Petroleum Geology of the Utica/Point Pleasant Play in Washington County, Ohio

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The early Late Ordovician interval, known as the Utica-Point Pleasant play, in southeastern Ohio is poorly constrained due to limited data sets. A previous study by the Appalachian Basin Oil & Natural Gas Research Consortium and partners evaluated the interval across the Appalachian Basin using five cores. For this study, unpublished data from well Farley 1305-H, located in Washington County, Ohio, was used to better evaluate the Utica-Point Pleasant play in southeastern Ohio. The data include geophysical logs, Rock-Eval pyrolysis, mineralogy, triaxial testing, gas desorption, and porosity data. The Point Pleasant Formation, in regards to well Farley 1305-H and proximal area, has sufficient TOC (avg. 2.4 wt. %), gas-filled porosity (avg. 4.75 %), minerology (normalized clay value of 32%), and geomechanical properties to be a successful unconventional play. Geophysical logs correlate the formation's high organic content and porosity. Calculations of % Ro values (avg. 1.6) are parallel to gas composition data, which indicates that a good portion of gas in place is wet and dry. The Utica Shale was determined to be a poor unconventional reservoir in regards to well Farley 1305-H, lacking conducive TOC (< 1 wt. %), gas-filled porosity (< 2 %), mineralogy (normalized clay value of 49 %), and geomechanical properties.

Petroleum Geology of the Utica/Point Pleasant Play in Washington County, Ohio

A Thesis

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by

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Table of Contents

List of Tables

List of Figures

Introduction

This study presents pertinent geochemical and mechanical data for the early Late Ordovician interval in Washington County, Ohio, using data from well Farley 1305-H. These strata include the Utica Shale, Point Pleasant Formation, and Lexington Limestone, which are of great interest to all parties involved with natural gas production in the Appalachian Basin. The aforementioned data set delineates geological parameters within the interval that dictate many aspects of gas production potential.

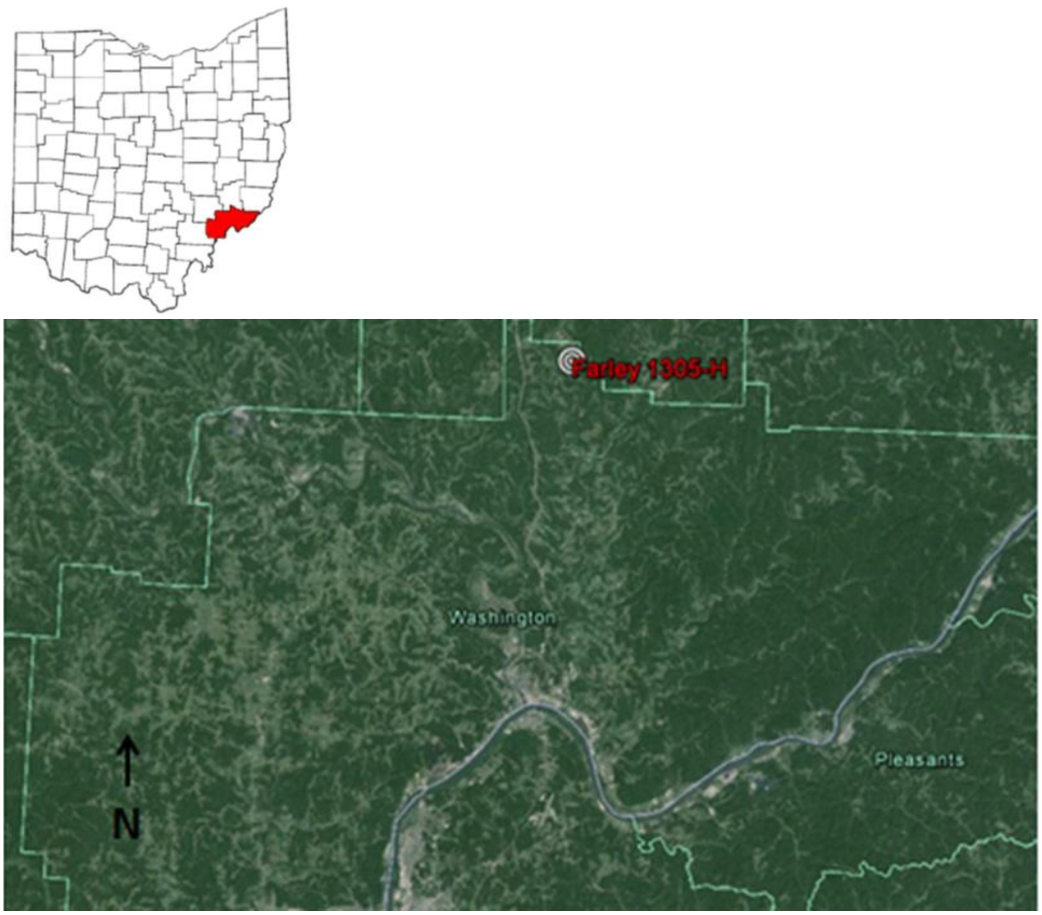
Modern production from the Late Ordovician interval (represented by the encompassing term, "Utica Shale") began in Ohio in 2011 (ODNR). As of May, 2016, the state has issued 2176 horizontal permits, with 1744 of those presently drilled. However, only five producing wells exist in Washington County. Because of this shortage of wells in Washington County, the petroleum geology of the Utica Shale is not well understood. In this thesis, I characterize the Late Ordovician interval via well Farley 1305-H in terms of its petroleum geology in order to better assess future hydrocarbon exploration in the county and proximal areas.

Previous Studies

An extensive research project on the same strata, "The Geologic Play Book for Utica Shale Appalachian Basin Exploration," (hereafter known as the Utica Playbook and formally cited as Patchen and Carter, 2015) was completed in 2015 through a coordinated effort of personnel from the Appalachian Basin Oil & Natural Gas Research Consortium (AONGRC), the Kentucky Geological Survey (KGS), the Ohio Division of Geological Survey (ODGS), The Pennsylvania Geological Survey; the West Virginia Geological and Economic Survey (WVGES), the U.S. Department of Energy (DOE), and with financial support of fifteen oil and gas companies. The Utica Playbook's mission was to: "(1) characterize and assess the lithology, source rock geochemistry, stratigraphy, depositional environment(s) and reservoir characteristics of Utica and equivalent rocks in the northern Appalachian basin; (2) define Utica oil and gas fairways by integrating regional mapping work with drilling activity and production tracking efforts; and (3) provide probabilistic and volumetric Utica resource assessments informed by geologic and geochemical data" (Patchen and Carter, 2015). Despite the large scale of the Utica Playbook, the researchers were limited to five cores to analyze and limited data from those cores. Therefore, the data sets within this study contribute to the mission of the Utica Playbook, and offer the largest agglomeration of core analyses to date on the Utica/Point Pleasant interval, including organic geochemistry, thermal maturity, mineralogy, gas composition, porosity and permeability, and geomechanical moduli through core Farley1305-H.

Study Area

The study area is limited to Washington County, Ohio (Figs. 1a & 1b). However, much of the data can be extrapolated outside the county. The Farley 1305-H well head is at 39.6189429° and -81.419324°. The well is owned and operated by Triad Hunter, LLC, a subsidiary of Magnum Hunter Resources Corporation. The well was assigned the API number 34167297200100.



Figures 1a, Washington County, Ohio shown in red. Figure 1b, shows the location of well Farley 1305-H in northern Washington County.

Geologic Background

In the Early to Middle Ordovician, the southern margin of Laurentia was located between 20-25° south latitude (McLaughlin et al., 2004) (Blakey, 2011, Fig. 2). The craton's passive margin was covered by shallow water during the development of the Great American Carbonate Bank, an umbrella term used to describe a system of carbonates and siliciclastics (Cornell, 2008). Tectonism related to the Taconic orogeny accreted island arcs, creating the Point Pleasant sub-basin through fault movement and subsidence (Cornell, 2008) (Fig. 3).

Figure 2, Paleogeographic map of North America during the Late Ordovician, modified from Blakey (2011).

Surrounding the sub-basin, carbonate platforms formed, called the Trenton to the northwest and the Lexington to the southeast. The Trenton and Lexington shoaled upward as the epeiric seas transgressed, with the Point Pleasant Formation forming coevally within the sub-basin during the late Mohawkian/early Cincinnatian (McClain, 2012) (Fig. 3). Eustatic fluctuations and tectonics caused the Point Pleasant Formation to have alternating limestone and shale as the result of variable sediment flux (Fig. 4). As a second-order transgression continued in the Late Ordovician, the Point Pleasant Formation and surrounding carbonates were drowned and overlain by the Utica Shale.

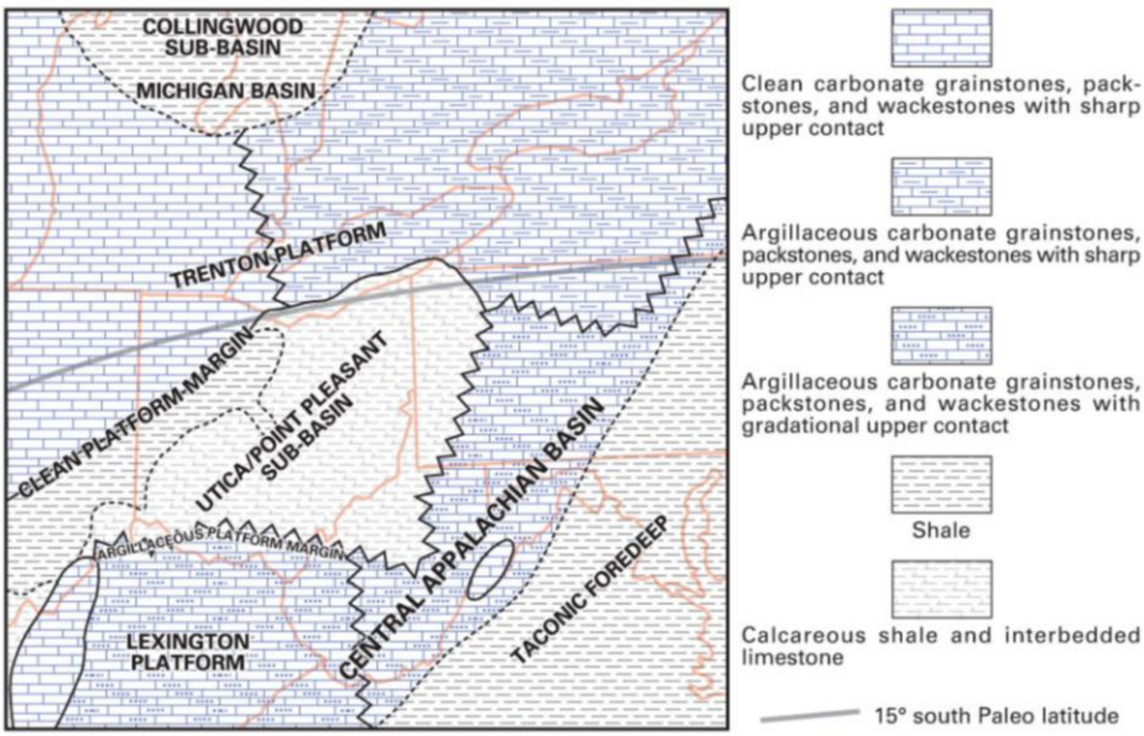


Figure 3, Diagram of the study area during early Late Ordovician, Wickstrom, (2013), from Patchen et al., (2006).

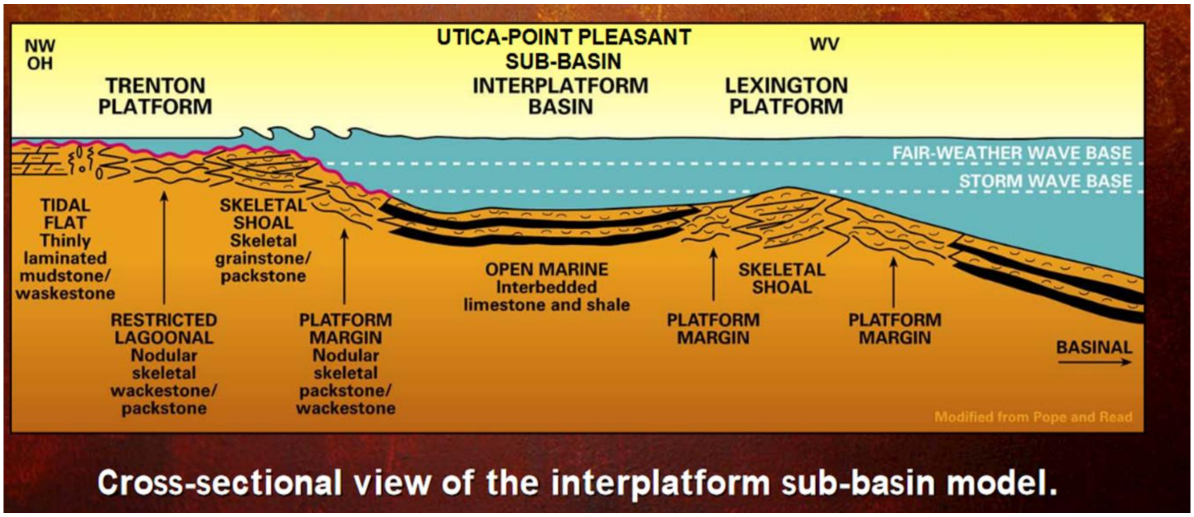


Figure 4, Cross-section representation of the Point Pleasant sub-basin model, modified from Wickstrom et al., (2012).

Lithostratigraphy

This study focuses on the petroleum geology of a large portion of the early Late Ordovician strata of eastern Ohio. These strata include the Utica Shale, Point Pleasant Formation, and Lexington Limestone (Fig. 5). Two members make up the lower half of the Lexington Limestone: the Logana and the Curdsville, which are mainly differentiated based on their organic-rich (Logana) versus organic-poor and carbonate-rich (Curdsville) lithology (Patchen and Carter, 2015). Because the Point Pleasant Formation is the main hydrocarbon target, the underlying members will be informally referred to as the Lexington Limestone.

