Analysis of Appalachia’s Utica/Point Pleasant and Marcellus Formations’ Geology on Estimated Ultimate Recovery

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Abstract:
The purpose of this study was to identify the optimum horizontal wellbore azimuths in the Ordovician Utica/Point Pleasant Formation and Devonian Marcellus Formation unconventional petroleum plays in three locations in Ohio, Pennsylvania, and West Virginia, from data contributed by Knobloch Petroleum of Marietta, Ohio. The assumption was that the stress state in the crust determined both the orientations of natural hydraulic fractures formed during the Pennsylvanian Alleghanian orogeny would control the orientation of the fractures formed during present day hydraulic fracturing of horizontal wells. Therefore, the orientation of the horizontal wellbores with respect to fracture orientations would affect the estimated ultimate recovery of petroleum. Multivariable regression analyses, with estimated ultimate recovery as the dependent variable and amount of water used during hydraulic fracturing, amount of sand used as a fracture proppant, and the horizontal wellbore azimuth as the independent variables, were run using data from 1400 wells.

A brief overview of the geology of the Appalachian basin, the basin in which both the Utica/Point Pleasant and Marcellus formations were deposited, along with an explanation of the conditions under which natural hydraulic fracturing occurs were included in the study.

The study concluded that the amount of water used during hydraulic fracturing in Ohio has the largest effect on the estimated ultimate recovery and the amount of sand used as a fracture proppant in Pennsylvania and West Virginia a numerically large effect on the estimated ultimate recovery, whereas the orientation (azimuth) of the wellbore appears to have an insignificant effect.
Objective Statement:

The purpose of this study was to identify the optimum horizontal wellbore azimuths in the Ordovician Utica/Point Pleasant Formation and Devonian Marcellus Formation unconventional petroleum plays in three locations in Ohio, Pennsylvania, and West Virginia, from data contributed by Knobloch Petroleum of Marietta, Ohio. The assumption was that the stress state in the crust determined both the orientations of natural hydraulic fractures formed during the Pennsylvanian Alleghanian orogeny and the orientation of the fractures formed during present-day hydraulic fracturing of horizontal wells. Therefore, the orientation of the horizontal wellbores with respect to fracture orientations would affect the estimated ultimate recovery of petroleum. Multivariable regression analyses, with estimated ultimate recovery as the dependent variable and amount of water used during hydraulic fracturing, amount of sand used as a fracture proppant, and the horizontal wellbore azimuth as the independent variables, were run using data from 1400 wells.

Introduction:

This research paper is organized as follows: the first section is a geologic background about the Appalachian basin and the two formations of interest with respect to current unconventional horizontal petroleum plays. The second section is a petroleum engineering case study of unconventional horizontal petroleum well data obtained from Knobloch Petroleum of Marietta, Ohio for locations in Ohio, Pennsylvania, and West Virginia.

Geological Background:

The two geologic units investigated in this study are the Ordovician Utica/Point Pleasant Formation and the Devonian Marcellus Formation, both of which were deposited in the Appalachian Basin. The following is a section describing the history of the basin with respect to
the two formations of interest, and the pertinent tectonic events that resulted in the natural hydraulic fracturing of the rocks of the basin.

The Appalachian Basin began forming 500 million years ago (mya) (Dutton, 2017). During this time, the continent of Laurentia straddled the equator, and was inundated by a tropical shallow sea, Figure 1 (Dutton, 2017). Much of the sediments deposited at this time were limestones (Dutton, 2017). A change in plate motion occurred about 440 to 480 mya, which caused the first Paleozoic mountains to form (Dutton, 2017). This mountain building event, or orogeny, was called the Taconic Orogeny. Convergent plate motion occurred as the lapetus plate collided with Laurentia, causing an uplift which resulted in the deposition of black shales (Dutton, 2017). These shales are known as the Utica Formation.
Figure 1: Laurentia during the Middle Ordovician Period (Blakey, 2019)
The Marcellus Formation was deposited approximately 380 million years ago in the Devonian Period, Figure 2 (Engelder & Lash, 2008). At this time, the Earth was divided into two separate continents: Gondwana and Laurentia (Hupp & Donovan, 2018). As Gondwana began colliding with Laurentia, a collision zone was created which caused the crust to thicken, forming an uplift at the colliding edge of the two continents (Engelder & Lash, 2008). This event was called the Acadian Orogeny, occurring around 315 million years ago (Engelder & Lash, 2008).

