (5YR 2/1), crinoidal intraclastic grainstone to hummocky cross laminated grainstone (facies 5A), Burrow type 4: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding, bio-brecciated

4000.85': Hardground/erosional surface

4007.6'-4001.3': Limestone/Dolomite, Light Olive Gray (5Y 5/2), Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled wackestone to packstone (facies 3), crinoids/bryozoans/brachiopods/bivalves/ostracods, sparse peloids, stylolites, grainier burrow fills, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, and moderate to dense cylindrical burrows (2 mm – 4 cm) wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)

4009.4'-4007.6': Limestone, Light Olive Gray (5Y 6/1), Light Olive Gray (5Y 5/2), peloidal packstone (facies 6), sparse vertical burrows, stylolites, FR occluded with dolomite, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) filled with coarsely crystalline dolomite/calcite
4024.0'-4009.4': Dolomitic Limestone, Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N5), Dark Gray (N3), Grayish Black (N2), burrow-mottled, mudstone to wackestone (facies 1), grainier burrow-fills, peloidal, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, and moderate to dense cylindrical burrows (2 mm – 4 cm) wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)

4016.7' - 4016.8': Skeletal packstone (facies 5), distal tempestites of fine-grained, crinoid and undifferentiated shell fragments

4024.5'-4024.0': Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), fine-grained intraclastic grainstone with hummocky cross laminations (facies 5A), burrows and sparse cross-laminations rip-ups/flat pebbles, Burrow types 2 & 4: bioturbated with sparse cylindrical and vertical (2 mm) burrows and stylobedded, and moderate to dense cylindrical burrows (2 mm – 4 cm) wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)

4031.5'-4024.5': Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N5), burrow-mottled mudstone to wackestone (facies 1), intercalated with coarse grained crinoidal debris (tempestites bed), sparse skeletal debris, stylolites, FR/VUG lined to occluded with dolomite, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, and moderate to dense cylindrical burrows (2 mm – 4 cm) wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)

4031.8'-4031.5': Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Medium Gray (N5), skeletal/bryozoan wackestone (facies 2), suture/wispy stylolites, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, and moderate to dense cylindrical burrows (2 mm – 4 cm) wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)

4037.8'-4031.7': Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N5), burrow-mottled mudstone to wackestone (facies 1), intercalated with grainy sediment (storm laminations of crinoids), stylolites, VUG (<1 cm) lined to occluded with dolomite, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 cm) burrows filled with coarsely crystalline dolomite/calcite, Burrow type 4: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)
4031.7': Possible hardground, crinoids

4031.7': Hardground

4038.8'-4037.8': Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), laminated crinoidal grainstone (facies 4) intercalated with burrow-mottled mudstone (facies 1), sparse brachiopods, Burrow type 2: bioturbated with sparse cylindrical (2 mm) burrows, stylobedded

4040.2'-4038.8': Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1) burrow-mottled wackestone (facies 1), intercalated with muddy sediment, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 -5 mm) burrows filled with coarsely crystalline dolomite/calcite

4039.5': Stylolite (suture)

4043.1’ – 4040.2’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), peloidal packstone to grainstone (facies 6) with vertical burrows, well-developed moldic porosity and sparse to well-developed fenestral porosity, suture stylolites

4047.2’ – 4043.1’: Dolomite, Olive Gray (5Y 4/1), Olive Black (5Y 2/1), burrow-mottled mudstone (facies 1), rare bryozoans partially occluded by dolomite, suture and wispy stylolites, sparse vugs, Burrow type 4: moderate cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding

4050.5’-4047.2’: Dolomite, Light Olive Gray (5Y 6/1), Light Olive Gray (5Y 5/2), Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Brownish Black (5YR 2/1), skeletal/bryozoan wackestone (facies 2), MO

4048.5’: Flooding surface

4055.5’-4050.5’: Dolomite, Olive Gray (5Y 3/2), Grayish Black (N2), Black (N1) bryozoan wackestone (facies 2), intercalated with muddy sediment, MO

4062.0’-4055.5’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1) Grayish Black (N2), burrow-mottled wackestone (facies 1), Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) filled with coarsely crystalline calcite/dolomite, Burrow type 4: moderate cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding, intercalated with distal tempestites of undifferentiated skeletal debris

4059.8’: Hardground
4058.4': Hardground

4057.8': Hardground
Marathon Oil Co., Warner-Fouty 9-8, Hillsdale County, Michigan
Permit # 41359
Cored Interval: 4216.0' – 4238.5'

4216.0' – 4220.6': Limestone, Light Gray (N7), Medium Gray (N5), Burrow-mottled mudstone to wackestone (facies 1), Burrow Type 1 & 4: moderate bioturbation, horizontal (2 – 4 mm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <10% fine-grained (0.125 mm) bivalves/trilobites/gastropods/brachiopods, stylolites and discrete horizontal and cylindrical burrows (2 – 15 mm)

4221.0 – 4225.4': Limestone, Tempestite, Light Olive Gray (SY 5/2), Dusky Yellowish Brown (10YR 2/2), Olive Black (5Y 2/1), Light Gray (N7), Medium Gray (N5), undifferentiated skeletal grainstone with hummocky cross laminations (facies 5A)

4225.4' – 4227.3': Preserved section

4227.3 – 4233.8': Limestone, Light Olive Gray (SY 6/1), Moderate Olive Brown (SY 4/4), Light Gray (N7), Medium Gray (N5), peloidal mudstone to grainstone (facies 6) of fine silt sized grains (0.016 mm), sparse horizontal and cylindrical, suture stylolites and wispy stylolite swarms, lenses or pods (2 – 4 cm) of laminated micritized skeletal grains (crinoids/brachiopods/bivalves/trilobites/bryozoans)

4233.8' – 4235.3': Limestone, Olive Gray (SY 4/1), Dusky Yellowish Brown (10YR 2/2), Light Gray (N7), Medium Dark Gray (N4), peloidal mudstone (facies 6), <10% skeletal debris (bryozoans/brachiopods/crinoids), peloids, Burrow Type 1 & 4: moderate bioturbation, horizontal (2 – 4 mm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, stylolites and discrete horizontal and cylindrical burrows (2 – 15 mm)

4235.3' – 4235.9': Limestone, Olive Gray (5Y 3/2), Medium Gray (N5), mudstone (facies 1), Burrow Type 2: Intense bioturbation with sparse recognizable cylindrical and vertical (2 mm) burrows, stylobedded

4235.9' – 4238.25': Limestone, Dusky Yellowish Brown (10YR 2/2), Brownish Black (5YR 2/1), Medium Dark Gray (N4), skeletal mudstone to wackestone (facies 1), <10% fine-grained (0.125 mm) bivalves/trilobites/gastropods/brachiopods, stylolites and discrete horizontal and cylindrical burrows (2 – 15 mm)
JEM Petroleum Co., Tolle 1-33, Jackson County, Michigan
Permit # 37507
Cored Interval: 4240.0’ – 4270.0’

4240.0’ – 4250.3’: Limestone, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Medium Gray (N5), burrow-mottled mudstone to wackestone (facies 1) with intercalations of distal tempestites (facies 5B) (2 mm – 4 cm). Burrow Type 1, 4 (BT1, BT4): Moderate bioturbation, horizontal and cylindrical burrows (2 - 20 mm) filled with coarsely crystalline dolomite, <10% skeletal debris (fine grained bivalves/trilobites/gastropods), wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous).

4250.3’ – 4252.0’: Limestone, Olive Gray (5Y 4/1), Brownish Black (5YR 2/1), Medium Light Gray (N6), Black (N1), mudstone to wackestone tempestite (facies 5), laminated black calcareous shale (4 cm) with mud rip-up clast with pyritized anhydrite inclusions, wisps of shale (2 mm – 2 cm) intercalated throughout, thin (5 mm – 3 cm) distal tempestites composed of brachiopods/bryozoans/bivalves and less common trilobites/crinoids debris (grain size less than 0.05 mm), stylolitic

4252.0’ – 4257.0’: Limestone, Olive Gray (5Y 4/1), Olive Gray (5Y 3/2), Yellowish Gray (5Y 7/2), Dusky Yellowish Brown (10YR 2/2), Olive Black (5Y 2/1), tempestites, hummocky cross-laminated skeletal grainstone (facies 5A)

4257.0’ – 4257.7’: Limestone, Olive Gray (5Y 4/1), Yellowish Gray (5Y 8/1), Olive Black (5Y 2/1), Medium Gray (N5), Burrow Type 2 (BT 2): bioturbated mudstone (facies 1) w/sparse recognizable cylindrical (2 mm) burrows, chert nodule (7 cm by 4 cm)

4257.7’ – 4260.0’: Limestone, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Medium Light Gray (N6), Medium Gray (N5), Burrow Type 2 (BT2): bioturbated mudstone (facies 1) with localized fine-grained (0.025 mm) micritized grainstone (facies 4), wispy stylolite swarms, suture stylolites, and high amplitude columnar stylolites

4260.0’ – 4266.5’: Limestone, Light Olive Gray (5Y 6/1), Olive Gray (5Y 3/2), Dusky Yellowish Brown (10YR 2/2), Medium Gray (N5), Burrow type 4 (BT4): burrow-mottled, mudstone to wackestone (facies 1), less than 10% skeletal debris (brachiopods/bryozoans/crinoids)