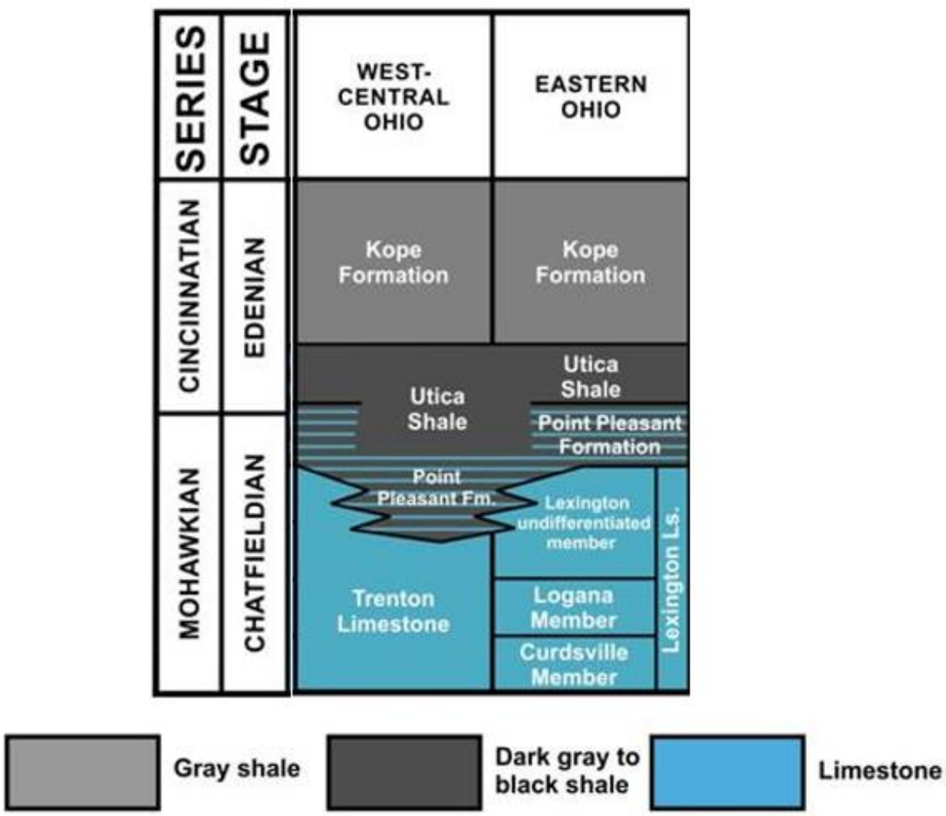


Figure 5, Stratigraphic column for early late Ordovician strata across Ohio, modified from "A Geologic Playbook for Utica Shale Appalachian Basin Exploration" (2015).

Utica Shale, as defined in the Utica Playbook, is a term used to represent the interval between the Kope and Point Pleasant Formations (Patchen and Carter, 2015). It is a clay-rich, organic-lean shale within the study area. It pinches out to the south in southern Ohio and West Virginia, and extends to the southwest towards the Kentucky-Indiana border and to the north, through New York and slightly into Canada (Fig. 6).

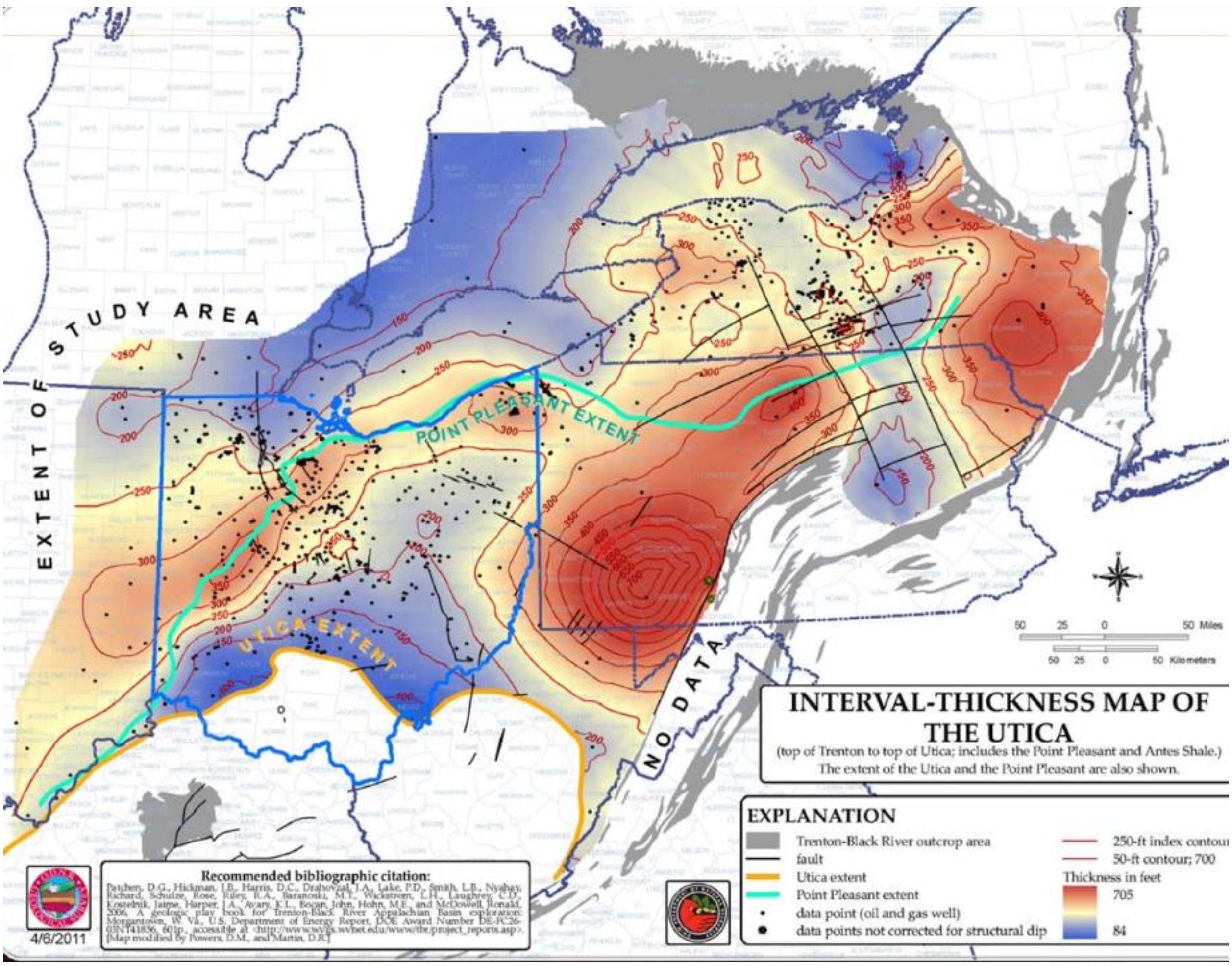


Figure 6, Isopach and extent map of the Utica Shale and Point Pleasant Formation, from Wickstrom (2012) via Patchen et al. (2011).

The Point Pleasant Formation includes alternating subunits of black shale and organic-rich limestone that are positioned between the Trenton Group and Lexington Limestone. It is from the Point Pleasant Formation that the main natural gas production is derived in eastern

Ohio. It pinches out to the south in southern Ohio and West Virginia, and extends to most of northern Ohio and northwestern and north-central Pennsylvania (Fig. 6).

The Lexington Limestone interval includes the "Lexington Undifferentiated Member," which is considered a cleaner limestone with abundant fossils (bryozoans, brachiopods, mollusks, and trilobite fragments) and clay-sized carbonate matrix. The Logana Member represents an interbedded calcisiltite, shale, and coquinoid limestone (Patchen and Carter, 2015). The Curdsville Member, the basal strata of the Lexington Limestone, is a bioclastic calcarenite that was deposited during the initial transgression of the Lexington Sea.

Sequence Stratigraphy

The Trenton/Lexington through Utica interval is interpreted as a transgressive systems tract within a second-order sequence and is representative of a transition from carbonates to siliciclastics (McClain, 2012). Within this interval, there are four third-order sequences. These sequences are delineated chronostratigraphically in southeastern Ohio as the Curdsville Member (S1); the Lexington/Logana Members (S2); Lower Utica/Point Pleasant Formation (S3); and the Upper Utica Shale (S4) (Fig. 7). These third-order sequences are regionally correlative and aggradation, without low-stand deposits, results in separation by type 3 sequence boundaries (McClain 2012).

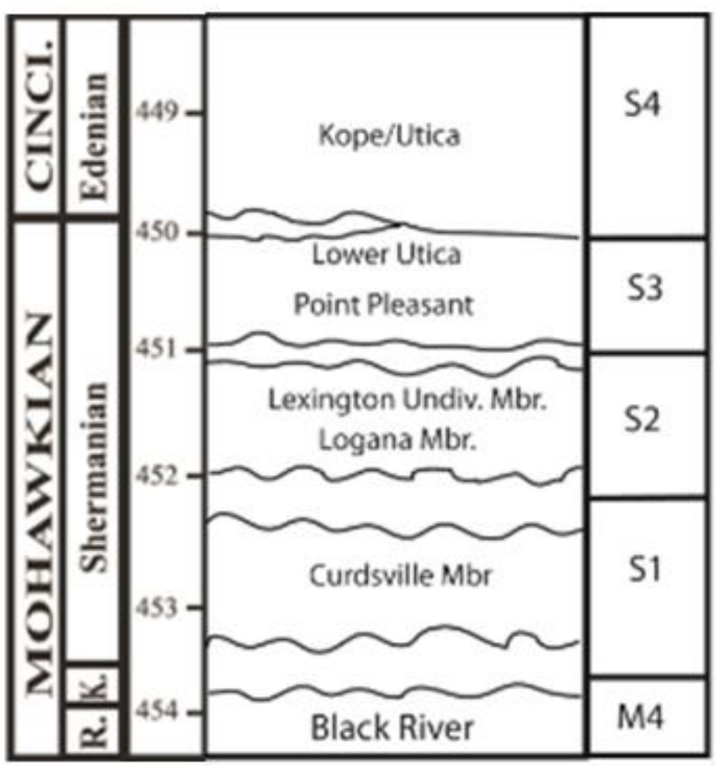


Figure 7, Chronostratigraphic and sequence stratigraphic diagram of the Late Ordovician strata in eastern Ohio, modified from

Methods

All of the datasets in this study (were generously provided) and represent well Farley 1305-H in Washington County, Ohio. The Farley 1305-H well is located at 39.636447 latitude and -81.419324 longitude. The well was drilled to a depth of 8164 feet, with a bottom temperature of 149 ºF. Much of the data was attained from analysis on ~195 feet of core that came from an interval of 7785 to 7980 feet, approximately. This study contains the following datasets and analyses:

- Source rock analysis (Rock-Eval 6: Version 4.09), performed by Core Laboratories.
- Porosity analysis, performed by Core Laboratories.
- Whole rock mineralogy via XRD analysis, performed by Core Laboratories.
- Triaxial compressive test data, performed by Core Laboratories.
- Core degassing and gas composition analysis data, performed by Core Laboratories.
- Geophysical logs, performed by Halliburton, used to correlate third-order sequence boundaries.

Results

Rock-Eval Pyrolosis

Core Farley 1305-H was analyzed via Rock-Eval pyrolysis by Core Laboratories. Core Laboratories tested for total organic carbon (TOC), S1 through S3, and Tmax. The values include 13 samples for the Utica Shale, 16 samples for the Point Pleasant Formation, and 9 samples for the Lexington Limestone (Table 1).

Total Organic Carbon

A table of total organic carbon (TOC) values in weight percent for core Farley1305-H is shown in Table 1. The TOC distribution ranges from 0.16 to 0.91 % in the Utica Shale, 0.72 to 4.6 % in the Point Pleasant Formation, and 0.03 to 2.06 % in the Lexington Limestone.

S1, S2, S3, & Tmax

Values of S1, S2, and S3 for core Farley1305-H are shown in Table 1. The S1 distribution ranges from 0.04 to 0.22 (mg HC/g) in the Utica Shale, 0.14 to 1.34 (mg HC/g) in the Point Pleasant Formation, and 0.03 to 0.59 (mg HC/g) in the Lexington Limestone. The S2 distribution ranges from 0.09 to 0.31 (mg HC/g) in the Utica Shale, 0.29 to 1.83 (mg HC/g) in the Point Pleasant Formation, and 0.07 to 0.68 (mg HC/g) in the Lexington Limestone. The S3 distribution ranges from 0.06 to 0.11 (mg CO_2/g) in the Utica Shale, 0.08 to 0.16 (mg CO_2/g) in the Point Pleasant Formation, and 0.06 to 0.19 (mg CO_2/g) in the Lexington Limestone.

Tmax values were discerned from S2 results and included 11 samples (2 were considered unreliable) for the Utica Shale, 16 samples for the Point Pleasant Formation, and 6 (3 were considered unreliable) samples for the Lexington Limestone (Table 1). The Tmax distribution ranges from 491 to 503 (°C) in the Utica Shale, 471 to 491 (°C) in the Point Pleasant Formation, and from 487 to 501(°C) in the Lexington Limestone.

