2013

Sequence Stratigraphy and Petrophysics of the late Ordovician Utica-Point Pleasant Interval in the Middle Appalachian Basin, Eastern Ohio and Western Pennsylvania

Taylor McClain
West Virginia University

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

McClain, Taylor, "Sequence Stratigraphy and Petrophysics of the late Ordovician Utica-Point Pleasant Interval in the Middle Appalachian Basin, Eastern Ohio and Western Pennsylvania" (2013). *Graduate Theses, Dissertations, and Problem Reports*. 328.

<https://researchrepository.wvu.edu/etd/328>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

Sequence Stratigraphy and Petrophysics of the late Ordovician Utica-Point Pleasant Interval in the Middle Appalachian Basin, Eastern Ohio and Western Pennsylvania

Taylor McClain

Thesis submitted to the
College of Arts and Sciences
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Geology

Dr. Timothy Carr, Ph.D., Chair
Dr. Jaime Toro, Ph.D.
Dr. Shikha Sharma, Ph.D.
William Zagorski

Department of Geology and Geography

Morgantown, West Virginia
2013

Keywords: Utica Shale; Point Pleasant; Sequence Stratigraphy; Petrophysics; Appalachian Basin; Late Ordovician

ABSTRACT

Sequence Stratigraphy and Petrophysics of the late Ordovician Utica-Point Pleasant Interval in the Central Appalachian Basin, Eastern Ohio and Western Pennsylvania

Taylor McClain

Approximately 400 well logs and two drill cores from eastern Ohio, western Pennsylvania, and northern West Virginia are used to construct a depositional model of the Utica Shale and associated Upper Ordovician strata. Previous studies of outcrop data from the Cincinnati arch and Jessamine dome recognized a number of Late Mohawkian to Early Cincinnati third-order sequences deposited in an active foreland basin during onset of the Taconic orogeny. Sequences consist of deepening upward successions of transgressive limestone and shale, recording a period of sustained subsidence and rising sea-level along the eastern margin of North America. The transition from a carbonate-dominated system to a clastic-dominated system reflects the drowning of a widespread carbonate platform. The units of the Trenton Group and Lexington Limestone through Utica Shale comprise the transgressive systems tract (TST) of a large second-order sequence, composed of three, smaller scale third-order composite sequences. Third order sequences are regionally correlative, aggradational, and lack low-stand deposits. Sequences are separated by type 3 sequence boundaries that amalgamate with transgressive surfaces and separate the underlying highstand system tract (HST) from the overlying transgressive systems tract (TST). Chronostratigraphic surfaces demonstrate that basinal interbedded lime mudstone, shale, and marl facies of the Logana Shale and Point Pleasant Formations are contemporaneous and genetically related to platform limestone on the flanking Trenton and Lexington platforms. Average gamma-ray value contour maps of systems tracts and composite sequences indicate significant accumulation of carbonate sediment and build-up of the platforms during the Late Mohawkian, followed by increased clastic sedimentation and basin fill in the cross-strike Sebree trough and Point Pleasant sub-basin during the early Cincinnati. Intervals with potentially high total organic carbon (TOC) content were identified using the Passey ΔLogR method and a regression fit between bulk density and TOC, and compared to publicly available source rock data. The Logana through Point Pleasant intervals contain the highest amount of TOC in the area of the Point Pleasant sub-basin in eastern Ohio, with the Utica Shale containing marginal amounts of TOC in the Sebree trough and along the Trenton platform in northwestern Pennsylvania. Rock-eval geochemical data were used to map source potential and thermal maturity. The data shows southwest-northeast trending zones of maximum oil generation, a narrow liquids window, and a wide dry gas window. Maturity maps combined with porosity maps indicate a southwest-northeast trending prospective play fairway of the highest porosity and ideal thermally mature Point Pleasant reservoir, confined to eastern Ohio.

Table of Contents

ACKNOWLEDGEMENTS	v
LIST OF FIGURES.....	vi
Introduction	1
Study Area.....	4
Geologic Background	5
Tectonic, Climatic and Paleogeographic Background.....	5
Stratigraphy of the Study Interval.....	10
New York Stratigraphic Nomenclature	10
Kentucky and Ohio Stratigraphic Nomenclature	11
Sequence Stratigraphy of the Study Interval.....	12
Methodology and Dataset	16
Chapter 2: Sequence Stratigraphy of the Utica-Point Pleasant.....	17
Sequence Stratigraphy.....	17
Methodology.....	18
Sequence Hierarchy	19
Subsurface well log stratigraphy.....	20
Mohawkian Series M5 Stratigraphy.....	28
Mohawkian Series M6 Stratigraphy.....	30
Cincinnatian Series C1 Stratigraphy	35
Cincinnatian Series C2 Stratigraphy	38
Controls on Depositional Patterns.....	41
Stratigraphic Discussion.....	42
Chapter 3: Total Organic Carbon Modeling	45
Methodology.....	45
Regional Maps and Interpretations	55
Chapter 4: Hydrocarbon Potential of the Utica-Point Pleasant Interval	61
Porosity Modeling.....	61
Water Saturation Modeling	62
Rock-Eval Geochemistry	65
Play Fairway and “Sweet Spot” Identification	69

Summary and Conclusions.....	77
References Cited	80
Appendix A: Fred Barth core log.....	86
Appendix B: Power Oil core log	88
Appendix C: Summary of core analysis data for the Fred Barth core.....	90

ACKNOWLEDGEMENTS

I would like to express my appreciation to Dr. Tim Carr for his support of this thesis.

Thank you for accepting me as a graduate student, providing financial assistance, guidance, and feedback throughout the research track of this thesis. This thesis also benefitted from the feedback of the committee, Dr. Jaime Toro and Dr. Shikha Sharma.

I am grateful for the funding and support provided for this research by Range Resources, the mentorship and guidance provided by Bill Zagorski, and feedback from George Roth, Martin Emory, and Chuck Moyer. A special thanks goes to the Horace R. Collins Core Laboratory for providing access to cores for observation, as well as Jessica Moore, Eric Lewis, and the West Virginia Geological and Economic Survey for access to their core annex. Thanks also to the Ohio Division of Geological Survey for the publication of collected source rock data performed on samples from their collection, as well as the many companies that contributed this data.

LIST OF FIGURES

1.1 Map of study area with well and cross section locations	5
1.2 Late Ordovician Paleogeographic map of eastern North America	7
1.3 Late Ordovician depositional features of northeastern North America	9
1.4 Chronostratigraphy and lithostratigraphy of the study interval	15
2.1 Log correlation between published core data and study area well logs	23
2.2 Type logs and sequence stratigraphic surfaces	24
2.3 A Regional cross section A-A'	25
2.3 B Regional cross section B-B'	25
2.3 C Regional cross section C-C'	26
2.3 D Regional cross section D-D'	27
2.3 E Regional cross section E-E'	27
2.4 M5 Sequence gamma-ray contour map	30
2.5 M6 TST gamma-ray contour map	34
2.6 M6 HST gamma-ray contour map	35
2.7 C1 TST gamma-ray contour map	37
2.8 C1 HST gamma-ray contour map	38
2.9 Chronostratigraphic diagram of Trenton-Utica units, Ontario to New York	40
3.1 Well log showing Passey method TOC overlay	47
3.2 Density – Resistivity cross plot	49
3.3 LogR separation – TOC cross plot	51
3.4 Density – TOC cross plot	52
3.5 Gamma-ray – TOC cross plot	53
3.6 Modeled TOC curves	54
3.7 M6 TOC contour map	56
3.8 M6 TST TOC contour map	57
3.9 M6 HST TOC contour map	58
3.10 C1 TOC contour map	60
4.1 Porosity vs. Bulk Density on the Fred Barth Core	61
4.2 Porosity model curve for the Fred Barth well	62
4.3 Pickett plot showing Trenton through Utica	63
4.4 Well log analysis display	65
4.5 Rock-Eval data schematic	67
4.6 Normalized oil content contour map	69
4.7 Contour map of 90 th percentile porosity in the Point Pleasant	71
4.8 Overlay of porosity and normalized oil content	72
4.9 Normalized oil contour map and percentage of liquids from reported IP's	73
4.10 Contour map and reported IP rates in BOE/d	75

4.11 Cross section F-F' showing petrophysical logs and reservoir properties	76
---	----

Introduction

Recent natural gas exploration has sparked interest in the Utica Shale, a thick succession of Middle Ordovician black shale and organic-rich limestone that overlies and interfingers the carbonate units of the Lexington Limestone and Trenton Group in the Appalachian basin (Ruedemann, 1925; Fisher, 1977). By virtue of its favorable total organic content and expected pore pressures due to burial depth, the Utica Shale is an evolving shale-gas play in western Pennsylvania, northern West Virginia, and eastern Ohio. This succession of organic shale and limestone has been attributed as the primary source rock for the lower Paleozoic total petroleum system in the Appalachian basin (Ryder, 2008). Utica Shale is used as a blanket term referring to any number of subunits comprised of black shale or organic-rich limestone overlying the Trenton Group. Evaluation and standardization of the Trenton Group through Utica Shale stratigraphy by the Ohio Geologic Survey has identified the Point Pleasant Formation, the transitional formation overlying the Lexington Limestone and underlying the Utica Shale, as the most organic-rich and attractive target (Riley, 2010). While the play is generally referred to as the Utica Shale play, it should more accurately be termed the Point Pleasant play, as the Point Pleasant Formation is the most organic-rich unit within the Trenton through Utica interval. The first commercialization of the play was from interbedded dark grey limestone and black shale in the Trenton Limestone along the Lake Ontario shoreline and in the Blue Tail Rooster field of Cayuga County, New York (W.A. Zagorski, 2013, personal communication). Further production from this interval occurred in fractured limestone and interbedded shale reservoirs in West Virginia, Kentucky, and Ohio (Nutall, 1996), as well as the massive Lima-Indiana trend in Indiana and northwestern Ohio (Patchen et al., 2006). Great

Lakes Energy Partners encountered major gas shows in the Trenton Limestone and Point Pleasant Formation with a deep test well in southwestern Pennsylvania in 2003, and pioneered the play when they drilled the Zahn #1 well in 2007, which was the first horizontal, hydraulically fractured well in the play. Modern discoveries also include the Fortuna-Seneca #3 well in Elk County, Pennsylvania which was a vertical gas discovery well that produced from the Utica Shale (W.A. Zagorski, 2013, personal communication). Historic production has shown that the Utica-Point Pleasant interval has significant potential as an unconventional shale gas play, with recent exploration and results of test wells drilled in eastern Ohio and western Pennsylvania displaying that the Utica-Point Pleasant is a significant unconventional hydrocarbon play accessible via horizontal drilling and hydraulic fracturing technologies. Initial results from test wells in Ohio have reported a major hydrocarbon liquids discovery, unleashing a leasing frenzy in the Utica of eastern Ohio. Leasing and drilling activity reports have begun to show a developing Utica play fairway with reports of successes most localized in eastern Ohio.

The stratigraphy of the Utica and late Ordovician has been extensively studied in the outcrop belt of the Mohawk River Valley of New York State (Baird and Brett, 2002; Brett and Baird, 2002; Goldman et al., 1999; Joy et al., 2000). Facies transitions and age relationships have been established for the strata of the late Ordovician on a depositional dip transect across the Mohawk Valley by means of graphic correlation, biostratigraphy, and bentonite ash bed age dating. Similarly, the graptolite-rich shale and limestone units of the coeval Lexington Limestone and Kope Formation in southwest Ohio and Kentucky have been extensively studied where they outcrop on the Cincinnati arch, refining the age boundaries and stratigraphic relationships between these strata (Holland, 1993; Holland and Patzkowsky, 1998; Kirchner and

Brett, 2008; McLaughlin et al., 2004; McLaughlin and Brett, 2007). Brett et al. (2004) presented a sequence stratigraphic correlation between the Trenton shelf in the Mohawk Valley outcrop of New York to the Lexington platform in the Cincinnati arch outcrop of Kentucky-Ohio. The authors correlated formations and members between the two locations (100's of miles apart) using biostratigraphy and ash-bed dating, conforming to the established sequence stratigraphic hierarchy for the Upper Ordovician (Holland and Patzkowsky, 1998).