As shown in Figure 2, most of what is now the Appalachian Basin was covered in marine water. During the Taconic orogeny, the extreme force of this event caused the Appalachian Basin seabed to rapidly subside as the continental margin to bent, similar to water rippling (Engelder & Lash, 2008). Organic-rich sediments were deposited in deep water as the collision continued. Thrust loading caused a cutoff of the river system into the sea which created a calm environment for accompanying black shales to be deposited (Engelder & Lash, 2008). Once rivers eroded channels back into the sea, clastic sediments were brought into the environment which subsequently formed grey shales (Engelder & Lash, 2008). For a period of 20 million years, at least eight depositions of black and grey shales happened from this thrust loading cycle (Engelder & Lash, 2008).
The Utica Formation is an Ordovician age, organic rich shale that can be found throughout much of the Appalachian Basin (King, 2019). This formation is known for its large amounts of natural gas and oil (King, 2019). A western facies of the Utica Formation is the Point Pleasant Formation which consists of the interbedded black shales and limestones which overlie
the Lexington/Trenton Formation. The Point Pleasant Formation is located in parts of Ohio, Kentucky, Pennsylvania, and West Virginia and is comprised of shales, fossiliferous limestones, and siltstones (West Virginia University 2015).

Figure 3 shows the thickness and areal extent of the Point Pleasant Formation throughout the Appalachian Basin. The formation thickness ranges between 30 to 210 feet, the thickest in Pennsylvania and thinning towards southeastern Ohio and Kentucky. Figure 4 shows the structure of the Point Pleasant Formation throughout the Appalachian Basin. This formation is as deep as 13,000 feet in southwestern Pennsylvania and shallows in Ohio, Kentucky, and West Virginia. Figure 5 shows the stratigraphic column of the Utica/Point Pleasant Formations.
Figure 3: Isopach map of the Point Pleasant Formation, showing its areal distinction (EIA, 2017)
Figure 4: Structural Map of the Point Pleasant Formation (EIA, 2017)
Figure 5: Stratigraphic Column of the Utica/Point Pleasant Formations (West Virginia University, 2015)
The Devonian Marcellus Formation is an organic rich shale that extends from the northern part of New York to northeastern Kentucky and Tennessee, Figure 6 (EIA, 2017). The formation is a carbonaceous and silty shale that contains small amounts of pyrite, scarce fossils, and carbonate concretions (EIA, 2017). The formation is very important to the petroleum industry as it is currently one of the largest gas plays in the United States, containing oil reserves of 143 million barrels and gas reserves of 77.2 trillion cubic feet of natural gas (EIA, 2017).

Figure 6 shows the structure map of the Marcellus Formation. The depth of the formation decreases gradually from southeast to northwest along with an outcrop formed by an uplift along the Appalachian Mountains (EIA, 2017). The deepest part of the formation can be found throughout the state of Pennsylvania and is approximately 6000 feet. Oil reserves are found in this formation at subsea depths from 1,000 to 5,000 feet, and natural gas is found at subsea depths of 3,000 to 6,500 feet (EIA, 2017).

Figure 7 shows the Isopach map of the Marcellus Formation which illustrates the thickness of the formation, which ranges from 0 to 950 feet. There is a general decrease in the thickness of the formation westward and northwestward (EIA, 2017). The thickest part of the Marcellus Formation can be found in south-central New York state where it is 900 feet thick, then generally decreases moving towards the south and the east of the Appalachian Basin (EIA, 2017).
Figure 6: Structural Map of the Marcellus Formation (EIA, 2017)
Figure 7: Isopach Map of the Marcellus Formation (EIA, 2017)
Figure 8: Stratigraphic Map of the Marcellus Formation (Milici & Swezey, 2006)
Natural hydraulic fracturing of the organic-rich Appalachian Basin rocks

Oil and gas within the black shales was generated approximately 300 million years ago from organic matter (Engelder & Lash, 2008). In organic-rich rocks, solid kerogen organic matter converts to liquid crude oil during catagenesis. This increases the amount of fluid, while porosity remains constant; therefore, pore fluid pressures increase, resulting in natural hydraulic microfractures. Fracturing continues as more kerogen converts from solid to liquid crude oil, eventually forming macroscopic joints (Engelder & Lash, 2008).

