The Relationship Between the Taghanic Unconformity and Marcellus Shale Production in Doddridge and Ritchie Counties, West Virginia

by

Emily N. Adams

July, 2016

Director of Thesis: Dr. Donald W. Neal

Major Department: Geological Sciences

The Marcellus Shale, a geologic unit that extends from New York to West Virginia within the Appalachian region, is the source of trillions of cubic feet of natural gas due to organic-rich properties. The formation of the unit was coupled with a period of eustatic sea-level rise that resulted in reactivation of a peripheral bulge leading to the development of the Taghanic unconformity. Stratal variances such as thinning or removal of units within the region are predominately found within the Marcellus Shale as a result of the Taghanic unconformity. Most specifically, in West Virginia, the Taghanic unconformity dominates Marcellus Shale thickness deviations. Areas where thickness of the unit varies considerably are located within Doddridge and Ritchie counties. This project aids in understanding how stratigraphic thinning or removal of the Marcellus Shale in relation to hydrocarbon production differences between Doddridge and Ritchie counties, West Virginia may be a result of the Taghanic unconformity.

Data are derived from log images obtained by the West Virginia Geological and Economic Survey that are correlated to establish the stratigraphy. This study shows the Middle Devonian Marcellus Shale thins from ~55-95 feet in the northeast to ~15-60 feet in the southwest of the counties. This is the result of depositional thinning of the lower Marcellus Shale and erosional removal of part of the upper Marcellus Shale. Additionally, the erosional boundary becomes more extensive towards the southwest. The average first 12 months of gas

production from the Marcellus Shale indicates a larger quantity produced within Doddridge County (656,411 MCF) in comparison to Ritchie County (94,209 MCF). Variations in production values may be attributed to erosional features and thinning trends of the Marcellus Shale related to the Taghanic unconformity as well as additional factors such as gas extraction method, and reservoir properties.

The Relationship Between the Taghanic Unconformity and Marcellus Shale Production in Doddridge and Ritchie Counties, West Virginia

A Thesis

Presented To the Faculty of the Department of Geological Sciences

East Carolina University

In Partial Fulfillment of the Requirements for the Degree

Master of Science Geology

by

Emily Adams

July, 2016

Relationship Between the Taghanic Unconformity and Marcellus Shale Production in Doddridge and Ritchie Counties, West Virginia

by

Emily Adams

APPROVED BY:

DIRECTOR OF
THESIS: ____
Donald Neal, PhD

COMMITTEE MEMBER: ____
Richard Spruill, PhD

COMMITTEE MEMBER: ____
David Mallinson, PhD

COMMITTEE MEMBER: ____
Katharine Lee Avary, M.S.

CHAIR OF THE DEPARTMENT
OF GEOLOGICAL SCIENCES: ______________________________________
Steven Culver, PhD

DEAN OF THE
GRADUATE SCHOOL: ____
Paul J. Gemperline, PhD

ACKNOWLEDGEMENTS

I would like to give a special thanks to my advisor, Dr. Donald Neal for the support and encouragement along the way. Additionally, I would like to extend thanks to my committee, Dr. Richard Spruill, Dr. David Mallison and Katharine Lee Avary as well as East Carolina University's Department of Geological Sciences. Furthermore, I would like to also thank my parents, David and Susan Adams for their continuing support along with Andrew Roberts for his love and kindness throughout this process.

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

Occurring since the late 1800s, oil and gas production within the Appalachian basin has been thriving and increasing (Milici & Sweezy, 2006). This basin, Paleozoic in age, is the birthplace of the modern petroleum industry within the United States (Miller, 1975). Production within the region is attributed to a variety of factors including numerous oil-and gas-rich geologic units, variations in stratigraphy, and thickness of “pay” zone units. However, most importantly, the nature of the scale of the Appalachian basin itself plays a major role for the large quantities of oil and gas produced within the region. The Appalachian basin spans from Virginia, Kentucky, West Virginia, Ohio Maryland, Pennsylvania, and New York, extending over 100 million surface acres (Miller, 1975).

Devonian-age reservoirs, which are typically organic-rich black shales dominate production in the region. According to Burns and Claus (1985) and Ettensohn (2008) these units are estimated to contain 71% of the basin’s oil and 46% of its gas (As cited in Cummings, 2014). Most specifically, and the most plausible cause for these oil and gas estimates, is the Marcellus Shale. Within the Appalachian basin, the Marcellus Shale extends from New York to Ohio, Pennsylvania, and West Virginia in layers 3,000-7,000 feet below the land surface ranging from 0-350+ feet thick (Penn State Marcellus Center for Outreach and Research, 2010) (Fig. 1). This geologic unit is believed to hold 500 trillion cubic feet of gas, with 50 trillion cubic feet of potential recoverable gas (Harper, 2008). The Marcellus is a member of the Hamilton Group with the Tully Limestone and/or Mahantango Formation above and the Onondaga Limestone, Huntersville Chert, or Needmore Shale below (Fig. 2).

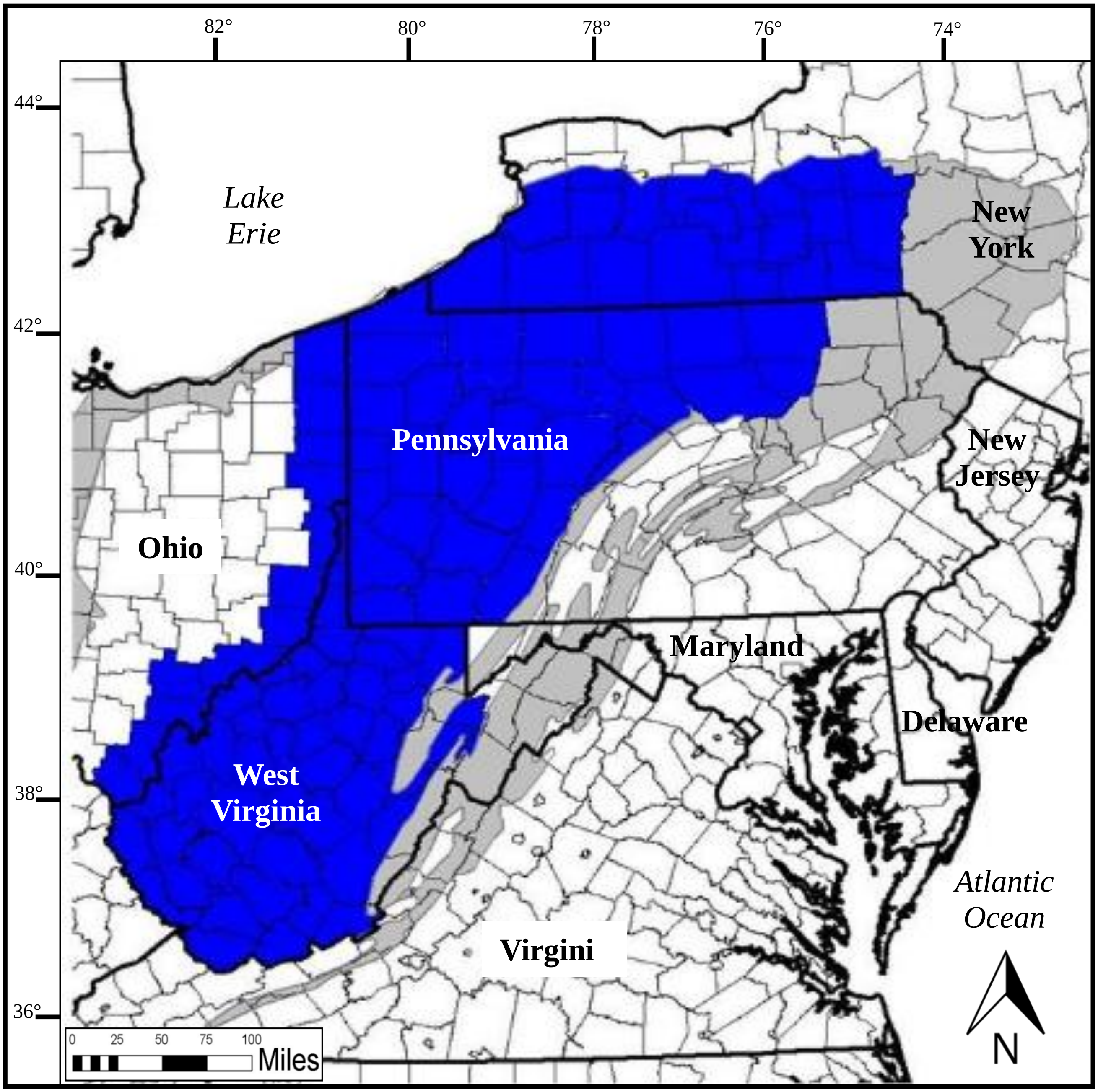


Figure 1. Marcellus Shale (blue) location map in New York, Pennsylvania, Ohio, and West Virginia with additional Devonian outcrops (grey). From VanMeter (2014).

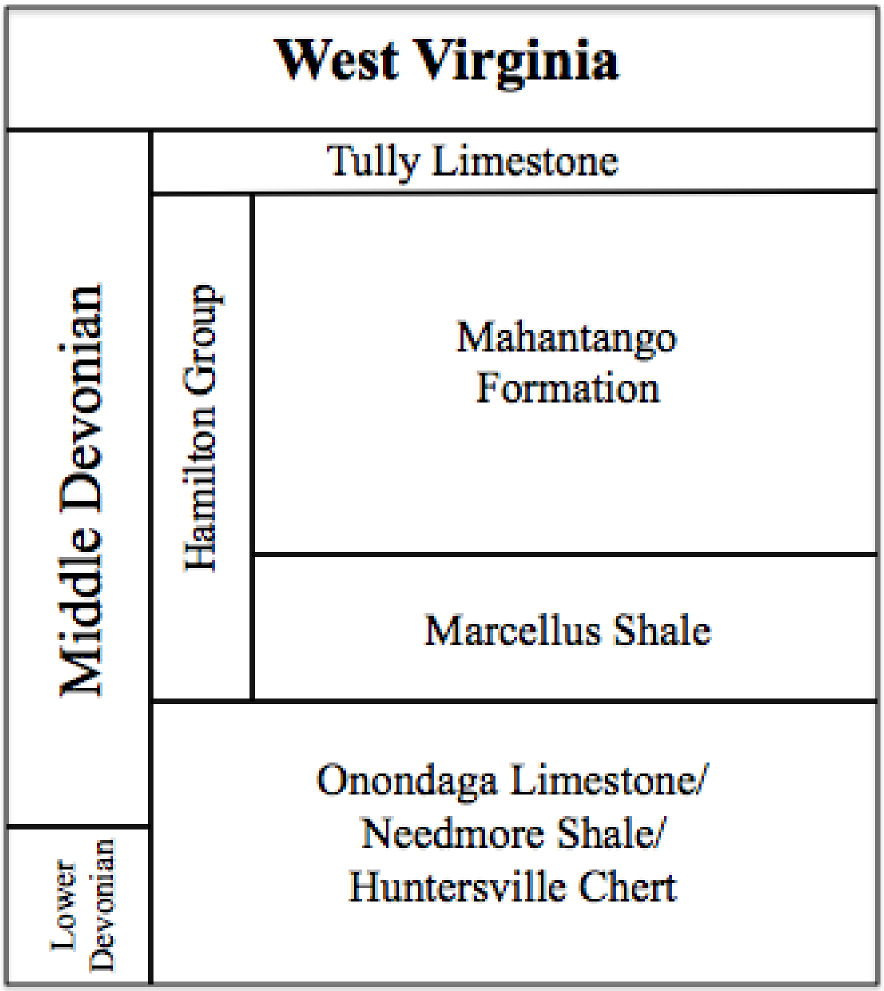


Figure 2. General stratigraphic nomenclature of West Virginia Middle-Lower Devonian Units. Modified from Milici and Sweezy (2006).

Deposition of the Marcellus Shale occurred during the Acadian Orogeny (419-360 mya) and is one of the most recognized periods of extensive transformation within the region (Murphy & Keppie, 2005). Coupled with the formation of the Marcellus Shale was a reactivation of a peripheral foreland basin, which resulted in a system known as the Catskill Delta complex (Van Tassell, 1987). The formation of a peripheral bulge and a lowering of sea level resulted in an erosional feature known as the Taghanic unconformity leading to stratigraphic stratigraphic thinning of Devonian-aged units, most specifically the Marcellus

Shale. Most of the Hamilton Group, including the upper part of the Marcellus Shale, has been removed in southwestern West Virginia (Neal, 2010) (Fig 3). Stratal thinning within the region are primarily found within West Virginia where the Taghanic unconformity dominates Marcellus Shale thickness variations. Within the state, the Marcellus Shale exists in thinning layers and is most affected by the Taghanic unconformity in the west and southwestern part.

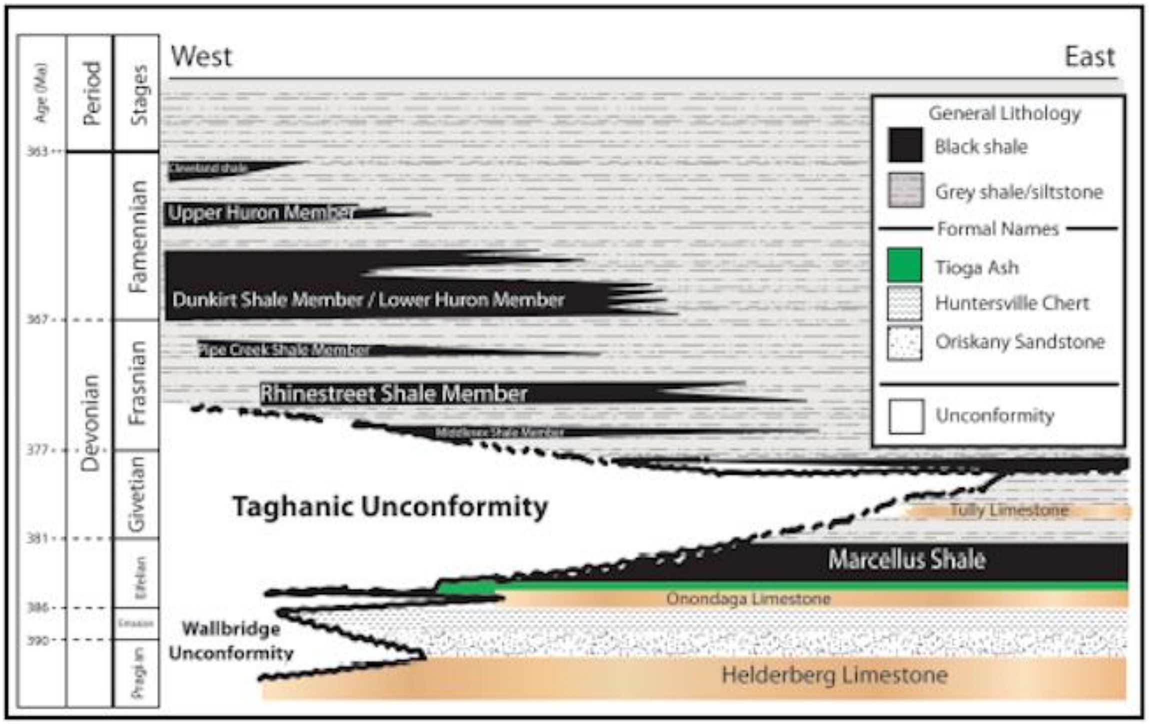


Figure 3. Stratigraphic nomenclature displaying removing of Devonian Age units, most specifically, the Marcellus Shale as a result of the Taghanic Unconformity. Modified from Avary and Patchen (2008) as cited in Smith (2012).

For the past two decades, the Marcellus Shale has been a large producer of natural gas within West Virginia. However, despite the abundance of natural gas production from the Marcellus Shale in West Virginia, there is a lack of stratigraphic knowledge linking stratal variances such as thinning or removal of units related to the Taghanic unconformity and production values within the state.

Areas where thickness of the unit varies considerably as an outcome of the Taghanic unconformity are located within Doddridge and Ritchie counties. These two counties, located in northwestern West Virginia, comprise roughly 774 square miles (Fig. 4). These counties were selected for this study due to the wealth of available well log and production data.

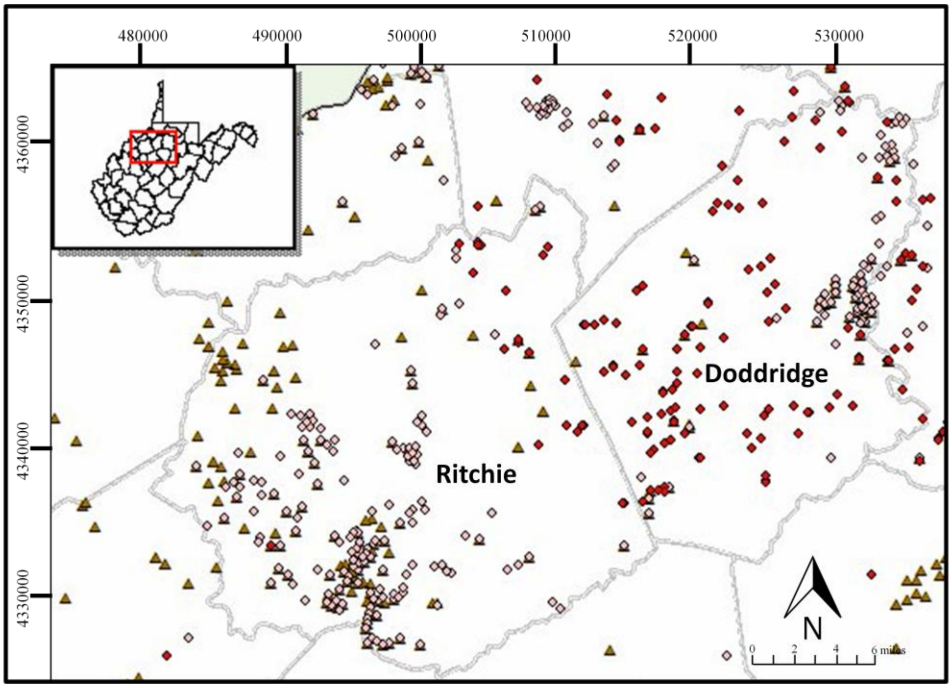


Figure 4. Location of study area in Doddridge and Ritchie counties, West Virginia. Dots represent completed well locations from the West Virginia Geological and Economic Survey. Triangles represent well locations with available geophysical logs from the West Virginia Geological and Economic Survey. Both represent geographic coordinates in UTM eastings and northings in meters.

The first objective for this study is to aid in understanding how thinning and/or removal of the Marcellus Shale as a result of the Taghanic unconformity may play a role in hydrocarbon production variances between Doddridge and Ritchie counties. In order to effectively understanding thinning and removal of the Marcellus Shale within the study area, well log lithology was assessed on a well to well basis throughout examination of gamma ray log signatures and corresponding density logs of the Middle-Upper Devonian Marcellus Shale.

Stratigraphic trends associated with well log lithology were used as a proxy for stratal variances such as thinning or removal of units resulting from the Taghanic unconformity. Additionally, evaluation of log-determined productivity via mapping of production intervals for the first 12 months of production within Doddridge and Ritchie counties based on gas extraction method is used to highlight how the Taghanic unconformity may be a factor of gas produced from the Marcellus Shale in this region. Data are derived from log images obtained by the West Virginia Geological and Economic Survey (WVGES).

A second objective is to aid in understanding location of depositional thinning as well as scenarios for thinning of the lower Marcellus Shale and erosional removal of part of the upper Marcellus Shale. Image gamma ray logs are correlated to form comparisons of these processes occurring within Doddridge and Ritchie counties. Isopach and structure contour maps are created to identify thicknesses and depths of the upper and lower Marcellus Shale in Doddridge and Ritchie counties as well as understanding processes related to thinning and removal of the unit.

The third objective is to evaluate additional factors that may play a role in variations in production between Doddridge and Ritchie counties. Additional factors include assessment of extraction method of gas, structural controls and reservoir characteristics within the study area such as mineralogy, organic-matter richness, thermal maturity, and fracture porosity.

A final objective is to identify potential areas for production with respect to erosional features and thinning trends of the Marcellus Shale related to the Taghanic unconformity, gas extraction method, structural control, and reservoir properties within the study area. Such factors allowed for understanding of best areas/methods for gas production within Doddridge and Ritchie counties.

2.0 BACKGROUND

2.1 TECTONIC HISTORY

During the Paleozoic Era, four orogenic events produced what is now known as the Appalachian basin. Categorized as a retroarc foreland basin, the Appalachian basin includes parts of New York, Pennsylvania, Ohio, West Virginia, Maryland, Kentucky, Virginia, Tennessee, Georgia, and Alabama (Etthensohn, 2008) (Figure 5). This basin formed along the eastern Laurentian margin, which subsequently followed the destruction of supercontinent Rodinia (Hatcher, 2010) (Figure 5). The birth of this basin was an outcome of the Potomac, Taconic, Acadian, and Alleghenian orogenies that culminated in the formation of Pangaea (Beardsley & Cable, 1983).

Out of the four orogenic events, one of the most recognized periods of extensive transformation within the Appalachian basin is the Acadian orogeny. This long-term event, which occurred from the Middle to Late Devonian (419-360 mya), resulted in wide-ranging deformation and destruction (Murphy& Keppie, 2005). Over a time-span of roughly 60 million years, the Acadian orogeny resulted from oblique convergence along a strike slip fault zone between North America and the micro-continent Avalonia (Ettensohn, 2008). This convergence affected regions spanning from the Canadian Maritime provinces to southwest Alabama along with areas from New England to northeastern parts of Canada (Ettensohn, 2008). As a result of the collision between North America and Avalonia, plate overriding of North America occurred over continental lithosphere, which initiated the development of a foreland basin due to crustal thickening, deformation and compressional tectonics (Figure 6). This basin has been categorized as a retroarc foreland basin and is known as the Appalachian foreland basin (Jacobi, 2008).

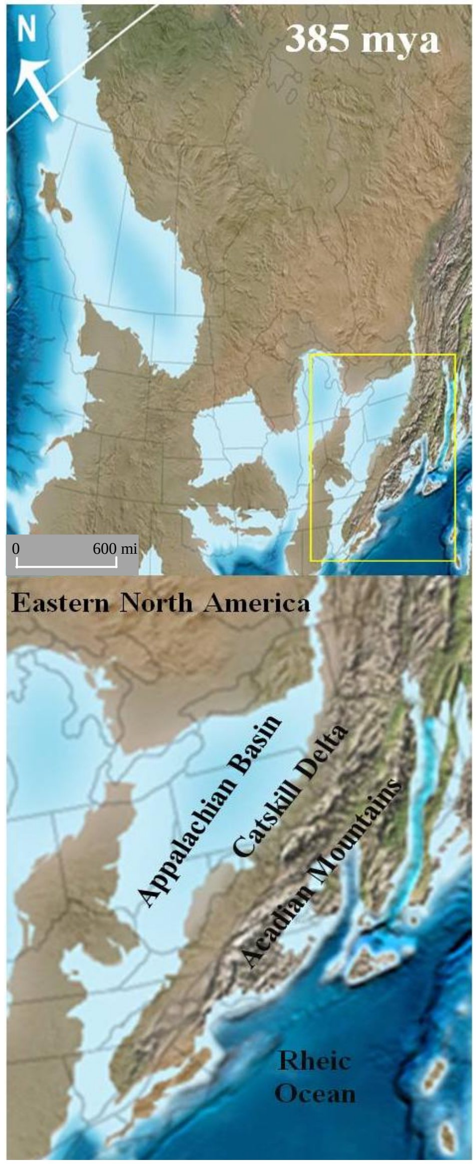


Figure 5. Relative location of the Appalachian basin, Acadian Mountains and Catskill Delta during the Middle Devonian (385ma). Modified from Blakey (2009).

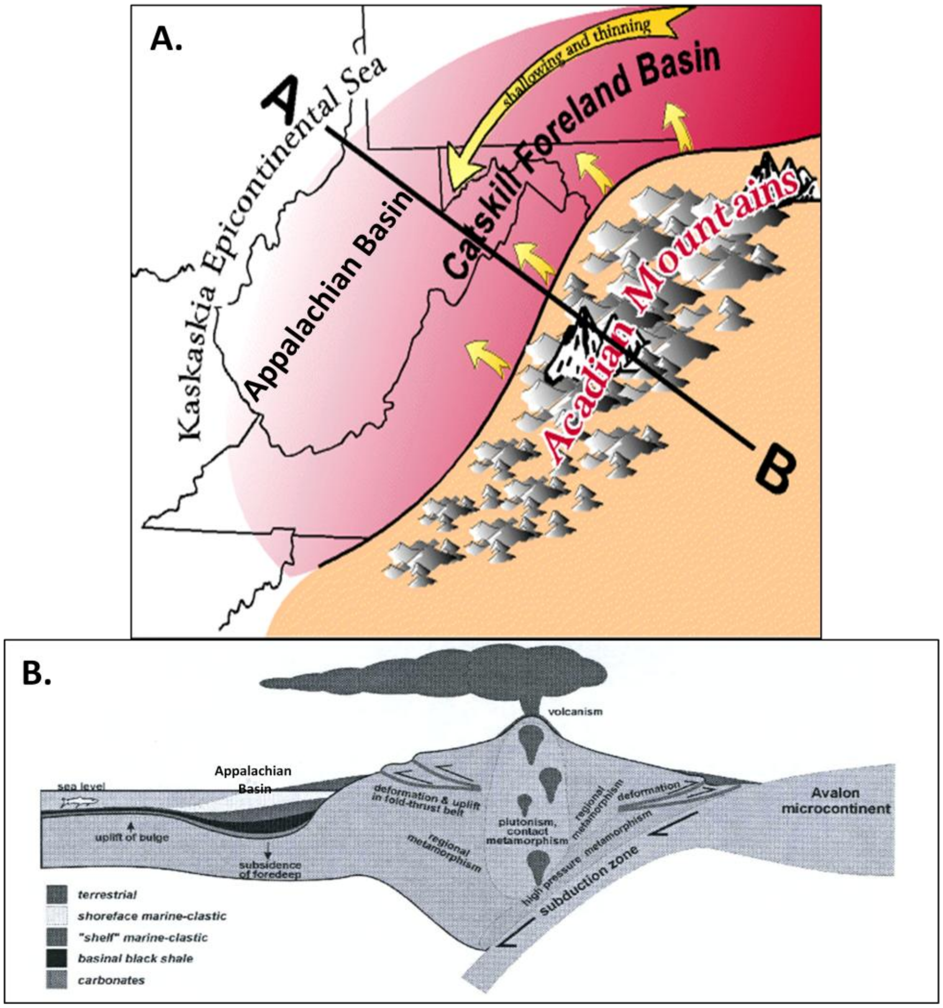


Figure 6. Figure A. is an aerial view of the location of the development of the Appalachian Basin. Modified from Ver Straeten (2009). Figure B. is a schematic cross section of tectonic development of the Appalachian basin with relative location as seen in cross section A-B in Figure A above. Modified from Fichter & Baedke (2000).

During Acadian orogenic events in the Middle Devonian (393-360 mya), the Appalachian foreland basin was initially filled by sedimentary material from the Catskill delta complex (Ettensohn, 2008) (Figure 5). This large delta complex was the result of a number of small to medium sized rivers forming at the delta mouth (Kent, 1985). These rivers contributed to sediments that formed the extensive delta complex. Additionally, deposition of the Catskill delta complex resulted in the accumulation of organic-rich sediments distal to the prograding delta.

2.2 STRATIGRAPHY

The stratigraphy associated with the Middle Devonian Catskill delta complex was a direct result of depositional cycles attributed to global eustatic sea-level fluctuations coupled with climate and sediment input variances (Slingerland et al., 2009). Fluvial, deltaic, shelf, slope and basin deposits are the typical stratigraphy of the Catskill delta complex (Van Tassell, 1994) (Figure 7). Sediments range from fluvial/deltaic clastics, siltstones, sandstones, turbidites, to organic-rich black shales. Sediments of the Catskill delta extend from east-central New York, southward into Pennsylvania, Maryland, eastern Ohio, eastern Tennessee, western Virginia, and West Virginia (Faill, 1985).

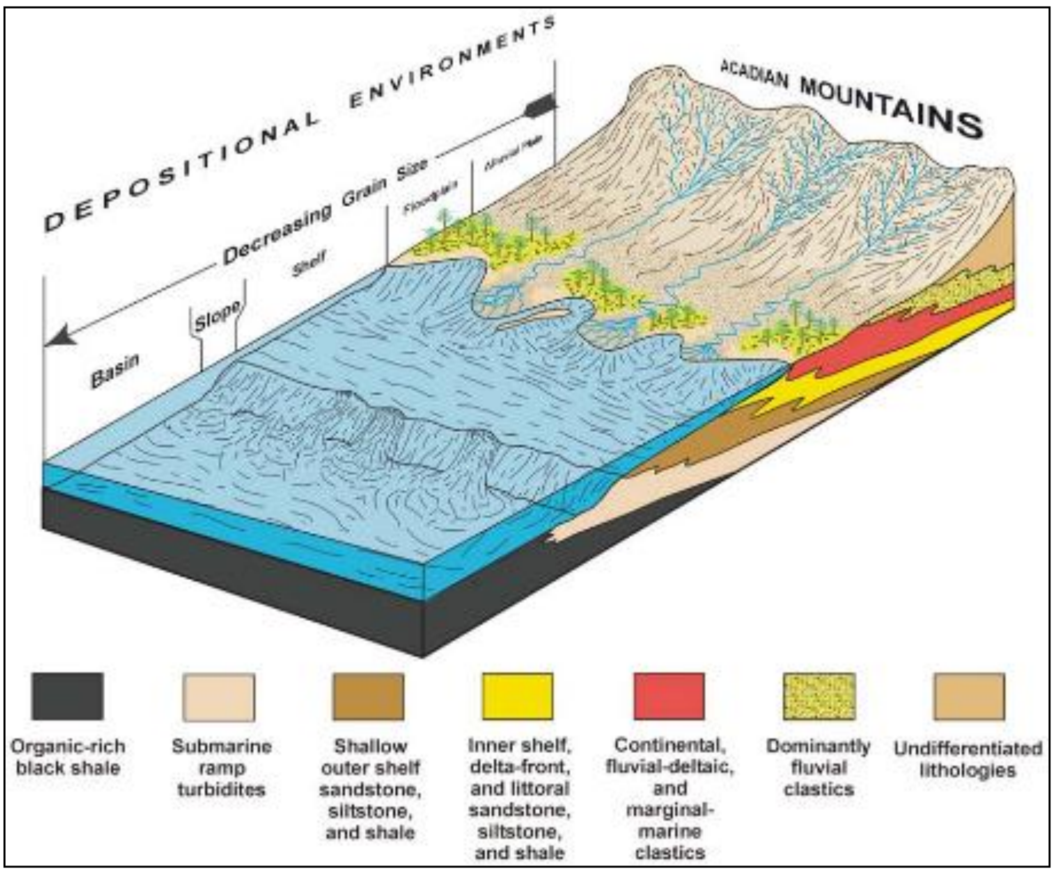


Figure 7. Depositional Environments and resulting stratigraphy of the Acadian mountain complex. From Laughrey (2009).