While extensive research has been completed in the Utica and equivalent Ordovician units in outcrop in Kentucky, Ohio, and New York (i.e. Brett et al, 2004), the subsurface sequence stratigraphic correlation requires additional investigation. With increased drilling activity, the Utica subsurface stratigraphic nomenclature has become complicated, with different operators, companies, and state geological surveys assigning their individual nomenclature to the stratigraphy of the late Ordovician interval. I propose a standardized subsurface stratigraphic nomenclature and stratigraphic model that is consistent between states and geographic areas.

Major shale plays have the greatest production within a "sweet spot" areas with optimum total organic content (TOC), mineralogy, porosity, permeability, and thermal maturity. While the Utica Shale has a widespread distribution in the Appalachian basin, covering areas from New York to Kentucky, facies with high organic carbon content are confined to smaller geographic areas. As in other shale plays, such as the Marcellus Shale, Eagle Ford, and Barnett, the most prolific Utica wells are found in geographically confined sweet spots. In this thesis I propose the Utica-Point Pleasant "sweet spot" area in which TOC, porosity and permeability, in

conjunction with ideal thermal maturity, are conducive to the most prolific hydrocarbon production.

I also correlate the units of the Utica-Point Pleasant interval in the subsurface to create a basin-wide depositional model in order to better understand the controls on regional facies, and to better predict regional distribution of hydrocarbon productive sweet-spots characterized by organic-rich, high porosity rocks. I define the structural and stratigraphic geological controls on the deposition of organic-rich strata in the basin during the late Ordovician. Wireline logs integrated to core data are used to identify and predict the occurrence of organic-rich facies. Paleogeographic studies of the late Ordovician have suggested the existence of a number of sub-basins within the Taconic foreland basin, that control the spatial distribution of organic rich facies. By mapping the occurrence of organic-rich facies, I confirm the role that basement structures and faults, and paleogeography play in the distribution of organic-rich Utica and Point Pleasant facies.

Study Area

The study area includes western Pennsylvania, eastern Ohio, and northern West Virginia (Figure 1.1). Although the Utica Shale covers a broad area of the Appalachian basin, the study area was narrowed to this region based on the thermal maturity and reservoir properties of the Utica-Point Pleasant and the interest of industry as expressed by permitting and drilling activity.

Figure 1.1: Map of the study area in eastern Ohio, western Pennsylvania, and northern West Virginia, showing locations of wells used in mapping and correlation, cross section index lines, and measured core locations. Mapped structures are Ordovician and older faults and lineaments. Rome trough structure outlined in red dashed line. TMU – Tyrone-Mount Union lineament, PMW – Pittsburgh-Mount Washington lineament.

Geologic Background

Tectonic, Climatic and Paleogeographic Background

During the early to middle Ordovician, the North American craton was situated at 20-25° south latitude, with a passive margin along its present day Atlantic seaboard (Witzke, 1990, via McLaughlin et al., 2004)(Figure 1.2). Shallow water depths along the margin paired with the

tropical climate resulted in widespread deposition of shallow-water carbonate beds across what is known as the “Great American Carbonate Bank” (Cornell, 2008). Starting in the late middle Ordovician and continuing into the early Silurian, an island arc along a westward subducting plate collided with North America, emplacing an accretionary prism on top of the Laurentian craton (Cisne et al., 1982). This event is called the Taconic orogeny. During this time, the craton margin to the east was uplifted and over thrust onto the craton leading to subsidence and drowning of the carbonate bank through development of the Taconic foreland basin (Rowley and Kidd, 1981). The collision zone consisted of smaller micro-plates, back-arc basins, and small volcanic islands, causing the kinematics and timing of deformation to vary along the orogen of convergence (Ettensohn and Brett, 2002). Heterogeneity along the orogenic front also caused fault movement along cross-strike discontinuities, leading to the formation of smaller pocket sub-basins within the greater Taconic foreland basin (Brett et al., 2004). Subsidence was in part a result of northeast-southwest striking high-angle normal faults, down-dropped to the east, creating half grabens. The east to west diachronous progression of basin subsidence is evident in the transition from siliciclastic dominated sedimentation in the east to carbonate dominated sedimentation to the west (Bradley and Kidd, 1981).

Figure 1.2: Paleogeographic map of eastern North America during the late Ordovician showing approximate paleolatitudes major paleogeographic features (1 – Great American Carbonate Bank, 2 – Taconic foreland basin, 3 – Avalonian terrane). Modified from Blakey, (2011); paleolatitudes from Witzke, (1990).

Through the progression of the Taconic orogeny and the formation of the Taconic foreland basin, smaller sub-basins and troughs developed within the greater foreland basin. One such feature is the Sebree trough (Figure 1.3) – a narrow, shale-filled sedimentary feature extending along a southwest-northeast trend across the carbonate platform (Kolata et al., 2001). The Sebree trough was connected to the deeper foreland basin by a cross-strike feature termed the Pennsylvania basin (Brett et al., 2004) (Figure 1.3). The Sebree trough is bounded

by three flanking carbonate platforms: the Galena shelf to the west, the Trenton shelf to the north, and the Lexington platform to the south-southeast. This feature is marked by dark grey and black shales in contrast to the coeval clean carbonate units of the flanking platforms. This trough developed during Mohawkian time as a depression over the late Precambrian-Early Cambrian Reelfoot rift (Kolata et al., 2001). As sea level rose during the late Ordovician, the carbonate platforms continued to grow upward, further exaggerating the difference in the depth and facies between the carbonate platforms, and sub-basins.

Figure 1.3: Paleogeographic map of northeastern North America during the late Ordovician showing sub-basin provinces and major depositional features after Brett et al., 2004 (left) and revised after interpretations of this thesis (right). Dotted areas indicate locations of outcrop stratigraphic studies, of Brett et al., 2004. CA – Cincinnati Arch outcrop belt, MV – Mohawk Valley outcrop belt.

Stratigraphy of the Study Interval

The Middle to Upper Ordovician sequence in the Taconic foreland basin represents an overall transgressive succession of facies, from shallow-water carbonate of the Black River Group, to the shallow to deep-water bioclastic tempestites and turbidites of the Trenton Group, to organic-rich, siliciclastic shale of the Utica and Antes formations (Smosna and Patchen, 1991). This succession corresponds to the M5, M6 and C1 second-order sequences, and was deposited during a transgression on a tectonically active ramp over a time interval of approximately five million years (Holland and Patzkowsky, 1998) (Figure 1.4a). Brookfield and Brett (1987) argue that the limestone of the Trenton Group was deposited on an eastward sloping carbonate bank in a shoal-basin rather than a flat epicontinental sea. They conclude that topographic differentiation of a carbonate bank better explains the abrupt changes in facies and thicknesses in the Trenton limestone than the flat shelf model of carbonate deposition.

New York Stratigraphic Nomenclature

The Utica Shale is best known in the Ordovician outcrop belt of the Mohawk River Valley of New York State (Figure 1.3), where the abrupt vertical and lateral facies changes within the Utica Shale and adjacent limestone of the Trenton Group have been the source of considerable debate and study in surface correlations (Lehmann et al., 1995; Baird and Brett, 2002; Finney et al., 1996). Correlation of graptolite zones and bentonite (ash) beds in the Mohawk Valley of New York determined that the lower Utica Shale is coeval with the upper portion of the Trenton Group through a westward facies transition from calcareous black shale of the Flat Creek Formation to interbedded limestone and shale of the Dolgeville Formation (Fisher, 1977; Cisne et al., 1982) (Figure 1.4b). As time constraints were placed on the stratigraphy, it was concluded that the Utica Shale onlaps and interfingers with shelf and slope carbonate units of the Trenton

Group expressing diachronous subsidence of the Taconic foredeep (Mitchell et al., 1998). At more westward locations, the Utica Shale disconformably overlies the Trenton on a contact referred to as the Thruway disconformity; a time transgressive contact that becomes younger from east to west. This disconformity in New York has been interpreted to represent a drowning unconformity resulting from non-deposition in deep water at the base of a transgressive systems tract during eustatic sea-level rise (Baird et al., 1992; Lehman et al., 1995), or as a slide scar resulting from fault block rotation where the Upper Trenton slid into a trough (Jacobi and Mitchell, 2002).

Kentucky and Ohio Stratigraphic Nomenclature

A narrow trough known as the Sebree trough connected the Taconic foreland basin to the midcontinent United States (Kolata et al., 2001). This structural feature was bounded by carbonate platforms: the Galena shelf to the north and west, and the Lexington platform to the south and east (Figure 1.3). This trough is expressed in a thicker succession of black and dark grey shale that lie within the same graptolite zonation as the flanking carbonate platforms, indicating that the Utica Shale was deposited contemporaneous with the adjacent Trenton/Lexington limestone (Kolata et al., 2001). As a result, the limestone-shale contact within the Sebree trough represents a diachronous surface. In outcrop in the Cincinnati arch region of Kentucky and southwestern Ohio, the age equivalent limestone unit to the Trenton Limestone is referred to as the Lexington Limestone. The lower member of the Lexington Limestone is named the Curdsville Member, which is overlain by the dark grey to black lime mudstone of the Logan Member, and capped by a cleaner limestone referred to as the Lexington undivided member. The Lexington Limestone grades laterally into black shale in the

basin and into its equivalent clean limestone in the Trenton platform. Overlying the Lexington Limestone is the Point Pleasant Formation, which grades basinward into black shale, and laterally into its cleaner platform equivalent in the Trenton Limestone. The Point Pleasant is overlain by the Utica Shale, which partially grades into and overlies the Trenton Limestone in northwest Pennsylvania and western Ohio. In a subsurface study, Patchen et al. (2006) hypothesized that the top of the Curdsville of south-central to southwest Ohio represents a flooding surface with the Logana Shale being a highstand deposit. They hypothesized that the top of the Curdsville is a time-transgressive surface, becoming younger from west to east moving from the Sebree trough to the Lexington platform. The clean, Curdsville Member of the Lexington Limestone thins from east to west toward southwest Ohio. The Curdsville is overlain by the Logana Shale, which is in turn overlain by the Lexington undivided member. The Lexington undivided member becomes much thicker in south-southwestern Ohio, and thins to an indistinguishable 2-10 foot (0.8 to 3m) thick bed in east central Ohio, barely identifiable on well logs by an increase in density relative to the overlying Point Pleasant and underlying Logana Shale.

Sequence Stratigraphy of the Study Interval

The Late Mohawkian-Cincinnatian sequence is a mixed carbonate-clastic system in which carbonate facies back-step westward toward the carbonate bank top through time, and organic-rich shale progrades westward through time. The sequence is underlain by limestone units of the Black River Group deposited under high-energy conditions on the top of a carbonate bank. The basal contact of the Mohawkian-Cincinnatian sequence is unconformable in certain areas of the basin, and this unconformity and correlative conformity is used as the

lower (M4/M5) sequence boundary in this study. The M4/M5 sequence boundary lies just above the Deicke/Millbrig bentonite couplet, which are prominent within the limestone gamma-ray signature, and strengthen the pick for this timeline (Figure 1.4).

Large scale depositional sequences have been identified in the Upper Ordovician strata of northeastern North America by various authors (Figure 1.4). Pope and Read (1997, 1998) subdivided the Ordovician of eastern North America into three second-order sequences, each representing 10-30 m.y. They further subdivided the late Middle to Late Ordovician (Mohawkian – Cincinnati) second-order Taconic supersequence of Kentucky and Virginia into four large third-order sequences, each deposited in less than 12 m.y. with a thickness of 40-150 meters. The maximum flooding surface (MFS) of this second order sequence approximately coincides with the contact of the Lexington Limestone with the Point Pleasant – Utica Shale. Based on outcrop research using stratigraphic and biostratigraphic correlation on the Nashville dome of Tennessee and the Cincinnati arch of Kentucky and Ohio, Holland and Patzkowsky (1996, 1997) divided the Mohawkian-Cincinnati interval into eight third-order sequences (M5, M6, and C1-C6), each with a duration of 1-3 m.y., of which, the interval of the Trenton/Lexington Limestone through Utica Shale fall within the M5, M6, and C1 sequences of Holland and Patzkowsky (2008) (Figure 1.4a). Joy et al. (2000) recognized three sequences contained within the Trenton through Utica strata of the Mohawk Valley (Figure 1.4b). McLaughlin et al. (2004), Brett et al. (2004), and McLaughlin and Brett (2007) proposed a third-order sequence stratigraphic pattern for the strata of the Cincinnati arch of Kentucky and southwestern Ohio contained within Holland and Patzkowsky's (1996) M5 and M6 sequences, dividing them into six third-order sequences each with a duration on the order of 1 M.y. (Figure

1.4c). These six sequences were termed M5A-C, and M6A-C, and were mapped across the Cincinnati arch. Brett et al. (2004) presented a comparative sequence stratigraphy between the Ordovician of Kentucky and New York claiming to have been able to trace these third-order sequences from the Cincinnati arch to New York State, recognizing their counterparts in outcrop in the Mohawk Valley. Given that Holland and Patzkowsky recognize their sequences as third-order scale, the sequences proposed by Brett et al. (2004) as subdivisions of the M5 and M6 sequences would technically be smaller scale fourth-order para-sequence or cycle sets.

