CONNECTIVITY OF THE ORISKANY SANDSTONE WITH THE MARCELLUS SHALE: EFFECTS ON SHALE GAS OPERATIONS IN NORTH CENTRAL PENNSYLVANIA

by

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Marcellus Shale flowback and produced waters from lateral wells in North Central Pennsylvania have higher overall total dissolved solids and lower overall gas production than other areas of the Appalachian Basin. Marcellus Shale development in North Central Pennsylvania is unique in that it is the only area developed where historic vertical well gas fields exist in the Oriskany Sandstone, approximately 7-26 meters below the Marcellus Shale. This research explores potential effects on Marcellus Shale lateral well operations and production due to hydraulic connections between the Oriskany Sandstone and the Marcellus Shale. This connectivity is thought to adversely affect Marcellus Shale production operations in North Central Pennsylvania, but thus far, mechanistic clarification of production in North Central Pennsylvania has not been formalized and/or reported. The stratigraphic and structural review of the study area within North Central Pennsylvania identifies which Marcellus Shale lateral well pads are most likely to be connected with the Oriskany. The data reveals that the presence of the Oriskany Sandstone does not significantly affect formation breakdown pressures during the completion of the Marcellus laterals, nor percent fluid recovered during flowback, nor the volume of gas and water, nor the produced water geochemistry. The $\delta^{18}O$ and $\delta^{2}H$ isotopic composition of produced waters from the study area suggest possible mixing between waters characteristic of Oriskany and Marcellus Formations. A structural complexity calculator was developed to analyze if the structural profile of a lateral well (presence of faults, extreme bed dips, etc.) affects the completion or production of the laterals. The structural complexity calculations reveal that Marcellus Shale lateral well formation breakdown pressure, gas and water production volumes, and produced water geochemistry are affected by pre-existing structural features that the lateral wells intercept. This research identifies important interactions among lateral wells, historic gas fields, and structure. Clarification of these interactions will allow more efficient future Marcellus Shale lateral wells in North Central Pennsylvania.

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PREFACE

I began this endeavor in 2012. I knew that it would be a slow, steady process, but I was committed. At the time, I had already been working as a geoscientist in environmental consulting for four years. I was married and our first son was a year and a half old. One year into my studies I was delighted to begin a new job as an operations geologist with EQT Production. I took a six month hiatus from my studies to learn my new job. I resumed class in the summer of 2014. Meanwhile I was expecting our second son and also studying for the Pennsylvania Professional Geologists examination. I successfully passed the PG exam, just 11 days before our second son was born. Again, I took nearly a year hiatus from my academic studies, all the while mothering two young boys and honing my skills as an operations geologist. When I resumed classes and defined my thesis project in 2015/2016, it was time to get things done! As I complete this thesis, my husband and I are eagerly awaiting for the arrival of our third son in just five weeks' time. Looking back, it has certainly been a long journey and I have learned so much. I thank my parents for teaching me to not give up.

Of course, none of this would have been possible without the perpetual support and encouragement from my husband, Matthew. My extended family has also played a key role in helping us keep our home running smoothly. At the start, Jeff, Kelly and all my friends at Tetra Tech helped me believe that I should pursue this degree. Ashley, Joe, Luke, Chris, Craig and all my friends at EQT Production were instrumental in making this research possible. Finally, my boys – Liam, Miles, and little man – bring so much joy to my life. I dedicate this work to them.

Thank you all very, very much.

1.0 INTRODUCTION

Marcellus Shale drilling activities peaked in the North Central Pennsylvania (Figure 1-1) counties of Clarion, Forest, Elk, Cameron, Clearfield and Jefferson in 2011 and again in 2015, when the Henry Hub Natural Gas Spot Price in the previous year had averaged $4.38 per million BTU (EDWIN, 2016 and EIA, 2017). Since November 2014, the monthly Henry Hub Natural Gas Spot Price has averaged $2.69. In the current price environment, Marcellus Shale development has shifted from North Central Pennsylvania to other areas in the Appalachian Basin, such as southwestern and northeastern Pennsylvania where natural gas drilling and extraction is more economically viable. When the price of natural gas rises again, Marcellus Shale lateral well drilling activities will likely increase in North Central Pennsylvania. Using data collected from previously drilled wells, the opportunity exists to improve future development in North Central Pennsylvania. This research reviews geologic context, lateral completions data, and gas and water production data from lateral Marcellus Shale wells in North Central Pennsylvania to determine factors influencing gas production in North Central Pennsylvania.

In 2015, EQT Production (my employer) observed that Marcellus Shale flowback and produced waters from lateral wells in North Central Pennsylvania have higher overall total dissolved solids (TDS) and lower overall gas production than other areas of the Appalachian Basin (A. Douds, pers. comm.). Many of EQT's Marcellus Shale lateral wells in North Central Pennsylvania are underlain by the Oriskany Sandstone, the target of previous vertical gas drilling (Figure 1-2a). EQT's Marcellus Shale lateral wells also often encounter a significant amount of structure, such as faulting and significant bed dip changes, over short distances in North Central Pennsylvania. These observations lead to an overarching hypothesis that Marcellus Shale lateral wells in North Central Pennsylvania are hydraulically connected to the deeper Oriskany Sandstone reservoir and vertical Oriskany wells due to an existing fracture network and pressure gradient (Figure 1-2b).

Figure 1-1. Index map of North America. North Central Pennsylvania is denoted by orange circle (Maps of the World, 2016)

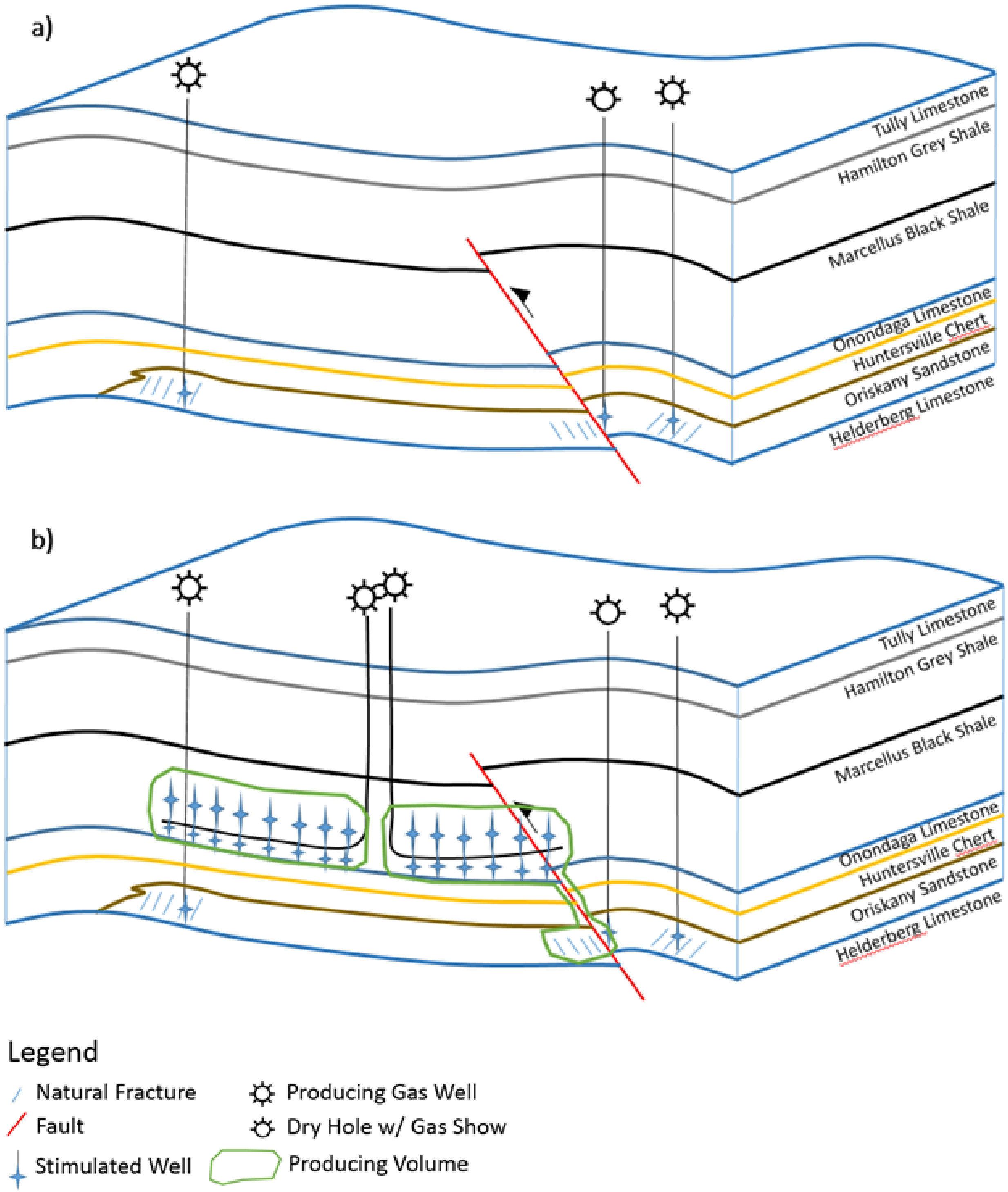


Figure 1-2. Conceptual model of formation response to unconventional gas extraction in North Central Pennsylvania

The drilling and hydraulic fracturing of the Marcellus Shale may enhance the connection of the Marcellus laterals with the deeper Oriskany Sandstone in North Central Pennsylvania (Figure 1-2b). This leads to two hypotheses: 1) The Marcellus Shale laterals are hydraulically connected with the Oriskany Sandstone via existing fractures, faults, or legacy vertical wells in the North Central Pennsylvania region; and 2) Connection to the Oriskany Sandstone diffuses stimulation energy during hydraulic fracturing (via flow through the existing fractures or faults) and therefore the Marcellus Shale reservoir is ineffectively propped and gas production is diminished. These questions will be examined using multiple lines of evidence throughout this thesis. Specifically, formation breakdown pressure data collected during hydraulic fracturing, percent of fluid recovered during flowback, and gas and water production data together provide insight into connections between the Marcellus Shale and Oriskany Sandstone. The synthesis of produced gas and water volume, chemistry, and produced water and gas isotope data with structural complexity (derived from geosteering data) provide insight into variability in well performance.

This thesis provides information that can contribute to development of methods to maximize hydrocarbon recovery and minimize brine water recovery in North Central Pennsylvania. When wells are drilled efficiently, as to produce the greatest amount of hydrocarbon and minimize brine water recovery, operators' net income will increase and more importantly, environmental impacts will be reduced.

1.1 GEOLOGIC FRAMEWORK

1.1.1 History of Oil & Gas in North Central Pennsylvania

Drilling activities came to North Central Pennsylvania in the 1940's, most notably in the Leidy field in Clinton County (Figure 1-3). In 1951, the Driftwood gas field was discovered in southwestern Cameron County (Fettke, 1953). By 1954, the Driftwood gas field had been renamed to the Benezette-Driftwood gas field and was extended into southeastern Elk County (Fettke, 1955). In 1955, the Rockton Field was discovered southwest of the Benezette-Driftwood Field in northwestern Clearfield County (Fettke, 1956). The occurrence of gas in the Oriskany in North Central Pennsylvania is due to structurally controlled fracture-type porosity (Fettke, 1955). Between 1946 and 1990, it is estimated that over 650 vertical wells were drilled and producing from the Oriskany Sandstone (EDWIN, 2016). The locations of the main Oriskany Sandstone gas fields are shown in Figure 1-3.

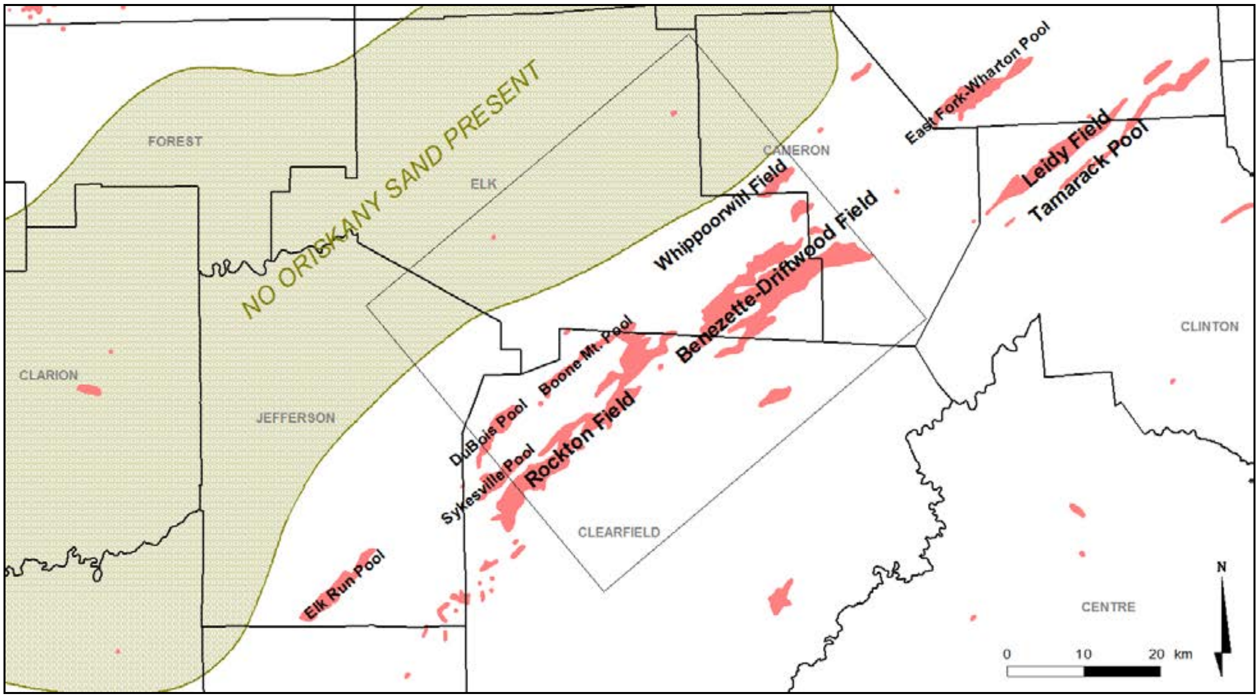


Figure 1-3. Location of vertical Oriskany Sandstone gas fields

In 1955, the completion method "hydrafracing" came into use in the Oriskany Sandstone vertical well fields. Hydrafracing, or what we know today as hydraulic fracturing, used pressurized water to fracture not only the Oriskany Sandstone, but also the Helderberg Limestone below the Oriskany Sandstone and the Onondaga Chert above the Oriskany Sandstone. Hydrafracing was determined to be more effective than 'shooting' (the previous preferred completions method that involved dropping explosives into the wellbore) (Fettke, 1956). Vertical Oriskany Sandstone wells were also often completed with acid because the acid etching would prevent complete fractures closure and further increased productivity.

The production of vertical Oriskany Sandstone wells is maintained through activities like swabbing, i.e., the use of a small rig to remove fluids from the well. As fluids in the well increase, bottom hole water pressure inhibits gas flow to the surface. Recompletion is another way to maintain a well's production. Once these maintenance activities no longer enhance natural gas production, a well will be abandoned.

The first lateral Marcellus Shale well was drilled and completed in North Central Pennsylvania in Elk County by EOG Resources (API #3704723983) in the fall of 2007 (EDWIN, 2016). Since then, over 300 lateral Marcellus Shale wells have been drilled in North Central Pennsylvania in Clarion, Forest, Elk, Cameron, Clearfield, and Jefferson Counties.

Lateral, or horizontal, drilling begins by drilling vertically to some depth above the Marcellus Shale. The point at which the well changes from being vertical to deviated is called the kick-off point. For the driller to begin to drill at an angle other than vertical the lower portion of the drill string, the bottom hole assembly, is replaced with a bottom hole assembly that includes directional, measurement-while-drilling, and logging-while-drilling tools (Schlumberger, 1998). Directional tools commonly use a downhole steerable motor with a bend near the bit which points the bit in a direction different from the axis of the wellbore, enabling the well to intentionally deviate from the relatively straight path it would naturally take. Measurement-while-drilling tools evaluate the physical properties of a wellbore, including pressure, temperature, and wellbore trajectory in three-dimensional space. Logging-while-drilling tools measure formation parameters such as the gamma ray readings of the rock encountered. Measurement-while-drilling and logging-while-drilling measurements are made downhole, generally 9 – 18 meters behind the drill bit. The measurements are stored in solid-state memory and are generally transmitted to the surface once for every 18 – 27 meters of rock drilled. Data transmission usually involves digitally encoding data and transmitting to the surface as pressure pulses in the mud system. Reports including the directional surveys, or location of the wellbore in 3-dimensional space, and the gamma measurements recorded while drilling are generated from the data transmissions.

Using measurement-while-drilling readings, directional drillers control the left/right direction of the path of the wellbore. Generally, horizontal well paths are planned on a preferred azimuth. This preferred azimuth varies across the Appalachian Basin, but is usually parallel to the local minimum horizontal stress (Zinn, 2011). Drilling parallel to the minimum horizontal stress enables induced hydraulic fractures to grow in the direction of the maximum horizontal stress and therefore maximize gas flow into the wellbore.

In the Marcellus Shale, measurement-while-drilling and logging-while-drilling gamma ray readings are used to guide the up/down direction of a well by a method called geosteering. Marcellus Shale lateral wells target a portion of the Marcellus formation where modeled clay content is expected to be low and where modeled gas concentrations are predicted to be high. This target interval will have a distinct 'gamma' signature, which is a measurement of the radioactivity of the rock. Marcellus black shale contains radioactive isotopes of U, K and Th in higher concentrations than those of less-organic rich grey shales, limestone, or sandstone. This is because U preferentially bonds to organic matter and K and Th preferentially bond to clays, which compose most of the sediment at the paleo-ocean floor. Ultimately, black shales, like the Marcellus, contain more organic matter and clay and therefore are more radioactive than other shales or sedimentary rocks (Perry, 2011).

Geosteering is done by correlating the gamma ray readings collected in the horizontal well to gamma ray readings previously collected in a vertical pilot hole well (Pitcher, 2012). As shown in Figure 1-4, the horizontal well gamma ray readings (blue line) are correlated to the pilot hole gamma ray curve (black line). The correlation is composed of several small segments (colored lines) because each segment of horizontal well gamma ray readings was stretched or squeezed in a unique way to fit the pilot hole gamma ray curve. Geosteering software uses the manipulation of horizontal gamma ray readings to fit the pilot hole gamma ray readings to generate a bed dip and horizon. The bed dips and horizons interpret the location of the wellbore relative to a target interval. The directional drillers then use this geosteering interpretation to guide the up/down direction of the horizontal path of the wellbore. Additionally, the wellbore, kick-off point, formation horizons, target interval, gamma curves, and bed dips are labeled in the geosteering profile shown in Figure 1-4 When the driller has finished drilling the well it is said that the well reached 'total depth', or TD.

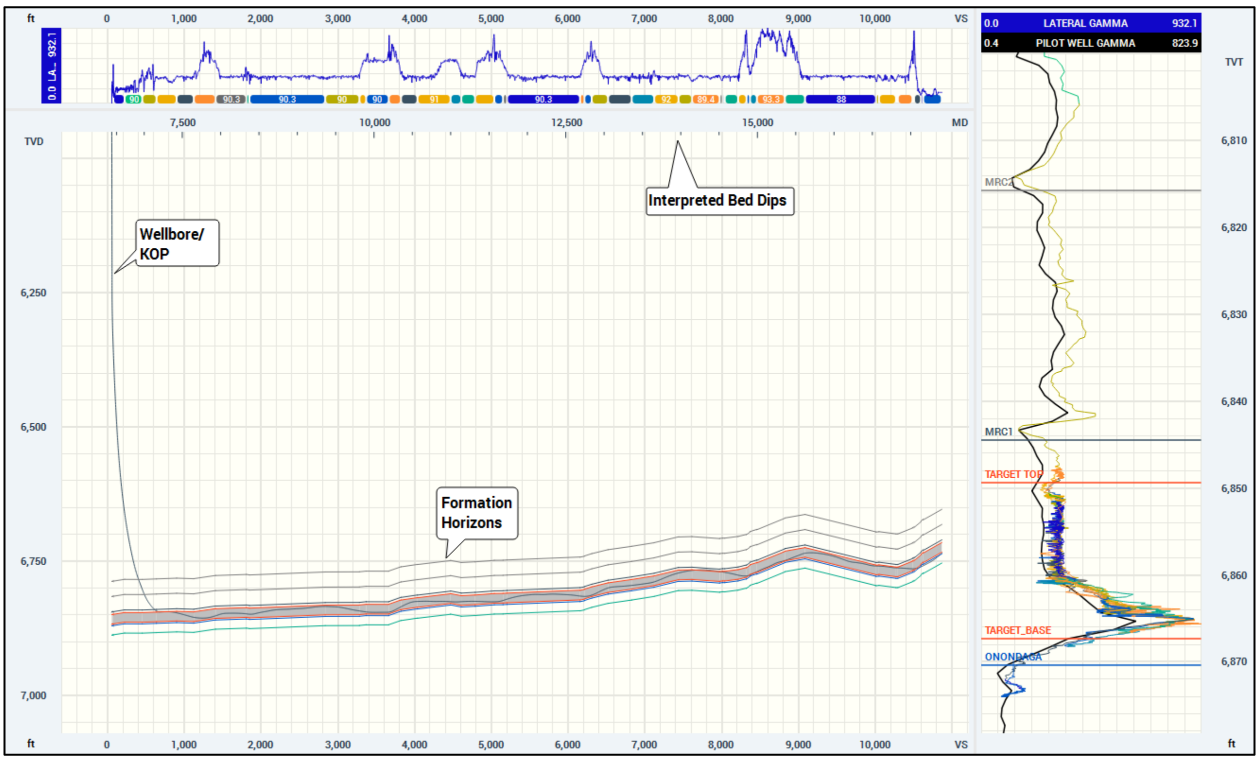


Figure 1-4. Example of geosteering. Software shown is StarSteer by Rogii

1.1.2 Stratigraphy of North Central Pennsylvania Study Area

The study area of this research is defined as the black rectangle shown in Figure 1-5. It ranges from EQT's Monarch Pad in Jefferson County in the northwest to the Turkey Pad in Clearfield County in the south and from the Frano Pad in Jefferson County in the west to the Whippoorwill Pad in Cameron County in the east (Figure 1-5). The study area contains two subdivisions: a southern portion where the Oriskany sand is present and a northern portion where the Oriskany sand is absent.

The Oriskany is a Lower Devonian sandstone separated from the underlying Lower Devonian Helderberg Limestone and the overlying Middle Devonian Huntersville Chert by unconformities (Figure 1-6). The use of the name Oriskany Sandstone has been extended throughout the basin, although the presence of the unconformities above and below the Oriskany suggests several erosional events that resulted in deposition of local sandstones in the approximate stratigraphic position of the Oriskany (Patchen, 1996). In the "no-sand area", the Oriskany is thin or absent due to erosion or non-deposition (Diecchio, 1985). Local sandstones include the Sylvania Sandstone in Ohio, the Springvale Sandstone in New York, and the Ridgeley Sandstone in Pennsylvania. The Oriskany Sandstone is generally thought to have been deposited in a shallow-marine environment (Dresel and Rose, 2010).

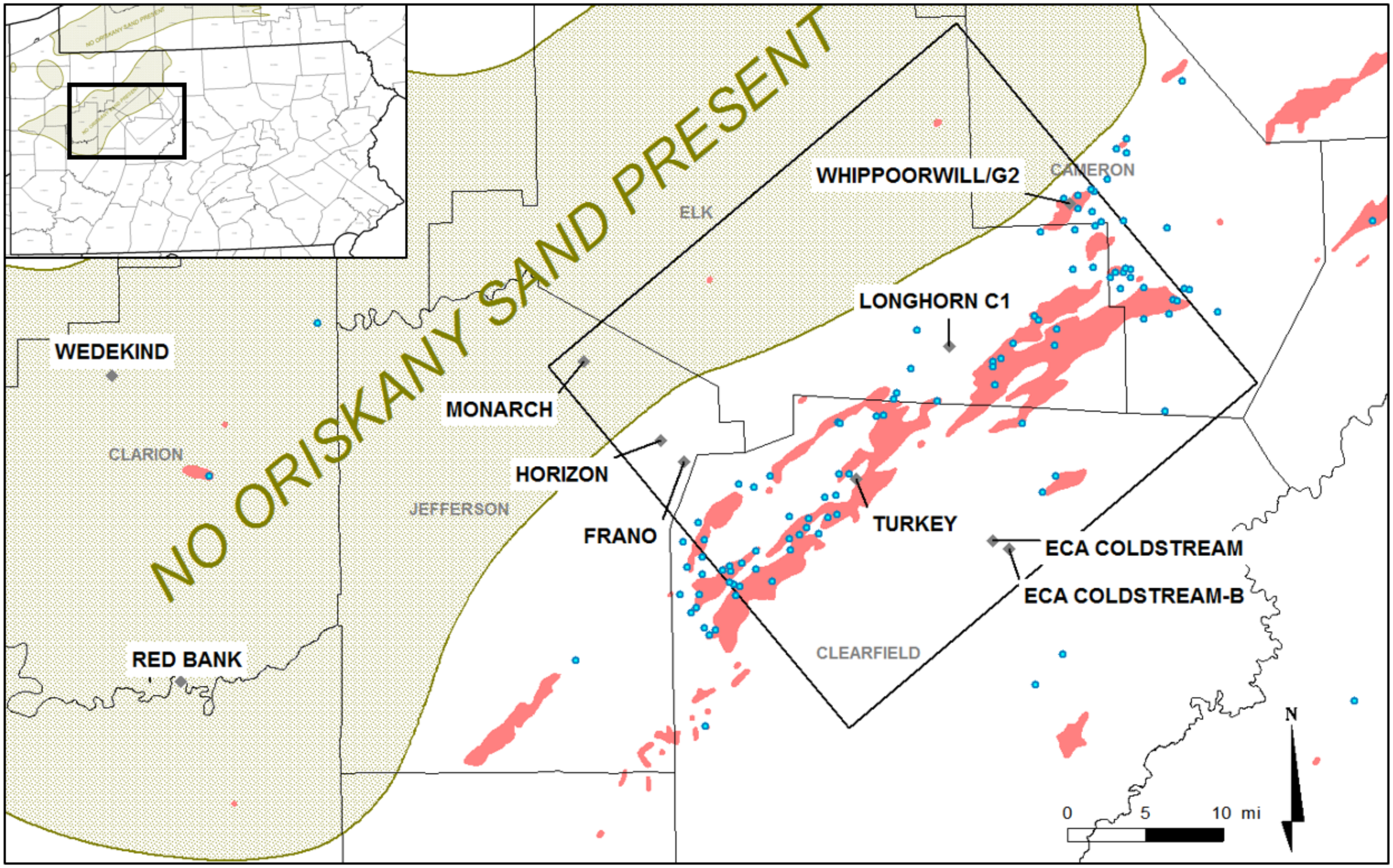


Figure 1-5. Location of study area. Black rectangle represents the study area. Blue dots represent Oriskany vertical wells that contain brine (EDWIN, 2016)

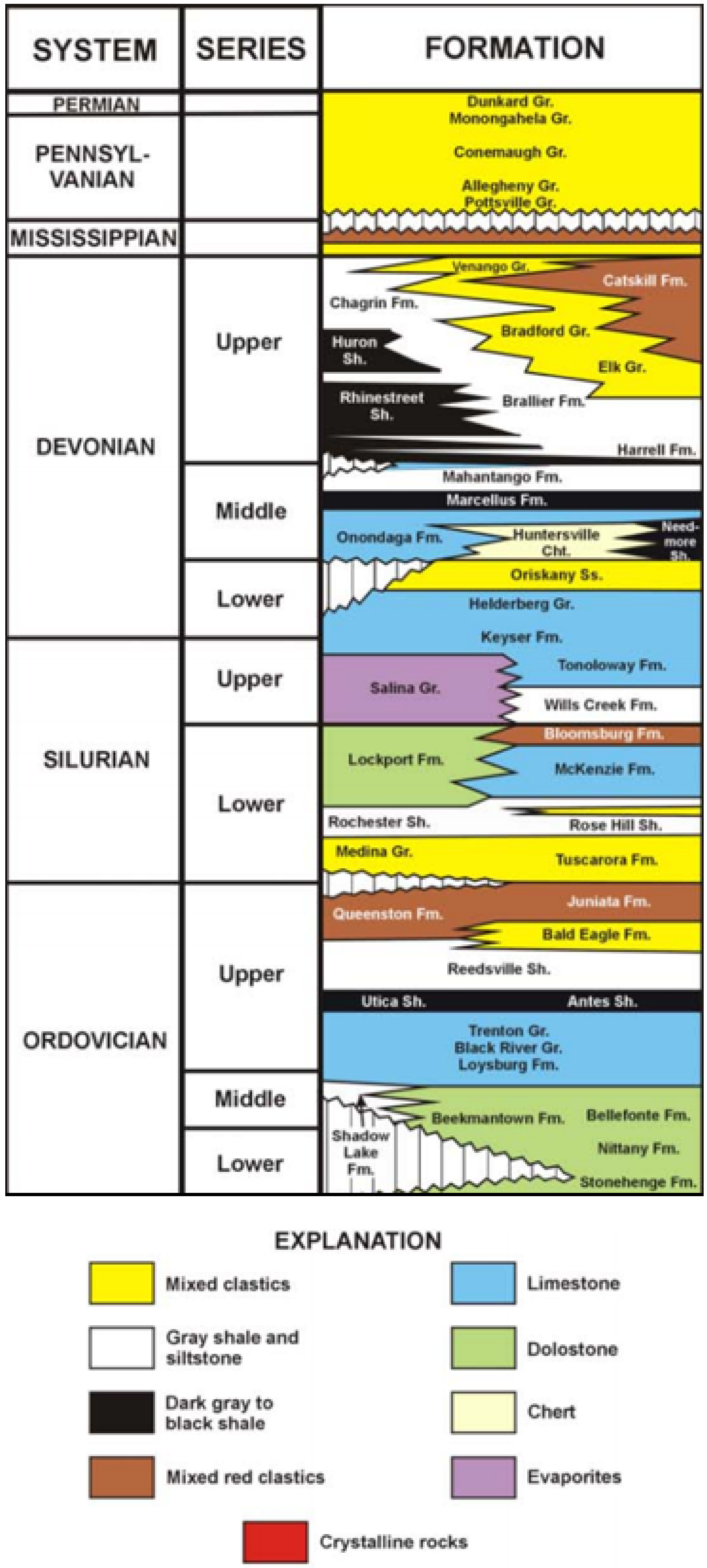


Figure 1-6. Generalized stratigraphic column of Pennsylvania (PA DCNR, 2003)

1.1.3 Mineralogy of the Oriskany Sandstone

The Oriskany Sandstone in the Elk Run Pool of Jefferson County, PA has been described as very fine to coarse-grained, calcerous, poorly sorted, quartoze sandstone composed of mainly subrounded, frosted grains (Heyman, 1969). It is light grey in a clean sample and light orange in outcrop.