2.2.1 Tully Limestone

The Tully Limestone, described by Heckel (1973), is an anomalous unit, ranging from 200-100 feet thick that interrupts the thick sequence of detrital rocks constituting the Catskill Delta, which can be anywhere from 200-1000 feet thick. The Tully limestone extends from New York southward into Pennsylvania, West Virginia, north and easternmost Ohio, and westernmost Maryland (de Witt, Roan & Wallace, 1993). Deposition of the Middle Devonian Tully Limestone was controlled by coeval structures towards the east where an anticline, and a down-to-the-east fault (or monocline), formed a clastic trap towards the east and posed as a barrier to the foremost westward spread of Catskill Delta clastics (Heckel, 1973).

Several facies are recognized within the Tully Limestone and include detrital and carbonate attributes. Detrital facies include laminated muddy quartz siltstone and burrowed quartz siltstone (Heckel, 1973). Laminated siltstone displays traces of restricted fauna as compared to the burrowed sandstone that exhibits more diverse fauna (Grabau, 1977). The difference in fauna between the detrital facies is indicative of slower deposition under a stable clastic source within a marine environment producing laminated siltstone versus rapid deposition with a very active clastic source producing the siltstone. Within the carbonate facies realm, the Tully Limestone exhibits abraded calcarenites, chamosite oolite, skeletal calcilutite, barren shaly calcilutite, mound calcilutite, backmound calcilutite, and encrinites (Heckel, 1973). Deposition of these facies is attributed to a northern source of limey mud among a shoal with large quantities of carbonate-secreting organisms present (Baird & Brett, 2006). Carbonate facies were also likely protected by a clastic trap resulting from the Catskill delta complex.

An additional stratigraphic feature within the Tully Limestone is displayed within an upper bounding unconformity. This geologic anomaly, known as the Taghanic unconformity is abruptly overlain by Genesee Formation deposits, most commonly the basal back shale member, the Geneseo Shale (Woodrow & Sevon, 1985). The Geneseo Member is organic-rich and is mainly attributed to a phase within the Acadian orogeny related to tectonic downwarping as a result of isostasy (Heckel, 1973).

2.2.2 Mahantango Formation

The Mahantango Formation, Middle Devonian in age, underlies the Tully Limestone unit and extends from New York southward into Pennsylvania, New Jersey, Maryland, Virginia, and West Virginia (Woodrow, Dennison, Ettensohn, Sevon & Kirchgasser, 1988). It is recognized as part of the Hamilton Group and can range from 0-1100 feet thick. Deposition of the unit is represented by a terrestrial to marine transitional area that exhibited multiple of transgressive and regressive sequences (Prave, Duke & Slattery, 1996).

The Mahantango Formation is best described as fossiliferous sandstone interbedded with shale. Several distinct lithologies within the unit are recognized as shale, siltstone and sandstone. The shale is often gray, pale-green, and black that weathers to silvery gray, which has minor interbedded siltstones (Willard, 1935). The siltstone lithothogy is best described as greenish-gray with interbedded shale (Willard, 1935). Lastly, the sandstone is often a fossiliferous greenish-gray to grayish-brown, fine-grained lithology (Willard, 1935). Within all lithologies, a distinct pattern of spheroidal weathering is present. Depositional environments of the fine-grained lithologies represent a shallow marine environment, which often accounts for the rock being fossiliferous (Prave, Duke & Slattery, 1996). Coarser sediments are attributed to near-shore environments, such as beaches or delta lobes (Prave, Duke & Slattery, 1996). The Mahantango Formation was deposited during a tectonic phase within the Acadian orogeny that is credited to a deep, sediment depleted, anoxic environment (Ettensohn, 1985).

2.2.3 Marcellus Shale

Another resulting stratigraphy of the Catskill delta complex is the Middle Devonian Marcellus Shale, which ranges from 1-890 feet thick. Sediments forming the Marcellus Shale are remnants of the Acadian mountains that washed through braided streams into the Catskill Delta. These silty and fine-grained particles accumulated within the deepest part of the Appalachian basin (Curtis & Klemow, 2011). The Marcellus Shale was a direct result of deposition occurring at maximum water depths and under extreme anoxic conditions (Piotrowski & Harper, 1979). Along with the Mahantango Formation, the Marcellus Shale is a part of the Hamilton Group and occurs in New York, Pennsylvania, Ohio, Virginia, New Jersey, Maryland and West Virginia. Within the Hamilton Group, the Marcellus Shale contains the greatest amounts of organic rich rocks and is a large producer of natural gas.

The Marcellus Shale is best described as an organic-rich black shale that is sparsely fossiliferous. Often times it weathers to gray or brown chips on outcrop and contains pyritic zones and zones of calcareous concretions and limestone beds (Enomoto, Olea & Coleman, 2013). Layers of interbedded limestone are attributed to sea level fluctuations (Harper, Laughrey, Kostelnik, Gold & Doden, 2004). Zones of pyrite are often found near the base of the unit and lead to production of significant amounts of minerals containing more water in their chemical structure, such as gypsum (Hoover & Lehmann, 2007). Within the Marcellus Shale sparse remnants of marine fossils, such as bivalves, gastropods and brachiopods are present. The existence of these fossils is due to a downslope transport of sediments from a marginal marine environment that existed west of the Catskill Delta (Hill, 2007).

Within West Virginia, the Marcellus Shale can often be subdivided into two distinct units, the upper and lower, through assessment of stratigraphic trends. The upper Marcellus

Shale is defined as an organic-rich unit and is informally correlated as the Cherry Valley, Purcell, and Oatka Creek members (Kohl, Slingerland, Arthur, Bracht & Engelder, 2014). Additionally, the lower Marcellus Shale is informally named the Union Springs Member, which is a basal organic-rich unit (Kohl, Slingerland, Arthur, Bracht & Engelder, 2014).

The Marcellus underlies the Mahantango Formation and in places where this unit is nonexistent, the Tully Limestone is found above. Beneath the Marcellus Shale lies the Onondaga Limestone; the contact between the two units is sharp, gradational or erosional contact (Jackson, Hanley & Sak, 2007).

2.2.4 Onondaga Limestone

Middle Devonian in age, the Onondaga Limestone can range anywhere from 100-500 feet thick and occurs in New York, Pennsylvania, Maryland, Virginia, and West Virginia (Brett & Ver Straeten, 1994). Deposition of the limestone occurred in a high energy a shallow marine environment. A period of quiescence prior to the Acadian orogeny resulted in a shallow sea with an abundance of reef-bearing limestones (New York State Geological Survey, n.d.).

The Onondaga Limestone is subdivided into four members which include: Edgecliff, Nedrow, Moorehouse, and Seneca (USGS, n.d.). The Edgecliff is described as a grainstone that is chert-poor and has an abundance of crinoids (Bruner & Smosna, 2002). Within the Nedrow, rugose corals and scattered brachiopods are present, however this unit is typically acknowledged as sparsely fossiliferous (Brett & Ver Straeten, 1994). This unit is best described as a medium to dark grey calcareous shale that is nodular and highly argillaceous with chert-poor limestone (Van Tyne, 1996). Deposition of this unit is indicative of a minor transgressive cycle due to an influx of muddy sediments. The next recognized layer within the Onondaga Limestone, the Moorehouse Member, which is fossil-rich and interbedded with limestone and shales (Oliver, 1955). The last unit, Seneca, is defined as a general fining-upward trending unit, which has several bentonite beds throughout (Brett & Ver Straeten, 1994). Additionally, this unit contains low diversity fauna and has a fine to medium grained wackestone to packestone lithology (Oliver, 1955). Deposition of this unit is more complex than the preceding units, in that it is suggested that two sea level cycles are responsible for this unit (Feldman, 1994). Although these four units are typically recognized separately when defining stratigraphy, for purposes of this thesis, the Onondaga Limestone will be recognized as one unit.

2.3 PRODUCTION HISTORY

Oil and gas production within the Appalachian basin has had a long history since the drilling of the Drake Well in Pennsylvania in 1859 that led to further exploration and production within the region (McKithan, 1978). The Marcellus Shale is estimated to hold roughly 410 trillion cubic feet of gas (Hughes, 2014). According to the Energy Information Administration, the Marcellus Shale accounts for 90 percent of domestic natural gas production growth within the basin (As cited in Ross et al., 2013).

This large quantity of natural gas produced by the Marcellus Shale is credited to a variety of factors including net thickness, gas extraction method and reservoir properties such as pressure gradients and thermal maturation (Belyadi, 2011). The thickness of the shale is an important prediction tool due to the fact that the natural gas is extracted via horizontal or vertical drilling. Vertically drilled wells are able to access the natural gas that immediately surrounds the well bore. Horizontal wells are able to access the natural gas surrounding the entire portion of the horizontally drilled section. The thicker the shale, the more pressure the rock can withstand during the drilling process. This is why thickness variations of the Marcellus Shale make it a good candidate for this extraction process. Pressure gradient of the

Marcellus Shale is an average of 0.40 psi/ft, which is also an important feature in production trends (Belyadi, 2011). This gradient allows for proper hydraulic fracturing of the rock, which allows the fracture fluid to permeate the reservoir rock effectively (University of Colorado, n.d.). Overall, the pressure gradient of the Marcellus Shale is an important factor in the production of large volumes of natural gas. An additional element, thermal maturation, is another important aspect to the vast growth of Marcellus Shale production within the Appalachian basin. Thermal maturation is distinguished by a measure of the heat-induced process of converting organic matter to oil or natural gas (Belyadi, 2011). Once assessed, this term is converted to a universal standard defined as vitrinite reflectance (Ro). The Marcellus Shale has an average Ro value of 1.2%, which is considered to be one of the most profitable values for natural gas production (NETL, 2010).

Within West Virginia, the Marcellus Shale production has been booming for the past two decades. There are nearly 1,600 producing wells within the state and each alone can account for 800 thousand cubic feet (MCF) of natural gas per day when active (West Virginia Geological and Economic Survey, 2012). Within Doddridge and Ritchie counties alone, there are nearly 289 Marcellus Shale Wells (West Virginia Geological and Economic Survey, 2012). In a study conducted by Belyadi (2011), it was estimated that production of the Marcellus Shale within West Virginia could reach as much as 5.76 billion standard cubic feet when pumped for the next 30 years. Overall, these vastly growing production trends are attributed to thickness of the Marcellus Shale within West Virginia. Thicknesses of the unit within the state vary from 0-100 feet (Figure 8).

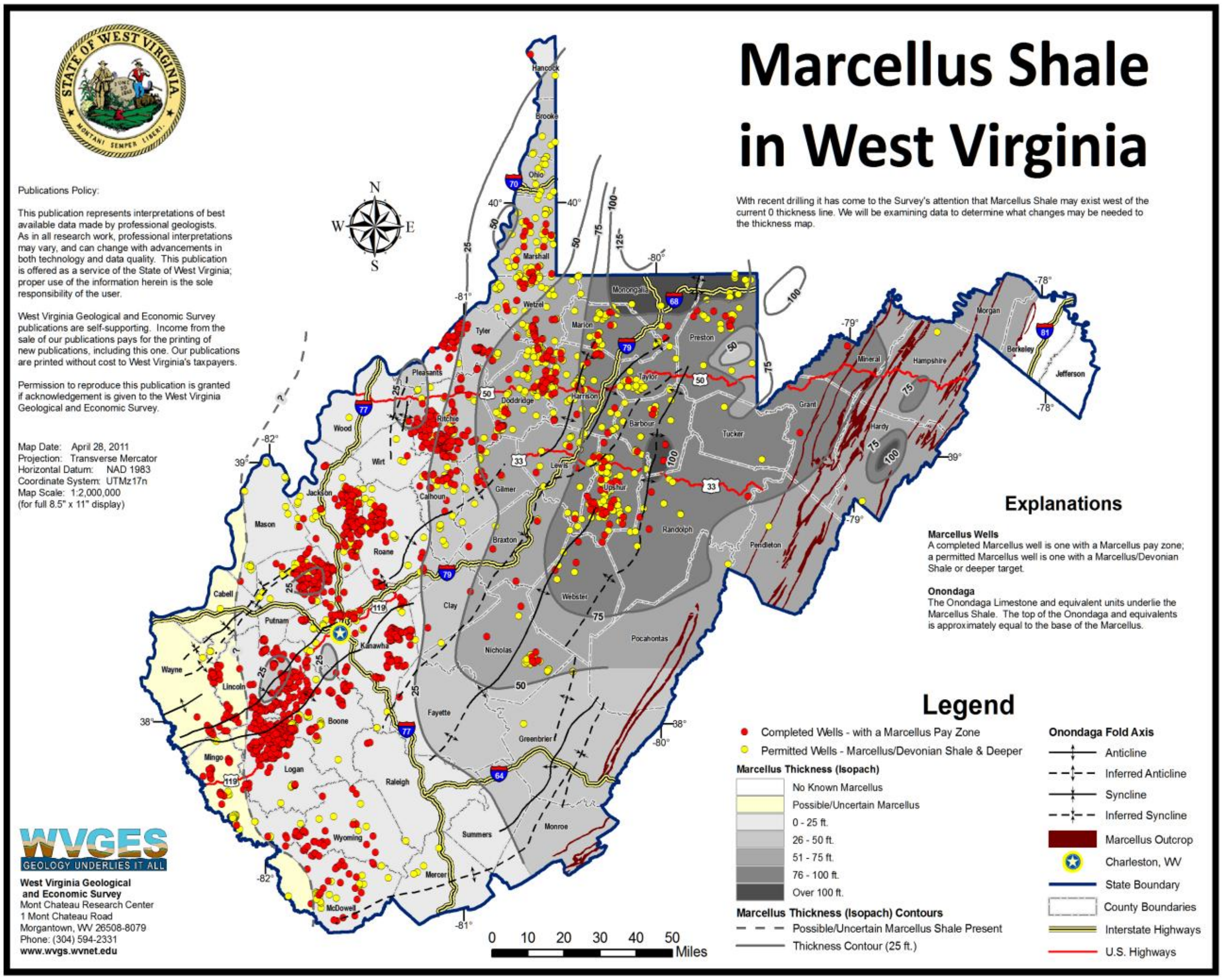


Figure 8. Isopach map of the Marcellus Shale within West Virginia. Map is from the West Virginia Geological and Economic Survey Interactive Mapping Application (n.d.). Map was to location well locations and Marcellus Shale thicknesses in Doddridge and Ritchie counties.

3.0 METHODS

3.1 DATA COLLECTION

The chosen area for this study, Doddridge and Ritchie counties of West Virginia, was selected based on the approximate location of the Taghanic unconformity and the abundance of accessible well and production data. Data for the purpose of this thesis are derived from subsurface gamma-ray and neutron density logs obtained from the West Virginia Geological and Economic Survey Pipeline database as well as the “Marcellus Interactive Mapping Application.” The Pipeline database is free for public use and is home to an estimated 34,000 logs for oil and gas wells within West Virginia. Access to this database is available at http://www.wvgs.wvnet.edu/oginfo/pipeline/pipeline2.asp, which allows for easy searching of well data by searching a ten-digit American Standard Institute (API) number that is assigned to each well. The first three numbers within the API are the state code, the next three are the county code, and the last five are the well number. Each well is assigned a unique API number in order to efficiently locate well data (West Virginia Department of Environmental Protection, n.d.). Once the well data are located via API number, gamma-ray and production data can be downloaded for each well. Gamma-ray logs were downloaded and examined via Brava! Reader, which is a free program for public use. In addition, to the Pipeline database, the “Marcellus Interactive Mapping Application” was used to gather geologic information on the Marcellus Shale within West Virginia including well locations, Marcellus Shale thickness, and production well data. This map was primarily used to locate wells within the study area based on the Universal Transverse Mercator (UTM) easting and northing coordinate system. Once well data were located and gathered from the Pipeline database and Interactive Mapping tool, they were organized and evaluated for generation of stratigraphic cross sections, subsurface maps, production maps, and graphs for the Marcellus Shale in Doddridge and Ritchie counties, West Virginia.

3.2 STRATIGRAPHY

3.2.1 Well Log Lithology

Well log lithology including the Geneseo Shale, Tully Limestone, Mahantango Formation, upper Marcellus Shale, lower Marcellus, and the Onondaga Limestone were determined using gamma-ray log signatures, the American Petroleum Institute (API) 0-400 value range, and the corresponding density logs. Figure 9 displays the typical gamma ray log signatures of the Geneseo Shale, Tully Limestone, Mahantango Formation, upper Marcellus Shale, lower Marcellus, and Onondaga Limestone within West Virginia, which was used as a proxy tool to define gamma ray correlations of units within Doddridge and Ritchie counties. The Marcellus Shale was subdivided into two units based on stratigraphic trends illustrated by individual gamma ray signatures, which indicated two distinctive units. Gamma ray signatures were color-coded based on API interval. Red gamma ray signatures indicate 0-200 API, and blue signatures indicates log wrap around at 200-400 API. Once well log lithology was distinguished, each unit was color-coded. Figure 10 displays a typical log for Ritchie County and Figure 11 displays a typical log for Doddridge County, which includes color-coded methodology used for this study.

Gamma-ray log signatures were used to aid in characterizing rock and sediment, based on naturally occurring gamma radiation. They are particularly helpful because shales and sandstones typically have different gamma-ray signatures that can be correlated readily between wells (Schlumberger, n.d.). Shale lithologies typically have increased gamma-ray levels due to high abundance of radioactive material, such as clay minerals and organic matter.

Additionally, non-shale lithologies such as sandstones or limestones have lower gamma-ray values due to decreased levels of radioactive material. This difference allows for easy identification of units within the study area to distinguish shales including the Geneseo Shale, Mahantango Formation, upper Marcellus Shale, and lower Marcellus Shale from non-shales including the Tully Limestone and the Onondaga Limestone.

All gamma-ray log lithologies within the study area were assessed based on the API value range, which measures radioactivity on a scale of 0-400. The gamma ray API unit is defined as 1/200 of the difference between the count rate recorded by a logging tool in the middle of the radioactive bed and that recorded in the middle of the nonradioactive bed (Crain, 2015). Shales typically have API values from 150-400 and non-shales have values from 0-150.

In addition to gamma-ray log signatures and API values, well log lithologies were determined using corresponding density logs. Density logs provide a continuous record of a rock formation's bulk density, which is a function of the minerals forming the rock and the fluid enclosed in the pore spaces. Furthermore, density logs provided identification of shale and non-shale lithologies due to easily distinguishable trends, such as moderate reading for shales and a low reading for non-shales.

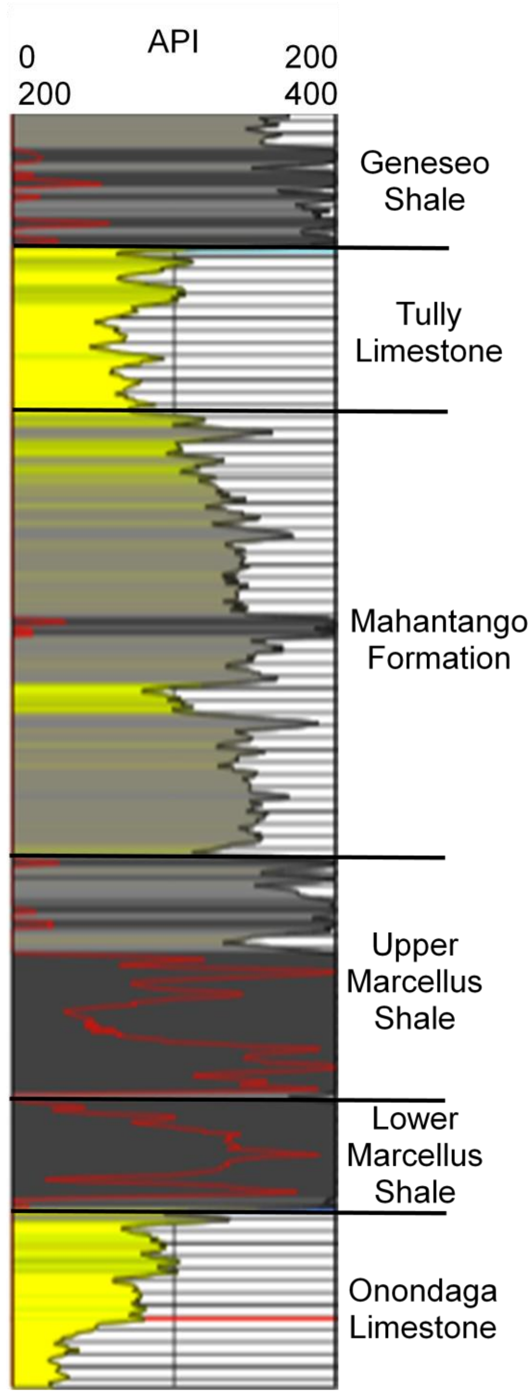


Figure 9. Typical gamma ray log signatures of the Geneseo Shale, Mahantango Formation, upper Marcellus Shale, lower Marcellus Shale, and Onondaga Limestone within West Virginia. The units labeled 0-200 and 200-400 at the top of the well are the API standard value range for radioactivity. Gamma ray exhibits wrap around once (200-400 API), which is depicted by the red gamma signature. Modified from Sexton (2011).

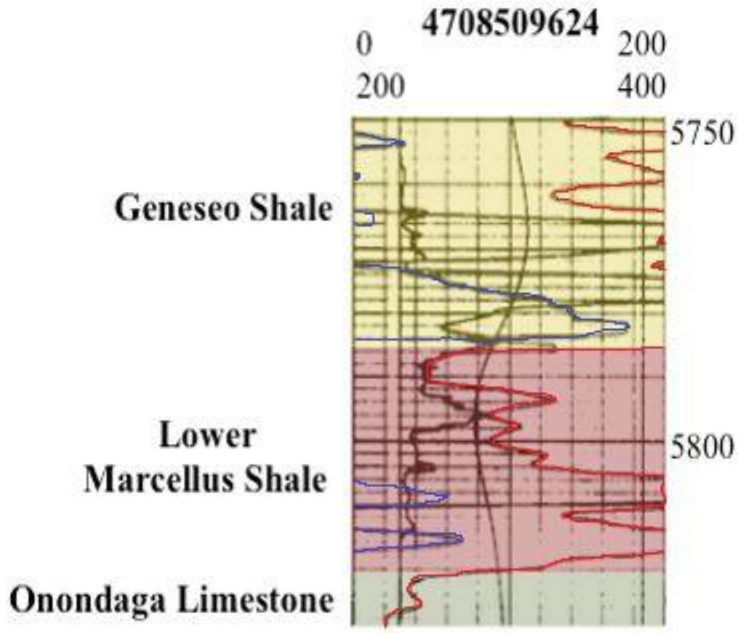


Figure 10. Typical Marcellus Shale log for Ritchie County, West Virginia. The displayed curve is the gamma-ray trend for the Geneseo Shale (yellow), Lower Marcellus Shale (red), and Onondaga Limestone (green). The top 10-digit number is the API well identification number. The units labeled 0-200 and 200-400 at the top of the well are the API standard value range for radioactivity. The red gamma ray signature is 0-200 API, and blue signature is log wrap around at 200-400 API. Depths are recorded in feet below the reference elevation from which the log was measured.

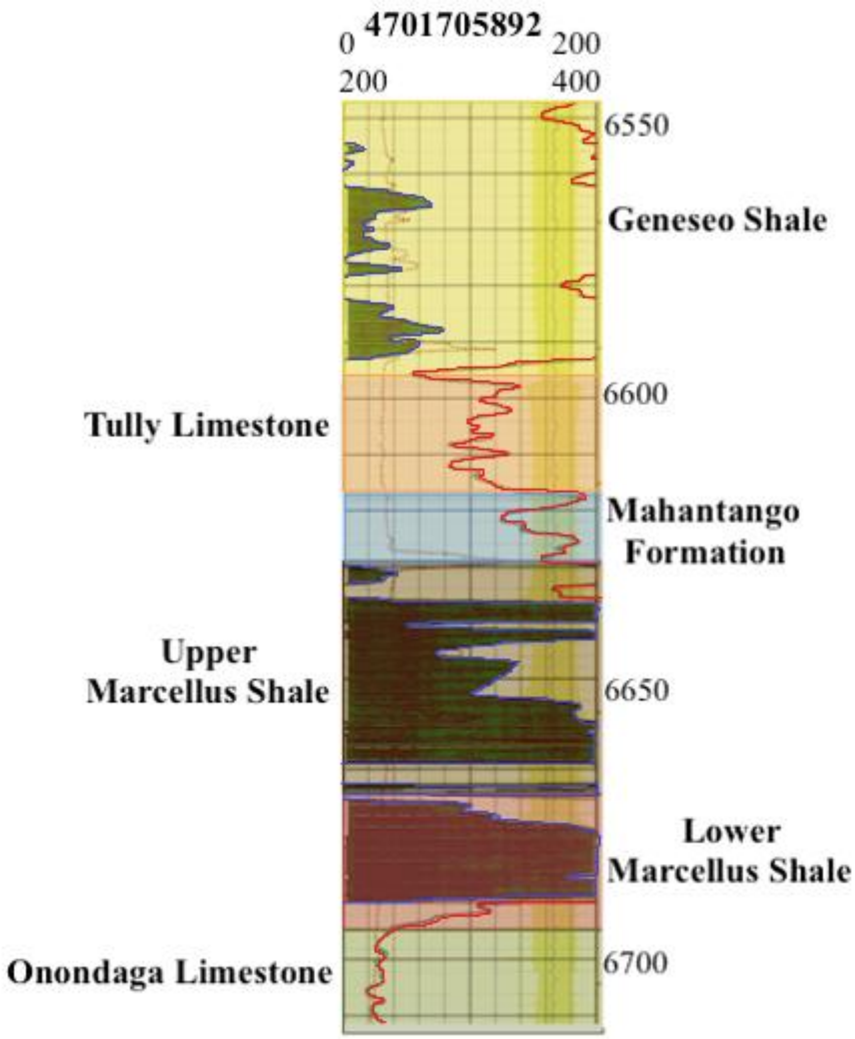


Figure 10. Typical Marcellus Shale gamma-ray log for Doddridge County, West Virginia. The displayed curve is the gamma-ray trend for the Geneseo Shale (yellow), Tully Limestone (orange), Mahantango Formation (blue), Upper Marcellus Shale (brown), Lower Marcellus Shale (red), and Onondaga Limestone (green). The top 10-digit number is the API well identification number. The units labeled 0-200 and 200-400 at the top of the well are the API standard value range for radioactivity. The red gamma ray signature is 0-200 API, and blue signature is log wrap around at 200-400 API. Depths are recorded in feet below the reference elevation from which the log was measured.

3.2.2 Cross Sections

In order to effectively define stratigraphy of the Marcellus Shale within Doddridge and Ritchie counties, gamma-ray logs downloaded from the WVGES pipeline database were used to make stratigraphic cross sections within the study area. A total of nine stratigraphic cross sections (Figure 12) were constructed across Doddridge and Ritchie counties to aid in understanding the stratigraphy of the Marcellus Shale and erosional features from the Taghanic unconformity exhibited within the unit. Cross sections 1-6 provide stratigraphic correlations from east to west and cross sections 7-9 provide stratigraphic correlations from north to south. Additionally, cross sections were used to determine thickness variations of the Marcellus Shale within the counties. Wells for the cross section transects were chosen of the basis of available gamma-ray data and best depiction of stratigraphic trends within the study area. Additionally, transects were chosen so that the cross sections were as straight across the counties in order to get the best depiction of stratigraphy and thicknesses. Three wells within Harrison County, two wells within Wirt County, and one well within Tyler County, were also used to in order to understand thicknesses and correlate trends most effectively. Cross sections were constructed from color-coding of well log lithologies as seen in Figures 10 and 11 above. Each cross section contains a vertical scale that varies for each section.

Within this study**,** the Geneseo Shale was chosen as the upper defining stratigraphic unit and the Onondaga Limestone was used for the lower defining stratigraphic unit. Both units were chosen based on their easily identifiable gamma-ray signatures and lateral continuity within Doddridge and Ritchie counties. The Geneseo was chosen as the datum line for all cross sections due to its continuous nature throughout the study area. Units presented within the cross sections include the Geneseo Shale, Tully Limestone, Mahantango Formation, the upper Marcellus Shale, lower Marcellus Shale, and Onondaga Limestone.