Methodology and Dataset

The data set includes approximately 400 well logs in eastern Ohio, western Pennsylvania, and northern West Virginia that penetrate the Utica-Point Pleasant interval. Logs were converted from raster image to digital format using IHS Petra® software. The dataset includes logs of a wide range of ages, dating from the 1960's to present day. As a result, gamma ray logs are widely variable in their calibration and scale. Gamma ray logs measured prior to 1990 were assumed to be less accurate than those measured after 1990, and were normalized accordingly. Gamma ray logs were normalized by adjusting the curve to a common scale range by stretching or compressing curves using high and low range values. On a local basis, older gamma ray curves were compared to newer, post-1990 curves. Two baselines were established; one in the higher gamma-ray "shaly" Utica section and one in the low gamma-ray "clean" Trenton section. Gamma ray values were averaged for each of these zones, respectively, and the older well log values were normalized to the newer well log values. In addition, two cores from Ohio and one core from West Virginia were studied in detail for stratigraphy and facies analysis. Core lithology and facies analysis are tied to well logs to correlate lithofacies to petrofacies, and petrofacies are correlated throughout the basin.

Chapter 2: Sequence Stratigraphy of the Utica-Point Pleasant

Sequence Stratigraphy

Research utilizes the sequence stratigraphic terminology of Embry (1995, 2002).

Sequence stratigraphy was defined by Vail et al. (1997, p.53), as “a stratigraphic unit composed of genetically related strata bounded at the top and bottom by unconformities or their correlative conformities”. Embry (1995) encountered difficulties in the objective recognition and correlation of the correlative conformity and defined a fourth type of sequence termed a T-R sequence. In the T-R sequence, the sequence boundary (SB) is placed at the subaerial unconformity and the correlative transgressive surface (TS) in the absence of the SB, or where the TS and SB merge. The T-R sequence is divided into an underlying transgressive systems tract (TST) and a regressive systems tract above, with the maximum flooding surface (MFS) representing the boundary between the two systems tracts. The sequence boundary identification scheme of Embry using the transgressive surface is practical for the late Ordovician because the transgressive surface and sequence boundary separates a distinctive lithology change and is identifiable in both the shelf and slope settings. The late Ordovician strata are contained within a second-order transgression and lack discernable lowstand deposits within third-order sequences, thus the identification of a transgressive surface is more reliable. Furthermore, the transgressive surface has minor diachroneity, and merges with the basinward termination of the unconformable portion of the sequence boundary (Embry, 1995). It must be noted that T-R sequence stratigraphy is only reliable in settings lacking significant lowstand deposits, as is the case with the strata of the late Ordovician Mohawkian-Cincinnatian second-order transgression where third-order sequences contain a combined sequence

boundary and transgressive surface (Holland and Patzkowsky 1997). In passive margin clastic systems there is considerable diachroneity between the transgressive surface and sequence boundary, which bound lowstand turbidites and incised valley fills (Vail 1997).

Methodology

Sequence boundaries are identified in the gamma ray log as the sharp transgressive surface between underlying limestone facies and overlying shale-rich facies. The sequence boundary surface is manifested by a sharp, subaqueous drowning unconformity at the platform top and near the platform edge, and a conformable transgressive surface in the basin setting. Flooding surfaces are identified in the gamma ray log as the transition from deepening upward (decreasing carbonate and increasing shale content) to shallowing upward (increasing carbonate and decreasing shale content, or increasing gamma-ray to decreasing gamma-ray in the Utica Shale). Gamma-ray contour maps were generated using the calculated mean value of the normalized gamma-ray log between sequence boundaries and flooding surfaces to map out the spatial distribution of log facies for sequences and systems tracts. These maps show the distribution of carbonate, marl, and shale sediment, and were used to interpret depositional patterns, paleogeography, and basin dynamics throughout the late Ordovician.

Correlating from the Point Pleasant sub-basin to the Trenton Platform proves difficult given the drastic facies changes between the two settings. Thus arises the need for marker beds to correlate chronostratigraphic surfaces between differing lithologies. Key bentonite ash bed marker horizons within the stratigraphy allow for chronostratigraphic correlation over large distances in the study area. The Millbrig and Deicke bentonite ash beds have proved a useful horizon in correlating the major chronostratigraphic units across eastern North America

(Mitchell et al. 2004), and this bentonite couplet is recognizable in the subsurface within the study area. These bentonites contain radioactive uranium, potassium, and thorium, and stand out in the gamma ray log as a sharp spike above the limestone values of the Black River limestone in which they lie stratigraphically within (Figure 2.1). The top of the Black River Limestone is used as the sequence boundary, and these bentonite horizons are located just below the top of this surface, strengthening the chronostratigraphic significance of this surface. A second bentonite horizon important in correlation between the platform-basin settings is identified stratigraphically overlying the M6 sequence boundary and top of the Point Pleasant in the basin setting, and overlying the shale-rich zone in the middle of the Trenton Limestone in the platform setting (Figure 2.2 B,D). This horizon is evident in a sharp gamma ray spike in these two type logs, but becomes difficult to discern at the platform slope break where it is either not deposited or eroded at the M6 SB, or unable to be identified within the high gamma-ray facies of the C1 TST (Figure 2.2 C). Based on the stratigraphic positioning of this bentonite, I hypothesize it to be the counterpart to either the East Canada bentonite or the Manheim bentonite in the Dolgeville and Flat Creek Shales of New York (Mitchell et al. 2004). These bentonite ash beds, along with three other marker horizons assumed to represent bentonite ash beds, were used to guide the correlation of chronostratigraphic surfaces through sharp facies changes from the carbonate platform to basin setting (Figure 2.3 B).

Sequence Hierarchy

McLaughlin et al. (2004) and McLaughlin and Brett (2007) studied the late Ordovician sequence stratigraphy in outcrop of the Cincinnati arch of Kentucky-Ohio, correlating a short distance into the subsurface of Kentucky and southwestern Ohio. They assumed the M5, M6,

and C1 third-order sequence hierarchy of Holland and Patkowski (1997), and recognized smaller scale fourth-order sequences contained within the M5 and M6 sequences. The core observations and interpretations published in these studies provided a valuable starting point in correlating the subsurface stratigraphy in this study. Published core logs for southwestern Ohio were digitized and correlated to gamma-ray logs to correlate lithofacies, flooding surfaces, and sequence boundaries interpreted by the authors to petrofacies and chronostratigraphic surfaces in the logs. An attempt was made to correlate the fourth-order para-sequences observed in southwest Ohio to the core study area in eastern Ohio, but this attempt proved to be futile as significant changes in facies and thickness limited accurate correlation of these para-sequence sets. However, correlation of the larger third-order sequences was possible to carry from the previously studied subsurface data to the core area, and is the focus of this study (Figure 2.1).

Subsurface well log stratigraphy

The Ohio Geological Survey established the lithostratigraphic nomenclature for the eastern Ohio core area of the play based on the OGS CO2 No. 1 well in Tuscarawas County (Riley 2010). The nomenclature in this well was correlated to the nomenclature and sequence stratigraphy of the wells used by McLaughlin et al. (2004) in southwestern Ohio (Figure 2.1). The Curdsville, Logana, and Lexington Undivided members all grade from southwest to northeast into the Curdsville Member of the Lexington Limestone, resulting in diachroneity between the lithostratigraphy in southwest Ohio and that of the study area in eastern Ohio. It is found that the Curdsville, Logana, and Lexington Undivided are contained within the M5 sequence in southwest Ohio, with the overlying Logana and Lexington Undivided falling within

the M6 sequence in eastern Ohio. Patchen et al. (2006) hypothesized that the top of the Curdsville of south-central to southwest Ohio represents a flooding surface with the Logana Shale being a highstand deposit. They further hypothesized that the top of the Curdsville is a time-transgressive surface, becoming younger from west to east moving from the Sebree trough to the Lexington platform. This hypothesis is consistent with the sequence stratigraphic interpretation of this work. The top of the Curdsville member is transgressive from west to east. In southwest Ohio, this surface marks the flooding surface of the M5 sequence, while moving east this surface marks the sequence boundary between the M5 and M6. The Logana shale represents the late TST to early HST of the M5 in southwest Ohio, and grades laterally into the Curdsville in the east, where the M5 flooding surface is in the middle of the Curdsville Member.

The M6 sequence contains the Point Pleasant Formation in southwestern Ohio, and the Logana, Lexington Undivided, and Point Pleasant in eastern Ohio and Pennsylvania. The Point Pleasant of southwest Ohio is relatively shaley with intermittent limestone beds that cap the fourth-order parasequences of McLaughlin et al. (2004) and McLaughlin and Brett (2007). Moving east, the Point Pleasant becomes markedly more calcareous at the base and contains more fossiliferous and skeletal debris within an organic rich, calcareous marl (see Barth Core, Appendix A). This calcareous lower Point Pleasant corresponds to the Logana and Lexington Undivided members of the Ohio Geological Survey in the OGS CO2 No. 1 type log in eastern Ohio. In the east, the usage of the Logana and Lexington Undivided members is a bit of a misnomer as the true Logana Shale and overlying Lexington Undivided members are found in southwestern Ohio, and grade laterally into the clean Curdsville Member to the east moving

out of the Sebree trough and into the Point Pleasant sub-basin. The flooding surface of the M6 in eastern Ohio corresponds to the top of the Lexington Undivided member. The top of the Lexington Undivided in the eastern core area is also a time-transgressive surface, becoming younger from south to north. In the southern core area (Guernsey, Belmont, Harrison counties, Ohio), the flooding surface is located in the middle of the Point Pleasant, above the top of the Lexington Undivided or calcareous lower point pleasant. Moving to the north in the core area, the sharp surface at the top of the Lexington Undivided marks the flooding surface of the M6, representing a drowning surface that gives rise to the sharp contact between the calcareous lower Point Pleasant and the shale and marl of the upper Point Pleasant.

Figure 2.1: Log correlation between core descriptions and correlations of McLaughlin et al. (2004) in southwestern Ohio and the study area in east central Ohio.

Figure 2.2 (Fold-out): Type logs from locale across the study area showing interpreted flooding surfaces, sequence boundaries, and inferred bentonite horizons correlated. A- David R. Hill Inc. Devco Unit #1-23, Guernsey Co. Ohio, API# 34-059-24067; B- Chesapeake Exploration LLC. White No. 1, Carroll co. Ohio, API# 34-019-22059; C- Range Resources Appalachia Brickner Unit #1, Crawford Co. PA, API# 37-039-23588; D- Eastern Amer. Energy Corp. Shutts-Cross #1, Erie Co. PA, API# 37-049-24979.

Figure 2.3 C (Fold-out): Cross section C-C' along a dip transect from Ashtabula County, Ohio to Armstrong County, Pennsylvania showing stratigraphic relationships and facies changes of the M5, M6, C1, and C2 sequences. Wells are proportionally spaced relative to the distance between well locations. Interpreted bentonite horizons are marked by dashed white lines. See figure 1.1 for locations.

Mohawkian Series M5 Stratigraphy

The M5 sequence falls within the lower Mohawkian Series, and corresponds to the *Corynoides americanus* graptolite zone (Holland and Patzkowsky, 1997, Lehmann et al., 1995, Brett et al., 2004). The M5 contains the Curdsville member of the Lexington Limestone in eastern Ohio, and in part the Trenton Limestone to the north.