4266.3’: Distal tempestites (facies 5A) with brachiopods/trilobites/bivalves/crinoids (grain size less than 0.05 mm)
4266.5' – 4270.0': Limestone, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Medium Gray (N5), Grayish Black (N2), burrow-mottled mudstone to wackestone (facies 1), skeletal debris consisting of brachiopods, trilobites, bivalves, crinoids, bryozoans, Burrow Type 4 (BT 4): discrete horizontal and cylindrical burrows (2 mm – 15 mm), burrows have a stromatactis-like texture, filled with coarsely crystalline dolomite, intense to total bioturbation, suture stylolites and sutured burrow-bounding stylolites
Amoco Production Co., Timm-Kennedy 1-14, Barry County, Michigan
Permit #30137
Cored Interval 3: 5110.0’ – 5171.0’
Cored Interval 4: 5230.0’ – 5289.0’

5110.0’ – 5115.5’: Limestone, Olive Gray (5Y 4/1), Medium Dark Gray (N4), Burrow-mottled mudstone (facies 1), Burrow Type 4 (BT4): discrete horizontal (up to 8cm wide and 2cm-3cm thick) and cylindrical burrows (2 mm – 15 mm), stylomottled, sparse low amplitude suture stylolites, and burrow-bounding suture seams. Intercalated with stylobreccioid, tubular tempestites filled with undifferentiated skeletal packstone, chert nodules (4 – 8 cm).

5111.0’: Graded tempestite of skeletal grainstone to skeletal wackestone (facies 5A) to laminated silt sized grainstone (?), bivalves/crinoids/trilobites, suture stylolites which can be burrow-bounding.

5115.5’- 5120.0’: Limestone, Olive Gray (5Y 4/1), Medium Gray (N5), Medium Dark Gray (N4), : Burrow-mottled mudstone to wackestone (facies 1) with moderate to dense bioturbation, Burrow Type 5 (BT5 cylindrical burrows (2 mm - 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations (argillaceous).

5117.7’: Burrow Type 3 (BT3): Undifferentiated skeletal grainstone (tubular tempestite), graded, 4cm.

5118.2’: Burrow Type 3 (BT3): Undifferentiated skeletal grainstone (tubular tempestite), 3 cm.

5120.0’ - 5127.0’: Limestone, Olive Gray (5Y 4/1), Olive Gray (5Y 3/2), Light Gray (N7), Medium Light Gray (N6), Medium Gray (N5), Burrow-mottled mudstone (facies 1), large horizontal burrows (8 cm wide and up to 4 cm thick), oxidized (lighter color) and filled with undifferentiated micritized skeletal grains, high amplitude suture stylolites/burrow-bounding suture seams/stylobreccioid, and abundant chert nodules (3 – 10 cm).

5127.0’ – 5128.0’: Limestone, Olive Gray (5Y 4/1), Olive Gray (5Y 3/2), Burrow Type 5 (BT5): Burrow-mottled mudstone (facies 1) with moderate to dense bioturbation, cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations (argillaceous). Upper 3 cm of burrows
filled with undifferentiated skeletal packstone to grainstone, fine sand sized micritized skeletal grains.

5128.0' - 5130.5': Limestone, Olive Gray (5Y 4/1), Medium Gray (N5), Medium Dark Gray (N4), Burrow-mottled mudstone to wackestone (facies 1), Burrow Type 4 (BT4): discrete horizontal (up to 8 cm wide and 2 cm – 3 cm thick) and cylindrical burrows (2mm-15mm), stylomottled, sparse low amplitude suture stylolites, and burrow-bounding suture seams. Intercalated with Burrow Type 5 (BT5): Burrow-mottled with moderate to dense bioturbation, cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations (argillaceous).

5130.0' - 5130.5': Limestone, Medium Dark Gray (N4), Burrow-mottled wackestone (facies 3) with moderate to dense bioturbation, Burrow Type 5 (BT5): cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations (argillaceous).

5131.0' - 5132.5': Limestone, Medium Dark Gray (N4), Burrow-mottled mudstone to wackestone (facies 1), Burrow Type 4 (BT4): discrete horizontal and cylindrical burrows (2 mm – 15 mm) stylomottled, sparse low amplitude suture stylolites, burrow-bounding suture seams.

5131.3': Burrow Type 3 (BT3): Undifferentiated skeletal grainstone (tubular tempestite), 2 mm thick, bored surface.

5131.9': Stylobreccioid

5132.5' - 5135.0': Limestone, skeletal wackestone to packstone (facies 3), Olive Gray (5Y 3/2), Medium Gray (N5), Burrow Type 2 (BT2): sparse burrows (cylindrical and vertical ~2 mm), stylobeded and burrow-bounded suture seams. Intercalated with Burrow Type 3 (BT3): Tempestites of sub-parallel fine grained skeletal debris (bivalves/trilobites), 5 mm thick, bounded by suture stylolites.

5135.0’ – 5141.8’: Limestone, Olive Gray (5Y 3/2), Medium Gray (N5), Burrow-mottled wackestone with moderate bioturbation, Burrow Type 1 (BT1): horizontal and cylindrical burrows (2 – 20 mm) filled with argillaceous material, <10% skeletal debris (fine grained bivalves/trilobites/gastropods), wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous)

5141.8’– 5142.0’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Undifferentiated skeletal grainstone (tempestite) (facies 5A), hummocky cross laminations, suture burrow-bounding stylolites.
5142.0’ - 5145.5’: Limestone, Olive Gray (5Y 3/2), Dark Yellowish Brown (10YR 4/2), Medium Gray (N5), Burrow-mottled mudstone to wackestone (facies 1), Burrow Type 4 (BT4): discrete horizontal and cylindrical burrows (2 mm – 15 mm), stylomottled, sparse low amplitude suture stylolites, and burrow-bounding suture seams.

5145.5 – 5146.0’: Limestone, Medium Dark Gray (N4), Undifferentiated skeletal grainstone (facies 4), coarse grained, moderately sorted, subangular to subrounded micritized abraded skeletal grains, sparsely burrowed, suture stylolites.

5146.0’ – 5146.2’: Limestone, Olive Gray (SY 3/2), Medium Gray (NS), Bioturbated mudstone (facies 1), Burrow Type 2 (B12): sparse burrows (cylindrical and vertical ~2 mm), stylobedded and burrow-bounded suture seams.

5146.2’ – 5148.8’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), Burrow-mottled mudstone to wackestone (facies 1), Burrow Type 4 (BT4): discrete horizontal and cylindrical burrows (2 mm – 15 mm), stylomottled, sparse low amplitude suture stylolites, and burrow-bounding suture seams.

5148.8’ – 5150.5’: Limestone, Dark Yellowish Brown (10YR 4/2), Medium Gray (N5), Burrow-mottled wackestone with moderate bioturbation (facies 1), Burrow Type 1 (BT1): horizontal and cylindrical burrows (2 – 20 mm) filled with coarsely crystalline dolomite, <10% skeletal debris (fined grained bivalves/trilobites/gastropods), stylonodular bedding (wispy and suture), with thick accumulations (argillaceous).

5150.5’ – 5151.0’: Limestone, Dark Yellowish Brown (10YR 4/2), Medium Gray (N5), Burrow-mottled mudstone (facies 1), Burrow Type 4 (BT4): discrete horizontal and cylindrical burrows (2 mm – 15 mm), stylomottled, sparse low amplitude suture stylolites, and burrow-bounding suture seams. Intercalated with Burrow Type 3 (BT3): Tempestites of sub-parallel fine grained skeletal debris (bivalves/trilobites), 5 mm thick, bounded by suture stylolites.

5151.0’ – 5152.0’: Limestone, Dark Yellowish Brown (10YR 4/2), Medium Gray (N5), Undifferentiated skeletal grainstone (facies 4), coarse grained, moderately sorted, subangular to subrounded micritized abraded skeletal grains, sparsely burrowed, suture stylolites.

5152.0’ – 5156.4’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), Burrow-mottled mudstone to wackestone with dense bioturbation (facies 1), Burrow Type 1 (BF1): horizontal (2cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <10% skeletal debris (fine grained bivalves/trilobites/gastropods), stylonodular bedding (wispy and suture).
5156.4’ – 5157.0’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), Bioturbated mudstone (facies 1), Burrow Type 2 (BF2): sparse burrows (cylindrical and vertical ~2 mm), stylobedded.

5157.0’ – 5157.3: Limestone, Medium Gray (N5), Undifferentiated skeletal grainstone (facies 4), coarse grained, partially micritized grains, bivalves/trilobites/gastropods.

5157.3’ – 5158.0’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), Burrow-mottled wackestone (facies 1) with dense bioturbation, Burrow type 1 (BT1): horizontal (2 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <15% skeletal debris (fine grained bivalves/trilobites/gastropods), wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous).

5158.0’ – 5159.0’: Dolomite, Light Olive Gray (5Y 5/2), Olive Black (5Y 2/1), Medium Gray (N5), Burrow-mottled wackestone to packstone (facies 3) with dense bioturbation, Burrow Type 1 (BT1): horizontal (2 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, 10% skeletal debris (fine grained bivalves/trilobites/gastropods) wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous). Intercalated with Burrow Type 3 (BT3): Tempestites of sub parallel fine grained skeletal debris (bivalves/trilobites), 5 mm thick, bounded by suture stylolites.