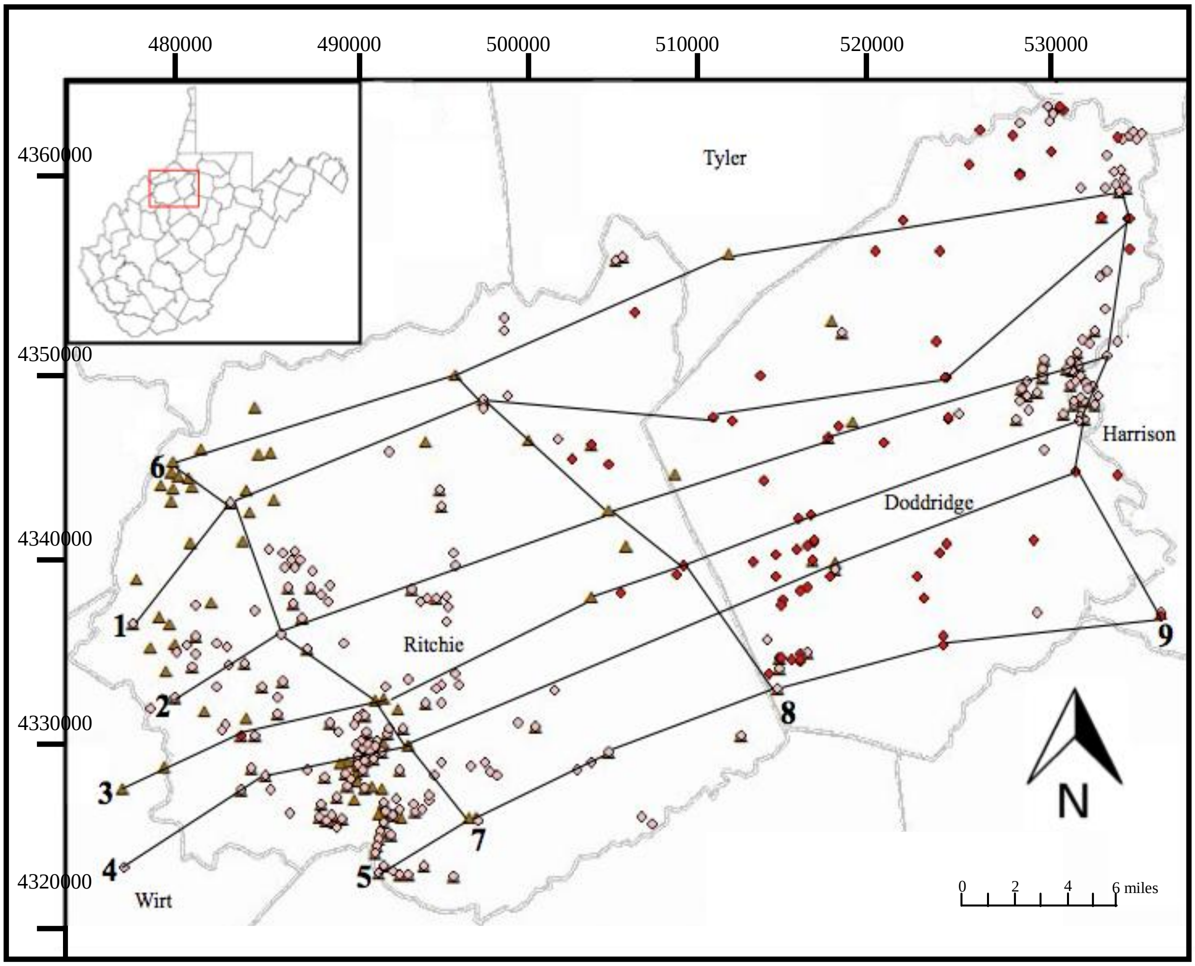


Figure 12. Location of transect used for cross sections. Lines indicate cross sections. Dots represent completed well locations from the West Virginia Geological and Economic Survey. Triangles represent well locations with available geophysical logs from the West Virginia Geological and Economic Survey.

3.3 MAPPING

3.3.1 Isopach Maps

Within the study area, isopach maps were created for the Tully Limestone, Mahantango Formation, upper Marcellus Shale, lower Marcellus Shale, and total Marcellus Shale. Data for these maps were gathered from thickness assessment of the units determined from wells used in constructing stratigraphic cross sections (Figure 12) as well as surrounding available data within the study area. Isopach maps were used as a tool to exemplify thickness variations as well as erosional removal of the units attributed to the Taghanic unconformity within the study area. Isopach maps were generated using the software, Surfer, which uses a grid method for contouring. This method includes XYZ data files, where X and Y were the well log locations in the study area and Z was the thickness of the unit. X and Y data was collected from UTM easting and northing coordinates obtained from the West Virginia Geological and Economic Survey “Marcellus Interactive Mapping” tool. Z data was collected from analysis of gamma-ray and corresponding density logs to determine unit thickness. Once data are input for grids, Surfer creates a regularly spaced file, which is ready for contour use. Within each map, the contour interval varies and was chosen based on best available depiction of thickness variations within the study area.

3.3.2 Structure Contour Map

In addition to isopach maps, a structure contour map of the top of the Onondaga Limestone was constructed. Data for this map were determined from the depth the of the boundary between the Marcellus Shale and the Onondaga Limestone from wells used in constructing stratigraphic cross sections (Figure 12) as well as surrounding available data within the study area. Additionally, depths for each unit were corrected for the corresponding elevations for each well log provided from log header. The data were used to draw a structure contour map to understand the structural trend of the Marcellus Shale within the study area. The structure contour map was also created through Surfer software by the same XYZ method used as the isopach maps. X and Y were the well log locations in the study area collected from UTM easting and northing coordinates obtained from the West Virginia Geological and Economic Survey “Marcellus Interactive Mapping” tool. The Z value is the depth of the bottom of the Marcellus Shale and the top of the Onondaga Limestone. Z data were collected from analysis of gamma-ray and corresponding density logs to determine unit depths. The contour interval was chosen on best available depiction of structure variations within the study area.

3.3.3 Production Maps

Production data from Doddridge and Ritchie counties were used to establish a workflow to evaluate Marcellus Shale production in relation to the Taghanic unconformity. Data were chosen based on the availability from the WVGES Pipeline database and also the lateral continuity of production data within Doddridge and Ritchie counties. Two types of gas extraction methods, horizontal and vertical, were identified within the two counties. Data for these maps were compiled from the first twelve months of Marcellus Shale production after completion of vertical or horizontal wells from data used in constructing stratigraphic cross sections (Figure 12) as well as surrounding available data within the study area.

Averages of first twelve months of production were established on a well-to-well basis for each county based on either vertical or horizontal gas extraction method. These averages were then used to create two production contour maps, vertical extraction production and horizontal extraction production of the Marcellus Shale for Doddridge and Ritchie counties.

Production of the upper and lower Marcellus Shale was mapped as one unit due to the availability of data from the WVGES Pipeline database. The production maps were also created through Surfer software by the same XYZ method used as the isopach maps. X and Y were the well log locations in the study area collected from UTM easting and northing coordinates obtained from the West Virginia Geological and Economic Survey "Marcellus Interactive Mapping" tool. The Z value was the production value for the Marcellus Shale, which was collected from averages of first twelve months of production and was established on a well-to-well basis for each county. Mapping of production data was used as a tool to understand the relationship between the Taghanic unconformity and Marcellus Shale production within Doddridge and Ritchie counties.

3.4 GRAPHING

Graphing was completed to compare production of the Marcellus for the first twelve months within Doddridge and Ritchie counties. Two production graphs, one for vertical extraction production, one for horizontal production were created using Excel and displays a point line graph trend of production for the counties The horizontal scale on the graph is labeled 1-12 for each month of production. The vertical is labeled as Gas Produced (MCF), which corresponds to thousands of cubic feet (MCF) of gas produced. Production of the upper and lower Marcellus Shale was graphed as one unit due to the availability of data from the WVGES Pipeline database. Graphing of production data was used as a tool to understand the relationship between the discrepancies of production for gas extraction method used between the two counties as well as aid to understanding production trends in relation to the Taghanic unconformity.

3.5 PRODUCTION PARAMETERS

3.5.1 Gas Extraction Method

Additional production parameters were assessed to aid in understanding Marcellus Shale production variations within the study area. This included data collection of horizontally drilled Marcellus Shale wells versus vertically drilled Marcellus Shale wells within Doddridge and Ritchie counties. Data for this evaluation were gathered from wells used in the stratigraphic cross sections (Figure 11) as well as surrounding available data within the study area from the WVGES Pipeline database. Well drilling information is listed on the WVGES Pipeline database under the Pay/Show/Water information labeled as “section.” Once collected, data were assessed to determine the average of wells drilled vertically and the average of wells drilled horizontally within Doddridge and Ritchie counties. Averages were used to aid in assessment of quantity of gas produced within the study area attributed to gas extraction methodology.

4.0 RESULTS & DISCUSSION

4.1 STRATIGRAPHY

Stratigraphic trends, thickness variations, relative location of the Taghanic unconformity and lateral extent of the Geneseo Shale, Tully Limestone, Mahantago Formation, upper Marcellus Shale, lower Marcellus Shale, and the Onondaga Limestone within Doddridge and Ritchie counties, West Virginia, were determined from the nine cross sections as seen in Appendix A. Additionally, thicknesses of the units can be seen in Appendix B. Stratigraphic cross sections 3 and 4 and 8 are presented in Figures 14, 15, and 16 below.

4.1.1 Geneseo Shale

The well log lithology for the Geneseo Shale was determined by using the American Petroleum Institute (API) value range, the log signature and the corresponding density log. Increased gamma-ray levels were indicated for the Geneseo Shale, thus indicating a high abundance of radioactive material and a shale lithology. API values for the Geneseo Shale range from 175-300. Thicknesses for the Geneseo Shale were not determined due to the fact that the unit was used a top defining stratigraphic boundary only.

4.1.2 Tully Limestone

The well log lithology for the Tully Limestone was determined by using the American Petroleum Institute (API) value range, the log signature and the corresponding density log. Decreased gamma-ray levels were indicated for the Tully Limestone, thus indicating a low abundance of radioactive material and a non-shale lithology API values for the Tully Limestone range from 15-60. Thickness of the unit within the area varies considerably, ranging from 0-57 feet, and is greatest in northeast and southeast Doddridge County. Within Ritchie

County, the Tully Limestone becomes progressively thinner in the northwest and southwest and eventually is absent.

4.1.3 Mahantango Formation

The well log lithology for the Mahantango Formation was determined by using the American Petroleum Institute (API) value range, the log signature and the corresponding density log. API values for the Mahantango Medium to high gamma-ray levels were indicated for the Geneseo Shale, thus indicating a medium to high abundance of radioactive material and a shale type lithology Formation range from 50-200. Thickness of the unit within the area varies considerably, ranging from 0-115 feet, and is thickest in northeast and southeast Doddridge County. Within Ritchie County, the Mahantango Formation becomes progressively thinner towards the northwest and southwest and eventually is absent.

4.1.4 Upper Marcellus Shale

The well log lithology for the upper Marcellus Shale was determined by using the American Petroleum Institute (API) value range, log signature and the corresponding density log. Increased gamma-ray levels were indicated for the upper Marcellus Shale, thus indicating a high abundance of radioactive material and a shale lithology API values for the upper Marcellus Shale range from 5-400. These values differ from the overlying Mahantango, which is typically 160-185. Additionally, in areas where the Mahantango Formation is absent, the overlying unit is the Geneseo Shale, which has typical values of 175-300. Furthermore, the underlying unit, the lower Marcellus Shale, has typical values of 50-400. The upper Marcellus Shale was carefully distinguished from the lower Marcellus Shale through assessment of distinctive gamma-ray and corresponding density log trends.

Thickness of the unit within the area varies considerably ranging from 0-47 feet, and is thickest in northeast and southeast Doddridge County. Within Ritchie County, the upper Marcellus Shale becomes progressively thinner towards the northwest and southwest and eventually is absent

4.1.5 Lower Marcellus Shale

The well log lithology for the lower Marcellus Shale was determined by using the American Petroleum Institute (API) value range, log signature and the corresponding density log. Increased gamma-ray levels were indicated for the lower Marcellus Shale, thus indicating a high abundance of radioactive material and a shale lithology API values for the upper Marcellus Shale range from 50-400. These values differ from the overlying unit, the upper Marcellus Shale, which is typically 5-400. Additionally, in areas where the upper Marcellus Shale is absent, the overlying unit is the Geneseo Shale, which has typical values of 175-300. Furthermore, the underlying unit, the Onondaga Limestone, has typical values of 10-50. The lower Marcellus Shale was carefully distinguished from the upper Marcellus Shale through assessment of distinctive gamma-ray and corresponding density log trends.

Unlike the upper Marcellus Shale, the lower Marcellus Shale is laterally continuous within the study area. Thickness of the unit within the study area does vary ranging from 15-50 feet. Within northwest and southwest Ritchie County, thickness variations of the lower Marcellus Shale are pronounced.

4.1.6 Onondaga Limestone

The well log lithology for the Onondaga Limestone was determined by using the American Petroleum Institute (API) value range, the log signature and the corresponding density log. Decreased gamma-ray levels were indicated for the Onondaga Limestone, thus indicating a low abundance of radioactive material and a non-shale lithology API values for the Onondaga Limestone range from 10-50. The Onondaga Limestone is laterally continuous throughout the study area. Thicknesses for the Onondaga were not determined due to the fact that the unit was used a bottom defining stratigraphic boundary only.

4.1.7 Taghanic Unconformity

The Taghanic unconformity was identified at the base of the Geneseo Shale and top of the lower Marcellus Shale. Figure 13 below displays the relative location of the unconformity with respect to gamma-ray trends of the Geneseo Shale and lower Marcellus Shale.

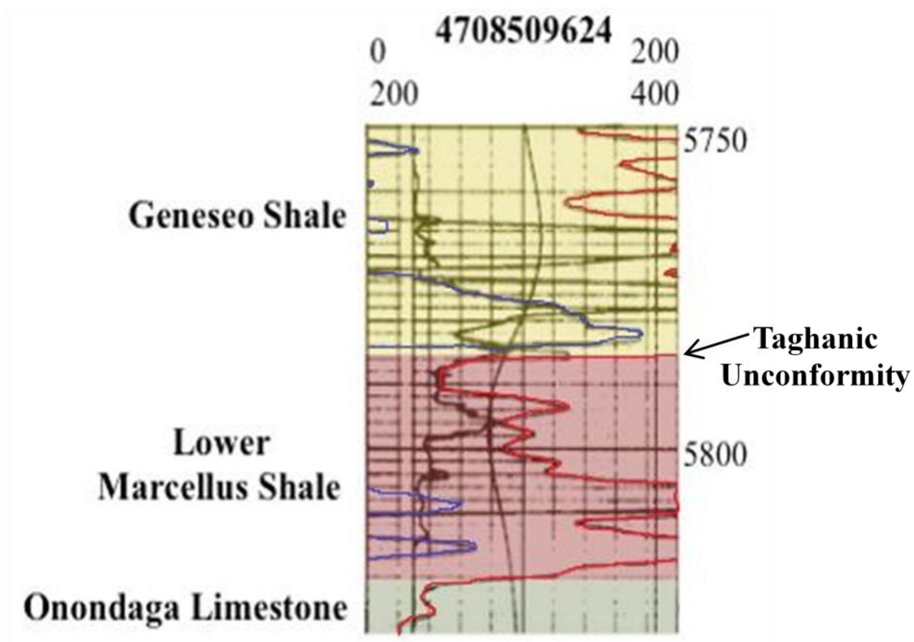


Figure 13. Relative location of the Taghanic Unconformity in a gamma ray log for Ritchie County, West Virginia. The displayed curve is the gamma-ray trend for the Geneseo Shale (yellow), Lower Marcellus Shale (red), and Onondaga Limestone (green). The top 10-digit number is the API well identification number. The units labeled 0-200 and 200-400 at the top of the well are the API standard value range for radioactivity. The red gamma ray signature is 0-200 API, and blue signature is log wrap around at 200-400 API. Depths are recorded in feet below the reference elevation from which the log was measured.

4.2 STRATIGRAPHIC CROSS SECTIONS

4.2.1 Stratigraphic Cross Section 3

Stratigraphic cross section 3 (Figure 14) consists of five well logs and has an east to west trend through Wirt, Ritchie, Doddridge, and Harrison counties. Within this cross section, the Geneseo Shale, lower Marcellus Shale and Onondaga Limestone are laterally continuous. Thickness of the lower Marcellus Shale is relatively constant at ~25 feet and is deepest at 7,565 feet in the easternmost log Harrison 5013 (API: 4703305013). The lower Marcellus Shale has a sharp base, which separates it from the underlying Onondaga Limestone. The API values of the lower Marcellus Shale decrease westward, which is suggestive of a decrease in organic shale content and a possibility of an increase of siliciclastic content from east to west.

Additionally, the Tully Limestone, Mahantango Formation and upper Marcellus Shale are shown on cross section 3. All three units become progressively thinner and are eventually absent in the westernmost logs. The Tully Limestone ranges from 5-28 feet where present in the cross section. The unit is absent in Ritchie 9833 (API: 4708509833) and is considerably thinner in Ritchie 4890 (API: 4708504890) relative to sections in the east. Furthermore, the Mahantango Formation averages from 4-88 feet where present in the cross section. Lastly, the upper Marcellus Shale averages from 22-28 feet where present in the cross section. The Mahantango Formation and upper Marcellus Shale have a similar pattern of absence and thinning as the Tully. The upper Marcellus is deepest at 7,565 feet is deepest in Harrison 5013 (API: 4703305013). Additionally, API values of the upper Marcellus Shale decrease westward, which is suggestive of a decrease in organic shale content a possibility of an increase of siliciclastic content from east to west.

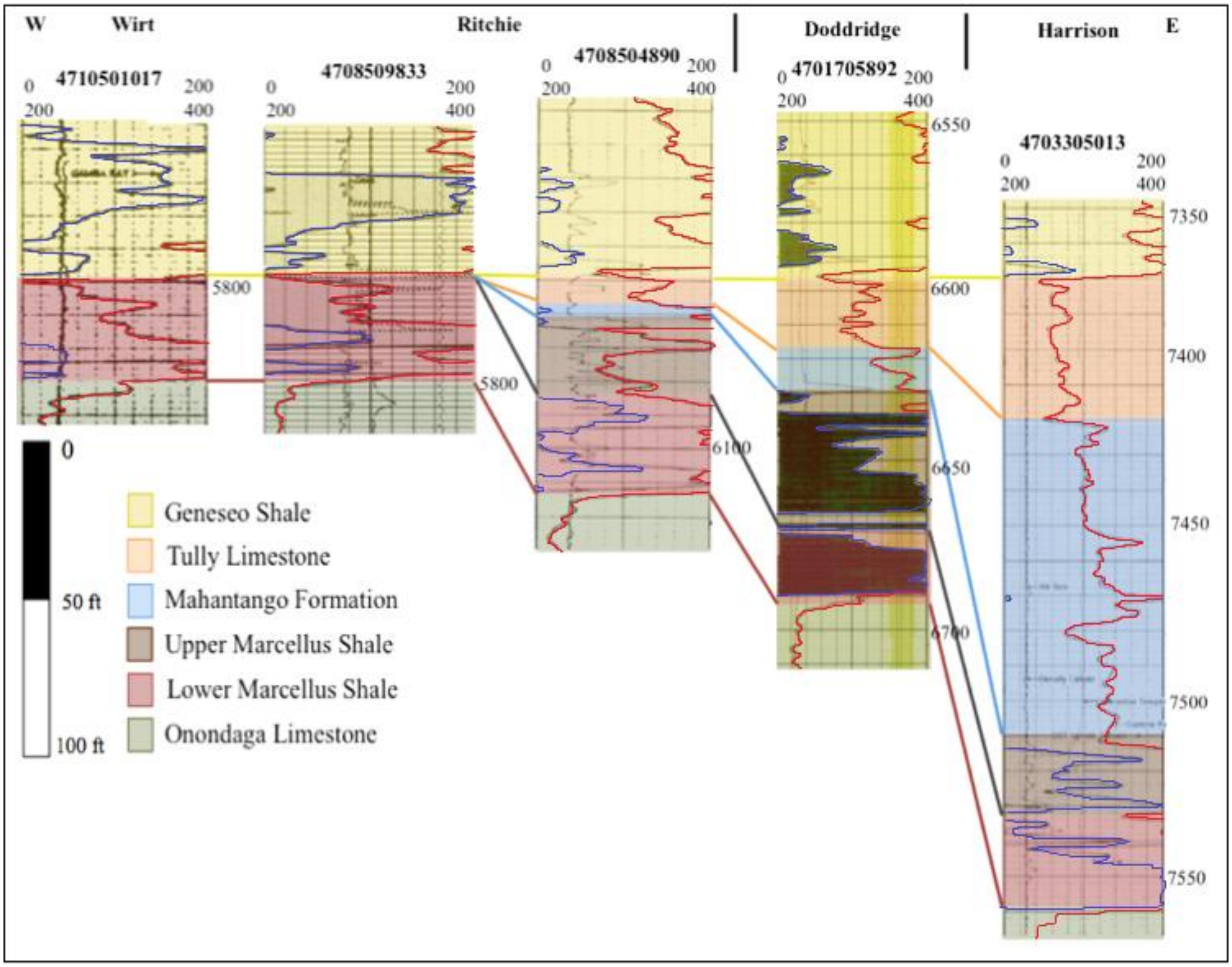


Figure 14. Stratigraphic cross section 3 along transect 3 in **Figure 12**. The logs displayed are gamma-ray logs with API values ranging from 0-400. The red gamma ray signature is 0-200 API, and blue signature is log wrap around at 200-400 API. Depths are recorded in feet below the reference elevation from which the log was measured. A vertical scale is provided along with well id (API) identification numbers at the top of each well. The datum line used for this cross section is the Geneseo Shale. The green shaded area represents the Onondaga Limestone, the red shaded areas represent the lower Marcellus Shale, the brown shaded areas represent the upper Marcellus Shale, the blue shaded areas represent the Mahantango Formation, the oranges shaded areas represent the Tully Limestone, and the yellow shaded areas represent the Geneseo Shale. The lower Marcellus Shale is laterally continuous across the transect, where as the upper Marcellus Shale is laterally discontinuous towards the east.

4.2.2 Stratigraphic Cross Section 4

Stratigraphic cross section 4 (Figure 15) consists of five well logs and has an east to west trend through Wirt, Ritchie and Doddridge counties. Within this cross section, the Geneseo Shale, lower Marcellus Shale and Onondaga Limestone are laterally continuous. Thickness of the lower Marcellus Shale ranges from 25-32 feet and is deepest at 7,600 feet in the easternmost log Doddridge 6227 (API: 4701706227). Thinning of the lower Marcellus is prominent from east to west. The lower Marcellus Shale has a sharp base, which separates it from the underlying Onondaga Limestone. The API values of the lower Marcellus Shale decrease westward, which is suggestive of a decrease in organic shale content a possibility of an increase of siliciclastic content from east to west.

Additionally, the Tully Limestone, Mahantango Formation and upper Marcellus Shale are shown on cross section 4. All three units become progressively thinner and are eventually absent in the westernmost logs. The Tully Limestone ranges from 8-15 feet thick where present in the cross section. Absence of the unit is first seen in Ritchie 9194 (API: 4708509194) followed by thinning in Ritchie 5924 (API: 47017055924). Furthermore, the Mahantango Formation ranges from 25-110 feet thick where present in the cross section. Absence of the unit is first seen in Ritchie 9194 (API: 4708509194) followed by thinning in Doddridge 5924 (API: 47017055924). Lastly, the upper Marcellus Shale ranges from 18-35 feet thick where present in the cross section. Absence of the unit is first seen in Ritchie 9624 (API: 4708509624) followed by thinning in Ritchie 9194 (API: 4708509194). The upper Marcellus is deepest at 7,560 feet is deepest in Doddridge 6227 (API: 4701706227). Additionally, API values of the upper Marcellus Shale decrease westward, which is suggestive of a decrease in organic shale content.

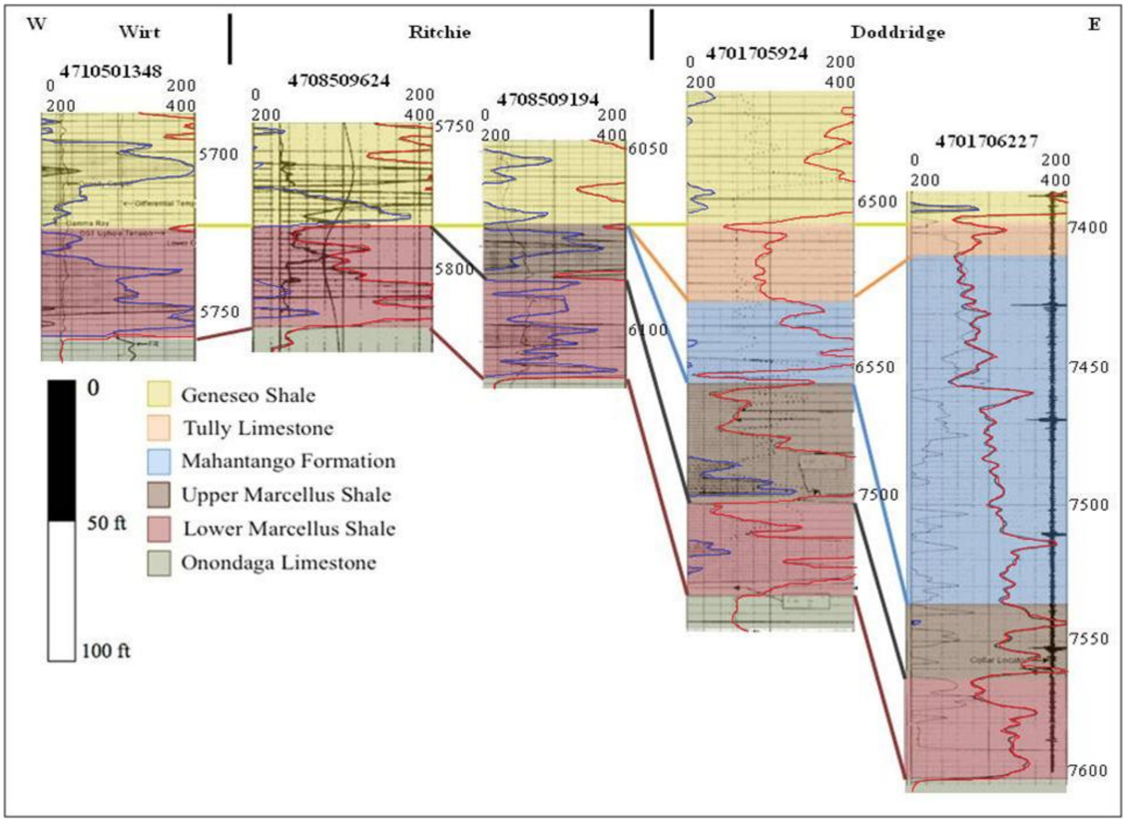


Figure 15. Stratigraphic cross section 4 along transect 4 in **Figure 12.** The logs displayed are gamma-ray logs with API values ranging from 0-400. The red gamma ray signature is 0-200 API, and blue signature is log wrap around at 200-400 API. Depths are recorded in feet below the reference elevation from which the log was measured. A vertical scale is provided along with well id (API) identification numbers at the top of each well. The datum line used for this cross section is the Geneseo Shale. The green shaded area represents the Onondaga Limestone, the red shaded areas represent the Lower Marcellus Shale, the brown shaded areas represent the Upper Marcellus Shale, the blue shaded areas represent the Mahantango, the oranges shaded areas represent the Tully Limestone, and the yellow shaded areas represent the Geneseo Shale. The Lower Marcellus is laterally continuous across the transect, where as the Upper Marcellus Shale is laterally discontinuous towards the east.

4.2.3 Stratigraphic Cross Section 8

Stratigraphic cross section 8 (Figure 16) consists of five well logs and has a north to south trend through Ritchie and Doddridge counties. Within this cross section, the Geneseo Shale, upper Marcellus Shale, lower Marcellus Shale and Onondaga Limestone are laterally continuous. Thickness of the lower Marcellus Shale ranges from 30-35 feet and is deepest at 6,290 feet in the easternmost log Doddridge 5629 (API: 4701705629). The lower Marcellus Shale has a sharp base, which separates it from the underlying Onondaga Limestone. Thickness of the upper Marcellus Shale ranges from 18-32 feet and is deepest at 6,265 feet in the easternmost log Doddridge 5629 (API: 4701705629). Thinning of the upper Marcellus is prominent from north to south and is credited to removal of portions of the unit through erosion from the Taghanic unconformity. The API values of the upper and lower Marcellus Shale decrease northward, which is suggestive of a decrease in organic shale content and a possibility of an increase of siliciclastic content from east to west.

Additionally the Tully Limestone, Mahantango Formation and upper Marcellus Shale are shown on cross section 8. All three units become progressively thinner and are eventually absent in the southernmost Ritchie County. The Tully Limestone ranges from 5-15 feet thick where present in the cross section. Thinning of the unit is first seen in Ritchie 9305 (API: 4708509305) followed by absence of the unit seen in Ritchie 9305 (API: 4708509305). Furthermore, the Mahantango Formation ranges from 4-15 feet where present in the cross section. Thinning of the unit is first seen in Ritchie 9305 (API: 4708509305) followed by absence of the unit seen in Ritchie 9305 (API: 4708509305).

Lastly, the upper Marcellus Shale ranges from 18-35 feet thick where present in the cross section. Thinning of the unit is first seen in Ritchie 9194 (API: 4708509194) followed by absence of the unit seen in Ritchie 9624 (API: 4708509624). The upper Marcellus is deepest at 7,560 feet is deepest in Doddridge 6227 (API: 4701706227). Additionally, API values of the upper Marcellus Shale decrease westward, which is suggestive of a decrease in organic shale content.

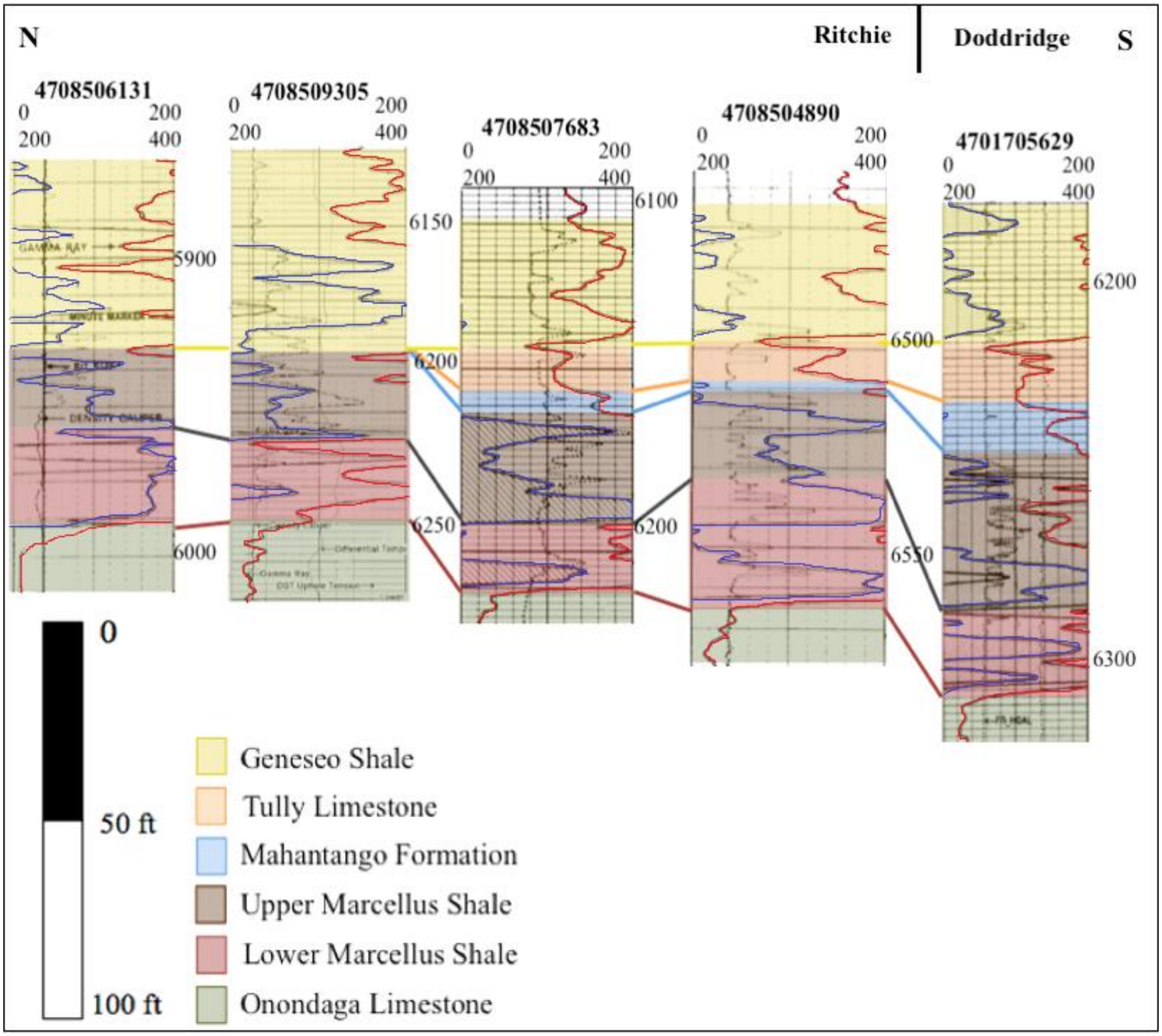


Figure 16. Stratigraphic cross section 8 along transect 8 in **Figure 12**. The logs displayed are gamma-ray logs with API values ranging from 0-400. The red gamma ray signature is 0-200 API, and blue signature is log wrap around at 200-400 API. Depths are recorded in feet below the reference elevation from which the log was measured. A vertical scale is provided along with well id (API) identification numbers at the top of each well. The datum line used for this cross section is the Geneseo Shale. The green shaded area represents the Onondaga Limestone, the red shaded areas represent the lower Marcellus Shale, the brown shaded areas represent the upper Marcellus Shale, the blue shaded areas represent the Mahantango Formation, the oranges shaded areas represent the Tully Limestone, and the yellow shaded areas represent the Geneseo Shale. The Upper and Lower Marcellus Shale are laterally continuous across the transect.