The Power Oil core (Appendix B) contains the upper most portion of the Curdsville member of the Lexington Limestone of the M5 HST. The Curdsville is comprised of two main limestone dominated facies:

Fossiliferous to sparse micrite – micrite, lenticular to hummocky cross-stratified at top, occasional thin mud drapes, reworked fossil fragments and skeletal grains.

Sharply interlaminated skeletal packstone and micrite – sharply interlaminated skeletal packstone and micrite, basal skeletal packstone unit with undulating scoured base, escape burrows, reworked rounded micrite intraclasts, grading up into grey micrite with thin (2-5mm) shale partings.

The fossiliferous to sparse micrite facies is interpreted to represent the highstand keep-up phase of carbonate production, below fair weather wave base but above storm wave base as evidenced by the presence of hummocky cross-strata. The sharply interlaminated skeletal packstone and micrite facies is interpreted to represent a depositional environment below fair weather wave base but above storm wave base. Skeletal packstone event beds of this facies indicates storm wave action, with skeletal fragments and rip-up intraclasts resulting from highstand shedding from the Lexington shoal platform top.

The M5 sequence consists of clean, shallow water carbonate across the study area. The normalized gamma-ray map shows widespread deposition of relatively clean carbonates across the study area during the M5, with the exception of marly, shale-rich carbonate in the southeast in the area of the Rome Trough (Figure 2.4). These carbonates become more shale-rich proximal to the orogenic front and Taconic foreland basin basin as subsidence begins and causes a relative rise in sea level. Low gamma-ray values to the north and west during deposition of the M5 indicate the early distinction between a northeast-southwest trending carbonate platform, and a proximal foreland basin to the southeast.

Figure 2.4: Contour map of the average normalized gamma ray value over the M5 interval (Black River to M5 sequence boundary). Includes the Curdsville Member and Trenton Group equivalents. Note the increased shale content in the zone of the Rome Trough.

Mohawkian Series M6 Stratigraphy

The M6 sequence is within the Mohawkian Series, and corresponds to the *Orthograptus ruedemanni* graptolite zone (Holland and Patzkowsky, 1997; Lehmann et al., 1995; Brett et al., 2004). The transgressive systems tract contains the Logana and Lexington Undivided members of the Lexington Limestone in the Point Pleasant sub-basin, and the equivalent Trenton Group limestone units on the Trenton platform.

In the Power Oil core (Appendix B), the M6 TST consists primarily of sharply interlaminated biomicrite and black lime mudstone. These form 6 to 12 (15 to 30 cm) inch fining upward sequences containing a sharp based skeletal debris packstone, grading up into fine grey micrite, sharply overlain by grey to black lime mudstone. To the northwest in the Barth core (Appendix A), there is a stark basinward facies change to marl and mudrock dominated facies (Figure 2.3E). The M6 TST in the Barth core consists of bioclastic packstone dominated by brachiopod and bivalve shells in a black marl matrix, interbedded with dark grey to black lime mudstone marl. The facies change across the platform to basin transect from the Power Oil core to the Barth core supports the evidence of the presence of the shallow-water Lexington shoal platform to the southeast. Facies of the M6 in the Power Oil core indicate a shallow marine environment, frequently disturbed by storm events. The facies of the M6 in the Barth core consist of black marlstone with fossiliferous horizons composed of Brachiopod shells, indicating a deeper marine environment. The lack of bedding structures indicates that these facies were deposited below storm wave base where traction currents would have disturbed bedding. Fossiliferous skeletal packstone units in the TST are most likely deposited in place rather than from transport mechanisms. Shelly material appears to be relatively whole and intact, indicating living colonization, rather than transportation from another source in which shelly debris would be broken down into fragments and show reworking. The presence and abundance of these horizons are most likely controlled by changes in bottom-water oxygen levels, in which increases in oxygen at the seafloor allow for the colonization of the seabed. Small-scale cyclicity in sea-level paired with seasonal or episodic mixing of the water column gave rise to an oxygenated seafloor. These events are relatively short-lived given the thin

nature of skeletal beds. Increases in oxygen occur relatively rapidly, resulting in the rapid appearance of sharp based fossil beds. As levels are depleted, colonization of the seafloor by brachiopods is more difficult.

Grading upward into the Point Pleasant in the Barth Core, there is a transition from marl with frequent skeletal packstone beds to dark, black marl with less abundant fossils. The maximum flooding surface for the M6 is placed at the transition from the more fossiliferous Lexington Undivided to the marl-rich Point Pleasant. Some thin, pyritized fossil lag beds occur near the flooding surface, indicating the deepest water conditions within the M6 interval. Facies within the Point Pleasant are dominated by calcareous black siltstone and marl, mostly devoid of significant skeletal horizons, interpreted to be highstand deposits. The lack of skeletal material indicates a deep marine setting where bottom waters are dysaerobic and not prone to the existence of organisms at the seafloor.

In the Power Oil core (Appendix A), the maximum flooding surface is placed at the transition from limestone dominated tempestite cycles to marl dominated cycles, indicating a deepening of depositional environment. Highstand facies in this core consist of dark grey marl interbedded with thin micrite storm beds that show small-scale ball and pillow structures draping into the underlying marl.

The transgressive systems tract shows the first significant formation and development of the Trenton shelf and Point Pleasant sub-basin. A clean carbonate shoal platform develops perpendicular to strike in an east-west orientation. The edge of the shoal platform appears to have a relatively gentle slope during the deposition of the M6 TST, given the gentle transition

from carbonate to marl facies (Figures 2.5, and 2.3 A,C). In contrast, normal faulting during the M6 HST along the southern edge of the platform in Crawford and Ashtabula counties generated a steep paleoslope, confining the edge of the platform giving rise to sharp facies transitions from the basin into the platform (Figures 2.3 A,B). During the HST, rise in relative sea level resulted in a retreat of the carbonate platform to the north and the progradation of marl facies out of the basin and over the carbonate platform margin (Figures 2.6, and 2.3 A,B).

Figure 2.5: Contour map of the average gamma ray value over the M6 transgressive systems tract (M5 sequence boundary to M6 flooding surface). Includes the Logana and Lexington Undivided members, the Trenton Limestone equivalents to the north, and Lexington Limestone equivalents to the south.

Figure 2.6: Contour map of the average gamma-ray value over the M6 highstand systems tract interval (M6 flooding surface to M6 sequence boundary). Includes the Point Pleasant Formation, Trenton Limestone equivalents to the north, and Lexington Limestone equivalents to the south.

Cincinnatian Series C1 Stratigraphy

The Utica Shale shows two distinct, high gamma-ray, upper and lower members based on two fining-coarsening patterns in the gamma-ray log (Figure 2.2C) in the area of northeastern Ohio and northwestern Pennsylvania. Through correlation of well logs, I determined the lower member to correlate to the the late TST to early HST of the C1 sequence in the core of the play and study area. The C1 TST thins toward the Trenton platform to the

north and downlaps onto a sediment bypass surface that amalgamates with the M6 sequence boundary (Figure 2.3B). Here, the C1 TST is absent and the C1 HST is expressed as a radioactive, organic-rich shale adjacent to the edge of the paleo Trenton Platform in Crawford County, Pennsylvania. Through correlation of gamma-ray markers and event beds from the organic shale of the C1 HST into the Trenton platform to the north, this unit sharply grades into clean platform carbonate. The C1 MFS sharply floods the Trenton Platform in southern Erie and northern Crawford counties, and passes into the uppermost unit of the Trenton Limestone (Steuben and Hillier Formations) on the platform to the north. The uppermost sharp limestone-shale contact at the platform forms the sequence boundary between the C1 and C2 sequences, and passes basinward into a correlative conformity separating the lower Utica of the C1 and the upper Utica of the C2 (Figure 2.3B).

To the south, the C1 thins moving out of the Point Pleasant sub-basin toward the Lexington platform (Figures 2.3A,E). This platform represents an expression of higher relief relative to the sub-basin as a result of buildup of carbonates during the M5 and M6, as well as flexure forming a forebulge and propping this platform up at a higher paleo-seafloor elevation. Higher relative sea level during this time shuts down the carbonate factory in the sub-basin and Lexington platform, causing a transition to the accumulation of deeper water clastic sedimentation (Figures 2.7 and 2.8). As a result the deeper water shale facies of the C1 are deposited as infill in the sub-basin and trough areas where accommodation space is higher, as is seen in the nodular, lense-shaped C1 package of sediments in the Point Pleasant sub-basin (Figure 2.3A). These facies thin toward the platform where accommodation space is lower.

Figure 2.7: Contour map of the average gamma-ray value over the C1 transgressive systems tract interval (M6 sequence boundary to C1 flooding surface). Includes the Utica Shale and Trenton Group limestone equivalents (Steuben Formation?) to the north.

Figure 2.8: Contour map of the average gamma-ray value over the C1 highstand systems tract interval (C1 flooding surface to C1 sequence boundary). Includes the Utica Shale and Trenton Group limestone equivalents (Hillier Formation?) to the north.

Cincinnatian Series C2 Stratigraphy

Previous work correlating the second-order Mohawkian-Cincinnatian transgression (McClain, 2011) recognized an upper and lower high gamma-ray zone in the northern part of the study area that gave rise to difficulty in placing the maximum marine flooding surface at either the lower or upper Utica. In conclusion, the maximum marine flooding surface was placed on the sharp contact between the Trenton Limestone and Utica Shale. Through more

detailed correlation, this contact is recognized to be highly diachronous, similar to its counterpart in the Mohawk Valley New York stratigraphy, and that this sharp contact represents two separate drowning surface unconformities of different age. As a result, we conclude that this lower and upper unit fall within two separate third-order sequences, with the upper unit (C2 sequence) younger than and not coeval with the Trenton Limestone facies (Figure 2.2 C,D).

A black shale unit was recognized early by Ruedemann (1912) in the Black River Valley of New York. Ruedemann found the shale to be younger than the upper Utica Shale in the Mohawk River Valley, only differentiated by means of biostratigraphy, and applied the name Deer River Shale. Lehmann et al. (1995) also recognized similar black shale in outcrop in the Gulf Stream of Jefferson County, New York, and proposed the unit be formally named the Gulf Stream Formation. The Gulf Stream Formation is separated from the Utica Formation by the siltstone tongue of the Hassencleaver Member of the Frankfort Formation (Figure 2.9). Similar to the Gulf Stream, the Upper Utica in northwest PA is separated by a siltstone tongue of the Queenston Formation (Figure 2.3B). I conclude that the Upper Utica Shale of the C2 sequence is lithologically separate from the Lower Utica shale to the south, and is similar in age to its counterpart of the Gulf Stream Formation recognized to the north in New York. The Upper Utica grades basinward into the Queenston Formation and Reedsville Shale, similar to the gradation of the Gulf Stream Formation into the siltstone and shale of the Frankfort Formation (Figures 2.3B, 2.9)

Figure 2.9: Chronostratigraphic diagram for black shale and correlative limestone units of the middle to upper Ordovician, west to east from Ontario, Canada to New York after Lehmann et al., 1995.

The Upper Utica unit of the C2 sequence floods the platform in Erie County, Pennsylvania, and to the north into New York. This sequence is most readily identifiable in gamma-ray as a radioactive, organic-rich shale in the area of Crawford, Pennsylvania and Ashtabula Ohio, while toward Pennsylvania and Ohio grading into grey, low gamma-ray shale of the Queenston and Reedsville. The presence of this organic facies within the upper Utica is strongly controlled by the proximity to the Tyrone-Mount Union cross-strike discontinuity (CSD) zone. This zone had an oblique sense of slip, generating a series of normal faults downdropped to the southwest. Normal faulting along this CSD generated a steep paleoslope along the edge of the Trenton platform, causing terrace-like drowning surfaces and dramatic facies changes from limestone to shale due to rapid changes in water depth along a transect perpendicular to the platform edge. A similar pattern of faulting and facies transitions was observed in the

Mohawk Valley outcrop belt by Baird and Brett (2002) and Brett and Baird (2002) who found evidence for changes in topography in the basin induced by flexure and normal faulting. The authors assert that models that invoke fault scarps with significant relief are unlikely, but rather synthetic normal faulting combined with flexure was the primary mechanism for basin topography. While fault activity is recognized as a contributing factor to topography on the platform, it is considered to be secondary to eustatic and flexural trends.