Across the Appalachian Basin, most of the sandstone is silica cemented, but there are highly calcareous areas (Krynine, 1941). The average composition reported by Rosenfeld (1953) for Ridgeley quartz sandstone is as follows: detrital silicates, 77.7 percent; authigenic silica, 9.5 percent; clastic carbonate, 7.1 percent; fixed crystalline carbonate, 3.8 percent; other clastics, 1.4 percent; and other cements and matrices, 0.5 percent. Detrital silicates reported by Rosenfeld (1953) include about 1 percent feldspar and 0.2 percent heavy minerals. The authigenic silica is mainly clear quartz overgrowths, but locally consists of microcrystalline quartz or quartz having flamboyant radiation extinction. The clastic carbonates are fossil fragments, whereas the fixed crystalline carbonate includes sparry calcite, and small rhombs of siderite or ankerite.

Welsh (1984) reported fractures in the Oriskany Sandstone healed by calcite, whereas Basilone and others (1984) noted quartz and ferroan calcite fracture fillings. Other clastics include rare biotite chlorite, and muscovite. Interstital limonite is commonly present, and one section had barite or celestine cement. Stow (1938) reported zircon, tourmaline, rutile, leuoxene, chlorite, and limonite as the Oriskany heavy minerals in Pennsylvania.

1.1.4 Porosity of the Oriskany Sandstone

Porosity occurs in the upper two-thirds of the sandstone. The existence of a limited fracture network in the Oriskany may have enhanced the overall quality of the reservoir (Heyman, 1969). The data indicate that intergranular and fracture porosity exist within the Oriskany, and overlying thick low-permeability zones within the Appalachian Basin provide the potential for vertical containment (Diecchio, et al., 1984; Gupta et al., 2005). Rosenfeld (1953) reported mean effective porosity of 7.6%, whereas Skeen (2010) reported a mean effective porosity of 8.08%.

1.1.5 Water Occurrence in the Oriskany Sandstone

The completion reports of 104 wells document that the Oriskany sandstone contains brine (EDWIN, 2016). The location of the Oriskany wells containing brine are indicated by the blue circles in Figure 1-5.

1.1.6 Pressure of the Oriskany Sandstone

Within the study area the Oriskany Sandstone is considered to be overpressured (as high as 31,026 kPa) because of initial open flow pressures in some areas of the basin, (Wickstrom et al., 2005). However, across the Appalachian Basin the Oriskany is generally underpressured with an average pressure gradient of 6.8 kPa/m of depth, compared to a hydrostatic freshwater gradient of 9.74 kPa/m for freshwater and approximately 10.71 kPa/m for brine. Final shut-in pressure in the Oriskany Sandstone within the study area ranges from 20 to 25 kPa (Skeen, 2010). Russel (1972) suggested that, on, average, the Oriskany Sandstone is not an overpressured reservoir, and that overpressuring is more common in areas of intense deformation. One example of overpressuring in the Oriskany Sandstone within the study area is from completion report of well API #3702320025 (EDWIN, 2016). The report records that the well was drilled to the Oriskany sandstone in the Driftwood Quadrangle of Cameron County, and that after drilling ceased, the water level in the well rose 36 m in 23 days.

1.1.7 Structure of North Central Pennsylvania Study Area

The gas reservoirs of the Oriskany Sandstone in North Central Pennsylvania occur within structural traps. These structural traps occur along a northeast trending belt, which actually extends from Fayette County on the southwest to Potter and Tioga Counties on the northeast (Wagner, 1973). A cross-section of the Leidy gas field illustrates the faults and anticline that create the structural trap (Figure 1-7). In the Oriskany Sandstone two gas fields are separated by faults; the Leidy pool and the Tamarack pool. Due to the faulting, the main gas trap, the Leidy pool, lies on the northwest side of the anticline near the crest, rather than on it. The Tamarack pool, a trap containing less gas, is in one of the faulted sections at the crest. The structure of the Leidy gas field is typical of the belt from Potter to Fayette Counties where gentle anticlines at the surface are faulted in the subsurface, resulting in entrapment of gas primarily on the flanks instead of the crest of the anticlines (Wagner, 1973).

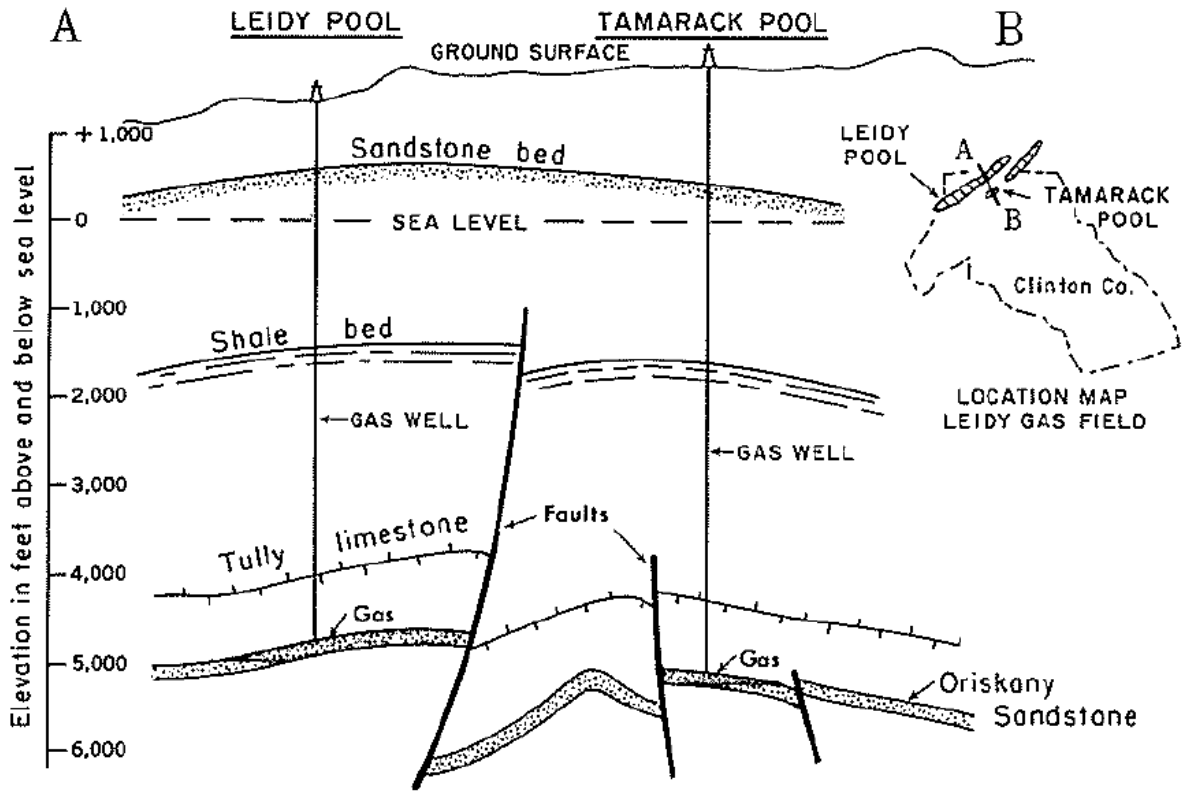


Figure 1-7. Cross section of Leidy gas field. Entrapment of gas in folded and faulted anticline. Note that faults in the Oriskany Sandstone and Tully Limestone do not propagate to the surface (Wagner, 1973)

1.2 NORTH CENTRAL PENNSYLVANIA VERTICAL GAS FIELDS RELATIVE TO THE APPALACHIAN BASIN

Marcellus Shale lateral well development in North Central Pennsylvania is one of the only areas of the Appalachian Basin where Marcellus Shale laterals have been developed over the historic Oriskany gas fields (Figure 1-8). Well completion reports indicate that Anadarko drilled and completed several wells over an unnamed Oriskany Field in Clinton County between 2010-2011 (EDWIN, 2016).

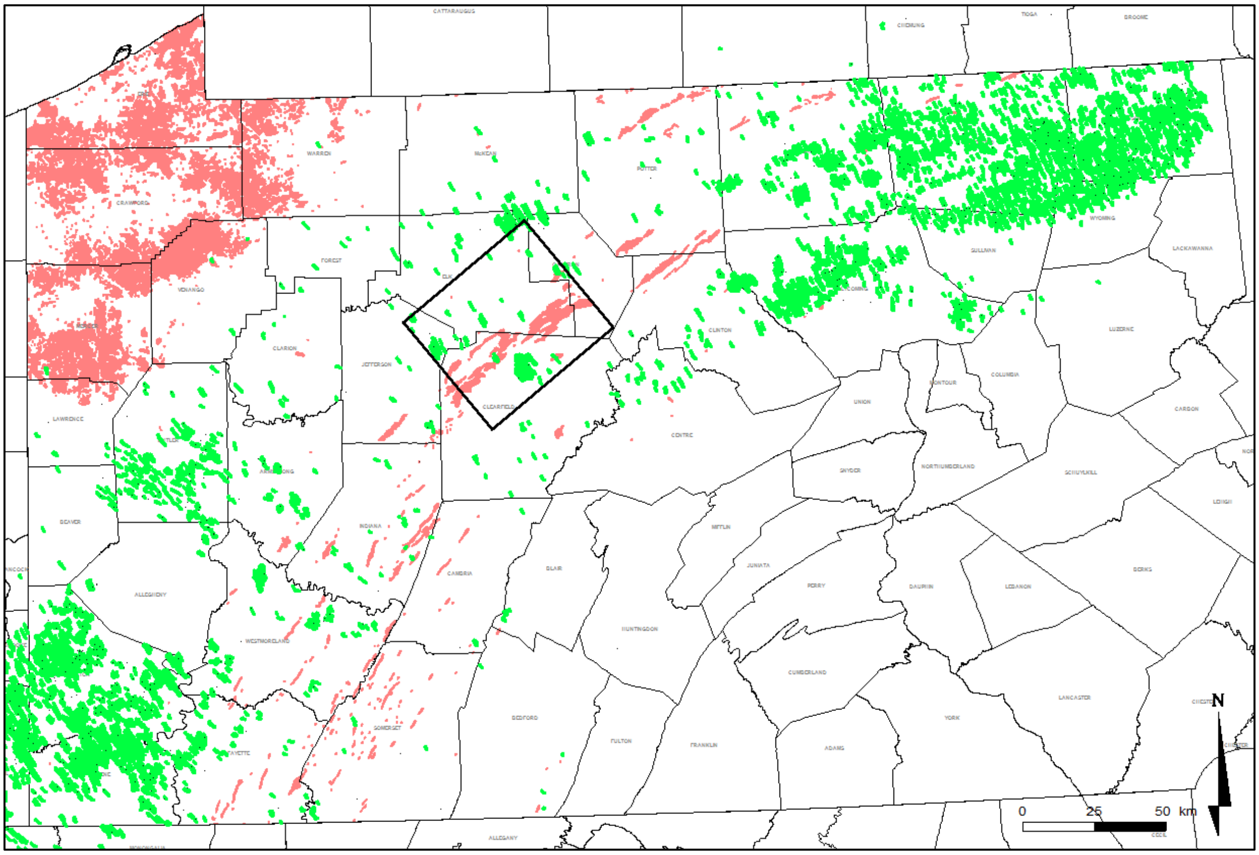


Figure 1-8. Pennsylvania deep gas fields in relation to Marcellus Shale development in the Appalachian Basin, as of August 2017. Black rectangle represents the study area. Red shapes delineate the deep gas fields. Green shapes delineate locations of Marcellus Shale lateral wells

1.3 CONCEPTUAL MODEL

The conceptual model relates vertical Oriskany wells and complex structure, such as faults and fractures, which existed in the study area prior to the drilling of Marcellus Shale laterals, to the producing rock volume of Marcellus Shale laterals (Figure 1-2). The model represents the Oriskany as a structural play within the study area. After the drilling, completion, and production of Marcellus Shale laterals by EQT Production, it is expected that some Marcellus Shale laterals in the study area may be connected with the Oriskany Sandstone. Therefore, the producing rock volume of the Marcellus Shale laterals also increases and extends into the Oriskany Sandstone through faults. Natural fractures and faults that developed after deposition of the Marcellus Shale created voids and secondary permeability. Hydraulic fracturing of Oriskany Sandstone vertical wells and Marcellus Shale laterals also generates permeability. Secondary permeability enhances the ability for rock to transmit fluids and increases the hydraulic conductivity. In turn, the flow pathways created by secondary permeability are also zones are where solutes collect and secondary minerals form over time.

2.0 METHODOLOGY

2.1 STRUCTURE AND STRATIGRAPHY

2.1.1 Structure

I generated a structural contour map of the subsea elevation (depth measured below zero elevation) of the Onondaga Limestone surface in GeoGraphix. First, in SeisVision, faults were identified in the seismic data. Then the Tully Limestone and Onondaga Limestone horizons were delineated. Next, the fault heave calculator tool was used to calculate fault offset. Then, where possible, the major faults were named and correlated across multiple 2D seismic lines and 3D surveys. Next, wells that had Tully and Onondaga formation tops picked were referenced to the Tully and Onondaga seismic data and seismic velocities were referenced to depth. At this point, a time map was generated, and then a velocity gradient map. The Onondaga velocity gradient map was converted to depth. This depth map was then brought into GeoAtlas and additional Onondaga depth points were added from geosteering data.

2.1.2 Stratigraphy

Using Geographix XSection, cross-sections of geophysical logs from the study area were interpreted (Figure 2-1). Using the density, gamma, photoelectric, and resistivity curves, I delineated the Marcellus Shale, Onondaga Limestone, Huntersville Chert, Oriskany Sandstone, and Helderberg Limestone horizons. As standard, the top of a formation serves as the base of the overlying formation. I also delineated the base of the Oriskany ‘pay zone’, which is defined as an interval within the Oriskany having a density of less than 2.55 g/cm^3. (This interval of low density sandstone is referred to as ‘pay zone’ because it contains the greatest pore space where hydrocarbons preferentially gather.) In total, over 170 well logs were reviewed and the intervals were delineated and saved as formation records in Geographix Wellbase. Using Geographix Isomap, Oriskany Sandstone Thickness, Oriskany Sandstone Net Pay, and Distance from Marcellus Shale to Oriskany Sandstone maps were generated.

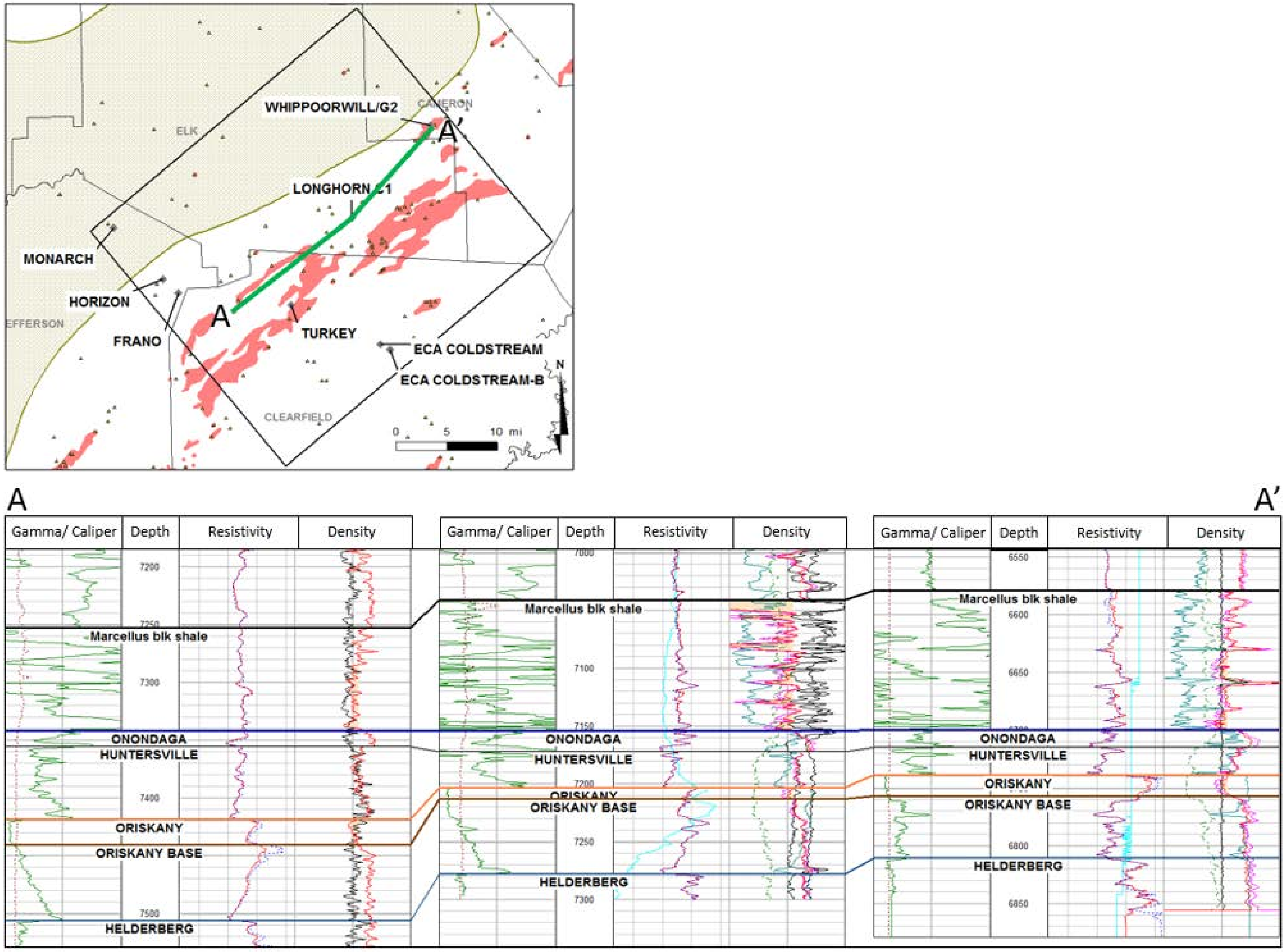


Figure 2-1. Example of stratigraphic interpretation in Geographix XSection. Cross-section taken along strike in study area

2.2 WATER AND GAS DATA COLLECTION

2.2.1 Water

2.2.1.1 Published Water Data Oriskany Sandstone produced water chemistry data were compiled from published datasets. Table 2-1 summarizes well location and construction details of the published data. The published data set includes water analyses from three Oriskany wells in the Rockton Field located in Clearfield County (Poth, 1962) and water analyses from 23 Oriskany wells across Jefferson, Clearfield, Cameron, and Elk Counties (Kelley et. al., 1973). The published data sets listed above were previously compiled in an Oriskany brine geochemical data set of over 220 analyses from throughout the Appalachian Basin (Skeen, 2010).

Additionally, published Oriskany produced water oxygen and hydrogen isotope analyses of three Oriskany wells located in Somerset County, PA (Dresel, 1985) were included in the dataset. While these samples are from wells located approximately 120 kilometers south of the study area, the analyses were included as there are very few isotope analyses of Oriskany waters to date.

2.2.1.2 Previous Water Collection by EQT In January 2013, a well tender collected flowback water samples from two different Marcellus Shale laterals on the Frano pad (Figure 2-2). The first day of flowback for these two wells was October 4, 2012. These water samples were analyzed by Multi-Chem Laboratories for total dissolved solids, pH, chloride, sulfate, Ca, Fe, K, Mg, Na, and Sr.

Table 2-1. Record of wells sampled

Well ID	County	API Number	Well Operator	Name	Date Drilling Complete	Date Completed	GL Elevation (m)	Total Vertical Depth (m)	Measured Depth to Bottom of Casing (m)	Aquifer	Oriskany Depth/Top (m)	Oriskany Depth/Base (m)
HORIZONTAL WELLS	**(NEW DATA COLLECTED FOR THIS THESIS)**											
591549	Jefferson	370652703901	EQT	Horizon	6/17/2014	10/28/2014	533	2090	5298	Marcellus	2116	unk
591668	Jefferson	370652704101	EQT	Horizon	7/8/2014	9/26/2014	533	2089	5287	Marcellus	2116	unk
591970	Jefferson	370652704201	EQT	Horizon	8/11/2014	4/8/2015	533	2078	5504	Marcellus	2116	unk
590515	Jefferson	370652686601	EQT	Frano	11/18/2010	1/2/2011	497	2033	3294	Marcellus	2033	unk
590516	Jefferson	370652686501	EQT	Frano	10/29/2010	1/8/2011	497	2003	3182	Marcellus	2033	unk
590983	Clearfield	370332704901	EQT	Turkey	11/15/2012	7/3/2014	525	2231	4177	Marcellus	unk	unk
590876	Cameron	370232015401	EQT	Whipporwill	4/13/2014	8/8/2014	506	2071	4727	Marcellus	2054	2076
591155	Jefferson	370652699501	EQT	Monarch	1/20/2013	8/10/2013	539	1899	4038	Marcellus	No Oriskany Present	
590389	Clarion	370312529701	EQT	Wedekind	1/17/2010	5/6/2010	432	1564	2352	Marcellus	No Oriskany Present	
590370	Clarion	370312529501	EQT	Redbank	12/21/2009	3/11/2010	447	1899	2756	Marcellus	No Oriskany Present	
CS-1	Clearfield	370332684801	ECA	Coldstream 1MH	unk	11/25/2010	541	unk	unk	Marcellus	unk	unk
CS-3	Clearfield	370332685501	ECA	Coldstream 3MH	unk	12/26/2010	539	unk	unk	Marcellus	unk	unk
CSB-5	Clearfield	370332713601	ECA	Coldstream-B 5MH-S	unk	1/1/2013	467	unk	unk	Marcellus	unk	unk
VERTICAL WELLS	**(NEW DATA COLLECTED FOR THIS THESIS)**											
591011	Clearfield	3703320252	EQT	Baummer 737	10/2/1959	10/27/1959	520	2213	2190	Oriskany	2202	2212
591060	Cameron	3702320015	EQT	Skillman Lee #1	3/16/1962	3/15/1962	463	2036	2038	Oriskany	2028	2036
591057	Clearfield	3703320110	EQT	COP 49 1	1/10/1958	1/15/1958	550	2198	2198	Oriskany	2176	2198
591034	Clearfield	3703320247	EQT	Desander Lewis 1	9/18/1959	9/25/1959	539	2256	2251	Oriskany	2246	2256
591059	Clearfield	3703320609	EQT	Ross 1548	9/15/1976	9/28/1976	704	2035	2025	see comments	1958	1961
591055	Elk	3704700036	EQT	CNG 430	unk	2/23/1955	387	1915	1907	Oriskany	1905	1912
591023	Elk	3704701503	EQT	Thurby #4	10/13/1953	unk	392	1949	1936	Oriskany	1943	1949
591099	Clearfield	3703320212	EQT	Palumbo #2	4/10/1959	4/20/1959	482	2180	2158	Oriskany	2171	2178
591069	Clearfield	3703320245	EQT	Gordon #12	8/7/1959	9/4/1959	444	2149	2108	Oriskany	2139	2149
COP 1	Clearfield	3703321396	ECA	COP 324 - 1	unk	12/6/1982	586	2242	2167	Oriskany	2198	2200
COP 2	Clearfield	3703321634	ECA	COP 324 - 2	unk	9/28/1983	650	2316	2309	Oriskany	2268	2274
COP 3	Clearfield	3703321739	ECA	COP 324 - 3	12/12/1983	12/20/1983	637	2308	2187	Oriskany	2247	2250
COP 4	Clearfield	3703321923	ECA	COP 324 - 4	9/1/1984	9/7/1984	638	2310	2199	Oriskany	2260	2263
COP 6	Clearfield	3703322015	ECA	COP 324 - 6	11/23/1984	12/4/1984	657	2334	2210	see comments	2279	2282
COP 10	Clearfield	3703324080	ECA	COP 324 - 10	2/2/1999	4/7/1999	655	2346	2339	Oriskany	unk	unk

nm = not measured
unk = unknown
NYSNG = New York State Natural Gas

Table 2-1. (continued)

Well ID	County	API Number	Well Operator	Name	Date Drilling Complete	Date Completed	GL Elevation (m)	Vertical Depth (m)	Depth to Bottom of Casing (m)	Aquifer	Oriskany Depth/Top (m)	Oriskany Depth/Base (m)
VERTICAL WELLS	**(PREVIOUSLY PUBLISHED DATA)**											
ED-82-37	Somerset	unk	unk	unk	1979	unk	646	unk	unk	Ridgeley	2694	2727
ED-82-38	Somerset	unk	unk	unk	1979	unk	570	unk	unk	Ridgeley	2676	2695
ED-82-40	Somerset	unk	unk	unk	1973	unk	718	unk	unk	Ridgeley	2604	2627
KELLEY_68	Clearfield	unk	NYSNG	Dufor #1	unk	5/29/1958	456	2223	2198	Oriskany	2214	2221
KELLEY_69	Clearfield	unk	unk	Bakers Run Reserve # 6	unk	5/29/1958	502	2316	2283	Oriskany	2295	unk
KELLEY_176	Jefferson	unk	NYSNG	Rhine #1	unk	4/22/1960	450	2224	2216	Oriskany	2212	2220
KELLEY_177	Clearfield	unk	NYSNG	Rivel #1	unk	8/1/1960	455	2224	2216	Oriskany	2212	2223
KELLEY_178	Clearfield	unk	unk	City of Dubois #1	unk	5/14/1960	460	2192	2173	Oriskany	2188	2191
KELLEY_179	Elk	unk	NYSNG	Palumbo #6	unk	6/8/1959	533	2251	2246	Oriskany	2240	2249
KELLEY_181	Elk	unk	NYSNG	Palumbo #8	unk	8/31/1959	478	2198	2190	Oriskany	2187	2197
KELLEY_185	Jefferson	unk	NYSNG	Walls #2	unk	5/24/1961	472	2273	361	Oriskany	2269	unk
KELLEY_185a	Jefferson	unk	NYSNG	Walls #2	unk	5/24/1961	472	2273	361	Oriskany	2210	unk
KELLEY_186	Clearfield	unk	NYSNG	Palumbo #10	unk	11/14/1959	352	2081	2096	Oriskany	2088	2099
KELLEY_187	Clearfield	unk	NYSNG	Barr #1	unk	11/4/1960	512	2267	2262	Oriskany	2256	2265
KELLEY_189	Clearfield	unk	NYSNG	Dunlap #1	unk	2/18/1960	487	2216	unk	Oriskany	2206	2215
KELLEY_190	Clearfield	unk	NYSNG	Shettler #1	unk	3/21/1961	471	2209	2198	Oriskany	2204	2208
KELLEY_191	Clearfield	unk	NYSNG	Keiner #1	unk	5/11/1960	443	2207	2203	Oriskany	2197	2206
KELLEY_192	Jefferson	unk	NYSNG	Walls #1	unk	11/8/1960	450	2220	2213	Oriskany	2211	2220
KELLEY_195	Elk	unk	NYSNG	Mt. St. John #2	unk	6/14/1962	516	2091	2089	Oriskany	2088	2088
KELLEY_197	Cameron	unk	NYSNG	Purdee #10	unk	11/28/1962	423	2024	2006	Oriskany	2013	2023
KELLEY_203	Clearfield	unk	NYSNG	Glenn Corp #4	unk	8/23/1963	501	2269	2243	Oriskany	2258	2266
KELLEY_204	Clearfield	unk	NYSNG	Horne	unk	8/14/1958	449	2189	2173	Oriskany	2186	2188
KELLEY_205	Clearfield	unk	NYSNG	unk	unk	9/27/1960	429	2216	2191	Oriskany	2213	unk
POTH_1101	Clearfield	unk	Manufacturers Light & Heat	unk	unk	1958	495	2254	2209	Oriskany	2246	unk
POTH_1102	Clearfield	unk	NYSNG	unk	unk	1958	456	2223	2198	Oriskany	2215	2222
POTH_1103	Clearfield	unk	F.C. Deemer	unk	unk	1958	502	2316	2283	Oriskany	2295	2301

nm = not measured
unk = unknown
NYSNG = New York State Natural Gas

Table 2-1. (continued)

Well ID	Distance Base Marcellus to Top of Onondaga (m)	Static Water Level Below Land Surface (m)	Date Water Sampled	Date Gas Sampled	Publication	Comments
HORIZONTAL WELLS						
591549	25	nm	9/12/2016	9/12/2016		
591668	25	nm	9/12/2016	9/12/2016		
591970	25	nm	9/12/2016	9/12/2016		
590515	24	nm	9/12/2016	9/12/2016		
590516	24	nm	9/12/2016	9/12/2016		
590983	unk	nm	9/13/2016	9/13/2016		
590876	13	nm	9/13/2016	9/13/2016		
591155	No Oriskany Present	nm	9/12/2016	9/12/2016		
590389	No Oriskany Present	nm	9/12/2016	9/12/2016		
590370	No Oriskany Present	nm	9/12/2016	9/12/2016		
CS-1	unk	nm	-	2/22/2016		
CS-3	unk	nm	2/22/2016	2/22/2016		
CSB-5	unk	nm	2/22/2016 (1)	2/22/2016		(1) Water chemistry analyzed, not water isotopes
VERTICAL WELLS						
591011	18	nm	4/9/2015	-		
591060	14	nm	-	9/14/2016		
591057	18	nm	-	9/13/2016		
591034	22	nm	-	9/13/2016		
591059	19	nm	9/14/2016	9/14/2016		5/26/1999 well was plugged, drilled out, and completed in the 1st Bradford, Sheffield, and Tiona Sands
591055	15	nm	-	9/14/2016		
591023	10	nm	-	9/14/2016		
591099	17	nm	-	9/14/2016		
591069	18	nm	-	9/14/2016		
COP 1	12	nm	1/24/2017	-		
COP 2	6 (2)	nm	-	2/22/2016		(2) Well encounters fault that results in repeat section in the Marcellus, and an abnormal distance from the Marcellus to the Oriskany
COP 3	23	nm	1/24/2017 (3)	-		(3) Sampled but not analyzed, tank was open to the environment
COP 4	13	nm	1/24/2017	-		
COP 6	13	nm	-	2/22/2016		3/26/2006 well was converted from Oriskany to Marcellus
COP 10	unk	nm	1/24/2017	-		

nm = not measured
unk = unknown
NYSNG = New York State Natural Gas

Table 2-1. (continued)