4.3 THICKNESS VARIATIONS

4.3.1 Isopach Maps

Thickness data of the Marcellus Shale were determined from all available data from the West Virginia Geological and Economic Survey (Appendix B). Isopach maps of the Tully Limestone, Mahantango Formation, upper Marcellus Shale, lower Marcellus, and the upper and lower Marcellus Shale combined were constructed in order to identify thickness variations within Doddridge and Ritchie counties (Figures 17-21).

4.3.1.1 Tully Limestone

Figure 17 displays an isopach map for the Tully Limestone. Thickness variations are present across the two counties with thicknesses of the unit ranging from 0-57 feet. The Tully Limestone is thickest in southeast and northeast Doddridge County ranging from 11-57 feet. Within Ritchie County, the Tully Limestone is thinnest ranging from 0-10 feet. This indicates a thickening trend of the unit from west to east. The most notable part of the map is the 0 foot isopach line, or the edge of the Tully. This line displays the extent of the Tully Limestone and indicates the erosional limit of the unit.

4.3.1.2 Mahantango Formation

Figure 18 displays an isopach map for the Mahantango Formation. Thickness variations are present across the two counties with thicknesses of the unit ranging from 0-115 feet. The Mahantango Formation is thickest in southeast and northeast Doddridge County ranging from 16-115 feet. Within Ritchie County, the Mahantango Formation is thinnest ranging from 0-15 feet. This indicates a thickening trend of the unit from west to east. The most notable part of the map was the 0 foot isopach line, or the edge of the Mahantango. This line displays the extent of the Mahantango Formation and indicates the erosional limit of the unit.

4.3.1.3 Upper Marcellus Shale

Figure 19 displays an isopach map for the upper Marcellus Shale. Thickness variations are present across the two counties with thicknesses of the unit ranging from 0-46 feet. The upper Marcellus Shale is thickest in southeast and northeast Doddridge County ranging from 30-47 feet. Within Ritchie County, the upper Marcellus Shale is thinnest, ranging from is 0-30 feet. This indicates a thickening trend of the unit from west to east. The most notable part of the map was the 0 foot isopach line, or the edge of the upper Marcellus. This line displays the extent of the upper Marcellus Shale and the close spacing of contours adjacent to the zero isopach line suggests it is an erosional limit of the unit.

4.3.1.4 Lower Marcellus Shale

Figure 20 displays an isopach map for the lower Marcellus Shale. The Lower Marcellus Shale is laterally continuous within the study area and is thickest in southeast and northeast Doddridge County. Thickness variations are present across the two counties with thicknesses of the unit ranging from 15-50 feet. Within Doddridge County the lower Marcellus Shale ranges from 36-50 feet and within Ritchie County the unit ranges from 15-36 feet. A thickening trend of the unit is apparent west to east from Ritchie to Doddridge. The most notable part of the map is the progressive thinning of the unit, which is apparent east to west from Doddridge to Ritchie. Uniform contours within the eastern half of the map followed by irregular contours to the west, suggests some erosional truncation to the west, but not sufficient erosion to remove the unit.

4.3.1.5 Total Marcellus Shale

Figure 21 displays an isopach map for the total Marcellus Shale thickness of the upper and lower Marcellus combined, which varies throughout the study area. In areas in Ritchie County where no upper Marcellus Shale was present, the lower Marcellus Shale value was used for total thickness. Thickness variations are present across the two counties with thicknesses of the unit ranging from 15-95 feet. Within Doddridge County the combined Marcellus Shale ranges from 55-95 feet and within Ritchie County the unit ranges from 15-60 feet. A thickening trend of the unit is apparent west to east from Ritchie to Doddridge. The most notable part of the map is the progressive thinning of the unit, which is apparent east to west from Doddridge to Ritchie.

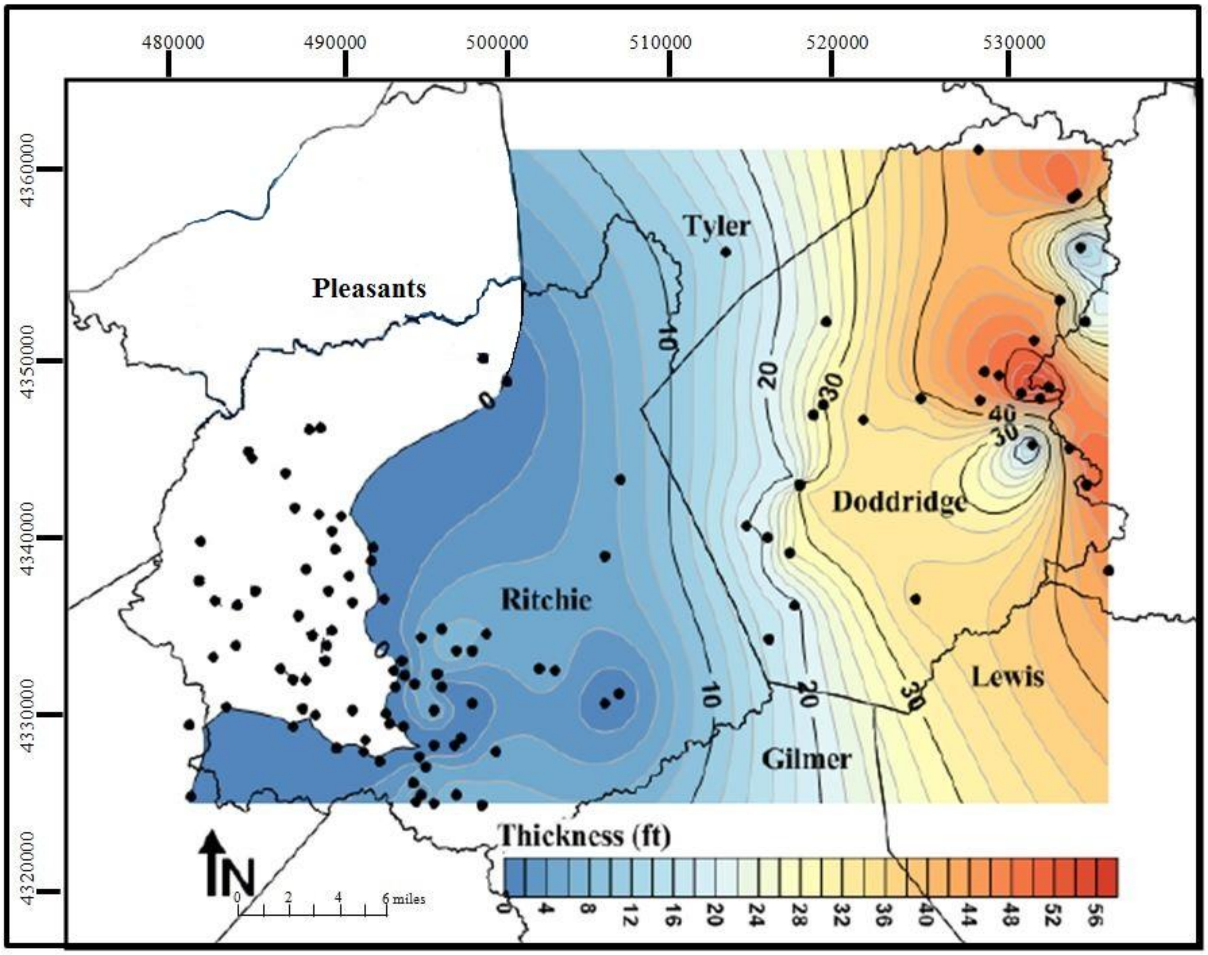


Figure 17. Isopach map for the Tully Limestone. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of red indicate thicker strata and the shades of teal indicate thinner strata. The Tully Limestone is thickest in northeast Doddridge County and thins and is absent in the eastern part of Ritchie County.

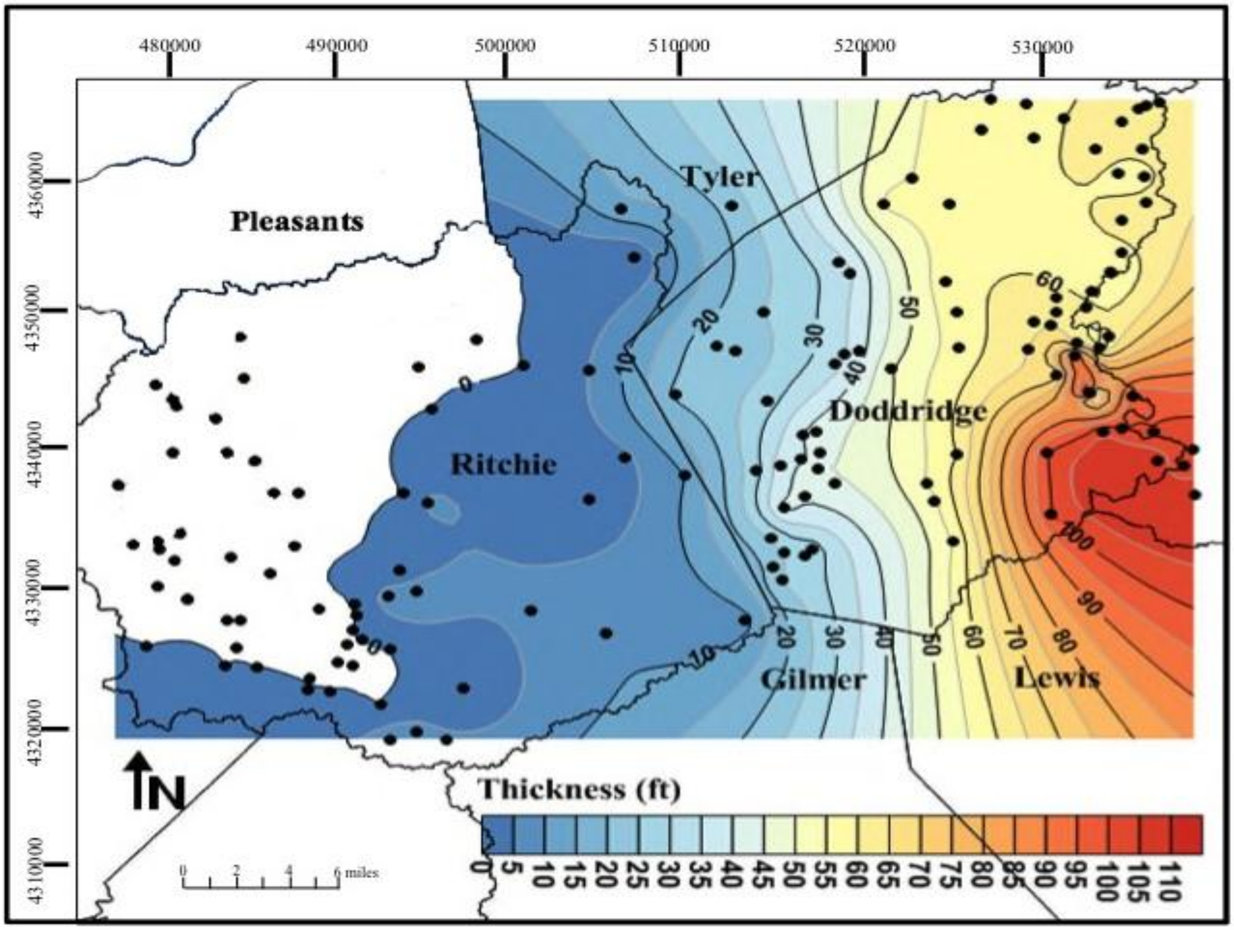


Figure 18. Isopach map for the Mahantango Formation. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of red indicate thicker strata and the shades of teal indicate thinner strata. The Mahantango Formation thickest in northeast Doddridge County and thins and is absent in the eastern part of Ritchie County.

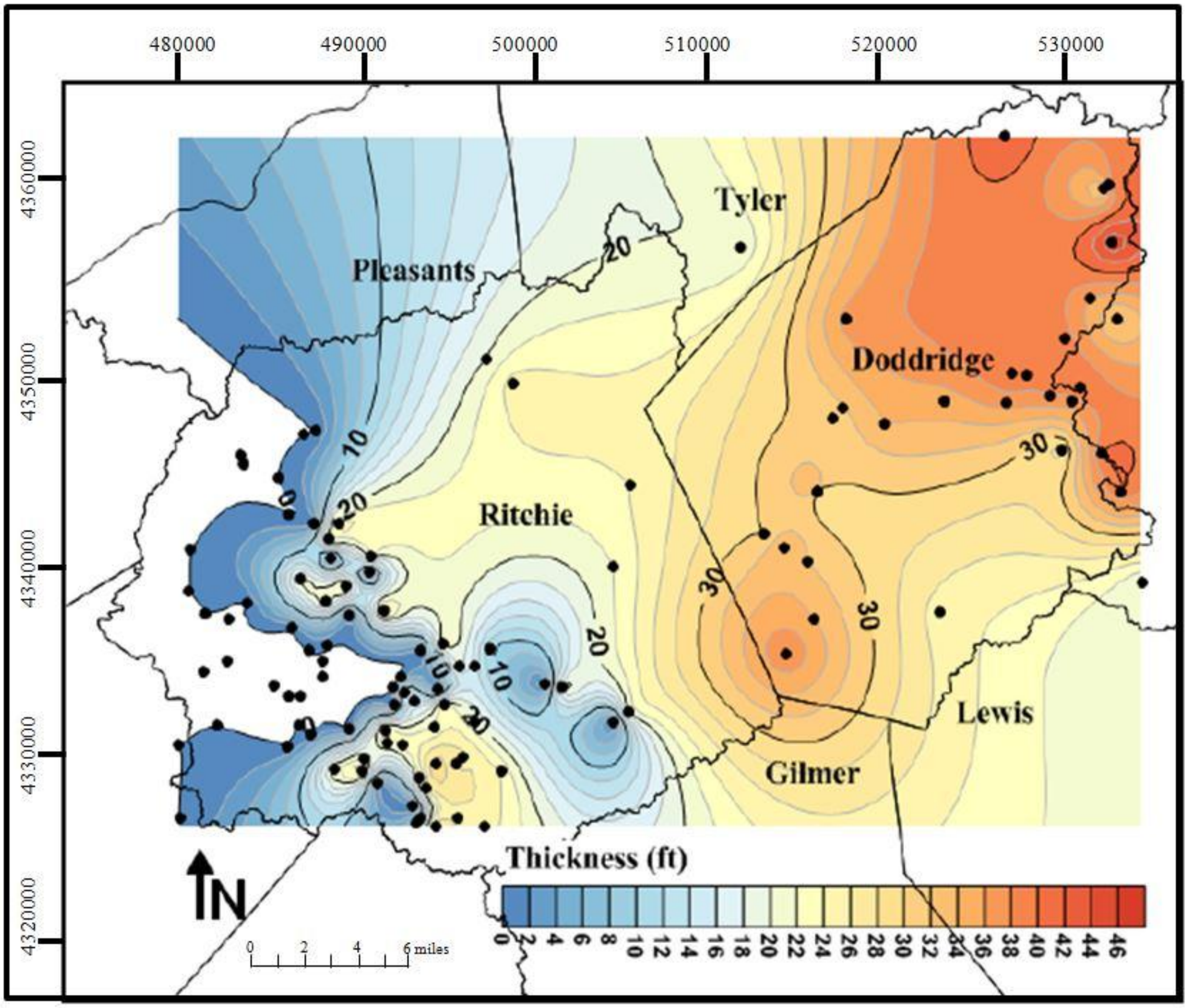


Figure 19. Isopach map for the upper Marcellus Shale. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of red indicate thicker strata and the shades of teal indicate thinner strata. The upper Marcellus Shale thickest in northeast Doddridge County and thins and is absent in the eastern part of Ritchie County.

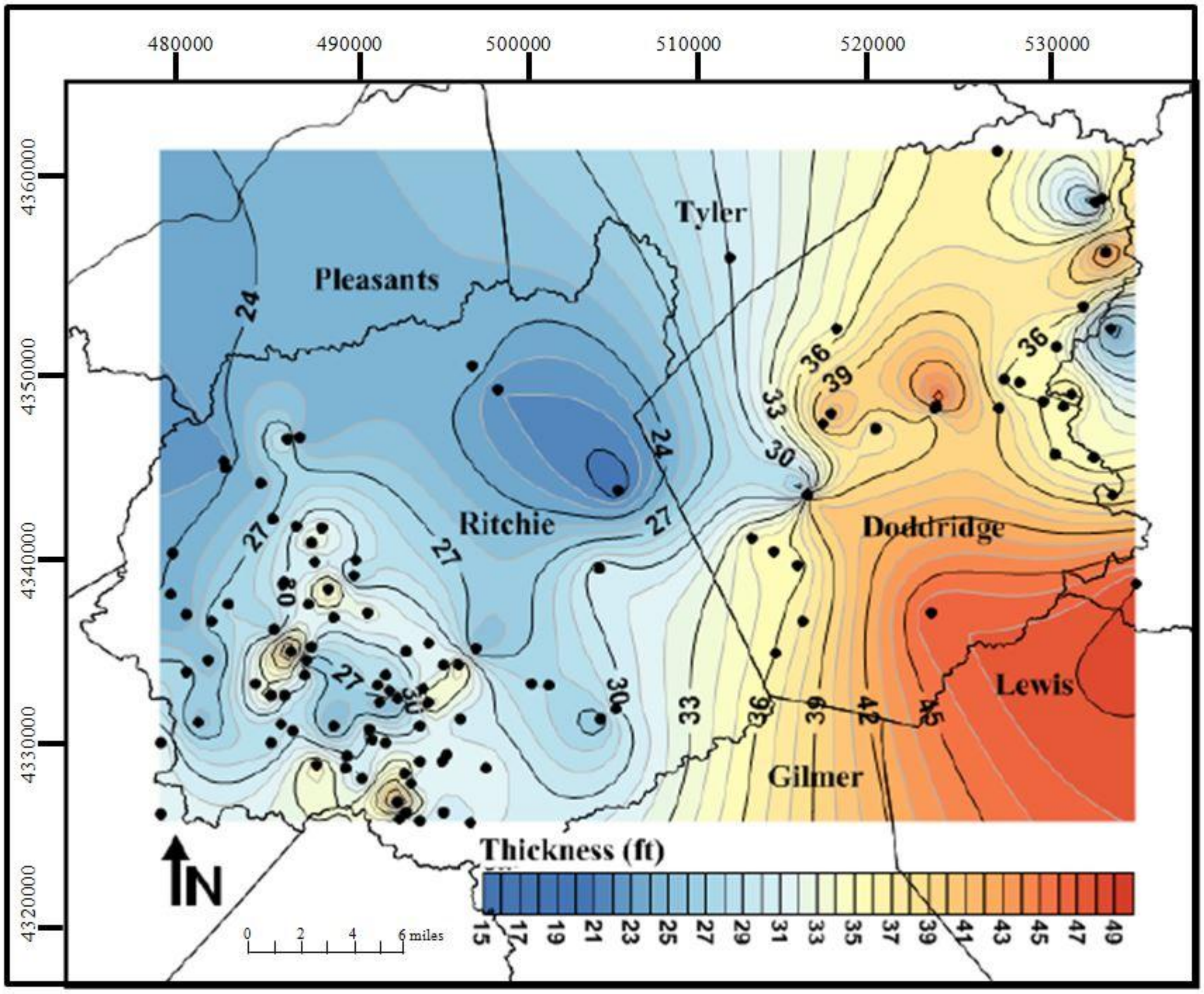


Figure 20. Isopach map for the lower Marcellus Shale. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of red indicate thicker strata and the shades of teal indicate thinner strata. The lower Marcellus Shale thickest in northeast Doddridge County and thins in western Ritchie County

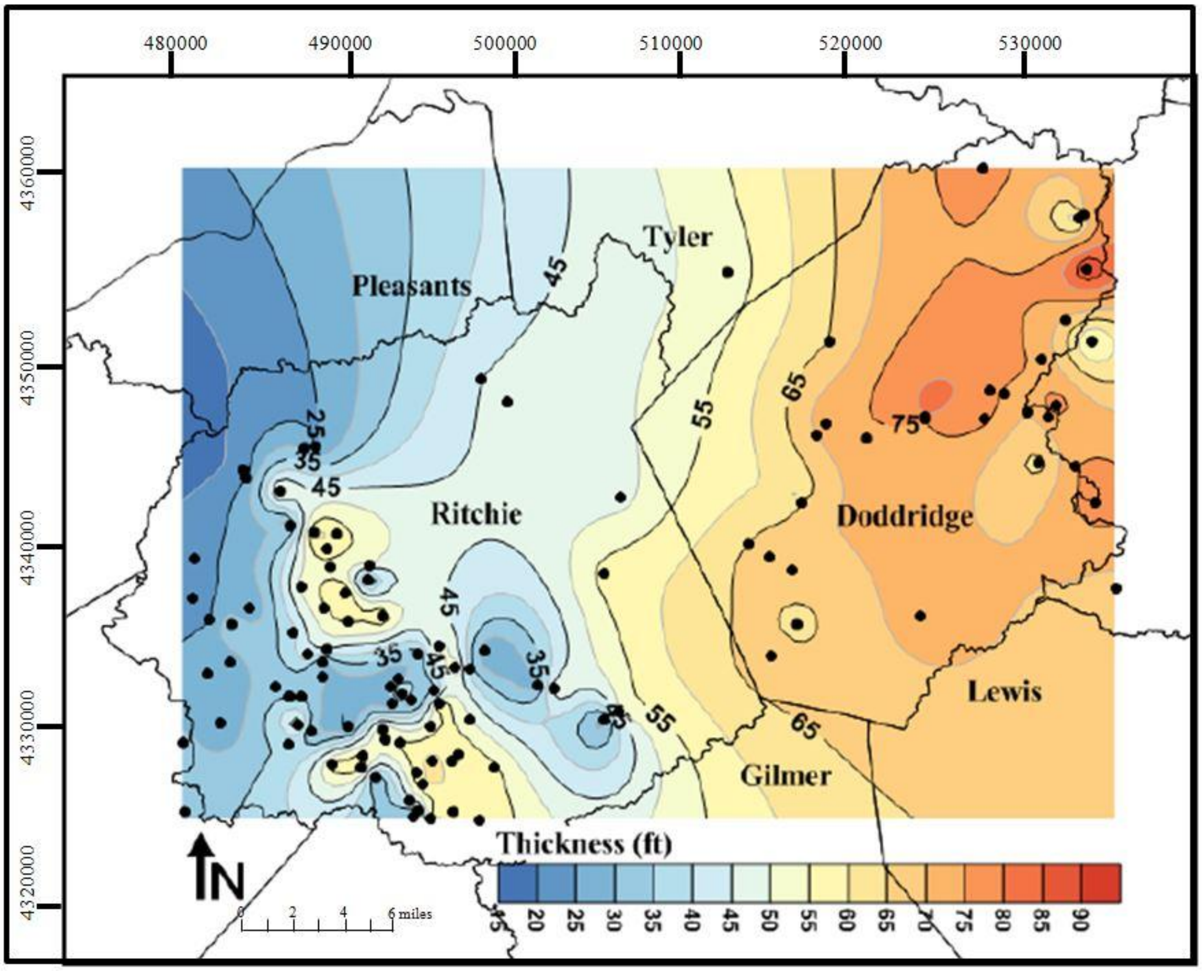


Figure 21. Isopach map for Total Marcellus Shale. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of red indicate thicker strata and the shades of teal indicate thinner strata. The upper and lower Marcellus Shale is thickest in northeast Doddridge County and thins in western Ritchie County.

4.4 MARCELLUS SHALE THINNING AND REMOVAL

4.4.1 Structural Controls

Within West Virginia, the possibility of structural control on the thinning and removal of the Marcellus Shale exists and coincides with the western boundary fault of the Rome Trough. Figure 22 displays the relative location of the northeast Rome Trough graben structure in West Virginia, which lies roughly -6000 feet below the land surface towards the southwest to -7400 feet below the land surface towards the northeast (Harris, 1978). The possibility of deepening of the Marcellus Shale occurs towards the northeast of the state due to the deepening of structural trends. Previous studies characterize the Rome Trough as a fault-bounded graben within a continental rift system (Kulander & Ryder, n.d.). Kulander (2001) reported the possibility of reactivation and uplift along the western border fault of the Rome Trough. Boyce (2010) suggested the presence of paleo-structures that influenced deposition of the Onondaga Limestone and subsequent Marcellus Shale.

A structure contour map (Figure 23) was developed and used as a tool to define possible structural trends associated with the Rome Trough within Doddridge and Ritchie counties. The map was created by taking depths below sea level of the bottom of the Marcellus Shale, from available data from the West Virginia Geological and Economic Survey (Appendix C). In western Doddridge County, the Marcellus ranges from -6000 to -6800 feet below sea level. In central Doddridge County and central Ritchie County, the Marcellus Shale is shallower and ranges from -5400 to -5600 feet below sea level. In Ritchie County, the Marcellus is found at depths ranging from -3400 to -5200 feet below sea level where it approaches the Burning Springs anticline.

Most noticeable in the map is a rapid eastward-deepening trend near the border between Ritchie County and Doddridge County. Additionally, Doddridge County appears to have more variable relied on the structural surface, as indicated by the multiple closed contours. This pattern is suggestive of a steepening slope or the possibility of faulting between the two areas. As seen in Figure 22, the Marcellus Shale within Doddridge and Ritchie counties is potentially impacted by the Rome Trough and associated faults. Erosion of the units may result from uplift of the western margin of the Rome Trough due to reactivation of basement faults allowing for the folding and subsequent truncation of the uplifted strata, however the trends presented in Figure 23 suggest they are a result of Alleghenian deformation rather than Acadian or reactivation of the Rome Trough.

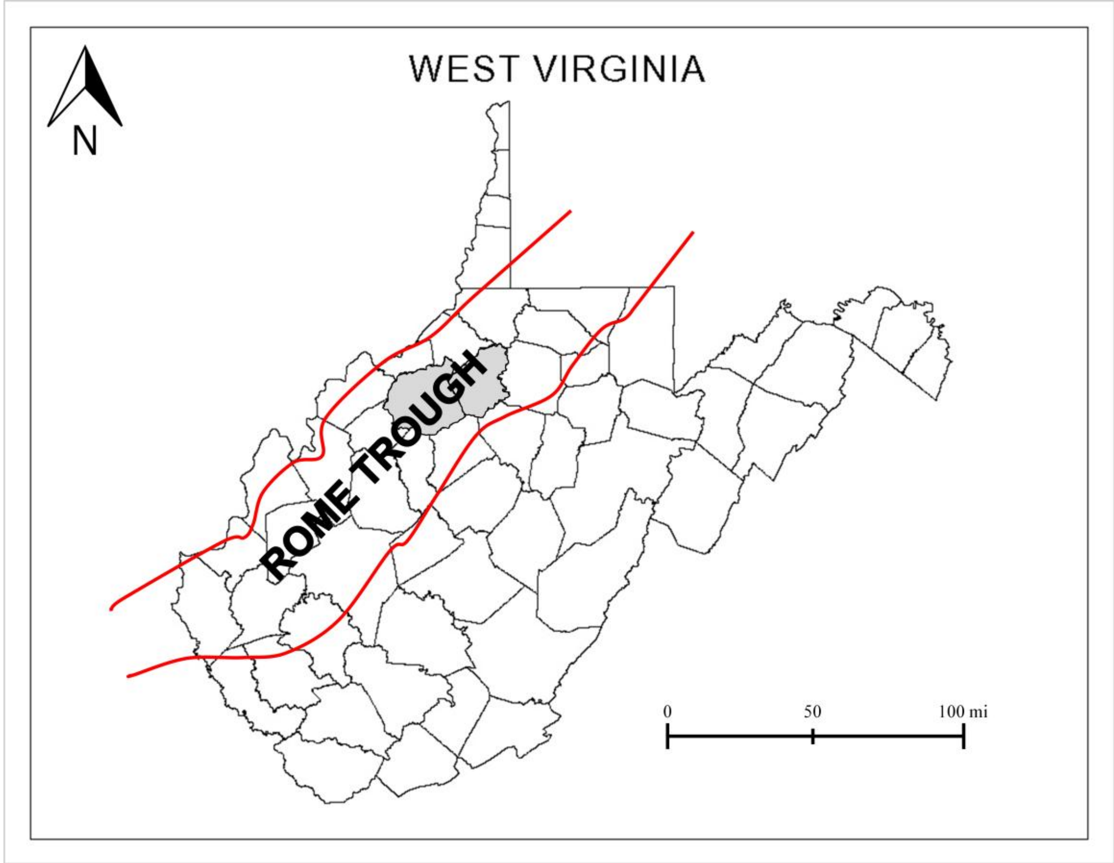


Figure 22. Red lines showing extent of faults, which bound the Rome Trough graden structure in West Virginia. Grey shaded areas are Doddridge and Ritchie counties. Modified from McDowell et al. (2014).