Sample ID	Depth ft.	Sample Wt. mg	TOC wt%	S1 mg HC/g	S2 mg HC/g	S3 CO_2 mg CO2/g	S3 CO mg CO/g	Tmax ˚ C	HI S2x100/TOC	OI S3x100/TOC	PI (S1/(S1+S2))	(S1/TOC)*100 mg HC/g TOC	MINC %	Remarks Comments
1	7787.15	60.2	0.23	0.04	0.09	0.08	0.01	491	39.13	34.78	0.31	17.39	2.34	Upper and lower temperature S2 shoulders
2	7792.1	60.5	0.19	0.05	0.11	0.06	0.02	330	57.89	31.58	0.31	26.32	1.43	Unreliable Tmax
3	7797	60.8	0.31	0.06	0.17	0.07	0.01	501	54.84	22.58	0.26	19.35	1.17	Upper and lower temperature S2 shoulders
4	7802.1	60.1	0.25	0.09	0.2	0.08	0.01	495	80.00	32.00	0.31	36.00	1.28	Upper and lower temperature S2 shoulders
5	7807.05	60.7	0.19	0.05	0.15	0.08	0.01	501	78.95	42.11	0.25	26.32	1.91	Upper and lower temperature S2 shoulders
6	7812	60.5	0.16	0.05	0.14	0.07	0.01	341	87.50	43.75	0.26	31.25	2.14	Unreliable Tmax
7	7817.35	60	0.32	0.1	0.14	0.06	0.01	503	43.75	18.75	0.42	31.25	3.57	Upper and lower temperature S2 shoulders
8	7822	60	0.35	0.09	0.17	0.08	0.02	496	48.57	22.86	0.35	25.71	1.97	Upper and lower temperature S2 shoulders
9	7827	60.9	0.65	0.17	0.25	0.08	0.01	493	38.46	12.31	0.40	26.15	1.85	Upper and lower temperature S2 shoulders
10	7832	61.3	0.5	0.15	0.25	0.09	0.01	491	50.00	18.00	0.38	30.00	2.40	Upper and lower temperature S2 shoulders
11	7837	60	0.68	0.14	0.24	0.08	0.01	495	35.29	11.76	0.37	20.59	2.88	Upper and lower temperature S2 shoulders
12	7842	61.1	0.49	0.14	0.23	0.08	0.02	495	46.94	16.33	0.38	28.57	2.47	Upper and lower temperature S2 shoulders
13	7847.3	60.4	0.91	0.22	0.31	0.11	0.01	496	34.07	12.09	0.42	24.18	2.59	high temperature S2 shoulder
14	7852	60.5	2.93	0.34	0.91	0.16	0.02	486	31.06	5.46	0.27	11.60	3.24	high temperature S2 shoulder
15	7857	60.2	0.72	0.23	0.29	0.1	0	474	40.28	13.89	0.44	31.94	7.91	high temperature S2 shoulder
16	7862	59.5	1.86	0.68	0.7	0.11	0	483	37.63	5.91	0.49	36.56	5.27	high temperature S2 shoulder
17	7867	60	1.77	0.44	0.72	0.1	0.01	491	40.68	5.65	0.38	24.86	4.34	high temperature S2 shoulder
18	7872	59.9	1.9	0.42	0.76	0.11	0.01	491	40.00	5.79	0.36	22.11	4.39	high temperature S2 shoulder
19	7877.6	60	2.33	0.5	0.79	0.1	0.04	486	33.91	4.29	0.39	21.46	3.73	high temperature S2 shoulder
20	7882	59.3	2.25	0.62	0.91	0.1	0.01	487	40.44	4.44	0.41	27.56	3.99	high temperature S2 shoulder
21	7887	60.4	2.13	0.9	0.75	0.13	0.01	479	35.21	6.10	0.55	42.25	5.23	high temperature S2 shoulder
22	7892	59.9	2.59	0.52	0.96	0.11	0.03	486	37.07	4.25	0.35	20.08	4.63	high temperature S2 shoulder
23	7897	60.1	3.63	1.04	1.45	0.14	0.01	486	39.94	3.86	0.42	28.65	4.29	high temperature S2 shoulder
24	7902	59.8	2.41	0.85	0.53	0.13	0.01	471	21.99	5.39	0.62	35.27	4.84	high temperature S2 shoulder
25	7907.4	59.5	3.25	0.7	0.95	0.15	0.01	482	29.23	4.62	0.42	21.54	4.48	high temperature S2 shoulder
26	7912	60.5	3.5	0.67	1.25	0.11	0.01	490	35.71	3.14	0.35	19.14	4.32	high temperature S2 shoulder
27	7917	60.7	2.39	0.81	1.04	0.08	0.01	497	43.51	3.35	0.44	33.89	7.29	high temperature S2 shoulder
28	7922	61.2	4.53	1.22	1.71	0.14	0.02	486	37.75	3.09	0.42	26.93	4.26	high temperature S2 shoulder
29	7927	60.2	4.6	1.34	1.83	0.13	0.02	488	39.78	2.83	0.42	29.13	4.15	high temperature S2 shoulder
30	7932.45	60.7	0.68	0.14	0.26	0.09	0.01	490	38.24	13.24	0.35	20.59	6.50	high temperature S2 shoulder
31	7937	60.1	1.28	0.37	0.55	0.1	0.01	487	42.97	7.81	0.40	28.91	5.50	high temperature S2 shoulder
32	7942.95	61.1	2.02	0.59	0.68	0.14	0.01	498	33.66	6.93	0.46	29.21	7.25	high temperature S2 shoulder
33	7947	60	1.57	0.29	0.55	0.14	0.01	498	35.03	8.92	0.35	18.47	8.10	high temperature S2 shoulder
34	7952	59.6	2.06	0.21	0.61	0.19	0.02	498	29.61	9.22	0.26	10.19	7.59	high temperature S2 shoulder
35	7957	60.4	0.8	0.02	0.28	0.08	0.01	501	35.00	10.00	0.07	2.50	3.55	Upper and lower temperature S2 shoulders
36	7962	60.3	0.88	0.39	0.37	0.19	0.02	307	42.05	21.59	0.51	44.32	5.59	Unreliable Tmax
37	7967	59.9	0.34	0.19	0.19	0.12	0.01	383	55.88	35.29	0.50	55.88	8.97	Unreliable Tmax
38	7972	60	0.03	0.03	0.07	0.06	0.01	378	233.33	200.00	0.30	100.00	8.12	Unreliable Tmax
	Utica	Point Pleasant	Lexington											

Table 1, Rock-Eval pyrolysis results on core Farley 1305-H, performed by Core Labs.

Porosity

Porosity was measured for 23 samples on Core Farley 1305-H, including gas-filled porosity and porosity (%) via Dry & Dean-Stark extracted conditions (Table 2). Of the 23 samples, 5 were from the Utica, 9 from the Point Pleasant Formation, and 9 from the Lexington Limestone. (Gas-filled porosity is a percentage of how much of actual porosity is filled by gas.)

- Gas-filled porosity for the Utica Shale ranged from 0.70 to 2.54 %, the Point Pleasant from 0.35 to 6.01 %, and the Lexington Limestone from 0.84 to 3.61 %.
- Porosity % from the Utica Shale ranged from 3.03 to 4.69, the Point Pleasant Formation from 1.73 to 8.41, and Lexington Limestone from 1.67 to 1.31.

		As received		Dry & Dean Stark Extracted Conditions
Sample	Depth (ft)	Bulk Density (g/cc)	Gas-filled Porosity (%)	Porosity (%)
1 GRI	7785.60 - 7786.10	2.691	1.20	3.89
2 GRI	7802.50 - 7803.00	2.717	0.90	3.16
3 GRI	7815.80 - 7816.35	2.718	0.70	3.03
4 GRI	7832.50 - 7833.00	2.688	1.43	3.87
5 GRI	7845.90 - 7846.40	2.643	2.54	4.69
6 GRI	7862.50 - 7863.00	2.497	5.69	8.21
7 GRI	7876.10 - 7876.60	2.533	5.07	6.58
8 GRI	7888.15 - 7888.65	2.501	5.26	7.30
9 GRI	7894.10 - 7894.60	2.474	4.79	7.66
10 GRI	7900.15 - 7900.65	2.497	6.01	7.91
11 GRI	7905.90 - 7906.40	2.506	4.39	6.66
12 GRI	7911.85 - 7912.35	2.466	5.83	8.14
13 GRI	7917.90 - 7918.40	2.460	5.40	8.41
14 GRI	7923.90 - 7924.40	2.677	0.35	1.73
15 GRI	7930.95 - 7931.45	2.667	1.78	2.79
16 GRI	7934.50 - 7935.00	2.653	2.15	3.80
17 GRI	7941.45 - 7941.95	2.592	3.61	4.90
18 GRI	7947.45 - 7947.95	2.634	2.60	3.10
19 GRI	7953.30 - 7953.80	2.594	3.34	5.08
20 GRI	7959.50 - 7959.95	2.678	1.36	2.43
21 GRI	7964.60 - 7965.10	2.694	0.84	1.31
22 GRI	7971.75 - 7972.30	2.695	1.11	1.67
23 GRI	7977.90 - 7978.40	2.675	1.01	2.53

Averages	Utica	P.Pleasant	Lexington
Gas-filled Porosity	1.36	4.75	1.98
Porosity	3.73	6.96	3.07

Table 2, Porosity data for core Farley 1305-H, modified from Core Labs.

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Mineralogy

Whole rock mineralogy was determined on the Farley 1305-H core via X-ray Diffraction by Core Laboratories (Table 3). A total of 13 samples were analyzed: 3 from the Utica Shale; 4 from the Point Pleasant Formation; and 5 from the Trenton Limestone.

The Utica Shale samples came from depths of 7786, 7816, and 7846 feet. The quartz content ranged 20.4 to 27.1 %. Calcite content ranged from 14.8 to 27.8 %. Total clay content ranged from 41.9 to 53.6 %. The 4 Point Pleasant Formation samples came from depths between 7876 and 7918 feet. Quartz content ranged from 14.4 to 26.6 %. Calcite content ranged from 28.6 to 49.9 %. Clay content ranged from 24.90 to 36.0 %. The Trenton Limestone samples came from depths between 7931 and 7978 feet. Quartz content values were 1.4 and 20.9 %. Calcite content values were between 47.8 and 95.4 %. Clay content values were from 2.1 and 34.9 %.

	Whole Rock Mineralogy (Weight %)							Clay (Phyllosilicate) Mineralogy (Weight %)			
Depth	Quartz	K Feldspar	Plagioclase	Calcite	Dolomite & Fe-Dolomite	Pyrite	Total Clay	Illite / Smectite *	Illite & Mica	Kaolinite	Chlorite
7786.10	27.1	0.3	5.4	14.8	2.7	3.1	46.6	7.4	22.4	1.4	15.4
7816.35	21.6	0.5	6.4	12.2	2.2	3.6	53.6	8.5	26.1	1.6	17.4
7846.40	20.4	0.9	3.8	27.8	3.0	2.2	41.9	6.9	22.1	1.5	11.4
7876.60	26.6	0.6	3.7	31.4	0.0	3.1	34.7	6.2	17.3	0.0	11.2
7894.60	25.1	0.4	5.6	28.6	0.8	3.6	36.0	7.7	17.4	0.0	10.9
7906.40	14.4	0.9	3.1	49.9	1.7	5.1	24.9	6.3	12.5	0.0	6.1
7918.40	17.8	0.3	3.4	44.9	1.3	5.0	27.3	8.2	13.8	0.0	5.3
7931.45	8.1	0.0	1.2	69.4	4.8	1.5	15.0	4.2	7.6	0.0	3.2
7941.95	10.7	0.7	2.5	57.6	0.9	3.7	24.0	5.9	10.5	0.0	7.6
7953.80	9.5	0.8	2.4	47.8	0.7	4.0	34.9	11.1	16.9	0.0	6.9
7965.10	1.4	0.0	0.0	95.4	0.0	1.0	2.1	0.7	1.4	0.0	0.0
7978.40	20.9	0.0	1.3	65.5	1.1	1.6	9.6	2.6	5.0	0.0	2.0
Formations	Utica	P. Pleasant	Lexington			* Mixed Layer Illite/Smectite contains 10-15% Smectite					

Table 3, XRD analysis results from core Farley 1305-H, modified from Core Labs.

Geomechanical

Triaxial testing was performed on four samples from Farley 1305-H core. One sample, 1VRM, was Utica Shale from a depth of 7790.10 feet. Two samples were taken from the Point Pleasant Formation: 2VRM from 7859.00 feet and 3VRM from 7900.90 feet. The last sample

4VRM was Lexington Limestone, from ~7929.13 feet. The triaxial test provided bulk density, compressive strength, Young's modulus, and Poisson's ratio data for each sample (Table 4).

Sample 1VRM, the Utica Shale sample, has a bulk density of 2.73 $\frac{g}{cm^3}$, a compressive strength of 14820 psi (0.102 GPa), a Young's modulus of $2.58 \cdot 10^6$ psi (17.79 GPa), and a Poisson's ratio of 0.27. Sample 2VRM has a bulk density of 2.63 $\frac{g}{cm^3}$, a compressive strength of 14099 psi (0.097 GPa), a Young's modulus of $2.19 \cdot 10^6$ psi (15.1 GPa), and a Poisson's ratio of 0.25. Sample 3VRM has a bulk density of 2.54 $\frac{g}{cm^3}$, a compressive strength of 15843 psi (.109 GPa), a Young's modulus of $3.03 \cdot 10^6$ psi (20.89 GPa), and a Poisson's ratio of 0.24. Sample 4VRM has a bulk density of 2.70 $\frac{g}{cm^3}$, a compressive strength of 29747 psi (.205 GPa), a Young's modulus of $5.23 \cdot 10^6$ psi (36.06 GPa), and a Poisson's ratio of 0.28.

Triaxial Static Young's Modulus, Poisson's Ratio and Compressive Strength

Sample Number	Depth (ft)	Confining Pressure (psi)	Bulk Density (g/cm^3)	Compressive Strength (psi)	Young's Modulus (10^6 psi)	Young's Modulus (GPa)	Poisson's Ratio	Formation
1VRM	7790.10	1520	2.73	14820	2.58	17.79	0.27	Utica
2VRM	7859.00	1520	2.63	14099	2.19	15.10	0.25	PP
3VRM	7900.90	1520	2.54	15843	3.03	20.89	0.24	PP
4VRM	7929.10-7929.16	1520	2.70	29747	5.23	36.06	0.28	Lex

Table 4, Triaxial test results for core Farley 1305-H.

Gas Composition

Gas desorption analysis was completed on core Farley 1305-H by Core Laboratories. Gas composition and dry and saturated BTU values were determined from 20 different samples, including 3 from the Utica Shale, 8 from the Point Pleasant Formation, and 9 from the Lexington Limestone (Table 5). Gas produced from the three Utica Shale samples range from 56.71 to 77.03 % methane, 17.21 to 28.87 % ethane, and 4.73 to 13.60 $C_{3\text{-}6}^{+}$ % hydrocarbons. Gas produced from the 8 Point Pleasant Formation samples range from 4.59 to 69.79 % methane, 20.57 to 40.25 % ethane, and 8.41 to 62.37 C_{3-6}^{+} % hydrocarbons. Gas produced from 9 underlying Lexington Limestone samples range from 52.51 to 86.10 % methane, 17.21 to 28.87 % ethane, and 4.73 to 13.60 C_{3-6}^{+} % hydrocarbons. Carbon dioxide levels are negligible for all 20 samples. Nitrogen levels were also negligible, except for sample TH-FA-19 within the Lexington Limestone, at a mole % of 4.18.

Calorific values for the Utica Shale samples range from 1216 to 1465.47 BTU/ft^3 under dry combustion conditions and from 1194 to 1440 BTU/ft^3 under wet combustion conditions. Calorific values for the Point Pleasant Formation samples range from 1323 to 2482 BTU/ft^3 under dry combustion conditions and from 1301 to 2438 BTU/ft^3 under wet combustion conditions. Calorific values for the underlying limestone samples range from 1120 to 1684 BTU/ft^3 under dry combustion conditions and from 1101 to 1654 BTU/ft^3 under wet combustion conditions.