Well ID	Distance Base Marcellus to Top of Onondaga (m)	Static Water Level Below Land Surface (m)	Date Water Sampled	Date Gas Sampled	Publication	Comments
VERTICAL WELLS						
ED-82-37	unk	unk	~9/1982	unk	Dresel, 1985	
ED-82-38	unk	unk	~9/1982	unk	Dresel, 1985	
ED-82-40	unk	unk	~9/1982	unk	Dresel, 1985	
KELLEY_68	unk	nm	1/9/1959	-	Kelley, 1973	Sample collected after frac
KELLEY_69	unk	nm	1/9/1959	-	Kelley, 1973	Sample collected after frac
KELLEY_176	unk	nm	4/18/1961	-	Kelley, 1973	
KELLEY_177	unk	nm	4/1/1961	-	Kelley, 1973	
KELLEY_178	unk	nm	4/1/1961	-	Kelley, 1973	
KELLEY_179	unk	nm	6/23/1961	-	Kelley, 1973	
KELLEY_181	unk	nm	6/23/1961	-	Kelley, 1973	
KELLEY_185	unk	nm	5/1/1961	-	Kelley, 1973	
KELLEY_185a	unk	nm	unk	-	Kelley, 1973	
KELLEY_186	unk	nm	11/4/1960	-	Kelley, 1973	
KELLEY_187	unk	nm	11/4/1960	-	Kelley, 1973	
KELLEY_189	unk	nm	10/26/1961	-	Kelley, 1973	
KELLEY_190	unk	nm	1/31/1961	-	Kelley, 1973	
KELLEY_191	unk	nm	11/4/1960	-	Kelley, 1973	
KELLEY_192	unk	nm	11/4/1960	-	Kelley, 1973	
KELLEY_195	unk	nm	6/1/1962	-	Kelley, 1973	
KELLEY_197	unk	nm	11/21/1962	-	Kelley, 1973	
KELLEY_203	unk	nm	8/23/1963	-	Kelley, 1973	
KELLEY_204	unk	nm	10/26/1961	-	Kelley, 1973	
KELLEY_205	unk	738	5/13/1960	-	Kelley, 1973	
POTH_1101	unk	flowing	~1960	-	Poth, 1962	
POTH_1102	unk	244	~1960	-	Poth, 1962	
POTH_1103	unk	274	~1960	-	Poth, 1962	

nm = not measured
unk = unknown
NYSNG = New York State Natural Gas

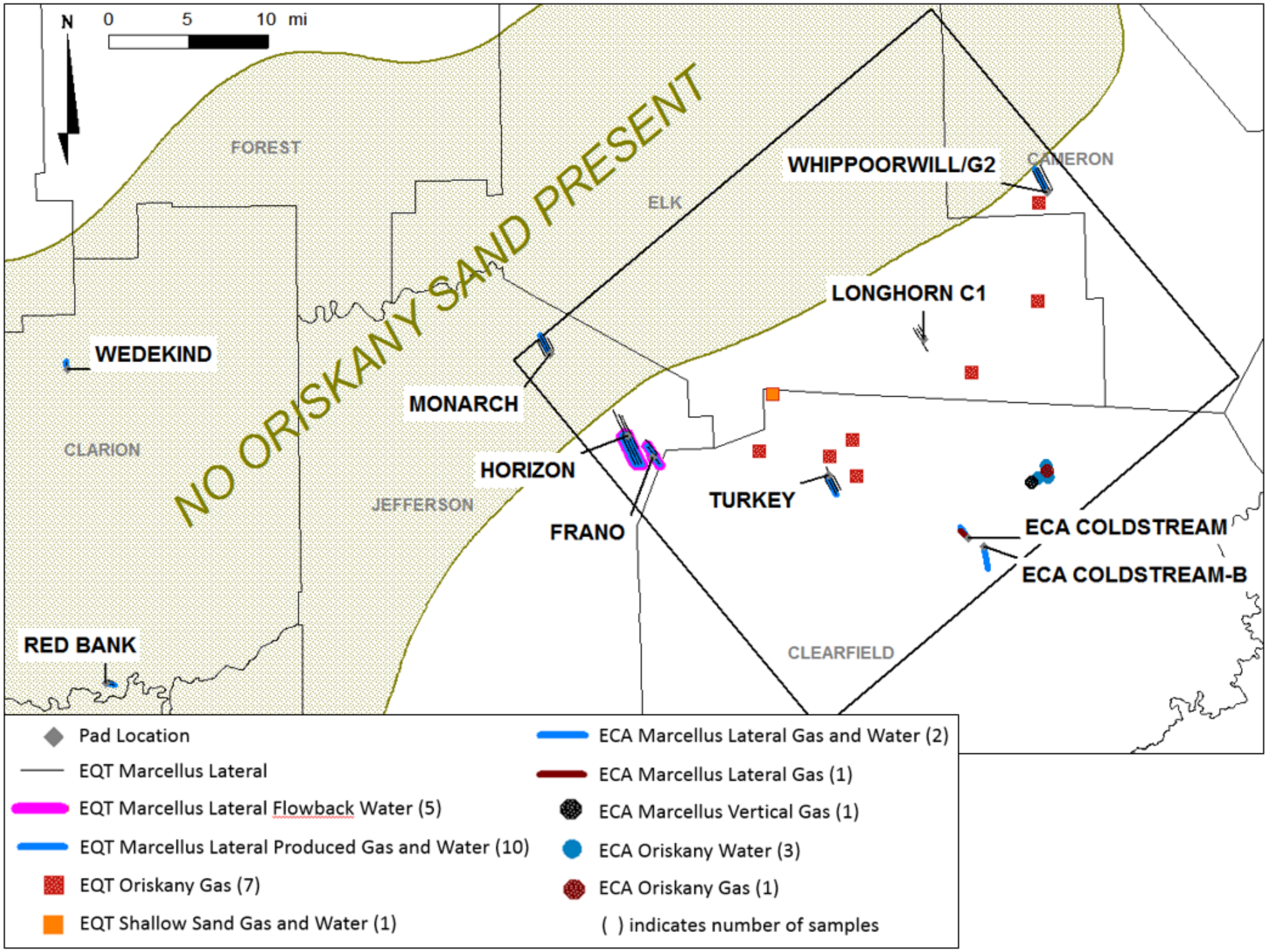


Figure 2-2. Water and gas sample location map

An EQT engineer collected six samples of the water to be used for hydraulic fracturing on the Horizon Pad over a three-day period in October 2014 (Figure 2-2). Multi-Chem Laboratories analyzed the water to be used for hydraulic fracturing for total dissolved solids, pH, alkalinity, density, chloride, sulfate, Ba, Ca, Fe, K, Mg, Mn, Na, Pb, Sr, and Zn. After hydraulic fracturing, flowback water sampling was performed on the Horizon Pad. On the first day of flowback, a well tender collected 19 flowback water samples from three different Marcellus Shale laterals on the Horizon Pad over an 11-day period in December 2014. Fairway Laboratories analyzed the flowback water for total dissolved solids, specific gravity, pH, alkalinity, specific conductance, bromide, chloride, sulfate, Ba, Ca, Cu, Fe, K, Li, Mg, Mn, Na, Pb, Sr, and Zn.

The produced water of six Oriskany Sandstone wells was collected by a well tender in July 2015 (Figure 2-2). These water samples were analyzed by Fairway Laboratories for total dissolved solids, specific gravity, pH, alkalinity, specific conductance, bromide, chloride, sulfate, Ba, Ca, Cu, Fe, K, Li, Mg, Mn, Na, Pb, Sr, and Zn. These six Oriskany wells are located in Elk and Clearfield Counties, 16-32 kilometers from EQT's Horizon Pad in Jefferson County. The completion reports of the Oriskany wells indicate that the Marcellus Shale formation base is, on average, 16 meters above the top of the Oriskany Sandstone formation (Table 2-1) (EDWIN, 2016).

2.2.1.3 2016-2017 Produced Water Sample Collection In September of 2016, and January and February of 2017, with the help of well tenders, I collected water samples from producing wells in North Central Pennsylvania (Figure 2-2). Well completion information is included in Table 2-1. Whether a sample was taken from a separator, production tank, or a drip-tank, the well tender, filled a clean, non-preserved sampling bottle, which was used to fill the remaining bottles.

For each produced water sample collected, four bottles were filled for chemical analysis. This included two 250 mL unpreserved high-density polyethylene (HDPE) bottles (specific gravity, pH, alkalinity, specific conductance, bromide, chloride, and sulfate), one 250 mL 1% nitric acid preserved HDPE bottle (metals: Ba, Ca, Cu, Fe, K, Li, Mg, Mn, Na, Pb, Sr, and Zn), and one 500 mL unpreserved HDPE bottle (TDS). The bottles for chemical analysis were held on ice and were delivered to Test America, Inc., located in RIDC Park in Pittsburgh. One 100 mL unpreserved HDPE bottle was filled for isotopic analysis and delivered to Gas Analytical in Washington, Pennsylvania. Gas Analytical packed the bottles as hazardous material and shipped them to Isotech Laboratories in Champaign, Illinois.

On September 12 through 14, 2016, water was collected from ten Marcellus Shale laterals and one Oriskany vertical well (all owned by EQT). Water was taken from the Marcellus laterals at the separator, with the exception of the Wedekind Pad, well 590389, where samples had to be taken from a valve on the bottom of the production tank. The Wedekind pad is in a wet gas area, and the production tank contained condensate in addition to water. I attempted to collect water from eight vertical Oriskany Sandstone wells, however these wells were constructed in the 1950's-70's, are not currently producing, and have not been swabbed for many years. I collected water from the drip tank of one Oriskany well (Ross Guy 1 – 591059). To collect the sample, the well tender slowly opened the drip tank pipe until the pressure rose in the pipe, causing water to spurt out. The drip tank is an underground pipe with a diameter of 0.2 -0.3 meters with ends welded onto it to catch free fluids when gas flow enters the larger diameter production casing and loses velocity. After this 'Oriskany' produced water sample had been collected and analyzed by the lab, I discovered that the Ross Guy 1 - 591059 well was originally an Oriskany well that had been reworked in 1999 so that only the Bradford formation and shallower sands are the producing intervals. Therefore, this sample is omitted from subsequent analysis, but the data for this sample remains in the analytical results tables, as it is interesting to compare the water chemistry, and water and gas isotopes.

To expand my Oriskany Sandstone produced water dataset, on January 24, 2017, water was collected from the production tanks of four additional Oriskany wells that are owned by Energy Corporation of America (ECA): COP-1, COP-3, COP-4, and COP-10. The ECA well tender stated that the wells had been shut in for a year or more. The production tank for wells COP-1, COP-3, and COP-4 were 2270-liter vertical plastic storage tanks. The tank of well COP-3 did not have a lid over the approximately 45 cm diameter hatch and was open to the environment. The ECA well tender sampled water from the tanks of COP-1, COP-3, and COP-4 by slowly dropping a stainless steel sampling bomb, or in the instance of COP-1 the water level was very low and a plastic bucket was slowly lowered, to the bottom of the tank. He pulled the water out and then I filled the sample bottles. The production tank for well COP-10 was roughly a 3 m tall, 22,712-liter fiberglass tank. Three 10 cm diameter vents on the top of this tank were open to the environment. A sample was collected from the COP-10 production tank by opening the valve located on the bottom of the tank.

The last round of sampling was performed on February 22, 2017. I returned to ECA's operating area to sample two of their lateral Marcellus Shale wells: Coldstream 3 and Coldstream B 5 wells. This sampling grew from the previous sampling trip, when the ECA well tender had mentioned that they had suspected the Coldstream 3 lateral well was connected with the Oriskany Sandstone. Similar to the COP-10 Oriskany well, the production tanks were roughly 3 m tall, 23,000-liter fiberglass tanks. Three 10 cm diameter vents on the top of the tanks were open to the environment. Water was collected from Coldstream B 5 by opening the valve located on the bottom of the tank. We could not access the valve at the bottom of the Coldstream 3 tank because a transducer was in place. The well tender sampled this tank by climbing a ladder to the top of the tank and slowly dropping a plastic bucket into the tank. He pulled the water out and I then filled the sample bottles.

2.2.1.4 Water Chemistry Analysis Produced water samples were received by Test America at <3.8˚ C. The samples were analyzed for bromide, chloride, and sulfate using ion chromatography method 300.0. Metals (Ba, Ca, Cu, Fe, K, Li, Mg, Mn, Na, Pb, Sr, and Zn) were analyzed using ICP method 200.7 Rev 4.4. Specific gravity and bulk density were analyzed using method D5057-90. Alkalinity was analyzed using method SM 2320B. Conductivity and specific conductance were analyzed using method SM2510B. TDS was analyzed using method SM 2540C. Finally, pH was analyzed by method SM4500 H+ B.

The produced water chemical concentrations of the 7 EQT Marcellus laterals with Oriskany were compared to the 3 EQT Marcellus laterals without Oriskany. Also, the produced water chemical concentrations of the 10 EQT Marcellus laterals were compared to each of the four structural complexity characteristics for the same lateral using step-wise calculations in R Studio.

2.2.1.5 Water Isotope Analysis Isotech Laboratories, Inc. analyzed the produced water samples for isotopic analysis of hydrogen and oxygen. Isotech utilized a Thermo GasBench II coupled to a Thermo Delta V Plus IRMS for δD CF-IRMS analysis of water. A preparatory cryogenic, vacuum distillation was performed to remove as many contaminants as possible from the sample prior to analysis. Samples were then analyzed using the technique described in the Finnigan GasBench II Operating Manual (Thermo Electron Corporation, 2004). A flushing gas was introduced to a vial containing the water sample and after a period of time isotopic equilibrium was reached between the gas in the headspace and the liquid. For isotopic analysis of oxygen, the flushing gas was a mixture of He and CO_2 and the equilibrium time was a minimum of 18 hours. For isotopic analysis of hydrogen, the water sample was loaded into the vial along with a platinum catalyst stick. The flushing gas was 2% H_2 gas in helium to result in a signal height of 9 V, and the equilibrium time was a minimum of 40 minutes at room temperature. Once equilibrated, a pure helium carrier gas carried the headspace gas to a sample loop via a pure helium gas, which allowed multiple aliquots of the sample to be measured in each analytical run. The oxygen and hydrogen isotopic results were reported relative to Vienna Standard Mean Ocean Water (VSMOW).

The produced water isotopic concentrations of the 7 EQT Marcellus laterals with Oriskany were compared to the 3 EQT Marcellus laterals without Oriskany. Also, the produced water isotopic concentrations of the 10 EQT Marcellus laterals were compared to each of the four structural complexity characteristics for the same lateral using step-wise calculations in R Studio (RStudio Team, 2015).

2.2.2 Gas

2.2.2.1 Produced Gas Sample Collection Produced gas samples were collected on two difference occasions. First, ten Marcellus laterals and eight Oriskany vertical wells were sampled between September 12 and 14, 2016 (Figure 2-2). At the Marcellus laterals, gas was collected at the wellhead, except for one well (Horizon 591549) where the water would not bleed off at the wellhead and the gas sample had to be collected after the separator. At the Oriskany wells, gas was collected at the wellhead or from a line leading off the wellhead.

On February 22, 2017, I collected produced gas from five ECA wells. One sample was collected from a vertical Oriskany well, one sample was collected from a vertical Marcellus well, and one sample was collected from three different Marcellus laterals. All gas samples from ECA wells were collected at the wellhead.

The gas was collected using single-use Isotubes and an Isotube wellhead sampling device. The Isotube wellhead sampling device comprises a filter, inlet and outlet gauge, a 3-way value handle, and chuck. The sampling device was threaded into a clean port with a control valve by a well operator. The Isotube was then inserted into the sampler by pushing it into the chuck. With the 3-way sampler valve in the shut position, the control value was opened at the sampling port. The 3-way value was then turned to 'shut' and 'open' for 10 cycles to alternately pressurize and vent the Isotube. After filled for the last time, the 3-way valve was left open and the sleeve of the chuck was slid down and the Isotube was pulled off quickly. End caps were screwed onto the Isotube and a label was affixed. The Isotubes were shipped to Isotech in Champaign, Illinois by Gas Analytical.

2.2.2.2 Gas Compositional Analysis & Isotopic Analysis The gas was analyzed via gas chromatography for helium, argon, oxygen, nitrogen, carbon dioxide, methane, ethane, propane, Iso-butane, N-butane, Iso-pentane, N-pentane, and hexanes. Methane, ethane, and propane were analyzed for hydrogen and carbon isotopic composition. Isotopic composition of hydrogen is relative to VSMOW. Isotopic composition of carbon is relative to Vienna Pee Dee Belemnite (VPDB). BTU and specific gravity were calculated per ASTM method D3588 (ASTM, 2017).

2.3 STRUCTURAL COMPLEXITY CALCULATION

Marcellus Shale laterals in the Appalachian Basin are geosteered using gamma ray logs and wells surveys (Section 1.1.1 and Figure 1-4). Geosteering using gamma ray is by far the preferred method used to ensure that laterals are drilled in the shale intervals that are modeled to have the most gas and hydrocarbon in place. Geosteering is so popular, that the structural profiles generated while geosteering are likely the largest and most comprehensive dataset for all lateral wells drilled in the Appalachian Basin, yet not much analysis is done on geosteering data and the resulting structural profiles.

The structural profile derived from geosteering is unique for every lateral. Often, laterals that are drilled offsetting each other will share the same general trends in structure. Geosteered profiles can range from very simple to very complex. An example of a simple profile would be if the formation horizons were completely flat, or dipping at a constant inclination. Complex profiles may include rolling, or even faulted formation horizons.

I designed a calculator in Microsoft Excel to quantify what I call the 'structural complexity' of a geosteered lateral. The input to the structural complexity calculator includes three parameters; the measured depth (MD) along the wellbore, the interpreted bed dips, and the Onondaga total vertical depth (TVD) horizon from the interpreted geosteering profile. The data in the geosteering export file generally has a one-foot resolution (Figure 1-4). Because structural complexity will be compared to completions and production data, the input data began at the top perforation and ended at the bottom perforation, this interval will be referred to as 'lateral length'. I designed the structural complexity calculator to quantify four characteristics of the geosteered lateral export file. The characteristics or outputs are; the maximum slope from within the completed portion of the wellbore [(maximum Onondaga TVD-minimum Onondaga TVD)/(MD at maximum Onondaga TVD-MD of minimum Onondaga TVD)], the overall range in bed dips in the lateral (maximum bed dip-minimum bed dip), a summation of all bed dips changes that are greater than a 0.5 degree change over a 30.5 cm interval normalized to the lateral length (summation of bed dips changes whose absolute value is greater than 0.5 degree), and finally a summation of all faults that have a TVD change greater than 61 cm over a 30.5 cm interval normalized to lateral length (summation of TVD changes whose absolute value is greater than 61 cm). The calculation tab of the structural complexity calculator is shown in Table 2-2. Geosteering export data (lateral MD, dip, and TVD of the Onondaga horizon) is input to the calculator. Blue cells are input cells. Yellow cells are output cells. The completed structural complexity summary tab for Turkey well 591240 is shown in Table 2-3 and the geosteering profile for Turkey well 591240 is shown in Figure 2-3.

Table 2-2. Structural complexity calculator, calculation tab.

INPUT: MD	INPUT: Dip	INPUT: Onondaga horizon	Dip: Deg. of change in one step	Dip?	**Dip: change greater than 0.5 deg over one step**	Fault: TVD change in one step	Fault?	**Fault: TVD change greater than 2' over one step**	MAX	MIN	Value	
									0	0	0	ONON TVD
			0	no change	0	0	no fault	0	#N/A	#N/A	#N/A	MD from max to min
											#N/A	**rise/run (max tvd to min tvd)**
									0	0	0	**DIP RANGE**
											0	**sum of dip changes greater than 0.5 Deg**
											0	**sum of faults greater than 2'**
									Top Perf			
									Bottom Perf			
									Completed Lateral Length			

Table 2-3. Structural complexity calculator, summary tab for Turkey well 591240.

Structural Characteristics	**Well Score**
TOTAL RELIEF	0.13449
DIP RANGE	0.00483
INFLECTIONS (sum>0.5 deg)	0.01375
FAULTS (sum >2')	0

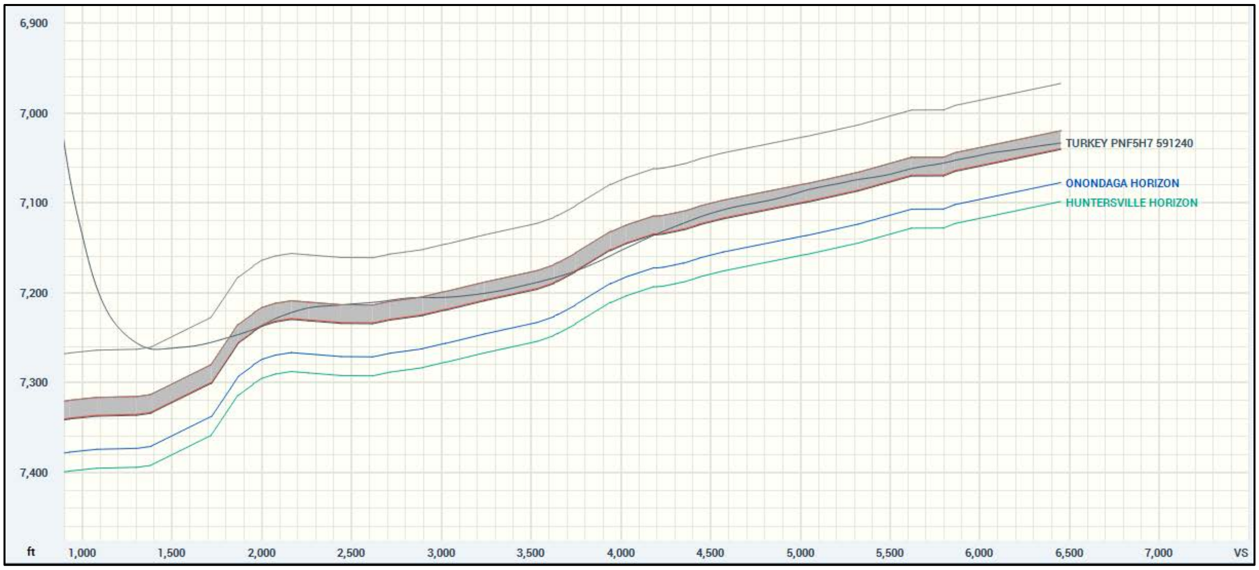


Figure 2-3. Geosteering profile of Turkey well 591240.

2.4 FORMATION BREAKDOWN PRESSURE

During completion activities, formation breakdown pressure of each stage was recorded. Formation breakdown pressure is the pressure at which the rock matrix of an exposed formation (exposed by perforation of the wellbore) fractures and allows fluids to be injected. Figure 2-4 provides an example of pressure data that EQT collects while completing stages. The graph shows that the formation was fractured at 40,955 kPa.

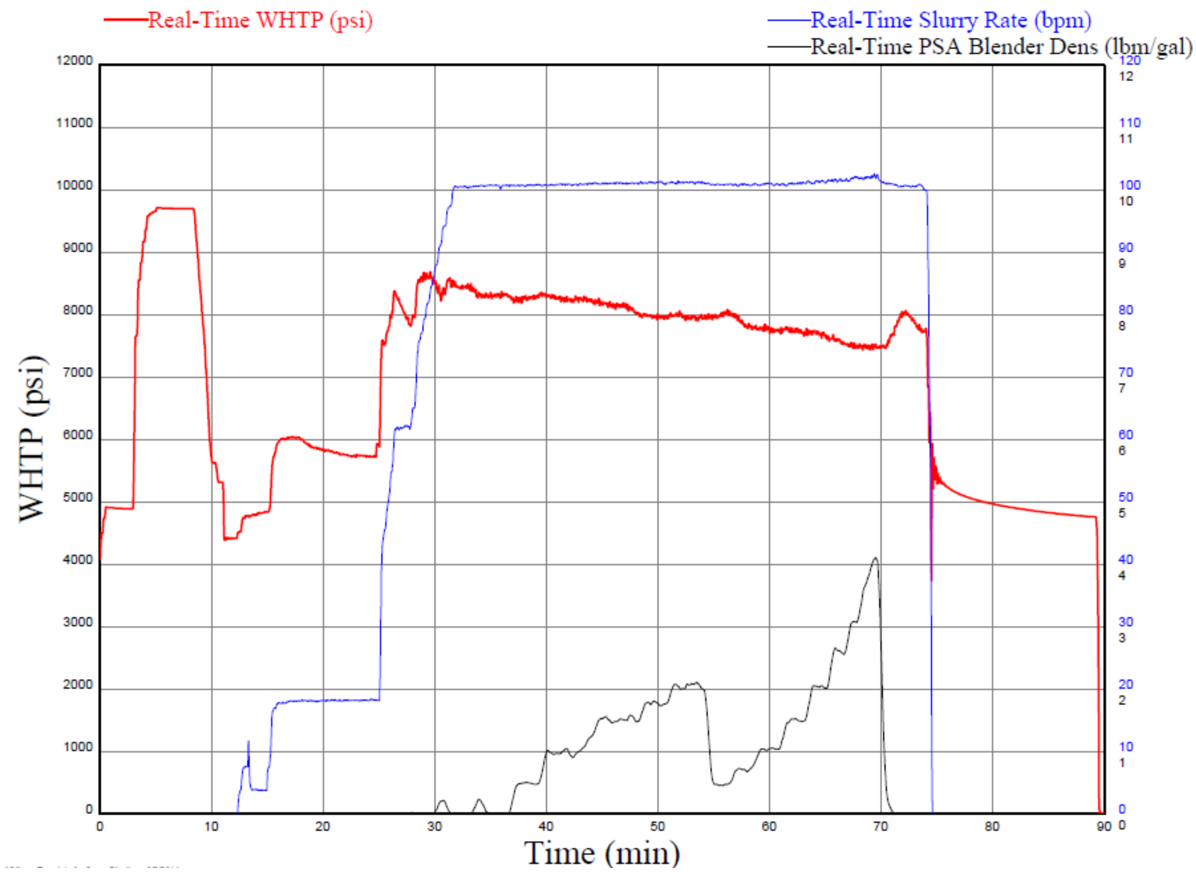


Figure 2-4. Example of pressure graph during well completion (Oil and Gas, 2015)

The raw formation breakdown pressure of each stage was plotted with the geosteering profile to determine correlations between formation breakdown pressure and features, such as faults, identified in the geosteering profile (Figure 2-5). The green boxes represent formation breakdown pressure of each completion stage. Note that formation breakdown pressure is greatest at the well toe and decreases toward the heel.

Figure 2-5. Geosteering profile of Whippoorwill well 590876. The green boxes along the wellbore represent each completion stage. The height of the boxes are proportional to formation breakdown pressure. The nearly vertical black lines represent interpreted faults and the number below the vertical lines represent the offset of the fault. The grey shaded interval represents the target interval within the Marcellus Shale

I averaged the formation breakdown pressure of each stage completed in a lateral to determine the average formation breakdown pressure for each lateral. Formation breakdown pressure is influenced by depth (Figure 2-6), so the average formation breakdown pressure of a lateral was normalized by dividing the average formation breakdown pressure by the average depth of the lateral.

The depth normalized average formation breakdown pressure for 31 Marcellus laterals was then compared to the four structural complexity characteristics for the same lateral using step-wise calculations in R Studio.

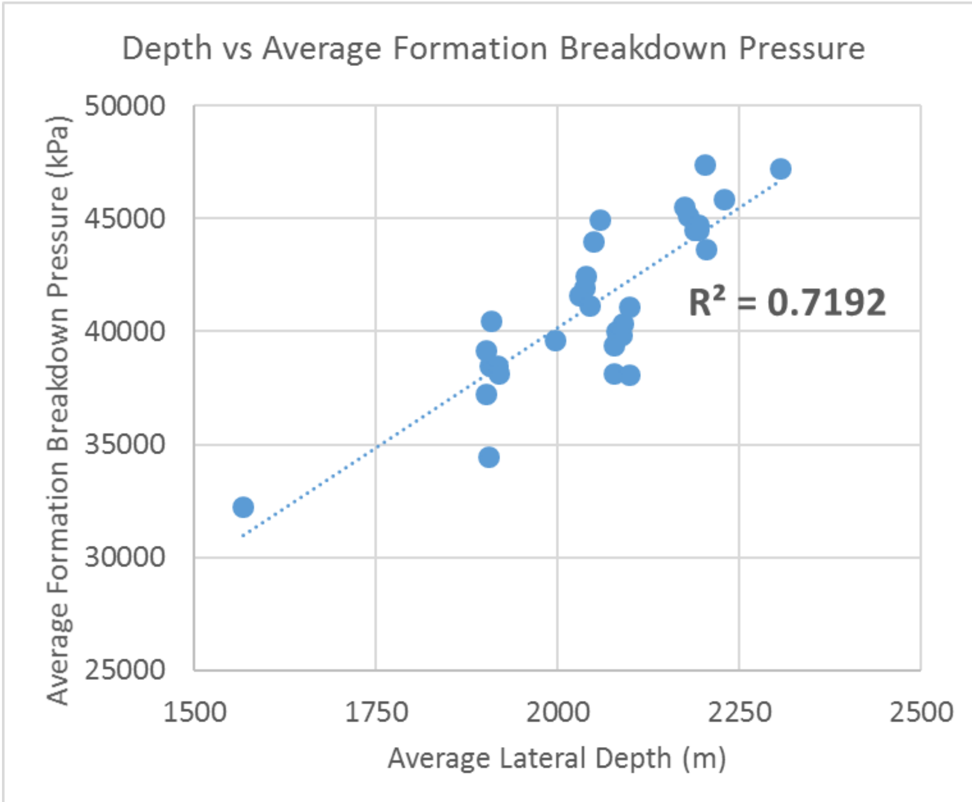


Figure 2-6. Average lateral total vertical depth versus average lateral formation breakdown pressure

2.5 PERCENT OF FLUID RECOVERED DURING FLOWBACK

Percent fluid or load recovered is a comparison of how much fluid flows back to the surface after hydraulically fracturing the well compared to the total volume of fluid used in the completion job. Load recoveries ranged from just 2.38% on Turkey well 590983 to 15.8% on Whippoorwill well 590878. The length of time of flowback is different for every well, and for this dataset the flowback period ranged from 59 to 370 hours. (The flowback period lasts until the volume of water coming out of the well decreases and when sand and plug parts stop flowing out of the well.)

Percent load recovered of 31 laterals was compared to the four structural complexity characteristics for the same lateral using step-wise calculations in R Studio.

2.6 MARCELLUS SHALE LATERAL WELL GAS AND WATER PRODUCTION VOLUMES

Gas and water production data were reviewed for 24 Marcellus lateral wells within the study area, and nine additional Marcellus laterals located within 60 kilometers of the study area. (Four wells on the Longhorn C Pad were flowed back, but not produced.) Gas and water production data were reviewed for 274 Marcellus lateral wells located in Greene County, PA, as a point of comparison. It should be noted that gas volumes are measured continuously. In contrast, water volumes are determined from sporadic water truck hauler receipts.

Gas and water volumes were summed over months 2 through 7 of a well's production and were normalized to lateral length. A gas-to-water ratio was also calculated for each well over months 2 through 7 of production. (This avoided production data from month one, and potential errors from wells being that started producing partway through the month.) The lateral length normalized gas production, lateral length normalized water production, and the gas-to-water ratios of 27 laterals were compared to each of the four structural complexity characteristics for the same lateral using step-wise calculations in R Studio.

3.0 RESULTS

3.1 REGIONAL STRUCTURE AND STRATIGRAPHY

The structure contour map of the top of the Onondaga Limestone reveals that the strike of structure is orientated on a northeast-southwest trend, and beds are dipping toward the southeast (Figure 3-1). Two anticlines and two synclines are apparent. The anticline running from just north of Whippoorwill to Frano is the Sabinsville anticline, and the southernmost anticline is the Chestnut Ridge Anticline. The historic Oriskany sandstone vertical gas fields are denoted by pink shading.