During the Alleghanian Orogeny, a stress field was created over the continent as Gondwana was sliding past Laurentia (Engelder & Lash, 2008). The maximum horizontal stress, which controlled the joints of the Appalachian Basin, was approximately N 60° E (Engelder & Lash, 2008). Around 290 mya (Figure 9), Gondwana and Laurentia were locked in place by a continental promontory which caused the continents to begin pivoting and continued to pivot for 15 million years (Engelder & Lash, 2008). This event created fold-thrust belts of Central and Southern Appalachian Mountains, changing the intracontinental stress and forming the first set of joints, J₁ (Engelder & Lash, 2008). The second set of joints, J₂, oriented N 60° W, formed in the grey shales overlaying the Marcellus Formation cutting into J₁ as Gondwana was pivoting clockwise into Laurentia (Engelder & Lash, 2008). These two stress states are nearly perpendicular; therefore, these two joint sets are nearly perpendicular. The two phases of jointing are separated by about 25 million years should be seen not just in the Devonian rocks but also older rocks such as the Utica/Point Pleasant.
Figure 9: The Laurentia/Gondwana collision in the Permian Period (Blakey, 2019).
Case Study:

In the Marcellus and Utica/Point Pleasant formations, it is common practice to drill in the direction of Northwest to Southeast. Is this practice because of the natural fracture system or the existing acreage left from previous acreage dealings? It is common practice to inject more proppant to receive more hydrocarbons, based on the data, how true is that practice?

The goals of this study are:

1) Identify the potential economic or numerical impact wellbore azimuth has on a well’s estimated ultimate recovery (EUR) in Appalachia.

2) Determine the optimum wellbore azimuth range in Belmont County, Ohio, Wetzel County, West Virginia, and Susquehanna County, Pennsylvania?

3) Evaluate the most important variable in a well’s EUR. A) Water used in hydraulic fracturing, B) sand measured in pounds, and C) wellbore azimuth measured in degrees? What is the significance of the most important variable in completions in both conventional and unconventional reservoirs?

Wellbore azimuth is the compass direction of a wellbore. Wellbore azimuth is defined in the drilling survey and is in units of degrees of 0° to 360°. The figure below represents a general example and is a good visual representation of the optimum fracture plane. The optimum fracture plane is one oriented perpendicular to the wellbore azimuth. When modelling the wellbore before drilling, it is important to know the orientation of the optimum fracture plane.
Figure 10: The 10° to 15 degree zone that will produce the optimum fracture design (No copyright found)

The optimum direction to drill a horizontal well is to drill parallel to the minimum horizontal stress and perpendicular to the maximum horizontal stress. This is because an induced fracture network opens in the direction of the minimum horizontal stress, yielding the greatest number of natural fracture intersections, draining the highest volume of fractured reservoir, that resulting in a larger production. However, drilling in this direction does tend to be associated with higher cost in drilling as wellbores require a mud with a higher density to prevent wellbore collapses (Rahim, 2011).
Figure 11: Longitudinal Lateral vs. Transverse Lateral. A longitudinal fracture system occurs when the wellbore azimuth is parallel to the maximum horizontal stress of the reservoir and a transverse fracture system occurs when the wellbore azimuth is parallel to the minimum horizontal stress (Rahim, 2012).

Figure 11 illustrates that drilling parallel to the minimum horizontal stress will create a transverse fracture system and have the most surface area in contact with the reservoir, while drilling perpendicular to that same stress will create a longitudinal fracture system. A transverse system occurs when the wellbore azimuth is perpendicular to the fractures and the maximum horizontal stress. This system type is ideal because the contacted reservoir is much greater, allowing for a larger estimated ultimate recovery (EUR) and initial production (IP). Alternatively, a completion that yields the longitudinal fracture system will have a very small
bilateral wing length. A wells bilateral wing length is the length the fracture system reaches out on each side of the reservoir, measured in units of length.