Wellsite Canister Top Depth (ft)	Wellsite Canister Bottom Depth (ft)	Canister ID	Gas Analysis (Adjusted for Air), mole %						Calorific Value	
			C_1	C_2	C_{3-6+}	N_2	CO_2	Total	Dry BTU/cu.ft	Saturated BTU/cu.ft
7786.1	7787.1	TH-FA-01	77.03809	17.21379	4.730392	0.893442	0.124285	100	1215.566	1194.415
7816.35	7817.35	TH-FA-02	56.71631	28.87167	13.60704	0.013693	0.791295	100	1465.474	1439.974
7846.4	7847.35	TH-FA-03	67.49815	22.34871	9.388948	0.675186	0.089008	100	1344.143	1320.755
7876.6	7877.6	TH-FA-04	22.12524	30.02873	47.5178	0.14226	0.185975	100	2194.012	2155.836
7888.65	7889.65	TH-FA-05	11.58324	38.03382	49.42318	0.860267	0.099489	100	2222.871	2184.193
7894.6	7895.6	TH-FA-06	7.216705	33.4988	58.95587	0.107119	0.221504	100	2441.752	2399.265
7900.65	7901.65	TH-FA-07	6.477056	36.76351	56.49293	0.058969	0.207533	100	2378.58	2337.193
7906.4	7907.4	TH-FA-08	69.78992	21.48611	8.419803	0.00901	0.295162	100	1323.89	1300.855
7912.35	7913.35	TH-FA-09	7.268247	29.97723	62.36688	0.157698	0.229948	100	2481.526	2438.347
7918.4	7919.4	TH-FA-10	4.594965	40.25034	54.74925	0.18686	0.218582	100	2383.935	2342.455
7924.4	7925.4	TH-FA-11	65.53434	20.56736	13.13775	0.685749	0.074797	100	1409.057	1384.54
7931.45	7932.45	TH-FA-12	64.83322	20.50698	13.85395	0.725872	0.079983	100	1423.764	1398.991
7935	7936	TH-FA-13	66.2966	17.61764	15.49475	0.203892	0.38712	100	1456.773	1431.425
7941.95	7942.95	TH-FA-14	52.51211	27.53576	19.41793	0.24337	0.29083	100	1584.247	1556.681
7947.95	7948.95	TH-FA-15	58.02437	24.51385	16.29169	0.860304	0.309786	100	1493.797	1467.805
7953.8	7954.8	TH-FA-16	43.97729	31.81223	23.14212	0.754739	0.313618	100	1683.628	1654.332
7959.95	7960.95	TH-FA-17	72.59115	20.51863	6.393563	0.280992	0.215672	100	1279.693	1257.427
7965.1	7966.1	TH-FA-18	81.70957	14.67318	2.935249	0.470429	0.21157	100	1172.974	1152.564
7972.25	7973.25	TH-FA-19	80.35052	11.40417	3.699447	4.184548	0.361321	100	1121.273	1101.763
7978.4	7979.4	TH-FA-20	86.09908	11.79457	1.367301	0.134261	0.604783	100	1120.394	1100.899
Utica	P. Pleasant	Lexington								

Table 5, Gas desorption summary for core Farley 1305-H, modified from Core Labs.

Geophysical Logs

Various geophysical logs were completed on well Farley 1305-H by Halliburton, including: gamma ray, resistivity, density, and porosity. The results for the interval of study are below (Fig. 8).

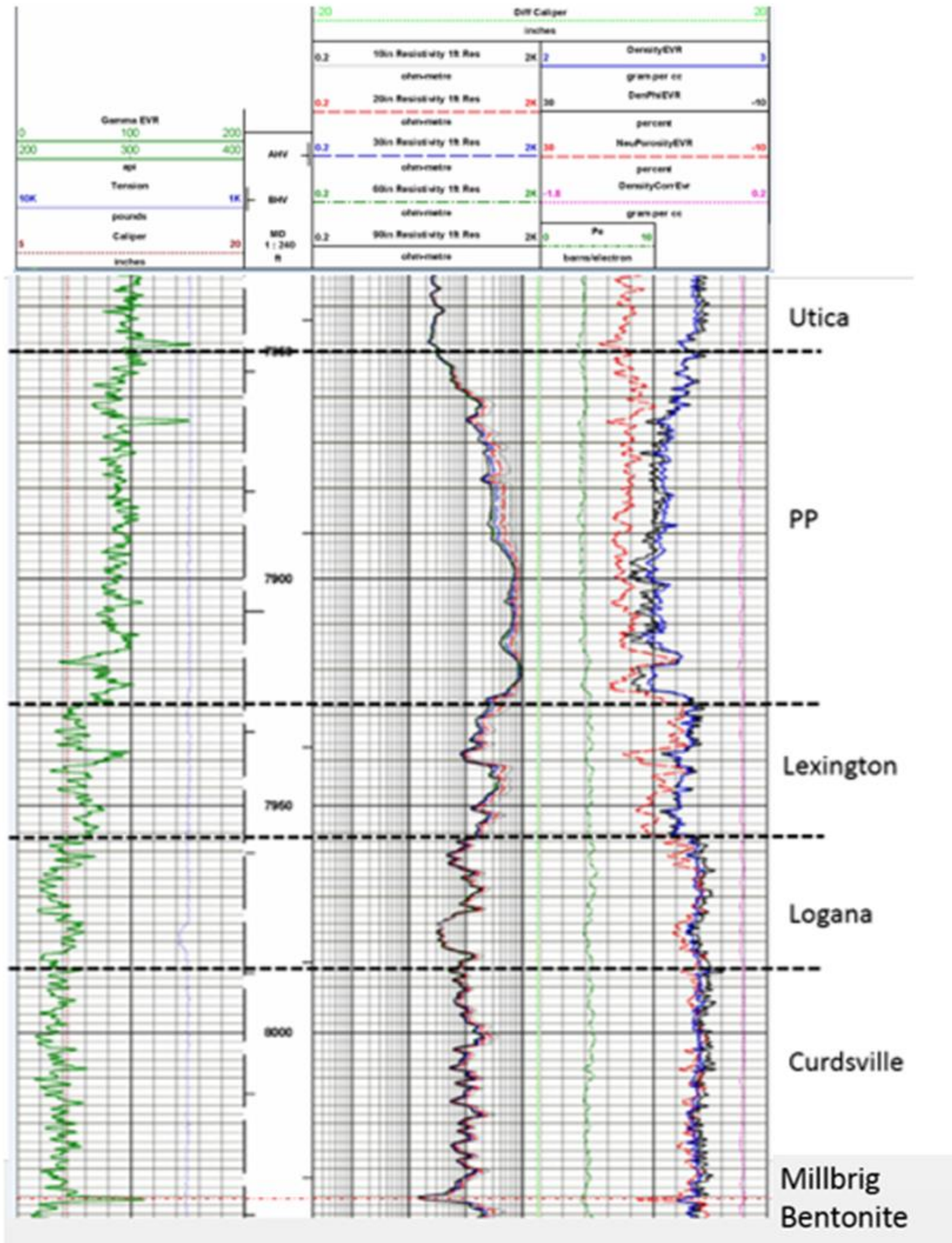


Figure 8, Geophysical logs from Farley 1305-H. Cored interval is from 7787 – 7972 feet.

Discussion

Geochemistry

Organic carbon is a requisite for gas production (as is hydrogen). It has been suggested that for a shale gas system to be effective, a TOC content greater than 1 wt. % is required (Curtis, 2002 and Jarvie et al., 2007). The values of TOC for the Utica Shale range from 0.16 to 0.91 wt. % and average of 0.4 wt. % for core Farley 1305H (Table 1). Therefore, the low TOC in the Utica discourages its recognition as a target for gas production. The TOC for the Point Pleasant Formation ranges from 0.72 to 4.53 wt. %, for an average of 2.4 wt. %. The 2.4 average TOC wt. % of the Point Pleasant Formation is regarded as an acceptable level for gas production (Jarvie et al., 2007). The TOC for the Lexington Limestone is mostly > 1 wt. % for the upper 20 feet, with an average of 1.5 wt. %, indicating that it does have some gas potential. The maximum TOC value of 4.6 wt. % for the entire Farley 1305-H core can be compared with the TOC Maximum Map produced by the Ohio Department of Natural Resources Division of Geological Survey (ODNR) (Fig. 9).

The TOC Maximum Map produced by ODNR uses a color scheme to rank grades of highest TOC value across the state for the "Upper Ordovician Shale Interval," which includes the Utica, Point Pleasant, and Lexington, and where hotter colors represent a higher TOC wt. %. Washington County is represented by only one data point that represents the "Good" color scheme of 1-2 TOC wt. %. The maximum value of 4.6 TOC wt. % within the Farley 1305-H core classifies as "Excellent" on ODNR's TOC map. Further, the core's maximum is the second highest value for southeastern Ohio. With this better knowledge of TOC potential in southeastern Ohio, perhaps a TOC-rich hotspot exists in areas of Washington, Noble, and Monroe counties.

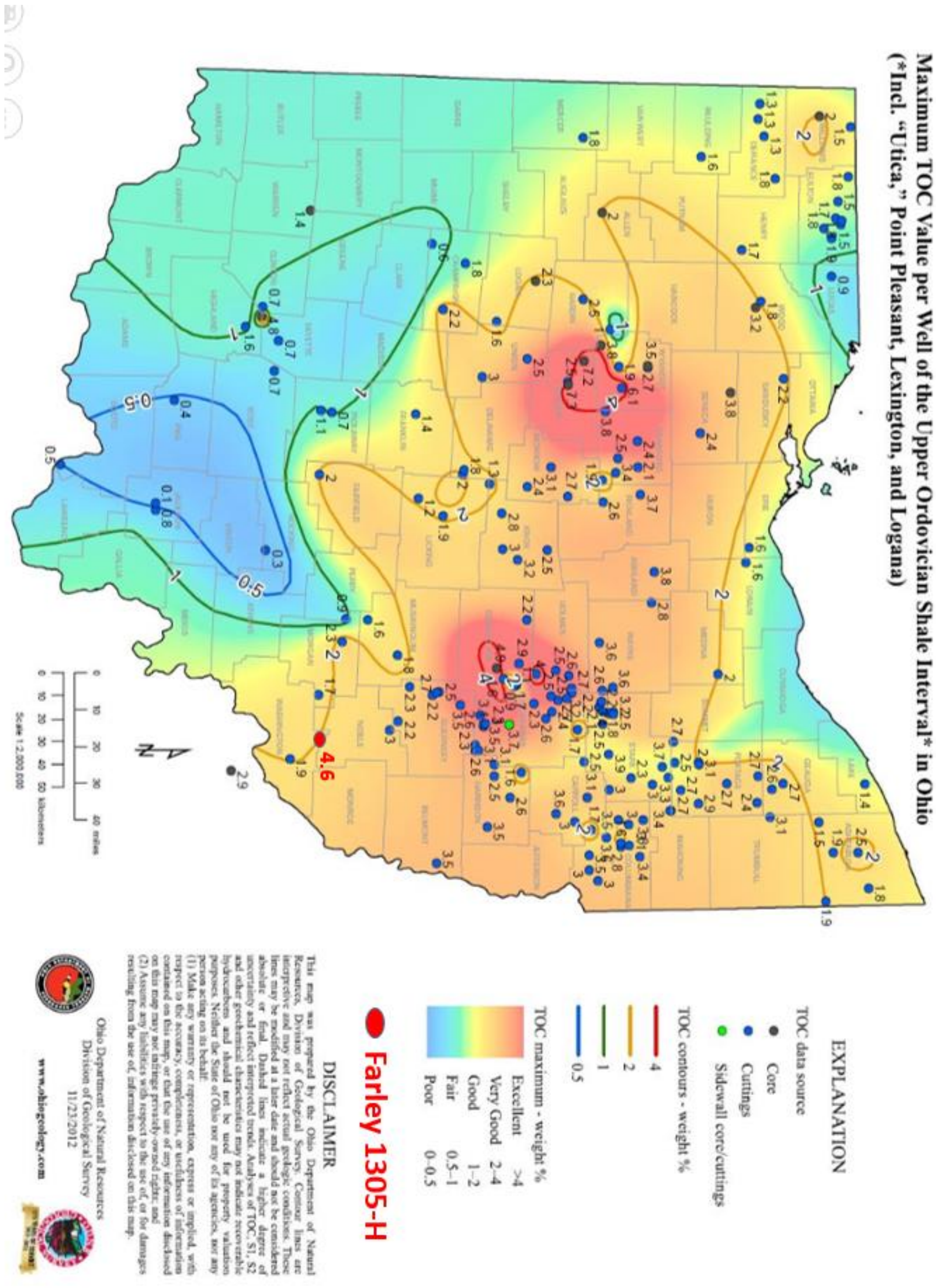


Figure 9: Map showing maximum TOC wt. % for the Upper Ordovician Shale Interval across Ohio, modified from Wickstrom et al., (2012).

The S1, S2 and Tmax, and S3 parameters produced via Rock-Eval pyrolysis can be used to indicate various geochemical characteristics, thermal maturation, and hydrocarbon potential of a source rock (El Nady et al., 2015). S1 is the amount of free oil and gas (mg HC / g of sample) that is produced from heating a sample at 300º C. S2 is the amount of hydrocarbon (mg HC / g of sample) that is produced from a sample by the way of cracking the existing kerogen within the rock by heating it from 300 to 500º C. S2 represents the remaining convertible organic matter within the rock that could still generate hydrocarbons. The temperature at which S2 peaks is called Tmax and is a function of kerogen type and maturity and S3 is the carbon dioxide released from the pyrolysis measured in mg of CO_2 / gram of sample. S1, S2 & Tmax, S3, and TOC wt. %, are used to produce the hydrogen, production, and oxygen indices.

The hydrogen index (HI) is equal to $(\frac{S2}{TOC})100$, and provides a measure of the hydrogen left in the rock relative to carbon and an inference of kerogen type (Jarvie et al., 2011). The production index (PI) is calculated as $(\frac{S1}{S1+S2})$, indicating level of thermal maturation and the generation of oil versus gas by creating a ratio of generated hydrocarbons to potential hydrocarbons. The oxygen index is derived by $(\frac{S3}{TOC})100$, creating a ratio between oxygen and carbon content. The oxygen index will not be addressed for this study because shales with high carbonate content distort and misrepresent oxygen richness (Pennsylvania DCNR).

A general standard of S1 and S2 values for what makes a "good source rock" are thus:

- S1 $\geq$ 1.0 mg HC/g dry rock
- S2 $\geq$ 5.0 mg HC/g dry rock (PA DCNR)

The S1 values measured from the Farley 1305-H core for the Utica Shale range from 0.04 to 0.22 mg HC/g in the Utica Shale, 0.14 to 1.34 mg HC/g in the Point Pleasant Formation, and

0.03 to 0.59 mg HC/g in the Lexington Limestone. Three of the data points within the Point Pleasant exceed the 1.0 mg HC/g "good" threshold. The S2 distribution ranges from 0.09 to 0.31 mg HC/g in the Utica Shale, 0.29 to 1.83 mg HC/g in the Point Pleasant Formation, and 0.07 to 0.68 (mg HC/g) in the Lexington Limestone. All of the S2 values qualify as poor for core Farley 1305-H, and because S2 indicates the hydrocarbon generation potential left in the rock, the potential of Farley 1305-H is considered "poor."

S2 values plotted against TOC wt. % can be used to classify kerogen type and thermal maturity (Langford and Blanc-Valleron, 1990). This is possible because different kerogen types have different ratios of hydrocarbon potential (e.g., Type 1 corresponds from 600 to 800 mg HC/g) with Type 1 having the highest. Thus, the hydrocarbon potential to TOC wt % ratio decreases from Type 1 to Type 3 kerogen and from oil to dry gas generation, as hydrogen decreases through the thermal maturity process. If the samples are below the Type-3 window, the kerogen type cannot be discerned. A S2 vs TOC plot was created for all values from the Farley 1305-H core (Fig. 10). All values from the core plot in the dry gas prone area, indicating indiscernable kerogen type, a mature shale gas reservoir, and poor remaining hydrocarbon potential.