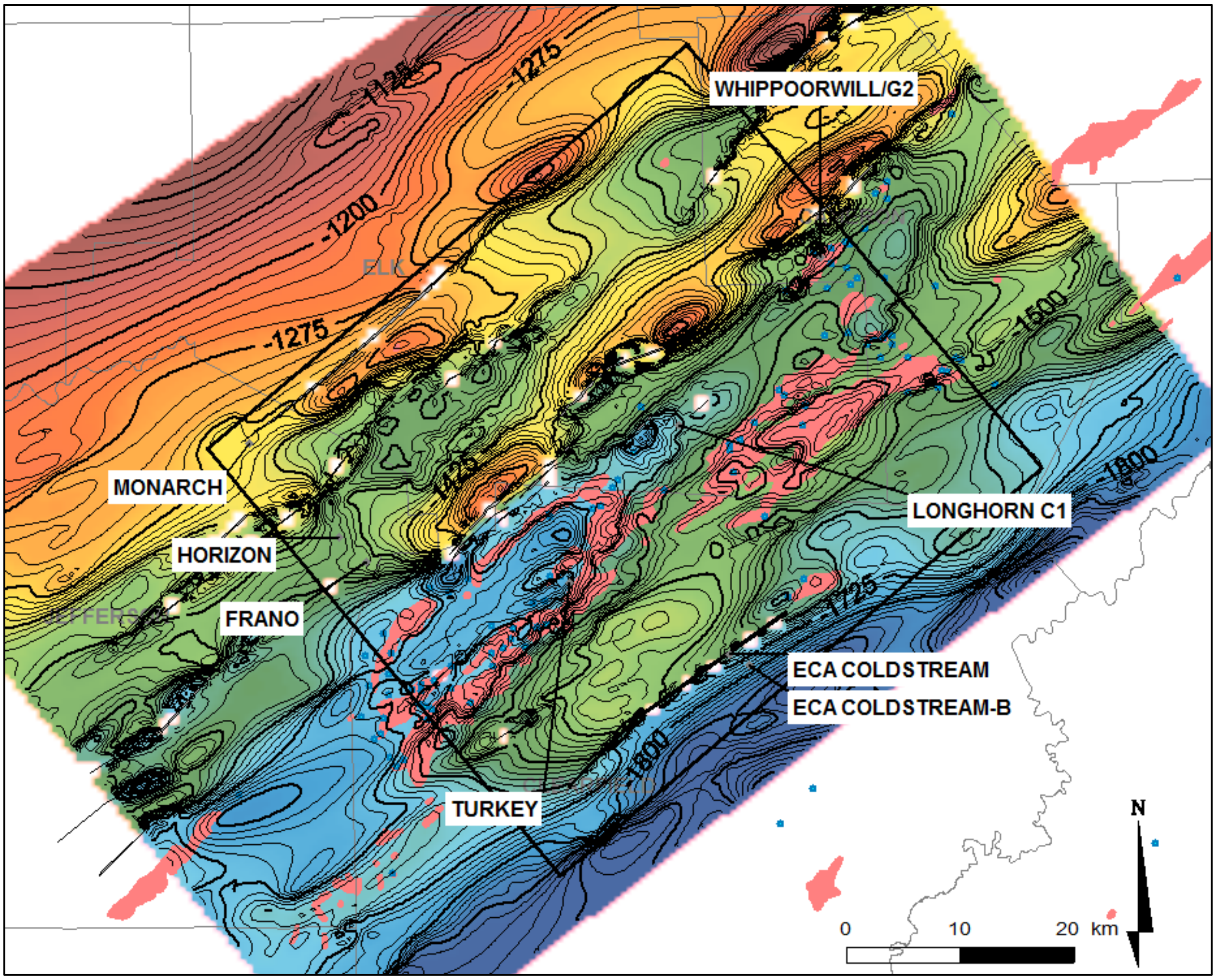


Figure 3-1. Structural map of the top of the Onondaga Limestone. Well pads are labeled. Study area is denoted by black rectangle. Contour interval is 15 meters

The Oriskany sandstone exists at depths of 2000 to 2400 m below the ground surface within the study area (Figure 3-2). The depth to the Oriskany increases to the southeast. This map shows one syncline and one anticline trending to the northeast within the study area.

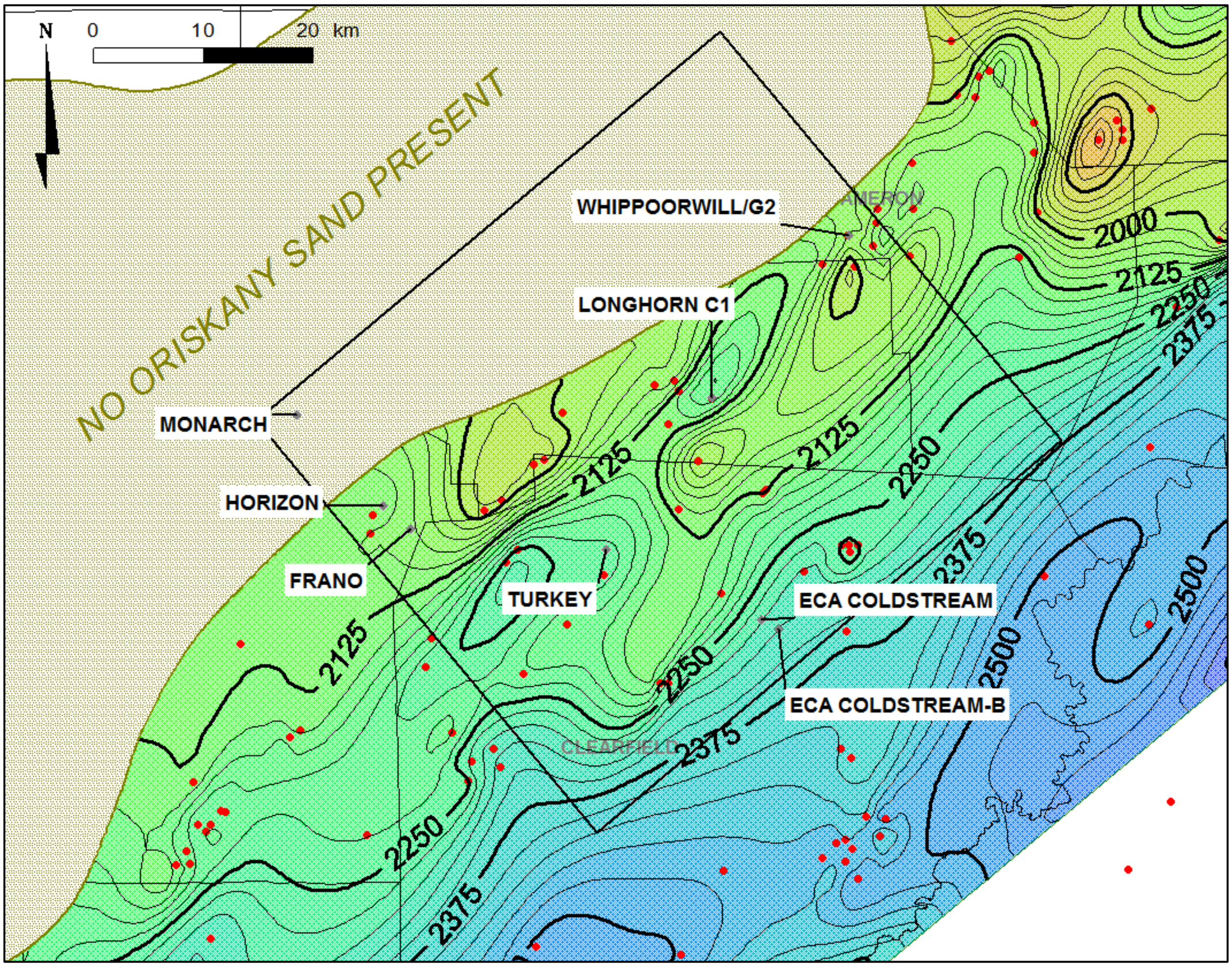


Figure 3-2. Depth to the top of the Oriskany Sandstone. Red circles represent data points used to create the map. Study area is defined by black rectangle. Contour interval is 25 meters

In areas within the study area where the Oriskany sand is present, the Oriskany net thickness as interpreted in well logs ranges from 10 to 30 meters thick (Figure 3-3).

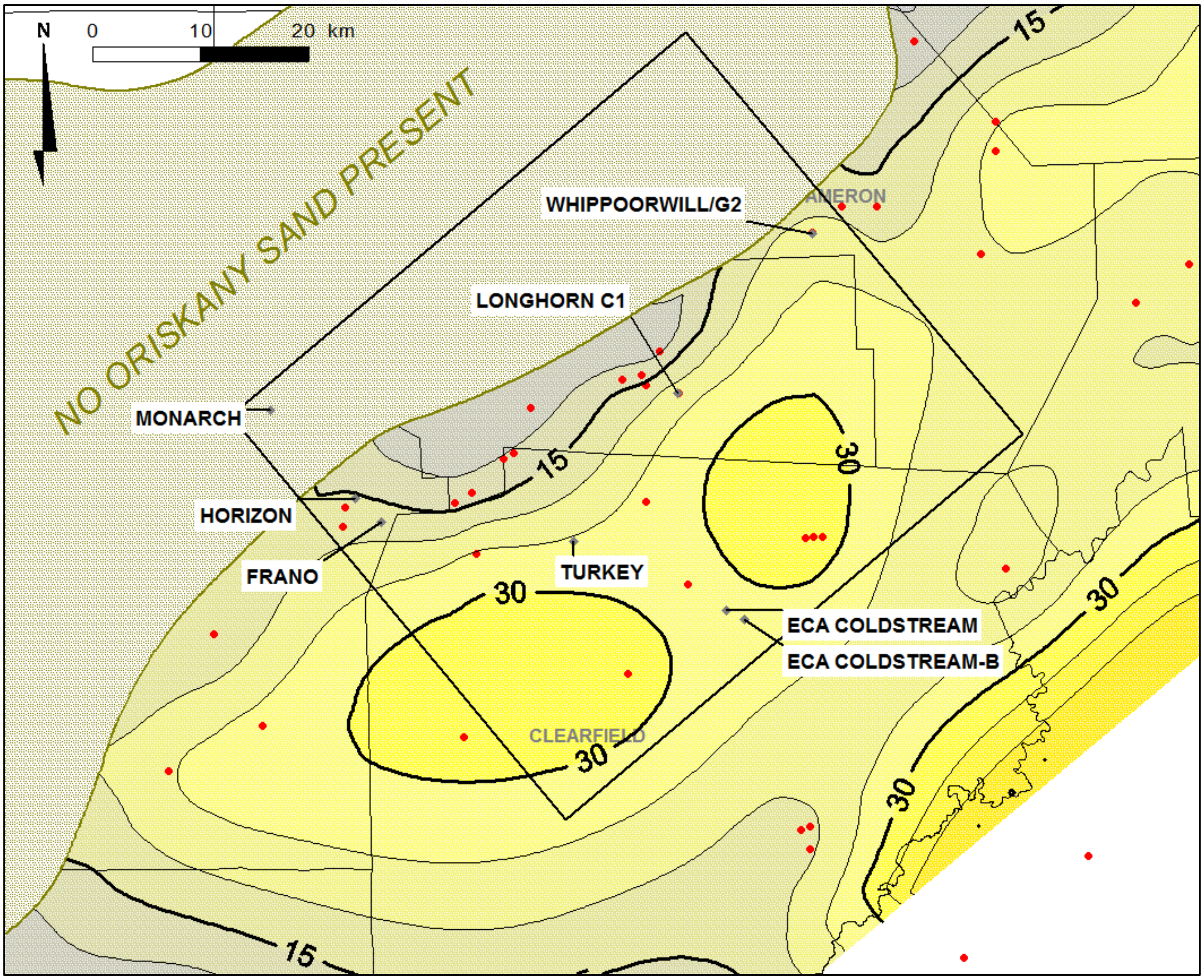


Figure 3-3. Map of thickness from Oriskany top to Oriskany base. Red circles represent data points used to create the map. Study area is defined by black rectangle. Contour interval is 5 meters

Oriskany ‘pay zone’ thickness, defined as having density of <2.55 g/cm3, ranges from zero to 7 m thick across the study area (Figure 3-4). Within the study area, there are two areas where the Oriskany pay thickness is at least 6 m, west of the Turkey Pad and near the Whippoorwill Pad.

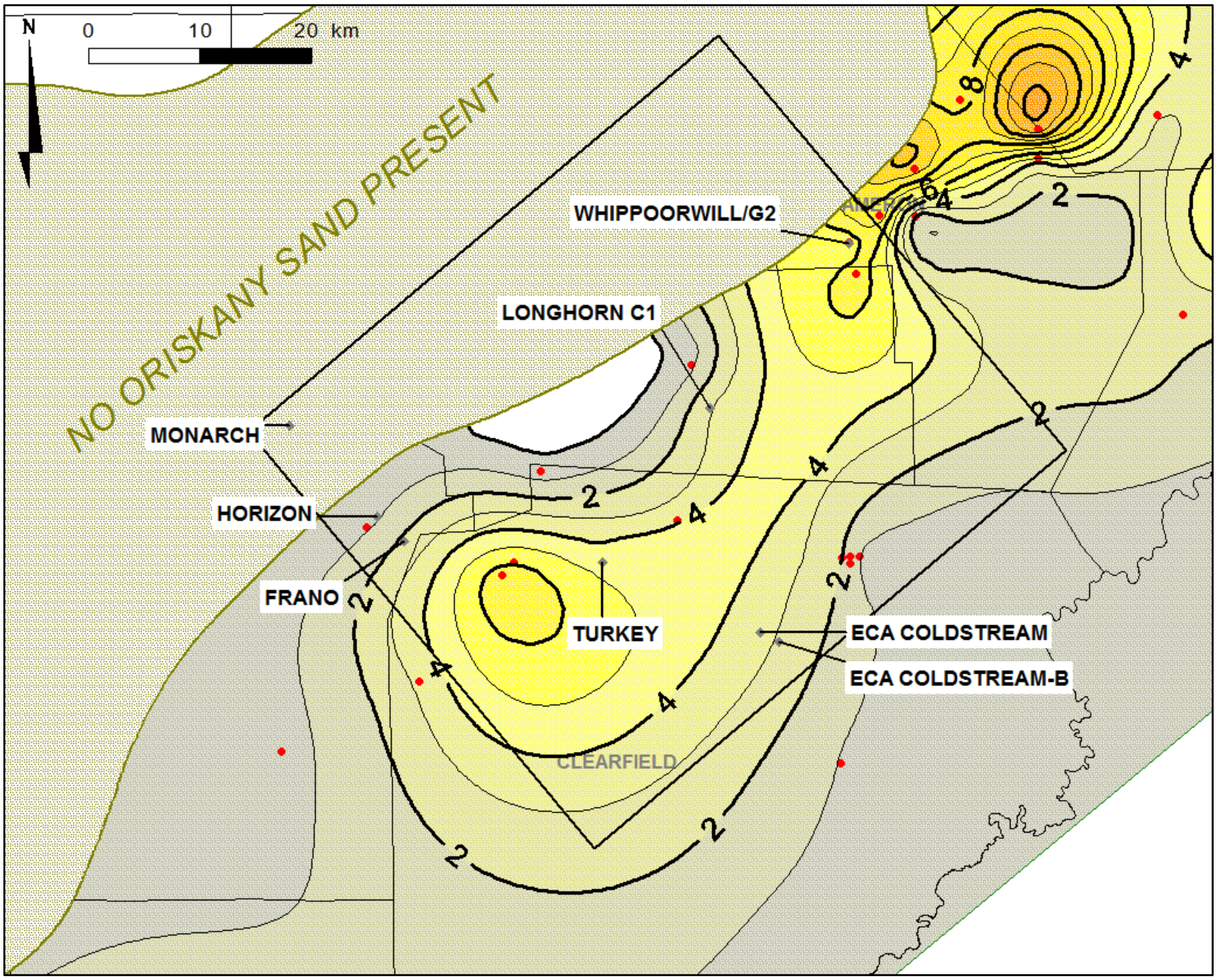


Figure 3-4. Oriskany Sandstone thickness with density of less than 2.55 g/cm3. Red circles represent data points used to create the map. Study area is defined by the black rectangle. Contour interval is 1 meter.

The Oriskany Sandstone lies below the Marcellus Shale at depths ranging from 7 to 25 meters within the study area (Figure 3-5). The distance separating the Marcellus Shale from the Oriskany Sandstone decreases to the northeast. The formations separating the Marcellus Shale from the Oriskany Sandstone are the Onondaga Limestone and the Huntersville Chert. The Marcellus Shale lateral well pad with the shortest distance from the Marcellus Shale Base to the Oriskany Sandstone Top within the study area is Whippoorwill Pad (12 meters). The Horizon and Frano Marcellus pads have the greatest distance from the Marcellus Shale Base to the Oriskany Sandstone Top within the study area (25.5 meters).

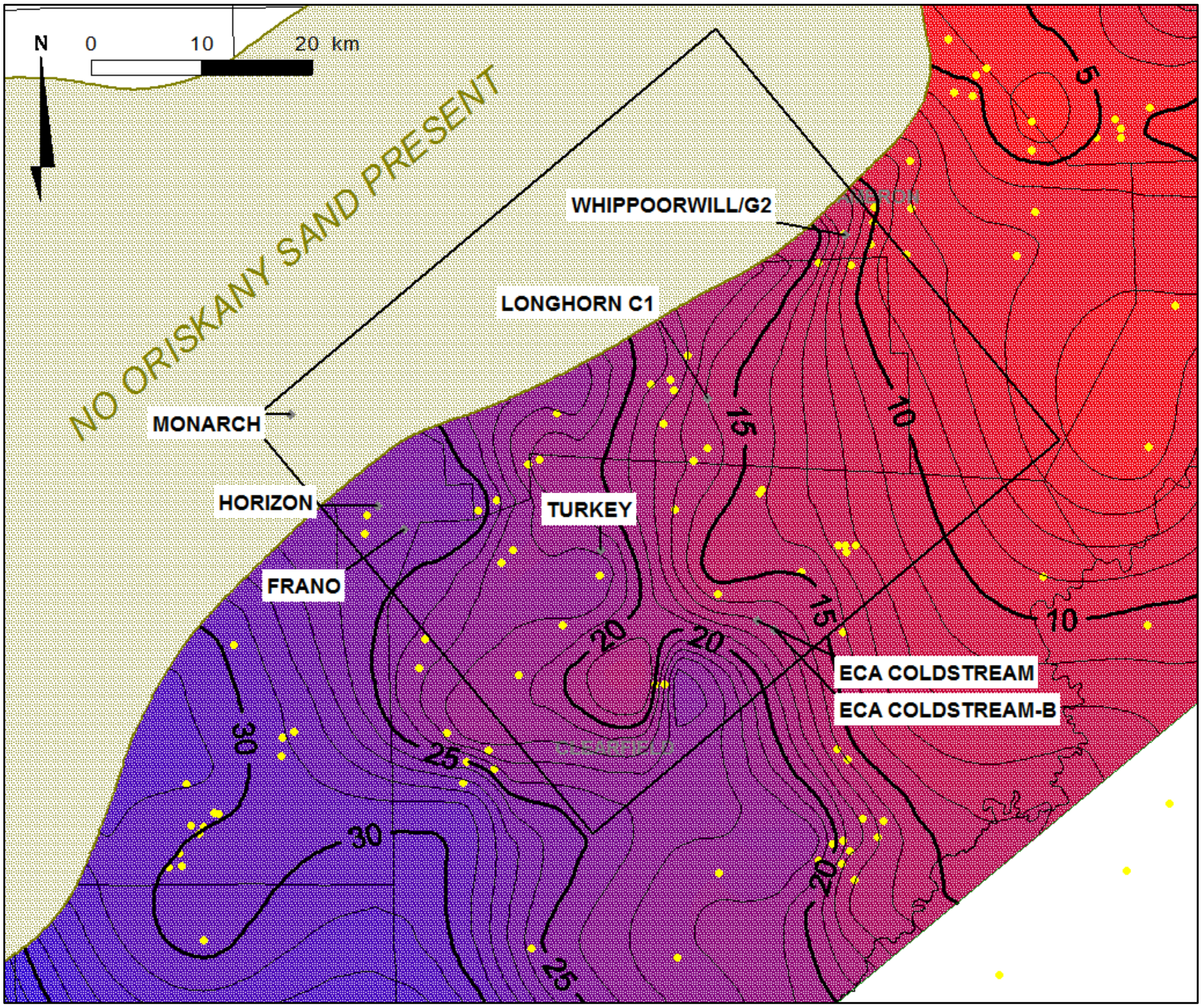


Figure 3-5. Distance from base of Marcellus Shale to the top of the Oriskany Sandstone. Yellow circles represent data points used to create the map. Study area is defined by the black rectangle. Contour interval is 1 meter.

3.2 WATER ISOTOPES

Water isotopic compositions were measured in Marcellus and Oriskany produced water grab samples collected from the study area (Figure 3-6 and Table 3-1). Grab samples of Marcellus produced waters from three wells located in the ‘no sand area’ plot in a tight grouping, as shown by the light blue circles, with $\delta^{18}O$ ranging from -2.45 to -2.60 and a $\delta^{2}H$ ranging from -50.8 to -53.2. Grab samples of Marcellus produced waters from eight wells that are underlain by the Oriskany have $\delta^{18}O$ ranging from -0.97 to -3.60 and a $\delta^{2}H$ ranging from -49.2 to -53.8.

The results were compared with isotopic values of three Ridgley Sandstone water samples from Somerset County, PA that were published by Dresel and Rose (2010). The isotopic values of produced water collected from production tanks of three Oriskany vertical wells collected in January 2017 are also included in Figure 3-6. The water in the production tanks of two of the Oriskany wells may be contaminated with meteoric water, as the O isotope ratios trend toward the meteoric water line. When considering the Dresel (1985) samples, the Oriskany produced water isotopes range from a $\delta^{18}O$ of 2 to -0.5 and a $\delta^{2}H$ ranging from -34 to -42. The Dresel and Rose sample ED-82-38 is potentially an outlier, with a $\delta^{18}O$ of -1.7 and a $\delta^{2}H$ of -51. However, very little information is available regarding the method in which the sample was collected. While the Oriskany produced water dataset is small, it suggests that water from the Oriskany is enriched in $\delta^{18}O$ and $\delta^{2}H$ relative to the Marcellus produced water.

In addition, an annual average surface water isotopic value for the location of the Longhorn C Pad was pulled from the Online Isotopes in Precipitation Calculator (Bowen, 2017, Bowen and Revenaugh, 2003, IAEA/WMO, 2015, and Welker, 2000) and is plotted on Figure 3-6. This calculated surface water isotopic value should approximately represent the isotopic composition of the freshwater used in hydraulically fracturing Marcellus Shale laterals in the study area.

Table 3-1. Results of produced water isotopic analysis

Sample Name	Sample Date	Analysis Date	δD H_2O ‰	$\delta^{18}O$ H_2O ‰	Vacuum Distilled? (1)
HORIZONTAL WELLS					
Horizon_591970	9/12/2016	10/23/2016	-50.3	-2.13	Yes
Horizon_591668	9/12/2016	10/23/2016	-53.8	-3.60	Yes
Horizon_591549	9/12/2016	10/23/2016	-50.2	-2.12	Yes
Frano_590515	9/12/2016	10/23/2016	-49.2	-1.63	Yes
Frano_590516	9/12/2016	10/23/2016	-52.6	-2.67	Yes
Turkey_590983	9/13/2016	10/23/2016	-51.9	-2.55	Yes
Whippoorwill_590876	9/13/2016	10/23/2016	-52.3	-0.97	Yes
Monarch_591155	9/12/2016	10/23/2016	-53.2	-2.60	Yes
Wedekind_590389	9/12/2016	10/23/2016	-50.8	-2.54	Yes
Red Bank_590370	9/12/2016	10/23/2016	-52.6	-2.45	Yes
Oriskany_591059	9/14/2016	10/23/2016	-120.7	-11.23	Yes
ECA-CS-3	2/22/2017	3/28/2017	-53.8	-1.82	Yes
VERTICAL WELLS					
ECA-COP1	1/24/2017	2/15/2017	-33.9	0.74	Yes
ECA-COP4	1/24/2017	2/15/2017	-32.9	-2.93	Yes
ECA-COP10	1/24/2017	2/15/2017	-37.4	-3.25	Yes
PUBLISHED VERTICAL WELLS (2)					
ED-82-37	~9/1982	unk	-41	-0.5	unk
ED-82-38	~9/1982	unk	-51	-1.7	unk
ED-82-40	~9/1982	unk	-42	2	unk

(1) Indicates if vacuum distillation was utilized for hydrogen and oxygen isotopic analysis of water.

(2) From Dresel, 1985.

unk = unknown

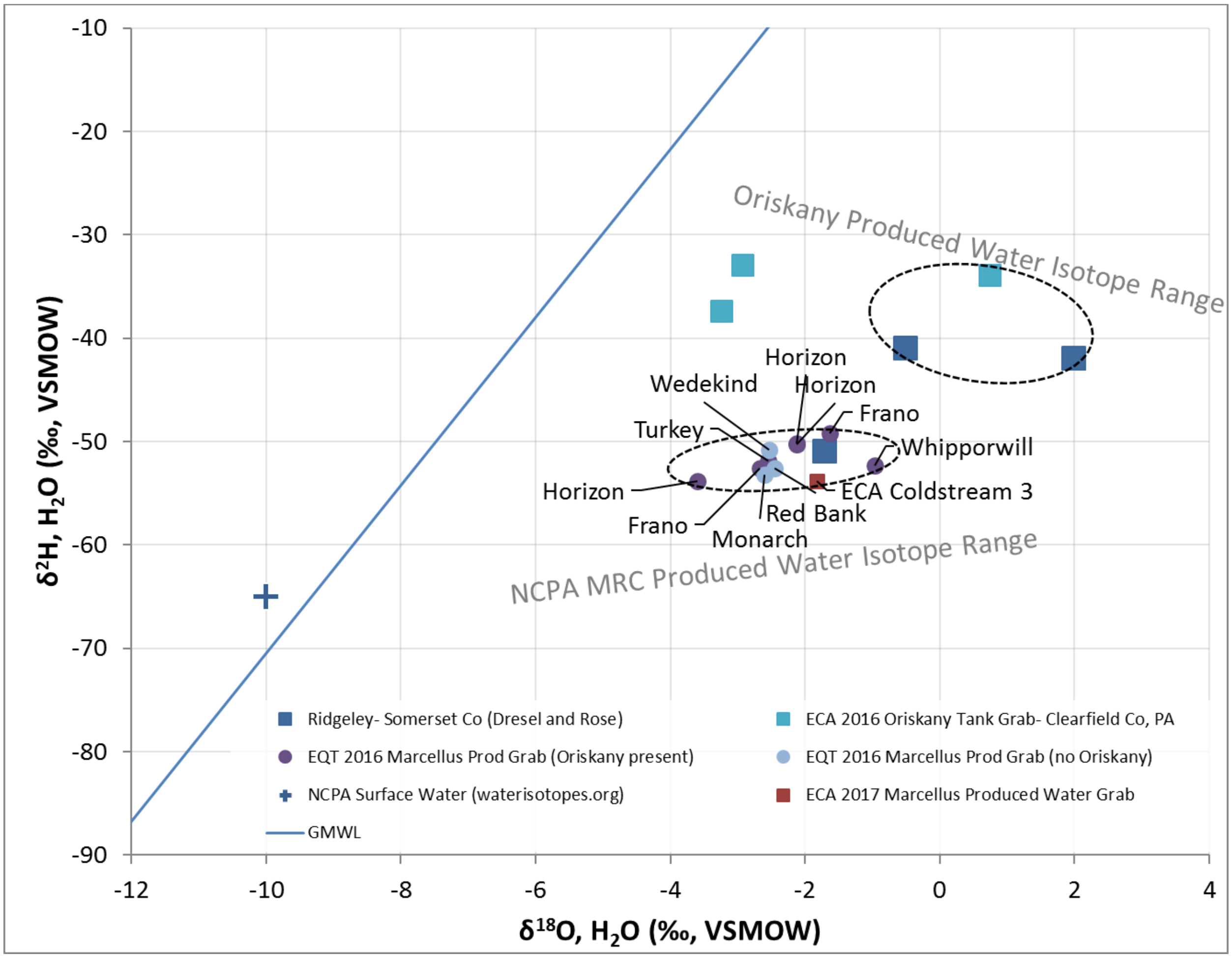


Figure 3-6. Plot of ^{18}O and ^{2}H composition of Marcellus and Oriskany produced waters.

3.3 WATER CHEMISTRY

Water chemistry was analyzed in both Marcellus and Oriskany produced water grab samples collected from the study area, as well as flowback waters from the Horizon Pad. These data were compared with published analyses of Oriskany produced water from Jefferson, Elk, Clearfield, and Cameron Counties (Tully, 1973 and Poth, 1962) (Table 3-2). The calcium and chloride concentrations of produced water from Marcellus laterals are similar to or greater than published and recently sampled produced water concentrations from Oriskany vertical wells (Figures 3-7 and 3-8).

