Evaluating the Effects of Lithofacies and Thin Shales on the Lateral Distribution of Hydrothermal Dolomite Reservoirs in the Michigan Basin

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EVALUATING THE EFFECTS OF LITHOFACIES AND THIN SHALES ON THE LATERAL DISTRIBUTION OF HYDROTHERMAL DOLOMITE RESERVOIRS IN THE MICHIGAN BASIN

by

Peter J. Feutz

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

Western Michigan University
Kalamazoo, Michigan
April 2012
WE HEREBY APPROVE THE THESIS SUBMITTED BY

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ENTITLED Evaluating the Effects of Lithofacies and Thin Shales on the Lateral Distribution of Hydrothermal Dolomite Reservoirs in the Michigan Basin

AS PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science

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EVALUATING THE EFFECTS OF LITHOFACIES AND THIN SHALES ON THE LATERAL DISTRIBUTION OF HYDROTHERMAL DOLOMITE RESERVOIRS IN THE MICHIGAN BASIN

Peter J. Feutz, M.S.
Western Michigan University, 2012

The southern Michigan Basin contains numerous hydrothermal dolomite hydrocarbon fields, including the giant Albion-Scipio Field. The fields typically encompass narrow zones of faulting and fracturing which have been altered from a tight host limestone into a more porous and permeable dolomite by upward-moving hydrothermal fluids. Alternating layers of dolomite that spread laterally away from the main vertical fault conduits imply that structure alone may not define the resulting reservoir architectures within the region. A detailed analysis of primary depositional facies and thin shale seams suggests that secondary stratigraphic controls play a significant role in the development of reservoir rock within these Ordovician-aged Trenton and Black River fields. This study incorporates core analysis, wireline logs, petrography and X-ray diffraction to investigate preferential migration of hydrothermal dolomite away from vertical faults.

The results of this project will help eliminate the risk of drilling close, step-out dry holes along the elongate trends and may lead drillers to more accurately pinpoint the hydrocarbon-producing zones.
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I would first like to thank my fiancée, Shannon. Without her encouragement and motivation, I would have never thought to change my life so drastically and pursue a career in geology. I would also like to thank the rest of my family, my committee members and my friends at MGRRE.

Peter J. Feutz
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CHAPTER I
INTRODUCTION

Albion-Scipio and Stoney Point fields are major oil/gas producing reservoirs within the Michigan Basin (cumulative production: ~147 MMBO and ~260 BCF of gas). The fields are characterized by fault-induced hydrothermal dolomite (HTD) reservoirs within the Ordovician-aged Trenton and Black River limestones. Albion-Scipio Field, founded in 1959, was first drilled based on advice from a local psychic. Stoney Point Field was discovered twenty years later despite being located only five miles to the east of the major Albion-Scipio trend (Hurley and Budros, 1990). Historically, the fields have produced hydrocarbons along narrow fairways of a wrench-fault system and have been infamous for close, step-out dry holes within 0.25 miles (0.4 kilometers) of the edge (Hurley and Budros, 1990). Further investigation by Wilson et al. (2001) noted that production within the narrow fairways is comprised of a smaller set of en echelon structural lineaments. Reservoir quality dolomite is not only pervasive along vertical to sub-vertical fractures and faults, but also within dolomitized zones of the host limestones where dolomitizing fluids have spread laterally away from the main faults (Hurley and Budros, 1990) (Figure 1A and Appendix G). Little work has been done, however, to evaluate the controls on the lateral distribution of dolomite. This study works towards a better understanding of reservoir geometries and architecture within Albion-Scipio and Stoney Point fields to ultimately aid in successful drilling laterally away from the major faults. Most importantly, any knowledge gained in this region can be applied to hydrothermal systems elsewhere in the world (Figure 2).
Figure 1. Cross sections of Albion-Scipio Field. A. This cross section, using gamma ray and neutron logs, runs in dip direction to the Albion-Scipio fault trend. Dolomite, highlighted in purple, is seen to finger out laterally away from zones interpreted as main vertical faults. Various components such as stratigraphic changes or subsurface obstructions may influence the resulting architecture. B. Cross section along the strike of Albion-Scipio Field which intersects cross section A through the well indicated with the blue star. Dolomite is more prevalent when following the fault trend. Cross sections were generated using Petra Software.

The purpose of this study is to investigate the controls on dolomite that spreads laterally away from vertical faults and fractures with a particular focus on the primary depositional facies and fabrics and also on the distribution of dolomite associated with thin (centimeter to millimeter thick) shales and K-bentonites (volcanic ash) that appear throughout the Trenton and Black River formations. Certain original facies could contribute to enhanced migration of fluids more so than others thus shaping the reservoirs in a stratigraphic framework. Additionally, thin seams of clay may have acted as baffles or barriers to the upward migration of hydrothermal fluids. Had the shales acted as hydrothermal aquitards, the limestone below the seams would have been preferentially dolomitized and opened up into a more porous and permeable reservoir-quality rock. A preliminary investigation showed that there is a recurring trend of producing zones located beneath gamma ray spikes related to shale or K-bentonite seams on wireline logs (example seen in Figure 3). According to these initial results, almost 40% of the wells in the Albion-Scipio area show some sort of correlation between shale seams and production.

Published research on the role thin shales play on general fluid flow within various reservoir types has been done in a number of previous studies (e.g. Hongmei and Caers, 2007; Howell et al., 2008; Downey, 1994; Bradley and Powley, 1994). Research on the effects of thin shales as baffles or barriers specifically in
hydrothermal dolomite reservoirs, however, is limited to a few simple observations (Hurley and Budros, 1990; Smith and Davies, 2006; Sharp et al., 2010). Research investigating primary depositional facies is also limited to a select few studies by authors such as Davies and Smith (2006), Smith (2006), Lindsay et al. (2006) and Sharp et al. (2010). Using the few published hydrothermal dolomite studies as a starting point, this project delves deeper into what controls lithofacies, thin shales and K-bentonites have on reservoir architecture and should provide a better predictive tool as to where additional hydrocarbons may be extracted.

Due to the lack of outcrops in the region, various subsurface tools were needed to make interpretations. Detailed core analysis and wireline logs were used to identify and describe the shale/K-bentonite seams as well as the facies and lithology. X-ray diffraction was utilized to differentiate the mineralogies of K-bentonites and shales, and petrographic analysis of thin sections was used for a detailed evaluation of the core facies, associated dolomite, and the amount and types of visual porosity in the areas of interest.

Overall, the goals of this project are to answer the following questions: 1) Is there a relationship between primary depositional facies and reservoir quality? 2) Do certain lithologic fabrics contribute to the migration of hydrothermal fluid flow more than others? 3) Do thin shales/K-bentonites act as vertical baffles or barriers to fluid flow, thus affecting the lateral distribution of hydrothermal dolomite away from faults?
Figure 2. Global distribution of hydrothermal dolomite in Mississippi Valley Type deposits, hydrocarbon reservoirs, and HTD outcrops. Conclusions made in this project may be applicable to many other areas, as seen in this map. Understanding such unconventional plays and their geometries will be important for future hydrocarbon extraction (from Davies and Smith, 2006).
Figure 3. Cross section of initial production intervals and gamma ray spikes on logs. This cross section of four Albion-Scipio wells illustrates a correlation between initial production intervals, as documented in drilling reports, and gamma ray spikes on wireline logs. The gamma ray spikes are interpreted to represent thin intervals of marine shale or volcanic ash beds. 36% of the 106 wells analyzed show similar trends as illustrated in this example. The production zones are interpreted, primarily using neutron logs, to be porous dolomitized zones in an otherwise tight limestone section.

Geologic Background

Michigan Basin

Albion-Scipio and Stoney Point fields are located on the southern edge of the circular-shaped, intracratonic Michigan Basin of the central North American craton. The Michigan Basin covers approximately 198,387 km² in areas of eastern Wisconsin, northeastern Illinois, northern Indiana and Ohio, and all of Michigan with the exception of the western Upper Peninsula (Fisher et al. 1988). The Basin is
bordered to the southwest by the Kankakee arch, the south-southeast by the Findlay-Algonquin arches, to the west by the Wisconsin arch, and to the north by the Precambrian Canadian Shield (Hurley and Budros, 1990) (Figure 4).

**Figure 4.** Structure map of the Michigan Basin. It shows locations of major structural highlands, arches and sags that may have influenced sea water flow and depositional environments, (modified after Ives, 1960 and Ells, 1969).

In the lower peninsula of Michigan, the basement is made up of Archean crystalline rocks of the Central Province to the west, the Penokean Province to the north, and metamorphic rocks of the Grenville Province to the east (Bickford et al., 1986; Van Breemen and Davidson, 1988). The Basin is intersected by the northwest-trending Keweenawan rift that contains arkoses, redbeds, and volcanic rocks (Hurley
and Budros, 1990).

Subsidence of the Michigan Basin allowed for the deposition of approximately 5 kilometers of sedimentation over a period of more than 200 million years during the Paleozoic (Howell and Van der Pluijm, 1999). Remnants of Jurassic-age sediment remain in the center of the Basin and Quaternary glacial drift covers the bedrock with 0 to 305 meters (0 – 930 feet) throughout the entire Basin (Howell and Van der Pluijm, 1999). Isopach maps of the Michigan Basin from King (1977) suggest that the Basin was subsiding from Cambrian through Mississippian time. According to Howell and Van der Pluijm (1999), various mechanisms for basin subsidence have been proposed including thermal contraction following development of an isolated “hot spot”, metamorphic phase changes in the crust, lithospheric stretching, free thermal convection, and intraplate stress mechanisms. None of these proposals has been thoroughly agreed upon by the scientific community and the true origin of subsidence continues to be unresolved.

**Middle Ordovician in the Michigan Basin**

The Michigan Basin during the Middle Ordovician was centered at approximately 25 degrees south latitude (Scotese and McKerrow, 1991) in the tropic-subtropic region of the planet (Figures 5 & 6). The Basin was covered by a warm and shallow (10-100 feet, 3-30 meters) intracratonic sea that was conducive to carbonate sedimentation (Hurley and Budros, 1990). It was in this setting that the Trenton and Black River limestones were deposited.

According to Haq and Schutter (2008), average sea level during the Middle Ordovician (i.e. Trenton and Black River formations) was between 150-200 meters above today’s mark. Ross and Ross (1992) characterize the Mid-Late Ordovician as a
time with several, rapid transgressions that flooded cratons worldwide. Between these transgressions were many lowstands, some of which caused hiatuses in deposition. Evidence of sea level change has been found within the Albion-Scipio Trenton-Black River core samples during this study, such as the presence of tidal flat and subaerial exposure surfaces supporting the idea that the Michigan Basin was subjected to various sea level fluctuations during the Middle Ordovician.

Figure 5. Paleogeographic map of Earth during the Middle Ordovician. Red arrow points to the location of the Michigan Basin, approximately 25° south latitude in the tropic to subtropic zone, (modified after Scotese PALEOMAP project at www.scotese.com).
Figure 6. Paleogeographic map of the Michigan Basin during the Ordovician. Zoomed-in map of Laurentia (present-day North America) with the Michigan Basin circled in red. Warm, shallow seas (as indicated by the lighter blue colors) covered much of the craton and carbonate factories were widespread, (modified from Blakey Paleogeography and Geologic Evolution of North America, www4.nau.edu/geology/blakey.html).

During the Ordovician, the eastern half of the North American craton experienced multiple episodes of explosive volcanism related to the Taconic Orogeny (Huff et al. 2010) (Figure 7). Evidence of such events is preserved in multiple layers of tephra, or volcanic ash, throughout Ordovician sediment. In some eastern states, 50 to 100 separate beds have been documented (Huff et al. 1996, Kolata et al., 1996). Two large ash beds present in the Trenton-Black River have been correlated into the Michigan Basin from proximal source locations in the southeast United States by Huff and Kolata (1990) and a third smaller one by Trevail (1990). The major eruptions occurred during the closing of the Iapetus Ocean when Laurentia (present-day North America) collided with island arcs in the first of three major orogenies that
formed today’s Appalachian Mountains (Stanley, 1985). Continuous tephra layers are not only found throughout present-day North America, but also across Scandinavia, which was part of the nearby landmass of Baltica during the Ordovician (Huff et al., 2010).

**Figure 7.** Paleogeographic map of the Taconic Orogeny. The Taconic Orogeny produced supervolcanoes during the closing of the Iapetus Ocean. The eruptions, highlighted in yellow, deposited multiple layers of tephra, or volcanic ash, across Laurentia (present-day North America) and Baltica (present day northwest Europe), (modified from Bergstrom et al., 1997).

**Albion-Scipio and Stoney Point Fields**

This project is focused around Albion-Scipio and Stoney Point fields which are located on the southern edge of the Michigan Basin (Figure 8) in the Central
Lowlands physiographic province (Hurley and Budros, 1990). Albion-Scipio Field, located in Hillsdale, Jackson and Calhoun counties, is the largest hydrocarbon-bearing field in Michigan at approximately one mile wide and over 35 miles long (35 mi², 56 km²) and is composed of a system of fractured hydrothermal dolomite. Stoney Point Field, smaller in comparison (7.2 mi², 12 km²), is located approximately 5 miles east and is comprised of a similar faulting and fracturing network. The fields together have produced approximately 147 MMBO and 260 BCF of gas, according to the Michigan Department of Environmental Quality (MDEQ). The producing formations within both fields are the Middle Ordovician-aged Trenton and Black River limestones. According to Hurley and Budros (1990), the top seal is a combination of the overlying Utica Shale and a tight, ferroan dolomite in the upper Trenton (see Figure 9). Lateral seals are attributed to the surrounding non-dolomitized host limestone. The source rock for Albion-Scipio and Stoney Point fields is a highly debated subject, but many suspect the hydrocarbons are self-sourced from organic-rich shales within the Trenton and Black River formations (Budros, personal communication, 2010) while others insist the overlying Utica and Collingwood formations to be the primary source (MDEQ).
Figure 8. Hydrocarbon production map of lower Michigan with Albion-Scipio Field. Albion-Scipio-Stoney Point fields flank the southern edge of the Michigan Basin. Cumulative production of Albion-Scipio and Stoney Point is approximately 147 MMBO and 260 BCF of gas. Production focuses around closely-spaced *en echelon* lineaments within a wrench fault system that is caused by the reactivation of deep basement faults (Hurley and Budros, 1990). (Production map generated from MDEQ and Albion-Scipio figures modified from Ells, 1962).

Albion-Scipio has a structure composed of a series of narrow *en echelon* faults (Figure 8), which are part of a wrenching system, that lie separated by a few hundred yards and trend N30-35°W (Wilson et al. 2001). Prouty (1988) outlined this structure using left-lateral wrench fault models to account for the shear faults and folds that are seen in Albion-Scipio Field. Vertical fault displacement is minimal to absent according to Wilson et al. (2001). Hurley and Budros (1990) note that these wrench faults probably formed during multiple reactivations of Precambrian basement structures. The timing of the fault reactivations has been proposed as Late-
Ordovician–Early Silurian (Dellapenna and Chaivre, 1988) Late Silurian–Early Devonian (Burgess, 1960; Davis, 1962; Bishop, 1967), and Mississippian (Ells, 1962). These strike-slip faults are widely interpreted to be the conduits in which hydrothermal fluids from underlying formations or the basement rock have ascended to dolomitize the local limestones (Ells, 1962) (Figures 9 & 11).

Figure 9. Hydrothermal fluids migrating up Trenton-Black River faults. The fluids used the strike-slip faults as vertical conduits. The fluids preferentially dolomitized the tight host limestones of the Trenton and Black River formations and created porosity in the rock that subsequently captured and stored hydrocarbons, (modified from Hurley and Budros, 1990).

Albion-Scipio and Stoney Point fields lie on a regional northeast-dipping homoclinal surface (plunge/dip = N15°E/0.5°) toward the center of the Michigan Basin. Unlike most hydrocarbon-bearing structures which are typically structural highs, Albion-Scipio and Stoney Point fields are synclinal sag-like features (Hurley
and Budros, 1990). The sag feature has been attributed to strike-slip tectonics and alternate mechanisms such as volume reductions from dolomitization (Burgess, 1960). Davies and Smith (2006), in their study of hydrothermal dolomite reservoirs, explain how sags shown on seismic expressions are related to classic “negative flower structures” below the sag which are caused by the transtensional, pull-apart wrench fault system (Figure 10).

**Figure 10.** Seismic expression of hydrothermal structural setting. This seen with a structural sag (arrows) above the negative flower structure. Production occurs within the sag, and is highlighted in green (from Davies and Smith, 2006)
Dolomite Models

Evaporative (Sabkha) Dolomite

Sabkha dolomite forms when storm surges force seawater over peritidal environments in arid regions. The ratio of Mg/Ca increases in this hypersaline environment during the formation of evaporites, such as gypsum and anhydrite, which can preferentially remove calcium from the seawater thus leaving a dense brine containing unchanged amounts of magnesium. The dense fluids move downwards, dolomitizing the underlying lime sediments in which hydrodynamic head provides the hydrologic pumping (Allan and Wiggins, 1993). This type of dolomite can be identified with the presence of supratidal sediments and associated sedimentary structures such as algal beds, rip up clasts, nodular anhydrites and eolian interbeds. Dolomite crystals are typically microcrystalline (< 15 microns). Subsurface geometries are often erratically distributed throughout a section and are locally and rapidly shifted vertically and laterally into evaporites, siliciclastics and limestones (Allan and Wiggins, 1993). δ¹⁸Oxygen compositions should be heavy, strontium and sodium contents should be high, manganese and iron contents should be low, and strontium isotopic compositions should be similar to values for seawater at the time of deposition since sabkha dolomites form from the evaporation of seawater (Tucker and Wright, 1990). Modern examples of evaporative dolomite formation include the Trucial Coast in the Arabian Gulf, Andros Island in the Bahamas, Baffin Bay, the Coorong region in Australia, and Sugarloaf Key in Florida (Tucker and Wright, 1990).
Reflux Dolomite

Reflux dolomite forms similarly to sabkha dolomite with the exception that it occurs in a restricted lagoon or basin setting. Intense evaporation leads to brine concentration and evaporite precipitation. Downward movement of the dense, magnesium-rich brines dolomitizes the underlying lime sediment. Associated sediments can be any depositional facies, not strictly supratidal (Allan and Wiggins, 1993). Subsurface geometries can range from thin, porous units beneath layers of evaporites to thicker units along regional shelf and shelf margin environments. Typically, reflux dolomites are sealed by evaporites and will crosscut depositional contacts to follow the evaporitic trends. Percentage of dolomite decreases away from the evaporites and is generally fabric-preserving, most likely because it is formed before compaction (Allan and Wiggins, 1993). Dolomite crystal sizes vary from micro to medium crystalline. While not always definitive, reflux dolomite typically has heavy δ18O compositions and contains single phase-fluid inclusions, indicating precipitation at lower temperatures. Reflux dolomite contains the strontium isotope ratio of the evaporite containing the brine in which it was created, thus the strontium isotope values fall on the seawater strontium isotope curve at the point corresponding to the age of the associated evaporite deposit (Tucker and Wright, 1990). Modern reflux dolomite is not as prevalent as evaporative dolomite, but has been documented in such places as Bonaire, Netherlands Antilles (Tucker and Wright, 1990).

Marine-Meteoric Mixing Zone Dolomite

The idea behind this model is that the mixing of meteoric and sea water produces a fluid that is supersaturated with dolomite and undersaturated with calcite and aragonite. Hydrodynamic head provides the hydrologic pumping. This model is
flawed, however, in that there are few modern examples of dolomite in mixing zones and it has been proven that seawater alone contains higher concentrations of dolomite than a meteoric water-seawater mix (Allan and Wiggins, 1993). If this model holds true, however, there is a likelihood of a lack of nearby evaporites and more prominence of meteoric diagenetic fabrics such as moldic porosity and meteoric vadose or phreatic cements (Allan and Wiggins, 1993). There are likely few inclusions and numerous complex intercalations of calcite and dolomite. It will also likely contain radiogenic strontium isotope compositions from the fresh water which may have passed through siliciclastic aquifers. A modern example is interpreted in southwest Andros Island, Bahamas (Tucker and Wright, 1990).

**Marine Dolomite**

Marine dolomite can derive its magnesium straight from seawater. The magnesium can be transported through tidal pumping or by inflow and buoyant rise of geothermally heated seawater at continental margins. There is most likely a lack of nearby evaporites. This dolomite should have a strontium isotope similar to that of the seawater at the time of sediment deposition. It should contain single-phase fluid inclusions with lower salinities (35 wt. % NaCl) (Allan and Wiggins, 1993). Modern, anoxic marine dolomite is forming in pelagic sediment in the Guaymas Basin in the Gulf of California (Tucker and Wright, 1990).

**Microbial Dolomite**

Dolomite formation from microbials was discovered in the 1990’s. A study of dolomite located in lagoons off the coast of Rio de Janeiro in the Brazilian Lagoa Vermelha play indicates its formation from sulfate-reducing bacteria. Lagoonal
hydrological cycles vary with alternating wet and dry seasons in that region. During the wet season, rain and continental groundwater discharge raise water levels while in the dry season, seawater recharges the lagoon creating increasing salinities and evaporation. The dynamic environment supplies the ions needed for dolomite precipitation (magnesium, calcite, calcium carbonate) and anaerobic microbial activity (sulfate) (Al-Awadi et al., 2009). Subsequent lab experiments also proved various bacterias to precipitate dolomite in similar environments as above in as little as 30 days (Al-Awadi et al., 2009).

**Burial Dolomite**

Burial dolomite forms in the subsurface after the lime sediments lithify. Increasing temperatures during burial decreases the Mg/Ca ratio needed to produce dolomite. The most documented fluid sources are magnesium-rich residual evaporitic brines, modified seawater and shale compaction waters. The waters are generally transported along aquifers or faults by mechanisms such as sediment compaction, thermal convection and topographically or tectonically driven flow (Allan and Wiggins, 1993). Saddle dolomite crystallization is present and considered to represent a late, high temperature phase of dolomitization, often found within nearby vugs and fractures (Tucker and Wright, 1990). Subsurface geometries can take many shapes and sizes resulting from lateral and cross-formational fluid flows as well as downward and upward fluid flows (Allan and Wiggins, 1993). Burial dolomite typically contains more negative δ18O compositions compared with earlier formed dolomites due to higher temperature precipitations. It commonly contains two-phase aqueous fluid inclusions with high salinities and homogenous temperatures (> 50°C) and may contain petroleum inclusions. Many of these dolomites contain radiogenic
strontium isotope compositions as well as iron and manganese enrichments. These minerals derive from the dolomitizing brines that may have passed through siliciclastic sediments or basement rocks full of potassium feldspar (Tucker and Wright, 1990). The dolomite may also contain minerals associated with Mississippi Valley-type deposits such as galena, sphalerite, barite, fluorite and marcasite. The Trenton and Black River formations in Albion-Scipio Field represent a reservoir consisting of a specific type of burial dolomite (Hurley and Budros, 1990).

The Origin of Reservoir Dolomite in Albion-Scipio and Stoney Point Fields

Ells (1962) proposed the idea of magnesium-bearing waters ascending through fractures as being responsible for the dolomitization of Albion-Scipio and was the first to publish the theory of the similarity of Albion-Scipio Field to Mississippi Valley-Type (MVT) lead-zinc mineral deposits (see Figures 9 & 11). An alternative idea was proposed by authors DeHaas and Jones (1989), who argue that the diagenesis of the Trenton-Black River in the Albion-Scipio area occurred during a top-of-Trenton unconformity. They cite the facts that present-day Trenton Formation water is less saline than water in shallower horizons and claim that karstic structures such as caverns account for the dolomitization of the upper Trenton section.
Despite the differing hypotheses, most authors lean towards a hydrothermal origin for the Trenton and Black River reservoirs (Hurley and Budros, 1990; Taylor and Sibley, 1986; Budai and Wilson, 1986; Shaw, 1975). DeHaas and Jones’s (1989) alternative model points to a period of exposure as the leading cause of diagenesis and compare it with Mammoth Cave in Kentucky. They base their conclusions on the frequent bit drops and lost circulation zones that occur while drilling Albion-Scipio. However, there is more evidence to support the hydrothermal model than the cave level model for the following reasons (Hurley and Budros, 1990). Geochemical data from authors such as Taylor and Sibley (1986), Budai and Wilson (1986), Allan and Wiggins (1993) and Shaw (1975) suggest that the dolomite precipitated from heated
(approximately 80 - 160° C), saline solutions. According to Radke and Mathis (1980) and Machel (1987), saddle dolomite found in reservoirs precipitates from hypersaline brines at temperatures between 60-150° C; therefore supporting the hydrothermal origin. Isopach maps and cross sections from Davis (1962) and Bishop (1967) describe how the structural synclinal sag above the reservoir extends up-section into Devonian rocks. This indicates that faulting and solution collapse must have occurred post-Ordovician and most likely during the Late Silurian or Early Devonian. If there were caverns and karsting on the Trenton surface, they would have likely been filled with pre-Devonian sediment before the Devonian and no sag would be evident. Hurley and Budros (1990) finalize their arguments against the cave theory by investigating the bit drops and lost circulation zones that led DeHaas and Jones (1984, 1989) to assume caverns and karsting. Hurley and Budros (1990) concluded that the bit drops and lost circulation zones were a result of fracturing and vuggy rock, not due to large, empty voids.

Reservoir Stratigraphy and Facies

Regional Trenton and Black River Formations

The Trenton and Black River formations are part of a major Middle to Late Ordovician platform carbonate package that extends from the Appalachian Basin to the Rocky Mountains (Catacosinos et al., 1990) (Figure 13). By name, the Trenton and Black River cover areas from Wisconsin to New York and the southern Upper Peninsula in Michigan to Kentucky. Cohee (1948) noted that the Trenton and Black River in the Michigan Basin are mostly dolomite in eastern Wisconsin, northeastern Illinois, and northwestern Indiana. With few exceptions, the rocks are dominantly
crystalline limestone in the central part of the Michigan Basin. In the southern peninsula of Michigan, the Black River is 150-517 feet (45-158 meters) thick and consists of light brown and gray, fossiliferous limestone with some dolomite and a possible argillaceous base in some areas. Chert nodules are noted in local areas. The Trenton in the southern peninsula is 203-479 feet (62-146 meters) thick and of similar lithology to the Black River (Cohee, 1948). Major Trenton-Black River hydrocarbon reservoirs within Michigan include Albion-Scipio-Stoney Point, Deerfield, Napoleon and Northville fields (Figure 12).

Middleton (1990) researched the Trenton and Black River in southwestern Ontario and characterized the two as supratidal – shallow subtidal lithologies. The Trenton is described as gray or brown, interbedded or nodular, argillaceous, fossiliferous carbonate, and the Black River as a monotonous brown or gray and occasional black mudstone with abundant bioturbation. Middleton notes echinoderms, brachiopods, bryozoans, and to a lesser extent, trilobites, nautiloids, corals, gastropods, and bivalve bioclasts in both formations. In these rocks there is also faulting and fracturing with similar types of dolomite and potential MVT deposits as seen in Albion-Scipio. Hydrocarbon reservoirs in the fractured dolomites of southwestern Ontario (Figure 12) include the Hillman, Wheatley, Rewick, Rochester and Dover fields that have cumulatively produced 177,188 m³ (approximately 1.1 million barrels) of oil as of 1989 (Middleton, 1990).

Fara and Keith (1988) detail the Trenton limestone in Indiana as a skeletal sand and organic buildup facies that was deposited on a carbonate ramp. The skeletal sand facies includes echinoderm-brachiopod packstones and grainstones and the organic buildups consist of lime-mud-rich bryozoan, echinoderm packstones, wackestones, and mudstones. Among both facies are a series of thin, graded
tempestite beds. Also noted are various hardgrounds attributed to periods of non-deposition. Similar to the Trenton in the Michigan Basin and in southwest Ontario, oil production has only occurred where the rock has been dolomitized. In a prior study, Keith (1981) lists total Trenton production out of Indiana as 105 MMBO, most of which was extracted from the enormous Indiana-Lima Field in the late 1800’s-early 1900’s (Figure 12).

The Trenton Formation in Ohio has also produced significant amounts of oil (~380 MMBO total) in fracture-related, dolomitic reservoirs such as the giant Indiana-Lima Field and the much smaller Saybrook (Wickstrom and Gray, 1988; Sagan and Hart, 2006) (refer to Figure 12). Here, the Black River is described as a tan, light-brown, or gray micritic to very finely crystalline limestone 300-560 feet (90-170 meters) thick. Burrows, fenestral pores and small amounts of chert are present and few fossils are noted but include brachiopods, ostracods, gastropods, mollusks, tabulate coral, and trilobites. The Trenton generally consists of fossiliferous, fine, dark-gray to light brown lithologies 40-330 feet (12-90 meters) thick. Multiple layers of centimeter-scaled bentonite layers and thin to very thin gray or black shale beds are noted throughout both the Trenton and Black River formations (Wickstrom and Gray, 1988).