5159.0’ – 5161.0’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Burrow-mottled wackestone to packstone (facies 3) with dense bioturbation, Burrow Type 1 (BT1): horizontal (2 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite 15% skeletal debris (fine grained bivalves/trilobites/gastropods) wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous). Intercalated with Burrow Type 3 (BT3): Tempestites of sub-parallel fine grained skeletal debris (bivalves/trilobites), 5 mm thick, bounded by suture stylolites.

5161.0’ – 5163.6’: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Burrow-mottled wackestone (facies 3) with dense bioturbation, Burrow Type 1 (BT1): horizontal (2 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <10% skeletal debris (fine grained bivalves/trilobites/gastropods) wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous).

5163.6’ – 5163.8: Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Bioturbated mudstone (facies 1), Burrow Type 2 (BT2): sparse burrows (cylindrical and vertical ~2 mm), stylobedded.
5163.8' – 5165.5': Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), Burrow-mottled mudstone to wackestone (facies 1) with dense bioturbation, **Burrow Type 1 (BT1):** horizontal (2 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <10% skeletal debris (fine grained bivalves/trilobites/gastropods) wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous).

5165.5' – 5165.9': Limestone, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Undifferentiated skeletal grainstone (facies 4 grading into facies 5A), fine silt sized micritized skeletal debris, laminated to hummocky cross laminations.

5165.9' – 5167.0': Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Burrow-mottled mudstone (facies 1), **Burrow Type 2 (BT2):** sparse burrows (cylindrical and vertical ~2 mm), stylobedded.

5167.0' – 5169.0': Limestone, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Medium Gray (N5), Burrow-mottled mudstone to wackestone (facies 1), horizontal burrows are re-burrowed and geochemically altered (horizontals are oxidized, cylindrical re-burrows reduced?), coarse crystalline dolomite, wispy stylolites.

5169.0' – 5171.0': Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Burrow-mottled mudstone to wackestone (facies 1) with moderate bioturbation, **Burrow Type 1 (BT1):** horizontal (2 - 4 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <10% skeletal debris (fine grained bivalves/trilobites/gastropods), wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous). Intercalated with **Burrow Type 3 (BT3):** Tempestites (packstone to grainstone) of sub-parallel fine grained skeletal debris (bivalves/trilobites), 5 mm thick, bounded by suture stylolites.

**CORE FOUR**

5230.0' – 5259.3': Limestone, Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), burrow-mottled mudstone (facies 1), sparse skeletal debris (crinoids/brachiopods/bryozoans), peloids, abundant wispy stylolites, common suture stylolites.

5230.2' – 5230.6': Burrow-mottled wackestone, tempestites?

5231.5' – 5232.0': Burrow-mottled wackestone, large coral intraclasts (2 cm by 4 cm).
5233.0': Laminations (3.5 cm)

5233.3': Cross-laminated (5cm)

5234.8': Laminated (5 cm)

5242.5': Laminations (3 cm)

5230.2' – 5230.6': Limestone, burrow-mottled wackestone

5259.3' – 5267.5': Limestone, mudstone intercalated with undifferentiated grainstones 1 – 7 cm thick, Light Olive Gray (5Y 5/2), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), minor suture stylolites associated with grainstones, recognizable burrows are sparse.

5261.1': Boring

5267.5' – 5289.0': Limestone, burrow-mottled mudstone to wackestone, Light Olive Gray (5Y 5/2), Light Olive Brown (5Y 5/6), Olive Black (5Y 2/1), Medium Gray (N5), Medium Dark Gray (N4), sparse skeletal debris (crinoids/brachiopods/bryozoans), peloids, abundant wispy stylolites, common suture stylolites, chert nodules (1 – 8 cm).

5267.6' – 5268.0': Vertical burrows (hardground).

5269.6': Borings, micro-fractures occluded with HTD.

5269.8': Burrowed surface

5279.2': Micro-fractures occluded with HTD.

5287.8': Hardground
Marathon Oil Co., Skinner #1, Hillsdale County, Michigan  
Permit # 21833  
Cored Interval: 3875.0’ – 4000.0’

3890.7’ – 3875.1’: Dolomite (38903.7’ – 3888.0’ Limestone), Light Olive Gray (5Y 5/2), Light Olive Gray (5Y 6/1), Olive Gray (5Y 3/2), Medium Gray (N5), burrow-mottled grainstone, burrow-mottled mudstone to wackestone (facies 1), stylolitic, small infrequent zones of laminations (2 – 4 mm), bryozoans/brachiopods/crinoids/gastropods (~10% skeletal), small infrequent zones of mixed skeletal hash, MO (lined with dolomite)/FR (occluded by dolomite), Burrow types 1, 2, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarse-grained undifferentiated skeletal debris or fine grained micritized grains; bioturbated with sparse cylindrical burrows, stylobedded; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.

3889.9’: Black River shale (missing core?)

3887.0’: Trenton/Black River contact

3886.2’: Chert nodule

3885.7’: Laminations capped by undifferentiated skeletal grainstone.

3879.9’: Chert nodule

3893.2’ – 3890.7’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Light Gray (N7), skeletal grainstone (facies 4), storm deposits composed of: large (1-2 cm) skeletal debris consisting of mostly bryozoans/crinoids, zones of small (mm’s) skeletal hash consisting of bryozoans/crinoids/brachiopods/undifferentiated debris and intraclasts, zones of burrow-mottled wackestone MO (lined with dolomite and anhydrite)/ FR (occluded by dolomite).

3891.5’: Hummocky cross-laminated grainstone (facies 5A).

3891.6’: chert nodule (3 cm)

3903.7’ – 3903.2’: Dolomite, Olive Gray (5Y 4/1), Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Medium Gray (N5), Dark Gray (N3), burrow-mottled mudstone to wackestone (facies 1), bryozoans/brachiopods/crinoids/gastropods, MO (lined or occluded by dolomite)/FR (occluded by dolomite); Burrow type 1: horizontal (2 – 4 cm)
cm) and cylindrical (1 – 5 mm) burrows filled with coarse-grained undifferentiated skeletal debris or fine grained micritized grains.

3896.0': chert nodule (3 cm)

3899.4': chert nodule (4 cm)

3999.9': Burrow-mottled mudstone to wackestone (facies 1), Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarse-grained undifferentiated skeletal debris, chert nodule (2 cm).

3901.5': Skeletal grainstone, tempestite, large gastropod (1 cm) (facies 5A).

3901.8’ – 3902.55’: missing core

3902.55’ – 3903.7’: Burrow-mottled mudstone to wackestone (facies 1), Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarse-grained undifferentiated skeletal debris.

3913.6’ – 3903.7’: Limestone (3906.0’ – 3903.7’: Dolomitic-Limestone), Light Olive Gray (5Y 6/1), Medium Dark Gray (N4), Dark Gray (N3), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, brachiopods, crinoids, stylolitic, BC/MO, suture stylolites, sparse intraclastic grainstone storm deposits, BP/BC/FR (occluded by dolomite), Burrow types 1, 2, 3, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; bioturbated with sparse cylindrical and vertical (2 mm) burrows, stylobedded; sparse, discrete horizontal and cylindrical burrows (2 mm – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.

3904.7’: Tubular tempestite with undifferentiated skeletal grain fills.

3909.2’: hardground

3909.8’: chert nodule (3 cm)

3910.0’: Skeletal grainstone (facies 4), micritized grains and mud clasts (5 cm).

3910.2’: contact

3910.4’: contact

3911.5’: Skeletal grainstone (facies 4).
3912.9': Distal tempestite (facies 5A), sub-parallel shell fragments (2 mm).

3913.1': hardground

3913.2': Distal tempestite (facies 5A), sub-parallel shell fragments (2 mm).

3913.4': Intraclastic grainstone (facies 5B) containing mud-clasts w/undifferentiated skeletal material (2 cm).

3913.6' – 3914.6': Dolomite, Olive Gray (5Y 3/2), Dark Yellowish Brown (10YR 4/2), Medium Light Gray (N6), burrow-mottled wackestone to packstone (facies 3), >10% bryozoans, brachiopods, crinoids, gastropods, bivalves, Burrow type 4: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.

3926.0' – 3914.6': Dolomite, Olive Gray (5Y 3/2), Dark Yellowish Brown (10YR 4/2), Medium Light Gray (N6), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, brachiopods, crinoids, stylolitic, BC/MO, Burrow type 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; ); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3914.6': tabulate coral (storm deposit)

3917.8': chert nodule (5 cm)

3918.2': Laminated to cross-laminated, Burrow type 4: sparse to moderate, dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3918.7': contact

3919.8': Stylolite

3920.4' – 3921.5': Skeletal grainstone (facies 4), grains are partially to completely micritized, subangular to subrounded, moderately- to well-sorted, fine (0.125 mm) to medium (0.5 mm) carbonate sand grains, Burrow type 3: sparse, discrete horizontal and cylindrical burrows (2 mm – 15 mm).

3922.2': Intraclastic grainstone (facies 5B), 6 cm.