Table 3-2. Results of produced water geochemistry analysis

Sample Name	Formation	Sample Date	Barium mg/L	Bromide mg/L	Calcium mg/L	Chloride mg/L
VERTICAL WELLS						
ORISKANY_591011	Oriskany	4/9/2015	147	1330	24300	129000
ORISKANY_591059	shallow sand	9/14/2016	10	14	320	1100
EQT_ECA_COP1	Oriskany	1/24/2017	190	980	24000	130000
EQT_ECA_COP4	Oriskany	1/24/2017	150	800	18000	110000
EQT_ECA_COP10	Oriskany	1/24/2017	43	260	5000	36000
HORIZONTAL WELLS						
HORIZON_591970	Marcellus	12/5/2014	2430	624	13100	75800
HORIZON_591970	Marcellus	12/6/2014	2480	727	14900	97900
HORIZON_591970	Marcellus	12/7/2014	3140	936	15700	130000
HORIZON_591970	Marcellus	12/8/2014	7630	942	17200	123000
HORIZON_591668	Marcellus	12/9/2014	1790	562	9950	68800
HORIZON_591668	Marcellus	12/10/2014	1510	623	8170	73300
HORIZON_591549	Marcellus	12/10/2014	2020	860	13700	113000
HORIZON_591549	Marcellus	12/11/2014	2267	na	15150	109874
HORIZON_591668	Marcellus	12/11/2014	2112	na	11158	81906
HORIZON_591549	Marcellus	12/11/2014	1910	796	12100	92800
HORIZON_591668	Marcellus	12/11/2014	2300	623	12400	86300
HORIZON_591668	Marcellus	12/12/2014	2240	660	11800	79000
HORIZON_591549	Marcellus	12/12/2014	2410	972	16600	118000
HORIZON_591549	Marcellus	12/13/2014	2220	984	15400	110000
HORIZON_591668	Marcellus	12/13/2014	2200	665	11400	76500
HORIZON_591668	Marcellus	12/14/2014	2070	673	10700	76700
HORIZON_591549	Marcellus	12/14/2014	2430	980	17000	113000
HORIZON_591668	Marcellus	12/16/2014	2400	706	11500	84400
HORIZON_591668	Marcellus	12/16/2014	2560	712	12300	78800
FRANO_590515	Marcellus	1/9/2013	na	na	23188	140000
FRANO_590516	Marcellus	1/9/2013	na	na	23775	145000
HORIZON_591549	Marcellus	9/12/2016	3500	1700	27000	170000
HORIZON_591668	Marcellus	9/12/2016	4600	1100	20000	130000
HORIZON_591970	Marcellus	9/12/2016	4800	1300	26000	160000
FRANO_590515	Marcellus	9/12/2016	4600	1400	25000	160000
FRANO_590516	Marcellus	9/12/2016	7800	1500	26000	150000
MONARCH_591155	Marcellus	9/12/2016	3000	1800	38000	160000
WEDEKIND_590389	Marcellus	9/12/2016	35	1900	36000	170000
REDBANK_590370	Marcellus	9/12/2016	1200	1500	29000	170000
TURKEY_590983	Marcellus	9/13/2016	9100	1400	26000	150000
WHIPPORWILL_590876	Marcellus	9/13/2016	6800	2600	44000	210000
EQT_ECA_CS-3	Marcellus	2/22/2017	4700	1400	36000	220000
EQT_ECA_CSB-5	Marcellus	2/22/2017	3900	770	11000	88000

Table 3-2. (continued)

Sample Name	Formation	Sample Date	Barium mg/L	Bromide mg/L	Calcium mg/L	Chloride mg/L
PUBLISHED VERTICAL WELLS						
KELLEY_68 [1]	Oriskany	1/9/1959	na	1260	34700	154000
KELLEY_69 [1]	Oriskany	1/9/1959	na	1400	38400	170000
KELLEY_176 [1]	Oriskany	4/18/1961	na	1860	39300	200602
KELLEY_177 [1]	Oriskany	4/1/1961	na	2240	46800	208040
KELLEY_178 [1]	Oriskany	4/1/1961	na	1580	38500	198947
KELLEY_179 [1]	Oriskany	6/23/1961	na	1032	21400	117301
KELLEY_181 [1]	Oriskany	6/23/1961	na	1095	26200	142265
KELLEY_185 [1]	Oriskany	5/1/1961	na	1050	44000	202560
KELLEY_185a [1]	Oriskany	unk	na	1056	44400	207277
KELLEY_186 [1]	Oriskany	11/4/1960	na	1500	36000	148062
KELLEY_187 [1]	Oriskany	11/4/1960	na	1520	33400	168666
KELLEY_189 [1]	Oriskany	10/26/1961	na	930	24400	117151
KELLEY_190 [1]	Oriskany	1/31/1961	na	2120	57400	201120
KELLEY_191 [1]	Oriskany	11/4/1960	na	1460	42500	200059
KELLEY_192 [1]	Oriskany	11/4/1960	na	640	54100	196389
KELLEY_195 [1]	Oriskany	6/1/1962	na	690	36058	166674
KELLEY_197 [1]	Oriskany	11/21/1962	na	780	41438	193986
KELLEY_203 [1]	Oriskany	8/23/1963	na	810	11193	166847
KELLEY_204 [1]	Oriskany	10/26/1961	na	1740	42000	202181
KELLEY_205 [1]	Oriskany	5/13/1960	na		36000	134000
POTH_1101 [2]	Oriskany	~1960	na	1440	35900	169000
POTH_1102 [2]	Oriskany	~1960	na	1260	34700	154000
POTH_1103 [2]	Oriskany	~1960	na	1400	38400	170000

(1) From Kelley, 1973.
(2) From Poth, 1962.
nd = not detected
na = not analyzed
unk = unknown

Table 3-2. (continued)

Sample Name	Copper mg/L	Iron mg/L	Lead mg/L	Lithium mg/L	Magnesium mg/L	Manganese mg/L
VERTICAL WELLS						
ORISKANY_591011	2.66	3860	0.964	172	2270	21.5
ORISKANY_591059	0.18	180	0.021	0.32	19	3.8
EQT_ECA_COP1	0.23	72	nd	180	2700	7.9
EQT_ECA_COP4	0.42	170	nd	160	1800	3.6
EQT_ECA_COP10	nd	97	nd	56	640	3.3
HORIZONTAL WELLS						
HORIZON_591970	<1.00	70.4	<.400	85.6	856	7.13
HORIZON_591970	<1.00	72.5	<.400	118	1120	5.1
HORIZON_591970	1.02	66.3	<.400	124	1200	5.4
HORIZON_591970	1.05	70.8	<.400	135	1310	6.08
HORIZON_591668	<1.00	78.5	<.400	74.7	732	3.97
HORIZON_591668	<1.00	36.6	<.400	63.2	603	2.53
HORIZON_591549	<1.00	56.1	<.400	98.4	1050	3.5
HORIZON_591549	na	80.3	0	na	1203	3.9
HORIZON_591668	na	43.9	2	na	869	3.2
HORIZON_591549	<1.00	48.3	<.400	87.5	938	3.09
HORIZON_591668	<1.00	46.3	<.400	96.3	922	3.66
HORIZON_591668	<1.00	43.8	<.400	92.4	885	3.65
HORIZON_591549	1.11	69.2	<.400	120	1280	4.45
HORIZON_591549	1.21	71	<.400	118	1240	4.18
HORIZON_591668	<1.00	44.7	<.400	91.2	859	3.57
HORIZON_591668	<1.00	44.6	<.400	85.1	809	3.27
HORIZON_591549	1.26	73.4	<.400	127	1330	4.5
HORIZON_591668	1.05	47.5	<.200	94.2	888	3.45
HORIZON_591668	1.03	49.5	<.200	100	947	3.69
FRANO_590515	na	127.87	na	na	1900.59	na
FRANO_590516	na	103.63	na	na	1907.52	na
HORIZON_591549	nd	150	nd	200	2200	7
HORIZON_591668	nd	110	nd	150	1600	7
HORIZON_591970	0.33	150	nd	180	2100	9
FRANO_590515	nd	140	nd	190	2000	6.7
FRANO_590516	0.37	130	nd	190	2100	12
MONARCH_591155	nd	140	nd	190	2400	14
WEDEKIND_590389	nd	89	nd	180	3200	9.3
REDBANK_590370	nd	68	nd	170	2800	10
TURKEY_590983	nd	140	nd	180	2200	14
WHIPPORWILL_590876	nd	180	nd	280	2800	20
EQT_ECA_CS-3	0.41	100	nd	230	2300	27
EQT_ECA_CSB-5	0.35	470	nd	65	970	8.3

Table 3-2. (continued)

Sample Name	Copper mg/L	Iron mg/L	Lead mg/L	Lithium mg/L	Magnesium mg/L	Manganese mg/L
PUBLISHED VERTICAL WELLS						
KELLEY_68 (1)	na	na	na	na	1250	na
KELLEY_69 (1)	na	na	na	na	3700	na
KELLEY_176 (1)	na	na	na	na	2400	na
KELLEY_177 (1)	na	na	na	na	2900	na
KELLEY_178 (1)	na	na	na	na	2400	na
KELLEY_179 (1)	na	na	na	na	1736	na
KELLEY_181 (1)	na	na	na	na	2016	na
KELLEY_185 (1)	na	na	na	na	3040	na
KELLEY_185a (1)	na	na	na	na	3040	na
KELLEY_186 (1)	na	na	na	na	2500	na
KELLEY_187 (1)	na	na	na	na	2400	na
KELLEY_189 (1)	na	112	na	na	1856	na
KELLEY_190 (1)	na	na	na	na	3500	na
KELLEY_191 (1)	na	na	na	na	2800	na
KELLEY_192 (1)	na	na	na	na	3650	na
KELLEY_195 (1)	na	2838	na	na	1252	na
KELLEY_197 (1)	na	389	na	na	1944	na
KELLEY_203 (1)	na	220	na	na	971	na
KELLEY_204 (1)	na	16.5	na	na	3840	na
KELLEY_205 (1)	na	na	na	na	8000	na
POTH_1101 (2)	na	na	na	na	3510	na
POTH_1102 (2)	na	na	na	na	1250	na
POTH_1103 (2)	na	na	na	na	3700	na

(1) From Kelley, 1973.
(2) From Poth, 1962.
nd = not detected
na = not analyzed
unk = unknown

Table 3-2. (continued)

Sample Name	Potassium mg/L	Sodium mg/L	Strontium mg/L	Zinc mg/L	Total Dissolved Solids mg/L	Sulfate mg/L
VERTICAL WELLS						
ORISKANY_591011	2170	47700	3090	7.97	266000	270
ORISKANY_591059	1.3	280	27	0.027	3400	7.6
EQT_ECA_COP1	1300	47000	8000	0.66	230000	nd
EQT_ECA_COP4	1400	37000	8100	0.17	180000	nd
EQT_ECA_COP10	400	13000	2800	nd	62000	36
HORIZONTAL WELLS						
HORIZON_591970	455	37600	255	<1.00	129000	138
HORIZON_591970	557	47600	281	<1.00	150000	<100
HORIZON_591970	563	66000	343	<1.00	176000	<100
HORIZON_591970	611	89100	3430	<1.00	165000	<100
HORIZON_591668	293	27800	2170	<1.00	130000	<100
HORIZON_591668	241	23200	1770	<1.00	110000	<100
HORIZON_591549	552	34600	2490	2.46	173000	<100
HORIZON_591549	603	48951	2883	4.09	181173	0
HORIZON_591668	314	36535	2402	1.55	135505	0
HORIZON_591549	460	31500	2560	<1.00	156000	<100
HORIZON_591668	358	34600	2620	<1.00	124000	<100
HORIZON_591668	336	32400	2600	<1.00	120000	<100
HORIZON_591549	688	42300	3340	<1.00	152000	<100
HORIZON_591549	699	40000	3080	<1.00	141000	<100
HORIZON_591668	326	31700	2610	<1.00	105000	<100
HORIZON_591668	301	29500	2400	1.93	104000	<100
HORIZON_591549	750	43500	3330	<1.00	146000	<100
HORIZON_591668	342	31100	2620	1.36	107000	<100
HORIZON_591668	368	33000	2760	0.78	107000	<100
FRANO_590515	774.43	55810	28.2	na	231731	1
FRANO_590516	494.12	57267	na	na	241631	11
HORIZON_591549	1300	57000	5600	0.57	300000	nd
HORIZON_591668	510	51000	5100	0.56	230000	nd
HORIZON_591970	840	62000	6100	0.89	280000	440
FRANO_590515	1100	53000	5900	0.4	290000	300
FRANO_590516	610	59000	7900	2	290000	nd
MONARCH_591155	630	53000	8400	4.6	310000	nd
WEDEKIND_590389	1000	51000	5600	nd	310000	320
REDBANK_590370	840	55000	8000	0.63	300000	nd
TURKEY_590983	490	52000	7600	1.1	280000	nd
WHIPPORWILL_590876	1400	51000	8000	3	370000	nd
EQT_ECA_CS-3	740	60000	16000	0.23	370000	300
EQT_ECA_CSB-5	150	27000	3100	0.61	150000	180

Table 3-2. (continued)

Sample Name	Potassium mg/L	Sodium mg/L	Strontium mg/L	Zinc mg/L	Total Dissolved Solids mg/L	Sulfate mg/L
PUBLISHED VERTICAL WELLS						
KELLEY_68 (1)	2780	55000	na	na	248511	na
KELLEY_69 (1)	3260	56200	na	na	274763	na
KELLEY_176 (1)	3400	78700	na	na	327262	10
KELLEY_177 (1)	3700	74200	na	na	338440	20
KELLEY_178 (1)	3500	78700	na	na	324112	10
KELLEY_179 (1)	1576	47600	na	na	191311	na
KELLEY_181 (1)	1968	58000	na	na	232255	na
KELLEY_185 (1)	3440	73400	na	na	328338	na
KELLEY_185a (1)	3440	76000	na	na	336042	na
KELLEY_186 (1)	2500	19000	na	na	240329	100
KELLEY_187 (1)	2900	65300	na	na	274977	100
KELLEY_189 (1)	1704	43600	na	na	190401	na
KELLEY_190 (1)	4900	55700	na	na	325408	20
KELLEY_191 (1)	3300	74200	na	na	325054	100
KELLEY_192 (1)	4900	55700	na	na	316299	100
KELLEY_195 (1)	1760	60000	na	na	268721	na
KELLEY_197 (1)	1600	85000	na	na	325009	na
KELLEY_203 (1)	1040	93000	na	na	274542	na
KELLEY_204 (1)	3344	74400	na	na	330058	na
KELLEY_205 (1)	2000	64000	na	na	250203	1
POTH_1101 (2)	3260	57100	na	na	312000	na
POTH_1102 (2)	2780	55000	na	na	279000	na
POTH_1103 (2)	3260	56200	na	na	311000	na

(1) From Kelley, 1973.
(2) From Poth, 1962.
nd = not detected
na = not analyzed
unk = unknown

Table 3-2. (continued)

Sample Name	Specific Gravity No Unit	Total Alkalinity as CaCO3 to pH 4.5 mg/L	Bicarbonate Alkalinity as CaCO3 mg/L	Specific Conductance umhos/cm	pH SU
VERTICAL WELLS					
ORISKANY_591011	1.153	130	na	219000	5.66
ORISKANY_591059	1.0	320	320	38	5.1
EQT_ECA_COP1	1.1	nd	nd	190	4.4
EQT_ECA_COP4	1.1	26	26	170	5.7
EQT_ECA_COP10	1.0	46	46	82	6.0
HORIZONTAL WELLS					
HORIZON_591970	1.096	na	na	157000	6.09
HORIZON_591970	1.127	na	na	175000	6.25
HORIZON_591970	1.128	na	na	190000	6.21
HORIZON_591970	1.13	na	na	187000	6.18
HORIZON_591668	1.088	na	na	152000	6.59
HORIZON_591668	1.093	na	na	149000	6.23
HORIZON_591549	1.121	na	na	192000	6.5
HORIZON_591549	na	na	na	na	7.1
HORIZON_591668	na	na	na	na	7.1
HORIZON_591549	1.114	na	na	41200	6.19
HORIZON_591668	1.094	na	na	129000	6.29
HORIZON_591668	1.096	na	na	149000	6.36
HORIZON_591549	1.123	na	na	190000	6.29
HORIZON_591549	1.124	na	na	131000	6.2
HORIZON_591668	1.099	na	na	136000	6.34
HORIZON_591668	1.099	na	na	124000	6.62
HORIZON_591549	1.128	na	na	168000	6.35
HORIZON_591668	1.103	na	na	141000	6.48
HORIZON_591668	1.102	na	na	165000	6.37
FRANO_590515	na	na	na	na	5.7
FRANO_590516	na	na	na	na	5.6
HORIZON_591549	1.1	88	88	210000	5.4
HORIZON_591668	1.1	120	120	190000	5.6
HORIZON_591970	1.2	110	110	200000	5.4
FRANO_590515	1.2	110	110	210000	5.5
FRANO_590516	1.1	94	94	210000	5.6
MONARCH_591155	1.2	110	110	210000	5.5
WEDEKIND_590389	1.2	84	84	210000	5.1
REDBANK_590370	1.2	64	64	210000	5.1
TURKEY_590983	1.1	130	130	200000	5.7
WHIPPORWILL_590876	1.1	40	40	210000	4.3
EQT_ECA_CS-3	1.2	nd	nd	210000	5.1
EQT_ECA_CSB-5	1.1	nd	nd	140000	5.6

Table 3-2. (continued)

Sample Name	Specific Gravity No Unit	Total Alkalinity as CaCO3 to pH 4.5 mg/L	Bicarbonate Alkalinity as CaCO3 mg/L	Specific Conductance umhos/cm	pH SU
PUBLISHED VERTICAL WELLS					
KELLEY_68 (1)	na	na	na	na	2.65
KELLEY_69 (1)	na	na	na	na	3.2
KELLEY_176 (1)	na	na	na	na	3.95
KELLEY_177 (1)	na	na	na	na	4.55
KELLEY_178 (1)	na	na	na	na	5
KELLEY_179 (1)	na	na	na	na	3.8
KELLEY_181 (1)	na	na	na	na	4.8
KELLEY_185 (1)	na	na	na	na	4.85
KELLEY_185a (1)	na	na	na	na	4.9
KELLEY_186 (1)	na	na	34	na	3.55
KELLEY_187 (1)	na	na	16	na	3.15
KELLEY_189 (1)	na	na	28	na	4.9
KELLEY_190 (1)	na	na	76	na	5.8
KELLEY_191 (1)	na	na	na	na	3.03
KELLEY_192 (1)	na	na	33	na	2.9
KELLEY_195 (1)	na	na	na	na	3.6
KELLEY_197 (1)	na	na	na	na	4.1
KELLEY_203 (1)	na	na	na	na	3.7
KELLEY_204 (1)	na	na	na	na	3.5
KELLEY_205 (1)	na	na	10	na	5.1
POTH_1101 (2)	1.2	na	na	210000	2.35
POTH_1102 (2)	1.2	na	na	209000	2.65
POTH_1103 (2)	1.2	na	na	210000	3.2

(1) From Kelley, 1973.
(2) From Poth, 1962.
nd = not detected
na = not analyzed
unk = unknown

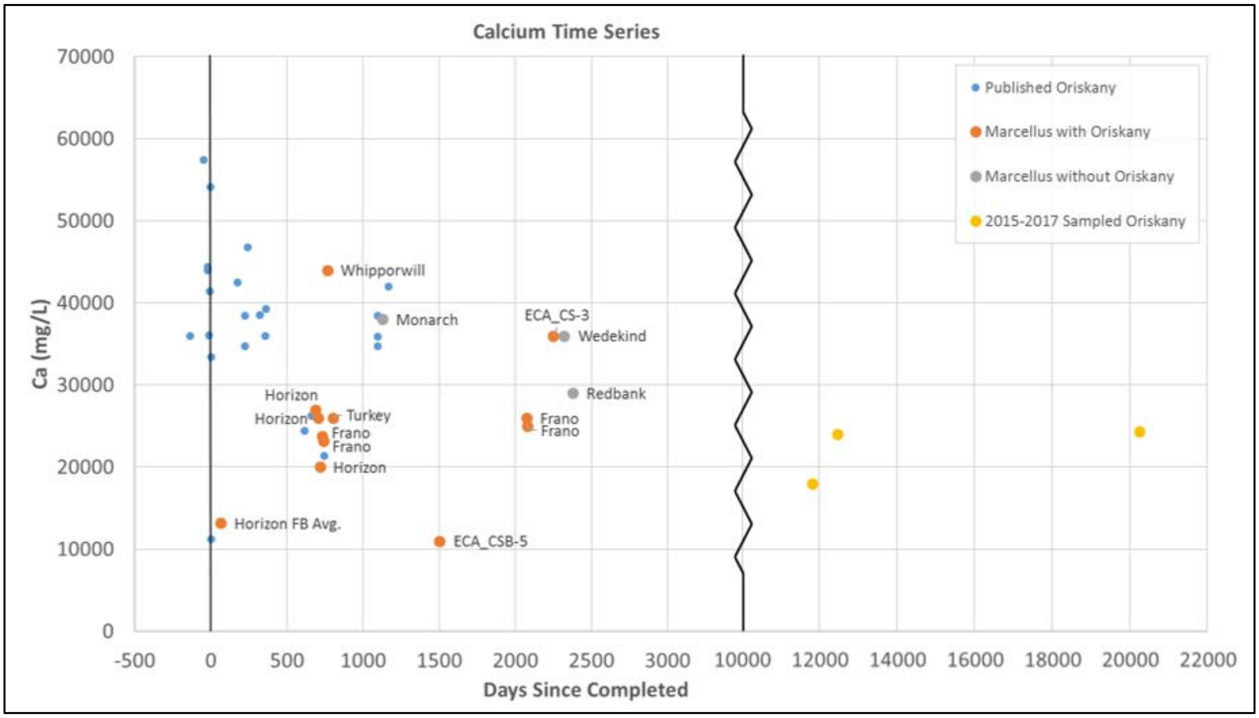


Figure 3-7. Calcium Time Series in Oriskany vertical wells and Marcellus laterals

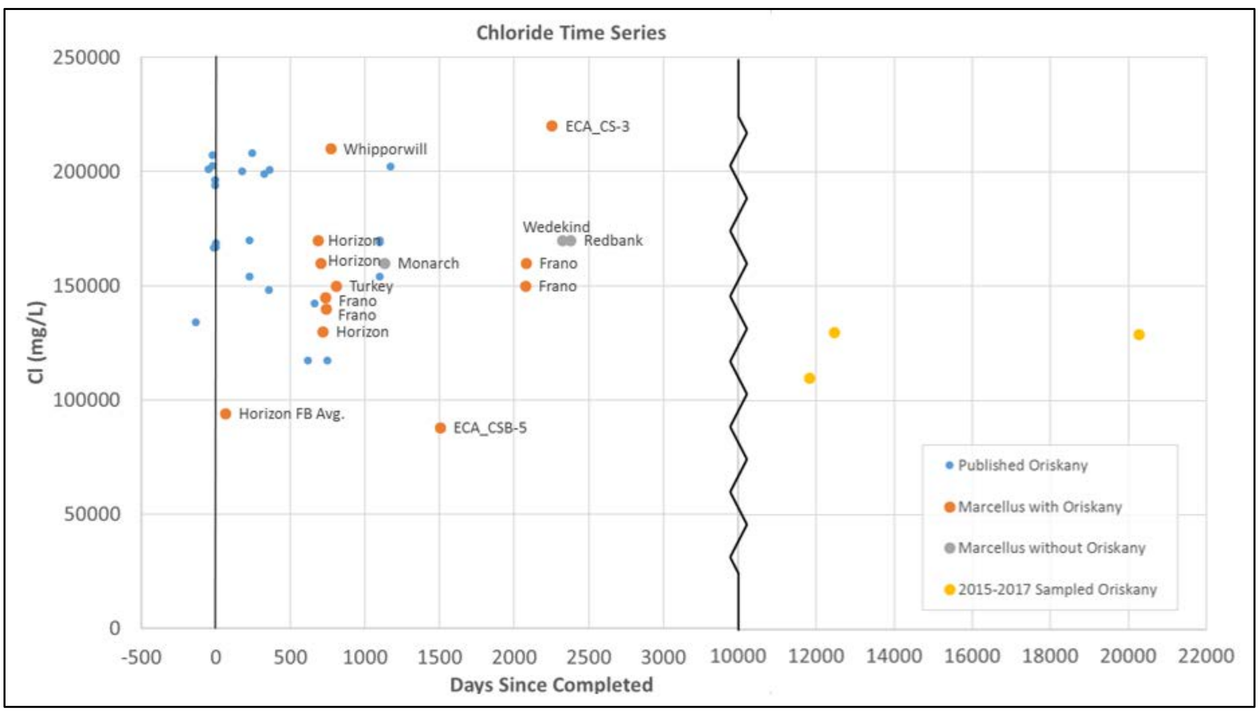


Figure 3-8. Chloride Time Series in Oriskany vertical wells and Marcellus laterals

The time series plots indicate that the chemistry of produced water from Marcellus laterals that are underlain by the Oriskany and from Marcellus laterals that are not underlain by the Oriskany are not clearly different, as the concentrations in the Monarch, Redbank, and Wedekind samples reach similar levels as Marcellus Shale laterals that are underlain by the Oriskany Sandstone. The small sample size of Marcellus and Oriskany produced waters may obscure any differences in the median concentrations of Ca and Cl in each formation, but there is clearly substantial overlap. In addition to the seven samples collected in the fall of 2016, the group 'Marcellus with Oriskany' contains a Horizon flowback average concentration, two early production samples from the Frano Pad, and two produced water samples from ECA wells.

To assess the effect of the Oriskany Sandstone on Marcellus Shale produced water chemistry, I compared the ratios of the average concentrations of a range of elements in the two produced fluids (Table 3-3).

Table 3-3. Ratio of average Marcellus Shale produced water chemistry

ANALYTE	Average 2016 Marcellus with Oriskany Produced Water Result (n=7)	Average 2016 Marcellus no Oriskany Produced Water Result (n=3)	Ratio of Marcellus with Oriskany to Marcellus no Oriskany Produced Waters	Error Associated with Ratio
Barium (mg/l)	5886	1412	4.17	3.84
Bromide (mg/l)	1571	1733	0.91	0.28
Calcium (mg/l)	27714	34333	0.81	0.22
Chloride (mg/l)	161429	166667	0.97	0.14
Copper (mg/l)	0	ND	-	-
Iron (mg/l)	143	99	1.44	0.48
Lead (mg/l)	ND	ND	-	-
Lithium (mg/l)	196	180	1.09	0.21
Magnesium (mg/l)	2143	2800	0.77	0.15
Manganese (mg/l)	11	11	0.97	0.45
p H	5	5	1.02	0.09
Potassium (mg/l)	893	823	1.08	0.47
Sodium (mg/l)	55000	53000	1.04	0.08
Strontium (mg/l)	6600	7333	0.90	0.21
Sulfate (mg/l)	370	320	1.16	0.22
TDS (mg/l)	291429	306667	0.95	0.13
Total Alkalinity (MgCaCO3/l)	99	86	1.15	0.41
Zinc (mg/l)	1.22	2.62	0.47	0.49

After averaging the concentrations of each analyte of the seven Marcellus laterals with Oriskany and averaging the concentrations of each analyte of the three Marcellus laterals without Oriskany, a ratio of the averages was calculated to compare effects of the presence/absence of the Oriskany on water chemistry. The ratios show that five out of the 18 analytes are noticeably different when the Oriskany underlies the Marcellus Shale. Produced water from Marcellus laterals underlain by the Oriskany contain lower concentrations of calcium, magnesium, and zinc (highlighted in green, Table 3-3), than produced water from Marcellus laterals that are not underlain by the Oriskany. The ratios indicate that produced water from Marcellus laterals underlain by the Oriskany contain greater concentrations of barium and iron (highlighted in yellow, Table 3-3), than produced water from Marcellus laterals that are not underlain by the Oriskany. However, errors were propagated for these ratios and the uncertainties suggest that there may not actually be any difference in the produced water chemistry of Marcellus laterals with Oriskany and Marcellus laterals without Oriskany.

The water chemistry data set is small with only seven data points in the 'Marcellus laterals underlain by the Oriskany' group and three data points in the Marcellus laterals not underlain by the Oriskany' group. Box plots were generated to better illustrate the distribution and variability of the water chemistry data (Figures 3-9 through 3-41).

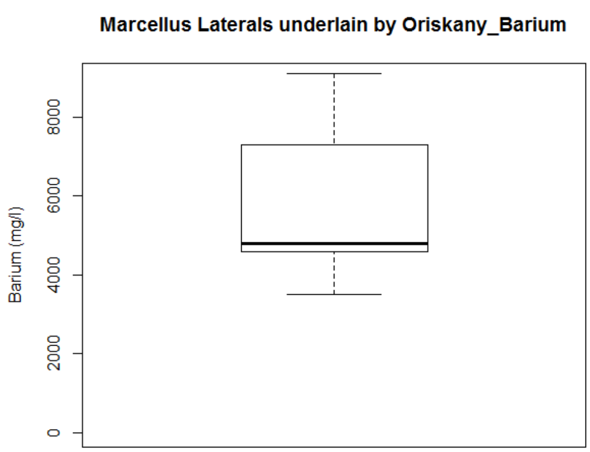


Figure 3-9. Barium in Marcellus laterals underlain by Oriskany

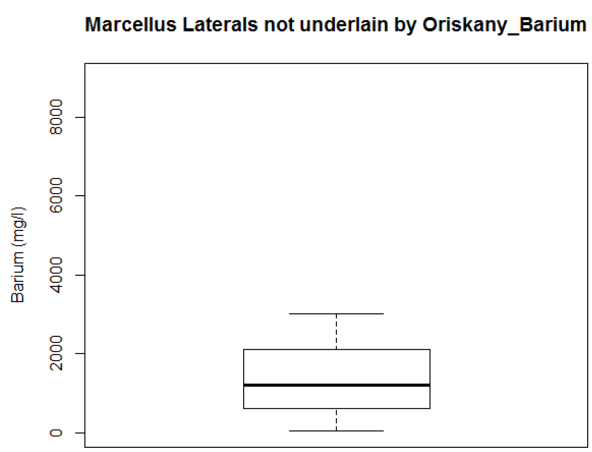
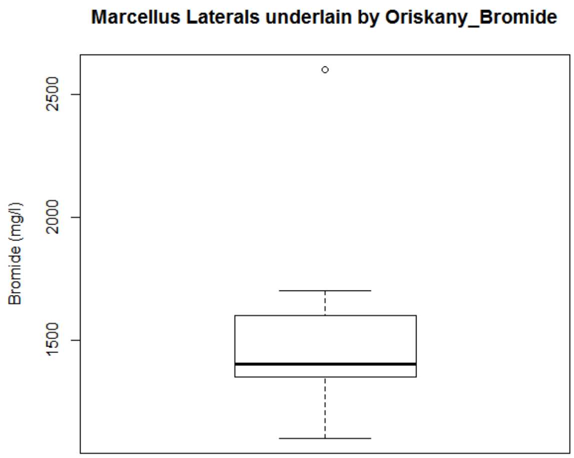


Figure 3-10. Barium in Marcellus laterals not underlain by Oriskany



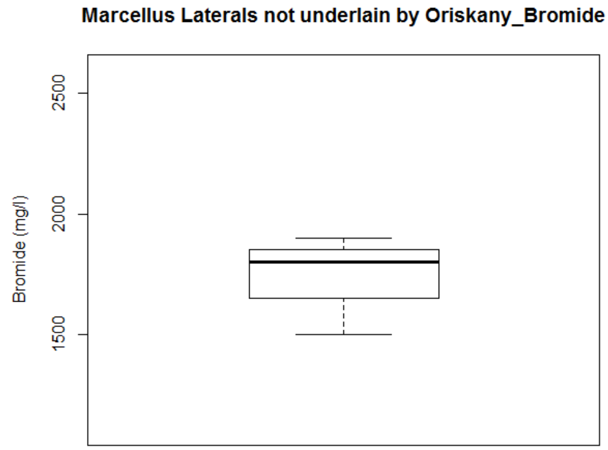
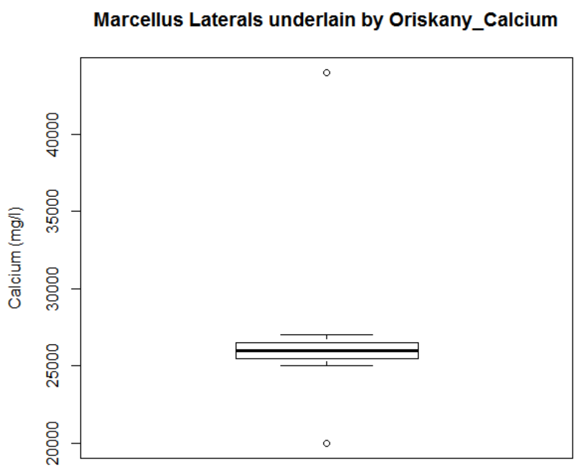