The Trenton-Black River carbonates in New York State are also prolific hydrocarbon producers, again primarily in hydrothermal dolomite settings. Since 1986, at least 20 fields have been discovered with several wells producing sustainable rates of gas greater than 10 MMCF/day (Smith, 2006) (see Figure 12). Smith (2006) classified the Black River as a shallow, tropical carbonate ramp depositional setting. The rock types include mudstone, with occasional fenestrae and clay drapes, fine-to coarse-grained skeletal wackestone, and very fine to fine peloidal packstone and
grainstone. Smith (2006) describes the Trenton as having grainstones and packstones that are coarser and more fossiliferous than the Black River and that also has common dark gray to black intercalated shales. The Trenton is more argillaceous than it is in Ohio, Michigan and Ontario and thus is uncommonly dolomitized in comparison to the older Black River (Smith, 2006). Both formations thin in eastern New York due to uplifts associated with the Taconic Orogeny. Also noted are various volcanic ash beds that are also attributed to the orogeny.

Figure 12. Hydrothermal dolomite hydrocarbon fields across North America. Map consists of Trenton-Black River hydrothermal dolomite fields across eastern North America, (modified after Smith, 2006).

Trenton and Black River Formations in the Michigan Basin

The Albion-Scipio and Stoney Point reservoirs lie within the Middle Ordovician-aged Trenton and Black River formations (Figure 13). Within the Albion-Scipio area, the average depths to the top of the younger Trenton range from 3,500 feet (1,083 meters) to a maximum of 4,000 feet (1,220 meters) downdip. The entire Trenton-Black River is approximately 600 feet (183 meters) thick locally. Both
formations are interpreted as open-marine, subtidal, shallow-shelf carbonates estimated to have been deposited in 10 to 100 feet (3 to 30 meters) of water (Hurley and Budros, 1990). Separation of the Trenton from the underlying Black River is generally placed above a widespread, regional gamma-ray marker, known throughout the oil industry as the “Black River Shale”, which is presumed to be a K-bentonite (volcanic ash beds) (Wilson et al., 2001). In addition to the Black River Shale, various other K-bentonites in the Albion-Scipio-Stoney Point Trenton-Black River sequences have been cited by previous authors (Hurley and Budros, 1990; Catacosinos et al., 1990; Wilson and Sengupta, 1985; DeHaas and Jones, 1984). The Black River Group is conformably underlain by the Glenwood Formation (Figure 13), which is a black-to-green shale that varies in thickness from 5-100 feet (1.5-30 meters) (Catacosinos et al., 1990; Prouty, 1988). The Trenton Group is overlain by 200-400 feet (60-120 meters) of the Utica and Collingwood Shales (Hurley and Budros, 1990).

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<th>Subsurface Nomenclature</th>
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<td>Cincinnatian</td>
<td>Utica Shale</td>
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<td>Middle</td>
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**Figure 13.** Stratigraphic column of southern Michigan. The Trenton and Black River formations are highlighted in green, (modified from Catacosinos et al., 2000).
The Trenton and Black River lithologies in Albion-Scipio have been described by Hurley and Budros (1990) as typically mudstones, crinoidal wackestones, and crinoidal packstones. They indicate that the Black River contains fewer fossil allochems, some pellet grainstones, and chert in comparison to the Trenton. Studies by Western Michigan University graduate students Jennifer Schulz (2011) and John Thornton (2011) have documented grainier textures in both the Trenton and Black River, some with evidence of cross laminations. They also note a major difference between the two formations with the presence of tidal flat facies in the Black River, suggesting a shallower, higher energy environment than the Trenton. Extensive burrowing and burrow-mottled textures in the Black River have also been documented by Schulz (2011).

Hurley and Budros (1990) used drilling reports to show that productive reservoirs in the Trenton and Black River formations occur where the limestone has been replaced by porous and permeable dolomite. The typical reservoir rock is a dense, gray-brown dolomite with intercrystalline, vuggy, and/or fractured porosity. Vugs and fractures are frequently lined or filled with white, very coarsely crystalline saddle or baroque dolomite (Radke and Mathis, 1980). In the upper 40 feet (12 meters) of the Trenton below the Utica Shale, a finely crystalline, non-porous “cap dolomite” of regional extent is present. The interval is tight and considered by Hurley and Budros (1990) as part of the reservoir seal along with the overlying Utica Shale. Taylor and Sibley (1986) used chemical analysis and found that the cap dolomite is ferroan in composition, and suggest that waters released by the compaction of the overlying Utica Shale were partly responsible for developing this unit. Collapse breccias, commonly associated with cavernous and vuggy porosity are present in some cored intervals and represent intense zones of fracturing and dolomitization.
Hurley and Budros (1990) report porosity values between 2 and 5% with localized zones of porosity in the 8 to 12% range. Permeabilities range from 0.01 to 8000 millidarcies, with 85% of permeability values being less than 10 mD. The rocks with over 1000 mD are generally in areas with fractures or interconnected vugs. In 70-75% of the high-porosity samples (porosity > 3.99%), permeability tends to be very low (< 10 mD).

K-bentonites and Shale

This study focused in part around the thin shales and K-bentonites within the Trenton and Black River limestones in the region encompassing Albion-Scipio and Stoney Point reservoirs. The K-bentonites represent volcanic eruptions that occurred during the Middle Ordovician Taconic Orogeny (Huff et al. 2010) (Figure 7). It was during this time period that Laurentia (present-day North America) began a series of collisions with island arcs off the east coast during the closing of the Iapetus Ocean (Stanley, 1985). K-bentonites form as the result of the alteration of volcanic glass by a fluid phase, meaning they form in aqueous environments, in this case a shallow, intracratonic sea. Outside of diagenetic alterations of volcanic glass, hydrothermal alterations containing Mg-rich fluids also play an important role in bentonite formation (Christidis and Huff, 2009). Both types of K-bentonite formation fit in well with the Albion-Scipio area. The thin marine shale seams have a lesser known depositional history but have been interpreted as influxes of argillaceous sediment and/or periods of quiet-water deposition and sedimentation from suspension (Hurley and Budros, 1990). Both K-bentonites and shales have been compacted from sediment overburden and pressure solution and range in thickness from a millimeter to 10-15 centimeters.
Two well-studied K-bentonites, sourced from the modern equivalent of South Carolina, have been correlated across eastern North America (ancient Laurentia) and northwestern Europe (ancient Baltica) by authors such as Huff et al. (1990, 1992, 1996) and Kolata et al. (1996). The K-bentonites are referred to as the Deicke and Millbrig (Figures 15), with the Deicke being the first deposited. The original tephra, or volcanic ash, of the Deicke and Millbrig blanketed areas as large as $2.2 \times 10^6$ km$^2$ of eastern North America and $6.9 \times 10^5$ km$^2$ in northwestern Europe during a single eruption (Huff et al., 1996). These two ancient tephras have been correlated into the Michigan Basin and mineralogically matched with the widespread Millbrig and Deicke from other areas (Calvert, 1964; Kolata et al., 1996). In the subsurface of the southern Michigan Basin, the Millbrig and Deicke are marked by prominent spikes on gamma ray (see Figure 14), resistivity and neutron wireline logs just below the Trenton and Black River contact. Separation of the two is only a few meters stratigraphically.

Collectively, the Deicke and Millbrig have been referred to by many authors such as Lilienthal (1978), Wilson et al. (2001), and Hurley and Budros (1990) as the ‘Black River Shale’. A third K-bentonite has been traced from outside the Michigan Basin by Trevail (1990). This K-bentonite is characterized on wireline logs similarly to the Deicke and Millbrig (see also Figure 14), but with a smaller gamma ray spike. Hurley and Budros (1990) refer to this K-bentonite as the ‘E’ Shale, which generally lies ~45 meters (~150 feet) below the Trenton-Utica contact in the Albion-Scipio region. Numerous other bentonites have been documented in the Michigan Basin Trenton-Black River, but are not as readily identifiable in the Albion-Scipio wells as the three mentioned above (Hussey, 1952; Votaw, 1980; Lilienthal, 1978; Templeton and Willman, 1963). The preservation and alteration of these layers can be attributed
to the high sea levels present in the Ordovician which reduced the effects of subaerial erosion and diagenetically altered the parent volcanic ash rock (Christidis and Huff, 2009). The K-bentonites appear as dark gray to greenish-black, with some yellow-orange colors in cores and outcrop (Hurley and Budros, 1990; Huff, 2008).

**Figure 14.** Gamma ray wireline log typical of the local Trenton and Black River. The gamma ray spikes below the Trenton-Black River contact represent the Deicke and Millbrig K-bentonites. The smaller, less prominent spike in the mid-upper Trenton is referred to as the ‘E’ Shale – also a K-bentonite.
Figure 15. Maximum thickness isopach maps for Deicke and Millbrig K-bentonites. The Deicke (orange) and Millbrig (green) K-bentonites spread across eastern North America. Thicknesses are recorded in centimeters. The Deicke preceded the Millbrig K-bentonite during the Middle Ordovician Taconic Orogeny. The volcanic ash deposits derived from a present-day source centered in South Carolina. The two beds are thought to represent some of the largest ash fall deposits known in the Phanerozoic record. (Modified from Huff et al., 1996).

Numerous thin (millimeter-centimeter sized) marine shales and shaley wisps have been documented throughout the Trenton and Black River (Hurley and Budros, 1990; Wilson et al., 2001). These authors note that the marine shales can have a high total organic carbon (TOC) level, up to 25%, and could serve as excellent source rocks (Budros, personal communication, 2010). According to oil industry standards, typical source rocks have at least 0.5% TOC and rich source rocks will have at least 10% TOC. The shales appear in core as black-colored with some fossil fragments intermixed. They range from stylolitic-looking wisps of millimeter thickness to slightly fissile 1-2 centimeters (.4-.8 inch) thickness. The shales are primarily identified in physical core examination because they rarely show prominent marks on wireline logs, most likely because of the shale’s limited thickness and resolution of
the logging tools or possibly due to lack of radioactive mineral composition. Because of this, correlation of most thin marine shale well-to-well may be problematic.

Despite the thin physical nature of the K-bentonites and shales, studies have shown that they may play a significant role on the diversion of the hydrothermal fluids that ultimately shaped Albion-Scipio and Stoney Point reservoirs (Hurley and Budros, 1990). Other studies worldwide also show that similar seams have affected upward fluid flow in hydrothermal systems such as the one observed in this study.

Types of Hydrothermal Dolomite

Three types of dolomite have been identified in the Trenton-Black River formations within the Michigan Basin (Taylor and Sibley, 1986). (1) regional dolomite – not associated with Albion-Scipio area; (2) cap dolomite; and (3) fracture-related dolomite. The separation of the cap dolomite and the fracture-related dolomite comes from mineralogical differences in that the cap dolomite is pervasively ferroan whereas the fracture-related dolomite is not. Taylor and Sibley (1986) suggest that the ferroan dolomitic fluid source that altered the upper Trenton derived from the dewatering of the overlying Utica Shale during compaction. Hurley and Budros (1990) indicate that the tight cap dolomite in addition to the Utica Shale act as the vertical seal to the reservoir.

The fault-related dolomite in Albion-Scipio is important for the porosity that it creates. Landes (1946) wrote how dolomitic fluids enter limestone and precipitate as a primarily crystalline structure and at the same time dissolve some of the calcite away without re-precipitating. This results in porosity not only between the crystal structure of the dolomite (intercrystalline porosity) but also from dissolution cavities. Taylor and Sibley (1986) describe the sucrosic dolomite found within the matrix of
the rock away from the fracturing as a relatively coarse-grained (.15-.7 mm), non-ferroan rock with intercrystalline porosity (Figure 16 & 17). The fracture-filling dolomites themselves are generally white, coarse-grained (.2-3.5 mm) saddle dolomite (Figure 16 & 18). Porosity in the fracture-related dolomite is generally in the form of vugs. Hurley and Budros (1990) describe the breccias formed in close proximity to the faults as generally being tightly cemented with white, pore-filling dolomite. Taking this into consideration, production in Albion-Scipio rarely occurs directly along the main faults but rather adjacent along open fractures and vugs and laterally within the sucrosic matrix. The primary focus for this study addresses the question of the lateral extent of the matrix dolomite away from the more obvious fractures and faults.
**Figure 16.** Hydrothermal dolomite textures. Core photo of Trenton (~4031 ft) in Albion-Scipio displaying classic hydrothermal dolomite textures. The white saddle dolomite commonly precipitates along planes of weakness and the sucrosic textures modify the surrounding matrix rock. Scale bar is in centimeters.
Figure 17. Photomicrograph of sucrosic dolomite. This is found in the facies matrix of the Trenton. Pore space has been impregnated with blue dye, (photo taken by G. Michael Grammer).

Figure 18. Photomicrograph of saddle dolomite. These show the structure of saddle, or baroque, dolomite in the Trenton. Note the coarsely crystalline nature and curved crystal faces typical of saddle dolomite, (photos taken by G. Michael Grammer).

Previous Studies

Studies on how thin shales affect general fluid flow in a reservoir setting have been undertaken in the past, but few focus on how thin shales affect hydrothermal
fluid flow in faulted carbonate rocks. Authors such as Hongmei and Caers (2007) studied how thin (1 cm – 1 meter) shale drapes can successfully compartmentalize a channelized mixed-system reservoir and Howell et al. (2008) studied how centimeter-sized shale drapes on deltaic clinoforms controlled reservoir fluid flow. Thin shales functioning as reservoir seals have been studied by authors such as Downey (1994) in which he stated “several centimeters of ordinary clay shale are theoretically adequate to trap a large vertical column of hydrocarbons” and Bradley and Powley (1994) who said “theoretically, the seal could be extremely thin, a membrane one grain thick… the actual seal thickness is somewhere between the normal and the fully abnormal pressure measurement and a membrane...”. While this previous research supports the basic theory that thin shales can act as some sort of control on various types of fluid flow, none specifically address the importance of thin shales in hydrothermal dolomite reservoirs. The few studies that make mention of shales in hydrothermal dolomite reservoirs are presented below.

The most analogous study to this project is from Hurley and Budros (1990). They originally observed dolomitized zones preferentially beneath shales in Albion Field and concluded that it was the result of the impermeable shale seams blocking the upward flow of hydrothermal fluids from below. The authors apparently overlapped ‘net shale isopach maps’ of the ‘E’ and Black River Shales with maps of dolomitized zones and found a correlation. Although the maps are not presented in their publication, they do plot gamma ray and neutron log signatures side by side and show areas of higher porosity, which are assumed to be the more porous dolomites, underneath prominent gamma ray spikes (Figure 19). Old neutron logs without scales are used in the display and do not quantitatively measure porosity but simply the relative amounts of hydrogen molecules (usually water or hydrocarbons) in
surrounding void spaces. The areas could also be undolomitized fractures or vugs. The neutron logs may not even detect tight dolomite intervals or dolomite that houses gas as opposed to liquid hydrocarbons. The major gamma ray spikes, also without scales, are presumed to be either the ‘E’ Shale or the Black River Shale based on stratigraphic locations and according to the amount of deflection alone. This project is focused on taking Hurley and Budros’s (1990) observation a step further to explain the significance of porosity zones below the shales throughout the Albion-Scipio-Stoney Point region, if there is one.

**Figure 19.** Wireline logs exhibiting porosity beneath gamma ray spikes. Porosity increases to the left on neutron logs. The zones of higher porosity are presumed to be dolomite that preferentially formed underneath the shale when rising hydrothermal fluids were trapped. (From Hurley and Budros, 1990).

Davies and Smith’s (2006) research on structurally controlled hydrothermal
dolomites worldwide (Figure 2) led them to the same observations/conclusions as Hurley and Budros (1990). According to Davies and Smith (2006), there are numerous examples in Ordovician, Devonian, and Mississippian hydrothermal dolomite reservoirs in western Canada, as well as other regions of the world, that host thin shale seams or beds that form internal aquitards to upward-migrating hydrothermal fluids. In a single paragraph, the authors mention that observations of core led them to support the idea of centimeter-thick shales, argillaceous limestone, or even styloseams as sufficient barriers to the fluids. They reference the illustrations by Hurley and Budros (1990) as seen in Figure 19 above and add internal aquitards to their own model (Figure 10). The only supportive figure they provide is a gamma ray log from New York that shows spikes, labeled as bentonite ash falls, and a horizon line across the gamma ray spikes indicating the top of the local HTD reservoir facies. No quantitative values of thin shales and their thicknesses or specific examples of cores are ever given, just simplified observations with little evidence to back it up.

Tinker et al. (2004) characterized a hydrothermal dolomite reservoir in South Dagger Draw Field in New Mexico. According to their models, acidic hydrothermal fluids migrated upward from depths below and were “dammed” below shale aquitards forming mushroom-shaped dissolution zones, conducive to hydrocarbon storage. The shales in their study were determined to be transgressive marine shales, similar to what may be seen in Albion-Scipio. They reference Hurley and Budros (1990) when mentioning the “dammed” hydrothermal fluids. However, Tinker et al.’s main data source was from seismic surveys and the shales that were seismically resolvable were minimally 10 feet thick. To identify the shale that thinned below seismic data resolution, the authors compared acoustic impedance from the seismic data with a computed gamma ray log. Thinner shales were not identified or quantified in any of
the models and resolution to a smaller degree than the 10-foot-thick shales was not accounted for. Further evaluation of the effects of the shales was not pursued as the Tinker et al. (2004) study was focused primarily on creating a 3D model of South Dagger Draw Field, as opposed to focusing on the mechanics of thin shale aquitards.

More recently, an outcrop study in the Zagros Mountains of Iran by Sharp et al. (2010) noted how thin shales and marls could have formed significant barriers/baffles to both dolomitizing fluids and hydrocarbons. Sharp et al. continuously refer to thin, argillaceous transgressive mudstones that cap cycles as sufficient flow barriers by observing preferential dolomitization below the contacts. They note that partially saddle dolomite cemented, non-fabric selective vugs are also prevalent immediately below the capping mudstones. They describe many of the mudstones as dark, laminated and organic rich. While they did not elaborate on specific attributes of each mudstone layer, they do mention the thicknesses of two in particular, which are 5 cm and 5-20 cm thick. They also mention that in a certain case the lateral spread of dolomite beneath one of the thin mudstones stretched 1-10 meters away from the local fault - a statistic they found to be minor compared to previous, undocumented spreads. Their research displays multiple outcrop photos that highlight the contacts of the dolomitized zones directly below the ‘thin’ mudstone intervals as well as a couple of block diagrams. The study done by Sharp et al. displays how cycle boundaries control HTD fluids using outcrops but did not tie the information to wireline log data. They made several observations of baffling mudstone intervals but did not detail each one like the other so as to compare/contrast attributes such as mudstone thickness, proximity to faults, lateral spread of dolomite beneath the contacts, or even exact lithology descriptions of each.

Previous studies have also been published on how primary depositional facies
may affect the flow of fluids in the subsurface. Authors such as Davies and Smith (2006), Smith (2006), Lindsay et al. (2006) and Sharp et al. (2010) support and provide examples of how hydrothermal dolomite has been controlled stratigraphically through specific primary depositional facies. An example from Lindsay et al. (2006) illustrates how a primary facies composed of coarse, grained-filled *Thalassinoides* burrows was preferentially dolomitized but the surrounding mudstone facies were not. The original porosity and permeability in that example, as well as further examples mentioned by the authors, were determined to have influenced secondary diagenetic flow of fluids. This being said, the spread of hydrothermal fluids around the shales and K-bentonites may be a function of both the shale/K-bentonite physical and chemical properties, as well as the properties of the primary depositional facies deposited in the given area. This original porosity/permeability may or may not work hand-in-hand with baffling shales/K-bentonites and a closer examination is undertaken in this project.
CHAPTER II

METHODOLOGY

Core Selection

The cores selected for this project are stored in Western Michigan University’s Michigan Geological Repository for Research and Education (MGRRE) in Kalamazoo, Michigan. The following criteria were used when selecting the cores:

- The cores must have been taken in the Trenton and Black River intervals within the three major counties surrounding Albion-Scipio and Stoney Point fields; Hillsdale, Calhoun, and Jackson counties.
- The cores must contain physically preserved samples of thin shales or K-bentonites.
- Core length must dictate a diverse range of stratigraphy to allow for a variety of facies and overall reservoir coverage. Core length must also be great enough to examine facies surrounding shales and K-bentonites.
- Cores must be both dolomitized and undolomitized in order to observe reasonable causes for preferential dolomitization in certain intervals over others.
- Associated wireline logs and whole core analysis is ideal.

Table 1 lists the 6 cores that best fit the criteria.
Table 1. Six selected cores for this study. Whole core analysis was available from previous research and appeared to be focused on dolomite intervals and limestone intervals that were in close proximity to the dolomite.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Permit Number</th>
<th>County</th>
<th>Field</th>
<th>Whole Core Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whitaker 2</td>
<td>28407</td>
<td>Hillsdale</td>
<td>N/A</td>
<td>N</td>
</tr>
<tr>
<td>Arco Conklin 1-31</td>
<td>37385</td>
<td>Hillsdale</td>
<td>Stoney Point</td>
<td>Y</td>
</tr>
<tr>
<td>Faist 2-12</td>
<td>33673</td>
<td>Jackson</td>
<td>Henrietta</td>
<td>limited</td>
</tr>
<tr>
<td>Luck 2-12</td>
<td>33258</td>
<td>Jackson</td>
<td>Henrietta</td>
<td>limited</td>
</tr>
<tr>
<td>Hergert 2</td>
<td>22196</td>
<td>Hillsdale</td>
<td>Scipio</td>
<td>limited</td>
</tr>
<tr>
<td>Mann6</td>
<td>22381</td>
<td>Hillsdale</td>
<td>Scipio</td>
<td>limited</td>
</tr>
</tbody>
</table>

Figure 20. Core location map in Albion-Scipio region. This Petra map displays the locations of the 6 cores from MGRRE that were used in this project.
Wireline Logs

The three counties around Albion-Scipio contain approximately 1,200 wells with digital wireline log data. Gamma ray logs are sufficient in identifying thin shales and argillaceous seams, as measured by the increase of radioactive materials most concentrated in mudrocks such as thorium, potassium and uranium (as seen in Figure 14). Neutron, neutron porosity, photoelectric factor, density and acoustic image logs were used collectively to best identify and interpret the porous, sometimes fractured hydrothermal dolomite from the tight limestone. Neutron logs measure porosity using qualitative counts/second units that measure the amount of hydrogen ion concentration in void spaces within the host rock, i.e. the liquid-filled porosity (where shale is not present). The newer, compensated neutron porosity logs are measured similarly to the old neutron logs but can be recorded in apparent limestone porosity units which will equal true porosity when the rock is limestone. Continuous Borehole Image Log (CBIL) acoustic imaging logs illustrate vuggy and fractured hydrothermal dolomite with darker colors compared with the lighter colored dense limestone in the Trenton-Black River intervals using borehole images. Photoelectric factor lithology logs measure dolomite with values that typically range between 3-3.5 barns/electron versus calcite which ranges from 4.5-5 barns/electron. Density logs were also employed to help pick dolomite which typically has a higher density of approximately 2.87 g/cm³ and limestone has a lower density of approximately 2.71 g/cm³; however, dolomite as seen in the Albion-Scipio region may reveal slightly lower bulk densities due to the enlargement of pore space from the dolomitization process (Hurley and Budros, 1990).
Whole Core Analysis and Drilling Reports

Whole core analysis (WCA) was available for some of the cores (see Table 1). The data, averaged by foot, identifies porosity and permeability.

Original drilling reports also proved invaluable by providing core descriptions from mudloggers that were compared with the wireline logs and core analyses. Additionally, the driller’s reports recorded bit drop and lost circulation data which gave clues to where faulting and/or dissolution likely occurred.

Core Description

This project involved the description and interpretation of primary depositional facies, the documentation of alternating intervals of limestone and dolomite and how the dolomitization related to primary facies, as well as analysis of several different layers of shale and K-bentonites. The Dunham classification (Dunham, 1962) was utilized where appropriate, and special attention was directed towards establishing any trends of dolomitization and porosity development within each primary depositional facies. Initially, core facies were observed by hand sample and further analysis was then undertaken by looking at thin sections.

Petrography

One hundred seventy-seven thin sections were analyzed for facies description and visual estimations of dolomite and porosity, and 34 were analyzed specifically for the presence and character of stylolites. The thin sections were made by National Petrographic in Houston, Texas using a standard thickness of thirty microns and vacuum impregnated with blue epoxy. Thin sections were photographed using a Leica M420 petrographic microscope and attached Leica DC480 digital camera. The
software used to capture images was the Leica IM50 Image Management suite. All thin sections were documented under 12.5 X and 35 X magnifications for consistency and comparison, but were also observed using a variety of magnifications.

Thin sections were initially taken when there appeared to be an interval of dolomite baffled by shale/K-bentonite (i.e. dolomite directly beneath the shale/K-bentonite). Thin sections were specifically taken from the facies in the dolomitized interval (there were sometimes more than one facies type in the dolomitized interval in which case multiple thin sections were taken) as well as from the intervals of limestone above and below the dolomitized zone to see if there were any differences in the primary facies type.

Further detailed thin section analysis detailed the various facies types throughout the entire Trenton-Black River section. This analysis documented patterns of dolomitization and porosity trends within specific facies types. Additionally, 34 thin sections containing stylolites were analyzed to evaluate the possible effects of stylolitization on dolomite distribution.

Petrography also helped to compare visual porosity estimates with porosity obtained by whole core analysis and to provide visual porosity estimates when whole core analysis data was not available. Visual porosity was estimated using comparison charts from Baccelle & Bosellini (1965). Comparing visual estimations of porosity with whole core analysis leads to a better understanding of the heterogeneity of carbonates and the presence of microporosity (such as some types of intercrystalline porosity). Whole core analysis is averaged by the foot which can combine data from multiple, (< 1 foot thick) facies intervals that have completely different petrophysical properties. It can, however, measure microporosity not readily observable at the magnifications utilized in the thin section analysis. Visual porosity estimates add
value by eliminating the foot scale averages of whole core analysis and more accurately classifies the distributions of specific pores and pore types.

X-Ray Diffraction

Because mineralogical differences between the shales and K-bentonites may lead to different controls in the lateral distribution of hydrothermal dolomite, X-ray diffraction (XRD) was utilized to distinguish between shale and K-bentonite layers and to provide insight into the relative effectiveness of various shales as baffles or barriers to vertical fluid flow. X-ray diffraction data was obtained from 11 shale/K-bentonite samples. Two samples were collected from the overlying Utica Shale in order to compare the other samples with a known marine shale. Three samples were collected from the multiple influxes of the Black River Shale K-bentonite in order to have a known volcanic ash for comparison. These samples are assumed to embody a part of the Black River Shale based on their physical texture, the correlating signatures on the gamma ray log and citations from research conducted by authors such as Hurley and Budros (1990). One sample was collected from the ‘E’ Shale K-bentonite in order to have a genetically different volcanic ash to compare with. This sample is assumed to be the ‘E’ Shale because of its physical appearance and texture, its correlating signature on the gamma ray log and citations from previous research conducted by Trevail (1990). Four of the remaining five samples were tested because they exhibited patterns of dolomite directly below but not above thus making them considerations for shale baffles. X-ray diffraction analysis was performed at Weatherford Laboratories in Houston, Texas and required a crushed sample of approximately one gram.
Data Limitations

The most significant limitation to this study was the lack of structural data. Fractures and faulting played a major role as fluid conduits in forming these reservoirs. In order to truly understand the dynamics of the lateral spread of hydrothermal dolomite it would have been enormously helpful to know exactly where the main, vertical flow of fluids derived from. This study focused on the influence of primary depositional facies and thin shales on reservoir development but many assumptions had to be made on precise proximity of log and core data to the faulting. Estimating the lateral extent of dolomite formation away from an unknown source was a difficult task to undertake. The best clues to estimate fault location came from wells with extensive dolomitized intervals (as indicated from core or wireline log data), evidence of brecciation and saddle dolomite within cores, and driller’s reports with bit drop and lost circulation records.