Controls on Depositional Patterns

Flexure is assumed to have less of an impact on the steepening of the topography at the edge of the platform in northwest Pennsylvania. With an approaching orogenic belt to the east and a northeast-southwest trending Taconic basin, one would expect flexure to produce a flexural bulge that trends northeast-southwest similar to the depositional trends in the middle Devonian Marcellus Formation (Lash and Engelder, 2009). Carbonate deposition would dominate the shallow-water environment along the forebulge transitioning into deeper-water facies basinward of the forebulge, as is seen in the relationship between the middle Devonian Onondaga Limestone and Union Springs Member of the Marcellus Formation (Lash and Engelder, 2009; Kohl, 2012). The edge of the carbonate platform in northwest Pennsylvania, however, trends perpendicular to strike, inconsistent with what would be expected for a flexurally controlled carbonate platform (Figures 2.6, 2.7, and 2.8). I assume rather that synthetic normal faulting is the primary mechanism for topography in the northern part of the basin, as evidenced by the striking correlation between the orientation of the platform edge and the Tyrone-Mount Union cross-strike discontinuity. This lineament did not act as a single, major strike-slip fault, but rather consisted of a series of smaller wrench faults with a strong

down to the southwest normal component, as evidenced by the progressive step-wise drowning surfaces on the Trenton Platform (Figure 2.3B).

Sea-level rise played a key role in the existence of the platform top and edge. The long term transgressive trend throughout the Late Ordovician served to both generate accommodation space for carbonate growth, and sufficiently drown carbonate production as the seabed was pushed out of the photic zone. During the M6 HST and the C1, only the most shallow areas of the platform were well situated to be productive carbonate factories (Figures 2.6, 2.7, and 2.8). As sea level rose, these areas experienced keep-up style of carbonate generation and growth (Catuneanu 2008), while adjacent slope settings were pushed out of the photic zone, leading to the formation of sharp drowning surfaces and sediment starvation. High productivity in the shallower areas led to the upward growth of the platform top which kept pace with relative sea-level rise, further exacerbating topographic relief from the platform to slope transition. Dessication of the platform slope occurred in a step-wise manner from south to north, with the platform retreating to the north (Figures 2.6 and 2.7). A major tipping point occurred across the transition from the C1 to C2 sequence, at which time deposition ceased on the Trenton platform. A phase of increased subsidence and relative sea level rise pushed the entire platform area out of the photic zone, shutting off carbonate production and forming the sharp unconformity at the top of the Trenton Group.

Stratigraphic Discussion

The lithostratigraphy of the units within the Trenton – Utica interval is highly variable across time throughout the basin. The hypothesis of this research is that the late Ordovician strata of eastern Ohio and western Pennsylvania consist of deepening upward successions of

transgressive limestone and shale, recording a period of sustained subsidence and increasing sea level along the eastern margin of North America. The upward transition of facies during the late Ordovician from a carbonate-dominated system to a clastic-dominated system reflects the collapse and drowning of a widespread carbonate platform. A platform to basin facies transition exists similar to that observed in New York from black shale into carbonate along strike of the carbonate platform in the area of the basin in northwestern Pennsylvania. The Trenton Group and Lexington Limestone through Utica Shale comprise the transgressive systems tract (TST) of a large second-order sequence, superimposed with three, smaller scale third-order composite sequences consistent with the M5, M6, and C1 sequences of Holland and Patzkowsky (1998)(Figure 1.4d). The M4/M5 contact is correlative to the top of the Black River Limestone and base of the Curdsville Member of the Lexington Limestone, and is the lower sequence boundary of this second-order transgression. Holland and Patzkowsky (1997) recognized a major shift in facies and depositional environment across this surface, reflecting a transition from tropical-type carbonate to more temperate-type carbonate. The presence of the Deike-Millbrig bentonite couplet just below this surface strengthens the chronostratigraphic significance of this sequence boundary. These third order sequences are regionally correlative, generally show aggradational stacking patterns, and lack significant low-stand deposits. Type 3 sequence boundaries separate sequences and reflect drowning surfaces on carbonate platform tops. Type 3 sequence boundaries amalgamate with transgressive surfaces and separate underlying highstand system tracts (HST's) from overlying transgressive system tracts (TST's.) Chronostratigraphic surfaces demonstrate that basinal interbedded lime mudstone, shale, and marl facies of the Logana, Point Pleasant, and Lower Utica Shale units are

contemporaneous with and genetically related to platform limestone on the flanking Trenton and Lexington platforms.

Chapter 3: Total Organic Carbon Modeling

The Utica-Point Pleasant interval is considered to be the primary source rock for the Lima Indiana trend of the Trenton-Black River hydrothermal dolomite play in northwest Ohio, and the Clinton and Medina Sandstone play of eastern Ohio and northwestern Pennsylvania (Ryder et al., 1999). Advances in horizontal drilling and slickwater hydrofracturing techniques have shifted focus from conventional reservoirs to unconventional source-rock shale reservoirs. The factors that control production in shale-gas systems are unique, and a critical parameter is total organic carbon (TOC). TOC is a crucial factor in shale gas systems, as the total porosity and gas saturation are directly related to the TOC content of the rock (Passey et al. 2010). As such, TOC is an important parameter to address when evaluating potential shale-gas reservoirs.

Methodology

To assess the quantity and richness of organic material in the Utica-Point Pleasant, core data was integrated with conventional well logs to generate a set of petrophysical equations that predict total organic content. Two methods were used to predict organic matter using well logs; a simple cross-plot method using the relationship between bulk density and core TOC, and a technique using the response of the porosity and resistivity logs.

The delta log R technique of Passey et al. (1990) utilizes a combination of resistivity and sonic or density or neutron porosity logs, which reflect organic material and hydrocarbons in the rock matrix of organic-rich mudrocks. This technique involves overlaying a porosity log on a resistivity curve. The curves are overlain in water saturated or organic-lean intervals and parallel each other. In organic-rich source rocks, there is a separation between the two curves reflecting increased resistivity in response to the formation fluid, and increased apparent

porosity in response to the low density of the kerogen present. In immature source rocks with no hydrocarbons present in the matrix, the separation occurs due to the low density of the kerogen present within the matrix. In mature source rocks, separation occurs due to both the apparent porosity curve response, as well as the resistivity curve responding to the presence of generated hydrocarbons. By overlaying the two logs and scaling to fit a baseline in organic-lean mudrock intervals (shale/limestone), one can generate a “quick look” of a well log, which highlights organic-rich intervals, where the porosity and resistivity logs separate from the baseline intervals (Figure 3.1).

Figure 3.1: Well log showing Passey delta log R method overlay of density-resistivity and sonic-resistivity logs, along with core TOC and calculated TOC model curve.

The magnitude of the separation between the porosity and resistivity curves can be used to estimate total organic content (TOC). The modified delta log R technique of Bowman (2010) involves taking the Log10 of the resistivity log to generate a LogR curve, and cross plotting LogR against the sonic or a porosity log (e.g. bulk density, sonic or neutron porosity) (Figure 3.2). A low resistivity shale line (for organic shale plays) or low resistivity limestone line (for organic carbonate plays) is determined from the plot. A new porosity curve (pseudo-density RhobR) is calculated from the slope of the non-organic shale/limestone line [$R_{hobR} = b - m \cdot \text{LogR}$]. The new pseudo-density (RhobR) is overlain with the bulk density curve (Rhob) to highlight the separation between Rhob and RhobR to interpret organic intervals where separation occurs.

Figure 3.2: Bulk density – log resistivity cross plot used in the modified ΔLogR method of Bowman (2010). Trendline is set on clean limestone, with organic-rich low density, high resistivity carbonates plotting above the limestone trendline. The clean limestone trendline is used to calculate a pseudo-density curve, which is then plotted against density to separate organic-rich intervals where the two curves separate.

The Utica Shale portion of the stratigraphy and the limestone portion of the stratigraphy have different baselines for resistivity and density so the calculation was made in two parts, one for the shale-rich portion defined as anything above 100 API units, and one for the lime-rich portion defined as anything below 100 API. These best fit lines are used to calculate a new porosity log (pseudo-density RhobR; $\text{RhobR} = m \cdot \text{LogR} + b$), where rock below 100 API was

calculated with the limestone best fit and rock above 100 API was calculated with the shale best fit. The calculated pseudo density log is then plotted on the same track and scale as the density log, with the cross over interval highlighted to show organic rich intervals where the two logs separate. To quantify the amount of separation between the logs and the relationship to TOC, the difference between the bulk density and pseudo-density log was plotted against core TOC (Figure 3.3). A reasonable relationship exists where increasing amount of log separation correlates to increasing TOC. A second relationship exists in the data, where wells within the dry-gas window of the play plot on a steeper trend than wells within the wet-gas window, due to decreased resistivity that is a result of increased maturity (Figure 3.3). Passey et al. (1990, 2010) noted a similar trend where different organic matter types and maturity levels plotted out on different trends based on the S2 content of the source rock.

Figure 3.3: Cross-plot of core TOC versus $\Delta RHOB-RHOB$ separation for the Utica-Point Pleasant interval, after Passey et al. (1990). The data indicate a trend of increasing TOC with increasing magnitude of separation between the RHOB and RHOB curves, with an r^2 correlation value of 0.819.

TOC has also been shown to correlate strongly with rock bulk density, which was tested for the Utica. The resulting plot shows a strong relationship between bulk density and TOC (Figure 3.4). Gamma ray has been used to identify organic-rich zones in the Marcellus Shale due to organic material rich in uranium (Boyce 2010). Gamma-ray was plotted against TOC in the Utica-Point Pleasant to test the ability to use gamma-ray to predict TOC in this play with

little success. Although the plot shows some internal trends, there is a poor correlation between gamma-ray and TOC (Figure 3.5).

Figure 3.4: Cross-plot of core TOC versus bulk density for the Utica-Point Pleasant interval. The data show a strong trend of increasing TOC with decreasing bulk density, with an r^2 value of 0.704. The bulk density log decreases in organic-rich intervals reflecting the low density of organic material, as well as the increase in organic porosity generated by diagenesis of organic material. The fit between bulk density and core TOC was used to generate a continuous TOC model curve for the interval, and extrapolated to map average TOC for the organic rich facies on a regional scale.

Figure 3.5: Cross-plot of core TOC (weight percent) versus normalized gamma-ray for the Trenton Limestone through Utica Shale. The data show some internal correlation trends for separate lithologies, but do not indicate a strong correlation trend between gamma-ray and total organic carbon content. The organic-rich facies within the interval are carbonate marlstone and express a low gamma-ray signature in spite of the fact that it would be expected that the Uranium content of the organic matter would result in a high gamma-ray signature.

The best-fit lines for the plot of density-resistivity separation versus TOC and density versus TOC were used to calculate continuous TOC curves through the Utica-Point Pleasant interval. These plots show that the Point Pleasant through Lexington Limestone undivided member and Logana Shale contain the most organic material, with low-grade source potential within the Utica Shale (Figure 3.6).

Figure 3.6: Standard conventional well logs and organic richness analysis of the Utica-Point Pleasant interval for the Chesapeake White #1 well in Carroll County, Ohio, USA. Track 4 shows the modeled TOC curve computed from the relationship between the bulk density log and core-derived TOC (Figure 3.4), overlain with core TOC points in red. Track 5 shows logs used in the modified Passey ΔLogR method for identifying organic-rich intervals, where the magnitude of separation between the Rhob and pseudo-Rhob curves increases with increasing TOC. The TOC curve derived from the Passey method is shown with core points in track 6.

Regional Maps and Interpretations

A continuous TOC curve was calculated from the density log for all wells in the dataset based on the relationship between bulk density and TOC. The average TOC value for each sequence was calculated and extrapolated to a regional scale to map and interpret the distribution of organic-rich facies. The most organic-rich facies are deposited within the deeper water Sebree trough and Point Pleasant sub-basin, distal to the shallow carbonate depositional environments of the Trenton shelf and Lexington platforms (Figure 3.7). The distribution of organic-rich facies trends perpendicular to depositional strike. This depositional pattern is interpreted to be a result of large-scale cross-strike lineaments that acted as strike slip faults during the Taconic orogeny, which advanced from east to west. These large-scale cross-strike faults bounded large fault blocks that were down-dropped, creating the Point Pleasant sub-basin and Sebree Trough. As a result, organic-rich facies were deposited in these deeper-water settings while cleaner carbonate-rich facies were deposited contemporaneously on the flanking Trenton and Lexington platforms. The location and settings of the paleogeographic trough, sub-basin, and platform features show a strong control on the distribution of organic-rich facies in the Utica-Point Pleasant interval. The most organic-rich marl and shale facies are deposited in the Sebree trough and Point Pleasant sub-basin settings while clean platform limestone facies are deposited on the Trenton and Lexington platforms, coeval with the organic-rich basin sediments.