3923.4': Tubular tempestites filled with micritized grains.
3924.6' – 3924.0': missing core

3928.5': surface

3926.0' – 3930.0': Dolomite, Olive Gray (5Y 4/1), Olive (5Y 3/2), Dark Gray (N3), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, brachiopods, crinoids, stylolitic, BC/MO, Burrow type 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; ); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-binding.

3927.0': Intraclastic grainstone (facies 5B), 3 cm.

3927.9' – 3928.5': Skeletal grainstone (facies 4), micritized grains (0.5 mm).

3929.3': Intraclastic grainstone (facies 5B), 3 cm.

3929.5': Skeletal grainstone (facies 4), 4 cm.

3930.0' – 3931.0': Dolomite, Olive Gray (5Y 4/1), Olive (5Y 3/2), Dark Gray (N3), burrow-mottled wackestone to packstone (facies 3), >10% bryozoans, brachiopods, crinoids, gastropods, bivalves, Burrow type 4: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.

3931.0' – 3931.7': Dolomite, Olive Gray (5Y 4/1), Olive (5Y 3/2), Dark Gray (N3), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, brachiopods, crinoids, stylolitic, BC/MO, Burrow type 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; ); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-binding.

3931.7' – 3933.0': Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 3/2), Intraclastic grainstone (facies 5B), containing rip-up clasts of lime or dolomitic mudstone (2 mm – 4 cm), undifferentiated skeletal debris.

3933.0' – 3934.0': Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 3/2), Burrow-mottled mudstone to wackestone (facies 1) with peloids and sparse skeletal debris (brachiopods, bivalves, crinoids), stylobedded.

3935.8' – 3934.0': Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 3/2), Undifferentiated skeletal grainstone (facies 4), grains are partially to completely micritized, subangular to subrounded, moderately- to well-sorted, fine (0.125 mm) to medium (0.5 mm) carbonate sand grains.
3939.3′ – 3935.8′: Dolomite, Olive Gray (5Y 3/2), Dusky Yellow (5Y 6/4), Peloidal packstone to grainstone (facies 6), MO/Vug lined with dolomite.

3936.5′: Burrow-mottled wackestone to packstone, crinoids, bryozoans, bivalves, trilobites, 6 cm thick.

3939.6′ – 3939.3′: Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 3/2), burrow-mottled mudstone to laminated mudstone (facies 1), Burrow types 3 & 4: discrete horizontal and cylindrical burrows (2 – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3940.7′: surface

3941.2′ – 3939.6′: Dolomite, Dusky Yellowish Brown (10YR 2/2), Dusky Brown (5YR 2/2), Bryozoan Wackestone (facies 2), burrowed-mottled, encrusting bryozoan replaced with dolomite, BC (in the burrow fills)/FR (occluded by dolomite), stylolitic.

3942.0′ – 3941.2′: Dolomite, Dusky Yellowish Brown (10YR 2/2), skeletal grainstone (facies 4), primarily crinoidal, enhanced isolated vugs (mm’s) lined with dolomite, FR (occluded by dolomite), stylo-brecciated, Burrow type 2: bioturbated with sparse recognizable cylindrical burrows.

3950.0′ – 3942.0′: missing core

3962.4′ – 3950.0′: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Gray (5Y 3/2), Dusky Yellowish Brown (10YR 2/2), Medium Gray (N5), burrow-mottled mudstone to wackestone (facies 1) with grainy dolomite fills, peloidal, layering of solution enhanced moldic porosity liked with dolomite and burrow-mottled with minor skeletal fragments (bryozoans/brachiopods/crinoids), stylolitic, fractures occluded by dolomite, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite or micritized grains; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3960.5′: Skeletal Grainstone (facies 4), primarily crinoids, laminated (8 cm).

3959.8′: Skeletal Grainstone (facies 4), primarily micritized skeletal grains.

3957.3′ – 3957.5′: Skeletal Grainstone (facies 4), primarily crinoids, laminated to cross-laminated with stylolites.
3952.7': Mud rip-up clasts (2 mm – 2 cm)

3963.0’ – 3962.4’: Dolomite, Light Olive Gray (5Y 6/1), crystalline (?), peloidal grainstone (facies 6), solution enhanced moldic porosity lined with dolomite, burrow-mottled, fractures occluded by dolomite.

3964.4’ – 3963.0’: Dolomite, Light Olive Gray (5Y 6/1), Dark Yellowish Brown (10YR 4/2), Olive Black (5Y 2/1), burrow-mottled mudstone to wackestone (facies 1) intercalated with intraclastic grainstone (facies SA), <10% bryozoans and crinoids, BC/FR (occluded by dolomite), stylolitic, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3965.1’ – 3964.4’: missing core

3969.3’ – 3965.1’: Dolomite, Olive Gray (5Y 4/1), Dusky Yellowish Brown (10YR 2/2), Olive Black (5Y 2/1), Medium Light Gray (N6), burrow-mottled mudstone to wackestone (facies 1), bryozoans/brachiopods/crinoids (minor component), intercalations of undifferentiated skeletal grainstone (5 mm – 3 cm), stylolitic, MO/Vug/Pinpoint/FR, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3965.2’: Undifferentiated Skeletal Grainstone (facies 4), primarily crinoids, laminated, 10 cm thick.

3968.3’: Intraclastic Grainstone (facies SB), mud rip-up clasts (2 mm – 1 cm), 4 cm thick.

3970.2’ – 3969.3’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Medium Light Gray (N6), bryozoan wackestone (facies 2), burrow-mottled with grainy dolomite fills, BC/MO/Vug (lined/occluded by dolomite), stylolites, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite.

3971.0’ – 3970.2’: Dolomite, Dusky Yellowish Brown (10YR 2/2), Olive Black (5Y 2/1), burrow-mottled mudstone (facies 1), intense to total bioturbation.

3973.3’ – 3971.0’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Dark Yellowish Brown (10YR 4/2), Brownish Black (5YR 2/1), Black (N1), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans/brachiopods/crinoids,
stylolitic, BC/MO, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite.

3971.9’: Intraclastic Grainstone (facies 5B), mud rip-up clasts (1 mm – 2 cm).

3973.6’ – 3973.3’: Dolomite, Light Olive Gray (5Y 6/1), Peloidal grainstone (facies 6), suture stylolite, rare bryozoans/crinoids, MO/FE.

3976.5’ – 3976.5’: Dolomite, Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), Medium Gray (N5), burrow-mottled mudstone (facies 1) capped with skeletal wackestone (bryozoans/brachiopods/crinoids/gastropods), topped by muddy (?) interval with minor burrows filled with grainer dolomite and some bryozoans, solution enhanced stylolites, minor fracture porosity, *Burrow types 1, 3, & 4*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; discrete horizontal and cylindrical burrows (2 – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3974.0’ – 3976.0’: Tubular tempestites filled with undifferentiated skeletal grains.

3975.6’: Burrow-mottled wackestone to pack stone (facies 3) with bryozoans, brachiopods, crinoids, gastropods, and bivalves.

3976.2’: Bryozoan wackestone (facies 2), 10 cm.

3981.7’ – 3976.5’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Dusky Yellowish Brown (10YR 2/2), Olive Black (5Y 2/1), burrow-mottled mudstone to wackestone (facies 1), coarse grained crystalline dolomite (grainer burrow fills), BC/MO, minor skeletal debris (bryozoans/brachiopods/crinoids), 1.5 cm interval of grainstone, suture stylolites, *Burrow types 1, 3, & 4*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; discrete horizontal and cylindrical burrows (2 – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3978.8’: Intraclastic Grainstone (facies 5B), mud rip-up clasts (1 mm – 1 cm).

3979.2’: Hummocky Cross-laminated Grainstone (facies 5A), primarily crinoids, 3 cm thick.
3979.9': Skeletal Grainstone (facies 4), crinoidal, laminated.

3980.0': Skeletal Grainstone (facies 4), crinoidal, laminated.

3981.0': surface

3981.5': Stylo-bedding

3981.7': Intraclastic Grainstone (facies 5B), mud rip-up clasts (1 mm – 1 cm).

3987.2': Skeletal Grainstone (facies 4), crinoidal, 3 cm thick.

3990.9': Skeletal Grainstone (facies 4), crinoidal, 1 cm thick.

3991.3': Intraclastic Grainstone (facies 5B), rip-up mud clasts (1 mm – 2 cm), 5 cm thick.

3991.7': Skeletal Grainstone (facies 4), crinoidal, 3 cm thick.

3993.3': Hardground

3995.3': Rip-ups (2 mm – 1 cm)

3995.6' – 3981.7': Dolomite, Olive Black (5Y 2/1), Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), Medium Light Gray (N6), burrow-mottled mudstone to wackestone (facies 1), BC/MO/Vug (solution enhanced, partially to completely occluded by dolomite), suture stylolites, minor skeletal debris (bryozoans/crinoids), thin (1.5 cm) zones of grainstone intercalated throughout, Burrow types 1, 3, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; discrete horizontal and cylindrical burrows (2 – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3997.6' – 3997.3': Dolomite, Dusky Yellowish Brown (10YR 2/2), Brownish Black (5YR 2/1), burrow-mottled mudstone to wackestone (facies 1), burrow fills display well developed BC/BP, minor vugs partially to completely occluded by dolomite, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite.