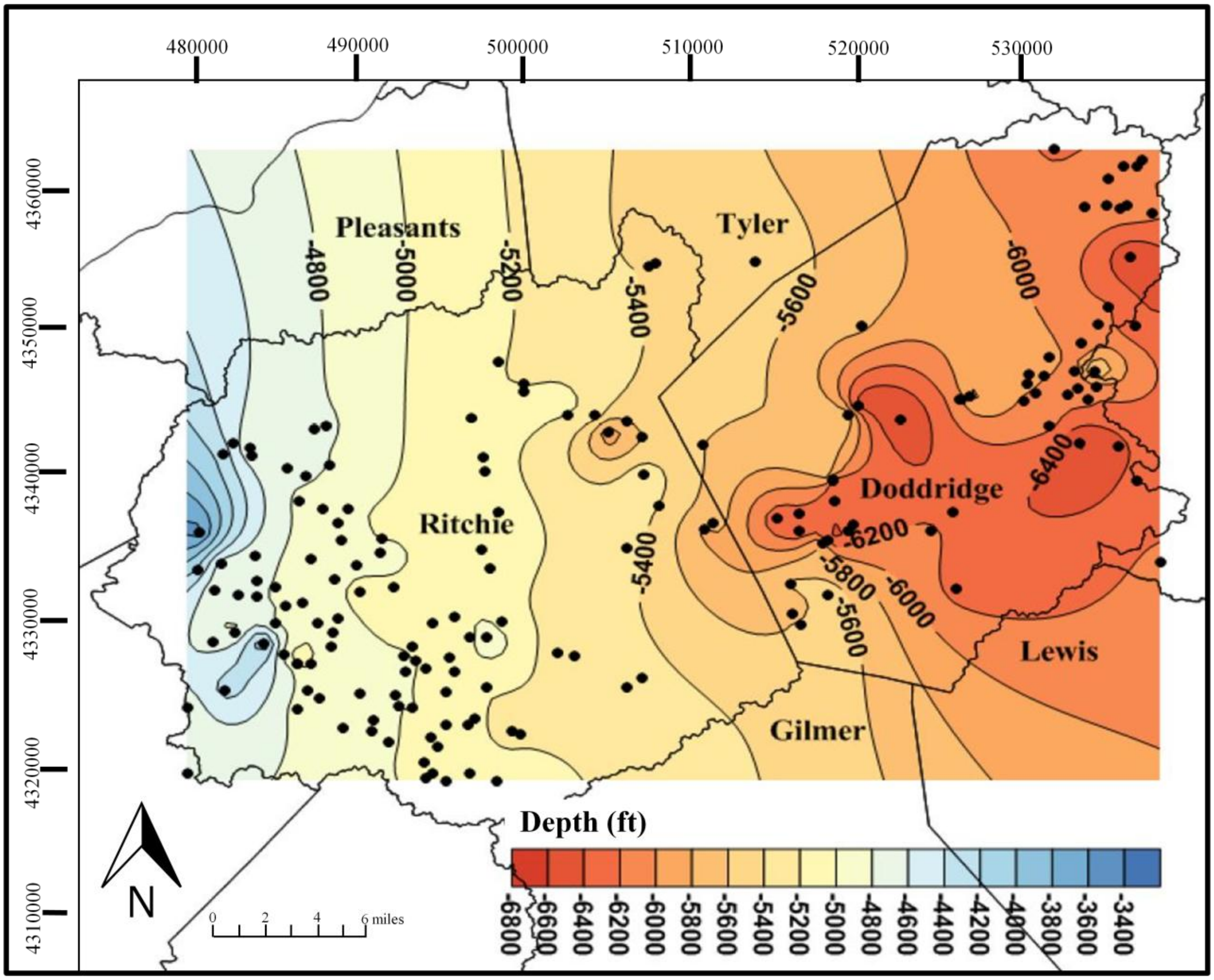


Figure 23. Structure contour map of the bottom of the lower Marcellus Shale and top of the Onondaga Limestone in Doddridge and Ritchie counties. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of dark red indicate structurally deeper areas and the shades of blue indicate structurally shallower areas. The Marcellus Shale is structurally deeper in northeast Doddridge County and becomes structurally shallower towards the west within Ritchie County.

4.4.2 Sea-Level Controls

During the Middle Devonian, changes in sea-level may have played a large role in controlling stratigraphic variations and thickness disparities of the Tully Limestone, Mahantango Formation, Upper Marcellus Shale, and Lower Marcellus Shale. These units formed during the Eifelian-Givetian, during periods of sea-level rise. In addition, the Taghanic unconformity, which occurred is in response to a decrease in sea-level (Ettensohn & Barron, 1981). The erosional surface occurred during the Givetian, and is considered a major sequence boundary of second order magnitude that is associated with an abrupt fall in sea-level (Johnson et al., 1985). This sea-level fall coupled with the previous periods of sea-level rise, suggests periods of oscillations in sea-level cycles. In Ritchie County, the Taghanic unconformity was identified at the base of the Geneseo Shale and top of the lower Marcellus Shale, which would have allowed for sub-aerial erosive processes to occur. This would have left these units exposed to a variety of weathering processes allowing thinning and/or removal.

4.4.3 Possible Scenarios

Within Doddridge and Ritchie counties, thickness variations of the upper Marcellus are noticeable. As seen in the isopach maps and the cross sections (Figures 17-21), the upper Marcellus Shale is thickest towards the east of the study area (Doddridge County) and begins to thin towards the west (Ritchie County). Additionally, stratal inconsistencies of the upper Marcellus Shale such as thinning or absence of the unit are seen in towards the east of the study area. As cited in Baird and Brett (1986), explanations for thickness variations and removal of black shales are attributed to the erosional surfaces as a result of the Taghanic unconformity during a period of sea level fall. The Taghanic unconformity is unusual in the sense that it occurred during a period of sea level fall, which allowed for basal discontinuities of units such as paleontologic and lithologic changes and reworking of sediments (Baird & Brett, 1986). During this time within the late Devonian, the Appalachian basin was undergoing a transformational period in which weathering and erosional features on strata outweighed uplift of the Acadian Mountains (Ettehnsohn & Barron, 1981).

Previously mentioned in section 4.1, stratigraphic correlations allowed for the recognition of the erosional surface related to the Taghanic unconfomity. Similar studies have identified erosional features seen within intervals of correlative units from New York, Pennsylvania, and Kentucky (Baird, 1979; Baird & Brett, 2006; Brett, Baird, and Bartholomew, 2004). Within these areas, the Taghanic unconformity has locally removed portions or all of the subjacent Middle Devonian units. Additionally, limestone units similar to the Tully overlie regionally extensive unconformities at the basin margins, which are interpreted as depositional sequence boundaries (Baird, 1979). Similar characteristics such as thinning or absence of units were exhibited throughout sequence stratigraphy within Doddridge and Ritchie counties, which were interpreted to be subaerial erosion surfaces that developed during low stands of sea-level (Baird & Brett, 1986)(Figure 24). The concurrence of the zero isopachs of the upper Marcellus Shale, Mahantango Formation and Tully Limestone suggests these limits are erosional rather than depositional. As previously mentioned, the degree of erosion may result from uplift of the western margin of the Rome Trough due to reactivation of basement faults allowing for the folding and subsequent truncation of the uplifted strata. Alternatively, a fault roughly parallel to these structures, but unrelated to the basement structures and active prior to the deposition of the Geneseo Shale allowed for the erosion of units down to the lower Marcellus Shale on the upthrown block and preservation of these strata on the downthrown block. There is no way to definitively argue for one scenario or the other based on the available data.

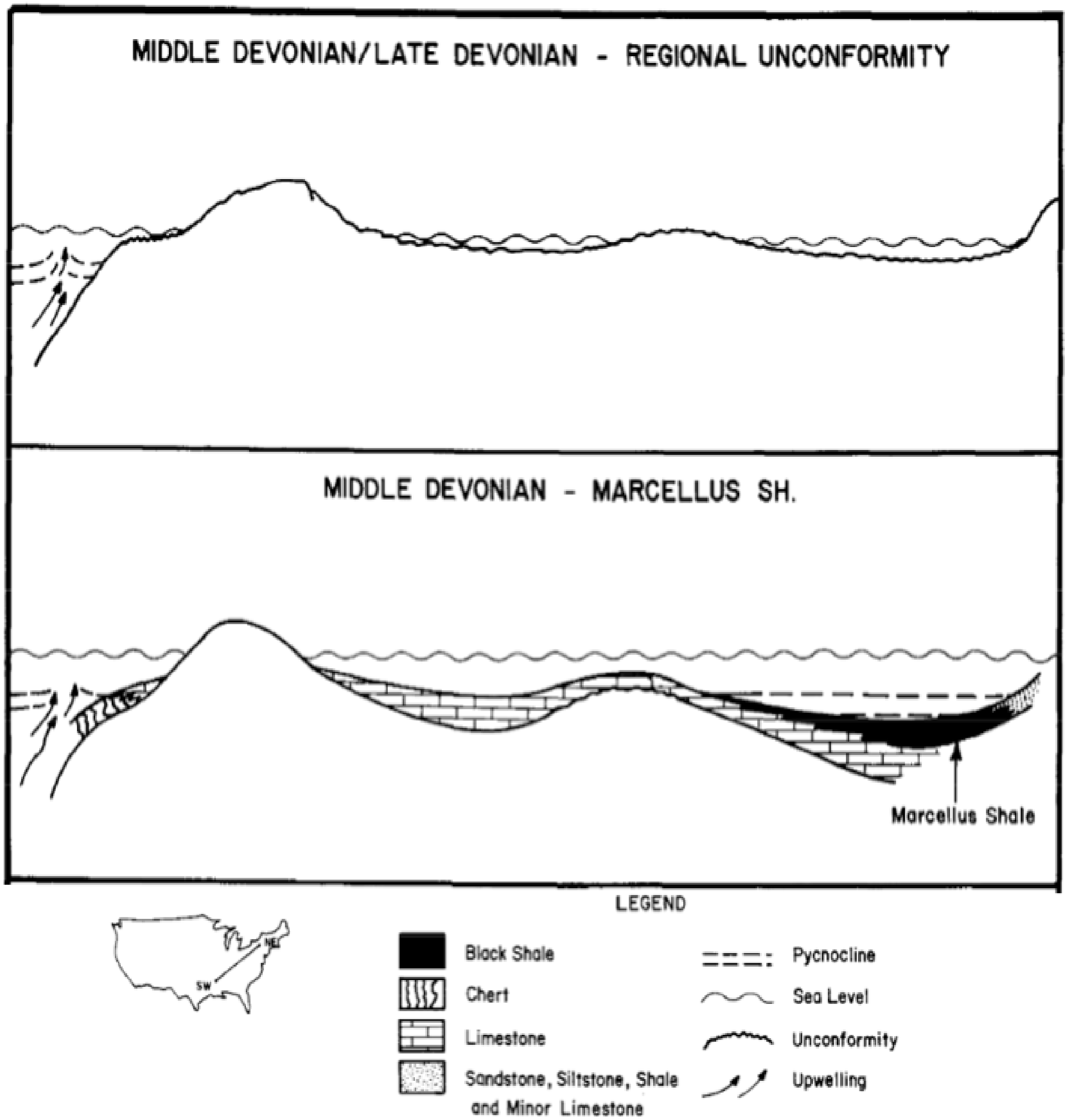


Figure 24. Schematic cross sections of Middle/Late Devonian strata undergoing erosional features that are attributed to the Taghanic unconformity. From Etthensohn and Barron (1981).

4.5 PRODUCTION

4.5.1 Gas Extraction Method

A factor to consider when assessing production trends within Doddridge and Ritchie counties is the extraction method used to obtain the natural gas of the Marcellus Shale. Within the study area, two possible extraction methods exist, which include vertical drilling and horizontal drilling. Vertical drilling as seen in "A" in Figure 25 involves drilling a well straight until the drill bit reaches the formation being developed (Fox, n.d.). Horizontal drilling as seen in "B" in Figure 25 is a drilling process in which the well is turned horizontally at depth to reach the formation being developed (Curtis & Klemow, 2011). Vertically drilled wells are only able to access the natural gas that immediately surrounds the well bore. Horizontal wells are able to access the natural gas surrounding the entire portion of the horizontally drilled section. Overall, horizontally drilled wells allow for better extraction and recovery of natural gas. Within Ritchie County the most common extraction method is vertically drilled wells. Of the 94 sampled wells within the county, 88 were drilled vertically with only 6 drilled horizontally. Within Doddridge County, the primary extraction method was horizontal drilling. Of the 67 sampled wells within the county, 53 were drilled horizontally with only 14 drilled vertically.

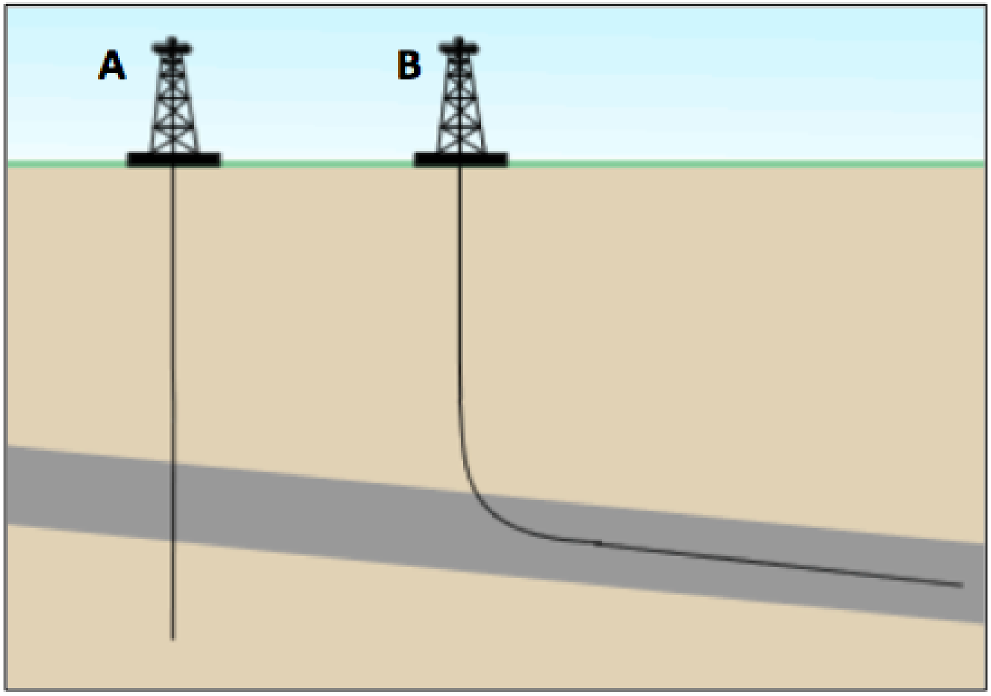


Figure 25. Vertical drilling method "A" versus horizontal drilling method "B." Modified from King (2015).

4.5.2 Production Trends

In order to aid in understanding production trends within Doddridge and Ritchie counties, West Virginia, production maps based on gas extraction methods for Doddridge and Ritchie countries were created using the values of the first twelve months of production from producing Marcellus Shale wells only. Maps were created to show production for vertically drilled versus horizontally drilled wells within the two counties. All available data for production were collected from the West Virginia Geological and Economic Survey (Appendix D). Production values were in thousands of cubic feet (MCF) of gas produced. Additionally, a production chart was generated for Doddridge and Ritchie countries displaying averages of first twelve months of production within the study area for the vertical gas extraction method and for the horizontal extraction method.

Figure 26 is a production map for all vertically drilled wells within Doddridge and Ritchie counties representing averages for the first twelve months of production. Averages are in thousands of cubic feet of gas (MCF) produced, which were taken from available production data from the WVGES. Averages for Ritchie County range from 1,000 to 50,000 MCF, which vary dramatically as compared to Doddridge County, which range from 45,000 to 110,000 MCF. This large difference in production values between the two counties may be attributed to the fact that the majority of Marcellus Shale present within Doddridge County is a complete section versus within Ritchie County where the majority of the Marcellus Shale is truncated. An additional factor to consider, which are reservoir properties will further be discussed in section 4.5.5. A comparative analysis for the two counties can be seen in Figure 27, which is a chart displaying the first twelve months production trends for the Marcellus Shale for vertically drilled wells only, which were calculated based on an average of all wells for each month. The highest production values are illustrated within both counties during the first month with averages of 13,900 MCF within Doddridge County and 1,900 MCF within Ritchie County. After this, a typical decline for both counties is seen with averages of 8,000 MCF in Doddridge County and 850 MCF in Ritchie County for the last producing month.

Figure 28 is a production map for all horizontally drilled wells within Doddridge and Ritchie counties for the first twelve months of production. Averages are in thousands of cubic feet of gas (MCF) produced, which were taken from available production data from the WVGES. Averages for Ritchie County range from 13,000 to 2,400,000 MCF, which vary dramatically as compared to Doddridge County, which range from 13,000 to 1,600,000 MCF. A comparative analysis for the two counties can be seen in Figure 29, which is a chart displaying the first twelve months production trends for the Marcellus Shale for horizontally drilled wells only, which were calculated based on an average of all wells for each. The highest production values are illustrated within both counties during the first month with averages of 150,000 MCF within Doddridge County and 118,000 MCF within Ritchie County. After this, a typical decline for both counties is seen with averages of 62,000 MCF in Doddridge County and 56,000 MCF in Ritchie County for the last producing month.

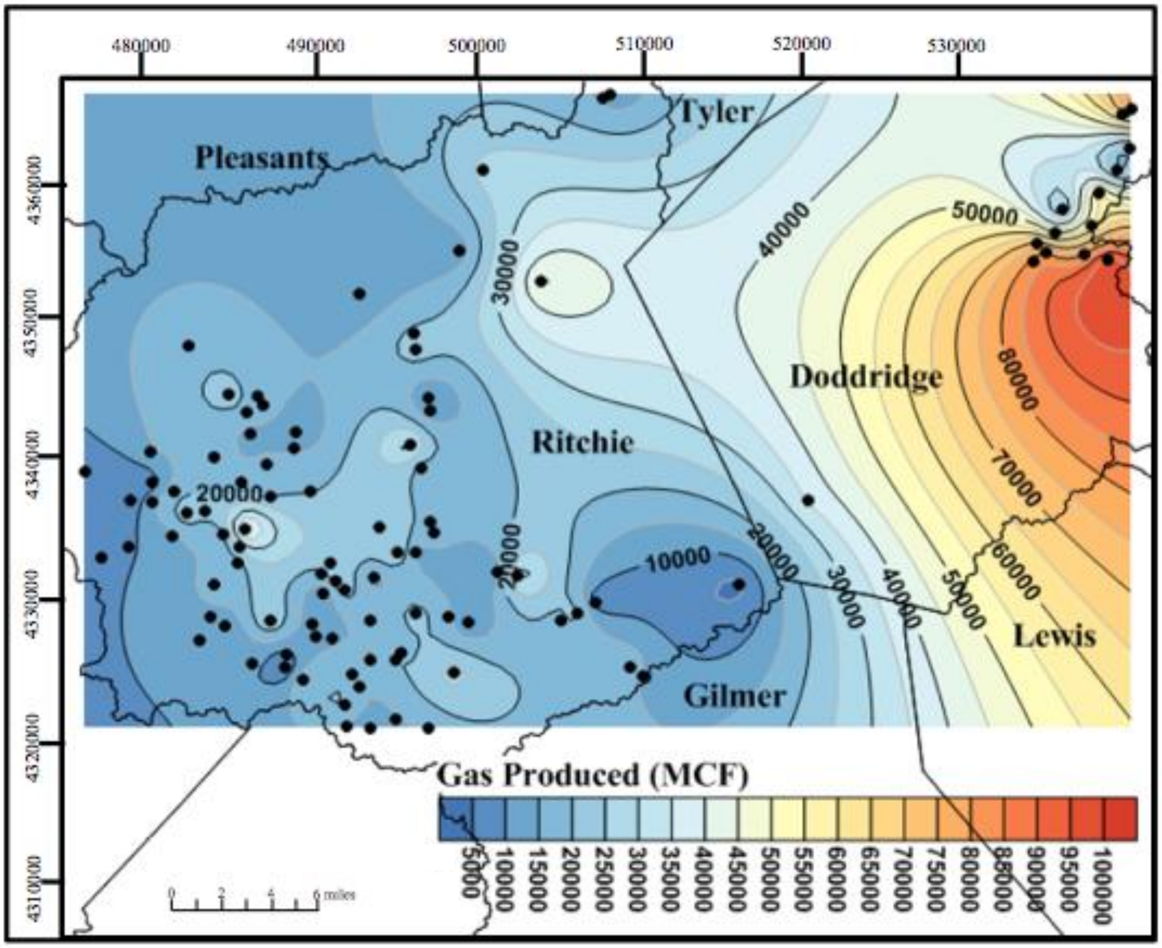


Figure 26. Production map the Marcellus Shale in Doddridge and Ritchie counties of the first twelve months of production from vertically drilled wells only. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of dark red indicate higher production values in MCF of gas and the shades of dark blue lower production values in MCF of gas.

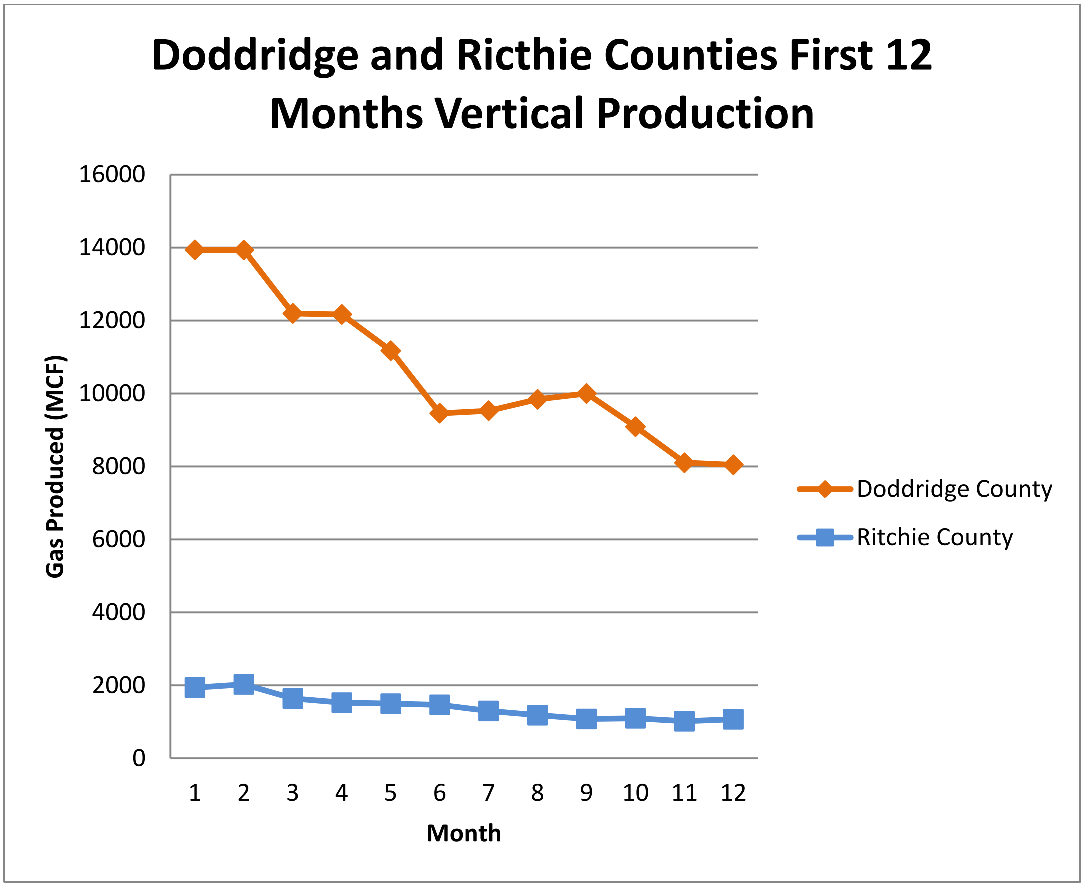


Figure 27. Production chart of production of Marcellus Shale within the first twelve months within Doddridge and Ritchie counties from vertically drilled wells only. Values are in thousands of cubic feet of gas produced and were calculated based on averages of all wells for each month. Values were taken from available well production from the West Virginia Geological and Economic Survey. A typical decline in the values is displayed for both counties.

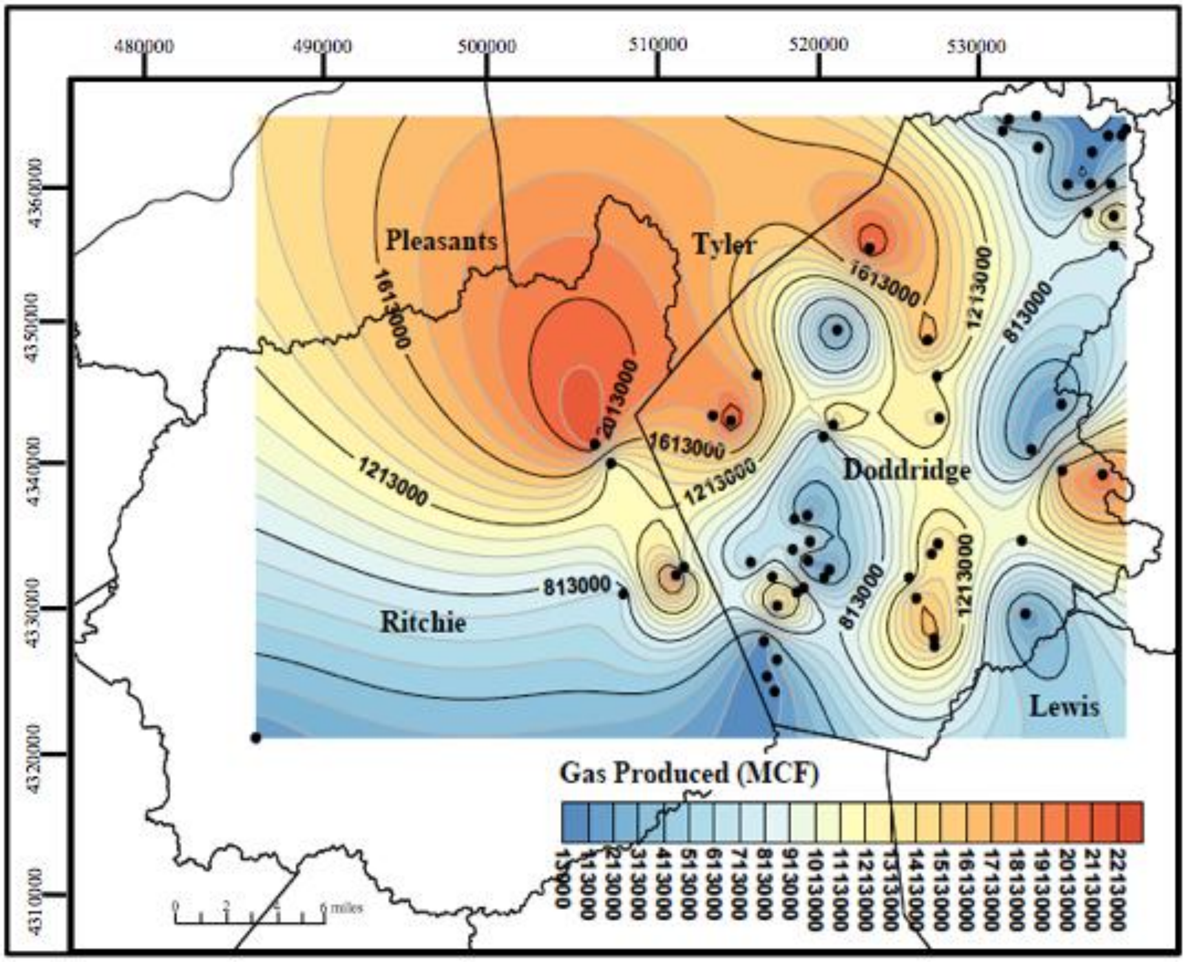


Figure 28. Production map the Marcellus Shale in Doddridge County and Ritchie counties of the first twelve months of production from horizontally drilled wells only. The dots signify location of available data points from the West Virginia Geological and Economic Survey**.** Geographic coordinates were obtained from the WVGES and are UTM eastings and northings. The shades of dark red indicate higher production values in MCF of gas and the shades of dark blue indicate lower production values in MCF of gas.

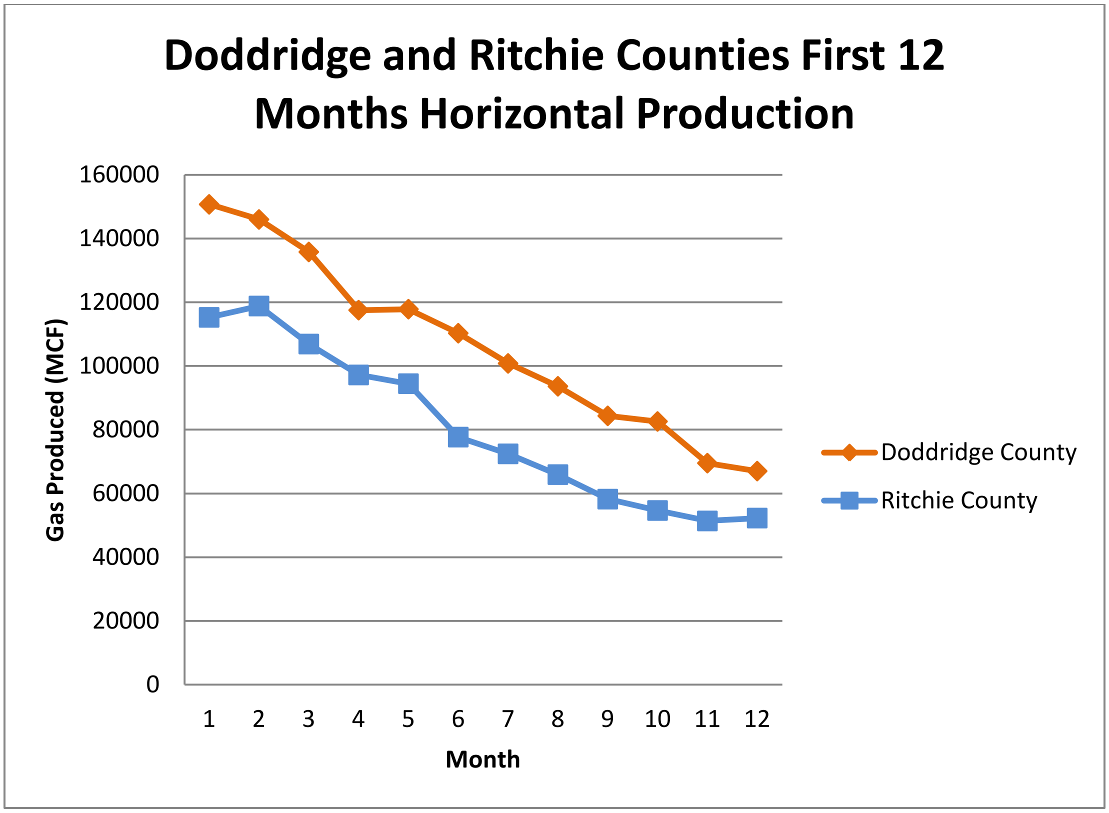


Figure 29. Production chart of production of Marcellus Shale within the first twelve months within Doddridge and Ritchie counties from horizontally drilled wells only. Values are in thousands of cubic feet of gas produced and were calculated based on averages of all wells for each month. Values were taken from available well production from the West Virginia Geological and Economic Survey. A typical decline in the values is displayed for both counties.