Figure 3-11. Bromide in Marcellus laterals underlain by Oriskany

Figure 3-12. Bromide in Marcellus laterals not underlain by Oriskany



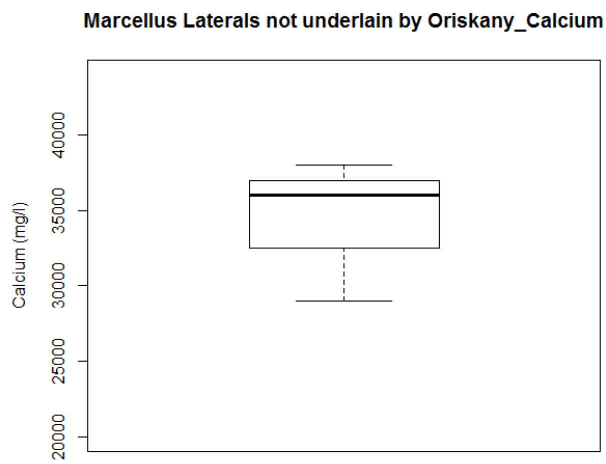


Figure 3-13. Calcium in Marcellus laterals underlain by Oriskany

Figure 3-14. Calcium in Marcellus laterals not underlain by Oriskany

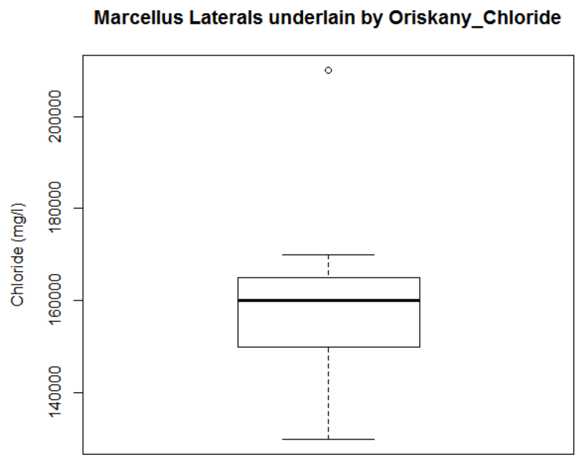


Figure 3-15. Chloride in Marcellus laterals underlain by Oriskany

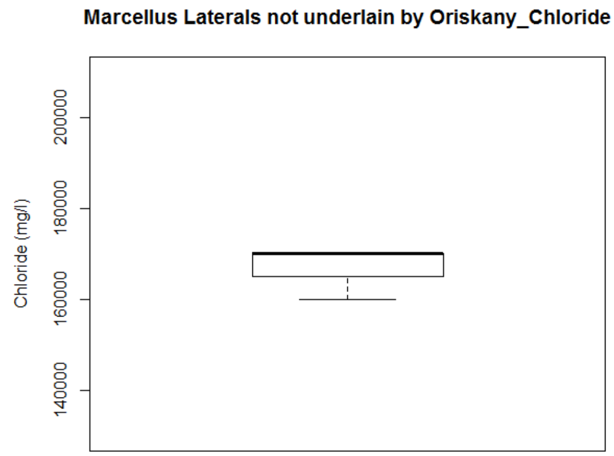


Figure 3-16. Chloride in Marcellus laterals not underlain by Oriskany

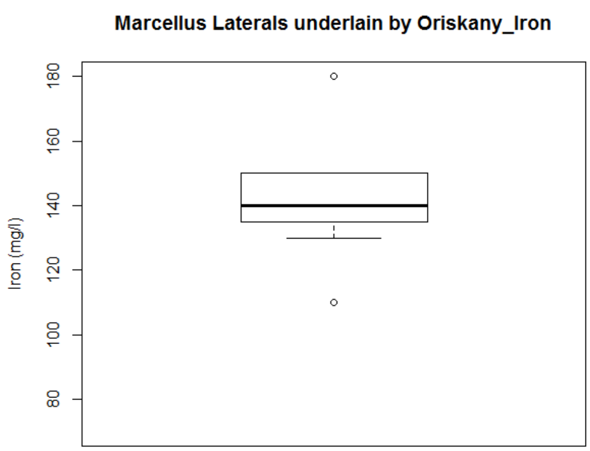


Figure 3-17. Iron in Marcellus laterals underlain by Oriskany

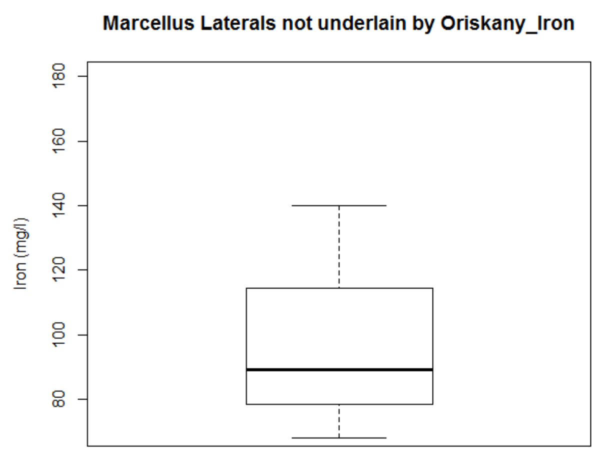


Figure 3-18. Iron in Marcellus laterals not underlain by Oriskany

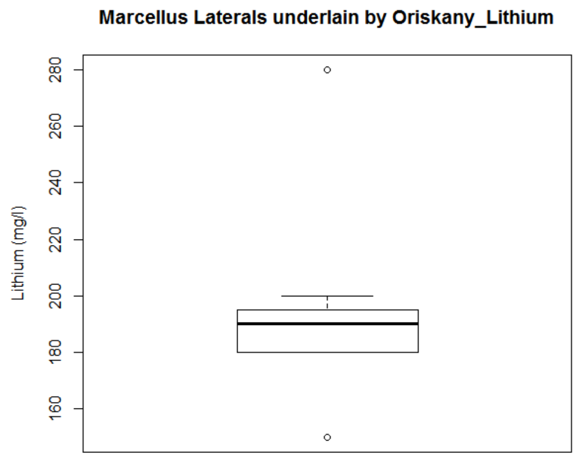


Figure 3-19. Lithium in Marcellus laterals underlain by Oriskany

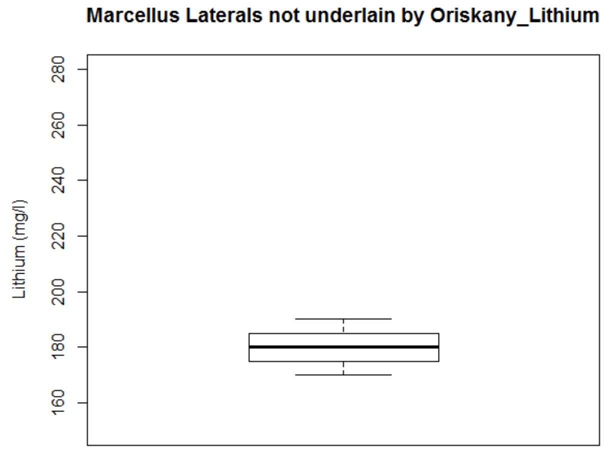


Figure 3-20. Lithium in Marcellus laterals not underlain by Oriskany

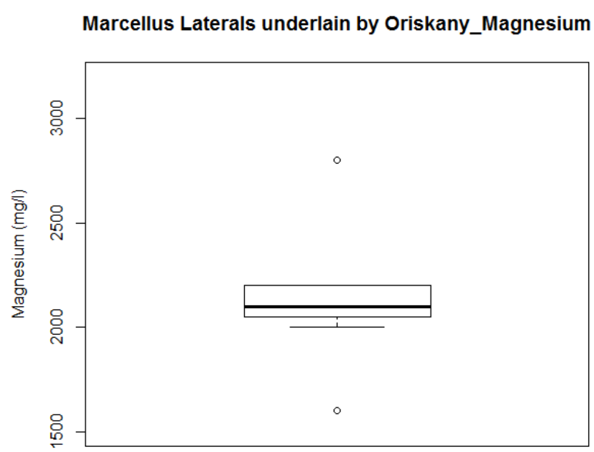


Figure 3-21. Magnesium in Marcellus laterals underlain by Oriskany

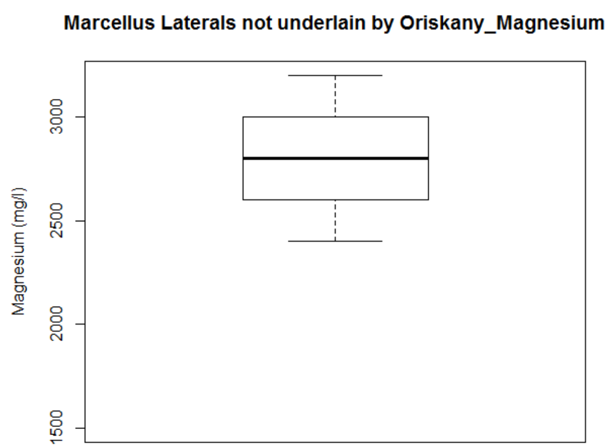
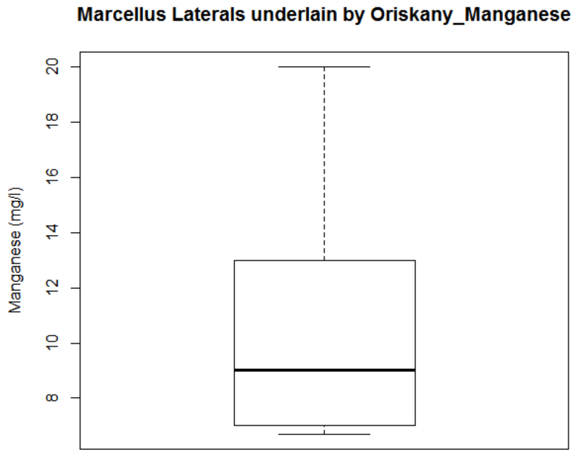


Figure 3-22. Magnesium in Marcellus laterals not underlain by Oriskany



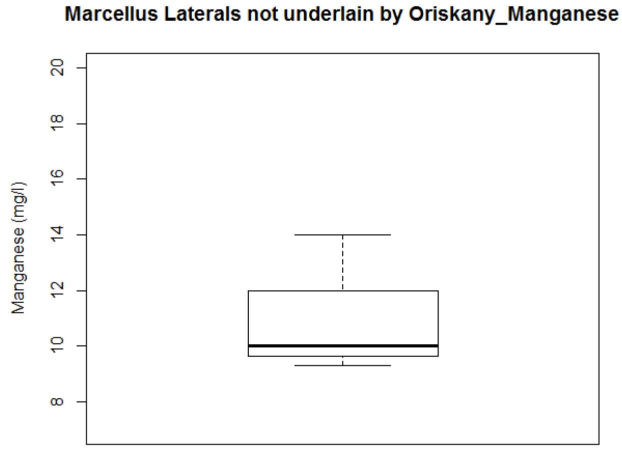
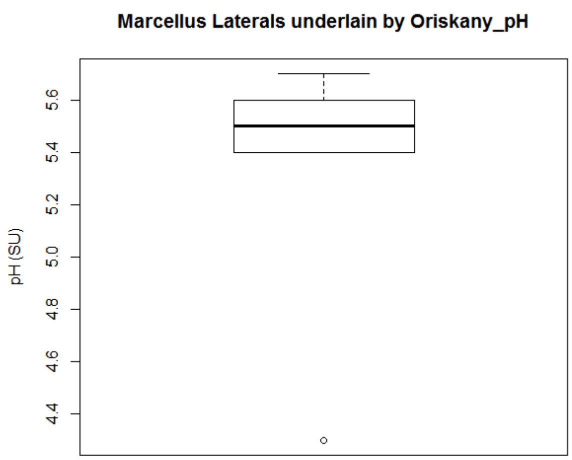


Figure 3-23. Manganese in Marcellus laterals underlain by Oriskany

Figure 3-24. Manganese in Marcellus laterals not underlain by Oriskany



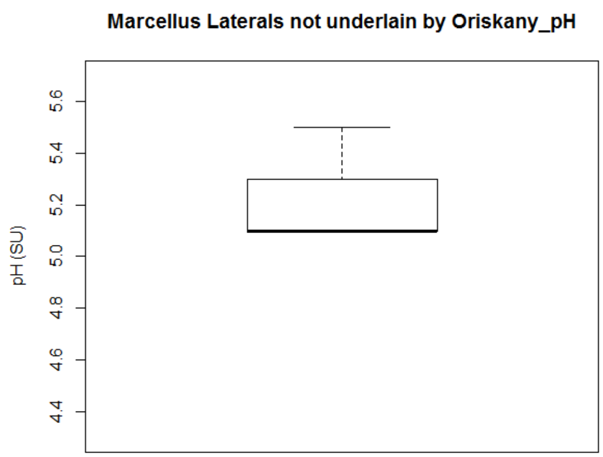
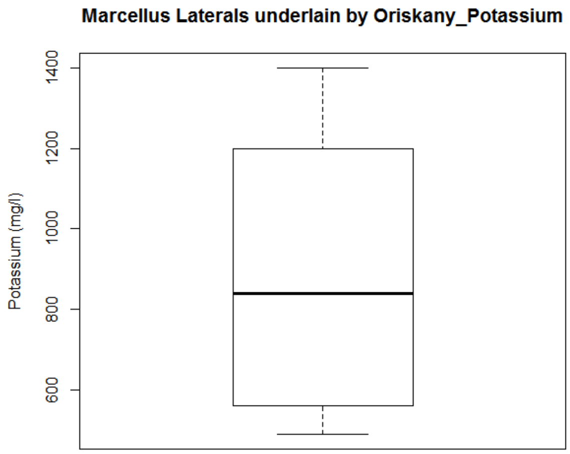


Figure 3-25. pH in Marcellus laterals underlain by Oriskany

Figure 3-26. pH in Marcellus laterals not underlain by Oriskany



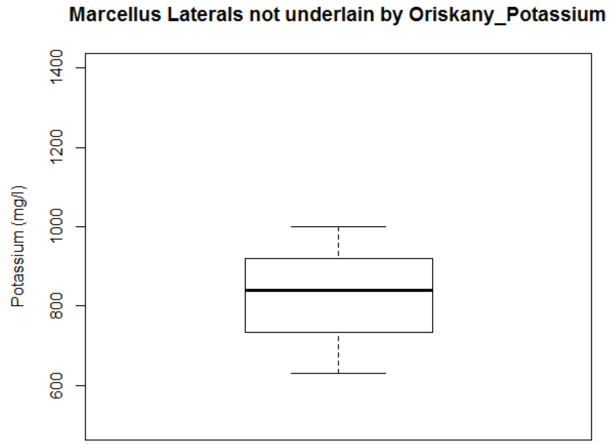
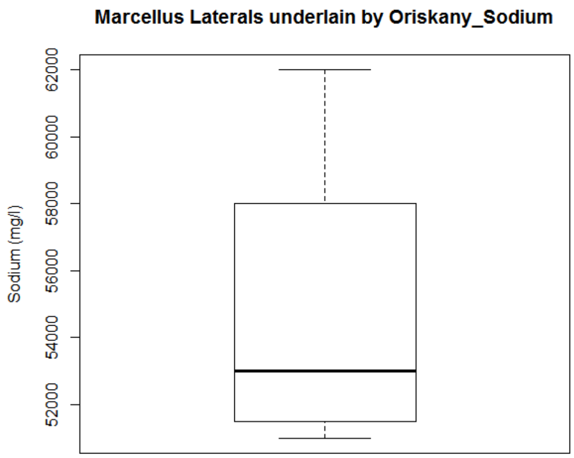


Figure 3-27. Potassium in Marcellus laterals underlain by Oriskany

Figure 3-28. Potassium in Marcellus laterals not underlain by Oriskany



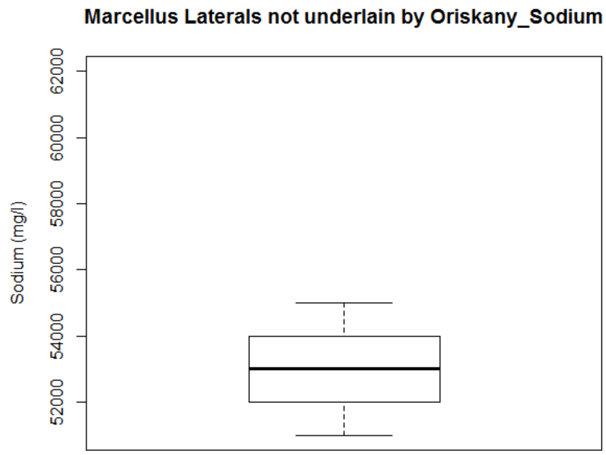
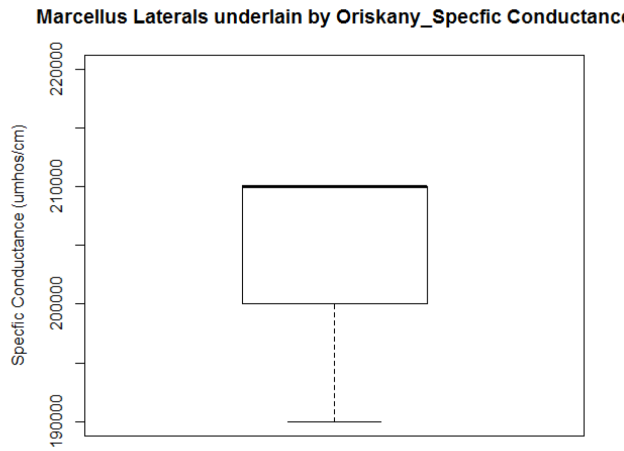


Figure 3-29. Sodium in Marcellus laterals underlain by Oriskany

Figure 3-30. Sodium in Marcellus laterals not underlain by Oriskany



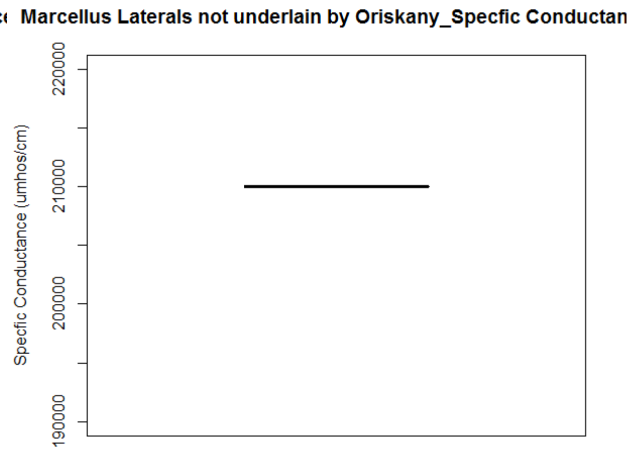
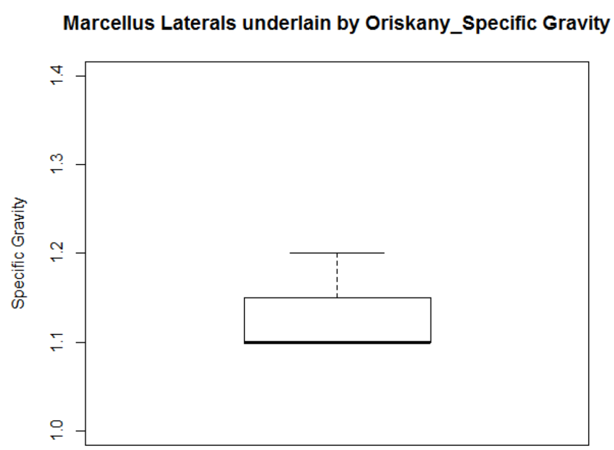


Figure 3-31. Specific conductance in Marcellus laterals underlain by Oriskany

Figure 3-32. Specific conductance in Marcellus laterals not underlain by Oriskany



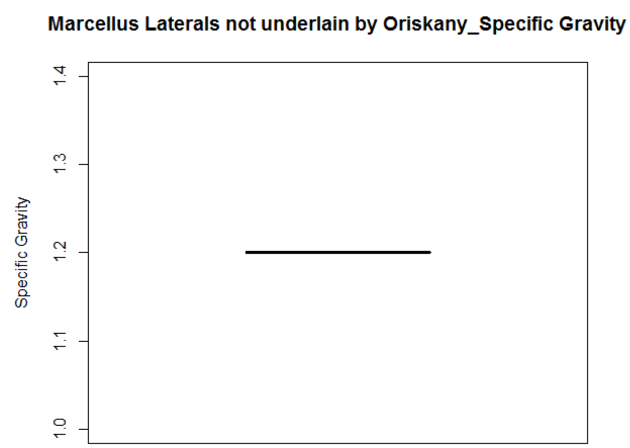


Figure 3-33. Specific gravity in Marcellus laterals underlain by Oriskany

Figure 3-34. Specific gravity in Marcellus laterals not underlain by Oriskany

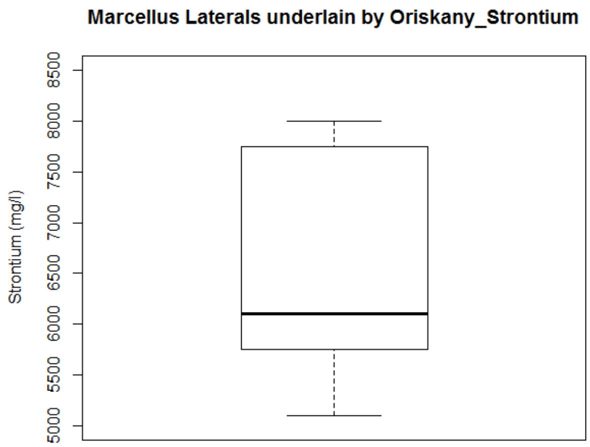


Figure 3-35. Strontium in Marcellus laterals underlain by Oriskany

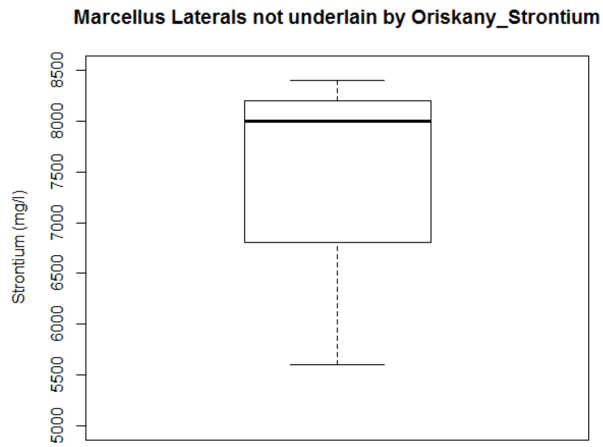


Figure 3-36. Strontium in Marcellus laterals not underlain by Oriskany

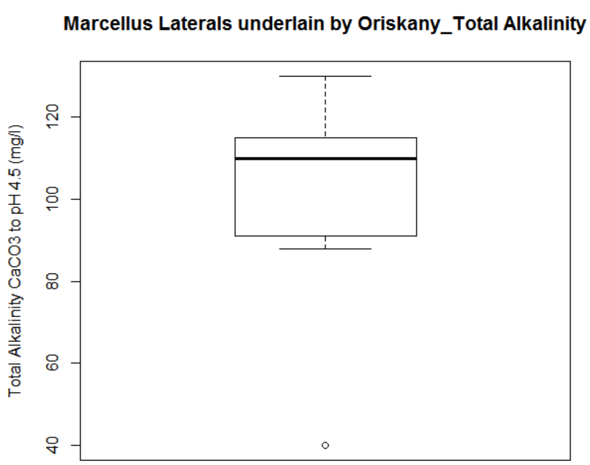


Figure 3-37. Total Alkalinity in Marcellus laterals underlain by Oriskany

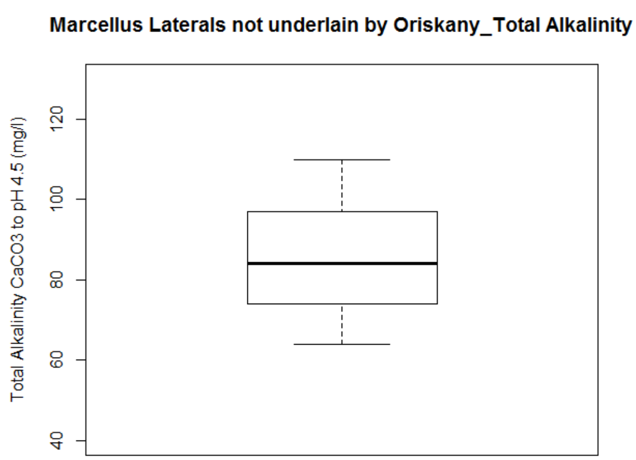


Figure 3-38. Total Alkalinity in Marcellus laterals not underlain by Oriskany

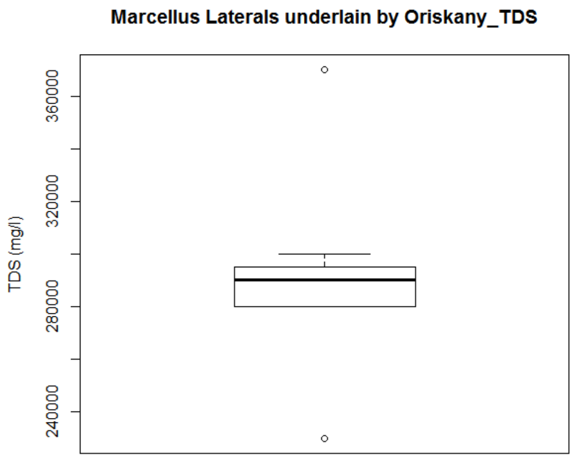


Figure 3-39. TDS in Marcellus laterals underlain by Oriskany

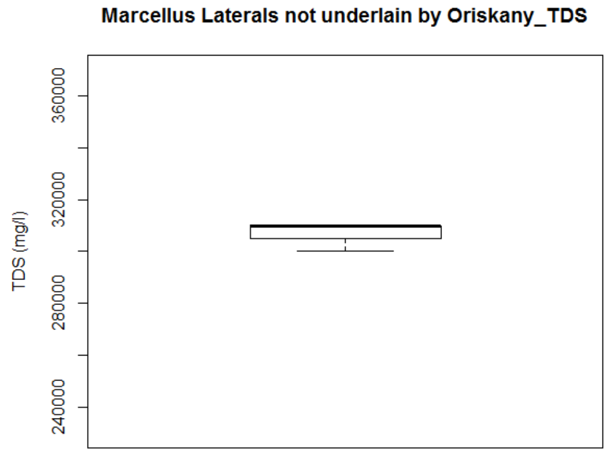


Figure 3-40. TDS in Marcellus laterals not underlain by Oriskany

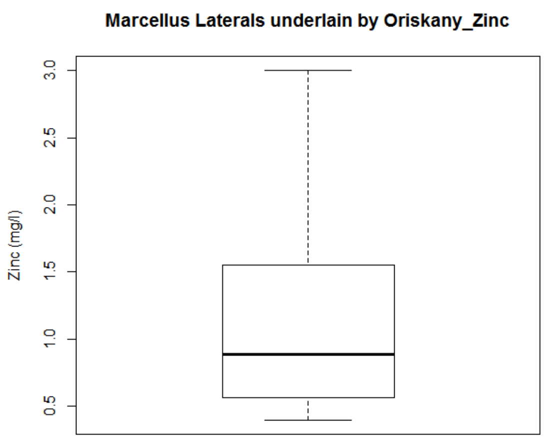


Figure 3-41. Zinc in Marcellus laterals underlain by Oriskany

3.4 STRUCTURAL COMPLEXITY USING GEOSTEERING DATA

Within the study area, EQT has drilled 28 Marcellus laterals. The structural complexity characteristics of these 28 wells, along with another three wells located just outside of the study area (Redbank and Wedekind Pads), were calculated and included in the structural complexity dataset (Table 3-4).

Of the Marcellus lateral well pads that are underlain by the Oriskany Sandstone, structural complexity is greatest at the Longhorn C Pad, followed by the Whippoorwill Pad, then Turkey Pad and lowest at the Horizon and Frano Pads. Of the Marcellus lateral well pads where the Oriskany Sandstone is absent, structural complexity is greatest at the Monarch Pad, followed by the Redbank Pad, and then Wedekind Pad. Laterals with the greatest structural complexity include Longhorn C laterals590846, 590845, 590842, followed by Whippoorwill lateral 590876, and finally Monarch laterals 591763 and 591762. Longhorn C lateral 590846 has an unusually high normalized total relief value of 46.73. This is due to a TVD change of 140 feet that occurs over a three-foot interval due to a fault.

Table 3-4. Summary of completions, production, and structural complexity results

Pad Name	Well	Gas and Water Sampled	COMPLETIONS DATA		PRODUCTION DATA			STRUCTURAL COMPLEXITY			
			Average FBP/ Average Onondaga Lateral TVD (kPa/m)	% Fluid Recovered	Month 2-7 Gas Volume / Treated Lateral Length (mmcf/m)	Month 2-7 Water Volume/ Treated Lateral Length (bbls/m)	Month 2-7 Gas to Water Ratios	Length Normalized Relief	Length Normalized Dip Range	Length Normalized Inflections	Length Normalized Faults
Marcellus Shale Laterals underlain by Oriskany Sandstone											
Horizon	591548		19.59	7.62	95.4	9.4	10.1	0.03177	0.00129	0.00701	0
	591549	x	18.97	5.99	161.9	16.9	9.6	0.04014	0.00085	0.00545	0
	591668	x	19.24	4.19	140.1	17.8	7.9	0.03708	0.00082	0.00476	0
	591669		19.09	6.19	177.8	12.5	14.2	0.01031	0.00169	0.00514	0
	591667		19.31	5.75	79.3	8.8	9.0	0.02406	0.00154	0.00758	0
	591970	x	18.37	3.53	140.2	10.7	13.1	0.01926	0.00084	0.01010	0
	591670		18.15	6.02	66.5	9.9	6.7	0.05793	0.00136	0.01049	0.00045
Frano	590516	x	19.83	2.73	503.4	7.3	69.0	0.03605	0.00160	0.00513	0
	591718		20.59	4.05	436.9	11.8	37.1	0.01927	0.00190	0.00625	0.00063
	590515	x	20.49	2.80	461.8	7.9	58.4	0.02364	0.00380	0.02135	0.00095
Turkey	590983	x	21.53	2.38	254.8	13.1	19.5	0.05445	0.00959	0.03266	0.00683
	590985		20.31	3.16	247.5	12.4	19.9	0.21631	0.00550	0.01533	0
	591240		19.81	3.20	220.0	16.2	13.6	0.13449	0.00483	0.01375	0
	591242		20.46	4.26	36.0	6.6	5.5	0.14053	0.01378	0.06444	0.00686
	591244		20.59	2.73	183.1	9.5	19.4	0.07102	0.00380	0.01188	0.00430
Whipporwill	590876	x	20.13	5.00	188.0	20.5	9.2	0.19302	0.00907	0.05617	0.00897
	590873		21.84	11.06	95.9	20.7	4.6	0.08192	0.00583	0.04594	0.00312
	590877		20.82	4.80	231.6	24.1	9.6	0.14855	0.01364	0.06966	0.00596
	590878		21.47	15.76	136.5	17.7	7.7	0.19731	0.00797	0.02832	0.00612
Longhorn C	590842		20.71	5.27	NP	NP	NP	0.20965	0.01178	0.07835	0.04250
	590846		20.32	8.36	NP	NP	NP	46.73000	0.01836	0.06666	0.07570
	590845		20.40	4.31	NP	NP	NP	0.41561	0.01458	0.06036	0.01563
	590844		20.95	8.20	NP	NP	NP	0.02510	0.00279	0.01039	0.01968
Marcellus Shale Laterals not underlain by Oriskany Sandstone											
Wedekind	590389	x	20.58	5.39	58.6	25.1	2.3	0.01419	0.01517	0.05083	0
Monarch	591155	x	21.22	4.87	79.7	15.4	5.2	0.10196	0.01020	0.07804	0.00551
	591156		20.18	2.87	75.2	18.4	4.1	0.16679	0.00596	0.04839	0.01077
	591593		20.10	4.60	52.4	13.4	3.9	0.14749	0.00917	0.06047	0.00314
	591762		19.58	4.56	67.8	19.0	3.6	0.14963	0.01132	0.08996	0.00334
	591763		19.89	3.41	179.8	19.9	9.0	0.18302	0.01059	0.05695	0.02123
Redbank	590370	x	20.61	5.18	211.3	11.7	18.1	0.03840	0.01021	0.06435	0.00754
	590373		18.09	4.98	229.8	9.9	23.1	0.01509	0.01289	0.04588	0.00482
Hurd	590383				291.3	8.2	35.6				
	590398				275.9	9.6	28.7				
	590399				263.3	8.1	32.6				
	591186				396.6	7.2	55.3				
Huey	590561				52.7	5.4	9.7				
	590562				32.3	3.1	10.4				

NP = not produced

3.5 FORMATION BREAKDOWN PRESSURE

The average formation breakdown pressures ranged from 32,254 kPa in Wedekind lateral 590389 to 47,422 kPa in Turkey lateral 590983 (Table 3-4). Formation breakdown pressure is affected by depth (Figure 2-6). The depth normalized average of the average formation breakdown pressures from Marcellus laterals where the Oriskany is present is 20.13 kPa/m, n = 23. The depth normalized average of the average formation breakdown pressures from Marcellus laterals where the Oriskany is not present is 20.03 kPa/m, n = 8). This difference is not statistically significant (two-tailed t-test, p = 0.80). When comparing the Marcellus laterals with Oriskany to Marcellus laterals without Oriskany, the ratio of the depth normalized average of the average formation breakdown pressures is 1.005.