3997.6' – 3997.3': Dolomite, Dusky Yellowish Brown (10YR 2/2), Crinoidal/peloidal Grainstone (facies 4), solution enhanced BC/MO/Vug, sparse tubular tempestites with dolomite or micritized grain fill.
3997.6' – 3999.9': Dolomite, Olive Black (5Y 2/1), Dark Yellowish Brown (10YR 4/2), Medium Light Gray (N6), Burrow-mottled Mudstone to Wackestone (facies 1), burrow-mottled, BC, large brachiopods (2 -5 cm), isolated vugs/fractures partially to completely occluded by dolomite, capped by muddier zone with wispy stylolites, Burrow type 4: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3999.6': Skeletal Grainstone, cross-bedded, primarily crinoids and undifferentiated shells, 10 cm thick.
Marathon Oil Co., Buehrer #1, Hillsdale County, Michigan
Permit # 21064
Cored Interval: 3610.0’ – 4000.0’
Examined Interval: 3948.9’ – 3832.3’

3832.3’-3839.8’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N5), Grayish Black (N2), burrow-mottled wackestone to packstone (facies 3), bryozoans, brachiopods, crinoids, mollusks, peloids, intraclasts, sparse laminations, grainier burrow-fills, FR/MO, Burrow type 1: moderate horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

3838.4’-3838.6’: Shale (flooding surface)

3839.8’-3844.0’: Dolomite, Light Olive Gray (5Y 6/1), Light Olive Gray (5Y 5/2), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Dark Gray (N4), Grayish Black (N2), burrow-mottled wackestone to packstone (facies 3), intercalated with skeletal grainstone (facies 4), bryozoans, brachiopods, crinoids, gastropods, sparse peloids, BP/FR, Burrow type 1: moderate horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

3844.0’-3850.8’: Dolomite, Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Dark Gray (N4), skeletal grainstone (facies 4), brachiopods, crinoids, mollusks, laminations, FR.

3845.0’-3850.8’: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), Light Gray (N7), Medium Dark Gray (N4), skeletal, grainstone (facies 4), crinoids, brachiopods, mollusks, sparse peloids, grainier burrow-fills, normal graded bedding MO/VUG, Burrow type 1: sparse horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

3846.3’: Hardground

3849.4’: Hardground

3849.5’: Intracasts (1.5 cm), differential compaction surface (?)

3850.8’-3853.4’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Gray (5Y 3/2), Brownish Black (5YR 2/1), Grayish Black (N2), Black (N1), burrow-
mottled skeletal wackestone to packstone (facies 3), closely intercalated with skeletal grainstone (facies 4), bryozoans/brachiopods/crinoids/gastropods, FR, *Burrow type 1*: sparse horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

3851.2*: Chert nodule with burrows and skeletal debris (7 cm).

3852.6*: Intraclasts (1 mm - 3 cm)

3853.3*: Hardground/boring

3853.4*-3858.0*: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), burrow-mottled skeletal wackestone to packstone (facies 3), bryozoans, brachiopods, crinoids, gastropods, sparse peloids, grainier burrow-fills, MO/FR/VUG, *Burrow type 1*: moderate horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

3858.0*-3862.0*: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Brownish Black (5YR 2/1), Very Light Gray (N8), Grayish Black (N2), burrow-mottled skeletal packstone (facies 3) to skeletal grainstone (facies 4), bryozoans, brachiopods, crinoids, gastropods, peloids, intraclasts and rip-up clasts, sparse burrows, MO/FR/VUG, *Burrow type 1*: sparse horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

3862.0*-3866.0*: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), burrow-mottled wackestone to packstone, bryozoans, brachiopods, crinoids, mollusks, peloids, intercalated zones of undifferentiated skeletal grainstone (facies 4), chert nodules, stylolite, MO/FR/VUG, *Burrows 4*: moderate cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3866.0*-3871.0*: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), Dark Gray (N3), burrow-mottled skeletal wackestone to packstone (facies 3), bryozoans/brachiopods/crinoids/gastropods, sparse peloids, laminations, stylolites, FR/MO/VUG, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3866.1*: Hummocky cross-laminated grainstone (facies 5A).

3870.0*: Skeletal grainstone (facies 4).

3871.0*-3876.0*: Dolomite, Light Olive Gray (5Y 6/1), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (bryozoans/brachiopods/crinoid), peloidal, intercalated zones of
sucrosic grainstone (facies 4), stylolites, MO/FR/VUG, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3876.0’-3877.0’: Dolomite, Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), burrow-mottled skeletal wackestone to packstone (facies 3), bryozoa, brachiopods, crinoids, tabulate coral, sparse peloids, MO/FR, Burrow type 1 & 4: moderate horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows; moderate cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.

3876.0’-3879.0’: Dolomite, Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), burrow-mottled skeletal wackestone to packstone (facies 3), crinoids, brachiopods, mollusks, intercalated with intraclastic wackestone to grainstone (facies 5A), peloids, intraclasts, laminations, stylolites, MO/FR, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3879.0’-3882.0’: Dolomite, Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (bryozoa/brachiopods), peloids, laminations, stylolites, MO/FR, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3882.0’ – 3882.9’: Dolomite, Olive Gray (5Y 3/2), Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), skeletal grainstone (facies 4), crinoids, brachiopods, mollusks, undifferentiated skeletal fragments, fine- (0.125 mm) to medium- (0.5 mm) sand size grains.

3883.0’ – 3883.9’: Dolomite, Olive Gray (5Y 3/2), Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), bryozoo wackestone to crinoidal grainstone (facies 2), bryozoa measuring 3 – 10 mm in length.

3882.0’-3882.9’: Dolomite, Olive Gray (5Y 3/2), Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), burrow-mottled skeletal wackestone to packstone (facies 3), bryozoa/brachiopods, peloids, MO/FR.

3884.0’-3894.6’: Dolomite, Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (bryozoa/crinoids), intercalated sucrosic grainstone and intraclastic grainstone, chert nodules (3 mm - 4 cm), stylolites, MO/FR, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.
3897.0’ – 3894.6’: Dolomite, Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), burrow-mottled skeletal wackestone to packstone (facies 3), brachiopods/crinoids/gastropods, peloids, stylolites, MO, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3898.1’ – 3897.0’: Dolomite, Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), skeletal grainstone (facies 4), crinoids, brachiopods, mollusks, undifferentiated skeletal fragments, fine- (0.125 mm) to medium- (0.5 mm) sand size grains.

3898.1’ – 3902.0’: Dolomite, Olive Gray (5Y 3/2), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), burrow-mottled skeletal wackestone to packstone (facies 3), brachiopods/crinoids/gastropods, peloids, stylolites, MO, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3902.0’ – 3912.3’: missing core

3912.3’ – 3914.6’: Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N6), bryozoan wackestone to crinoidal grainstone (facies 2), bryozoans measuring 3 – 10 mm in length, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.

3914.6’-3934.5’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N6), burrow-mottled mudstone (facies 1), sparse skeletal debris (bryozoans/brachiopods/crinoids), chert nodules (1.5-4 cm), intercalated sucrosic grainstone (facies 4), MO/FR, *Burrow types 1 & 3*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, moderate discrete horizontal and cylindrical burrows (2 – 15 mm).

3930.0’ – 3030.9’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Medium Gray (N6), bryozoan wackestone to crinoidal grainstone (facies 2), bryozoans measuring 3 – 10 mm in length.

3934.5’-3938.0’: Dolomite, Light Olive Gray (5Y 5/2), Olive Gray (5Y 3/2), burrow-mottled skeletal wackestone to packstone (facies 3), brachiopods/crinoids/gastropods, peloids, stylolites, MO, intercalated with coarse grained skeletal tempestites of sub-parallel shell fragments and graded bedding, *Burrow types 1 & 4*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite; moderate cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.
3938.0' – 3939.8’: Dolomite, Light Olive Gray (5Y 5/2), Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), skeletal grainstone (facies 4), ~80% crinoids, very coarse grained (> 0.5 mm).

3939.8’-3942.0’: Dolomite, Light Olive Gray (5Y 5/2), Dark Yellowish Brown (10YR 4/2), Dusky Yellowish Brown (10YR 2/2), burrow-mottled mudstone to packstone (facies 3), intercalated with skeletal grainstone (facies 4), brachiopods, mollusks, crinoids, stylolites, MO, Burrow type 3: moderate discrete horizontal and cylindrical burrows (2 – 15 mm).

3942.0’-3946.0’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), peloidal wackestone to packstone (facies 6), laminated, stylolites, MO.

3946.0’ – 3948.9’: Dolomite, Light Olive Gray (5Y 6/1), Olive Gray (5Y 4/1), Olive Black (5Y 2/1), Dusky Yellowish Brown (10YR 2/2), peloidal packstone to grainstone (facies 6), brachiopods, mollusks, moldic porosity, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite.
Jem Petroleum Corp., Hall et al. #1-13, Jackson County, Michigan
Permit # 36384
Cored Interval: 4307.0’ – 4360.7’

4307.0’ – 4308.0’: Limestone, olive gray (5Y 4/1), light gray (N7), hummocky-cross laminated grainstone (facies 5A), very fine (0.125 – 0.063 mm) sand sized undifferentiated skeletal to peloidal grains, hummocky cross laminations bounded by sutured stylolites and stylolite swarms, thin (2 – 5 mm) intercalations of fine- (0.125 mm) to very fine-grained (0.063 mm) sub-parallel undifferentiated shelly fragments.