4.5.3 Thinning of the Marcellus Shale with Respect to Production

As previously mentioned in section 4.4.3, the Taghanic unconformity may play a major role in the thickness variances of the Marcellus Shale within Doddridge and Ritchie counties. Removal of the Marcellus Shale by erosion attributed to the Taghanic unconformity is one factor that aids in understanding production variances within the study area. As seen in Figure 19, thickness of the upper Marcellus varies throughout the study area. Thickness of this unit is variable anywhere from 0 to 86 feet. This is attributed to the removal and/or thinning of the unit in areas through erosion by the Taghanic unconformity. Given this nature, the large variations in production may be attributed the lack of uniformity in distribution of the unit. The progressive thinning and eventual removal of the Marcellus Shale to the west is a large indicator for the low quantities of gas produced within Ritchie County (94,209 MCF). To the east, the Marcellus Shale thickens to 86 feet, which suggests that thinning of the unit as a result of the Taghanic unconformity is one factor in the large scale of gas produced within Doddridge County (656,501 MCF).

4.5.4 Additional Production Considerations

As presented within the results above, thinning of the Marcellus Shale as well as gas extraction method may play a role in production variances between Doddridge and Ritchie counties. In addition, other production considerations may also be a factor that could possibly affect production between the two counties. As previously mentioned, production averages vary greatly between the two counties with the more gas being produced within Doddridge County.

Reservoir properties such as mineralogy, organic-matter richness, thermal maturity, and fracture porosity of shales are additional factors to consider when assessing production variations between Doddridge and Ritchie counties. These factors are imperative to understand gas-producing potential of geologic units. The Marcellus Shale, in particular, displays unique reservoir properties, which allows for large quantities of gas produced from this unit within West Virginia. Within Doddridge County, the lower Marcellus Shale displays a low clay and high quartz content, which is typically indicative of a poor gas potential reservoir (Ward & Schuler, 2012). However, the Marcellus Shale is unique within Doddridge County in the sense that it is the largest producer of gas within this study, which may be attributed to high organic matter content, thermal maturity, and porosity. In addition, organic-matter richness, most typically identified as total organic carbon (TOC) content, is an essential parameter in determining reservoir characteristics and gas potential of shales. Within West Virginia, TOC of the Marcellus Shale can have a weight percent range of 3.8-10.5, which makes Doddridge and Ritchie counties both good candidates for the production of natural gas (Hill, Fishman, Claypool, Blum & Danny, 2009) (Figure 30). Furthermore, thermal maturity is an important characteristic in determining reservoir properties. Within West Virginia, the Marcellus Shale has average R_o values of 0.6-3.0% and within Doddridge and Ritchie counties, average $\%R_o$ values range from 1-1.7%, which places the maturity assessment range within the wet/dry gas window, additionally making both counties good candidates for production (Figure 31). Finally, fracture porosity is an additional consideration to take when defining reservoir properties of a source rock. The Marcellus Shale has average fracture porosity as high as 9.0%, which allows for estimations of gas-in-place within West Virginia to be of high range compared to the rest of the Appalachian region, thus placing both Doddridge and Ritchie counties in high rank for gas producing ability (Lee, Herman, Elsworth, Kim & Hyun, 2011).

Quality	TOC (wt%)
Poor	<0.5
Fair	0.5 to 1
Good	1 to 2
Very Good	2 to 4
Excellent	>4

Figure 30. Total Organic Carbon classification chart. Measurements are recorded in weight percent. Modified from Weatherford Laboratories, 2009.

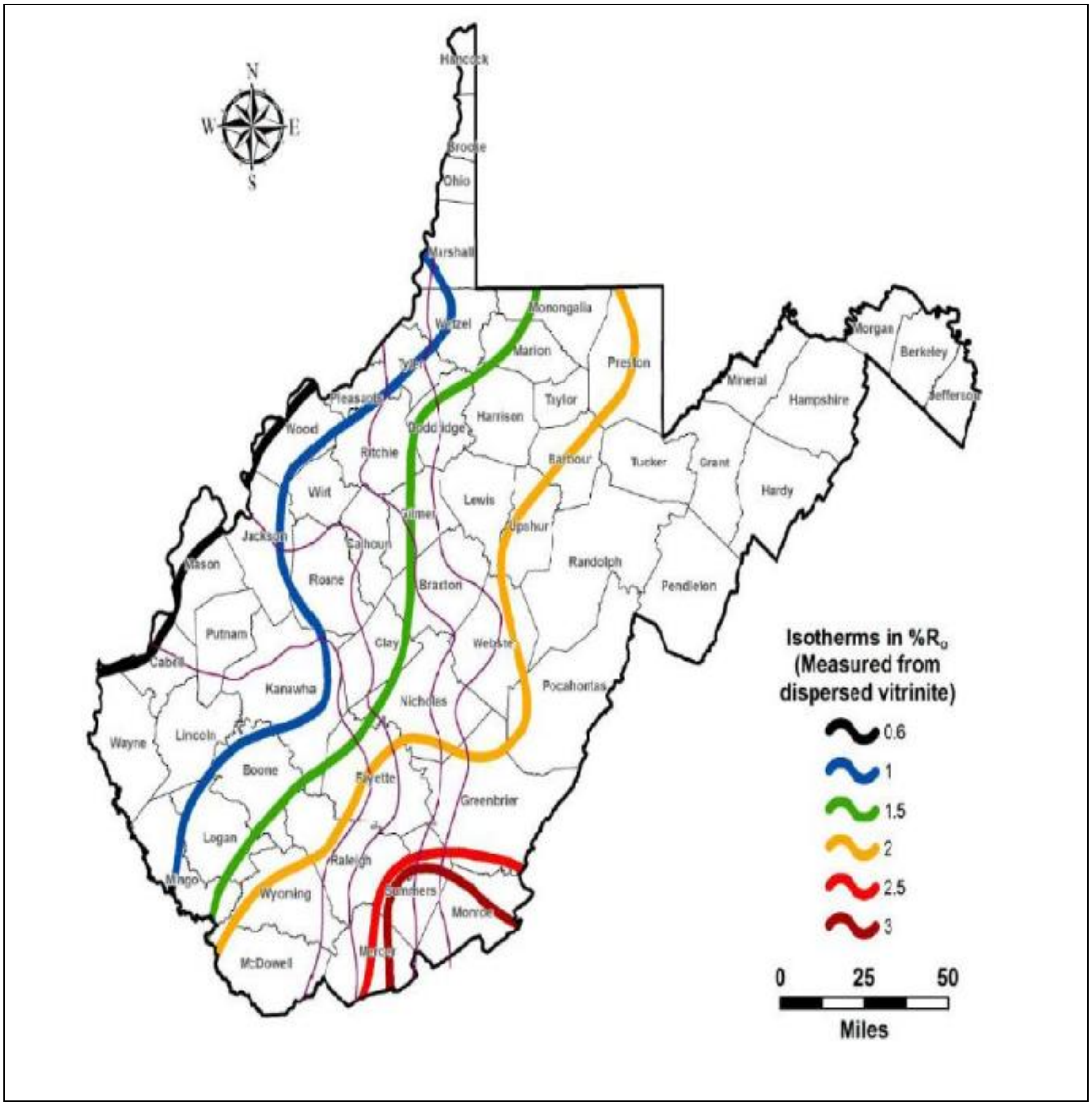


Figure 31. Thermal Maturity of the Marcellus Shale within West Virginia. Purple lines indicate Conodont Alteration Index. From NETL, 2010.

4.5.5 Potential Production

As stated above, thickness discrepancies of the Marcellus Shale resulting from the Taghanic unconformity, gas extraction method, and reservoir characteristics aid in understanding that a variety of factors control production discrepancies between Doddridge and Ritchie counties. However, these factors also assist to identify production potential of the Marcellus Shale within the study area.

Given the reservoir characteristics of mineralogy, organic-matter richness, thermal maturity, and fracture porosity of shales as stated above, both Doddridge and Ritchie counties are excellent candidates for gas production. Therefore, this places emphasis on additional factors such as gas extraction method to be explored in regards to production potential. Within Ritchie County the most common extraction method is vertically drilled wells. Of the 94 sampled wells within the county, 88 were drilled vertically with only 6 drilled horizontally. The 6 horizontally drilled wells accounted for much higher production averages at 1,229,036 MCF for the first twelve months versus the vertically drilled wells at 16,834 MCF for the first twelve months within Ritchie County. Within Doddridge County, the primary extraction method was horizontal drilling. Of the 67 sampled wells within the county, 53 were drilled horizontally with only 14 drilled vertically. The 14 vertically drilled wells accounted for much lower production averages at 57,090 MCF for the first twelve months versus the horizontally drilled wells at 656,501 MCF for the first twelve months within Doddridge County. Given this trend for the two counties, the vast difference in production could be attributed to the majority of Doddridge wells being drilled horizontally. The horizontal drilling method in Doddridge could account for natural gas extraction occurring by increasing the thickness of the pay zone of the Marcellus Shale, thus allowing for more extraction of natural gas. Additionally, horizontal drilling in

Doddridge County could allow for improved recovery of the Marcellus Shale natural gas due to the fact that it aids in accurately hitting pay zones that vertical drilling cannot reach.

Furthermore, there is possibility for increased values of gas production in underutilized areas within Ritchie County. As seen in Figure 28, the horizontal gas extraction has only been employed within 6 wells, which resulted in much higher production values within the County as compared to the vertical extraction method. The values were of similar comparison to the gas production values within Doddridge County via horizontal extraction. This leaves potential for underutilized areas within Ritchie County to produce larger quantities of natural gas extracted from the Marcellus Shale via horizontal drilling.

5.0 SUMMARY

1. The Marcellus Shale can be subdivided into two distinct units, the upper and lower, throughout Doddridge and Ritchie counties, West Virginia. Upper and lower units were distinguished through API ranges and gamma-ray signatures accessed within well logs.
2. The lower Marcellus Shale is laterally continuous throughout the study area and has thickness variations that may be attributed to depositional processes or erosion from the Taghanic unconformity.
3. The upper Marcellus Shale has thickness variations throughout the study area and becomes progressively thinner and sometimes absent towards the west that may be attributed to erosion from the Taghanic unconformity.
4. The upper and lower Marcellus Shale grouped as one unit becomes progressively thinner towards the west.
5. Sea-level oscillations may play a large role in controlling stratigraphic variations and thickness disparities of the Tully Limestone, Mahantango Formation, upper Marcellus Shale, and lower Marcellus Shale.
6. Available data suggest there is the possibility for structural control in relation to thinning and removal on the upper and lower Marcellus Shale due to reactivation of movement along the Rome Trough fault at the time of deposition.
7. The API values of the upper Marcellus Shale decrease westward, which suggests a decrease in organic shale content and a possibility for increase of siliciclastic content from east to west due to truncation of the unit.

8. The API values of the lower Marcellus Shale increase eastward, which suggests an increase in organic shale content and for possibility of decrease of siliciclastic content from west to east.
9. Production within the study area varies from west to east with highest production in Doddridge County (656,411 MCF) and lowest production within Ritchie County (94,209 MCF).
10. Production variances between Doddridge and Ritchie counties may be attributed to a variety of factors including thickness discrepancies of the unit as a result of the Taghanic unconformity, gas extraction method, and reservoir characteristics such as mineralogy, organic-matter richness, thermal maturity, and fracture porosity.
11. A possibility for larger quantities of natural gas production exists in underutilized areas within Ritchie County as a result of gas extracted from the Marcellus Shale via horizontal drilling.

6.0 REFERENCES

Avary K.L., and Patchen,D.G. (2008). WVGS page http://www.wvgs.wvnet.edu/www/datastat/Marcellus/Images/WVStratigraphicNomenclature_Marcellus.png, modified from Patchen and Hohn, 1993.

Baird, G. C. (1979). Sedimentary relationships of Portland Point and associated Middle Devonian rocks in central and western New York. *New York State Museum Bulletin, 433*(24).

Baird, G. C., & Brett, C. E. (1986). Erosion on an anaerobic seafloor: significance of reworked pyrite deposits from the Devonian of New York State. *Palaeogeography, Palaeoclimatology, Palaeoecology 57,* 157–193. DOI 10.1016/0031-0182(86)90012-X

Baird, G. C., & Brett, C. E. (1991). Submarine erosion on the anoxic seafloor, paleoenvironmental and temporal significance of reworked pyrite-bone deposits, 223 257. In Tyson, R.V. & Pearson, T.H. (eds) *Modern and Ancient Continental Shelf Anoxia. Geological Society Special Publication 58*.

Baird, G. C., & Brett, C. E. (2006). Shelf and off-shelf deposits of the Tully Formation in New York and Pennsylvania: Faunal incursions, eustasy and tectonics. *Bulletin of Geosciences, 83*(4), 357-370.

Beardsley, R. W., & Cable, M. S., (1983). Overview of the evolution of the Appalachian basin. *Northeastern Geology,* 5. 137-145

Belyadi, H. (2011). Production Analysis of Marcellus Shale. *Department of Petroleum and Natural Gas Engineering, West Virginia University, 109 p*.

Blakey, R., (2009), Paleogeography and geologic evolution of North America, in Sedimentary rocks on the Colorado Plateau. Retrieved from http://jan.ucc.nau.edu/rcb7/namD385.jpg.

Boyce, M. L. (2010). Sub-surface stratigraphy and petrophysical analysis of the Middle Devonian interval of the central Appalachian basin; West Virginia and southwest Pennsylvania, West Virginia University, dissertation, 1-158

Brett, C.E., and Ver Straeten, C.A., (1994). "Stratigraphy and Facies Relationships of the Eifelian Onondaga Limestone (Middle Devonian) in Western and West Central New York State." *Field Trip Guidebook (New York State Geological Association),* 221–227.

Brett, C. E., Baird, G. C., & Bartholomew, A. J. (2004). *Sequence stratigraphy of highly variable Middle Devonian strata in central Kentucky: Implications for regional correlations and depositional environments.* (Open-File No. 04-05). Indiana Geological Survey: Annual Field Conference of the Great Lakes Section of SEPM.

Brunner, K., & Smosna, R. (2002). Cherty sponge reefs in the Devonian Onondaga Limestone Newly discovered gas reservoir in Pennsylvania. *Northeastern Geology and Environmental Sciences, 24*(3), 185-191. doi:01941453

Burns, P.J., & Claus, R.C., (1985). An overview of hydrocarbon production in the Appalachian basin-a glance at the forest. *Oil and Gas Journal*, 83, 116-122.

Curtis, R. & Klemow, R., (2011). How did Marcellus shale form?. *Institute for Energy and Environmental Research of Northeastern Pennsylvania Clearinghouse* Retrived from http:energy.wilkes.edu/155.asp.

Curtis, R. (2011). What is horizontal drilling, and how does it differ from vertical drilling? *Institute for Energy and Environmental Research of Northeastern Pennsylvania Clearinghouse*. Retrieved from http:energy.wilkes.edu/158.asp.

Crain. (2015). Shale volume from gamma ray logs. Retrieved from https://spec2000.net/11-vshgr.htm

Cummings, K. L. (2014). *Stratigraphy and petroleum geology of the Alexander silstone in Doddridge and Ritchie counties, West Virginia* (M.S.), East Carolina University, ?? p.

de Witt, W., Roen, J.B. and Wallace, L.G., (1993). Stratigraphy of Devonian black shales and associated rocks in the Appalachian basin, In Roen, J.B., & Kepferle, R.C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America. *U.S. Geological Survey Bulletin,* 1909. B1-B57.

Ettensohn, F.R. and Barron, L.S. (1981). Depositional model for the Devonian-Mississippi black shales of North America: a paleoclimatic-paleogeographic approach. In: T.G. Roberts (editor). *G.S.A. Cincinnati '81 Field Trip Guide Books, volume II: Economic geology, Structure*. American Geological Institute, 344-361.

Ettensohn, F.R., (1985). Controls on development of Catskill delta complex basin-facies, In: Woodrow, D.L. & Sevon, W.D., eds., *The Catskill delta: Geological Society of America Special Paper* 201, 65-77.

Ettensohn, F. R. (2008). Chapter 4, The Appalachian Foreland Basin in Eastern United States. In Miall, A.D., *Sedimentary Basins of the World*, 5, 105-179.

Enomoto, C.B., Olea, R.A., & Coleman, J.L., (2013). Characterization of the Marcellus Shale Based on Computer-Assisted Correlation of Wireline Logs in Virginia and West Virginia.. USGS Scientific Investigations Report 2013-5131,21 p., 4 plates.

Faill, R.T., (1985).The Acadian Orogeny and the Catskill Delta: The Catskill Delta. *Geological Society of America Special Paper*, 201, 15-38.

Feldman, H. (1994). Brachiopods of the Onondaga Formation, Moorehouse Member (Devonian, Eifelian), in the Genesee valley, western New York. *Bulletins of American Paleontology, 107*(346).

Fichter, L. S., & Baedke, S. J. (2000). *The Devonian Acadian Orogeny And Catskill Clastic Wedge*. Retrieved 2015, from The Geological Evolution Of Virginia and the Mid-Atlantic Region : http://csmres.jmu.edu/geollab/vageol/vahist/J-MidlatD.html

Fox, E. (n.d.). Horizontal vs. vertical drilling. Retrieved from http://www.ehow.com/about_ 6554355_horizontal-drilling_.html

Grabau, A. W. (1977). Stratigraphic relationships of the Tully Limestone and the Genesee Shale in eastern North America. *Bulletin of the Geological Society of America, 28*, 945-958.

Harper, J. A, Laughrey, C.D., Kostelnik, J., Gold, D.P., & Doden, A.G. (2004). "Trenton and Black River Carbonates in the Union Furnace Area of Blair and Huntingdon Counties, Pennsylvania : Introduction." Field Trip Guidebook for the Eastern Section AAPG Annual Meeting. *Pennsylvania Geological Survey, ?? p.*.

Harper, J. A. (2008). The Marcellus Shale; an old "new" gas reservoir in Pennsylvania. Pennsylvania Geology, *Pennsylvania Bureau of Topographic and Geologic Survey , 38* (1), 2-13.

Harris, L. D., and Milici, R. C., (1977). Characteristics of thin-skinned style of deformation in the southern Appalachians, and potential hydrocarbon traps: U.S. Geol. Survey Prof Paper 1018, 40 p.

Hatcher, R. (2010). The Appalachian orogen: A brief summary. *GSA Memoirs , 206*, 1-19.

Heckel, P.H. (1973). Nature, Origin, and significance of the Tully Limestone. *Geological Society of America*, *Special Paper139*, 1–244.

Hill, R., Fishman, N., Claypool, G., Blum, A., & Danny, E. (2009). Evaluating Devonian Gas Shales from the Appalachian Basin, U.S.A. *AAPG Annual Convention.* San Antonio: AAPG.

Hill, H., (2007). "Chapter 3 Fossils and Geologic Time." The Big Dig. *North Carolina State University*, *Kenan Fellows Program.*

Hoover, S. E., & Lehmann, D. (2007). The expansive effects of concentrated pyritic zones within the Devonian Marcellus Shale formation of North America. *Quaterly Journal of Engineering, Geology and Hydrogeology, 42*(2), 157-164. doi:10.1144/1470-9236/07-086

Hughes, J. D. (2014). Drilling deeper: A reality check on US government forecasts for a lasting tight oil & shale gas boom. *Post Carbon Institute.*

Jackson, M.S., Hanley, P.M., & Sak, P.B., (2007). [Preliminary Bedrock Geologic Map of the Middle Portion of the Susquehanna River Valley, Cumberland, Dauphin, and Perry Counties, Pennsylvania.] Retrieved from http://www.dcnr.state.pa.us/topogeo/index.aspx

Jacobi, R. J. (2008). Peripheral bulge—a causal mechanism for the Lower/Middle Ordovician unconformity along the western margin of the Northern Appalachians. *Earth and Planetary Science Letter*s, 56, 245-251.

Johnson, J.G., Klapper, G. & Sandberg, C.A. (1985). Devonian eustatic fluctuations in Euramerica. *Geological Society of America Bulletin 96,* 567–587.

Kent, D.V., (1985). Paleocontinental setting for the Catskill Delta: The Catskill Delta. *Geological Society of America Special Paper*, 201, 9-13.

King, H. (2015). Directional and horizontal drilling in oil and gas wells. Retrieved from http://geology.com/articles/horizontal-drilling/

Kohl, D., Slingerland, M., Arthur, M., and Bracht, R. E. (2014). Sequence stratigraphy and depositional environments of the Shamokin (Union Springs) member, Marcellus formation, and associated strata in the middle Appalachian basin *AAPG Bulletin, 98*(5), 483-513. doi:10.1306/08231312124

Kulander, C.S., (2001). Regional seismic lines in West Virginia- A preliminary look at the Rome trough and its implication for energy resources: U.S. Geological Survey Open-File Report 01–127, 28.

Kulander, C.S., and Ryder, R.T., (2005). Seismic lines across the Rome trough and Allegheny Plateau of northern West Virginia, western Maryland, and southwestern Pennsylvania: U.S. Geological Survey Geologic Investigations Series Map I–2791, 9 p, ?? plates.

Lash, G. (2008). Revised stratigraphy of the Upper Middle Devonian Windom Shale-Tully Limestone interval (Givetian), subsurface of western New York and northwestern Pennsylvania: *Northeastern Geology and Environmental Sciences, 30*(1), 7-20.

Laughrey, C. (2009). Applied petroleum geology and geochemistry for thermogenic shale- gas evaluation – A primer focused on Marcellus exploration and development in the Appalachian basin Pittsburgh, PA. *Pittsburgh Association of Petroleum Geologists and Pittsburgh Geological Society, ?? p.*

Lee, D. S., Herman, J. D., Elsworth, D., Kim, H. T., & Hyun, S. L. (2011). A critical evaluation of unconventional gas recovery from the Marcellus Shale, northeastern United States *KSCE Journal of Civil Engineering, 15*(4), 679-687. doi:10.1007/s12205-011-0008-4

McDowell, R., Lewis, E., & Dinterman, P. (2014). West Virginia earthquakes: crustal adjustments along the rome trough or something else? Retrieved from West Virginia Geological and Economic Survey:http://www.wvgs.wvnet.edu/www/ presentations/2014/WV-seismic_2014.pdf

McKithan, C. (1978). Drake oil well. Retrieved from http://www.wow.com/wiki/Drake_Well

Milici, R.C., & Swezey C.S. (2006). "Assessment of Appalachian Basin Oil and Gas Resources: Devonian Shale–Middle and Upper Paleozoic Total Petroleum System". *Open-File Report Series 2006-1237*. United States Geological Survey.

Miller, B. M. (1975). A Summary of Oil and Gas Production and Reserve Histories of the Appalachian Basin, *Geological Survey Bullentin*. 1859-1982.

Murphy, J.B., & Keppie, J.D., (2005), The Acadian Orogeny in the Northern Appalachians, *International Geology Review,* 47(7), 663.

Neal, D. W. (2010). Stratigraphy and Gas Production from the Marcellus Shale in Southern West Virginia. *GSA Northeastern Secton: Baltimore: Geological Society of America*. 42,137.

NETL. (2010). *Projecting the Economic Impact of Marcellus Shale Gas Development in West Virginia Projecting the Economic Impact of Marcellus Shale Gas Development in West Virginia: A Preliminary Analysis Using Publicly Available Data.* National Energy Technology Laboratory.

New York State Geological Survey. (n.d.). Acadian mountain building and the Catskill delta. Retrieved from http://www.nysm.nysed.gov/nysgs/contact.html

Oliver, W.A. (1955). Stratigraphy of the Onondaga Limestone in Eastern New York. *Geological Society of America Bulletin.* 67(11), 1441-1474.

Penn State Marcellus Center for Outreach and Research. (2010). "Resources." *The PennState Marcellus Center for Outreach and Research.* The Pennsylvania State University.

Piotrowski, R. G., & Harper, J. A., (1979). Devonian black shale and sandstone facies of the "Catskill" clastic wedge in the subsurface of western Pennsylvania. *USDOE/METC, = EGSP Series*, 40(13), 39, Morgantown, WV.

Prave, A.R., Duke, W.L., & Slattery, W. (1996). A depositional model for storm- and tide dominated prograding siliciclastic shorelines from the Middle Devonian of the central Appalachian foreland basin, USA. *Sedimentology*, 43, 611-629.

Ross, Michael, Voetan, E. (2013). What Have We Learned About the Resource Curse? Retrieved from http://www.ssrn.com/abstract=2342668

Sexton, Roy. (2011). Sequence stratigraphy, distribution and preservation of organic carbon, and reservoir properties of the middle devonian marcellus shale, of the central appalachian basin; northern west Virginia and southwestern Pennsylvania (Order no. 1520766) Available from ProQuest Dissertations & Theses Global (1220695893).

Schlumberger. (n.d.). Fracture porosity. Retrieved from http://www.glossary.oilfield.slb.com/ Terms/f/fracture_porosity.aspx

Slingerland, R., Patzkowski, M., & Peterson, D. (2009). Facies and Sedimentary Environments of the Catskill Systems Tract in Central Pennsylvania. Retrieved from Pittsburgh Association of Petroleum Geologist: http://www.papgrocks.org/ PAPGGuidebook_Spring09.pdf

Smith, C. (2012). *The Devonian West Falls formation, implications of sedimentation controlled by preexisting structures, West Virginia University* (M.S.).

University of Colorado (2015). Hydraulic fracturing. Bolder, CO. Retrieved from http://www.oil and gasbmps.org/resources/fracing.php

USGS. (n.d.). Onondaga limestone. Retrieved from http://mrdata.usgs.gov/geology/state/sgmc-unit.php?unit=NYDon;2

VanMeter, J. (2014). *Regional mapping and reservoir analysis of the Middle Devonian Marcellus Shale in the Appalachian basin* (Order No. 1565542). Available from ProQuest Dissertations & Theses Global. (1617436012). Retrieved from http://search.proquest.com.jproxy.lib.ecu.edu/docview/1617436012?accountid=10639

Van Straeten, C. A. (2009). *The Classic Devonian of the Catskill Front: A Foreland Basin Record of Acadian Orogenesis.* New York State Museum. Albany: The State Education Department.

Van Tassell, J. (1994) Cyclic Deposition of the Devonian Catskill Delta of the Appalachians, USA, In: *Orbital Forcing and Cyclic Sequences* (eds P. L. de Boer and D.G.Smith),Blackwell Publishing Ltd., Oxford, UK. doi: 10.1002/9781444304039.ch24

Van Tyne, A.M., (1996). Play Dol: Middle Devonian Onondaga limestone reef play, In: Roen, J.B., and Walker, B.J., eds., The Atlas of Major Appalachian Gas Plays, West Virginia Geological and Economic Survey Publication. 25, 100-102.

Ward, J., & Schuler, J. (2012). Contrasting Marcellus production in Ritchie, Pleasants, Tyler, Doddridge and Harrison counties, West Virginia [Abstract]. *AAPG Search and Discovery,* 22-26.

Weatherford. (2009). Sweetspot identification in unconventional reservoirs. Retrieved from http://labs.weatherford.com/play-types/unconventional#page3

West Virginia Department of Environmental Protection. (n.d.). API number explanation. Retrieved from http://www.dep.wv.gov/oil-and-gas/GI/Documents/API% 20 Number %20Explanation.pdf

"West Virginia Geological and Economic Survey (WVGES) (n.d.). West Virginia Department of Commerce. *West Virginia Department of Commerce. "*Welcome Page." State of West Virginia.