Albion-Scipio Field is an old field (discovered 1959) and Stoney Point is only a little younger (discovered 1980). Cores are old and have passed through several hands throughout the years and some of the first things to get lost are shale fragments. This made it difficult to find shale samples or accurately measure thicknesses of the shale samples that were present. Wireline log quality gets increasingly worse the older they are, making some interpretations difficult. This may be due to careless calibrations, poor resolution and lack of scales. Physical quality of the original paper copies are often in disrepair and therefore produce unreadable digital scans. An important consideration for this project was that the majority of the wells in Albion-Scipio used old neutron logs that were measured using counts/second. This differs from the modern neutron porosity because it simply measures the amount of hydrogen ion concentration in void spaces within the host rock, i.e. the liquid-filled
porosity (where shale is not present). The newer compensated neutron porosity can be recorded in apparent limestone porosity units which will equal true porosity when the rock is limestone. Another disadvantage with neutron logs is they will show anomalous readings of less than 0% porosity, mostly in zones with a lack of cement behind borehole casing or where there is poor cement bond. This has also been recorded where gas-bearing porosity or gas pockets occur behind casing (Hurley and Budros, 1990). The neutron log will also fail to recognize tight dolomites, which are present in this reservoir. The use of neutron and neutron porosity logs, however, was the best tool that this project had for overall subsurface interpretations due to the abundance of wells containing this particular data. The combination of neutron porosity, density, photoelectric factor and acoustic image logs greatly enhanced the certainty of dolomite picks but were available for only a limited number of wells. The lack of modern wireline log data limited detailed observations of dolomite and its relationship with stratigraphic changes throughout a majority of the Albion-Scipio region.

Whole core analysis data is patchy from core to core. The original data was collected from previous researchers and appears to have been selectively measured primarily in regions surrounding the dolomite intervals. In many cores, whole core analyses were not performed. This limits porosity and permeability data as measured from core.

Determining a marine shale from a K-bentonite also proved ambiguous. According to authors such as Huff (2007), K-bentonites have gone through multiples phases of diagenesis that leave them mineralogically similar, if not the same, as a marine shale. This makes it close to impossible to definitively pinpoint the original deposition of the thin, muddy seams using mineralogy alone.
CHAPTER III
RESULTS

Petrography: Lithofacies

The overarching goal of this project was to better understand the controls on the lateral distribution of hydrothermal dolomite away from vertical fault planes. Previous work by Schulz (2011) and Thornton (2011) have shown that specific facies types, including burrow-mottled mudstones to packstones, may be more susceptible to hydrothermal dolomitization than other facies within the Albion-Scipio region. These results have led to a better understanding of the stratigraphic control that primary depositional facies may have on preferential dolomitization in the Trenton and Black River formations. Schulz (2011) focused her research on burrow types found within the Black River interval and Thornton (2011) worked on the petrophysical aspects of the facies throughout the Trenton and Black River formations. This project builds off of this previous work with detailed petrographic research to test the conclusions made by the two authors and to try and establish a relationship of preferential dolomitization between primary depositional facies and thin shale seams that may behave as baffles.

Eight lithofacies were categorized by texture, grain types, sedimentary structures and faunal diversity using the Dunham Classification (Dunham, 1962) and specific depositional environments were interpreted for each facies (see Figure 21 and Table 2). Facies types were studied from both the Trenton and Black River formations because both intervals have undergone hydrothermal dolomitization and produced hydrocarbons commercially. The facies classification is a modified version
of the one used by Schulz (2011), but in this study, the classification serves the purpose of representing general facies encountered and is not used to build a detailed depositional model. The intention of analyzing each facies type is to determine whether one or more serves as a preferential zone for hydrothermal fluid flow. The individual facies were identified using one hundred seventy-seven thin sections that were taken from the six selected cores. Each individual facies was then organized and quantified based on 1) estimated visual percentage of dolomite using comparison charts from Baccelle & Bosellini (1965), 2) visible porosity also using comparison charts from Baccelle & Bosellini (1965), 3) pore types and 4) whole core analysis porosity and permeability (see Appendix C for complete analysis). The 177 samples yield a moderate sampling bias in which the percentage of each particular facies seen in the overall thin section collection does not identically match the percentage of the same particular facies throughout the cored intervals; for example, Facies 4 is described in 9% of the overall core but is described in 45 out of the 177 thin sections (25%). To remedy this bias, Table 3 offers an approximation of gross thicknesses and volume percentages for each individual facies in relation to overall thickness of the six cored intervals to offer the reader clarity on true regional abundance and spacial distribution of each facies.
Table 2. Eight lithofacies categories. The Trenton and Black River formations are broken down based on texture, grain types, sedimentary structures and faunal diversity. This table lists each facies and detailed written descriptions can be found throughout the ‘Lithofacies’ section in this paper. Below is a figure that visually portrays the depositional environments in which each facies was deposited.

**Figure 21.** Eight facies on generalized carbonate ramp. Facies are numbered in an updip direction with exception of Facies 2, which appears locally throughout both Trenton and Black River intervals. The debris flow (Facies 7) and marine shale/volcanic ash (Facies 8) are not tied to a specific environment and thus are numbered at the end (Modified from Robinson, 2011.)
Table 3. Total gross thickness of each facies from the six cores. Overall core footage of the six studied cores is approximately 1125.6 feet. The percentage of each facies within the 1125.6 feet of core is shown in the lower table. Data is approximated using core descriptions from this study in addition to Schulz’s (2011) Hergert 2 core description.

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

Observations: Thirty-four thin sections interpreted to be Facies 1 were taken from five of the six cores (Table 4). Facies 1 constitutes approximately 22% of the gross thickness of the six studied cores (Table 2). This facies is comprised of mudstone to wackestone with varying degrees of burrow-mottling ranging from none to near-homogenization by bioturbation (Figures 22 & 23). Burrows are commonly filled with coarser grains than the surrounding matrix. Skeletal debris and peloids constitute less than 10% of the rock. In relative order of abundance, grains consist of
shell fragments (ostracods, brachiopods, and unidentifiable mollusks), crinoids, bryozoans and lesser amounts of gastropods and trilobites. Stylolites are common and occur as single sutures or clustered swarms. Thicknesses range from wispy to thick (millimeter scale) and amplitudes range from small to large. Pore types, in relative order of abundance, include intercrystalline (particularly for sucrosic dolomite), fractures, vugs, and molds.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Thin Sections (Marked by Depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mann 6</td>
<td>3974.3, 3983.6, 3985.4, 3987.5, 4014.0, 4015.0, 4042.0, 4055.4, 4058.9, 4075.0, 4076.0</td>
</tr>
<tr>
<td>Whitaker 2</td>
<td>3064.0, 3041.0</td>
</tr>
<tr>
<td>Arco-Conklin 1-31</td>
<td>3718.8, 3788.0, 3799.0</td>
</tr>
<tr>
<td>Hergert 2</td>
<td>3927.1, 3941.0, 3942.8, 3966.0, 3973.0, 4002.5, 4008.0, 4008.6, 4010.0, 4015.0,</td>
</tr>
<tr>
<td>Total Faist 2-12</td>
<td>4877.0, 4877.5, 4880.2, 5058.0</td>
</tr>
</tbody>
</table>

**Table 4.** Facies 1 thin sections and placement in core. Core placement (measured in feet) of 34 thin sections.
Figure 22. Core photograph of Facies 1: Burrow-mottled Mudstone to Wackestone. Core photograph from the Hergert 2 well (4002.5'). Burrows (Brw) can be seen highlighted by stylolites.

Figure 23. Photomicrograph of Facies 1: Burrow-mottled Mudstone to Wackestone. This Hergert 2 well example exhibits partial dolomitization with rhombs ‘floating’ in the limestone matrix (see arrows). Fossils are not evident and the lack of sedimentary structures indicates complete homogenization through bioturbation.
**Interpretation:** The abundance of mud suggests quiet water deposition below fair weather wave base with a lack of significant winnowing (Wilson and Jordan, 1983). Fauna present also represent a shallow to moderately deep (10-100 feet) subtidal environment (Stearn and Carroll, 1989). This facies can span from the mid to outer ramp or possibly in a semi-restricted lagoonal setting that still allows for the influx of nutrients, oxygenation and normal salinities (~35 ppm NaCl). Both environments are suitable for the diverse assemblage of fauna to exist in place (Wilson and Jordan, 1983).

**Dolomitization, petrophysics and reservoir potential:** Of the 34 thin sections analyzed, 22 are completely dolomitized, six are partially dolomitized and six are non-dolomitized (Table 5). Dolomite types include sucrosic and baroque (saddle) dolomite. Porosity values average 2.62% (WCA) and 3% (Visual – averaged from all thin sections of the appropriate facies) for the dolomitized facies, 2.43% (WCA) and 1% (Visual) for partially dolomitized, and 0% (Visual) for the limestone facies. Permeability values from whole core analysis average 2.43 millidarcies for the dolomitized facies, 0.30 millidarcies for the partially dolomitized facies, and are unavailable for the limestone facies. The lack of whole core analysis data from limestone intervals may reflect the notion that previous researchers, who collected the data, were only concerned about the potential of the dolomitized facies as a reservoir. This however, is an assumption based on limited knowledge of the original data collection methods employed by those previous researchers. When limestone facies were observed petrographically in thin section, porosity was rarely seen and is mostly related to open microfractures.
Table 5. Semi-quantitative analysis of Facies 1 using thin sections.
Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates were made from thin section. The 34 samples represent a smaller fraction of the gross volume of Facies 1 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.

Various physical characteristics of sucrosic dolomite are seen throughout Facies 1. Dolomite fabrics range from nonplanar (xenotopic) with anhedral crystals to planar-euhedral and planar–subhedral (idiotopic) crystals (Sibley and Gregg, 1987). Crystal sizes were classified throughout this document relative to one another using the following categories seen in Table 6. Crystal sizes in Facies 1 range from fine to medium. The majority of fine dolomite rhombs are seen along stylolitic seams but also less often within the mud matrix. The larger rhombs are concomitant with grainier fabrics. Facies 1 exhibits various forms of partial to complete dolomitization. Fine to small dolomite rhombs are commonly seen ‘floating’ in an undolomitized muddy matrix. Another form of partial dolomitization, noted also by Schulz (2011), is the preferential dolomitization of burrow fills while the surrounding matrix is predominantly limestone. The reverse is also seen where the matrix is dolomitized while the burrows are not, however, the former is most common. Complete dolomitization of Facies 1 was observed either when the facies was completely
homogenized by bioturbation or when bioturbation was infrequent (occurring throughout less than 10% of the sample). In most instances (approximately 50-75% of the time), burrows were distinguishable in the completely dolomitized sample. When Facies 1 is fully dolomitized, intercrystalline porosity occurs in both the burrows and within the matrix. Larger pores are best seen in the fabrics with larger grains, whether it be inside or outside of the burrows.

<table>
<thead>
<tr>
<th>Dolomite Crystal Size Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
</tr>
<tr>
<td>Small</td>
</tr>
<tr>
<td>Medium</td>
</tr>
<tr>
<td>Large</td>
</tr>
</tbody>
</table>

Table 6. Dolomite crystal size classifications.

Reservoir potential for Facies 1 is high in this region most particularly when the rock consists of dolomitized burrow networks. Porosity values recorded from whole core analysis and visual estimates (Table 5) throughout the intervals meet the standards of a reservoir dolomite in this particular field as defined by Hurley and Budros (1990). The authors note that the majority of reservoir porosity values fall within the 2-5% range. They set no minimum required permeability values, but note that values are commonly less than 10 mD. Volumetrically, this facies constitutes ~22% of the Trenton and Black River formations as seen in the six studied cores (Table 3) which can be assumed to extrapolate regionally when considering the interpreted depositional environments of the Trenton and Black River intervals as being a low declivity carbonate ramp in a ubiquitous epeiric sea that stretched minimally across the lower flanks of the Michigan Basin (Figures 6 & 21). Together,
the overall volume and porosity/permeability values (when dolomitized), suggest that 
Facies 1 could serve as an excellent secondary reservoir away from the main faults.

Facies 2: Bryozoan Wackestone to Packstone – Mid Ramp to Near Shoal Facies

Observations: Facies 2 constitutes approximately 4% of the gross thickness of 
the six studied cores (Table 2). From analysis of core and six thin sections (Table 7) 
this facies is comprised of wackestone to packstone that is dominated (> 90%) by 
bryozoan debris (Figures 24 & 25). The surrounding matrix is muddy but can also 
contain intercalated beds of crinoidal grainstones. Smaller amounts (< 5%) of shell 
fragments and peloids are also intermixed. Stylolites are commonly seen throughout 
these intervals, particularly in the form of stylolaminations. Pore types, in relative 
order of abundance, are moldic, vugular, and intercrystalline (when dolomitized). 
Only three of the six cores contained intervals of Facies 2 thus suggesting that it 
occurred on a local scale.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Thin Sections (Marked by Depth)</th>
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<tbody>
<tr>
<td>Mann 6</td>
<td>3945.0</td>
</tr>
<tr>
<td>Whitaker 2</td>
<td>3175.6, 3223.8, 3231.0</td>
</tr>
<tr>
<td>Hergert 2</td>
<td>4051.8, 4053.0</td>
</tr>
</tbody>
</table>

Table 7. Facies 2 thin sections and placement in core. Core placement (measured in feet) of six thin sections.
Figure 24. Core photograph of Facies 2: Bryozoan Wackestone to Packstone. Example is from the Hergert 2 well (4052.0’). This particular section is dolomitized and partially filled bryozoans molds (Mo) can be seen replacing skeletal debris.

Figure 25. Photomicrograph of Facies 2: Bryozoan Wackestone to Packstone. Intercrystalline porosity (Ix) is seen in the partially filled bryozoans molds, highlighted with blue epoxy.
*Interpretation:* Bryozoans can live in a variety of subtidal depths generally less than 100 meters deep (Stearn and Carroll, 1989). When a muddy matrix is present in Facies 2, the environment could reflect a deeper, less agitated setting. Thin beds of crinoidal grainstones that are locally intercalated within this facies could represent a shallower setting with stronger winnowing, possibly indicating a position proximal to higher energy shoal environments (Wilson and Jordan, 1983).

*Dolomitization, petrophysics and reservoir potential:* Facies 2 was only observed in six of the 177 thin sections. This ratio (3.3%) is a close comparison to the volume of Facies 2 described in core (~4%); however, the rock texture is unique enough and distributed throughout multiple cores across the region to warrant its own classification. Five out of the six thin sections observed are completely dolomitized and one is completely non-dolomitized (Table 8). Whole core analysis was only available for the cored intervals where the five dolomitized thin section samples were taken so visual estimates account for the one remaining limestone sample. Porosity values average 2.15% (WCA) and 5% (Visual) for the dolomitized samples and 0% (Visual) for the undolomitized sample. Permeability averages 0.26 millidarcies (WCA).
Table 8. Semi-quantitative analysis of Facies 2 using thin sections.

Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates were made from thin section. The six samples represent a smaller fraction of the gross volume of Facies 2 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.

Dolomite fabrics in Facies 2 are nonplanar (xenotopic) with anhedral crystals to planar-euhedral and planar–subhedral (idiotopic) crystals (Sibley and Gregg, 1987). Crystal sizes range from small to medium-large (40-80 microns). Small-medium (30–50 microns) anhedral rhombs make up the muddy matrix and medium to medium-large sub-euhedral rhombs occur around the bryozoan fragments. The crinoidal grainstones are frequently cemented with medium-large sub-euhedral dolomite rhombs, often with fabric destructive textures.

Facies 2 could potentially serve as a hydrocarbon reservoir but not on a volumetrically large scale. The porosity is higher when dolomitized (2.5-5%) but the permeability (0.26 mD) remains lower in relation to other oil-producing rocks in the field (Hurley and Budros, 1990). This could be because the bryozoan molds containing the intercrystalline porosity may not be well connected. Overall, this facies alone most likely does not represent a significant storage zone for hydrocarbons mostly due to small volumes and local distributions; however, if it were
stratigraphically connected to another facies type with high volume/porosity/permeability, it could act as an extension to that particular reservoir rock.

**Facies 3: Burrow-mottled Wackestone to Packstone – Mid Ramp Facies**

*Observations:* Facies 3 constitutes approximately 48% of the gross thickness of the studied cores (Table 3). From analysis of core and 71 thin sections (Table 9), this facies is comprised of wackestone to packstone with varying degrees of burrow-mottling ranging from none to near-homogenization by bioturbation (Figures 26 & 27). Burrows are commonly filled with coarser grains than the surrounding matrix. Skeletal debris and peloids constitute more than 10% of the rock. In relative order of abundance, grains consist of crinoids, shell fragments (ostracods, brachiopods, and unidentifiable mollusks), bryozoans and lesser amounts of gastropods and trilobites. Stylolites are common and occur as single sutures or clustered swarms. Thicknesses range from wispy to thick (millimeter scale) and amplitudes range from small to large. Pore types, in relative order of abundance, include intercrystalline (particularly for sucrosic dolomite), fractures, vugs, and molds. This facies closely resembles Facies 1 with the exception that it contains more fossil fragments and less mud.
### Table 9

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<tr>
<th>Well Name</th>
<th>Thin Sections (Marked by Depth)</th>
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<tbody>
<tr>
<td>Mann 6</td>
<td>3938.6, 3995.8, 4028.0, 4036.0, 4046.0, 4064.0</td>
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<td>Whitaker 2</td>
<td>3017.0, 3044.0, 3048.0, 3058.1, 3060.0, 3070.0, 3083.0, 3085.0, 3095.2, 3117.9, 3121.6, 3122.5, 3129.5, 3148.8, 3174.0, 3201.0, 3212.2, 3230.0, 3255.5</td>
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<td>Arco-Conklin 1-31</td>
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</tr>
<tr>
<td>Hergert 2</td>
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<td>Total Faist 2-12</td>
<td>4922.0, 4944.0, 5002.0, 5011.9, 5072.0, 5093.4, 5104.0, 5110.0, 5122.0, 5144.0, 5198.0, 5242.9</td>
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<tr>
<td>Total Luck 2-12</td>
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</table>

Table 9. Facies 3 thin sections and placement in core. Core placement (measured in feet) of 71 thin sections.
Figure 26. Core photograph of Facies 3: Burrow-mottled Wackestone to Packstone. Photograph from the Whitaker 2 well (3060.0’). This facies is less muddy than Facies 1 which is sometimes hard to distinguish when observing core. Thin section analysis presents a far grainier texture, as seen in the next figure. Btbn = Bioturbation, Sktl Grns = Skeletal Grains.

Figure 27. Thin Section photograph of Facies 3: Burrow-mottled Wackestone to Packstone. Notice the coarser-grained burrow in the bottom right corner and the abundance of skeletal grains in the matrix. Os = Ostracod, Bra = Brachiopod, Cr = Crinoid, Brw = Burrow, Tr = Trilobite.
Interpretation: This facies is very similar to Facies 1 and yields similar interpretations. Mud content (< 10%) is lower than in Facies 1 but still indicates a subtidal environment below fair weather wave base (Wilson and Jordan, 1983). Lesser amounts of mud in Facies 3 may also rule out a deeper, quiet water setting. Fauna represents a shallow to moderately deep (10-100 feet) subtidal environment (Stearn and Carroll, 1989). Facies 3 is interpreted to have been deposited in a mid ramp environment.

Dolomitization, petrophysics and reservoir potential: Seventy-one thin sections of Facies 3 from the six selected cores were observed and 43 are completely dolomitized, nine are partially dolomitized and 19 are non-dolomitized limestone (Table 10). The 43 dolomitized thin sections yield average porosity values of 4.04% (WCA) and 3% (Visual) and an average permeability value of 103.54 millidarcies. The nine partially dolomitized thin sections have average porosity values of 1.40% (WCA) and 1% (Visual) and 0.10 millidarcies of permeability. Porosity values of the 19 limestone thin sections averaged 1.02% (WCA) and 0% (Visual) and an average permeability value of 0.10 millidarcies. The high average permeability values from whole core analysis associated with the dolomitized portions of Facies 3 contains a certain degree of error in that the presence of open fractures causes extremely high values (>800 mD). The true permeability average without the samples containing large fractures lies more in the range of 40-60 millidarcies.
Table 10. Semi-quantitative analysis of Facies 3 using thin sections.

Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates were made from thin section. The 71 samples represent a smaller fraction of the gross volume of Facies 3 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.

Dolomite fabrics in Facies 3 range from nonplanar (xenotopic) with anhedral crystals to planar-euhedral and planar–subhedral (idiotopic) crystals (Sibley and Gregg, 1987). Crystal sizes range from fine to medium. The fine dolomite rhombs are exclusively along stylolitic seams while the larger rhombs occur within the matrix and replacing skeletal grains. As observed in Facies 1, Facies 3 also has extensive burrow networks that are preferentially dolomitized when the surrounding matrix is not. Locally, the opposite occurs, where the matrix is dolomized and the burrows are not. The majority of Facies 3, when dolomitized, display dolomite both within and outside of the burrows. In these instances where Facies 3 is completely dolomitized, intercrystalline porosity may or may not be greater in zones of burrowing. Specific trends or patterns relating the completeness of dolomitization within the burrowed were not observed. Overall, Facies 3 is shown to have greater porosities and permeabilities (Table 10) than Facies 1 (Table 5), most likely due to the greater abundance of grains.
Facies 3 has a strong potential to be a hydrocarbon reservoir. Similar to Facies 1, Facies 3 has high porosity and permeability throughout (see Table 10) mostly seen through intercrystalline porosity and especially within bioturbated fabrics. Also similar to Facies 1 is the abundance (volume) Facies 3 comprises within the Trenton and Black River formations (~48%). The combination of both the apparent large storage space (volume of facies in the studied cores) and high porosity and permeability values could comprise a significant secondary reservoir in the field aside from the open faults.

Facies 4: Skeletal Grainstone - Ramp Crest Facies

*Observations:* Facies 4 constitutes approximately 9% of the gross thickness of the six studied cores (Table 3). From analysis of core and 45 thin sections (Table 11), this facies is categorized as a cemented grainstone with no mud present (Figures 28 & 29). In relative order of abundance, grains consist of crinoids, shell fragments (ostracods, brachiopods, and mollusks), bryozoans, intraclasts, and lesser amounts of gastropods, peloids and trilobites. Horizontal and cross laminations are present in select intervals, but are uncommon overall. Various forms of calcitic and/or dolomitic cement encapsulate the grains. Stylolites are rare. Pore types, in relative order of abundance, are intercrystalline (when dolomitized), vugs and fractures. This facies is rarely thicker than 10-20 centimeters in a single interval when observed in core.
<table>
<thead>
<tr>
<th>Well Name</th>
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<td>Mann 6</td>
<td>3938.6, 3947.0, 3990.5</td>
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<td>Whitaker 2</td>
<td>3109.0, 3128.0, 3130.0, 3143.0, 3150.0, 3166.0, 3178.6, 3201.0, 3221.0, 3243.1, 3252.9, 3254.5, 3265.0</td>
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<tr>
<td>Arco-Conklin 1-31</td>
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</tr>
<tr>
<td>Hergert 2</td>
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<tr>
<td>Total Faist 2-12</td>
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</tr>
<tr>
<td>Total Luck 2-12</td>
<td>5046.1, 5068.5, 5071.0, 5099.0, 5128.0</td>
</tr>
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</table>

**Table 11.** Facies 4 thin sections and placement in core. Core placement (measured in feet) of 45 thin sections.

**Figure 28.** Core photograph of Facies 4: Skeletal Grainstone. Photo from the Total Luck 2-12 well (5068’). This is an example of a grainstone that is not dolomitized.
**Figure 29.** Photomicrograph of Facies 4: Skeletal Grainstone. Photo from the Whitaker 2 well. Note the assorted skeletal grains and lack of mud. This undolomitized sample shows no visible porosity. Ec = Echinoderm, Msk = Mollusk, Ca Cmt = Calcite Cement, Bra = Brachiopod, Bry = Bryozoan.

*Interpretation:* The concentration of grains with a lack of mud suggests a high-energy environment with some sort of winnowing or wave action (Wilson and Jordan, 1983). The variety and types of fauna come from shallow to moderately deep (10-100 feet) water (Stearn and Carroll, 1989). This facies is interpreted to have been deposited on a shallow subtidal shoal or ramp crest, or possibly as lag from storm events.

*Dolomitization, petrophysics and reservoir potential:* Forty-five out of the 177 thin sections analyzed are comprised of Facies 4. While this facies is seen within each of the six cores analyzed in this study, the number of thin sections taken may mislead the reader into thinking there are extensive intervals of skeletal grainstones throughout the Trenton and Black River formations, which there are not (see Table...
3). The majority of thin section samples were passed on from previous researchers who had strong interests in the grainstone facies for one reason or another (possibly assuming that the grainstones would be the best reservoirs). Overall, of the 45 thin sections analyzed, 42.2% are dolomitized, 20% are partially dolomitized, and 37.8% are undolomitized (Table 12). The dolomitized samples yield average porosity values of 5.47% (WCA) and 5% (Visual) with an average permeability value of 55.79 millidarcies. The partially dolomitized samples average 9.03% (WCA) and 1% (Visual) porosity with an average permeability value of 34.70 millidarcies. Abundant open fractures account for the high WCA porosity/permeability values and do not represent the general fabric of the grainstone. Porosity estimates from visual estimations serve the purpose of correcting this error. The undolomitized samples average porosity values are 2.30% (WCA) and 0% (Visual) and average permeability values of 0.10 millidarcies.

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<tr>
<td>Dolomitized</td>
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<td>42.22%</td>
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<td>1%</td>
<td>5%</td>
<td>20%</td>
<td>55.79 md</td>
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<tr>
<td>Partial Dol.</td>
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<td>20.00%</td>
<td>9.03%</td>
<td>0%</td>
<td>1%</td>
<td>9%</td>
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<td>Limestone</td>
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<td>37.78%</td>
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<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>0.10 md</td>
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</table>

Table 12. Semi-quantitative analysis of Facies 4 using thin sections.
Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates are made from thin section. The 45 samples represent a smaller fraction of the gross volume of Facies 4 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.
Dolomite fabrics observed in Facies 4 range from nonplanar (xenotopic) with anhedral crystals to planar-euhedral and planar–subhedral (idiotopic) crystals (Sibley and Gregg, 1987). Crystal sizes range from medium to large. There is a broad spectrum of dolomitic fabrics in Facies 4. Locally, it can contain large intercrystalline and vuggy pores with higher porosity and permeability values. In other places it can be re-cemented with little to no porosity or permeability, thus acting as a type of seal as opposed to reservoir. The facies is also resistant to dolomitization almost 50% of the time and when it remains a limestone, it is typically bonded by a non-porous calcitic cement. There are few examples of skeletal grainstones that are partially dolomitized – only observed in 20% of the thin section samples analyzed for this study. The high porosities and permeabilities related to the partially dolomitized Facies 4 reflect similar pore types as the completely dolomitized Facies 4; however, those statistics are inflated due to an abundance of fractures.

A dolomitized Facies 4 may seem like an ideal reservoir when looking at whole core analysis data alone, but the overall porosity/permeability may not be entirely consistent. This facies appears to only be dolomitized ~50% of the time, and is sometimes cemented as an impermeable layer with little to no porosity. Overall, the total volume of Facies 4 is low (Table 3) and the individual intervals are not extensive as mentioned earlier. Facies 4 should not be a primary target when drilling.

Facies 5: Peloidal Packstone – Lagoon Facies

Observations: Facies 5 constitutes approximately 5% of the gross thickness of the six studied cores (Table 3). From analysis of core and 24 thin sections (Table 13), this facies is categorized as a peloid-dominated packstone to grainstone with less than 10% skeletal debris intermixed (Figures 30 & 31). In relative order of abundance,
grains consist of crinoids, shell fragments (ostracods, brachiopods, and mollusks), bryozoans, and lesser amounts of gastropods and trilobites. Stylolites are common and occur as single sutures or clustered swarms. Thicknesses range from wispy to thick (millimeter scale) and amplitudes range from small to large. Burrows range in abundance from none to near-homogenization through bioturbation. Burrows also can contain coarser grain fills similar to Facies 1 and 3. Porosity is rare, with minor intercrystalline (when dolomitized) and open fractures. Peloids are seen mixed within various facies types, but are also seen to dominant the lithology with little other grains intermixed. While not widespread or extensive, these intervals still warrant their own classification. It is sometimes difficult to differentiate peloids from muddy sediment in core due to compaction and their small sizes and therefore it can be assumed that Facies 5 is more prevalent throughout the section than what is reflected in the thin section analysis.

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<tr>
<th>Well Name</th>
<th>Thin Sections (Marked by Depth)</th>
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<td>Mann 6</td>
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<tr>
<td>Arco-Conklin 1-31</td>
<td>3806.1</td>
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<tr>
<td>Hergert 2</td>
<td>3907.0, 3910.0, 3912.0, 3924.0, 3927.5, 3938.6, 3951.6, 395639, 3958.7, 3959.2, 3986.8, 4013.0, 4058.2</td>
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<td>Total Faist 2-12</td>
<td>5244.1, 5245.3, 4249.4, 5243.0, 4977.0, 4232.0, 5243.3</td>
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</table>

**Table 13.** Facies 5 thin sections and placement in core. Core placement (measured in feet) of 24 thin sections.
Figure 30. Core photograph of Facies 5: Peloidal Packstone to Grainstone. Example from the Mann 6 well (3967.5'). This facies is dominated by peloids (Plds) and lesser amounts of skeletal debris. As highlighted in the photo, burrows (Brw) are also a common occurrence.