4308.0’ – 4309.5’: Limestone, olive gray (5Y 4/1), light gray (N7), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), Burrow type 4: intense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate) and stylobrecciation.

4309.5’ – 4310.5’: Limestone, olive gray (5Y 4/1), peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, <10% undifferentiated shelly fragments, high amplitude suture stylolites, less than 5% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).

4310.5’ – 4312.4’: Limestone, olive gray (5Y 4/1), undifferentiated skeletal grainstone (facies 4), identifiable skeletal grains include: mollusks, crinoids, bryozoans, brachiopods, and ostracods, large mud clasts (2 mm – 1 cm) contain skeletal debris, calcite cement present between grains.

4312.4’ – 4314.4’: Limestone, olive gray (5Y 4/1), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), Burrow type 4: intense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate) and stylobrecciation.

4314.4’ – 4316.5’: Dolomite, olive gray (5Y 4/1), light gray (N7), peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, <10% undifferentiated shelly fragments, high amplitude suture stylolites, less than 5% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).

4316.5’ – 4336.5’: Dolomitic limestone, olive gray (5Y 4/1), light gray (N7), olive black (5Y 2/1), dusky yellowish brown (10YR 2/2), burrow-mottled mudstone to
wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), stylomottled, Burrow types 1: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite and undifferentiated micritized skeletal grains.

4336.5’ – 4339.0’: Limestone, dusky yellowish brown (10YR 2/2), olive gray (5Y 4/1), olive black (5Y 2/1), peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, <10% undifferentiated shelly fragments, high amplitude suture stylolites, less than 5% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).

4339.0’ – 4346.4’: Limestone, dusky yellowish brown (10YR 2/2), olive gray (5Y 4/1), olive black (5Y 2/1), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), Burrow types 1, 2 & 3: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, stylobedding and stylomottling, discrete horizontal and cylindrical burrows (2 – 15 mm) that are coarsely crystalline dolomite.

4346.4’ – 4352.6’: Limestone, dusky yellowish brown (10YR 2/2), olive gray (5Y 4/1), olive black (5Y 2/1), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), Burrow types 1: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.

4352.6’ – 4355.8’: Limestone, olive black (5Y 2/1), dusky yellowish brown (10YR 2/2), burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), Burrow types 1 & 4: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite and burrows with a nodular appearance, wispy and suture stylolites that can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stilocumulate).

4355.8’ – 4356.0’: Limestone, olive black (5Y 2/1), dusky yellowish brown (10YR 2/2), Limestone, olive gray (5Y 4/1), olive black (5Y 2/1), peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, high amplitude suture stylolites, less than 10% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).
4356.0' – 4359.0': Limestone, olive black (5Y 2/1), dusky yellowish brown (10YR 2/2), burrow-mottled wackestone to grainstone (facies 3), crinoids, brachiopods, bryozoans, ostracods, bivalves, gastropods, sparse peloids, coarse grained burrow-fills (tubular tempestites), *Burrow types 1 & 4:* moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite and burrows with a nodular appearance, wispy and suture stylolites that can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate).

4359.0’ – 4360.0’: Limestone, olive gray (5Y 4/1), olive black (5Y 2/1), peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, high amplitude suture stylolites, less than 5% FE (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (*Burrow type 2*).
APPENDIX B

Core Plates

All scales in centimeters. Red discoloration the result of modern leaching from colored paper.
MCCLURE OIL CO., MCCLURE-HERGERT #2, HILLSDALE COUNTY, MICHIGAN
Dolomitic Limestone, burrow-mottled wackestone to packestone (facies 3), crinoids, trilobites, bryozoans, bivalves. Burrow type 4: moderate to dense cylindrical burrows 92 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.
Limestone, burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (crinoids, brachiopods, bryozoans). Burrow types 3 & 4: discrete horizontal and cylindrical burrows (2 - 15 mm), moderate to dense cylindrical burrows (2 mm - 4 cm), wispy/suture stylolites which can be burrow-bounding. Hardground and boring at 3940.6'.
Limestone, burrow-mottled mudstone to wackestone (facies 1), sparse skeletal debris (bryozoans, brachiopods, crinoids), stylolites. Burrow types 3 & 4: discrete horizontal and cylindrical burrows (2 – 15 mm), moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.
Dolomite, crinoidal grainstone with bryozoans (2 mm – 1 cm) (facies 4).
Dolomite, mudstone to intraclastic grainstone (facies 5B), mud rip-ups (2 mm – 5 cm) which grade into crinoidal grainstone, *Burrow type 1* (in mudstone): horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite.
Dolomite, burrow-mottled mudstone to packstone (facies 1 & 3), stylolites, MO/FR
Limestone, peloidal packstone (facies 6), sparse vertical burrows, stylolites, FR occluded with dolomite. *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) filled with coarsely crystalline dolomite/calcite.
Dolomitic Limestone, burrow-mottled, mudstone to wackestone (facies 1), grainier burrow-fills, peloidal, Burrow types I & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, and moderate to dense cylindrical burrows (2 mm – 4 cm) wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite).
Dolomite, burrow-mottled mudstone to wackestone (facies 1), intercalated with grainy sediment (storm laminations of crinoids), stylolites, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 cm) burrows filled with coarsely crystalline dolomite/calcite, *Burrow type 4*: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations between burrows (dolomite)
Dolomite, bryozoan wackestone to crinoidal grainstone (facies 2), intercalated with muddy sediment, MO.
MARATHON OIL CO., WARNER-FOUTY 9-8, HILLSDALE COUNTY, MICHIGAN
Limestone, Tempestite, undifferentiated skeletal grainstone with hummocky cross laminations.
Limestone, Tempestite, undifferentiated skeletal grainstone with hummocky cross laminations, wispy/suture stylolites.
JEM PETROLEUM CO., TOLLE 1-33, JACKSON COUNTY, MICHIGAN
Limestone, mudstone to wackestone tempestite, laminated black calcareous shale (4 cm) with mud rip-up clast with pyritized anhydrite inclusions, wisps of shale (2 mm – 2 cm) intercalated throughout, thin (5 mm – 3 cm) distal tempestites composed of brachiopods/bryozoans/bivalves and less common trilobites/crinoids debris (grain size less than 0.05 mm), stylolitic.
Limestone, tempestites, hummocky cross-laminated skeletal grainstone (facies 5A).
Limestone, *Burrow type 4 (BT4)*: burrow-mottled, mudstone to wackestone (facies 1), less than 10% skeletal debris (brachiopods/bryozoans/crinoids).
Graded tempestite of skeletal grainstone to skeletal wackestone to laminated silt sized grainstone (?), bivalves/crinoids/trilobites, suture stylolites which can be burrow-bounding.
Burrow-mottled mudstone, large horizontal burrows (8 cm wide and up to 4 cm thick), oxidized (lighter color) and filled with undifferentiated micritized skeletal grains, high amplitude suture stylolites/burrow-bounding suture seams/stylobrecciod, and abundant chert nodules (3 – 10 cm).
Limestone, Burrow-mottled mudstone to wackestone, discrete horizontal and cylindrical burrows (2 mm – 15 mm), stylomottled, sparse low amplitude suture stylolites, and burrow-bounding suture seams.
Limestone, Burrow-mottled wackestone with dense bioturbation, horizontal (2 cm) and cylindrical burrows (1 – 5 mm) filled with coarsely crystalline dolomite, <15% skeletal debris (fine grained bivalves/trilobites/gastropods), wispy/hummocky stylolites which can be burrow-bounding with thick accumulations (argillaceous).
Limestone, burrow-mottled mudstone (facies 1), sparse skeletal debris (crinoids/brachiopods/bryozoans), peloids, abundant wispy stylolites, common suture stylolites.
Limestone, mudstone intercalated with undifferentiated grainstones 1 – 7 cm thick, minor suture stylolites associated with grainstones, recognizable burrows are sparse.
MARATHON OIL CO., SKINNER #1, HILLSDALE COUNTY
Dolomite, burrow-mottled mudstone to wackestone (facies 1), stylolitic, bryozoans/brachiopods/crinoids/gastropods (~10% skeletal). Burrow types 1, 2, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarse-grained undifferentiated skeletal debris or fine grained micritized grains; bioturbated with sparse cylindrical burrows, stylolobed; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.
Dolomite, burrow-mottled mudstone to wackestone (facies 1), stylolitic, small infrequent zones of laminations (2 – 4 mm), bryozoans/brachiopods/crinoids/gastropods (~10% skeletal), small infrequent zones of mixed skeletal hash, MO (lined with dolomite)/FR (occluded by dolomite), Burrow types 1, 2, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarse-grained undifferentiated skeletal debris or fine grained micritized grains; bioturbated with sparse cylindrical burrows, stylobedded; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.
Dolomite, grainstone, storm deposits composed of: large (1-2 cm) skeletal debris consisting of mostly bryozoans/crinoids, zones of small (mm’s) skeletal hash consisting of bryozoans/crinoids/brachiopods/undifferentiated debris and intraclasts, zones of burrow-mottled wackestone MO (lined with dolomite and anhydrite)/ FR (occluded by dolomite).
Intraclastic grainstone (facie 5A) containing mud-clasts w/undifferentiated skeletal material (2 cm).
Dolomite, burrow-mottled wackestone to packstone (facies 3), >10% bryozoans, brachiopods, crinoids, gastropods, bivalves, *Burrow type 4*: moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.
Dolomite, Olive Gray (5Y 3/2), Dusky Yellow (5Y 6/4), Peloidal packstone to grainstone (facies 6), MO lined with dolomite.
Dolomite, grainstone (?), Bryozoan Wackestone (facies 2), burrowed-mottled, encrusting bryozoan replaced with dolomite, BC (in the burrow fills)/FR (occluded by dolomite), stylolitic.
Dolomite, burrow-mottled mudstone to wackestone (facies 1) with grainy dolomite fills, peloidal, layering of solution enhanced moldic porosity liked with dolomite and burrow-mottled with minor skeletal fragments (bryozoans/brachiopods/crinoids), stylolitic, fractures occluded by dolomite, Burrow types 1 & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite or micritized grains; moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.
Skeletal Grainstone, (facies 4), primarily micritized skeletal grains.
Dolomite, burrow-mottled mudstone (facies 1), intense to total bioturbation.
Dolomite, bryozoan wackestone to crinoidal grainstone (facies 2), burrow-mottled with grainy dolomite fills, BC/MO/Vug (lined/occluded by dolomite), stylolites, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite.
Intraclastic Grainstone (facies 5B), mud rip-up clasts (1 mm – 1 cm) to Hummocky Cross-laminated Grainstone (facies 5A), primarily crinoids, 3 cm thick.
Dolomite, burrow-mottled mudstone to wackestone (facies 1), BC/MO/Vug (solution enhanced, partially to completely occluded by dolomite), suture stylolites, minor skeletal debris (bryozoans/crinoids) in thin (1.5 cm) zones of grainstone intercalated throughout, Burrow types 1, 3, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; discrete horizontal and cylindrical burrows (2 – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.
Limestone, Intraclastic Grainstone (facies 5B), rip-up mud clasts (1 mm – 2 cm), 5 cm thick to Skeletal Grainstone (facies 4), crinoidal, 3 cm thick. Burrow-mottled mudstone to wackestone (facies 1).
Dolomite, burrow-mottled mudstone to wackestone (facies 1), burrow fills display well developed BC/BP, minor vugs partially to completely occluded by dolomite, *Burrow type 1*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite.