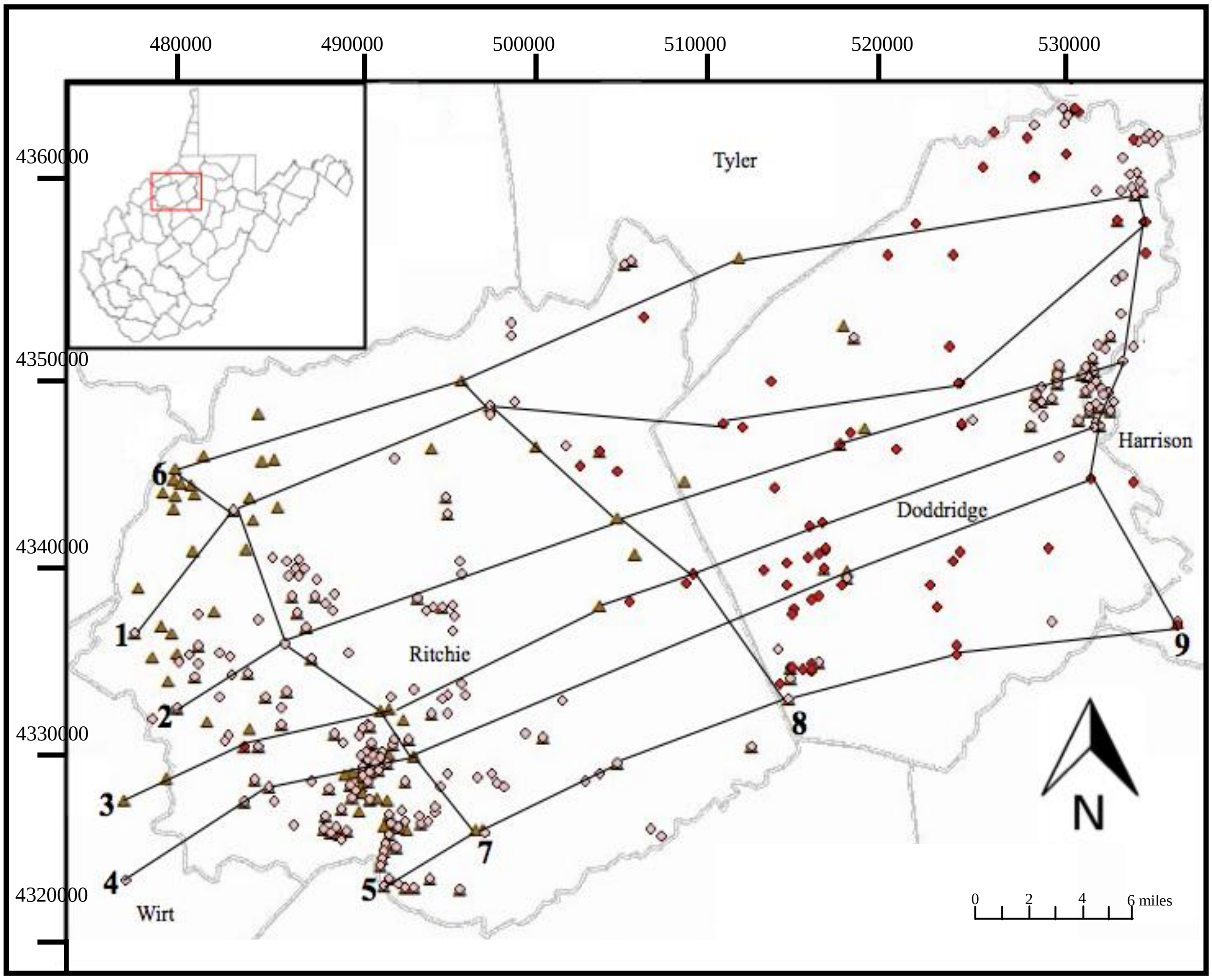
Willard, B., (1935). Hamilton Group of central Pennsylvania: Geological Society of America Bulletin, 46(2), 195–224. Retrieved from http://dx.doi.org/10.1130/GSAB-46-195

Woodrow, D. L., & Sevon, W. D. (1985). *The Catskill Delta* (Special Paper 201.). Boulder, CO: Geological Society of America, ?? p.

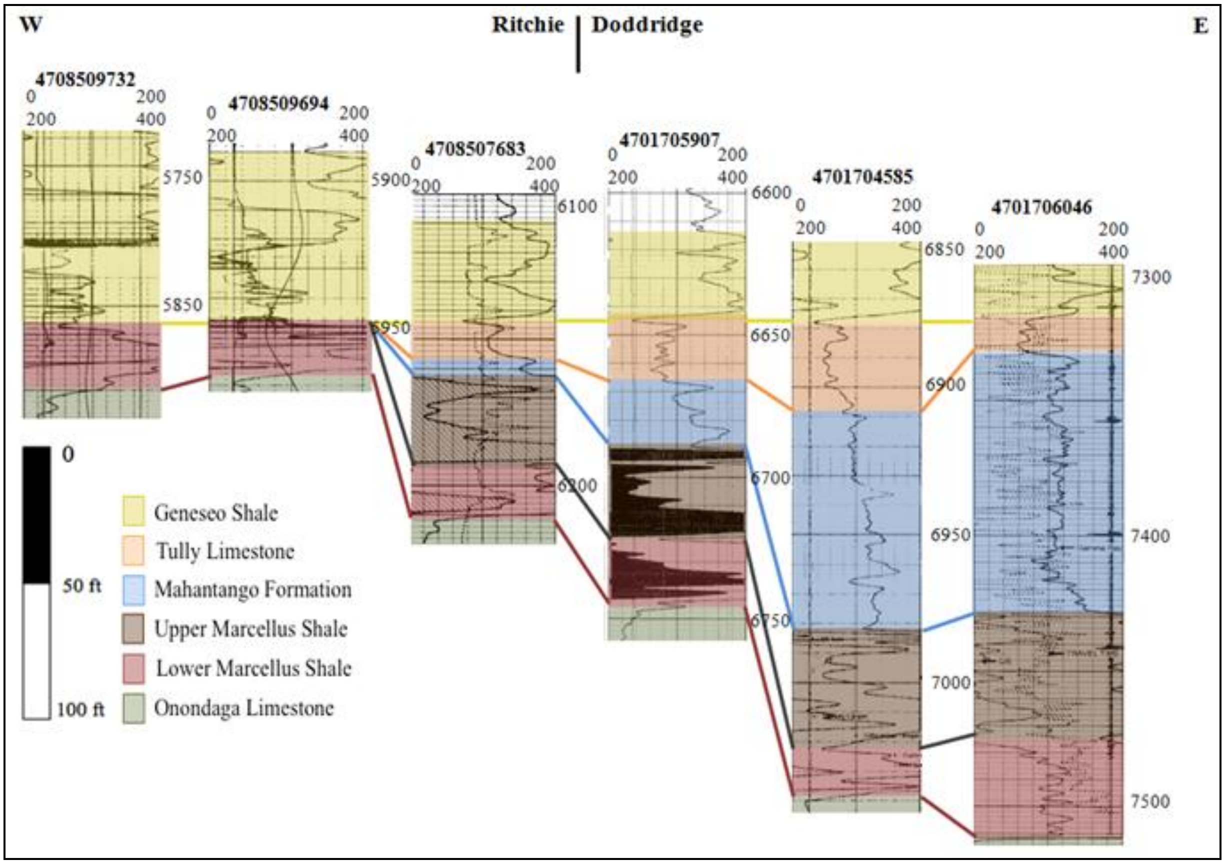
Woodrow, D.L., Dennison, J.M., Ettensohn, F.R., Sevon, W.T., & Kirchgasser, W.T., (1988). Middle and Upper Devonian stratigraphy and paleogeography of the central and southern Appalachians and eastern mid-continent, U.S.A., In McMillan, N.J., Embry, A.F., and Glass, D.J., eds., *Devonian of the World: Canadian Society of Petroleum Geologists Memoir*, 14(1), 277-301.

APPENDIX A: STRATIGRAPHIC CROSS SECTIONS

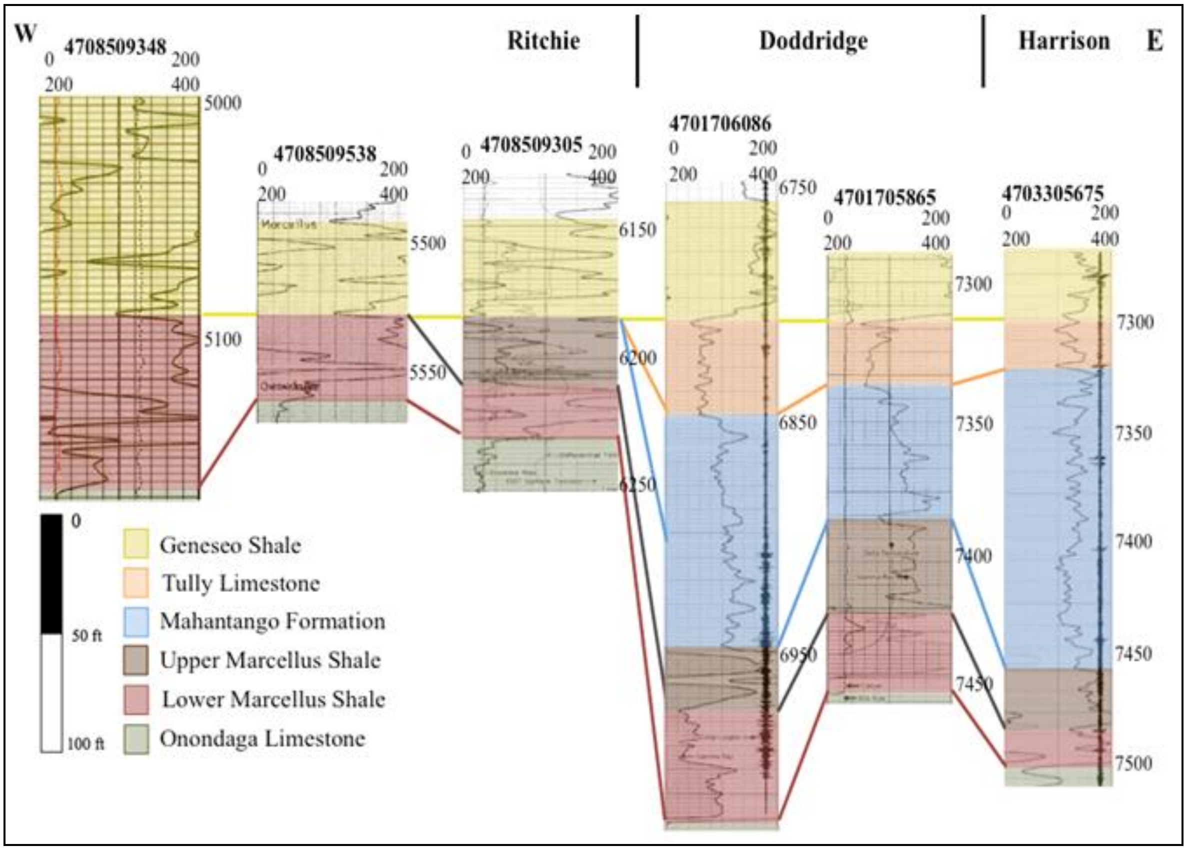
Below is a map illustrating the transect and well locations used for the nine stratigraphic cross sections constructed across the study area within Doddridge and Ritchie counties. Cross sections were constructed by examining gamma-ray logs and identifying the Marcellus Shale on each log. The Mahantango Formation was used as the top identifying unit above the Marcellus Shale and where it is absent, the Geneseo Shale was used. The Onondaga Limestone was used as the bottom identifying unit below the Marcellus Shale. The Geneseo Shale was used as a datum line due to lateral continuity across the study area. Cross sections are color coded as follows: Geneseo Shale (yellow), Tully Limestone (orange), Mahantango Formation (blue), upper Marcellus Shale (brown), lower Marcellus Shale (red), and Onondaga Limestone (green). A vertical scale is provided for each section, but varies for each one.



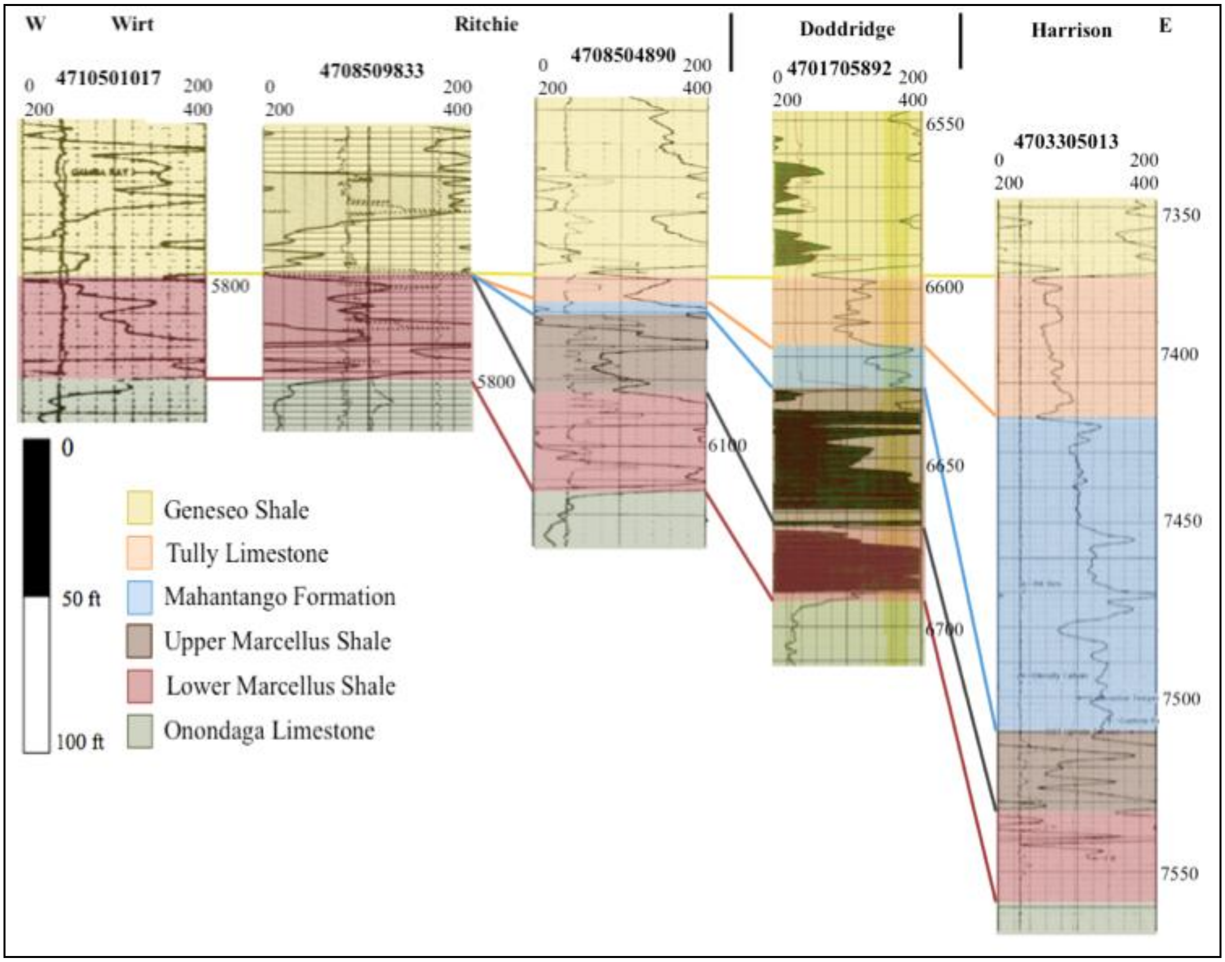
Location of transects used for cross sections. Lines indicate cross sections. Dots represent completed well locations from the West Virginia Geological and Economic Survey. Triangles represent well locations with available geophysical logs from the West Virginia Geological and Economic Survey.



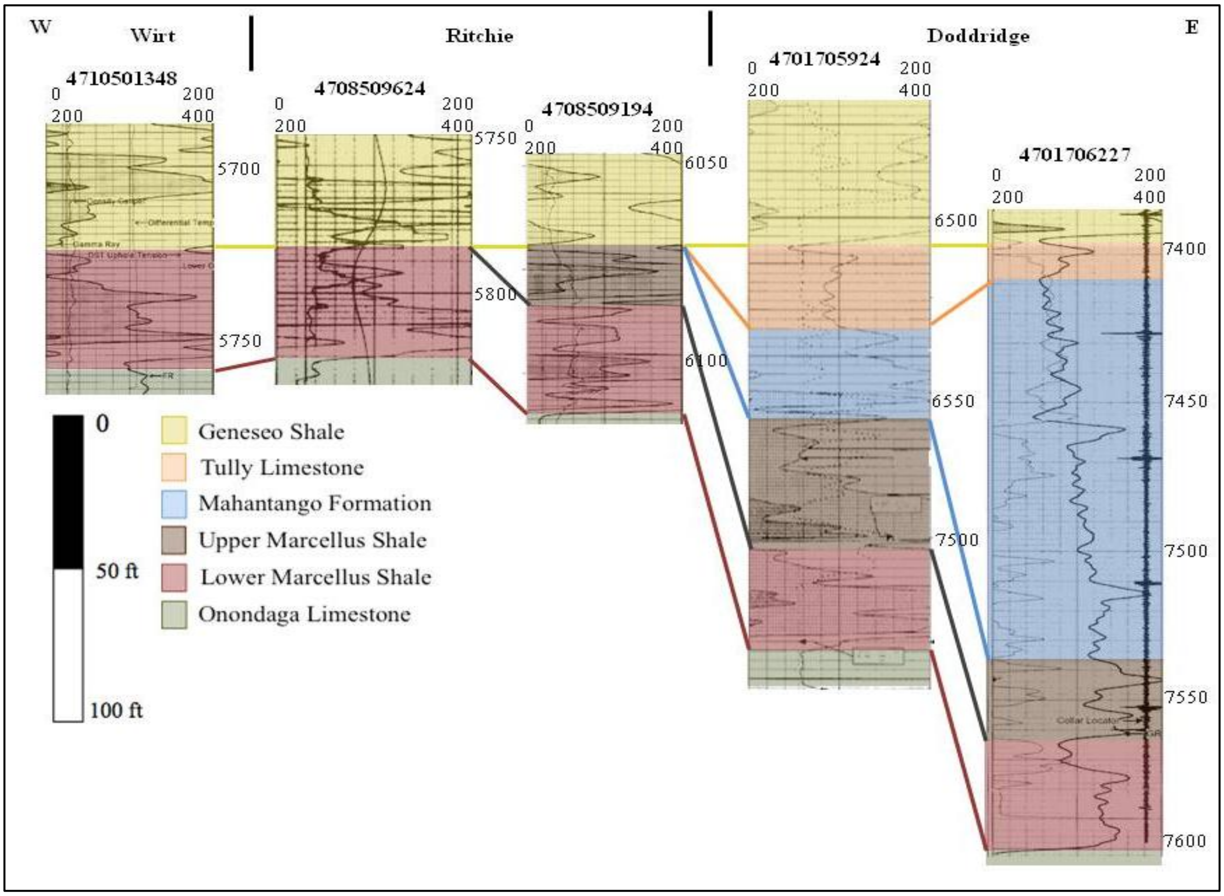
Stratigraphic cross section 1 across transect 1.



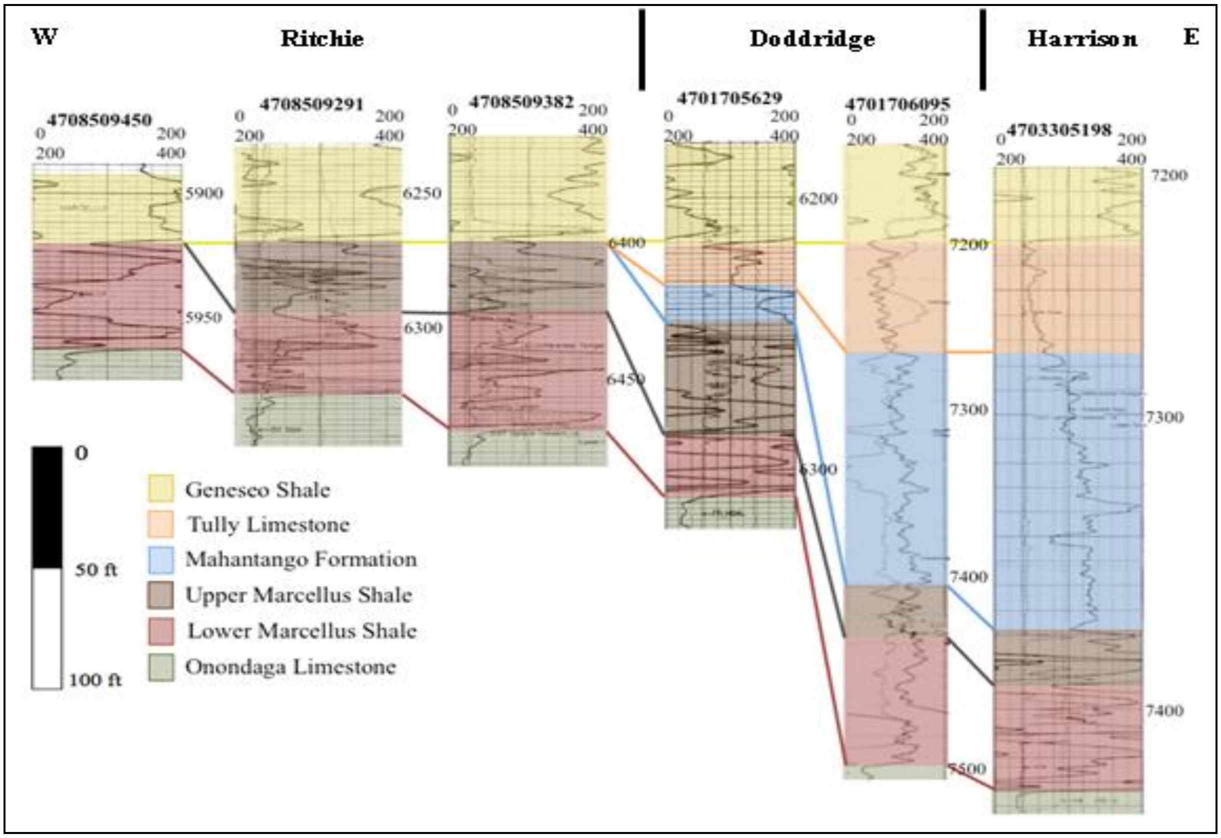
Stratigraphic cross section 2 across transect 2.



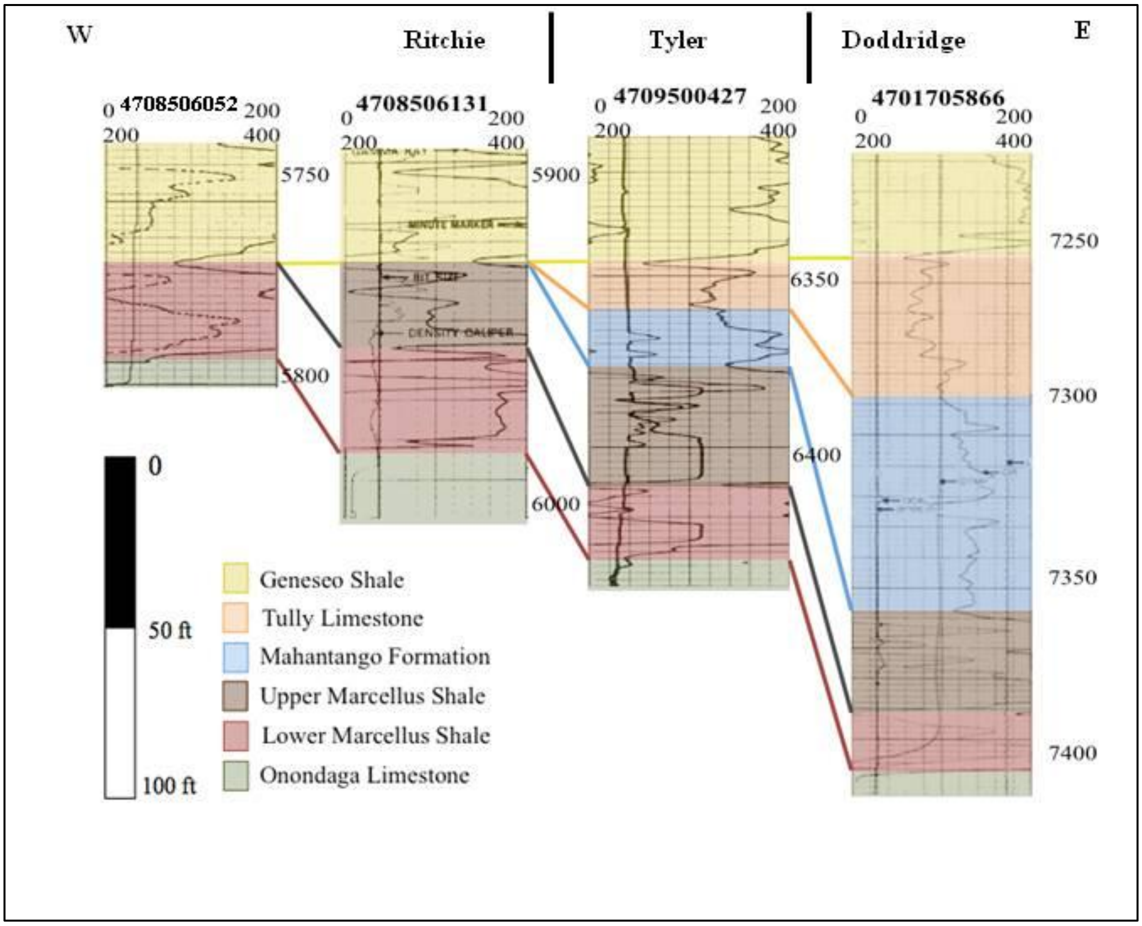
Stratigraphic cross section 3 across transect 3.



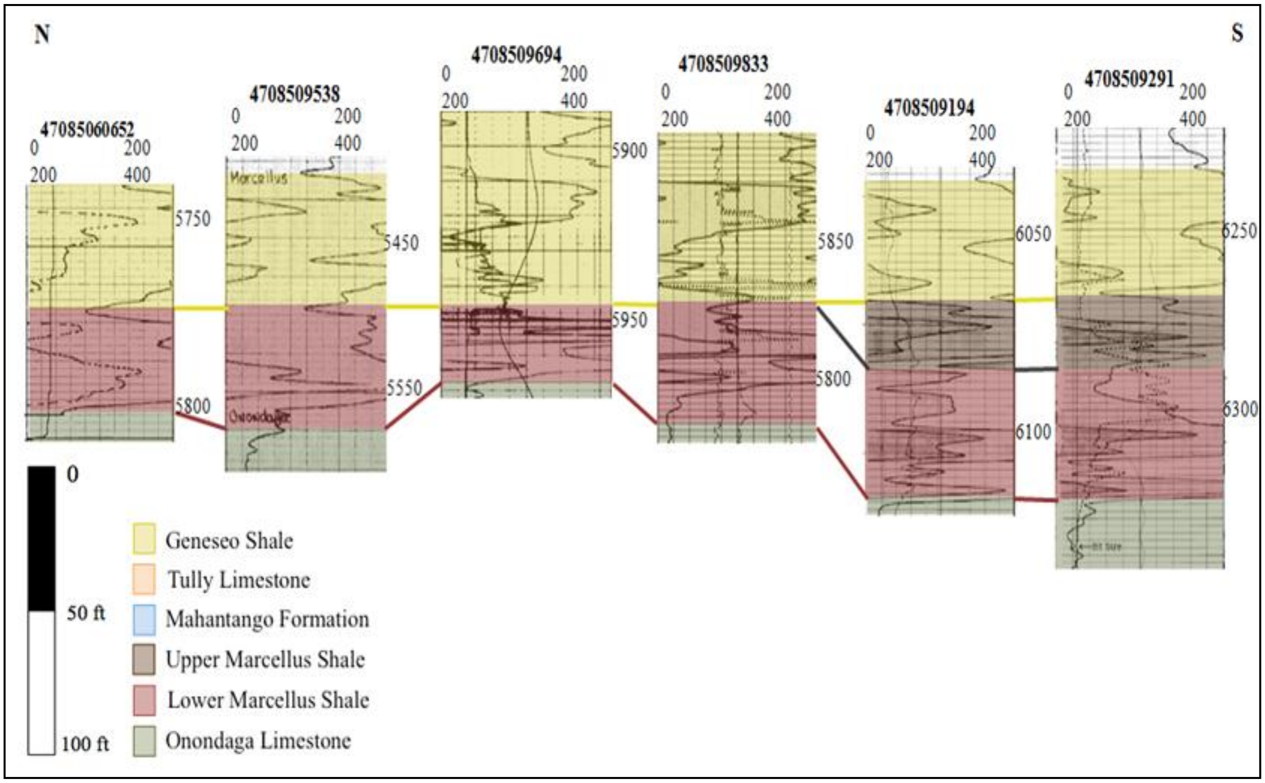
Stratigraphic cross section 4 across transect 4.



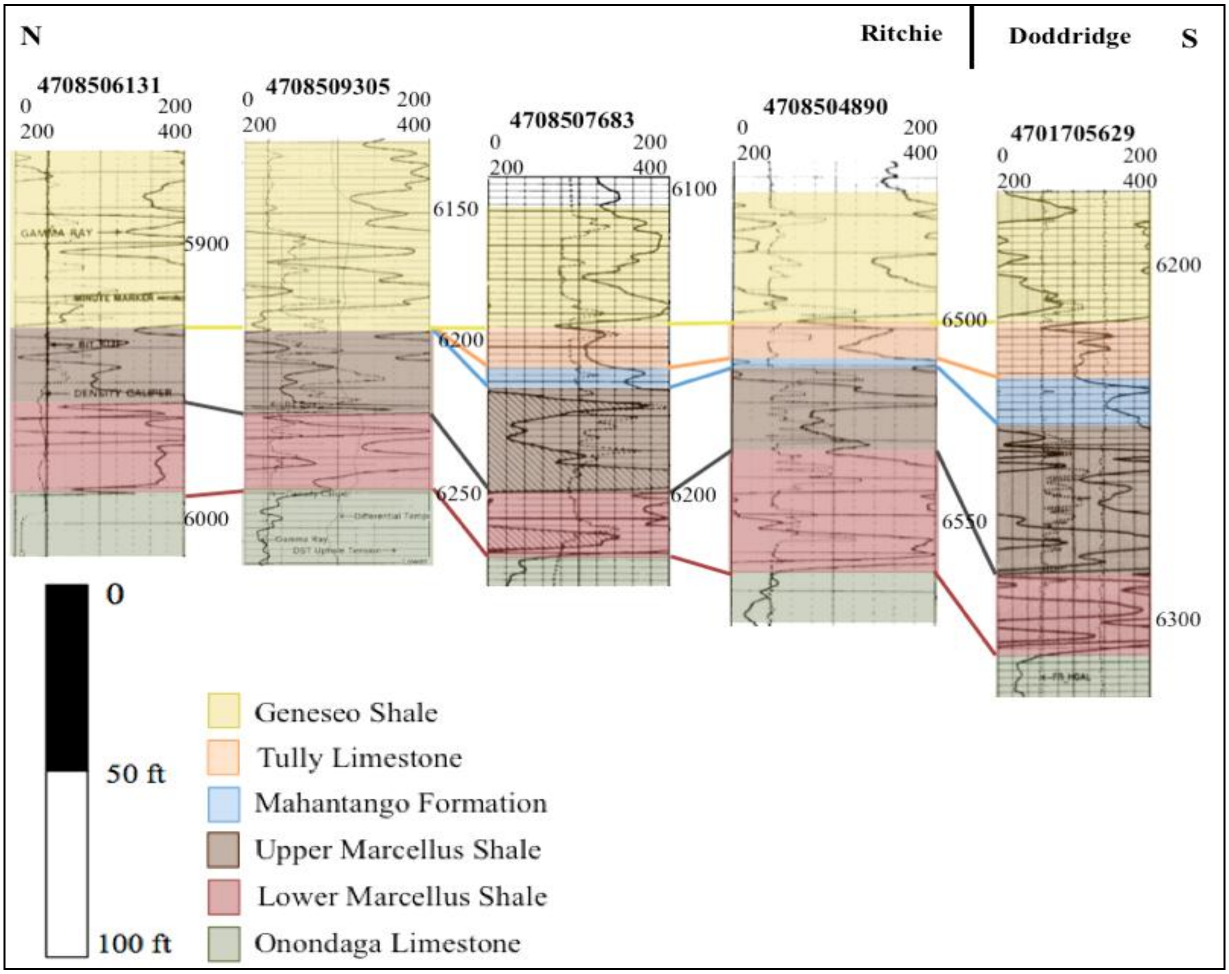
Stratigraphic cross section 5 across transect 5.