Figure 31. Photomicrograph of Facies 5: Peloidal Packstone to Grainstone. There is a dolomitized burrow (Brw) in the lower right corner with few dolomite (Dol) rhombs branching out into the peloidal matrix. No porosity is visible. Plds = Peloids.
Interpretation: The high concentrations of peloids observed in this facies are interpreted to be fecal pellets released by benthic organisms that filtered the muddy sediment of a quiet water environment (Tucker and Wright, 1990). The lack of skeletal debris suggests an environment where select organisms, such as the ones creating the fecal pellets may thrive when others (skeletal organisms) cannot (Enos, 1983). This may indicate open ocean cutoffs with less oxygenation or nutrients, or irregular temperature and salinity. This facies is classified as a lagoon environment, possibly restricted or semi-restricted.

Dolomitization, petrophysics and reservoir potential: Of the 24 thin sections, five are completely dolomitized, nine are partially dolomitized and 10 are non-dolomitized (Table 14). Porosity values average 2.84% (WCA) and 2% (Visual) for the dolomitized samples, 1.22% (WCA) and 0% (Visual) for the partially dolomitized samples and 1.11% (WCA) and 0% (Visual) for the non-dolomitized samples. Respective average permeability values are as follows: 0.36 millidarcies for the dolomitized samples, 0.08 millidarcies for the partially dolomitized samples, and 0.05 millidarcies for the non-dolomitized samples.
Table 14. Semi-quantitative analysis of Facies 5 using thin sections.

Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates were made from thin section. The 24 samples represent a smaller fraction of the gross volume of Facies 5 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.

Dolomite fabrics in Facies 5 range from nonplanar (xenotopic) with anhedral crystals to planar-euhedral and planar–subhedral (idiotopic) crystals (Sibley and Gregg, 1987). Crystal sizes range from fine to medium-large (40-80 microns). The peloids commonly exhibit a tight mosaic framework when dolomitized which occludes porosity. Visible porosity in thin section is rare for both dolomitized and non-dolomitized peloidal sediment. Visible porosity is observed exclusively within burrows of both completely and partially dolomitized zones. In the instances in partially dolomitized samples where the burrows alone are dolomitized, scattered dolomite rhombs radiate away from the burrows into the peloidal matrix, but not in a dense enough pattern to impact the overall framework (see Figure 31). Stylolites within the dolomitized peloids contain fine dolomite crystals but exhibit no visible porosity.

Facies 5 should not be considered a significant reservoir rock. Porosity values of the dolomitized samples minimally represent a reservoir (Hurley and Budros,
1990) but the low permeability values may not (Table 14). Only three of the 21 samples are fully dolomitized and the partially dolomitized samples show low porosity values (0-1.22%) and permeability values (0.08 mD). The total core volume (Table 3) of Facies 5 is low relative to other facies, such as Facies 1 and 3. This limits the reservoir size even if it could sustain the capture of hydrocarbons.

Facies 6: Fine Grained, Oxidized Mudstone – Tidal Flat Facies

*Observations:* Facies 6 constitutes approximately 1% of the gross thickness of the six studied cores (Table 3). From analysis of core and three thin sections (Table 15), this facies is comprised of fine grained, oxidized mudstone (Figures 32 & 33). The oxidized sediment is apparent by a light gray-brown color. Little to no bioturbation is seen. The sediment appears as fine mud-sized particles with no skeletal grains, although the mud interpretation is difficult to determine when nearly 100% of the facies samples are recrystallized with fabric destructive dolomite. Pore types, in relative order of abundance, include intercrystalline, fenestral and microfractures. Stylolites are rare but observed with high amplitudes.

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<tr>
<th>Well Name</th>
<th>Thin Sections (Marked by Depth)</th>
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<td>Hergert 2</td>
<td>3970.0</td>
</tr>
</tbody>
</table>

*Table 15.* Facies 6 thin sections and placement in core. Core placement (measured in feet) of three thin sections.
Figure 32. Core photograph of Facies 6: Fine Grained, Oxidized Mudstone. Note the lighter coloration and presence of visible fenestral (Fe) pores.

Figure 33. Photomicrograph of Facies 6: Fine grained, Oxidized Mudstone. Sample is dolomitized. Porosity, highlighted by blue epoxy, is seen in a fenestral pore (Fe) as well as intercrystalline pores (Ix).
**Interpretation:** The light coloration of Facies 6 relative to the surrounding darker lithologies suggests that a high degree of oxidation took place. This type of oxygenation is suggestive of a very shallow, possibly subaerially exposed environment (Shinn, 1983). Fenestral pores are indicators of a supratidal environment where gas bubbles form from events such as air escapes during flooding or when organic decay releases gas in mud. Early lithification in the supratidal environment preserves such gas pockets as pores (Shinn, 1983). Burrows and skeletal debris are not prevalent and may be due to a dynamic environment too hostile for organisms to live in. This facies is interpreted to represent a tidal flat.

**Dolomitization, petrophysics and reservoir potential:** Three of the 177 thin sections taken from the six selected cores are interpreted to represent Facies 6. This facies is exclusive to the upper Black River Formation throughout the Albion-Scipio region. Volumetrically, it is a small portion of the overall Trenton-Black River section (~1% as described in the six cores) and a single interval never exceeds two to four feet. All three thin sections of Facies 6 observed are completely dolomitized (Table 16). The average porosity values are 2.70% (WCA) and 3% (Visual) and the average permeability value is 37.40 millidarcies. Under the microscope, porosity is visible in as intercrystalline, fenestral and occasional microfractures.
Table 16. Semi-quantitative analysis of Facies 6 using thin sections.

Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates were made from thin sections. The three samples represent a smaller fraction of the gross volume of Facies 6 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.

Dolomite fabrics in Facies 6 range from nonplanar (xenotopic) with anhedral crystals to planar (idiotopic) subhedral crystals (Sibley and Gregg, 1987). Crystal sizes range from fine to small. In all three thin sections, the dolomitized fabric exhibits fenestral pores and intercrystalline porosity.

Volumetrically, Facies 6 would not make for a prominent reservoir rock (see Table 3), but the average porosity and permeability values suggest it may transmit and/or store hydrocarbons well according to standards marked by Hurley and Budros (1990). The fenestral pores most likely do not interconnect so it may be the intercrystalline porosity that connects the void spaces 3-dimensionally. Open microfractures may add to the high petrophysical values as well. Overall, Facies 6 may represent a small scale zone for hydrocarbon storage.
Facies 7: Intraclastic Floatstone – Debris Flow Facies

*Observations:* Facies 7 constitutes approximately 11% of the gross thickness of the six studied cores (Table 3). From analysis of the two Henrietta Field cores and six thin sections (Table 17), this facies is comprised of a wackestone matrix filled with various multi-oriented, poorly sorted intraclasts (few millimeters to multiple centimeters in diameter) and resembles a type of breccia (Figures 34 & 35). The irregular intraclasts vary but are largely sub-angular to sub-rounded. In some instances the clasts are separated in the matrix almost uniformly and other times the clasts are compacted together. Similar grains are present in both the wackestone matrix as well as the clasts themselves. The grains, in relative order of abundance, consist of shell fragments (ostracods, brachiopods, and mollusks), crinoids, bryozoans, and lesser amounts of gastropods. Stylolites are common and occur as single sutures or clustered swarms. Thicknesses range from wispy to thick (millimeter scale) and amplitudes range from small to large. They occur not only horizontally but also sub-vertically. Fractures and intercrystalline pores characterize the limited porosity.

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<td>Total Luck 2-12</td>
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*Table 17.* Facies 7 thin sections and placement in core. Core placement (measured in feet) of six thin sections.
Figure 34. Core photograph of Facies 7: Intraclastic Floatstone. Sample taken from the Faist 2-12 well at 4987.0’ depth. The intraclasts in this image are non-compacted and of variable diameters, roundness and orientation as outlined with white dashed lines.

Figure 35. Photomicrograph of Facies 7: Intraclastic Floatstone. Sample taken from the Faist 2-12 core as seen in the above figure. An intraclast takes up the lower half of the image (outlined with dotted line). The grains are similar in both the matrix and the clast but oriented differently. Os = Ostracod, Cr = Crinoid, Ga = Gastropod, Bra = Brachiopod.
Interpretation: What separates this facies from the others is the presence of the randomly assorted intraclasts ‘floating’ in the surrounding matrix. Without evidence of geopetal structures, irregular cementation, vertical conduits, or cave structures, a karst environment is unlikely (Esteban and Klappa, 1983). The variety of intraclasts and the surrounding matrix have similar faunal content which suggests that both originated from similar environments and were displaced and brought together in a common matrix. The intraclasts may have derived from a separate environment which contributed to more rapid cementation than the matrix such as an environment with higher bottom currents that enhanced the degree of interstitial circulation and inhibited the settling of un lithified mud (Mullens et al., 2006). The lack of saddle dolomite helps eliminate a hydrothermal brecciation origin (Davies and Smith, 2006). Angled stylolites (up to 45 degrees) also indicate a possible slope for which the bathymetry was oriented. This facies is interpreted to be a debris flow.

Dolomitization, petrophysics and reservoir potential: This facies is exclusive to, and locally extensive in the Total Luck 2-12 and the Faist 2-12 wells of the Henrietta Field northeast of the Albion-Scipio trend. While this facies is seen throughout the majority of the Henrietta cores, only six thin sections were taken due to its absence in the remaining four cores used in this study. Of the six thin sections observed only one is completely dolomitized and the other five are undolomitized (Table 18). This facies typically remains undolomitized unless a fracture or shear invades the region as observed in core. Average porosity of the dolomitized sample is 1.80% (WCA) and 1% (Visual) and permeability measures 0.10 millidarcies. In thin section, the non-dolomitized samples show no visible porosity.
Table 18. Semi-quantitative analysis of Facies 7 using thin sections.

Porosity/permeability values were measured by whole core analysis that encompassed the intervals around the thin sections and average visual estimates were made from thin section. The six samples represent a smaller fraction of the gross volume of Facies 7 throughout the six studied cores. Table 3 identifies the overall core volumes to illustrate the regional distribution and abundance in relation to the other facies. Visual porosity was estimated under 12.5X and 35X magnifications.

Dolomites fabrics in Facies 7 range from nonplanar (xenotopic) with anhedral crystals to planar–subhedral (idiotopic) crystals (Sibley and Gregg, 1987). Crystal sizes range from small to medium. Intercrystalline porosity and small vugs are exclusive to intraclasts comprised of skeletal grainstone, as observed in the one dolomitized thin section.

Facies 7 does not have high porosity or permeability values, is rarely dolomitized and is exclusive to a select area within the Albion-Scipio region. Its relative importance in understanding the regional hydrothermal dolomite reservoir trends is insignificant.

Facies 8: Shale and Volcanic Ash Facies

Observations: Thin sections were not taken from Facies 8. The purpose of observing facies in thin section was to better distinguish and interpret the facies texture, grain types, sedimentary structures and faunal diversity and also gain a semi-

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<td>Dolomitized</td>
<td>1</td>
<td>16.67%</td>
<td>1.80%</td>
<td>1%</td>
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<td>2%</td>
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<td>Partial Dol.</td>
<td>0</td>
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<td>Limestone</td>
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<td>83.33%</td>
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quantitative collection of porosity and permeability data and then relate it all to dolomitization and reservoir quality. Since thin shales and K-bentonites do not constitute a possible hydrocarbon reservoir in this field, it was unnecessary to analyze them under a microscope for preferential dolomite trends. However, observations made from core were collected. The shales/K-bentonites range from a few millimeters to ~15 centimeters thick. The majority of the samples are black or gray and fewer samples, presumably K-bentonites, have orange and sometimes greenish coloration (Christidis and Huff, 2009). Some are fissile while others are cemented, dominantly with calcite. Fossil fragments and bioturbation occur in some samples making them more calcareous. Further detailed descriptions from select samples are found in the X-ray diffraction section of this study.

**X-Ray Diffraction Analysis**

X-ray diffraction (XRD) data was analyzed from two Utica marine shale samples, three ‘Black River Shale’ K-bentonite samples, one ‘E Shale’ K-bentonite sample, one random ‘shale’ sample and the four shale baffle samples. Due to the amount of diagenetic changes that have altered the shales/K-bentonites since deposition, mineralogical data is not definitive in separating a marine shale from a volcanic ash without additional supporting data (Huff, 2007). K-bentonites begin as smectite-rich, but gradually convert to interstratified illite-smectite clay-rich beds over time (Christidis and Huff, 2009). Typically, a K-bentonite is composed of some particles of volcanic glass, biotite, idiomorphic apatite and zircon crystals, sanidine, ilmenite, magnetite, β-quartz, and potassium (Weaver, 1953; Christidis and Huff, 2009). Marine shales may contain some of the same elements, but they are likely not as prominent. Generally, a typical marine shale contains a mix of clay minerals and
quartz grains with a small percentage of other minerals and/or organic material (Blatt et al., 1980). The XRD data can, however, show commonalities and/or differences between each sample and interpretations can be made as to what may make thin shales effective baffles/barriers. A ternary diagram below (Figure 36) is normalized to three of the most common minerals (clays, quartz and K-feldspar) and compares the 11 samples by relative mineral abundance. This chart visually depicts the clusters of marine shales, K-bentonites and their relationship to the four shale baffles.

**Figure 36.** Ternary diagram of shales. Diagram is normalized to compare relative percentages of clay, quartz and potassium feldspar content between the 11 thin shale samples. Samples highlighted in blue with diamond points = the four potential ‘shale’ baffles/barriers, green (triangle points) = Black River Shale K-bentonite samples, red (circle points) = Utica Shale samples, black (cross point) = a non-baffle/barrier shale of unknown depositional origin, and purple (triangle point) = ‘E’ Shale K-bentonite.
Three of the four shale baffles contain a significant weight percentage of carbonates (35-45%) with a lesser amount of clay as illustrated in Figure 37. While this statistic does not give definitive clues to the origins of deposition, it does imply that the shales were reworked with the surrounding carbonate sediment at some point after deposition or that carbonate cement precipitated within. The resulting mix of fine, shaley sediment with a cemented carbonate may combine to form a sufficient barrier to fluid, as seen with the three of the four shale baffles in this study. It is important to note from this data that it may not take a uniform, undisturbed shale or volcanic ash seam to sufficiently block high-pressure fluids.

**Figure 37.** Scatter plot of clays versus carbonates using X-ray diffraction values. The 11 clay seams show the percentage of total clay and carbonate content by weight percentage. Samples highlighted in blue with diamond points = the four potential ‘shale’ baffles/barriers, green (triangle points) = Black River Shale K-bentonite samples, red (circle points) = Utica Shale samples, black (cross point) = a non-baffle/barrier shale of unknown depositional origin, and purple (triangle point) = ‘E’ Shale K-bentonite.
Clues to the origins of the four shale baffles may be interpreted using the data seen in Figure 38. The cross plot most notably separates the two Utica Shale samples from the other samples with high amounts of quartz and lower amounts of potassium feldspar. The four shale baffles share similar amounts of quartz and relatively similar amounts of K-feldspar as the four known K-bentonite samples.

**Figure 38.** Scatter plot of K-feldspar versus quartz using X-ray diffraction values. The 11 clay seams show the percentage of total potassium feldspar and quartz content by weight percentage. Samples highlighted in blue with diamond points = the four potential ‘shale’ baffles/barriers, green (triangle points) = Black River Shale K-bentonite samples, red (circle points) = Utica Shale samples, black (cross point) = a non-baffle/barrier shale of unknown depositional origin, and purple (triangle point) = ‘E’ Shale K-bentonite.

A typical marine shale, such as the Utica Shale, may contain high amounts of quartz (~30%) and low amounts of K-feldspar (~5%, unless in the vicinity of volcanic activity), as shown in Figure 38 (Blatt et al., 1980). Before settling as a marine shale, sediment is generally eroded to a great extent leaving behind certain mechanically...
durable minerals such as quartz and completely breaking down weaker minerals such as K-feldspar (Blatt et al., 1980). Quartz, or silica, may derive from such weathering of detrital sediment from the hinterland or even as the remnants of marine pelagic organisms – the latter of which obviously points to a marine depositional setting. This study does not have data to support either argument detailing the quartz content specifically, but regardless the Utica Shale samples do uphold the general classification of a marine shale containing less K-feldspar and more quartz.

All the known K-bentonites as well as the four shale baffles differ from the Utica Shale samples in that they contain more K-feldspar and less quartz, as seen in Figure 38. Higher amounts of K-feldspar, which is volcanic in origin, may indicate that a lesser degree of erosion has occurred (Blatt et al., 1980). This may be due to a rapid period of deposition from the air into the ocean water without land transport. The higher weight percentage of K-feldspar is also likely the source of the potassium in these potassium-bentonites. Lesser amounts of quartz could indicate less detrital or pelagic input.

The data from Figure 38, although relatively simplistic, may support the idea that all four of the shale baffles/barriers may be volcanic in origin. Again, this is impossible to fully conclude without knowing what other minerals, chemicals, pressures and temperatures have affected the shales through various stages of diagenesis. Regardless of origin, the data does suggest that the particular assemblages of clay, K-feldspar and quartz observed in the four ‘shales’ may play a role in baffling fluids.

Shale/K-bentonite as Baffles and Barriers

Thin seams of shale and K-bentonite in the Trenton-Black River have been
identified across the Albion-Scipio region using wireline logs and core. Thirty-eight physical samples of thin shales/K-bentonites have been identified within the six observed cores. The physically preserved samples range from millimeter sized shale seams that resemble thick stylolites to 15 centimeter thick volcanic ash beds. Four of the 38 identified samples exhibit intervals of dolomite directly beneath them and undolomitized limestone directly above. This feature has been documented in hydrothermal dolomite settings by previous authors such as Hurley and Budros (1990), Davies and Smith (2006) and Sharp et al. (2010). They state that this “pooling effect” of dolomite may be the result of upward-moving hydrothermal fluids getting trapped below thin, shaley aquitards. The first example from this study comes out of the Mann 6 core from the southern end of the Albion-Scipio, two come from the Whitaker 2 core southwest of the major Albion-Scipio trend, and one from the Faist 2-12 core northeast of the Albion-Scipio trend in Henrietta Field. The physical examples come from different fields that are geographically distant from one another but within the same region. Additional evidence of possible shale baffles across the region is observed using wireline log suites from Rice Creek and Napoleon fields. The combination of neutron porosity, density and photoelectric factor logs displays what is interpreted as porous hydrothermal dolomite directly beneath gamma ray markers and not above.

Shale Baffles on Wireline Logs

Without the use of core, wireline log data remains the best tool in identifying the effects of thin shales on the distribution of hydrothermal dolomite. As seen in Figure 39, modern logs can be used to pick zones of porous hydrothermal dolomite with relative certainty. The well used in the figure comes from Rice Creek Field in
the northern Albion-Scipio trend and produced hydrocarbons from the dolomitic interval beneath the shale. A cross section seen in Figure 40 illustrates the significance that thin shales have on local distribution of hydrothermal dolomite. All five wells exhibit intervals of dolomite directly below thin shale seams (indicated by similarly placed gamma ray spikes) that are stratigraphically located where authors correlate the ‘E’ Shale (Hurley and Budros, 1990; Trevail, 1990). Drilling reports from each well reveal hydrocarbon production out of the same dolomitic intervals. The gamma ray spikes can also be traced 15-20 miles southeast to a gamma ray spike on a wireline log from Stoney Point Field’s Arco Conklin 1-31 well (Figure 41). A sample of core at that gamma ray spike reveals 2.5 centimeters of a fissile, greasy, gray-yellow/orange thin ‘shale’. X-ray diffraction data indicates that it is comprised of small amounts of clay (9 wt% of illite, 3 wt% of mixed illite/smectite) and quartz (6 wt%) and large amounts of feldspar (26 wt% potassium feldspar, 6 wt% of plagioclase) and sanidine (33 wt%) (Figures 37 & 38, Appendix E). Sanidine is a higher temperature form of potassium feldspar and typically found in felsic volcanic rocks such as obsidian, rhyolite and trachyte (Huff, 2007). The texture, mineralogy, regional correlations and documentation from previous authors (Trevail, 1990; Hurley and Budros, 1990) suggest that this Rice Creek Field baffle is the ‘E’ Shale volcanic ash bed.
Figure 39. Shale baffle on wireline logs. Logs are from the Kilbourn Farm 5-2 well in Rice Creek Field, paired with the respective image log illustrate what is interpreted to represent a thin shale seam (at 4,290’ in the upper Trenton Formation) with dolomite pooled directly below. Data similar to this is seen in subsurface logs throughout the Albion-Scipio region. Cross section was made using Petra Software.
Figure 40. Cross section of localized shale baffle. It goes across Rice Creek Field highlighting hydrothermal dolomite (purple coloration) that appears trapped below thin shale seams. This occurrence is also clearly seen in Napoleon Field, located east of the major trend. Production data indicates that hydrocarbons are readily extracted from such dolomite intervals suggesting that thin shales play an important role in reservoir development. Cross section and maps were made using Petra Software.

Figure 41. Core sample and gamma ray signature of ‘E’ Shale. Log is from the Arco-Conklin 1-31 well. This gamma ray spike correlates across the region including Rice Creek Field wells shown with dolomite pooled beneath (Figure 38 & 39).

Mann 6 Shale Baffle

A 2.5 centimeter thick calcareous shale (see Figure 42 & 43) at 3,984.4 feet in the Mann 6 core from the southern end of Albion-Scipio Field appears to be a barrier to vertical fluid flow. X-ray diffraction identifies this shale (by weight percentage) as 43% carbonate (39% calcite, 4% Fe-dolomite) with 9% clay (8% illite, 1% mixed illite/smectite) and 35% K-feldspar. Based on what is known about the chemical
composition and physical attributes of K-bentonites from previous research (Christidis and Huff, 2009; Huff, 2008), this shale may or may not have been derived from a volcanic event. The fact that nearly all the clay content is non-swelling illite to illite-smectite is consistent with a K-bentonite, although the alteration of the clay into illite-smectite is not always exclusive to a K-bentonite. The preservation of a high weight percentage of K-feldspar may indicate rapid deposition without prolonged periods of erosion suggesting that the sample may have been aerially transported. Physically, the sample appears to have no coloration besides a dark gray-black hue and is not fissile or greasy to the touch. However, the sample does appear to be intermixed to an extent with the surrounding carbonate mud which may have altered important clues to its origin of deposition due to various cementation and mixing of outside minerals. Gamma ray signatures do not exhibit a strong spike alongside this shale when compared to other less-calcareous shales/K-bentonites in the core or surrounding region probably due to the high amounts of carbonate. The gamma ray signature is also not traceable locally or regionally, which may shed some doubt on a fast-deposited, ubiquitous drape of ash.
Figure 42. Mann 6 shale baffle in core boxes. Approximately four vertical feet of dolomite lie directly below the 2.5 centimeter thick shale as indicated by the purple highlights.
Figure 43. Core photograph of Mann 6 shale. It is located at 3984.4’ in the Scipio Field. Composition is 43% carbonate and 9% clay suggesting a history of mixing with surrounding carbonate mud.

Whole core analysis data show that porosity throughout the four foot interval of dolomite consistently hovers around 3%. This number is confirmed through thin section analysis of two samples (see Figure 45B & C) at 3985.4’ and 3987.5’ where visual estimates show porosity of approximately 3%. While no whole core analysis data is available for the limestone units directly above the thin shale or below the dolomite interval, petrographic analysis indicates that these sampled intervals are non-porous (Figure 45A & D respectively).

Facies analysis through the use of thin sections indicates a variety of facies in both the limestone and dolomite units. A thin section taken from the limestone at 3983.6’ directly above the thin shale consists of a tight mudstone to wackestone (Facies 1) with sparse skeletal debris (< 10%), including shell fragments, and few peloids (Figure 44 & 45A). Two thin sections were taken from the dolomitized unit at 3985.4’ and 3987.5’ (Figures 44, 45B & C) and both consist of burrow-mottled
wackestone with coarsely crystalline burrow fills and less coarse matrix with scattered crinoidal debris (Facies 1). The porosity is seen primarily within the coarser crystals of the burrow fills and supports the conclusions of Schulz (2011) that burrow networks may enhance reservoir rock within these Trenton and Black River sections. Additional porosity appears outside of the coarse burrow fills within the smaller-grained, dolomitic matrix. Research by Thornton (2011) suggests that the pore types (intercrystalline) seen within this dolomitized facies have a greater chance of having higher permeability than most other pore types within this type of reservoir, thus suggesting that this dolomitized interval could be a storage zone for hydrocarbons. A thin section taken from 3990.5’ within the limestone unit below the dolomite displays a tight, calcite-cemented skeletal grainstone (Facies 4) with cemented microfractures (Figures 44 & 45D). This facies throughout the region is shown in petrographic analysis to be divided 50/50 in terms of dolomite/limestone and when not dolomitized, they exhibit little to no porosity.
Figure 44. Overall facies placement around Mann 6 shale baffles. Shows distribution of the limestone, shale and dolomite. Porosity values reflect visual estimates from the thin sections, whole core analysis data was unavailable.
**Figure 45.** Photomicrographs from the Mann 6 core in Scipio Field. (A) an undolomitized tight mudstone to wackestone facies found directly above the shale baffle. Little to no porosity is evident. (B) A dolomitized burrow-mottled wackestone facies taken in the dolomite interval below the shale baffle. The largest pores occur in the coarsely crystalline burrow fills (outlined in black) and smaller intercrystalline pores occur throughout entire facies. (C) A dolomitized burrow-mottled wackestone taken in the dolomite interval below the shale baffle. Arrows point to various intercrystalline porosity throughout both the less coarse matrix and the coarsely crystalline burrow fills. Burrows can be seen bordered by dark stylolites. (D) An undolomitized skeletal grainstone found below the baffled dolomite zone. The entire facies is cemented with calcite and exhibits no porosity. Ix = Intercrystalline porosity, Bra = Brachiopod, Os = Ostracod, Pld = Peloid, Cr = Crinoid, Fr = Fracture, Ca Cmt = Calcite Cement. Pore space has been impregnated with blue epoxy.
Interpretation of Baffling Effect in Mann 6

Using the given data and the understanding of hydrothermal dolomite systems (as described by authors such as Davies and Smith, 2006), it seems possible that this thin, calcareous shale redirected the upward flow of hydrothermal fluids laterally away from the main vertical to subvertical fault conduits. The magnesium-rich brines may have encountered the shale and pooled beneath, all the while preferentially dolomitizing the previously tight limestone. As the fluids moved laterally beneath the shale, the burrowed facies may have encouraged the flow. The presence of intercrystalline porosity and associated permeability in the dolomitized interval suggests that hydrocarbons may be able to invade and use the unit as a reservoir, or more likely as an extension of a larger reservoir.

Whitaker 2 Shale Baffles

The Whitaker 2 well is a bit anomalous in that it does not lie within a particular hydrocarbon field. It is located southwest of the Albion-Scipio trend by approximately 10 – 15 miles (Figure 20). It is only one of two producing wells in the area and thus far no extensive trends have been discovered around it. Upon examining core however, the reservoir maintains characteristics of hydrothermal origin and generally holds all the same features of an Albion-Scipio, Stoney Point or Henrietta well. Two shale seams, each with separate underlying dolomitized zones, exist within this core (Figure 46). The two shales are separated by approximately 7.5 feet. The youngest shale, at 3122.0’, is 1.5 – 2 centimeters thick, non-fissile and slate-black in color (Figures 46 & 47). By weight percentage, XRD analysis indicates this shale to be 29% illite, 17% mixed illite/smectite, and 32% K-feldspar (Figures 37 & 38). The higher percentage of illite and illite/smectite as well as K-feldspar could point to a
volcanic origin, but not definitively. The second potential shale baffle, at 3129.0’, is a ~5 centimeter thick, highly calcareous-argillaceous interval rather than a condensed muddy seam (Figures 46 & 48). XRD analysis indicates a weight percentage of 13% illite, 6% illite/smectite, 36% calcite, and 29% K-feldspar (Figures 37 & 38). High percentage of K-feldspar and moderate amounts of illite/smectite may support a volcanic origin but the large amounts of mixed carbonates inhibit a definitive interpretation. As may be the case in most of the shale seams in these Ordovician rocks, millions of years of diagenetic alterations may have removed or added various minerals rendering them difficult to identify as a marine shale or volcanic ash deposit (Huff, 2007). Regardless of origin, the importance remains with the intervals of dolomite directly below each thin shale as seen in Figure 46.
Figure 46. Whitaker 2 shale baffles in core boxes. Approximately four vertical feet of dolomite extends below the 1.5-2 centimeter thick upper shale (3122.0’). Approximately 20 vertical feet of dolomite extends below the 5 centimeter thick calcareous lower shale (3129.0’). Of the 20 feet, ~2.5 feet can be seen in this figure.
**Figure 47.** Core photograph of shale at 3122.0’ from the Whitaker 2 well. With a composition of 29% illite, 17% mixed illite/smectite, and 32% K-feldspar there is a likelihood of a volcanic origin. Physical texture and color, however, are not synonymous with a bentonite. Small amounts of calcitic fossils can also be seen intermixed.