Crinoidal/peloidal Grainstone (facies 4), solution enhanced BC/MO/Vug, sparse tubular tempestites with dolomite or micritized grain fill.
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, brachiopods, crinoids, stylolitic, BC/MO, suture stylolites, sparse intraclastic grainstone storm deposits, BP/BC/FR (occluded by dolomite), Burrow types 1, 2, 3, & 4: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite; bioturbated with sparse cylindrical and vertical (2 mm) burrows, stylobedded; sparse, discrete horizontal and cylindrical burrows (2 mm – 15 mm); moderate to dense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which are burrow bounding.
Dolomite, Intraclastic grainstone (facies 5B), 3 cm.
Dolomite, Intraclastic grainstone (facies 5B), containing rip-up clasts of lime or dolomitic mudstone (2 mm – 4 cm), undifferentiated skeletal debris.
Dolomite, crystalline (?), peloidal grainstone (facies 6), solution enhanced moldic porosity lined with dolomite, burrow-mottled, fractures occluded by dolomite.
Dolomite, Skeletal Grainstone, cross-bedded, primarily crinoids and undifferentiated shells, 10 cm thick.
MARATHON OIL CO., BUEHRER #1, HILLSDALE COUNTY, MICHIGAN
Dolomite, skeletal grainstone (facies 4), crinoids, brachiopods, mollusks, undifferentiated skeletal fragments, fine- (0.125 mm) to medium- (0.5 mm) sand size grains.
Dolomite, burrow-mottled skeletal wackestone to packstone (facies 3), brachiopods/crinoids/gastropods, peloids, stylolites, MO, Burrow type 1: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows.
Dolomite, burrow-mottled mudstone, sparse skeletal debris (bryozoans/brachiopods/crinoids), chert nodules (1.5-4 cm). *Burrow types 1 & 3*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, moderate discrete horizontal and cylindrical burrows (2 – 15 mm).
Dolomite, burrow-mottled skeletal wackestone to packstone (facies 3), brachiopods/crinoids/gastropods, peloids, stylolites, MO, intercalated with coarse grained skeletal tempestites of sub-parallel shell fragments and graded bedding, *Burrow types 1 & 4*: horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows, filled with coarsely crystalline dolomite/calcite; moderate cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding.
JEM PETROLEUM CORP., HALL ET AL. #1-13, JACKSON COUNTY, MICHIGAN
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), *Burrow type 4*: intense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate) and stylobrecciation.
Dolomite, peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, <10% undifferentiated shelly fragments, high amplitude suture stylolites, less than 5% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).
Dolomitic limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), stylomottled, Burrow types I: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite and undifferentiated micritized skeletal grains.
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), Burrow type 4: intense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate) and stylobrecciation/stylomottling.
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), **Burrow type 4**: intense cylindrical burrows (2 mm – 4 cm), wispy/suture stylolites which can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate) and stylobrecciation/stylomottling.
Dolomitic limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), stylomottled, *Burrow types 1*: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite and undifferentiated micritized skeletal grains.
Limestone, peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, <10% undifferentiated shelly fragments, high amplitude suture stylolites, less than 5% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), *Burrow types 1, 2 & 3*: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, stylobeding and stylomottling, discrete horizontal and cylindrical burrows (2 – 15 mm) that are coarsely crystalline dolomite.
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), *Burrow types 1, 2 & 3*: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite, stylol bedding and stylomottling, discrete horizontal and cylindrical burrows (2 – 15 mm) that are coarsely crystalline dolomite.
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Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), *Burrow types 1*: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite.
Limestone, burrow-mottled mudstone to wackestone (facies 1), <10% bryozoans, trilobites, crinoids, gastropods, undifferentiated shelly fragments, and peloids, skeletal fragments range from fine- to very coarse-grained (0.125 – 2 mm), *Burrow types 1 & 4*: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite and burrows with a nodular appearance, wispy and suture stylolites that can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate).
Limestone, peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, high amplitude suture stylolites, less than 10% FE/MO (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (Burrow type 2).
Limestone, burrow-mottled wackestone to grainstone (facies 3), crinoids, brachiopods, bryozoans, ostracods, bivalves, gastropods, sparse peloids, coarse grained burrow-fills (tubular tempestites), Burrow types 1 & 4: moderate burrowing with horizontal (2 – 4 cm) and cylindrical (1 – 5 mm) burrows filled with coarsely crystalline dolomite/calcite and burrows with a nodular appearance, wispy and suture stylolites that can be burrow-bounding with thick accumulations of coarsely crystalline dolomite (stylocumulate).
Limestone, peloidal packstone to grainstone (facies 6), fine- to very-fine silt sized peloids, high amplitude suture stylolites, less than 5% FE (occluded by anhydrite and pyrite), intense bioturbation with rare distinguishable vertical burrows (**Burrow type 2**).
APPENDIX C