3.6 PERCENT FLUID RECOVERED DURING FLOWBACK

The percentage of fluid recovered during flowback ranges from 2.38% in well 590983 on the Turkey pad to 15.76% on lateral 590878 on the Whippoorwill Pad (Table 3-4). The average percent fluid recovered from Marcellus laterals where the Oriskany is present is 5.54%, n =23. The average percent fluid recovered from Marcellus laterals where the Oriskany is not present is 4.48%, n = 8. When comparing the Marcellus laterals with Oriskany to Marcellus laterals without Oriskany, the ratio of the average percentage of fluid recovered is 1.24. However, the averages are not significantly different, (two-tailed t-test, p = 0.15). However, given the small sample size and the variability in these measurements, this difference may become significant with a larger sample.

3.7 MARCELLUS SHALE LATERAL WELL GAS AND WATER PRODUCTION

In the study area, Marcellus laterals completed in areas underlain with Oriskany (n = 19) produce an average of 1.25 times more gas and 1.04 times more water compared to Marcellus laterals that are not underlain by the Oriskany (n = 14) (Table 3-4, Figures 3-42 and 3-43). As a point of reference, EQT's Marcellus laterals completed in North Central Pennsylvania (n = 27) produce on average 0.22 times less gas and 1.25 times more water compared to EQT's Marcellus laterals completed in Greene County, PA (n = 274). Production data in figures 3-42 and 3-43 have been normalized to the values in the "North Central Pennsylvania w/ Oriskany" group.

Marcellus laterals completed in areas underlain with Oriskany produced an average of 203.0 mmcf of gas per lateral meter over months 2-7 of production, whereas Marcellus laterals completed in areas that are not underlain with the Oriskany produced an average of 161.9 mmcf of gas per lateral meter over months 2-7 of production. This difference is not significant (two-tailed t-test, p = 0.35). The average mmcf of gas produced per lateral meter over months 2-7 of production for Greene County, PA is 840.8, which is significantly different than the average mmcf of gas produced per lateral meter over months 2-7 of production of 185.6 for all Marcellus laterals in North Central Pennsylvania (two-tailed t-test, $p = 9.2 \times 10^{-42}$).

Marcellus laterals completed in areas underlain with Oriskany produced an average of 13.4 barrels of water per lateral meter over months 2-7 of production, whereas Marcellus laterals completed in areas that are not underlain with the Oriskany produced an average of 12.5 barrels of water per lateral meter over months 2-7 of production. This difference is not significant (two-tailed t-test, $p = 0.66$). The average barrels of water produced per lateral meter over months 2-7 of production for Greene County, PA is 10.37, which is significantly different than the average barrels of water produced per lateral meter over months 2-7 of production of 13.0 for all Marcellus laterals in North Central Pennsylvania (two-tailed t-test, $p = 0.016$).

A gas to water ratio was also calculated. The average gas to water ratio over months 2-7 of production for the “North Central Pennsylvania w/ Oriskany” group is 18.1, the average ratio over months 2-7 of production for the “North Central Pennsylvania w/out Oriskany” group is 17.3 (Table 3-4 and Figure 3-44). This difference is not significant (two-tailed t- test, $p = 0.89$). The gas to water ratio over months 2-7 of production for Greene County, PA is 121.6, which is significantly different than the average ratio over months 2-7 of production of 17.75 for all Marcellus laterals in North Central Pennsylvania (two-tailed t-test, $p = 4.2 \times 10^{-14}$).

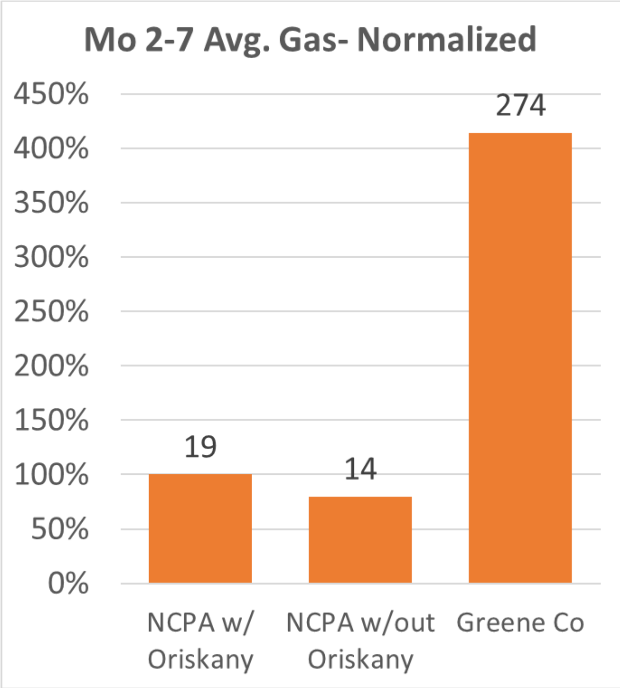


Figure 3-42. Gas production total volumes, normalized to NCPA w/ Oriskany group

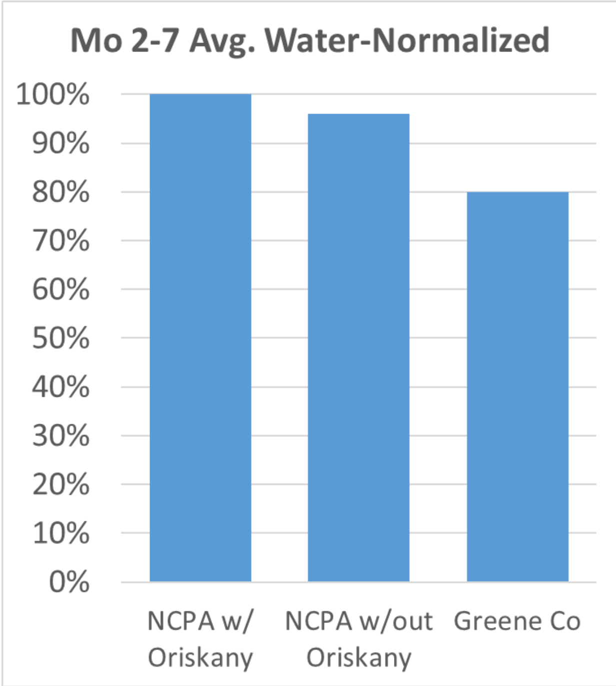


Figure 3-43. Water production total volumes, normalized to NCPA w/ Oriskany group

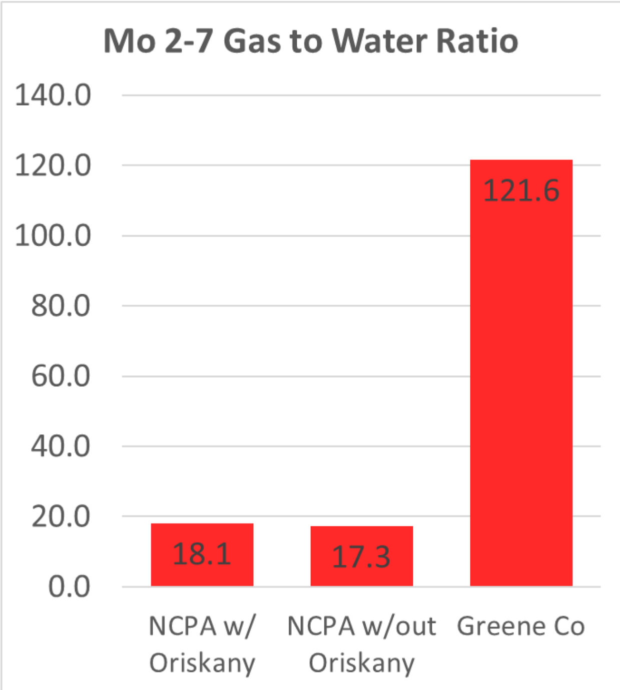


Figure 3-44. Gas-to-water production ratios

3.8 STRUCTURAL COMPLEXITY VERSUS WELL CHARACTERISTICS

The step-wise regression of the four length normalized measurements of structural complexity mentioned in Section 2.3 (total relief, bed dip range, sum of inflections points of at least 0.5 degrees or more, and sum of faults of at least 2 feet or greater) was determined based on 27 well characteristics ranging from completions data, to production data, to water chemistry and isotopes. The model for some of the well characteristics worked best with only one measurement of structural complexity, while other models used two, three, or even all four structural complexity measurements (Table 3-5). Total relief most frequently explained the greatest amount of variability, followed by bed dip range, then sum of inflection points, and finally sum of faults.

Table 3-5. Step-wise regression modeling of structural complexity

Model	AIC	Multiple R-squared	p-value	Modeled Structural Complexity Equation
EUR Model	328.38	0.308	0.01207	= -2106.2(Total.Relief) - 6173.8(Norm.Inflections) + 1187.1
6 Month Produced Gas Model	195.08	0.1307	0.06392	= -505.91(Norm. Inflections) + 71.48
6 Month Produced Water Model	21.55	0.2031	0.01831	= 26.496(Norm.Inflections) + 3.4649
Average Formation Breakdown Pressure Model	-78.68	0.1251	0.05096	= 19.52048(Norm.Dip.Range) + 5.98881
Percent Fluid Recovered Model	NA	NA	NA	unable to model
Barium Model	153.69	0.6371	0.02879	= -116438.9(Norm.Inflections) + 768745.0(Norm.Faults) + 6081.2
Bromide Model	109.68	0.8347	0.009248	= 8140.3(Total.Relief) + 42659.6(Norm.Dip.Range) - 61147.0(Norm.Faults) + 1082.8
Calcium Model	161.89	0.9174	0.00646	= 117039(Total.Relief) + 592144(Norm.Dip.Range) + 107649(Norm.Inflections) - 1159236(Norm.Faults) + 19403
Chloride Model	195.19	0.4723	0.02809	= 261325(Total.Relief) + 148413
Copper	NA	NA	NA	not enough data to run model
Iron Model	64.19	0.6465	0.02627	= 539.54(Total.Relief) - 764.18(Norm.Inflections) + 124.71
Lead	NA	NA	NA	not enough data to run model
Lithium Model	60.91	0.7177	0.001977	= 534.488(Total.Relief) + 161.165
Magnesium Model	113.64	0.7088	0.002247	= 75693.1(Norm.Dip.Range) + 1869.6
Manganese Model	16.78	0.8144	0.002755	= 63.046(Total.Relief) + 184.501(Norm.Dip.Range) + 6.234
Potassium Model	NA	NA	NA	unable to model
Sodium Model	163.54	0.3493	0.07197	= -430780(Norm.Dip.Range) + 57077
Strontium Model	136.63	0.587	0.009758	= 258172.5(Norm.Faults) + 6050.5
Zinc Model	-3.23	0.8419	0.01906	= 30.4757(Total.Relief) + 675.3974(Norm.Dip.Range) - 883.7394(Norm.Faults) - 0.9126
TDS Model	204.2	0.6262	0.03194	= 407751(Total.Relief) + 2199742(Norm.Dip.Range) + 259570
Sulfate	NA	NA	NA	not enough data to run model
Specific Gravity Model	-63.71	0.6926	0.05571	= -0.83034(Total.Relief) - 5.98226(Norm.Dip.Range) + 2.65621(Norm.Inflections) + 1.14617
Total Alkalinity Model	65.47	0.3005	0.1009	= -276.03(Total.Relief) + 110.41
Specific Conductance Model	177.66	0.2081	0.1851	= 115544(Norm.Inflections) + 202200
pH Model	-21.6	0.4901	0.02419	= -5.3098(Total.Relief) + 5.6164
δD Isotope Model	NA	NA	NA	unable to model
δO Isotope Model	-7.82	0.2923	0.1066	= 6.9316(Total.Relief) - 2.7129

Yellow highlighting indicates R-squared of 0.5 or greater
Green higlighting indicates p-value of 0.05 or smaller

3.8.1 Structural Complexity versus Depth Normalized Formation Breakdown Pressure

Of the four structural complexity characteristics, a laterals' length normalized dip range is most strongly associated with the depth normalized average formation breakdown pressures (Figure 3-45). Depth normalized average formation breakdown pressure increases as structural complexity increases in both laterals underlain by the Oriskany and laterals not underlain by the Oriskany. The Akaike information criterion, R-squared, p-value, and equation of this model are listed in Table 3-5.

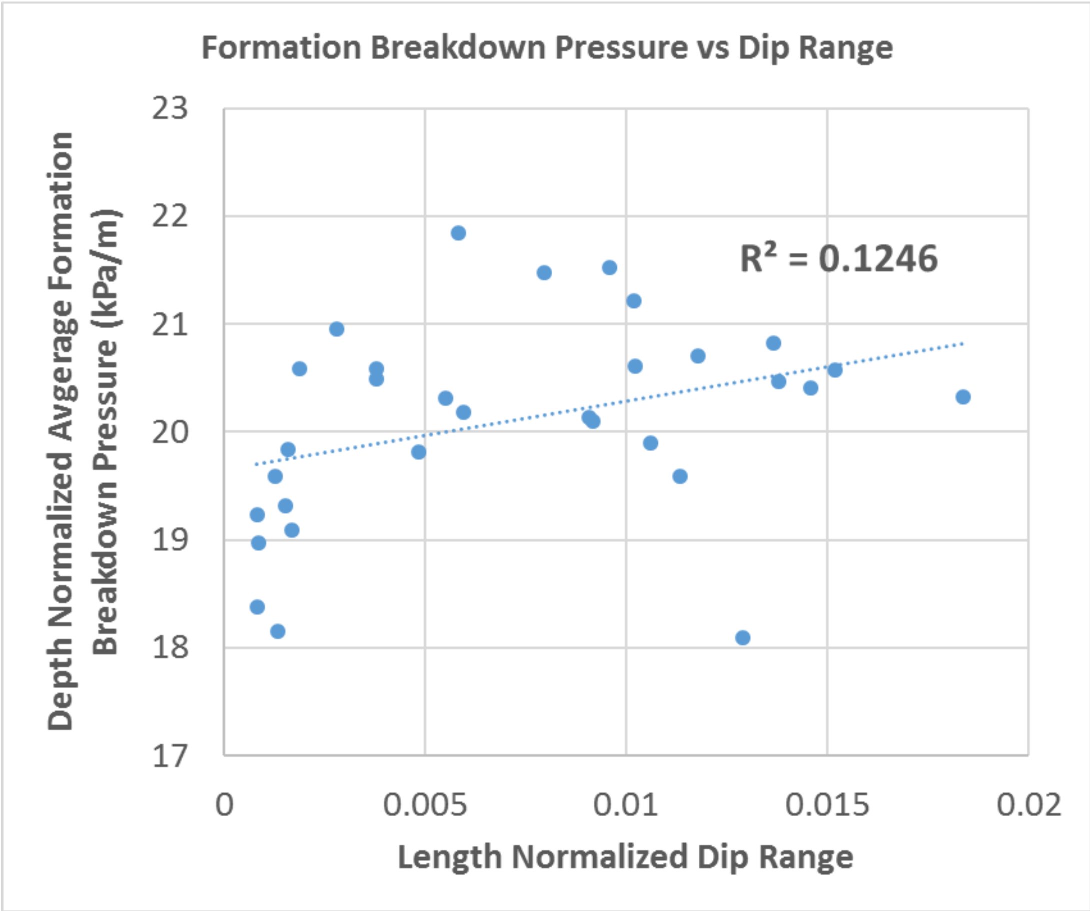


Figure 3-45. Depth normalized average formation breakdown pressure during completions versus structural complexity

3.8.2 Structural Complexity versus Percent Fluid Recovered

A laterals' percent fluid recovered was not associated with any of the four structural complexity characteristics. This suggests that structural complexity of a lateral does not influence the proportion of fluid recovered in a lateral.

3.8.3 Structural Complexity versus Gas and Water Production

Of the four structural complexity characteristics, a laterals' length normalized sum of inflections is most strongly associated with the laterals' length normalized total gas and total water production over months 2-7 (Figures 3-46 and 3-47). The length normalized total gas production over months 2-7 decreases as structural complexity increases in both laterals underlain by the Oriskany and laterals not underlain by the Oriskany. However, the length normalized total water production over months 2-7 increases as structural complexity increases. The Akaike information criterion, R-squared, p-value, and equation of these models are listed in Table 3-5.

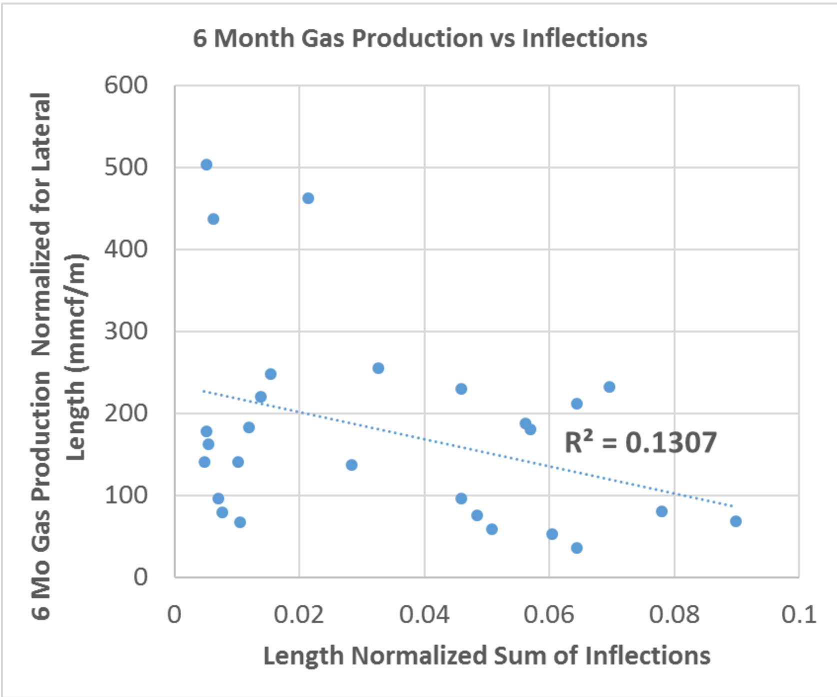


Figure 3-46. Length normalized 6 month gas production versus length-normalized sum of inflections

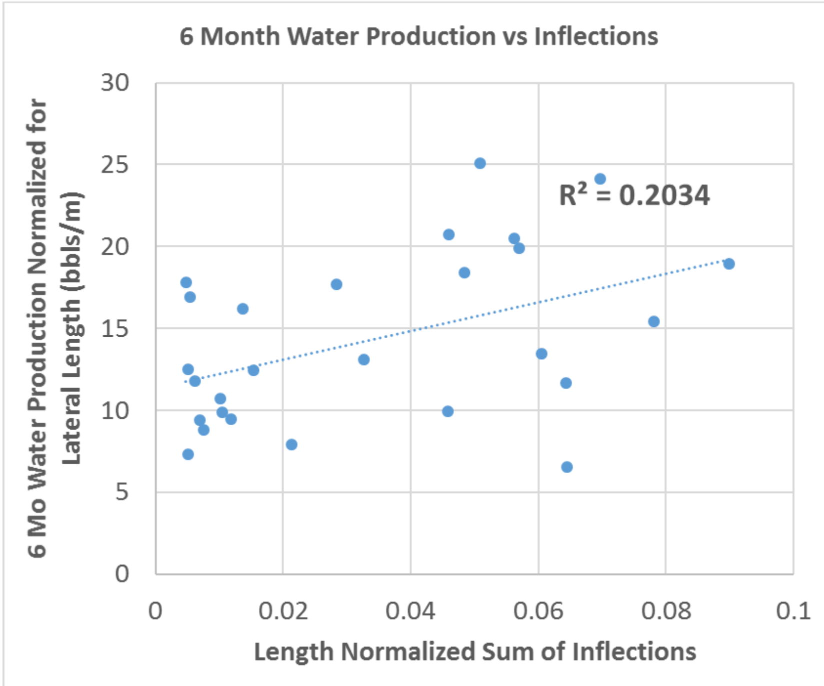


Figure 3-47. Length normalized 6 month water production versus length-normalized sum of inflections

I also used step-wise regression modeling to compare each lateral's structural complexity characteristics with expected gas production normalized to lateral length. A laterals' total relief and the length-normalized sum of inflections best explain the variability in a lateral's expected gas production normalized to lateral length. The Akaike information criterion, R-squared, p-value, and equation of this model (labeled as EUR Model) are listed in Table 3-5.

3.8.4 Structural Complexity Correlated with Produced Water Chemistry

Next, using step-wise regression modeling Marcellus lateral produced water chemical concentrations were compared to each of the four structural complexity characteristics (Figures 3-48 through 3-53). The model for some produced water chemical concentration data worked best with only one measurement of structural complexity, while other models used two, three, or even all four structural complexity measurements to best explain variability in produced water chemical concentrations. The Akaike information criterion, R-squared, p-value, and equation of these model are listed in Table 3-5.

Produced water concentrations of all of the analytes, except for pH and sodium, increase as structural complexity increases. The step-wise regression model was unable to model potassium and hydrogen isotopes. Not enough data was available for sulfate, copper, or lead to run the model (due to non-detect results).

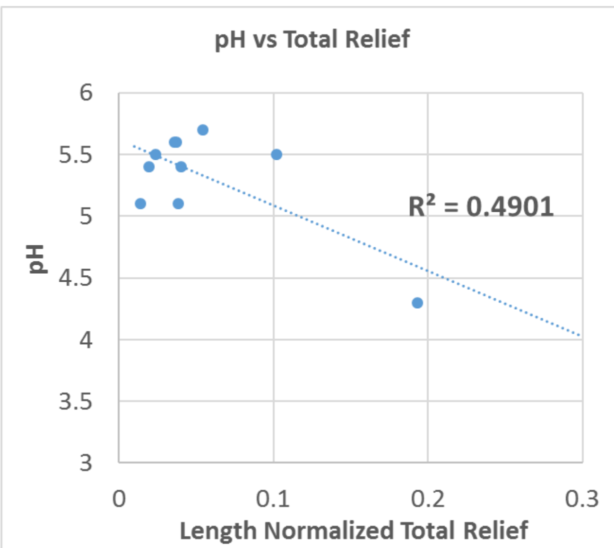


Figure 3-48. pH versus length-normalized total relief

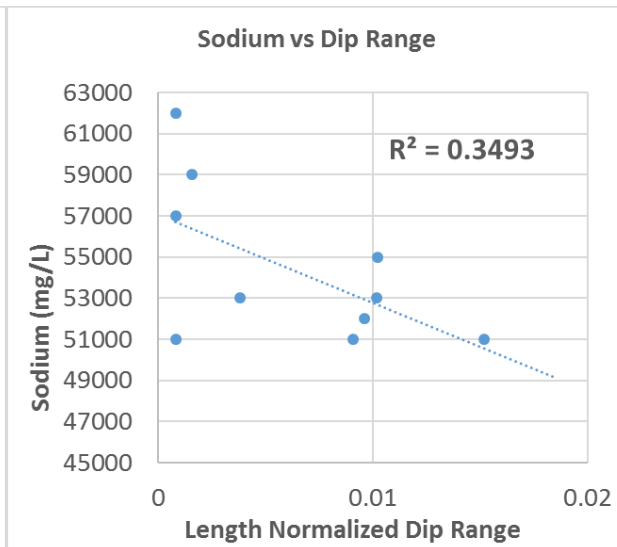


Figure 3-49. Sodium versus length-normalized dip range

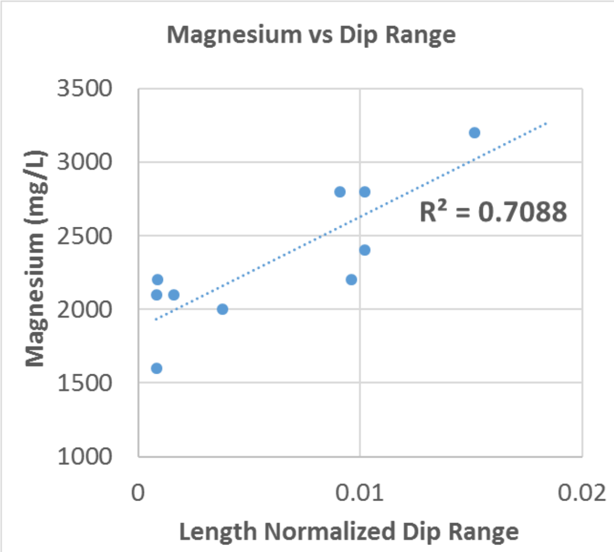


Figure 3-50. Magnesium versus length-normalized dip range

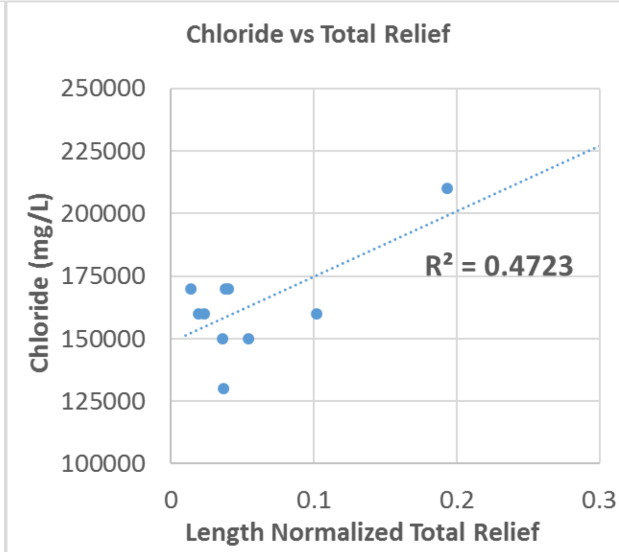


Figure 3-51. Chloride versus length-normalized total relief

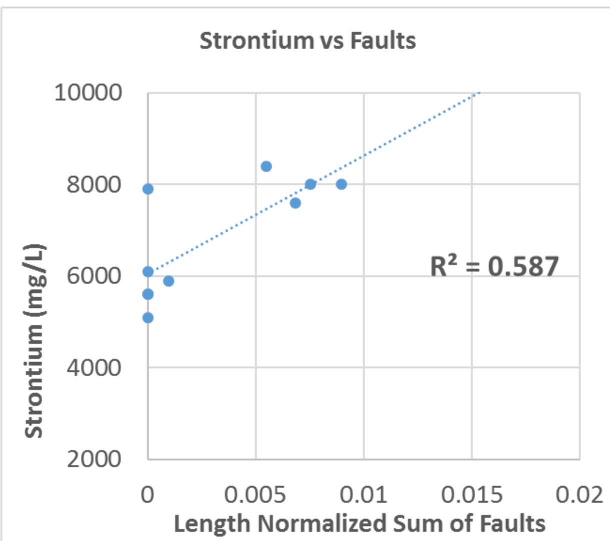


Figure 3-52. Strontium versus length-normalized sum of faults

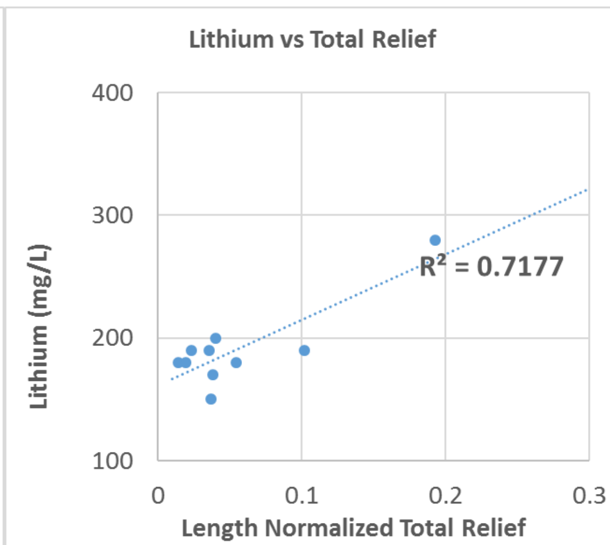


Figure 3-53. Lithium versus length-normalized total relief

It is possible that solute concentrations increase with greater structural complexity because structural complexity implies that a wellbore may be exposed to a greater degree of mineralized fractures and faults. It could be possible that these fractures or faults may even be capable of transmitting fluids. For example, historic manganese levels in Oriskany water in North Central Pennsylvania are not available. However, a USGS report by Force and Cox (1991) details elevated manganese in the Ridgeley and Helderberg in Northwest Virginia, where the Ridgeley outcrops and manganese mines are common.

4.0 DISCUSSION

4.1 SAMPLE LIMITATIONS FOR MARCELLUS SHALE LATERAL WELLS IN THE PRESENCE/ABSENCE OF THE ORISKANY SANDSTONE IN NORTH CENTRAL PENNSYLVANIA

Marcellus laterals in North Central Pennsylvania have higher overall TDS in flowback and produced waters and lower overall gas production than other areas of the Appalachian Basin (A. Douds, pers. comm., 2015), particularly Southwestern Pennsylvania. Many of EQT's Marcellus lateral wells in North Central Pennsylvania are underlain by the Oriskany Sandstone, the historical target of vertical gas drilling. EQT's Marcellus lateral wells in North Central Pennsylvania also often encounter a significant amount of structure, such as faulting and significant bed dips changes over short distances. This leads to the underlying question in this research, does drilling and hydraulic fracturing of Marcellus laterals in North Central Pennsylvania create or enhance connections between Marcellus laterals the deeper Oriskany Sandstone? This research identified characteristics of completions activities and/or production that can be used to maximize hydrocarbon recovery and minimize brine recovery from future Marcellus lateral wells drilled in North Central Pennsylvania.

In the North Central Pennsylvania study area, EQT has drilled 23 Marcellus laterals that are underlain by the Oriskany Sandstone and five Marcellus laterals that are not underlain by the Oriskany sandstone. Four of the 23 Marcellus laterals that are underlain by the Oriskany sandstone are not producing, so production data and water samples were not available for this well pad (Longhorn C). Additional data were added by including laterals outside of the study area, and published water chemistry data. The resulting datasets remained relatively small (i.e., 3-31 data points in most sets). This relatively small sample size raises the challenges of statistics of small samples, and limits statistical inference. For example, significance tests often failed (i.e. p-values were greater than an alpha of 5%). However, the nature of gas production and the remaining uncertainty in this new frontier in hydrocarbon production limits our ability to build datasets that adequately sample the realm of possibilities. The analytical framework developed here provide a means to continue examination of these questions as additional wells are developed and data are collected.

4.2 ORISKANY SANDSTONE PRESENCE AND MARCELLUS SHALE LATERAL WELL CHARACTERISTICS

4.2.1 Well Completions

Formation breakdown pressures and percent of fluid recovered during flowback were examined to determine the influence of the presence/absence of the Oriskany Sandstone (generally within 7-26 meters by depth) of the Marcellus Shale laterals on lateral well completions. I would expect that the presence of the Oriskany Sandstone under the Marcellus laterals might cause formation breakdown pressure to be lower overall and that the percent of fluid recovered during flowback would be greater than in Marcellus laterals that are not underlain by the Oriskany. However, the depth normalized average formation breakdown pressures generated when hydraulically fracturing and the percent of fluid recovered after hydraulically fracturing are not statistically different in Marcellus laterals completed where the Oriskany Sandstone is present compared to laterals completed where the Oriskany is absent. The formation breakdown pressures confirm that these pressures clearly correlate with depth below the ground surface (Figure 2-6), but no trends could be attributed to the Oriskany Sandstone. The formation breakdown pressures and percent of fluid recovered data do not support the hypothesis that Marcellus laterals in the study area are influenced by hydraulic connection with the Oriskany Sandstone.