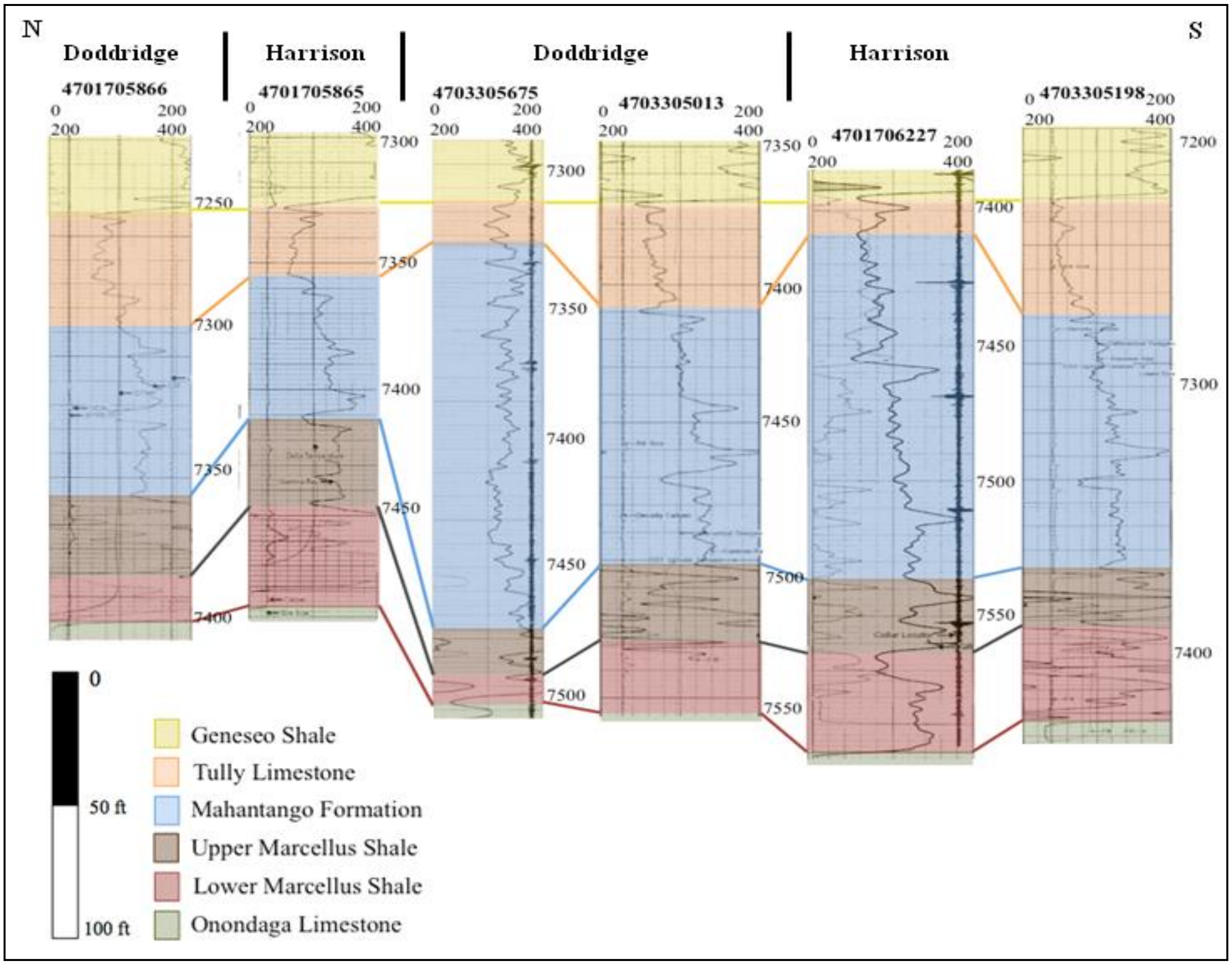
Stratigraphic cross section 6 across transect 6.



Stratigraphic cross section 7 across transect 7.



Stratigraphic cross section 8 across transect 8.



Stratigraphic cross section 9 across transect 9.

APPENDIX B: ISOPACH MAP DATA

Thickness in feet of Tully Limestone, Mahantango Formation, upper Marcellus Shale, lower Marcellus Shale, and the upper and lower Marcellus Shale combined. Total Marcellus Map (Figure 18) used thickness of the lower Marcellus only when no upper Marcellus was present. API is well identification number. UTMs listed were locations used for Surfer mapping application.

API	UTME	UTMN	Tully Limestone Thickness (ft)	Mahantango Formation Thickness (ft)	Upper Marcellus Shale Thickness (ft)	Lower Marcellus Shale Thickness (ft)	Both Upper & Lower Marcellus Shale Thickness (ft)
4701705892	518028.9	4341575	20	11	34	25	59
4701705462	519986.8	4352725	25	34	37	28	65
4701705629	517743.7	4333226	17	26	38	30	68
4701705638	535246.9	4347463	52	59	37	35	72
4701705645	534793.8	4351490	48	57	39	35	74
4701705651	536554.1	4354142	42	58	36	33	69
4701705664	515914.2	4331017	26	55	32	43	75
4701705669	530896.7	4347364	45	42	37	39	76
4701705774	532225.3	4349107	48	65	39	35	74
4701705817	533861.3	4347795	57	63	38	32	70
4701705865	537823.2	4361459	35	61	39	34	73
4701705889	518037.5	4341565	32	42	28	40	68
4701705907	519094.6	4346297	28	33	30	40	70
4701705912	519727.7	4347023	30	35	32	42	74
4701705927	514344	4338772	20	28	30	35	65
4701705952	530762.5	4364656	41	58	41	33	74
4701706080	526642.1	4347416	35	57	35	39	74
4701706112	517356.3	4336961	28	40	32	35	67
4701706135	522607.2	4345969	34	50	34	26	60
4701706143	537280.9	4344033	47	60	40	35	75
4703305651	538551.5	4341554	49	62	40	38	78
4708505202	476448.8	4333578	0	0	0	24	24
4708505337	482164.8	4340027	0	0	0	27	27
4708505450	479057.9	4343349	0	0	0	24	24
4708505734	484009.5	4345451	0	0	0	24	24
4708505775	475478.5	4337722	0	0	0	24	24
4708506052	478867	4343861	0	0	0	22	22
4708506258	483172.4	4345308	0	0	0	30	30

4708507738	499547.8	4329016	0	0	0	28	28
4708509158	489768.4	4329489	0	0	0	27	27
4708509219	488671.8	4325929	0	14	28	31	59
4708509224	489844.7	4325010	10	10	28	31	59
4708509260	488847.8	4325188	0	0	0	26	26
4708509268	493623.9	4320286	8	4	24	33	57
4708509269	495458.3	4319689	4	5	21	35	56
4708509273	491049.8	4322916	0	0	22	35	57
4708509293	504180.1	4326571	0	0	0	26	26
4708509325	484432.6	4330528	0	0	0	25	25
4708509326	484584.4	4334314	0	0	22	32	54
4708509327	488586	4333760	0	0	27	33	60
4708509330	490652.1	4327927	0	0	0	24	24
4708509335	492262.1	4328649	0	0	0	32	32
4708509342	489236.7	4328846	0	0	0	30	30
4708509348	475358.4	4334998	0	0	0	24	24
4708509352	492066.7	4326139	0	0	0	35	35
4708509359	487204.8	4324096	0	0	0	22	22
4708509365	487091	4323308	0	0	0	24	24
4708509373	488179.8	4322603	0	0	0	29	29
4708509375	493692.8	4330193	0	0	0	32	32
4708509393	500672	4328807	0	0	0	22	22
4708509398	482072.7	4324943	0	0	0	35	35
4708509413	491499.8	4322224	0	0	28	30	58
4708509431	492096.7	4323768	0	0	30	32	62
4708509445	495817.7	4331323	0	0	0	25	25
4708509449	490759.1	4319891	0	0	0	30	30
4708509476	490581.4	4321077	0	0	0	45	45
4708509482	485160	4323521	0	0	22	35	57
4708509487	492602.8	4331663	0	0	0	30	30
4708509505	488272.9	432846	0	0	0	22	22
4708509530	489316.1	4327687	0	0	0	24	24
4708509531	490024.3	4328473	0	0	0	27	27
4708509536	493947.6	4324217	0	0	27	32	59
4708509537	476357.9	4329807	0	0	0	28	28
4708509538	481437.5	4342394	0	0	18	34	52
4708509539	483821.5	4339503	3	8	28	34	62
4708509541	486241.9	4326115	0	0	0	24	24

4708509551	482767.2	4326282	0	0	21	30	51
4708509568	481116.8	4328925	0	0	0	32	32
4708509572	482360.4	4332645	0	0	0	38	38
4708509583	484366.4	4329514	0	0	0	31	31
4708509587	478089.4	4333219	0	0	0	35	35
4708509602	492076.9	4319756	6	2	22	35	57
4708509610	493528.9	4323751	0	0	25	32	57
4708509622	484817.3	4338407	4	6	25	34	59
4708509624	483603.1	4325761	0	0	0	30	30
4708509626	487607.8	4336294	0	0	0	27	27
4708509628	487721.9	4337291	0	6	22	30	52
4708509634	485495.1	4339451	5	7	25	32	57
4708509655	482945.7	4335819	0	0	22	30	52
4708509694	485997.2	4335363	10	8	25	37	62
4708509729	486284.3	4333458	4	8	19	37	56
4708509730	483452.1	4331178	0	0	0	45	45
4708509733	479294	4334302	0	0	0	24	24
4708509734	485017.5	4337182	5	10	22	30	52
4708509746	482947.4	4328212	0	0	0	34	34
4708509768	484795.6	4331515	0	0	0	46	46
4708509777	494747.5	4326568	0	0	20	30	50
4708509891	491165.2	4331140	0	0	0	31	31
4708509910	494736	4330173	0	0	0	36	36
4708509918	482098.8	4328227	0	0	0	35	35
4710500901	477242.3	4326341	0	0	0	25	25
4708509732	477921	4330527	0	0	0	28	28
4708507683	505308.6	4341923.6	12	4	28	20	48
4701704585	531208.3	4349280.7	40	72	40	23	63
4701706046	538029	4357771	10	98	47	48	95
4708509305	497326.9	4348573.8	0	0	25	22	47
4701706086	526661	4347478	40	98	35	50	85
4703305675	538390.6	4352741.7	22	115	31	22	53
4710501017	474654.6	4325041.9	0	0	0	32	32
4708509833	482089.2	4328217.5	0	0	0	35	35
4708504890	504170.8	4336687.5	10	4	24	34	58
4701705892	518028.9	4341574.9	20	13	44	35	79
4703305013	535822.5	4348286.3	40	92	20	27	47
4710501348	474736.7	4320242.8	0	0	0	32	32

4708509194	492647.5	4327715.5	0	0	24	35	59
4701705924	515776.4	4337875.6	20	22	34	36	70
4701706227	534635.4	4344281.3	12	110	27	36	63
4708509450	491157.4	4320314.1	0	0	0	35	35
4708509291	496506.2	4323330.5	0	0	24	32	56
4708509382	505241.7	4327215.2	0	0	24	34	58
4701706095	526339	4333720	35	80	25	50	75
4703305198	540064	4335666.2	45	112	20	48	68
4708506131	495568.8	4350156.9	0	0	20	25	45
4709500427	512834.5	4357467.4	12	18	31	25	56
4701705866	537435.5	4361232.9	50	70	25	15	40

APPENDIX C: STRUCTURE MAP DATA

Subsea Elevation in feet of the top of the Onondaga Limestone. API is well identification number. UTMs listed were locations used for Surfer mapping application.

API	UTME	UTMN	Onondaga Subsea Elevation (ft)
4708506068	477749.8125	4344270.4	-4499
4708502005	477087.8125	4343467.4	-4289
4708505450	479057.9063	4343349.4	-4718
4708506052	478867	4343861.2	-4800
4708506258	483172.4063	4345308.1	-4780
4708505734	484009.5	4345451.2	-4762
4708505400	482683.0938	4341811.8	-4770
4708505775	475478.5	4337722	-3521
4708505325	484245.6875	4342613.2	-4800
4708505337	482164.8125	4340026.5	-4850
4708505290	476969	4335448.3	-4750
4708505202	476448.8125	4333577.9	-4750
4708505347	477242.3125	4326340.6	-4310
4708505868	479766.8125	4329717.3	-3981
4708505979	493764.5	4346113.4	-5184
4708504832	500197.3125	4346239.8	-5197
4708504872	506388.8125	4339746.8	-5400
4708509537	476357.9	4329807.3	-4684
4708509587	478089.4	4333219.1	-4676
4708509733	479294	4334302.2	-4707
4708509540	479218.2	4336085.8	-4717
4708509589	479308	4333167.5	-4785
4708509550	480548.6	4333775.9	-4824
4708509509	481302	4332470.6	-4795
4708509525	480542.5	4331136.6	-4802
4708509572	482360.4	4332645.2	-4844
4708509568	481116.8	4328925.4	-4846
4708509918	482098.8	4328226.7	-5339
4708509746	482947.4	4328211.9	-4900
4708509730	483452.1	4331178.3	-4954
4708509768	484795.6	4331515.1	-4935
4708509325	484432.6	4330527.6	-4955
4708509583	484366.4	4329513.8	-4931

4708509398	482072.7	4324943.1	-4874
4708509551	482767.2	4326282.3	-4879
4708509482	485160	4323520.5	-4881
4708509655	482945.7	4335819.3	-4887
4708509326	484584.4	4334314.2	-4940
4708509729	486284.3	4333458.2	-5071
4708509327	488586	4333760.3	-5028
4708509539	483821.5	4339502.9	-4886
4708509634	485495.1	4339451.4	-4984
4708509622	484817.3	4338406.6	-4930
4708509734	485017.5	4337181.7	-4949
4708509628	487721.9	4337291.1	-5013
4708509626	487607.8	4336293.5	-4922
4708509541	486241.9	4326114.6	-4939
4708509219	488671.8	4325928.8	-4980
4708509224	489844.7	4325009.9	-4990
4708509260	488847.8	4325188.2	-5006
4708509359	487204.8	4324096.3	-4968
4708509365	487091	4323308	-4923
4708509373	488179.8	4322603.3	-4960
4708509505	488272.9	432846	-4963
4708509342	489236.7	4328845.9	-4922
4708509158	489768.4	4329488.9	-5177
4708509530	489316.1	4327687.1	-4975
4708509531	490024.3	4328472.9	-4992
4708509330	490652.1	4327926.8	-5034
4708509335	492262.1	4328649.3	-5064
4708509352	492066.7	4326138.9	-5087
4708509891	491165.2	4331139.8	-5040
4708509487	492602.8	4331663.4	-5027
4708509375	493692.8	4330193	-5121
4708509910	494736	4330173	-4711
4708509445	495817.7	4331323.2	-5136
4708509476	490581.4	4321077.2	-5119
4708509273	491049.8	4322916.3	-5101
4708509413	491499.8	4322223.8	-5106
4708509431	492096.7	4323768.1	-5105
4708509610	493528.9	4323750.8	-5136
4708509536	493947.6	4324217.2	-5160

4708509777	494747.5	4326567.5	-5183
4708509758	497017.4	4323066.3	-5220
4708509449	490759.1	4319891	-5058
4708509602	492076.9	4319756	-5052
4708509268	493623.9	4320285.7	-5107
4708509269	495458.3	4319689	-5094
4708507738	499547.8	4329015.8	-5289
4708509393	500672	4328806.6	-5279
4708509293	504180.1	4326570.8	-5242
4708509917	92884.3	4337143	-5091
4708509479	494403.9	4336543.3	-5062
4708509691	495030.9	4335169.9	-5138
4708509671	495531.7	4339294.6	-5082
4708509707	494728.3	4342180.8	-5157
4708509700	494591.8	4343174.2	-5132
4708509261	497310.8	4348026.6	-5117
4708509654	502064.1	4346256.2	-5263
4708509988	502960.7	4345007.3	-6000
4708509930	504185	4345860	-5584
4708509951	505242	4344702.8	-5594
4708509337	505697	4357051.1	-5424
4708509195	506131.2	4357325	-5576
4708509970	509484	4337989	-5860
4708509960	509994	4338479	-5670
4701702909	509384.9	4344132.3	-5600
4701705912	519727.7	4347023.4	-6520
4701706135	522607.2	4345969.3	-6615
4701706080	526642.1	4347416.4	-6046
4701705966	527264.7	4347705.5	-5749
4701705462	519986.8	4352724.6	-5747
4701705927	514344	4338771.7	-6357
4701705857	515814.9	4339181	-6250
4701705853	518206.9	4340008.3	-6325
4701705889	518037.5	4341564.9	-6430
4701706112	517356.3	4336961	-5760
4701705918	517783.3	4337221.9	-6448
4701705643	519142.8	4337852.8	-6382
4701705746	519471.7	4338318	-6272
4701705592	515215.2	4334024.9	-5562

4701705792	515403.9	4331909	-5850
4701705664	515914.2	4331016.8	-5456
4701706156	524675	4337851	-6137
4701706096	526136.1	4339274.6	-6390
4703305651	538551.5	4341553.7	-6333
4701706143	537280.9	4344033	-6438
4701705874	532642.2	4345532.1	-6132
4701705669	530896.7	4347363.9	-6024
4701705605	531650.8	4347930.2	-6017
4701705609	531133.4	4348507.5	-5964
4701705774	532225.3	4349107.4	-5985
4701705781	532603.2	4350503	-5853
4701705817	533861.3	4347794.7	-6121
4701705638	535246.9	4347462.9	-6117
4701705691	534599.5	4348248.6	-6153
4703305050	535736.7	4349433.7	-5463
4701705604	534352.2	4349524	-6127
4701705645	534793.8	4351489.5	-6205
4701705749	535858.5	4352833.5	-6159
4701705651	536554.1	4354142.1	-6168
4703305136	539576.4	4360969.9	-6136
4701705402	536519.5	4361457.1	-6046
4701705577	535005.5	4361446.8	-5987
4701705681	536603.8	4363390.7	-6090
4701705711	538817.8	4364769.5	-6088
4701705712	538527.1	4364399.4	-6090
4701705555	537661	4364377.5	-6182
4701705578	532974.8	4365547	-6253
4708509732	477921	4330527	-4842
4708509694	485997.2	4335362.7	-4950
4708507683	505308.6	4341923.6	-5257
4701705907	519094.6	4346297.1	-5611
4701704585	531208.3	4349280.7	-5973
4701706046	538029	4357771	-6589
4708509348	475358.4	4334997.5	-4216
4708509538	481437.5	4342394	-4788
4708509305	497326.9	4348573.8	-5251
4701706086	526661	4347478	-6129
4701705865	537823.2	4361459.2	-6008

4703305675	538390.6	4352741.7	-6350
4710501017	474654.6	4325041.9	-4744
4708509833	482089.2	4328217.5	-4891
4708504890	504170.8	4336687.5	-5295
4701705892	518028.9	4341574.9	-5722
4703305013	535822.5	4348286.3	-6173
4710501348	474736.7	4320242.8	-4742
4708509624	483603.1	4325760.6	-4916
4708509194	492647.5	4327715.5	-5168
4701705924	515776.4	4337875.6	-6388
4701706227	534635.4	4344281.3	-6634
4708509450	491157.4	4320314.1	-5131
4708509291	496506.2	4323330.5	-5281
4708509382	505241.7	4327215.2	-5328
4701705629	517743.7	4333225.6	-5454
4701706095	526339	4333720	-6282
4703305198	540064	4335666.2	-6150
4708506131	495568.8	4350156.9	-5182
4709500427	512834.5	4357467.4	-5475
4701705866	537435.5	4361232.9	-6091

APPENDIX D: PRODUCTION MAP DATA

Production Map data for the Marcellus Shale in thousand cubic feet (MCF). API is well identification number. UTMs listed were locations used for Surfer mapping application. Drilling method for gas extraction is listed either as vertical or horizontal.

API	UTME	UTMN	First 12 Months Production (MCF)	Drilling Method
4701705402	536519.5	4361457.1	24,549	Horizontal
4701705462	519986.8	4352724.6	13,684	Horizontal
4701705553	536639.0	4356444.0	81,206	Vertical
4701705555	537661.0	4364377.5	46,627	Horizontal
4701705577	535005.5	4361446.8	73,080	Horizontal
4701705578	532974.8	4365547.0	54,247	Horizontal
4701705592	515215.2	4334024.9	13,411	Horizontal
4701705604	534352.2	4349524.0	55,154	Vertical
4701705605	531650.8	4347930.2	82,181	Vertical
4701705609	531133.4	4348507.5	71,783	Vertical
4701705629	517743.7	4333225.6	35,638	Vertical
4701705638	535246.9	4347462.9	99,157	Vertical
4701705640	516057.0	4332915.1	244,337	Horizontal
4701705643	519142.8	4337852.8	311,989	Horizontal
4701705645	534793.8	4351489.5	58,561	Vertical
4701705646	536190.0	4356120.0	68,819	Vertical
4701705651	536554.1	4354142.1	18,911	Vertical
4701705664	515914.2	4331016.8	60,310	Horizontal
4701705669	530896.7	4347363.9	81,652	Vertical
4701705681	536603.8	4363390.7	25,276	Horizontal
4701705691	534599.5	4348248.6	84,099	Horizontal
4701705701	532248.8	4335675.2	65,151	Horizontal
4701705711	538817.8	4364769.5	91,694	Horizontal
4701705712	538527.1	4364399.4	91,694	Horizontal
4701705717	531165.3	4365360.1	128,439	Horizontal
4701705746	519471.7	4338318.0	106,281	Horizontal
4701705749	535858.5	4352833.5	17,936	Vertical
4701705774	532225.3	4349107.4	48,070	Vertical
4701705781	532603.2	4350503.0	23,104	Vertical
4701705792	515403.9	4331909.0	36,798	Horizontal
4701705817	533861.3	4347794.7	411,953	Vertical

4701705851	518093.0	4338853.9	35,136	Horizontal
4701705853	518206.9	4340008.3	602,746	Horizontal
4701705865	537823.2	4361459.2	121,637	Horizontal
4701705889	518037.5	4341564.9	62,442	Horizontal
4701705890	517079.5	4339537.4	457,350	Horizontal
4701705894	517192.9	4341351.0	571,835	Horizontal
4701705907	519094.6	4346297.1	1,439,808	Horizontal
4701705912	519727.7	4347023.4	827,988	Horizontal
4701705918	517783.3	4337221.9	1,133,524	Horizontal
4701705923	515760.6	4337884.8	566,898	Horizontal
4701705927	514344.0	4338771.7	771,157	Horizontal
4701705928	533105.4	4363668.0	678,167	Horizontal
4701705929	533096.9	4363655.8	627,533	Horizontal
4701705952	530762.5	4364656.4	991,908	Horizontal
4701705962	536325.1	4359751.2	1,651,698	Horizontal
4701706035	516074.7	4336146.8	752,808	Horizontal
4701706044	538020.0	4357771.0	1,606,365	Horizontal
4701706079	514765.0	4350019.0	1,651,378	Horizontal
4701706080	526642.1	4347416.4	1,350,465	Horizontal
4701706094	526337.0	4333717.0	1,432,479	Horizontal
4701706096	526136.1	4339274.6	1,387,451	Horizontal
4701706097	526552.0	4339885.0	1,436,737	Horizontal
4701706102	526291.0	4334212.0	1,688,182	Horizontal
4701706112	517356.3	4336961.0	1,234,555	Horizontal
4701706117	538004.0	4359554.0	1,606,992	Horizontal
4701706128	525878.0	4352107.0	1,707,172	Horizontal
4701706143	537280.9	4344033.0	2,039,541	Horizontal
4701706144	534644.0	4344273.0	1,744,531	Horizontal
4701706156	524675.0	4337851.0	1,083,948	Horizontal
4701706160	532017.0	4340070.0	1,014,526	Horizontal
4701706169	511885.0	4347572.0	1,843,716	Horizontal
4701706194	522094.0	4357628.0	2,164,136	Horizontal
4701706202	526488.0	4349927.0	1,192,735	Horizontal
4701706211	513047.0	4347263.0	2,228,600	Horizontal
4708506359	496641.5	4326373.4	16,735	Vertical
4708507738	499547.8	4329015.8	10,125	Vertical
4708509158	489768.4	4329488.9	23,895	Vertical
4708509195	506131.2	4357325.0	9,567	Vertical
4708509219	488671.8	4325928.8	12,202	Vertical

4708509224	489844.7	4325009.9	14,016	Vertical
4708509260	488847.8	4325188.2	13,231	Vertical
4708509261	497310.8	4348026.6	11,216	Vertical
4708509268	493623.9	4320285.7	14,787	Vertical
4708509269	495458.3	4319689.0	15,428	Vertical
4708509273	491049.8	4322916.3	19,821	Vertical
4708509293	504180.1	4326570.8	23,007	Vertical
4708509325	484432.6	4330527.6	26,379	Vertical
4708509326	484584.4	4334314.2	15,894	Vertical
4708509327	488586.0	4333760.3	19,706	Vertical
4708509330	490652.1	4327926.8	23,725	Vertical
4708509335	492262.1	4328649.3	11,786	Vertical
4708509337	505697.0	4357051.1	14,616	Vertical
4708509342	489236.7	4328845.9	18,526	Vertical
4708509348	475358.4	4334997.5	7,426	Vertical
4708509352	492066.7	4326138.9	16,454	Vertical
4708509359	487204.8	4324096.3	8,159	Vertical
4708509365	487091.0	4323308.0	5,102	Vertical
4708509373	488179.8	4322603.3	19,226	Vertical
4708509375	493692.8	4330193.0	27,421	Vertical
4708509382	505241.7	4327215.2	6,682	Vertical
4708509393	500672.0	4328806.6	33,527	Vertical
4708509398	482072.7	4324943.1	13,203	Vertical
4708509402	513637.4	4328207.2	3,606	Vertical
4708509413	491499.8	4322223.8	14,833	Vertical
4708509431	492096.7	4323768.1	13,542	Vertical
4708509445	495817.7	4331323.2	18,798	Vertical
4708509449	490759.1	4319891.0	14,818	Vertical
4708509476	490581.4	4321077.2	20,602	Vertical
4708509479	494403.9	4336543.3	33,306	Vertical
4708509482	485160.0	4323520.5	11,494	Vertical
4708509487	492602.8	4331663.4	22,494	Vertical
4708509505	488272.9	432846.0	18,923	Vertical
4708509509	481302.0	4332470.6	24,124	Vertical
4708509525	480542.5	4331136.6	13,571	Vertical
4708509530	489316.1	4327687.1	9,399	Vertical
4708509531	490024.3	4328472.9	21,862	Vertical
4708509536	493947.6	4324217.2	17,538	Vertical
4708509537	476357.9	4329807.3	8,734	Vertical

4708509538	481437.5	4342394.0	18,069	Vertical
4708509539	483821.5	4339502.9	22,067	Vertical
4708509540	479218.2	4336085.8	14,575	Vertical
4708509541	486241.9	4326114.6	26,101	Vertical
4708509549	485792.9	4338887.6	19,532	Vertical
4708509550	480548.6	4333775.9	17,061	Vertical
4708509551	482767.2	4326282.3	13,891	Vertical
4708509572	482360.4	4332645.2	20,204	Vertical
4708509583	484366.4	4329513.8	18,069	Vertical
4708509587	478089.4	4333219.1	6,231	Vertical
4708509589	479308.0	4333167.5	14,474	Vertical
4708509602	492076.9	4319756.0	9,670	Vertical
4708509610	493528.9	4323750.8	20,548	Vertical
4708509622	484817.3	4338406.6	18,689	Vertical
4708509624	483603.1	4325760.6	8,624	Vertical
4708509626	487607.8	4336293.5	14,793	Vertical
4708509628	487721.9	4337291.1	9,319	Vertical
4708509634	485495.1	4339451.4	17,340	Vertical
4708509636	498684.2	4352811.2	26,762	Vertical
4708509654	502064.1	4346256.2	46,028	Vertical
4708509655	482945.7	4335819.3	17,593	Vertical
4708509671	495531.7	4339294.6	9,074	Vertical
4708509676	495644.0	4338522.0	10,596	Vertical
4708509681	503280.4	4326151.9	17,359	Vertical
4708509689	507998.2	4322786.9	13,404	Vertical
4708509691	495030.9	4335169.9	17,611	Vertical
4708509694	485997.2	4335362.7	16,838	Vertical
4708509699	507337.6	4323301.3	19,575	Vertical
4708509700	494591.8	4343174.2	21,006	Vertical
4708509707	494728.3	4342180.8	23,123	Vertical
4708509721	491472.9	4345487.9	10,700	Vertical
4708509729	486284.3	4333458.2	19,391	Vertical
4708509730	483452.1	4331178.3	17,686	Vertical
4708509732	477921.0	4330527.0	9,180	Vertical
4708509733	479294.0	4334302.2	6,538	Vertical
4708509734	485017.5	4337181.7	12,581	Vertical
4708509746	482947.4	4328211.9	17,011	Vertical
4708509758	497017.4	4323066.3	27,404	Vertical
4708509768	484795.6	4331515.1	44,253	Vertical

4708509777	494747.5	4326567.5	22,030	Vertical
4708509821	497842.6	4325984.5	8,537	Vertical
4708509910	494736.0	4330173.0	12,370	Vertical
4708509916	495585.2	4331990.1	18,772	Vertical
4708509917	92884.3	4337143.0	7,230	Vertical
4708509918	482098.8	4328226.7	139,119	Horizontal
4708509930	504185.0	4345860.0	2,259,393	Horizontal
4708509951	505242.0	4344702.8	1,133,849	Horizontal
4708509960	509994.0	4338479.0	1,053,042	Horizontal
4708509970	509484.0	4337989.0	2,114,693	Horizontal
4708509978	506044.0	4336870.0	698,274	Horizontal