Figure 12: Mohr-Coulomb failure space. (No Copyright found)

Figure 12 illustrates Mohr/Coulomb failure criterion. The y-axis is shear stress ($\tau$) and the x-axis is normal stress ($\sigma_n$). Left of the y-axis is tension; right of the y-axis is compression. $\sigma_3$ is minimum normal stress acting on a plane and $\sigma_1$ is the maximum normal stress acting on a plane. While $\sigma_2$ is not plotted, it still plays an important role in determining the ductility of the rock formation. If $\sigma_2$ is closer to $\sigma_3$ the formation will act more brittle while the opposite is true if $\sigma_2$ is closer to $\sigma_1$. The R is the radius and is defined by the two plotted principal stresses, $\sigma_1$ and $\sigma_3$. c, noted by the blue dot on the y-axis intercept, is the cohesive shear strength of the material. For a cohesive material, $\Phi$, the angle of internal friction, is simply the slope of the Mohr envelope for intact material (Bartlett, Marietta College). The coefficient of internal friction defines the friction shear resistance of rock and is a physical property of the material. The angle is inversely
proportional to the resistance. With Mohr’s circle, the failure state of the respective formation can be predicted at any stress state. For many sedimentary rocks under reasonable confining pressures of the shallow lithosphere (<100 MPa), the value of $\Phi$ varies between 28° and 40° and thus the angle of R counter clockwise to the x-axis is between 42° and 62° (Bartlett, Marietta College). Mohr envelope can be defined mathematically using:

$$|\tau_f| = \tau_o + \sigma \tan \Phi$$

$\tau_f$ - Shear Stress
$\tau_o$ - Apparent Cohesion
$\sigma$ - Normal Stress
$\Phi$ - Internal Angle of Friction

Figure 13: Mohr-Coulomb Failure Space with changing pore pressure
On Mohr’s Circle, the failure criterion (sloped line) is static and the rock stresses move with changes in pore pressure. When the rock stress semi-circle touches the envelope, the rock will undergo shear fracturing. Mohr’s circle is significant when defining the required hydraulic fracturing treatment pressure. The distance the semi-circle needs to move to become tangent to the failure criterion is the theoretical treatment pressure. In reference to figure 13, the treating pressure would equal to the measured horizontal move of the dotted lines from right to left, as formation pore pressure increases, the rock comes closer to fracturing. That horizontal movement is typically measured in units of mega pascals (MPa) which can be converted into field units (psi), (1 MPa = 145.038 psi).

The data was contributed by Knobloch Petroleum, Consultants in Marietta, OH. The data is real production data that is from Marcellus and Utica/Point Pleasant wells in Wetzel County, West Virginia (WV), Susquehanna County, Pennsylvania (PA), and Belmont County, Ohio (OH). This study uses only horizontal natural gas wells for EUR unit consistency, but the findings can still apply to vertical wells.
Figure 14: Birdseye view of well in Marcellus Wetzel County, WV. Yellow ellipse has a 5-mile radius (Knobloch Petroleum, 2018)

Color Key

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Figure 14 is of the Wetzel County assets in West Virginia. The data was organized so that only the red, or producing, wells were used in the study. The study is limited to 5-mile
radius to minimize the effect of geology in the wellbore azimuth vs. EUR plot. Also, these elliptical zones within the counties were selected because they had wells with wellbore azimuth variability that would give the best range to analyze.

In this study, multiple variables versus EUR were observed. First, water vs. EUR and sand vs EUR were plotted as separate variables. Next, the smaller data set of 150 wells was plotted/analyzed the relationship between wellbore azimuth and EUR. Finally, a multi-variable regression was run measuring all three of the variables (water injected, sand, and wellbore azimuth) simultaneously compared to EUR with the larger data set of roughly 2000 wells. The analyzed data was separated into the three states to see if there were any trends that could be seen between them. The purpose of the multi-variable regression is to see the magnitude of the affect each variable has on EUR in comparison to the other variables constant. With this, it can be seen which of the three variables has the greatest impact on EUR. This relationship is seen in the p-values of the regression, compared to the other variables’ p-values the highest value has the lowest impact on EUR. P-value is the probability value which numerically defines the chance of success of the null hypothesis, or the variable that trying to be disproved.