Figure 3.7: Contour map showing the average TOC value modeled from the density-TOC fit for the Point Pleasant (including the Logana sub-member) and coeval shallow platform facies of the flanking Trenton Shelf to the north and Lexington Platform to the south in western Pennsylvania and eastern Ohio.

The amount of organic matter deposited and preserved increases from the time of deposition of the M6 TST into the Point Pleasant of the M6 HST (Figures 3.8, 3.9). As observed in the Barth core (Appendix A), there is a transition from highly fossiliferous facies in the M6 TST to fossil bare facies in the HST, reflecting deeper water conditions and the development of a permanent stratified water column with anoxic bottom waters. Organic-rich facies also

prograde further south during the M6, indicating relative sea-level rise, deepening of the sub-basin, and formation of anoxic bottom-water conditions in a more widespread area in comparison to the TST.

Figure 3.8: Contour map showing average TOC for the M6 TST, including the Lexington and Logana members, and the Trenton Limestone equivalents to the north. Note the restriction of organic-rich facies to the Point Pleasant sub-basin, with a narrow tongue extending northwest into the Sebre Trough.

Figure 3.9: Contour map showing the average TOC for the M6 HST, including the Point Pleasant and the Trenton Limestone equivalents to the north.

During the time of the C1, there is a total shift of the depocenter of organic-rich facies in the Utica strata from the Point Pleasant sub-basin to the Pennsylvania basin (Figure 3.10). Facies in the Utica are more organic-lean than the Point Pleasant in eastern Ohio, but the Utica Shale becomes an organic rich unit moving into northwestern Pennsylvania in what Brett et al., 2004 refer to as the Pennsylvania basin (Figures 1.3 and 3.10). While the TOC content in the Utica Shale of the C1 appears to be nominal in the average TOC map, TOC values in the middle

Utica and upper Utica zones reach peak values of three to four weight percent, indicating that it is a viable source rock. Peak organic facies in the middle and upper Utica are easily identified by a high gamma-ray signature. These organic units are restricted to the area near the edge of the Trenton platform in Crawford County Pennsylvania and Ashtabula County Ohio, with a thin, organic, middle Utica zone extending south to the area between Columbiana County Ohio, and Butler and Armstrong County Pennsylvania (see figures 2.3 A, B, and C). In summary, the Point Pleasant contains the most organic rich facies to the south in eastern Ohio. Moving to the north, the Utica Shale becomes organic rich, a result of relative sea-level rise and deepening of the basin to the north.

Why organic-rich facies would move from distal to proximal in a subsiding basin during the progression of an orogeny is troublesome, and is interpreted to be a result of basement fault movement. While the C1 organic facies are more proximal to the source of the orogeny than the M6, the study area is still relatively distal with respect and the observed change is likely due to the formation of a separate sub-basin in which organic Utica shale units are deposited. Based on the trend of the distribution of organic-rich facies in the C1, the “Pennsylvania basin” is bounded to the north by the Tyrone-Mount Union lineament and to the south by the Pittsburgh-Mount Washington lineament. This basin is expressed as a pocket of organic facies in a cross-strike basin bounded by these lineaments.

Figure 3.10: Contour map showing the average TOC for the C1 TST, including the Utica Shale and the upper Trenton Limestone Equivalent to the north. Note the change in the depocenter of organic rich facies to coincide with the Pennsylvania Basin, in contrast to the Point Pleasant of the M6 sequence.

Chapter 4: Hydrocarbon Potential of the Utica-Point Pleasant Interval

Porosity Modeling

Porosity was modeled using data from the Barth #1 well in Coshocton County, Ohio (Appendix C, Figure 4.1). Porosity as a percentage of bulk volume was found to have a strong linear relationship of increasing porosity with decreasing bulk density, with an r^2 value of 0.832.

Figure 4.1: Porosity data vs. bulk density for the Fred Barth No. 1 (API 3403122838) in Coshocton County, Ohio. Porosity data from Wickstrom (2012).

The equation for the trend between porosity and bulk density was used to compute a continuous porosity model curve from the bulk density curve in the well logs. Porosity trends along with TOC (Figure 4.2), confirming the relationship between the two properties and the importance of TOC as a critical parameter in the evaluation of shale plays.

Figure 4.2: Well logs for the Fred Barth well showing the calculated porosity curve calibrated to core point values.

Water Saturation Modeling

Water saturation was modeled from the Archie Method using a user defined model in Petra after Crain (1986). The model uses effective porosity (PHIE), apparent water resistivity (R_w), formation resistivity (RES), and shale volume (VSH). Porosity is derived from the relationship between porosity and bulk density for the data from the Fred Barth core (Figure 4.1). Volume of shale (VSH) is computed from gamma ray using the equation:

$$VSH = \frac{(GR - GR_{clean})}{(GR_{shale} - GR_{clean})}$$

Where GR_{clean} is 20 API as read in the clean Trenton Limestone and GR_{shale} is 180 API as read in the highest gamma-ray Utica Shale. Pickett plots were generated for wells to determine the water resistivity at formation temperature (R_w)(Figure 4.3). The cementation, saturation, and tortuosity exponents were assumed to be 2.2, 2, and 1, respectively, and the R_w value was adjusted to fit the 100 percent water saturation line to the Trenton Limestone.

Figure 4.3: Pickett plot for the Utica-Point Pleasant using the calculated porosity log derived from the Fred Barth core data.

The most organic-rich, high porosity, and gas-bearing facies occur within the Point Pleasant and Logana submembers. In contrast to the organic-rich units in the Marcellus which are easily identified based on high gamma-ray signatures, the organic-rich units in the Utica-Point Pleasant are expressed in the gamma-ray log as dirty or shaly carbonates and do not stand out in gamma-ray as organic-rich units. The resistivity and density logs in the Point Pleasant show a strong deviation from the baseline values in the underlying clean Trenton Limestone, reflecting the organic richness in the Logana and Point Pleasant submembers (Figure 4.4). The modeled TOC curve computed from the trend of the density log with core derived TOC values shows the greatest TOC quantities in the Point Pleasant and Logana submembers, sharply decreasing into the underlying clean Trenton Limestone. The overlying Utica Shale shows marginal TOC quantities (1-2 weight percent) at this location in eastern Ohio, likely due to dilution from increased deposition of clastic and clay material as seen in the increase in the shale volume (VSH). The elevated resistivity in the Point Pleasant through Utica Shale indicates the presence of organic matter and associated in-situ hydrocarbons. The logs reflect the extremely low water saturation in the Point Pleasant where hydrocarbons dominate pore volume contents. Resistivity decreases into the organic-lean Utica Shale where water saturation increases.

Figure 4.4: Well log analysis of the Utica-Point Pleasant interval on the Chesapeake White #1 well in Carroll County, Ohio, USA. Normalized gamma-ray, RLA5 - Schlumberger Mode 5 laterolog resistivity, NPHI DM - neutron porosity dolomite matrix, RHOB - bulk density, TOC MOD - model computed TOC curve, CORE TOC - core sample TOC values, PHIA - average porosity from neutron/density porosity, VSH - shale volume from gamma-ray, SW - Archie generalized water saturation.

Rock-Eval Geochemistry

Rock-Eval pyrolysis is a method employed in determining the petroleum generative potential of source rocks. During the Rock-Eval Pyrolysis process, a sample of core or cuttings of organic

source rock is heated in the absence of oxygen to volatilize organic compounds. During heating, free organic compounds (bitumen) are distilled, after which pyrolytic products from remaining organic matter (kerogen) are cracked. These events are expressed as peaks on a plot in which the S1 peak corresponds to the amount of bitumen or free hydrocarbons within the sample, and the S2 peak corresponds to the remaining insoluble organic kerogen within the sample (Peters 1986). The results of this method are relatively simple and straightforward, in which the S1 and S2 peaks vary consistently with varying thermal maturity (Figure 4.5). In an organic-rich source rock, the S1 peak increases with increasing thermal maturity, reflecting the increase in the amount of organic matter that has been cracked to bitumen. Inversely, the S2 peak reflects generative potential or remaining insoluble organic kerogen and decreases with increasing maturity as the organic matter is consumed in generating bitumen or free hydrocarbons (Peters 1986). These trends are consistent with an ideal case in which none of the free hydrocarbons or bitumen has escaped the source rock. As maturity increases, much of the free hydrocarbons are cracked to lighter, gassier components (methane, ethane, propane) and escape the sample before Rock-Eval analysis is performed (Barker, 1974). The percentage of the S1 peak that is present as oil decreases as maturity increases, with the percentage of free gases increasing. In an actual case with gas escape, the S1 peak increases into the oil maturity phase, and decreases into the late oil to dry gas phase, reflecting the loss of free hydrocarbons from the sample due to organic permeability of the source rock. In theory, the S1 peak should reflect the total amount of hydrocarbons present within the rock. In reality, the S1 peak reflects the amount of oil present within the source rock due to the fact that free gaseous

hydrocarbons escape during sample recovery while oil is slower to migrate through low permeability shale and remains within the sample (Weinreich 2012).

Figure 4.5: Schematic of Rock-Eval pyrolysis data showing only the S1 and S2 peaks, modified from Peters (1986), Barker (1974), and Weinreich (2012).

Rock-Eval geochemistry data was used in this study to evaluate the thermal maturity and generative potential of organic-rich facies in the Utica-Point Pleasant interval. The S1 peak data were used in combination with TOC to calculate the normalized oil content (NOC) which is a key indicator of ideal maturity used in characterization and exploration in liquid-rich unconventional mudstone plays.

$$NOC = \frac{S1}{TOC} * 100$$

The normalized oil content trends with thermal maturity and consequently depth subsea, and shows a peak area indicating the zone of maximum oil generation. Moving to the

deeper and more mature areas, the NOC decreases as maturity increases indicating a greater proportion of gaseous hydrocarbons not detected in the S1 peak (Figure 4.6). To produce liquid hydrocarbons from horizontal wells in unconventional mudstone plays, there must be a drive to lift the heavier hydrocarbons up the wellbore. In order to produce liquids, there must be a component of gaseous hydrocarbons present to provide a driver for the expulsion of liquids. The peak area of NOC contour values corresponds to the maximum or peak oil generation line, indicating the zone of greatest liquids content, and is consistent with the findings of Cole et al. (1987) based on their geochemical analysis of samples of Point Pleasant rocks. Although this area contains the greatest proportion of liquids, there is a lack of gaseous hydrocarbons in the system resulting in low reservoir pressures and a lack of drive for the expulsion of liquids. Moving to the mature side increases the amount of gaseous hydrocarbons present in the system. On the mature downdip side of the NOC, gaseous hydrocarbons will be present to provide the reservoir drive for production of liquids (Weinrich 2012).

Figure 4.6: Contour map of the average normalized oil content of the Point Pleasant. The higher values in red indicate the most oil-rich rock, with the northeast-southwest trend corresponding to the maximum oil generation line. The thin interval with the transition from red to blue indicates the liquids rich fairway where a mixture of liquid and gaseous hydrocarbons is present. The blue indicates dry gas with little to no liquid hydrocarbons present.

Play Fairway and “Sweet Spot” Identification

The porosity curve computed with the data from the Fred Barth core was calculated using the bulk density log for all wells in the dataset. Two approaches were used in mapping the porosity data; one using the calculated average porosity for the Point Pleasant interval, and one using the calculated 90th percentile porosity value from the total range of values in the interval. The 90th percentile map is the focus here as it results in a peak porosity map showing

the distribution of the highest porosity Point Pleasant rocks. The porosity map correlates very strongly with the TOC map, as expected given that organic matter drives porosity within thermally mature mudstone (Passey et al., 2010)(Figure 4.7). The highest porosity Point Pleasant correlates with the regions of highest TOC in the Point Pleasant sub-basin where clastic and carbonate dilution are smallest. The edge of Washington and Greene counties, Pennsylvania, shows a sharp decrease in porosity likely due to clastic dilution where the Point Pleasant is more proximal to the clastic source to the east. A second trend is also present where porosity varies with thermal maturity. Porosity increases moving west to east from the immature window into the oil window (Figure 4.8), with western edge of the highest porosity rock correlating roughly with the zone of rich condensate maturity level. Porosity is highest where the Point Pleasant is in the dry gas window, where gas generation is at a maximum. As the organics in the Point Pleasant move from the oil window into the gas window, gaseous hydrocarbon generation increases organic porosity, which is at a maximum in the dry gas window.