Thin Section Plates and Descriptions
McClure-Hergert #2, Permit # 22196, Hillsdale County, Michigan
MH – 3940.7': Dolomite, burrow-mottled mudstone with borings. Burrows (tubular tempestites) are filled with bryozoan, brachiopod, mollusk, ostracod, and other undifferentiated micritized grains.
MH – 3940.7': Dolomite, burrow-mottled mudstone with borings. Burrows (tubular tempestites) are filled with bryozoan, brachiopod, mollusk, ostracod, and other undifferentiated micritized grains.
MH – 3961.2’ (actual thin section slide mislabeled as 4061.2’): Skeletal – peloidal packstone to grainstone. Primarily well-sorted crinoid debris with syntaxial overgrowths, burrows dolomitic with calcite cement. No visible porosity.
MH – 3961.2’ (actual thin section slide mislabeled as 4061.2’): Skeletal – peloidal packstone to grainstone. Primarily well-sorted crinoid debris with syntaxial overgrowths, burrows dolomitic with calcite cement. No visible porosity.
MH – 4028.2’: Dolomite, large burrows bounded by suture stylolites. Burrows are coarse dolomite crystals, finer grained dolomite crystal accumulations between burrows, no visible porosity.
MH – 4040': Dolomite mudstone (soft pellets?) with fenestral pores, pervasive recrystallization (compare to H – 4314’), hydrocarbons present at intercrystalline boundaries.
MH – 4040.5: Coarsely crystalline mudstone, possibly peloidal packstone to grainstone under white card technique (Dravis, 1990), mud rip-up clasts containing: bryozoans, mollusk shells, echinoid fragments, ostracods, and replacement dolomite, intercrystalline porosity within burrows, isolated molds/vugs (5% max porosity).
MH – 4051.8’: Crinoidal grainstone to Bryozoan wackestone, bryozoans have been partially replaced by dolomite, matrix is crinoidal based on presence of syntaxial cement and irregular shaped grains (seen under white card technique).
Warner-Fouty 9-8, Permit # 41359, Hillsdale County, Michigan
WF – 4220': Cross-laminated peloidal grainstone, micritic envelopes around peloids, sparse burrows filled with peloids and dolomite.
WF – 4220': Cross-laminated peloidal grainstone, micritic envelops around peloids, sparse burrows filled with peloids and dolomite.
Tolle 1-33, Permit # 37507 Jackson County, Michigan
T-4252': Peloidal grainstone (hard pellets, ~ 90%), peloids are uniform and fine-grained, sparse skeletal debris, hydrocarbons present at intercrystalline boundaries, intercrystalline porosity.
Timm-Kennedy 1-14, Permit #30137, Barry County, Michigan
TK – 5123': Limestone, skeletal wackestone with crinoids, ostracods, and bryozoans. Minor (<2%) micro and intracrystalline porosity. Sucrosic dolomite burrow fills and later diagenetic dolomite (saddle?) crystals within matrix (~20%).
**TK – 5151.7’**: Limestone, micritized grainstone with sparse mud clasts (5 – 0.25 mm composed of mud, mollusks, crinoids, and micritized grains) and early calcite cementation. Micritized grains are well-rounded and well-sorted, skeletal grains appear mostly as crinoidal debris and undifferentiated, bio-eroded skeletal grains with very minor (<2%) trilobites and brachiopods. Micritized grains appear somewhat imbricated.
TK – 5151.7°: Limestone, micritized grainstone with sparse mud clasts (5 – 0.25 mm composed of mud, mollusks, crinoids, and micritized grains) and early calcite cementation. Micritized grains are well-rounded and well-sorted, skeletal grains appear mostly as crinoidal debris and undifferentiated, bio-eroded skeletal grains with very minor (<2%) trilobites and brachiopods. Micritized grains appear somewhat imbricated.
**TK – 5151.5':** Mixed peloidal/micritized skeletal grainstone, grading into a skeletal wackestone.
TK – 5157.2': Undifferentiated skeletal grainstone, 50% of skeletal grains are micritized, sparse dolomitized burrows, and possible rip-ups?
Skinner #1, Permit # 21833, Hillsdale County, Michigan
S – 3892': Mudstone with sucrosic dolomite filling burrows, possible peloids that have been dolomitized, intercrystalline porosity.
S - 3877': Mudstone with sucrosic dolomite filling burrows, possible peloids that have been dolomitized, intercrystalline porosity.
S – 3886*: Peloidal packstone, total recrystallization resulting from pervasive dolomitization, intercrystalline porosity (< 5%).
Buehrer #1, Permit # 21064, Hillsdale County, Michigan
B – 3756*: Skeletal wackestone, most skeletal grains are undifferentiated although echinoid fragments and mollusk shells are clear.
B - 3756: Skeletal wackestone (as seen with white card technique), most skeletal grains are undifferentiated although echinoid fragments and mollusk shells are clear.
Hall et al. #1-13, Permit # 36384, Jackson County, Michigan
**H − 4312′**: Skeletal grainstone with mud clasts containing skeletal debris. Skeletal grains include: mollusks, echinoid debris, bryozoans, brachiopods, and ostracods.
H - 4312': Skeletal grainstone with mud clasts containing skeletal debris. Skeletal grains include: mollusks, echinoid debris, bryozoans, brachiopods, and ostracods.
H - 4314': Lime mudstone (soft pellets?) (~5% dolomite crystals replacing mud), fenestrae pores partially occluded by dolomite to calcite (in center), sparse skeletal debris (1 – 2 %): crinoids, mollusks, ostracods.
H-4314': Lime mudstone (soft pellets?) (~5% dolomite crystals replacing mud), fenestrae pores partially occluded by dolomite to calcite (in center), sparse skeletal debris (1 – 2 %): crinoids, mollusks, ostracods.
APPENDIX D

Adobe® Illustrator® CS2 Files
## Facies and Rock Type

<table>
<thead>
<tr>
<th>Facies Type</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>6</td>
<td>Inner-Ramp Peritidal (6) - Peloidal Packstone to Grainstone, Soft Pellet Mudstone</td>
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<tr>
<td>5A</td>
<td>Mid-Ramp to Outer-Ramp Distal Tempestite (5A) - Hummocky-Cross Laminated Skeletal to Peloidal Grainstone</td>
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<td>5B</td>
<td>Inner-Ramp to Mid-Ramp Proximal Tempestite (5B) - Intraclastic Grainstone with fine-grained, sub-parallel fossils (shelly fragments)</td>
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<td>4</td>
<td>Inner-Ramp Shoal (4) - Skeletal Grainstone (partial to total micritization)</td>
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<td>3</td>
<td>Mid-Ramp (3) - Burrow-mottled Wackestone to Packstone</td>
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<td>2</td>
<td>Proximal Mid-Ramp (2) - Crinoidal Grainstone</td>
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<td>1</td>
<td>Mid- to Outer Ramp (1) - Burrow-mottled Mudstone to Wackestone</td>
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</table>
Idealized vertical facies succession for the Albion-Scipio. With the outer-ramp facies representing the deepest sea level phase and shoaling upward to the peritidal facies.
<table>
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<tr>
<th>Lithologic Symbols</th>
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<td><strong>Major Boundary</strong></td>
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<td><em>(Sequence / Facies)</em></td>
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</tbody>
</table>
Legend

- Peloids
- Graded Bedding
- BC Intercrystalline

- Intralast
- Bored Surface
- BU Burrow/Boring

- Brachiopod
- Brecciated Zone
- BP Interparticle

- Gastropod
- Hardground
- FE Fenestral

- Undifferentiated Fossils
- Dolomite Cement
- FR Fracture

- Coral
- Calcite Cement
- MO Moldic

- Bryozoan
- Partially Filled Vug
- VUG Vug

- Trilobite
- Cemented Vug
- WC Intracrystalline

- Molluscs, undifferentiated
- Partially Filled Fracture
- WP Intraparticle

- Crinoids
- Cement Filled Fracture

- Horizontal Burrow
- Silicious Nodule

- Burrowed
- Hummocky Styloite

- Burrows w/ Alteration Halos
- Stylonodular

- Brecciated
- Stylomottled

- Fenestral Textures
- Stylolitic

- Stylolite Swarms
- Tempestite

- Laminated
- Cross Bedded

- Partially Filled Fracture
- Shallowing Upwards Cycle

- Burrows w/ Alteration Halos
- Regressive

- Brecciated
- Transgressive

- Fenestral Textures
- Stylolitic

- Stylolite Swarms
- Tempestite

- Laminated
- Cross Bedded
McClure Hergert #2, Hillsdale County, Michigan
Formation: Black River  Depth Interval: 3892.0' – 4062.0'
By: Jennifer Schulz
<table>
<thead>
<tr>
<th>Lithology</th>
<th>Grain Types</th>
<th>Facies Type</th>
<th>Sedimentary Structures</th>
<th>Thin Sections</th>
<th>Oil Staining</th>
<th>Porosity Types</th>
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Warner Fouty 9-8, Hillsdale County, Michigan
Formation: Black River  Depth Interval: 4240.0' – 4070.0'
By: Jennifer Schulz

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Tolle 1-33, Hillsdale County, Michigan
Formation: Black River  Depth Interval: 4240.0’ – 4070.0’
By: Jennifer Schulz

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Formaneri: Black River, Depth Interval (Core #): 5110.0 - 5171.0

Timm-Kennedy 1-14, Barry County, Michigan
### Timm-Kennedy 1-14, Barry County, Michigan

Formation: Black River  
Depth Interval (Core #4): 5230.0' – 5289.0'  
By: Jennifer Schulz

<table>
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## Skinner 1, Hillsdale County, Michigan

**Formation:** Black River  
**Depth Interval:** 3875.0' – 4000.0'  
**By:** Jennifer Schulz

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<th>Depth (ft)</th>
<th>Oil Staining</th>
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### Sedimentary Structures
- Thin Sections
- Oil Staining
- Higher Frequency
- Large-scale Cycles

### Lithology
- Mudstone
- Packstone
- Mud-Rich Packstone
- Grain-Rich Packstone
- Grainstone
- Roundstone
- Crystalline Dolomite
- Ooid
- Pisolite
- Porosity Types

### Facies Type
- Crinoid
- Cnidaria
- Bryozoa
- Gastropod
- Coral
- Cnidaria
- Ooid
- Psolite
- Other
Marathon Oil Co., Buehrer #1, Hillsdale County, Michigan
Permit # 21064
Cored Interval: 3610.0’ – 4000.0’
Examined Interval: 3948.9’ – 3832.3’

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<th>Porosity Types</th>
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**Textural Classification**
- Mudstone
- Wackestone
- Grainstone
- Coquina
- Breccia
- Other

**Grain Types**
- Foraminifera
- Ostracod
- Coquina
- Shelly
- Foraminifera
- Other

**Porosity Types**
- Permeable
- Porous
- Non-porous
- Other
Jem Petroleum Corp., Hall et al. #1-13, Jackson County, Michigan
Permit # 36384
Cored Interval: 4307.0’ – 4360.7’