The assumptions made for this case study include:

- The EUR values used were calculated based on the owner’s method of running reserves. Each company will have a different method of running reserves with differing recovery factors. So, there is variability that could not be accounted for in the EUR calculations.
- Each well has a different completion design. The study could not include variables such as chemical design or treatment pressure which could have a profound effect on the EUR of a well.
- Proppants were generalized as sand. Did not consider other forms of proppant.
Figure 15: EUR vs. Sand including trendline and slope of data trend
Figure 16: EUR vs. Water including trendline and slope of data trend.
The first step taken was to verify the validity of the data by plotting the data. The variables were separated to check the viability of the data by observing the trendline of the plotted data of the 2000 wells. The linear relationship between water/sand vs. EUR should have a positive slope. If it did not have a reasonable slope, the next step would be ensuring there was no major outlier points and if there were, removing those associated wells. If this study were to be replicated, a way to improve the methodology would be to separate the three states out. The resultant graph of this study indicates a lot of variability from the trendline, in other words, a low $R^2$ value. This does not mean the data is wrong, it means that the data was all combined and not separated out. In each state and formation, a unique hydraulic fracturing design is required and will yield a unique production. A high EUR in Pennsylvania may be a great EUR in West Virginia.

Wellbore azimuth vs. EUR was plotted for 150 well(Figure 7,8,9). Below are the graphs of the Ohio, West Virginia and Pennsylvania areas:
Figure 17: Belmont County EUR vs. Azimuth, Circled zone with the highest EUR averages
Figure 18: Susquehanna County EUR vs. Azimuth. Circled zone with the highest EUR averages across...
Figure 19: Wetzel County EUR vs. Azimuth, Circled zone with the highest EUR averages across spread
As shown by figures 17, 18, and 19, the circled areas have higher averages. This indicates that these are the zones with the historically highest chance of success because of the stresses and their respective directions. These zones are: Belmont (149-154 degrees), Susquehanna (150-155 degrees), Wetzel (163-168 degrees). These values should be in rough alignment with each other with some reasonable variation in the geology that accounts for the slight differences. The Utica and Marcellus were created under the same conditions so the two formations, while separated by about 3000 feet, have a very similar natural jointing system so the wellbore azimuth plane should very similar. However, these are just trends based on a small sample size of data thus the results are not conclusive. If a larger sample size was used and a similar result was found, conclusions might then be drawn of an “optimum” wellbore azimuth for each of the respective counties. For that to happen, a method to normalize or reduce the impact of other major variables including water and sand used, geology, etc. would be required to measure the success or failure of a well based on wellbore azimuth.

Finally, a multi-variable regression was run comparing the independent variables (wellbore azimuth, water used, and sand used) to the dependent variable (EUR). The goal was to find the most impactful variable of the three variables. The entire data set was used consisting of roughly 2000 wells around OH, WV, and PA. A linear regression is a form of data analysis that takes multiple independent variables and compares those variables to a single dependent variable. The regression will have multiple layers over comparing p-values which is based on the impact a particular independent variable has on the dependent variable. Once a layer has been analyzed, the p-value with the highest value can be removed from the next layer of analysis as a rejected variable that was not as impactful as the other independent variables. This process is repeated until all the variables have been removed and the last layer is left with a single
independent variable that stands out as the variable with the lowest p-value and the largest proportional relationship to the dependent variable. Below are the findings that show the relationship between the independent and dependent variables.

\[ Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \]

\( X_1 = \text{Water} \)
\( X_2 = \text{Sand} \)
\( X_3 = \text{Wellbore Azimuth} \)

Ohio: \( \hat{Y} = 1.181632 + 3.8 \times 10^{-8} X_1 \) (p-value = \( 0.0168 \times 10^{-38} \))