Figure 4.7: Contour map of 90th percentile of porosity values for the Point Pleasant through Logana Shale.

Figure 4.8: Overlay of 90th percentile porosity values for the Point Pleasant through Logana Shale with normalized oil content. Maturity lines from Wickstrom et al. (2012)

The overlay of the normalized oil content and porosity are a key tool in pin-pointing the sweet spot where the Point Pleasant has the best reservoir properties as well as the ideal thermal maturity to produce commercial volumes of liquid hydrocarbons (Figure 4.8). To test this method, initial production data was gathered from investor presentations and press releases for some of the major operators in the play and normalized to barrel of oil equivalents per day (BOE/d) and percent liquids of total production. Percent liquids was color-mapped with

normalized oil content, and confirms that percentage of liquids in the total production increases with increasing normalized oil content (Figure 4.9). The IP rates of these wells also drastically decline into the oil window, where reservoir pressures decline due to a lack of gas in the system.

Figure 4.9: Contour map of normalized oil content overlain with oil and gas window lines, showing permitted and drilled Utica-Point Pleasant wells with percentage of liquids from initial production rates reported for selected test wells. Maturity lines from Wickstrom et al. (2012)

Initial production volume in BOE/d is mapped as proportional bubbles with the 90th percentile porosity contour map (Figure 4.10). The highest production volumes generally correlate with the area of highest porosity, though with some discrepancy. The location of the highest producing wells is skewed to the southern portion of the sweet spot, with a sharp split between the two occurring between Carroll and Harrison counties. Wells drilled in lower porosity reservoir to the south report higher production volumes than wells drilled in higher porosity reservoir to the north. Given that the reservoir porosity and thickness are relatively similar, one significant change between the two areas in the play is that the Utica Shale transitions from a low porosity source rock to a non-porous seal rock moving from north to south. Based on log analysis, the Utica Shale of Columbiana, Carroll, and Beaver counties has some organic richness (1-2 wt% TOC), porosity (2-3%), and hydrocarbon saturation, while the Utica shale to the south in Harrison, Belmont, and Guernsey is non-organic and non-porous (Figure 4.11). An initial conclusion was that the presence of organic Utica facies overlying the Point Pleasant would serve as extra “pay”, resulting in higher production from additional organic-rich strata. Based on reported initial production data, wells with greater initial production volumes are located in the southern portion of the play with a sharp dividing line between the greater producing wells and lesser producing wells (Figure 4.10). Inspection of the reservoir properties shows that this dividing line occurs where the Utica Shale transitions from an organic source rock to a non-organic seal rock (Figure 4.11). I conclude that in the southern part of the play, the non-porous shale overlying the Point Pleasant acts as a seal rock for generated hydrocarbons, resulting in over-pressured reservoir rock. The southern area also represents a somewhat condensed section with the highest, most concentrated amount of TOC

accumulation (Figure 3.9). As a result, the best production in the Point Pleasant fairway exists not where the greatest gross thickness of organic rock exists, but rather in the area where TOC and subsequent organic porosity are greatest.

Figure 4.10: Contour map of 90th percentile porosity values overlain with oil and gas window lines, showing permitted and drilled Utica-Point Pleasant wells. Initial production rates in barrel of oil equivalents are shown in proportional bubble symbols. Dashed line indicates the transition from organic-rich Utica Shale overlying the Point Pleasant to the north, to non-organic, non-porous Utica Shale overlying the Point Pleasant to the south. Maturity lines from Wickstrom et al. (2012).

Figure 4.11: Cross section F-F' through the core area of the Utica-Point Pleasant shale play showing petrophysical logs and properties. See Figure 1.1 for location of section.

Summary and Conclusions

Through sequence stratigraphic correlation of subsurface well logs and limited measured core sections, I have determined that

- The Lexington Limestone and Trenton Group through Utica Shale are a coarsening upward sequence, corresponding to the transgressive systems tract of a second-order sequence, where the middle, high gamma-ray interval of the Utica Shale corresponds to the maximum marine flooding surface.
- Three, third-order sequences are contained within this second-order sequence, correlative to the M5, M6, and C1 sequences of Holland and Patzkowsky (1997).
- Lowstand deposits are absent or unrecognizable, and sequences are bound by type 3 sequence boundaries that correspond to the amalgamation of the transgressive surface with the sequence boundary.
- The clean carbonates of the Curdsville Member of the Lexington Limestone reflect tectonic quiescence and widespread shallow-water conditions across the central Appalachian basin.
- Marl and shales of the Logana Shale Member and Point Pleasant Formation indicate the first pulse of tectonism driving a rise in relative sea-level during the Taconic orogeny. Organic facies within these units were deposited contemporaneously with the cleaner Trenton carbonates on the flanking Trenton and Lexington platforms.
- High angle normal faults along the northern edge of the Point Pleasant sub-basin generate steep paleo-topography along the platform edge, resulting in a sharp facies gradation from the Utica Shale into the coeval Trenton Limestone.

- An upper Utica unit is recognized that overlies the Utica shale of eastern Ohio, most evident in the northern part of the study area adjacent to the Tyrone-Mount Union lineament and the edge of the carbonate platform. This upper Utica unit floods the Trenton platform to the north into western New York and Ontario, and is hypothesized to be the equivalent of the Gulf Stream Formation and placed into the C2 sequence of Holland and Patzkowsky (1997).

Methods for predicting and calculating TOC were tested and applied to the Utica-Point Pleasant interval.

- Gamma-ray is useful in predicting TOC in the Utica Shale, but does not reflect TOC in the calcareous Point Pleasant.
- Simple regression between density and TOC shows a strong correlation, and the density log can be used to model TOC, with the exception of conditions of logs read in rugose boreholes where density readings are unreliable.
- Porosity and resistivity log separation of the Passey delta logR method varies positively with increases in TOC. Thermal maturity must be accounted for when calculating TOC from logR separation due to the fact that the resistivity of the source rock varies with the level of maturity of the rock.
- The most organic-rich Point Pleasant facies are located in east-central Ohio and southwestern Pennsylvania, while the most organic-rich Utica Shale facies is located in northwestern Pennsylvania and northeastern Ohio.

- Highest organic matter deposition and preservation is confined to the deeper water and presumably restricted circulation Point Pleasant sub basin.
- Rock-Eval pyrolysis data, in particular the normalized oil content, is beneficial in mapping both source potential and thermal maturity trends. Normalized oil content of the Point Pleasant shows northeast southwest trending maturity zones of maximum oil generation, a narrow liquids window, and a dry gas window. The best locations for targeting exist in the thin liquids window where heavier hydrocarbons exist in the presence of lighter dry gas to increase reservoir pressures and recovery factors.

References Cited

- Baird, G. C., and Brett, C. E., 2002, Indian Castle Shale: late synorogenic siliciclastic succession in an evolving Middle to Late Ordovician foreland basin, eastern New York State: *Physics and Chemistry of the Earth*, v. 27, p. 203-230.
- Baird, G. C., Brett, C. E., and Lehmann, D., 1992, The Trenton-Utica problem revisited: new observations and ideas regarding middle-late Ordovician stratigraphy and depositional environments in central New York, *in* R. H. April, ed., *Field Trip Guidebook: New York State Geological Association, 64th Annual Meeting*, p. 1-40.
- Barker, C., 1974, Pyrolysis techniques for source-rock evaluation: *AAPG Bulletin*, v. 58, No. 11, p. 2349-2361.
- Blakey, R., 2011, North American paleogeographic maps, <http://www2.nau.edu/rcb7/nam.html> Accessed March 13, 2013.
- Bowman, T., 2010, Direct method for determining organic shale potential from porosity and resistivity logs to identify possible resource plays: *AAPG Search and Discovery Article*, no. 110128.
- Boyce, M. L., 2010, Sub-surface stratigraphy and petrophysical analysis of the Middle Devonian interval of the central Appalachian Basin; West Virginia and Southwest Pennsylvania, PhD Thesis, West Virginia University, Morgantown, West Virginia, 158 p.
- Bradley, D. C., and Kidd, W. S., 1991, Flexural extension of the upper continental crust in collisional foredeeps: *Geological Society of America Bulletin*, v. 103, p. 1416-1438.
- Brett, C. E., and Baird, G. C., 2002, Revised stratigraphy of the Trenton Group in its type area, central New York State: sedimentology and tectonics of a Middle Ordovician shelf-to-basin succession: *Physics and Chemistry of the Earth*, v. 27, p. 231-263.
- Brett, C. E., McLaughlin, P. I., Cornell, S. R., and Baird, G. C., 2004, Comparative sequence stratigraphy of two classic upper Ordovician successions, Trenton shelf (New York-Ontario) and Lexington platform (Kentucky-Ohio): Implications for eustacy and local tectonism in eastern Laurentia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 210, p. 295-329.
- Brookfield, M. E., and Brett, C. E., 1987, Paleoenvironments of the mid-Ordovician (Upper Caradocian) Trenton Limestones of southern Ontario, Canada: Storm sedimentation on a shoal-basin shelf model: *Sedimentary Geology*, no. 57, p. 75-105.
- Catuneanu, O., 2006, *Principles of Sequence Stratigraphy* ix: Amsterdam, Boston, Heidelberg, Elsevier, 375 p.

- Cisne, J., Karig, D., Rabe, B., and Hay, B., 1982, Topography and tectonics of the Taconic outer trench slope as revealed through gradient analysis of fossil assemblages: *Lethaia* v. 15, p. 229-246.
- Cole, G. A., Drozd, R. J., Sedivy, R. A., and Halpern, H. I., Organic geochemistry and oil-source correlations, Paleozoic of Ohio: *AAPG Bulletin*, v. 71, no. 7, p. 788-809.
- Cornell, S. R., 2008, The last stand of the great American carbonate bank: tectonic activation of the upper Ordovician passive margin in eastern North America, PhD Thesis, University of Cincinnati, Cincinnati, Ohio, 854 p.
- Crain, E. R., 1986, *The Log Analysis Handbook Volume One – Quantitative Methods*, Tulsa, Pennwell Books, 684 p.
- Ohio Division of Geological Survey, 2013, Utica Shale source rock data: Ohio Department of Natural Resources, Division of Geological Survey, 1 sheet, accessed at <http://www.ohiodnr.com/Portals/10/Energy/Utica/Utica_SourceRock_Analysis_Data_3_5_2013.xls>. [Updated March 5, 2013.]
- Embry, A. F., 1995, Sequence boundaries and sequence hierarchies: problems and proposals, *in* R. J. Steel et al., eds., *Sequence Stratigraphy on the Northwest European Margin: Norwegian Petroleum Society (NPF) Special Publication 5*, p. 1-11.
- Embry, A. F., 2002, Transgressive-regressive (T-R) sequence stratigraphy: Gulf Coast SEPM Conference Proceedings, p. 151-172.
- Ettensohn, F. R., and Brett, C. E., 2002, Stratigraphic evidence from the Appalachian Basin for continuation of the Taconian orogeny into early Silurian time: *Physics and Chemistry of the Earth*, v. 27, p. 279-288.
- Finney, S. C., Grubb, B. J., and Hatcher, R. D. Jr., 1996, Graphic correlation of middle Ordovician graptolite shale, southern Appalachians: An approach for examining the subsidence and migration of a Taconic foreland basin: *GSA Bulletin*, v. 108, no. 3, p. 355-371.
- Fisher, D. W., 1977, Correlation of the Hadrynian, Cambrian and Ordovician Rocks in New York State. New York State museum Map and Chart Series 25, 75 p.
- Goldman, D., Mitchell, C. E., and Joy, M. P., 1999, The stratigraphic distribution of graptolites in the classic upper Middle Ordovician Utica Shale of New York State: and evolutionary succession or a response to relative sea-level change?: *Paleobiology*, v. 25, no. 3, p. 273-294.