**Figure 48.** Core photograph of shale at 3129.0’ from the Whitaker 2 well. The composition is 13% illite, 6% illite/smectite, 36% calcite, and 29% K-feldspar suggesting homogenization with the surrounding carbonates. Note the abundance of fossils and the missing sections of core. Fragile shale samples could have been lost over time or never recovered during drilling.

The interval of dolomite beneath the upper shale at 3122.0’ extends approximately four vertical feet below (Figure 46 & 49). Sandwiched between that dolomite interval and the lower shale at 3129.0’ is a limestone unit approximately
three feet thick. Below the lower shale at 3129.0’, dolomite extends much further down to 3149.5’ making the interval approximately 20 vertical feet thick.

Whole core analysis is not available for the entire Whitaker 2 well, however visual estimations from various thin sections surrounding the shale intervals yield applicable porosity data. A thin section at 3121.6’ from the uppermost limestone unit directly above the 3122.0’ shale shows a tight facies with no visual porosity (Figure 50A). A thin section taken at 3122.5’ within the first dolomite interval, below the 3122.0’ shale, shows a dolomitized facies with an estimated 1 - 1.5% intercrystalline porosity (Figure 50B). A thin section at 3128.0’ from the middle limestone unit shows no visual porosity (Figure 50C). Three thin sections taken at 3129.5’, 3130.0’ and 3148.8’ in the lowermost dolomite interval below the 3129.0’ shale show complete dolomitization with estimated intercrystalline porosities around 1-5% (Figures 51A, B & C respectively). The deepest thin section, at 3150.0’, is in the limestone below the 20 foot dolomite interval and shows no visible porosity (Figure 51D). It is quite possible that microporosity may exist within the dolomitized facies but was undetectable petrographically.
Figure 49. Overall facies placement around both Whitaker 2 shale baffles. Shows distribution of the limestone, shales and dolomite. Porosity values reflect visual estimates using thin sections. Whole core analysis porosity and permeability was not available.
Figure 50. Photomicrographs of facies encompassing the uppermost Whitaker 2 shale at 3122.0’.(A) Packstone to grainstone facies located above the shale baffle, exhibits no porosity. Dolomite is present in ~20% but is mostly visible alongside the pressure solution seams. (B) Completely dolomitized packstone just below the uppermost shale baffle. Very little porosity is discernable in the mosaic texture. (C) Mud-lean packstone to grainstone with heavy stylolites in the limestone interval located between the two shales and associated dolomite intervals. This sample is very similar to the facies from (A) 3121.6’, but contains no dolomite and no visible porosity. Bra = Brachiopod, Bry = Bryozoan, Ec = Echinoderm, Sty = Stylolite, UnID = Unidentifiable Skeletal Grains, Dol = Dolomite, Ix = Intercrystalline Porosity, Cr = Crinoid. Porosity is filled with blue epoxy.
Figure 51. Photomicrographs of facies encompassing the lowermost Whitaker 2 shale at 3129.0’. (A) Packstone to grainstone facies found in the dolomite zone beneath the shale baffle exhibits intercrystalline porosity. (B) Skeletal grainstone facies seen in the dolomite interval below the shale baffle exhibits intercrystalline porosity. (C) Packstone facies seen in the lowest foot of the 20 foot dolomite interval that formed below the shale baffle. (D) Grainstone facies located in the limestone interval directly below the 20 foot dolomite interval that formed beneath the shale baffle. No porosity is evident. Ec = Echinoderm, UnID = Unidentifiable Skeletal Grains, Cr = Crinoid, Pld = Peloids, Os = Ostracod, Msk = Mollusk Fragment, Ca Cmt = Calcite Cement, Ix = Intercrystalline Porosity. Porosity impregnated with blue epoxy.

Facies analysis was done using the same thin sections as mentioned above in order to record any controls that the primary fabrics may have had in conjunction with or independently from the thin shales. Upon examination, the primary depositional facies did not vary greatly. The limestone facies at 3121.6’ is a
micritized mud-lean packstone to grainstone (Facies 3) with 20-25% dolomite. Most of the dolomite is seen along stylolites as fine rhombs and rarely observed as matrix-filling sucrosic dolomite. Visual porosity within the sample is non-existent (Figure 50A). The facies from 3122.5’ is also a packstone to grainstone (Facies 3), but completely dolomitized with sucrosic dolomite. This facies has a mosaic dolomite texture with 1-1.5% intercrystalline porosity (Figure 50B). The thin section taken at 3128.0’ within the middle limestone unit above the 3129.0’ shale shows a facies very similar to the type seen in the uppermost limestone unit at 3121.6’. It is a packstone to grainstone facies (Facies 3) with little to no mud and 0% dolomite (Figure 50C). Porosity is not visible in thin section. The facies directly below the 3129.0’ shale at 3129.5’ is completely dolomitized and is comprised of another packstone to grainstone (Facies 3) similar to both the dolomitized and non-dolomitized facies seen in the above section (Figure 51A). This fabric shows intercrystalline porosity estimated at 3% with more euhedral to subhedral dolomite rhombs compared to the anhedral, mosaic textures seen at 3122.5’. A thin section deeper in the lowermost dolomitized interval at 3130.0’ (Figure 51B) is a skeletal grainstone (Facies 4) that has been completely dolomitized with 4-5% intercrystalline porosity. A thin section taken from the deepest end of the 20 foot dolomite interval at 3148.8’ (Figure 51C) is another packstone (Facies 3) with intercrystalline porosity. This confirms porosity throughout the length of the lowermost dolomite interval associated with a shale baffle. When observing the thin section directly below the 20 foot dolomite interval at 3150.0’ (Figure 51D), it appears as a non-porous, calcitic grainstone (Facies 4). Two facies types, Facies 3 and 4, are observed in proximity to the two shale baffles. Both facies have dolomitic as well as limestone intervals.

The intervals of dolomite beneath each shale baffle could represent
hydrocarbon reservoirs. While the first interval of dolomite is not thick (~ 4 feet), the lower dolomite interval is more prominent at 20 feet thick. Porosities (Figure 49) and an assumed good permeability through intercrystalline porosity (Thornton, 2011) classify both dolomitized facies (Facies 3 and 4) as sufficient reservoir units (Hurley and Budros, 1990).

**Interpretation of Baffling Effect in Whitaker 2**

The two shales in the Whitaker 2 well share similar qualities with the thin shale from the Mann 6 core, but yield some unique trends as well. The two shales are stacked within a few feet of each other and the facies do not vary to a high degree between the limestone and dolomite intervals. Both intervals are mostly Facies 3 with few thin layers of Facies 4 and 1. As the hydrothermal fluids theoretically flowed upwards through the faults they were most likely impeded by the first, lowermost thin shale. Fractures and high pressures may have allowed the fluids to continue moving upward and meet the second, uppermost thin shale (Figure 52). Both shales, possibly aided by the packstone to grainstone facies, redirected the vertical flow in a horizontal direction radiating throughout the surrounding limestone unit. Pressure, velocity, mineral content and volume of the hydrothermal fluids most likely decreased as the fluids traveled further from the conduit source. This is illustrated by the three foot limestone unit between the two shales that contains similar facies as the dolomitized intervals. The lack of dolomite in this zone may not reflect a facies change but merely a lack of dolomitizing fluid. It is at this point that we observe lateral ‘fingering’ of dolomite. Both thin shales continued to redirect the hydrothermal fluids, creating zones of porous dolomite beneath them. Most importantly, the pooling effect of dolomite beneath the Whitaker 2 thin shales exemplifies that this phenomenon is not
unique to the Albion-Scipio trend and proves valuable to identify and understand in any hydrothermal dolomite setting.

**Figure 52.** Two dimensional theoretical model of Whitaker 2 shale baffles. Dolomite ‘fingering’ may appear in the Whitaker 2 core. HTD invades various facies types away from vertical faults. Red arrows = the migration of hydrothermal fluids, purple = dolomitized zones, yellow = Facies 1, green = Facies 3, red-orange = Facies 4. Drawing is not to scale.

**Faist 2-12 Shale Baffle**

A five centimeter thick calcareous shale at 5243.0’ in the Faist 2-12 core from Henrietta Field may represent a baffle to rising hydrothermal fluids (Figures 53 & 54). The interval surrounding this thin shale (Figures 53 & 55) is problematic, however, when compared to the previous examples. True dolomite (100% dolomite)
does not lie directly beneath the shale. Instead, limestone with various percentages of intermixed dolomite (10-70%) begins at the base of the shale and extends downward vertically for approximately one foot before transitioning into 100% dolomite. Pure (100%) limestone is presented immediately above the shale and continues vertically for ten’s of feet without any dolomite. This suggests the possibility of preferential dolomitization beneath the shale despite the fact that the zone is not 100% dolomite throughout.
Figure 53. Faist 2-12 shale baffle in core boxes. An ~5 centimeter thick shale is seen at 5243.0’. The dolomite interval is unique in that complete (100%) dolomitization does not occur until approximately one foot beneath the shale.
Figure 54. Core photograph of Faist 2-12 shale. It is seen at 5243.0’ in the Henrietta Field. Note the mixed carbonates in the upper few centimeters (indicated by red arrows).

XRD analysis shows the shale is composed (by weight percentage) of 23% illite, 1% illite/smectite, 33% calcite, and 25% K-feldspar (Figures 37 & 38). The percentage of non-swelling illite and presence of illite/smectite may indicate a volcanic origin. The high amounts of calcite as seen mineralogically and physically may point to mixing with surrounding carbonate sediment, perhaps through bioturbation or other disruptions in the water column due to wave or current activity. Stratigraphically, this thin shale lies just below the major gamma ray spike on wireline logs that correlate with the Black River Shale K-bentonite. This clay-rich seam may represent an early interval of the episodic Millbrig or Deicke ash falls. The physical and chemical changes could have caused it to resemble a marine shale or clay as previously discussed (Huff, 2007). The texture appears slightly fissile with localized carbonate-filled burrows. The sample is slightly greasy to the touch and is dark gray in color.

The interval beneath the shale that contains the various amounts of dolomite extends downward approximately six feet. The first 12 inches below the shale is
partially dolomitized (ranging from 10-70%) before becoming completely dolomitized for the next four feet. The bottom foot of the interval is partially dolomitized before transitioning downward into 100% limestone. The limestone interval only extends approximately two feet before becoming partially and then fully dolomitized again. At this point the core ends. Overall, an extension of dolomite is located precariously below a thin shale but not above.

Porosity values throughout the partially dolomitized, 12-inch interval below the shale average 0.65% and permeability averages 0.1 millidarcies. The interval of complete dolomitization has an average porosity of 5.1% and permeability of 0.5 millidarcies. The final partially dolomitized foot of the interval has a whole core analysis porosity of 2.0% and permeability of 0.1 millidarcies. The limestone unit below the dolomite has a 0.57% porosity and 0.1 millidarcies permeability. The entire dolomitized (partial and complete) interval is not extensive vertically (six feet) but may provide enough storage volume (for hydrocarbons) if the lateral geometry is widespread. Overall porosity values of the interval may be classified as reservoir quality by the standards expressed by Hurley and Budros (1990), but permeability values may be questionable reservoir quality.

Facies analysis was completed using thin sections to observe any possible trends of preferential dolomitization and visible porosity (Figure 55). Beginning with the limestone directly above the shale, there is a wackestone to mud-rich packstone (Facies 1) with a variety of skeletal grains (Figure 55 & 56A). Whole core analysis porosity/permeability data is not available in this section but porosity is not visible in thin section. Just below the shale (5243.0’), the facies at 5243.3’ contains two main textures: a bioturbated packstone to grainstone with abundant skeletal fragments (Facies 3) and a peloidal packstone to grainstone (Facies 5) with few large grains and
10-20% dolomitization (Figure 55 & 56B). Porosity (WCA) values average 0.7% and permeability averages 0.1 millidarcies. Further down the section at 5244.1’, the facies is a burrow-mottled peloidal packstone (Facies 5) with preferential dolomitization of burrows (Figure 55 & 56C). Seventy percent of this facies is dolomitized in and closely surrounding the burrows. Porosity (WCA) values average 0.6% and permeability averages 0.1 millidarcies. In the zone of 100% dolomite, a thin section taken at 5245.3’ shows a burrow-mottled peloidal packstone facies (Facies 5) (Figure 55 & 56D) quite similar to the facies seen at 5244.1’ and fairly similar to the facies at 5243.3’. The big difference between the three is the amount of dolomitization. Porosity (WCA) is also higher at 5.10% and permeability of 0.5 millidarcies. A thin section taken where the dolomite transitions to the lower limestone at 5249.4’ shows a limestone/dolomite mix with approximately 20-25% dolomite (Figure 55 & 56E). The facies is a dominantly homogenized peloidal packstone (Facies 5) with lesser amounts of preferentially dolomitized burrows when compared to the above sections. Porosity (WCA) values average 2% and permeability averages 0.1 millidarcies. The last thin section taken in proximity to the shale comes from the limestone beneath the dolomitized zone at 5250.2’ (Figure 55 & 56F). This facies is a calcite-cemented skeletal grainstone (Facies 4). Porosity (WCA) averages 0.57% and permeability averages 0.1 millidarcies.
Figure 55. Overall facies placement around Faist 2-12 shale baffle. Limestone, shale and dolomite is also seen. The burrowed fabrics appear to control dolomitization and may contribute to the lateral migration of HTD along with the shale baffle. Porosity and permeability taken from whole core analysis.
Figure 56. Photomicrographs of facies encompassing Faist 2-12 shale baffle. (A) Wackestone to mud-rich packstone directly above shale containing < 1% dolomite. Porosity not visible. (B) Packstone to grainstone directly below shale and only 10-20% dolomite. Porosity is scarce. (C) Burrow-mottled, peloidal packstone is 70% dolomite with majority of dolomite located in and around burrows. (D) Burrow-mottled peloidal packstone is 100% dolomite. Porosity occurs within coarser-grained burrows. (E) Homogenized peloidal packstone at the bottom of the dolomitized interval where rock transitions to limestone. The sample is 20-25% dolomite. Porosity is rarely visible. (F) Skeletal grainstone in limestone below the dolomite interval. Porosity is scarce. Bra = Brachiopod, Bry = Bryozoan, Os = Ostracod, Msk = Mollusk Fragment, Pld = Peloids, Tr = Trilobite, Dol = Dolomite, Brw = Burrow, Ec = Echinoderm, UnID = Unidentifiable Skeletal Fragment, Ca Cmt = Calcite Cement. Porosity impregnated with blue epoxy.
Interpretation of Baffling Effect in Faist 2-12

It is clear in this example that dolomitization occurs below the thin shale and not above. The patterns of dolomitization preferentially follow the burrowed fabrics and do not always dolomitize the peloidal matrix. Hydrothermal fluids may have flowed up the fault conduits and met the thin shale. The network of burrows within the otherwise non-porous, peloidal sediment may have encouraged the fluids to flow laterally, while the shale acted as an overlying buffer. It seems possible that closer to the main conduit, the primary depositional facies made little difference to the flow of the fluids but as the fluids lost their intensity further from the source, they followed a less resistant pathway; in this case, the burrow-mottled peloidal packstone. The thin shale examined in this section may illustrate the complexities involved in the shaping of hydrothermal dolomite reservoirs and how multiple factors may have to align in order to affect the overall architecture.

Role of Stylolitization

Shales of different genetic makeup, size and structure are studied earlier in this document to determine whether they influence the architecture of hydrothermal dolomite reservoirs by effecting fluid flow. The thinnest shale seams, which are possibly large stylolites, or pressure solution seams have been further analyzed to examine the minimum thickness it may take to influence fluid flow and resulting dolomitization. The details may be minute in the overall search for the best reservoir, but may lead to a better understanding of how sensitive the hydrothermal fluids are to even the smallest of changes in the reservoir rock’s properties which may translate to larger scales.

Stylolitization contributes to bulk volume reduction in carbonate units thus
altering the original thickness. This occurs as a result of pressure induced dissolution and grain interpenetration and leaves behind remnant insoluble material (Scholle and Scholle, 2003). Stylolite formation typically occurs under 500 – 900 meters of overburden (Ford and Williams, 2007; S.L. Sah, 2003). Stylolites come in a wide range of styles due to a variety of factors, including the differences in the fabrics and structures of the altered rocks (Flugel, 2004). These various seams of insoluble material are what may influence the hydrothermal fluid flow in carbonate units such as the Trenton and Black River formations. Thirty-four thin sections of partially dolomitized rock containing stylolites were analyzed petrographically, with results presented below.

Stylolites as Baffles or Barriers to Fluid Flow

Similar observations as those documented with centimeter-thick shales/K-bentonites, which suggest that they may act as fluid baffles or barriers, also occur with stylolites on the microscopic scale. An example is illustrated in Figure 57 which shows a single stylolite where the rock has been dolomitized immediately below the stylolite while maintaining a limestone composition directly above. The denser unit of insoluble material may obstruct the upward migration of hydrothermal fluid flow from below similarly to the thicker shale baffles observed in the previous chapter. If such an occurrence is common enough throughout the section, it may be a significant component to compartmentalizing a dolomitic reservoir.
Figure 57. Photomicrograph of stylolite baffle. The single, black stylolite shows complete dolomitization directly below it in a mixed peloidal/grainstone facies and a calcite-cemented grainstone directly above it. This seam of insoluble material could potentially represent a barrier to fluid flow.

The facies above the stylolite is a calcite-cemented skeletal grainstone (Facies 4) and below is a mud-lean peloidal packstone (Facies 5) with some grainstone components. This stylolite may represent a division between two different facies and an avenue of weakness that allowed dissolution to move fluids through during compaction.

**Stylolite-Controlled Dolomitization**

Observations show a recurring trend of fine dolomite rhombs floating within or in close proximity to different types of stylolites. This includes everything from single, small amplitude stylolite sutures to irregular, anastomosing stylolite swarms. In some instances, whether the surrounding rock fabric is dolomitized or not, these fine dolomite rhombs persist exclusively along the paths of stylolites. When the rock
has been fully dolomitized, most areas in and around these types of stylolites exhibit smaller dolomitic rhombs with larger rhombs occurring throughout the surrounding facies (see Figure 58A). Smaller dolomitic crystal textures are also observed along stylolites within rocks that are almost fully undolomitized (Figure 58B) as well as in rocks that are partially dolomitized (Figure 58C). It is evident that dolomite has preferentially formed along the routes of stylolites in these examples similarly to what has been observed by authors such as Miller and Folk (1994) and Warrlich et al. (2010). It remains unclear whether hydrothermal dolomite fluids traveled along these seams, but at one point in time, the stylolites most likely acted as conduits to some form of dolomitizing fluid.
Figure 58. Photomicrographs of stylolite conduits in dolomite, limestone and partial dolomite; stylolite in limestone. (A) Peloidal packstone facies from the Whitaker 2 core is 100% dolomitized. Wispy stylolites can be identified by the presence of much smaller dolomite rhombs compared to the larger rhombs seen in the surrounding matrix. (B) Stylolites from the Whitaker 2 core containing fine dolomite rhombs that cut across a limestone skeletal grainstone facies. The alizarin red staining highlights the calcite. (C) Stylolite from the Hergert 2 core contains fine dolomite rhombs. Larger rhombs can be seen throughout the partially dolomitized facies around the stylolite. Whether there was not enough fluid present or the host facies restricted flow, this rock is not completely dolomitized. (D) Stylolites from the Mann 6 core contain few fine dolomite rhombs within and the surrounding peloidal facies have not been strongly dolomitized. This particular facies may not be conducive to fluid flow.

The timing of stylolite formation and the occurrence of hydrothermal fracturing may render the idea of stylolite-controlled hydrothermal dolomite obsolete. The first reactivation of basement faults is thought to have occurred as early as the
Late Ordovician (Dellapenna and Chaivre, 1988), which at that time there was not nearly enough overburden to have created stylolites (Ford and Williams, 2007; S.L. Sah, 2003). If there were no stylolites present during the initial dolomitizing process, then there is no way the seams could have influenced the fluid flow. However, if there were reactivations of faults and multiple episodes of hydrothermal dolomitization later in geologic history, overburden may have been sufficient in creating stylolites, which in turn could then potentially influence the fluid flow.
CHAPTER IV
SUMMARY DISCUSSION

Seven of the eight lithofacies analyzed, with Facies 8 being the exception, produced samples exhibiting complete dolomitization. Facies 1, 2, 3, and 6 were observed as being the most consistently dolomitized facies and Facies 4 was split roughly 50/50 in dolomite versus limestone. Intervals containing undisturbed (i.e. little bioturbation or other sedimentary structures) carbonate mud or peloids appeared resistant to dolomitization, although such intervals are rarely observed throughout the regional Trenton and Black River formations. It remains difficult to draw definitive conclusions on preferential dolomitization without knowing how close each studied core was to the primary fault/fluid conduits. As mentioned earlier, it is reasonable that a core located closer to a fault would exhibit more overall dolomitization based on the pressure and volumes of the dolomitizing fluids alone. The cores further away from the faults are more likely to display selective dolomitization as the fluids seek the path of least resistance under less pressure.

Facies 3 (Burrow-mottled Wackestone to Packstone) portrays the best reservoir facies in this region based on overall regional abundance (Table 3) and the highest consistent porosity and permeability values (Table 10) when dolomitized. A higher grain content and pervasive bioturbation with coarse grain fills may explain why hydrothermal fluids travelled readily through this facies. Facies 1 (Burrow-mottled Mudstone to Wackestone) is quite comparable to Facies 3 but is less abundant and contains lower permeability values. Facies 2 (Bryozoan Wackestone to Packstone) has comparable porosity values but lacks the high permeability values and occurs locally in small intervals. Facies 6 (Fine Grained Oxidized Mudstone) and
sometimes Facies 4 (Skeletal Grainstone) also contain consistent patterns of dolomitization, but lack the consistent combination of having the large storage volume, spatial distribution and consistently high porosity and permeability that characterizes Facies 3.

Wireline log signatures observed from Rice Creek Field (Figures 39 & 40) exhibit intervals of reservoir dolomite directly beneath a thin layer of K-bentonite similar to what was observed by Hurley and Budros (1990). Multi-well cross sections were generated to illustrate possible well-to-well connections of these dolomitic zones. Whether the dolomite compartments actually connect between each well or not, it is apparent that the trends correlate across distances of a few miles. Similar observations of dolomite directly beneath thin seams of ‘shale’ also came from three cores in the Albion-Scipio region. The patterns of dolomite directly below and not above the shale layers resemble what was documented in a hydrothermal dolomite outcrop study by Sharp et al. (2010).

The theory behind these preferential zones of dolomite is that rising hydrothermal fluids were trapped or baffled by the thin shales and thus flowed laterally away from the main vertical fault conduits (Hurley and Budros, 1990; Sharp et al., 2010; Davies and Smith, 2006). Primary depositional facies may have aided in redirecting the fluid flow with the shales acting as overlying buffers. In an example from the Faist 2-12 core (Figures 55 & 56), complete dolomitization directly below the shale baffle occurred exclusively throughout bioturbated peloidal facies – with percent dolomite being directly related to degree of bioturbation. Three out of the four dolomite intervals below each shale baffle terminate, moving downwards, with the presence of a tightly (calcite) cemented skeletal grainstone. The limestone facies directly above each thin shale varied and were sometimes quite similar, if not the
same, as the facies directly below the shale. This suggests that the thin shales were sufficient barriers to fluids alone but the facies beneath them added a component to the continuation of preferential fluid flow.

X-ray diffraction data proved insufficient in definitively identifying each of the four thin shale baffles as either a marine shale or K-bentonite. This, however, was expected since authors such as Huff (2007) determined that diagenetic alterations can modify a volcanic ash to mineralogically resemble a marine shale. When plotted on various graphs, the four shale baffles exhibited mineralogical similarities closer to the known K-bentonites (Black River Shale, ‘E’ Shale) samples than the Utica Shale (marine shale) samples, especially with higher weight percentages of potassium feldspar and lower percentages of quartz (see Figures 37 & 38). Three of the four shale baffles contained a significant amount of carbonates intermixed, most likely due to reworking of the bottom sediment after deposition, that suggest it may not take a uniform, undisturbed shale or volcanic ash seam to sufficiently block high-pressure fluids.

Stylolites may have also controlled dolomitization similarly to the thicker shale baffles discussed above. An example of a millimeter-scale stylolite was observed in a thin section taken from the Faist 2-12 core as having completely dolomitized facies directly below but not above (Figure 57). Stylolites as dolomitic fluid barriers have also been documented by authors such as Miller and Folk (1994) suggesting that it may be possible that the example observed in this study impeded hydrothermal fluids, even on such a small scale. Additional analysis of stylolites reveal fine dolomite rhombs formed preferentially within the pathways of stylolites. This occurs throughout dolomitized, undolomitized and partially dolomitized facies (Figure 58). It cannot be concluded that the rhombs along the stylolites formed from
migrating hydrothermal fluids, but in fact may be the remnants of a separate diagenetic event. These dissolution seams could have been fluid conduits at one point in their history which support observations made by authors such as Warrlich et al. (2010) and Miller and Folk (1994).
CHAPTER V

CONCLUSIONS

1. Open faults and fractures are not the only significant reservoir type in hydrothermal dolomite systems. Cross sections and core illustrate how dolomite responds to stratigraphic (facies) changes, and interconnected pores seen in the surrounding matrix dictate a key secondary zone for hydrocarbon storage.

2. Thin shales can baffle and redirect rising hydrothermal fluids laterally, thus forming preferential zones of reservoir dolomite beneath.

3. It may not take a uniform, undisturbed shale or volcanic ash seam to sufficiently block high-pressure fluids.

4. Thin shales may be sufficient barriers to fluid flow by themselves, but primary depositional facies underneath the shales could also contribute to the preferential flow of hydrothermal fluids as well.

5. Burrow-mottled Wackestone to Packstone (Facies 3), when dolomitized, characterizes the best reservoir facies of the eight facies analyzed based on overall regional abundance and the most consistently high porosity/permeability values (for this particular reservoir dolomite).

6. Seven of the eight facies analyzed, with marine shale/volcanic ash being the exception, may undergo complete dolomitization, but whether this is due to close proximity to major fault conduits remains unknown.

7. Stylolites may obstruct the flow of dolomitic fluids similarly to a
thicker shale barrier. They may also act as conduits to dolomitic (not necessarily hydrothermal) fluid flow.
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Appendix A

Core Descriptions
The following written core descriptions serve the purpose of providing a general idea of the types and approximate abundance of facies seen throughout the Trenton-Black River. The purpose of this study did not weigh heavily on thorough interpretations of each facies and the original depositional environment but more so on the fabrics of each, the susceptibility of dolomitization and the relationship with the thin shales or volcanic ashes. Detailed facies descriptions were undertaken in the petrographic section of this study which in turn reflects the generalized whole core descriptions.
3935.0’ - 3940.0’ Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled with peloids, brachiopods, crinoids, bryozoans, and undifferentiated fossils and shell fragments.

3940.0’ – 3940.1’ Core Missing

3940.1’ – 3942.0’ Dolomite, Packstone to Grainstone (Facies 1), burrow-mottled with peloids, brachiopods, crinoids, bryozoans, and undifferentiated fossils and shell fragments.

3942.0’ – 3944.9’ Dolomite, Packstone (Facies 2), bryozoan packstone also containing few brachiopods and undifferentiated fossils.

3945.8’ – 3947.8’ Limestone, Packstone to Grainstone (Facies 3), burrow-mottled with wispy stylolites, with crinoids, brachiopods, and bryozoans.

3947.8’ – 3958.2’ Limestone, Peloidal Mudstone to Wackestone (Facies 5) with Packstone to Grainstone horizons (Facies 4) (< 7 cm thick) at 3956.2’, 3954.6’, 3954.1’, 3949.8’ totaling 1 foot thick, burrow-mottled, abundant stylolites, crinoids, mollusks, and brachiopods.