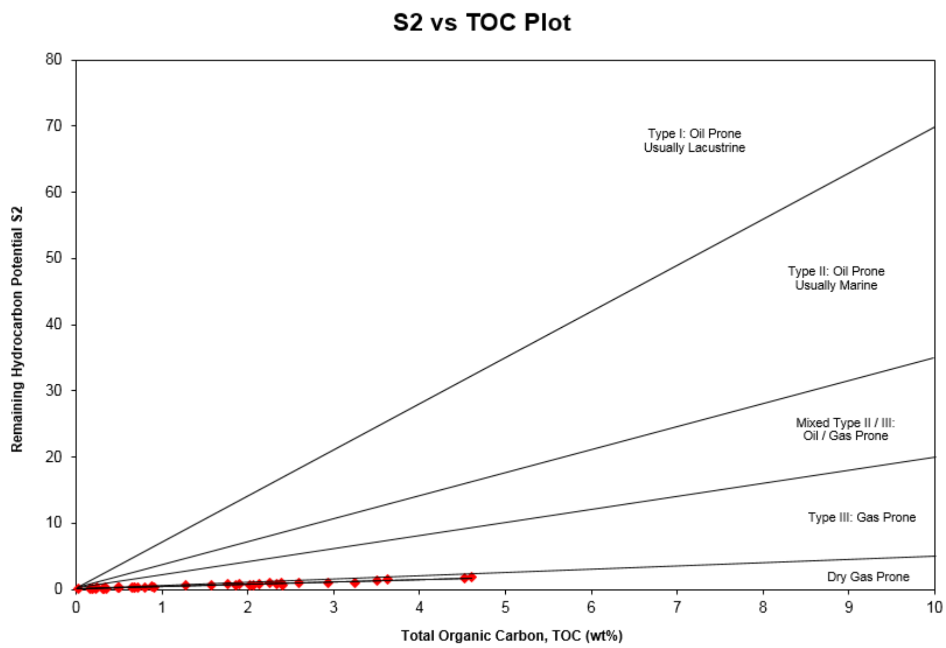


Figure 10, S2 vs TOC plot indicating the maturity of the Farley 1305-H core, modified from Core labs.

The Tmax values calculated from the Farley 1305-H core for the Utica Shale range from 491 to 503 º C , from 471 to 498 º C for the Point Pleasant Formation, and from 487 to 501 º C for Lexington Limestone. Jarvie et al. (2001) correlate the dry gas window with Tmax values at ~ > 470º C (Table 6). All samples from the Ordovician interval fit within the Jarvie dry gas window. Therefore, the gas composition should be expected to be mostly methane for well Farley 1305-H.

Tmax(ºC)	Maturity
431	Early Mature
448	Peak Oil Generation
453	Earliest Condensate-Gas window
459	
464	
470	
476	Dry Gas Window
492	Ref: Jarvie et al., 2001
509	

Table 6, Tmax correlations with oil and gas windows, modified from Jarvie et al., 2001

The HI values ($\frac{S2}{TOC}100$) from Farley 1305-H core for the Utica Shale range from 34.07 to 87.5 for the Utica Shale, from 21.99 to 43.51 for Point Pleasant Formation, and from 29.61 to 233.33 for the Lexington Limestone (Table 1). The PI values ($\frac{S1}{S1+S2}$) from Farley 1305-H core for Utica Shale range from 0.25 to 0.42, from 0.26 and 0.55 for the Point Pleasant Formation, and from 0.26 to 0.50 for the Lexington Limestone (Table 1). Using these indices along with the rest of the Rock-Eval pyrolysis data, graphical correlations can be made.

By graphing the HI vs Tmax, correlations of kerogen type and thermal hydrocarbon maturity can be discerned (El Nady et al., 2015, based on the work of J. Espitalie). Figure 11 is a plot of HI vs Tmax values. All data points lie within the post mature and dry gas zones.

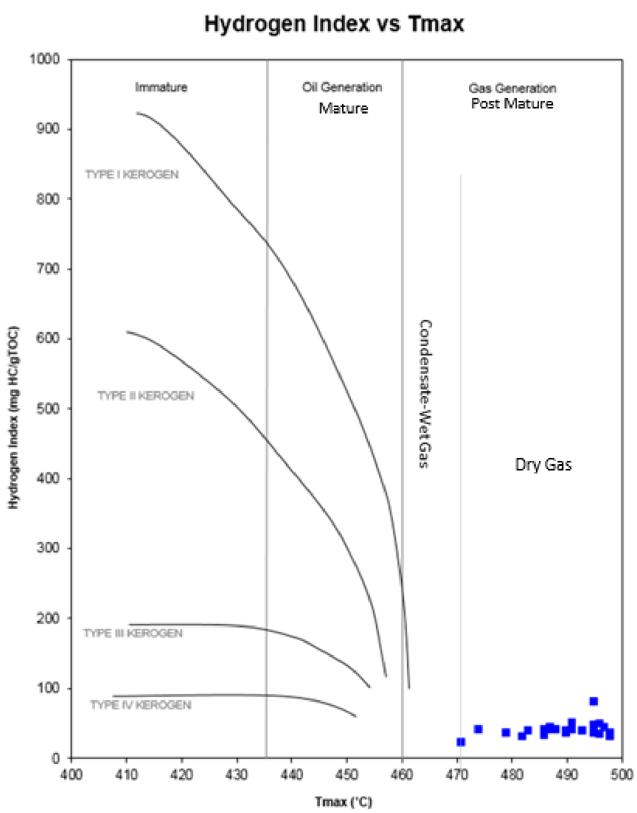


Figure 11, Hydrogen index versus Tmax for core Farley 1305-H, modified from Core Labs.

By graphing the PI vs Tmax, a correlation of thermal hydrocarbon maturity can also be established (El Nady et al., 2015, based on the work of J. Espitalie and Peters). Figure 12 is a plot of PI vs Tmax values. All data points lie within the dry gas zone, indicating again, a mature shale gas system.

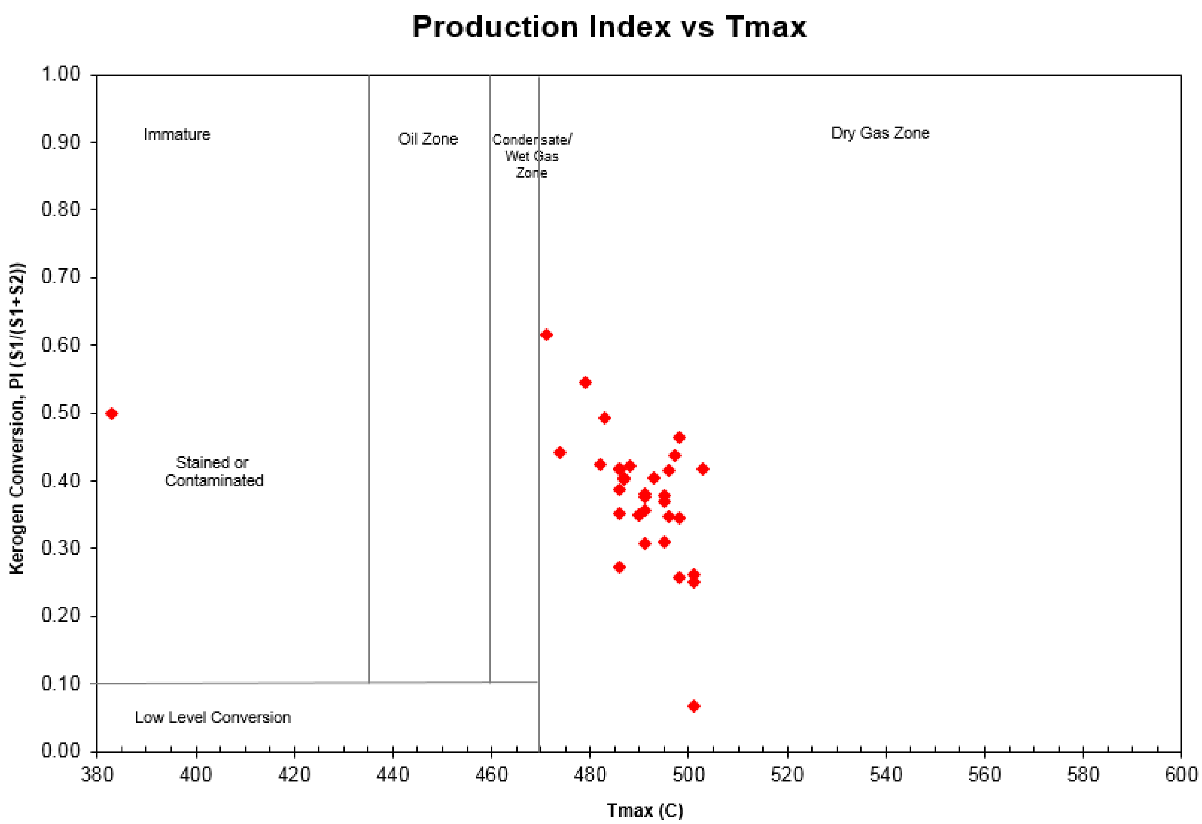


Figure 12, Production index versus Tmax for core Farley 1305-H, modified from Core Labs.

Vitrinite Reflectance

Thermal maturation processes dictate the quantity and type of hydrocarbons generated within organic-rich shales. With an increase in temperature, gas forms, chronologically, via decomposition of kerogen, bitumen, and cracking of oil (Fig. 13).

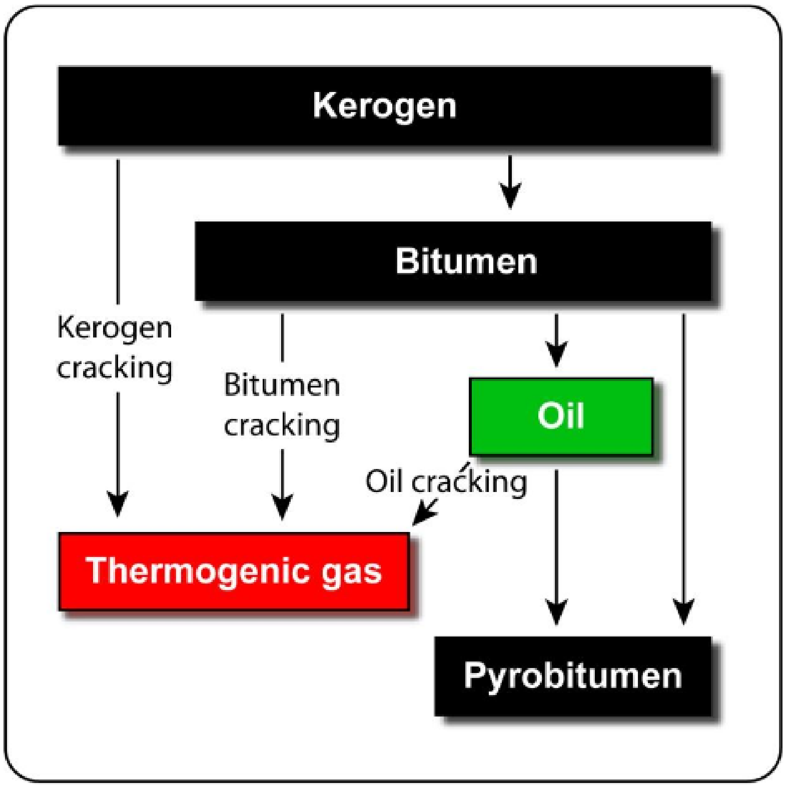


Figure 13, Flowchart summarizing processes of oil and gas genesis with increasing temperature, from Euneze, 2011.

Multiple methods are used to identify the thermal maturity of the organic matter within shales, including conodont alteration index, pollen translucency, isotope ratios, mass spectrometry analysis, and vitrinite reflectance (Euneze, 2011). The method of vitrinite reflectance, commonly used in the oil and gas industry, entails measuring the percentage of reflected incident light from the surface of vitrinite particles. This measured light is referred to as % Ro or % VRo. Dow (1977) correlates % Ro with oil and gas generation (Fig. 14). Dow associates ~ 1.0 % Ro with peak wet–gas generation, ~ 1.20 % Ro peak with dry gas generation, and as % Ro approaches 2.0, only dry gas will remain within a source rock.

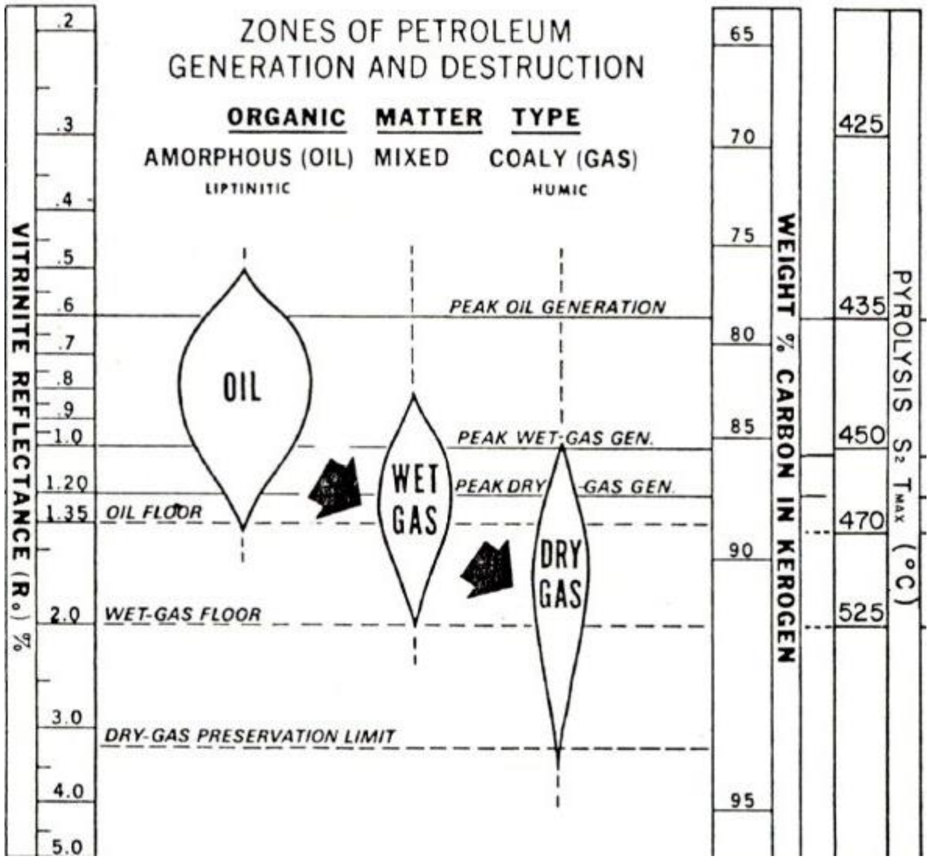


Figure 14, Correlation of hydrocarbon maturity indicators for oil and gas windows, modified from Dow (1977).

However, because vitrinite occurs only in post Silurian-age rocks, the visual method of vitrinite reflectance is of no use in the Ordovician-age Utica Shale or Point Pleasant (Cardott, 2012). However, Jarvie et al. (2001) suggest an approximation of % Ro can be calculated from Tmax values using the equation:

(Calculated) % Ro = 0.018(Tmax) – 7.16.

Table 7 shows % Ro values calculated following this equation for core Farley 1305-H, using the Tmax values deemed reliable (Table 1) from the Rock-Eval Pyrolysis data.

Sample	Tmax	%Ro
1	491	1.68
3	501	1.86
4	495	1.75
5	501	1.86
7	503	1.89
8	496	1.77
9	493	1.71
10	491	1.68
11	495	1.75
12	495	1.75
13	496	1.77
14	486	1.59
15	474	1.37
16	483	1.53
17	491	1.68
18	491	1.68
19	486	1.59
20	487	1.61
21	479	1.46
22	486	1.59
23	486	1.59
24	471	1.32
25	482	1.52
26	490	1.66
27	497	1.79
28	486	1.59
29	488	1.62
30	490	1.66
31	487	1.61
32	498	1.80
33	498	1.80
34	498	1.80
35	501	1.86

	AVG
Utica	1.77
P.Pleasant	1.57
Lexington	1.76
Entire Core	1.67

Table 7, Calculated % Ro values from Tmax for core Farley 1305-H.

The calculated % Ro values for the Utica Shale range from 1.68 to 1.89, from 1.32 to 1.79 for the Point Pleasant Formation, and from 1.61 to 1.86 for Lexington Limestone. These values, according to Dow, suggest that mostly dry gas should be generated from the Farley 1305-H well and surrounding areas. Further, the average 1.67 % Ro for the core Farley 1305-H can be compared with the maturity map presented by the Utica Playbook (2015) (Fig. 15).

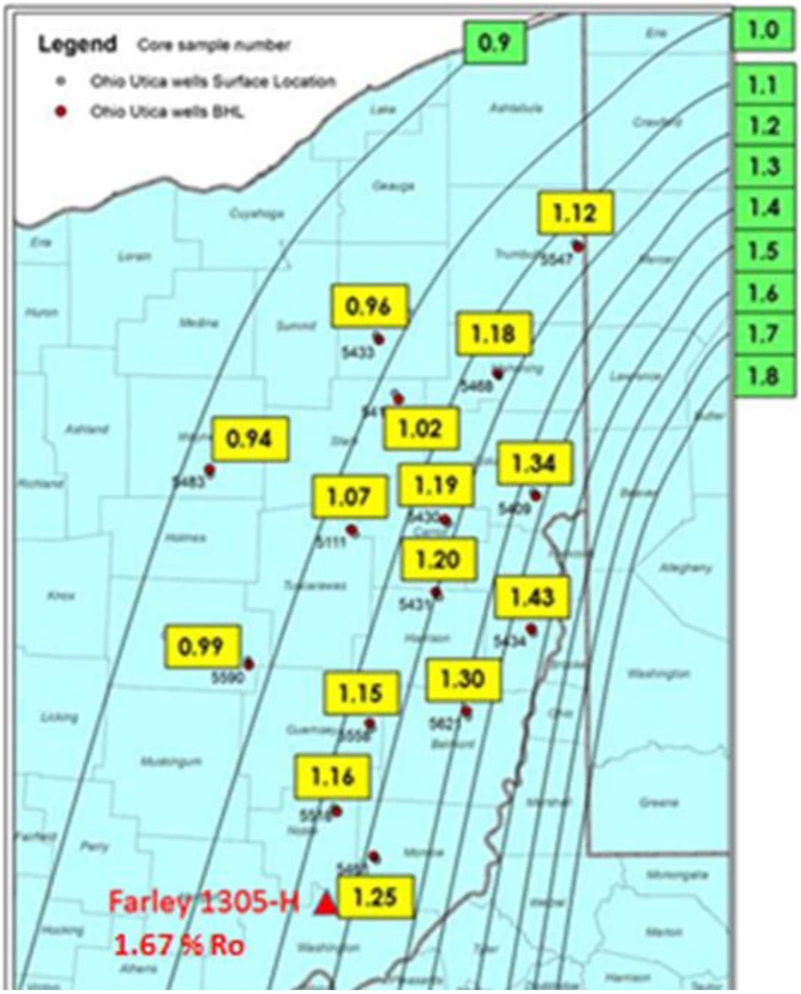


Figure 15, Map of eastern Ohio showing drawn lines of isoflectance with the location of Farley 1305-H represented by a triangle, modified from the Utica Playbook (2015).

The Utica Playbook has the Farley 1305-H well depicted between 1.1 and 1.2 isolines of % Ro for the Utica/Point Pleasant interval, which are much lower values than the average of this study (1.77 % Ro for the Utica Shale, 1.57 % Ro for the Point Pleasant Formation, and 1.67 % Ro for the entire core's shale samples). Thus, it is possible that the Utica Playbook maturity contours may need to be reevaluated to account for new data. Such an underestimation could affect gas composition and BTU estimations, which in turn could be detrimental to profitability.

The Ohio Department of Natural Resources Division of Geologic Survey (ODNR) (2012) mapped the % Ro average for the entire Ordovician Shale interval within Ohio (Fig. 16). On their map, all of Washington County is represented by a % R_o average > 1.4 that increases in a generally eastward direction. The ODNR map shows a closer relationship to the 1.67 % Ro average for core Farley 1305-H.

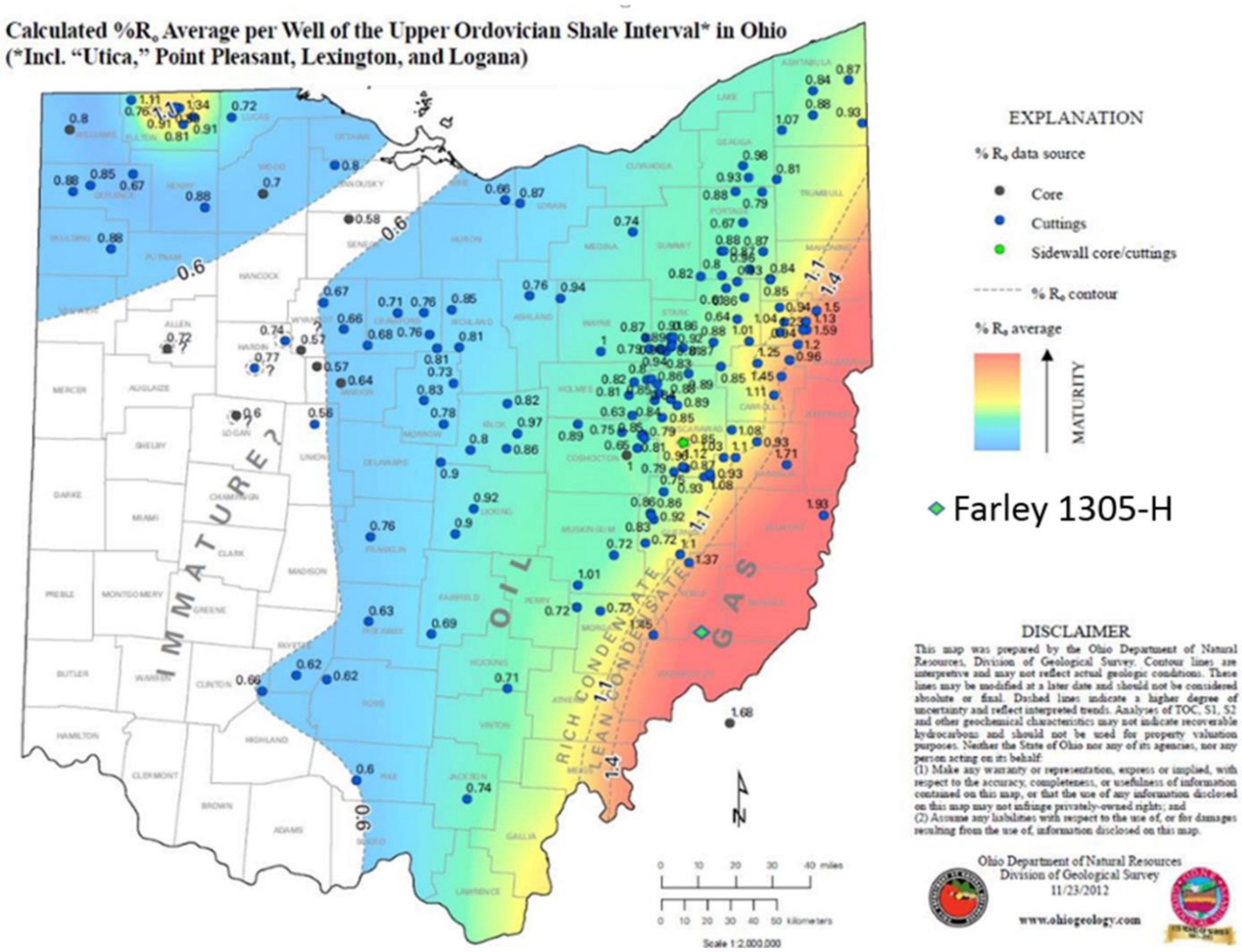


Figure 16, Map of % Ro produced by ODNR, from Wickstrom (2012).

Gas Composition

The composition of gas expelled by a particular well affects multiple facets of gas economics, including royalty rates, required infrastructure, and profitability. Desorption values for core 1305-H show that the overlying Utica Shale and underlying limestones produce mostly dry gas, yet the Point Pleasant Formation produces mostly wet gas (Table 5). And because the Point Pleasant Formation is the gas target, economic expectations and necessary infrastructure should be adjusted accordingly for the wet gas content.

The gas desorption data is helpful in that it can be compared to the aforementioned Rock-Eval pyrolysis data. Specifically, all reliable Tmax values and all samples from core Farley 1305-H plotted in the S2 vs TOC, HI vs Tmax, and PI vs Tmax qualitatively describe the entire cored interval as “Dry Gas Prone,” “Post Mature,” and in the “Dry Gas Zone or Window” (Table 7 & Figs. 10, 11, & 12). Although the gas composition of the overlying Utica Shale and underlying limestones is mostly dry gas, the Point Pleasant Formation predominately contains wet gas within core Farley 1305-H (Table 5). Therefore, Rock-Eval pyrolysis and gas analysis indicate that multiple datasets should be used for interpretation whenever possible.

Mineralogy

The economic success of shale reservoirs is dependent upon fracture development, as the flow of gas requires the connection of individual microreservoir compartments via hydraulic stimulation (Jarvie et al, 2007). The fracturing potential of a shale reservoir is a fundamental function of its brittleness. Higher quartz, feldspar, and carbonate percentages are associated with brittle shales and higher clay percentages are associated with a more ductile shale. Thus, the mineralogy of shale is directly correlated to its geomechanical properties (Ding et al, 2012).

Many authors have quantified brittleness in the context of shale gas production (e.g., Jarvie et al., 2007; Rickman et al., 2008; Wang and Gale, 2009). A three-component lithology model is used by Anderson (2014) to characterize 15 gas-producing shales via their respective mineralogies and relevance to ductility (Fig. 17). Anderson's model shows that most successful shale plays fall right of the ductile/brittle transition on the diagram, with only two within the transition zone. Though a simple model, it still illustrates the commonality of shale gas plays: low clay content. The normalized "brittle mineral" values (Quartz/Feldspar 27 %; Carbonate 41 %; Clay 32%) from core Farley 1305-H for the Point Pleasant Formation plot well into the brittle zone, indicating an apparent brittleness sufficient for hydraulic fracturing (Table 8). The clay-rich and organically lean Utica (normalized values of Quartz/Feldspar 30 %; Carbonate 21 %; Clay 49 %) plots within the "ductile/brittle transition zone," suggesting a tendency to respond "ductily" when hydraulically stimulated. Thus, even if the Utica Shale were more organically rich, it would not be as efficient as the Point Pleasant Formation within and proximal to well Farley 1305-H.

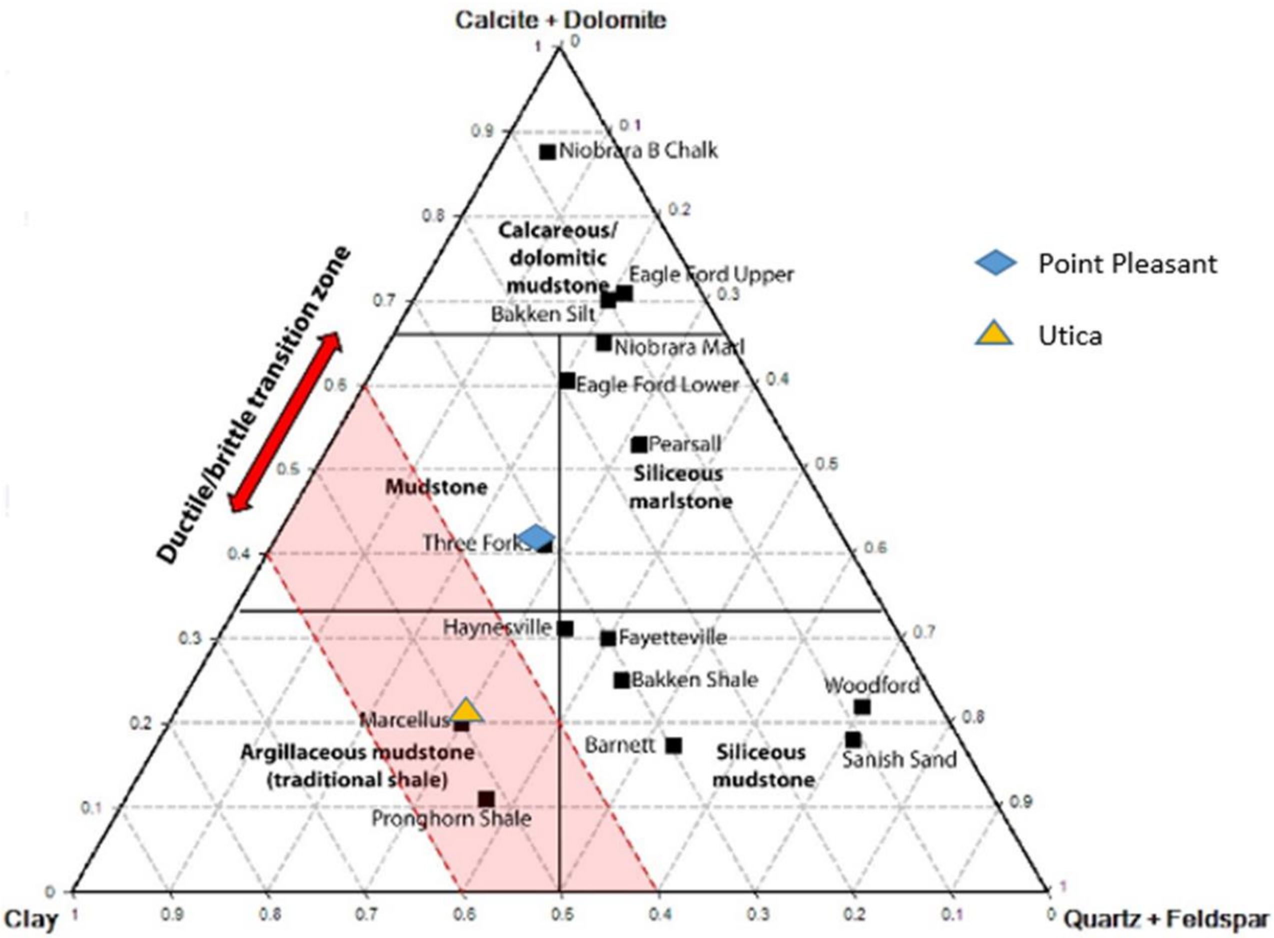


Figure 17, Ternary plot of normalized formation mineralogy from core Farley 1305-H, modified from Anderson 2014.

		Utica	
	QFP	Carbonate	Total Clay
	33.85	18.06	48.09
	29.53	14.92	55.54
	25.66	31.49	42.84
Average	**29.68**	**21.49**	**48.83**

		Point Pleasant	
	QFP	Carbonate	Total Clay
	31.86	32.37	35.77
	32.23	30.47	37.31
	19.39	54.37	26.24
	22.63	48.63	28.74
Average	**26.53**	**41.46**	**32.01**

Table 8, Normalized whole rock mineralogy values produced from Table 2 that are plotted in Figure 17.

Ottman and Bohacs (2014) use another method to classify brittleness and reservoir quality. Ottman and Bohacs specify that quality reservoirs require the fundamental elements of storage, conductivity, and drive (Fig. 18). Storage within a shale gas reservoir is normally associated with organic material, as it induces porosity and gas volume. Conductivity is mainly a function of mechanical rock properties, as unconventional reservoirs require hydraulic stimulation to create (brittleness) and maintain (stiffness) fractures. Drive is the necessary pressure within the system. When these elements coalesce, the formation is then considered a quality reservoir.

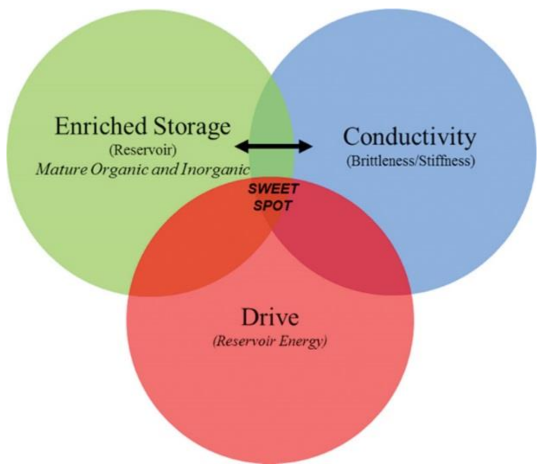
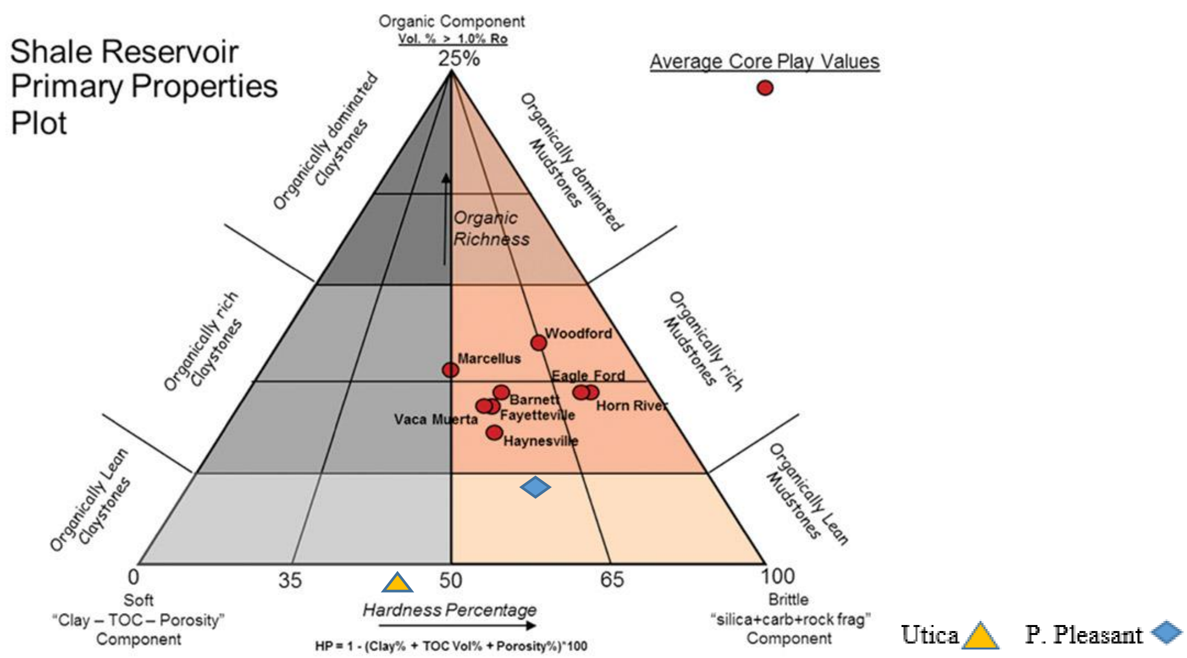


Figure 18, Venn diagram of desired reservoir qualities, from Ottman & Bohacs (2014)

Ottman and Bohacs' classification model uses quantifications of mineralogy, TOC Volume %, vitrinite reflectance, and Porosity %. In the classification scheme, a quantification of hardness percentage [1-(Clay% + Toc Vol % + Porosity %) * 100] is expressed horizontally and the organic matter volume % > 1.0% Ro is expressed vertically. Using their own classification scheme, Ottman and Bohac found that most successful plays group together under "Organically rich Mudstones."

The same quantifications were made from averaged data for the Point Pleasant Formation and Utica Shale from core Farley 1305-H and plotted on Ottman and Bohac's classification triangle (Fig. 19 & Table 9). The Point Pleasant plots within "Organically rich Mudstones," indicating a quality reservoir. The point for Utica plots within "Organically Lean Claystones." Thus, although the Utica Shale's large clay percentage is detrimental to gas production within itself, it improves gas production from the Point Pleasant Formation, as an overlying claystone aids pressure retention and in turn the aforementioned "Drive (Reservoir Energy)" element of a quality reservoir (Ottman and Bohacs, 2014).



(Figure 19, Ternary plot of reservoir quality values from Core Farley 1305-H and their relationship to other economically successful shales, modified from Ottman and Bohacs, 2014)

Formation	Clay %	TOC Vol%	Porosity %	Hardness Percentage
Utica	49	0.8	3.73	46.47
P. Pleasant	28	5.1	5.94	60.00

Table 9, values used to calculate Ottman and Bohacs' "Hardness Percentage." Because of previous discussion, all organic matter within the Point Pleasant & Utica has a R_o value greater than 1 %. Further, TOC volume % is approximated by doubling TOC weight %, according to Passey et al., 2010.

Porosity

Because gas shales are their own reservoir, porosity is critical because it controls the quantity of gas in place (Curtis et al, 2012). Further, porosity, in addition to natural fractures, forms the permeability pathways that enable gas to flow from induced fractures to the well bore (Loucks et al., 2012) (Fig. 20).

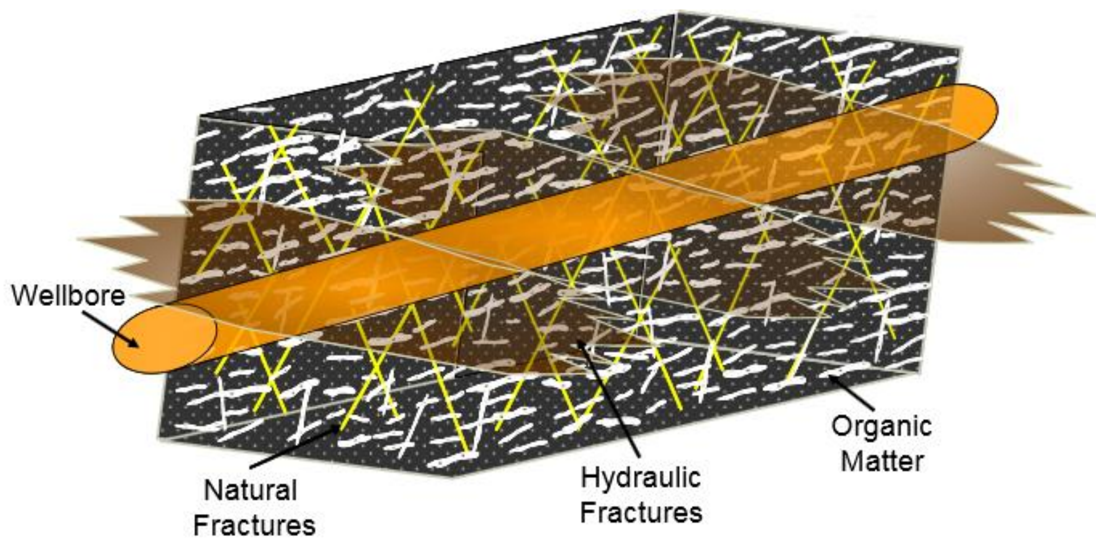


Figure 20, Schematic diagram illustrating the relationship between organic matter, porosity, and fractures for gas shales, modified from Wang and Reed (2009).

Measured shale nanopores have ranges from approximately 5 to 1000 nm within gas shale systems across the globe (Wang and Reed, 2009). Wang and Reed (2009) state that porosity in organic matter can be 5 times higher than in the nonorganic matrix. Ambrose et al. (2010) conclude that the organic material in shales makes up the majority of gas pore volume (Fig. 21). Loucks et al. (2009) state that a strong correlation exists between pore abundance and the amount of organic material and its thermal maturity, as immature source rocks lack interparticle porosity (specifically, Antrim and New Albany Shales). Therefore, as source rock approaches the dry gas window, porosity should be expected to increase and, in turn, potential flow rates of gas should increases as well. And because of the organic content and mature nature of the Ordovician formations within core Farley1305-H, sufficient porosity should be present.

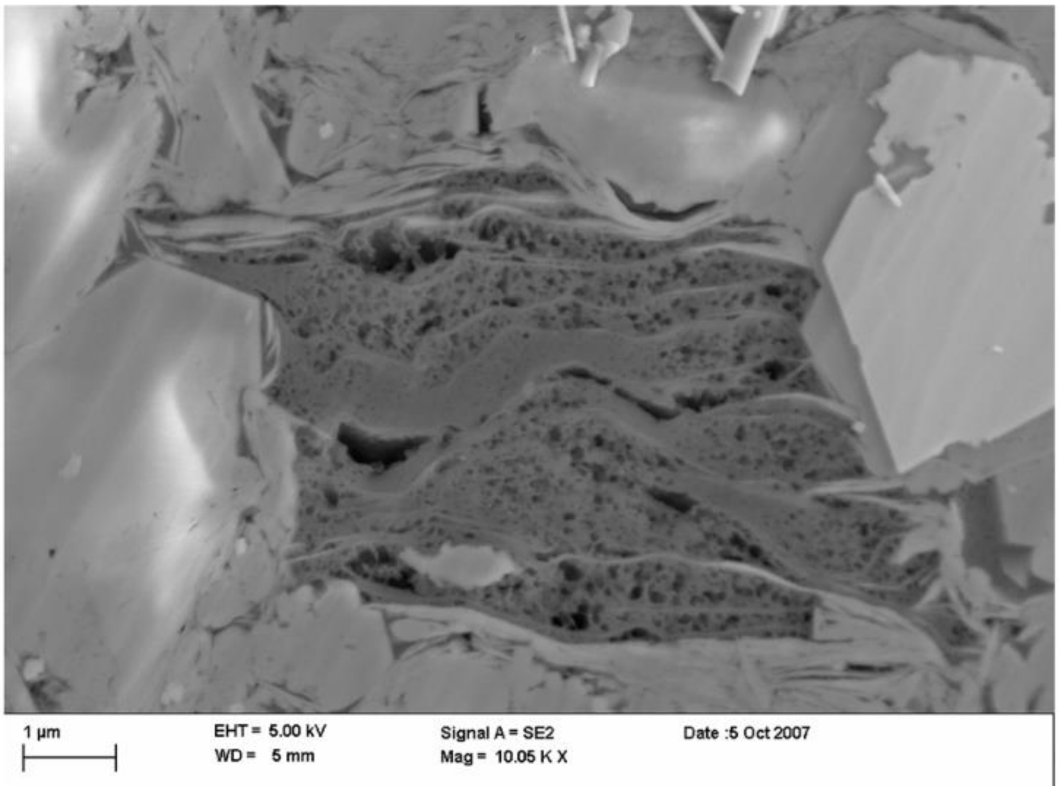


Figure 21, Scanning electron image of an Ar-ion beam milled surface on Barnett Shale sample, showing porosity within organic matter, modified from Wang and Reed (2009).

Olson and Grigg (2008) determined that 2-3 % gas-filled porosity is necessary for a shale reservoir to be successful. These are the standards used in evaluating the early Late Ordovician interval within southeastern Ohio in this study. The gas-filled porosity averages are 1.36% for the Utica Shale, 4.75 % for the Point Pleasant Formation, and 1.98 % for the Lexington Limestone (Table 2). Under the aforementioned standards established by Olsen and Grigg (2008), only the Point Pleasant Formation has sufficient gas-filled porosity to be considered a successful shale reservoir. However, some sufficient porosity overlaps formation boundaries, as portions of the lower Utica and most of the Lexington have gas-filled porosity values over 2 %, which should be taken into account by engineers prior to horizontal drilling in order to maximize gas production.

Miller (2014) considers any porosity lower than 2 % as a "shale killer." The porosity averages are 3.73 % for the Utica Shale, 6.96 % for the Point Pleasant Formation, and 3.07 % for the Lexington Limestone (Table 2). Under Miller's "shale killer" standard of a necessary porosity of 2 %, all the formations within core Farley 1305-H have sufficient porosity.

Geomechanical

Shale must fail under hydraulic stress in order to be a productive gas play. Experiments in the field show that gas production rates are improved with more effective hydraulic fracturing (Altamar and Marfurt, 2014). Thus, a brittle shale is desired over a ductile shale, as stated previously in the mineralogy section of this study. In addition to mineralogy, geomechanical properties are quantified as a means to differentiate between brittle and ductile sections within shale formations. These properties include the empirical relationship between Poisson's Ratio (a measure of expansion produced perpendicular to the direction of compression) and Young's Modulus (defines the relationship between stress and strain in a material) (Rickman et al, 2008).