- Holland, S. M., 1993, Sequence stratigraphy of a carbonate-clastic ramp: the Cincinnati Series (Upper Ordovician) in its type area, *Geological Society of America Bulletin*, v. 105, p. 306-322.
- Holland, S. M., and Patzkowsky, M. E., 1996, Sequence stratigraphy and long-term paleoceanographic change in the middle and upper Ordovician of the eastern United States, *in* B. J. Witzke et al., eds., *Paleozoic sequence stratigraphy: Views from the North American craton*: Geological Society of America Special Paper 306, p. 117–129.
- Holland, S. M., and Patzkowsky, M. E., 1997, Distal orogenic effects on peripheral bulge sedimentation: Middle and Upper Ordovician of the Nashville Dome: *Journal of Sedimentary Research*, v. 67, p. 250–263.
- Holland, S. M., and Patzkowsky, M. E., 1998, Sequence Stratigraphy and relative sea-level history of the middle and upper Ordovician of the Nashville dome, Tennessee: *Journal of Sedimentary Research*, v. 68, no. 4, p. 684-699.
- Holland, S. M., and Patzkowsky, M. E., 2008 Sequence Stratigraphy of the Middle and Upper Ordovician of the eastern United States, UGA Stratigraphy Lab, <http://strata.uga.edu/ordoss/Correlation2008d.pdf>, Accessed March 13, 2013.
- Jacobi, R. D. and C. E. Mitchell, 2002, Geodynamical interpretation of a major unconformity in the Taconic foredeep: slide scar or onlap unconformity?: *Physics and Chemistry of the Earth*, v. 27, 169-201.
- Joy, M. P., Mitchell, C. E., and Adhya, S., 2000, Evidence of a tectonically driven sequence succession in the Middle Ordovician Taconic foredeep: *Geology*, v. 28, no. 8, p. 727– 730
- Kirchner, B. T., and Brett, C. E., 2008, Subsurface correlation and paleogeography of a mixed siliciclastic-carbonate unit using distinctive faunal horizons: toward a new methodology: *Palaos*, v. 23, p. 174-184.
- Kohl, D., 2012, Sequence stratigraphy and depositional environments of the Shamokin (Union Springs) Mbr., Marcellus Fm. and associated strata in the middle Appalachian basin, MS thesis, Pennsylvania State University, University Park, Pa, 68 p.
- Kolata, D. R., Huff, W. D., and Bergstrom, S. M., 2001, The Ordovician Sebree trough: An oceanic passage to the Midcontinent United States: *GSA Bulletin*, v.113, no. 8, p. 1067-1078.
- Lash, G. G., and Engelder, T., Thickness trends and sequence stratigraphy of the Middle Devonian Marcellus Formation, Appalachian Basin: Implications for Acadian foreland basin evolution: *AAPG Bulletin*, v. 95, no. 1, p. 61-103.

- Lehmann, D., Brett, C. E., Cole, R., and Baird, G., 1995, Distal sedimentation in a peripheral foreland basin: Ordovician black shales and associated flysch of the western Taconic foreland, New York State and Ontario: *GSA Bulletin*, v. 107, no. 6, p. 708-724.
- McLaughlin, P. I., and Brett, C. E. 2007, Signatures of sea level rise on the carbonate margin of a late Ordovician foreland basin: A case study from the Cincinnati arch, USA: *Palaaios*, v. 22, p. 245-267.
- McLaughlin, P. I., Brett, C. E., Taha McLaughlin, S. L., and Cornell, S. R., 2004, High-resolution sequence stratigraphy of a mixed carbonate-siliciclastic, cratonic ramp (Upper Ordovician; Kentucky-Ohio, USA): insights into the relative influence of eustasy and tectonics through analysis of facies gradients: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 210, p. 267-294.
- Mitchell, C. E., Adhya, S., Bergstrom, S. M., Joy, M. P., and Delano, J. W., 2004, Discovery of the Ordovician Millbrig K-bentonite bed in the Trenton Group of New York State: implications for regional correlation and sequence stratigraphy in eastern North America: *Palaeogeography, Palaeogeography, Palaeoecology*, v. 210, p. 331-346.
- Mitchell, C. E., Joy, M. P., Adhya, S., and Delano, J. W., 1998, Onlap timing of the organic-rich Antes and Utica Shales (Middle Ordovician) in the Taconic foredeep of Pennsylvania and New York; the role of tectonic subsidence and eustasy: *Abstracts with Programs - Geological Society of America*, v. 30, no. 7, p. 396-396.
- Nuttall, B. C., 1996, Play Obc: Middle and Upper Ordovician bioclastic carbonate ("Trenton") play. *In* J. B. Roen, and B. J. Walker, eds., *The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25*, p. 168-171.
- Ohio Division of Geological Survey, 2012, Utica Shale source rock data: Ohio Department of Natural Resources, Division of Geological Survey, 1 sheet, accessed at <http://www.ohiodnr.com/Portals/10/Energy/Utica/Utica_SourceRock_Analysis_Data_12_18_2012.xls>. [Updated December 18, 2012.]>
- Passey, Q. R., Bohacs, K. M., Esch, W. L., Klimentidis, R., and Sinha, S., 2010, From oil-prone source rock to gas-producing shale reservoir: geologic and petrophysical characterization of unconventional shale-gas reservoirs: *Society of Petroleum Engineers paper 131350*.
- Passey, Q. R., Creaney, S., Kulla, J. B., Moretti, F. J., and Stroud, J. D., 1990, A practical model for organic richness from porosity and resistivity logs: *AAPG Bulletin*: v. 74, p. 1777-1794.
- Patchen, D. G., Hickman, J. B., Harris, D. C., Drahovsal, J. A., Lake, P. D., Smith, L. B., Nyahay, R., Schulze, R., Riley, R. A., Baranoski, M. T., Wickstrom, L. H., Laughrey, C. D., Kostelnik, J.,

- Harper, J. A., Avary, K. L., Bocan, J., Hohn, M. E., and McDowell, R., 2006, A geologic play book for Trenton-Black River Appalachian basin exploration:
- Peters, K. E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis: AAPG Bulletin, v. 70, no. 3, p. 318-329.
- Peters, K. E., Whelan, J. K., Hunt, J. M., Tarafa, M. E., 1983, Programmed pyrolysis of organic matter from thermally altered Cretaceous black shales: AAPG Bulletin, v. 67, no. 11, p. 2137-2146.
- Pope, M. C., and Read, J. F., 1998, Ordovician metre-scale cycles: Implications for climate and eustatic fluctuations in the central Appalachians during a global greenhouse, non-glacial to glacial transition: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 138, p. 27-42.
- Pope, M., and Read, J. F., 1997, High-resolution surface and subsurface sequence stratigraphy of Late Middle to Late Ordovician (Late Mohawkian-Cincinnatian) foreland basin rocks, Kentucky and Virginia: AAPG Bulletin, v. 81, no. 11, p. 1866-1893.
- Riley, R.A., 2010, A Utica-Point Pleasant type log for eastern Ohio: Ohio Department of Natural Resources, Division of Geological Survey, one sheet (PDF), available at <http://www.dnr.state.oh.us/Portals/10/Energy/Utica/TuscarawasWellRockAnalyses.pdf>
- Rowley, D. H., and Kidd, W. S. F., 1991, Stratigraphic relationships and detrital composition of the Middle Ordovician flysch of western New England: implications for the evolution of the Taconic Orogeny: *Journal of Geology*, v. 89, p. 199-218.
- Ruedemann, R., 1912, The lower Siluric shales of the Mohawk Valley: *New York State Museum Bulletin* 162, 151 p.
- Ruedemann, R., 1925, The Utica and Lorraine Formations of New York, part I: Stratigraphy: *New York State Museum Bulletin* 258, 176 p.
- Ryder, R. T., Burruss, R. C., and Hatch, J. R., 1999, Black shale source rocks and oil generation in the Cambrian and Ordovician of the central Appalachian basin, USA: AAPG Bulletin, v. 82, no. 3, p. 412-441.
- Ryder, R.T., 2008, Assessment of Appalachian basin oil and gas resources: Utica-Lower Paleozoic Total Petroleum System: U.S. Geological Survey Open-File Report 2008-1287, 29 p.
- Smosna, R., and Patchen, D. G., 1991, Ordovician Limestone and Shale in the Central Appalachian Basin: Early Sedimentary Response to Plate Collision. SEPM Core Workshop No. 15, Dallas, April 7, 1991.

- Vail, P. R., Mitchum, R. M. Jr., and Todd, R. G., 1977, Seismic stratigraphy and global changes of sea level, *in* C.E. Payton, ed., Seismic Stratigraphy: Applications to Hydrocarbon Exploration. AAPG Memoir 26, p. 49-212
- Weinrich, M., 2012, Petrophysical Evaluation of Mudstone Reservoirs: Eastern Section AAPG Short-Course, September 23, 2012.
- Wickstrom, L. H., Riley, R., Erenpreiss, M., and Perry, C., 2012, Geologic overview and activity update for the Utica-Point Pleasant shale play in Ohio: AAPG Search and Discovery Article No. 10409.
- Witzke, B. J., 1990, Palaeoclimactic constraints for Paleozoic palaeolatitudes of Laurentia and Euramerica, *in* W. S. McKerrow and C. R. Scotese, eds., Paleozoic Palaeogeography and Biogeography Memoir, vol. 12, Geological Society of London, London, England, pp. 57-74.

Appendix A: Measured core log and facies descriptions for the Fred Barth well, Redstone Corporation, Coshocton County, Ohio, API 34-031-22838, Lat. 40.306454°N, Lng. -81.779842°W.

Key to Symbols			
	Bryozoans		Wavy Lams
	Brachiopods		Soft sed def
	Intraclasts		Cross Bedding
	Burrows		Crinoids

Bioclastic packstones w/ scoured, undulating basal contacts
Trilobites, Brach's

Calc. black siltstone, shell hash horizons thinner and less abundant than below

Dk grey calcareous siltstone interbedded with shell hash horizons

Black Marl, PPL, some thin pyritized lag beds

Thin shell hash horizons

Grading up into black marl

6' packstone

Thin packstone, undulating base

Black marl, PPL, thin calcareous sand lenses.

Fossil hash beds thinner and less abundant than below

Bioclastic packstones (brach. shells) interbedded w/ dk. grey calc. mudstone, black siltstone rip-up clasts. Packstones with undulating, scoured basal surfaces, pinch and swell. Shells reworked and overturned.

Dark Grey to Black lime mudstone, brach. hash horizons with scoured, undulating base, gradational top.

Dark grey to black lime mudstone, brachiopod hash horizons with gradational to sharp base, coarsening up, sharp upper contact.

Appendix B: Measured core log and facies descriptions for the Power Oil Company Core Log, Wood County West Virginia, API 47-107-00351, Lat. 39-257038°N, Lng. -81.272220°W.

Appendix C: Summary of porosity and permeability analysis for the Fred Barth Core,
Coshocton County, Ohio, API 34-031-22838.

Depth (ft)	Dry helium porosity (%bv)	Pulse decay perm (md)	A-R bulk density (g/cm ³)	Dry bulk density (g/cm ³)
5630.4	4.1	2.41E-05	2.65	2.63
5640.8	5.2	1.09E-04	2.55	2.53
5660	4.7	2.04E-04	2.55	2.53
5661.5	4.9	5.63E-04	2.54	2.51
5664	4.5	5.70E-04	2.54	2.52
5674.5	6.5	2.19E-04	2.5	2.48
5678.5	5.2	3.39E-04	2.53	2.5
5680.5	5.2	4.30E-04	2.52	2.5
5681.5	5.3	1.26E-04	2.54	2.52
5682.5	6.8	6.63E-05	2.49	2.46
5684.5	6.6	1.68E-04	2.5	2.47
5701.6	4	4.70E-05	2.56	2.54
5704.6	3.7	8.96E-05	2.6	2.59
5715.5	4.1	2.23E-05	2.6	2.58
5716.9	3.8	4.83E-05	2.59	2.57
5734	4	1.60E-04	2.59	2.57
5737	4.1	3.81E-05	2.56	2.54
5738.5	4	1.38E-04	2.57	2.55
5740	4.1	3.18E-04	2.59	2.56
5745.5	3.5	6.98E-05	2.57	2.56