3958.2’ – 3958.4’ Core Missing

3958.4’ – 3959.4’ Limestone, Grainstone (Facies 4), skeletal grainstone.

3959.4’ – 3961.5’ Not Cored

3961.5’ – 3965.0’ Limestone, Wackestone to Packstone (Facies 1) with Grainstone (Facies 4) horizons (totaling 1 foot thick), with peloids and mollusks.

3965.0’ – 3970.1’ Limestone, Packstone to Grainstone (Facies 5), peloidal with burrows and with stylolites, unidentified shell fragments, crinoids, brachiopods and gastropods.

3971.1’ – 3974.0’ Limestone, Wackestone to Packstone (Facies 1), burrowed with coarse grain fills, stylolitic with thicker argillaceous seams.

3974.0’ – 3974.1’ Shale (Facies 8), black, fissile, 3 – 4 cm thickness in core.
3974.1’ – 3974.2’ Limestone, Mudstone (Facies 1).

3974.2’ – 3975.0’ Core Missing

3975.0’ – 3975.6’ Dolomite, Packstone to Grainstone (Facies 3), peloidal, oblique fracture filled with saddle dolomite, chert nodule present.

3975.6’ – 3976.0’ Limestone, Packstone (Facies 2), dominantly bryozoans and crinoids with gastropods and mollusks.

3976.0’ – 3981.9’ Limestone, Mudstone to Wackestone (Facies 1) with four Packstone to Grainstone (Facies 4) horizons totaling 1.5 foot thick, burrowed and stylolitic with crinoids, brachiopods, gastropods, bryozoans and abundant chert.

3981.9’ – 3984.5’ Limestone, Wackestone to Packstone (Facies 1), burrowed, stylolitic with peloids and chert nodules.

3984.5’ – 3984.7’ Shale (Facies 8), black, intermixed with skeletal debris (3 – 4 cm thick in core).

3984.7’ – 3986.4’ Dolomite, Packstone (Facies 1), peloidal, some burrows, crinoids, bryozoans, chert nodule @ 3985.4’.

3986.4’ – 3986.8’ Core Missing

3986.8’ – 3988.3’ Dolomite/Limestone, Wackestone to Packstone (Facies 1), burrows with coarse grain fills, mullusks, crinoids, peloids.

3988.3’ – 3990.3’ Core Missing

3990.3’ – 4003.1’ Limestone, Mudstone to Wackestone (Facies 1), burrow-mottled with coarse-grained burrow fill, small cycles are capped by skeletal grainstone layers (Facies 4) (2-3 cm thick), grainstone horizons at 4000.7’, 3999.9’, 3994.4’ totaling 1 foot thick, crinoids, brachiopods, mullusks, large tabulate corals at 3998.2’, rugose corals, chert at 3999.1’, thick stylolites.

4003.1’ – 4003.2’ Shale (Facies 8), black (1 cm thick).

4003.2’ – 4014.9’ Limestone, Mudstone to Wackestone (Facies 1), burrow-mottled with grainstone burrow fills, abundant thick stylolites (2-3 mm), crinoids, brachiopods, peloids, bryozoans; small cycles with grainstone caps (Facies 4) at 4013.2’, 4012.8’, 4010.1’, 4009.0’, 4008.1’, 4007.5’, 4004.0’ totaling 2 feet thick.
4014.9’ – 4016.3’ **Dolomite, Packstone (Facies 1)**, shoaling up into skeletal grainstone with stylolites, some hydrothermal replacement of larger grains.

4016.3’ – 4016.4’ **Core Missing**

4016.4’ – 4017.0’ **Dolomite, Mudstone to Wackestone (Facies 1)** with grainstone burrow fills.

4017.0’ – 4020.1’ **Dolomite, Grainstone, Tidal Flat (Facies 6)**, oxidized, fenestral porosity, stylolites, laminated dark gray grainstone from 4018.2’ to 4017.8’.

4020.1’ – 4022.9’ **Dolomite, Mudstone to Wackestone (Facies 1)**, burrows, brachiopods, hydrothermal dolomite precipitated in microfractures.

4022.9’ - 4024.9’ **Dolomite, Grainstone, oxidized Tidal Flat (Facies 6)**, burrows, fenestral porosity, grainstone laminations at the top, hydrothermal dolomite replacement and microfractures.

4024.9’ – 4030.4’ **Dolomite, Packstone to Grainstone (Facies 3)**, burrow-mottled with horizons of bryozoans and shell fragments.

4030.4’ – 4031.7’ **Core Missing**

4031.7’ – 4034.1’ **Dolomite, Packstone to Grainstone (Facies 3)**, burrow-mottled with coarse grain fills, stylolites and hydrothermal dolomite replacement in small fractures.

4034.1’ – 4034.2’ **Core Missing**

4034.2’ – 4034.3’ **Dolomite, Packstone to Grainstone (Facies 3)**, burrow-mottled with coarse grain fills, stylolites and hydrothermal dolomite replacement in small fractures.

4034.3’ – 4035.2’ **Core Missing**

4035.2’ – 4035.5’ **Dolomite, Skeletal Grainstone (Facies 4)**, with hydrothermal dolomite replacement, stylolitic, peloidal.

4035.5’ – 4037.1’ **Dolomite, Packstone to Grainstone (Facies 3)**, burrow-mottled with brachiopods, thick stylolites (1-2 mm) and hydrothermal dolomite replacement of large grains.

4037.1’ – 4038.0’ **Core Missing**
4038.0’ – 4040.7’ Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled with coarse grain fills, peloidal, few crinoids, hydrothermal dolomite replacement of large grains and burrows.

4040.7’ – 4041.9’ Dolomite, Tidal Flat (Facies 6), oxidized, fenestral porosity, moldic porosity, very thin laminations.

4041.9’ – 4044.4’ Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled with crinoids and brachiopods, some hydrothermal dolomite replacement.

4044.4’ – 4045.0’ Dolomite, Tidal Flat (Facies 6), oxidized, burrow-mottled, peloidal, hydrothermal dolomite replacement and a vertical fracture.

4045.0’ – 4048.5’ Dolomite, Packstone to Grainstone (Facies 5), burrow-mottled with abundant peloids accounting for coarse grain fills, undifferentiated fossils, few crinoids, brachiopods, hydrothermal dolomite replacement.

4048.5’ – 4050.4’ Limestone, Packstone to Grainstone (Facies 3), burrow-mottled with coarse grain fills, abundant stylolites.

4050.4’ – 4051.3’ Core Missing

4051.3’ – 4053.5’ Limestone, Wackestone (Facies 1) with burrow-mottled grainstone burrow fills.

4053.5’ – 4054.3’ Limestone, Grainstone, Tidal Flat (Facies 6), oxidized, burrows with coarse grain fills, stylolites, peloids, heavy hydrothermal fractures.

4054.3’ – 4055.0’ Limestone, Packstone (Facies 1), burrows-mottled, bryozoans.

4055.0’ – 4055.1’ Shale (Facies 8), black, some saddle dolomite (1-1.5 cm)

4055.1’ – 4064.2’ Limestone, Mudstone to Wackestone (Facies 1), burrow-mottled, thick, muddy stylolites (3-4 mm thick) with hydrothermal fractures.

4064.2’ – 4066.3’ Dolomite, Mudstone to Wackestone (Facies 1), burrow-mottled, few fossil fragments.

4066.3’ – 4070.2’ Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled with coarse grain fills and muddy stylolites (3-4 mm thick), heavy hydrothermal fractures.

4070.2’ – 4073.1’ Dolomite, Packstone (Facies 1), mud rich, some burrows, hydrothermal dolomite fractures.
4073.1’ – 4077.3’ Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled with coarse grain fill, few shell fragments, dark stylolites, vertical and horizontal hydrothermal dolomite fractures.

4077.3’ – 4078.5’ Dolomite, Skeletal Grainstone (Facies 4), dark shaley wisps, hydrothermal dolomite fractures and brecciation.

4078.5’ – 4080.8’ Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled with coarse grain fills, some shell fragments, hydrothermal dolomite fractures and brecciation.

4080.8’ – 4082.8’ Dolomite, Mudstone, Tidal Flat (Facies 6), fenestral porosity, peloidal, few stylolites.

END CORE

Facies 1 Total: 61.1’
Facies 2 Total: 3.3’
Facies 3 Total: 34.7’
Facies 4 Total: 8.0’
Facies 5 Total: 18.0’
Facies 6 Total: 9.7’
Facies 7 Total: 0.0’
Facies 8 Total: 0.5’
Total Luck 2-12
Permit # 33258, T1S R1W Sec. 12
Jackson County, Henrietta Field
Cored Interval: 4856.0’ - 4914.0’, 5017.0’ - 5133.0’

4856.0’ - 4858.5’: Facies 3 - Burrow-mottled Wackestone to Packstone

4858.5’ - 4861.0’: Facies 7 - Intraclastic Floatstone

4861.0’ - 4864.2’: Facies 3 - Burrow-mottled Wackestone to Packstone

4864.2’ - 4864.9’: Facies 7 - Intraclastic Floatstone

4864.9’ - 4870.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

4870.0’ - 4914.1’: Facies 7 - Intraclastic Floatstone

Core Missing 4914.0’ - 5017.0’

5017.0’ - 5035.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

5035.0’ - 5044.0’: Facies 7 - Intraclastic Floatstone

5045.8’ – 5044.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

5045.8’ - 5047.0’: Facies 4 - Skeletal Grainstone

5047.0’ - 5052.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

5052.0’ - 5053.2’: Facies 7 - Intraclastic Floatstone

5064.0’ – 5053.2’: Facies 3 - Burrow-mottled Wackestone to Packstone

5058.0’ - 5057.7’: Interbedded Facies 4 - Skeletal Grainstone

5064.0’ - 5065.5’: Facies 7 - Intraclastic Floatstone

5065.5’ - 5067.9’: Facies 3 - Burrow-mottled Wackestone to Packstone

5067.9’ - 5069.3’: Facies 4 - Skeletal Grainstone

5069.3’ - 5070.5’: Facies 3 - Burrow-mottled Wackestone to Packstone

5070.5’ - 5071.6’: Facies 4 - Skeletal Grainstone
Core Missing 5071.6’ - 5075.0’

5075.0’ - 5077.1’: Facies 3 - Burrow-mottled Wackestone to Packstone

5077.1’ - 5080.0’: Facies 7 - Intraclastic Floatstone

5080.0’ - 5088.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

5085.7’ – 5085.9’: Interbedded Facies 4 - Skeletal Grainstone

5083.9’ - 5084.2’: Interbedded Facies 4 - Skeletal Grainstone

5081.7’ – 5081.9’: Interbedded Facies 4 - Skeletal Grainstone

5088.0’ - 5089.5’: Facies 5 - Peloidal Packstone to Grainstone

5089.5’ - 5091.2’: Facies 4 - Skeletal Grainstone

5091.2’ - 5093.3’: Facies 3 - Burrow-mottled Wackestone to Packstone

5093.3’ - 5094.6’: Facies 4 - Skeletal Grainstone

5094.6’ - 5095.1’: Facies 3 - Burrow-mottled Wackestone to Packstone

5095.1’ - 5095.5’: Facies 4 - Skeletal Grainstone

5095.5’ - 5096.2’: Facies 3 - Burrow-mottled Wackestone to Packstone

5096.2’ - 5096.4’: Facies 4 - Skeletal Grainstone

5096.4’ - 5098.5’: Facies 3 - Burrow-mottled Wackestone to Packstone

5098.5’ - 5099.0’: Facies 4 - Skeletal Grainstone

5099.0’ - 5101.3’: Facies 3 - Burrow-mottled Wackestone to Packstone

5099.0’ – 5099.2’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

5101.3’ - 5102.2’: Facies 4 - Skeletal Grainstone

5102.2’ - 5106.3’: Facies 3 - Burrow-mottled Wackestone to Packstone
5104.4’ - 5104.5’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

5106.3’ - 5107.9’: Facies 4 - Skeletal Grainstone

5107.9’ - 5109.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

5109.0’ - 5111.0’: Facies 4 - Skeletal Grainstone

5124.8’ - 5130.5’: Facies 3 - Burrow-mottled Wackestone to Packstone

5120.5’ - 5121.2’: Interbedded Facies 4 - Skeletal Grainstone

5118.4’ - 5118.9’: Interbedded Facies 4 - Skeletal Grainstone

5117.3’ - 5117.7’: Interbedded Facies 4 - Skeletal Grainstone

5111.2’ - 5111.3’: Interbedded Facies 4 - Skeletal Grainstone

5130.5’ - 5131.1’: Facies 7 - Intraclastic Floatstone

5131.1’ - 5133.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

END CORE

Facies 1 Total: 0.0’
Facies 2 Total: 0.0’
Facies 3 Total: 75.8’
Facies 4 Total: 14.6’
Facies 5 Total: 1.8’
Facies 6 Total: 0.0’
Facies 7 Total: 62.5’
Facies 8 Total: 0.0’
Whitaker 2  
Permit # 28407, T7S R4W Sec. 29  
Hillsdale County, MI, southwest of Albion-Scipio Field  
Cored Interval: 3044.0 – 3265.0’

3044.0’ – 3065.0’ Dolomite, Packstone to Grainstone (Facies 3), with abundant crinoids, some shell fragments, peloids, thin stylolites.

3065.0’ – 3068.0’ Limestone, Wackestone to Packstone (Facies 1), crinoids, peloids, argillaceous, stylolites.

3068.0’ – 3080.2’ Dolomite, Packstone (Facies 3), crinoids, peloids, thin stylolites.

3080.2’ – 3080.5’ Dolomite, Grainstone (Facies 4), undifferentiated skeletal grainstone, possible crinoids.

3080.5’ – 3085.0’ Dolomite, Wackestone to Packstone (Facies 1), crinoids and peloids, horizontal vugs lined with saddle dolomite (2-3 cm diameter).

3085.0’- 3090.8’ Dolomite, Packstone to Grainstone (Facies 3), crinoids, brachiopods, trilobites, peloids, stylolites around burrows, saddle dolomite present in replaced large grains and micro-fractures.

3090.8’ – 3091.0’ Shale (Facies 8), fossiliferous (3-4 cm thick).

3091.0’ – 3095.0’ Dolomite, Packstone (Facies 1), crinoids, shell fragments, undifferentiated fossils, peloids, burrows.

3095.0’ – 3101.0’ Dolomite, Packstone to Grainstone (Facies 3), crinoids, trilobites, burrows with coarse grain fills.

3101.0’ – 3102.2’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils, stylolites appearing as thin shaley wisps.

3102.2’ – 3104.2’ Dolomite, Packstone to Grainstone (Facies 3), crinoids, brachiopods, peloids, burrows with coarse grain fills.

3104.2’ – 3104.5’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils.

3104.5’ – 3107.0’ Dolomite, Packstone to Grainstone (Facies 3), crinoids, shell fragments, peloids, burrows with coarse grain fills.
3107.0’ – 3107.2’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils.

3107.2’ – 3108.2’ Dolomite, Packstone to Grainstone (Facies 3), mud-lean packstone to mostly grainstone with crinoids, brachiopods, shell fragments, peloids, undifferentiated fossils, burrows with coarse grain fills.

3108.2’ – 3110.9’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils.

3110.9’ – 3113.0’ Dolomite, Packstone to Grainstone (Facies 3), mud-lean packstone to grainstone with crinoids, brachiopods, lithoclasts, burrows with coarse grain fills, vugs lined with saddle dolomite.

3113.0’ – 3114.9’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils and thin stylolites.

3114.9’ – 3115.0’ Dolomite, Packstone to Grainstone (Facies 3), mud-lean packstone to grainstone with crinoids, brachiopods, lithoclasts, undifferentiated fossils and stylolites.

3115.0’ – 3121.9’ Limestone, Packstone (Facies 3), mud-rich packstone, abundant crinoids, few burrows, stylolites.

3121.9’ – 3122.0’ Shale (Facies 8), black, fossiliferous with crinoids and shell fragments intermixed.

3122.0’ – 3125.0’ Dolomite, Packstone to Grainstone (Facies 3), mostly crinoids with lesser amounts of shell fragments and peloids, some burrows, thin stylolites.

3125.0’ – 3125.5’ Dolomite, Grainstone (Facies 4), skeletal grainstone with abundant crinoids.

3125.5’ – 3129.0’ Dolomite, Packstone to Grainstone (Facies 3), mostly crinoids with some shell fragments and peloids, burrows and stylolites.

3129.0’ – 3129.8’ Limestone, Packstone (Facies 3), mud-rich packstone, abundant crinoids, few burrows, stylolites.

3129.8’ – 3129.9’ Shale (Facies 8), fossiliferous with crinoids, has characteristics of a thick stylolite.
3129.9’ – 3130.0’ Dolomite, Packstone to Grainstone (Facies 3), abundant crinoids, with stylolites and burrows.

3130.0’ – 3130.5’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils.

3130.5’ – 3131.9’ Dolomite, Packstone (Facies 3), mud-rich packstone with crinoids, and burrows.

3131.9’ – 3132.4’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils.

3132.4’ – 3140.6’ Dolomite, Packstone (Facies 1), mud-lean packstone, fossiliferous with mostly crinoids and less amounts of shell fragments and peloids, burrows and stylolites are also seen.

3140.6’ – 3141.0’ Dolomite, Grainstone (Facies 4), skeletal grainstone with abundant crinoids and shell fragments.

3141.0’ – 3146.0’ Dolomite, Packstone to Grainstone (Facies 3), abundant crinoids with lesser amounts of brachiopods and undifferentiated fossils. There are burrows present along with stylolites. There are 2-inch thick grainstone (Facies 4) horizons at 3143.0’ - 3143.2’ and 3142.3’ – 3142.5’. Grainstone is skeletal with undifferentiated fossils.

3146.0’ – 3149.0’ Dolomite, Packstone to Grainstone (Facies 3), fossiliferous with crinoids, bryozoans, shell fragments, brachiopods, trilobites. There are some burrows and stylolites.

3149.0’ – 3151.5’ Limestone, Packstone to Grainstone (Facies 3), abundant crinoids with some stylolites. There is a 3-inch thick crinoidal grainstone horizon from 3149.7’-3149.9’.

3151.5’ – 3152.2’ Limestone, Grainstone (Facies 4), crinoidal grainstone similar to the horizons noted in the above interval.

3152.2’ – 3153.0’ Limestone, Packstone to Grainstone (Facies 3), mud-lean packstone with abundant crinoids. Stylolites are both thin (< mm) and thick (1-2 mm).

3153.0’ – 3157.0’ Dolomite, Packstone to Grainstone (Facies 3), abundant crinoids, peloids. Wispy stylolites or shale partings are evident. Saddle dolomite occurs along the grainy horizons.
3157.0’ – 3157.5’ Dolomite, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils. Small vugs (< 1 cm) are lined with saddle dolomite.

3157.5’ – 3167.5’ Dolomite, Packstone to Grainstone (Facies 3), mostly crinoids and brachiopods with some peloids. Wispy stylolites or shale partings are present. Saddle dolomite occurs along the grainy swaths (~1-2 cm thick) and small, vertical fractures.

3167.5’ – 3173.0’ Dolomite, Packstone to Grainstone (Facies 3), abundant crinoids with fewer brachiopods and bryozoa. Wispy stylolites or shale partings evident.

3173.0’ – 3173.2’ Shale (Facies 8), fissile, with gray and orangey colors, most likely volcanic in origin.

3173.2’ – 3178.2’ Dolomite, Packstone to Grainstone (Facies 3), abundant crinoids with fewer brachiopods and bryozoa. Wispy stylolites or shale partings evident.

3178.2’ – 3180.0’ Limestone, Packstone to Grainstone (Facies 3), mud-rich packstone to grainstone with many crinoids, bryozoa and brachiopods.

3180.0’ – 3190.0’ Dolomite, Packstone to Grainstone (Facies 3), mud-lean packstone to grainstone, very fossiliferous with mostly crinoids and lesser amounts of brachiopods, peloids, bryozoa. Some burrows are evident. Saddle dolomite occurs in grainstone horizons, large fossil replacement and fractures.

3190.0’ – 3190.2’ Shale (Facies 8), black, 2-3 cm, cemented carbonate, less fissile.

3190.2’ – 3194.0’ Dolomite, Packstone to Grainstone (Facies 3), mud-lean packstone to grainstone, very fossiliferous with mostly crinoids and less amounts of brachiopods, peloids, bryozoa. Some burrows are evident. Saddle dolomite occurs in grainstone horizons, large fossil replacement and fractures.

3194.0’ – 3202.0’ Dolomite, Grainstone to Rudstone (Facies 2), interchanging layers of skeletal/peloidal grainstone and bryozoan rudstone. Saddle dolomite occurs in grainstone, small vugs and as large bryozoan replacements.

3202.0’ – 3206.0’ Limestone, Packstone to Grainstone (Facies 3), fossiliferous with crinoids, brachiopods, bryozoa. Stylolites are prevalent with some burrows.

3206.0’ – 3211.7’ Dolomite, Grainstone to Rudstone (Facies 2), interchanging layers of skeletal/peloidal grainstone and bryozoan rudstone. Some burrows present.

3211.7’ – 3213.0’ Limestone, Packstone to Grainstone (Facies 3), fossiliferous with abundant brachiopods, some bryozoa and intraclasts.
3213.0’ - 3224.0’ Dolomite, Grainstone to Rudstone (Facies 2), interchanging layers of mostly skeletal/peloidal grainstone and lesser amounts of bryozoan rudstone. Saddle dolomite occurs in the skeletal grainstone horizons.

3224.0’ – 3229.2’ Limestone, Grainstone to Rudstone (Facies 2), interchanging layers of skeletal/peloidal grainstone and bryozoan rudstone.

3229.2’ – 3230.6’ Dolomite, Grainstone (Facies 4), skeletal grainstone consisting of bryozoans, crinoids, peloids, shell fragments. Vugs are present and filled with saddle dolomite.

3230.6’ – 3232.5’ Limestone, Grainstone to Rudstone (Facies 2), interchanging layers of skeletal/peloidal grainstone and bryozoan rudstone.

3232.5’ – 3240.5’ Limestone, Packstone to Grainstone (Facies 3), fossiliferous with bryozoans, brachiopods, crinoids, peloids. Stylolites are prevalent.

3240.5’ – 3240.9’ Limestone, Grainstone (Facies 4), grainstone with peloids, crinoids, undifferentiated fossils and shell fragments.

3240.9’ – 3242.0’ Limestone, Packstone to Grainstone (Facies 3), mud-rich packstone to grainstone with shell fragments, peloids, crinoids, and bryozoans. Shaley wisps and burrows occur.

3242.0’ – 3242.5’ Limestone, Grainstone (Facies 4), peloidal grainstone with crinoids intermixed.

3242.5’ – 3253.0’ Limestone, Packstone to Grainstone (Facies 3), packstone to grainstone with occasional grainstone horizons. Shell fragments, peloids, bryozoans, crinoids, and undifferentiated fossils are present. Burrows and shaley wisps occur throughout.

3253.0’ – 3254.0’ Limestone, Grainstone (Facies 4), grainstone composed of peloids, shell fragments, crinoids and undifferentiated fossils. Shaley wisps are common.

3254.0’ - 3255.0’ Dolomite, Grainstone (Facies 4), peloidal grainstone with a few bryozoans and shell fragments. Shaley wisps or stylolites occur throughout.

3255.0’ – 3262.0’ Limestone, Packstone (Facies 3), mud-rich packstone, fossiliferous with bryozoans, shell fragments, and crinoids. Burrows are present along with wispy shales or stylolites.
3262.0’ – 3262.3’ Limestone, Grainstone (Facies 4), skeletal grainstone composed of shell fragments, crinoids and undifferentiated fossils.

3262.3’ – 3265.0’ Limestone, Packstone (Facies 3), mud-rich packstone, fossiliferous with shell fragments, peloids, and some bryozoans and crinoids. Burrows are present and shaley wisps are prevalent.

END CORE

Facies 1 Total: 19.7’
Facies 2 Total: 31.8’
Facies 3 Total: 152.9’
Facies 4 Total: 14.9’
Facies 5 Total: 0.0’
Facies 6 Total: 0.0’
Facies 7 Total: 0.0’
Facies 8 Total: 0.8’
Faist 2-12
Permit # 33673, T1S R1W Sec. 12
Jackson County, MI, Henrietta Field
Cored Interval: 4874.0' - 5253.0'

4874.0' – 4875.0': Facies 1 - Burrow-mottled Mudstone to Wackestone
4875.0' – 4875.5': Facies 7 - Intraclastic Floatstone
4875.5’ – 4983.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
4983.0’ – 4990.0’: Facies 7 - Intraclastic Floatstone
4990.0’ – 5002.5’: Facies 1 - Burrow-mottled Mudstone to Wackestone
5002.5’ – 5004.5’: Facies 5 - Peloidal Packstone to Grainstone
5004.5’ – 5042.0’: Facies 7 - Intraclastic Floatstone
5042.0’ – 5044.0’: Facies 1 - Burrow-mottled Mudstone to Wackestone
5044.0’ – 5048.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
5048.0’ – 5048.8’: Facies 4 - Skeletal Grainstone
5048.8’ – 5067.0’: Facies 1 - Burrow-mottled Mudstone to Wackestone
5067.0’ – 5084.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
5084.0’ – 5088.0’: Facies 4 - Skeletal Grainstone
5088.0’ – 5089.0’: Facies 5 - Peloidal Packstone to Grainstone
5089.0’ – 5094.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
5094.0’ – 5095.0’: Facies 4 - Skeletal Grainstone

Core Missing 5095.0’ – 5102.0’
5102.0’ – 5103.5’: Facies 3 - Burrow-mottled Wackestone to Packstone
5103.5’ – 5106.0’: Facies 4 - Skeletal Grainstone
5106.0’ – 5130.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
5130.0’ – 5133.0’: Facies 4 - Skeletal Grainstone
5133.0’ – 5137.0’: Facies 7 - Intraclastic Floatstone
5137.0’ – 5139.0’: Facies 4 - Skeletal Grainstone
5139.0’ – 5149.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
5149.0’ – 5150.0’: Facies 7 - Intraclastic Floatstone
5150.0’ – 5155.0’: Facies 4 - Skeletal Grainstone
5155.0’ – 5162.0’: Facies 3 - Burrow-mottled Wackestone to Packstone
5162.0’ – 5186.0’: Facies 4 - Skeletal Grainstone
5186.0’ – 5193.0’: Facies 7 - Intraclastic Floatstone
5193.0’ – 5200.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

Core Missing 5200.0’ – 5204.0’

5204.0’ – 5205.1’ Limestone, Mudstone to Wackestone (Facies 1), burrow-mottled with a few shell fragments intermixed.

5205.1’ – 5205.5’ Limestone, Grainstone (Facies 4), abundant shell fragments, mainly brachiopods, sparse amounts of crinoids and the remainder consists of undifferentiated fossils.

5205.5’ – 5206.2’ Limestone, Mudstone to Wackestone (Facies 1), heavily burrowed, very few undifferentiated fossils in the matrix, some lithoclasts and peloids.

5206.2’ – 5206.6’ Limestone, Packstone to Grainsone (Facies 3), abundant shells along with undifferentiated fossils, peloids and lithoclasts.

5206.6’ – 5208.2’ Limestone, Mudstone to Wackestone (Facies 1), burrow-mottled with few shell fragments, most likely brachiopods, trace amounts of crinoids, and some undifferentiated fossils.

5208.2’ – 5208.4’ Limestone, Grainstone (Facies 4), skeletal grainstone with undifferentiated fossils and some wispy stylolites.
5208.4’ – 5215.7’ Limestone, Mudstone to Wackestone (Facies 1), contains sparse amounts of brachiopods, trilobites, crinoids and undifferentiated fossils. Sediment is burrow-mottled with thin stylolites throughout.

5215.7’ - 5216.0’ Limestone, Grainstone (Facies 4), skeletal grainstone that consists of brachiopods, shell fragments. There is one large, calcite-filled vug (1-2 cm) that replaced a large shell.

5216.0’ – 5220.3’ Limestone, Mudstone to Wackestone (Facies 1), with some shell fragments, undifferentiated fossils, oncolites, and burrows. *Hardground present at 5219.9’.

5220.3’ – 5221.9’ Limestone, Packstone to Grainstone (Facies 3), abundant brachiopod shells, undifferentiated fossils and rugose corals.

5221.9’ – 5229.2’ Limestone, Mudstone to Wackestone (Facies 1), few shell fragments and burrows. There are small (< 2 cm) stringer horizons of packstone to grainstone consisting of shells and skeletal debris. Throughout this interval are three to five (1 - 4 centimeter) volcanic ash beds interpreted to be episodes of the Millbrig K-bentonite. The ash is gray-black and fissile.