A rock's ability to fail under stress is reflected by Poisson's Ratio and to sustain a fracture (after fracture is initiated) is represented by Young's Modulus. Generally speaking, brittleness increases as Poisson's Ratio decreases and Young's modulus increases. Grieser and Bray (2007) used these components to differentiate brittle and ductile shale within the Barnett Shale, with a 0.25 brittle/ductile threshold for Poisson's Ratio and $3.1*10^6$ PSI for Young's modulus. Grieser and Bray's thresholds were used to characterize the data points (Table 3) from core Farley 1305-H (Fig. 22). The two data points from the Point Pleasant Formation plot as more brittle relative to the Utica Shale data point. If the Point Pleasant fractures anything like Barnett Shale, the data indicates that when stimulated it will develop a “complex fracture network” (Grieser, 2016, personal communication). The Lexington Limestone data point plots within the “Barrier Rock Region,” indicating that the unit is “fracable” but is prone to simple bi-wing fracture (a planar fracture geometry)..

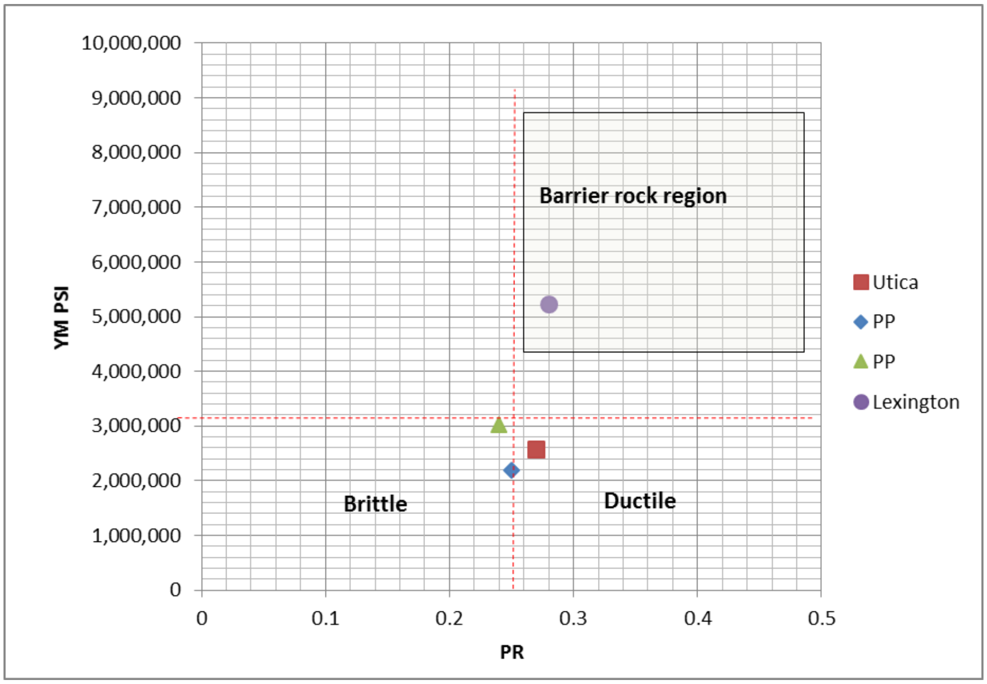


Figure 22, Young’s Modulus vs Poisson’s Ratio chart for the geomechanical data from core Farley 1305-H, modified from Grieser and Bray (2007).

Fracture geometry becomes more complex as brittleness increases (Rickman et al., 2008). And with increased brittleness, fractures extend into fracture networks, which increase primary permeability and productivity (Fig. 23). Therefore, under this current geomechanical understanding, the Point Pleasant is sufficiently brittle in a way that increases productivity. The Lexington Limestone could be hydraulically stimulated, but would produce minimal fracturing.

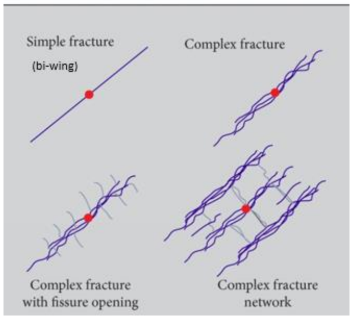


Figure 23, Illustration of fracture types, modified from Cipolla, Lolon, and Dzubin (2007).

Sequence Stratigraphy

Taylor McClain produced substantial studies on the sequence stratigraphy of the Late Ordovician strata of eastern Ohio, including second-order (2013) and third-order sequences (2012). His third-order study is of importance to this study, as it delineates the Point Pleasant Formation, which is the hydrocarbon target for the Ordovician interval in Washington and surrounding counties. Thus, recognizing the Point Pleasant Formation in geophysical logs will be vital to the economic success of future gas wells proximal to Farley 1305-H.

In McClain's (2012) third-order sequence study, the sequences were identified via gamma ray and density logs in two natural gas wells in Washington County (Fig. 24). The log signatures that delineate the four third-order sequences in McClain's Washington County wells were correlated with those from Farley 1305-H (Fig. 25). The resistivity and density logs of Farley 1305-H strongly indicate the high organic content of the Point Pleasant Formation. Recognizing and juxtaposing similar log signatures within undrilled regions can aid further hydrocarbon production from the Point Pleasant Formation.

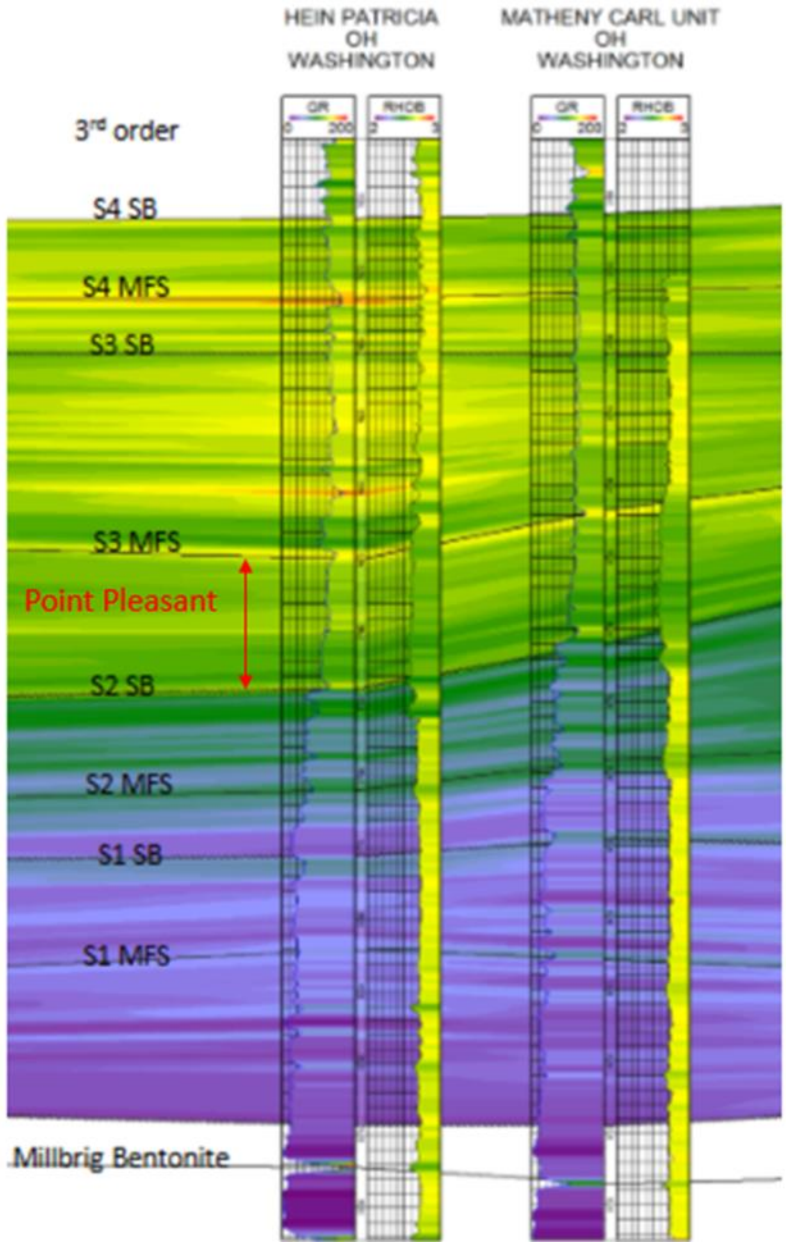


Figure 24, Gamma and density logs with third-order sequences delineated from wells in Washington County, Ohio, by McClain (2012). Note the Point Pleasant and the lower density signature in the logs. Modified from McClain (2012).

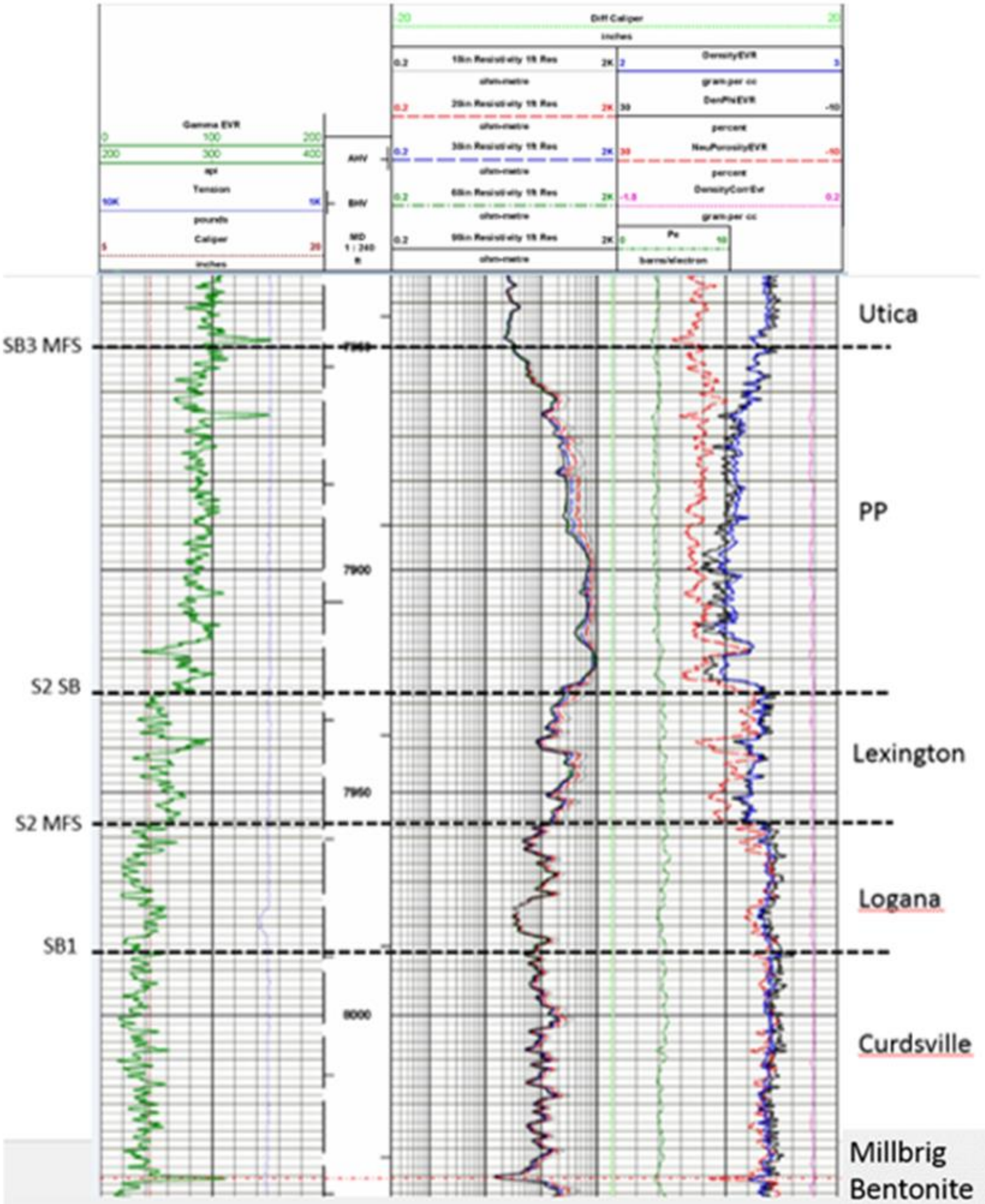


Figure 25, Geophysical logs from Farley 1305-H, imposed with McClain's third-order sequences. Note the high resistivity and low density within the Point Pleasant Formation, indicating its high organic content.

Conclusion

This study has determined the following pertinent observations about the geochemical and geophysical properties of well Farley 1305-H:

- Based on TOC wt. % data, the Utica Shale is considered too poor (< 1%) to have gas potential. The Point Pleasant Formation ranks from good to excellent. The Lexington/Trenton limestones rank from poor to good.
- Rock-Eval pyrolysis data indicates the cored interval to be a thermally mature gas shale system, yet it does not adequately describe in situ gas composition.
- Gas desorption analysis indicates the overlying Utica Shale and underlying limestones predominately produce dry gas, whereas the Point Pleasant produces wet gases.
- XRD mineralogy confirms that the Point Pleasant Formation is a highly calcareous shale with clay content increasing up section as it transitions into the Utica Shale.
- Mineralogy and Brittleness: Using Anderson's (2014) brittleness model, the Point Pleasant Formation near well Farley 1305-H shares similar traits to many successful unconventional shales and is most mineralogically similar to the Three Forks Shale. Under Ottman and Bohac's (2014) model to classify reservoir quality, the Point Pleasant Formation near well Farley 1305-H shares a general mineralogical hardness classification with the other gas producing shales, including the Barnett, Haynesville, and Woodford shales, yet the Utica Shale is less brittle and has little in common with any currently known productive shales.

- Porosity: The average gas-filled porosity of 5.94 % for the Point Pleasant Formation is much higher than the minimum threshold of 2-3% presented by Olsen and Grigg (2008) for a gas reservoir to be successful. However, the overlying Utica Shale and underlying limestones have insufficient porosity, except in areas adjacent to the Point Pleasant Formation.
- Geomechanically, the Point Pleasant Formation is classified as brittle in Grieser and Brey's (2007) classification scheme. This predicts it to break into fracture networks under hydraulic stress, and thus producing greater gas flow pathways. Conversely, the Utica Shale is classified as ductile and the Lexington Limestone is classified as a barrier rock, making both formations less than ideal for hydraulic fracturing.

In summary, the Point Pleasant Formation near well Farley 1305-H has sufficient TOC, porosity, minerology, and geomechanical properties to be a successful unconventional play, whereas the inverse is true for the Utica Shale. In relation to future exploration, geophysical logs can be used to recognize similar desired parameters in the Point Pleasant Formation within and outside of Washington County, Ohio.

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