4.2.2 Production Volumes

Gas and water production data were examined to evaluate effect of the Oriskany sandstone on lateral well production. Because gas production from Marcellus laterals in North Central Pennsylvania is lower than gas production from Marcellus laterals in Southwestern Pennsylvania I was expecting that the presence of the historic Oriskany vertical wells in North Central Pennsylvania might be affecting gas and water production volumes. Production data reveal that 1.25 times more gas and 1.04 times more water (when normalized by lateral distance) is produced from Marcellus laterals that are underlain by the Oriskany Sandstone than by Marcellus laterals that are not underlain by the Oriskany Sandstone. Statistical testing of the difference in these data sets indicates that the differences are not significant. However the 25% excess in the gas production from Marcellus laterals that are underlain by the Oriskany compared to Marcellus laterals in areas without the Oriskany is substantial. More production data from Marcellus laterals near the study area would be useful to further constrain the uncertainties and determine effects of the Oriskany Sandstone on production volumes. For comparison, production data did clarify that North Central Pennsylvania Marcellus laterals produce 0.22 times less gas and 1.25 times more water than Greene County Pennsylvania Marcellus laterals, both of which are statistically significant. Overall, differences in production volumes between Marcellus laterals underlain with the Oriskany Sandstone and Marcellus laterals where the Oriskany Sandstone is absent do not provide conclusive evidence that the Marcellus laterals are hydraulically connected with the Oriskany Sandstone.

4.2.3 Produced Water Chemistry

Produced water chemical data was also examined to identify influences of the Oriskany Sandstone on Marcellus laterals. The oxygen and hydrogen isotopes of produced Marcellus water from laterals that are not underlain by the Oriskany Sandstone vary over a relatively small range. The oxygen and hydrogen isotopes of produced Marcellus water from laterals that are underlain by the Oriskany Sandstone plot over a wider range, and may indicate mixing with Oriskany produced water, which is more enriched in the heavier isotopes of oxygen and hydrogen. If mixing is indeed happening, this would be clear evidence that the Marcellus laterals are hydraulically connected with the Oriskany Sandstone. A major limitation at this time is that it is difficult to collect Oriskany produced water (e.g. note the length taken in this project, Section 2.2.1.3) and there is very limited published isotopic analysis of Oriskany produced waters.

There is some variation in the produced water chemistry from Marcellus laterals underlain by Oriskany and Marcellus laterals not underlain by the Oriskany (Table 3-3). The concentrations of barium and iron are greater and the concentrations of calcium, magnesium, and zinc are reduced in production water from Marcellus lateral wells underlain by the Oriskany Sandstone relative to production water from Marcellus lateral wells not underlain by the Oriskany Sandstone. These differences in the produced water chemistry from Marcellus laterals may be attributed to some of the Marcellus produced water originating in the Oriskany Sandstone. Characterizing produced water chemistry on a regional basis may be helpful in optimizing well production equipment and produced water treatment and disposal.

Together, the water isotope and water chemistry data sets suggest that there are some differences in the produced water from Marcellus laterals underlain by the Oriskany Sandstone, produced water from Marcellus laterals not underlain by the Oriskany Sandstone, and produced water from the Oriskany Sandstone. However, due to the small data sets and the uncertainty in determining the end members of each formation, it is difficult to demonstrate statistically, particularly given the error associated with most samples can nearly as large as the difference between mean behavior in the sample sets. Regardless, if we assume that the data reflect actual differences, water (and gas) from the Oriskany Sandstone may be migrating to Marcellus laterals. This would imply that the Marcellus Shale is hydraulically connected with the Oriskany Sandstone in North Central Pennsylvania. In areas of high structural complexity, like North Central Pennsylvania, the Onondaga Limestone may not be an effective seal from deeper formations such as the Oriskany Sandstone.

4.3 STRUCTURAL COMPLEXITY AND MARCELLUS SHALE LATERAL WELL CHARACTERISTICS IN NORTH CENTRAL PENNSYLVANIA

While the findings of the evaluation of the presence/absence of the Oriskany Sandstone remains somewhat ambiguous, the systematic evaluation of structural complexity revealed important connections between geologic structure and well behavior. I defined the 'structural complexity' index to capture a suite of characteristics encountered during lateral drilling. Quantitatively defining the degree of structural complexity that a lateral encounters is important as it can be used to infer processes influencing the production of the well and the chemistry of the produced water. The regional structure in North Central Pennsylvania is highly variable (e.g., geosteering profiles and the top of the Onondaga Limestone structural map (Figures 2-3, 2-5, and 3-1)). Step-wise regression models indicate that the length-normalized sum of inflection points best explains gas and water production volumes (Table 3-5). In contrast, length-normalized dip range is most strongly associated with depth normalized average formation breakdown pressures. A combination of length-normalized total relief and inflections explains the variability in expected normalized gas production. The normalized dip range, or variability of bed dips throughout a lateral may suggest a significant difference exists between the orientation of the wellbore and the dip of the formation, as this would increase formation breakdown pressure. Likewise, normalized sum of inflection points and normalized total relief may indicate the presence of fractures that are not normally detected without image logging, which is rarely performed in Marcellus lateral wells, as these fractures would certainly effect on gas and water production volumes.

All four measures of structural complexity explain produced water chemistry from Marcellus lateral wells, however, the importance of these measures varies: Length-normalized total relief > length-normalized dip range > length-normalized sum of inflection points ~length-normalized sum of faults. Because large faults are easily detected when geosteering, I had expected that length-normalized sum of faults would have a greater influence on water chemistry. However, using the data available from the comparison of areas with and without Oriskany Sandstone, we cannot assume that faults in North Central Pennsylvania are able to transmit gas or water. One potential explanation as to why length normalized total relief is having the greatest influence on produced water chemistry is that changes in the relief of formation horizons imply that a significant amount of stress and deformation has occurred across an interval of rock, that may have created a high frequency of fractures. Therefore mineralization and/or movement of solute laden fluids may occur in or across the fractures. The greater the length-normalized relief, the greater likelihood of fractures that are not detected by geosteering interpretations. A lateral that has a significant about of fracturing could indicate an increase in hydraulic connectivity, causing the formation to act like a sump and increasing the influence on produced water chemistry. These results remain preliminary, but warrant continued examination as data sets grow with future extraction efforts.

The step-wise regression models explain the variability in the chemical concentration of 13 out of 17 solutes analyzed in Marcellus produced water chemistry (p-values range from 0.55 to 0.002 and R-squares range from 0.47 to 0.92 (Table 3-5). The decrease of both pH and total alkalinity with increasing structural complexity may mean that more flushing is occurring through the Marcellus Shale by a relatively fresher water. Furthermore, the decrease in sodium would indicate that the Marcellus produced water becomes diluted with increasing structural complexity, and the increased water flux. Ultimately, these influences likely require additional data on potential source waters (i.e., more Oriskany brine chemistry data) to clarify the influence of structural complexity on produced water chemistry.

5.0 CONCLUSION

The presence or absence of the Oriskany Sandstone seems to have relatively minimal effects on Marcellus lateral well characteristics in North Central Pennsylvania. Small sample sets were a challenge in the analyses. Continued analysis of future data collection may clarify effects.

However, the systematic comparison of structural complexity with lateral well completion, production, and water chemistry is a fruitful framework. There is a systematic variation between structural complexity and both Marcellus lateral completion parameters and well production in North Central Pennsylvania. As structural complexity increases, the depth normalized average formation breakdown pressures increase slightly. As structural complexity increases, produced gas volumes decrease and produced water volumes increase. As structural complexity increases, solute concentrations of Marcellus produced water frequently increase, although the concentrations of a few analytes (pH, sodium, and total alkalinity) decrease with structural complexity. Observed structural complexity as quantified from the geosteering data of laterals may reflect the degree at which the formation, in this case the Marcellus Shale, is hydraulically connected to other formations.

APPENDIX A

GAS ISOTOPE RESULTS

Gas isotopic compositions were measured in Marcellus Shale and Oriskany Sandstone produced water grab samples collected in the study area (Table A1).

Table A 1. Results of natural gas samples

Sample Name	Sample Date	GC Date	He %	H_2 %	Ar %	O_2 %	CO_2 %	N_2 %	CO %	C_1 %	C_2 %	C_2H_4 %	C_3 %	C_3H_6 %
HORIZONTAL WELLS														
Horizon_591970	9/12/2016	9/26/2016	0.0168	nd	nd	0.012	0.093	0.24	nd	96.70	2.80	nd	0.122	nd
Horizon_591668	9/12/2016	9/26/2016	0.0165	nd	nd	0.025	0.099	0.27	nd	96.56	2.89	nd	0.126	nd
Horizon_591549	9/12/2016	9/26/2016	0.0174	nd	0.0053	0.065	0.098	0.40	nd	96.32	2.95	nd	0.131	nd
Frano_590515	9/12/2016	9/26/2016	0.0155	0.0151	0.0100	0.18	0.12	0.80	nd	95.86	2.88	nd	0.110	nd
Frano_590516	9/12/2016	9/26/2016	0.0167	0.0157	0.0057	0.083	0.10	0.49	nd	96.16	3.00	nd	0.119	nd
Turkey_590983	9/13/2016	9/27/2016	0.0199	nd	nd	0.013	0.15	0.32	nd	97.02	2.38	nd	0.0882	nd
Whipporwill_590876	9/13/2016	9/27/2016	0.0201	0.0114	0.0050	0.089	0.053	0.63	nd	96.67	2.42	nd	0.0934	nd
Monarch_591155	9/12/2016	9/26/2016	0.0180	0.0233	nd	0.044	0.039	0.38	nd	94.87	4.25	nd	0.313	nd
Wedekind_590389	9/12/2016	9/26/2016	0.0232	0.0304	0.0128	0.26	0.042	1.30	nd	74.68	15.84	nd	5.26	nd
Red Bank_590370 (2)	9/12/2016	9/27/2016	0.0169	0.0316	0.0311	0.78	0.059	3.09	nd	88.63	6.44	nd	0.716	nd
Red Bank_590370_2 (3)	9/12/2016	9/27/2016	0.0168	0.0321	nd	0.029	0.059	0.34	nd	91.90	6.67	nd	0.741	nd
ECA-CSB-5	2/22/2017	3/1/2017	0.0237	2.46	0.0121	0.25	nd	1.04	nd	94.07	2.05	nd	0.0852	nd
ECA-CS-3	2/22/2017	3/1/2017	0.0229	0.131	0.0051	0.093	nd	0.55	nd	97.19	1.93	nd	0.0698	nd
ECA-CS-1	2/22/2017	3/1/2017	0.0239	0.0460	0.0123	0.26	0.037	1.18	nd	96.69	1.69	nd	0.0578	nd
VERTICAL WELLS														
Oriskany_591057	9/13/2016	9/27/2016	0.0167	nd	0.261	6.34	0.13	22.84	nd	68.70	1.65	nd	0.0555	nd
Oriskany_591034	9/13/2016	9/27/2016	0.0263	nd	0.0289	0.68	0.11	3.45	nd	93.82	1.83	nd	0.0510	nd
Oriskany_591060	9/14/2016	9/27/2016	0.0127	nd	0.500	11.46	0.068	41.22	nd	45.70	0.997	nd	0.0333	nd
Oriskany_591023	9/14/2016	9/27/2016	0.0200	nd	0.0801	2.26	0.12	8.37	nd	87.10	1.96	nd	0.0799	nd
Oriskany_591055	9/14/2016	9/27/2016	0.0216	nd	nd	0.054	0.12	0.47	nd	97.13	2.11	nd	0.0812	nd
Oriskany_591059 (1)	9/14/2016	9/28/2016	0.0244	0.0586	0.723	16.63	0.059	59.66	nd	22.12	0.646	nd	0.0547	nd
Oriskany_591069	9/14/2016	9/28/2016	0.0242	0.0114	0.0174	0.36	0.15	1.76	nd	95.78	1.83	nd	0.0586	nd
Oriskany_591099	9/14/2016	9/28/2016	0.0233	0.0595	0.0214	0.50	0.25	2.12	nd	94.42	2.51	nd	0.0858	nd
ECA-COP2	2/22/2017	3/1/2017	0.0218	0.0188	0.0062	0.11	0.11	0.65	nd	97.05	1.97	nd	0.0614	nd
ECA-COP6	2/22/2017	3/1/2017	0.0206	nd	0.0102	0.17	0.086	1.99	nd	95.70	1.93	nd	0.0810	nd

All samples collected at wellhead, unless noted.
All gas component carbon isotope values are reported on a scale defined by a two point calibration of LSVEC and NBS 19.
1 - After analysis, determined this well had been converted from Oriskany to a shallow sand well in 1999.
2 - Sample collected after separator.
3 - Propane concentration too low for $\delta^{13}C$ analysis.
nd = not detected
na = not analyzed

Table A 1. (continued)

Sample Name	iC_4 %	nC_4 %	iC_5 %	nC_5 %	C_6+ %	MS Date	$\delta^{13}C_1$ ‰	δDC_1 ‰	$\delta^{13}C_2$ ‰	$\delta^{13}C_3$ ‰	Specific Gravity	BTU
HORIZONTAL WELLS												
Horizon_591970	0.0022	0.0083	0.0005	0.0004	0.0001	10/4/2016	-36.47	-167.5	-42.22	-43.45	0.571	1034
Horizon_591668	0.0023	0.0084	0.0004	0.0004	0.0001	10/4/2016	-36.31	-163.7	-42.26	-43.49	0.571	1034
Horizon_591549	0.0024	0.0089	0.0004	0.0004	0.0001	10/4/2016	-36.54	-167.8	-42.35	-43.64	0.573	1033
Frano_590515	0.0017	0.0062	0.0003	0.0002	nd	10/4/2016	-36.71	-167.2	-42.40	-43.64	0.574	1026
Frano_590516	0.0019	0.0066	0.0003	0.0002	nd	10/4/2016	-36.53	-169.1	-42.33	-43.48	0.573	1032
Turkey_590983	0.0013	0.0051	0.0002	0.0002	nd	10/19/2016	-35.12	-167.3	-40.77	-42.43	0.569	1029
Whipporwill_590876	0.0016	0.0054	0.0003	0.0002	nd	10/19/2016	-36.05	-163.7	-42.14	-43.39	0.570	1026
Monarch_591155	0.0261	0.0292	0.0051	0.0022	0.0023	10/5/2016	-38.26	-172.6	-35.49	-30.03	0.581	1048
Wedekind_590389	0.479	1.31	0.214	0.312	0.232	10/5/2016	-44.69	-216.7	-34.25	-29.94	0.730	1265
Red Bank_590370 (2)	0.0757	0.0869	0.0207	0.0102	0.0119	10/6/2016	-40.04	-177.6	-31.70	-25.71	0.613	1039
Red Bank_590370_2 (3)	0.0783	0.0901	0.0216	0.0106	0.0128	10/6/2016	-40.09	-181.3	-31.70	-25.79	0.599	1077
ECA-CSB-5	0.0016	0.0062	0.0004	0.0003	nd	3/2/2017	-35.33	-167.8	-39.58	na(3)	0.559	1001
ECA-CS-3	0.0010	0.0043	0.0002	0.0002	nd	3/3/2017	-34.68	-166.5	-40.47	na(3)	0.566	1022
ECA-CS-1	0.0009	0.0034	0.0001	0.0001	nd	3/3/2017	-34.71	-167.3	-40.79	na(3)	0.569	1012
VERTICAL WELLS												
Oriskany_591057	0.0014	0.0028	0.0002	nd	nd	10/20/2016	-34.11	-166.6	-40.43	na(3)	0.695	727
Oriskany_591034	0.0013	0.0023	0.0002	nd	nd	10/20/2016	-33.93	-166.5	-40.60	na(3)	0.583	985
Oriskany_591060	0.0013	0.0021	0.0004	0.0002	0.0003	10/20/2016	-35.00	-160.6	-41.84	na(3)	0.797	482
Oriskany_591023	0.0039	0.0064	0.0010	0.0002	0.0003	10/20/2016	-34.89	-164.6	-41.36	na(3)	0.613	920
Oriskany_591055	0.0039	0.0062	0.0008	0.0002	0.0002	10/21/2016	-34.98	-165.0	-41.24	na(3)	0.568	1025
Oriskany_591059 (1)	0.0055	0.0096	0.0025	0.0017	0.0035	10/21/2016	-41.71	-216.9	-38.53	na(3)	0.902	238
Oriskany_591069	0.0015	0.0023	0.0001	nd	nd	10/21/2016	-34.65	-166.0	-40.73	na(3)	0.574	1005
Oriskany_591099	0.0018	0.0031	0.0002	nd	nd	10/20/2016	-34.70	-169.5	-40.93	na(3)	0.581	1005
ECA-COP2	0.0015	0.0025	0.0002	nd	nd	3/2/2017	-35.40	-169.0	-40.94	na(3)	0.568	1021
ECA-COP6	0.0015	0.0061	0.0003	0.0002	0.0001	3/2/2017	-35.35	-165.9	-41.08	na(3)	0.574	1007

The $\delta^{13}C$ and $\delta^{2}H$ of methane (C1) reveal that all of the Marcellus and Oriskany produced gas samples fall within the thermogenic gas range when comparing the $\delta^{13}C$ and the $\delta^{2}H$ of methane (C1) (Schoell, 1980). The $\delta^{13}C$ and $\delta^{2}H$ of methane (C1) reveal that gas samples from Marcellus laterals underlain by the Oriskany (green circles) cluster and the samples from Oriskany verticals blue triangles) cluster, while samples from Marcellus laterals not underlain by the Oriskany (red circles) plot over a wide range (Figure A1).

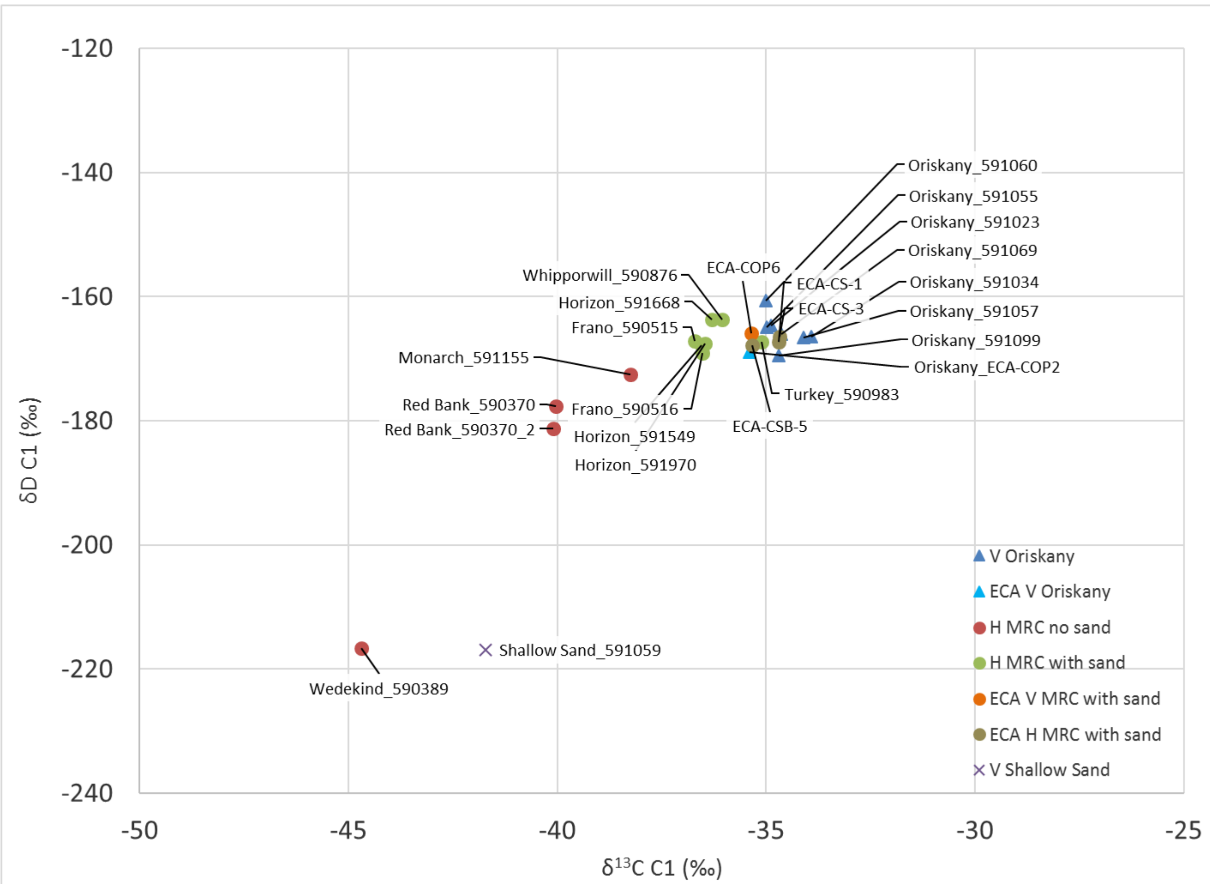


Figure A 1. C and H isotopes of C1 produced gas

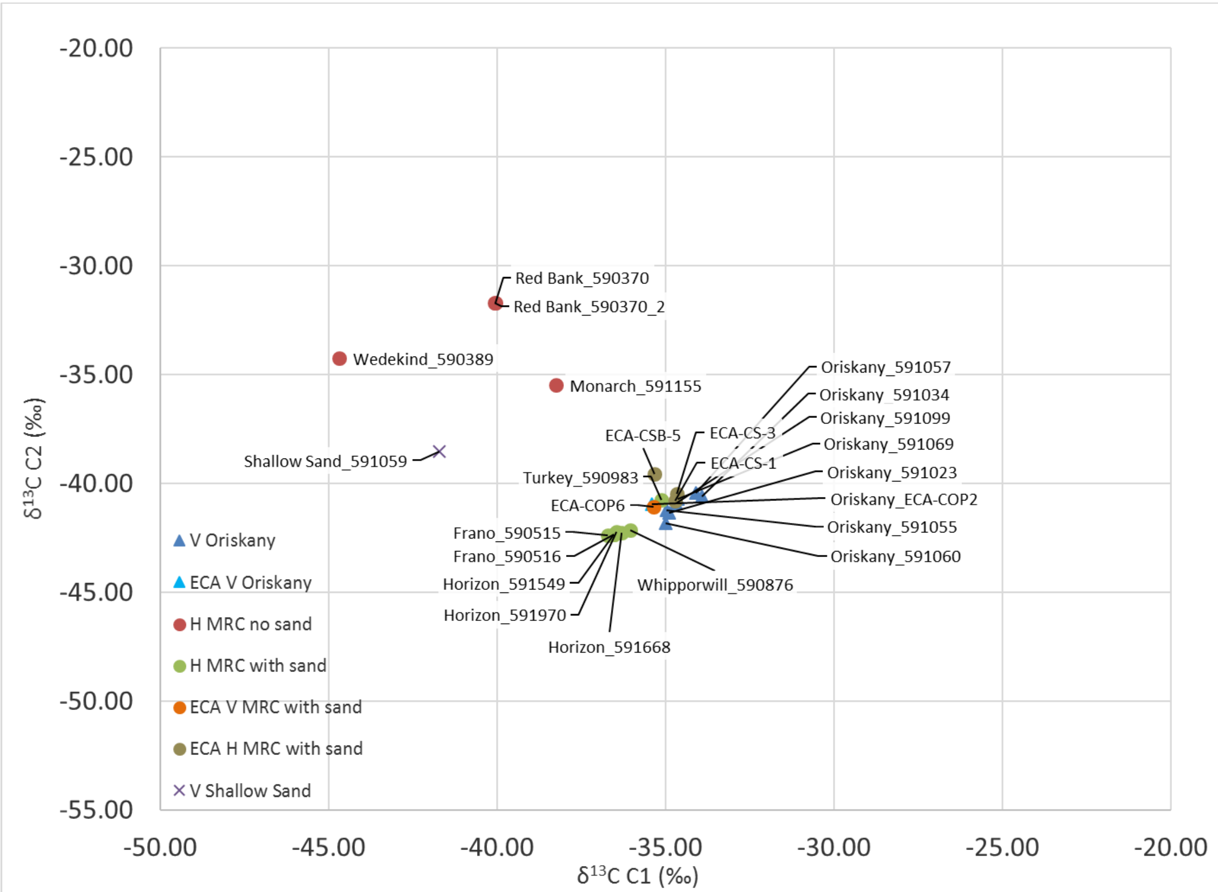


Figure A 2. C isotopes of C1 and C2 produced gas

The produced gas collected showed trends of thermal maturity (Figure A3). As thermal maturity of the gas increases, the portion of methane in the produced hydrocarbon increases.

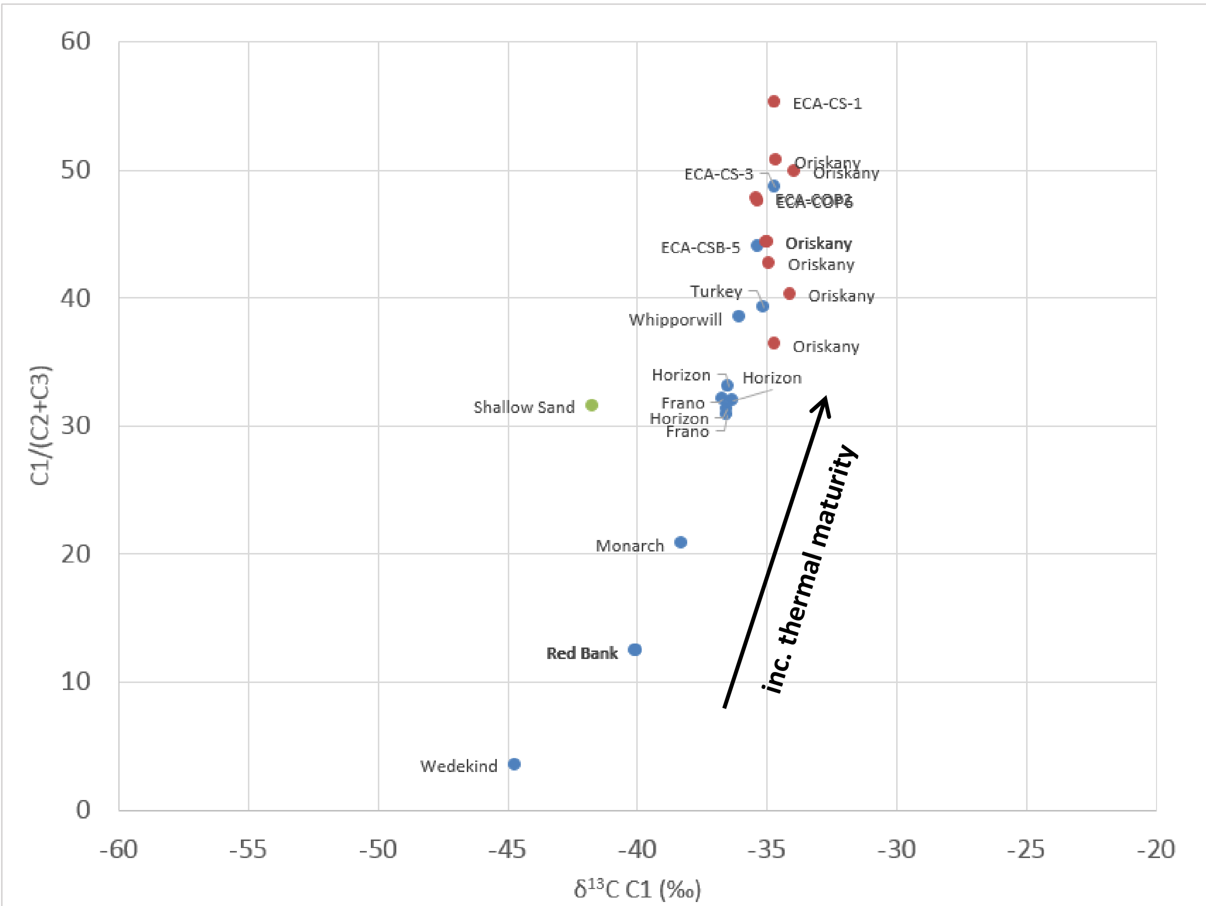


Figure A 3. Carbon isotope ratio of methane and hydrocarbon composition related to thermal maturity

The produced gas from Monarch, Redbank, and Wedekind all have a joules value of 1,107,810 or greater (Figures A4 and A5). Isotopic reversal occurs in dry gas stage and takes place when gas wetness decreases below 2% (Figure A4) (Qu, 2016). The isotope of ethane becomes more negative with increasing maturities. As a consequence $\delta^{13}C2$ rollover takes place with respect to the maturity trend (Figure A5) (Qu, 2016).

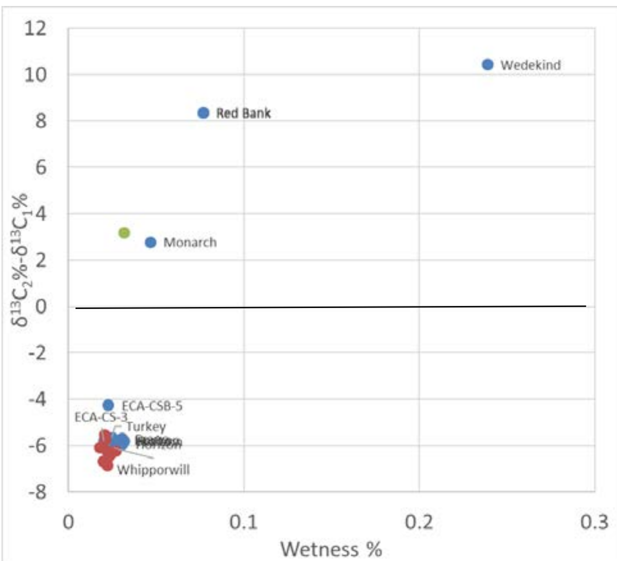


Figure A 4. The carbon isotope reversal

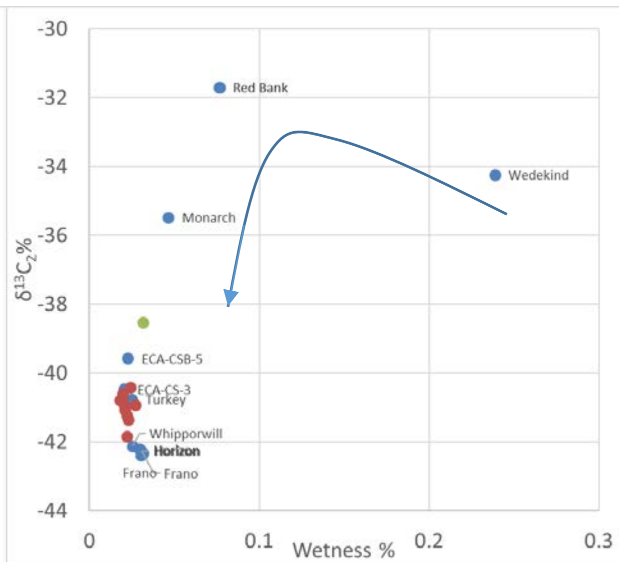


Figure A 5. The carbon isotope rollover

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