5229.2’ – 5229.5’ Limestone, Packstone to Grainstone (Facies 3), with shell fragments, most likely brachiopods, possible ostracods and several other undifferentiated fossils.

5229.5’ – 5230.4’ Limestone, Mudstone to Wackestone (Facies 1), few recognizable fossil fragments. Two layers of volcanic ash occur, 2-4 centimeters thick each, gray-black and fissile.

5230.4’ – 5230.7’ Limestone, Packstone to Grainstone (Facies 3), predominantly containing shell fragments and undifferentiated fossils.

5230.7’ – 5231.2’ Volcanic Ash, (Facies 8), light gray with some orange-yellow in color, fissile.

5231.2’ – 5235.0’ Limestone, Packstone to Grainstone (Facies 3), brachiopods fragments, undifferentiated fossils, peloids and abundant burrows. There are also large amounts of silica-chopt.

5235.0’ – 5236.0’ Limestone, Grainstone (Facies 4), skeletal grainstone consisting predominantly of brachiopod shells.

5236.0’ – 5242.0’ Limestone, Mudstone to Wackestone (Facies 1), bioturbated with many chert nodules, some sized at 4-7 centimeters in diameter.
5242.0’ – 5243.0’ Limestone, Wackestone to Packstone (Facies 3), with coarser packstone to grainstone horizons, possibly burrow-fills. Sediment is burrow-mottled.

5243.0’ – 5243.2’ Volcanic Ash, Shale Facies, carbonaceous, gray-black in color, fissile.

5243.2’ – 5243.5’ Limestone, Packstone (Facies 5), heavily bioturbated with skeletal debris including crinoids and peloids.

5243.5’ – 5244.5’ Limestone/Dolomite, Peloidal Packstone to Grainstone (Facies 5) with coarse-grained burrow fills. The limestone appears to be recrystallized. Sediment is burrow-mottled and contains brachiopods, peloids and crinoids.

5244.5’ – 5247.7’ Dolomite, Peloidal Packstone to Grainstone (Facies 5), burrow-mottled with coarse-grained burrow fills. Contains brachiopod shell fragments, peloids and crinoids. A 2-4 centimeter diameter chert nodule is present.

5247.7’ – 5248.5’ Limestone/Dolomite, Packstone to Grainstone (Facies 3), burrow-mottled containing crinoids, peloids and bryozoans.

5248.5’ – 5250.4’ Limestone, Wackestone to Packstone (Facies 5), mud-rich wackestone to packstone that has been bioturbated, almost homogenized with coarse grains among the burrowed areas. Stylolites are prevalent and chert nodules (1-3 cm diameter) are present.

5250.4’ – 5250.9’ Limestone, Grainstone (Facies 4), crinoidal grainstone with some shell fragments and peloids.

5250.9’ – 5253.0’ Dolomite, Wackestone to Packstone, Packstone to Grainstone Facies (Facies 5), burrow-mottled with coarse-grained burrow fills. Peloids, crinoids and brachiopods are present along with a 3.5 centimeter diameter chert nodule.

5253.0’ – 5254.0’ Limestone, Mudstone to Wackestone (Facies 1), few recognizable fossils with a small chert nodule, non-dolomitized fracturing and fracture-breccia.

END CORE

Facies 1: 63.9’
Facies 2: 0.0’
Facies 3: 81.2’
Facies 4: 44.7’
Facies 5: 11.5’
Facies 6: 0.0’
Facies 7: 57.0’
Facies 8: 0.7’
Arco-Conklin 1-31
Permit # 37385, T4S R2W Sec. 31
Jackson County, MI, Stoney Point Field
Cored Interval: 3705.0’ - 3899.5’

3705.0’ – 3714.9’: Facies 3 - Burrow-mottled Wackestone to Packstone

3710.9’ - 3711.1’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3714.9’ – 3721.5’: Facies 1 - Burrow-mottled Mudstone to Wackestone

3721.5’ – 3785.9’: Facies 3 - Burrow-mottled Wackestone to Packstone

3763.0’ – 3764.0’: Interbedded Facies 1 - Burrow-mottled Mudstone to Wackestone

3730.0’ – 3730.4’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3728.0’ – 3728.6’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3785.9’ – 3805.5’: Facies 1 - Burrow-mottled Mudstone to Wackestone

3805.5’ – 3823.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

3822.5’ – 3822.7’: Interbedded Facies 4 - Skeletal Grainstone

3821.0’ – 3821.2’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3817.9’ - 3818.2’: Interbedded Facies 4 - Skeletal Grainstone

3816.8’ - 3817.2’: Interbedded Facies 4 - Skeletal Grainstone

3814.0’ – 3814.2’: Interbedded Facies 4 - Skeletal Grainstone

3806.8’ - 3807.2’: Interbedded Facies 4 - Skeletal Grainstone
3806.0’ – 3806.4’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3823.0’ – 3823.5’: Facies 4 - Skeletal Grainstone

3823.5’ – 3851.3’: Facies 3 - Burrow-mottled Wackestone to Packstone

3849.7’ – 3849.8’: Interbedded Facies 4 - Skeletal Grainstone

3846.6’ – 3846.8’: Interbedded Facies 4 - Skeletal Grainstone

3843.2’ – 3842.8’: Interbedded Facies 4 - Skeletal Grainstone

3842.2’ – 3841.8’: Interbedded Facies 4 - Skeletal Grainstone

3826.6’ – 3826.8’: Interbedded Facies 4 - Skeletal Grainstone

3829.6’ – 3829.8’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3825.5’ – 3825.9’: Interbedded Facies 5 - Peloidal Packstone to Grainstone

3851.3’ – 3851.5’: Facies 8 - Volcanic Ash/Marine Shale

3851.5’ – 3853.1’: Facies 4 - Skeletal Grainstone

3853.1’ – 3856.0’: Facies 3 - Burrow-mottled Wackestone to Packstone

3856.0’ – 3857.0’: Facies 4 - Skeletal Grainstone

3857.0’ – 3861.4’: Facies 3 - Burrow-mottled Wackestone to Packstone

3861.4’ – 3862.1’: Facies 4 - Skeletal Grainstone

3862.1’ – 3873.5’: Facies 3 - Burrow-mottled Wackestone to Packstone
3864.8' – 3865.1': Interbedded Facies 4 - Skeletal Grainstone

3863.9' – 3864.1': Interbedded Facies 4 - Skeletal Grainstone

3873.5' – 3879.8': Facies 4 - Skeletal Grainstone

3879.8' – 3884.0': Facies 3 - Burrow-mottled Wackestone to Packstone

3884.0' – 3884.5': Facies 4 - Skeletal Grainstone

3884.5' – 3885.0': Facies 3 - Burrow-mottled Wackestone to Packstone

3885.0' – 3887.0': Facies 4 - Skeletal Grainstone

3887.0' – 3891.9': Facies 3 - Burrow-mottled Wackestone to Packstone

3889.0' – 3889.3': Interbedded Facies 4 - Skeletal Grainstone

3891.9' – 3892.0': Facies 5 - Peloidal Packstone to Grainstone

3892.0' – 3893.0': Facies 3 - Burrow-mottled Wackestone to Packstone

3893.0' – 3893.2': Facies 4 - Skeletal Grainstone

3893.2' – 3894.0': Facies 3 - Burrow-mottled Wackestone to Packstone

3894.0' – 3894.5': Facies 5 - Peloidal Packstone to Grainstone

3894.5' – 3899.3': Facies 3 - Burrow-mottled Wackestone to Packstone

3894.5' – 3894.7': Interbedded Facies 4 - Skeletal Grainstone

3895.0' – 3895.1': Interbedded Facies 4 - Skeletal Grainstone

3898.7' – 3898.8': Interbedded Facies 4 - Skeletal Grainstone

3899.3' – 3899.5': Facies 4 - Skeletal Grainstone
END CORE

Facies 1 Total: 27.2’
Facies 2 Total: 0.0’
Facies 3 Total: 147.5’
Facies 4 Total: 16.8’
Facies 5 Total: 2.5’
Facies 6 Total: 0.0’
Facies 7 Total: 0.0’
Facies 8 Total: 0.0’
Appendix B

Thin Section Photomicrographs and Facies Descriptions
The following photomicrographs and descriptions are ordered by well name and depth. Scales are included in the lower right corner of each photograph.

Abbreviations of Wells

**H2**: Hergert 2  
**M6**: Mann 6  
**TL 2-12**: Total Luck 2-12  
**W2**: Whitaker 2  
**F2-12**: Faist 2-12  
**AC1-31**: Arco Conklin 1-31

Abbreviations for fossils, pore types, textures, sedimentary structures

Cr = Crinoid, Bra = Brachiopod, Bry = Bryozoan, Msk = Mollusk, Os = Ostracod, In = Intraclast, Tr = Trilobite, Ga = Gastropod, Pld = Peloid, Rc = Rip-up Clast, Brw = Burrow, Sty = Stylolite, Lmt = Lamination, Mo = Mold, Vu = Vug, Ix = Intercrystalline Porosity, Fr = Fracture, Fe = Fenestral Pore, Intra = Intraparticle Porosity, Ca Cmt = Calcite Cement, Dol = Dolomite, LS = Limestone
H2 – 3879.0’: Limestone, burrow-mottled wackestone to packstone (Facies 3), grains include brachiopods, crinoids, peloids, intraclasts; burrows with coarser grains within, small euhedral dolomite rhombs randomly scattered throughout ~10% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0.05%.

H2 – 3907.0’: Limestone, peloidal packstone (Facies 5), peloid dominated with fewer ostracods, bryozoans; subvertical, low amplitude stylolites, burrows typically dolomitized with closely-packed peloids and various grains intermixed ~15% dolomite, rhombs are small-medium subhedral within burrows and medium euhedral rhombs radiating away from the burrows. Visible porosity for 12.5X magnification is ~0% and 35X is ~0.1%.
H2 – 3922.0’: Limestone, mud-lean packstone (Facies 3), grains include various shell fragments, bryozoans, brachiopods, crinoids, ostracods, peloids, and intraclasts; wispy stylolites occur with fine dolomite crystals following suit, small dolomite rhombs are also randomly scattered throughout facies, ~3% dolomite. Visible porosity for 12.5X magnification is ~0.2% and 35X is ~0.2%.

H2 – 3924.0’: Limestone, peloidal packstone to grainstone with sparse micritized crinoids and brachiopods (Facies 5), scattered pinpoint dolomite rhombs occur randomly through the matrix ~10% dolomite, microfracture porosity. Visible porosity for 12.5X magnification is ~0.5% and 35X is ~0.5%.
H2 – 3927.45’: Limestone, peloidal packstone to grainstone (Facies 5), peloids bound by an early form of calcite cement, less than 10% fossils which include ostracods, brachiopods, gastropods, possible burrows, few scattered dolomite rhombs – euhedral, small, ~5% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

H2 – 3935.05’: Limestone, mud-lean packstone to grainstone (Facies 3), grains include assorted shell fragments (brachiopods, ostracods), peloids, bryozoans, intraclasts, faint stylolites, sparse micro-fine dolomite rhombs scattered throughout ~2% dolomite, moldic porosity visible. Visible porosity for 12.5X magnification is ~1.0% and 35X is ~0.5%.
H2 – 3938.6’: Limestone, peloidal packstone (Facies 5), less than 10% fossils which include ostracods, brachiopods, bryozoans; some burrows evident with sucrosic dolomite within the boundaries, sparse scattered dolomite rhombs outside of burrows ~15% total dolomite, with fracture porosity. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0%.

H2 – 3941.0’: Limestone, burrow-mottled mudstone to wackestone (Facies 1); grains include brachiopods, crinoids, trilobites; burrows containing most coarse grains which are partially dolomitized ~5% dolomite; stylolite swarms occur throughout. Visible porosity for 12.5X magnification is ~0.1% and 35X is ~0%.
H2 – 3943.1’: Limestone, burrow-mottled wackestone to mud-rich packstone (Facies 3), composed of highly micritized grains which include bryozoans, mollusks; few small dolomite rhombs are scattered throughout ~5% dolomite. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0%.

H2 – 3956.9’: Limestone, laminated grainstone (Facies 5), contains peloids, bryozoans, trilobites, crinoids and rip up clasts all of which are cemented by early calcite cement; no porosity visible. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
H2 – 3963.0': Dolomite, skeletal grainstone (Facies 4), unidentifiable fossils, possible crinoids, medium anhedral dolomite mosaic with some intercrystalline porosity. Visible porosity for 12.5X magnification is ~0.5% and 35X is ~2.0%.

H2 – 3986.8': Dolomite, peloidal packstone to grainstone (Facies 5), almost 100% peloidal, no identifiable fossils perhaps due to the dolomitization, possible burrows, vertical fracture with porosity, small to medium anhedral mosaic dolomite throughout. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0.25%.
**H2 – 4015.0’**: Limestone/Dolomite, burrow-mottled wackestone (Facies 1), fossils include crinoids, bryozoans, brachiopods; burrows preferentially dolomitized with fine to small dolomite crystals, medium euhedral dolomite rhombs also are floating in the matrix and tiny subhedral dolomite rhombs occur along stylolites ~30% total dolomite. Visible porosity for 12.5X magnification is ~.01% and 35X is ~.01%.

**H2 - 4040.5’**: Dolomite, mudstone to wackestone (Facies 1), unidentifiable grains (soft pellet matrix?), small-fine anhedral-subhedral sucrosic dolomite rhombs, few small burrows, moldic, vuggy and intercrystalline porosity. Visible porosity for 12.5X magnification is ~10% and 35X is ~12%.
**H2 – 4053.0’**: Dolomite, bryozoan wackestone to packstone (Facies 2), completely recrystallized matrix with small-medium anhedral to subhedral dolomite rhombs and medium-large euhedral rhombs in vugs, elongate moldic porosity where bryozoan skeletons were, also intercrystalline porosity in the matrix. Visible porosity for 12.5X magnification is ~3% and 35X is ~2.5%.

**H2 – 4059.2’**: Dolomite, burrow-mottled mudstone to wackestone (Facies 1), grains include mollusk shells and peloids, wispy stylolites are common throughout, has intercrystalline porosity within medium subhedral dolomite matrix, tiny dolomite rhombs follow stylolites. Visible porosity for 12.5X magnification is ~3% and 35X is ~4%.
M6 – 3945.0’: Dolomite, bryozoan packstone (Facies 2), grainstone matrix with unidentifiable grains in which abundant bryozoan molds occupy, stylolites occur throughout, grainy matrix comprised of medium-large anhedral dolomite rhombs, vugs lined with medium-large euhedral dolomite rhombs, tiny rhombs occur along stylolites. Visible porosity for 12.5X magnification is ~5% and 35X is ~3%.

M6 – 3947.0’: Limestone/Dolomite, skeletal grainstone (Facies 4), grains consist of crinoids, brachiopods, bryozoans, mud clasts all cemented by early calcite or later dolomite; burrows evident, medium to large euhedral dolomite rhombs scattered randomly throughout, ~20% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
M6 – 3956.4’: Limestone, peloidal packstone to grainstone (Facies 5), dominated by small peloid clusters, few mollusk fragments, low amplitude stylolites, scattered euhedral dolomite rhombs floating in matrix, ~5% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

M6 – 3995.8’: Limestone/Dolomite, burrow-mottled packstone (Facies 3), micritized grains present include peloids, intraclasts, brachiopods, ostracods; very stylolitic-anastomosing, stylonodular with tiny dolomite rhombs along the seams, non-dolomitized coarse grained burrow fills. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
**M6 - 4014.0**: Limestone, mudstone (Facies 1), sparse crinoids intermixed, thick (2-4 millimeter) stylolites with tiny euhedral dolomite rhombs following trend, randomly floating medium dolomite rhombs in matrix, clusters of calcite crystals, ~5% dolomite overall, no visible porosity.

**M6 – 4019.0**: Dolomite, fine grained mudstone tidal flat (Facies 6), no visible grains or fossils, small anhedral dolomite rhomb matrix, fenestral and intercrystalline porosity. Visible porosity for 12.5X magnification is ~2% and 35X is ~2%.
M6 – 4036.0': Dolomite, burrow-mottled wackestone (Facies 3), grains include crinoids, brachiopods and other unidentifiable grains; larger subhedral dolomite rhombs occur in burrows while smaller, anhedral dolomite rhombs occur in the matrix, intercrystalline porosity present. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~2%.

M6 – 4047.5': Dolomite, peloidal packstone (Facies 5), peloid dominated with lesser amounts of crinoids and other unidentifiable fossils, possible burrowing; highly stylolitic-anastomosing with tiny dolomite rhombs along the paths, some intruding vertical microfractures, large subhedral dolomite rhombs in skeletal fragments, sparse intercrystalline porosity.
**M6 – 4055.4**: Limestone, burrow-mottled mudstone to wackestone (Facies 1), grains include bryozoans, ostracods, brachiopods; burrows mostly filled with peloids and some brachiopod fragments; small amplitude moderately thick stylolites with tiny dolomite following the seams, larger dolomite rhombs floating in matrix and sometimes clustered on the edges of the burrows, ~3% dolomite total; vertical microfracture porosity present. Visible porosity for 12.5X magnification is ~0.01% and 35X is ~0.01%.

**M6 – 4058.9**: Limestone, burrow-mottled mudstone to wackestone (Facies 1), grains include bryozoans, ostracods, brachiopods and peloids; abundant stylolites, many vertical fractures; burrows contain partially dolomitized coarse fill with small dolomite rhombs, few small-medium dolomite rhombs floating in matrix, ~3% total dolomite, no visible porosity.
M6 – 4064.0’: Dolomite, burrow-mottled packstone (Facies 3), few unidentifiable grains with possible crinoids and peloids, burrows with smaller euhedral to subhedral dolomite rhombs within, traces of intercrystalline porosity. Visible porosity for 12.5X magnification is ~0.01% and 35X is ~0.01%.

M6 – 4081.4’: Dolomite, mudstone tidal flat (Facies 6), no visible fossils, closely packed tiny dolomite rhombs, elongate fenestral pores. Visible porosity for 12.5X magnification is ~0.1% and 35X is ~0.1%.
**TL 2-12 – 4808.9’**: Limestone, wackestone to mud-rich packstone (Facies 3), contains bryozoans, ostracods, intraclasts and tiny shell fragments. Pinpoint dolomite rhombs are scattered through the matrix with 1% dolomite overall. Visible porosity is ~0% for 12.5X and 35X magnifications.

**TL 2-12 – 4856.2’**: Dolomite, packstone (Facies 3), composed mostly of a large pressure solution seam containing intraclasts, crinoids and brachiopods. Remaining volume is dark, presumably organic rich stylolite fill. Visible porosity is ~0% with 12.5X and 35X porosity.
**TL 2-12 – 4861.3’**: Limestone, wackestone to mud-rich packstone (Facies 3), mostly composed of bryozoans with lesser amounts of crinoids, intraclasts, few shell fragments and possible burrows. Less than 2% dolomite present in the form of a few tiny dolomite rhombs. Visible porosity is ~0% in both 12.5X and 35X magnifications.

**TL 2-12 – 4865.0’**: Limestone, wackestone to mud-rich packstone (Facies 3), contains ostracods, bryozoans, intraclasts, tiny shell fragments, brachiopods and some burrows. Few wispy stylolites occur throughout. ~2% dolomite. Visible porosity is ~0% in both 12.5X and 35X magnifications.
**TL 2-12 – 4885.0′**: Limestone, wackestone to mud-rich packstone breccia clasts within similar grained muddy matrix (Facies 7), debris flow facies containing crinoids, bryozoans and ostracods; thin anastomosing stylolites, sparse tiny euhedral dolomite rhombs (5% total dolomite) appearing in non-specified regions that are either randomly dispersed or in small clusters. No visible porosity evident at 12.5X and 30X magnifications.

**TL 2-12 – 4892.8′**: Limestone, wackestone to mud-rich packstone debris flow breccia (Facies 7), fossils include ostracods with lesser amounts of crinoids and bryozoans. Stylolites are stylomottled around grains, dolomite rhombs are small and occur mostly throughout the pressure solution seams and not as much scattered randomly in the matrix or as small clusters. ~5% dolomite. Visible porosity for 12.5X magnification and 35X is ~0%.
**TL 2-12 – 4913.0’**: Limestone, wackestone to packstone (Facies 7), homogenized debris flow facies appearing similar to Facies 3 containing crinoids, ostracods, bryozoans, peloids, gastropods, brachiopods, very thick wispy stylolites that are almost argillaceous in nature but lighter colored; sparse scattered tiny euhedral dolomite rhombs (5% total dolomite) that occur in small clusters near the stylolites. Visible porosity is ~0% using 12.5X and 35X magnifications.

**TL 2-12 – 5030.0’**: Dolomite, wackestone to packstone (Facies 3), abundant peloids, crinoids and unidentifiable fossils due to fabric destructive dolomite. Stylolites appear wispy, horsetail and anastomosing throughout, possible burrows, medium sized anhedral dolomite rhombs. Visible porosity is ~0.5% at both 12.5X and 35X magnifications.
**TL 2-12 – 5044.5’**: Limestone, packstone to grainstone (Facies 3), contains intraclasts, bryozoans, crinoids, gastropods, shell fragments, peloids, vertical fractures, possible burrows. Medium to small dolomite rhombs are scattered randomly throughout matrix with tiny dolomite rhombs occurring within the pressure solution seams. Total dolomite is ~5%. Visible porosity is ~0% in both 12.5X and 35X magnifications.

**TL 2-12 - 5046.1’**: Dolomite, packstone to grainstone (Facies 4), contains mostly crinoids with the remainder unidentified fossil fragments due to fabric destructive mosaic dolomite with medium to large sub-euhedral rhombs. Visible porosity for 12.5X magnification is ~7.5% and 35X is 7%.
**TL 2-12 – 5068.5’:** Limestone, packstone to grainstone (Facies 4), micritized grains of crinoids, intraclasts and shell fragments. Wispy stylolites occur throughout that have tiny dolomite rhombs floating within. ~3% dolomite. Visible porosity for 12.5X and 35X magnifications is ~0%.

**TL 2-12 – 5071.0’:** Limestone, skeletal grainstone (Facies 4), composed of crinoids, unidentifiable fossil fragments and bryozoans. Contains vertical microfractures; dark, thick stylolites with styloreactant including some skeletal debris and tiny dolomite rhombs. ~15% total dolomite. Visible porosity at 12.5X and 35X is ~0%.
TL 2-12 – 5085.4’: Limestone, argillaceous packstone to grainstone (Facies 3), fossils include shell fragments, crinoids and intraclasts. Bioturbation persists throughout. There is ~10% dolomite with ~.05% visible porosity in both 12.5X and 35X magnifications.

TL 2-12 – 5099.0’: Limestone/Dolomite, packstone to grainstone (Facies 4), micritized crinoids, shell fragments and intraclasts with burrows evident. Medium, sub-euhedral dolomite rhombs occur scattered around burrow fills. ~25% total dolomite and 0% visible porosity using 12.5X and 35X magnifications.
**TL 2-12 – 5114.0’:** Limestone/Dolomite, mud-rich packstone (Facies 3), contains shell fragments, brachiopods, ostracods, crinoids, peloids and bryozoans. Dolomite appears bordering and within burrows primarily with small to medium dolomite rhombs scattered throughout the remaining area. Dolomite is ~25% and visible porosity is ~0% using 12.5X and 35X magnifications.

**TL 2-12 – 5131.2’:** Limestone/Dolomite, wackestone to packstone (Facies 3), contains many small shell fragments, ostracods, some crinoids and bioturbation. Medium to medium-small dolomite rhombs occur in burrow fills and along wispy stylolite seams. Total dolomite is ~20% and visible porosity on 12.5X and 35X magnifications is ~.01%.
**W2 – 3044.0’**: Dolomite, packstone to grainstone (Facies 3), grains include crinoids, peloids and unidentifiable fossil fragments. Stylolite swarms are evident and the dolomite rhombs are medium, subhedral in texture and size. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

**W2 – 3048.0’**: Dolomite, packstone (Facies 3), contains crinoids, some mollusk fragments, peloids and a calcite-filled burrow. Stylolites are abundant in swarms. Total Dolomite is 90% and made up of medium subhedral dolomite rhombs. Visible porosity for 12.5X magnification is ~0.5% and 35X is ~1%.
W2 – 3058.1': Dolomite, packstone (Facies 3), grains include crinoids, intraclasts and unidentifiable fossils. Stylolite swarms are prevalent in which fine to small dolomite rhombs cluster around; dolomite in surrounding matrix is seen as medium, subhedral rhombs. Visible porosity for 12.5X magnification is ~0.10% and 35X is ~0.25%.

W2 – 3064.0': Dolomite, mudstone to wackestone (Facies 1), very muddy sediment with unrecognizable features due to fabric destructive dolomite, burrows with larger dolomite rhombs than seen in the matrix are evident, and there are abundant wispy stylolite swarms. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
**W2 – 3070.0’**: Dolomite, wackestone to packstone (Facies 3), contains crinoids, peloids with near homogenization due to burrows. Thin stylolite swarms occur throughout. Medium subhedral dolomite rhombs occur in the majority with larger euhedral rhombs in some skeletal fragments. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

**W2 – 3083.0’**: Dolomite, wackestone to packstone (Facies 3), contains crinoids, peloids and very wispy horsetail-sometimes nodular stylolites that are sometimes thick and light colored. Tiny dolomite rhombs occur along stylolites, medium eu-subhedral rhombs occur in the majority of areas and large euhedral rhombs occur as skeletal replacements. There is no visible porosity using 12.5X and 35X magnifications.
W2 – 3095.2': Dolomite, packstone to grainstone (Facies 3), grains include crinoids and unidentifiable fossil fragments. Burrows are present. Stylolites are anastomosing with small dolomite rhombs within. Dolomite rhombs in matrix are medium sized, euhedral to subhedral with high intercrystalline porosity. Visible porosity for 12.5X magnification is ~10% and 35X is ~10%.

W2 – 3117.9': Limestone, packstone to grainstone (Facies 3), contains unsorted skeletal debris, shell and mollusk fragments, brachiopods, intraclasts and abundant stylolites. Burrows are also present. Medium to small dolomite rhombs occur throughout the matrix. ~10% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
**W2 – 3140.0’**: Dolomite, layered crinoidal wackestone and grainstone (Facies 1), muddy matrix with crinoid fragments dispersed throughout. Fine, subhedral dolomite rhombs occur in the muddy layers and small to medium subhedral rhombs occur in the grainstone layers. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~2.5%.

**W2 – 3143.0’**: Dolomite, grainstone (Facies 4), contains crinoids, unidentifiable fossils and some stylolites. Destructive dolomite masks any other features. Intercrystalline porosity is evident. Visible porosity for 12.5X magnification is ~2% and 35X is ~4%.
**W2 – 3174.0’**: Dolomite, packstone (Facies 3), contains abundant peloids with lesser amounts of crinoids, shell fragments. Sediment is bioturbated. There is a vug lined with saddle dolomite and has a calcite core. Matrix has medium to small anhedral dolomite rhombs with euhedral to subhedral rhombs in replacement skeletal dolomite and in the saddle dolomite region. Visible porosity for 12.5X magnification is ~1.5% and 35X is ~2%.

**W2 – 3175.6’**: Dolomite, mud-rich bryozoan packstone to grainstone (Facies 2), contains abundant bryozoans and alternating laminations of crinoid beds, very stylolitic. Dolomite rhombs occur as anhedral around larger grains and smaller, euhedral rhombs in the muddy matrix. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0.25%.
W2 – 3178.6’: Limestone, skeletal grainstone (Facies 4), micritized grains encompassed in recrystallized calcite include shell fragments, unidentifiable fossils, intraclasts and peloids. This rock is entirely undolomitized. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

W2 – 3201.0’: Limestone/Dolomite, lower half of slide is limestone with skeletal grainstone (Facies 4) with calcite cement containing crinoids, brachiopods, unidentifiable broken skeletal debris, mud clasts and some peloids; the upper half is dolomitized peloidal packstone (Facies 3) with some crinoids intermixed. Abundant wispy stylolites filled with small dolomite rhombs occur throughout. Some grains in the skeletal packstone (the lower half) are dolomitized, complete dolomitization occurs in the peloidal packstone. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0.25%.
**W2 – 3212.2':** Limestone/Dolomite, packstone (Facies 3), contains bryozoans, intraclasts and low amplitude stylolites. The larger grains remain limestone while the matrix and smaller grains are dolomitized with small to medium rhombs; euhedral to subhedral tiny dolomite rhombs occur along the stylolites. Total dolomite is 50%. There is high intercrystalline and intraparticle porosity. Visible porosity for 12.5X magnification is ~5% and 35X is ~3.5%.

**W2 – 3221.0':** Dolomite, skeletal grainstone (Facies 4), unrecognizable grains due to fabric destructive dolomite, feint stylolites and possible black organics present, high intercrystalline porosity. Visible porosity for 12.5X magnification is ~12% and 35X is ~12%.
W2 – 3223.8': Dolomite, bryozoan grainstone (Facies 2), bryozoans dominate with lesser amounts of crinoids. Stylolaminations are abundant with tiny dolomite rhombs along the seams. Dolomite throughout the rest of the rock is subhedral to anhedral in texture. Porosity is intercrystalline and vuggy. Visible porosity for 12.5X magnification is ~1.5% and 35X is ~1%.

W2 – 3230.0': Dolomite, packstone to grainstone (Facies 3), contains unidentifiable fossils due to fabric destructive dolomite; also contains abundant peloids and burrows with large, euhedral rhombs and intercrystalline porosity. Also seen are irregular stylolites with tiny dolomite rhombs intermixed. Visible porosity for 12.5X magnification is ~4% and 35X is ~4%.
**W2 – 3231.0’**: Limestone, bryozoan grainstone with muddy horizons (Facies 2), includes large bryozoans with lesser amounts of crinoids, shell fragments, intraclasts. Dolomite rhombs are both scarce and scattered randomly throughout totaling ~5%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

**W2 – 3252.9’**: Limestone, grainstone (Facies 4), contains abundant bryozoans with lesser amounts of brachiopods, unidentifiable fossils, ostracods, trilobites and peloids. Dolomite is rare and occurs as small, scattered rhombs. Total dolomite is ~5%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%. 
W2 – 3254.5’: Dolomite, grainstone (Facies 4), contains unidentifiable grains due to fabric destructive dolomite. Dolomite appears as medium to large, subhedral rhombs with some intercrystalline porosity. Visible porosity for 12.5X magnification is ~0.75% and 35X is ~0.75%.

W2 – 3255.5’: Limestone, grainstone (Facies 3), contains little mud with shell fragments, bryozoans, peloids, crinoids and stylolites. Dolomite occurs in 5% of the rock as medium to small rhombs scattered throughout the matrix. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
W2 – 3265.0’: Limestone/Dolomite, skeletal grainstone (Facies 4), mostly limestone with scattered fine, dolomite rhombs. Grains include crinoids, brachiopods, ostracods, bryozoans, peloids and unidentifiable shell fragments. Burrows and anastomosing wispy or ‘smoky’ stylolites are present. Small dolomite rhombs occur throughout stylolites. ~15% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%
F2-12 – 4877.0': Dolomite, mudstone to wackestone (Facies 1), contains crinoids, shell fragments, unidentifiable fossils, wispy stylolites and vertical to subvertical microfractures with some fracture porosity. Dolomite occurs as anhedral, medium to small rhombs. Visible porosity for 12.5X magnification is ~0.01% and 35X is ~0.01%.

F2-12 – 4877.5': Dolomite, mudstone to wackestone (Facies 1), contains muddy matrix with crinoids, burrows and thick single stylolites along with swarms of stylolites. Tiny dolomite rhombs occur near stylolites and anhedral, medium to small dolomite rhombs occur throughout the rest of the matrix. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
F2-12 – 4880.2′: Dolomite, mudstone to wackestone (Facies 1), contains few recognizable fossils, some crinoids and possibly anhydrite. Wispy stylolite swarms are scattered throughout. Dolomite rhombs throughout are small to medium and subhedral textures. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

F2-12 – 4922.0′: Limestone/Dolomite, wackestone to mud-rich packstone (Facies 3), contains ostracods, bryozoans, crinoids, gastropods, burrows and wispy anastomosing stylolites. Medium, euhedral to subhedral dolomite rhombs focus near stylolites, burrow edges and sporadically in the matrix. This sample is 50/50 limestone versus dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
**F2-12 – 4944.0’**: Limestone, wackestone to mud-rich packstone (Facies 3), contains abundant ostracods with lesser amounts of gastropods, bryozoans and some crinoids and brachiopods. Burrows are also prevalent. There are argillaceous seams with tiny dolomite rhombs throughout and no further dolomite evident elsewhere. Total dolomite is ~5%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

**F2-12 – 4977.0’**: Limestone/Dolomite, the upper half of the slide is a calcitic grainstone (Facies 4 and 5) with equal parts peloids, shell fragments, ostracods and some brachiopods. The lower half of the thin section is the same facies as above but more argillaceous with high amplitude thick stylolites and some fractures. The dolomite here has medium to large euhedral to subhedral rhombs. Total dolomite is 50%. Visible porosity for 12.5X magnification is ~0.1% and 35X is ~0.1%.
F2-12 – 5002.0': Limestone, wackestone to mud-rich packstone (Facies 3), contains ostracods, brachiopods, bryozoans, gastropods, few crinoids and wispy argillaceous seams that contain tiny dolomite rhombs. Medium to large, euhedral dolomite rhombs occur dominantly along the edges of the stylolites and also randomly in the rest of the matrix. Total dolomite is ~10%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

F2-12 – 5011.9': Limestone, mud-rich packstone (Facies 3), contains ostracods, shell fragments, gastropods, brachiopods, some crinoids, wispy stylolites and bioturbation. Tiny to small dolomite rhombs are scattered randomly throughout the matrix for a total of 8% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
F2-12 – 5048.8': Limestone, grainstone (Facies 4), contains crinoids, abundant intraclasts and mud clasts, large amplitude stylolites, with few medium to small dolomite rhombs throughout making a total of 5% dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

F2-12 – 5058.0': Dolomite, wackestone (Facies 1), contains muddy matrix filled with crinoids and horizontal and vertical argillaceous seams/stylolites. Small dolomite rhombs occur around the stylolites and larger, anhedral rhombs occur in surrounding matrix. Vertical fractures and dolomite crystals offer porosity. Visible porosity for 12.5X magnification is ~5% and 35X is ~5%.
F2-12 – 5072.0’: Dolomite, wackestone to packstone (Facies 3), contains abundant peloids with some crinoids, oblique shears and fractures as well as some argillaceous material. Also seen is a large vug filled with saddle dolomite. Intercrystalline and fracture porosity is high. Visible porosity for 12.5X magnification is ~5% and 35X is ~5%.

F2-12 – 5085.5’: Dolomite, grainstone (Facies 4), unrecognizable grains due to fabric destructive dolomite, large subhedral to anhedral dolomite rhombs with intercrystalline porosity. Visible porosity for 12.5X magnification is ~3% and 35X is ~2.5%.
F2-12 – 5093.4’: Dolomite, wackestone to packstone (Facies 3), contains crinoids, peloids and oblique shears with argillaceous sediment. Dolomite is anhedral, medium sized rhombs. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0.25%.

F2-12 – 5096.2’: Dolomite, grainstone (Facies 4), unrecognizable grains shrouded by large, subhedral to euhedral dolomite rhombs, high intercrystalline porosity. Visible porosity for 12.5X magnification is ~3% and 35X is ~2.5%.
F2-12 – 5104.0': Dolomite, packstone to grainstone (Facies 3), contains little amounts of mud with peloids, crinoids, unidentifiable fossils and very wispy stylolites that contain small dolomite rhombs. The remaining rock contains medium, subhedral rhombs. Porosity occurs mostly within subvertical microfractures and intercrystalline. Visible porosity for 12.5X magnification is ~0.5% and 35X is ~0.5%.

F2-12 – 5110.0': Dolomite, wackestone (Facies 3), contains crinoids, unidentifiable fossils due to fabric destructive dolomite, stylonodular in some areas and anastomosing stylolites elsewhere, intercrystalline porosity. Dolomite is medium, anhedral in size and texture. Visible porosity for 12.5X magnification is ~1.5% and 35X is ~0.5%.
F2-12 – 5122.0’: Dolomite, wackestone to packstone (Facies 3), contains crinoids, peloids, small and narrow burrows, and argillaceous seams that orient vertical and horizontally. Dolomite rhombs are tiny near the argillaceous seams and medium to large, subhedral in the matrix. The rhombs are large, euhedral textured as vug-filling saddle dolomite. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~2.5%.

F2-12 – 5131.0’: Dolomite, grainstone (Facies 4), large, euhedral dolomite rhombs with unidentifiable fossils and high intercrystalline porosity. Visible porosity for 12.5X magnification is ~6.5% and 35X is ~7%.
F2-12 – 5144.0’: Limestone, packstone to grainstone (Facies 3), contains little mud with micritized peloids, crinoids, brachiopods, ostracods, bryozoans and gastropods. All grains are cemented by calcite with 10% dolomite. Small, subhedral rhombs follow along stylomottled stylolites. Euhedral rhombs also occur sporadically in surrounding grains and possible burrow fills. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

F2-12 – 5172.0’: Dolomite, packstone to grainstone (Facies 4), contains scarce amounts of mud with crinoids, unidentifiable fossils and intraclasts. Some wispy stylolites penetrate euhedral to subhedral dolomite rhombs. Some large clasts are replaced by large dolomite rhombs and vertical fractures are filled with saddle dolomite which in turn presents intercrystalline porosity. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~2.5%.
F2-12 – 5193.0’: Limestone, brecciated packstone (Facies 7), subvertical orientation of stylolite swarms and rip up clasts. Matrix is composed of mud, tiny shells, intraclasts, bryozoans and crinoids. The rip-up breccia clasts contain brachiopods, crinoids, ostracods and small shells. Contains ~2% total dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

F2-12 – 5198.0’: Limestone, packstone to grainstone (Facies 3), contains tiny shell fragments, brachiopods, peloids, ostracods, crinoids, wispy and argillaceous stylolites in a roughly laminated fashion; bioturbation and rare, randomly-placed small dolomite rhombs accounting for ~1% total dolomite. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
F2-12 – 5232.0': Limestone/Dolomite, grainstone grading up into mud-rich peloidal packstone (Facies 4 and 5), contains abundant peloids with lesser amounts of crinoids, shell fragments, bryozoans and horizontal stylolites. Within the wavy stylolites are euhedral, medium dolomite rhombs. Rhombs also cluster in muddier portions of the rock. The grainstone is tightly cemented with calcite. Limestone versus dolomite is 50/50. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

F2-12 – 5253.0': Limestone/Dolomite, peloidal packstone (Facies 5), dominantly peloidal with few crinoids, burrows and wispy stylolites. The burrows are filled with medium to small dolomite rhombs. Overall dolomite texture is euhedral to subhedral with a total of 5%. Visible porosity for 12.5X magnification is ~0.01% and 35X is ~0.01%.
**AC1-31 – 3706.0**: Dolomite, wackestone to packstone (Facies 3), contains crinoids, shell fragments and unidentifiable fossils due to fabric destructive dolomite. There is a large, oblique fracture filled with calcite. Mosaic dolomite dominates with anhedral rhombs. Total dolomite is 97%. Visible porosity for 12.5X magnification is ~0.01% and 35X is ~0.01%.

**AC1-31 – 3718.8**: Dolomite, mudstone to wackestone (Facies 1), completely dolomitized mudstone with rare crinoids and many burrows. Tiny to small dolomite rhombs occur in matrix and larger, subhedral rhombs occur in the burrow-fill. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
AC1-31 – 3732.0': Dolomite, wackestone to mud-rich packstone (Facies 3), completely dolomitized with crinoids, shell fragments and burrows with various changes in dolomite rhombs. It is larger and coarser in the burrow, tiny on the edges of the burrows and medium sized with euhedral to subhedral rhombs in the surrounding matrix. Some stringy stylolites are visible. Visible porosity for 12.5X magnification is ~1.5% and 35X is ~1.5%.

AC1-31 – 3747.9': Dolomite, grain-rich wackestone (Facies 3), completely dolomitized with crinoids, brachiopods and burrows. Burrows have coarser dolomite fill than the matrix which has tiny to medium-small rhombs. Wispy stylolites are prevalent and there is moldic porosity. Visible porosity for 12.5X magnification is ~0.25% and 35X is ~0.5%.
AC1-31 – 3765.0’: Dolomite, wackestone (Facies 3), completely dolomitized with crinoids, burrows and some wispy stylolites. Dolomite is tight outside of burrows and euhedral to subhedral rhombs with intercrystalline porosity within the burrows. There are two completely cemented vertical microfractures. Dead oil is visible as dark material between crystals. Visible porosity for 12.5X magnification is ~3% and 35X is ~3.5%.

AC1-31 – 3769.1’: Dolomite, wackestone (Facies 3), completely dolomitized with crinoids and unidentifiable fossils. Small to tiny subhedral dolomite rhombs occur throughout with few moldic and intercrystalline porosity. Visible porosity for 12.5X magnification is ~1% and 35X is ~1%. 
AC1-31 – 3782.1’: Dolomite, wackestone to packstone (Facies 3), completely dolomitized with unrecognizable fossils and bioturbation. Facies is very argillaceous with abundant stylolites with tiny dolomite rhombs following trend. Larger dolomite rhombs occur in surrounding matrix. It has intercrystalline and vuggy porosity. Visible porosity for 12.5X magnification is ~3.5% and 35X is ~3.5%.

AC1-31 – 3788.0’: Dolomite, mudstone to wackestone (Facies 1), contains unidentifiable fossils, small and cylindric burrows and very argillaceous wispy stylolites and a single thick stylolite. Multiple, vertical microfractures are present. There is intercrystalline and moldic porosity. Visible porosity for 12.5X magnification is ~2% and 35X is ~2.5%.
AC1-31 – 3799.0': Dolomite, mudstone to wackestone (Facies 1), completely dolomitized with shell fragments, crinoids and bioturbation. The dolomite rhombs range from tiny to medium with large rhombs occurring as saddle dolomite around a vug. Faint stylolites are evident. Porosity is intercrystalline and vuggy. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~3%.

AC1-31 – 3809.7': Limestone/Dolomite, mud-rich packstone (Facies 3), contains crinoids, ostracods, shell fragments, bioturbation and a stylolite swarm that surrounds a single thick, medium amplitude stylolite. Dolomite is scattered as medium to small rhombs throughout. Total dolomite is ~10%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
AC1-31 – 3819.0’: Limestone/Dolomite, mudstone to mud-rich packstone (Facies 3), bioturbation leads to grainstone horizons. Fossils include brachiopods, crinoids, gastropods, peloids and also argillaceous thick wisps. Small to tiny dolomite rhombs occur randomly scattered and in small clusters. Total dolomite is 20%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.

AC1-31 – 3821.0’: Limestone/Dolomite, skeletal grainstone (Facies 4), highly micritized calcitic grainstone with unidentifiable fossils. Some medium dolomite rhombs occur in the cementation. Total dolomite is ~25%. Visible porosity for 12.5X magnification is ~0.2% and 35X is ~0.1%. 
AC1-31 – 3824.0': Dolomite, wackestone to packstone (Facies 3), contains crinoids, shell fragments, bioturbation, anastomosing stylolite swarms. Tiny to small subhedral to anhedral dolomite rhombs occur near stylolites and small rhombs occur elsewhere as a mosaic framework. Porosity is intercrystalline and moldic. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~3%.

AC1-31 – 3861.0': Limestone, skeletal grainstone (Facies 4), includes brachiopods, crinoids, ostracods – all cemented by calcite cement. There are small amplitude stylolites with few intrusions of medium to small dolomite rhombs. Dolomite totals ~3%. Visible porosity for 12.5X magnification is ~0% and 35X is ~0%.
AC1-31 – 3874.2': Dolomite, grainstone (Facies 3 and 4), completely dolomitized with unidentifiable fossils and very high intercrystalline porosity. Dolomite rhombs are large. Visible porosity for 12.5X magnification is ~20% and 35X is ~20%.

AC1-31 – 3876.1': Limestone/Dolomite, grainstone (Facies 4), largely unidentifiable fossils, crinoids and large crystals of both calcite and dolomite. Dolomite rhombs are euhedral to subhedral. Intercrystalline porosity is present. Total dolomite is ~50%. Visible porosity for 12.5X magnification is ~9% and 35X is ~8%.
AC1-31 – 3876.9’: Limestone/Dolomite, grainstone (Facies 4) largely unidentifiable fossils, crinoids and large crystals of both calcite and dolomite. Stylolites with tiny dolomite rhombs along them are present. There is some intercrystalline porosity. Total dolomite is ~40%. Visible porosity for 12.5X magnification is ~1% and 35X is ~1%.

AC1-31 – 3877.0’: Dolomite, grainstone (Facies 4), completely dolomitized grainstone with unidentifiable fossils, crinoids. Intercrystalline porosity is high and dolomite rhombs are euhedral to subhedral. Visible porosity for 12.5X magnification is ~3% and 35X is ~3%.
AC1-31 – 3877.8’: Dolomite, grainstone (Facies 4), completely dolomitized grainstone with unidentifiable fossils, crinoids. Intercrystalline porosity is high and dolomite rhombs are euhedral to subhedral. Visible porosity for 12.5X magnification is ~2.5% and 35X is ~2.5%.

AC1-31 – 3891.0’: Dolomite, grainstone (Facies 4), completely dolomitized grainstone with unidentifiable fossils, crinoids. Intercrystalline porosity is high and dolomite rhombs are euhedral to subhedral. Visible porosity for 12.5X magnification is ~3% and 35X is ~3.5%. 
AC1-31 – 3896.65': Dolomite, wackestone to packstone (Facies 3), completely dolomitized with unrecognizable fossils, crinoids, stylolite swarms, single high amplitude stylolites and high intercrystalline porosity. Visible porosity for 12.5X magnification is ~2% and 35X is ~2%.

AC1-31 – 3897.0': Dolomite, wackestone (Facies 3), completely dolomitized with crinoids, unidentifiable fossils and abundant planar, low amplitude stylolite swarms and bioturbation. Dolomite rhombs are medium to small and subhedral texture. Intercrystalline porosity is present. Visible porosity for 12.5X magnification is ~1% and 35X is ~1%.
Appendix C

Thin Section Facies Analysis
Visual porosity values and dolomite percentages were estimated using comparison charts from Baccelle & Bosellini (1965) and were documented under 12.5 X and 35 X magnifications for consistency and comparison.

WCA = Whole Core Analysis, LS = Limestone, DOL = Dolomite, IX = Intercrystalline, FR = Fracture, VU = Vug, MO = Moldic, FE = Fenestral, NA = Not Available.
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<th>Depth</th>
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<th>Lithology</th>
<th>% Dolomite</th>
<th>Visible Porosity 12.5X</th>
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Appendix D

Marine Shale and K-Bentonites: Core Photographs
MANN 6

M6: 3974.0’

M6: 3975.0’
FAIST 2-12
Appendix E

X-Ray Diffraction
The data table and scatter plots in this section reflect data collected from 11 thin shale and K-bentonite samples found in six cored wells. X-ray diffraction separated the mineralogy of each sample by weight percentage as seen in the table below. The cross plots, made in Microsoft Excel, compare the separated minerologies of the shale baffles, known samples of marine shale and known samples of volcanic ash or K-bentonites. The colored wells from the table match the colored wells in the scatter plots. The Arco-Conklin 1-31 well at 3851.5’ was run under a different XRD test, thus explaining the different separations of minerologies from the rest of the samples.
# X-Ray Diffraction

(Weight %)

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<th>Fe-Dol</th>
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Appendix F

Stylolite Photomicrographs and Descriptions
The following photomicrographs and descriptions are ordered by well name and depth. Scales are included in the lower right corner of each photograph. Not every description has an accompanying photograph.

**Abbreviations of Wells**

**H2**: Hergert 2  
**M6**: Mann 6  
**TL 2-12**: Total Luck 2-12  
**W2**: Whitaker 2  
**F2-12**: Faist 2-12  
**AC1-31**: Arco Conklin 1-31
**H2 – 3907.0′**: Stylolites occur as a small amplitude, single stylolite with some minor swarms surrounding. Tiny dolomite rhombs occur along the seam and medium dolomite rhombs occur above and below the seam as scattered and somewhat clustered in areas. Facies consistent throughout. Could potentially serve as conduits, not as baffles.

**H2 – 3922.0′**: Single, low amplitude stylolite with tiny dolomite rhombs in and encompassing its boundary; stylolite swarms with some components of being stylonodular sweep across sample with tiny dolomite rhombs following suit, some areas contain stylocumulate/reactate. Facies consistent throughout. Dolomite is scarce outside of stylolite clusters. Stylolites may be conduits but not baffles.

**H2 – 4015.0′**: Thick, sweeping stylolite swarms with stylocumulate/reactate fills of tiny dolomite rhombs. The tiny rhombs preferentially continued along the stylolite and few other places. Facies remain consistent throughout. Stylolites may be conduits but not baffles.

**H2 – 4028.2′**: Stylonodular, non-parallel stylolites with stylocumulate/reactate filled with tiny grains and dolomite rhombs. Stylolites could possibly be conduits but it is hard to confirm with 100% throughout sample; stylolites not baffles.

**H2 – 4059.0′**: Stylolites occur as irregular, anastomosing swarms with patches of stylocumulates/reactates. Facies is consistent throughout sample. Small dolomite rhombs occur near stylolites and medium rhombs occur elsewhere. Cannot conclude stylolites as conduits due to complete dolomitization; stylolites not seen as baffles.
M6 – 3945.0’: Feint, anastomosing stylolite swarms appearing as horsetails within 100% dolomite. Facies remain consistent throughout. Dolomite rhombs are small to tiny, euhedral to subhedral texture around but not within the tight, black stylolites. Matrix is tight, mosaic dolomite. No evidence of baffles; stylolites could be possible conduits.

M6 – 3983.6’: Wispy, horsetail stylolite with no dolomite present anywhere. Facies remain consistent throughout. There are no instances of a baffle or conduit.
**M6 – 3990.5′**: Single, small amplitude stylolite ~.5 mm thick with tiny euhedral to subhedral dolomite rhombs occurring exclusively surrounding but not within the stylolite pathway. Small dolomite rhombs also occur in muddy peloidal facies under the stylolite and less so in the cemented grainstone above the stylolite. Stylolite does not appear to act as a conduit or a baffle.

**M6 – 3995.8′**: Wispy, semi-stylonodular and stylomottled stylolites occur with horsetail swarms. Small to tiny dolomite rhombs occur in the stylomottling seams and stylocumulate/reactate regions and within burrow fills. Dolomite does not occur when the stylolites intrude muddy matrix but do occur when they are close to burrows. Baffling is not evident but the stylolites could have acted as conduits.

**M6 – 4014.0′**: Thick, stylocumulate/reactate stylolites filled with tiny grains and dolomite rhombs. Dolomite does not infect surrounding limestone matrix other than a few dispersed, tiny rhombs in the muddy regions and within some burrows. Separate, single small amplitude stylolites also occur throughout. Stylolites could potentially be conduits but not baffles.

**M6 – 4058.9′**: Thick, stylocumulate/reactate stylolites filled with tiny grains and dolomite rhombs. Dolomite does not infect surrounding limestone matrix other than a few dispersed, tiny rhombs in the muddy regions and within some burrows. Separate, single small amplitude stylolites also occur throughout. Stylolites could potentially be conduits but not baffles.
**TL2-12 - 4856.2′**: High density of stylolite swarms, some of which are thick with grains inside of them and some are thin with tiny dolomite rhombs intermixed in a smaller grain matrix. It cannot be determined if stylolites are conduits with the amount of total dolomite; no baffles are evident.

**TL2-12 - 4892.8′**: Stylomottled stylolites around medium sized grains. Styllocumulate/reactate between grains contains tiny dolomite rhombs and the matrix has a few scattered tiny to small dolomite rhombs. The Facies are consistent throughout. Stylolites could have acted as conduits but not baffles.

**TL2-12 – 5068.5′**: Medium amplitude, loose stylolite swarms with rare dolomite rhombs scattered throughout entire sample. Facies are consistent throughout. There appears to be no connection between the stylolites and dolomite; no conduits and no baffles.

**TL2-12 – 5085.4′**: Irregular, anastomosing stylolite swarms, almost argillaceous and close to stylomottled. Styllocumulate/reactate with small grains and small to tiny dolomite rhombs occur speckled within. Facies remains consistent throughout. Stylolites could possibly be conduits but not baffles.

**W2 – 3048.0′**: Multiple irregular, anastomosing stylolite swarms that creates an almost argillaceous sediment. It is inconclusive whether stylolites affect surrounding sediment due to complete dolomitization.

**W2 – 3070.0′**: Wispy, anastomosing stylolites with tiny dolomite rhombs surrounding the seam. Small to medium dolomite rhombs occur away from the stylolite in the surrounding matrix. Facies are consistent throughout. Cannot determine stylolites as a conduit due to complete dolomitization; stylolite not a baffle.

**W2 – 3117.9′**: Multiple thin, single, black, small amplitude stylolites. Dolomite rhombs are scattered randomly throughout the consistent facies and the stylolites appear to have had no influence on the spread or baffling of dolomite.
**W2 – 3121.6‘:** Stylolite swarms with stylolcumulates/reactate bordering grains and burrows. Dolomite does not specifically occur in the stylolites but scattered between the large grains in the matrix. Facies remain consistent throughout. The stylolites exhibit no traits of a conduit or baffle.

**W2 – 3150.0‘:** Multiple single, low amplitude stylolites with some small and thin stylolite swarms breaking away from the single stylolites. Dolomite rhombs are scattered randomly with no visible connection to the stylolites. Baffling and conduits are not evident.

**F2-12 – 4922.0‘:** Very thin, feint stylolite swarms with dolomite rhombs scattered throughout entire sample. No specific trends between the dolomite and stylolites are evident. Facies stay relatively consistent throughout.
**F2-12 – 4944.0’**: Stylomottled with tiny (10-20 microns) dolomite rhombs within the seams and few rhombs occurring throughout the rest of the facies. Thick and dark stylcumulates/reactate is filled with dolomite rhombs as well. Facies remain consistent throughout. The stylolites may act as a conduit but not a baffle.

**F2-12 – 5232.0’**: Dolomite rhombs preferentially scatter along thick, condensed stylolite swarms. Dolomite occurs less frequently dispersing away from the swarms and into surrounding burrows. Facies remain consistent throughout. The seam could be acting as conduits but not baffles.
AC1-31 – 3782.1’: Wispy stylolites penetrate loosely held smaller, mosaic dolomite rhombs in a completely dolomitized sample. The dolomite rhombs tighten up away from the thin, black seams. It is not conclusive whether the stylolites acted as conduits due to the complete dolomitization. They did not act as baffles.

AC1-31 – 3788.0’: First type of stylolite is a single, medium amplitude, thick stylolite and the second type includes wispy, anastomosing stylolite swarms. Tiny dolomite rhombs encompass the region surrounding the stylolites and small to medium rhombs occur away from the seams. There is no major change of facies throughout the sample. No baffle is seen and a conclusive conduit is not determined due to complete dolomitization.

AC1-31 – 3809.7’: Single, small amplitude, thick black stylolite with smaller anastomosing swarms branching off the main seam. Dolomite rhombs occur sparsely surrounding the stylolites but do not appear to have any connection between the two. Facies are consistent throughout. No baffle or conduit is interpreted.

AC1-31 – 3831.6’: Wispy stylolite swarms with small dolomite rhombs following trend and larger rhombs occurring in surrounding matrix. Facies remain consistent throughout. No baffles occur and it is inconclusive if the stylolites act as conduits due to complete dolomitization of the sample.

AC1-31 – 3860.3’: Many anastomosing stylolites with features being stylo nodular and almost argillaceous around nodules and burrows. Smaller, broken up dolomite rhombs occur along the stylolite seams with the surrounding matrix appearing more mosaic in dolomite texture. Facies remain consistent throughout. Baffles are not seen and conduits are inconclusive due to complete dolomitization of the sample.
Appendix G

Cross Sections
The following images are modified cross sections that were originally created using the Petra software. Each cross section was generated using gamma ray and neutron/neutron porosity, density, photoelectric factor and acoustic image wireline logs to show the lateral spread of hydrothermal dolomite across the narrow fault zones of the various Trenton-Black River fields in the study region. The dolomite was picked using nearby core data in conjunction with lower neutron counts/second or higher porosity percentage on the neutron/neutron porosity, variable density values around 2.85 g/cm³, photoelectric factor values between 3-3.5 barns/electron, and dark colorations on acoustic image wireline logs which indicates a higher relative porosity in the subsurface. Cross sections were taken from Albion-Scipio, Rice Creek, Napoleon and Henrietta fields to compare the two-dimensional architecture of the reservoirs and the pooling effects of dolomite below thin shales.

The wells with significant intervals of dolomite are interpreted to be wells that were drilled in close proximity to the faults. The focus of this study was aimed at the surrounding wells in which the dolomite intervals spread laterally away from the main faults in a stratified manner. The gamma ray wireline logs served the purpose of displaying any connection with thin shale or K-bentonite beds with the dolomite intervals.