West Virginia: \( \hat{Y} = 1.31388 - 3.4 \times 10^{-8} X_1 + 4.11 \times 10^{-8} X_2 \) (p-value = \( 3.18 \times 10^{-83} \))

Pennsylvania: \( \hat{Y} = 3.143976 - 2.8 \times 10^{-7} X_1 + 3.23 \times 10^{-7} X_2 \) (p-value = \( 3.73 \times 10^{-57} \))

It is noteworthy that the West Virginia and Pennsylvania equations have two variables while the Ohio equation has one. These equations show only variables that have a p-value less than .05. That means that the equations only display variables that show strong evidence against the null hypothesis. In the Ohio equation, only \( X_1 \) is represented which means that sand and wellbore azimuth have been rejected as variables that did not impact the EUR largely enough to not be rejected. In all the cases wellbore azimuth was rejected as a variable that is not significantly impacting production compared to the other two independent variables. With this, wellbore azimuth can be removed from the analysis in all of the areas.
Further analysis of the regression:

**Belmont County, Ohio** $n = 543$

$X_1$: P-value = .016686  
$X_2$: P-value = .139349

**Wetzel, West Virginia** $n = 378$

$X_1$: P-value = .010835  
$X_2$: P-value = .001479

**Susquehanna, Pennsylvania** $n = 510$

$X_1$: P-value = 2.09E-8  
$X_2$: P-value = 1.27E-6

First, the n-values indicate the sample size. The lowest sample size is 378 wells which is well above the normal distribution threshold, so the sample size is large enough for a reliable analysis. Next, analyzing the p-values, the variable with the highest p-value will be rejected as not as impactful as the other variable. Analyzing the results for Ohio, the $X_1$ (water) p-value is smaller which indicates that water is more important in Belmont County, Ohio. Next, in West Virginia, the $X_2$ p-value is smaller. However, because both values are less than .05, the conclusion can be made that both variables are linearly related to EUR. Finally, in Susquehanna, PA the result is like that of West Virginia. In Pennsylvania, both variables are well below the .05 mark which means both have large impacts on EUR. This similarity is not surprising considering both Pennsylvania and West Virginia are producing out of the same formation with the average sample height having a negligible difference of about 100 ft. A hypothesis of the difference between the Ohio Utica/Point Pleasant and the West Virginia/Pennsylvania Marcellus is related to the sizeable difference in depth of the measured wells. The average sample depth of the Marcellus is roughly 7,000 ft and the average sample depth of the Utica/Point Pleasant is
9,300 ft. That means that for the Utica/Point Pleasant formation, the treatment pressure that is required to reach formation failure is much higher than the pressure of the Marcellus wells. What that means for future completions in the Utica/Point Pleasant is to apply a higher water to sand monetary ratio. More simply put, the data indicates that the more water pumped downhole, the more lifetime production and so investing in a higher than average amount of water (gal) used would lead to a higher EUR than typically would, according to the data yields a larger EUR. Tying these results back to the Mohr’s Circle and failure envelope, the Utica/Point Pleasant requires a higher pore pressure to have a shear failure. That why the most important design variable is water. More water injected leads to a larger pore pressure.

What is the application of horizontal completion techniques to conventional vertical wells? According to the industry literature, multistage fracturing completions in verticals is still very applicable in an industry that is dominated by the unconventional. According to a comparison study done in the Sultanate of Oman by Petroleum Development Oman (PDO), the typical plug and perf completions methods are economically worse than that of multistage frac completions in vertical wells. This study consisted of a vertical well with seven separate stages. PDO ran a multistage fracturing completion on the well and ran economics for the same well using a plug and perf completion method; the values were compared, and the test findings are below:
While the actual job has a higher $/day rate, the total job bill will be cheaper as the time saved with the multistage frac completion outweighs the daily rate. Now, some fallacies in comparing this study to the applicability of vertical completions in the three Appalachian states is that the geology is not parallel so the results in Oman are not conclusive to the Appalachian Basin. Also, the economics in the United States will be completely different as the national economies are much different.
Works Cited:


